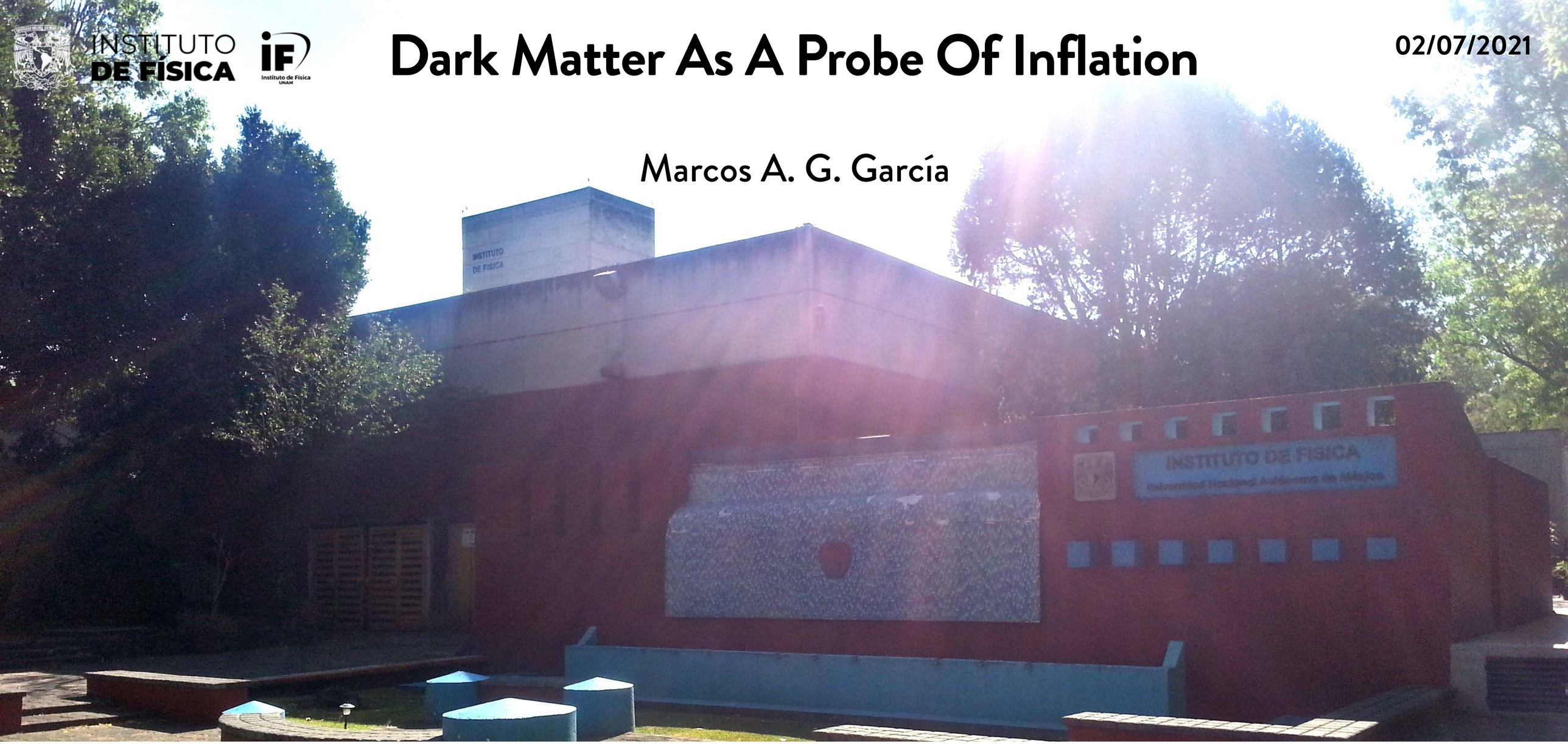
Dark Matter As A Probe Of Inflation

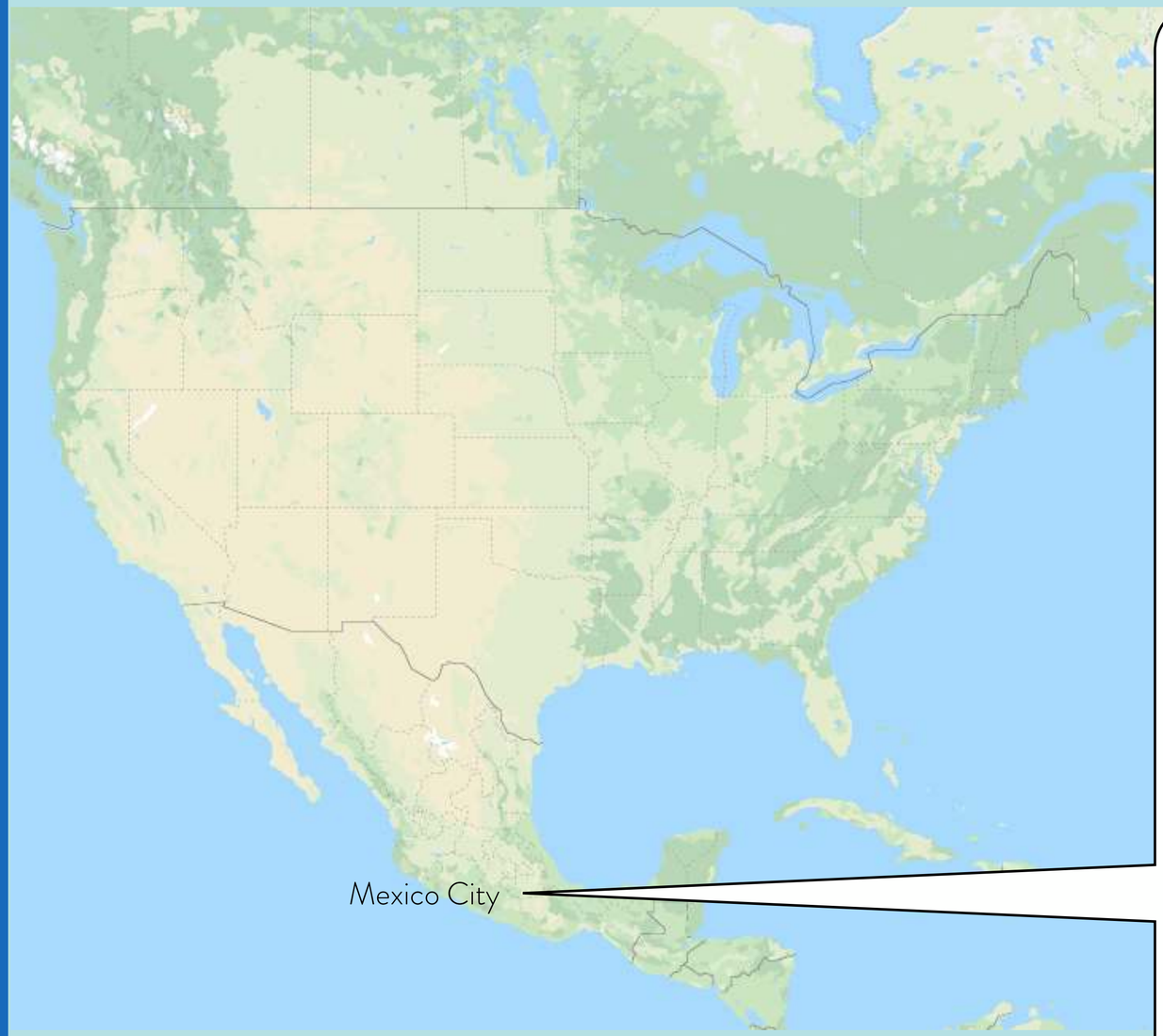
02/07/2021

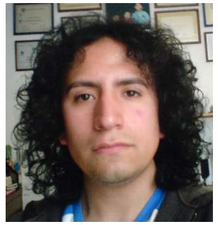
Marcos A. G. García



INSTITUTO DE FÍSICA
IF Instituto de Física UNAM
ift Instituto de Física Teórica UAM-CSIC
UAM Universidad Autónoma de Madrid
CSIC Consejo Superior de Investigaciones Científicas

About me

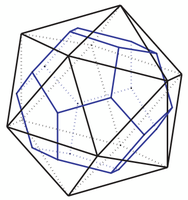


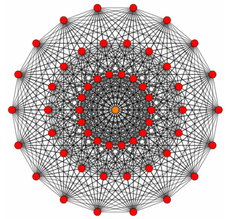


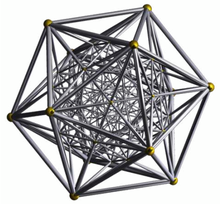
Licenciatura (Gabino Barreda), 2008
Maestría (Alfonso Caso), 2010
Doctorado (Alfonso Caso), 2011

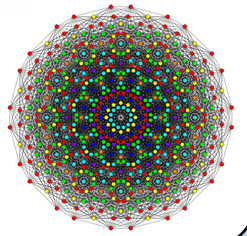
Thesis: *The H_3 and H_4 Integrable Systems*
(A. Turbiner, ICN)

Solvability of QM systems defined by crystallographic and non-crystallographic groups

H_3 

E_7 

H_4 

E_8 

About me

Minneapolis

Houston

Mexico City

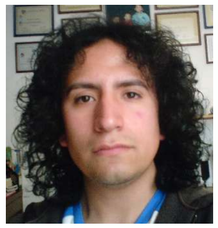
Ph.D. (High Energy Theory), 2016

Greiling Award (research)
TA Award (teaching)

Thesis: *No-Scale Inflation*
(K. Olive, FTPI)

Particle - Early Universe connection
(susy + inflation + baryogenesis)

(and a bit of Lorentz invariance violation)



PhD, math. phys.

About me

PhD, inflation, susy

Minneapolis

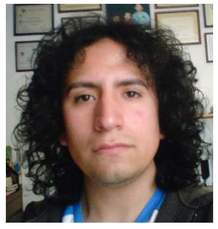
RICE

Postdoctoral Research Associate
(with M. Amin)

Inflation + GUT, dark matter,
disorder, gravitational waves, SNI

Houston

Mexico City



PhD, math. phys.

About me

PhD, inflation, susy

Minneapolis

Houston

Mexico City

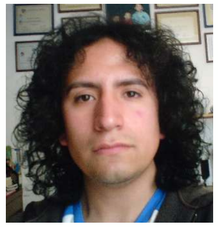
Madrid

RICE

Postdoc, CMB, GWs

UNIVERSIDAD NACIONAL AUTÓNOMA DE MÉXICO

POR MI RAZA HABLARÁ EL ESPÍRITU



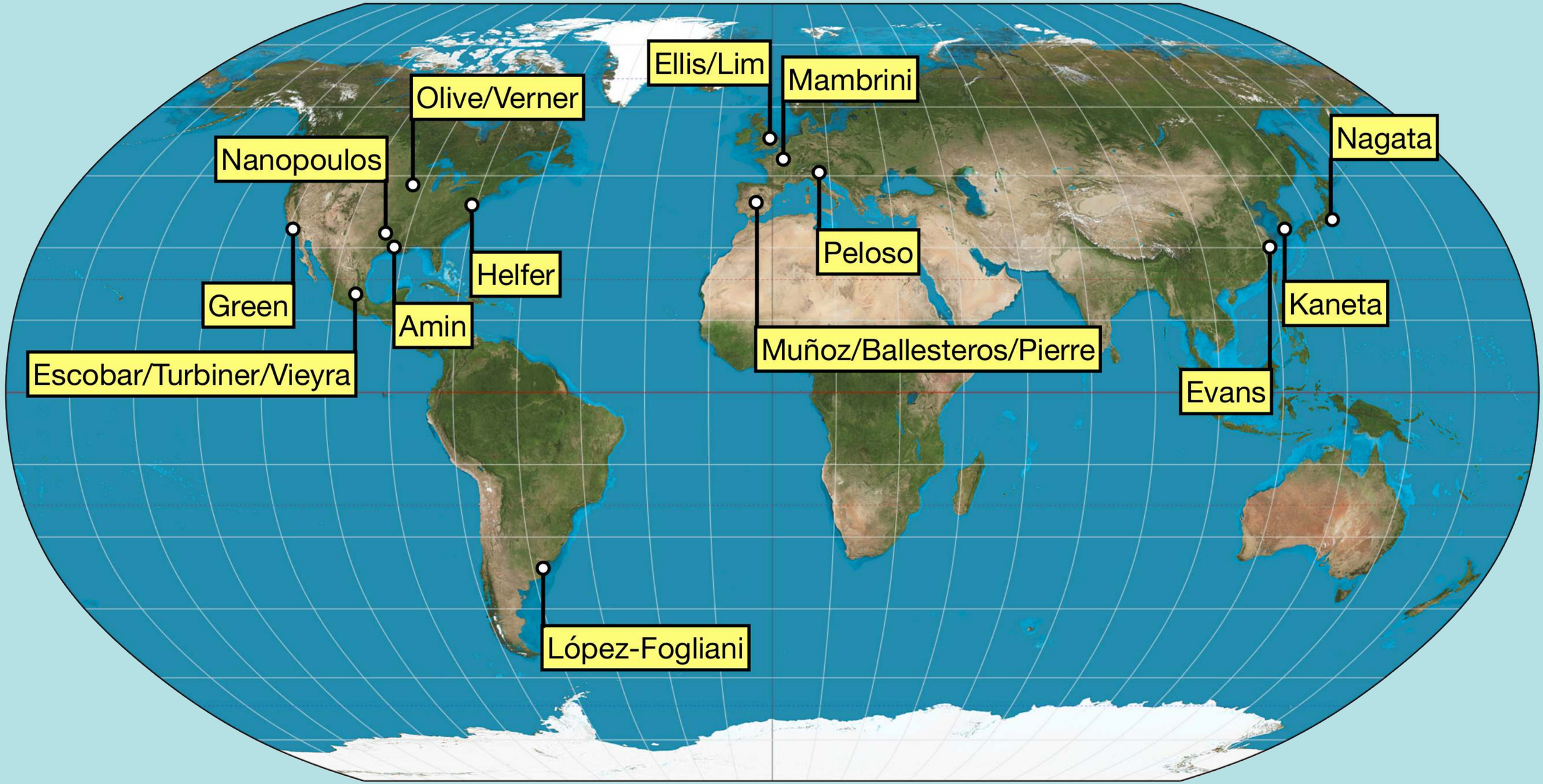
PhD, math. phys.

ift

Investigador Postdoctoral “Severo Ochoa”

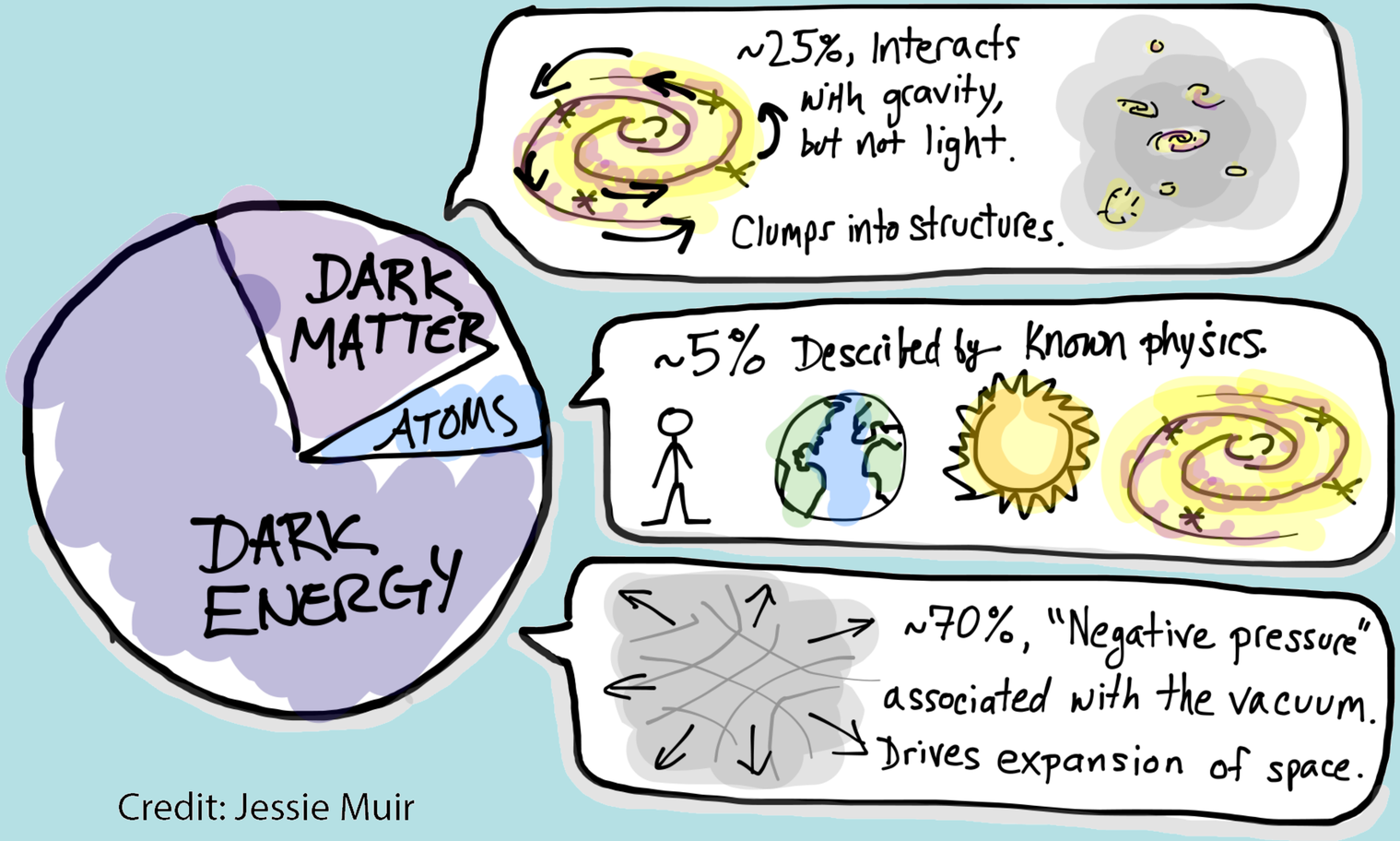
Reheating + Dark Matter, Beyond Boltzmann,
Primordial Black Holes (2 Master students)
2021 ISAPP DM Summer School

Main Collaborators



1. Beyond WIMPs
2. Inflation & reheating
3. FIMPs
4. Future prospects
5. Conclusion

Composition of the Universe



Credit: Jessie Muir

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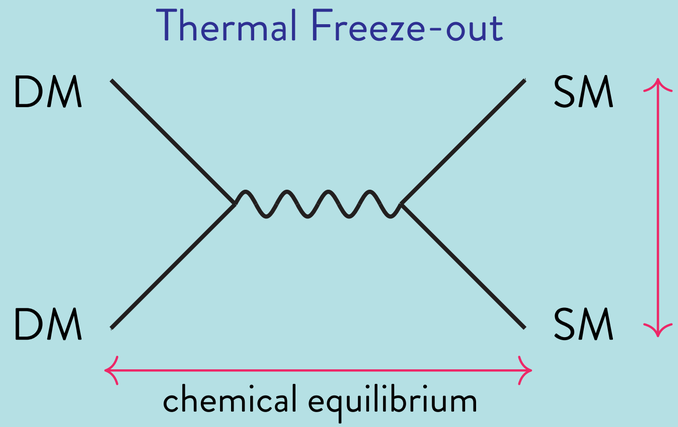
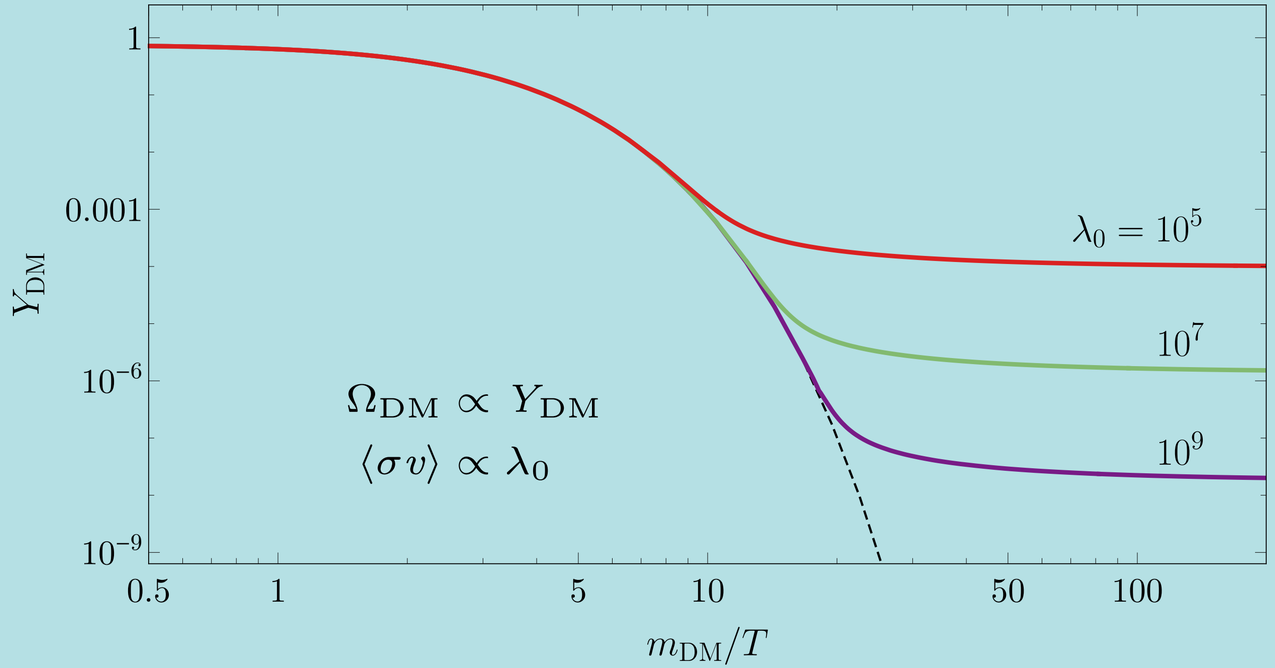
The many virtues of the WIMP





$$\Omega_{\rm DM} h^2 \equiv \frac{\rho_{\rm DM}}{\rho_{\rm tot}} h^2 \sim \frac{0.1\,{\rm pb}}{\langle \sigma v \rangle} \sim 0.1 \left(\frac{m_{\rm DM}}{100\,{\rm GeV}} \right)^2$$

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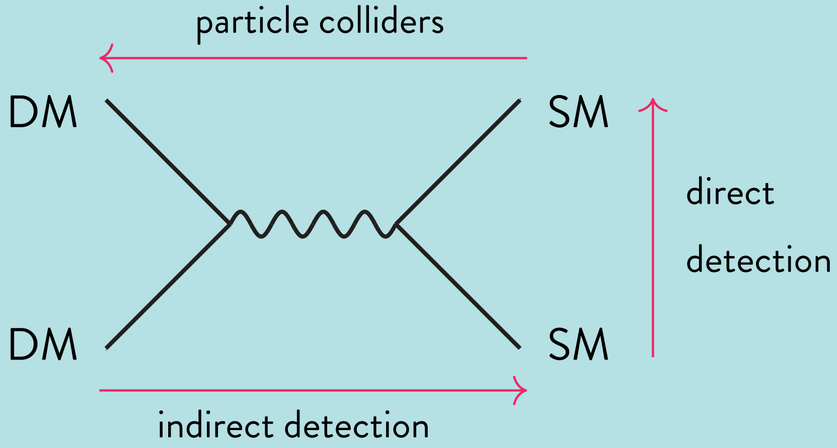
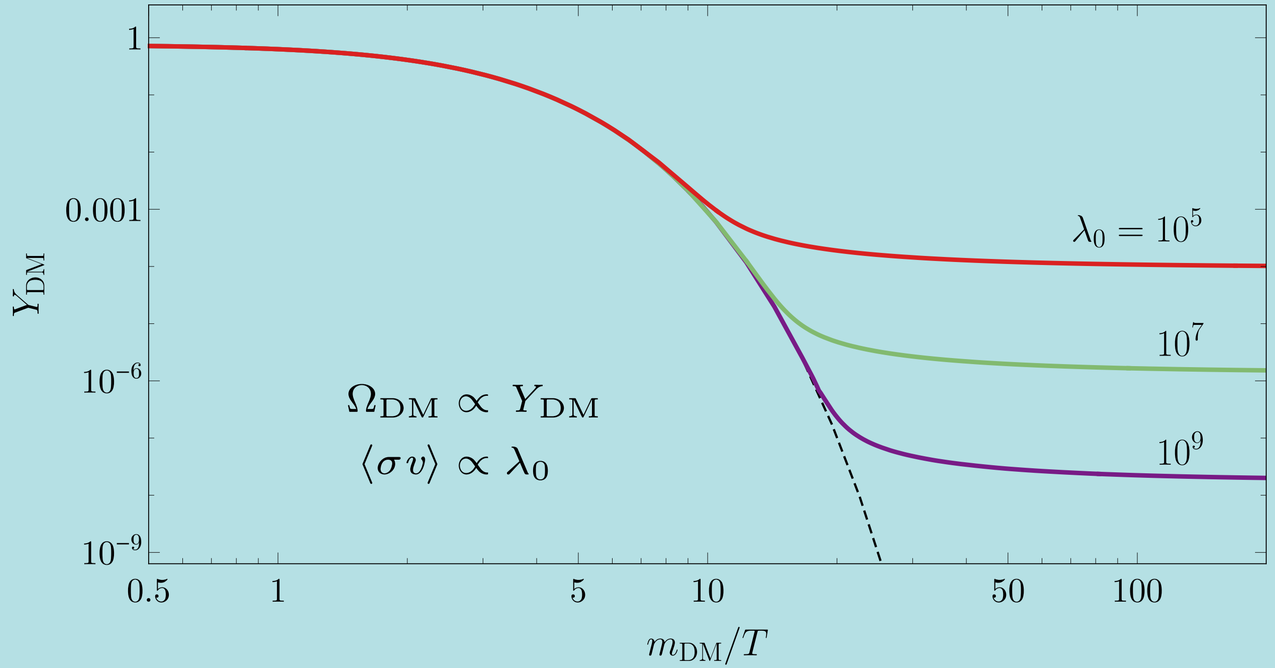
The many virtues of the WIMP





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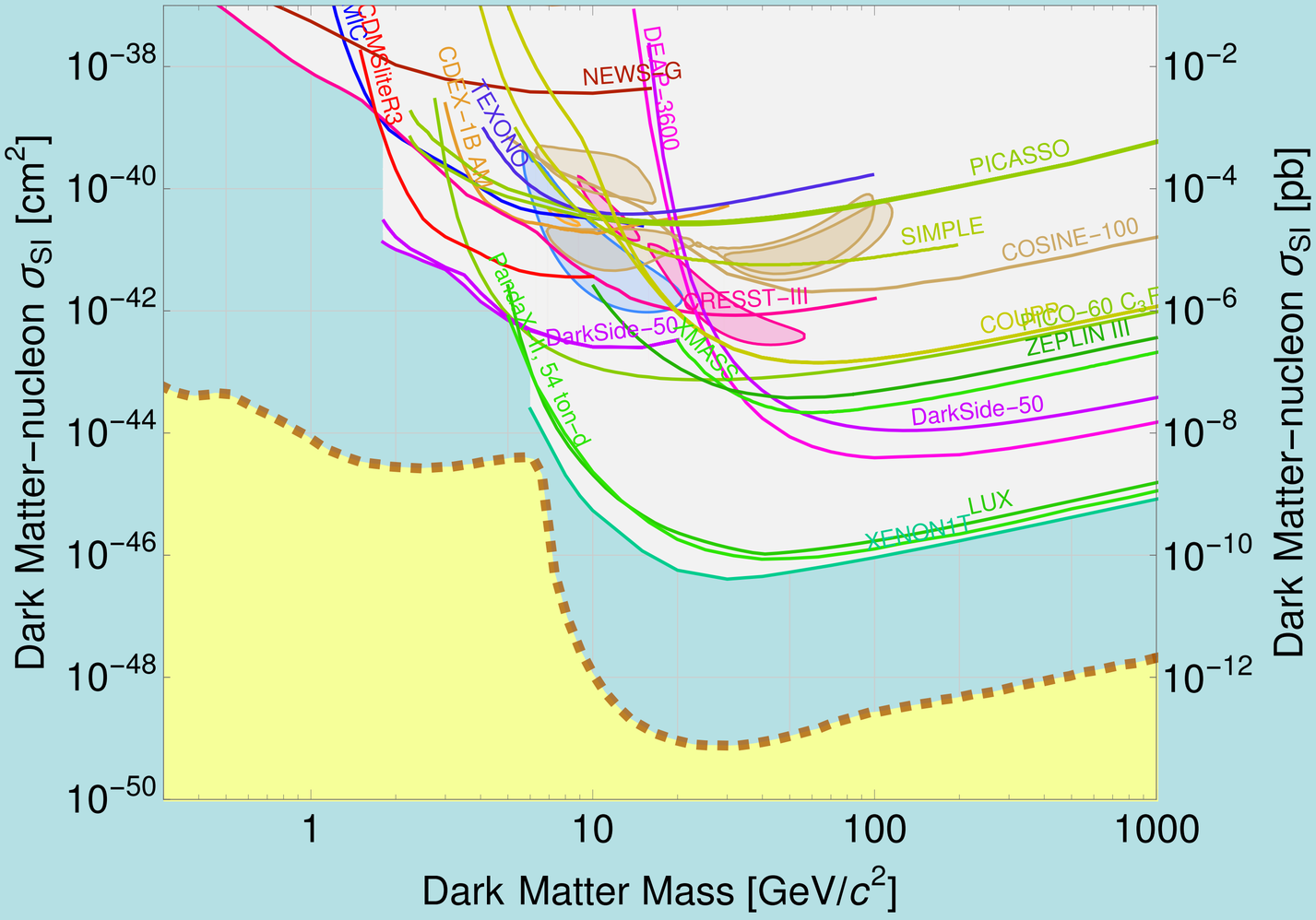
Where are the WIMPs?

Direct detection



SuperCDMS Dark Matter Limit Plotter

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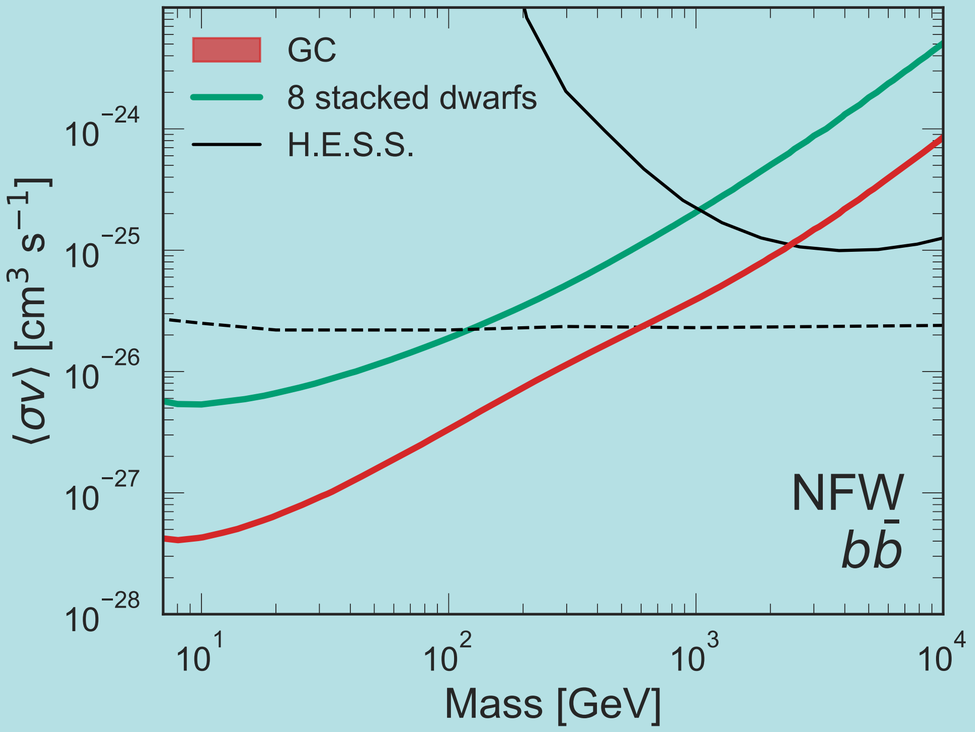
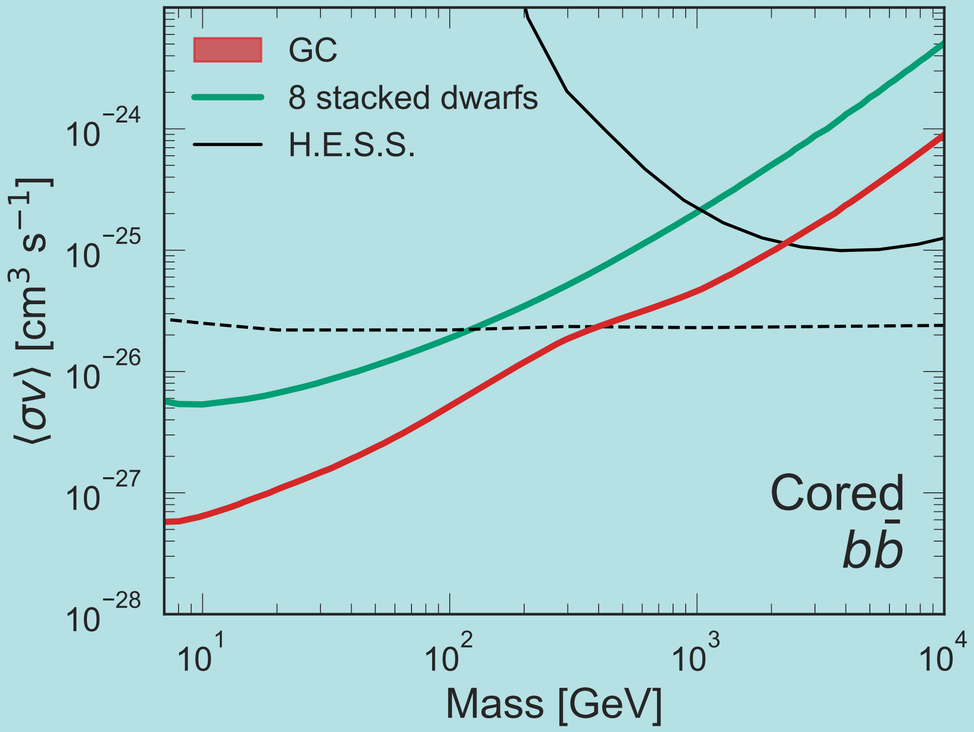
Where are the WIMPs?

DM annihilation in the Galactic Center





K. Abazajian et al., PRD 102 (2020), 043012 (Fermi-LAT)

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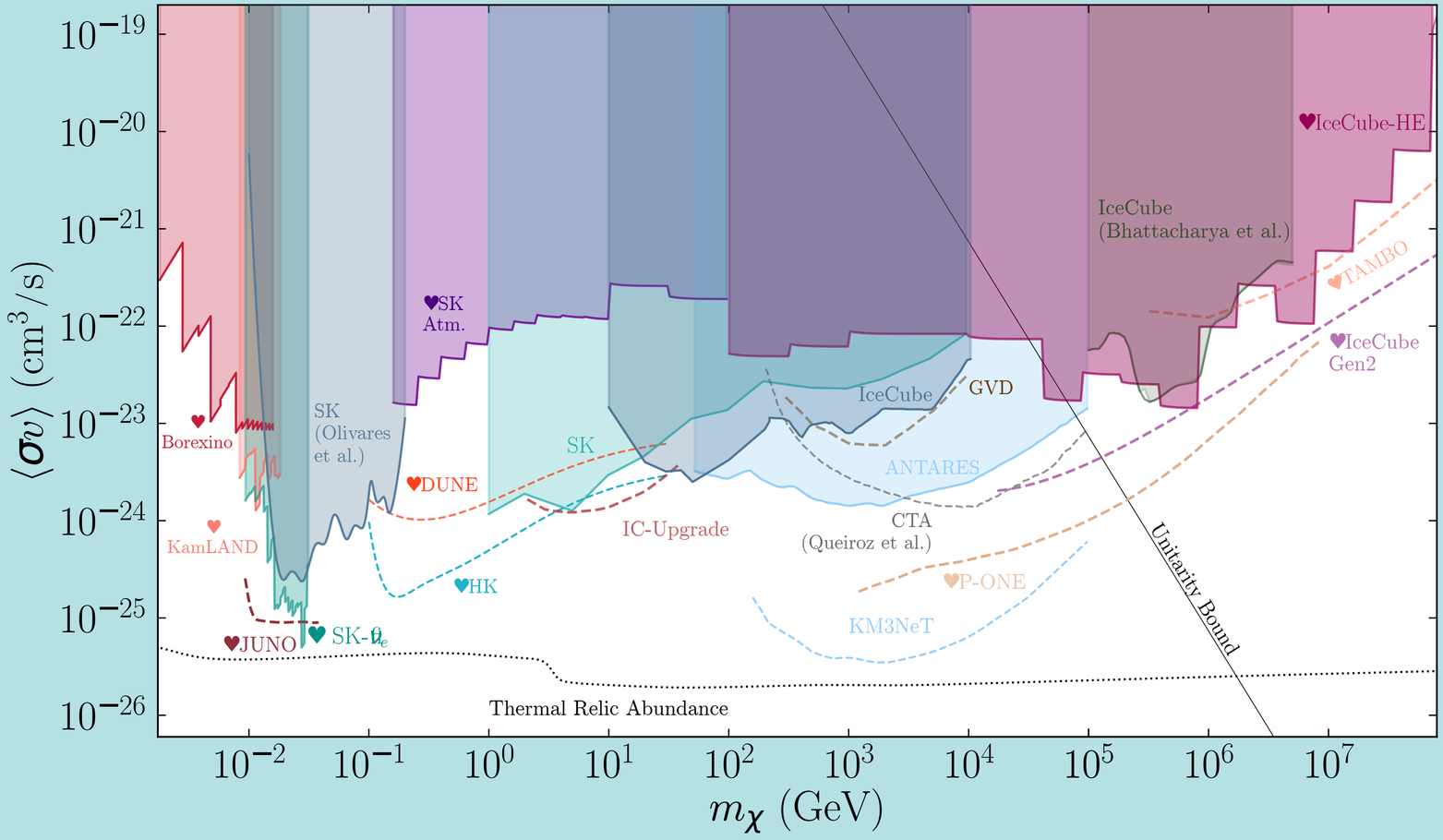
Where are the WIMPs?

