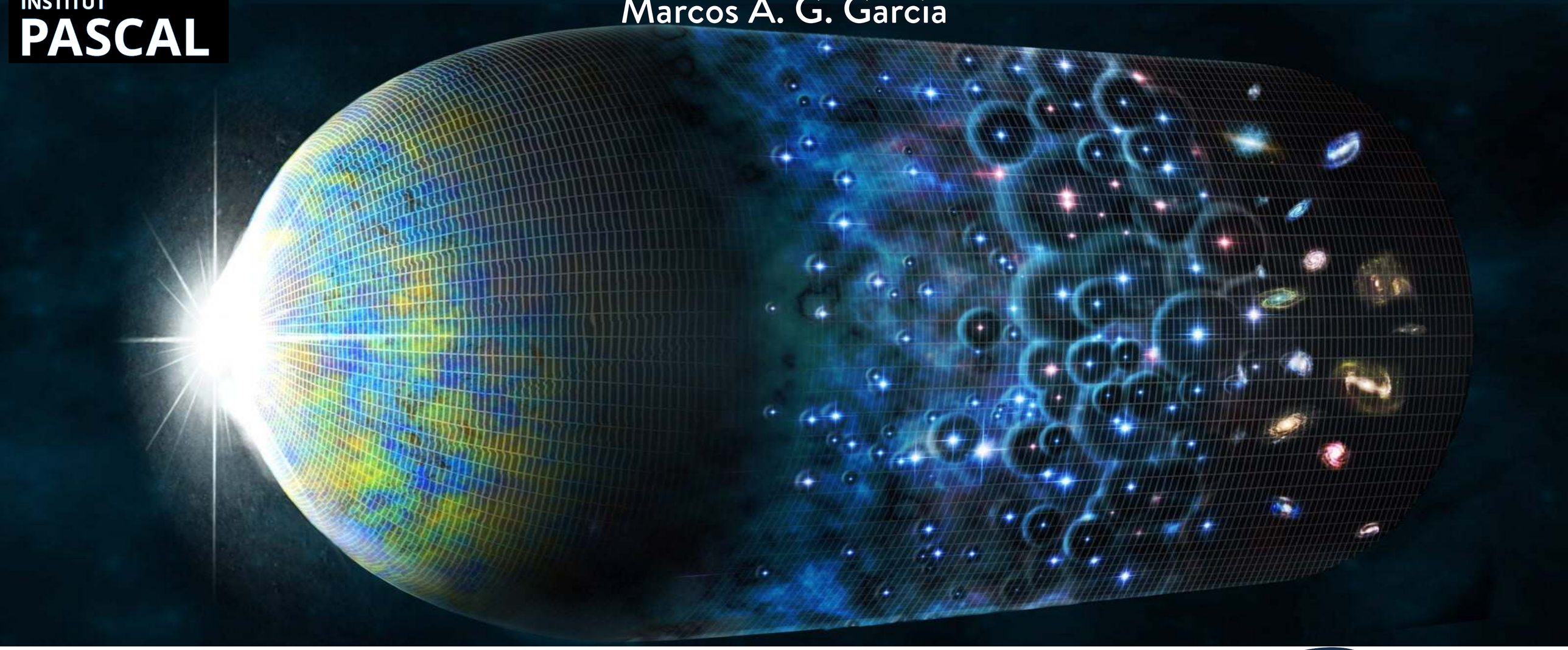
Dark Matter and Early Universe

Marcos A. G. García

04/11/2021



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INFN PADOVA
Istituto Nazionale di Fisica Nucleare
Sezione di Padova

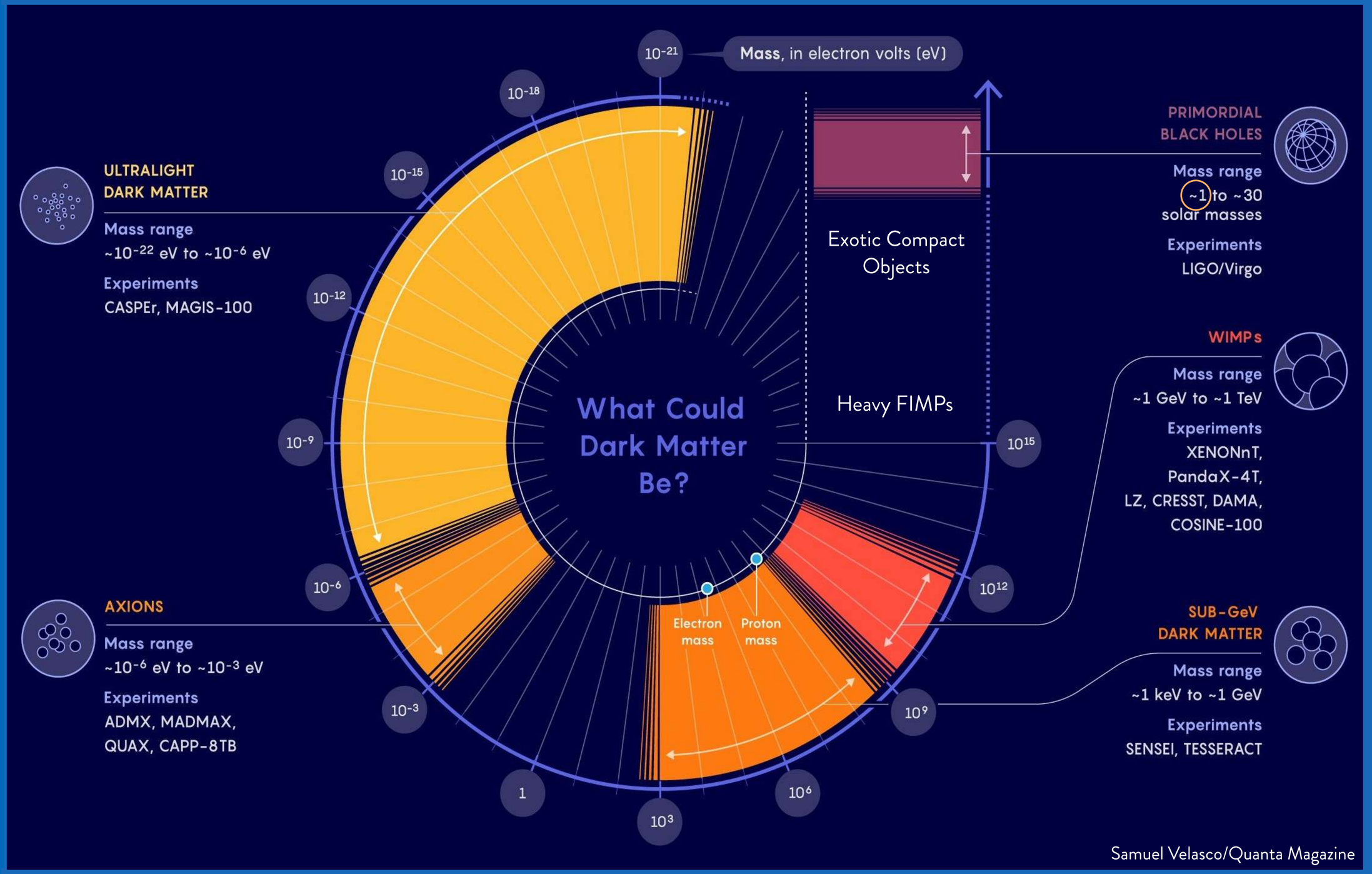
1. Beyond WIMPs

2. Inflation & reheating

3. FIMPs

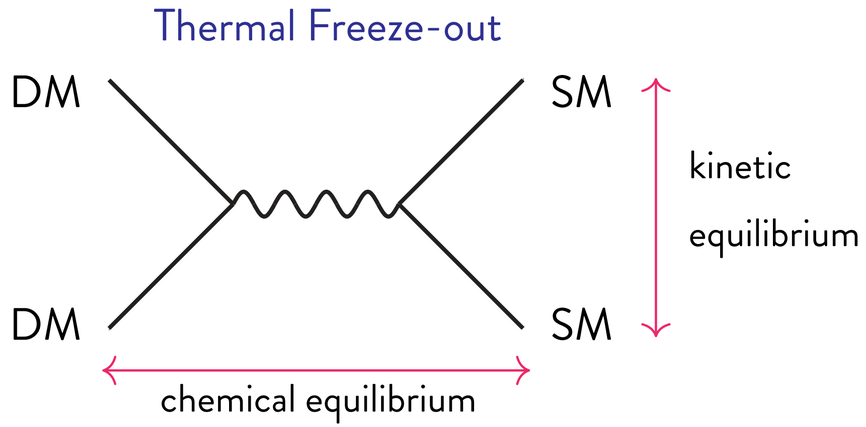
4. Compact objects

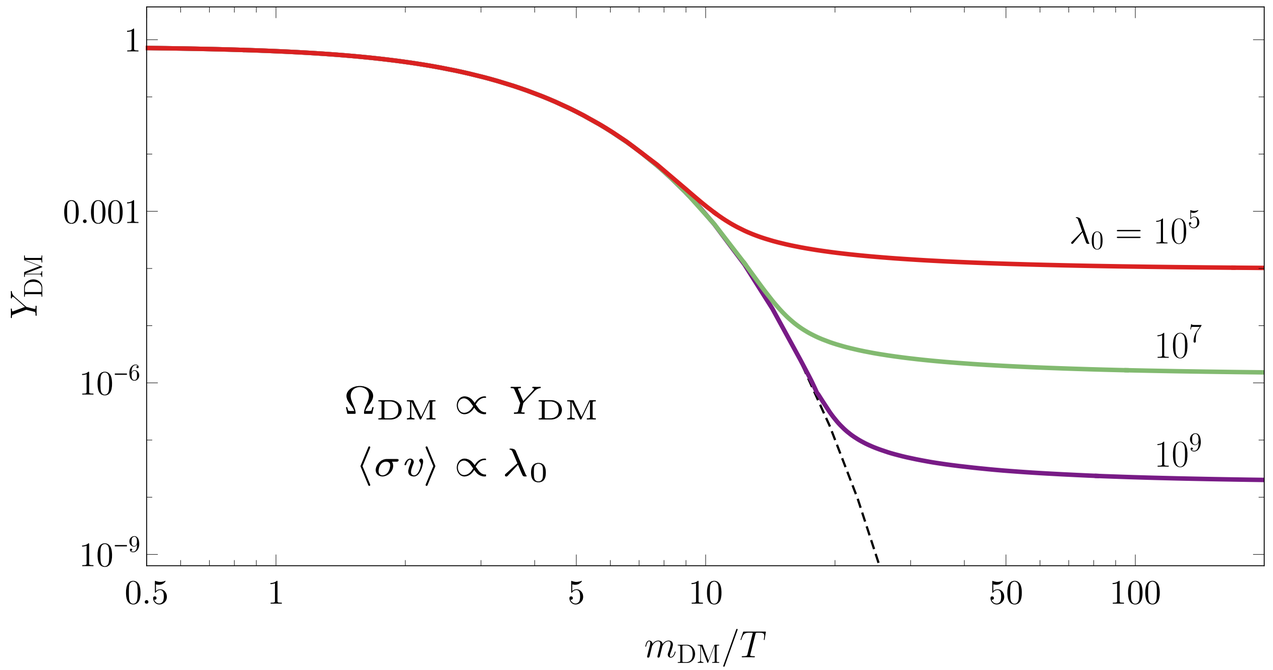
5. Prospects



Samuel Velasco/Quanta Magazine

The many virtues of the WIMP

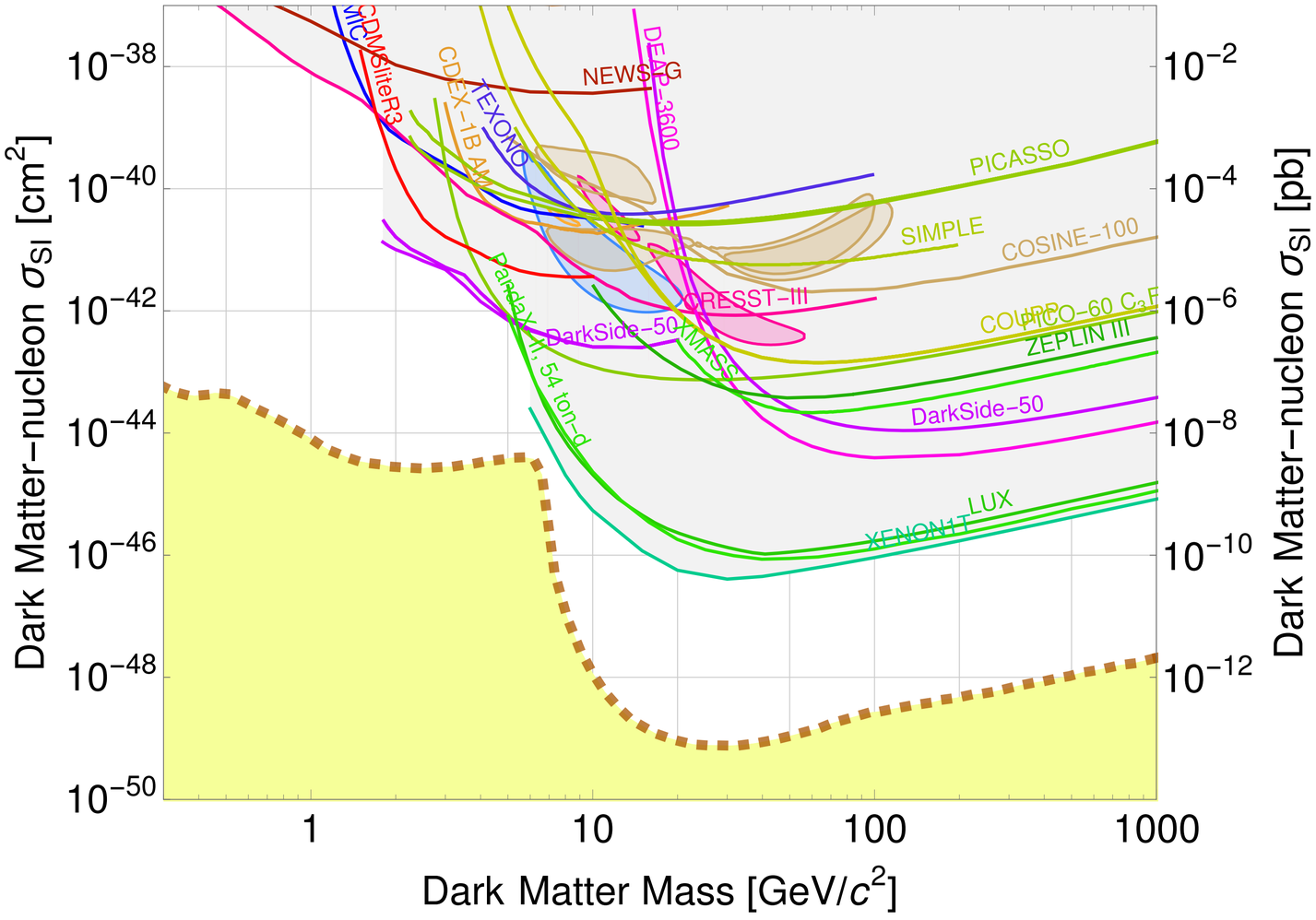




$$\Omega_{\rm DM} h^2 \equiv \frac{\rho_{\rm DM}}{\rho_{\rm tot}} h^2 \sim \frac{0.1\,{\rm pb}}{\langle\sigma v\rangle} \sim 0.1 \left(\frac{m_{\rm DM}}{100\,{\rm GeV}}\right)^2$$

Where are the WIMPs?

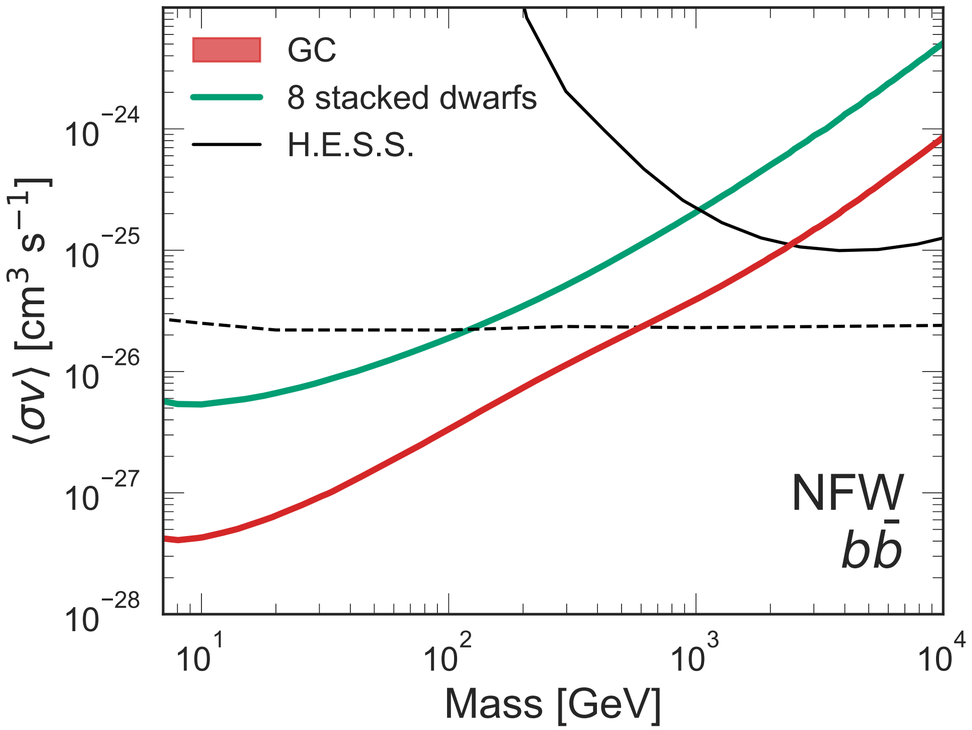
Direct detection

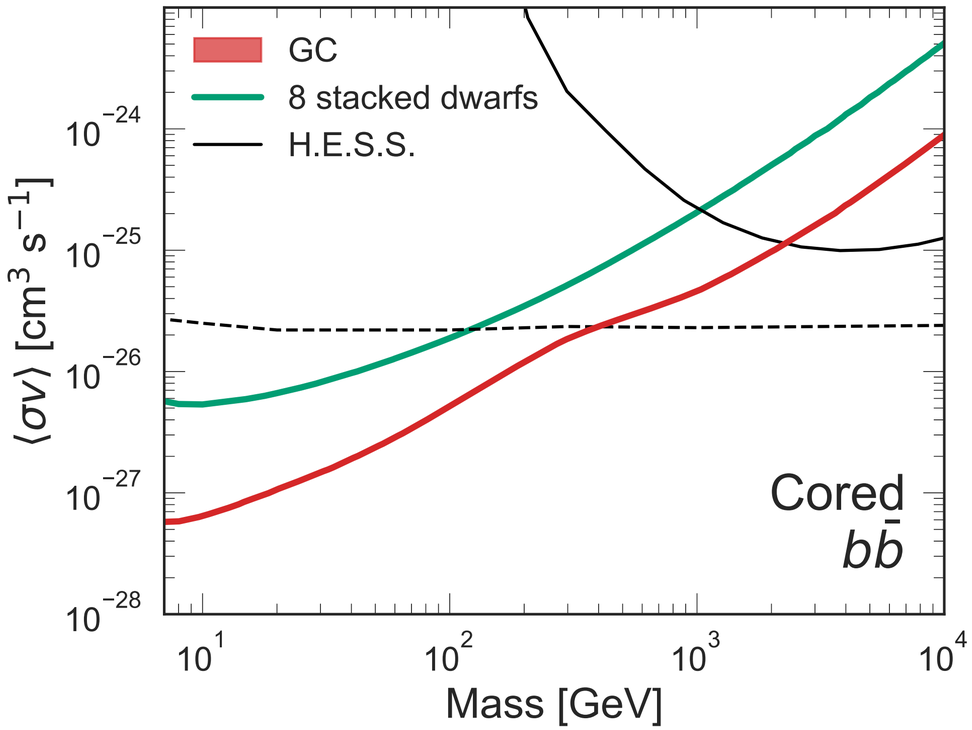


SuperCDMS Dark Matter Limit Plotter

Where are the WIMPs?

DM annihilation in the Galactic Center

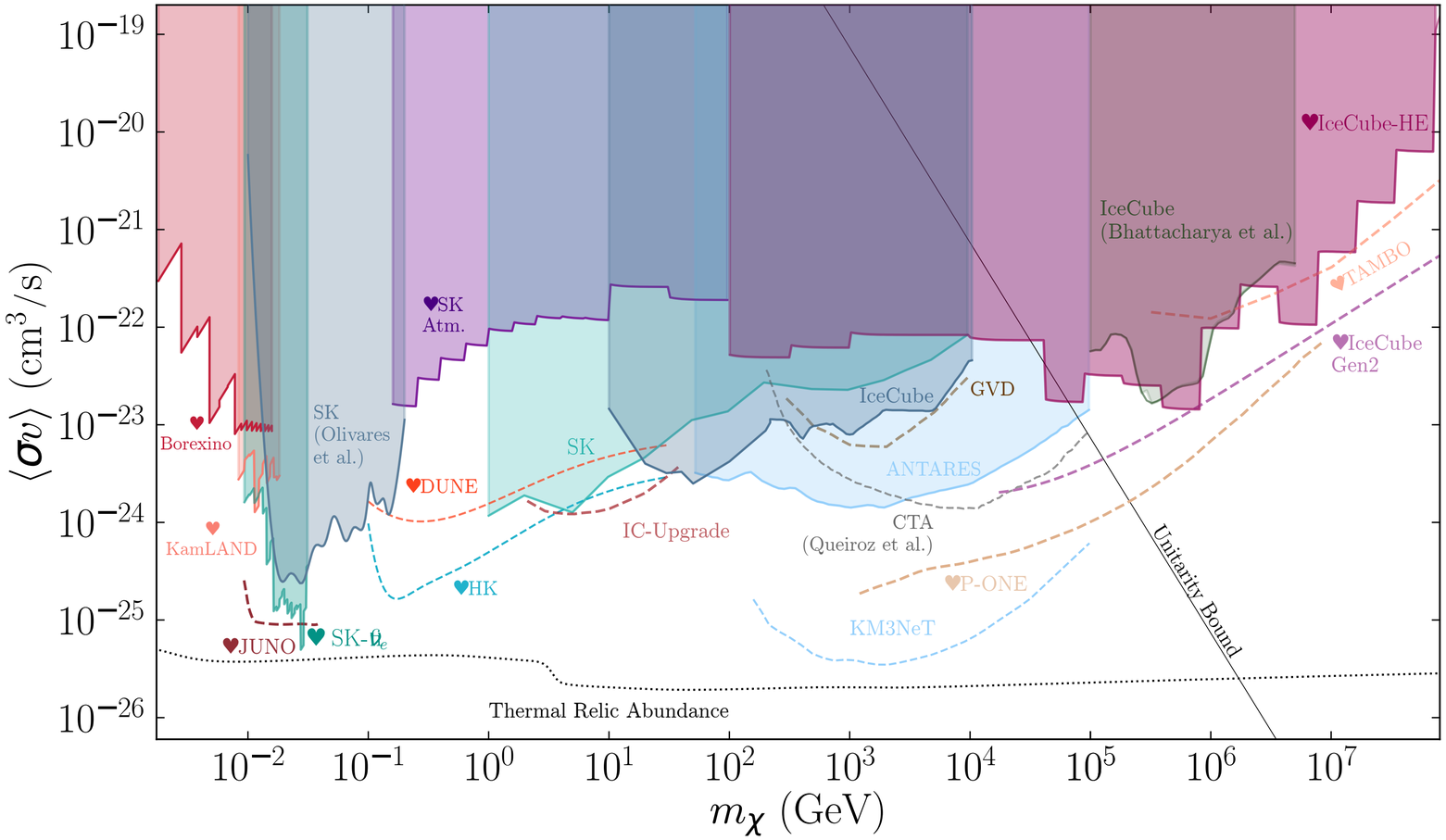




K. Abazajian et al., PRD 102 (2020), 043012 (Fermi-LAT)

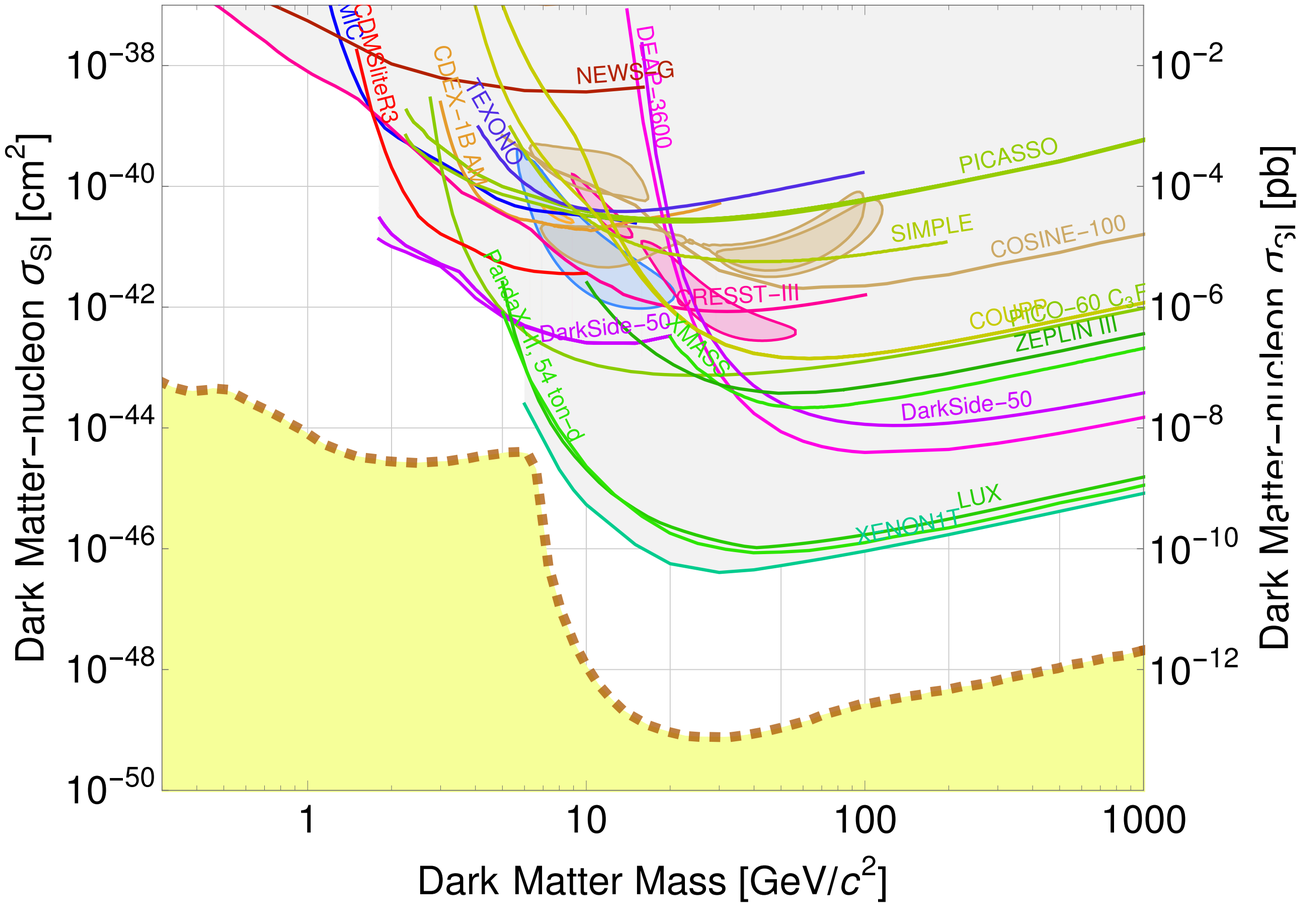
Where are the WIMPs?

