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29/06/2021

Dark Matter from Inflation

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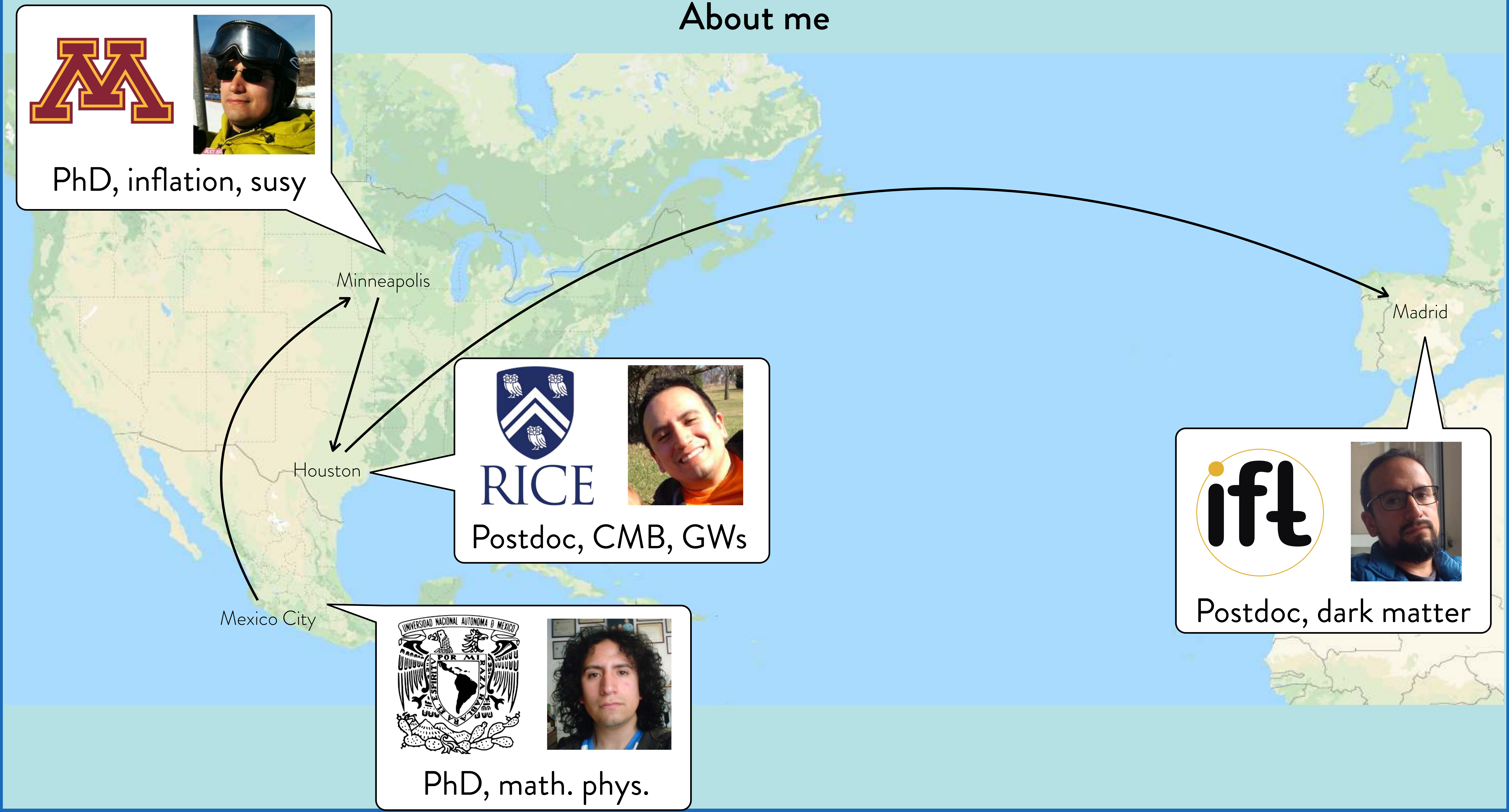
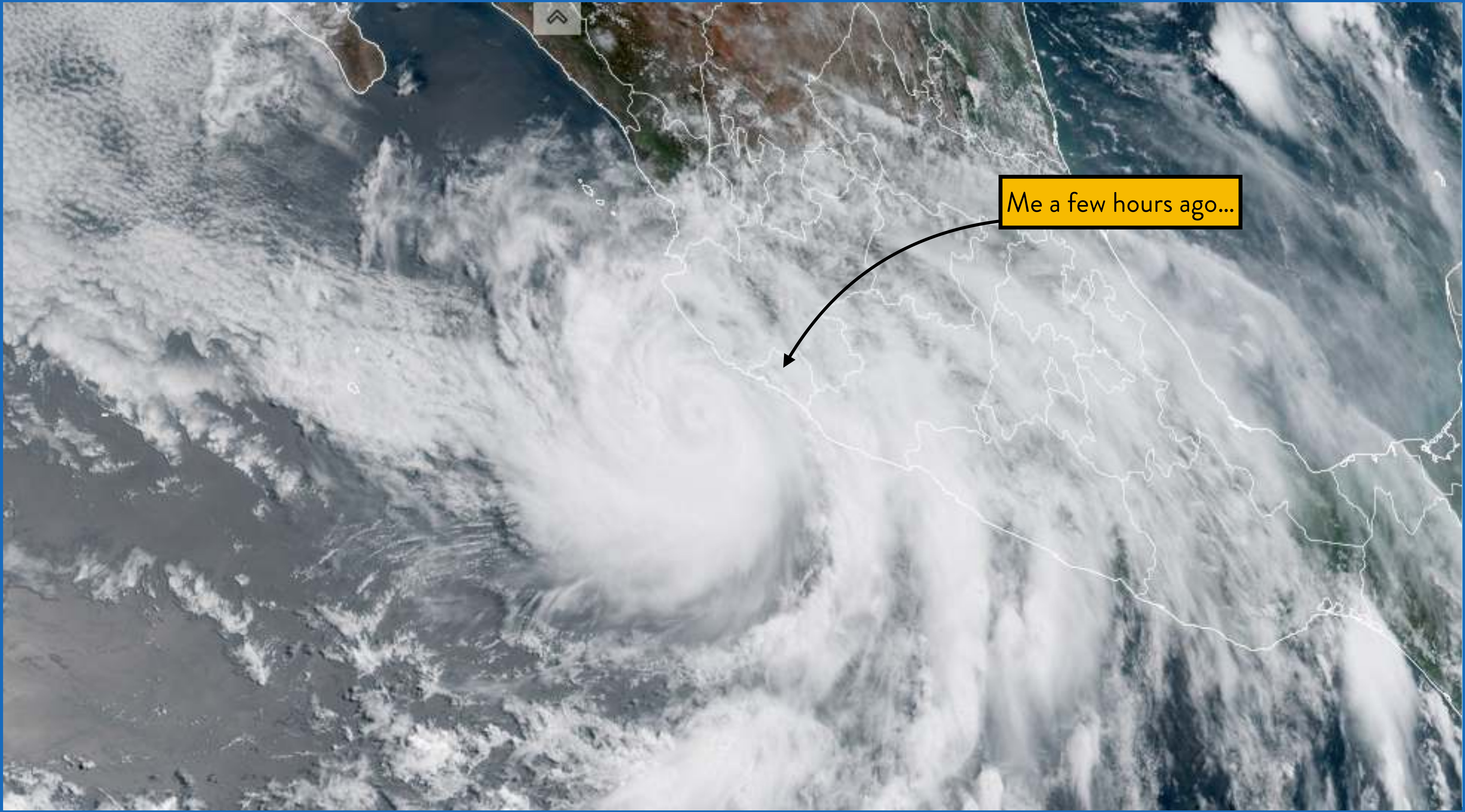
Consejo Superior de Investigaciones Científicas

About me



PhD, inflation, susy
Minneapolis
Houston
RICE
Postdoc, CMB, GWs
Mexico City
PhD, math. phys.
Madrid
ift
Postdoc, dark matter


Me a few hours ago...

1. Beyond WIMPs

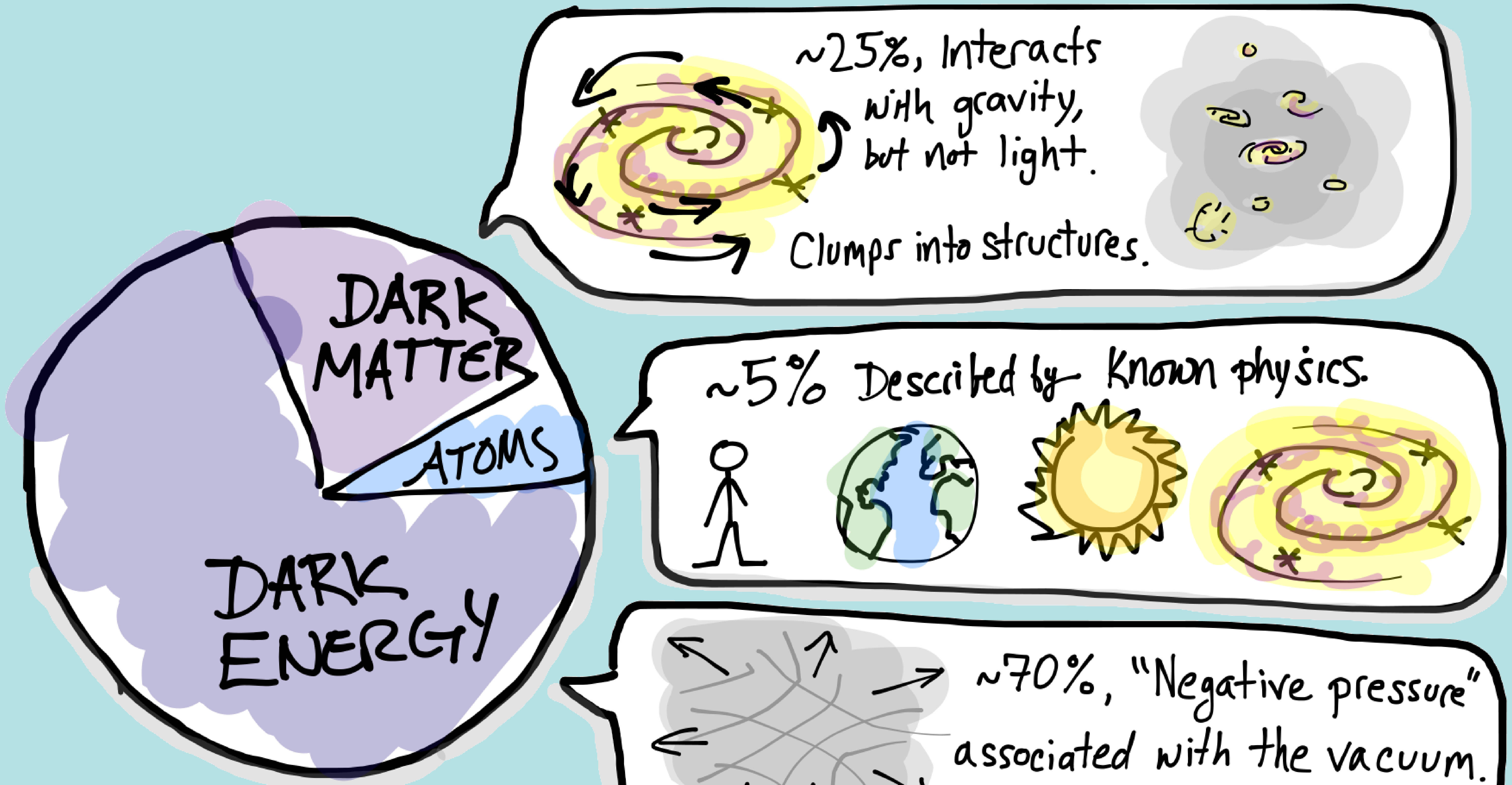
2. Inflation & reheating

3. FIMPs

4. Compact objects

5. Prospects

Solid evidence for Dark Matter



Credit: Jessie Muir

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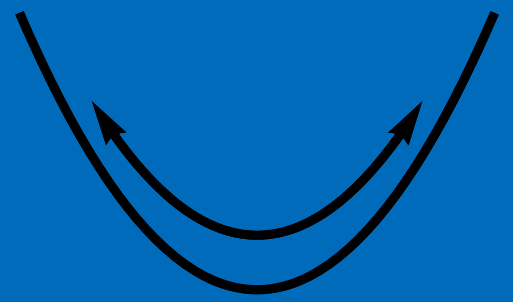
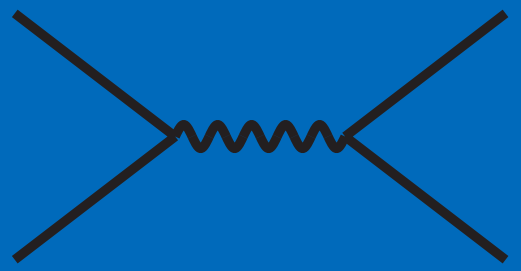


3. FIMPs



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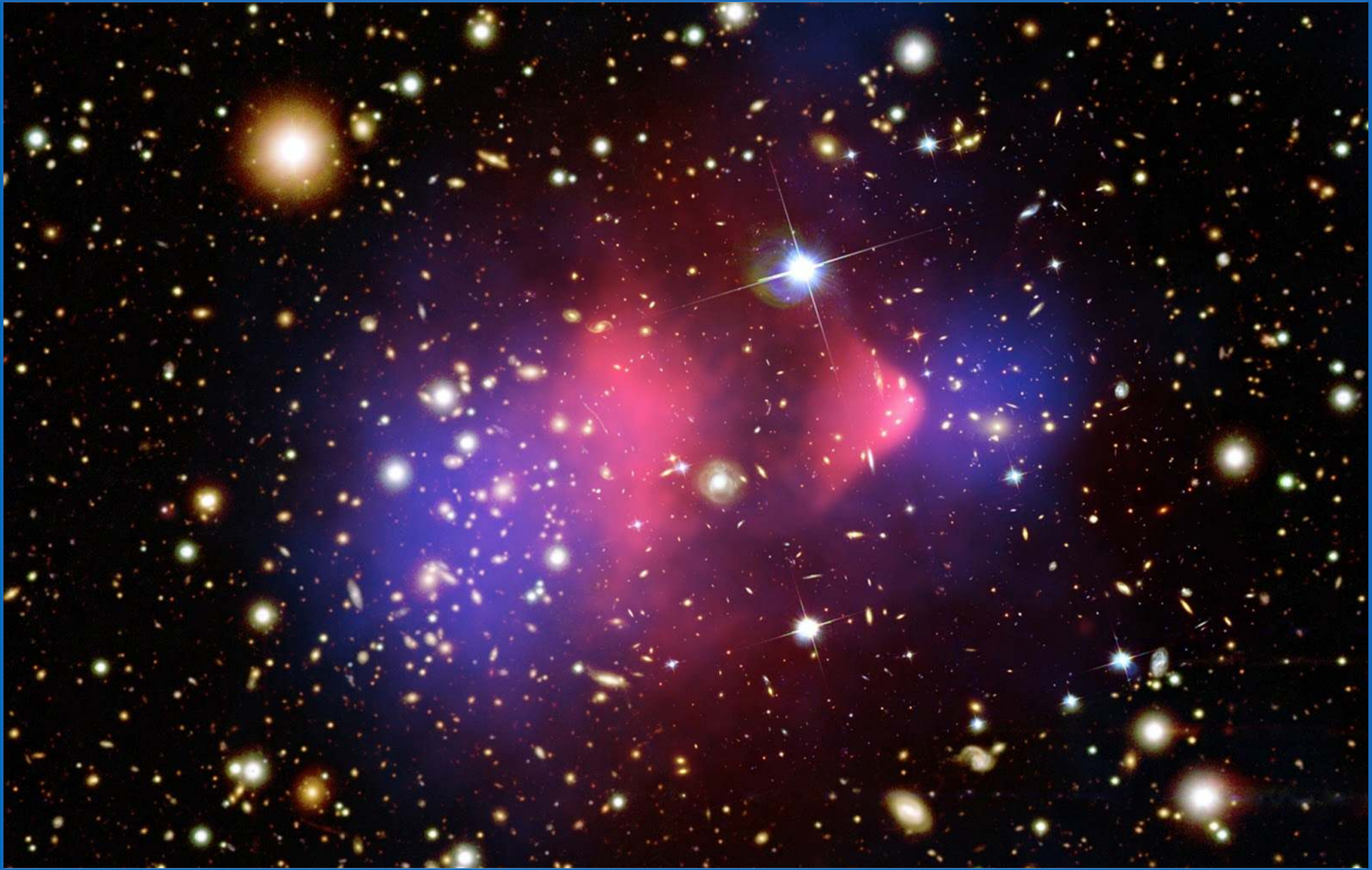

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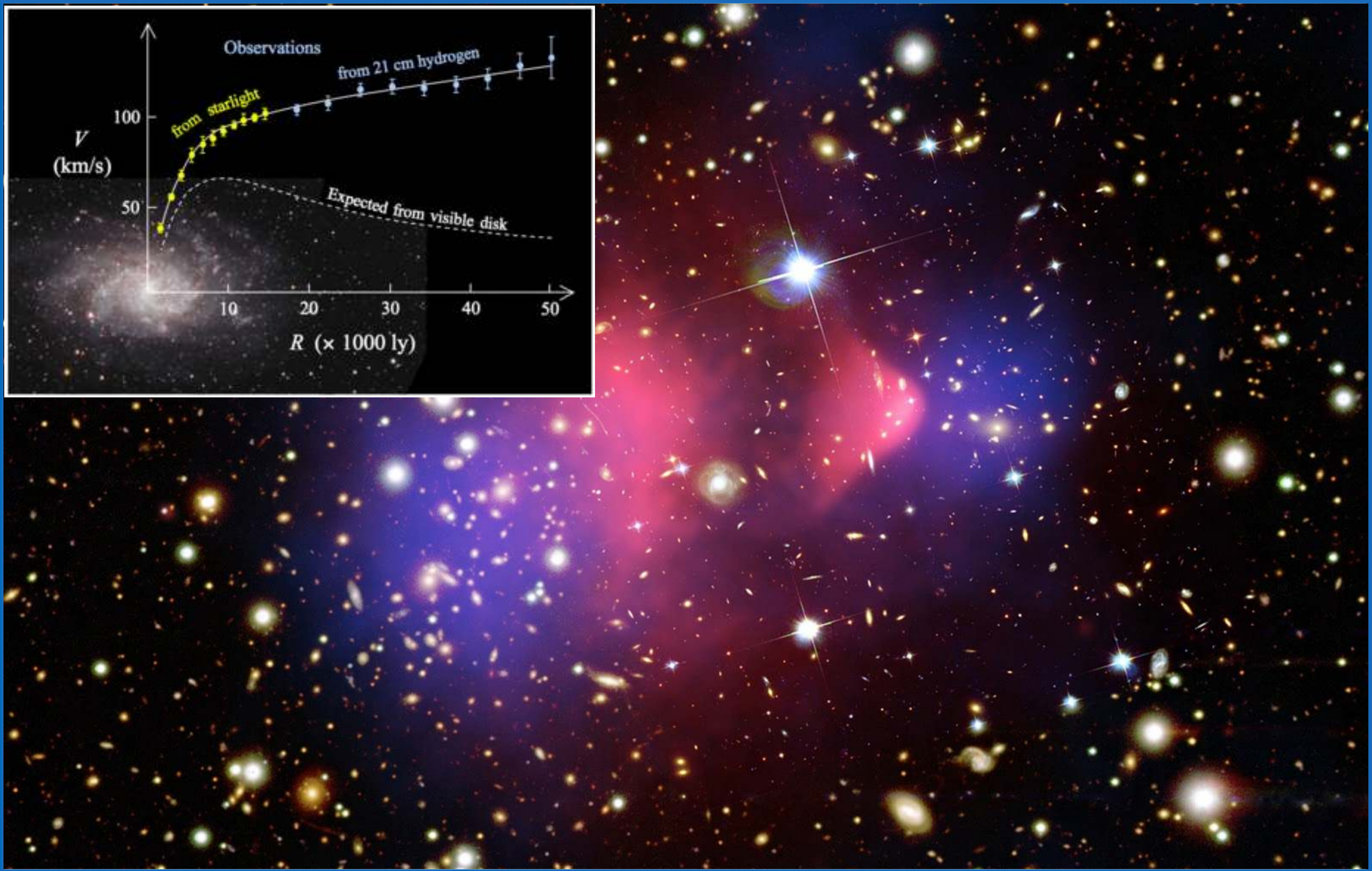

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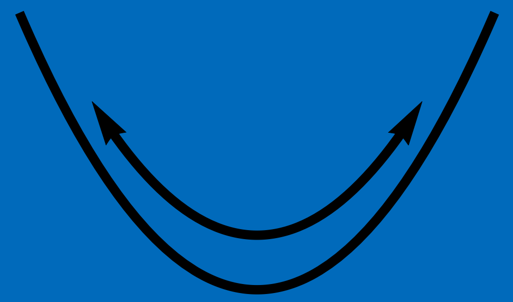

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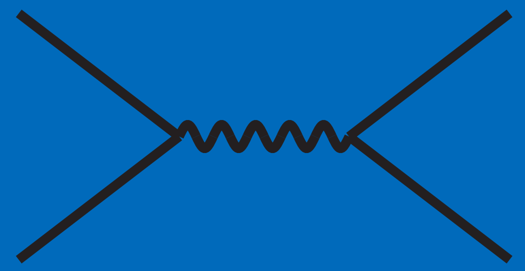