DM annihilation to neutrinos



C. Argüelles et al., arXiv:1912.09486 [hep-ph]

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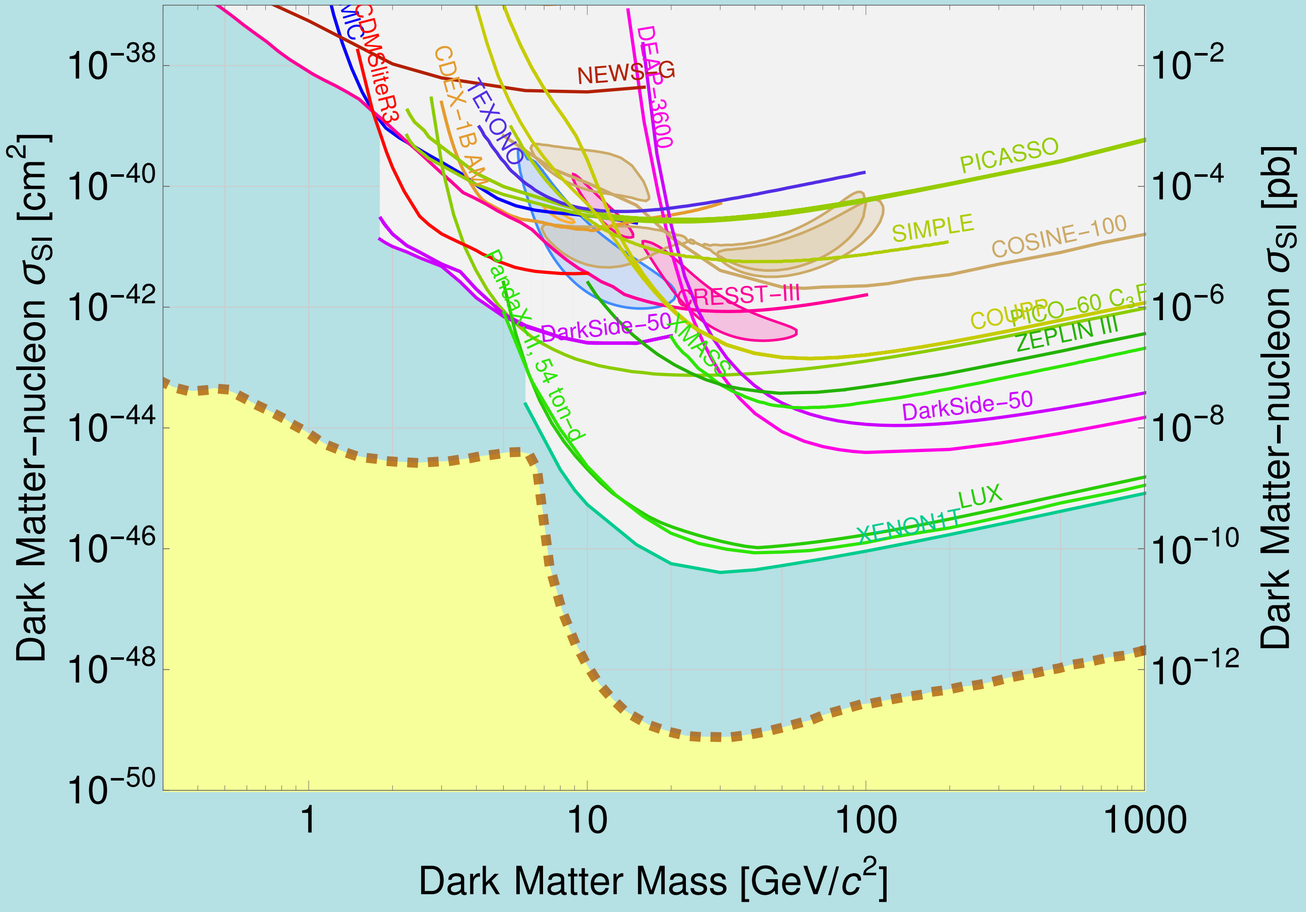
Beyond the WIMP

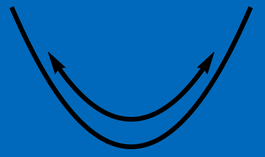


- [x] GRAVITY
- [x] ELECTROMAGNETISM
- [x] WEAK FORCE
- [x] STRONG FORCE

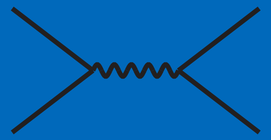
Feeble interactions =
dependence on initial conditions

1. Beyond WIMPs

2. Inflation & reheating



3. FIMPs



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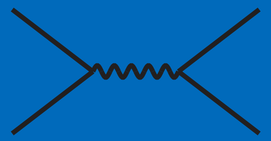
Beyond the WIMP

1. Beyond WIMPs

2. Inflation & reheating

3. FIMPs



4. Future prospects

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Inflating spacetime

Simplest incarnation: a slowly rolling scalar field in FRW spacetime, $ds^2 = dt^2 - a(t)^2\, d\boldsymbol{x}^2$

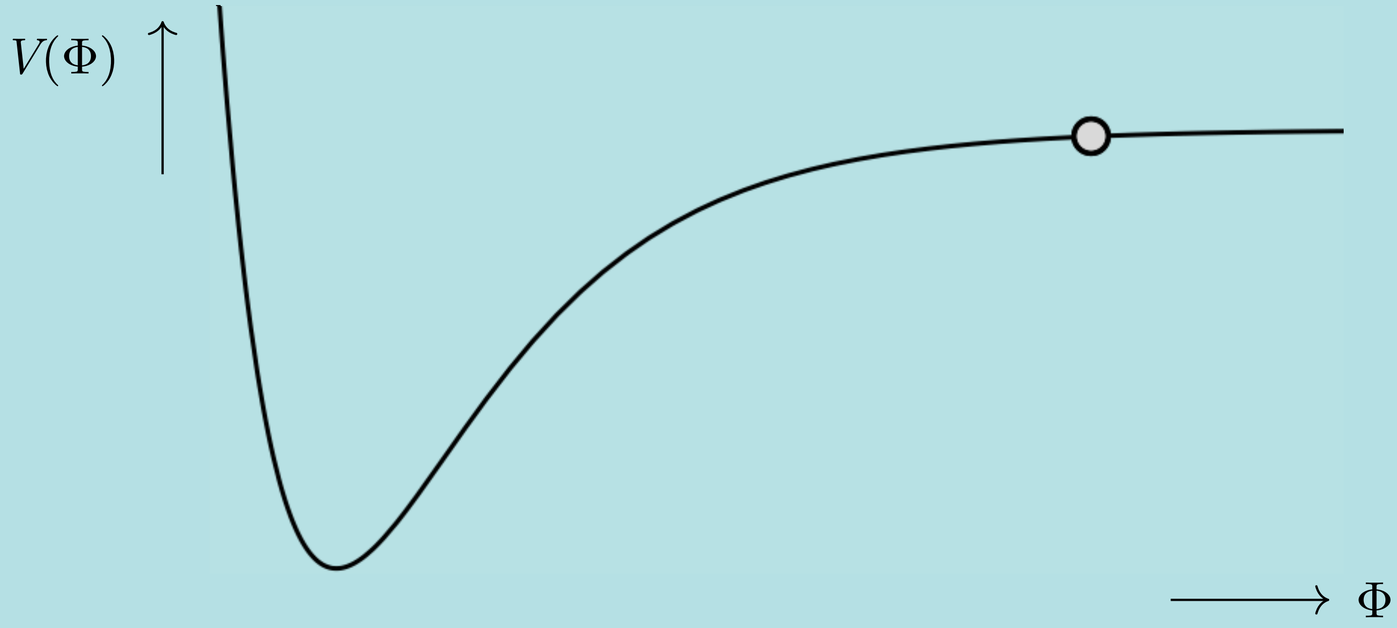
$$\ddot{\Phi} + 3H\dot{\Phi} + V'(\Phi) = 0$$

$$H \equiv \frac{\dot{a}}{a} = \left(\frac{\rho_\Phi}{3M_P^2}\right)^{1/2}$$

with

$$\rho_\Phi = \frac{1}{2}\dot{\Phi}^2 + V(\Phi)$$

$$P_\Phi = \frac{1}{2}\dot{\Phi}^2 - V(\Phi)$$



When inflation ends, reheating begins

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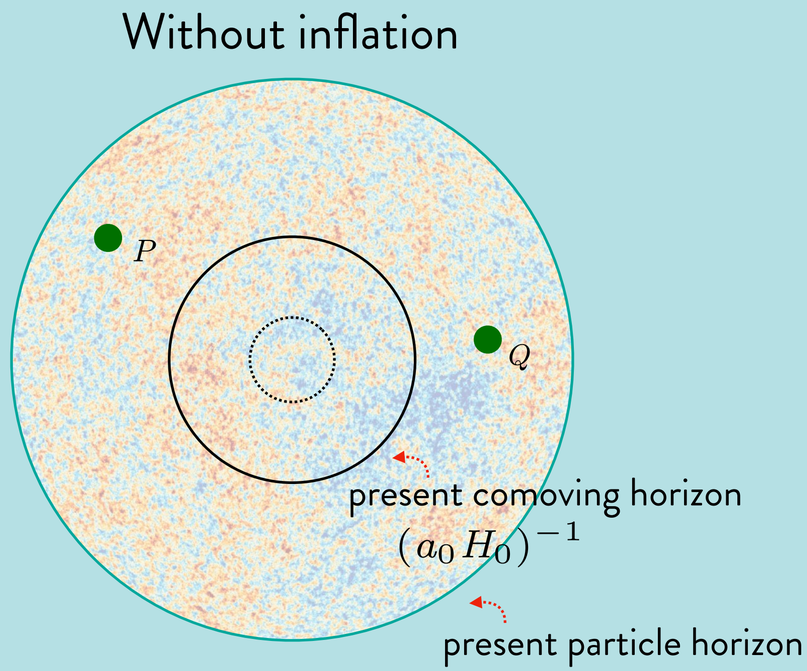
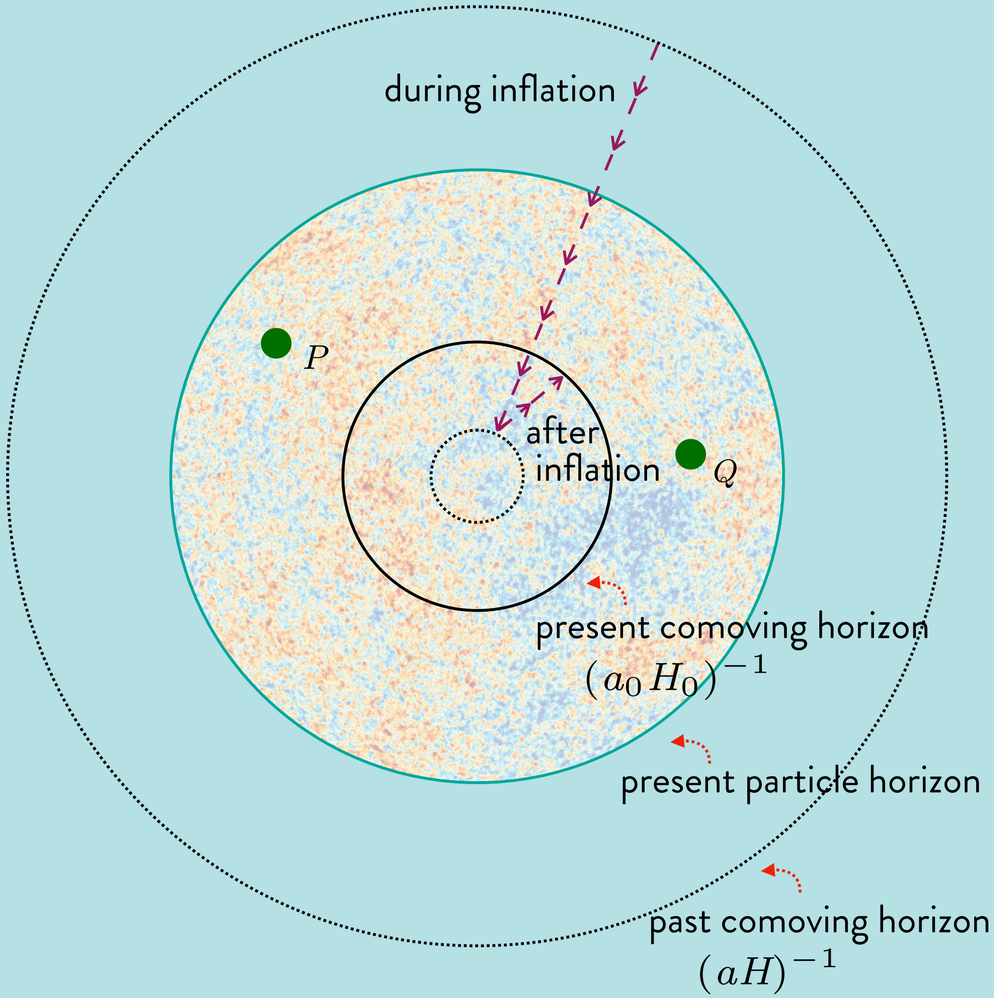
The horizon problem

$\Delta T/T \sim 10^{-5}$ in the CMB





Credit: Héctor Ramírez

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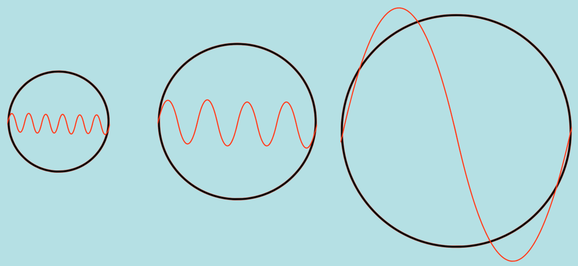
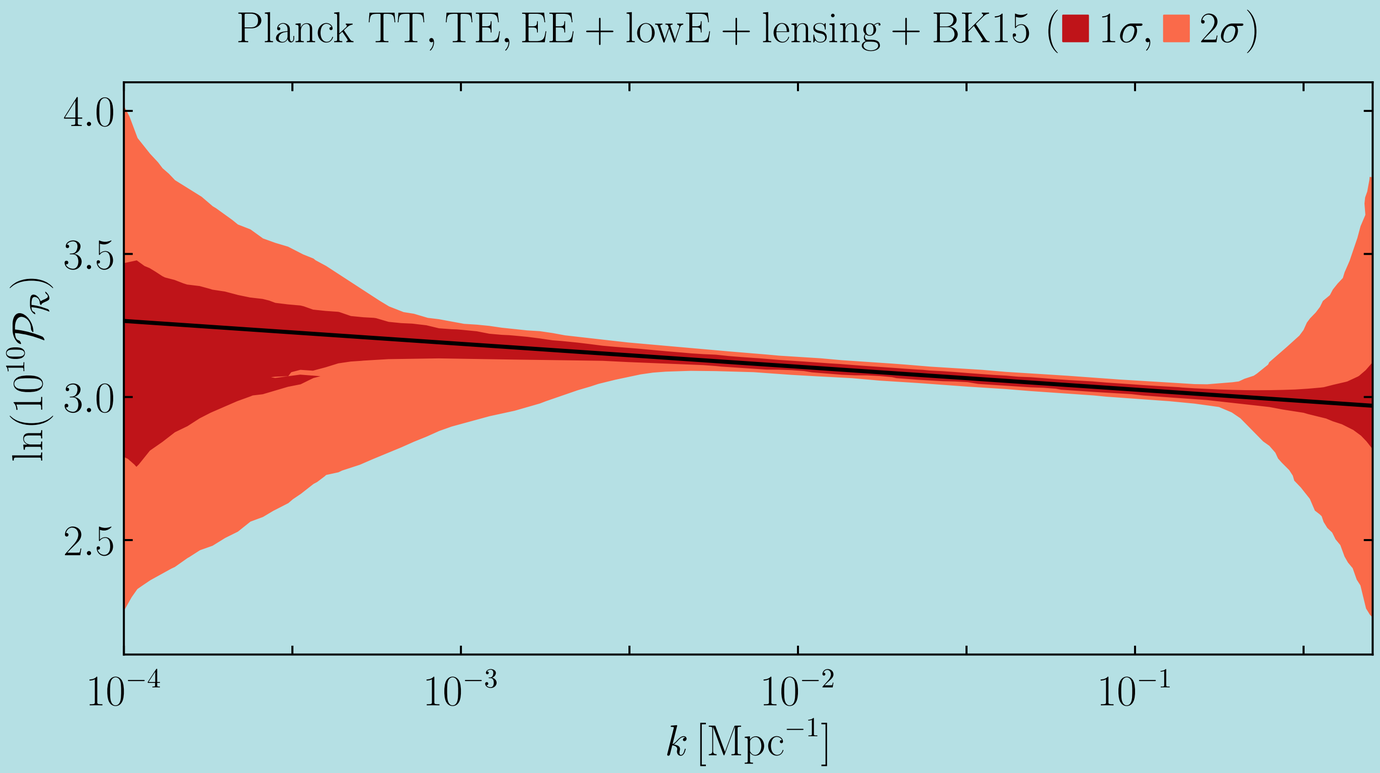
The primordial fluctuations



Quantum fluctuations in Φ, g, are strechted by expansion



Y. Akrami et al. [Planck], Astron. Astrophys. 641 (2020) A10

$$\mathcal{P}_{\mathcal{R}} = \frac{H_*^4}{4\pi^2 \dot{\Phi}_*^2} \left(\frac{k}{aH}\right)^{n_s - 1}$$

$$\mathcal{P}_{\mathcal{T}} = \frac{2H_*^2}{\pi^2} \left(\frac{k}{aH}\right)^{n_T}$$

1. Beyond WIMPs

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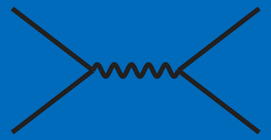
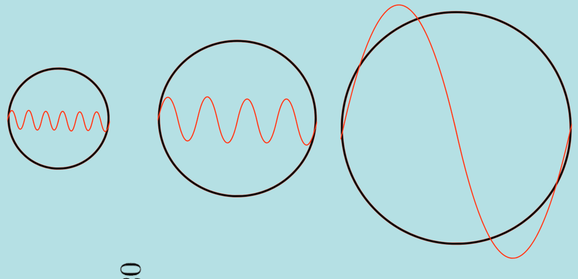


4. Future prospects

5. Conclusion

The primordial fluctuations



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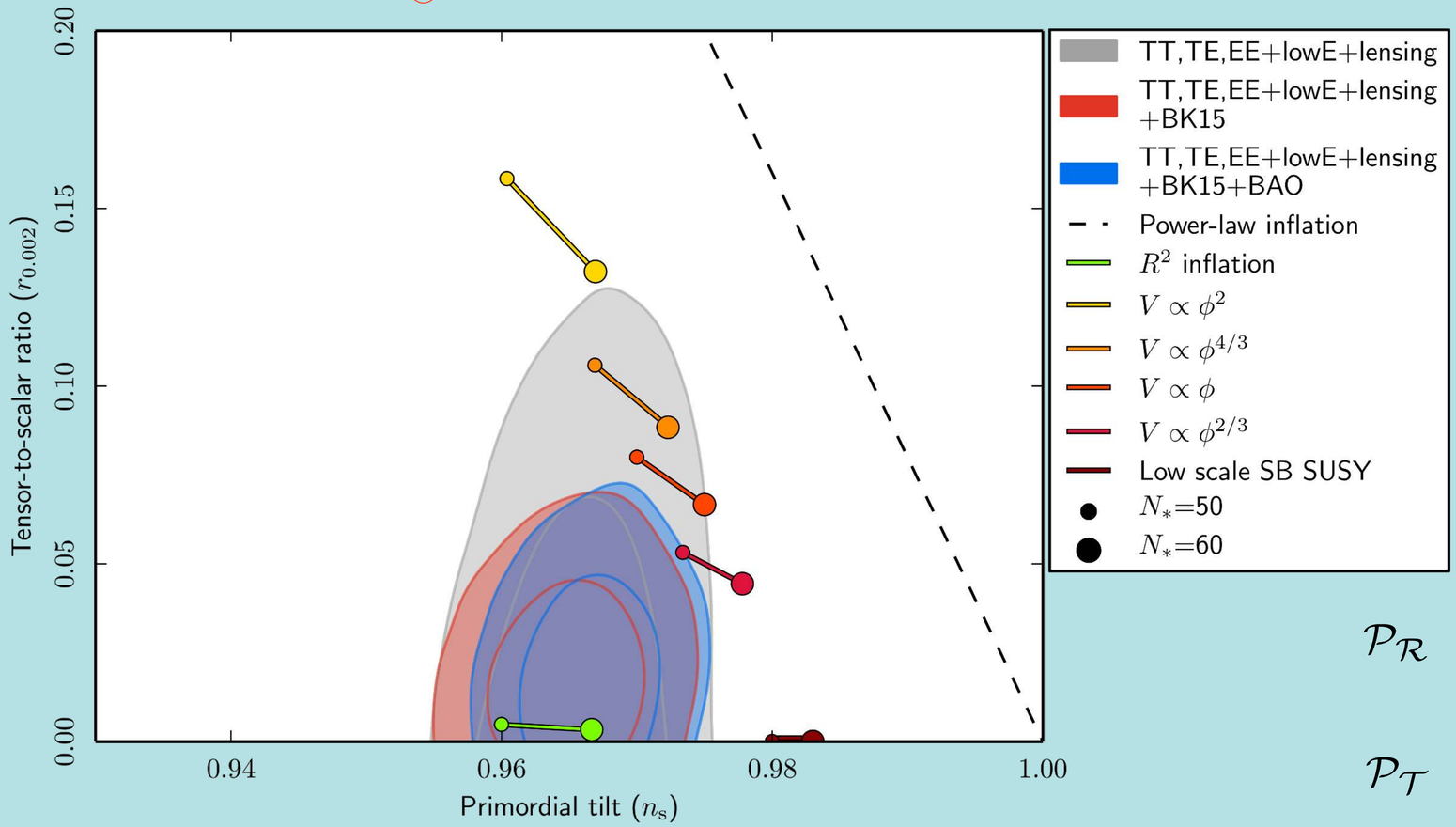

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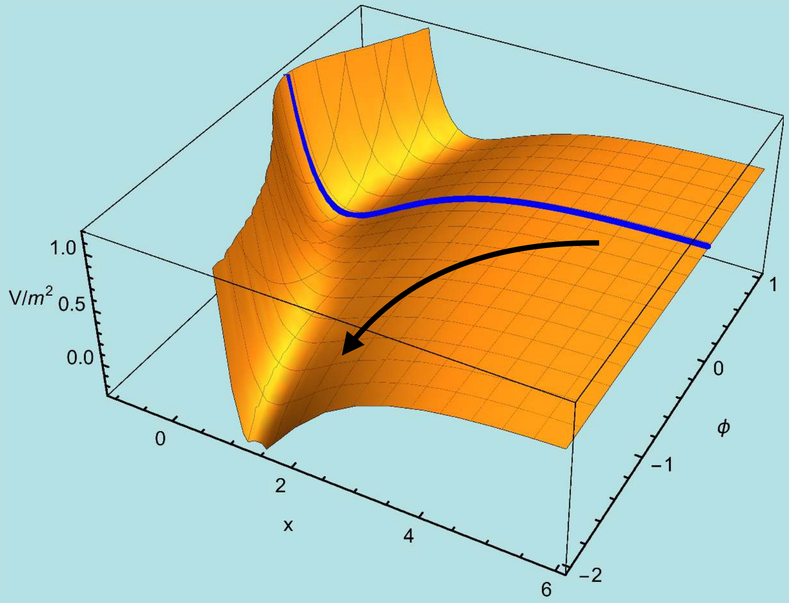
Problems and solutions for inflation

- Inflaton traverses trans-Planckian distances: radiative corrections

$\Rightarrow$ Supersymmetry:

- Coupling to gravity? $\Rightarrow$ Supergravity. But $V = e^G(G^i G_i - 3)$

- Add extra symmetry that flattens the potential $\Rightarrow$ No-Scale Supergravity



need stabilization

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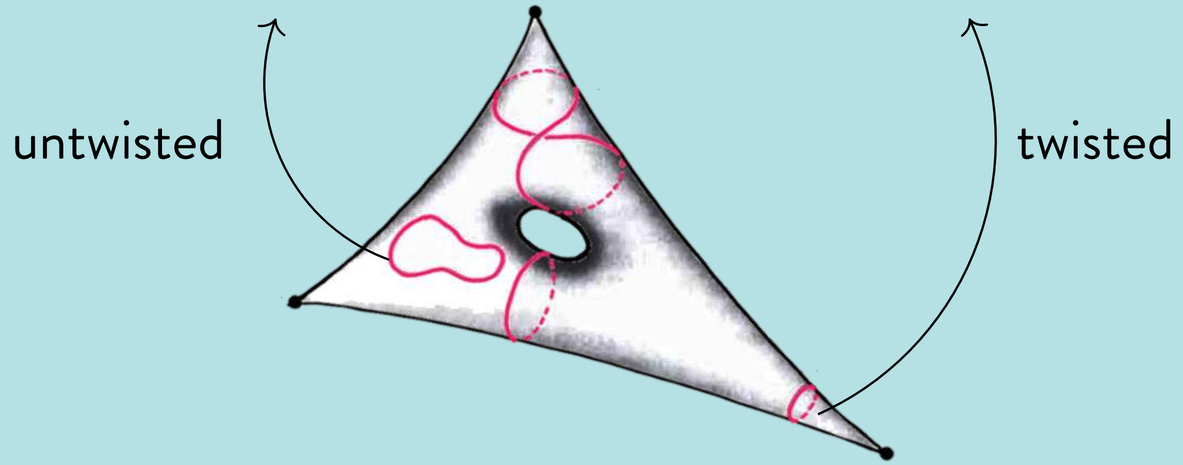
Problems and solutions for inflation

- A proposal: *Twisted No-Scale Inflation*

$$K = -3\ln\left[T+\bar{T}-\frac{1}{3}\sum_i|\phi|_i^2\right]+\sum_a\frac{|\varphi_a|^2}{(T+\bar{T})^{n_a}}$$



string orbifold compactification

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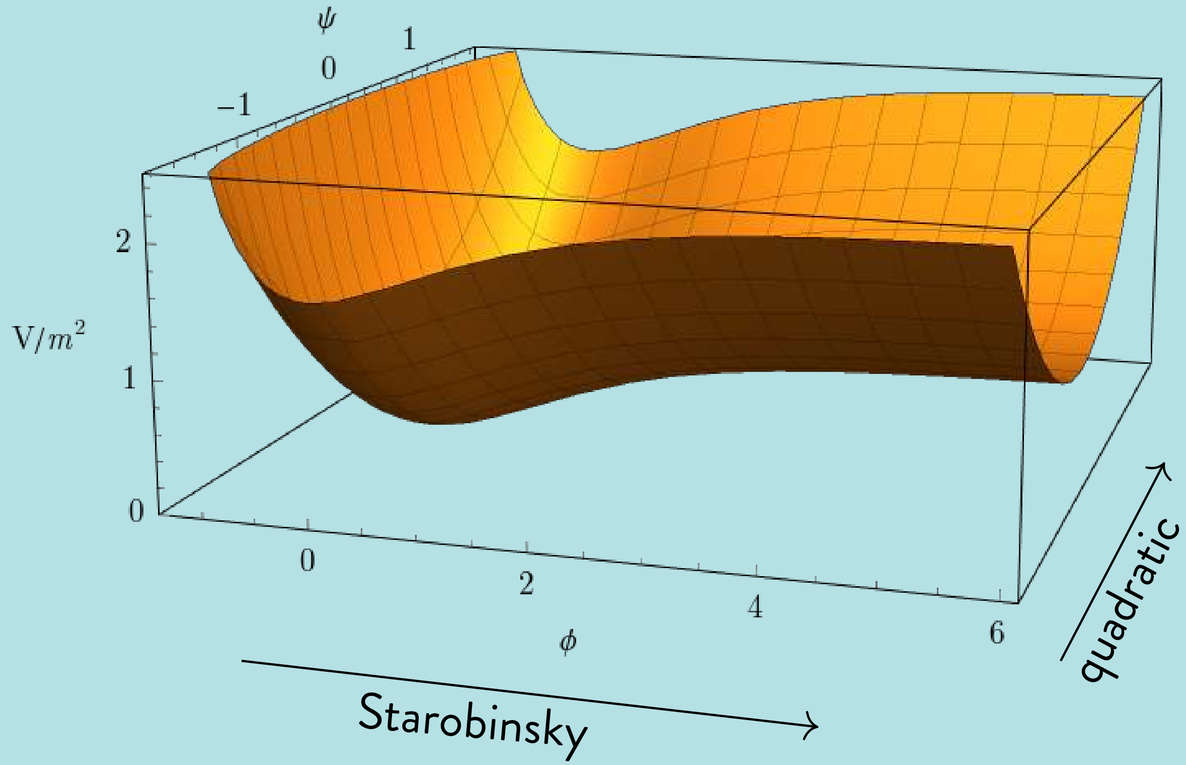
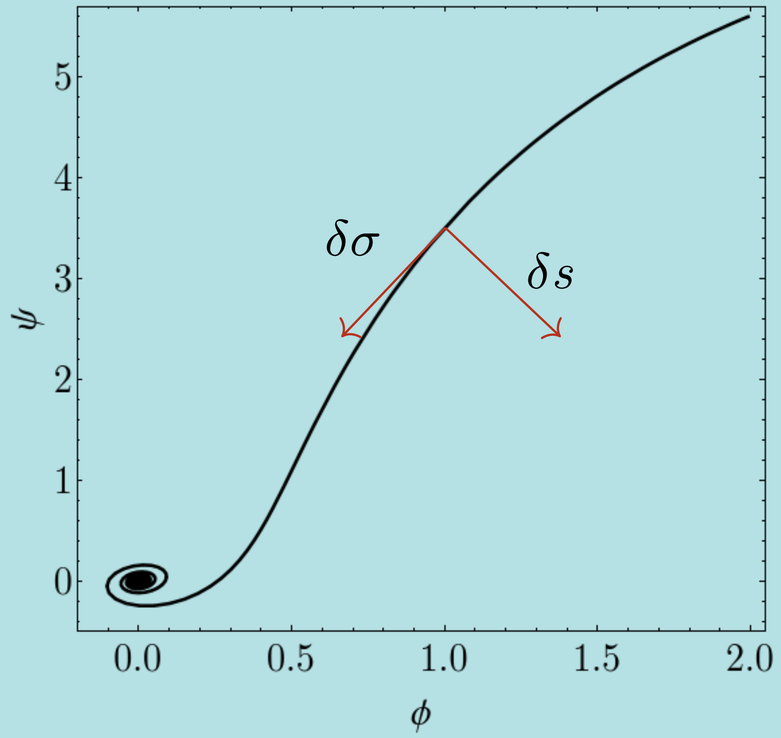
Problems and solutions for inflation

- A proposal: *Twisted No-Scale Inflation*





Twisted *Multifield* No-Scale Inflation ⇒ full Planck compatibility

J. Ellis, **MG**, D. Nanopoulos and K. Olive, JCAP 08 (2014), 044; JCAP 01 (2015), 010; JCAP 10 (2015), 003

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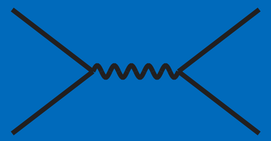

4. Future prospects

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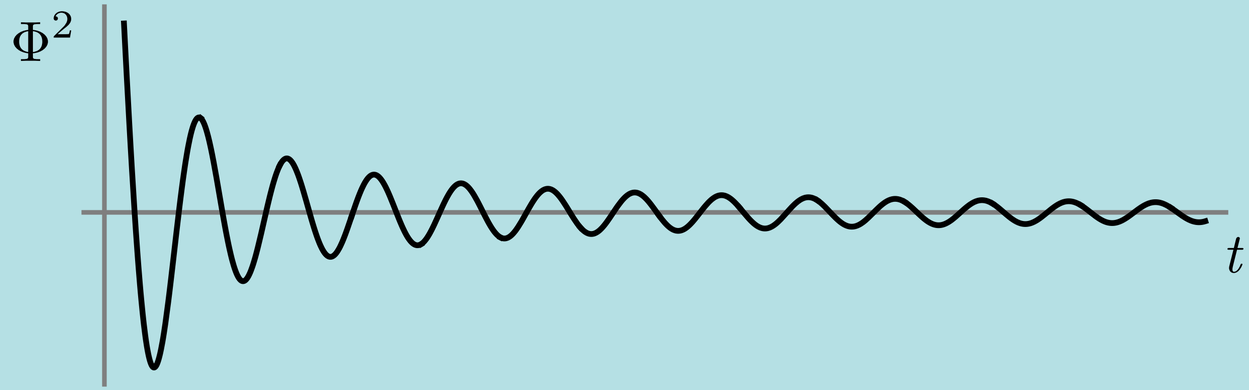
The vacuum can be excited!

During reheating, the inflaton provides an oscillating background



$$\mathcal{L}_\psi = y\,\Phi\bar{\psi}\psi \equiv m_\psi(t)\bar{\psi}\psi$$

$$\mathcal{L}_\chi = \frac{1}{2}\sigma\,\Phi^2\chi^2 \equiv \frac{1}{2}m_\chi^2(t)\chi^2$$

Mixing of +/- frequency modes $\rightarrow$ particle production!

1. Beyond WIMPs

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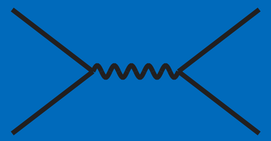

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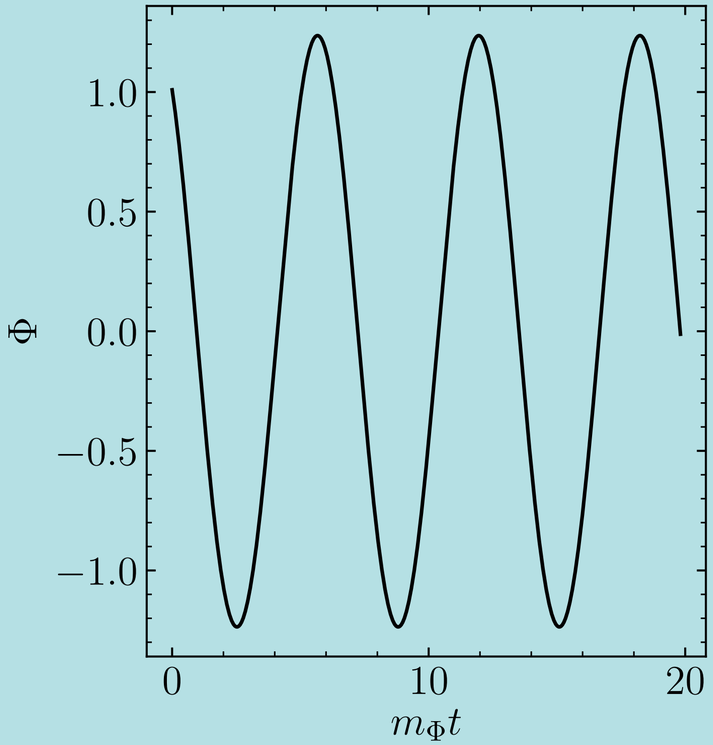
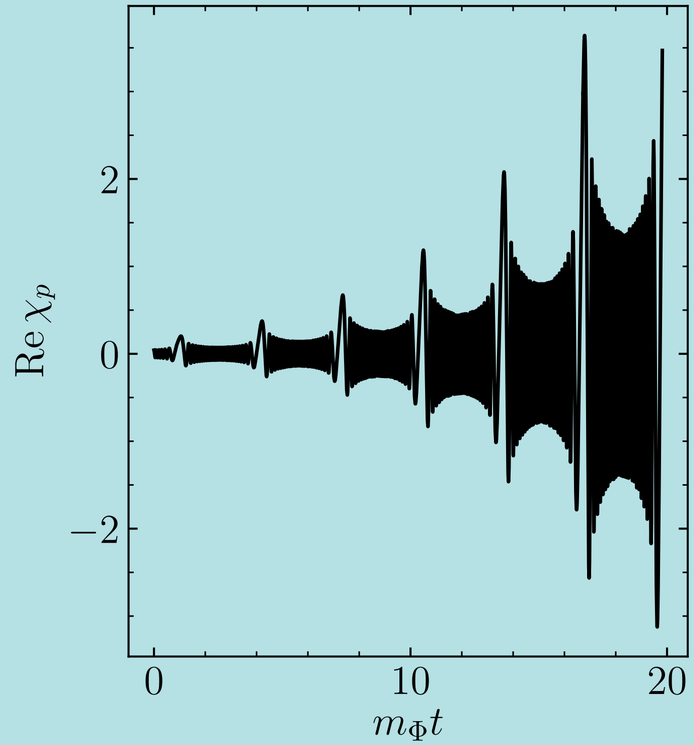
Scalar (p)reheating

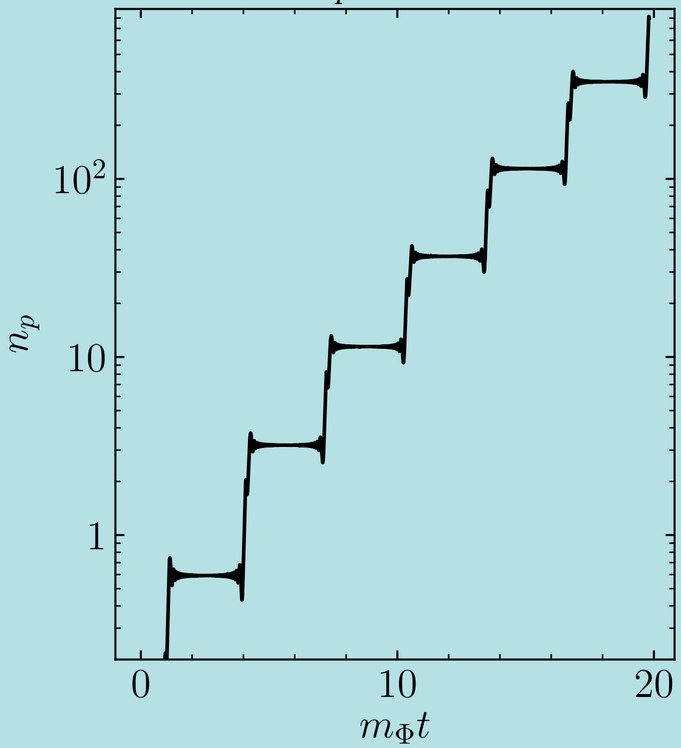
$$\ddot{\chi}_p + 3H\dot{\chi}_p + \left[\frac{p^2}{a^2} + m_\chi^2(t)\right]\chi_p \;=\; 0\,, \qquad m_\chi^2(t) = \sigma\Phi^2 + m_{\chi,0}^2$$

Neglecting expansion,

$$n_p = \frac{1}{2\omega_p}|\omega_p\chi_p - i\dot{\chi}|^2$$







1. Beyond WIMPs
2. Inflation & reheating
3. FIMPs
4. Future prospects
5. Conclusion

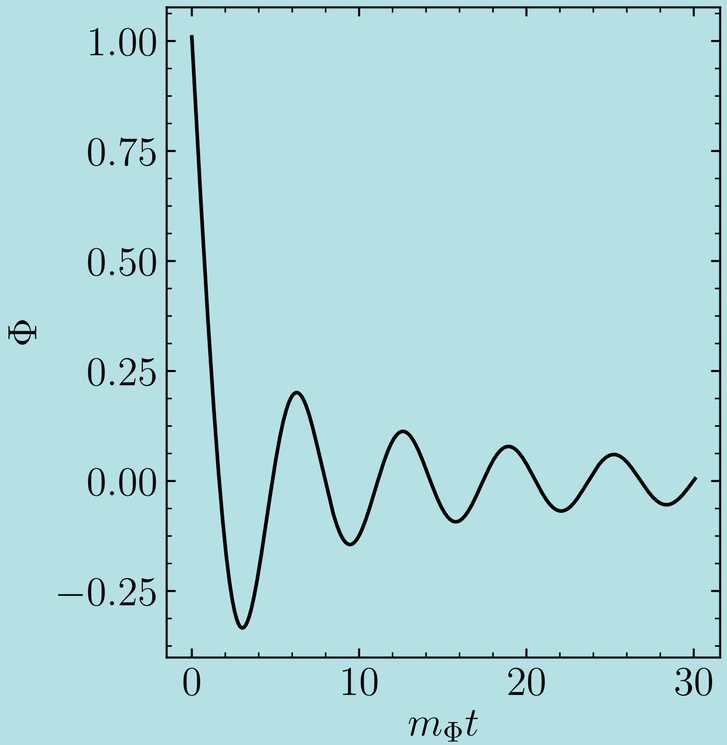
Scalar (p)reheating

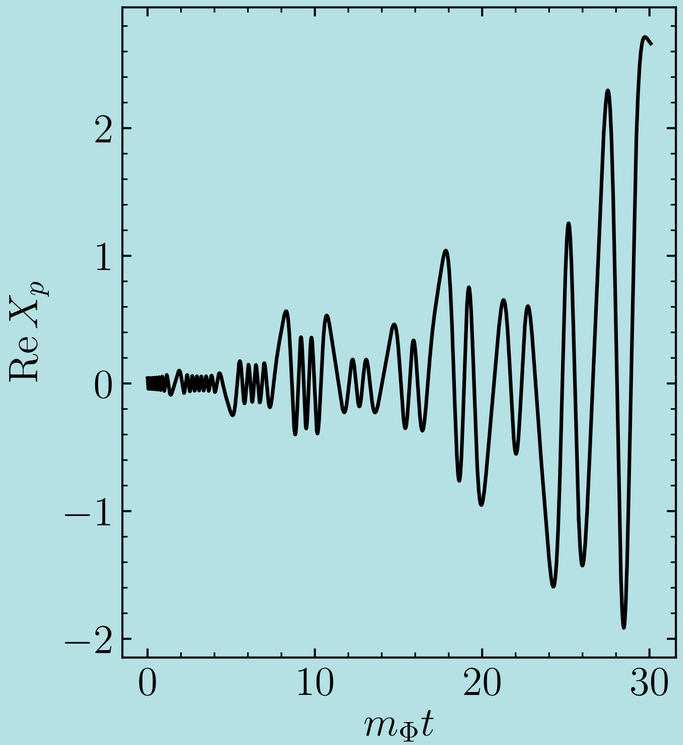
$$\ddot{\chi}_p + 3H\dot{\chi}_p + \left[\frac{p^2}{a^2} + m_\chi^2(t)\right]\chi_p \;=\; 0\,, \qquad m_\chi^2(t) = \sigma\Phi^2 + m_{\chi,0}^2$$