DM annihilation to neutrinos



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

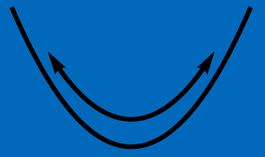
Beyond the WIMP



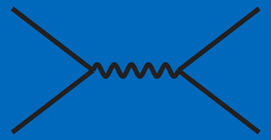
Feeble interactions =
dependence on initial conditions

1. Beyond WIMPs

2. Inflation & reheating

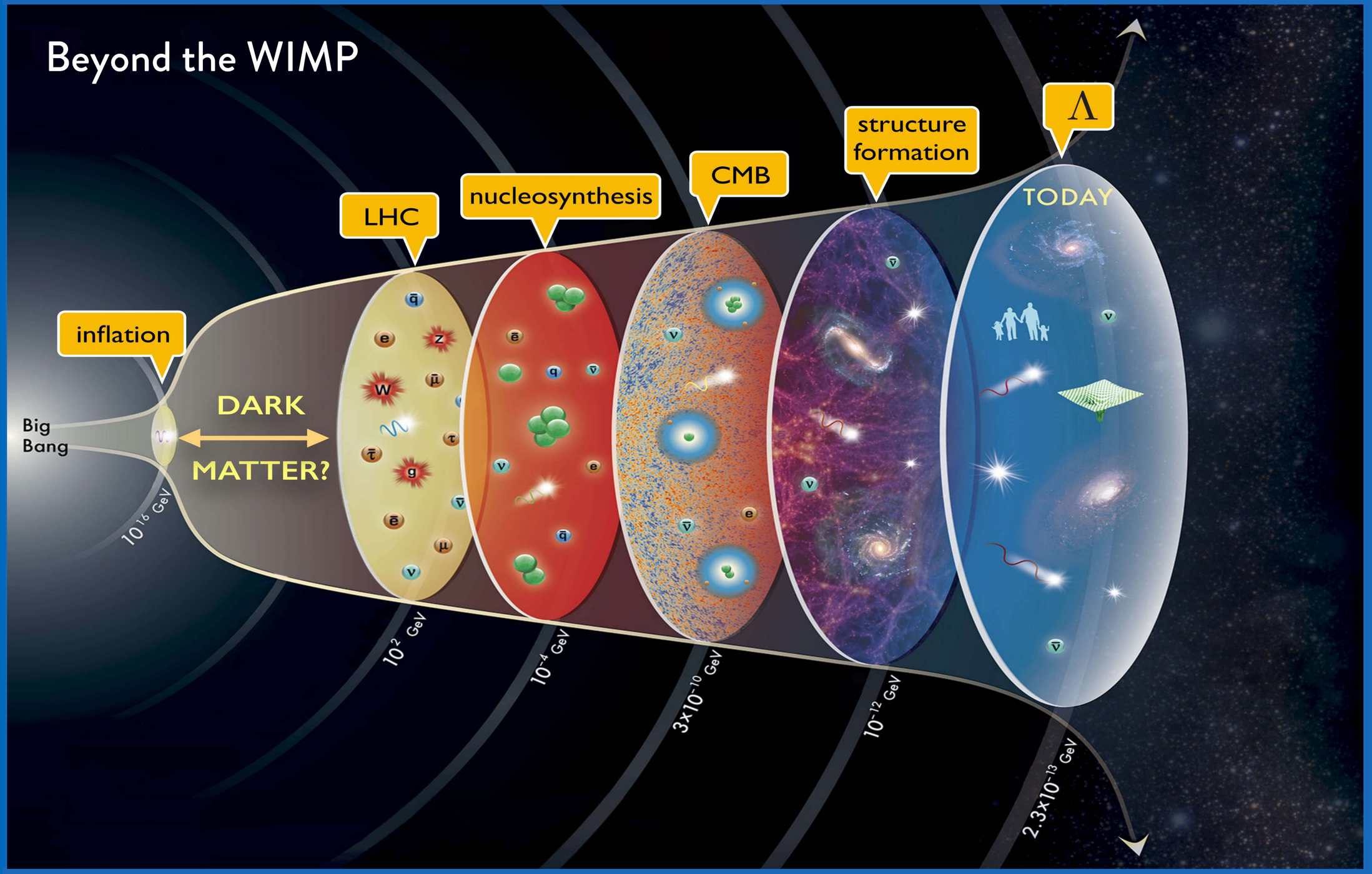


3. FIMPs



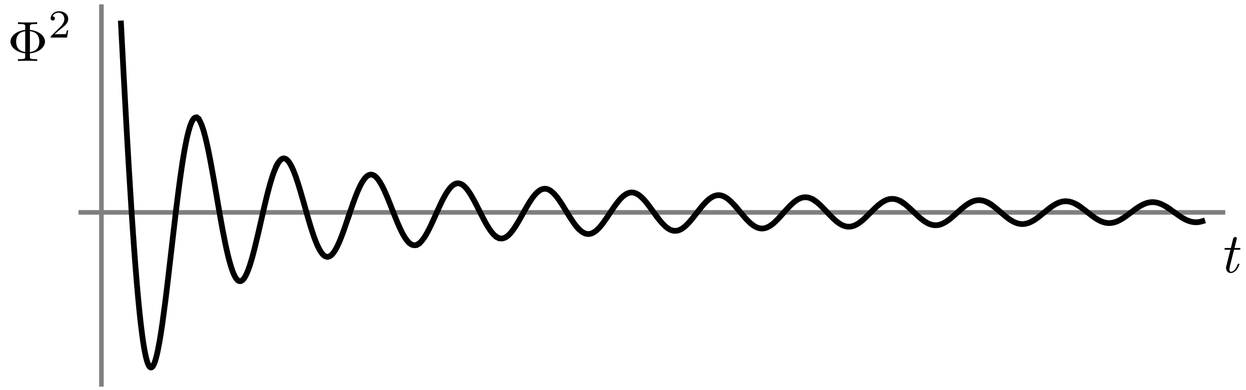
4. Compact objects

5. Prospects



The vacuum can be excited!

During reheating, the inflaton provides an oscillating background



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

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

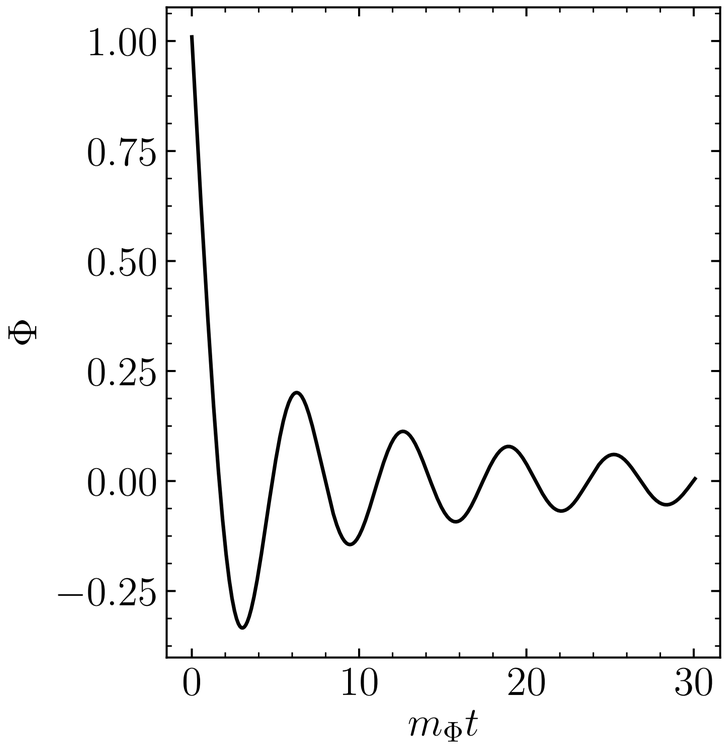
Mixing of +/- frequency modes $\rightarrow$ particle production!

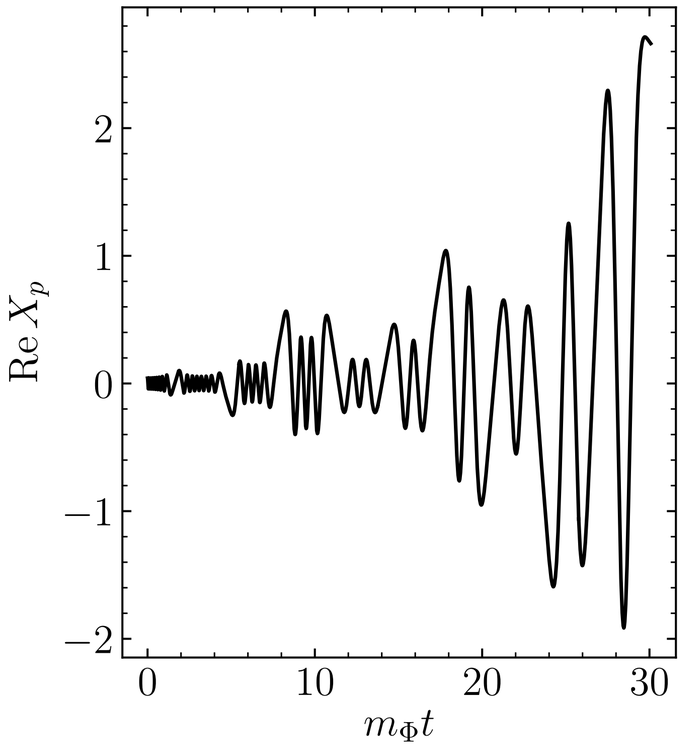
Scalar (p)reheating

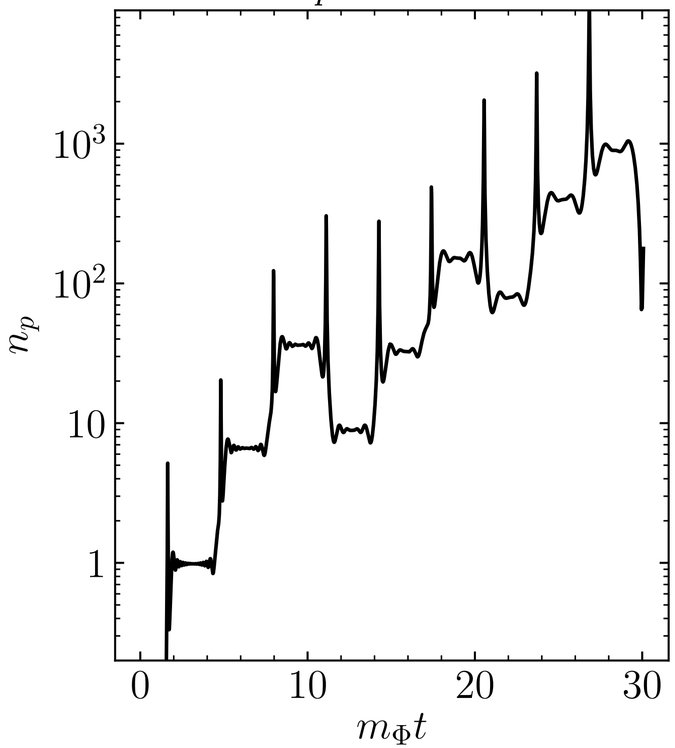
$$\ddot{\chi}_p + 3H\dot{\chi}_p + \left[\frac{p^2}{a^2} + m_\chi^2(t)\right]\chi_p \;=\; 0\,, \qquad m_\chi^2(t) = \sigma\Phi^2 + m_{\chi,0}^2$$

With expansion,

$$X = a\chi \qquad\qquad n_p = \frac{1}{2\omega_p}|\dot{X}_p\chi_p - iX'|^2$$



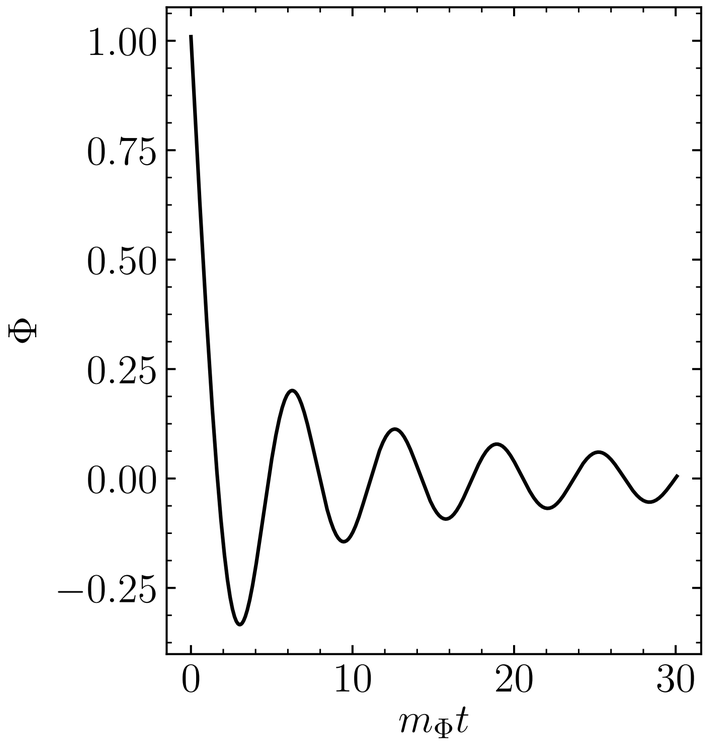


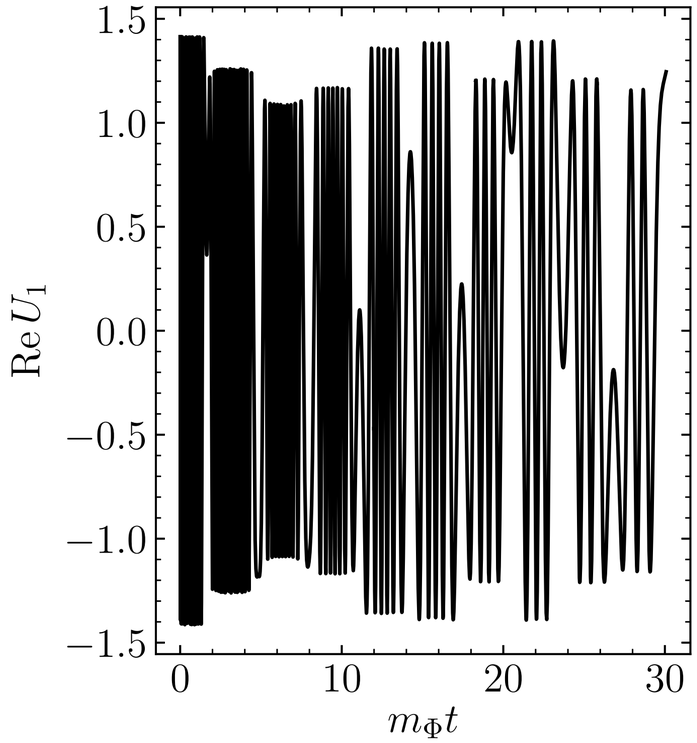


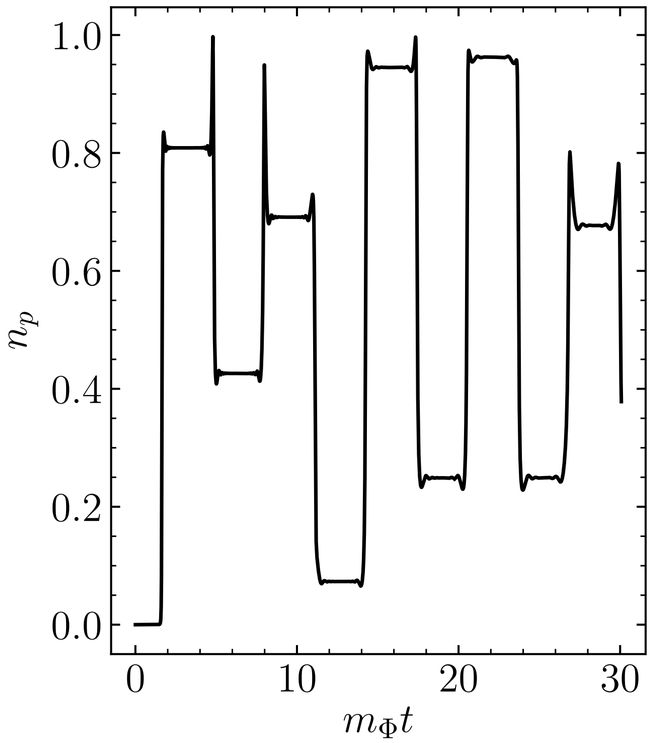
Fermion (p)reheating

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

With expansion,



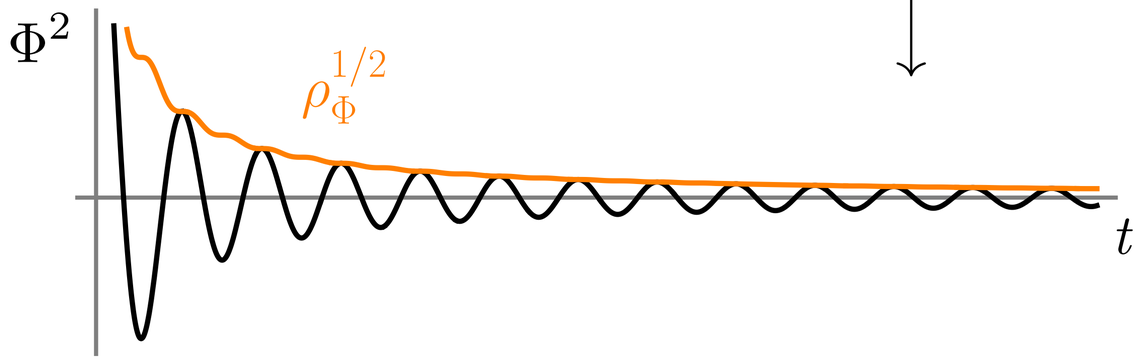




The perturbative (dissipative) picture

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)

The perturbative (dissipative) picture

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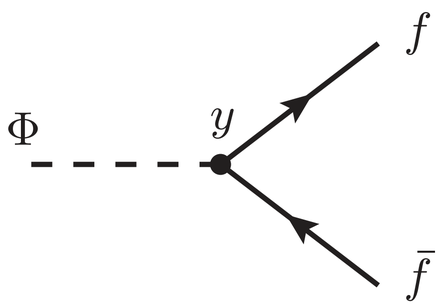
Conservation $\nabla_\mu T^{\mu\nu} = 0$,

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



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

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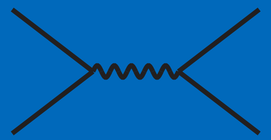

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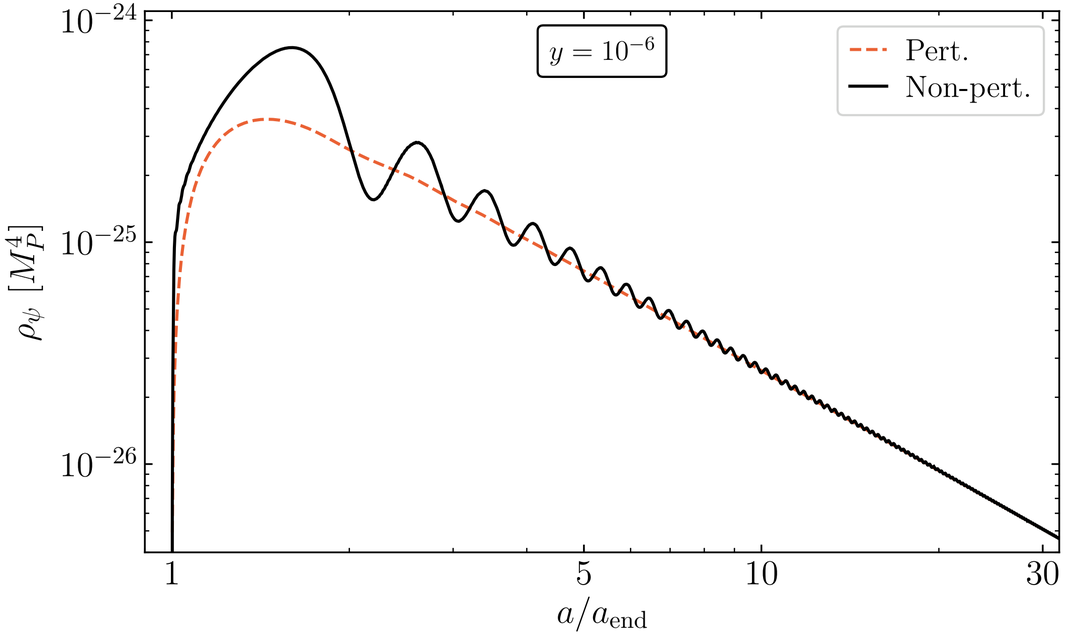