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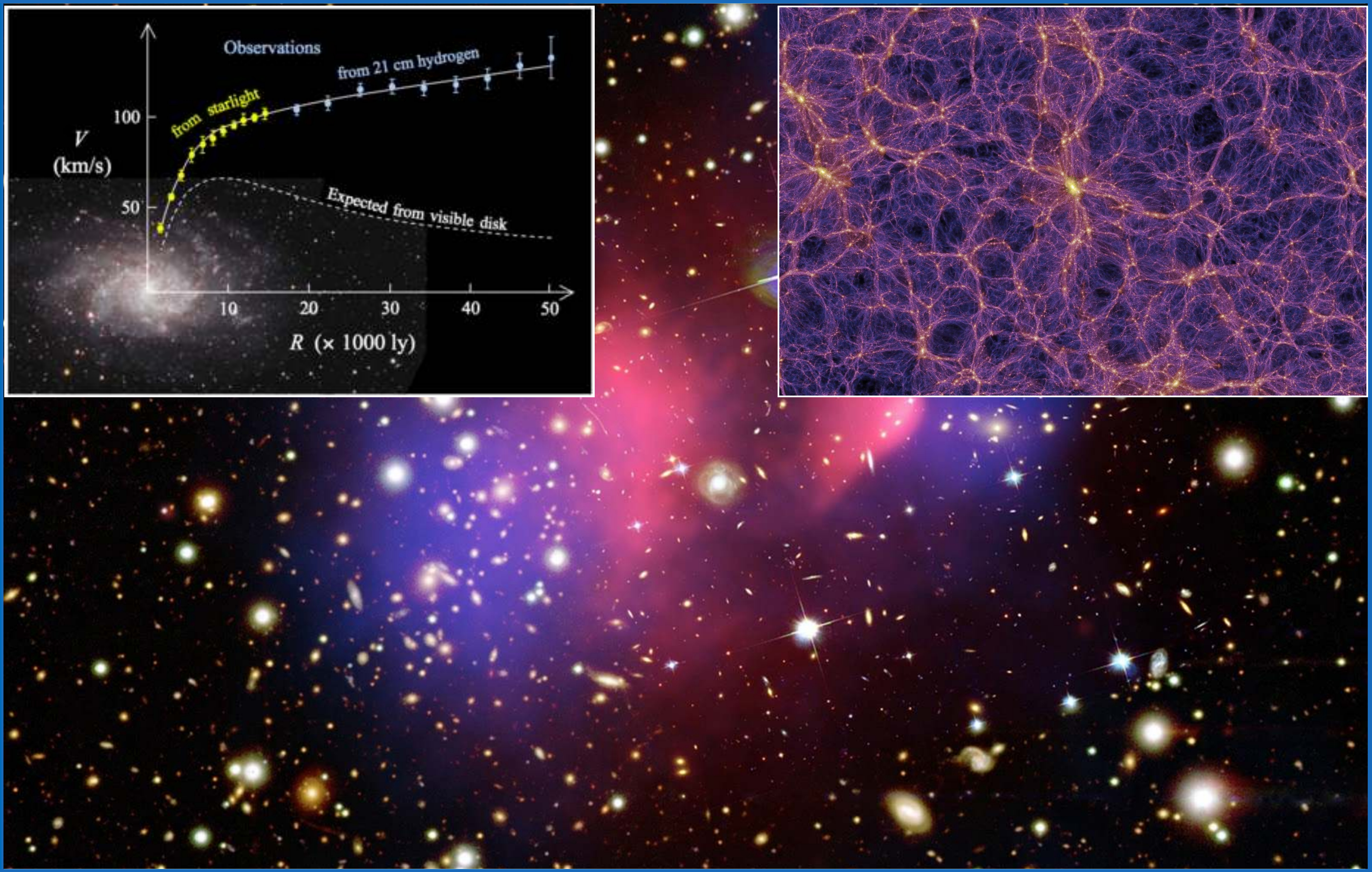

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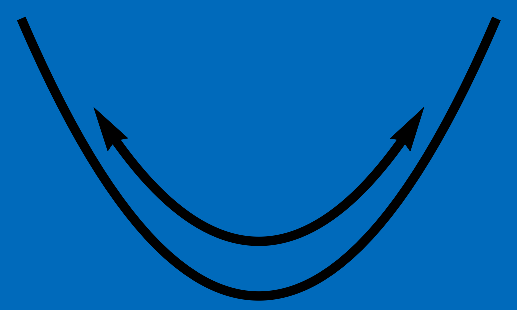

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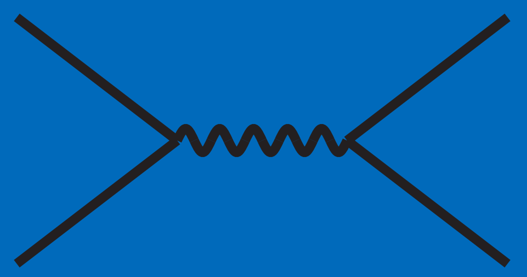

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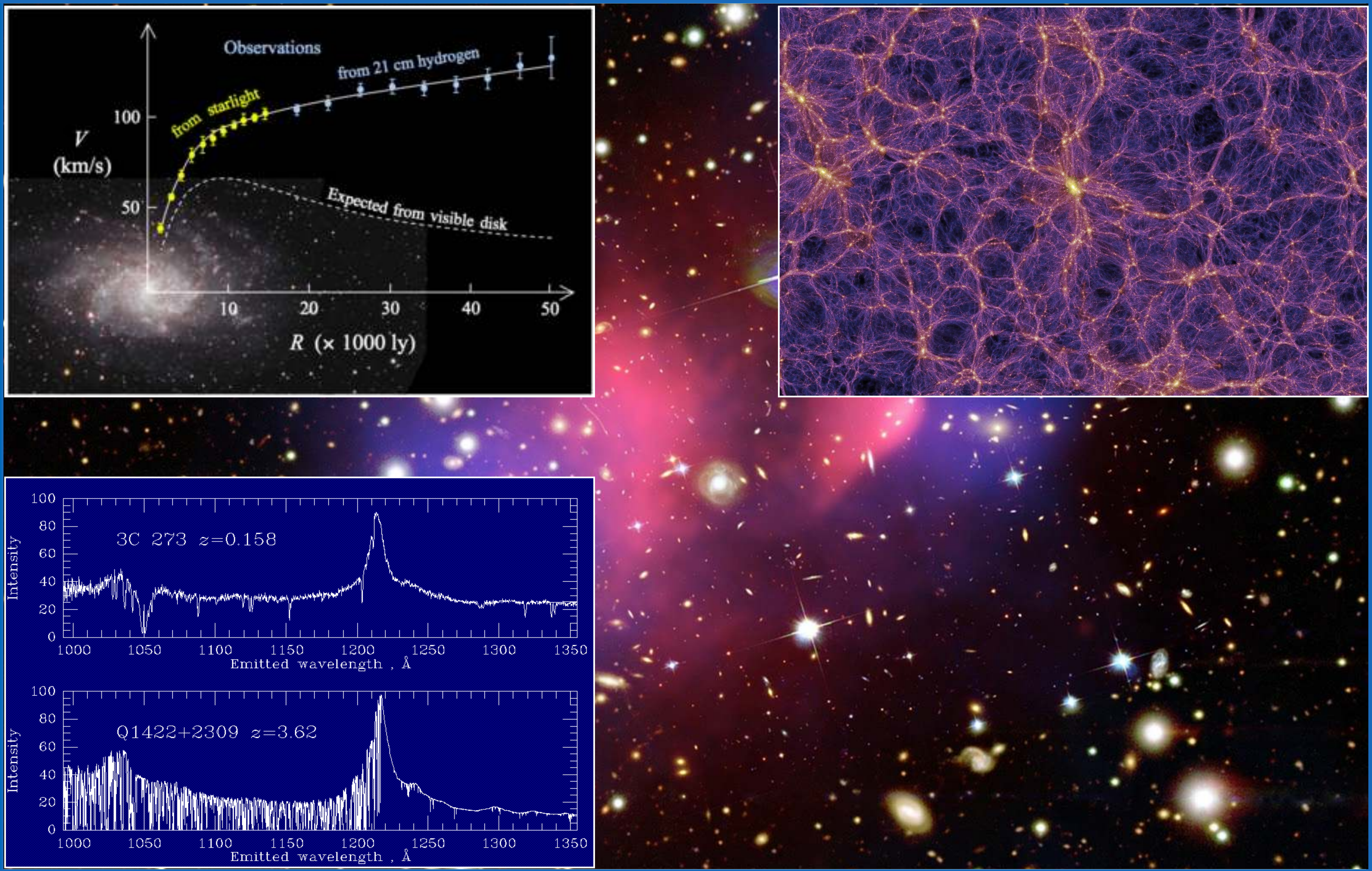

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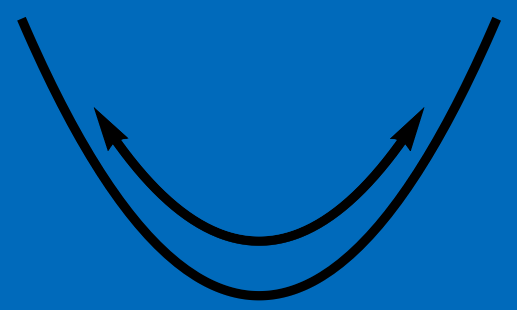

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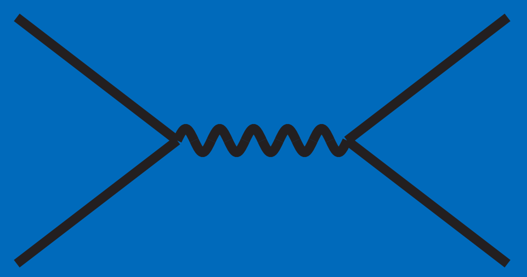

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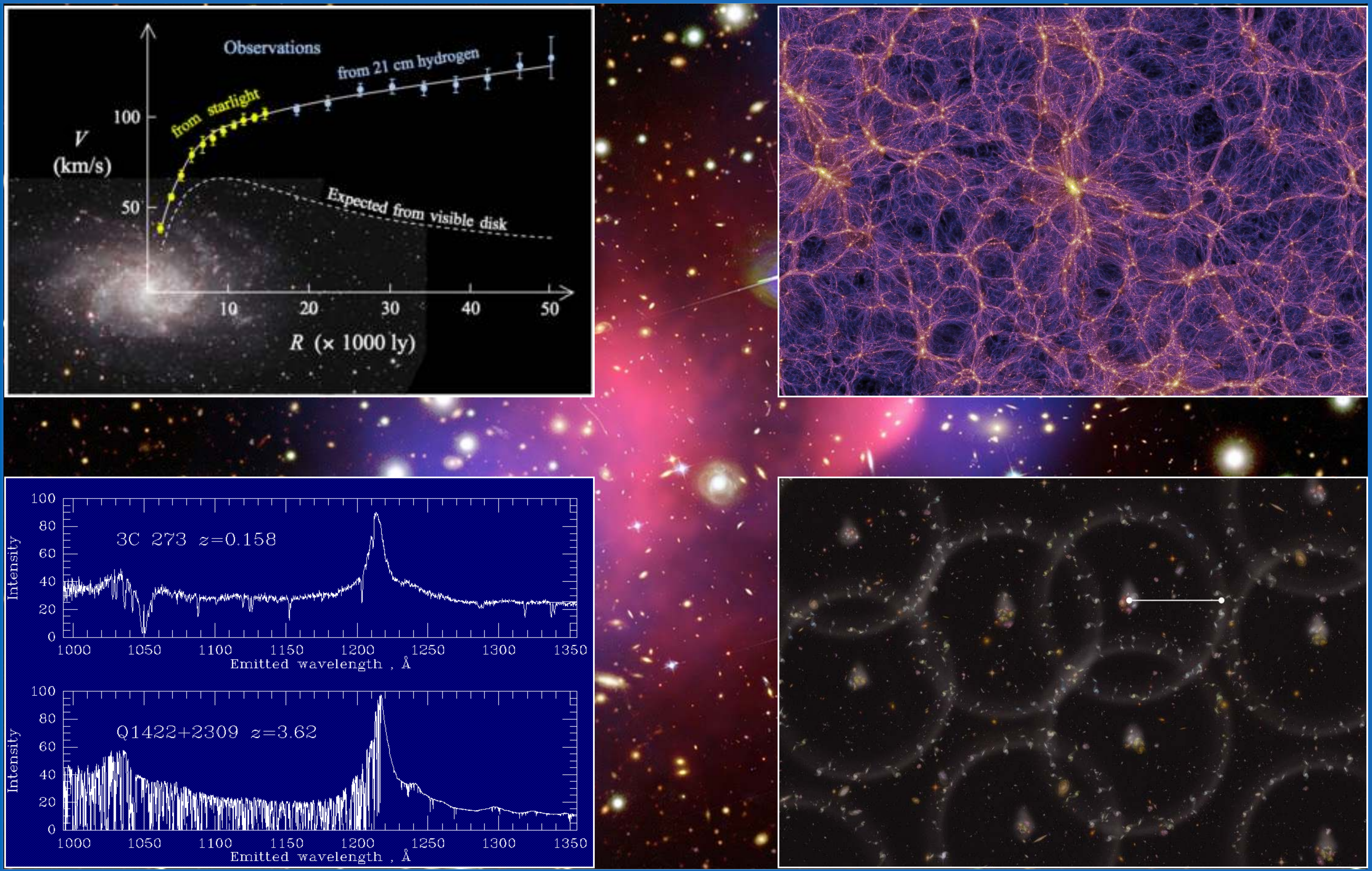

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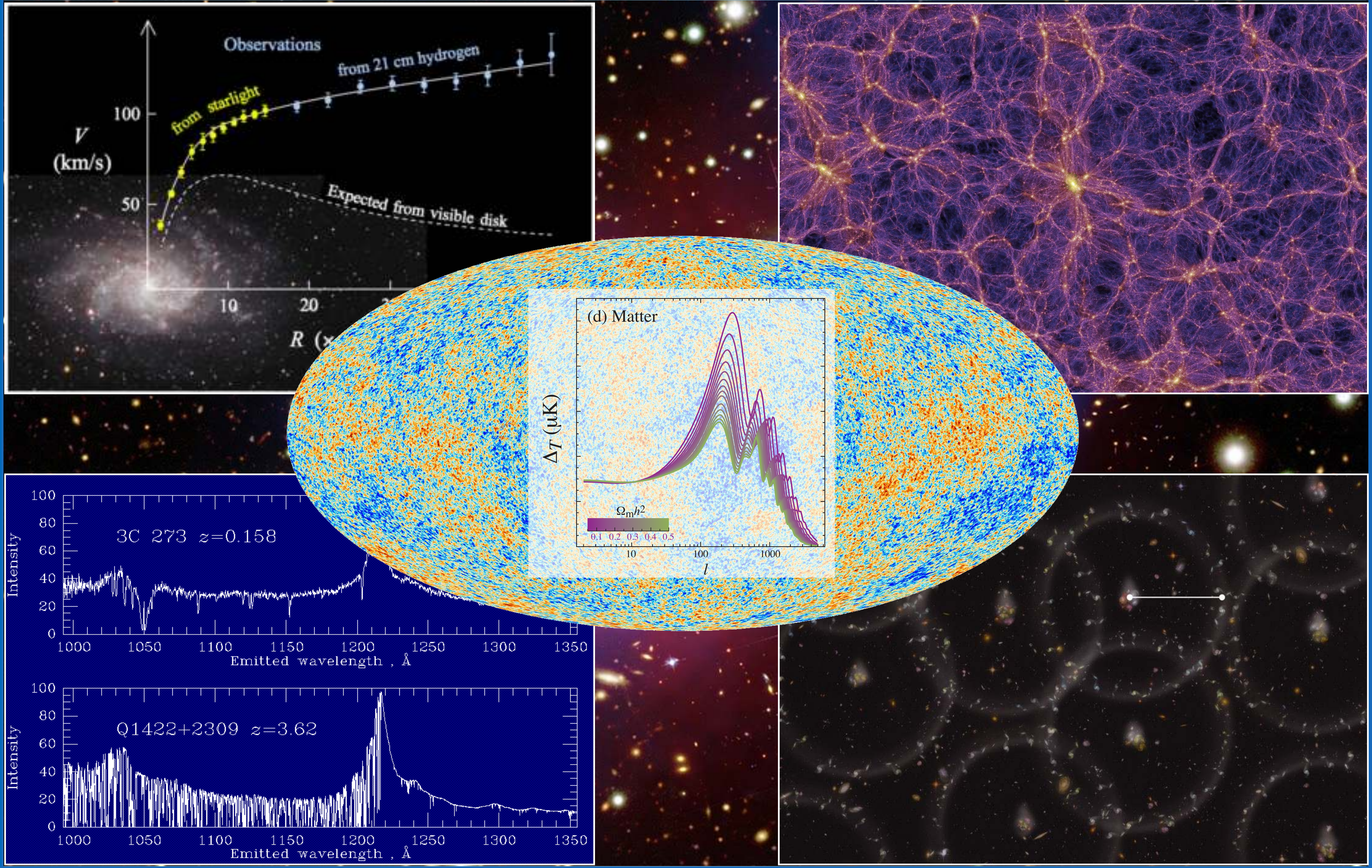

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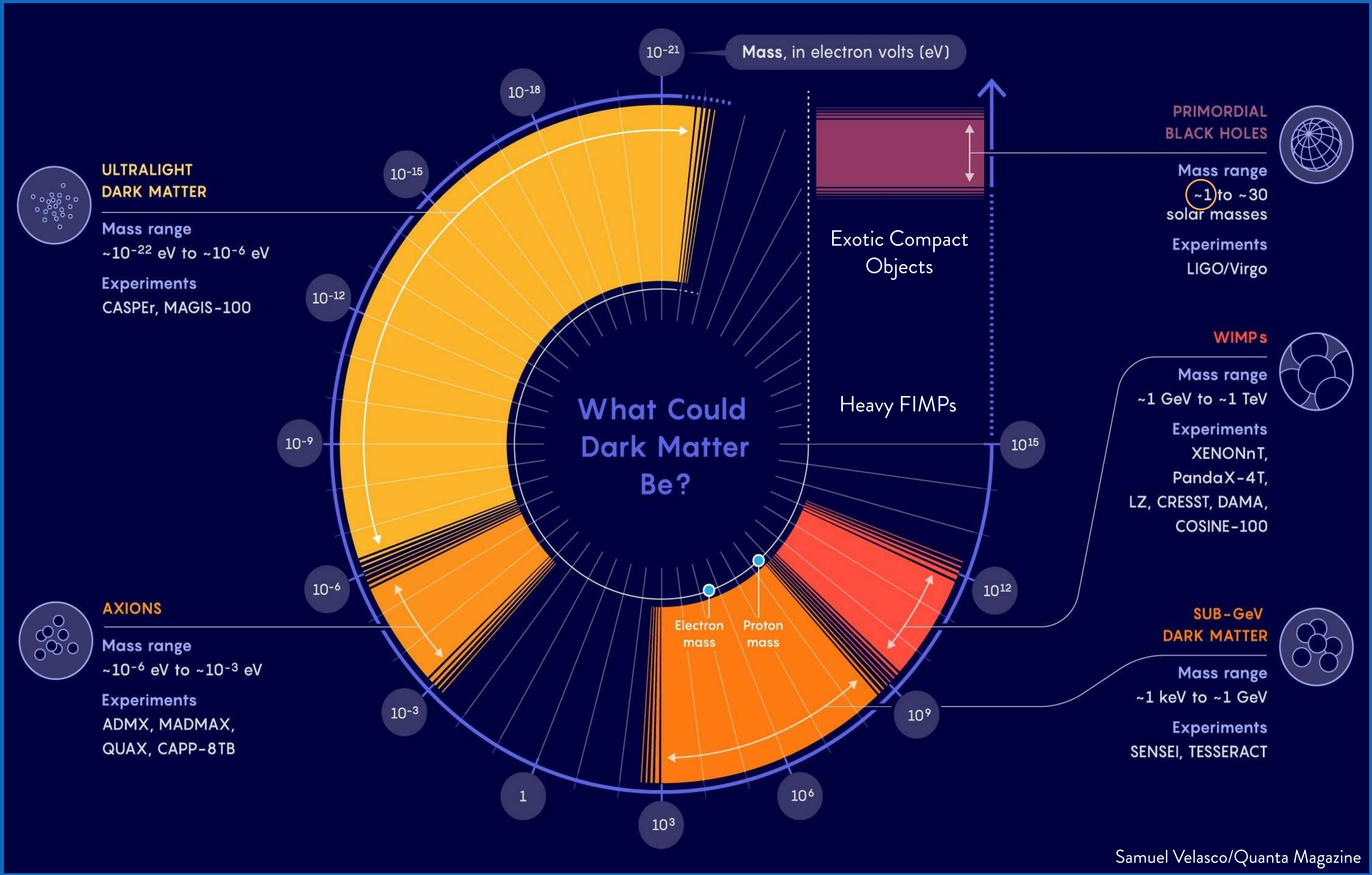
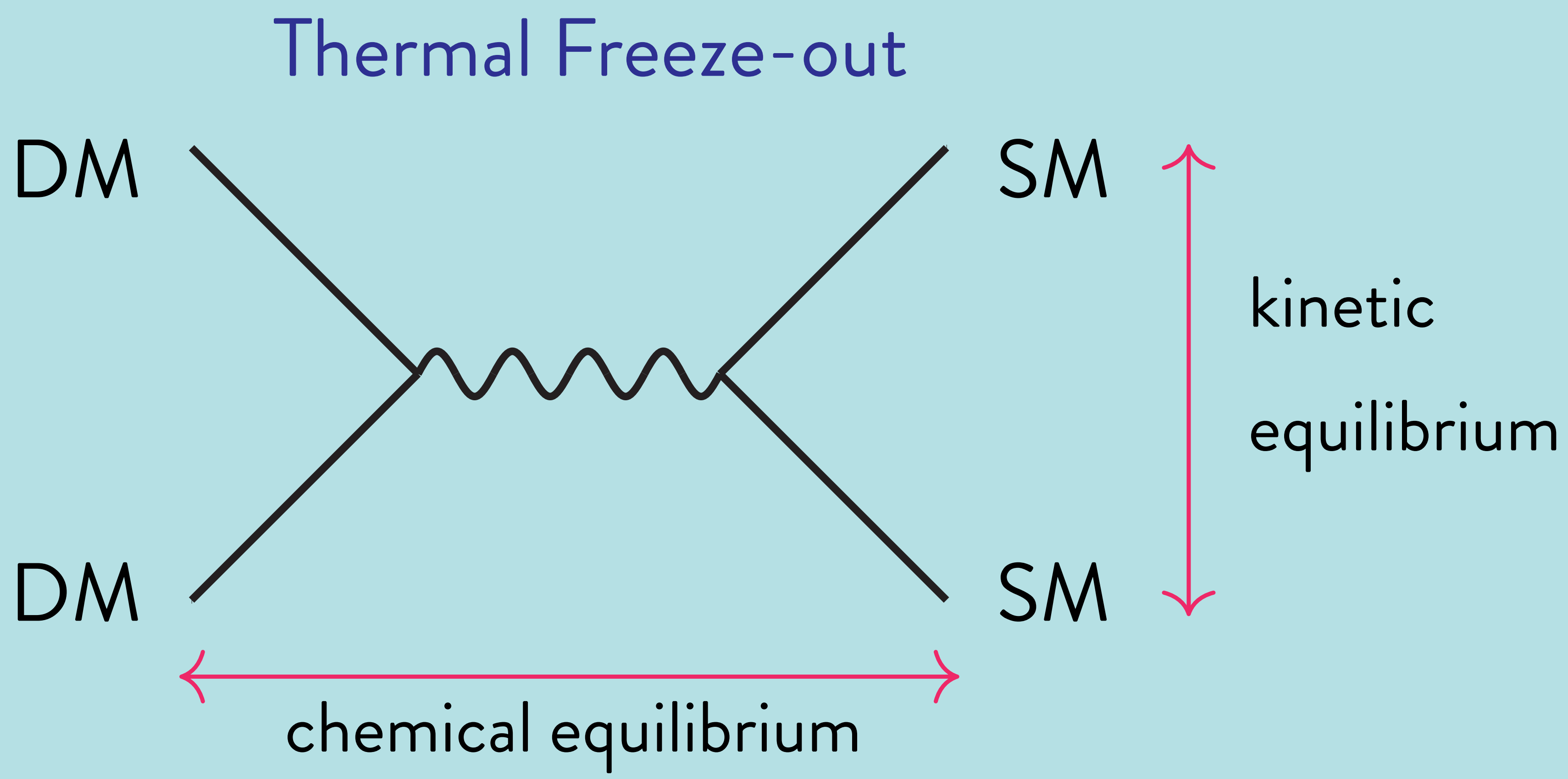
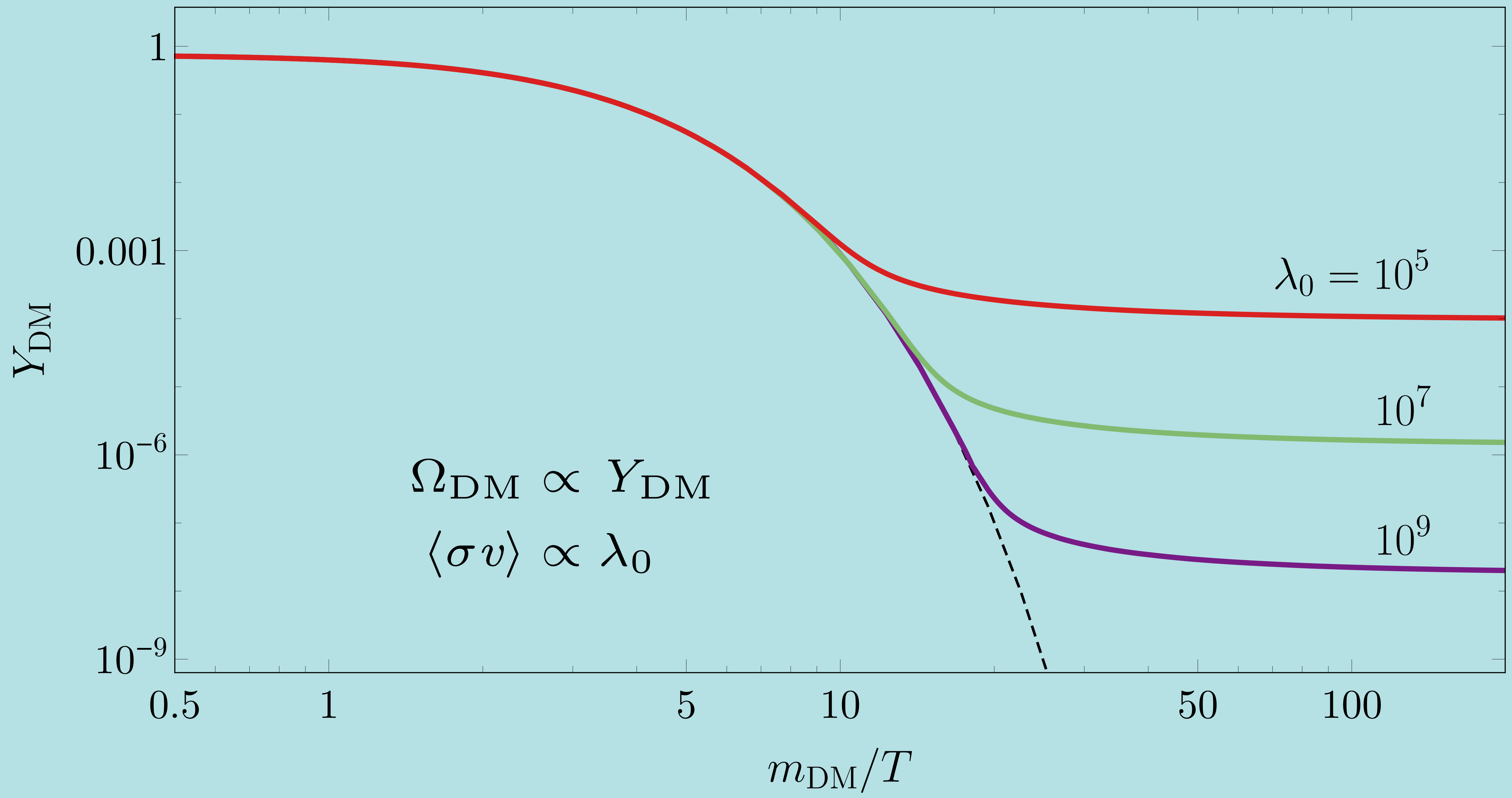