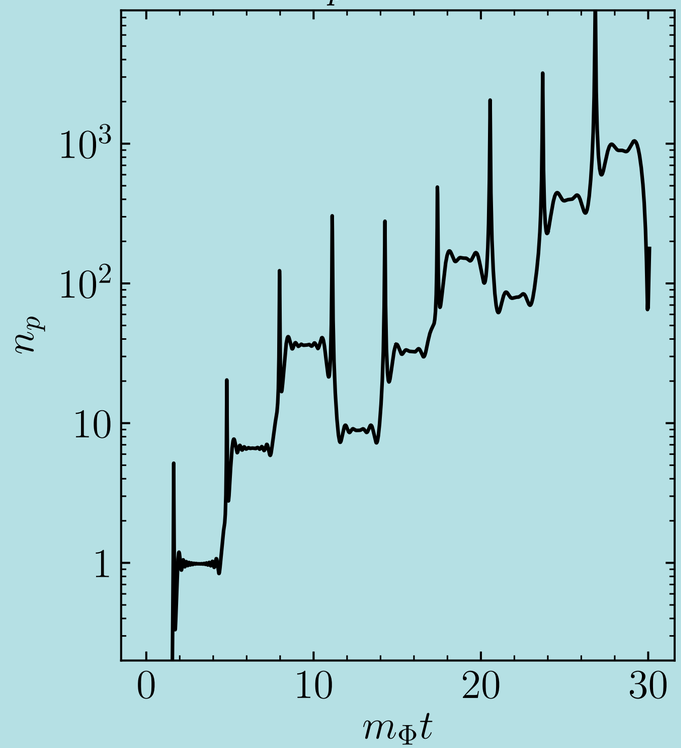
With expansion,

$$X = a\chi$$

$$n_p = \frac{1}{2\omega_p}\left|\omega_p\chi_p - i\chi'\right|^2$$





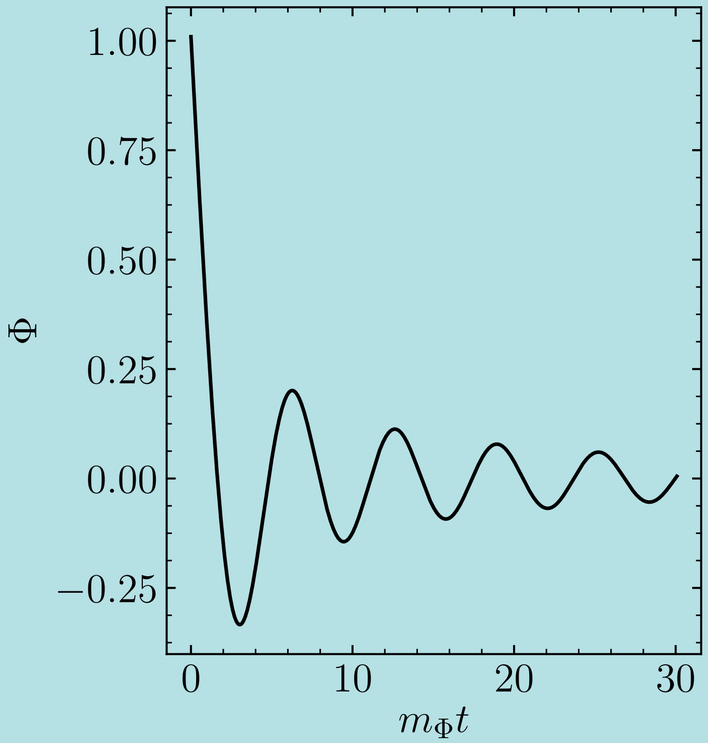


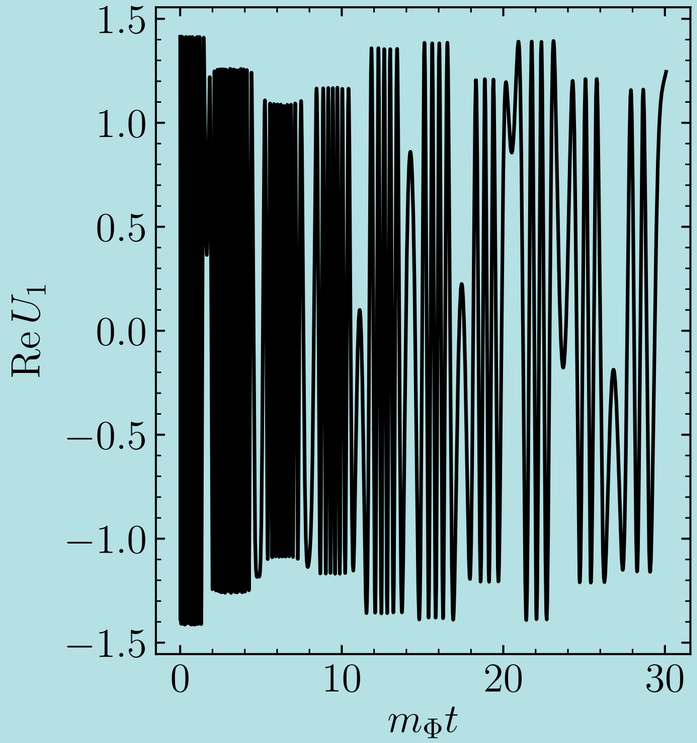
1. Beyond WIMPs
2. Inflation & reheating
3. FIMPs
4. Future prospects
5. Conclusion

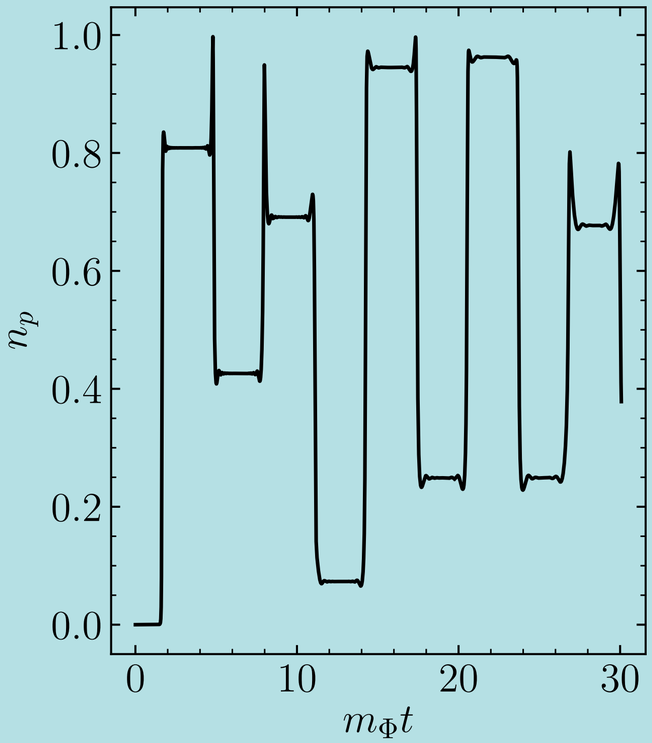
Fermion (p)reheating

$$\left[i\gamma^\mu \partial_\mu + i\frac{3a'}{2a}\gamma^0 - a m_\psi(\tau) \right] \psi \;=\; 0\,, \qquad m_\psi^2(\tau) = (y\Phi + m_{\psi,0})^2$$

With expansion,







1. Beyond WIMPs

2. Inflation & reheating

3. FIMPs

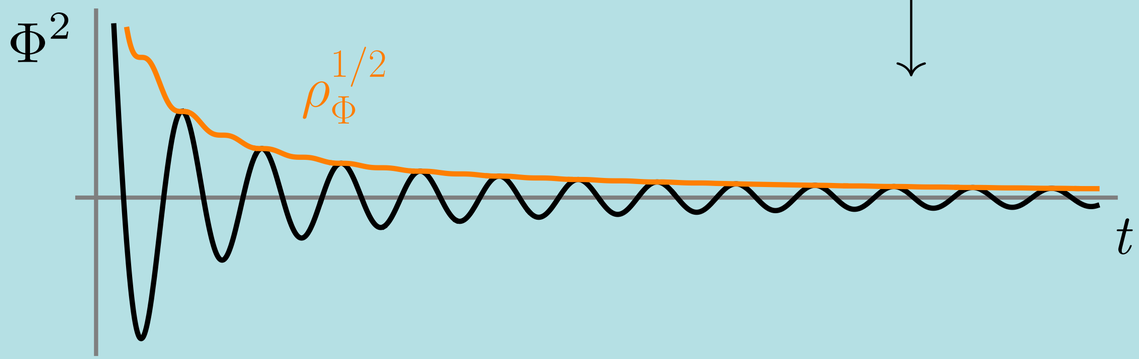
4. Future prospects

5. Conclusion

The perturbative (dissipative) picture

Reheating as the exchange of energy between two ideal fluids

$$T^{\mu\nu} = T^{\mu\nu}_{\Phi} + T^{\mu\nu}_{R} = \begin{pmatrix} \rho_\Phi & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix} + \frac{1}{3}\begin{pmatrix} 3\rho_R & 0 & 0 & 0 \\ 0 & \rho_R & 0 & 0 \\ 0 & 0 & \rho_R & 0 \\ 0 & 0 & 0 & \rho_R \end{pmatrix}$$



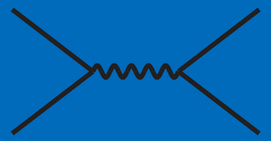
$$\langle p_\Phi \rangle = \tfrac{1}{2}\langle \dot{\Phi}^2 + m_\Phi^2 \Phi^2 \rangle \simeq 0$$

(matter)

1. Beyond WIMPs

2. Inflation & reheating

3. FIMPs



4. Future prospects

5. Conclusion

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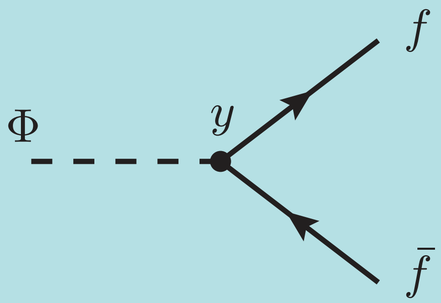
Conservation $\nabla_\mu T^{\mu\nu} = 0$,

$$\dot{\rho}_R + 4H\rho_R = -(\dot{\rho}_\Phi + 3H\rho_\Phi) \equiv \Gamma_\Phi \rho_\Phi$$

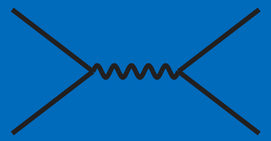


$$\Gamma_\Phi = \frac{y^2}{8\pi} m_\Phi$$

1. Beyond WIMPs

2. Inflation & reheating

3. FIMPs



4. Future prospects

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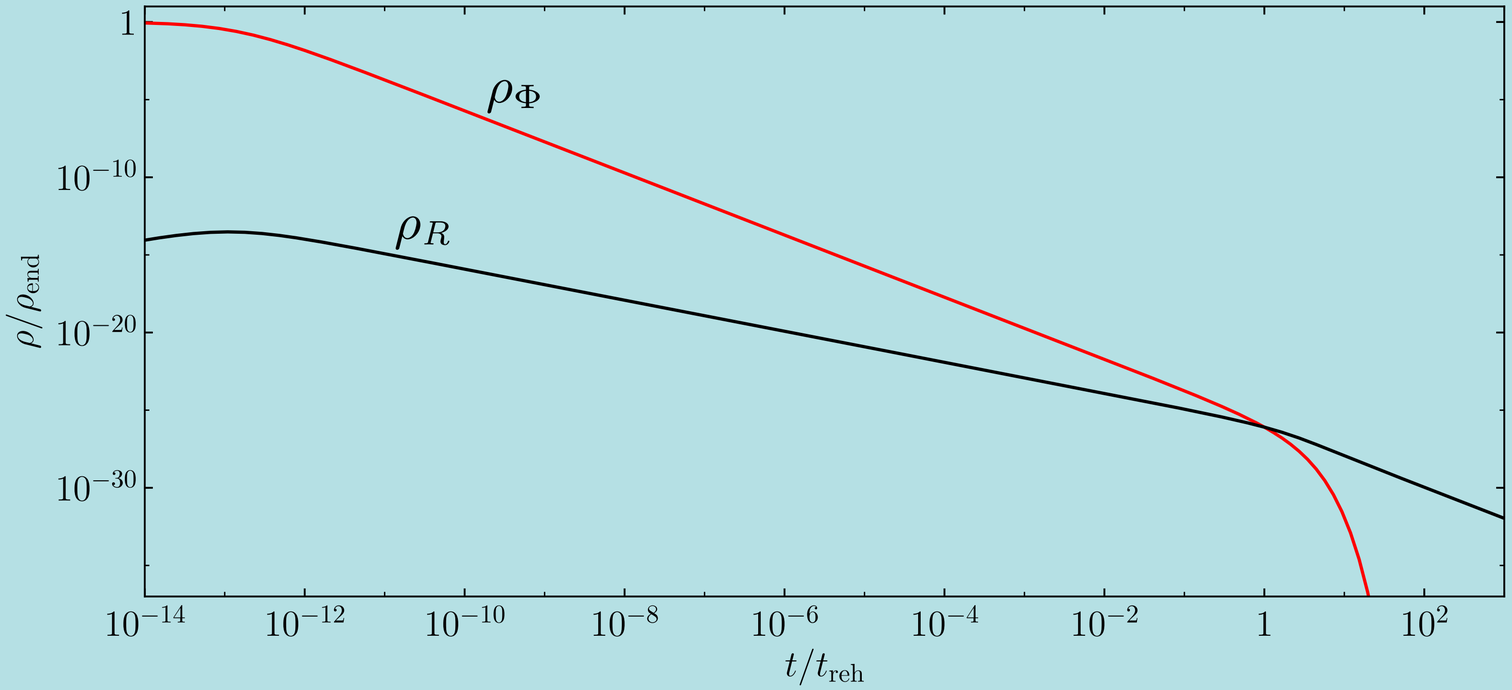
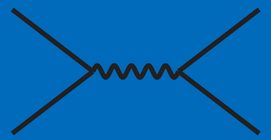


1. Beyond WIMPs

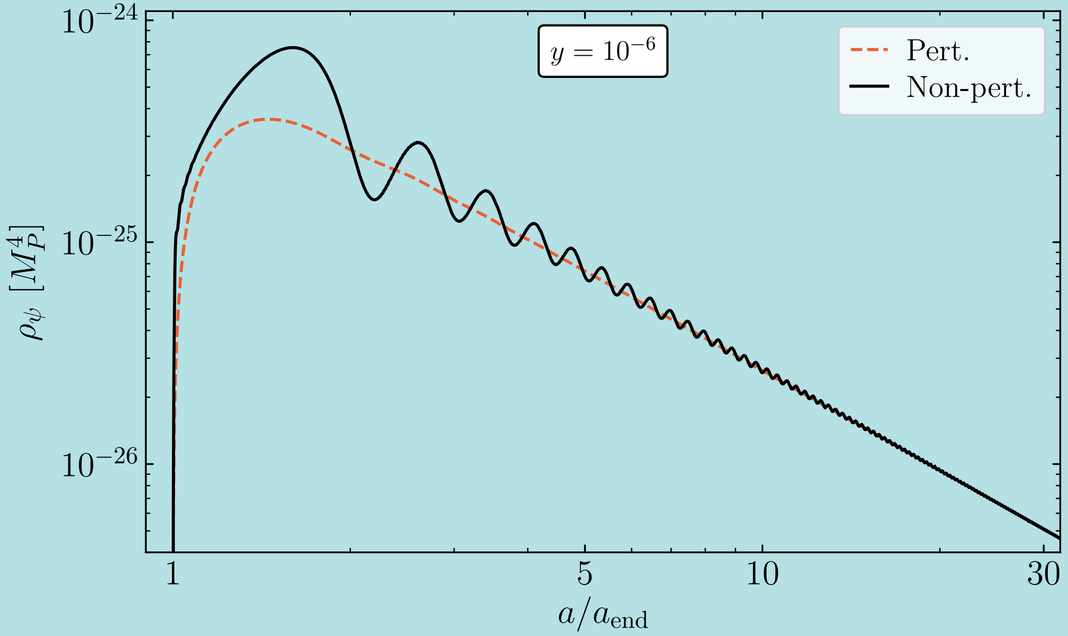
2. Inflation & reheating

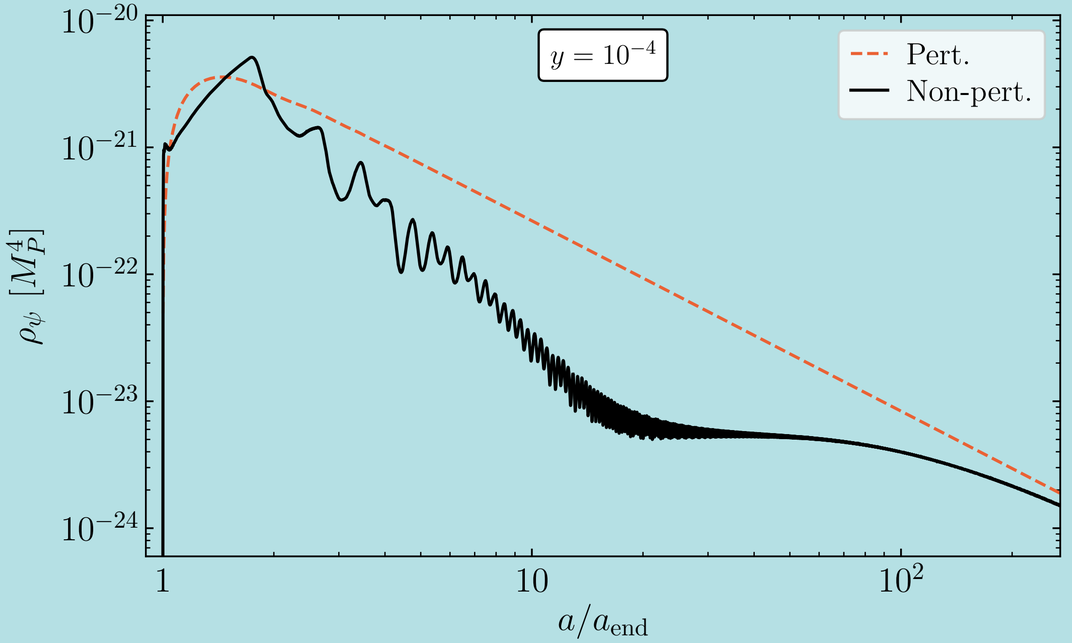
3. FIMPs

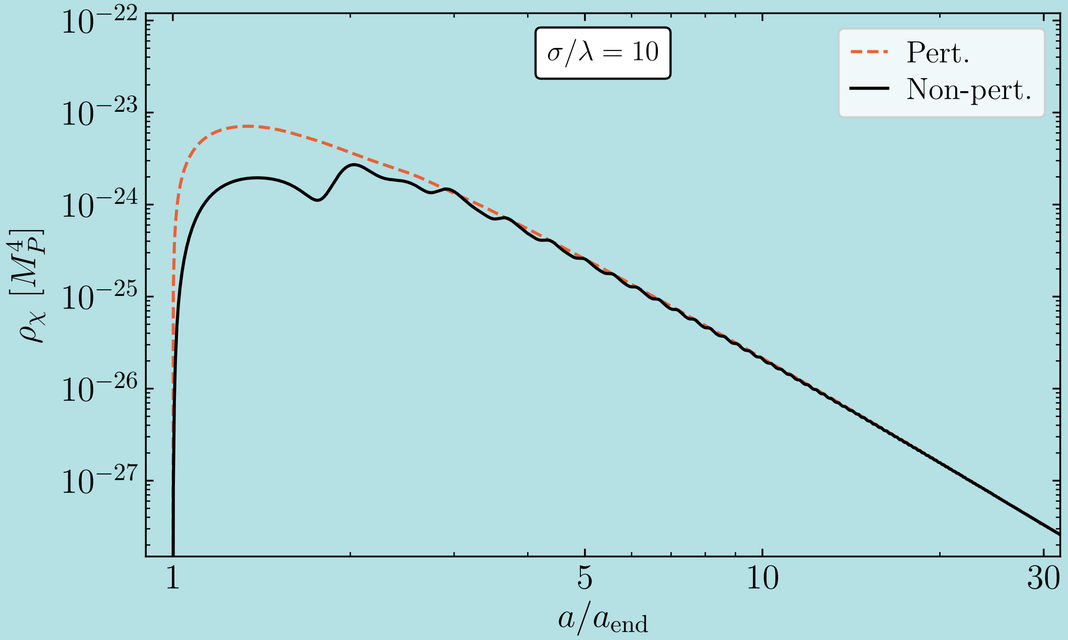


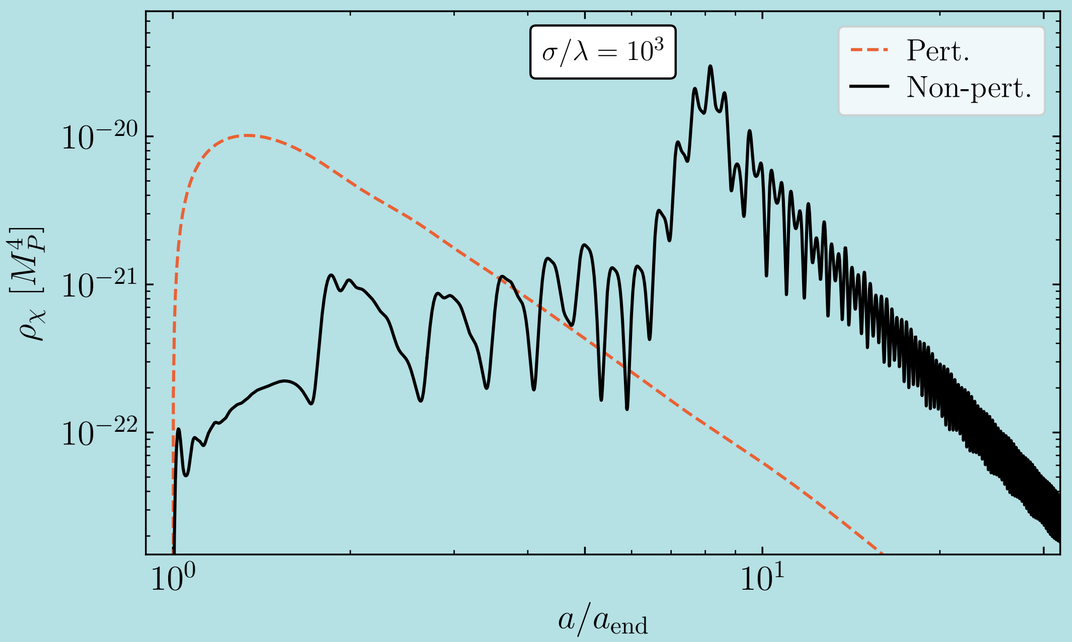
4. Future prospects

5. Conclusion





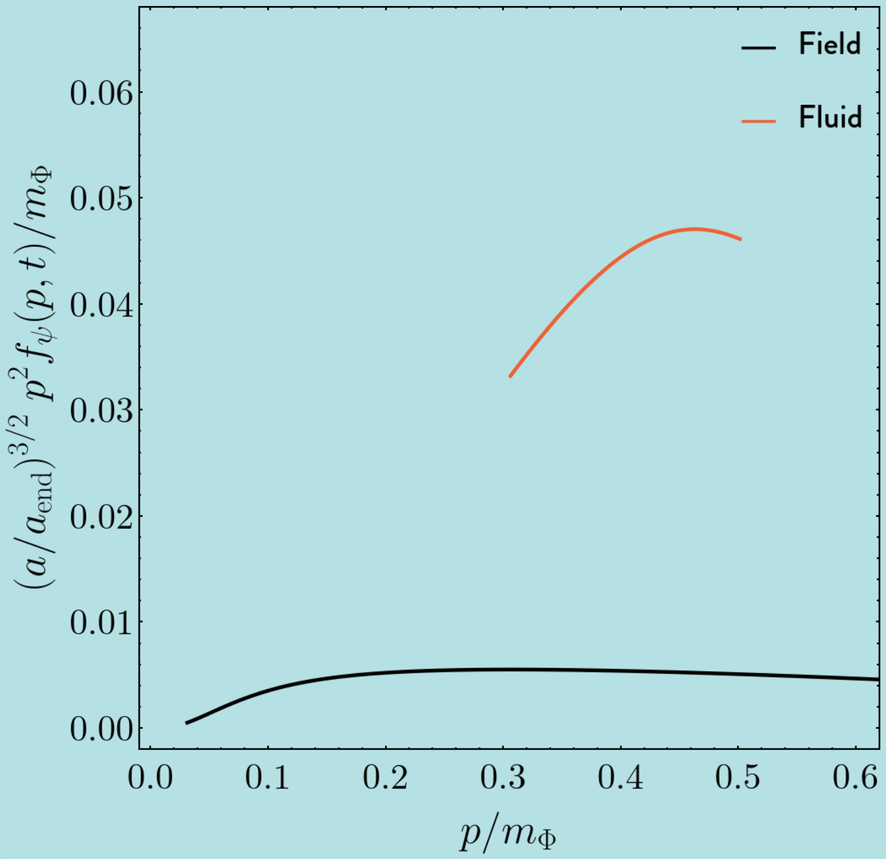




1. Beyond WIMPs
2. Inflation & reheating
3. FIMPs
4. Future prospects
5. Conclusion

The phase space distribution

$$n_\psi = \int \frac{d^3\boldsymbol{p}}{(2\pi)^3} f_\psi(p,t)$$



$$\frac{\partial f_\psi}{\partial t} - H|\boldsymbol{p}|\frac{\partial f_\psi}{\partial |\boldsymbol{p}|} = \frac{1}{2p_0}\int d\Pi\, |\mathcal{M}|^2_{\Phi\to\bar\psi\psi} n_\Phi \delta^{(3)}(\boldsymbol{P}) + \mathcal{C}^{\rm int}[f_\psi]$$

1. Beyond WIMPs
2. Inflation & reheating
3. FIMPs
4. Future prospects
5. Conclusion

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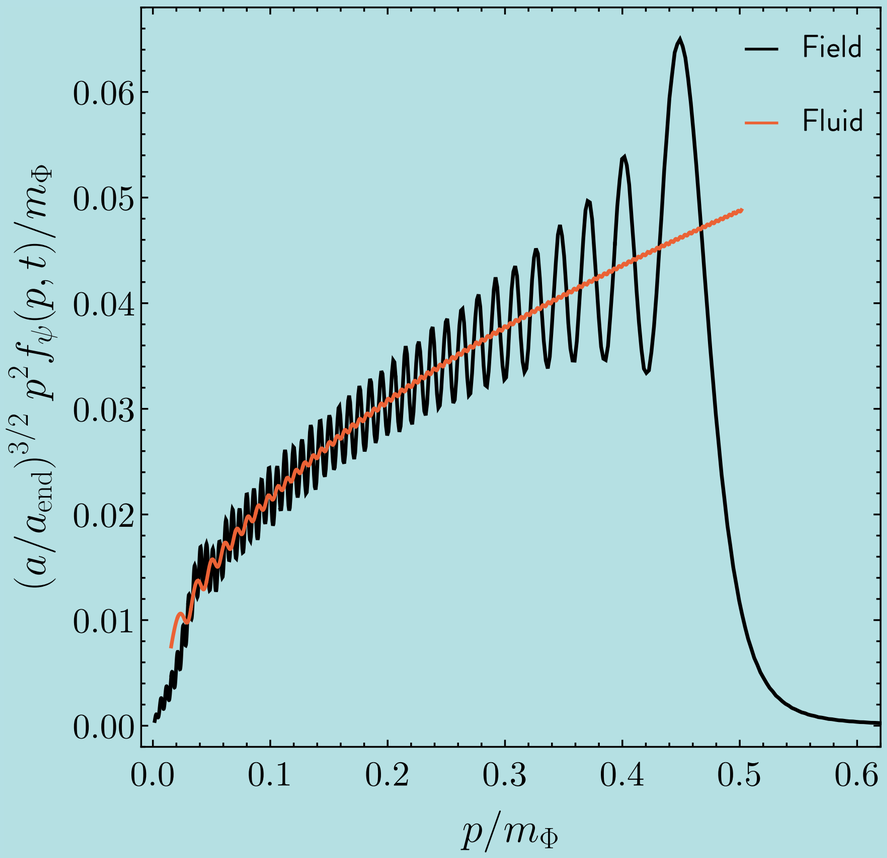
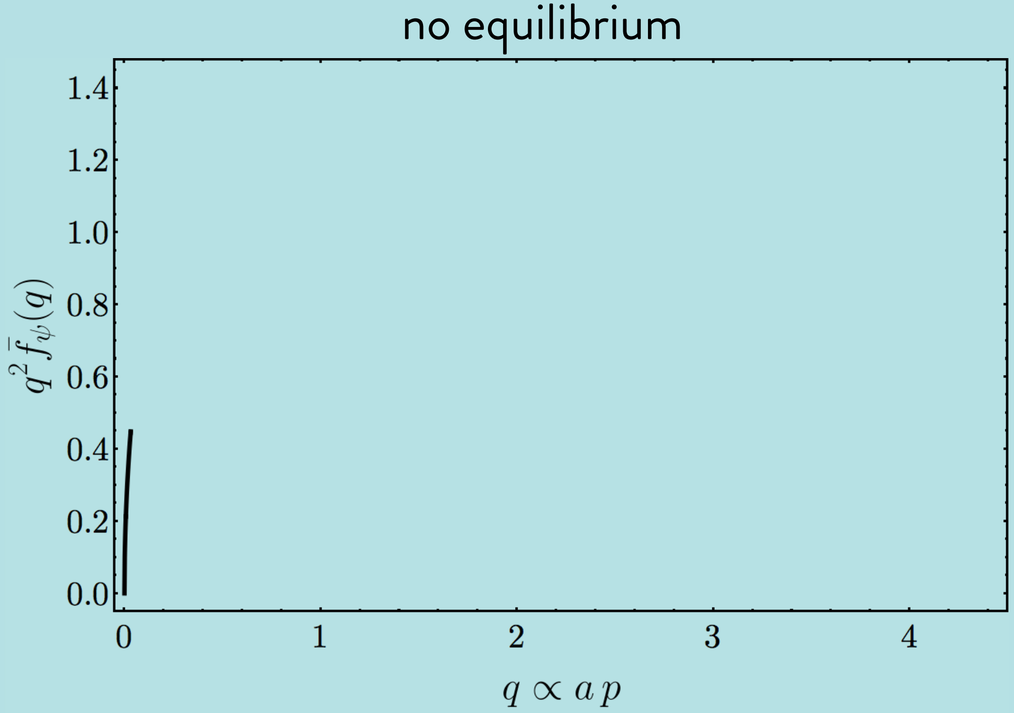


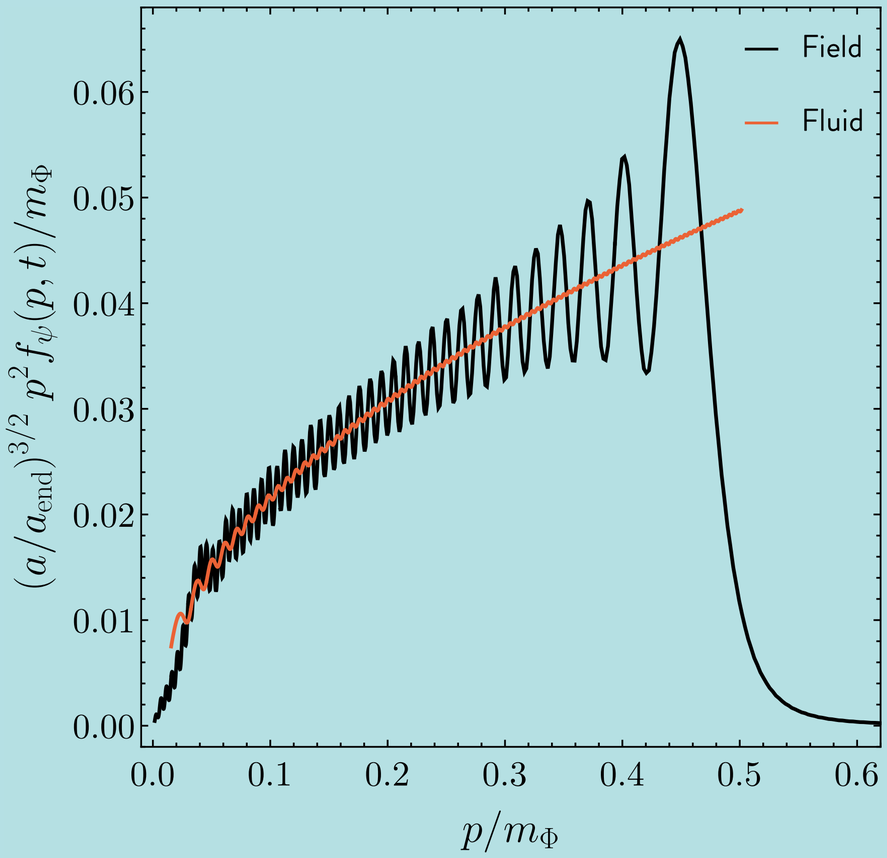


G. Ballesteros, **MG** and M. Pierre, JCAP 03 (2021), 101

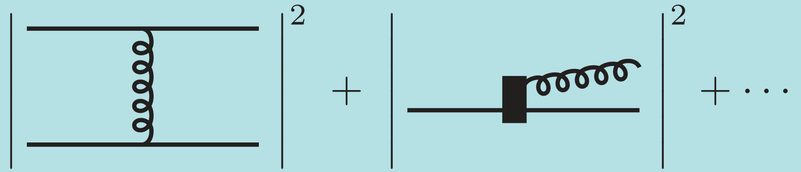
1. Beyond WIMPs
2. Inflation & reheating
3. FIMPs
4. Future prospects
5. Conclusion

The phase space distribution

$$n_\psi = \int \frac{d^3\boldsymbol{p}}{(2\pi)^3} f_\psi(p,t)$$



$$\mathcal{C}^{\rm int}[f_\psi] = \left| \quad \right|^2 + \left| \quad \right|^2 + \cdots$$

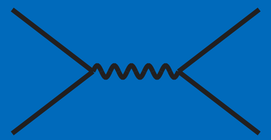


K. Harigaya, K. Mukaida, JHEP 05 (2014), 006

1. Beyond WIMPs

2. Inflation & reheating

3. FIMPs



4. Future prospects

5. Conclusion

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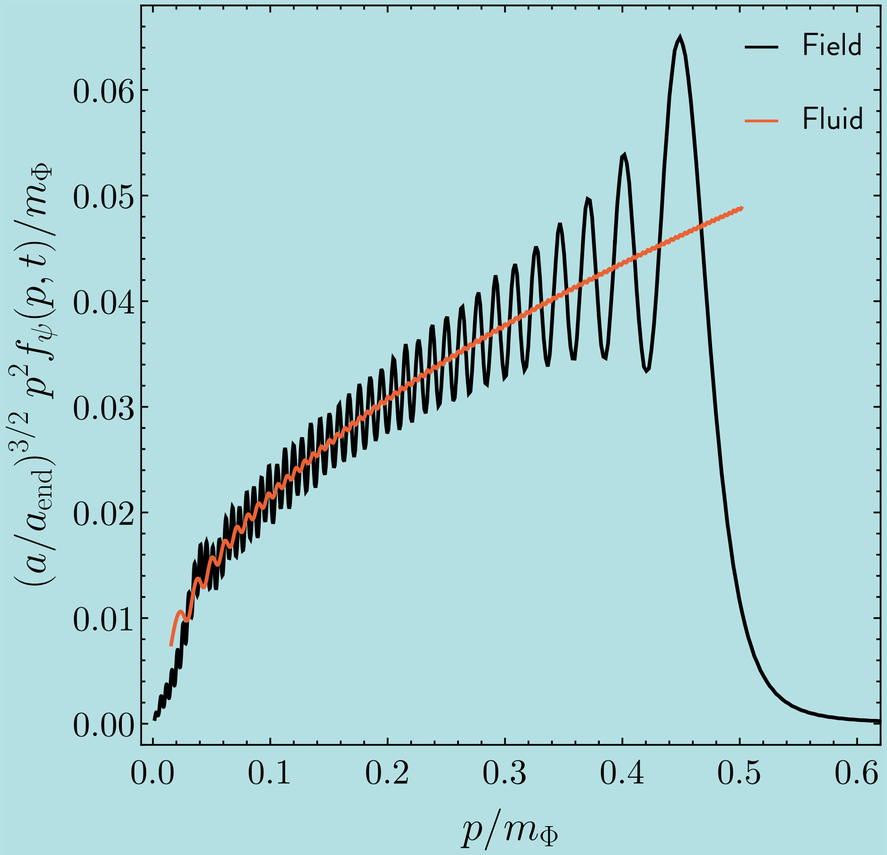
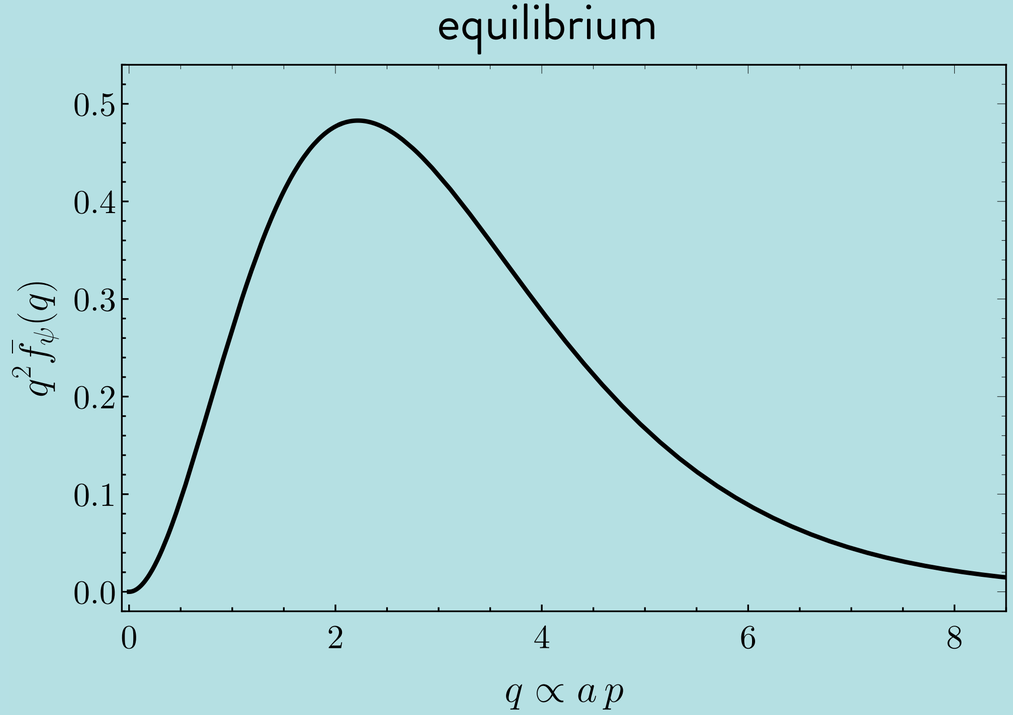
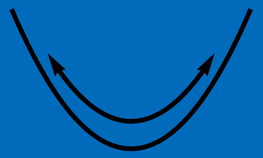
$$n_\psi = \int \frac{d^3\boldsymbol{p}}{(2\pi)^3} f_\psi(p,t)$$





1. Beyond WIMPs

2. Inflation & reheating

3. FIMPs

4. Future prospects

5. Conclusion

Is a spin-$\frac{3}{2}$ dark matter particle the missing piece in the puzzle?

	spin 0	spin 1/2	spin 1	spin 3/2	spin 2
SM:	H	u_L	W^0		G

1. Beyond WIMPs

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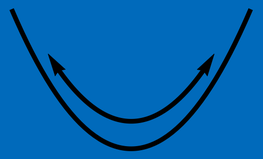

3. FIMPs

4. Future prospects

5. Conclusion

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	spin 0	spin 1/2	spin 1	spin 3/2	spin 2
SM+DM:	H	u_L	W^0	Ψ	G
				raritron	

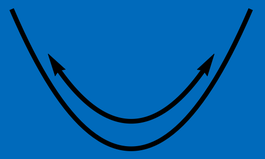
$$\mathcal{L} = -\frac{1}{2}\bar{\Psi}_\mu \left(i\gamma^{[\mu}\gamma^{\nu}\gamma^{\rho]}\partial_\rho + m_{3/2}\gamma^{[\mu}\gamma^{\nu]} \right) \Psi_\nu$$

(Rarita-Schwinger)

For gravitinos see e.g. J. Ellis, **MG**, D. Nanopoulos, K. Olive and M. Peloso, JCAP 03 (2016), 008;
E. Dudas, **MG**, Y. Mambrini, K. Olive, M. Peloso and S. Verner, PRD 103 (2021), 123519

1. Beyond WIMPs

2. Inflation & reheating



3. FIMPs

4. Future prospects

5. Conclusion

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	spin 0	spin 1/2	spin 1	spin 3/2	spin 2
SM+DM:	H	u_L	W^0	Ψ	G
				raritron	
	Φ	ν_R			
	inflaton	R-neutrino			

$$\mathcal{L} = -\tfrac{1}{2}\bar{\Psi}_\mu \left(i\gamma^{[\mu}\gamma^{\nu}\gamma^{\rho]}\partial_\rho + m_{3/2}\gamma^{[\mu}\gamma^{\nu]} \right) \Psi_\nu$$

$$+ yH\bar{\nu}_L\nu_R + \frac{M_R}{2}\bar{\nu}_R^c\nu_R \qquad (\nu \text{ masses through see-saw})$$

$$+ y_\nu \Phi \bar{\nu}_R \nu_R \qquad (\text{reheating})$$

1. Beyond WIMPs

2. Inflation & reheating

3. FIMPs

4. Future prospects

5. Conclusion

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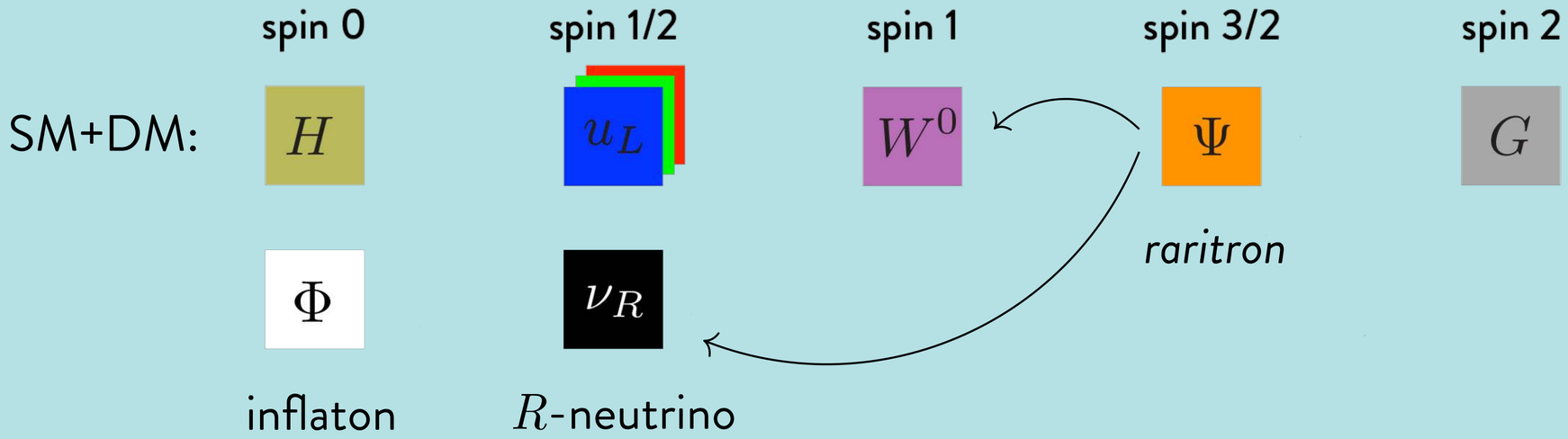
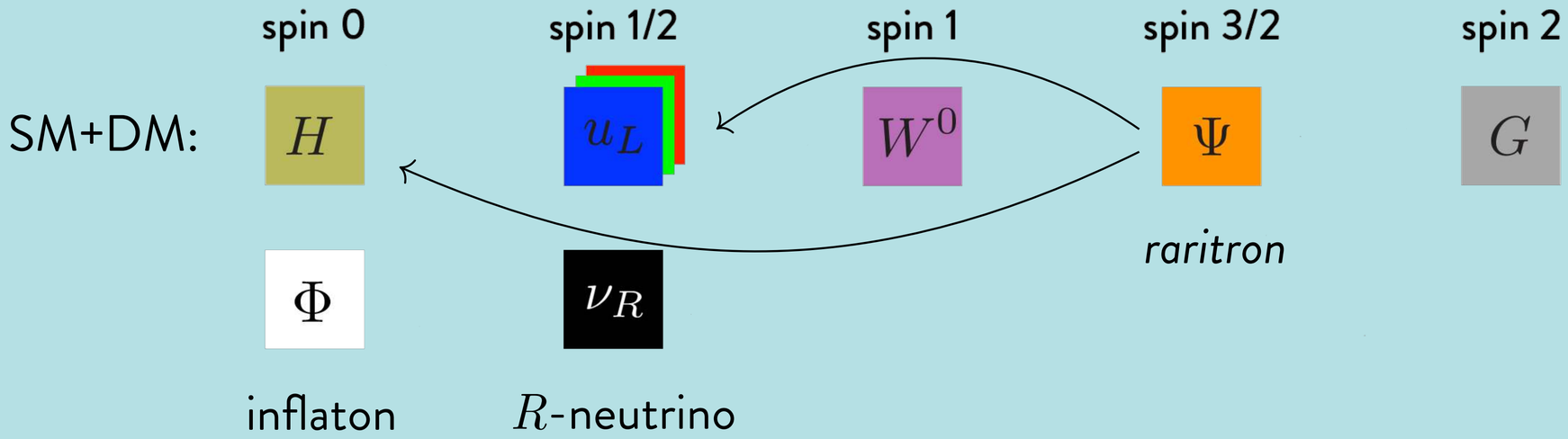


$$\begin{aligned}\mathcal{L} \;=\; & -\tfrac{1}{2}\bar{\Psi}_\mu \left(i\gamma^{[\mu}\gamma^{\nu}\gamma^{\rho]}\partial_\rho + m_{3/2}\gamma^{[\mu}\gamma^{\nu]} \right) \Psi_\nu \\ & + yH\bar{\nu}_L\nu_R + \frac{M_R}{2}\bar{\nu}_R^c\nu_R \\ & + y_\nu \Phi \bar{\nu}_R \nu_R \\ & + i\frac{\alpha_1}{2M_P}\bar{\nu}_R\gamma^\mu[\gamma^\rho,\gamma^\sigma]\Psi_\mu F_{\rho\sigma}\end{aligned}$$

1. Beyond WIMPs
2. Inflation & reheating
3. FIMPs
4. Future prospects
5. Conclusion

Is a spin-$\frac{3}{2}$ dark matter particle the missing piece in the puzzle?