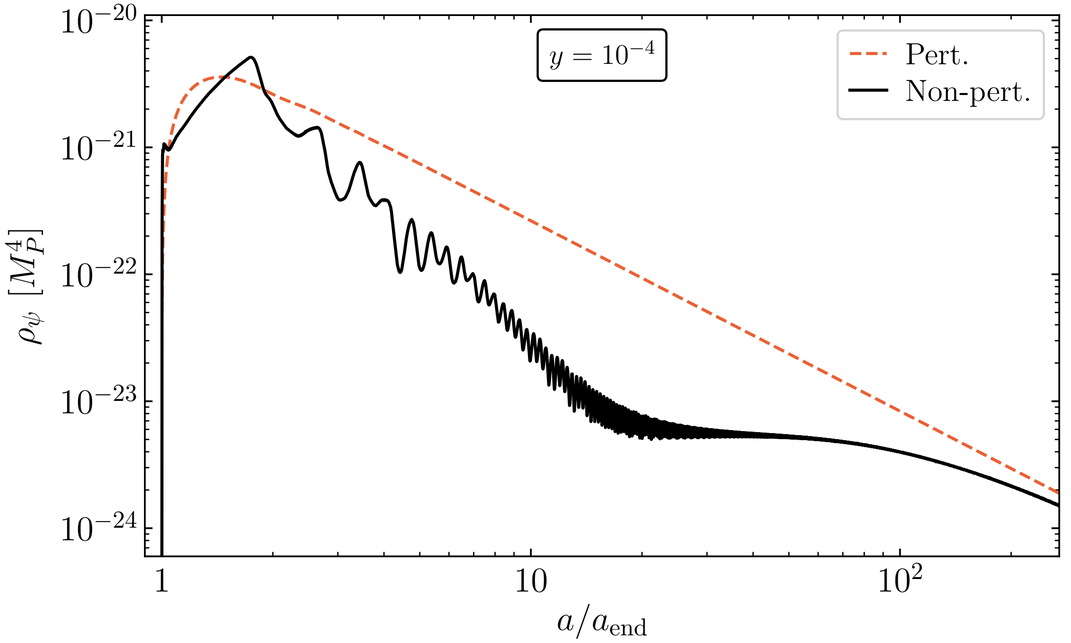

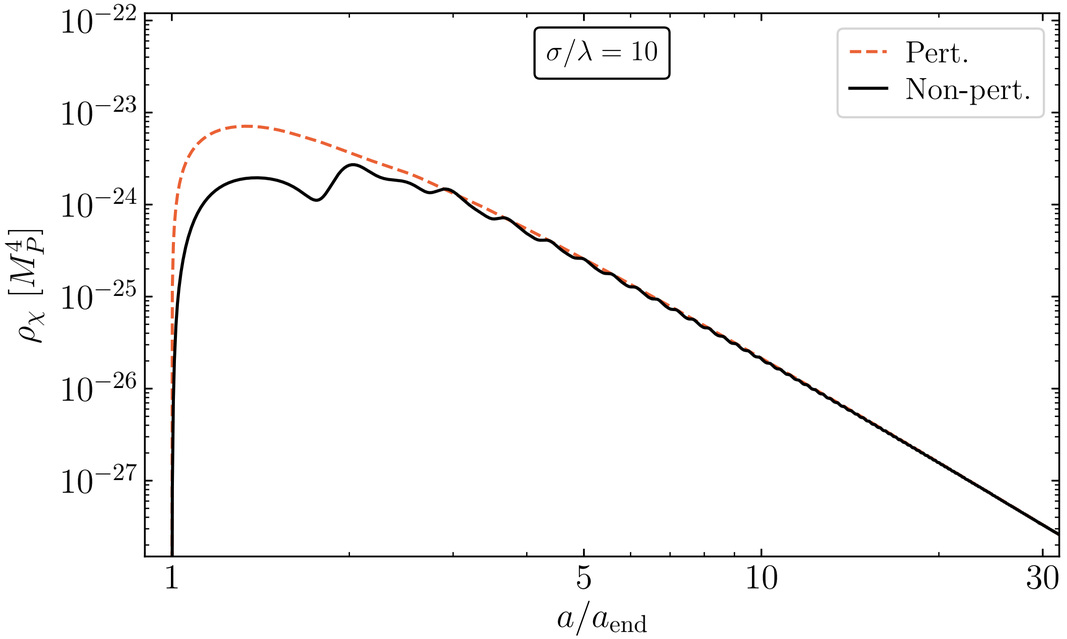

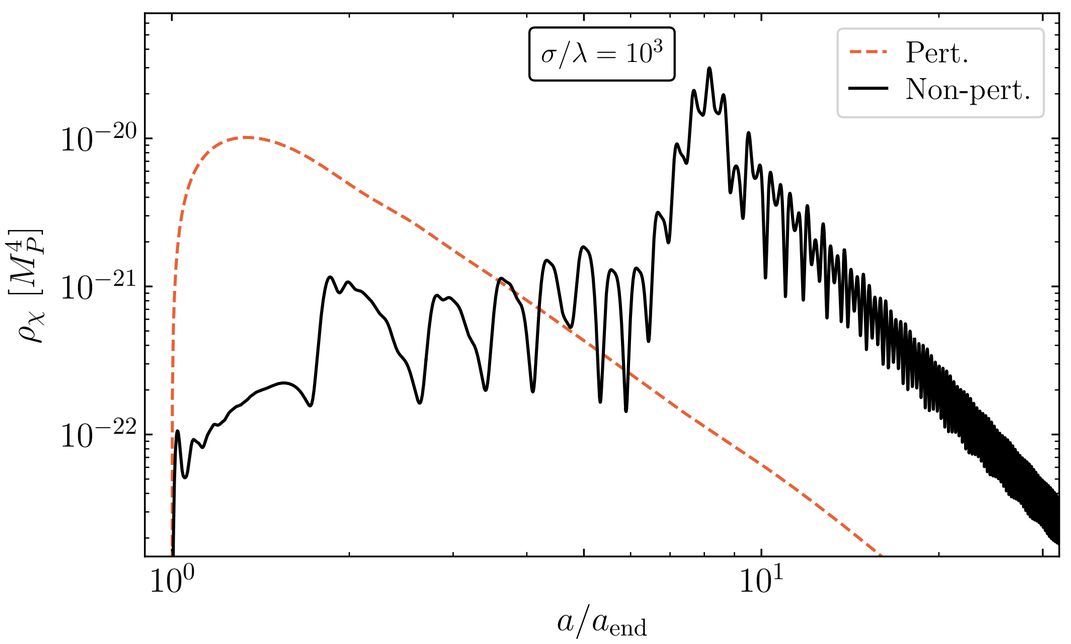

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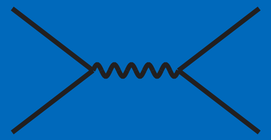

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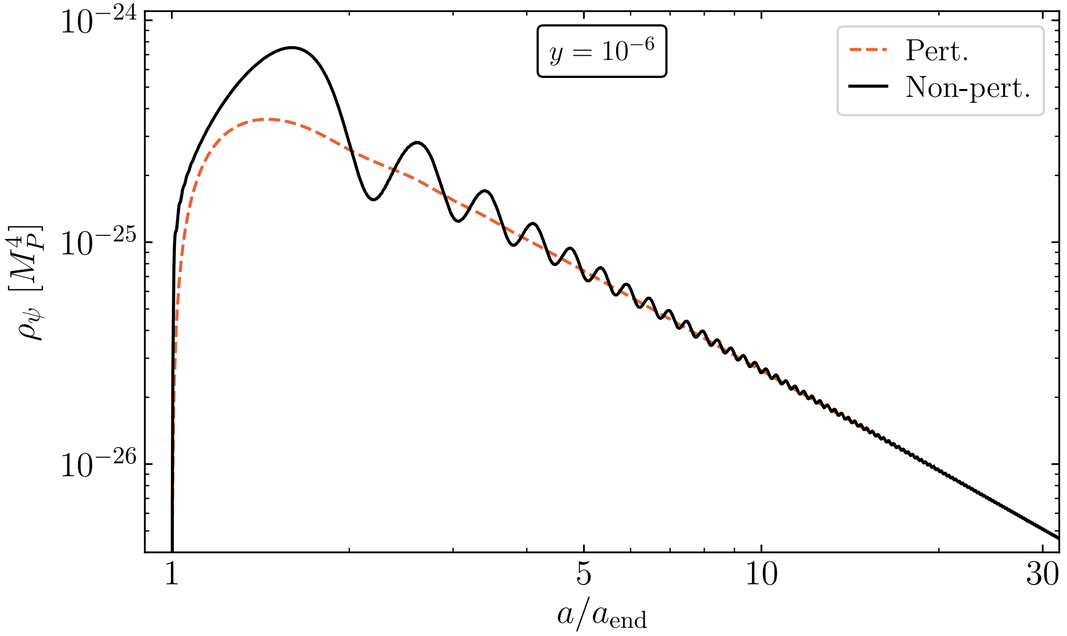

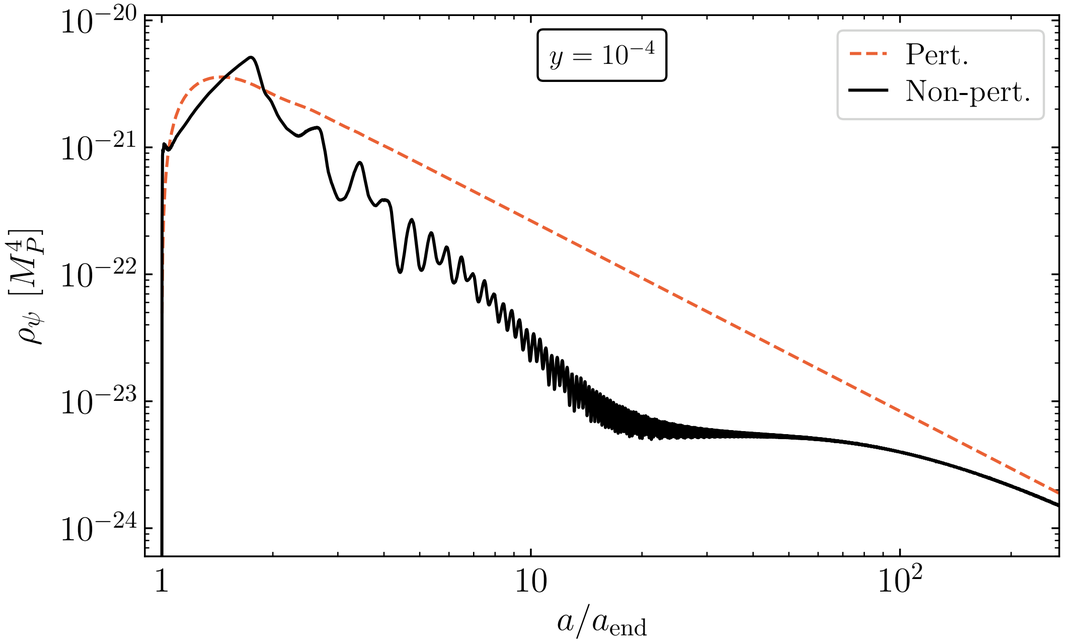

Early times: **field picture** (limited dissipation)

↓

interactions (thermalization)

↓

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

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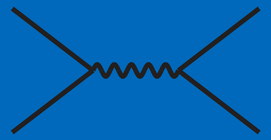

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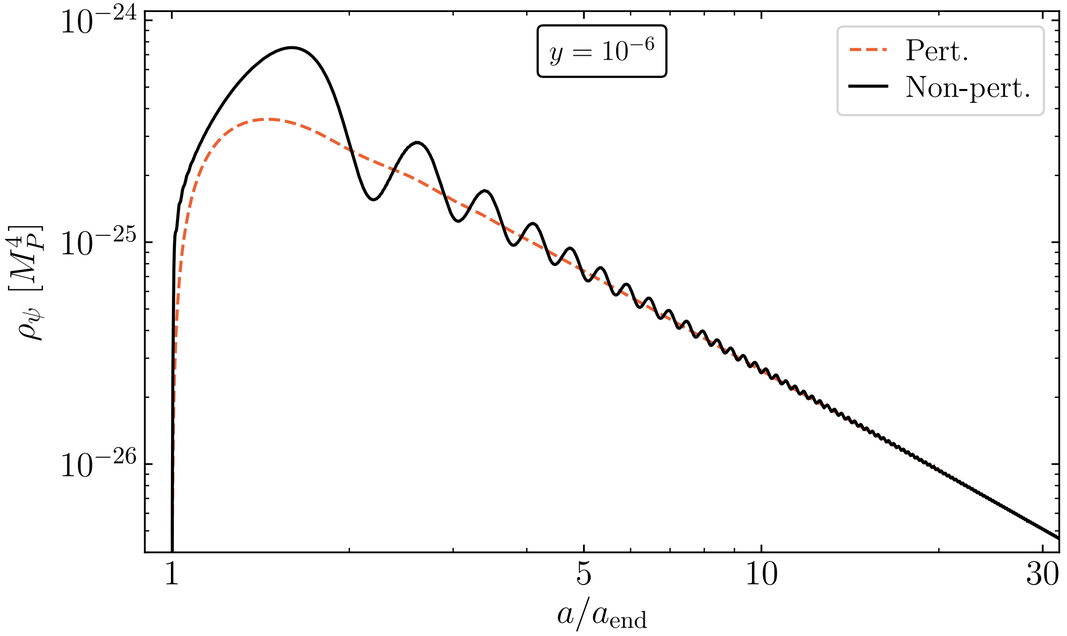
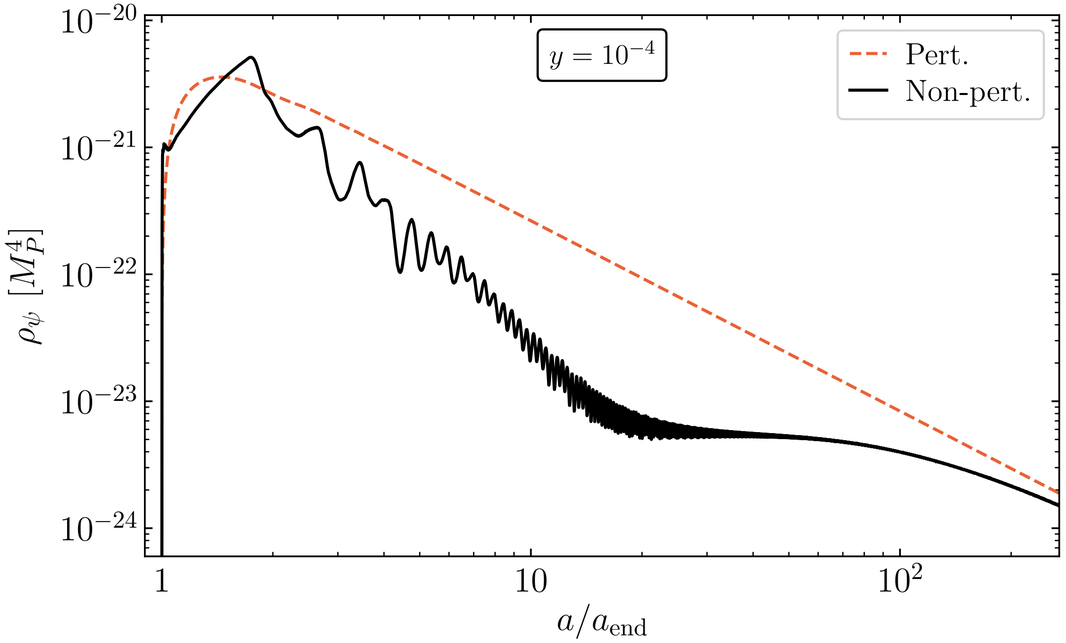




Early times: field picture (limited dissipation)

↓

Schiwnger-Keldysh / Kadanoff-Baym

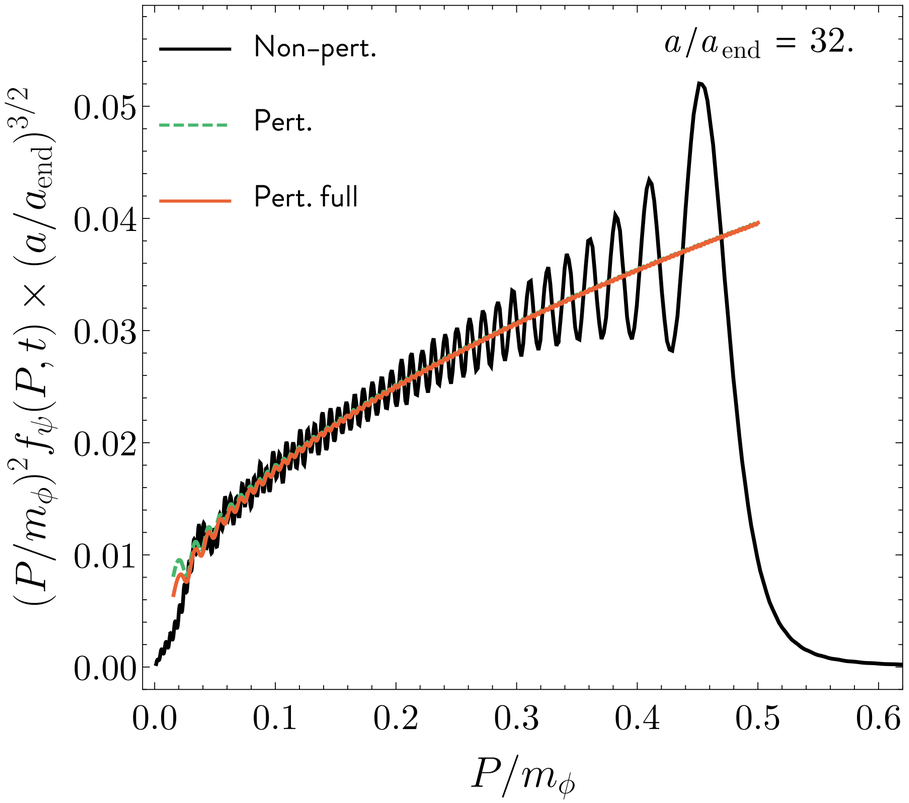
Boltzmann

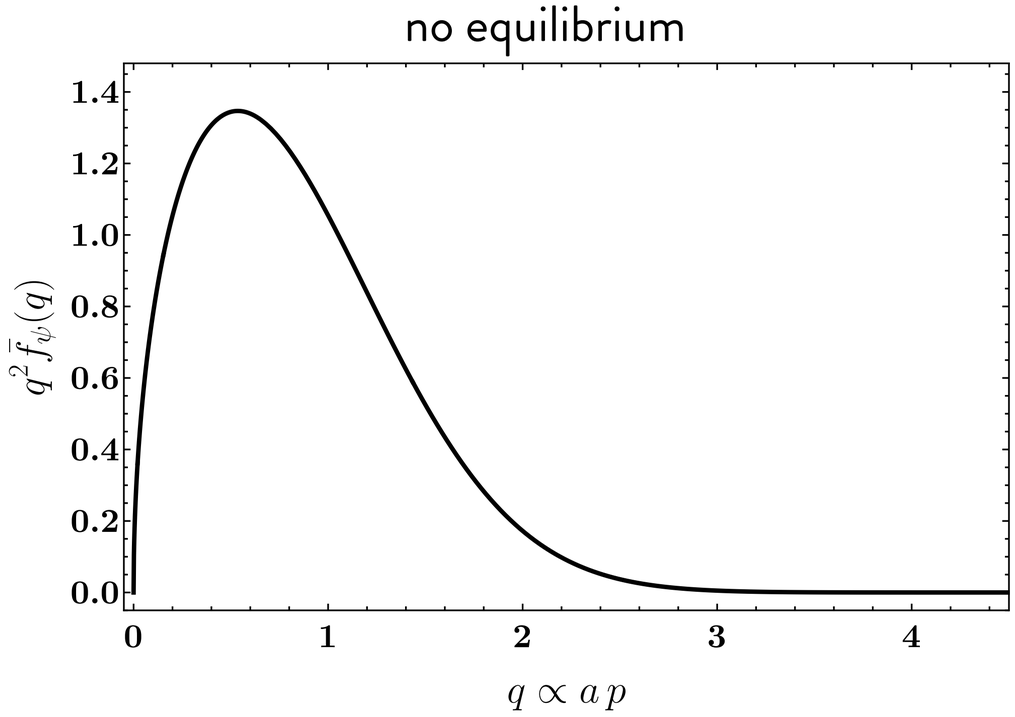
↓

Late times: fluid picture (no fluctuations)

The phase space distribution

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





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

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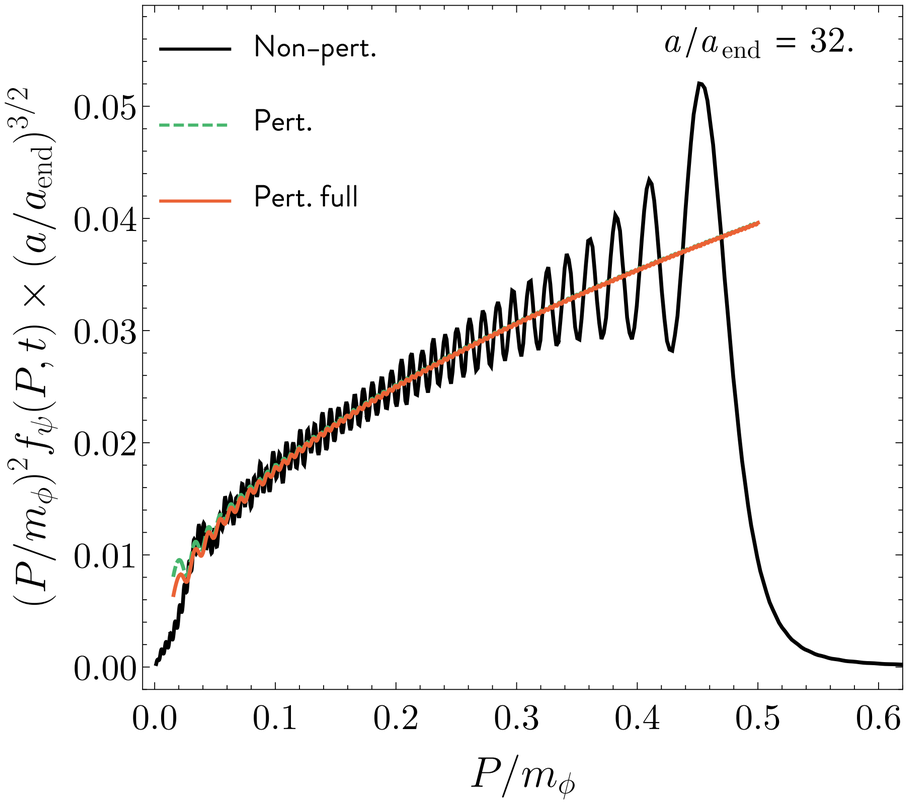
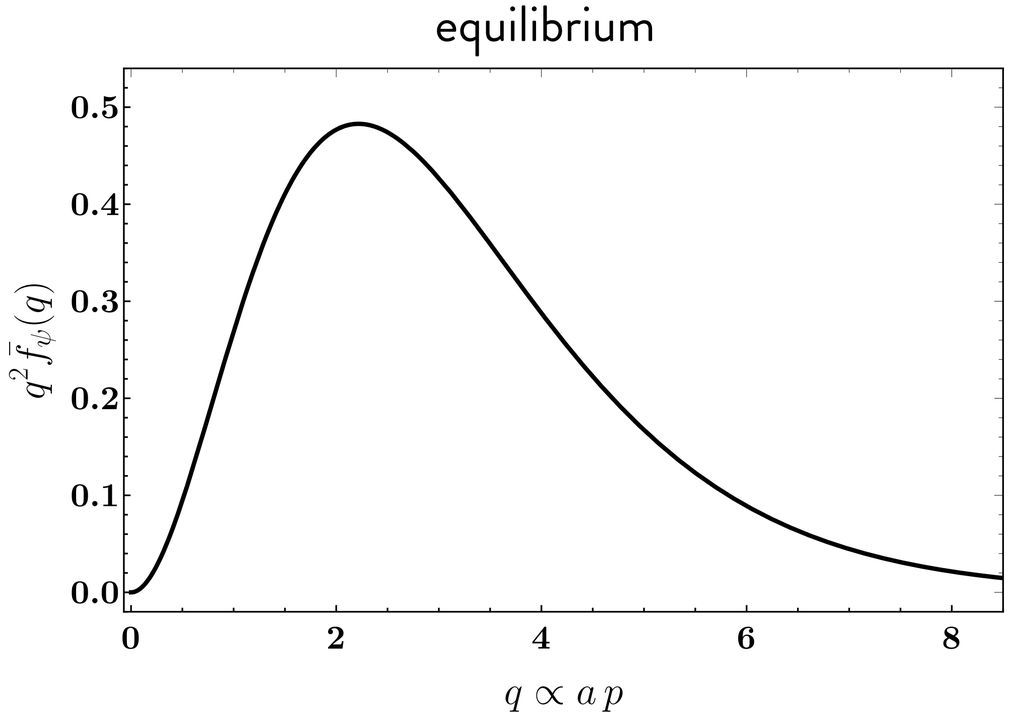




K. Harigaya, K. Mukaida, JHEP 05 (2014), 006

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+DM:	H	u_L	W^0	Ψ	G
				raritron	
	Φ	ν_R			
	inflaton	R-neutrino			

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

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

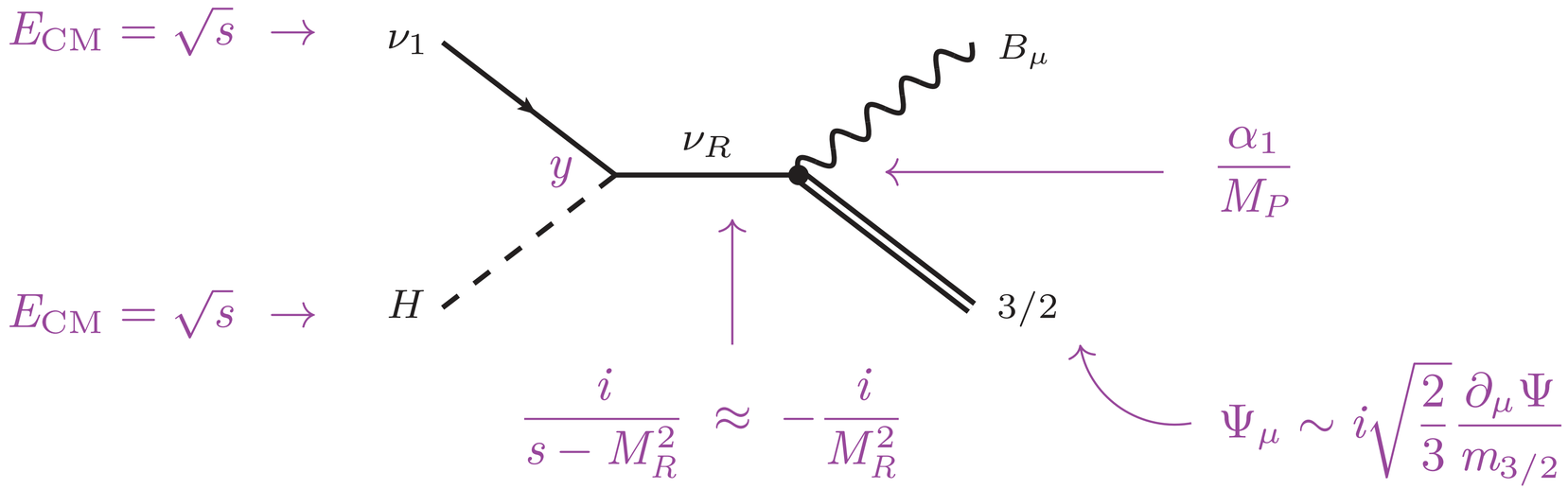
$$+ y_\nu \Phi \bar{\nu}_R \nu_R \qquad \text{(reheating)}$$

$$+ i\frac{\alpha_1}{2M_P}\bar{\nu}_R\gamma^\mu[\gamma^\rho,\gamma^\sigma]\Psi_\mu F_{\rho\sigma} + i\frac{\alpha_2}{2M_P} i\sigma_2 (D^\mu H)^* \bar{L}\Psi_\mu + \cdots$$