The many virtues of the WIMP





$$\Omega_{\mathrm{DM}} h^2 \equiv \frac{\rho_{\mathrm{DM}}}{\rho_{\mathrm{tot}}} h^2 \sim \frac{0.1\,\mathrm{pb}}{\langle \sigma v \rangle}$$

$$\sim 0.1 \left(\frac{m_{\mathrm{DM}}}{100\,\mathrm{GeV}} \right)^2$$

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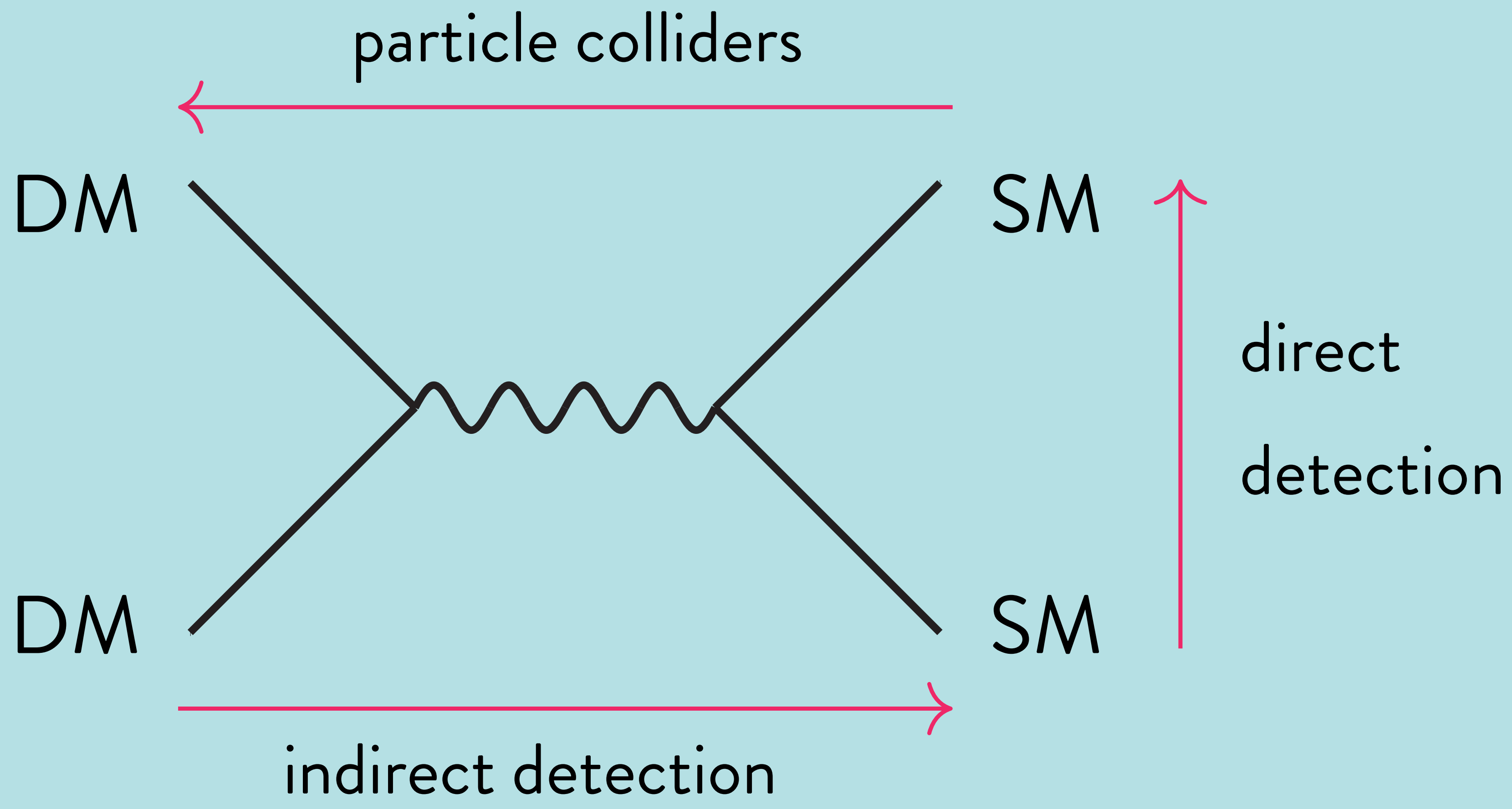
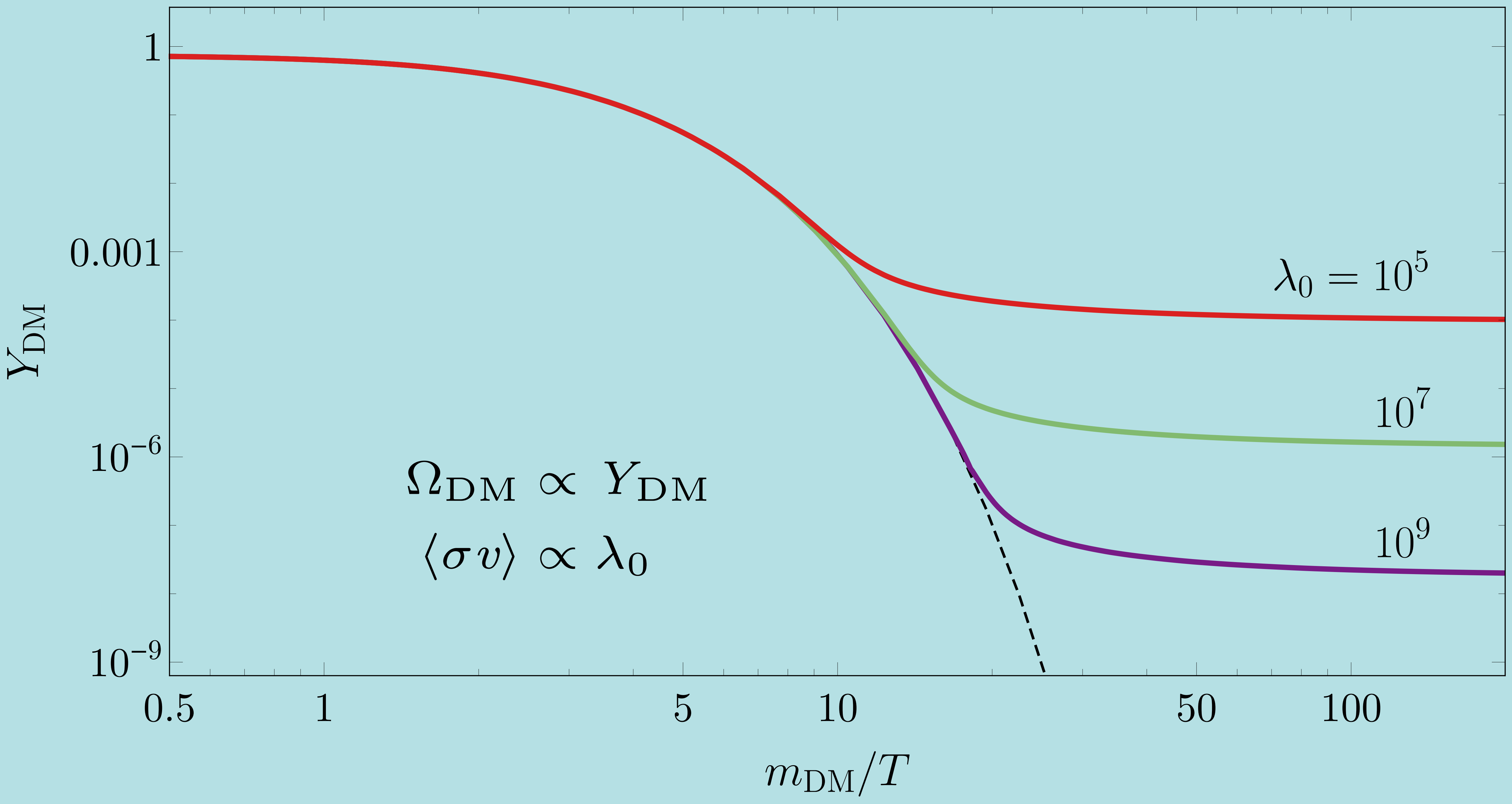
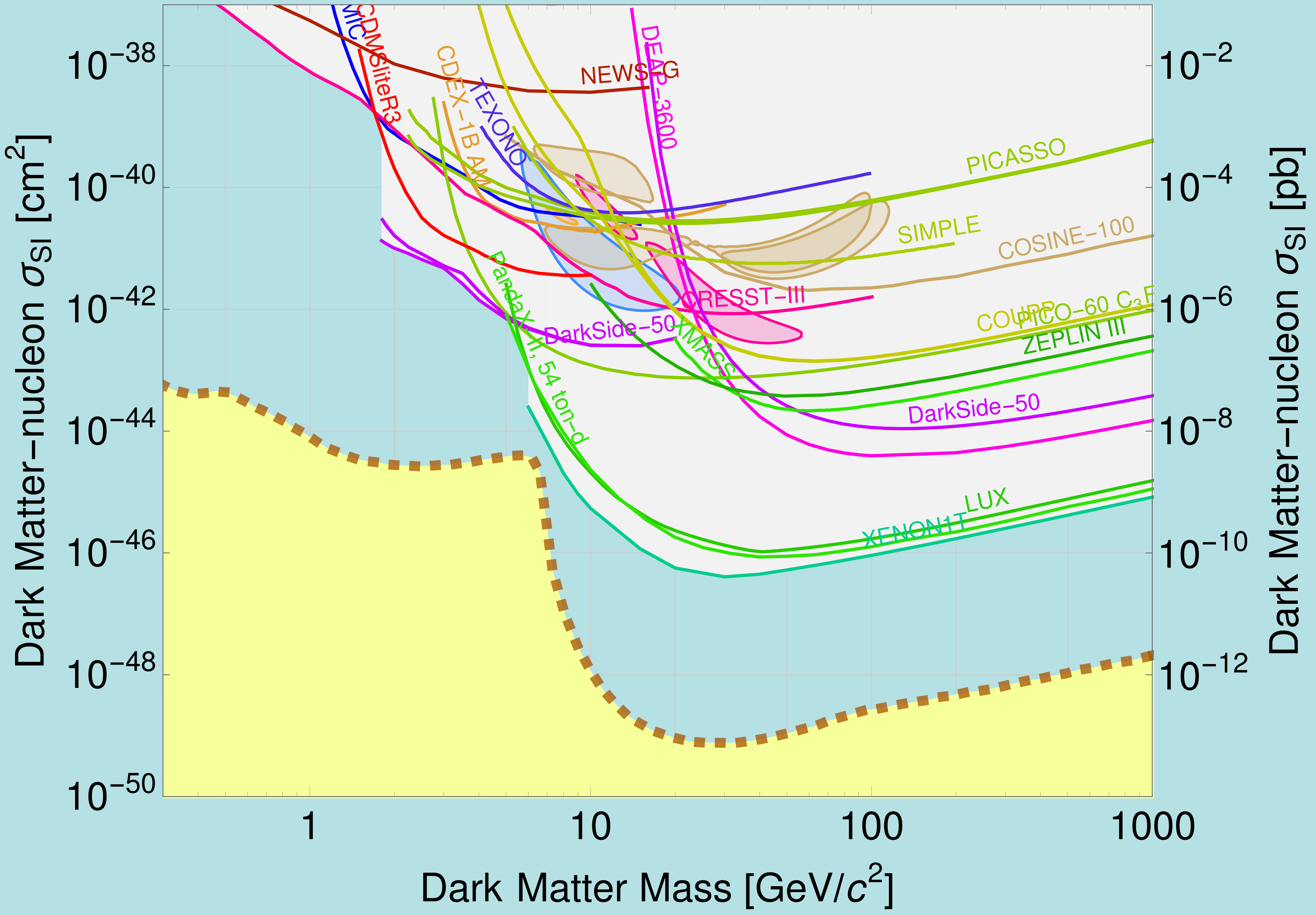




$$\Omega_{\rm DM} h^2 \equiv \frac{\rho_{\rm DM}}{\rho_{\rm tot}} h^2 \sim \frac{0.1\,{\rm pb}}{\langle \sigma v \rangle} \sim 0.1 \left(\frac{m_{\rm DM}}{100\,{\rm GeV}} \right)^2$$

Where are the WIMPs?

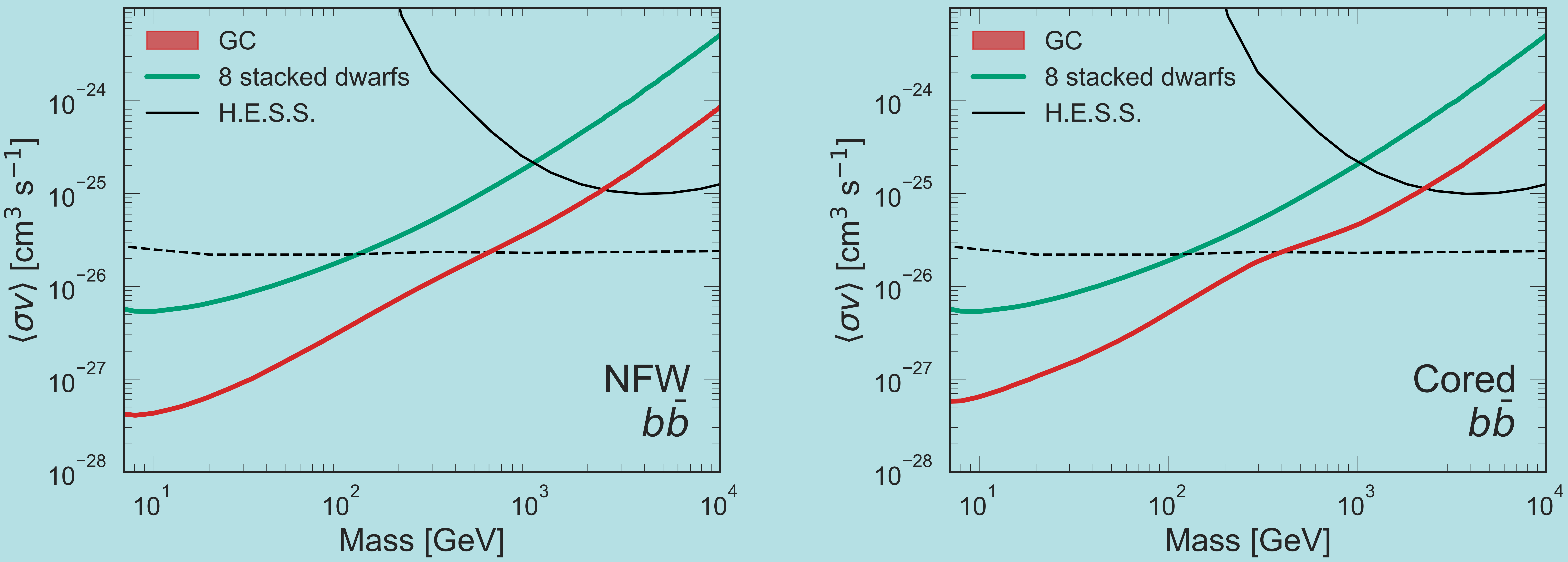
Direct detection



SuperCDMS Dark Matter Limit Plotter

Where are the WIMPs?