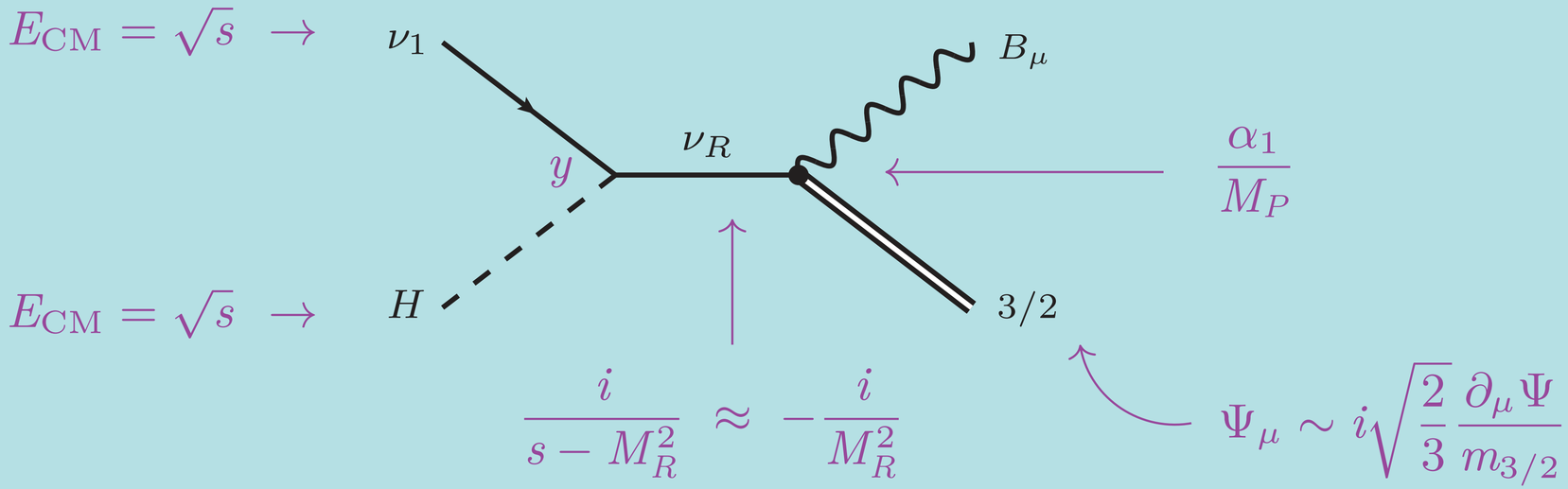
$$\begin{aligned}\mathcal{L} \;=\; & -\tfrac{1}{2}\bar{\Psi}_\mu \left(i\gamma^{[\mu}\gamma^{\nu}\gamma^{\rho]}\partial_\rho + m_{3/2}\gamma^{[\mu}\gamma^{\nu]} \right) \Psi_\nu \\ & + yH\bar{\nu}_L\nu_R + \frac{M_R}{2}\bar{\nu}_R^c\nu_R \\ & + y_\nu \Phi \bar{\nu}_R \nu_R \\ & + i\frac{\alpha_1}{2M_P}\bar{\nu}_R\gamma^\mu[\gamma^\rho,\gamma^\sigma]\Psi_\mu F_{\rho\sigma} + i\frac{\alpha_2}{2M_P} i\sigma_2 (D^\mu H)^* \bar{L}\Psi_\mu + \cdots\end{aligned}$$

MG, Y. Mambrini, K. A. Olive and S. Verner, PRD 102 (2020), 083533

1. Beyond WIMPs
2. Inflation & reheating
3. FIMPs
4. Future prospects
5. Conclusion

Scatterings and decays

$$\mathcal{L}_{3/2} = \boxed{i\frac{\alpha_1}{2M_P}\bar{\nu}_R\gamma^\mu[\gamma^\rho,\gamma^\sigma]\Psi_\mu F_{\rho\sigma}} + i\frac{\alpha_2}{2M_P}i\sigma_2(D^\mu H)^*\bar{L}\Psi_\mu + \text{h.c.}$$



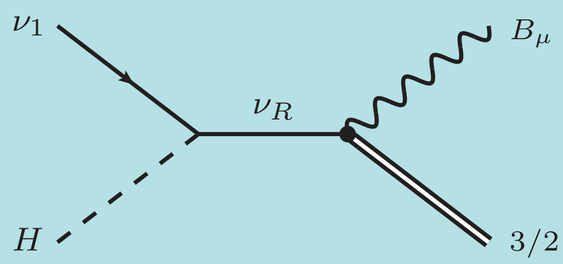
$$\Rightarrow \qquad \sigma(s) \propto \frac{\alpha_1^2 y^2 s^2}{m_{3/2}^2 M_R^2 M_P^2}$$

- Production peaked at high energies → reheating
- Ψ is never in thermal equilibrium (*freeze-in*)

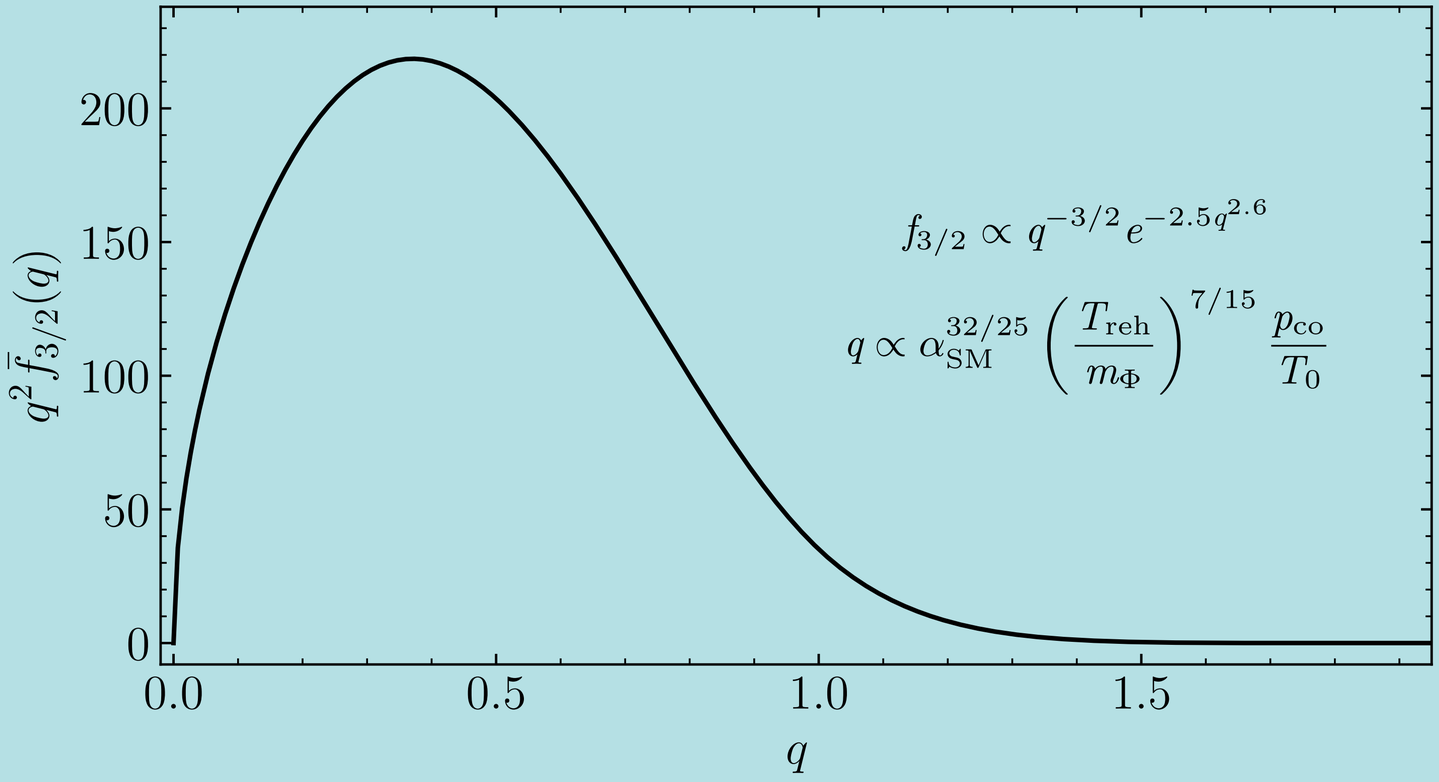
1. Beyond WIMPs
2. Inflation & reheating
3. FIMPs
4. Future prospects
5. Conclusion

Scatterings and decays

not equilibrated



$$\Omega_{3/2} \propto \alpha_1 \frac{m_\nu m_\Phi^2 T_{\rm reh}^3}{m_{3/2} M_R t_{\rm therm}}$$



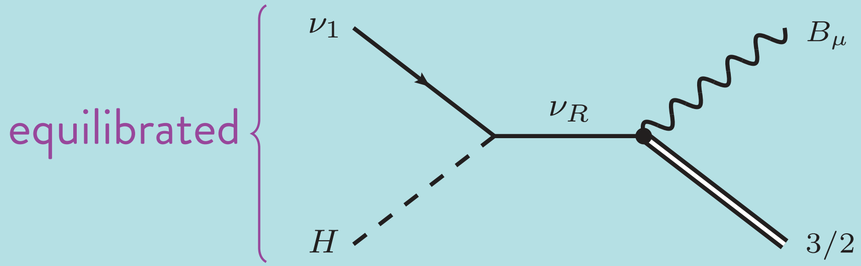
$$f_{3/2} \propto q^{-3/2} e^{-2.5 q^{2.6}}$$

$$q \propto \alpha_{\rm SM}^{32/25} \left(\frac{T_{\rm reh}}{m_\Phi} \right)^{7/15} \frac{p_{\rm co}}{T_0}$$

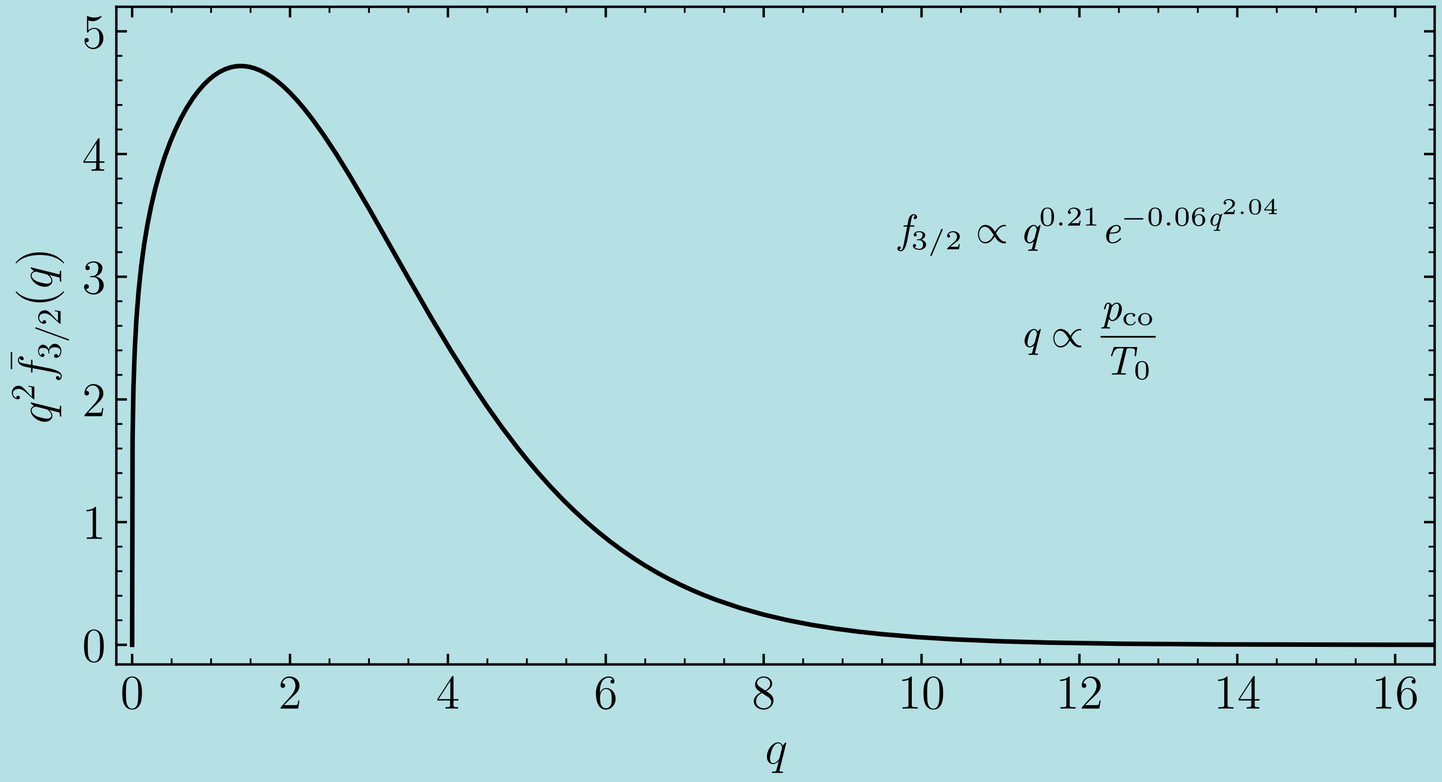
MG and M. A. Amin, PRD 98 (2018), 103504; G. Ballesteros, **MG** and M. Pierre, JCAP 03 (2021), 101

1. Beyond WIMPs
2. Inflation & reheating
3. FIMPs
4. Future prospects
5. Conclusion

Scatterings and decays



$$\Omega_{3/2} \;\propto\; \alpha_1 \frac{m_\nu\, T_{\rm reh}^5}{m_{3/2} M_R}$$



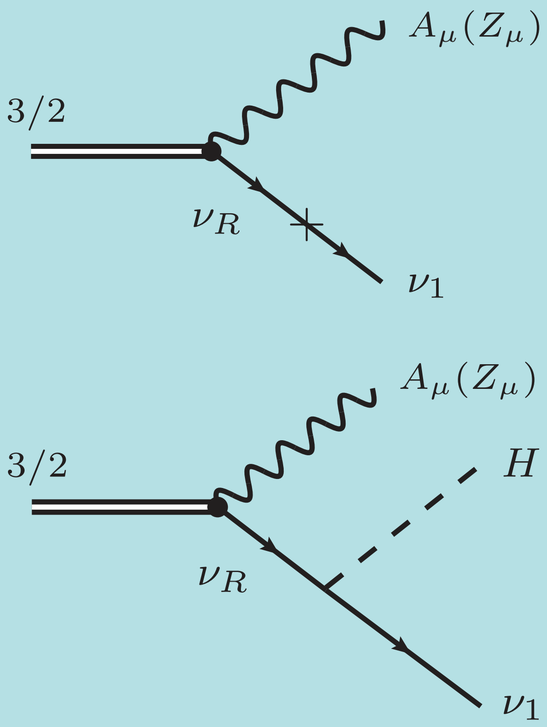
$$f_{3/2} \propto q^{0.21}\, e^{-0.06 q^{2.04}}$$

$$q \propto \frac{p_{\rm co}}{T_0}$$

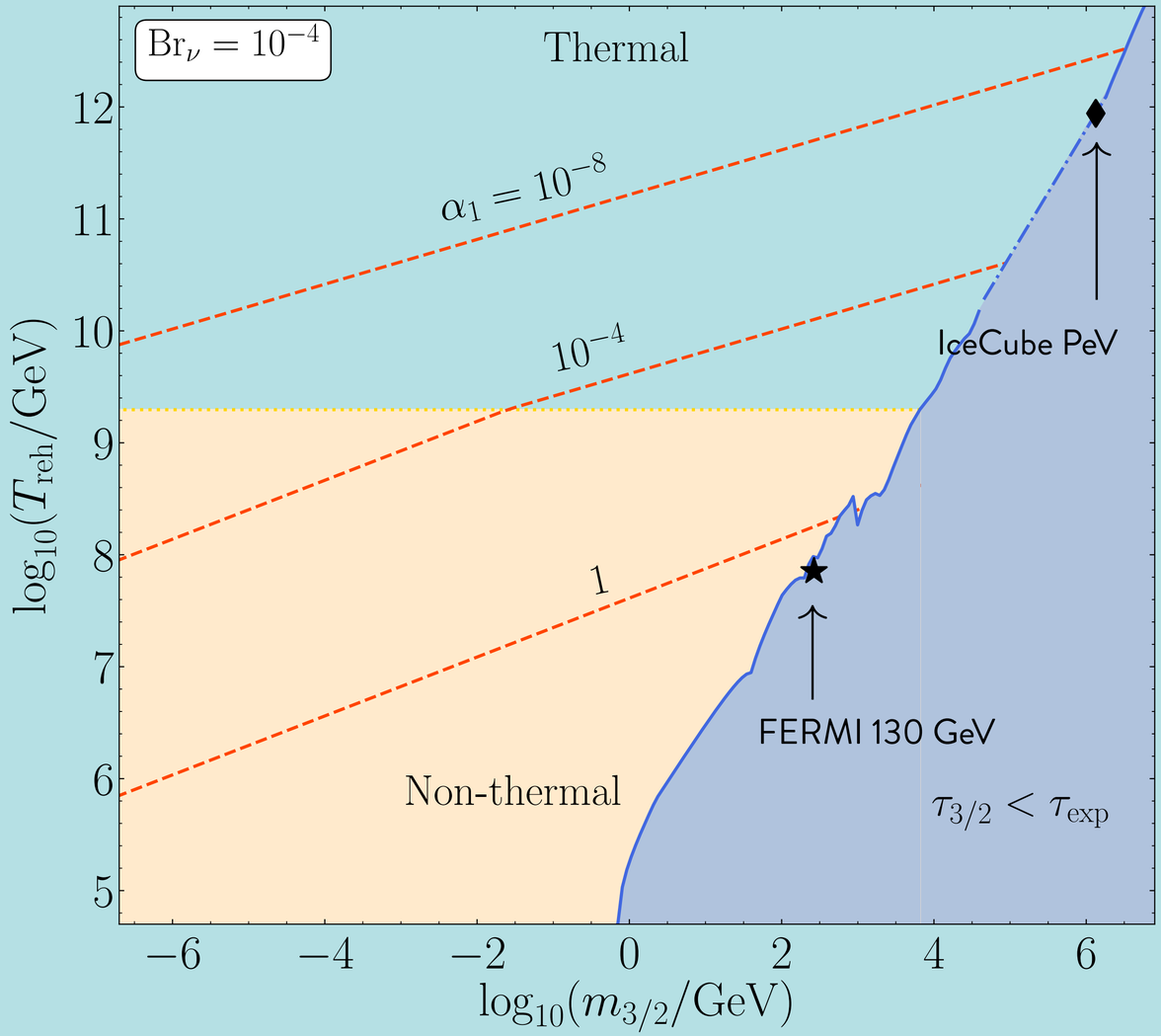
G. Ballesteros, **MG** and M. Pierre, JCAP 03 (2021), 101

1. Beyond WIMPs
2. Inflation & reheating
3. FIMPs
4. Future prospects
5. Conclusion

Scatterings and decays

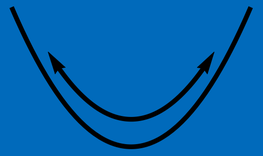


Scattering



1. Beyond WIMPs

2. Inflation & reheating

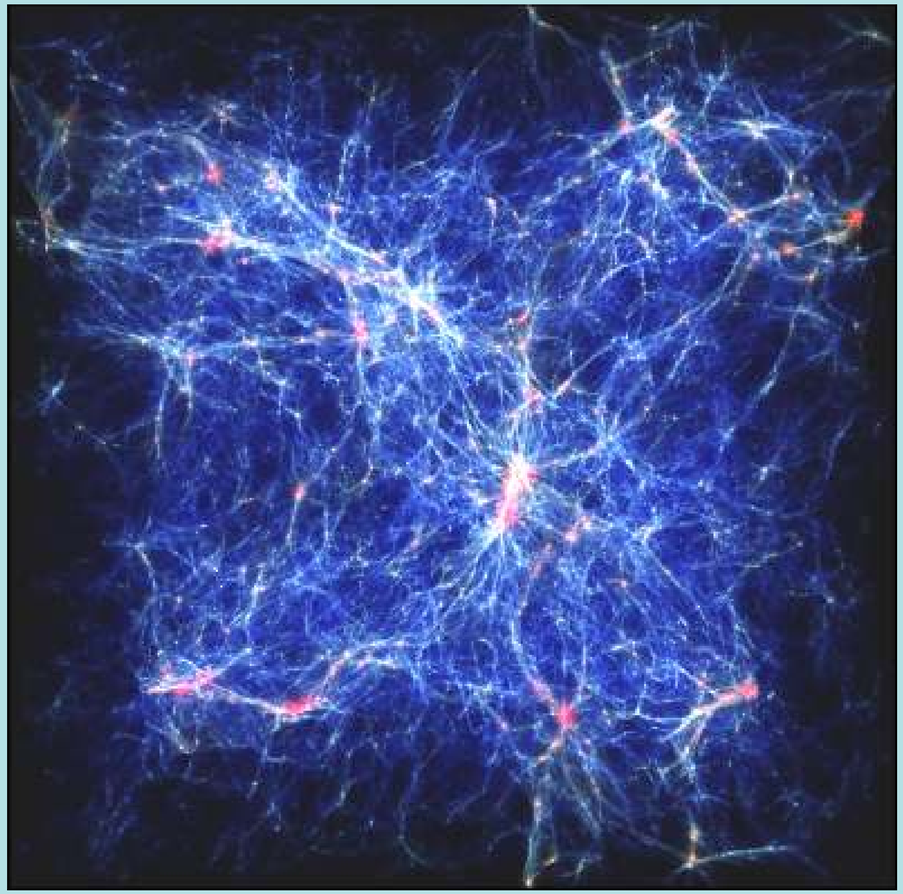


3. FIMPs

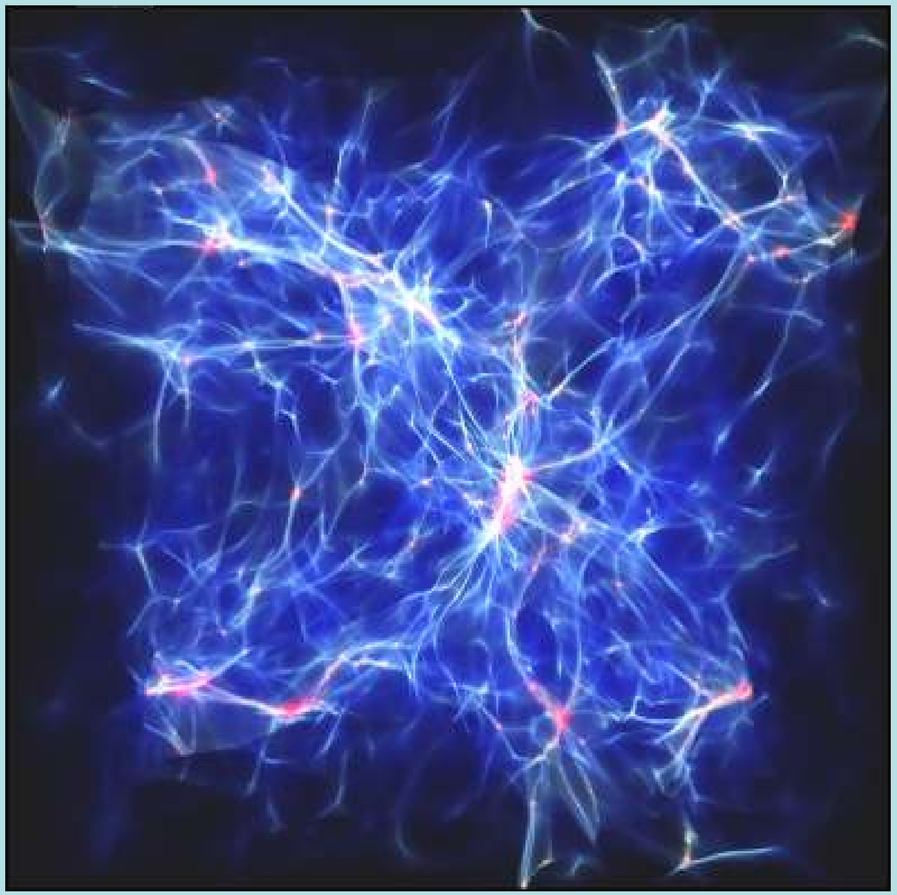
4. Future prospects

5. Conclusion

How warm is out-of-equilibrium dark matter?



CDM

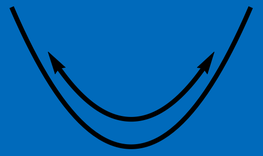


WDM (0.5 keV)

J. Baur et al., JCAP 08 (2016), 012

1. Beyond WIMPs

2. Inflation & reheating



3. FIMPs

4. Future prospects

5. Conclusion

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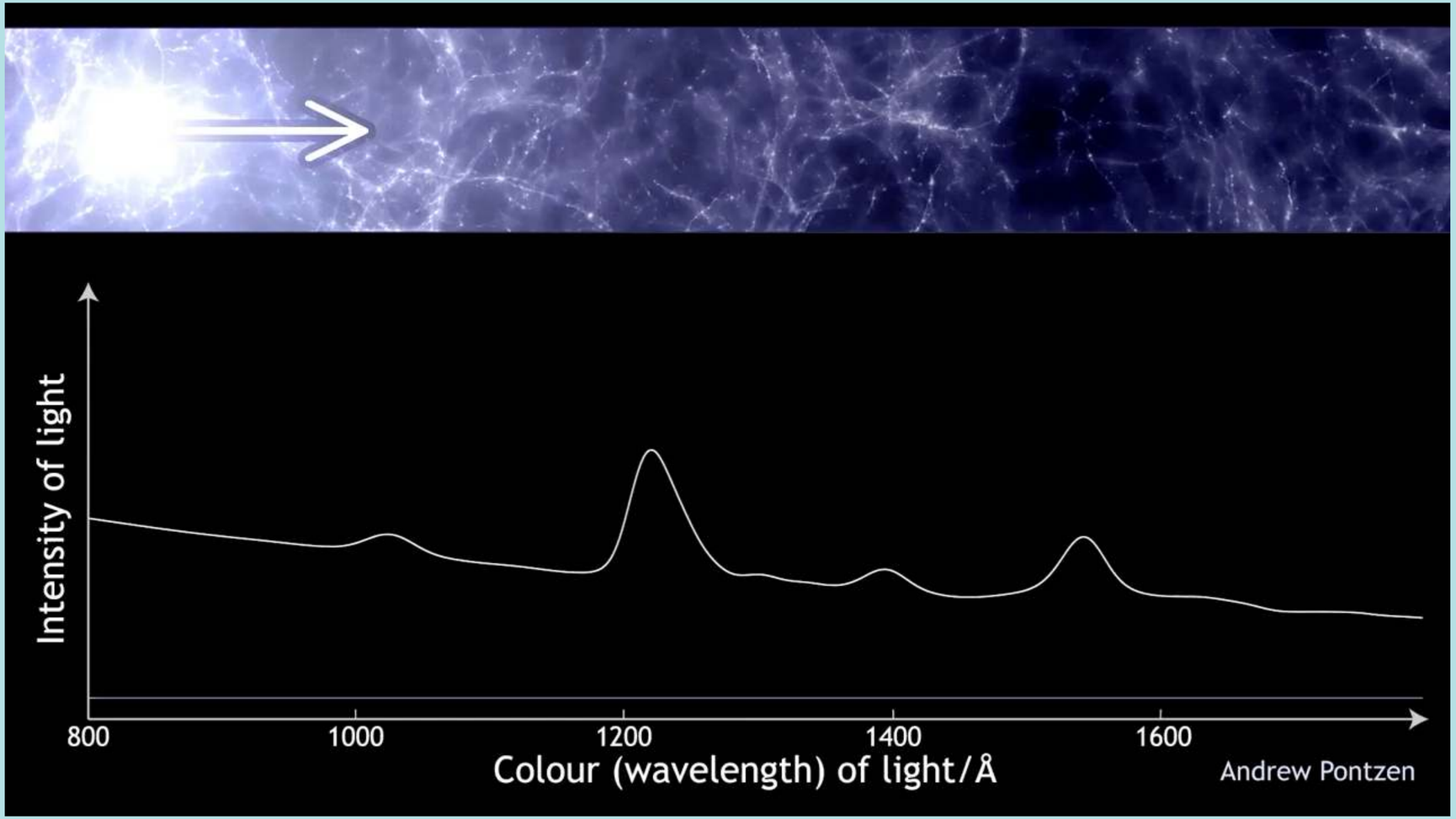

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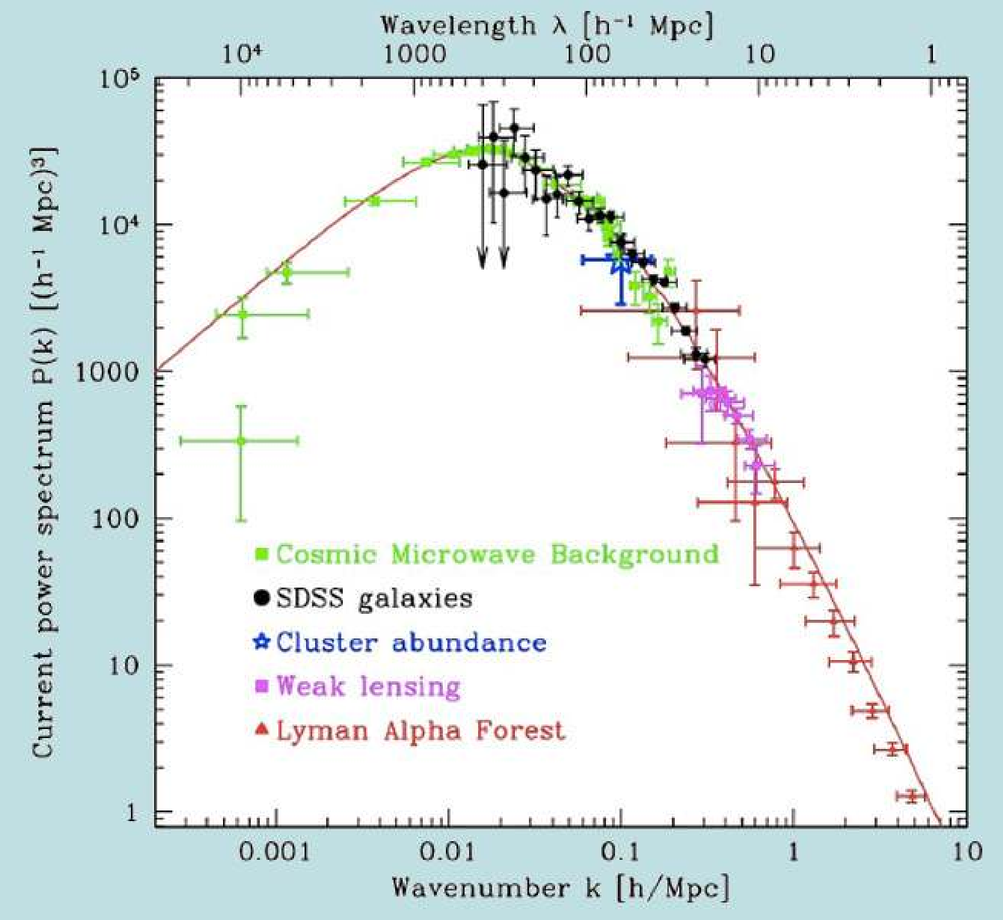
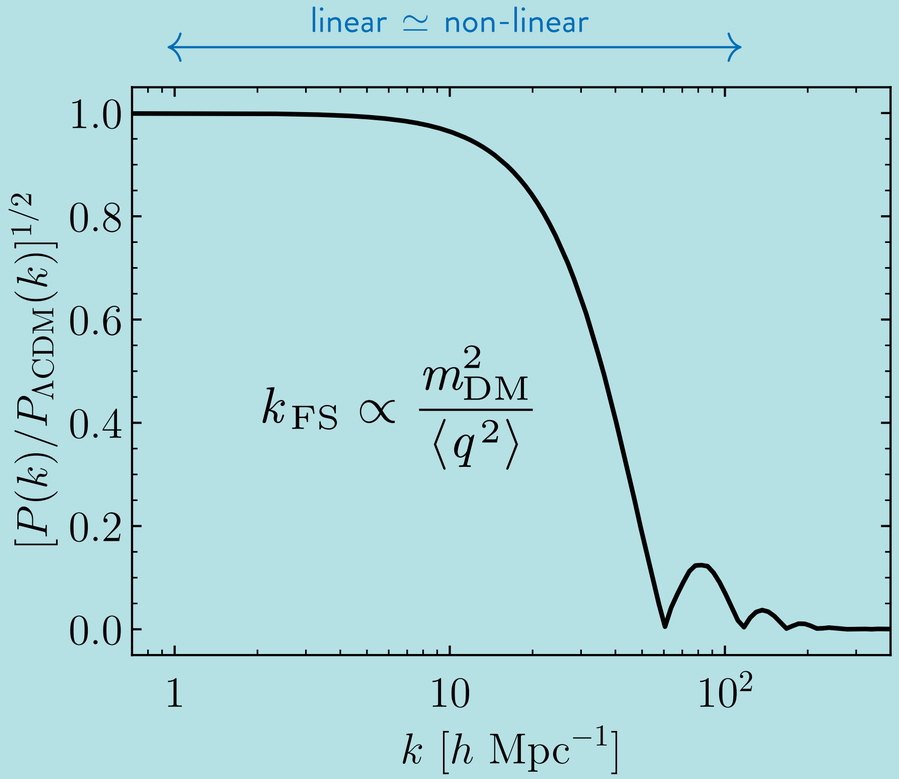