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

Scatterings and decays

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

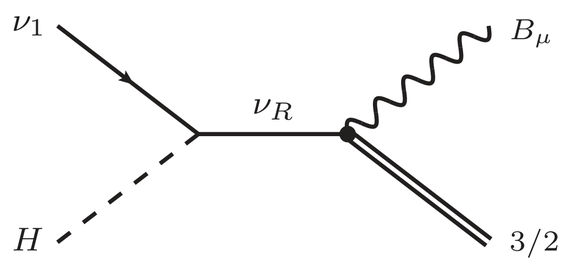


$$\Rightarrow \qquad \sigma(s) \propto \frac{\alpha_1^2 y^2 s^2}{m_{3/2}^2 M_R^2 M_P^2}$$

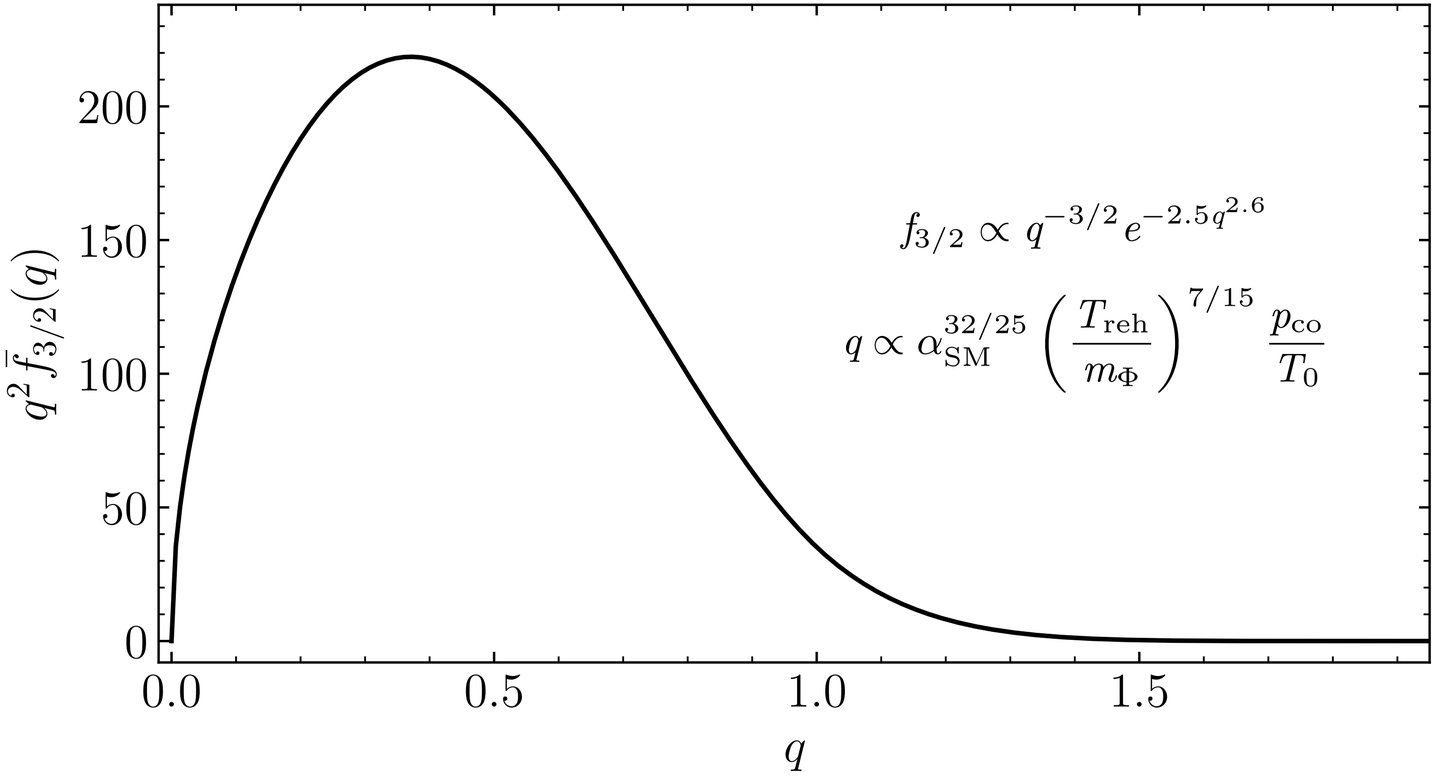
- Production peaked at high energies → reheating
- Ψ is never in thermal equilibrium (*freeze-in*)

Scatterings and decays

not equilibrated



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

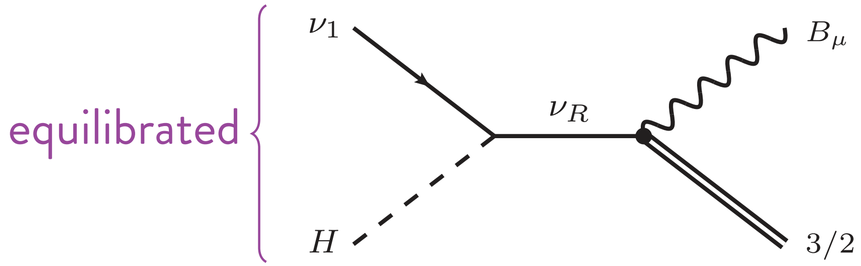


$$f_{3/2} \propto q^{-3/2} e^{-2.5 q^{2.6}}$$

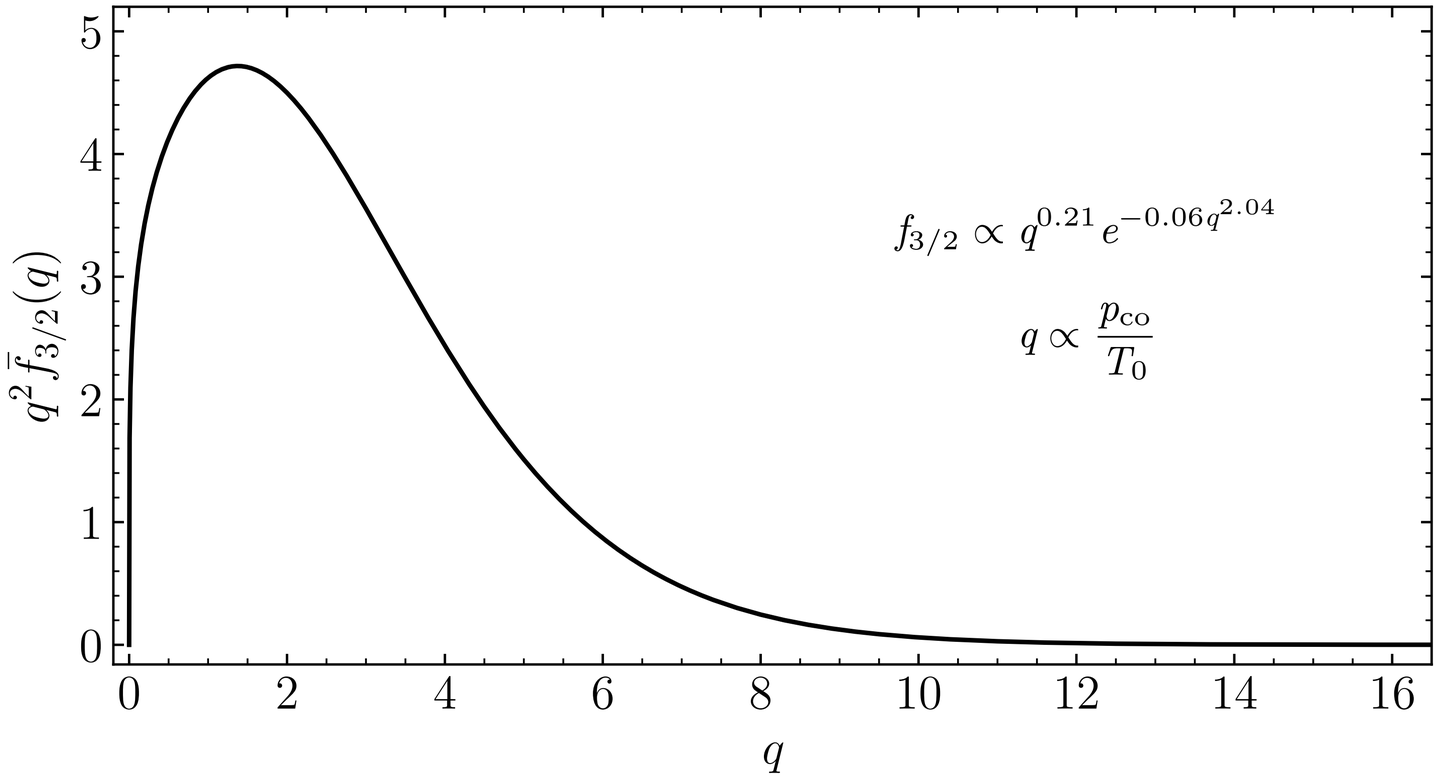
$$q \propto \alpha_{\rm SM}^{32/25} \left(\frac{T_{\rm reh}}{m_\Phi} \right)^{7/15} \frac{p_{\rm co}}{T_0}$$

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

Scatterings and decays



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



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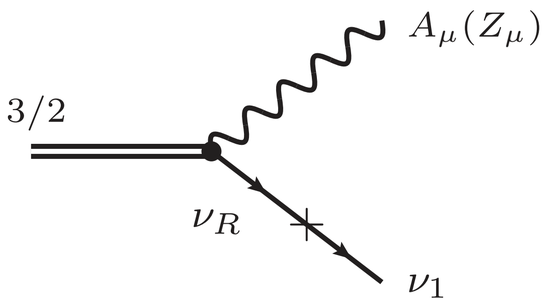
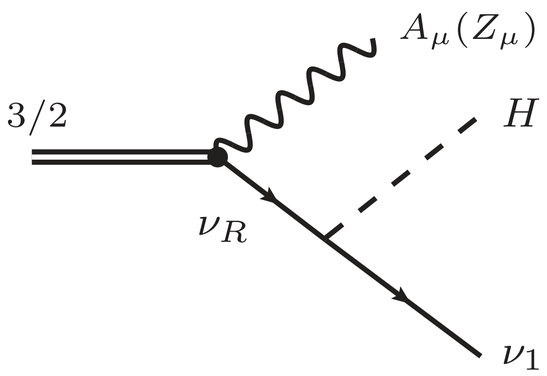
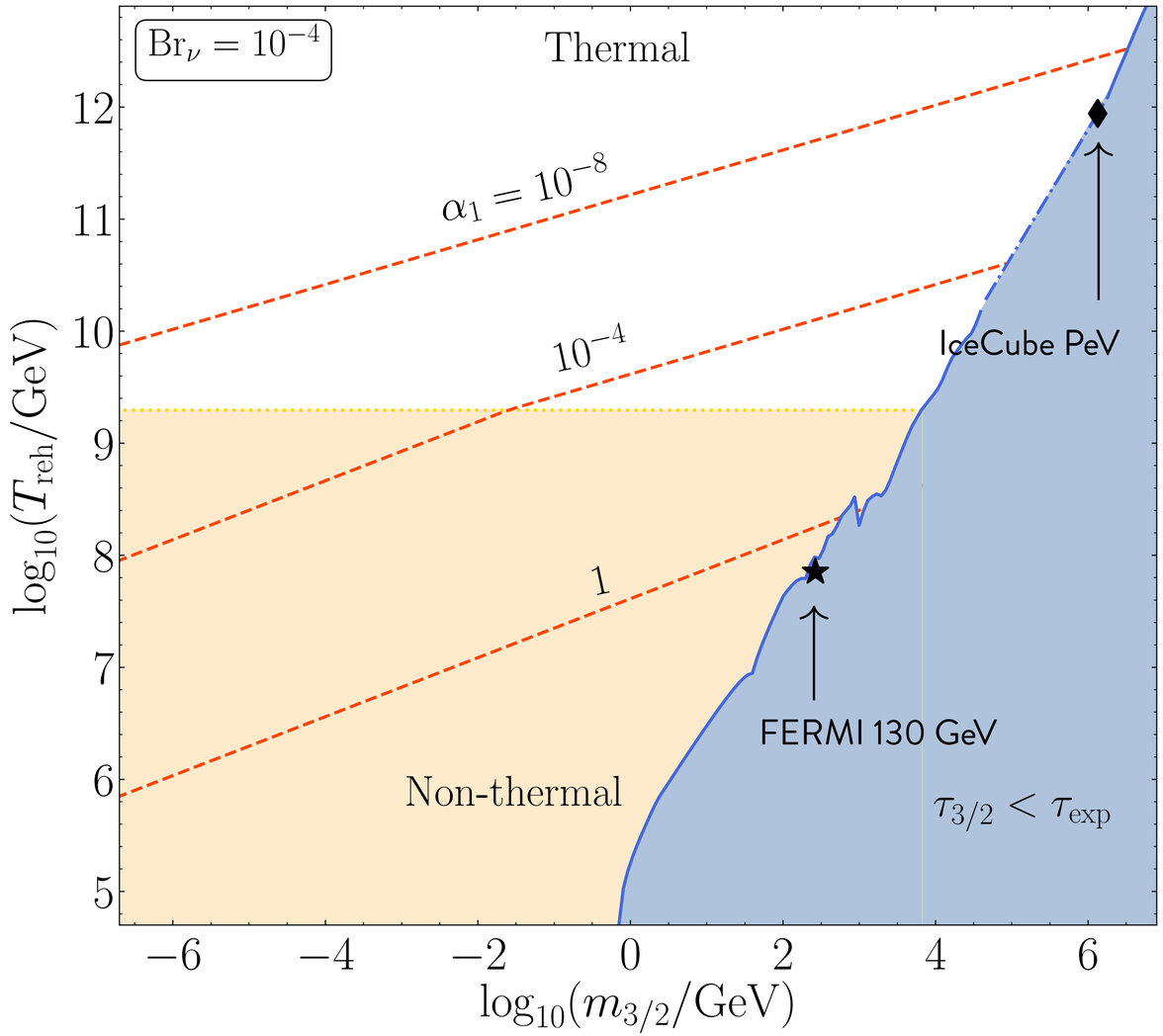
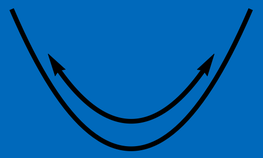


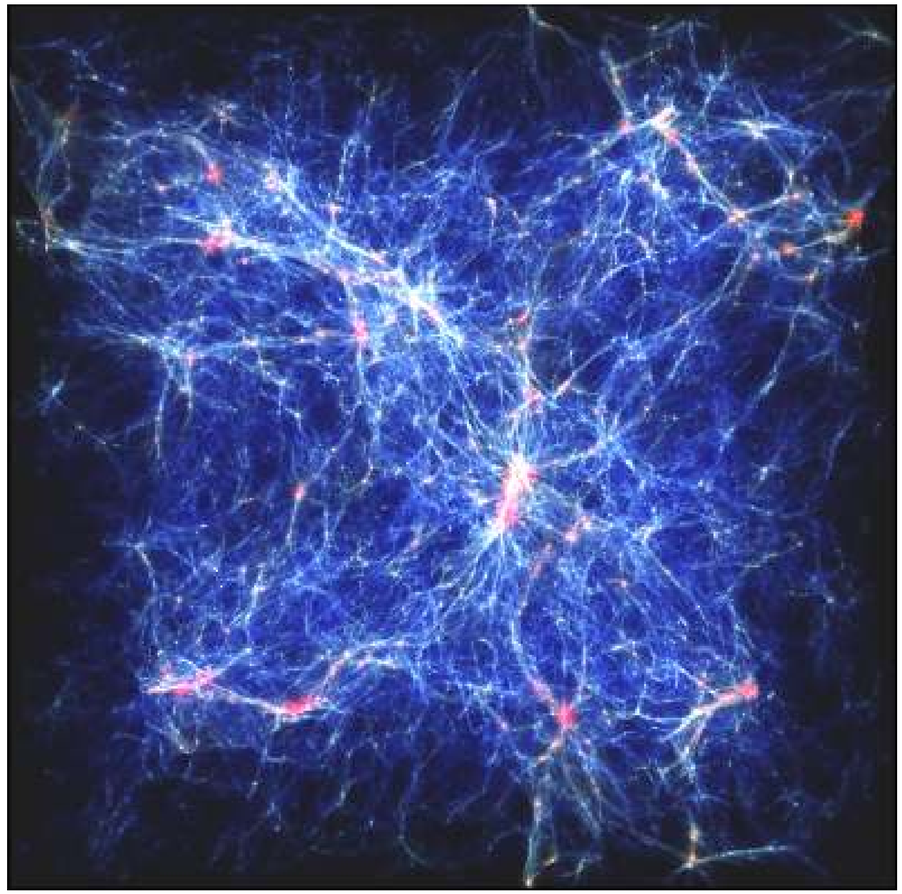


Scattering

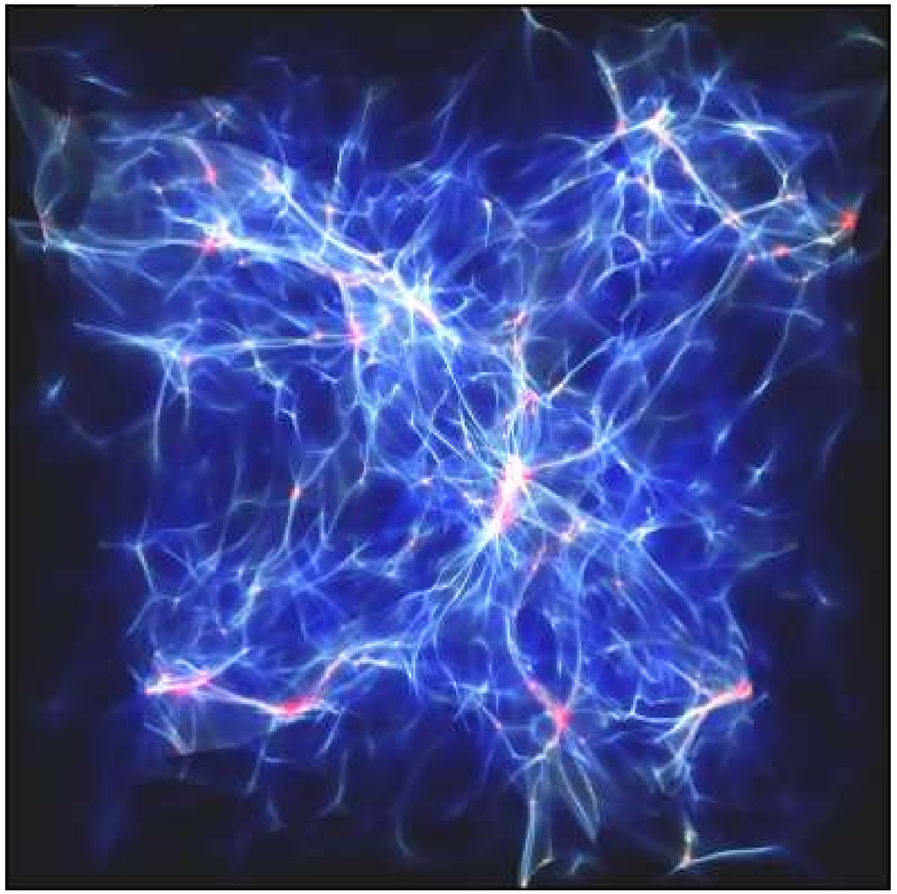




How warm is out-of-equilibrium dark matter?



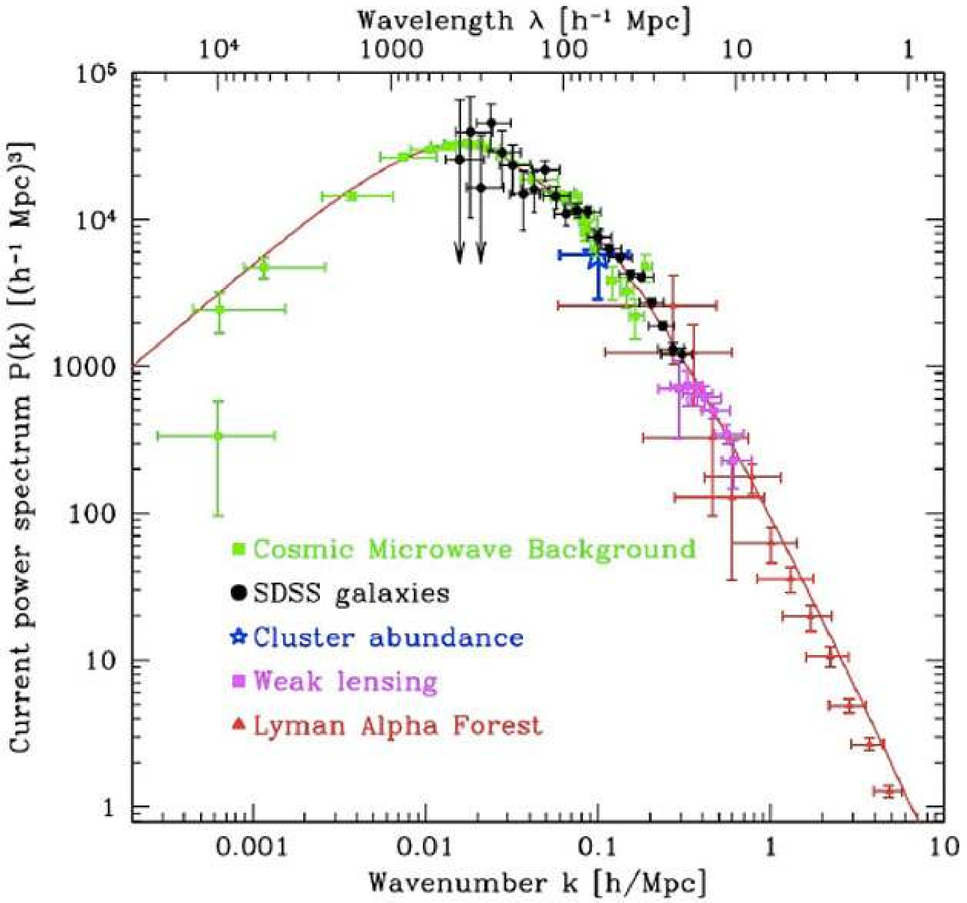
CDM



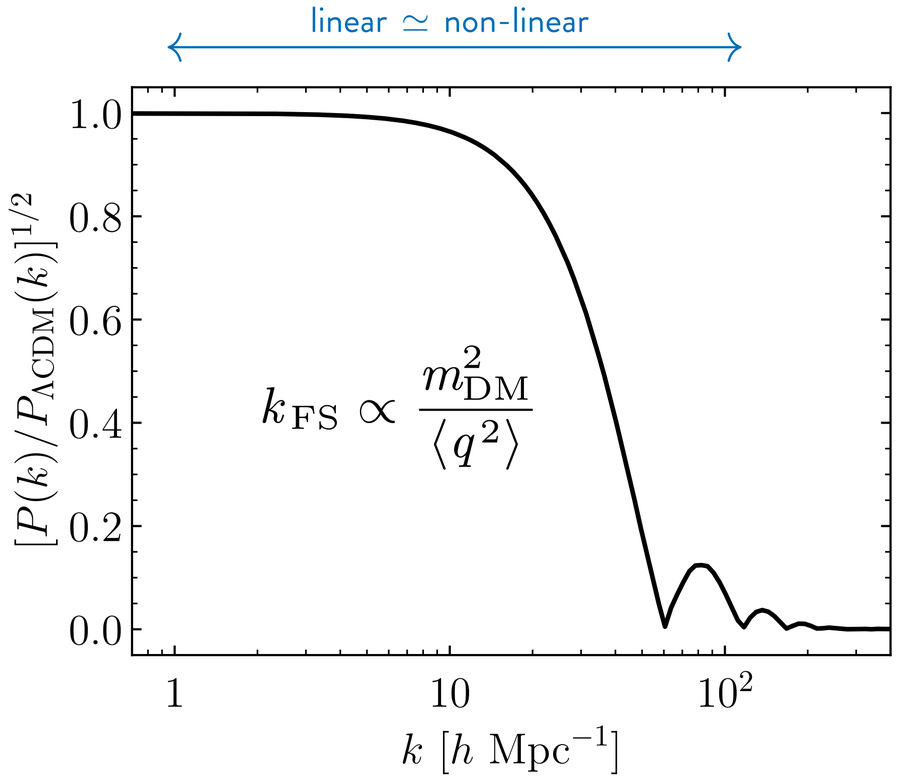
WDM (0.5 keV)

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

How warm is out-of-equilibrium dark matter?