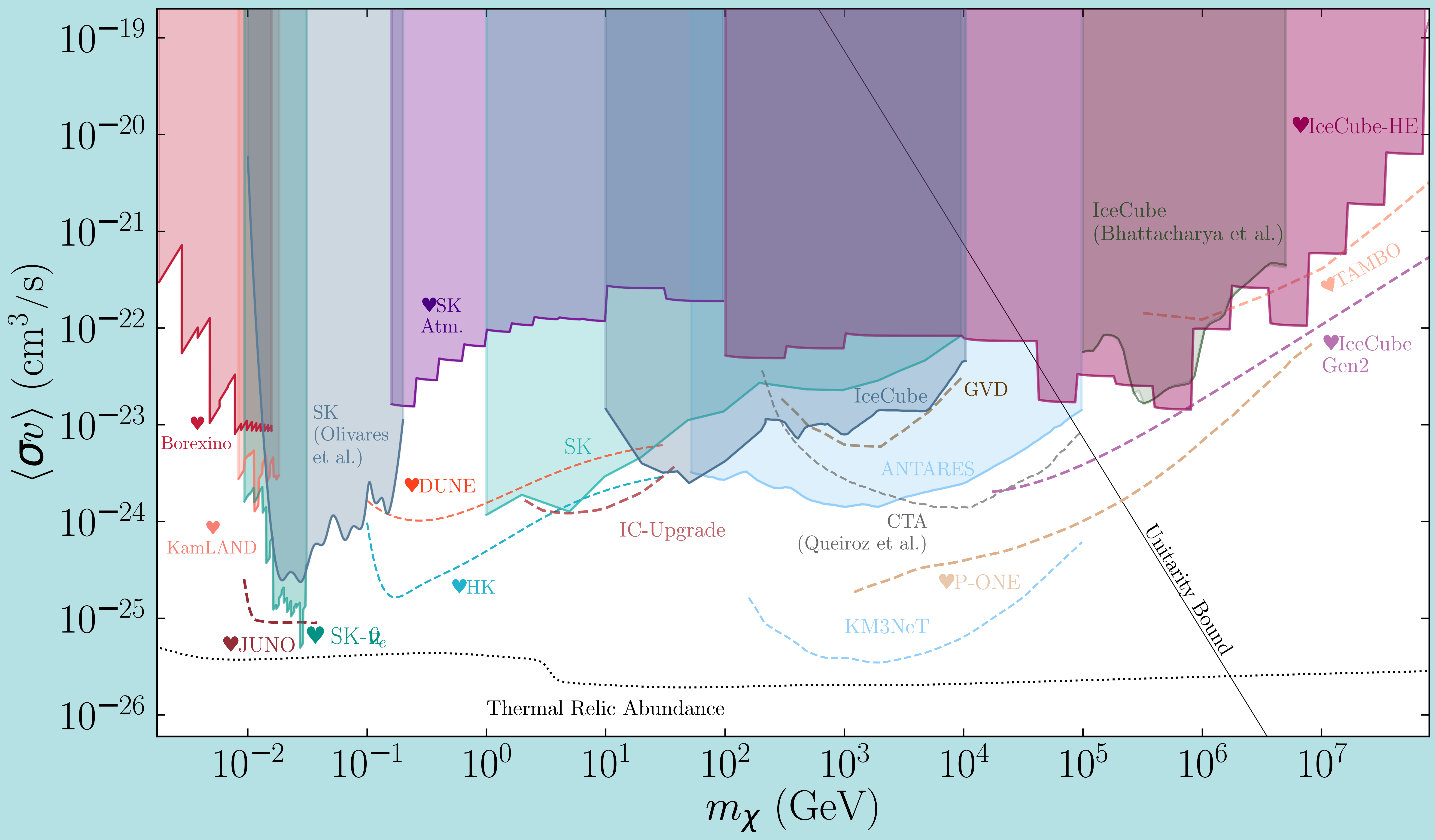
DM annihilation in the Galactic Center



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]

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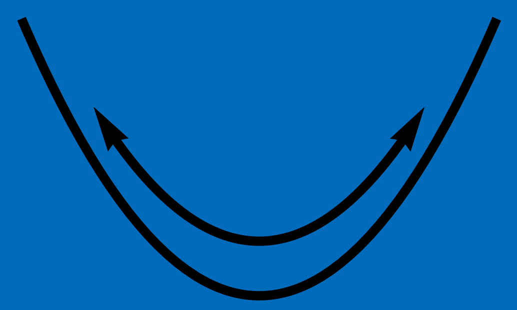

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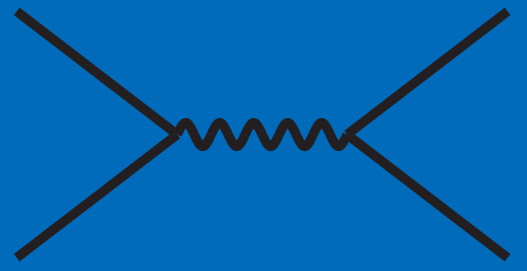

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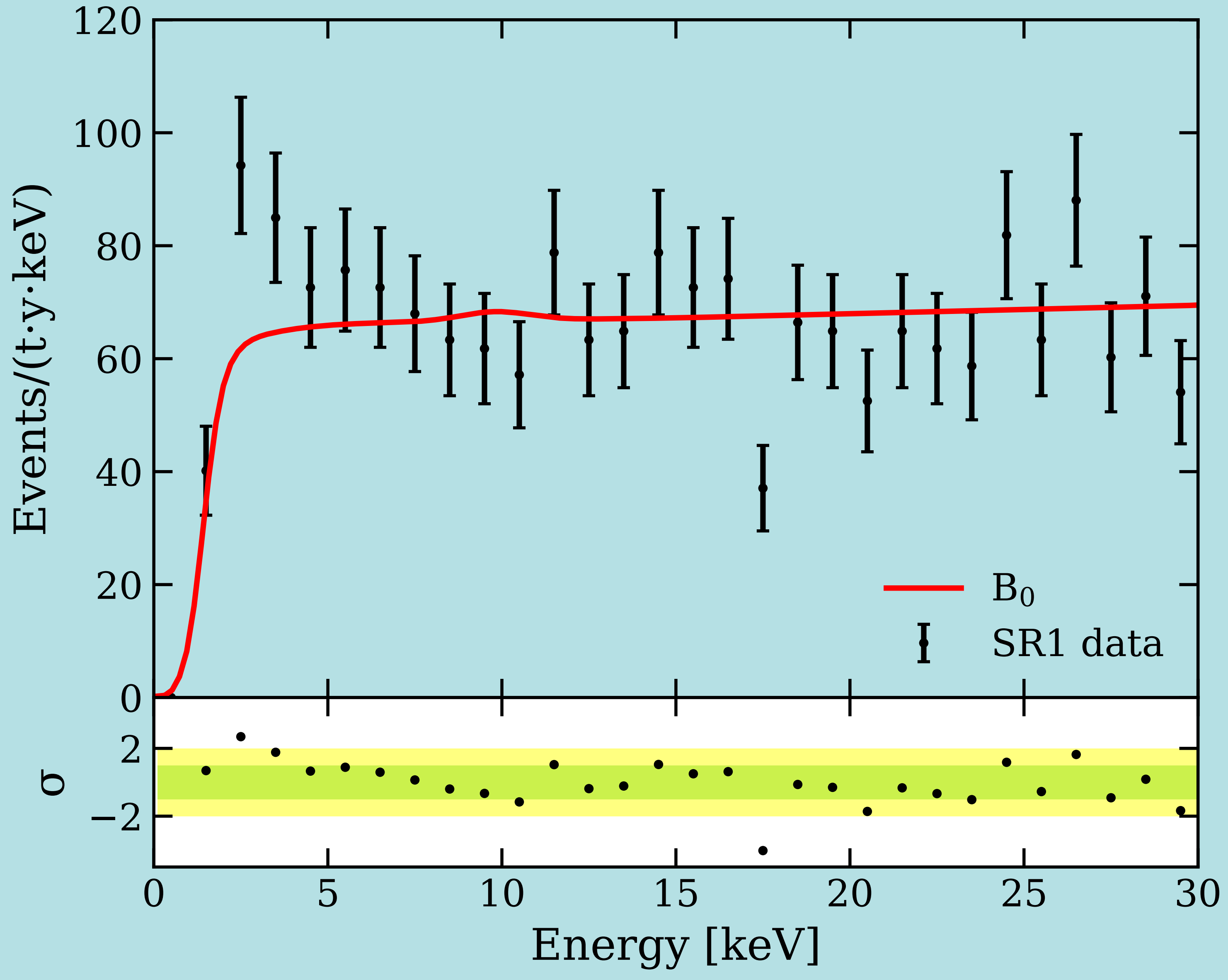
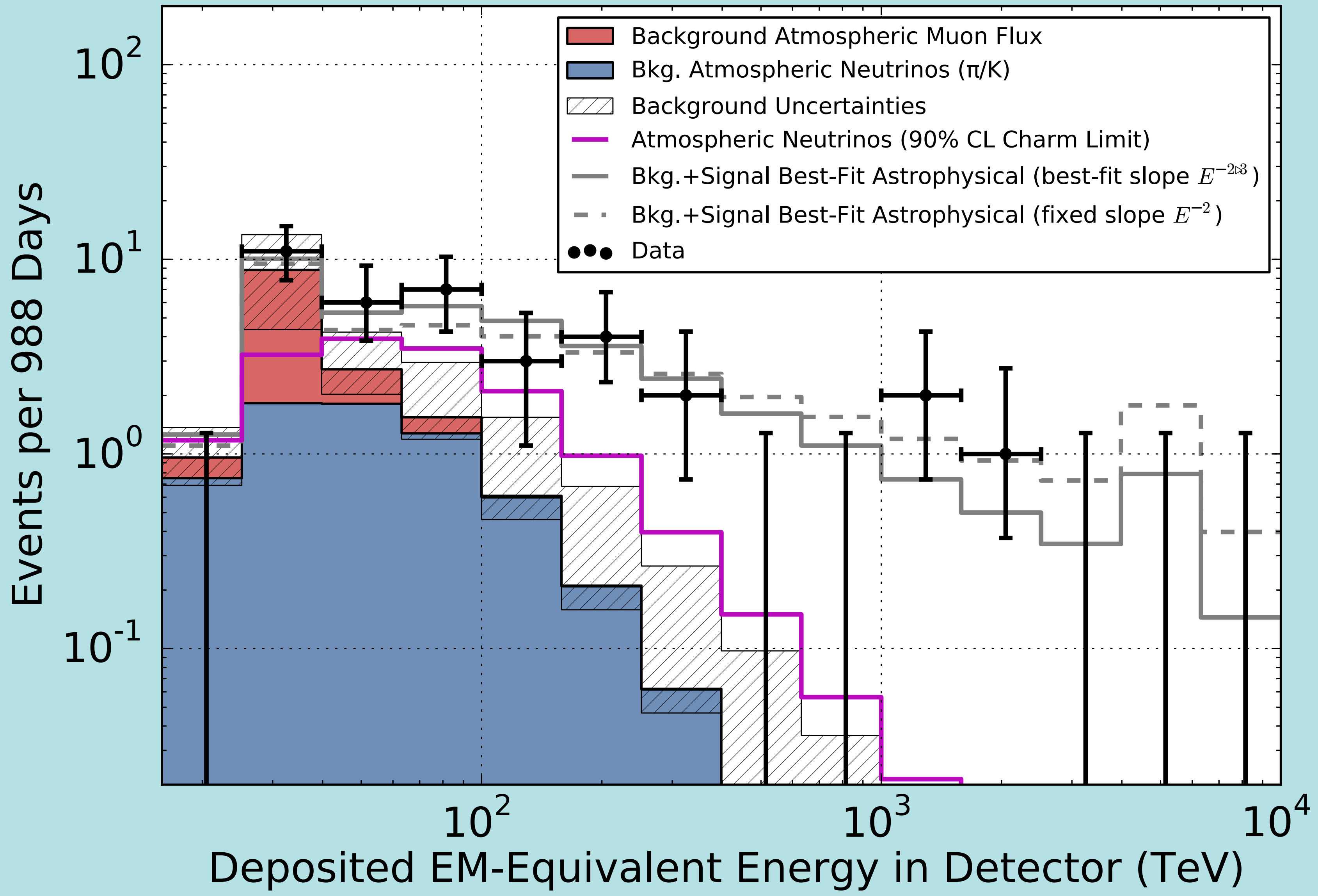
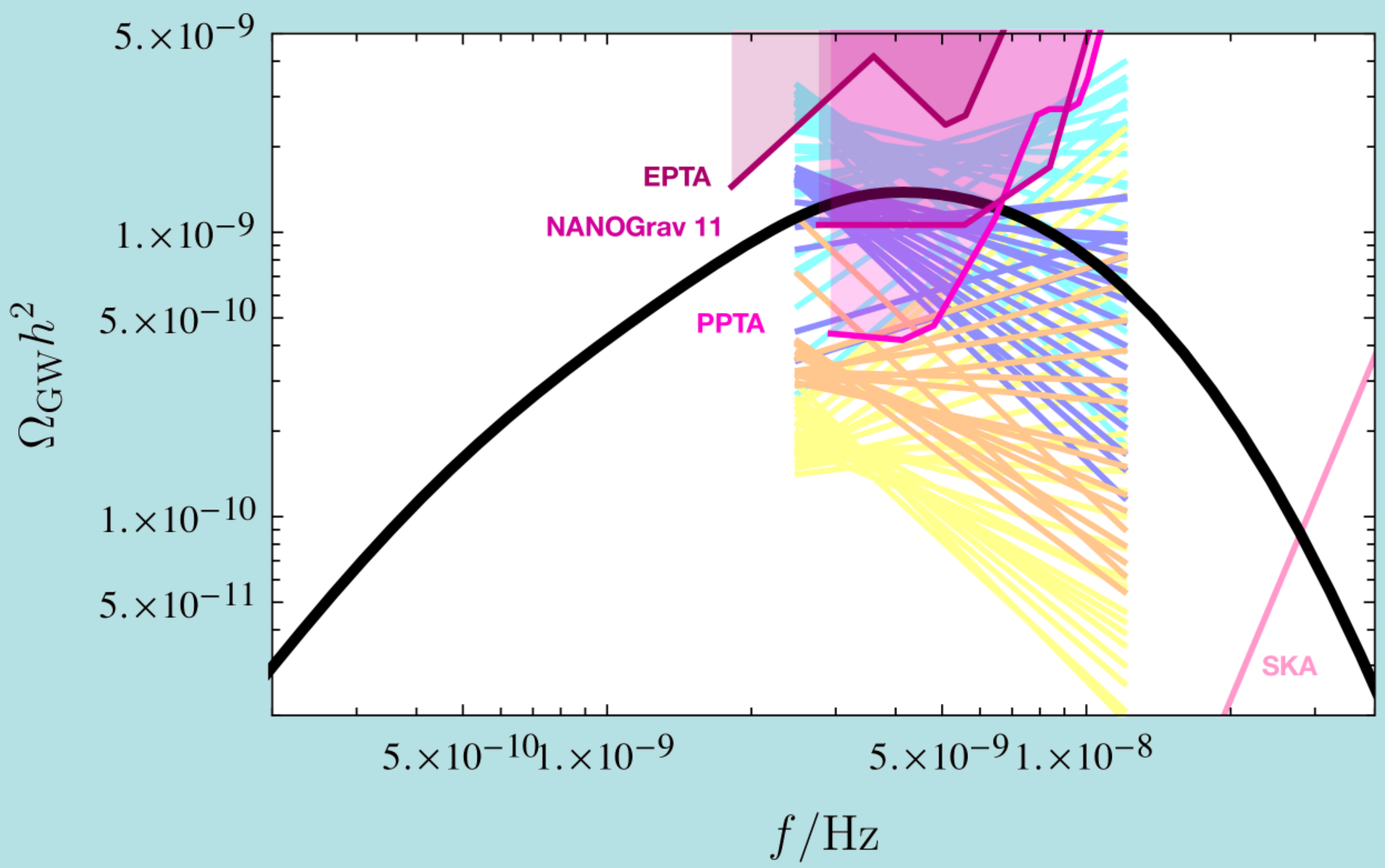
Other evidence for Dark Matter?



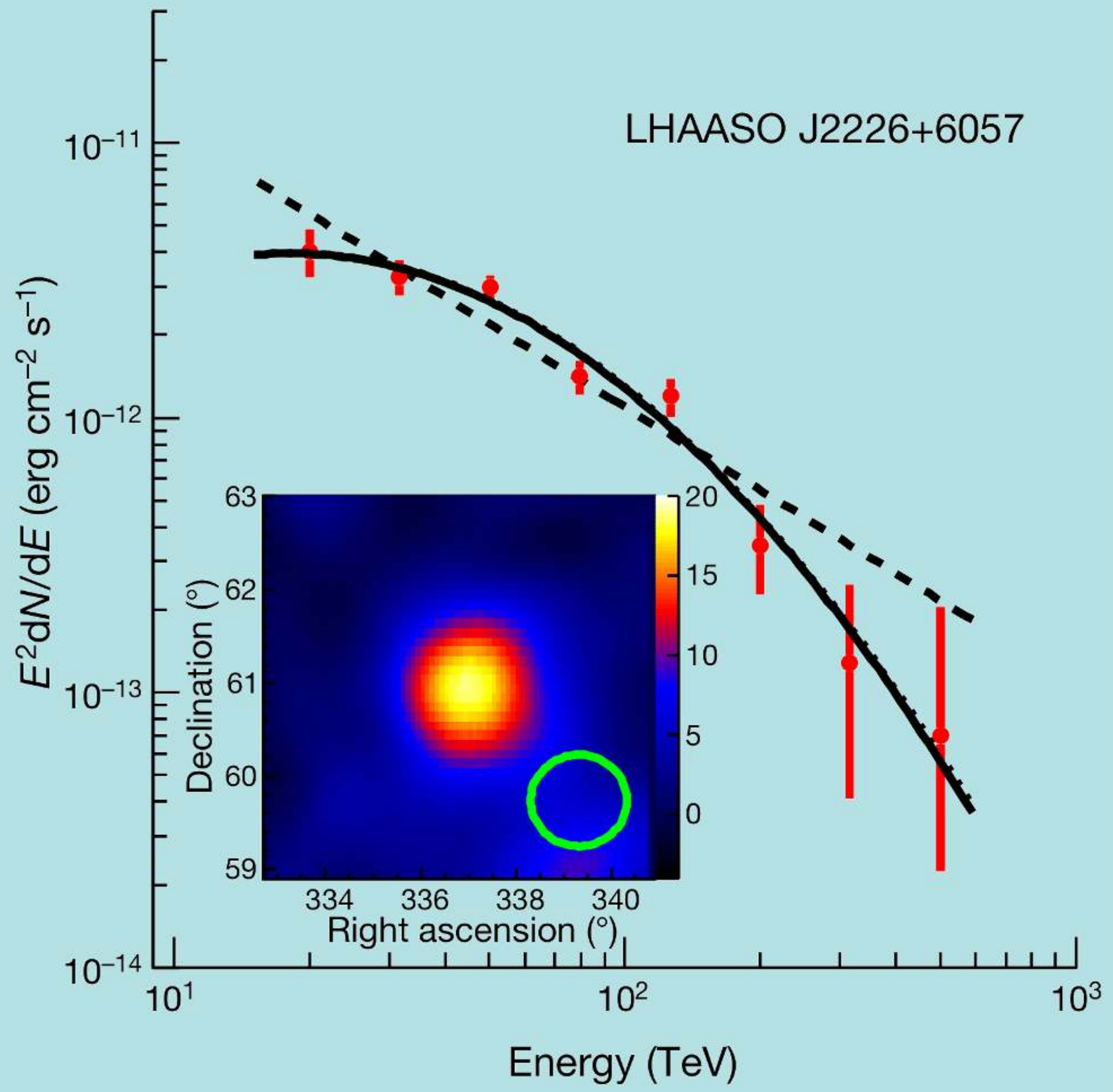
XENON, PRD 102 (2020), 072004



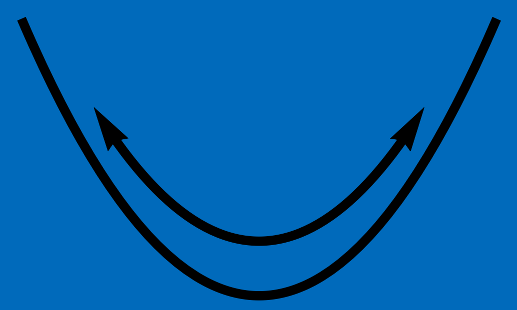
IceCube, PRL 113 (2014), 101101

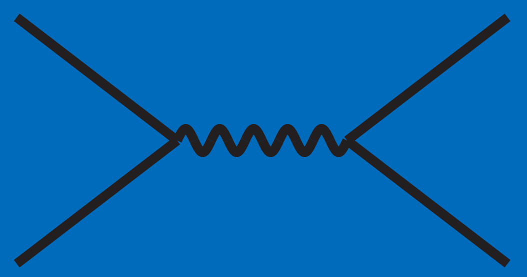


K. Kohri and T. Terada, PLB 813 (2021), 136040

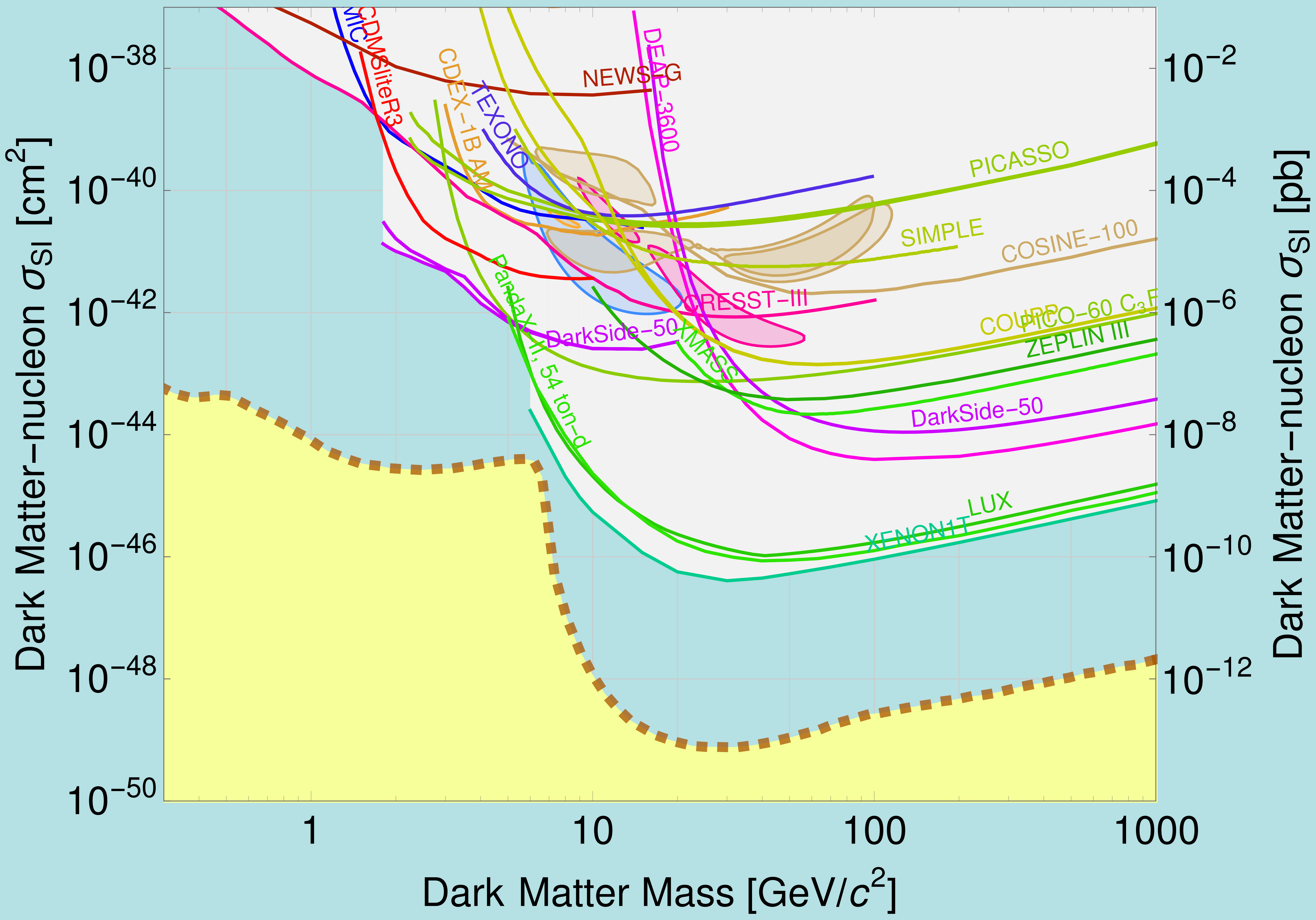


LHAASO, Nature 594 (2021), 33





Beyond the WIMP



Feeble interactions = dependence on initial conditions

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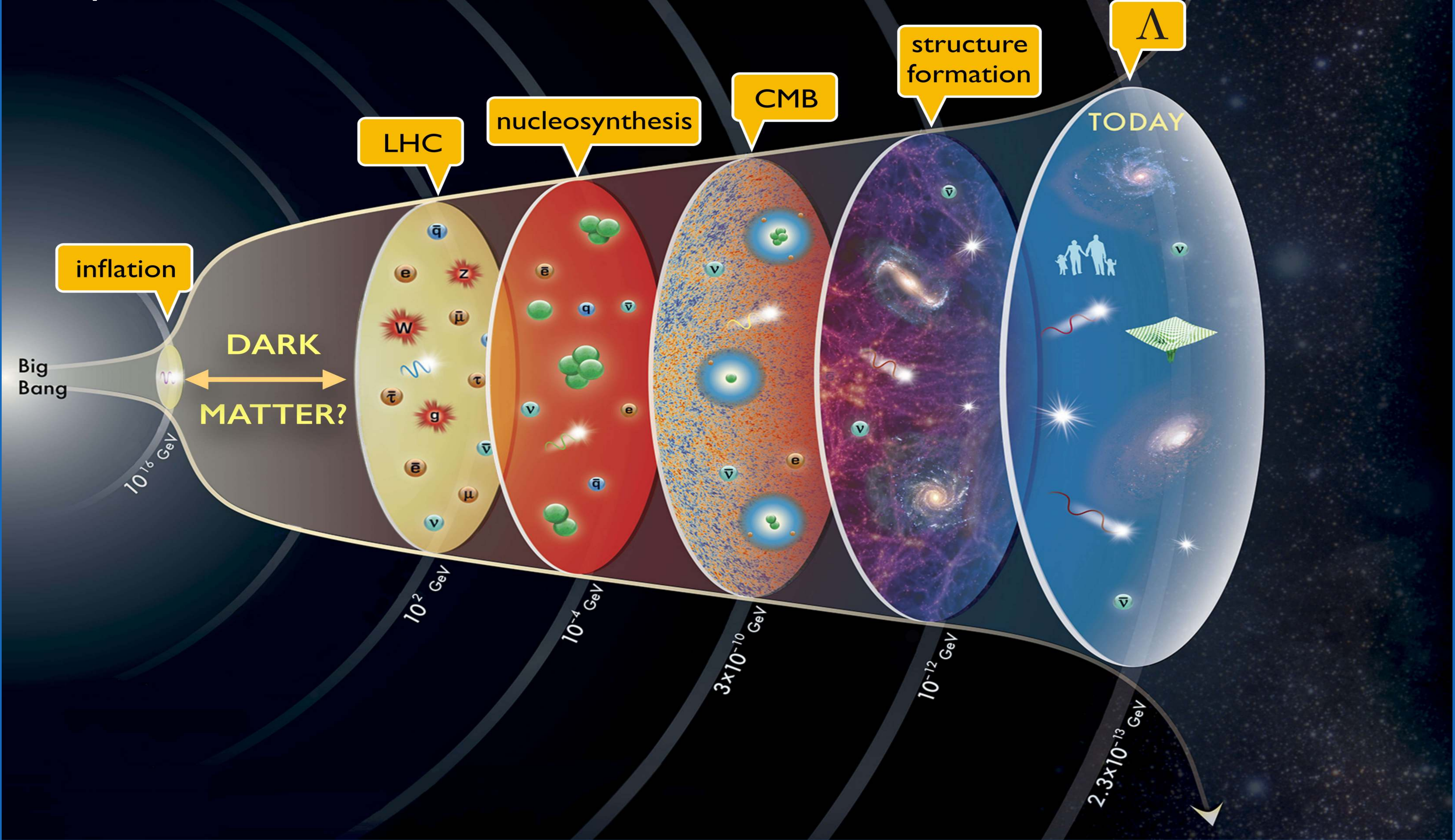
Beyond the WIMP