R. Murgia, V. Iršič and M. Viel, PRD 98 (2018), 083540



G. Ballesteros, **MG** and M. Pierre, JCAP 03 (2021), 101

1. Beyond WIMPs

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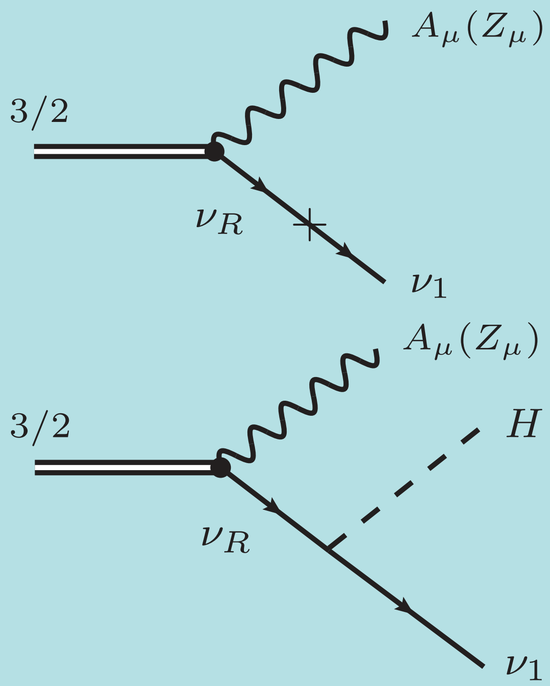
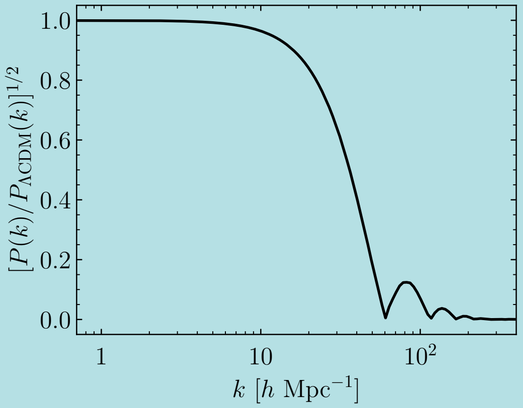
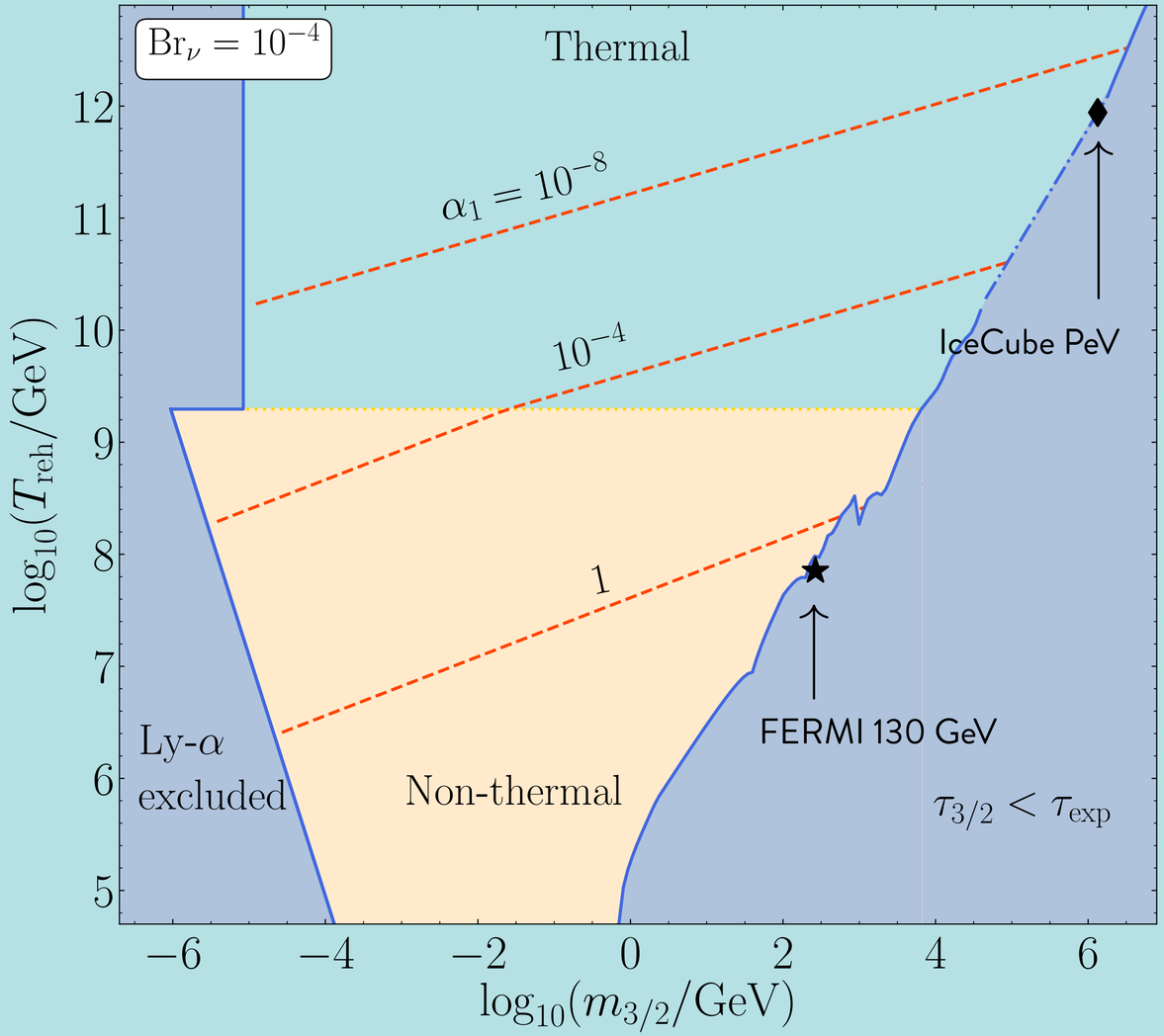
Constraints: $\Omega_{\rm DM} + \gamma + \nu +$ Lyman-α





Scattering



1. Beyond WIMPs
2. Inflation & reheating
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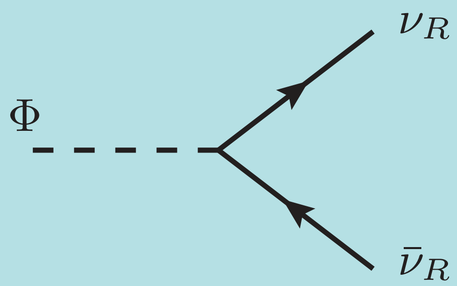
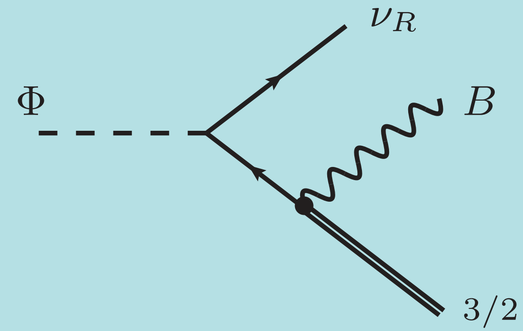
Production (via inflaton decay)

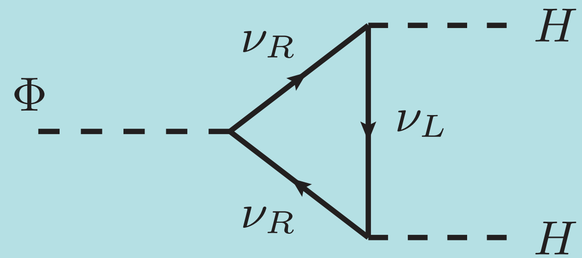
Via α_1,

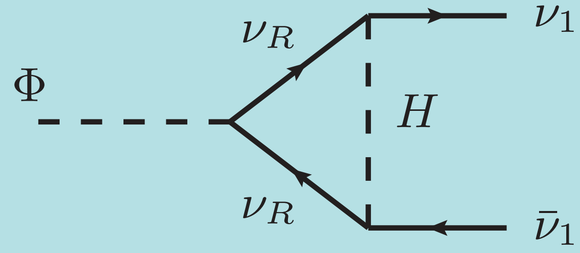
$M_R \ll m_\Phi$:

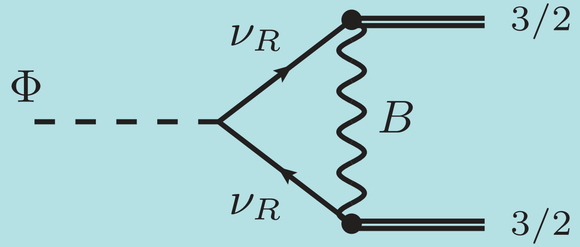




$M_R \gg m_\Phi$:







(via α_2 are 2-loop suppressed)

1. Beyond WIMPs

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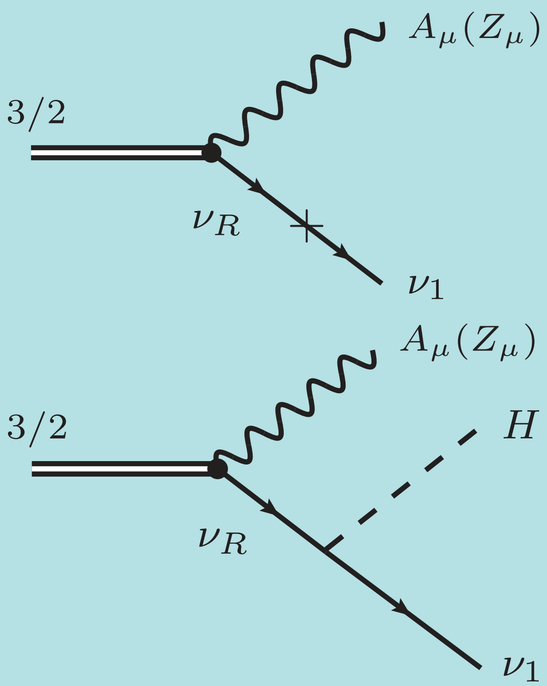
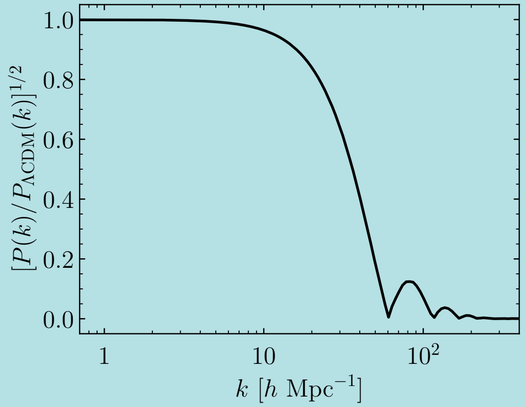
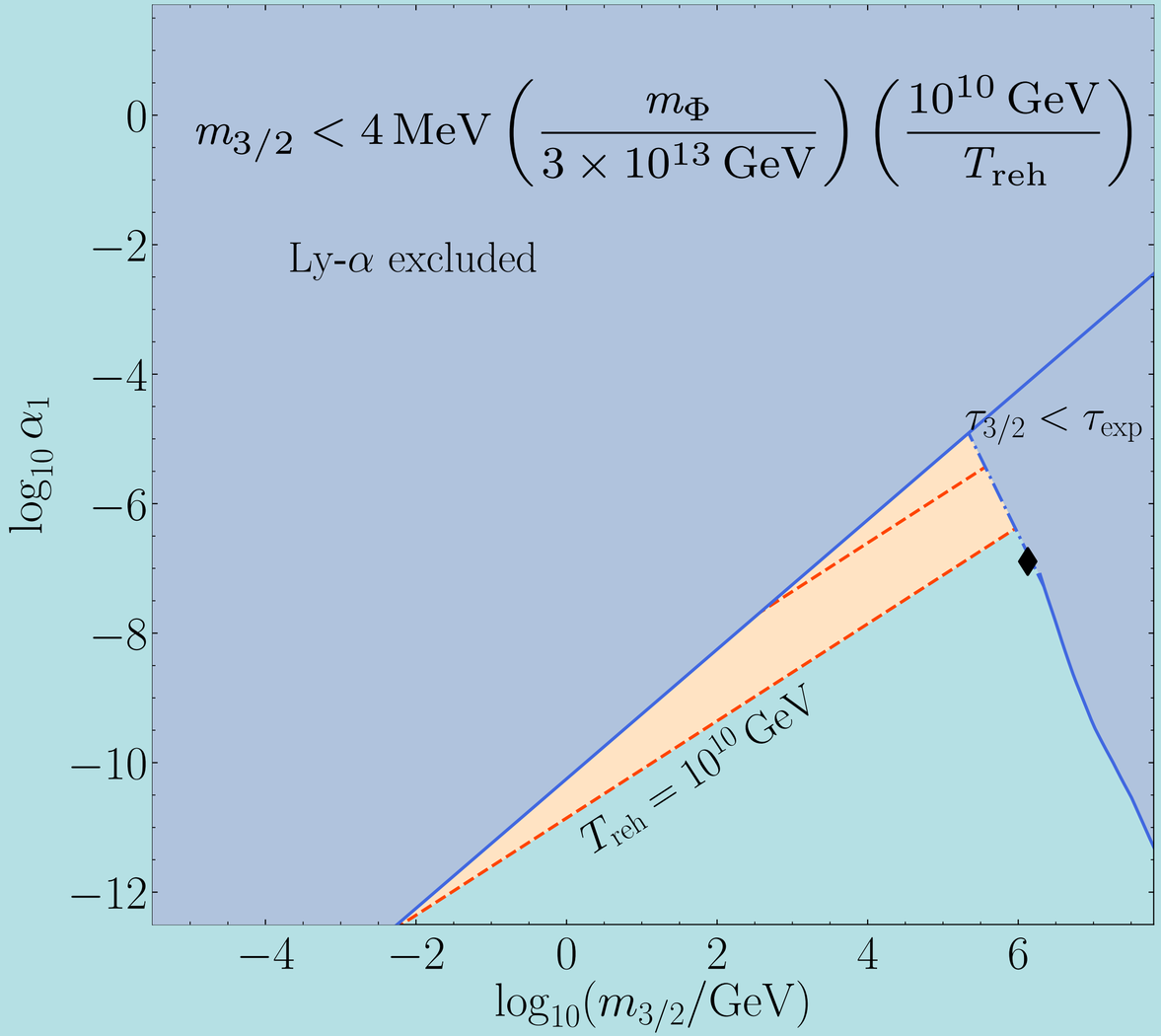
5. Conclusion

Constraints: $\Omega_{\rm DM} + \gamma + \nu +$ Lyman-α





Inflaton decay



1. Beyond WIMPs
2. Inflation & reheating
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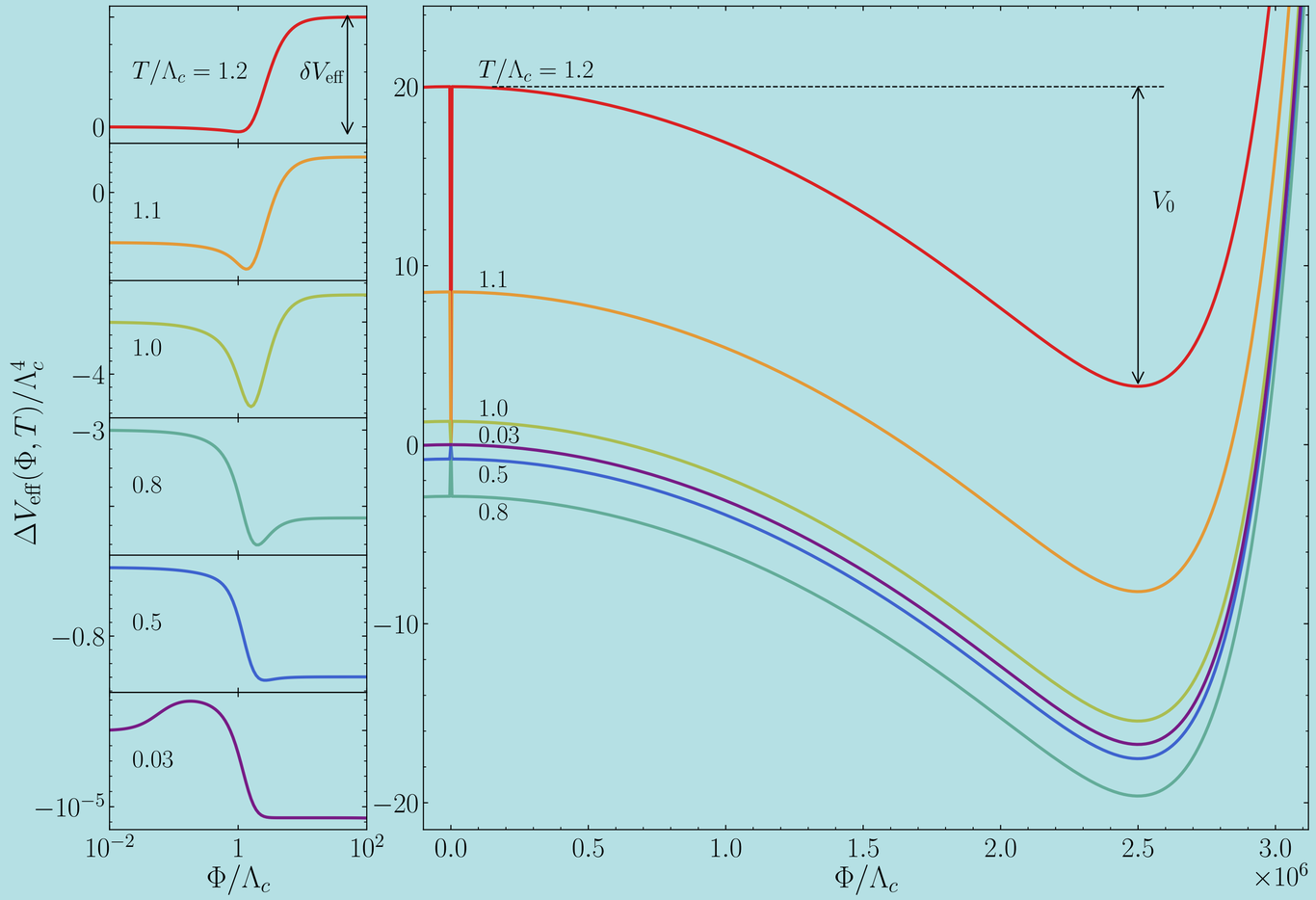
5. Conclusion

UV completions: No Scale Inflation + GUTs

Flipped SU(5)×U(1) → GUT symmetry breaking *after* inflation



J. Ellis, **MG**, N. Nagata, D. Nanopoulos and K. Olive, JCAP 07 (2017), 006; JCAP 04 (2019), 009; PLB 797 (2019), 134864

1. Beyond WIMPs

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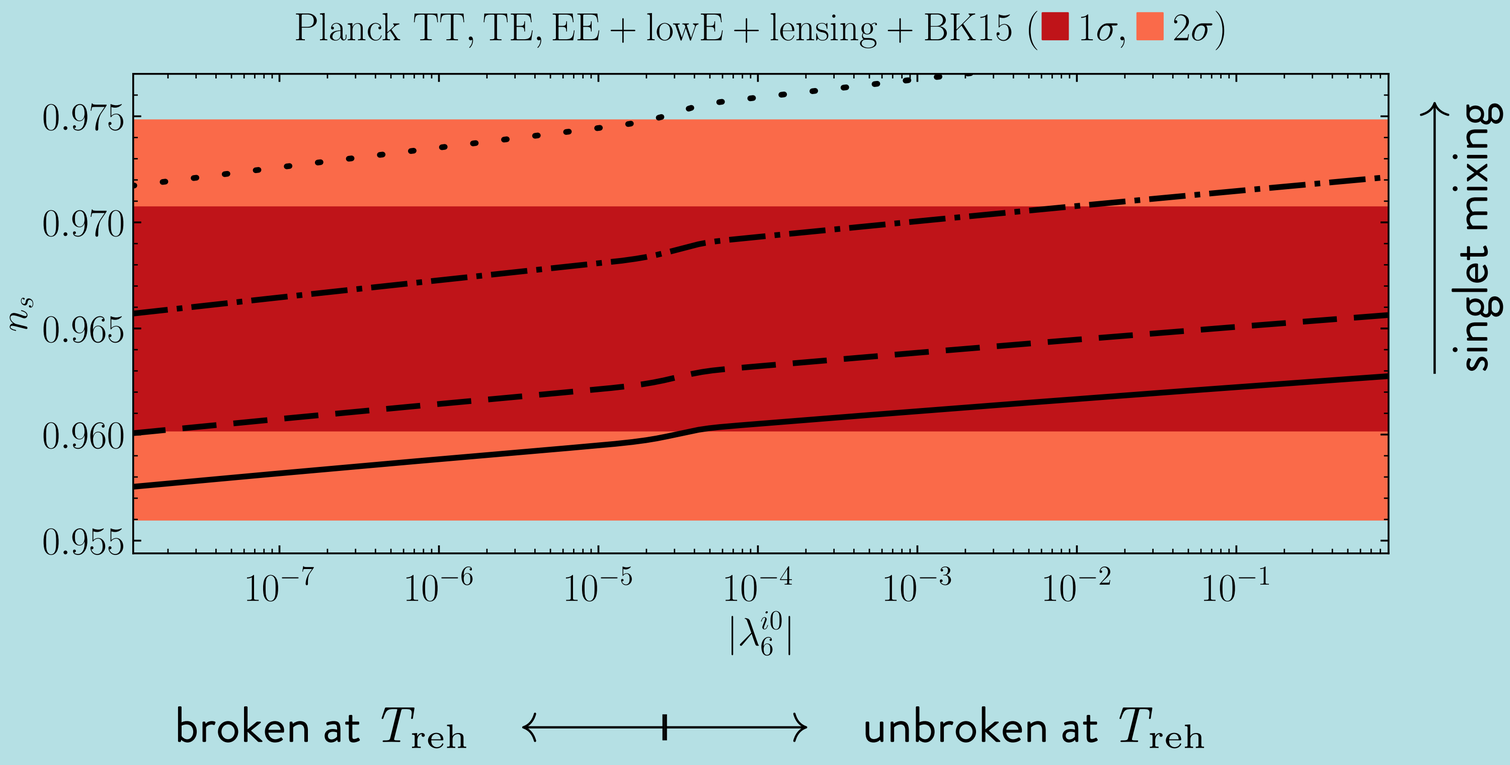
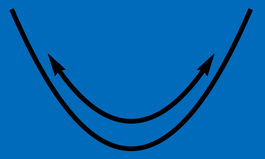


1. Beyond WIMPs

2. Inflation & reheating



3. FIMPs

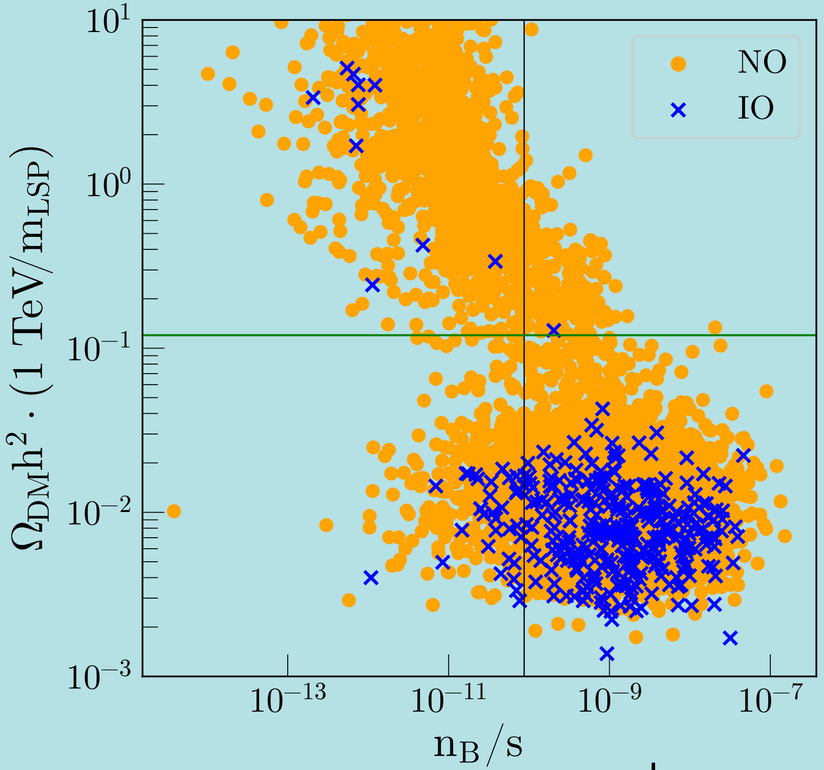
4. Future prospects

5. Conclusion

UV completions: No Scale Inflation + GUTs

Flipped SU(5)×U(1) → GUT symmetry breaking *after* inflation

dark matter



neutrino masses

baryon asymmetry

1. Beyond WIMPs
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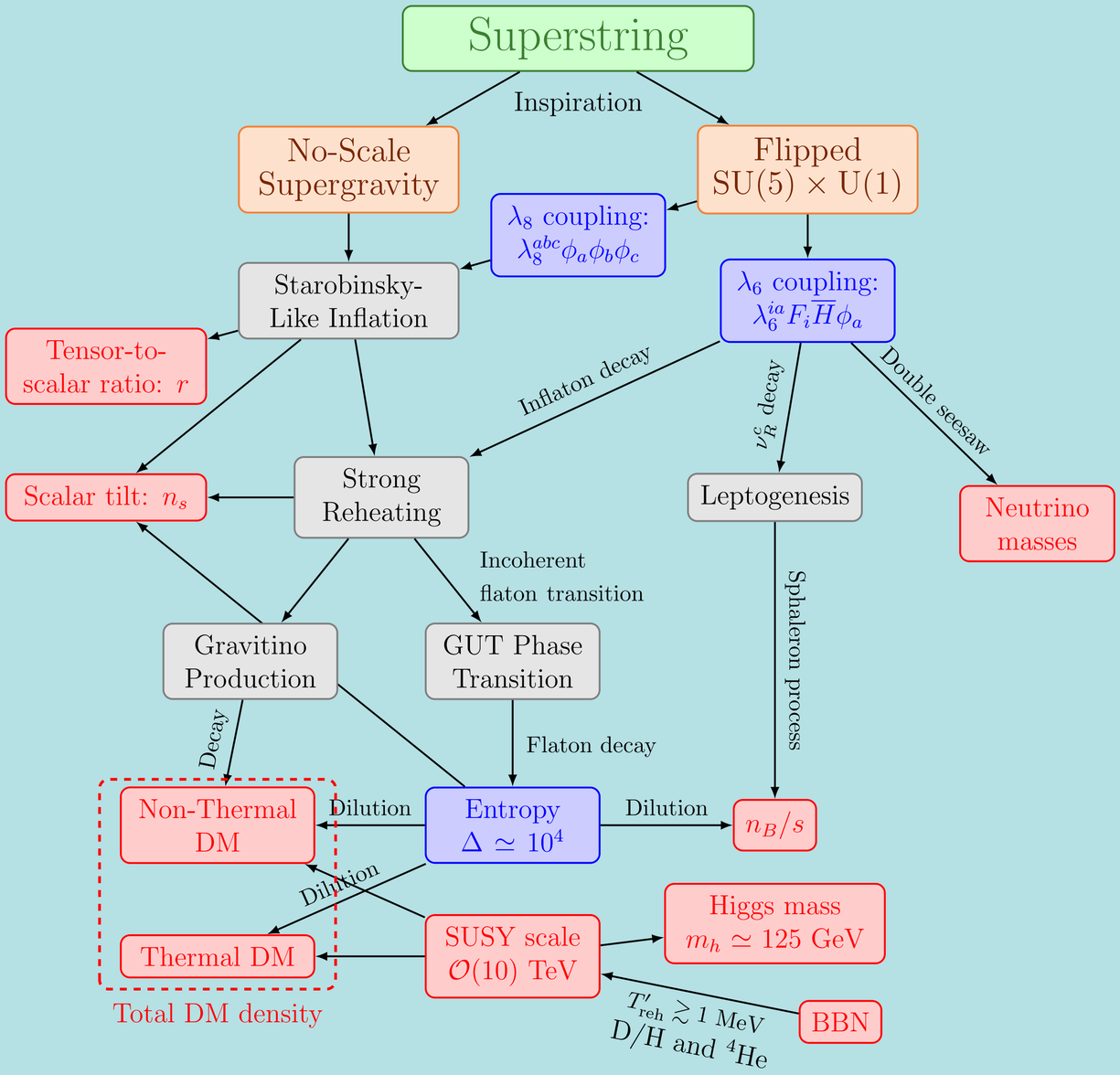
5. Conclusion

UV completions: Supercosmology



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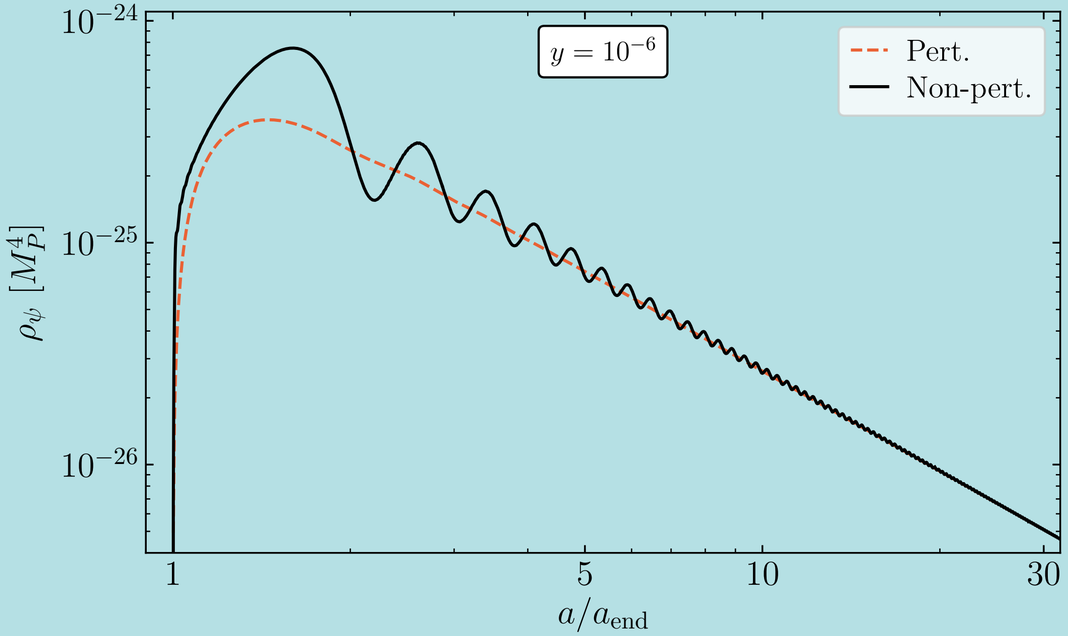
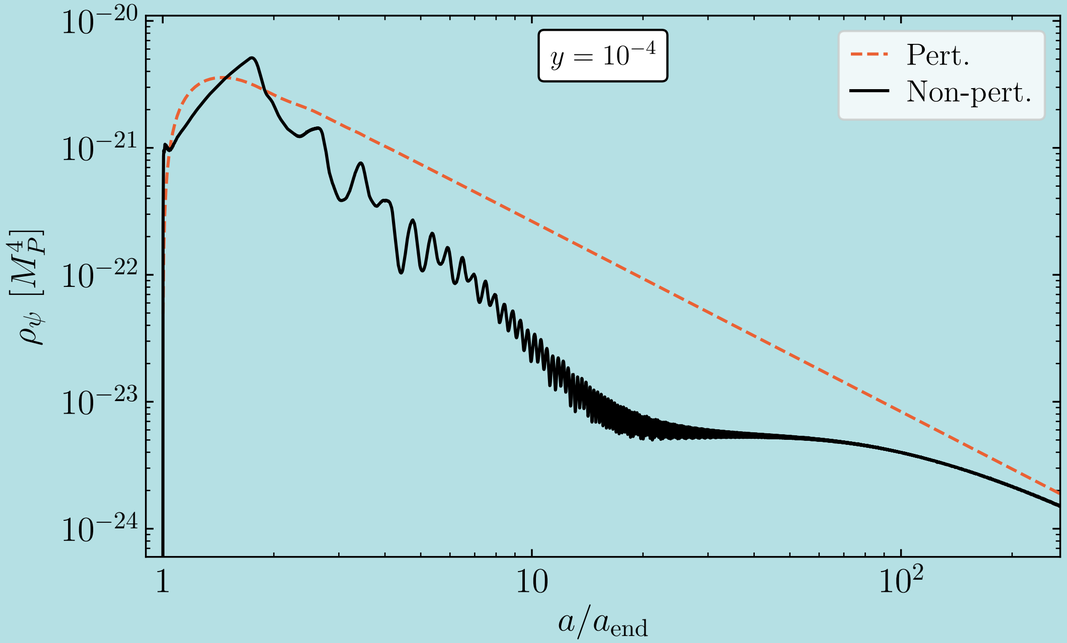
Preheating and Dark Matter

SHORT TERM





Early times: **field picture** (limited dissipation)

interactions (thermalization)

Late times: **fluid picture** (no fluctuations)

1. Beyond WIMPs

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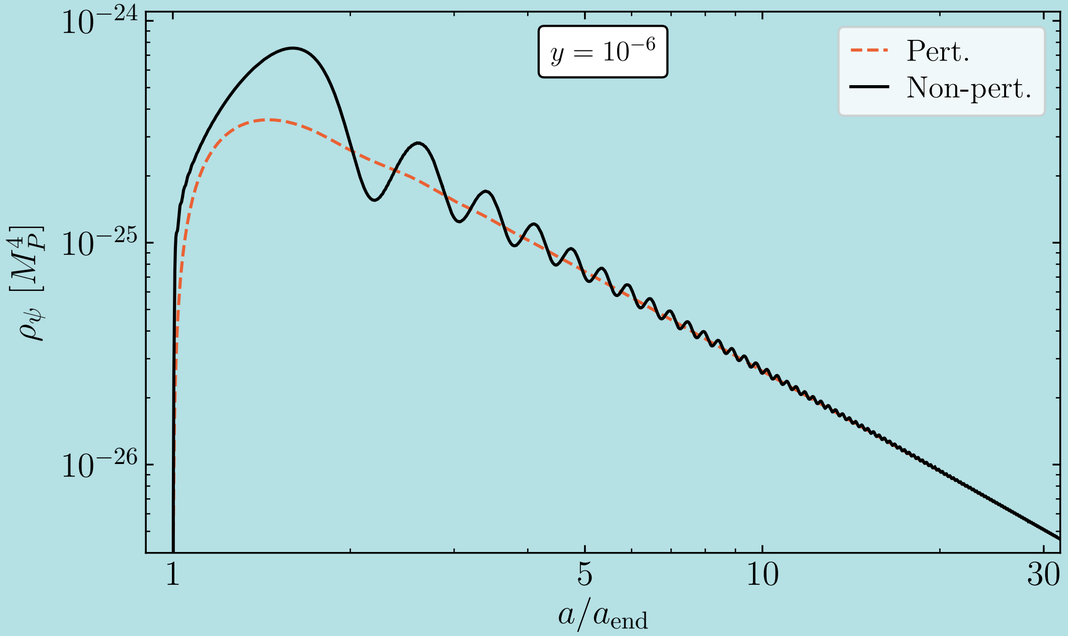
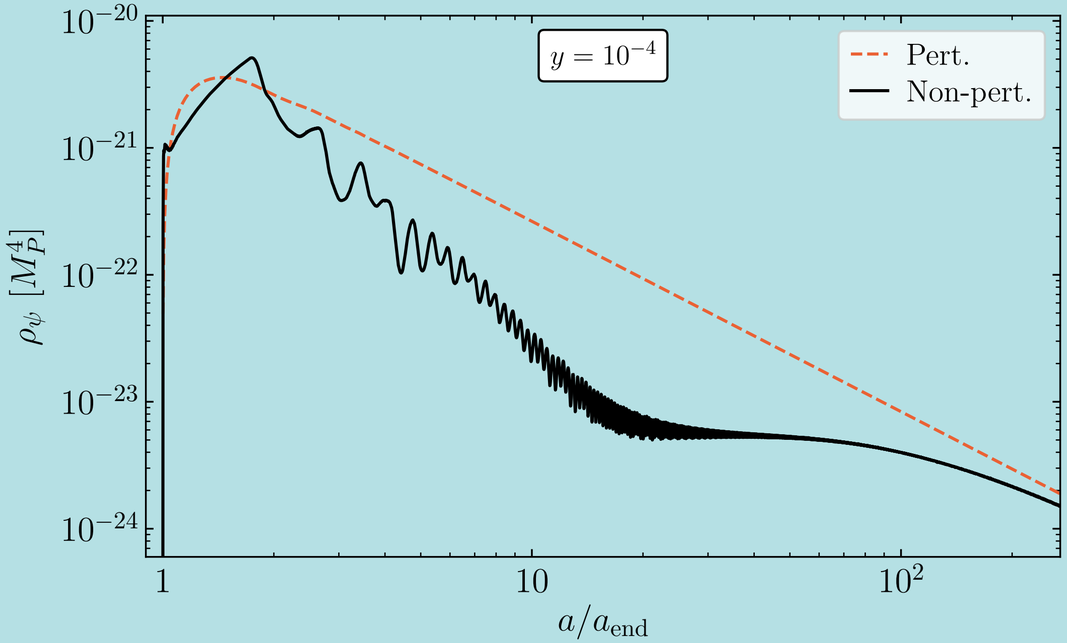
5. Conclusion

Preheating and Dark Matter

SHORT TERM





Early times: **field picture** (limited dissipation)

↓

Schiwnger-Keldysh / Kadanoff-Baym

Boltzmann

↓

Late times: **fluid picture** (no fluctuations)

1. Beyond WIMPs
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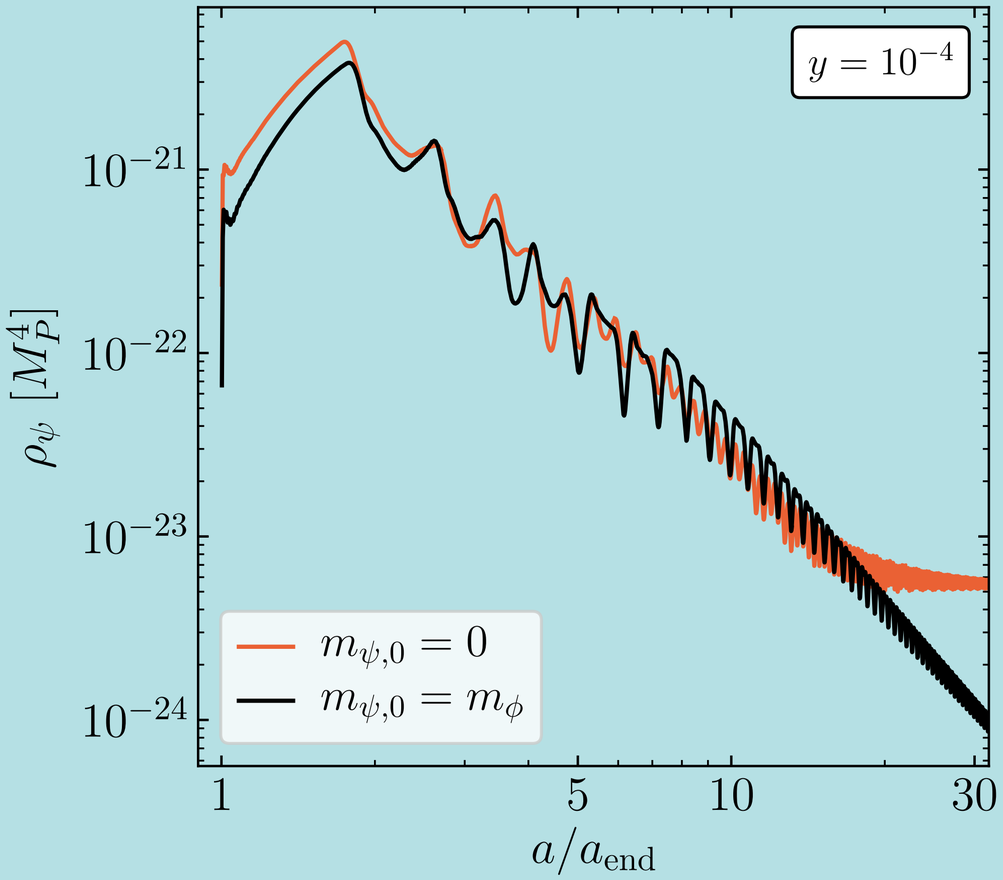
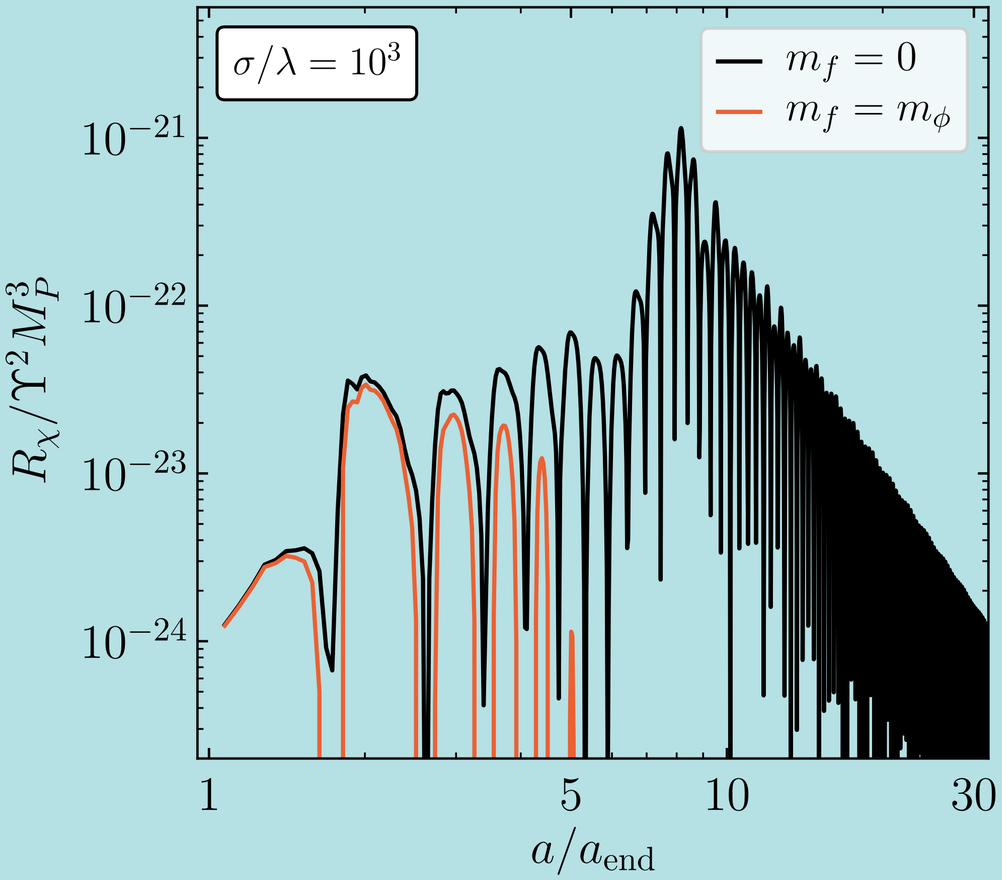
Beyond perturbation theory

SHORT TERM

Super-heavy dark matter (WIMPzillas, ...)