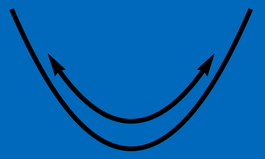
R. Murgia, V. Iršič and M. Viel, PRD 98 (2018), 083540



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

1. Beyond WIMPs

2. Inflation & reheating

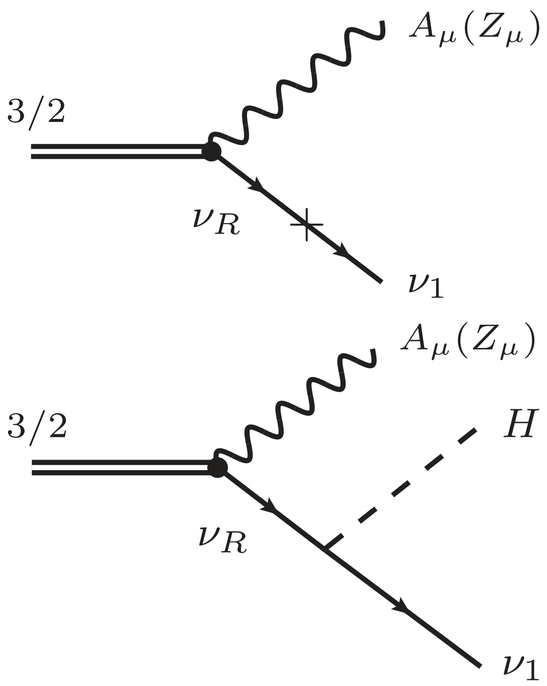


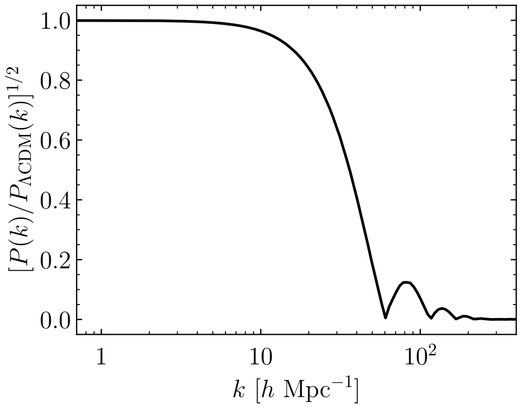
3. FIMPs

4. Compact objects

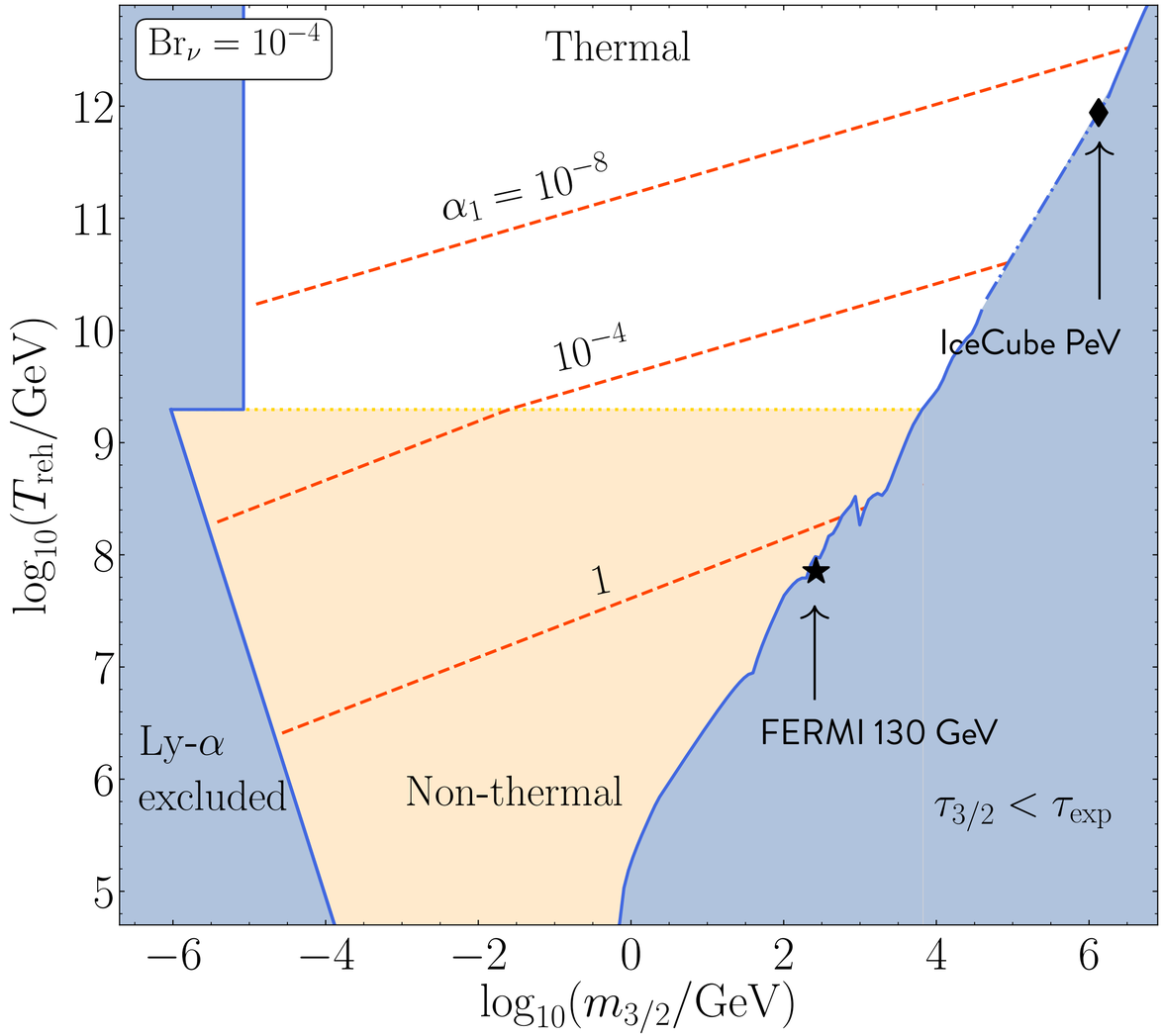
5. Prospects

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





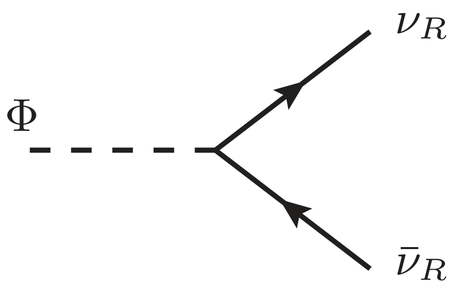
Scattering

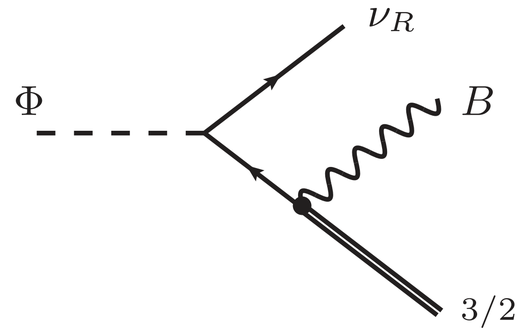


Production (via inflaton decay)

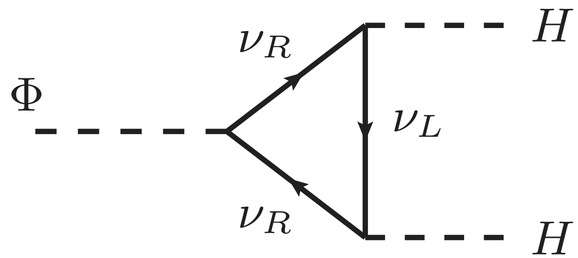
Via α_1,

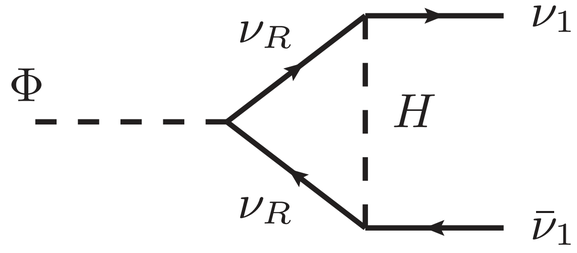
$M_R \ll m_\Phi$:

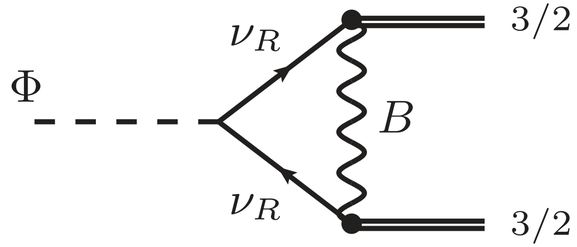




$M_R \gg m_\Phi$:

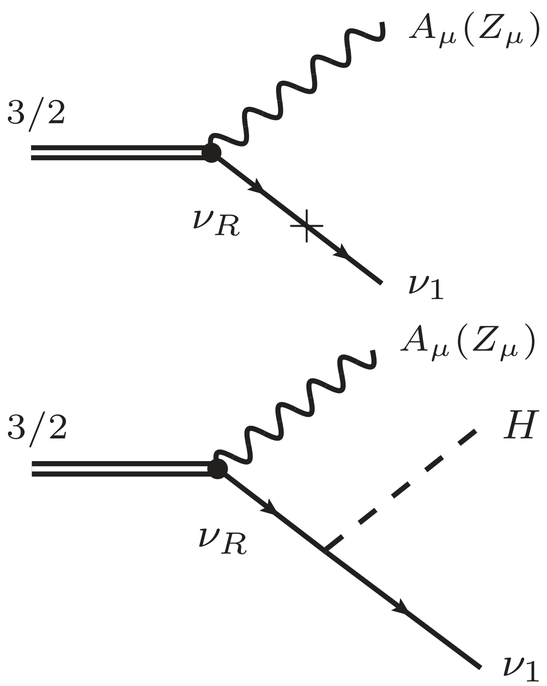


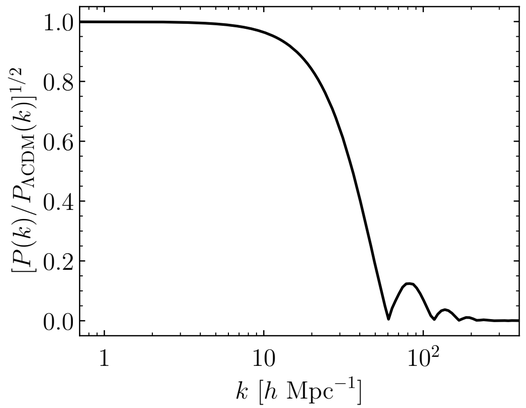




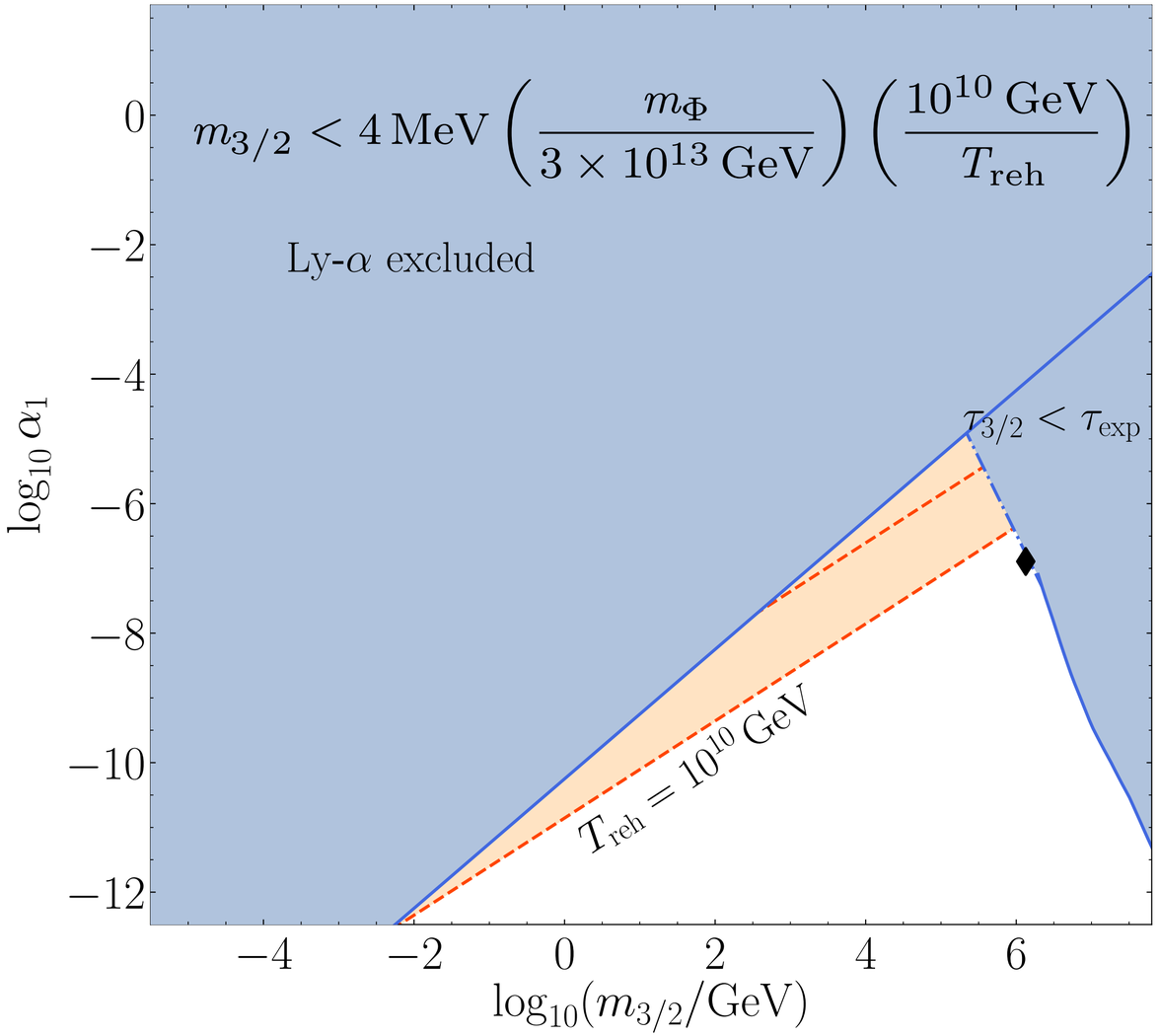
(via α_2 are 2-loop suppressed)

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





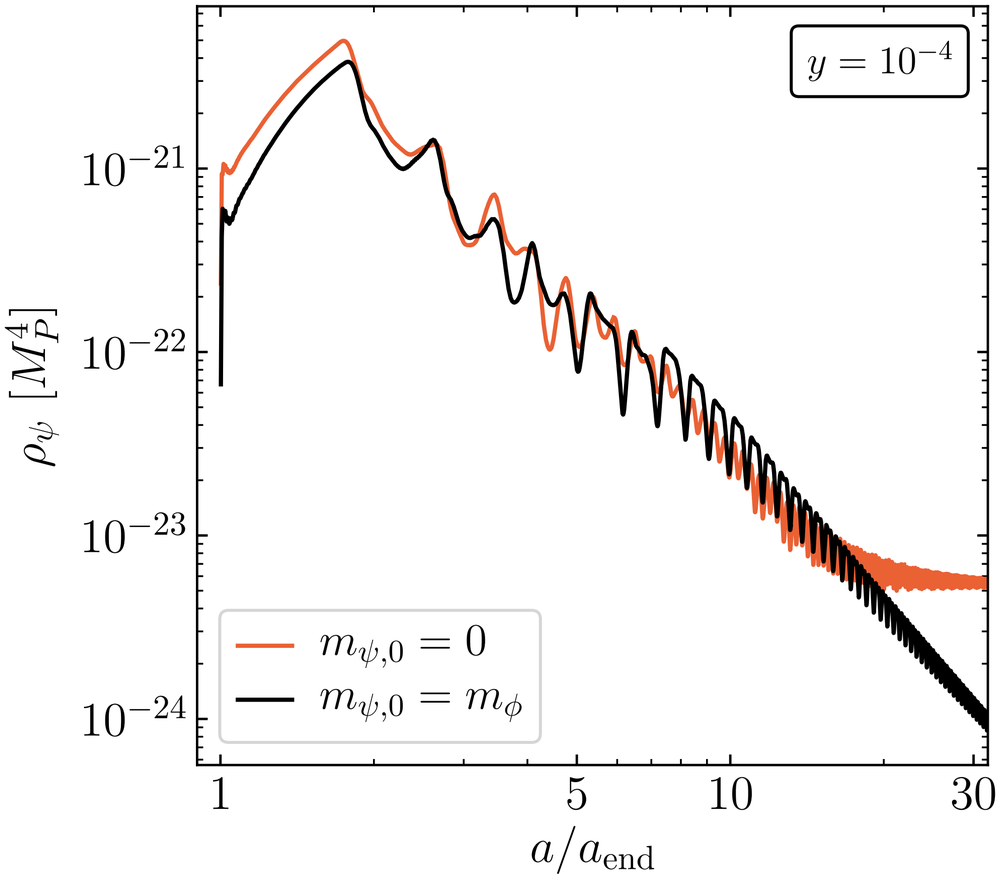
Inflaton decay

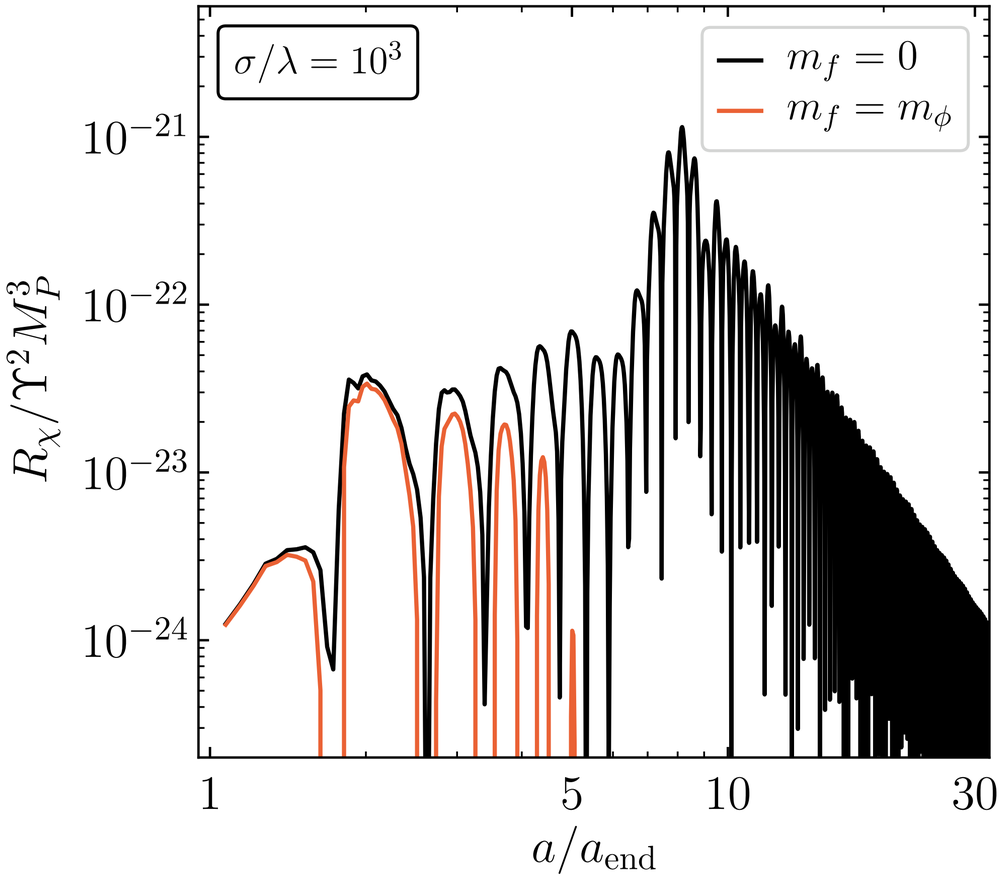


Beyond perturbation theory

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

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

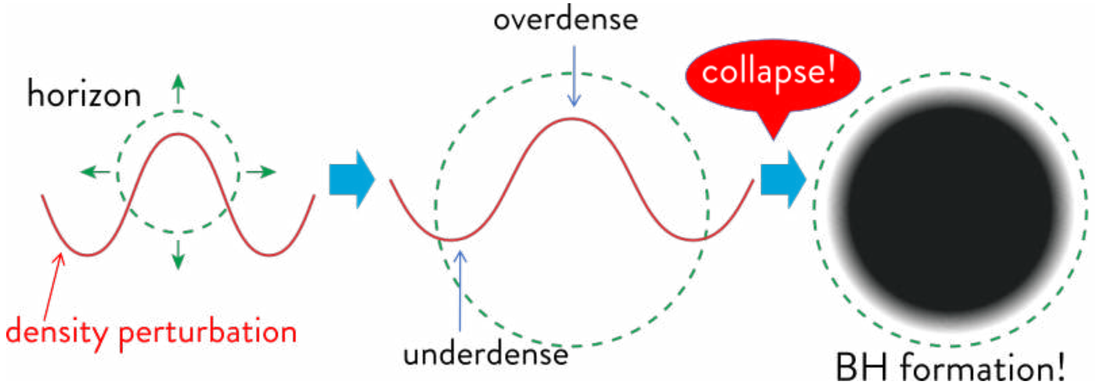




(but not thermally though)

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

Large metric fluctuations?



Credit: Naoya Kitajima

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

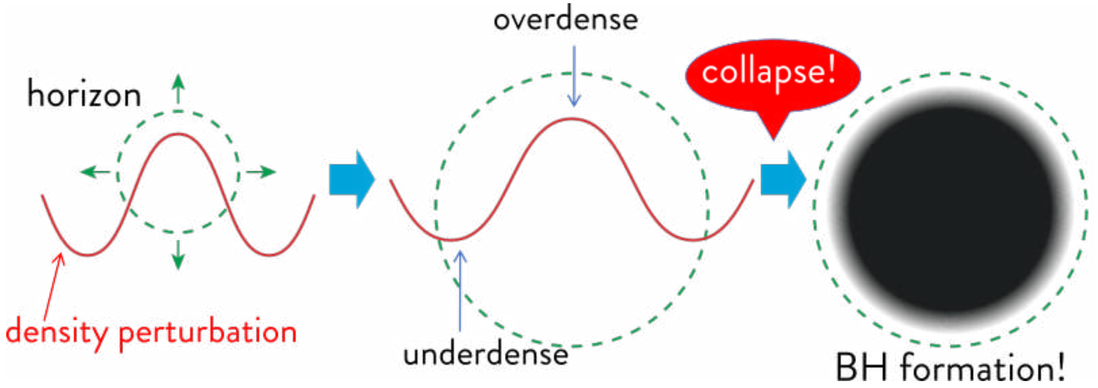
$M_{\rm BH}$	$\tau_{\rm BH}$
A man	10^{-12} s
10^{15} g	10^{10} y
Earth	10^{49} y
Sun	10^{66} y
Milky Way	10^{99} y

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

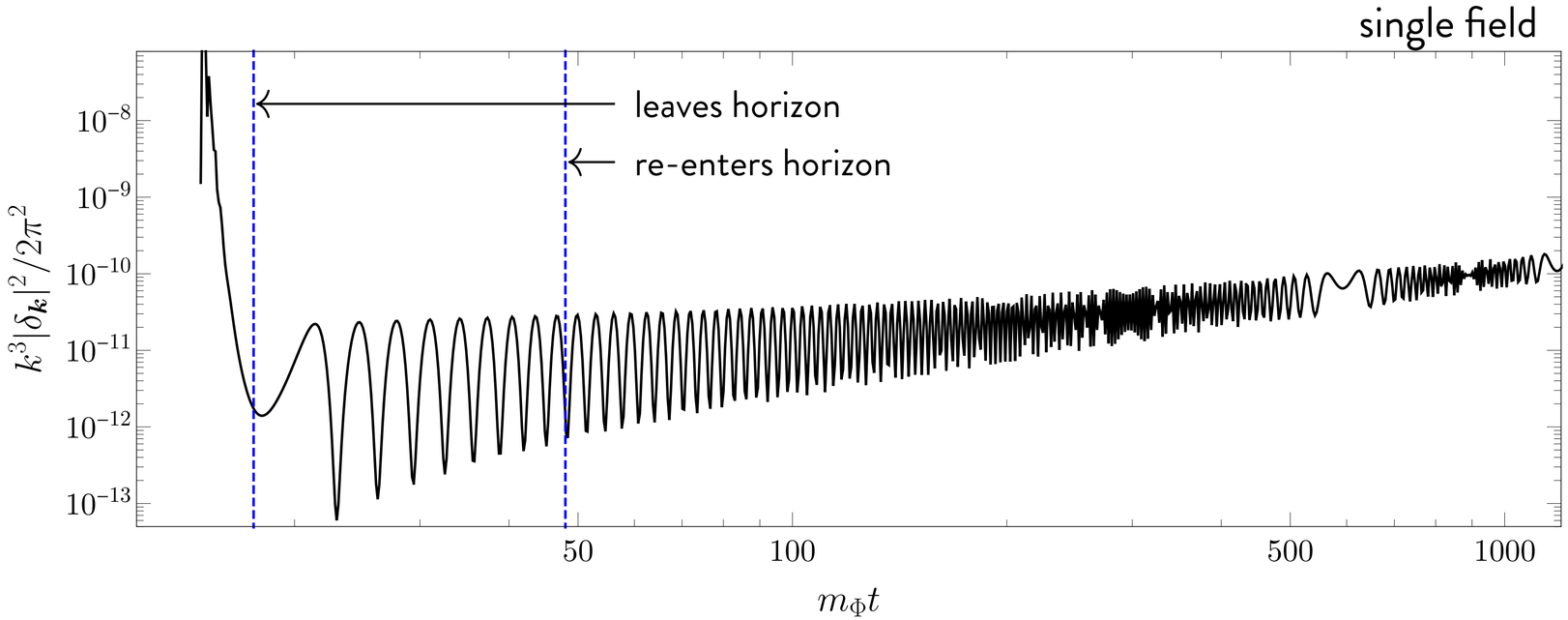
$$M_{\rm BH} \propto \rho_{\rm form}/H^3_{\rm form} < 10^9\,{\rm g}$$

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

Large metric fluctuations?