Inflating spacetime

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

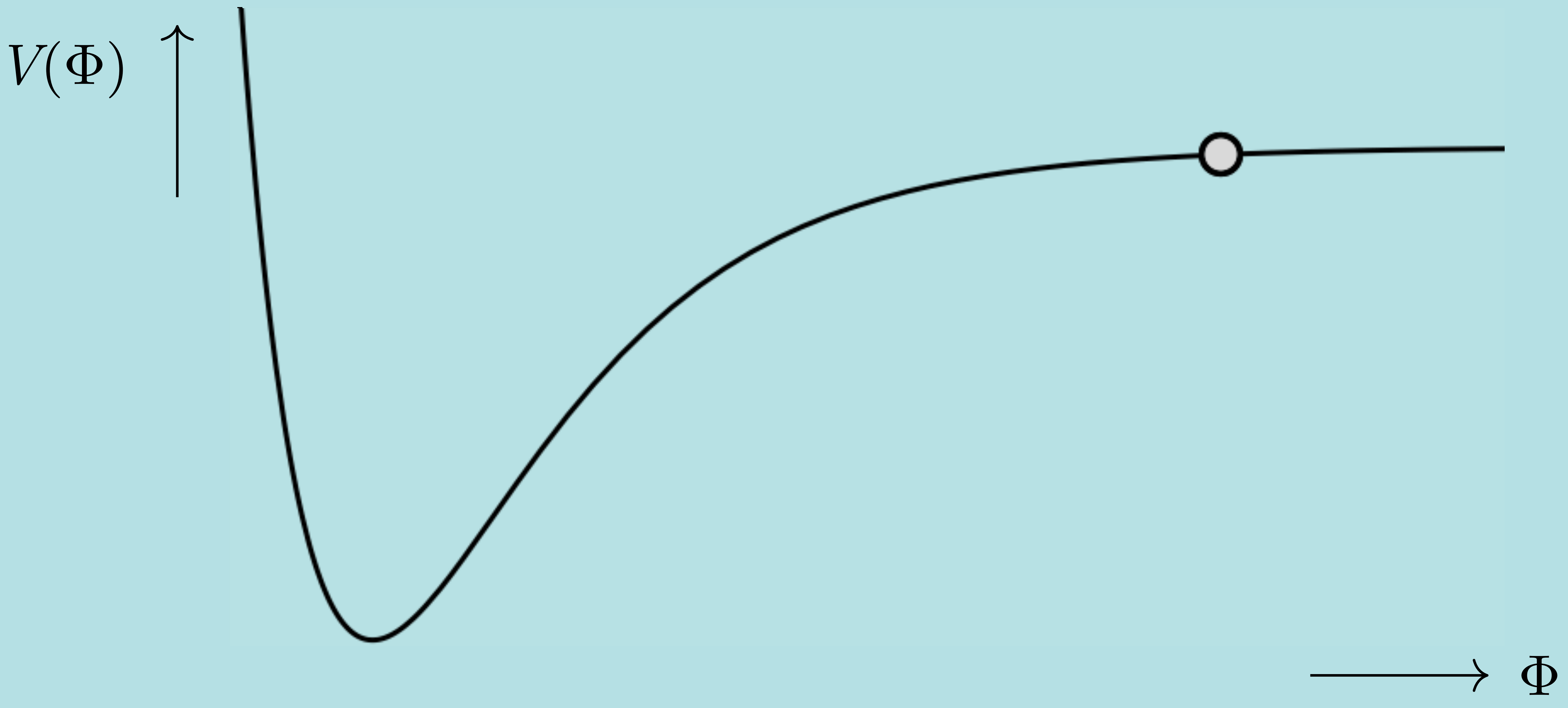
$$\ddot{\Phi} + 3H\dot{\Phi} + V'(\Phi) = 0$$

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

with

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

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

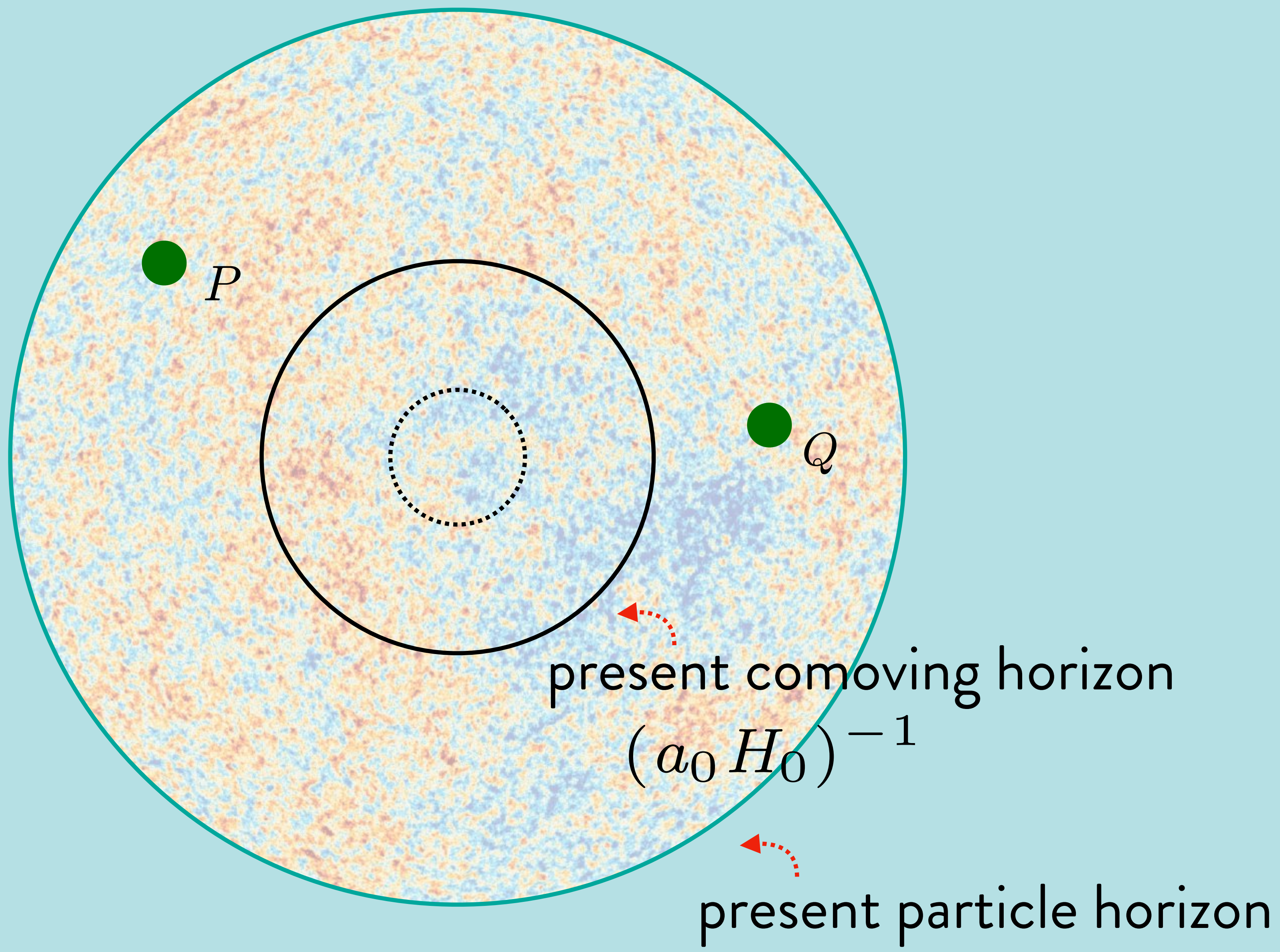


When inflation ends, reheating begins

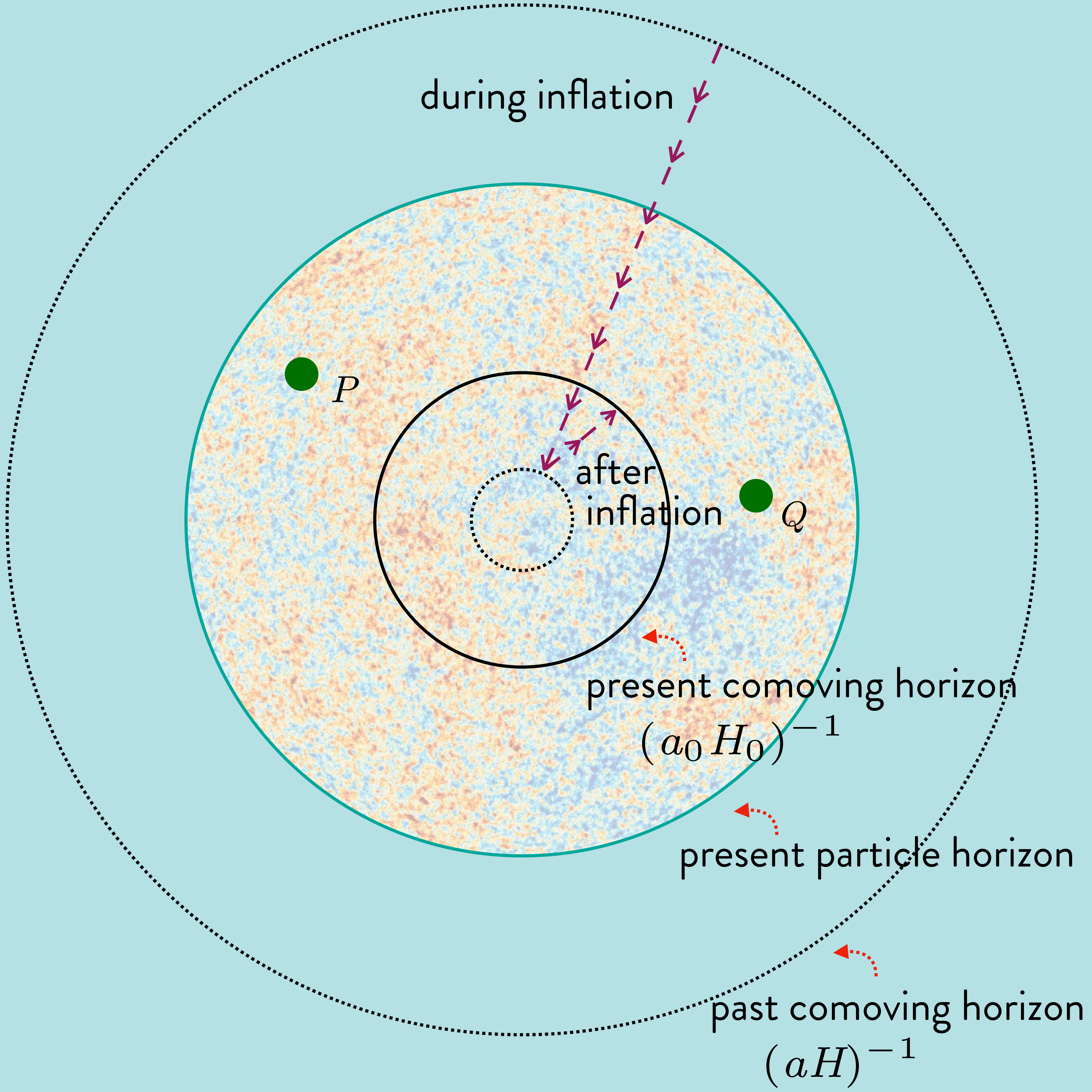
The horizon problem

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

Without inflation

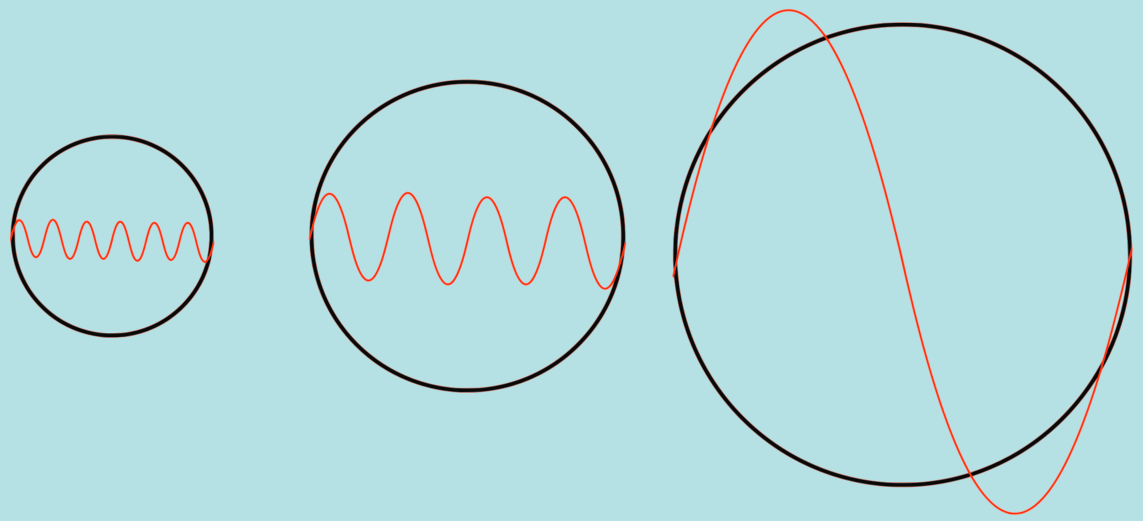


With inflation

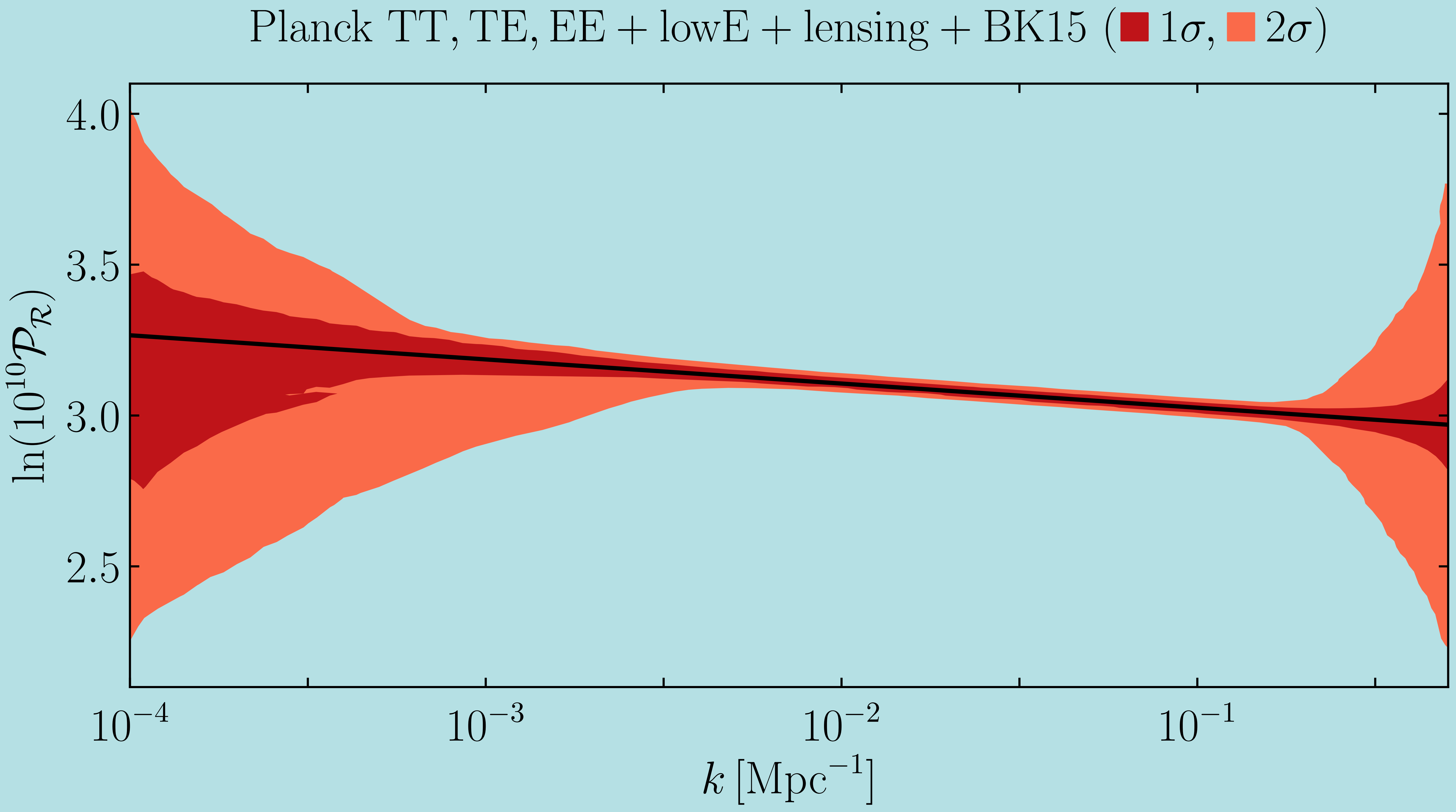


Credit: Héctor Ramírez

The primordial fluctuations



Quantum fluctuations in Φ, g, are strechted by expansion



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

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

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

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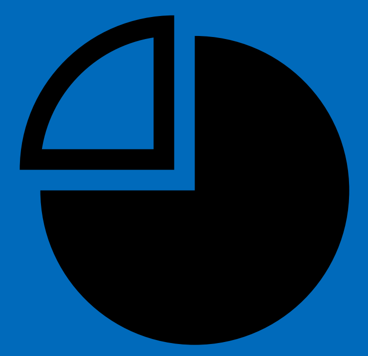

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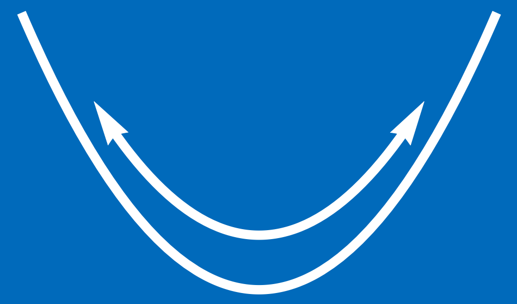

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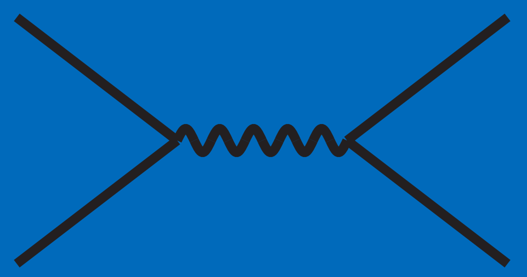

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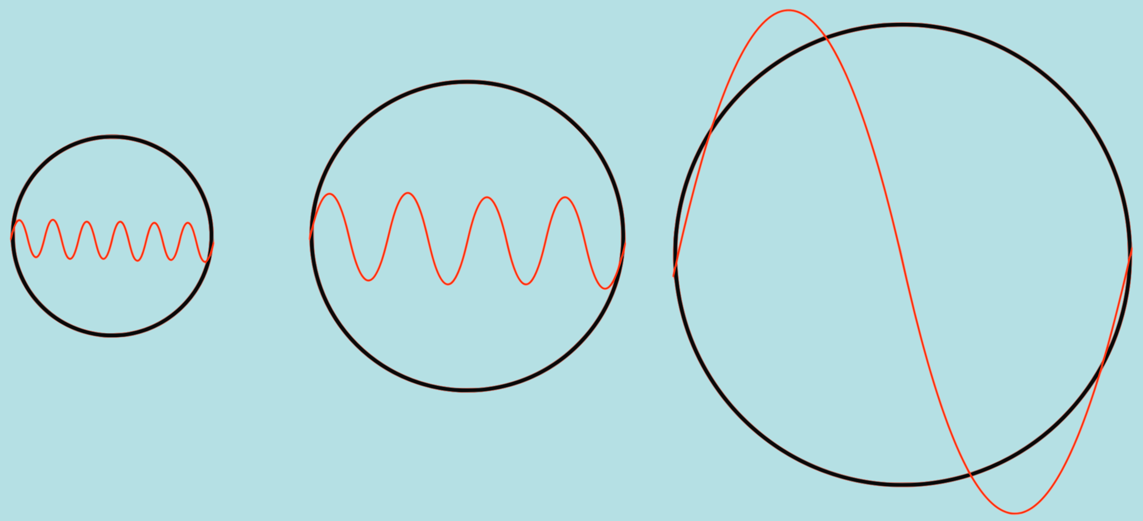