E. Kolb, D. Chung and A. Riotto, AIP Conf. Proc. 484 (1999), 91





(but not thermally though)

MG, K. Kaneta, Y. Mambrini and K. Olive, JCAP 04 (2021), 012

1. Beyond WIMPs
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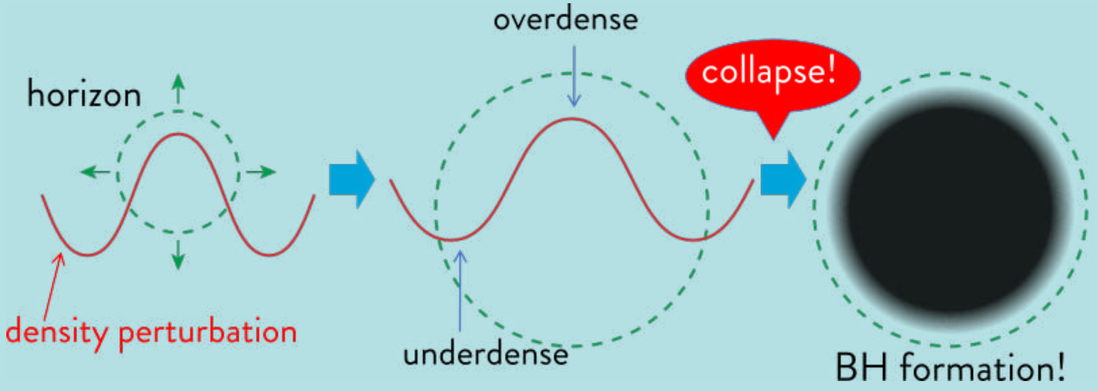
5. Conclusion

SHORT TERM

Large metric fluctuations?



Credit: Naoya Kitajima

Metric preheating $\rightarrow$ overdensities $\rightarrow$ light PBHs $\rightarrow$ (Hawking) reheating

$M_{\rm BH}$	$\tau_{\rm BH}$
A man	10^{-12} s
10^{15} g	10^{10} y
Earth	10^{49} y
Sun	10^{66} y
Milky Way	10^{99} y

$$\frac{\delta\rho_C}{\rho} \gtrsim 0.5$$

$$M_{\rm BH} \propto \rho_{\rm form}/H^3_{\rm form} < 10^9\,{\rm g}$$

$$\tau_{\rm BH} \approx 10^{64}\left(\frac{M}{M_\odot}\right)^3 {\rm y}$$

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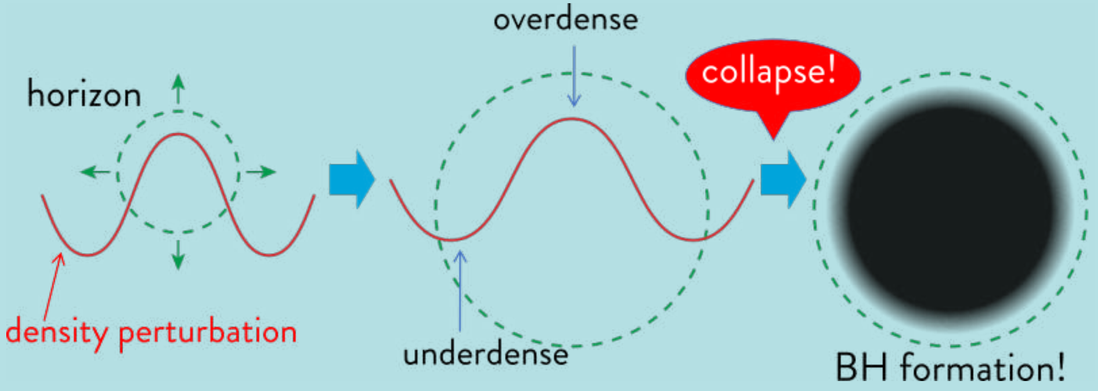
Large metric fluctuations?

SHORT TERM



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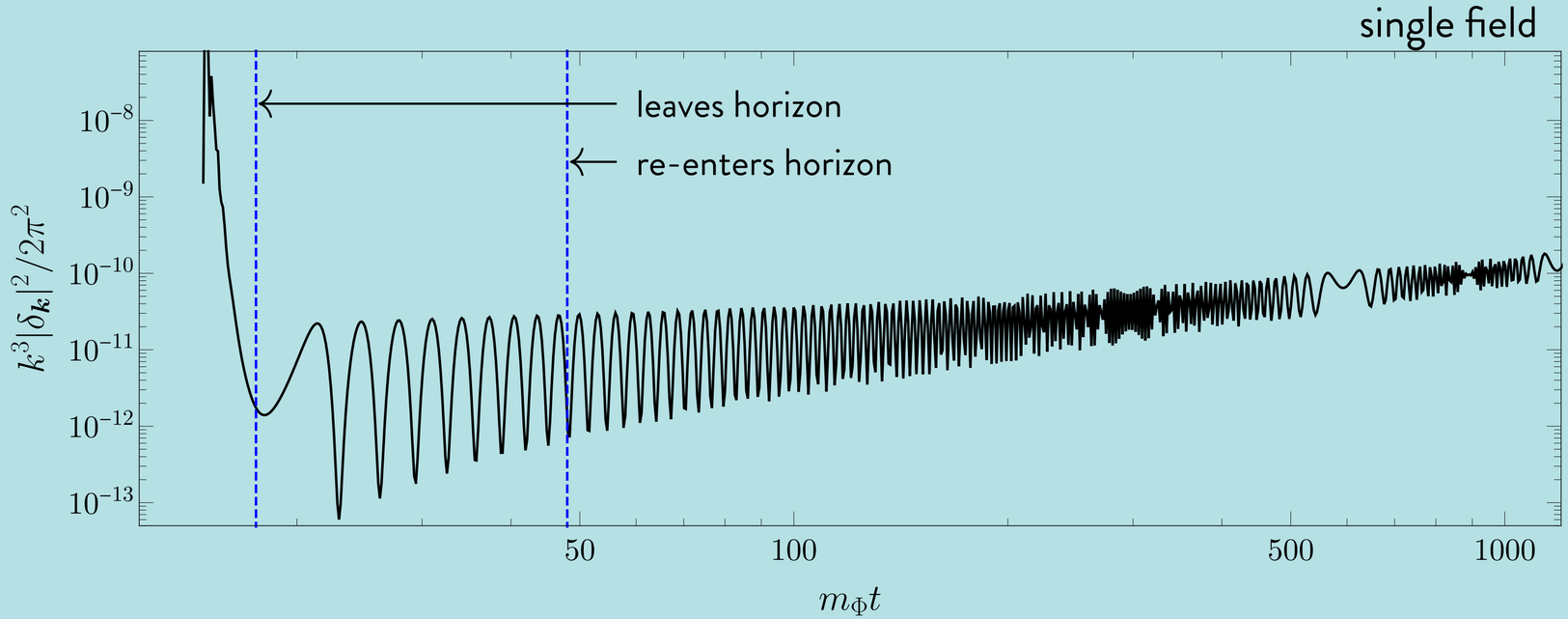


K. Jedamzik, M. Lemoine and J. Martin, JCAP 09 (2010), 034; A. Gómez, **MG**, G. Ballesteros, M. Pierre, *on it*

1. Beyond WIMPs
2. Inflation & reheating
3. FIMPs
4. Future prospects
5. Conclusion

Dark matter from inflation

SHORT TERM

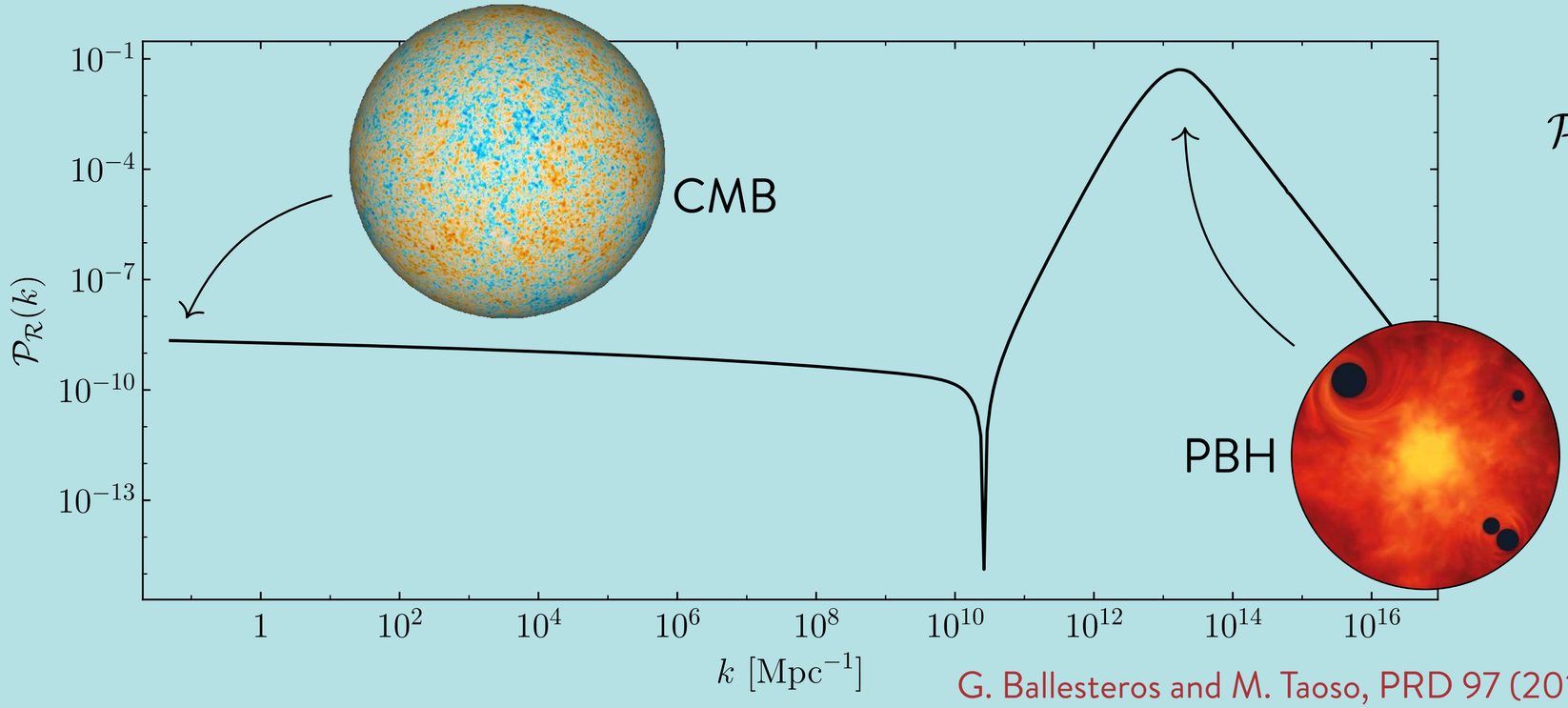
ON THE CONCENTRATION OF RELIC MAGNETIC MONOPOLES IN THE UNIVERSE

Ya.B. ZELDOVICH and M.Yu. KHLOPOV
Institute of Applied Mathematics, Academy of Sciences of the USSR, Moscow 125047, USSR

PLB 79 (1978), 239

Inflation efficiently dilutes relics, dangerous or not

But inflation can lead to overdensities



$$\mathcal{P}_\mathcal{R} \propto \dot{\Phi}^{-2}$$

G. Ballesteros and M. Taoso, PRD 97 (2018), 023501

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SHORT TERM

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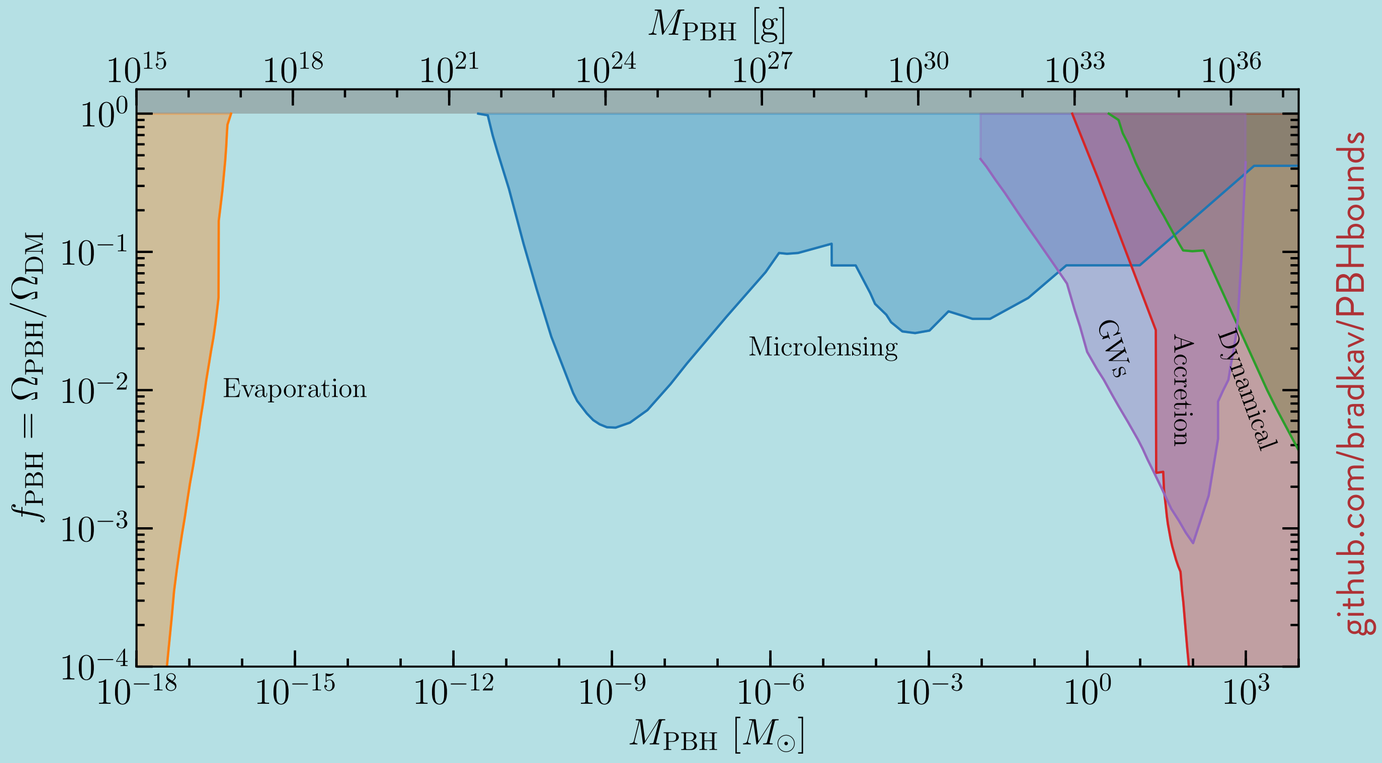

github.com/bradkav/PBHbounds

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2. Inflation & reheating
3. FIMPs
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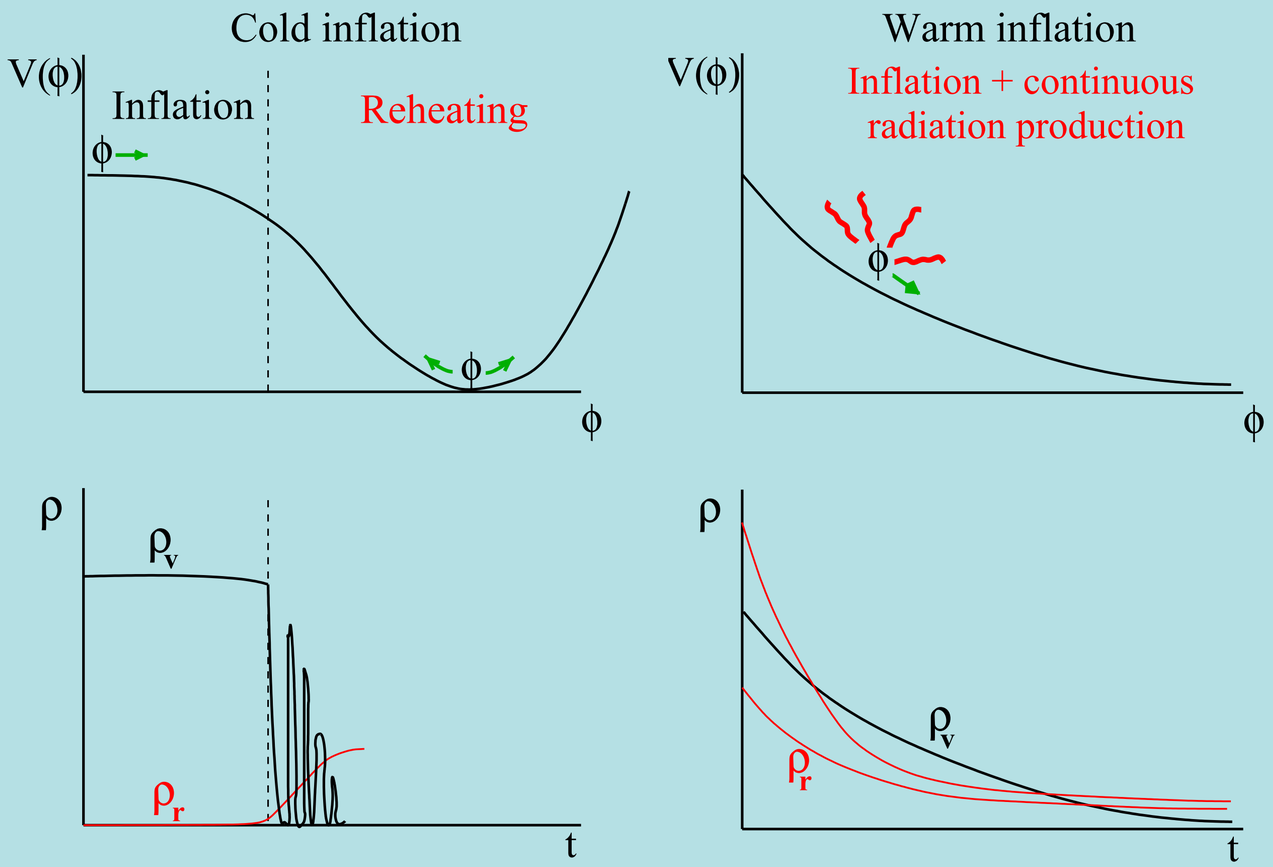
5. Conclusion

Warm inflation?

SHORT TERM



A. Berera, PRL 75 (1995), 3218

A. Berera, I. G. Moss and R. O. Ramos, Rept. Prog. Phys. 72 (2009), 026901

A. Pérez, **MG**, G. Ballesteros, M. Pierre, J. Rey, *on it*

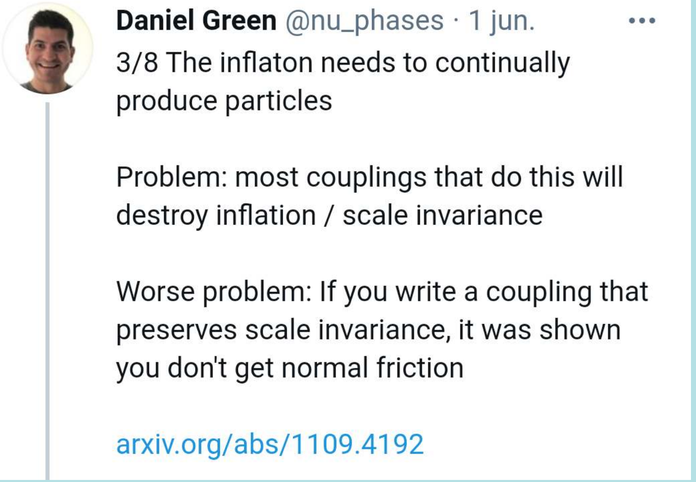
Inflaton slows down by thermal friction

$$\ddot{\Phi} + (3H + \Gamma)\dot{\Phi} + V_\Phi = 0$$

$$\dot{\rho}_r + 4H\rho_r - \Gamma\dot{\Phi}^2 = 0$$

Thermal noise is an extra source of density fluctuations

$$\delta\ddot{\Phi}_k + (3H + \Gamma)\delta\dot{\Phi}_k = \xi_k + \cdots$$



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5. Conclusion

Supersymmetry in the Early Universe

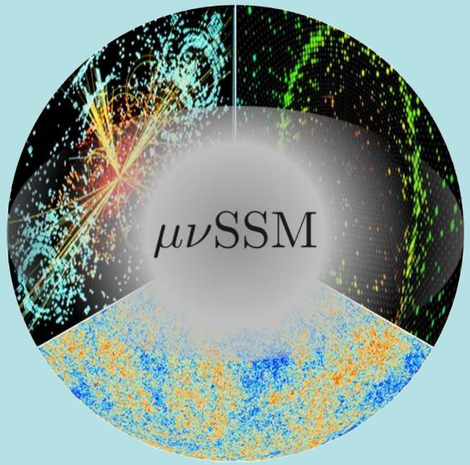
SHORT TERM

Is there a need for intermediate mass scales?

$$W = \lambda^i \nu_i^c H_1 H_2 + \kappa^{ijk} \nu_i^c \nu_j^c \nu_k^c$$

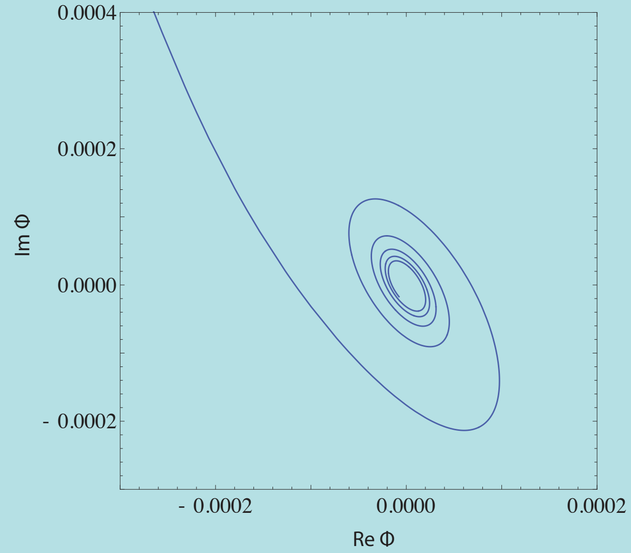
MG, D. López-Fogliani, C. Muñoz, *on it*

EW physics



ν spectrum

H-ν_R inflation



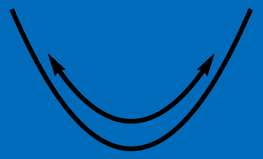
Origin of the matter-antimatter asymmetry
(Twisted Affleck Dine, non-perturbative leptogenesis, ...)

MG and K. A. Olive, JCAP 09 (2013), 007

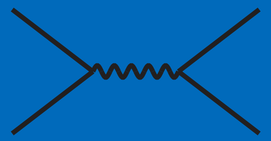
Initial conditions for inflation (non-perturbative: see next slide)

1. Beyond WIMPs

2. Inflation & reheating



3. FIMPs

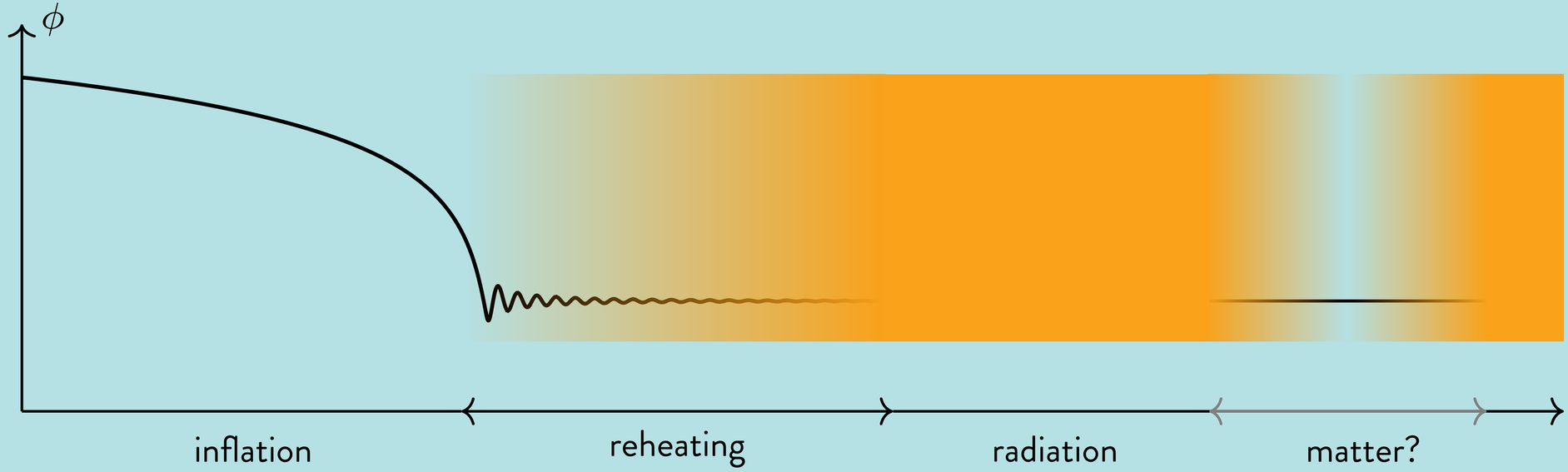


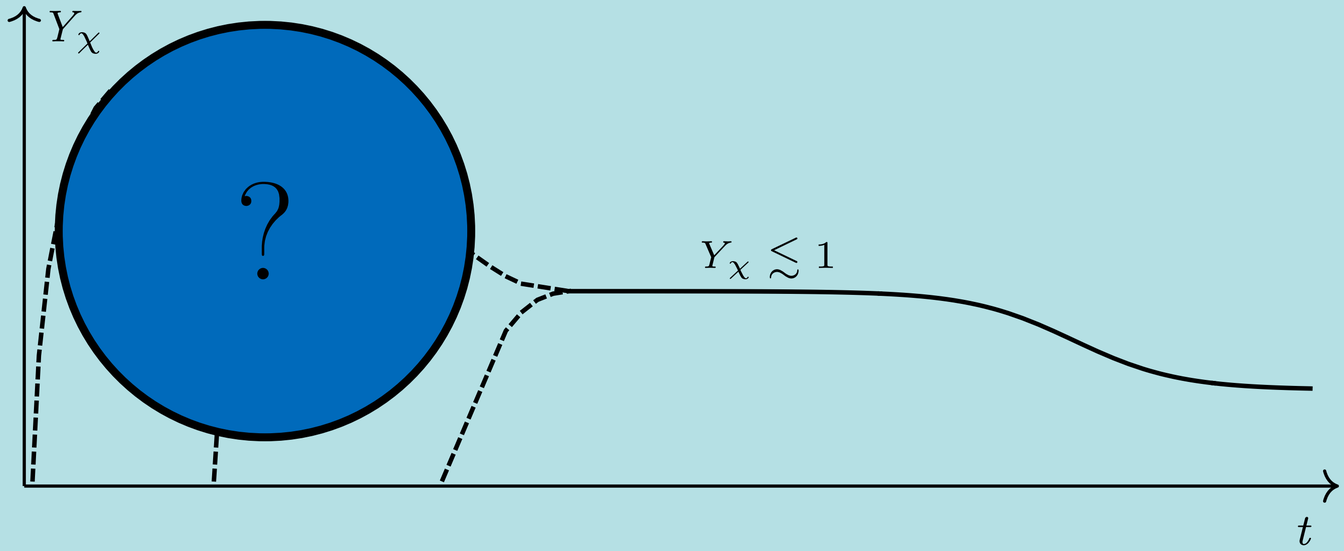
4. Future prospects

5. Conclusion

Reheating and Dark Matter Beyond Leading Order

LONG TERM





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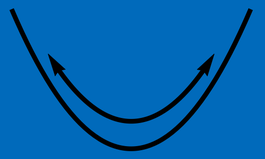

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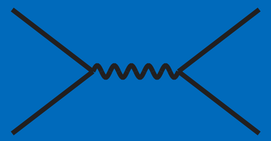

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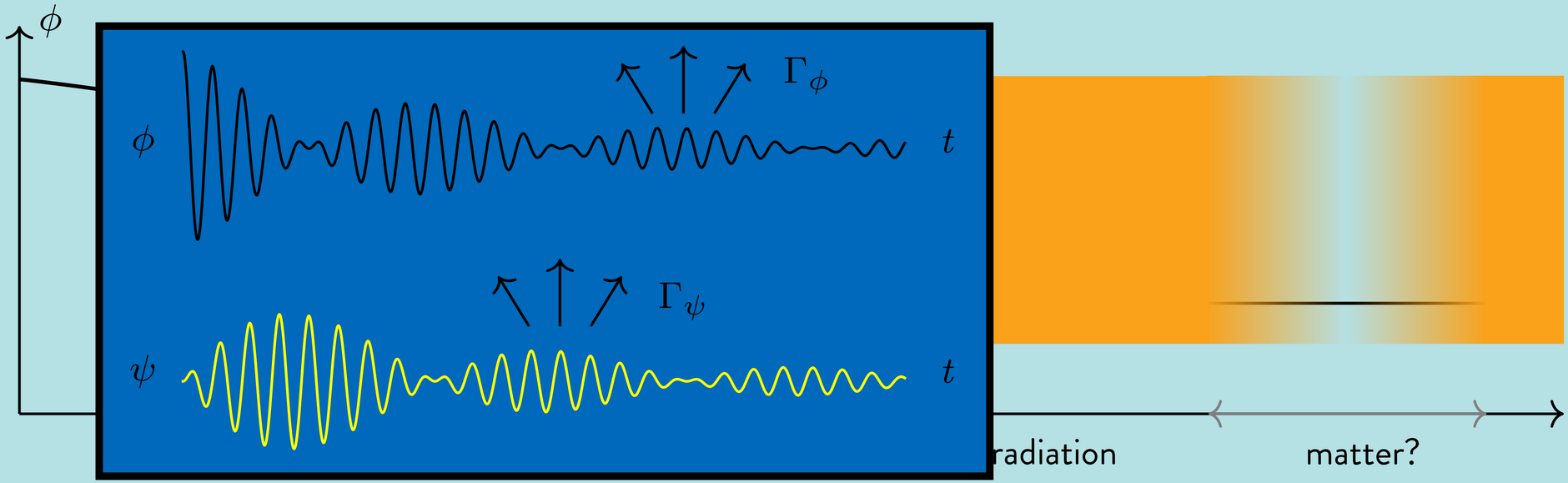

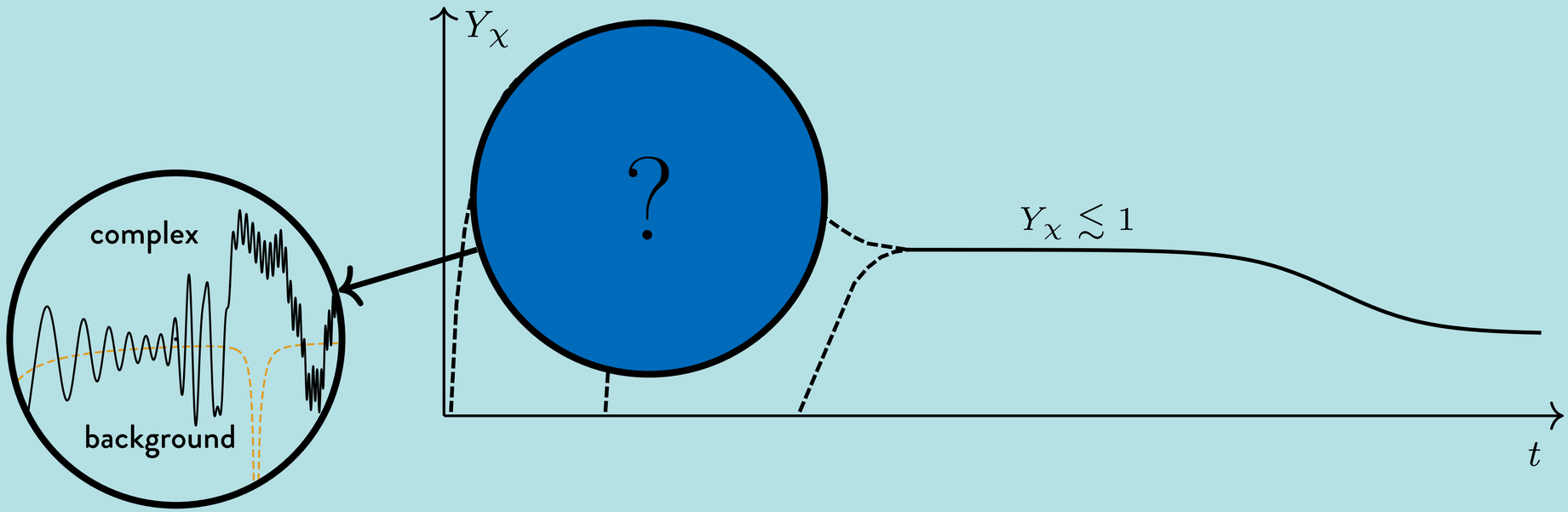

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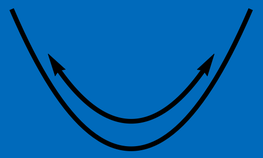

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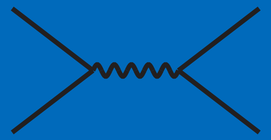

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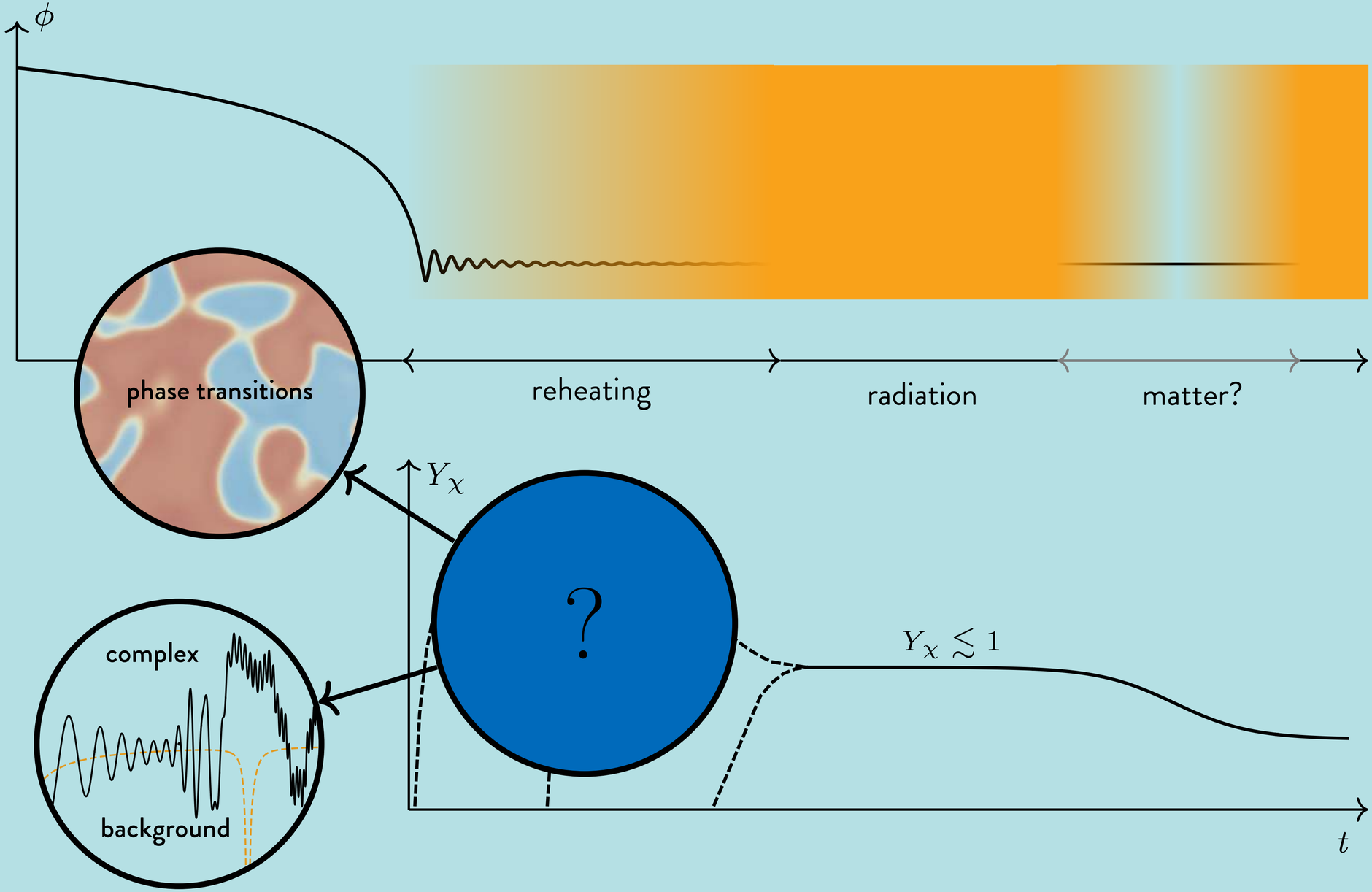
Reheating and Dark Matter Beyond Leading Order

LONG TERM



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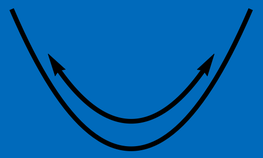

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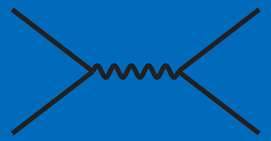

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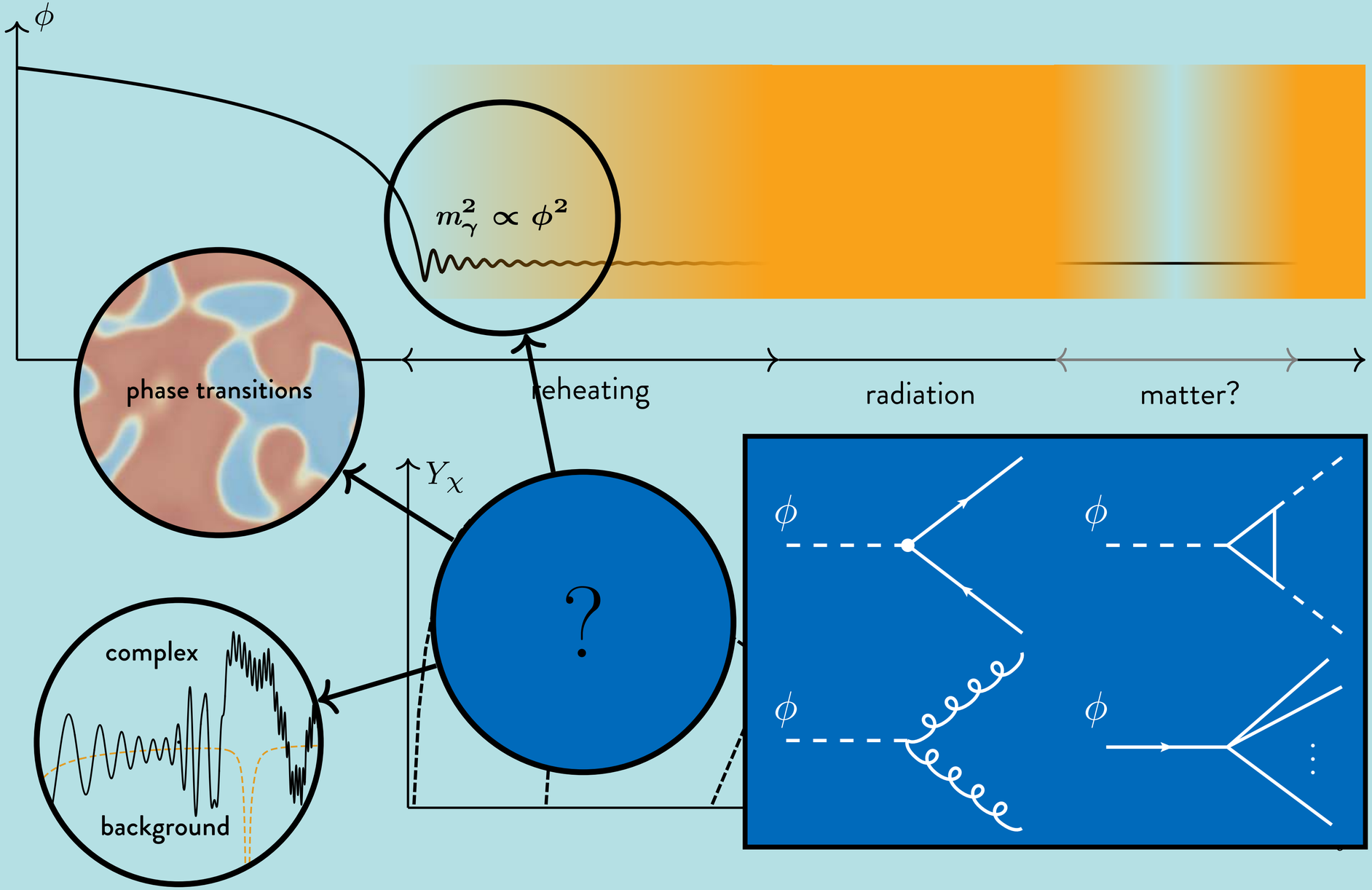
Reheating and Dark Matter Beyond Leading Order

LONG TERM



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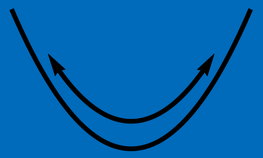