Credit: Naoya Kitajima

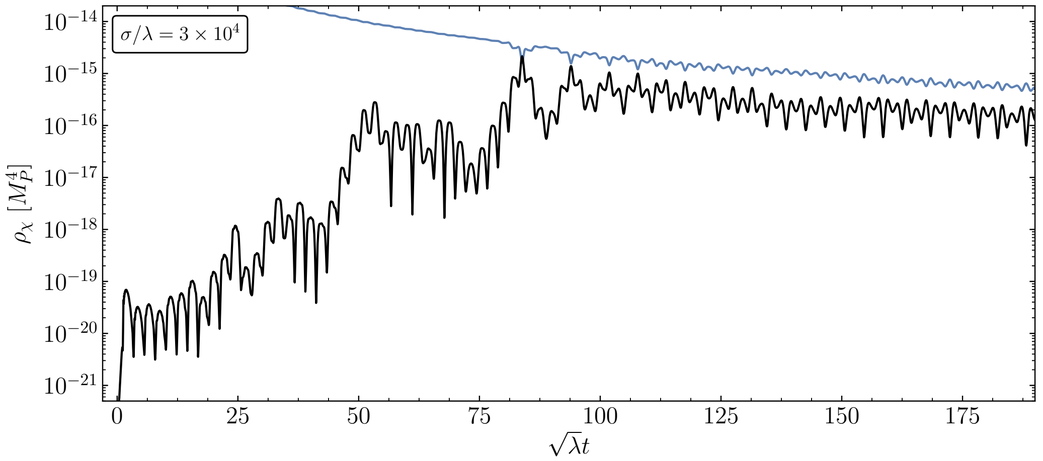


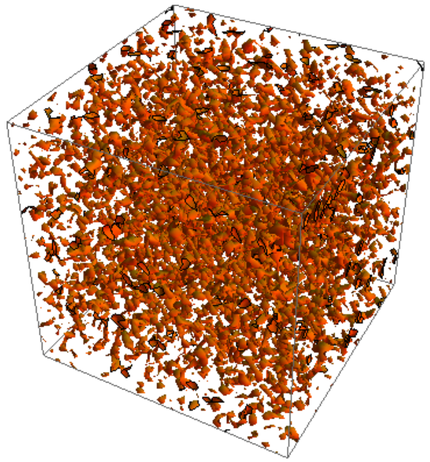
K. Jedamzik, M. Lemoine and J. Martin, JCAP 09 (2010), 034

Fragmenting the condensate

Backreaction

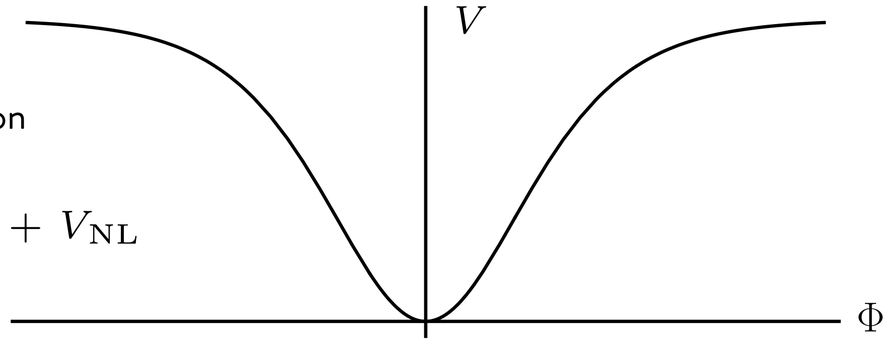
$\sigma \Phi^2 \chi^2$

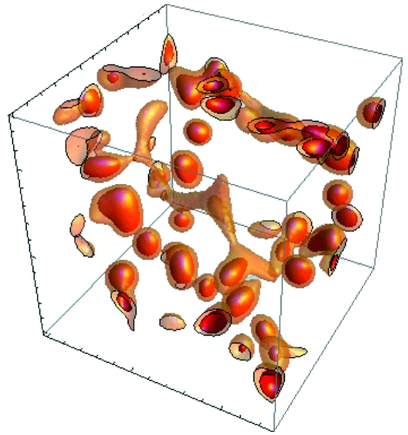




“opening up” = attractive interaction

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



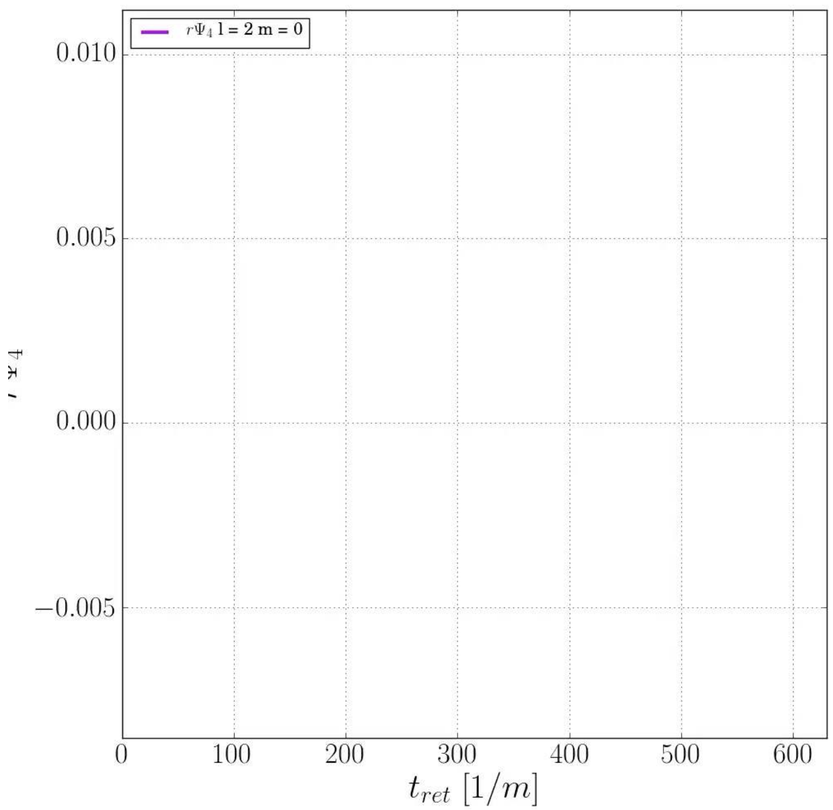


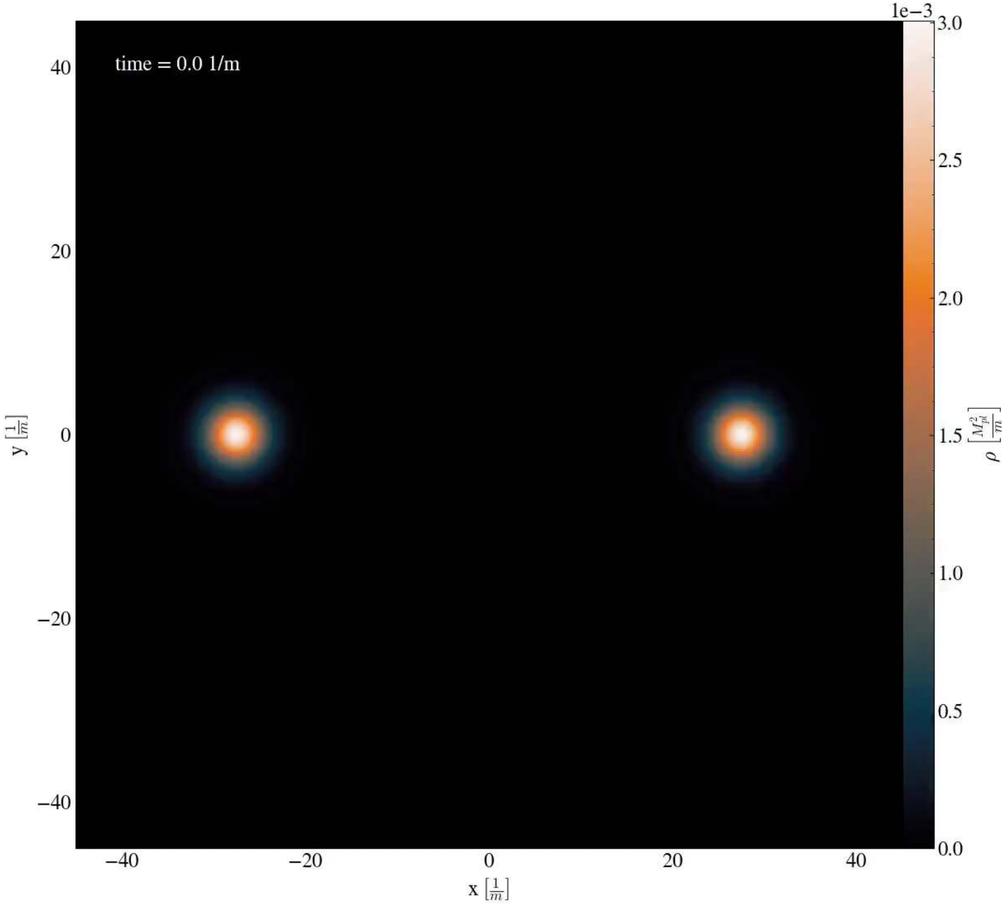
gravity

self-interaction

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

Oscillaton collisions

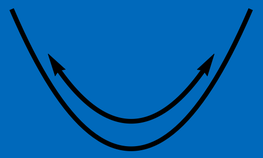




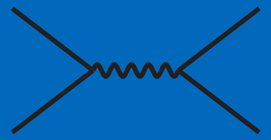
T. Helfer, E. A. Lim, MG and M. A. Amin, PRD 99 (2019), 044046