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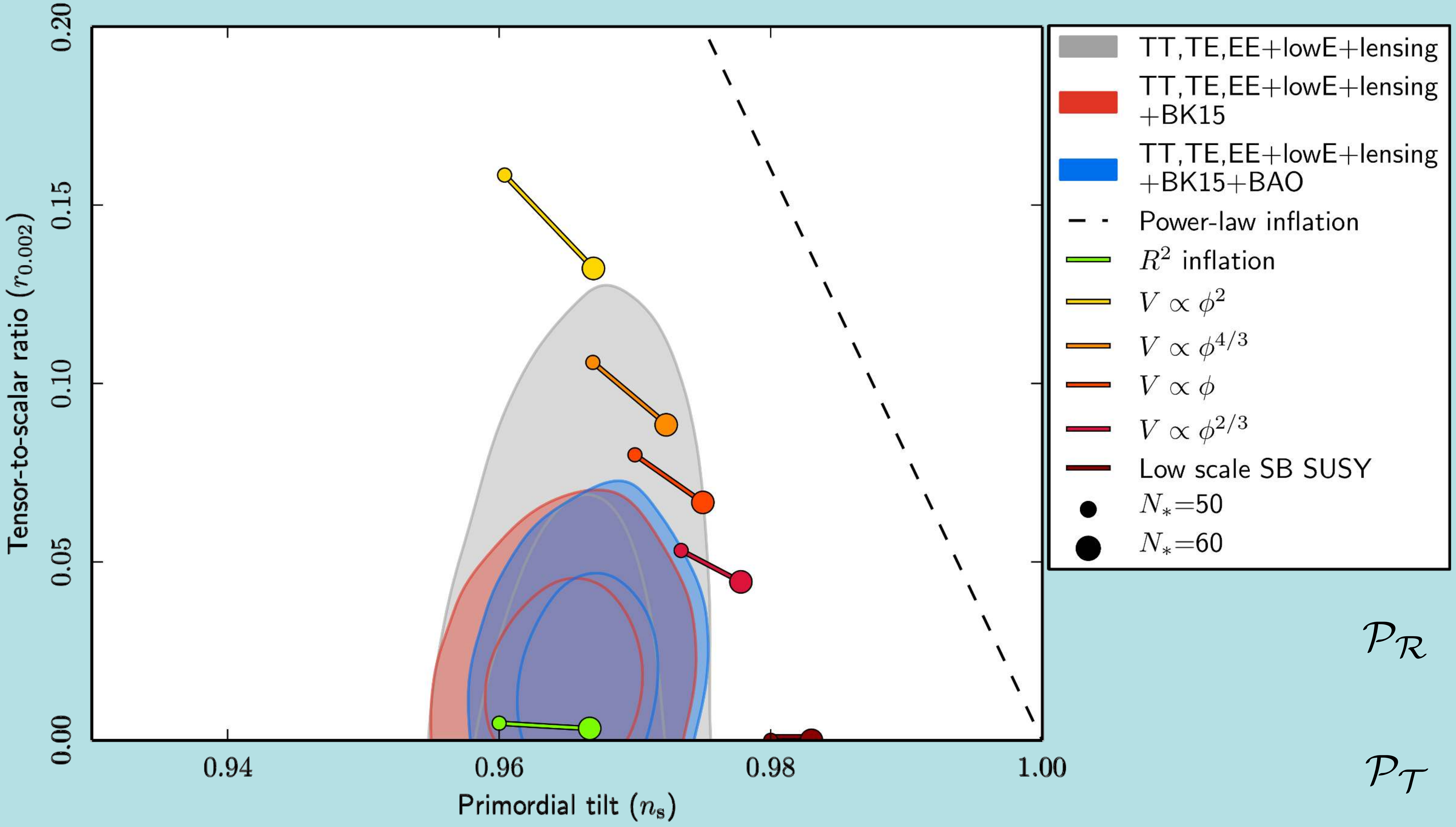


$$\mathcal{P}_{\mathcal{R}} = \frac{H_*^4}{4\pi^2 \dot{\Phi}_*^2} \left(\frac{k}{aH} \right)^{n_s - 1}$$

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

The vacuum can be excited!

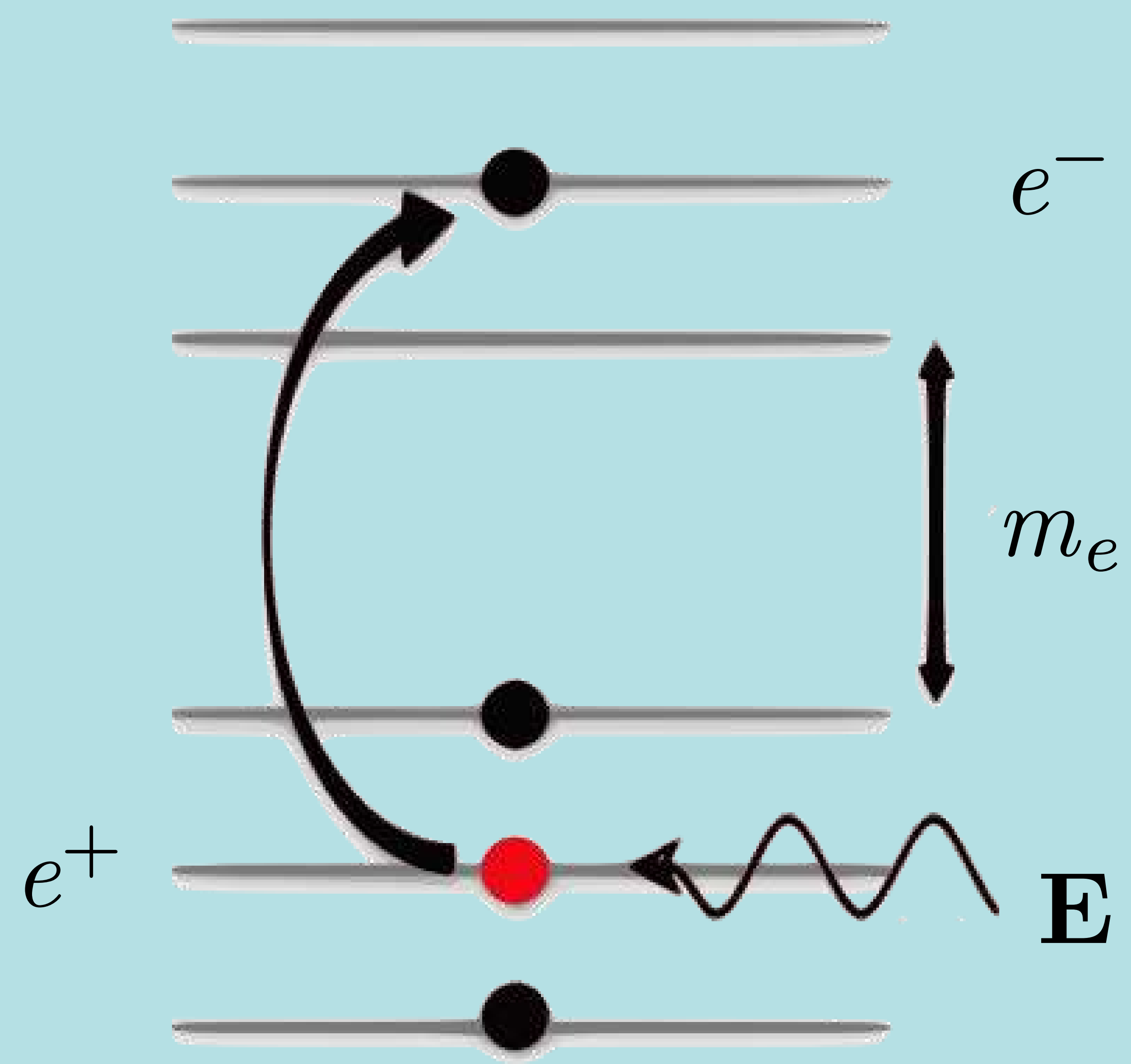
$$A_\mu = (0, 0, 0, Et)$$

$$\omega^2(t) = (p_z + gEt)^2 + \boldsymbol{p}_T^2 + m^2$$

mixing of +/- frequency modes

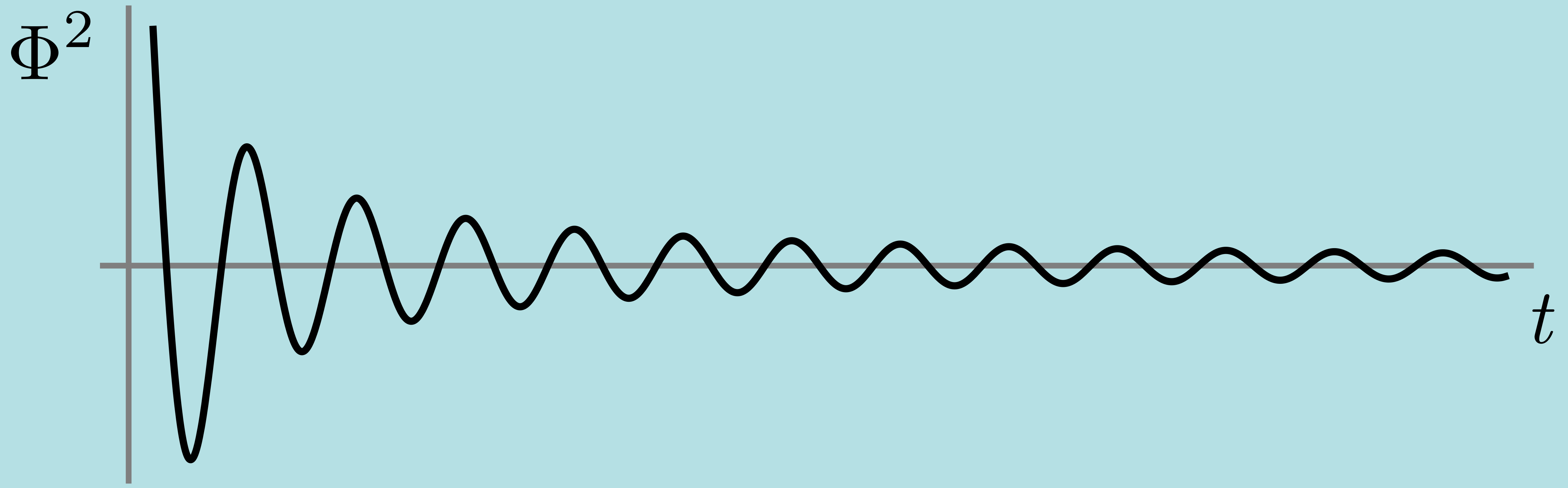
$\downarrow$

particle production! (Schwinger effect)



QED vacuum

During reheating, the inflaton provides an oscillating background



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

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

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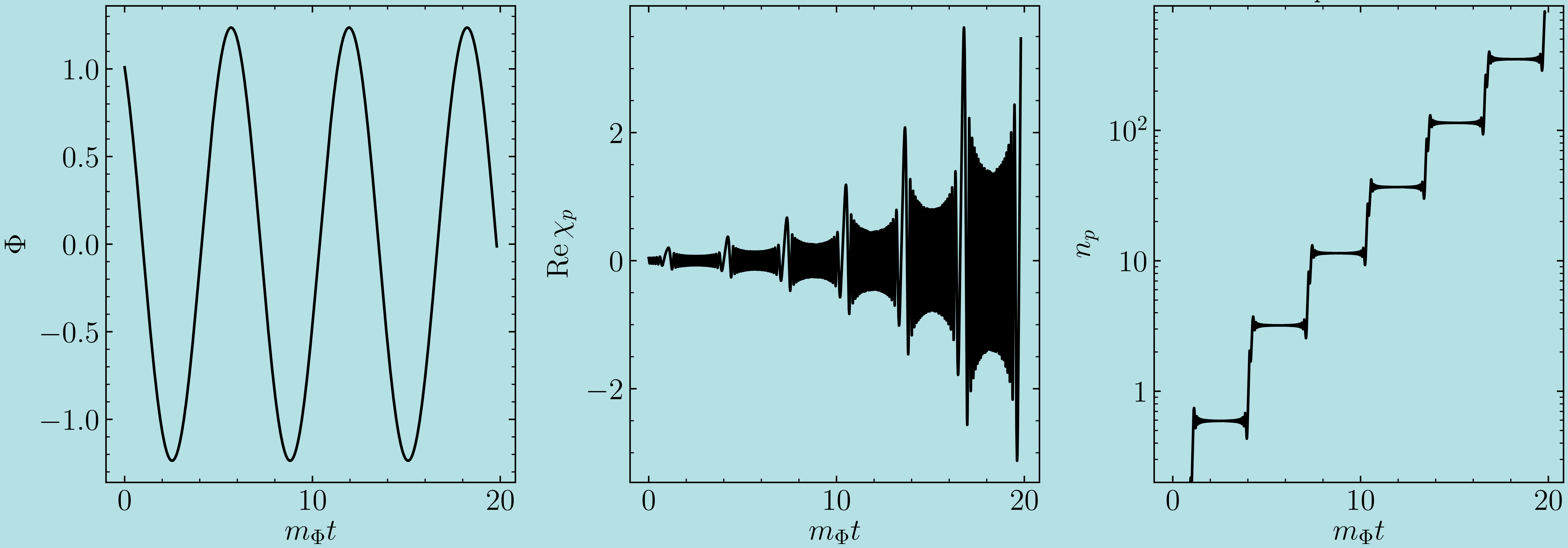
Scalar (p)reheating

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

Neglecting expansion,

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



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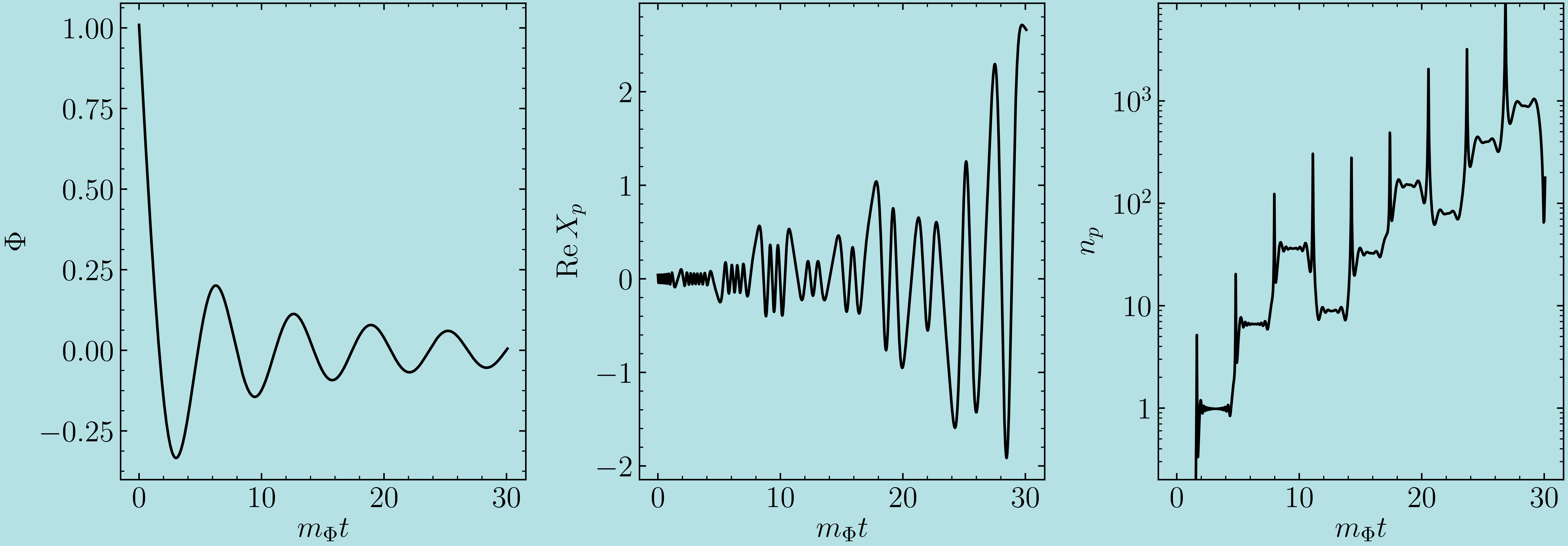
With expansion,

$X = a\chi$

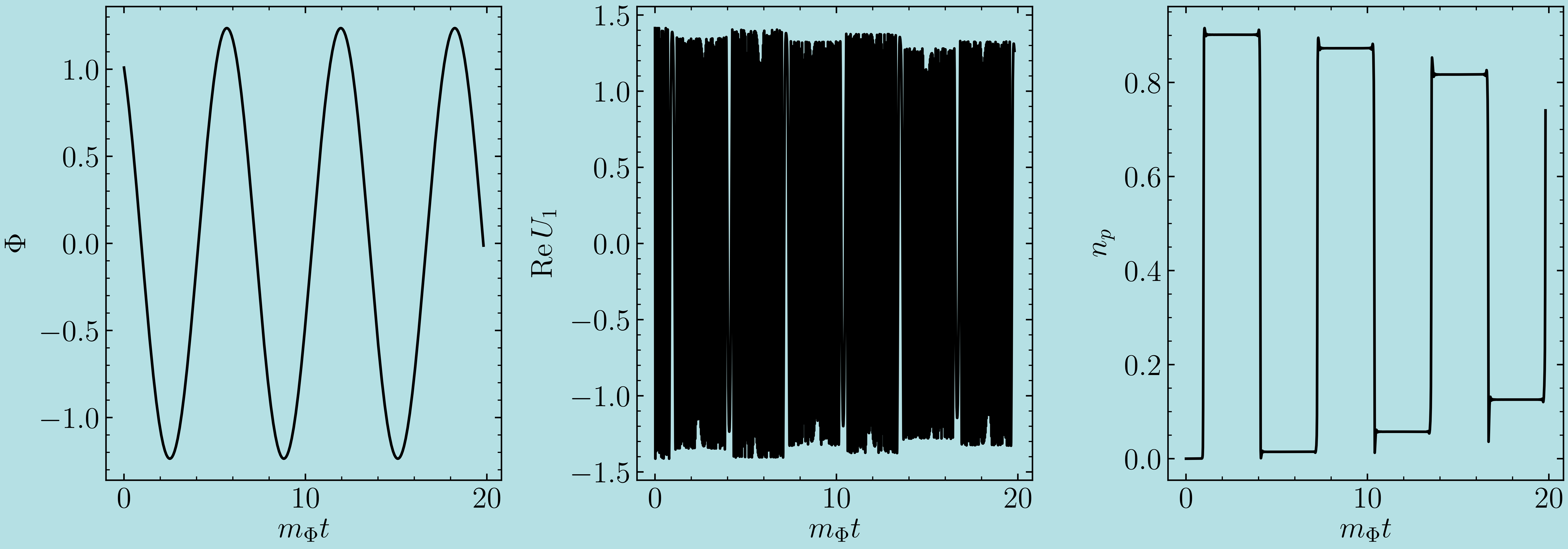
$$n_p = \frac{1}{2\omega_p}|\omega_p\chi_p - i\chi'|^2$$



Fermion (p)reheating

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

Neglecting expansion,*



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Neglecting expansion,*

*$dt/d\tau = a$ and

$$\psi(\tau,\mathbf{x}) \;=\; a^{-3/2}\sum_{r=\pm}\int\frac{d^3\boldsymbol{p}}{(2\pi)^{3/2}}\,e^{-i\boldsymbol{p}\cdot\boldsymbol{x}}\left[u_p^{(r)}(\tau)\,\hat{a}_{\boldsymbol{p}}^{(r)} + v_p^{(r)}(\tau)\,\hat{b}_{-\boldsymbol{p}}^{(r)\,\dagger}\right]$$

with

$$u_p^{(r)}(\tau) \;=\; \begin{pmatrix} U_1(\tau)\xi_r(\boldsymbol{p}) \\ U_2(\tau)\frac{\boldsymbol{\sigma}\cdot\boldsymbol{p}}{p}\xi_r(\boldsymbol{p}) \end{pmatrix}$$

Fermion (p)reheating

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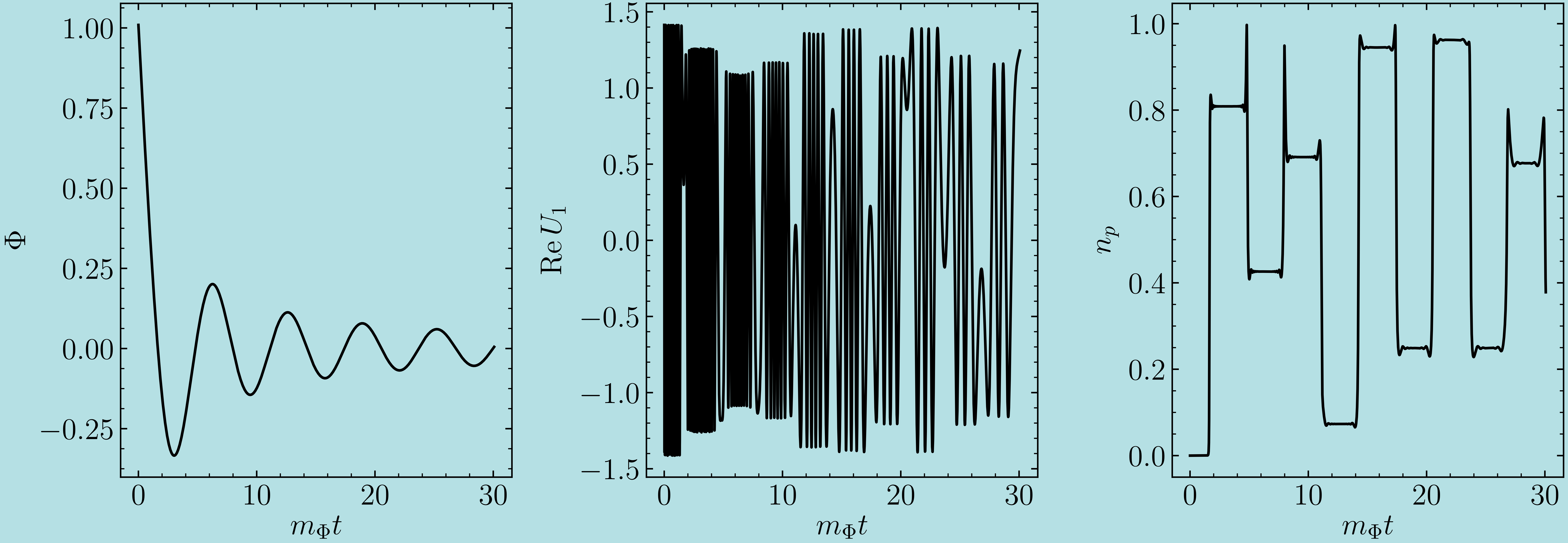
With expansion,