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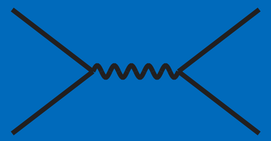

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Reheating and Dark Matter Beyond Leading Order

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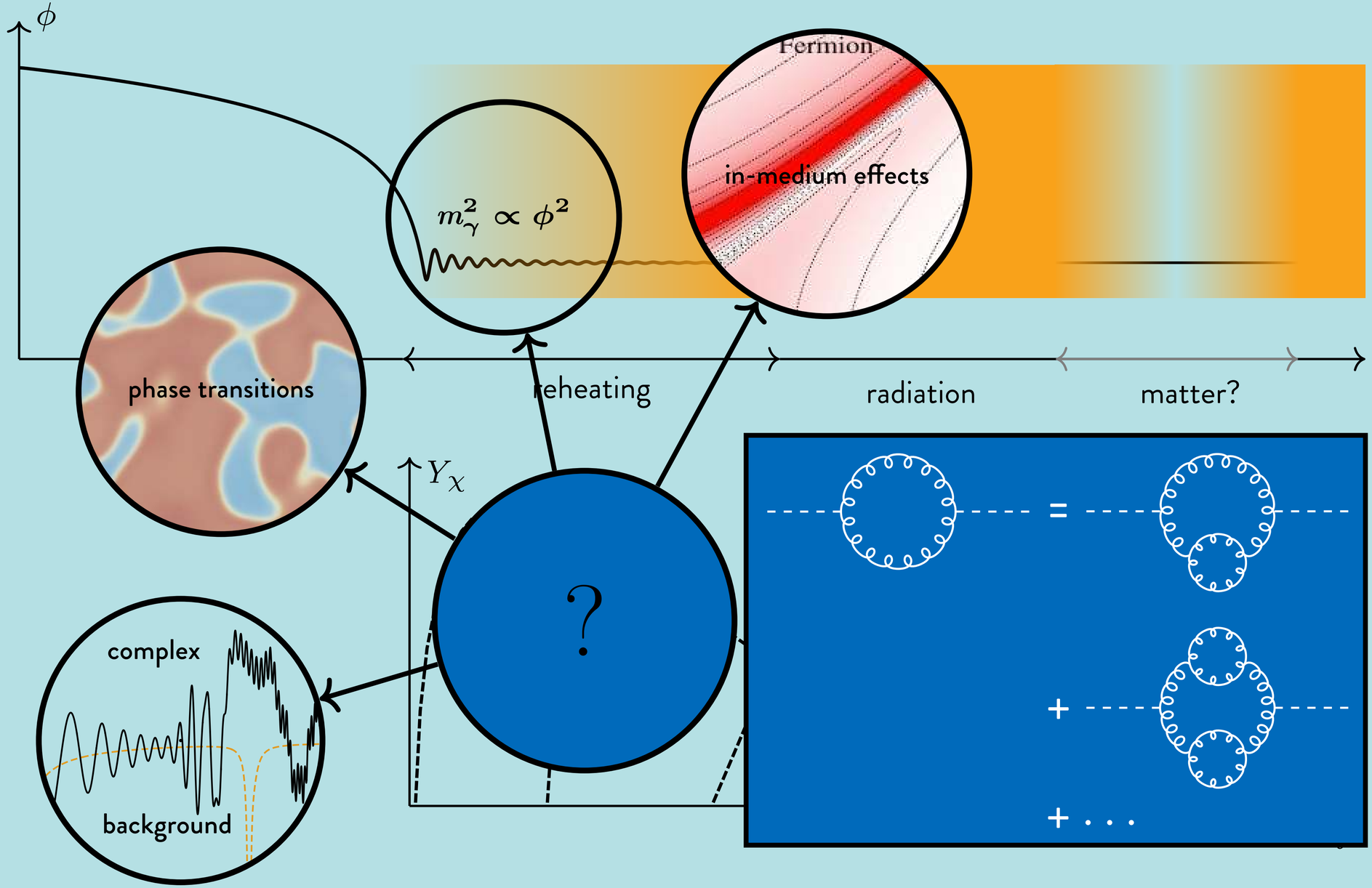

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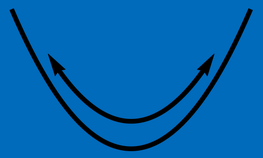

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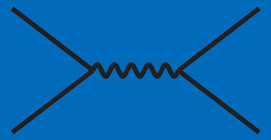

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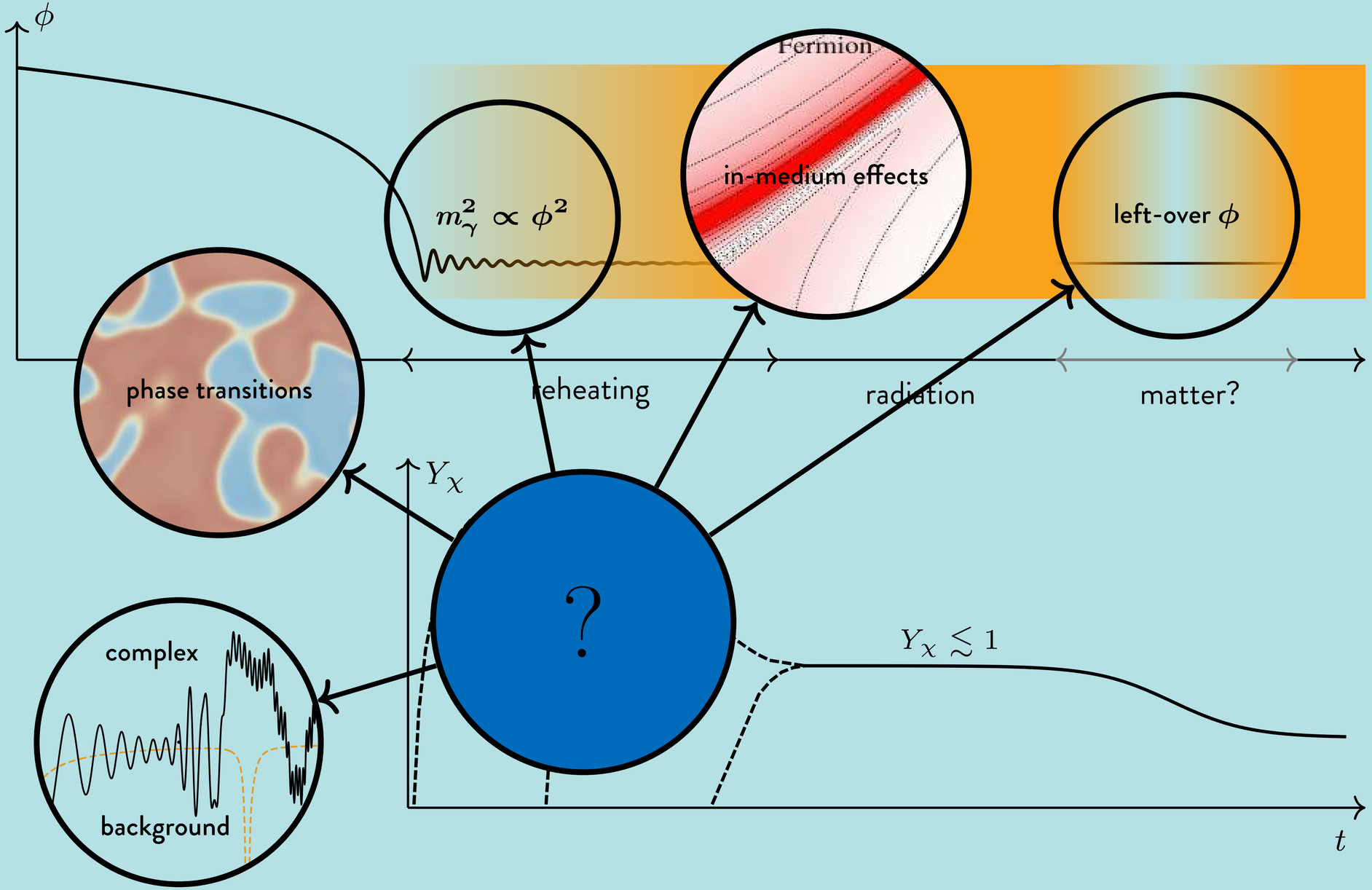
Reheating and Dark Matter Beyond Leading Order

LONG TERM



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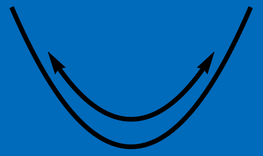

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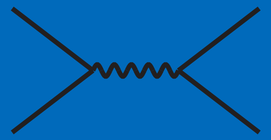

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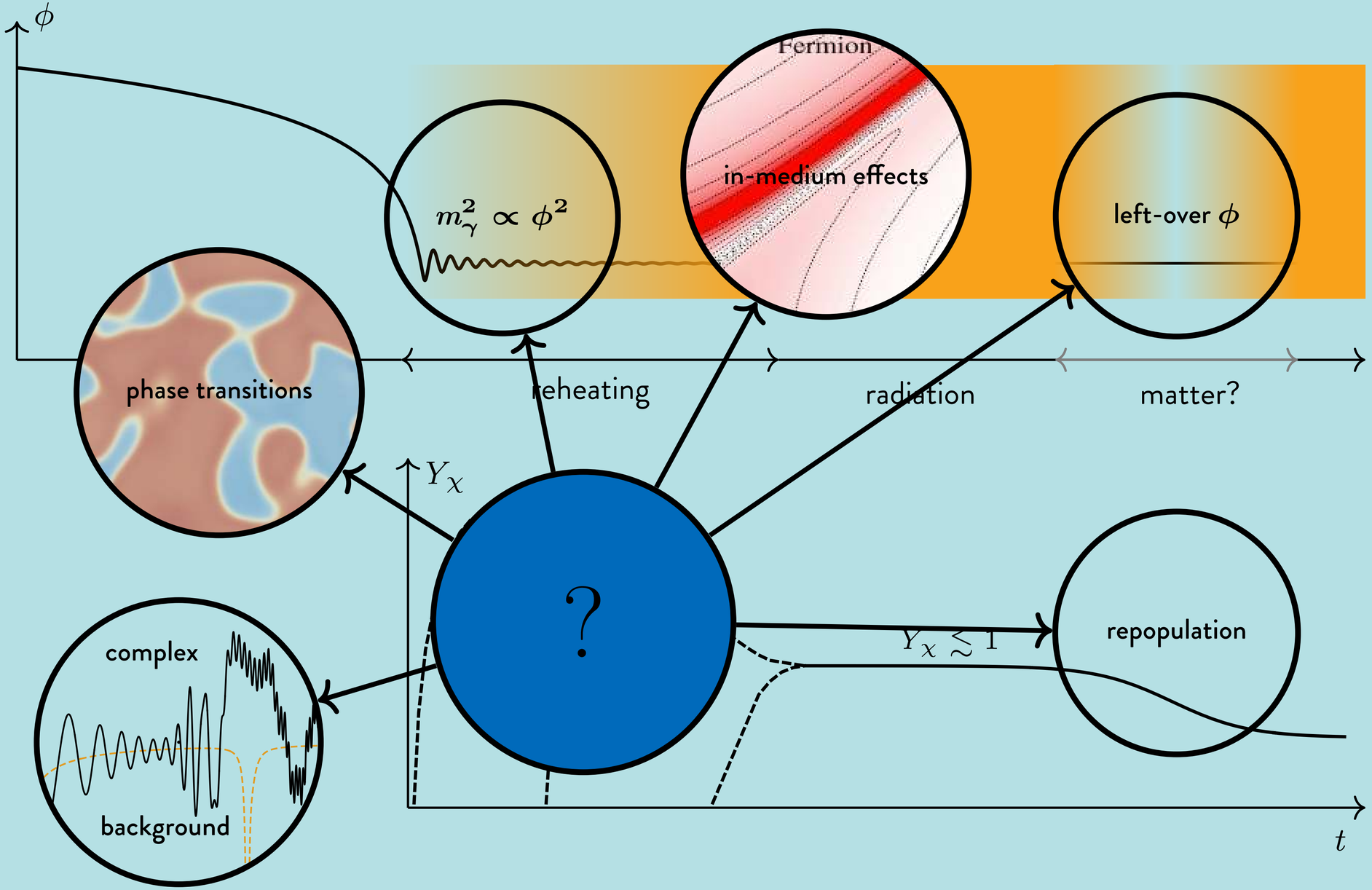
Reheating and Dark Matter Beyond Leading Order

LONG TERM



1. Beyond WIMPs
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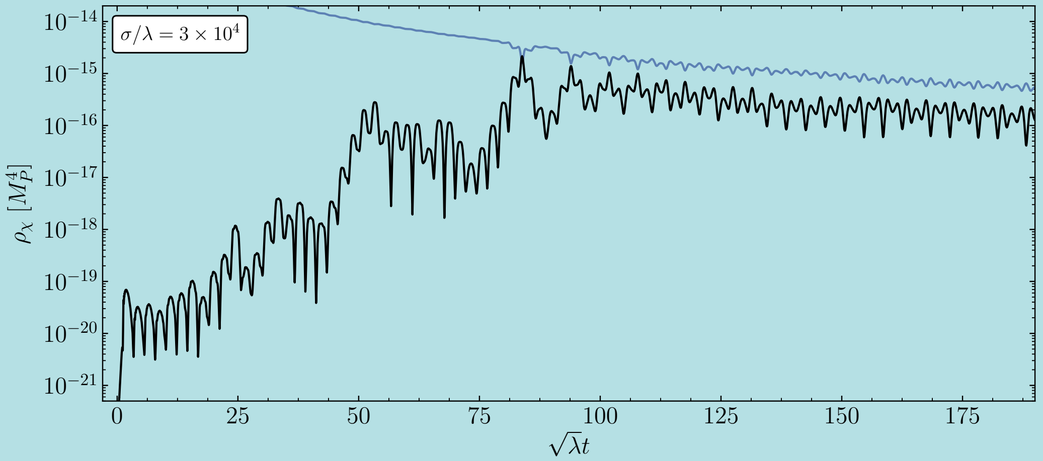
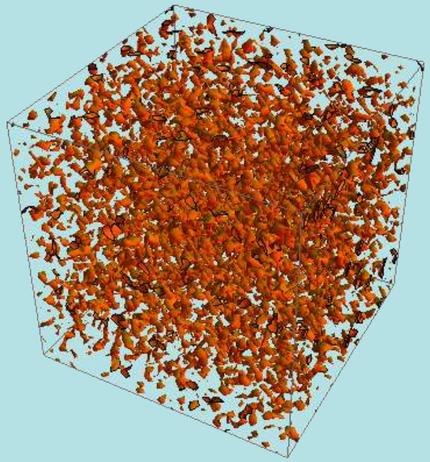
Fragmenting the condensate

LONG TERM

Backreaction

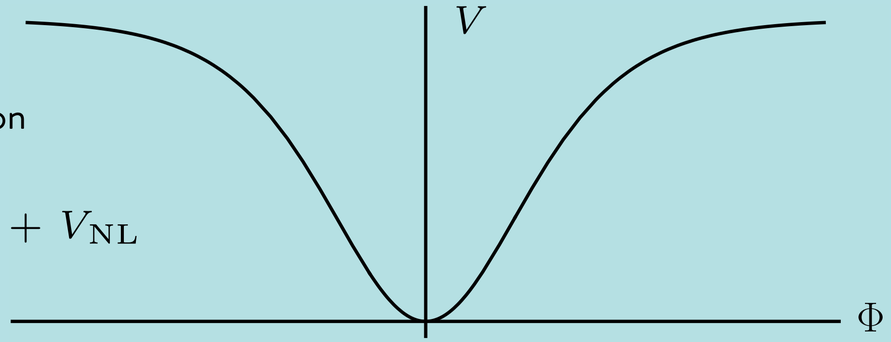
$\sigma\Phi^2\chi^2$

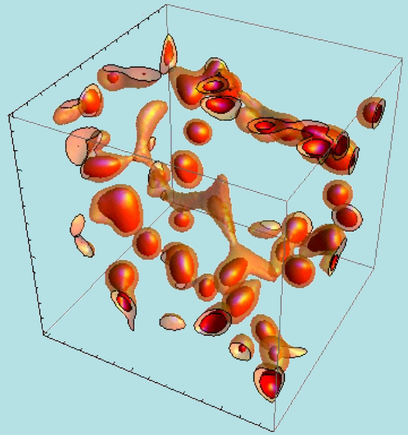




“opening up” =
attractive interaction

$$V = \frac{1}{2}m_\Phi^2\Phi^2 + V_{\rm NL}$$





gravity

self-interaction

Complex, U(1):	Q-Balls		Boson stars
Real:	Oscillons		Oscillatons

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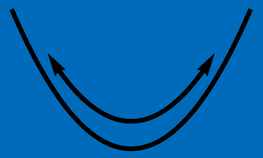

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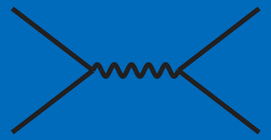

4. Future prospects

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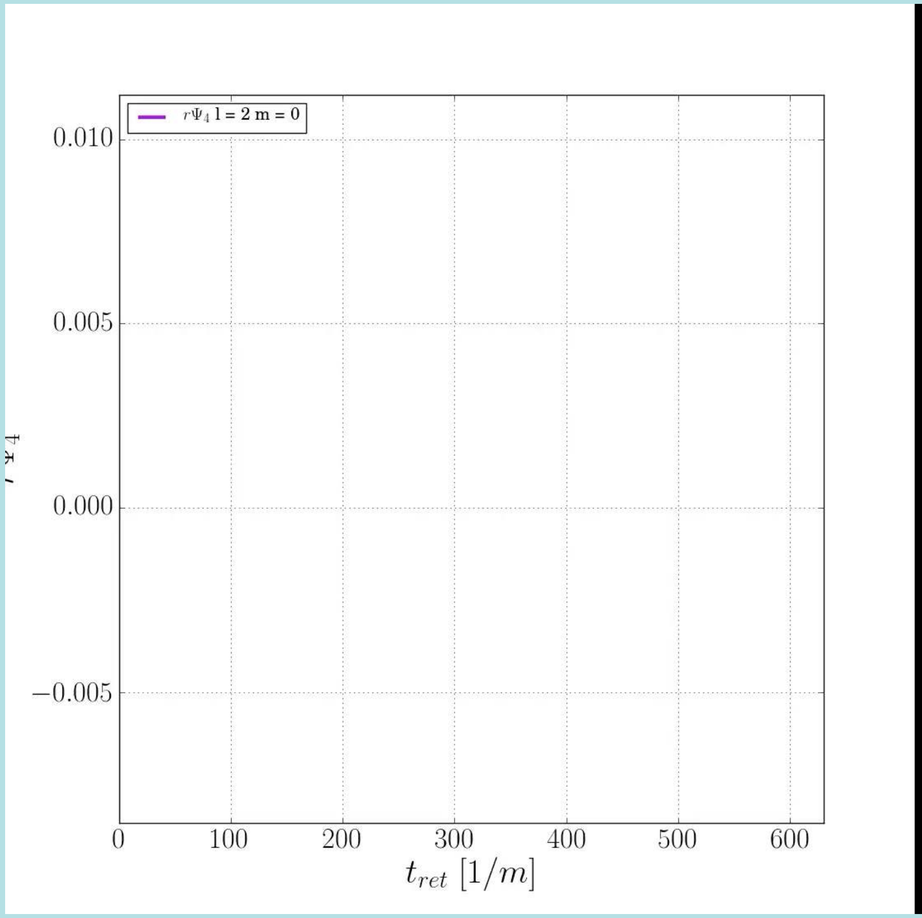
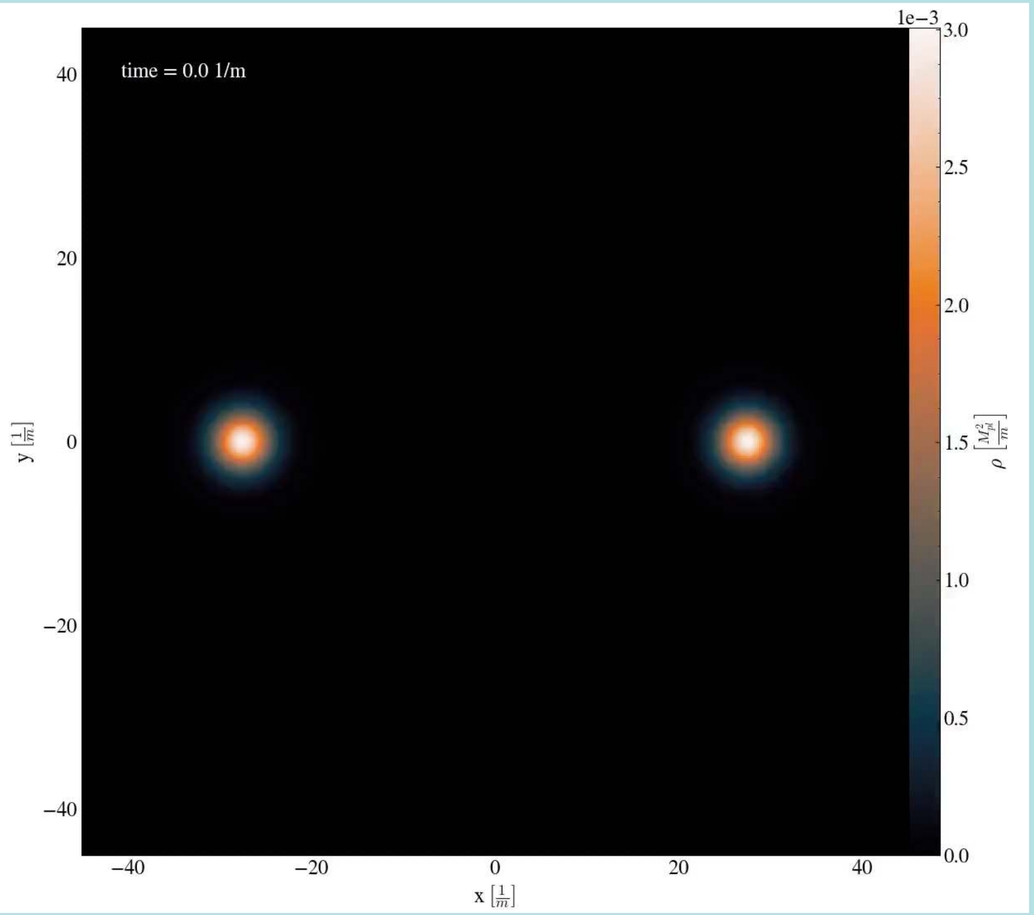
Head-on oscillaton collisions

LONG TERM





T. Helfer, E. A. Lim, **MG** and M. A. Amin, PRD 99 (2019), 044046

1. Beyond WIMPs
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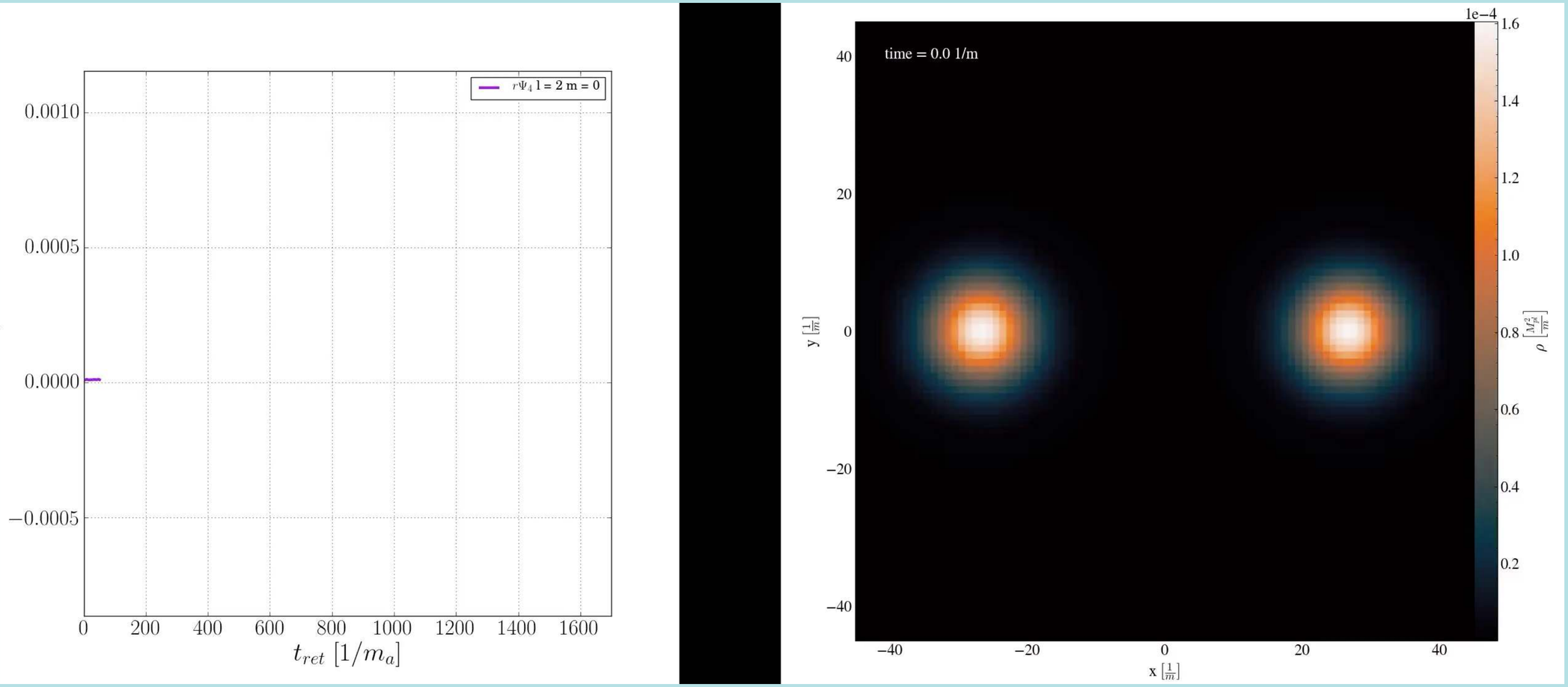
LONG TERM



T. Helfer, E. A. Lim, **MG** and M. A. Amin, PRD 99 (2019), 044046

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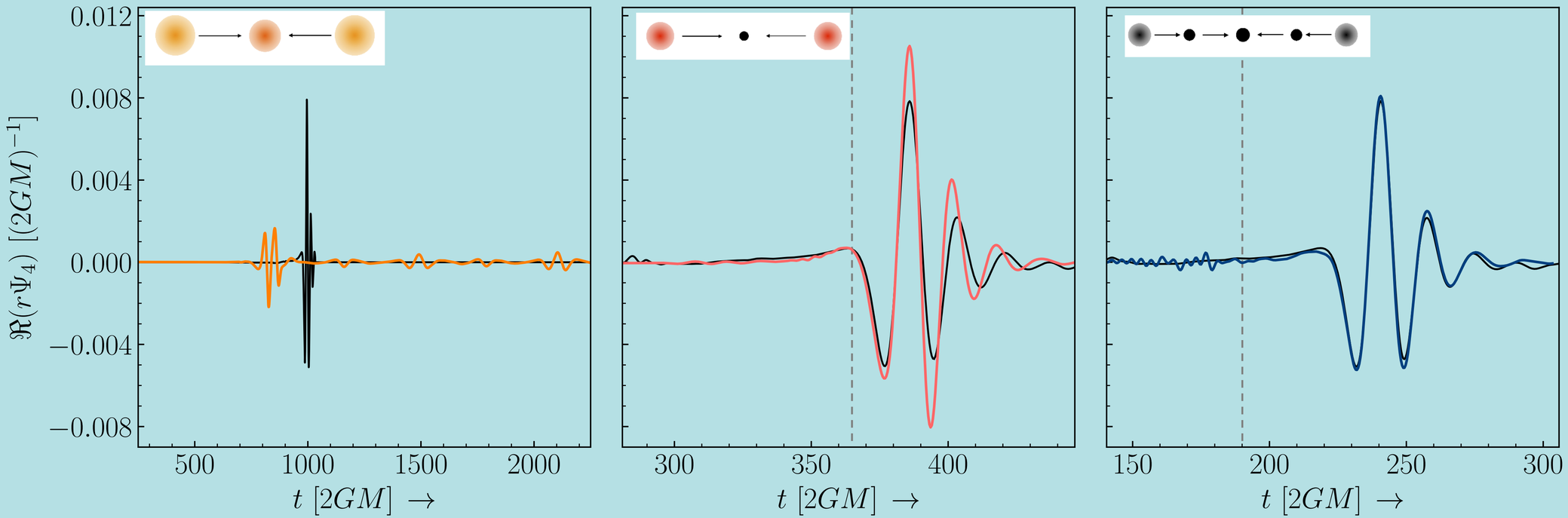

LIGO range 10^{-12} eV $\lesssim m \lesssim 10^{-10}$ eV

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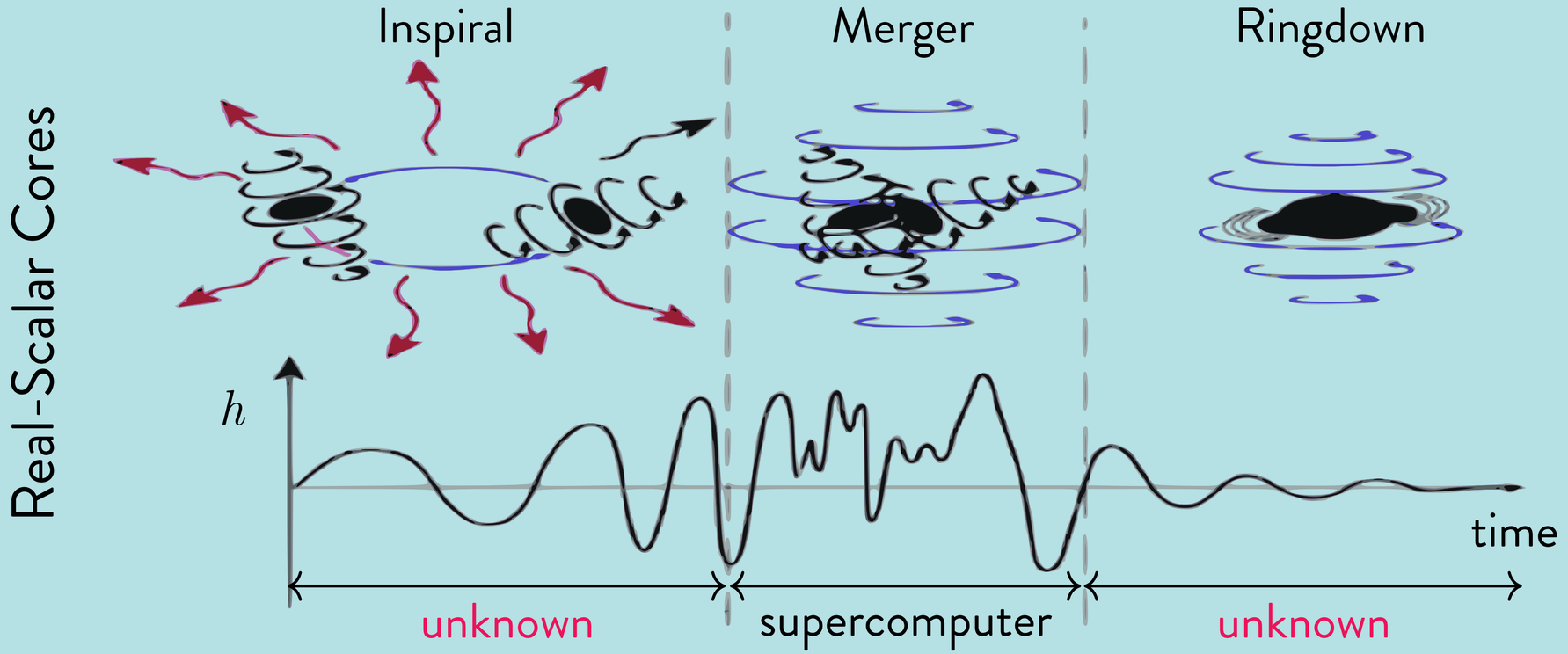
Axion Star Mergers

LONG TERM



Credit: Kip Thorne

- Saturation of the Kerr bound?
- Post-Newtonian, mass ejection, and elastic corrections to inspiral
- Quasi-normal modes

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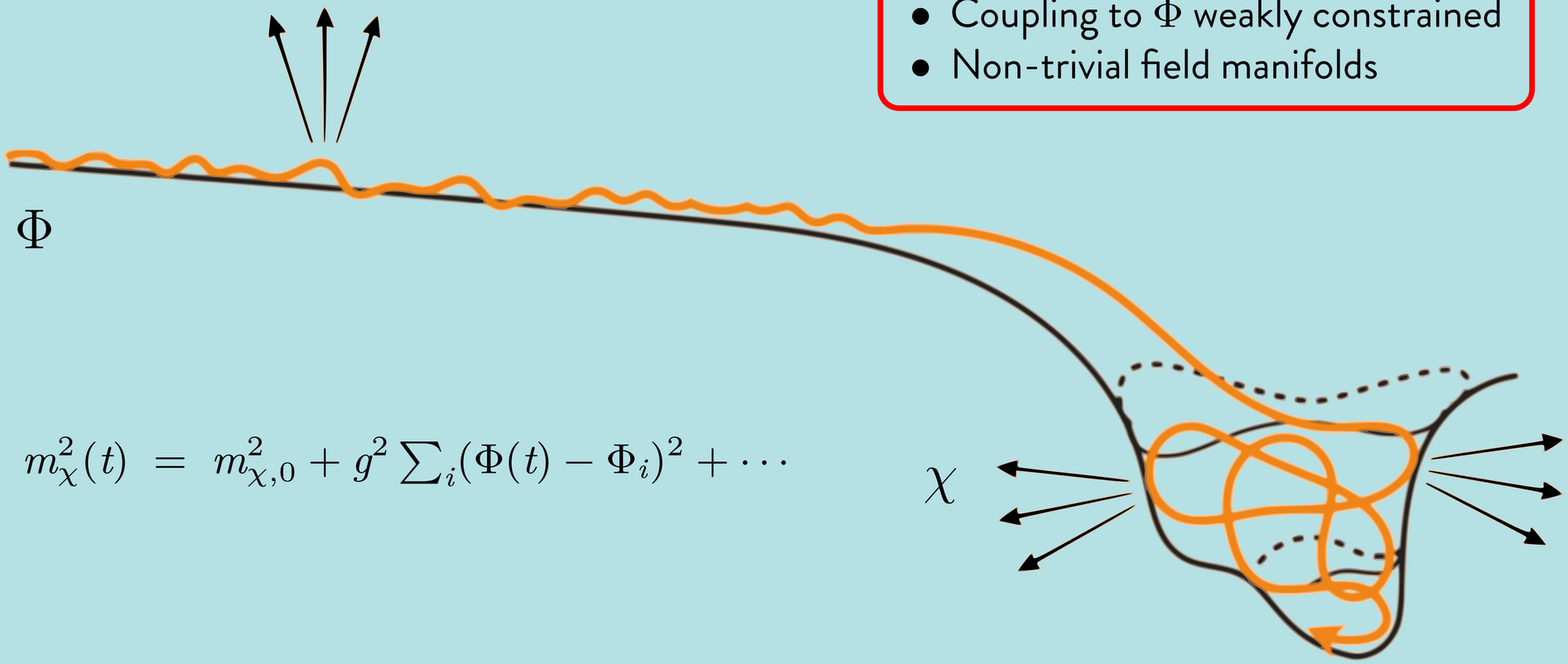
Complexity in the early Universe

LONG TERM

Particle theory

- SM UV completions $N_F \gg 1$
- Coupling to Φ weakly constrained
- Non-trivial field manifolds



$$m_\chi^2(t) \;=\; m_{\chi,0}^2 + g^2 \sum_i (\Phi(t) - \Phi_i)^2 + \cdots$$

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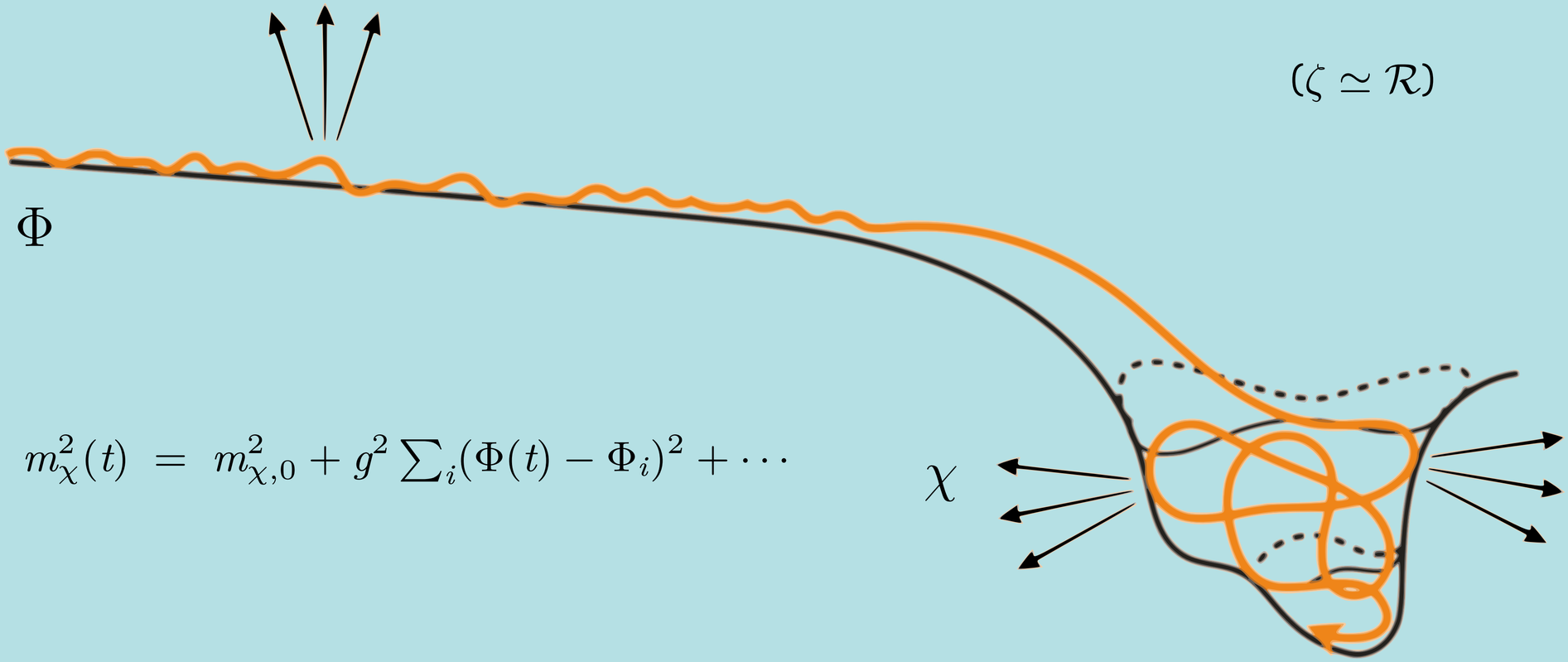
Complexity in the early Universe

LONG TERM

background dynamics $\longrightarrow$ particle production $\langle \chi_{k_1} \chi_{k_2} \cdots \rangle$ $\longleftrightarrow$ curvature fluctuations $\langle \zeta_{k_1} \zeta_{k_2} \cdots \rangle$

$(\zeta \simeq \mathcal{R})$



$$m_\chi^2(t) \;=\; m_{\chi,0}^2 + g^2 \textstyle\sum_i (\Phi(t) - \Phi_i)^2 + \cdots$$