1. Beyond WIMPs

2. Inflation & reheating



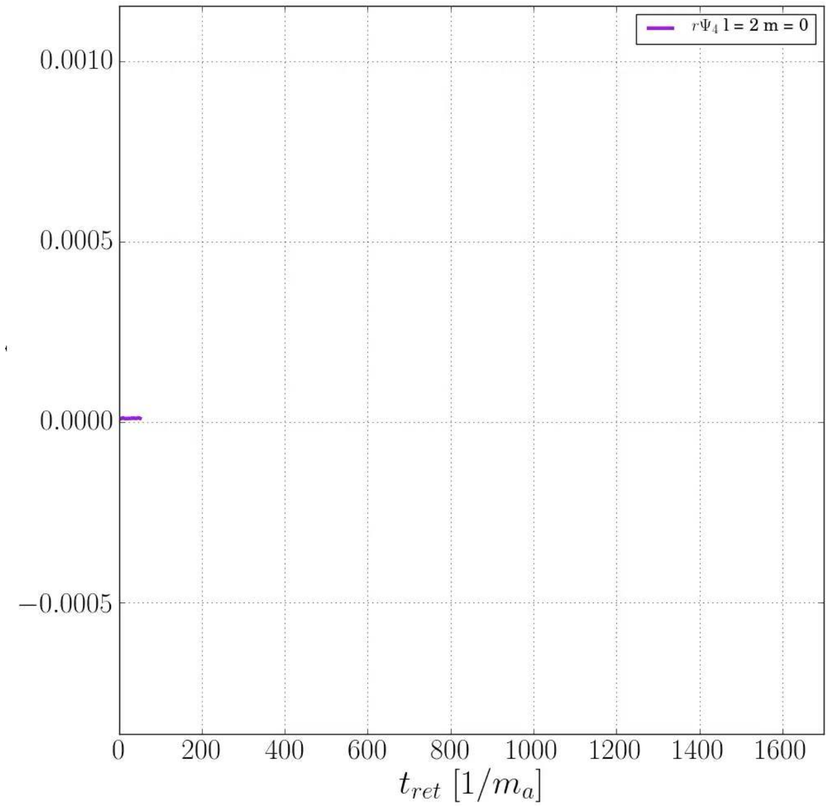
3. FIMPs

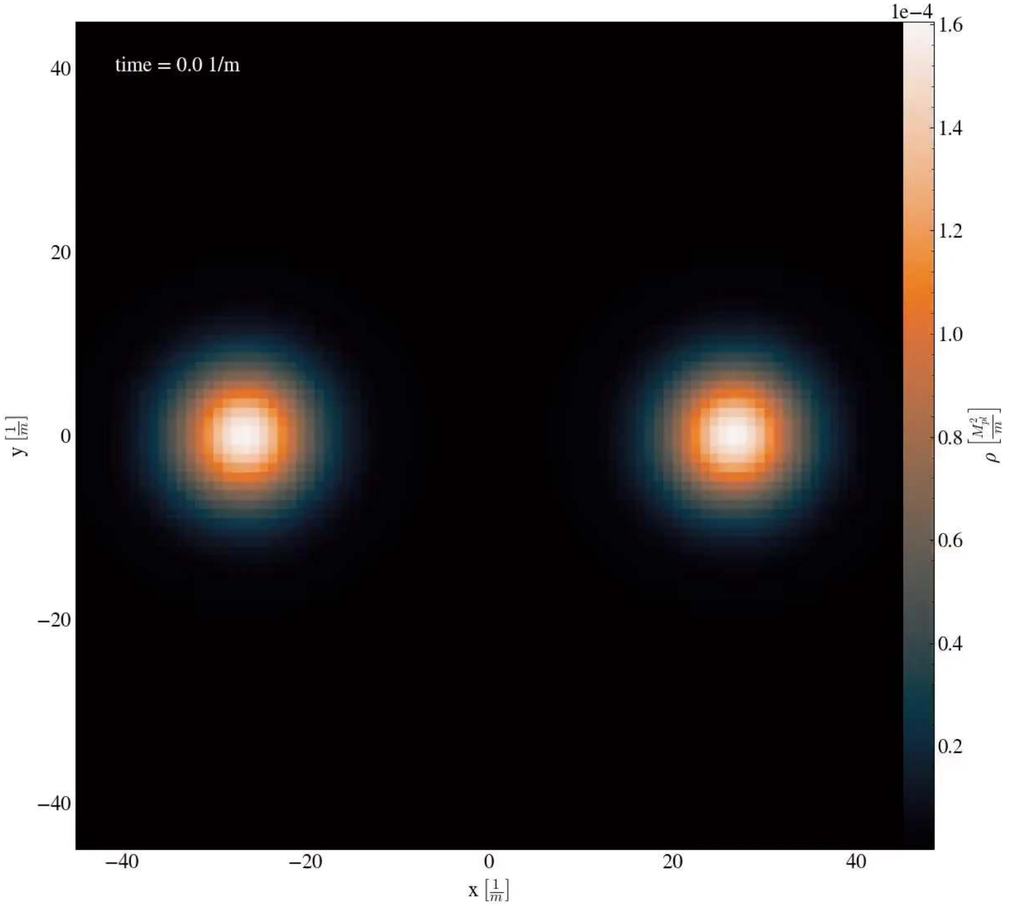


4. Compact objects

5. Prospects

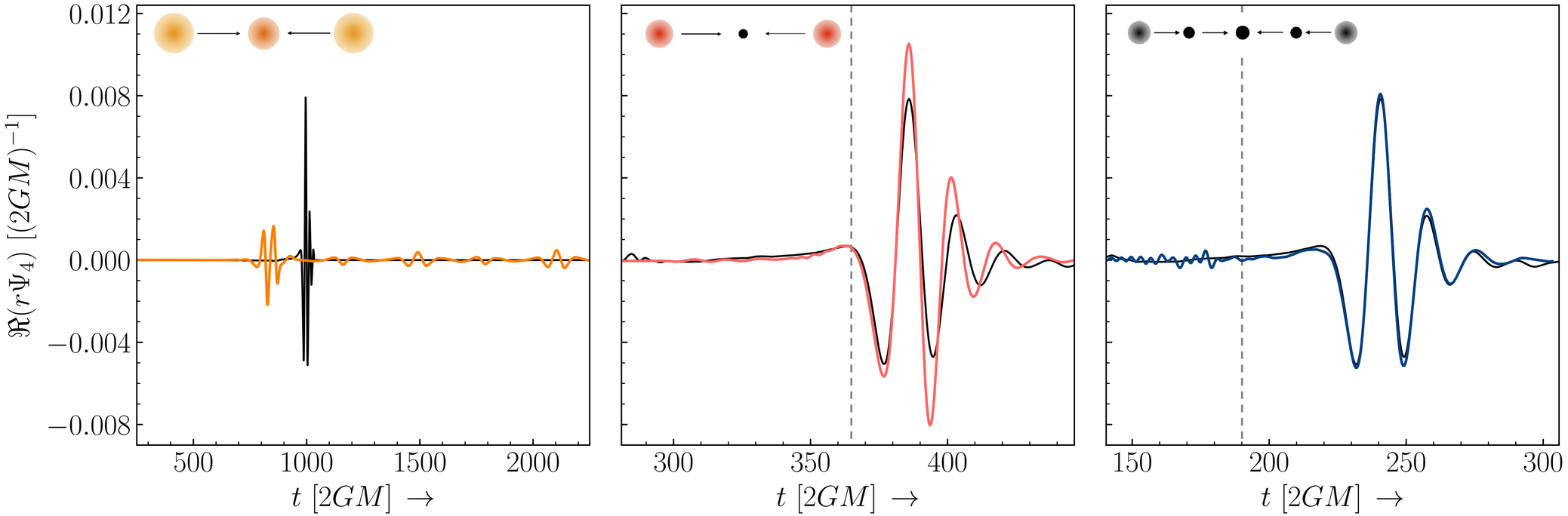
Oscillaton collisions





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

Oscillaton collisions



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

Dark matter from inflation

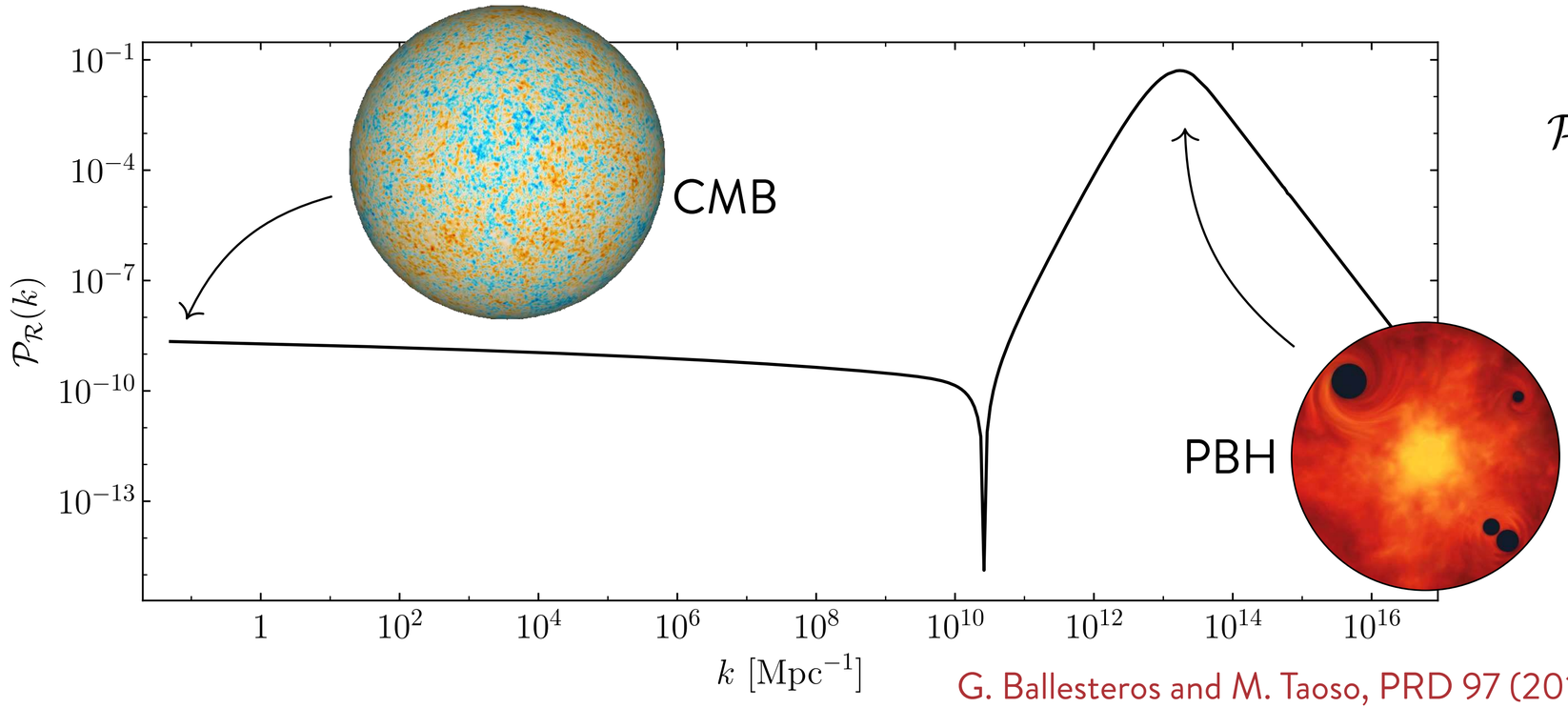
ON THE CONCENTRATION OF RELIC MAGNETIC MONOPOLES IN THE UNIVERSE

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

Dark matter from inflation

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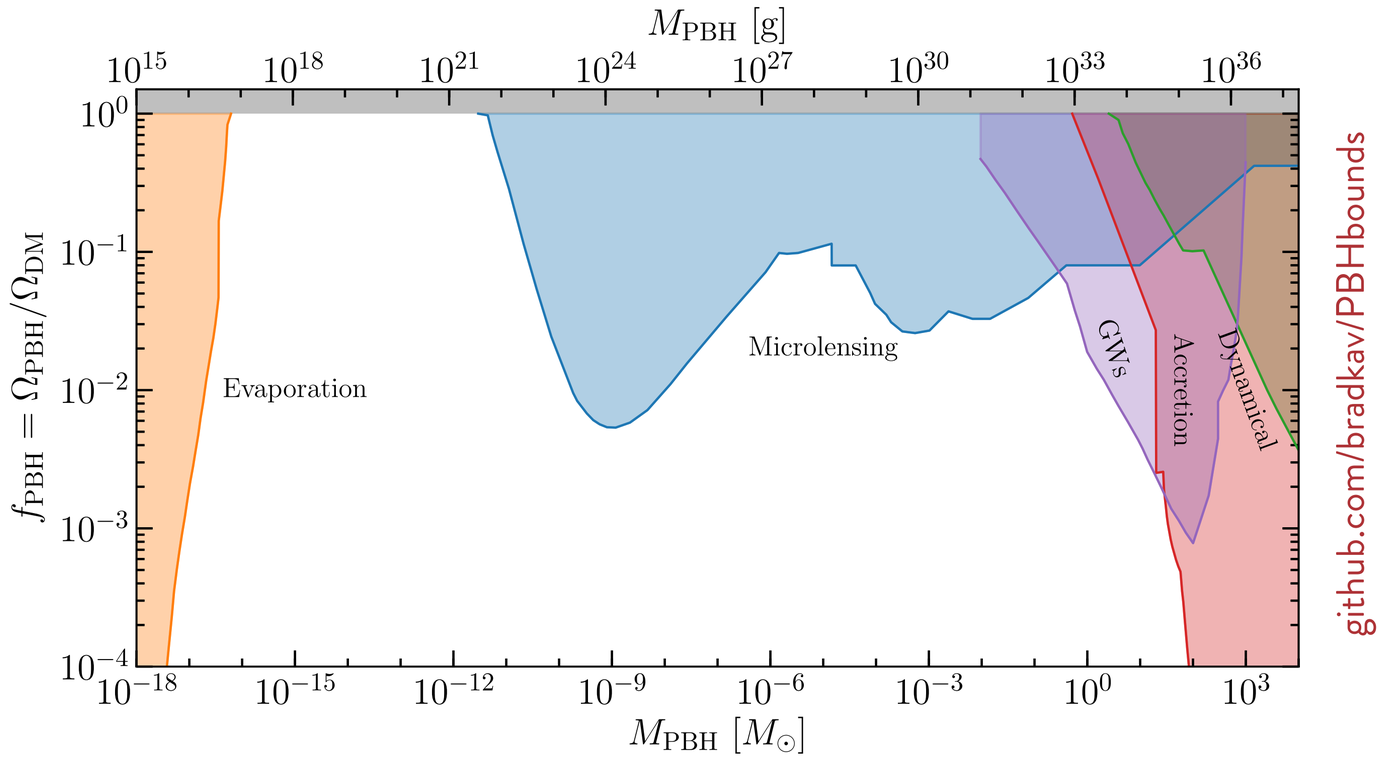
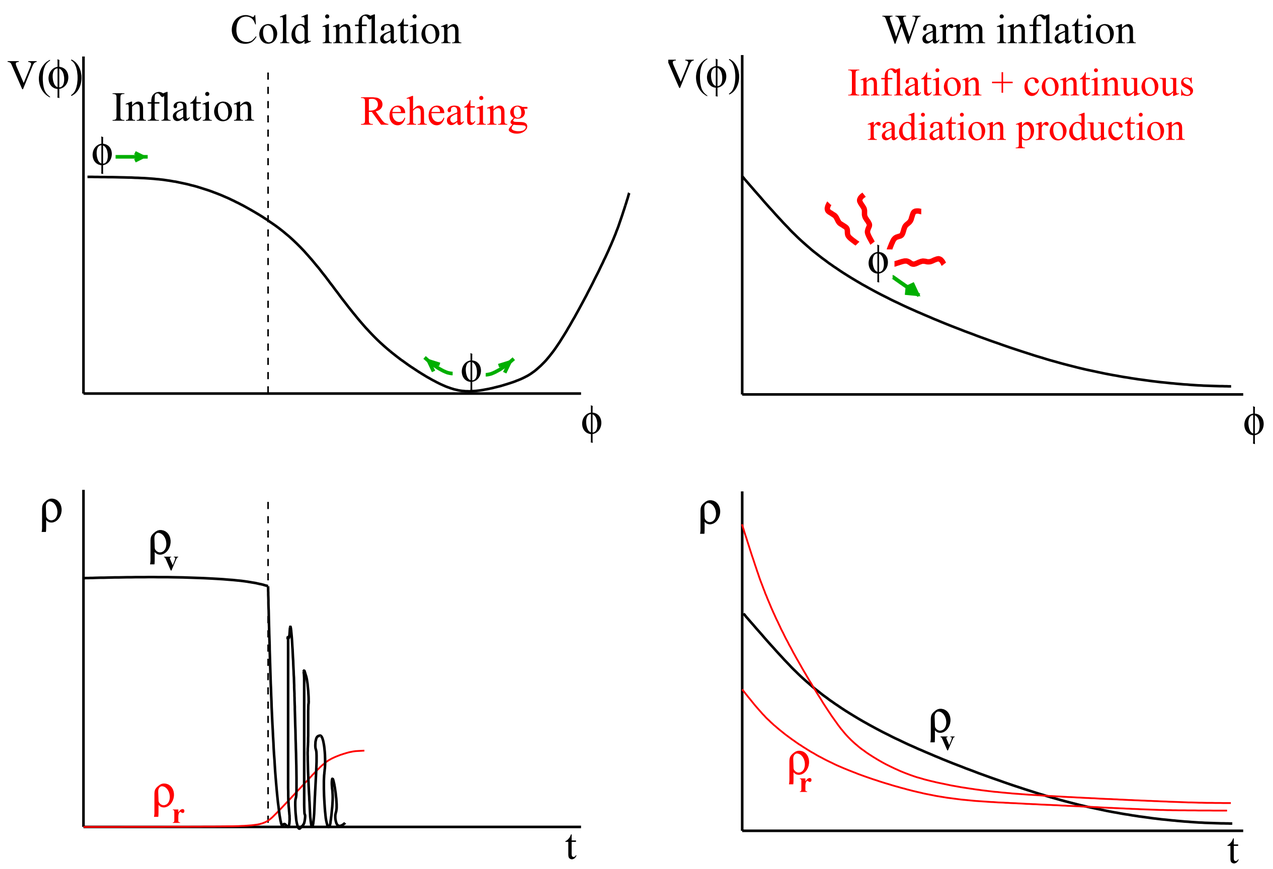


github.com/bradkav/PBHbounds

Warm inflation?



A. Berera, PRL 75 (1995), 3218

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

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

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

Daniel Green @nu_phases · 1 jun.

3/8 The inflaton needs to continually produce particles

Problem: most couplings that do this will destroy inflation / scale invariance

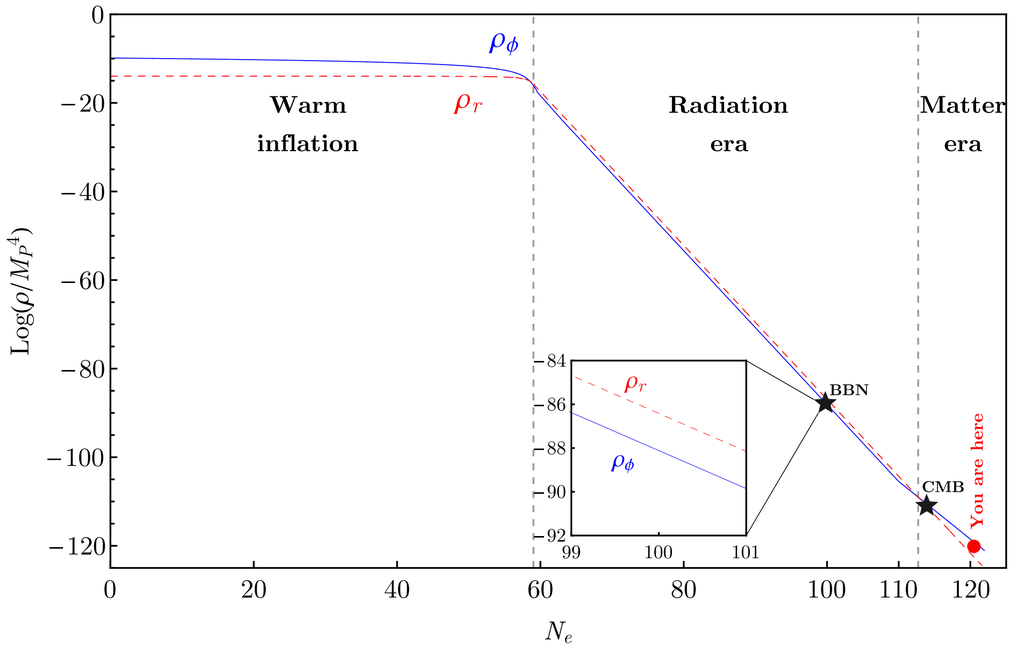
Worse problem: If you write a coupling that preserves scale invariance, it was shown you don't get normal friction

arxiv.org/abs/1109.4192

Warm inflation?

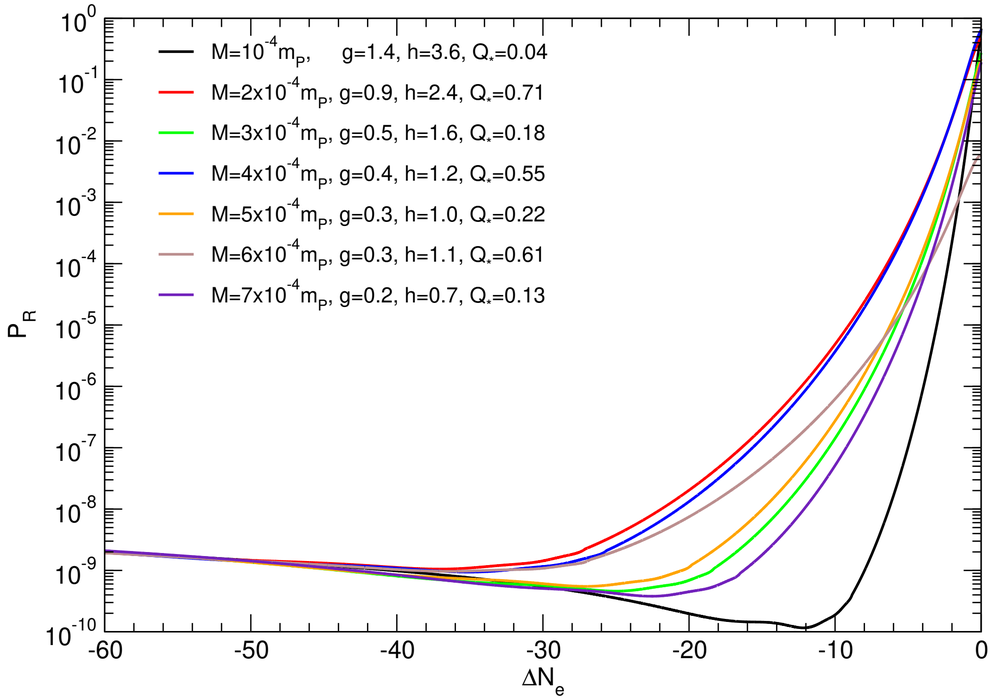
A way around? Warm Little Inflation (Φ as a pseudo-Nambu-Goldstone boson)

Leftover Φ as DM



J. Rosa and L. Ventura, PRL 122 (2019), 161301

PBH from WLI

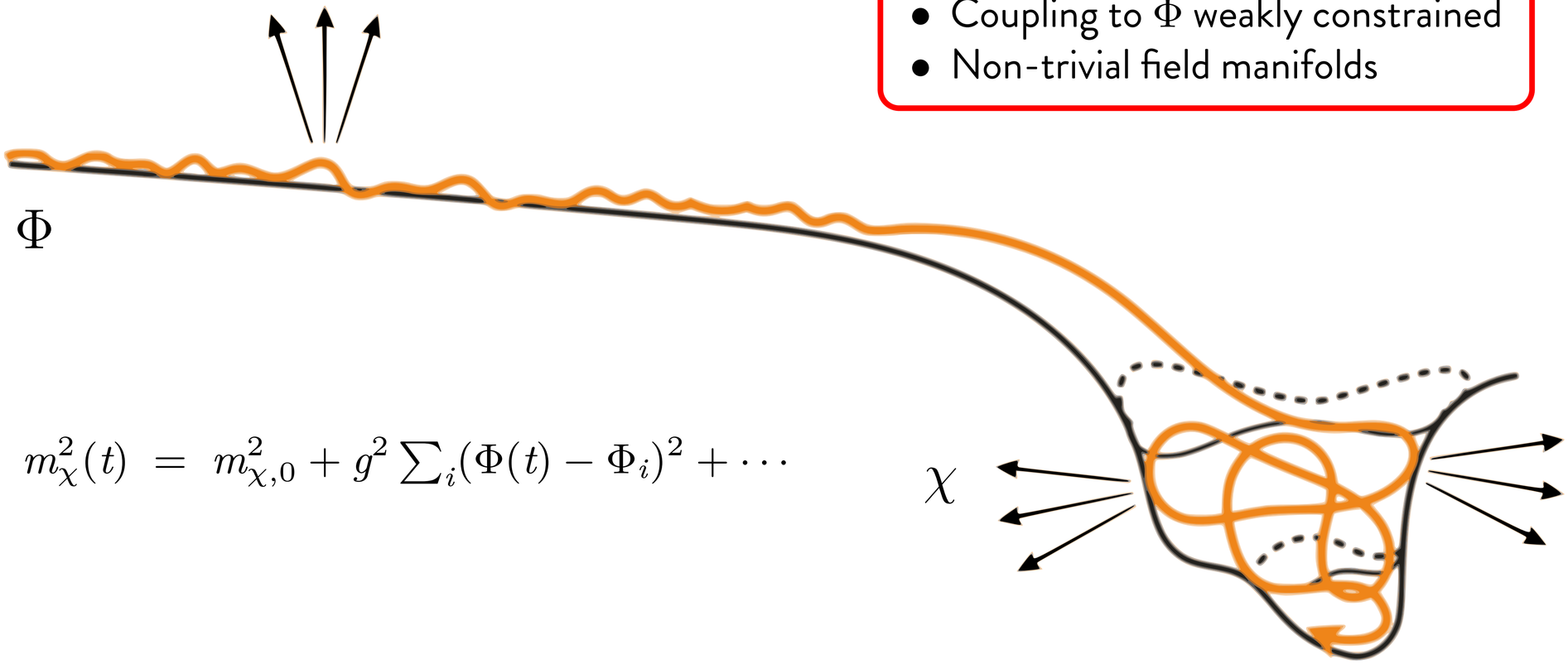


M. Bastero-Gil and M. Díaz-Blanco, arXiv:2105.08045 [hep-ph]

Complexity in the early Universe

Particle theory

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

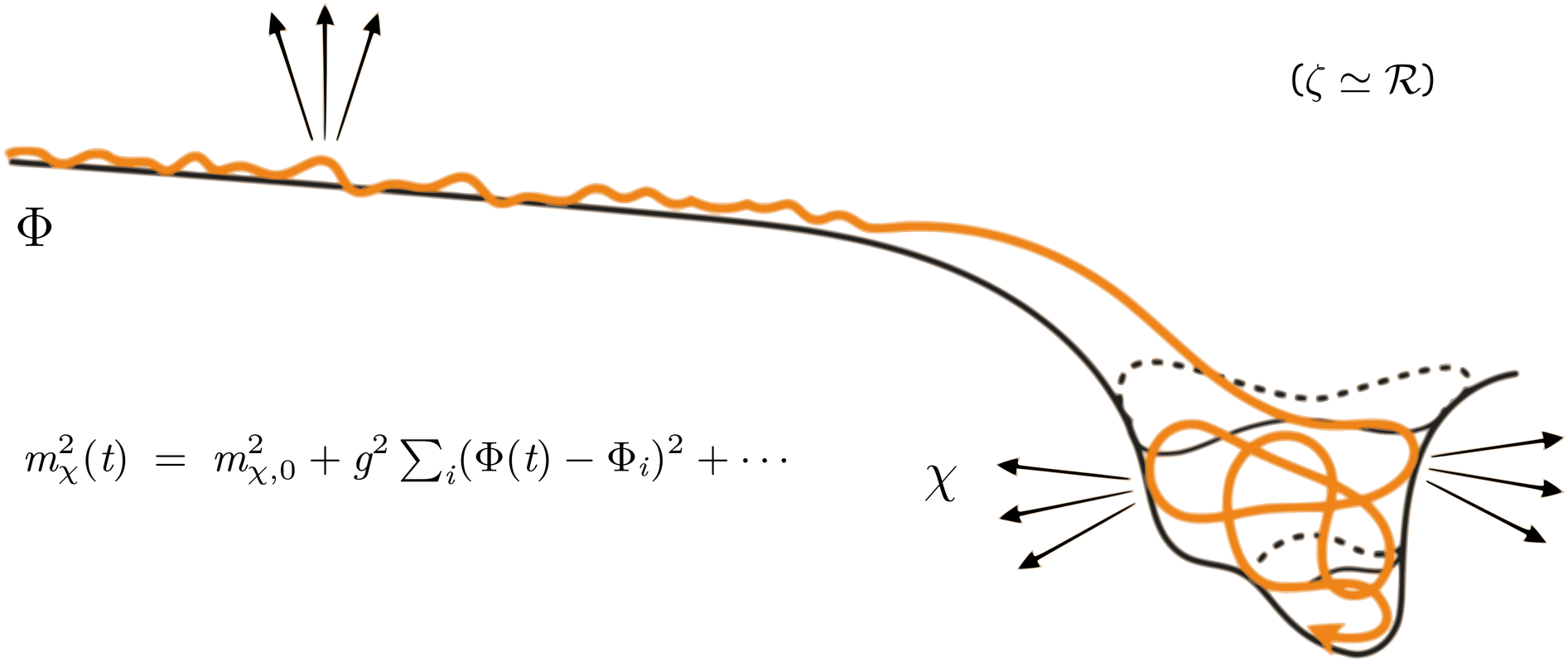


$$m_\chi^2(t) \;=\; m_{\chi,0}^2 + g^2 \sum_i (\Phi(t) - \Phi_i)^2 + \cdots$$

Complexity in the early Universe

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

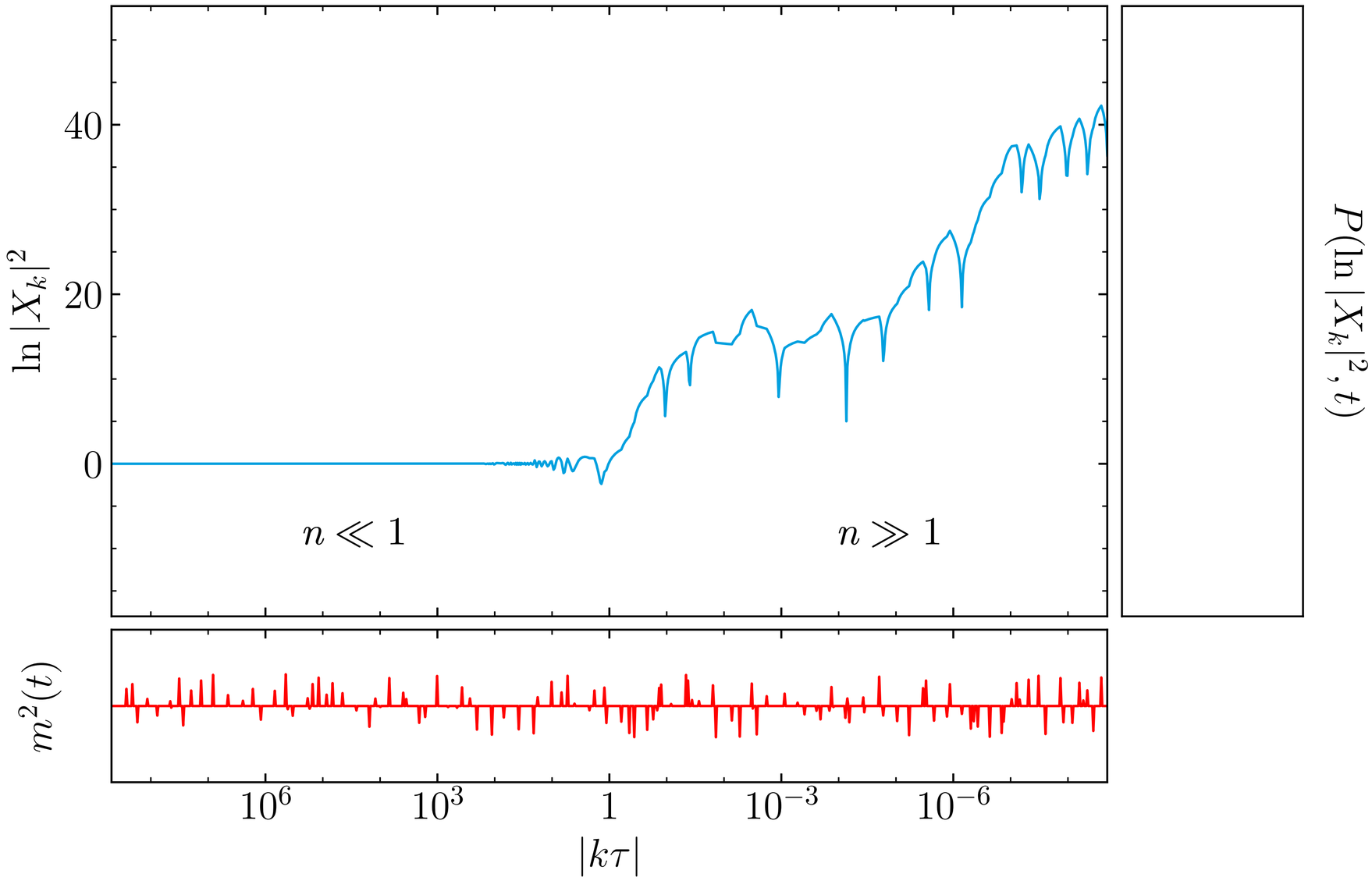
$(\zeta \simeq \mathcal{R})$



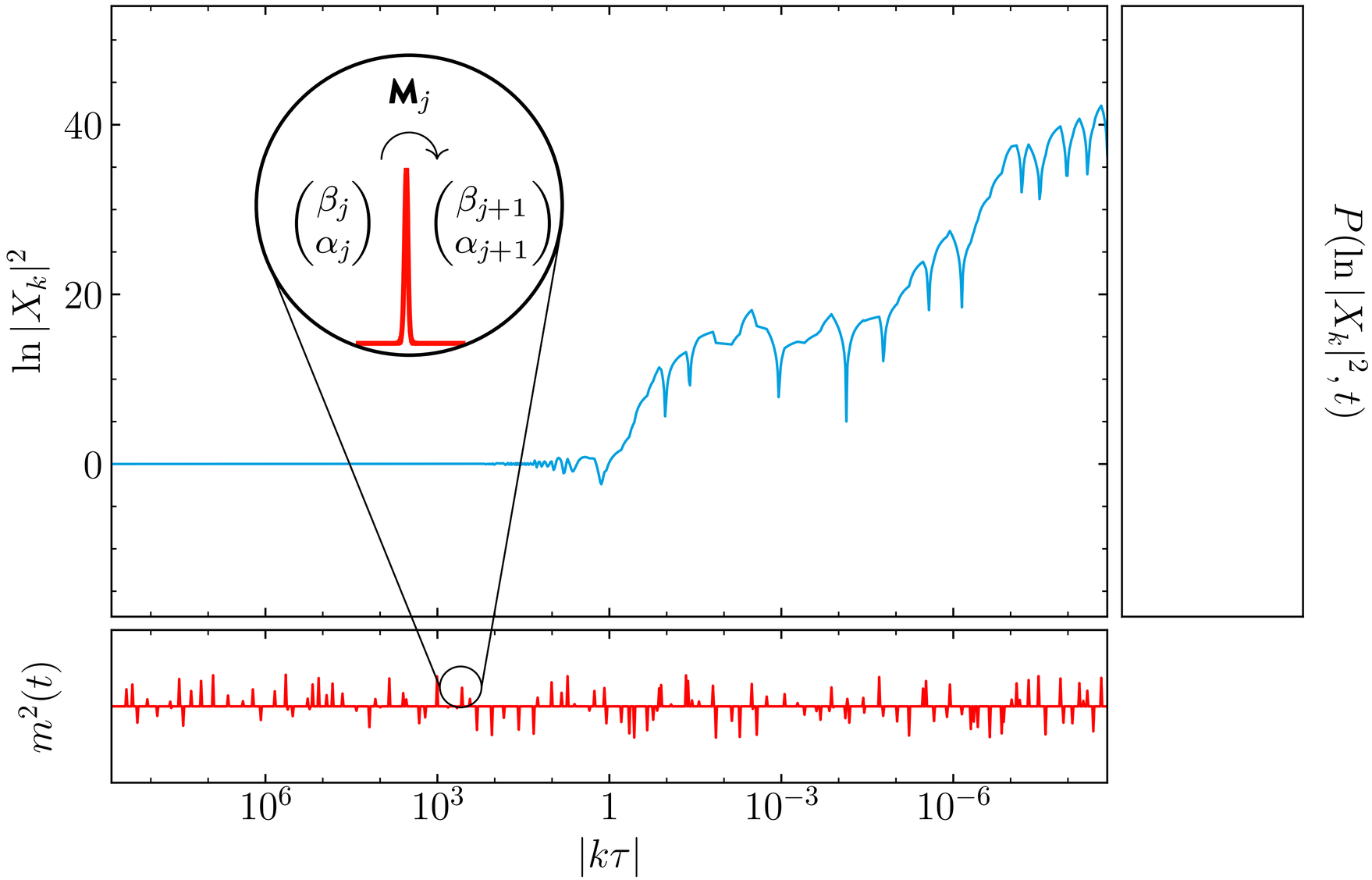
$$m_\chi^2(t) \;=\; m_{\chi,0}^2 + g^2 \textstyle\sum_i (\Phi(t) - \Phi_i)^2 + \cdots$$