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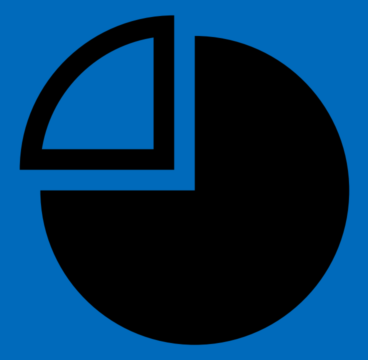

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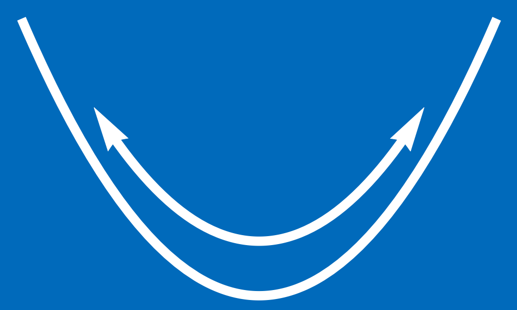

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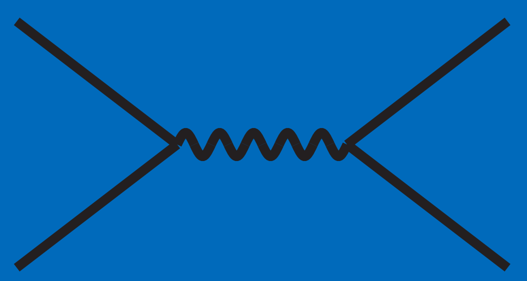

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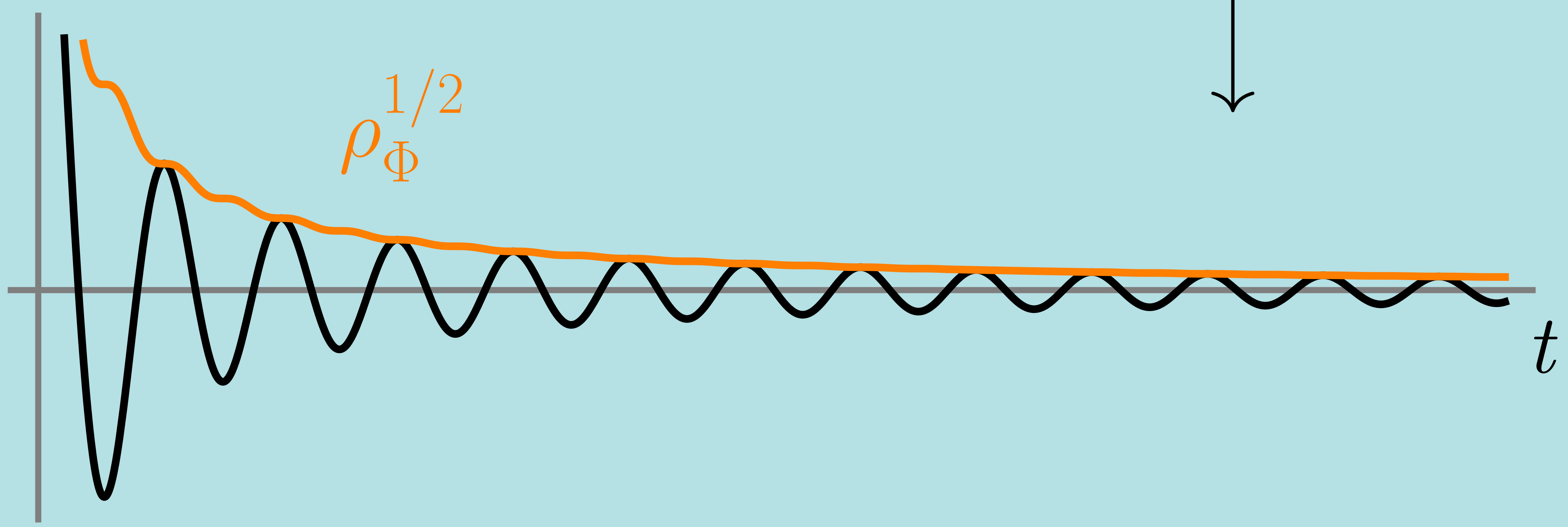
The perturbative (dissipative) picture

Reheating as the exchange of energy between two ideal fluids

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

$$\downarrow$$



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

(matter)

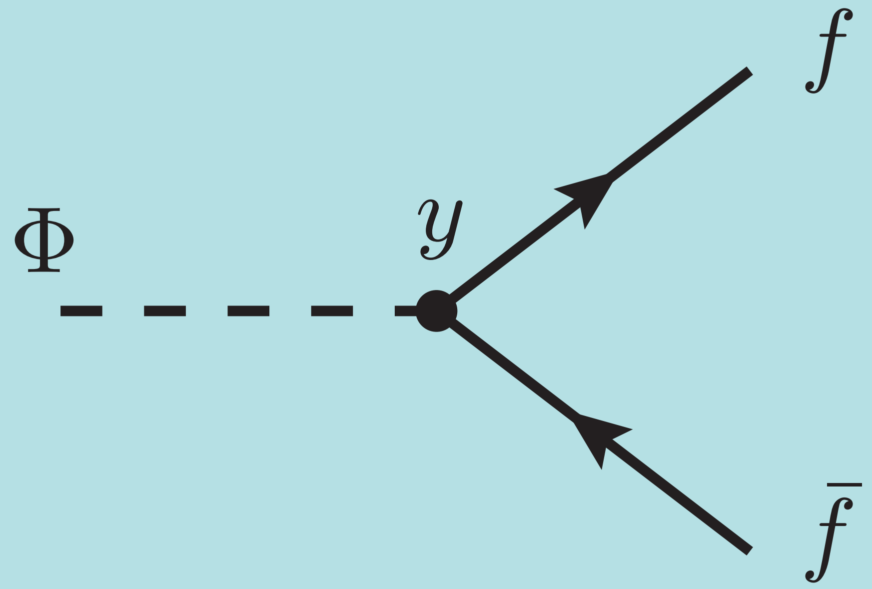
The perturbative (dissipative) picture

Reheating as the exchange of energy between two ideal fluids

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

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

$$\dot\rho_R + 4H\rho_R = -(\dot\rho_\Phi + 3H\rho_\Phi) \equiv \Gamma_\Phi \rho_\Phi$$

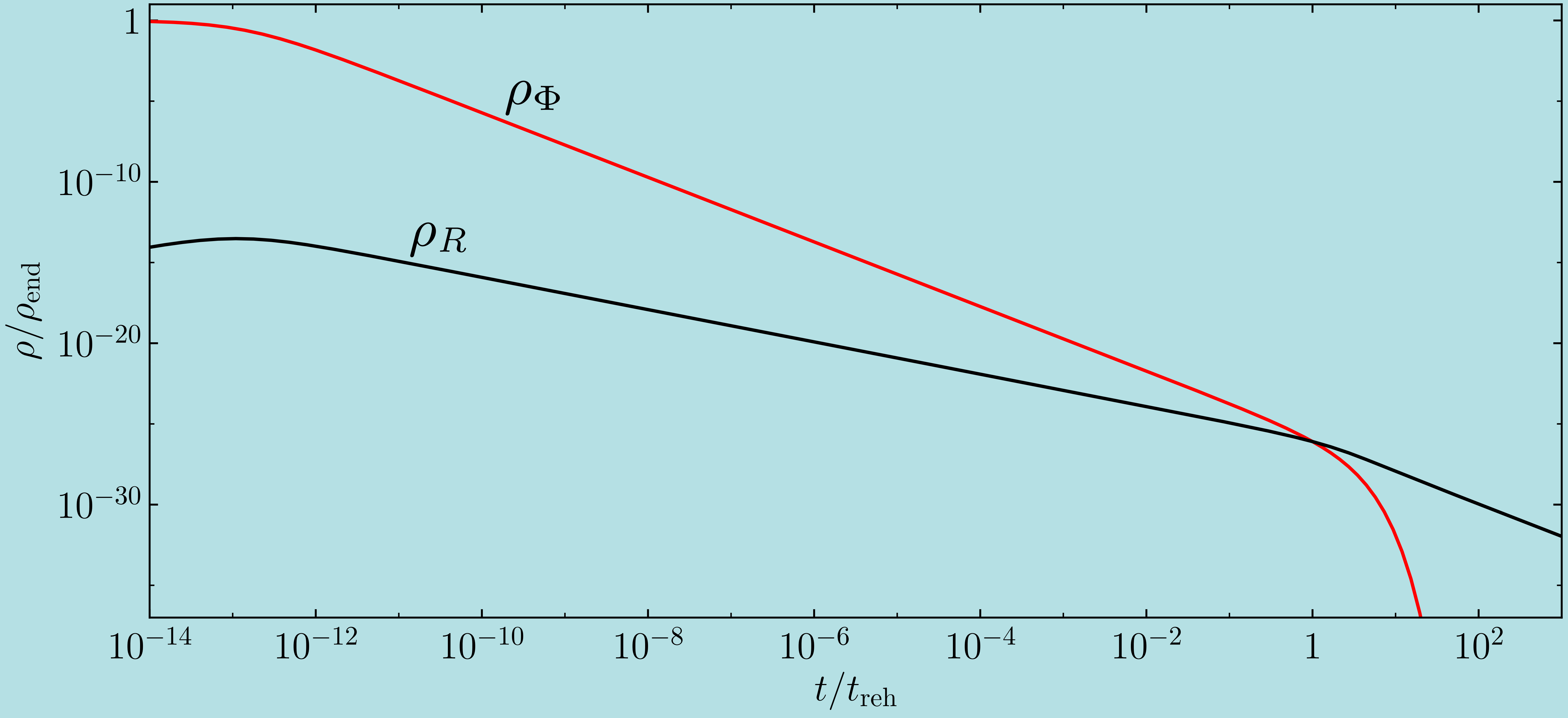


$$\Gamma_\Phi = \frac{y^2}{8\pi} m_\Phi$$

The perturbative (dissipative) picture

Reheating as the exchange of energy between two ideal fluids

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



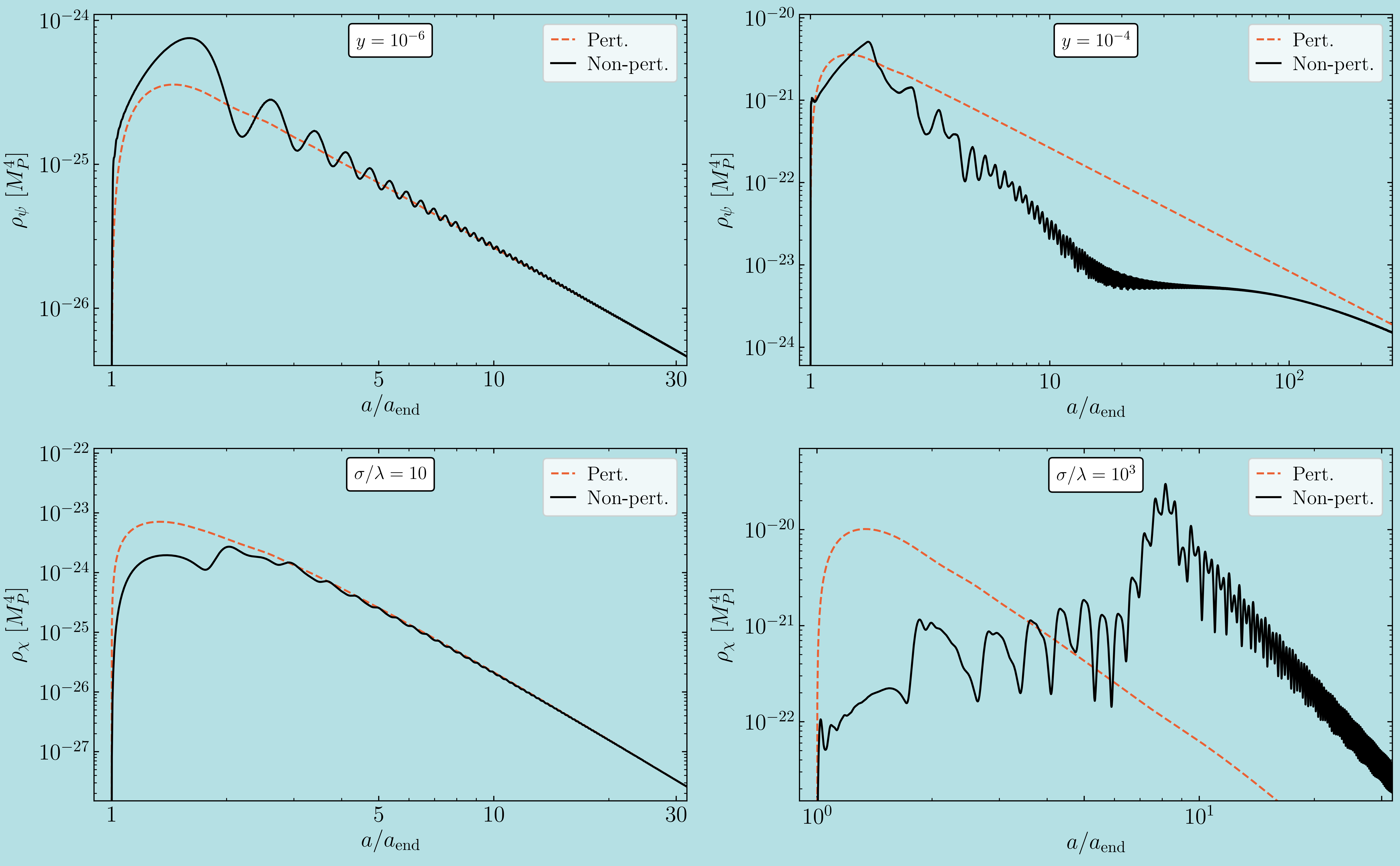
1. Beyond WIMPs

2. Inflation & reheating

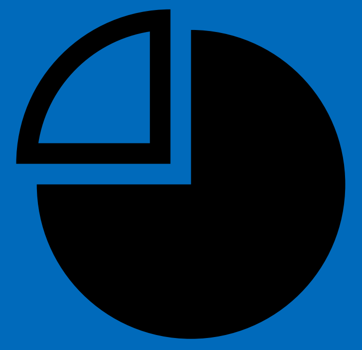
3. FIMPs

4. Compact objects

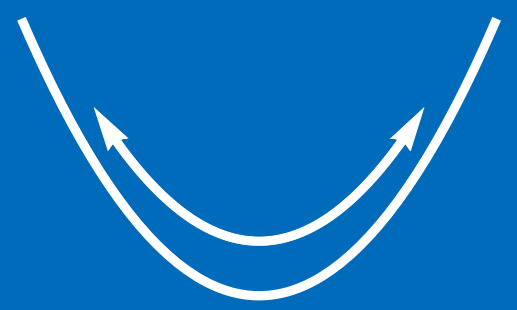
5. Prospects



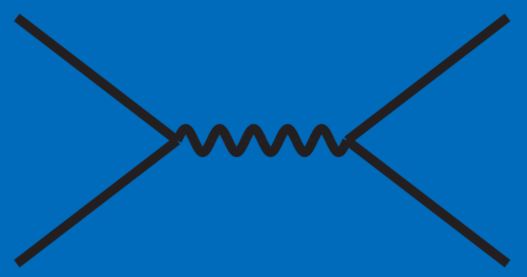
1. Beyond WIMPs



2. Inflation & reheating

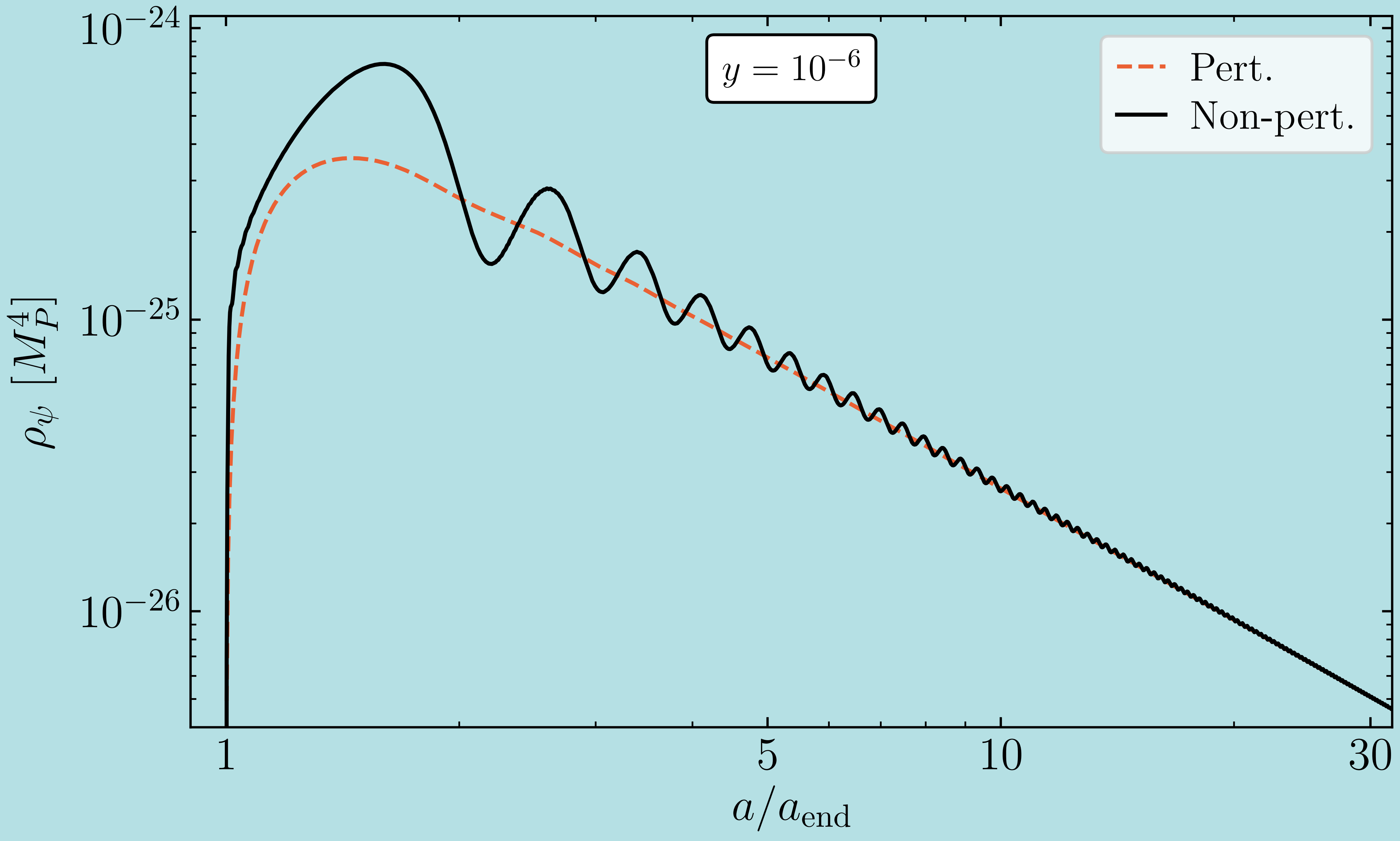


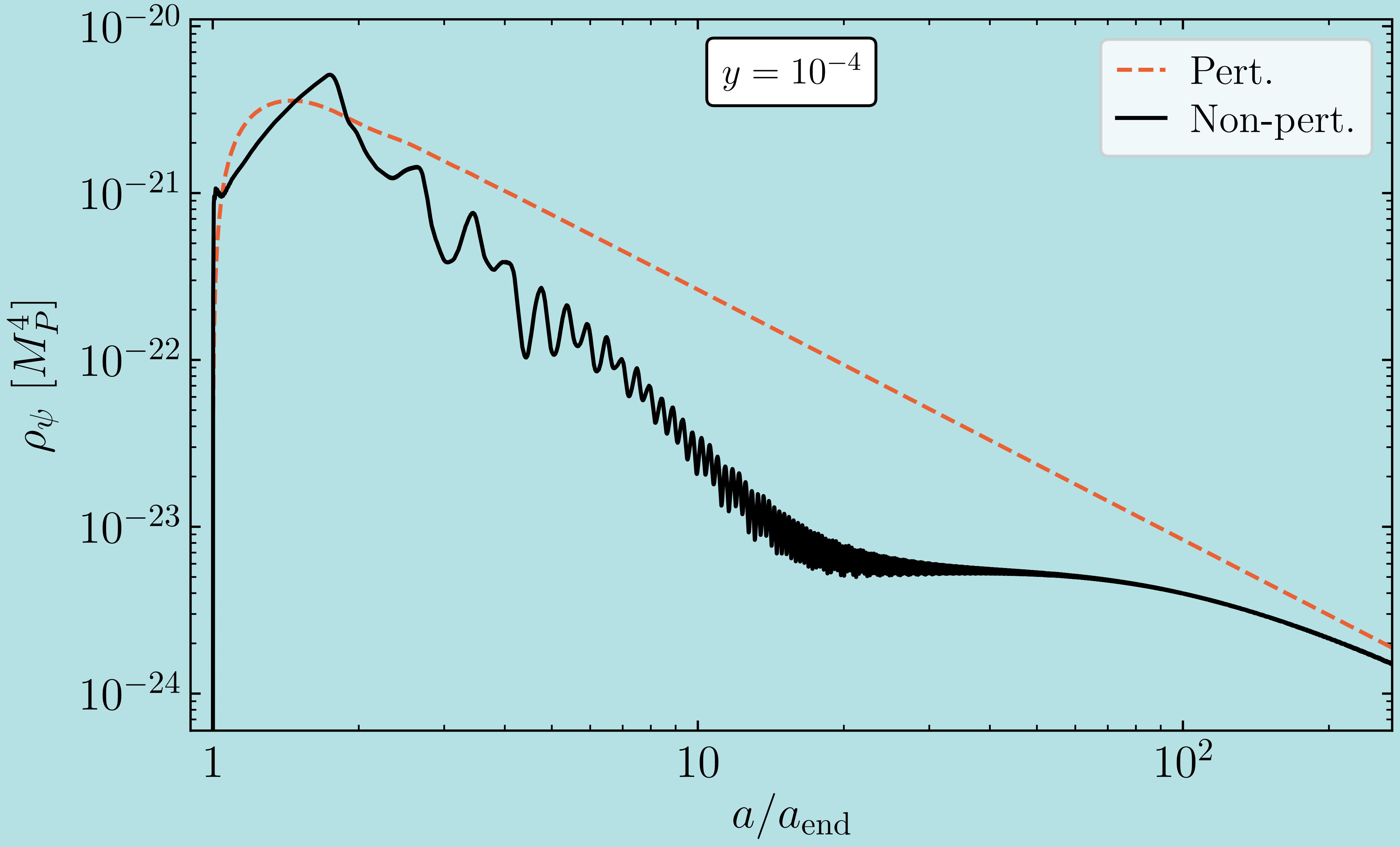
3. FIMPs



4. Compact objects

5. Prospects





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

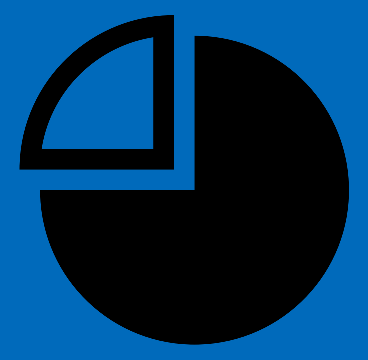
↓

interactions (thermalization)