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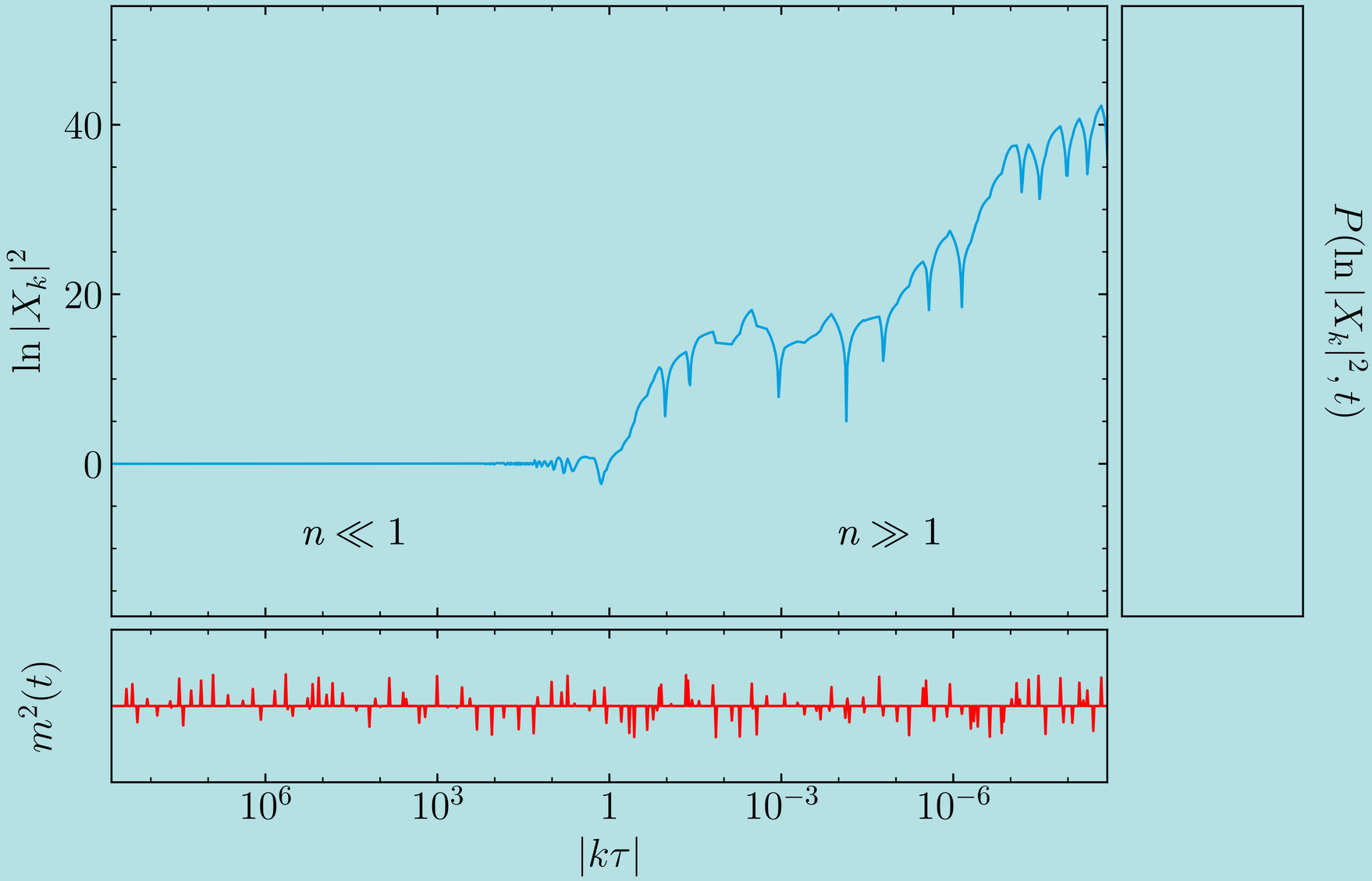
LONG TERM

A (conformal) spectator in dS

MG, M. Amin, S. Carlsten and D. Green, JCAP 05 (2019), 012



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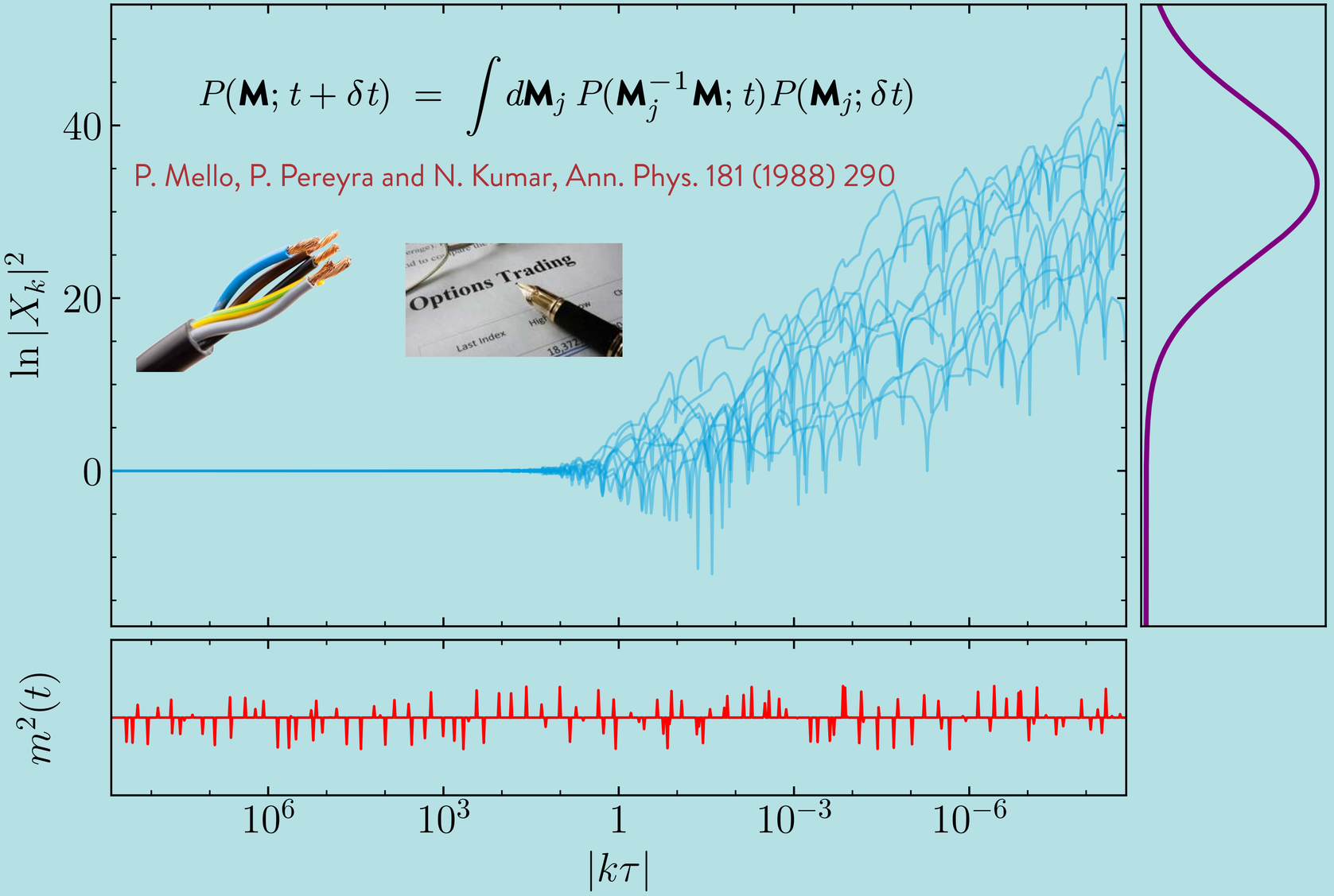
5. Conclusion

A (conformal) spectator in dS

LONG TERM

$$P(\mathbf{M}; t+\delta t) = \int d\mathbf{M}_j \, P(\mathbf{M}_j^{-1}\mathbf{M}; t) P(\mathbf{M}_j; \delta t)$$

P. Mello, P. Pereyra and N. Kumar, Ann. Phys. 181 (1988) 290



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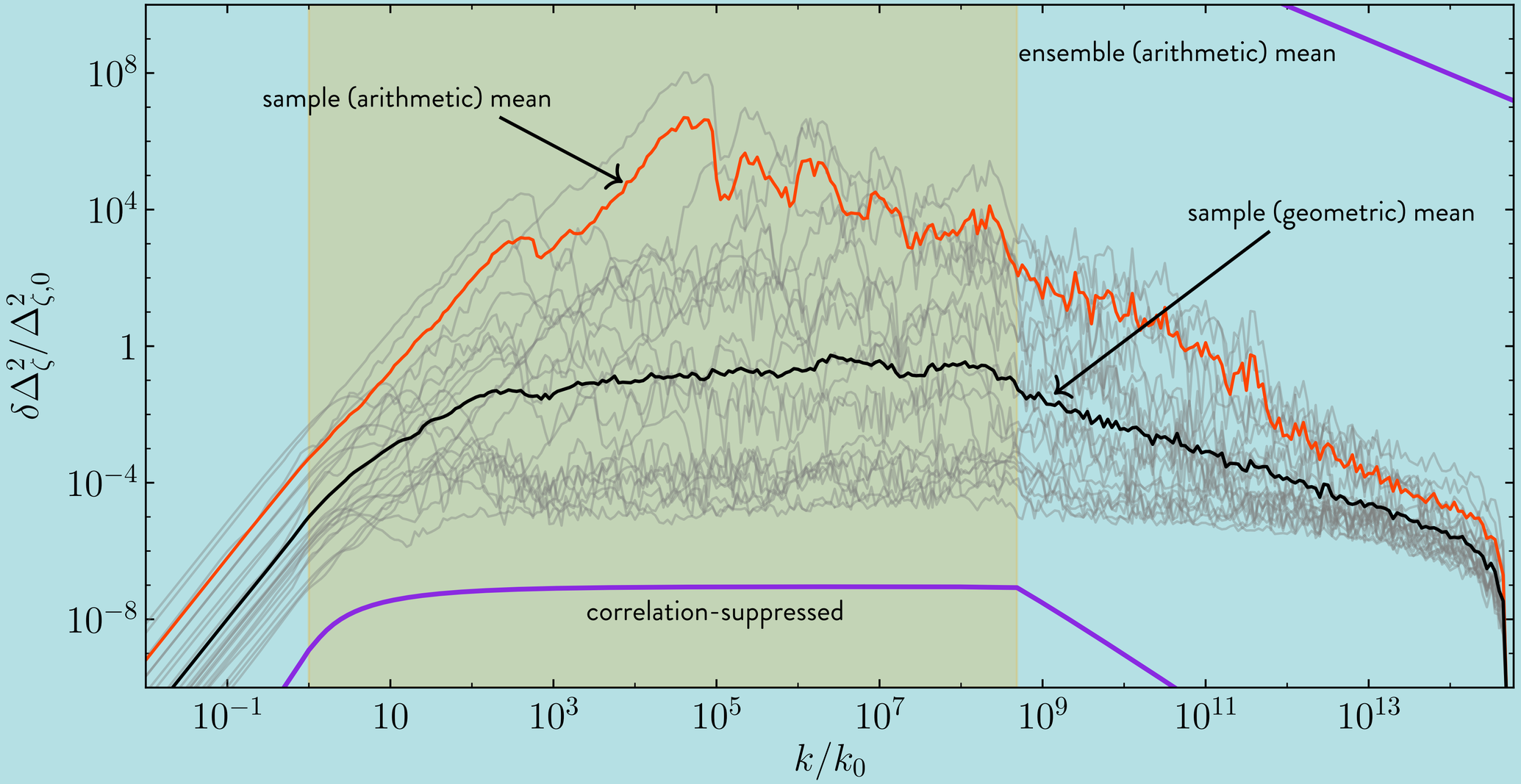
LONG TERM

Stochastically sourced power spectrum

MG, M. A. Amin and D. Green, JCAP 06 (2020), 039



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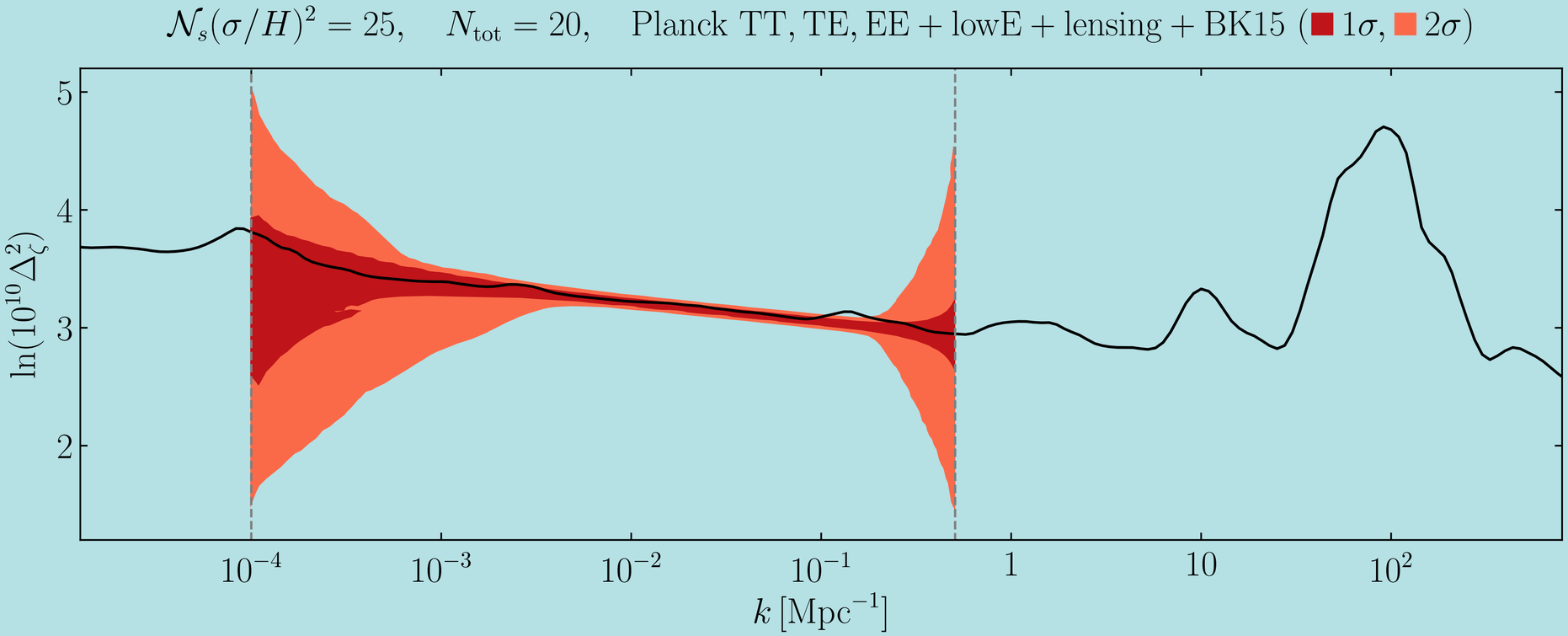
5. Conclusion

Disordered Dynamics Beyond Planck

LONG TERM



- Beyond the power spectrum: Non-Gaussianity, Spectral Distortions, Dissipation
- Higher spin fluctuations (Primordial Gravitational Waves)
- Primordial Black Hole **distribution**

1. Beyond WIMPs
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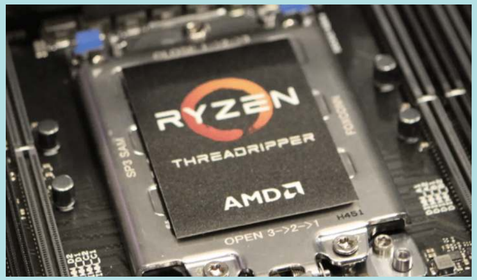
Infrastructure

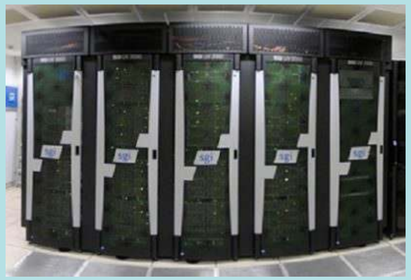
- An office

- Computing



Multithread Personal Computing

IFT Computing (Mingus, ...)

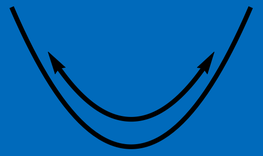


External Supercomputing (COSMOS, ...)

- Collaboration network. IF + travel + visitors
- Motivated students and postdocs

1. Beyond WIMPs

2. Inflation & reheating



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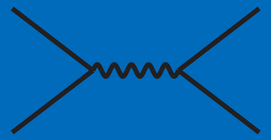

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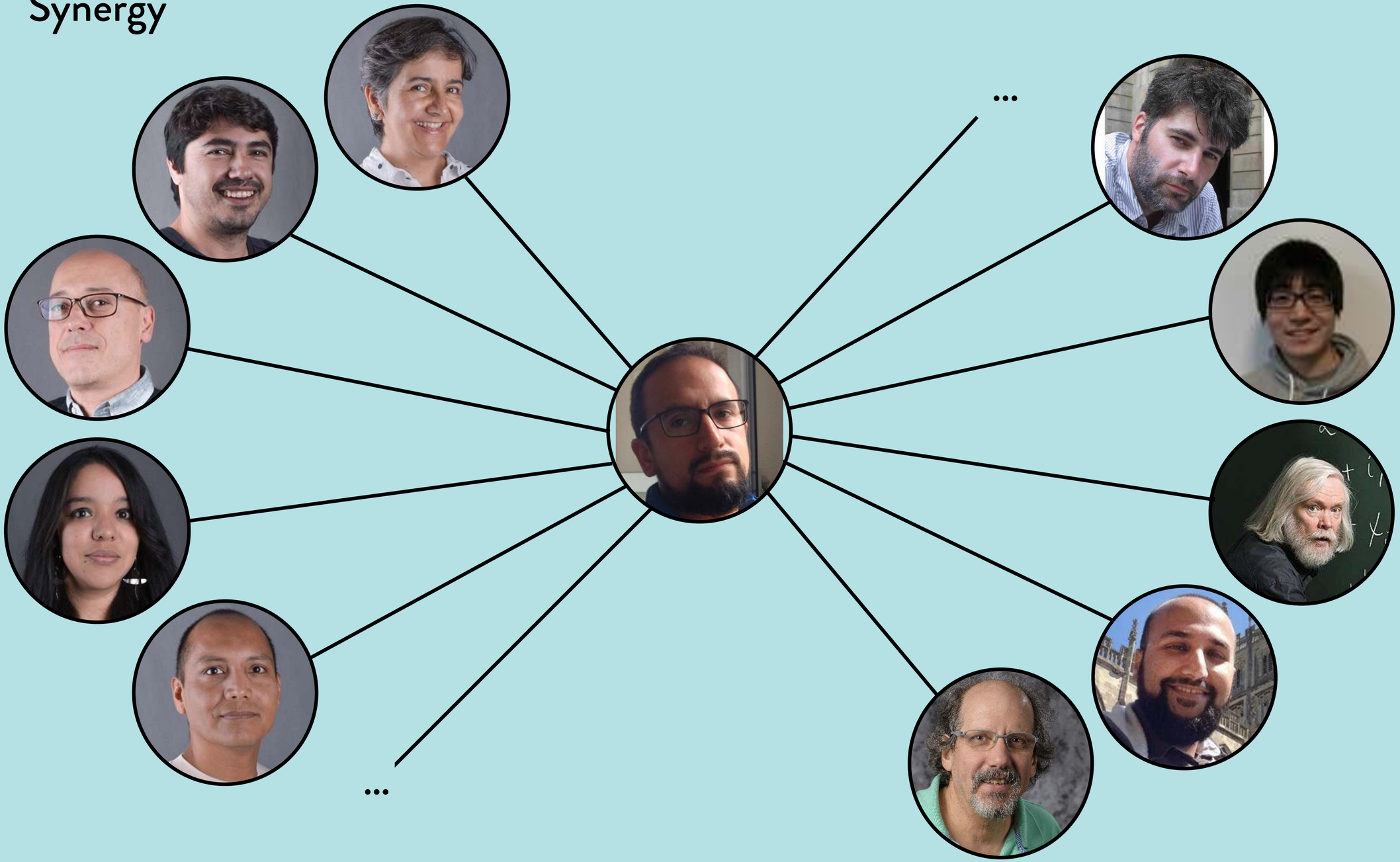
5. Conclusion

Synergy



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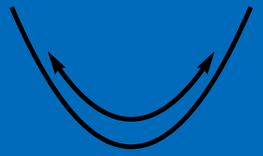
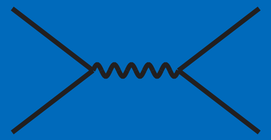


3. FIMPs

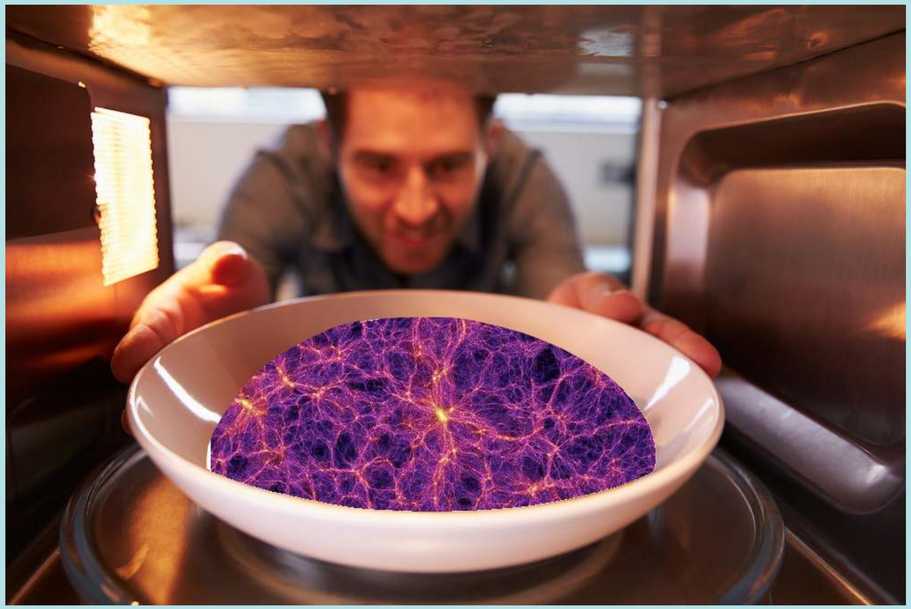


4. Future prospects

5. Conclusion

Conclusion

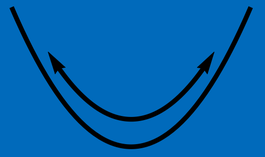
- The light beyond the WIMP: the Big Bang itself?
- Dark matter as a probe of early dynamics
- Indirect connection with low energy physics (neutrinos, CMB, proton decay, ...)
- Same ideas, different applications (condensed matter, baryon asymmetry, finance, ...)



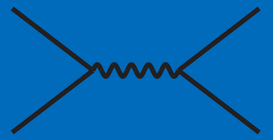
¡Gracias!

1. Beyond WIMPs

2. Inflation & reheating



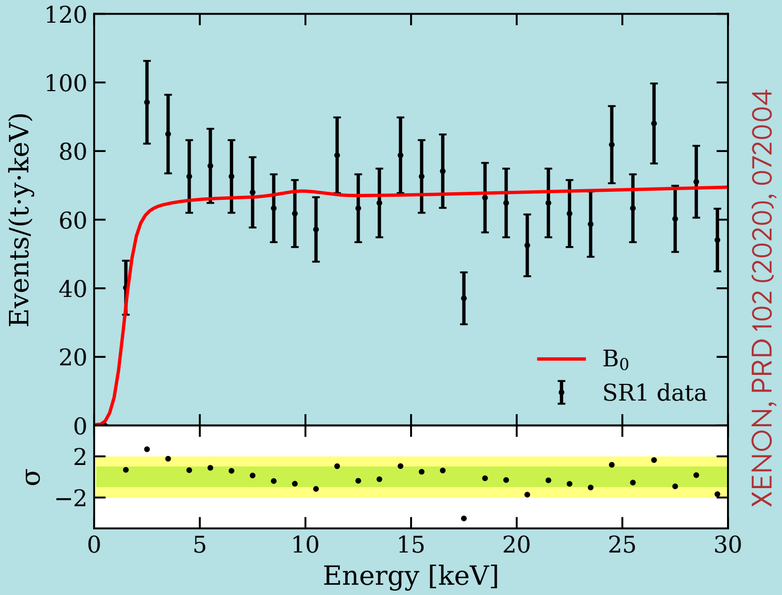
3. FIMPs



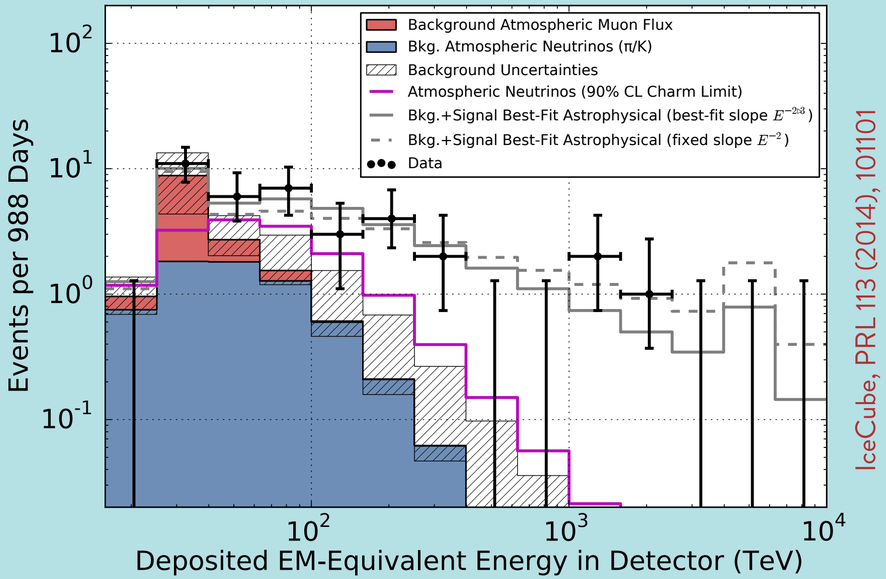
4. Compact objects

5. Prospects

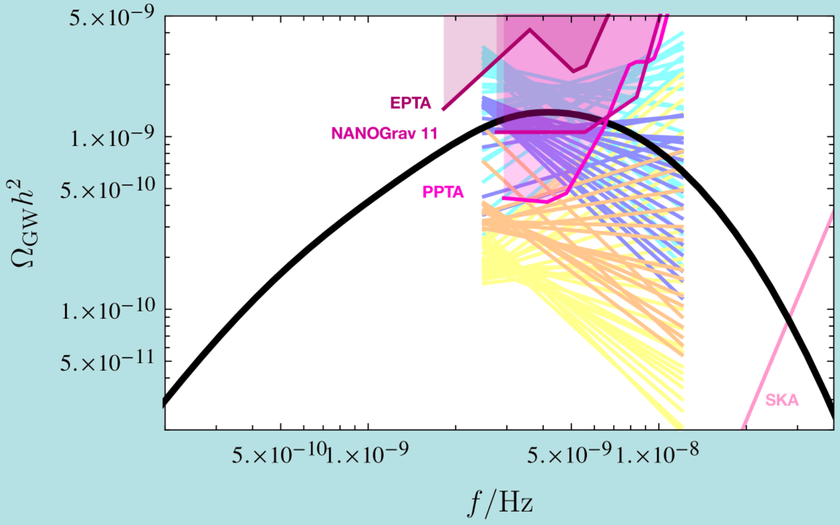
Other evidence for Dark Matter?



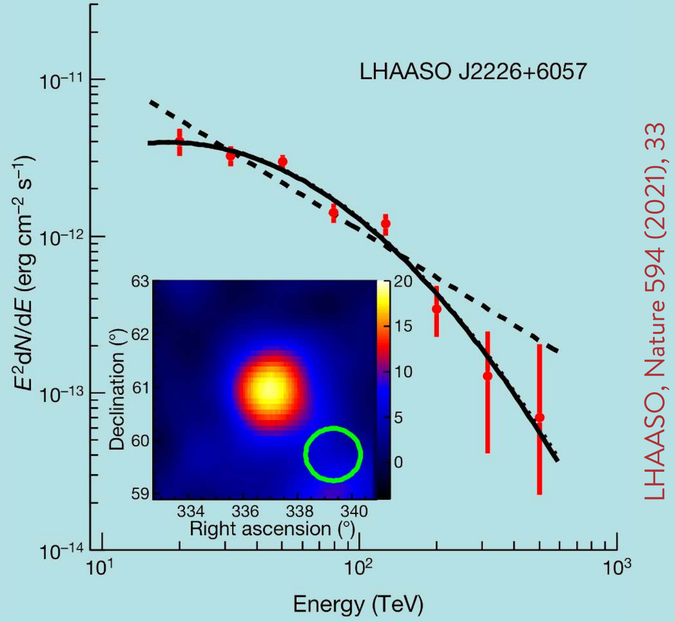
XENON, PRD 102 (2020), 072004



IceCube, PRL 113 (2014), 101101



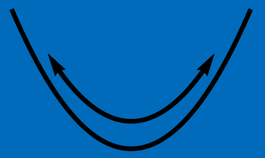
K. Kohri and T. Terada, PLB 813 (2021), 136040



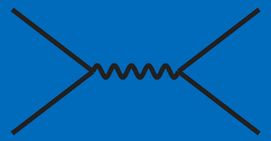
LHAASO, Nature 594 (2021), 33

1. Beyond WIMPs

2. Inflation & reheating



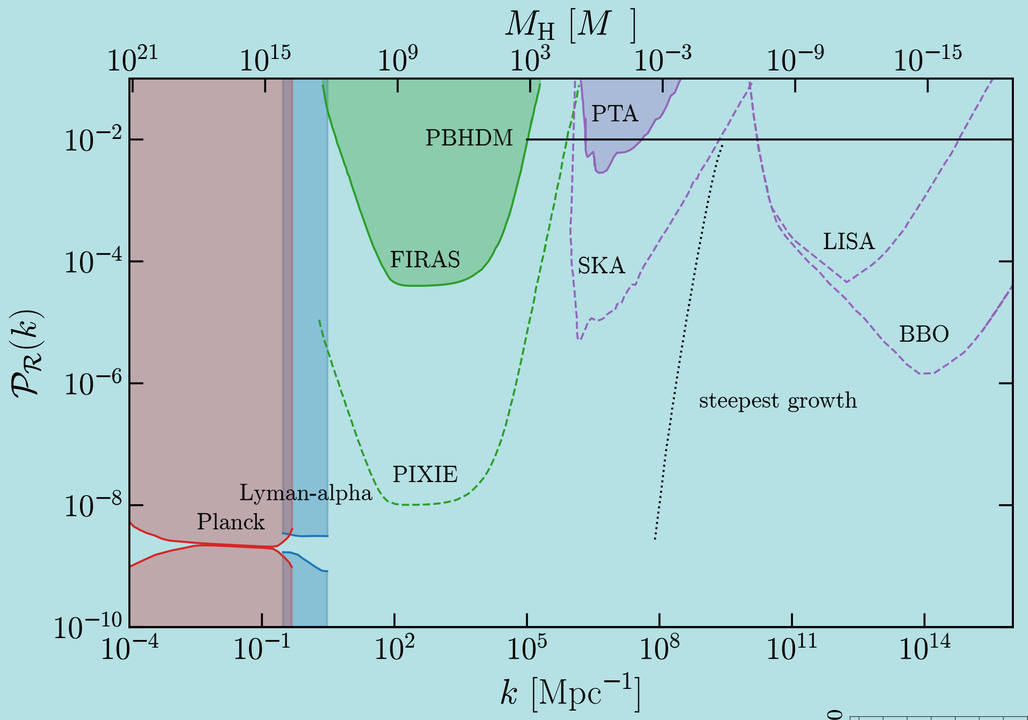
3. FIMPs

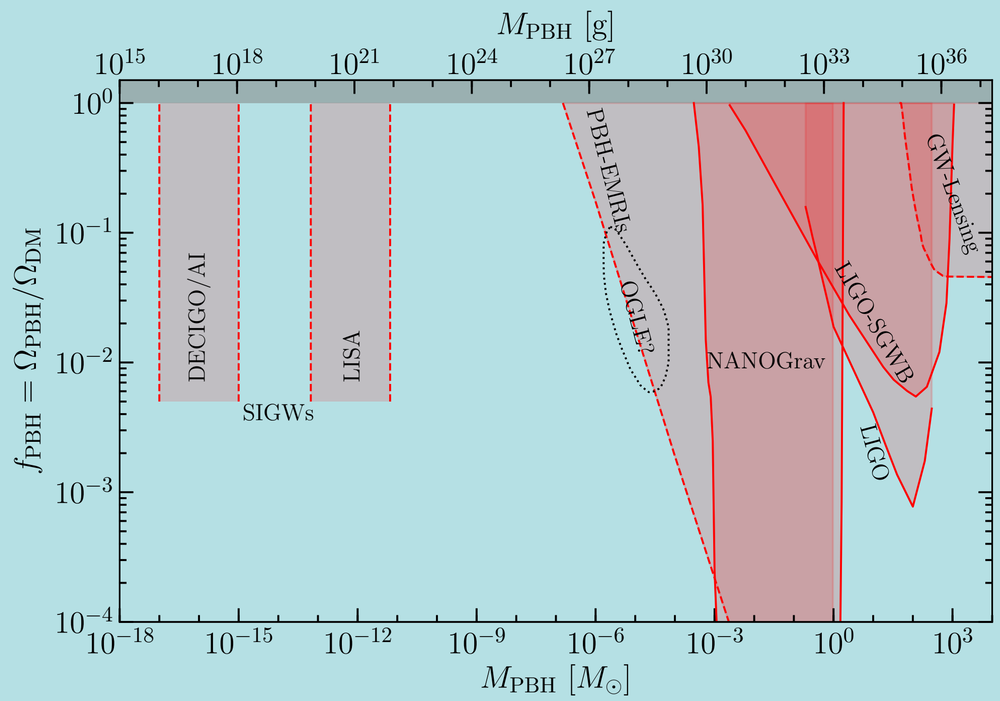


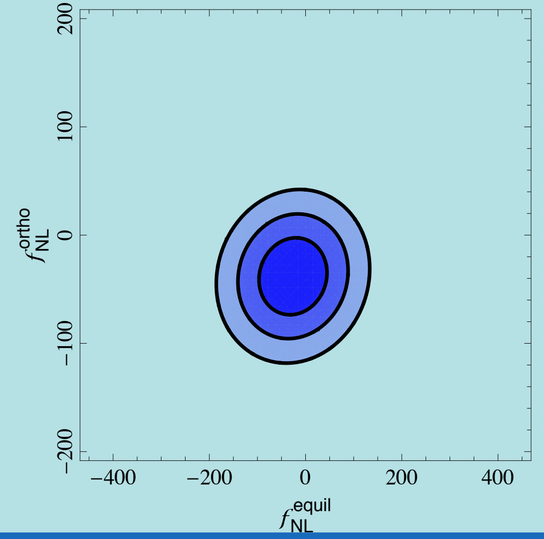
4. Compact objects

5. Prospects

Prospects

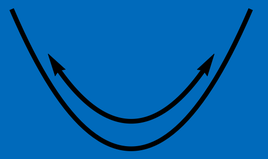




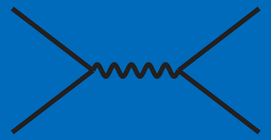


1. Beyond WIMPs

2. Inflation & reheating



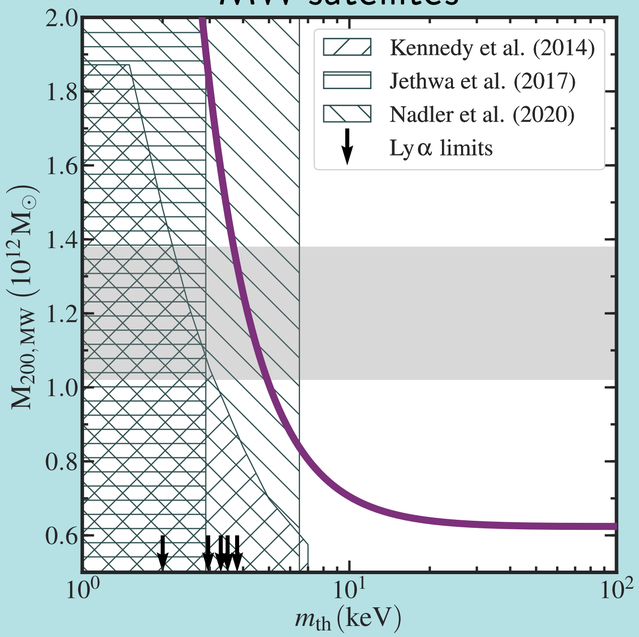
3. FIMPs



4. Compact objects

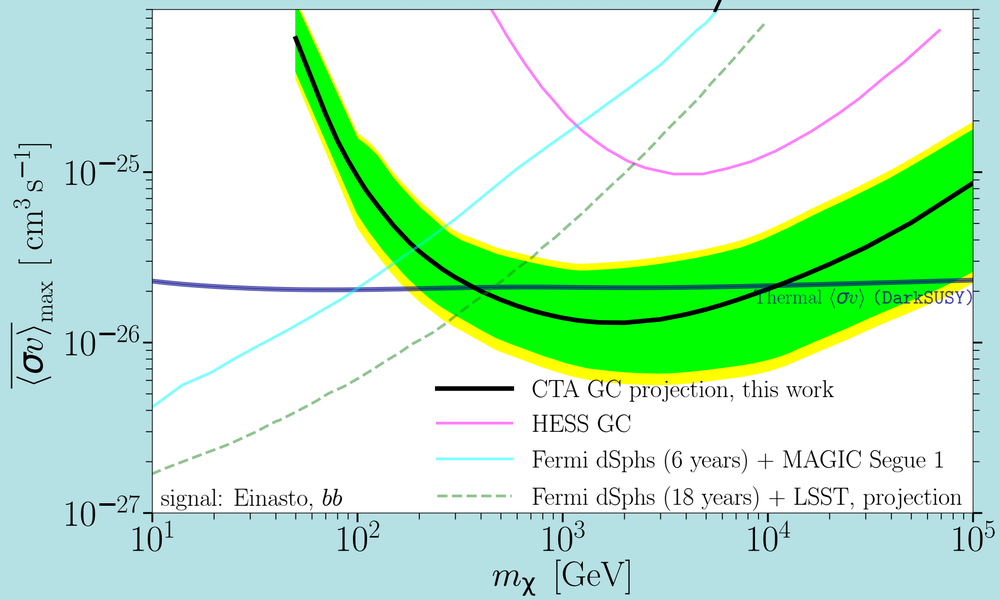
5. Prospects

MW satellites



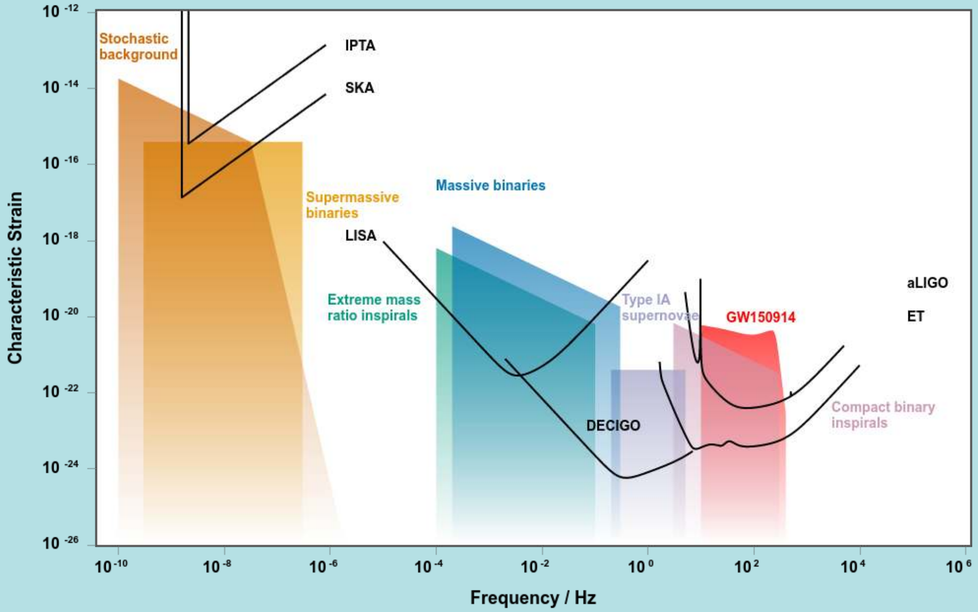
O. Newton et al., arXiv:2011.08865

Annihilation/decay



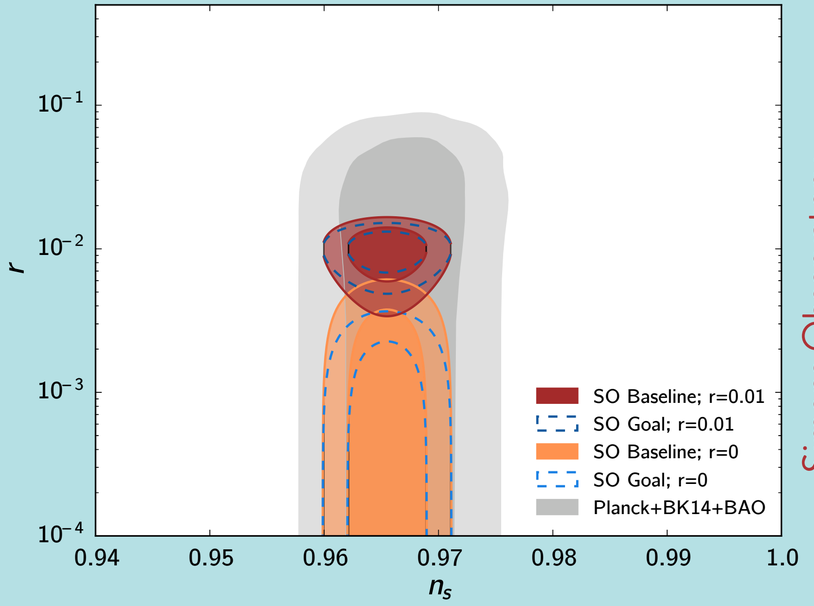
CTA, JCAP 01 (2021), 057

GWs



gwplotter.com

CMB



Simons Observatory, JCAP 02 (2019), 056