A (conformal) spectator in dS

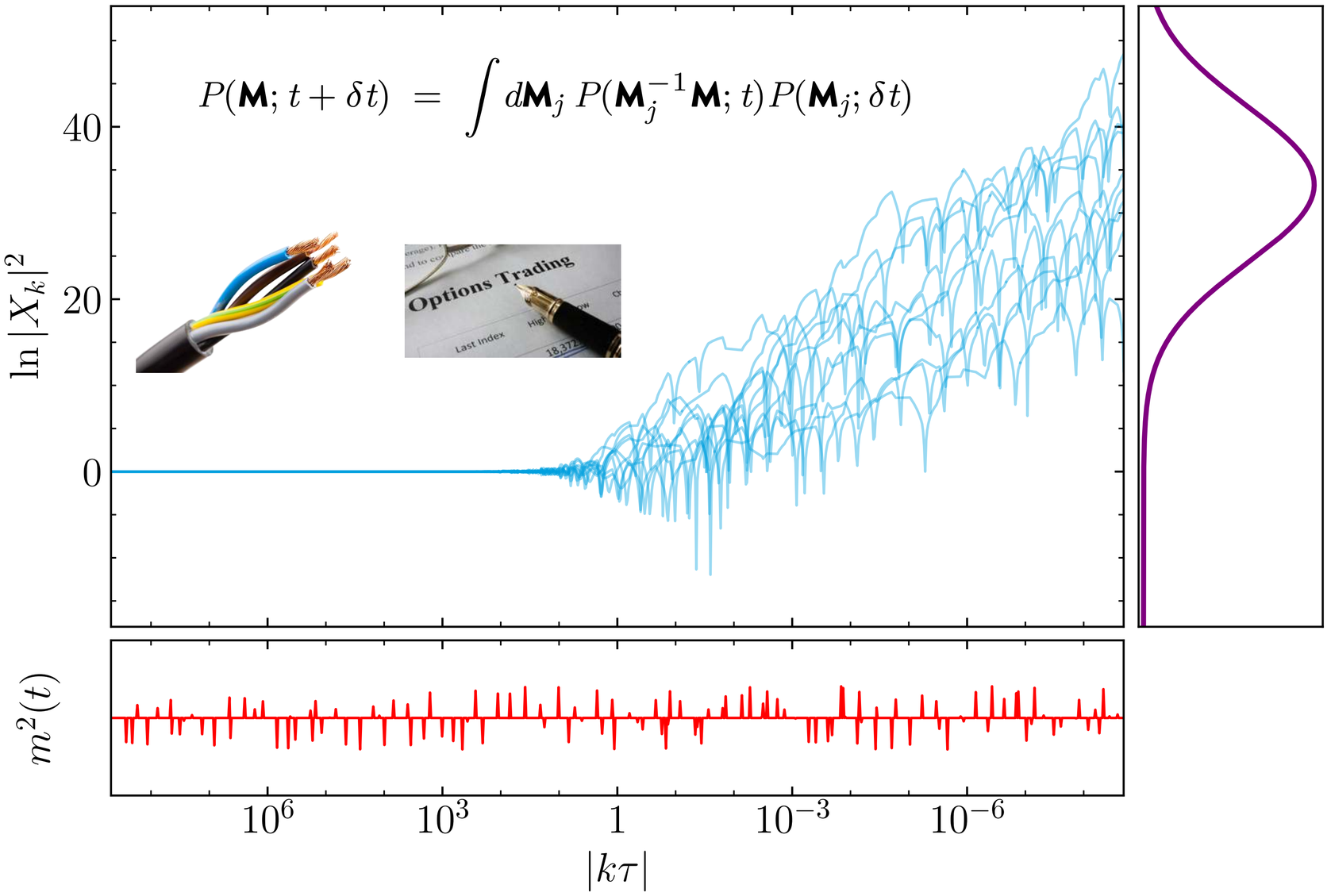
MG, M. Amin, S. Carlsten and D. Green, JCAP 05 (2019), 012



A (conformal) spectator in dS

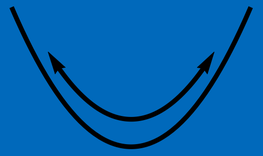


A (conformal) spectator in dS

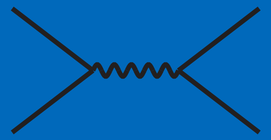


1. Beyond WIMPs

2. Inflation & reheating

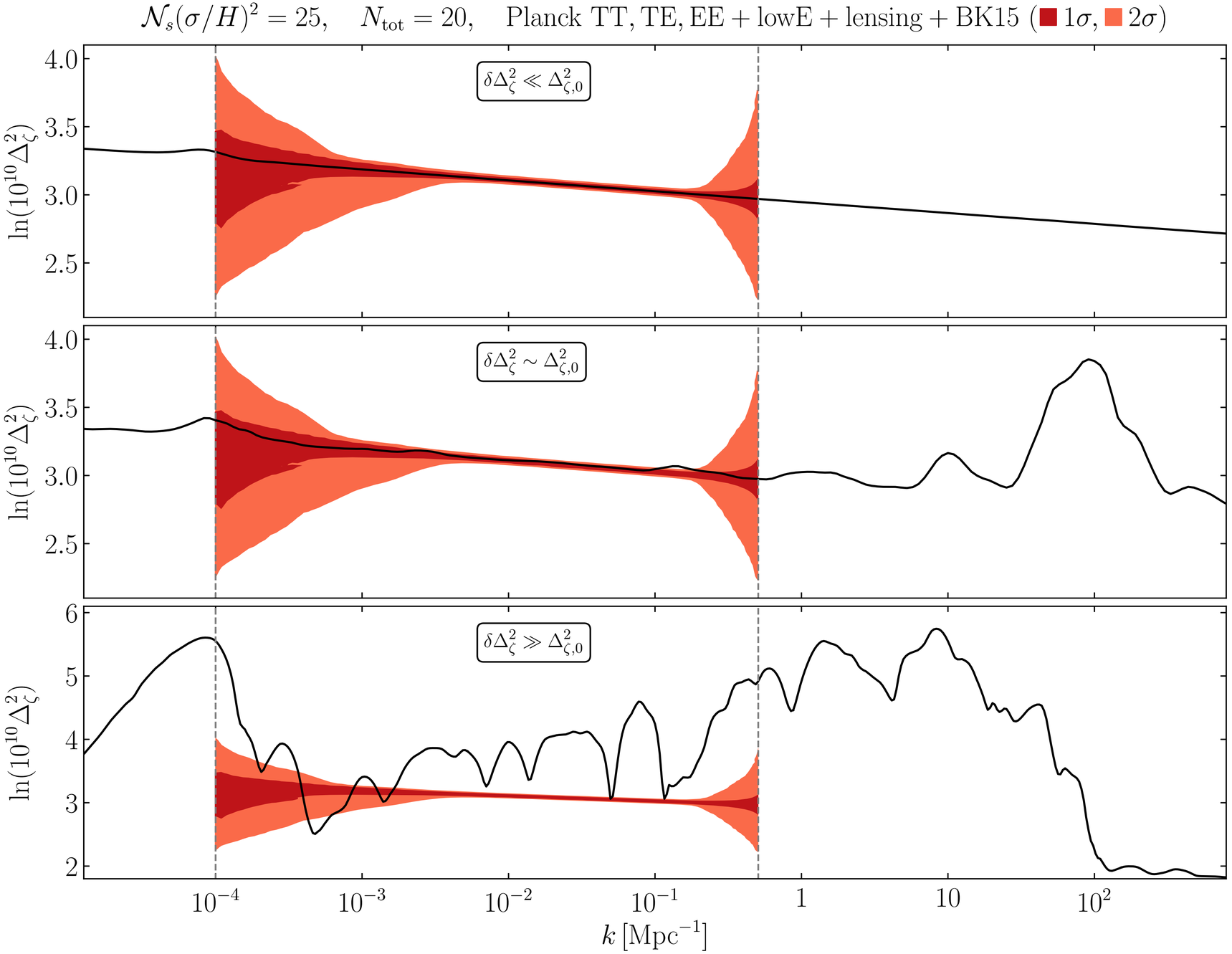


3. FIMPs



4. Compact objects

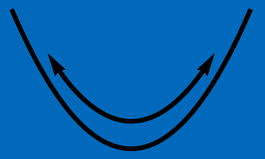
5. Prospects



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

1. Beyond WIMPs

2. Inflation & reheating



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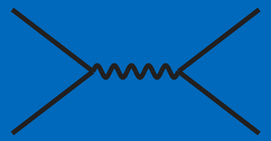

4. Compact objects

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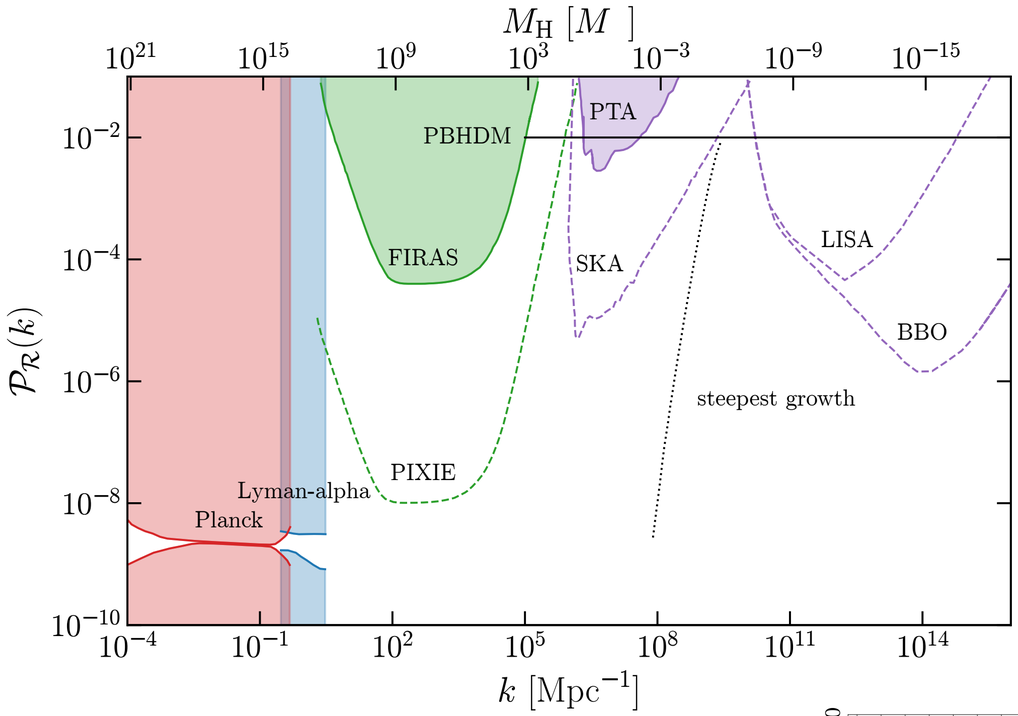
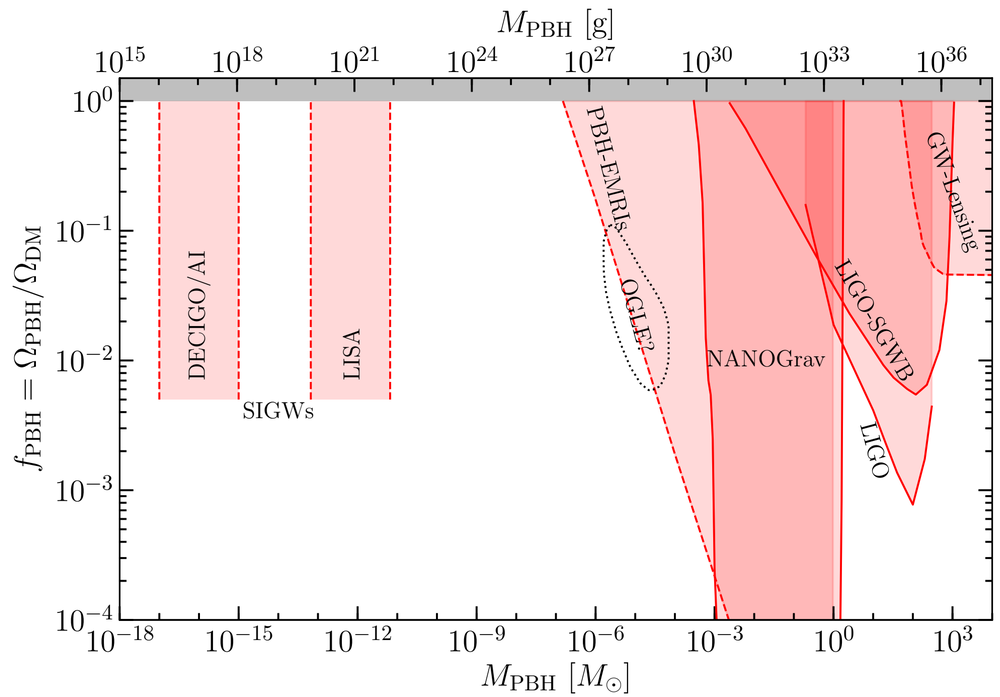
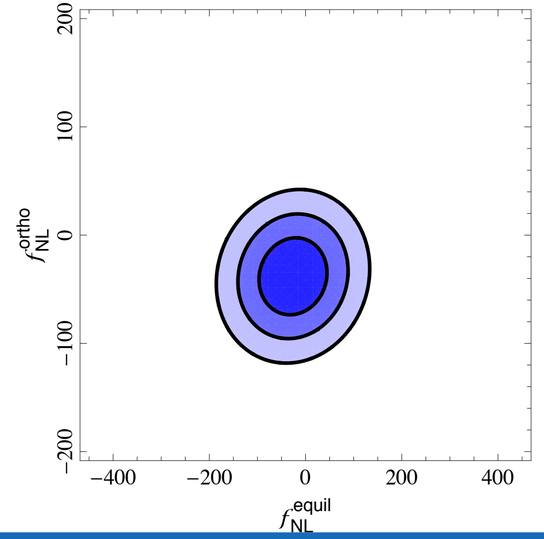
Prospects

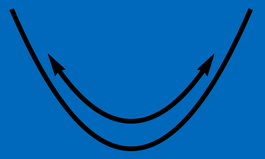




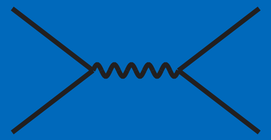


1. Beyond WIMPs

2. Inflation & reheating



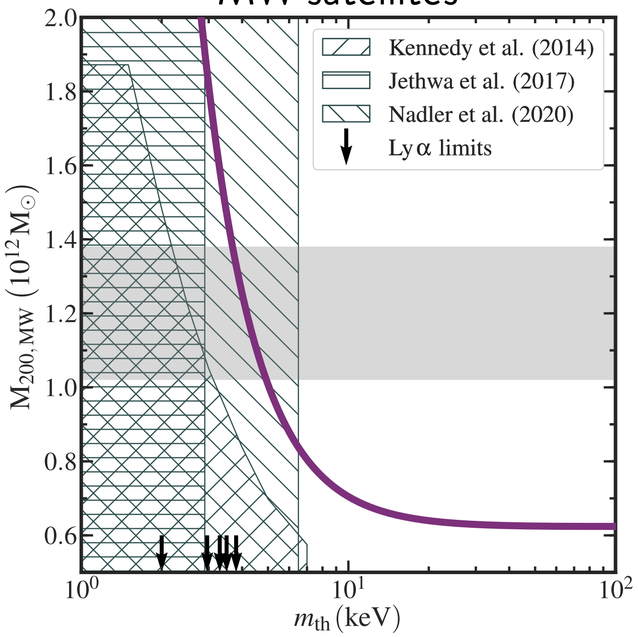
3. FIMPs



4. Compact objects

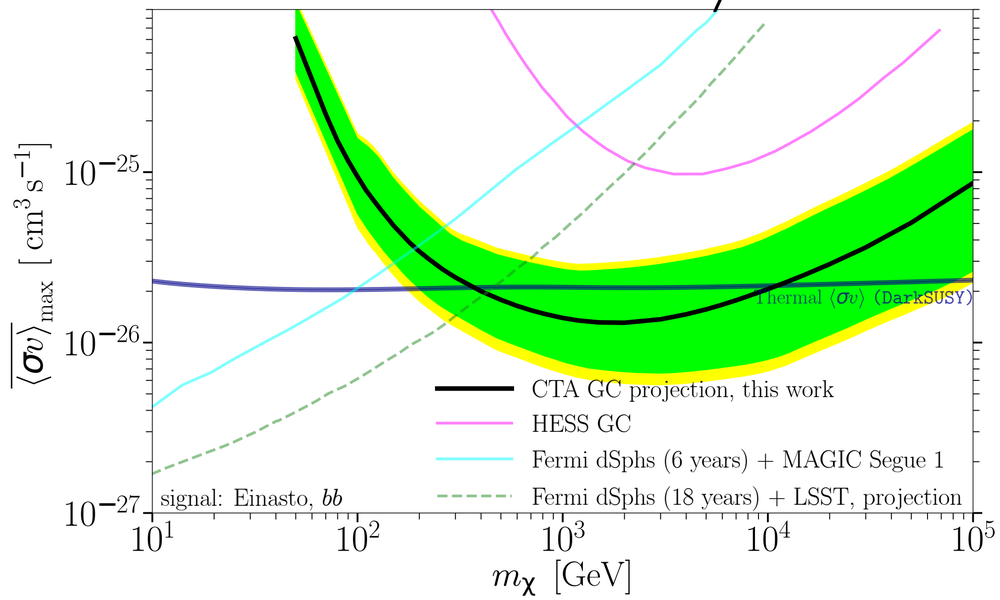
5. Prospects

MW satellites



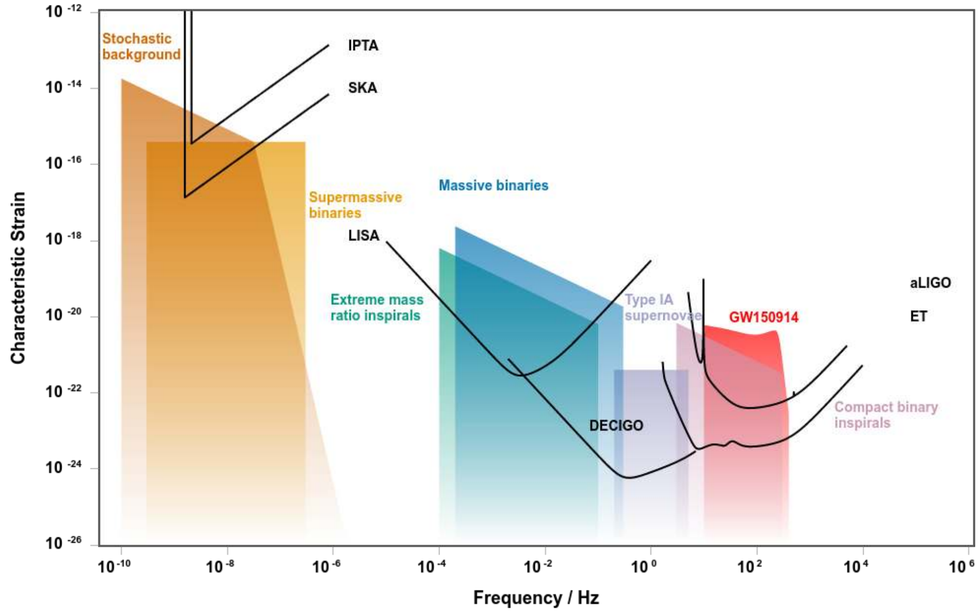
O. Newton et al., arXiv:2011.08865

Annihilation/decay



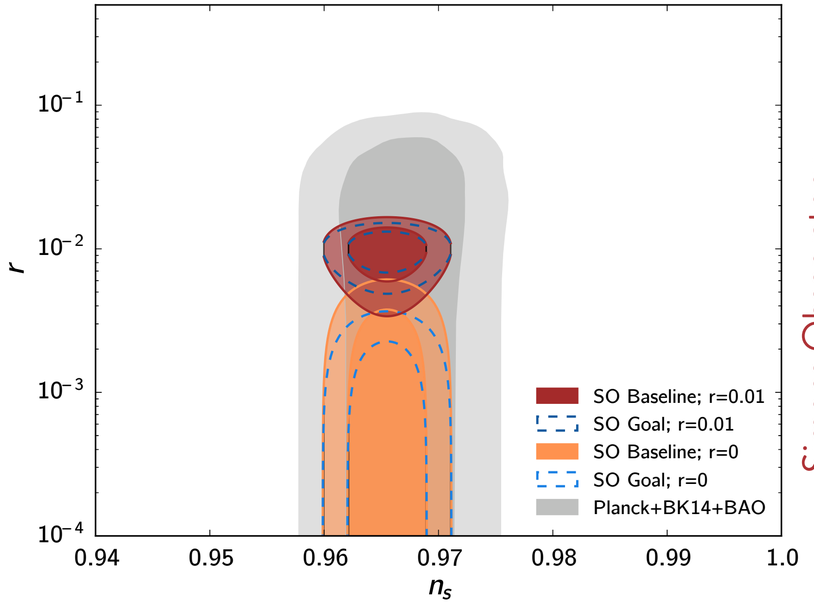
CTA, JCAP 01 (2021), 057

GWs



gwplotter.com

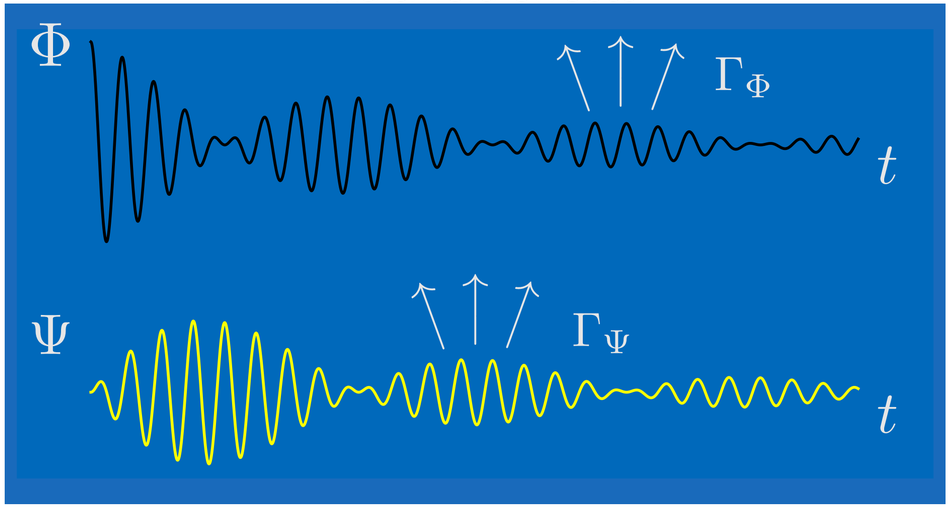
CMB



Simons Observatory, JCAP 02 (2019), 056

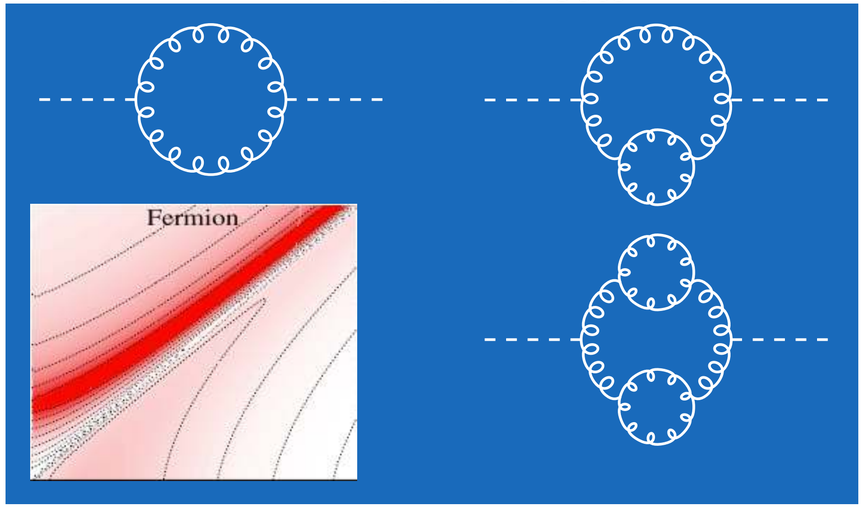
Reheating + BSM is not always simple

Multifield effects



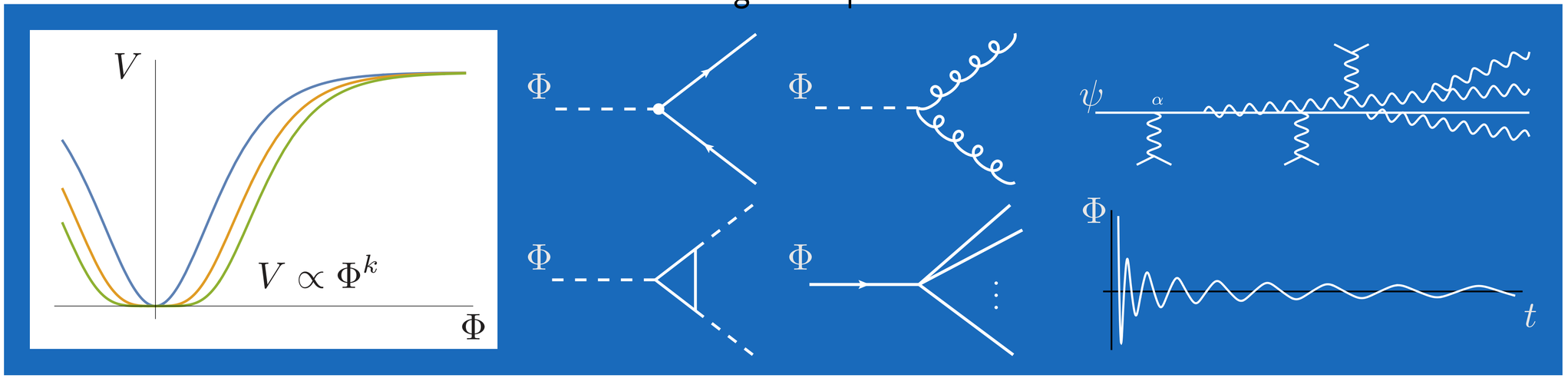
J. Ellis, MG, N. Nagata, D. Nanopoulos and K. Olive, JCAP 07 (2017), 006

In-medium effects



V. Rychkov and A. Strumia, PRD 75 (2007), 075011

More general potentials



MG, K. Kaneta, Y. Mambrini and K. A. Olive, PRD 101 (2020), 123507 ; MG, K. Kaneta, Y. Mambrini and K. A. Olive, JCAP 04 (2021), 012