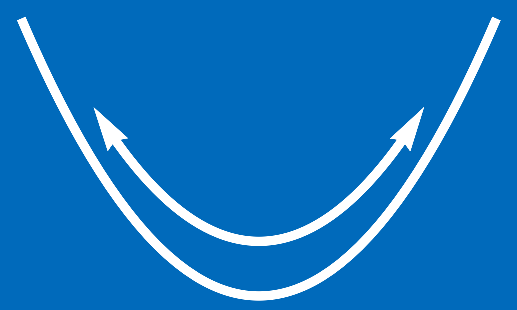
↓

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

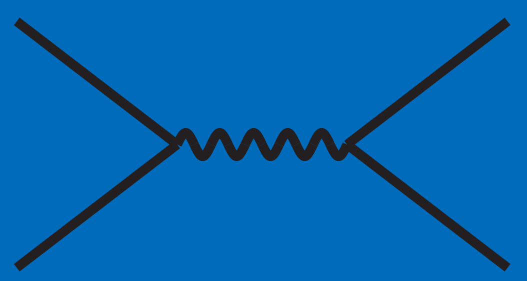
1. Beyond WIMPs



2. Inflation & reheating

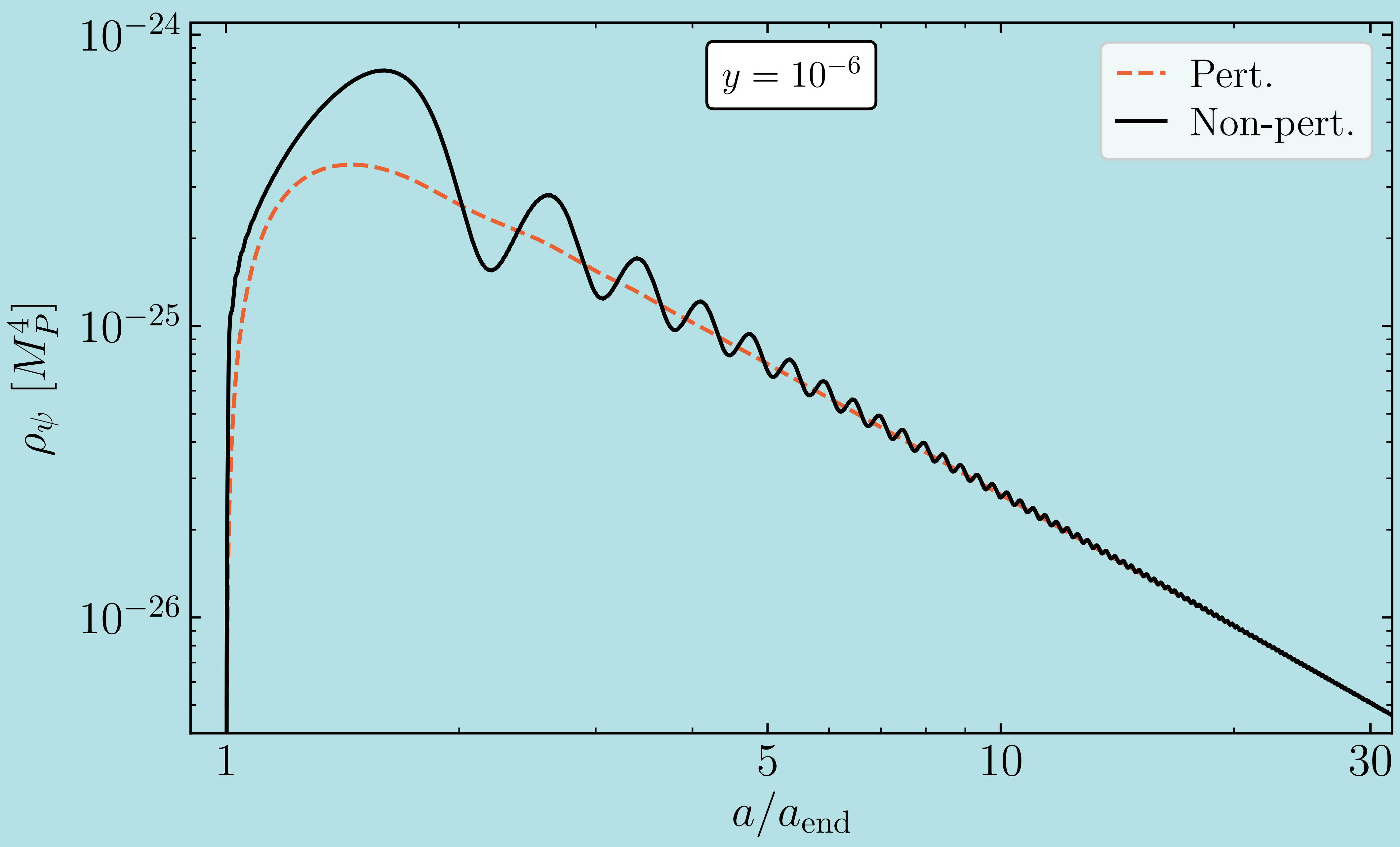


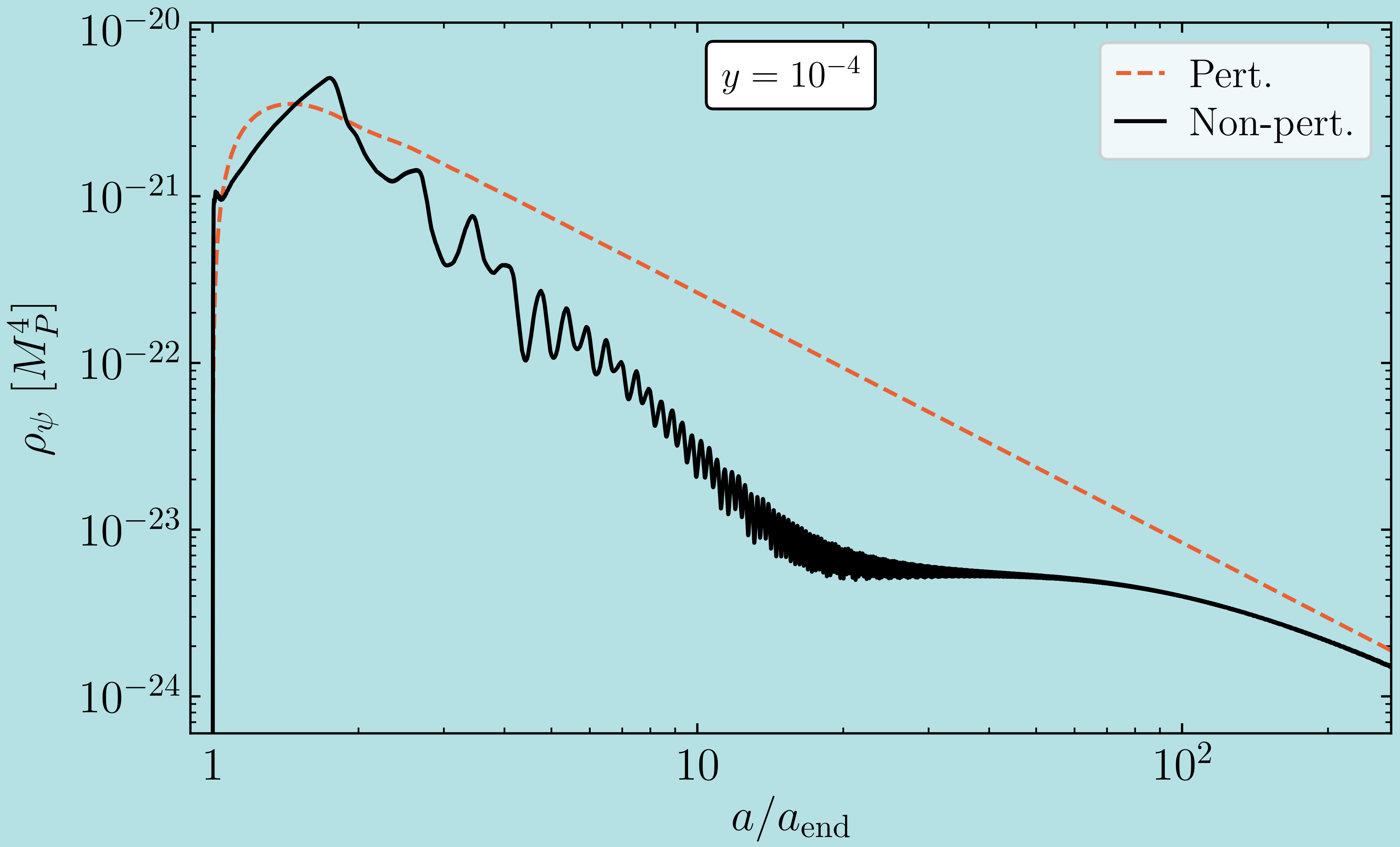
3. FIMPs



4. Compact objects

5. Prospects





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

↓

Schiwnger-Keldysh / Kadanoff-Baym

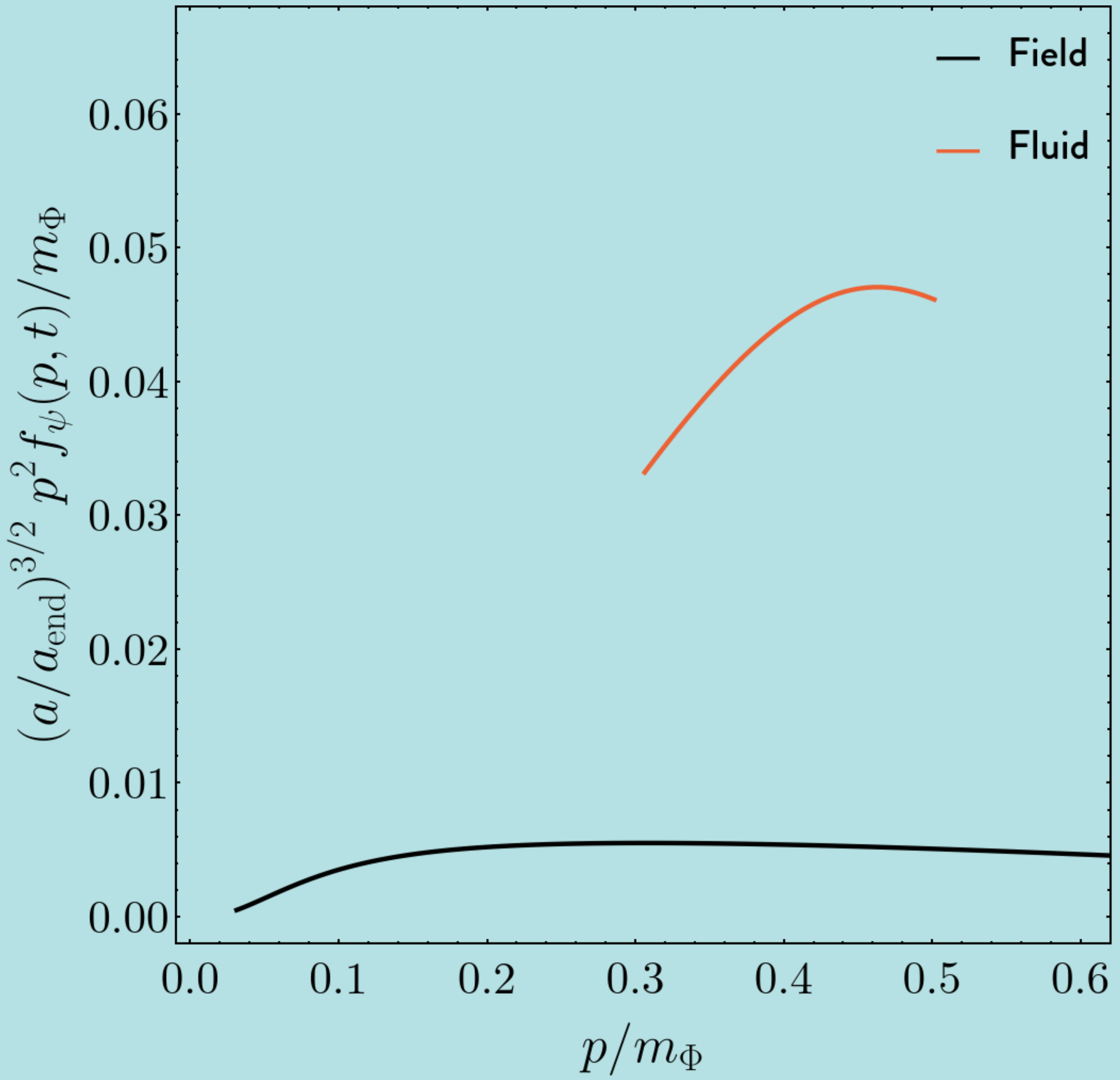
Boltzmann

↓

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

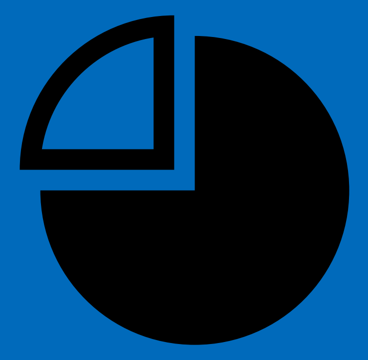
The phase space distribution

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

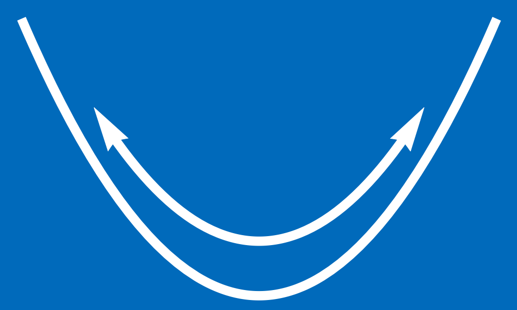


$$\frac{\partial f_\psi}{\partial t} - H|\boldsymbol{p}|\frac{\partial f_\psi}{\partial |\boldsymbol{p}|} = \frac{1}{2p_0}\int d\Pi \, |\mathcal{M}|^2_{\Phi\to\bar\psi\psi}\, n_\Phi \delta^{(3)}(\boldsymbol{P}) + \mathcal{C}^{\rm int}[f_\psi]$$

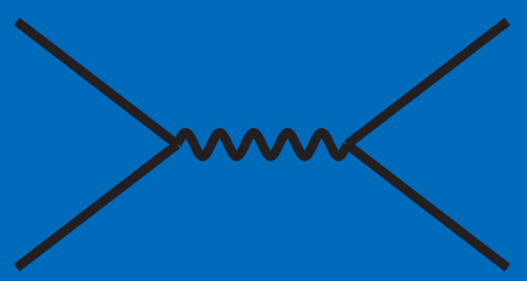
1. Beyond WIMPs



2. Inflation & reheating



3. FIMPs

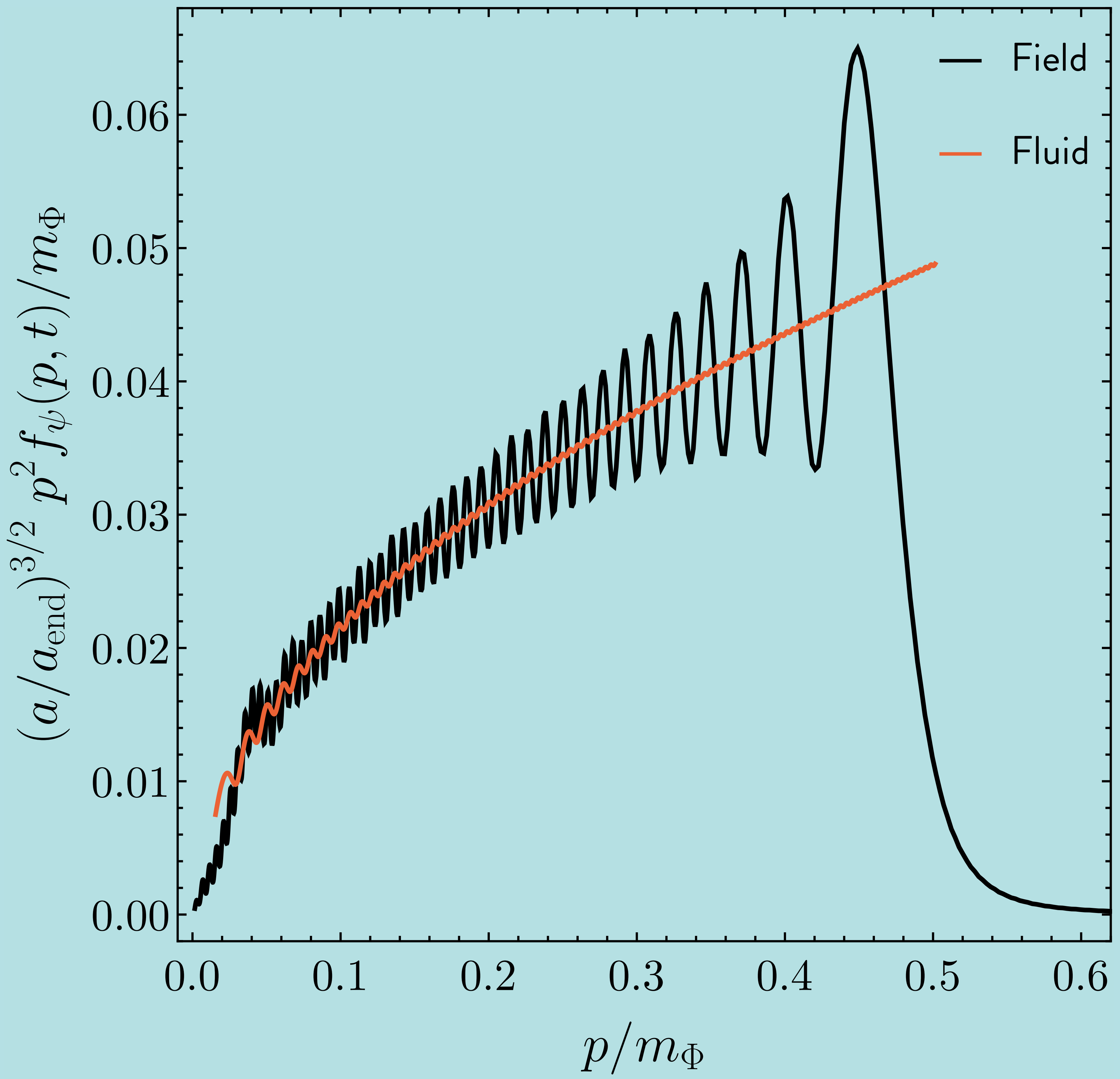


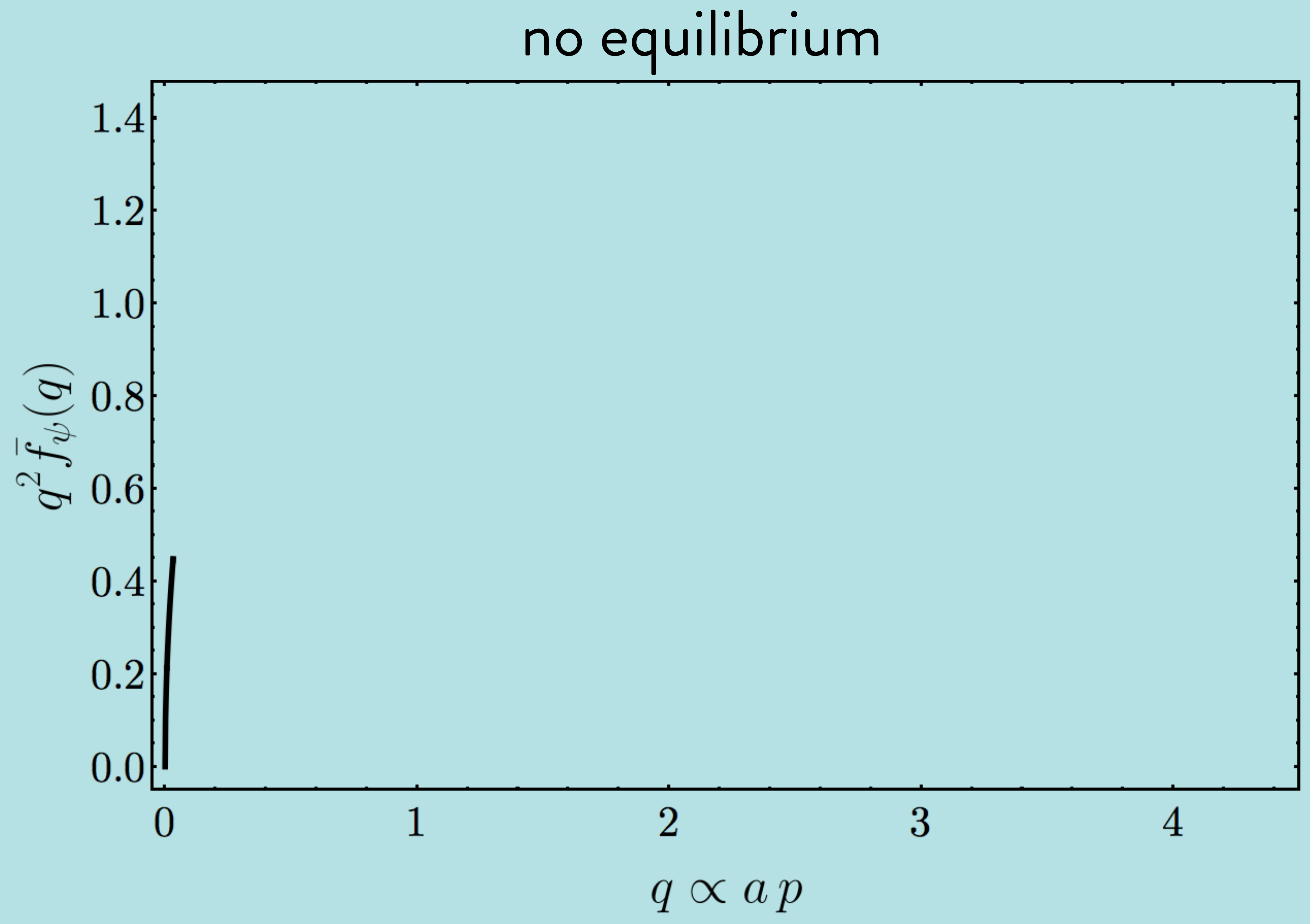
4. Compact objects

5. Prospects

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

1. Beyond WIMPs

2. Inflation & reheating

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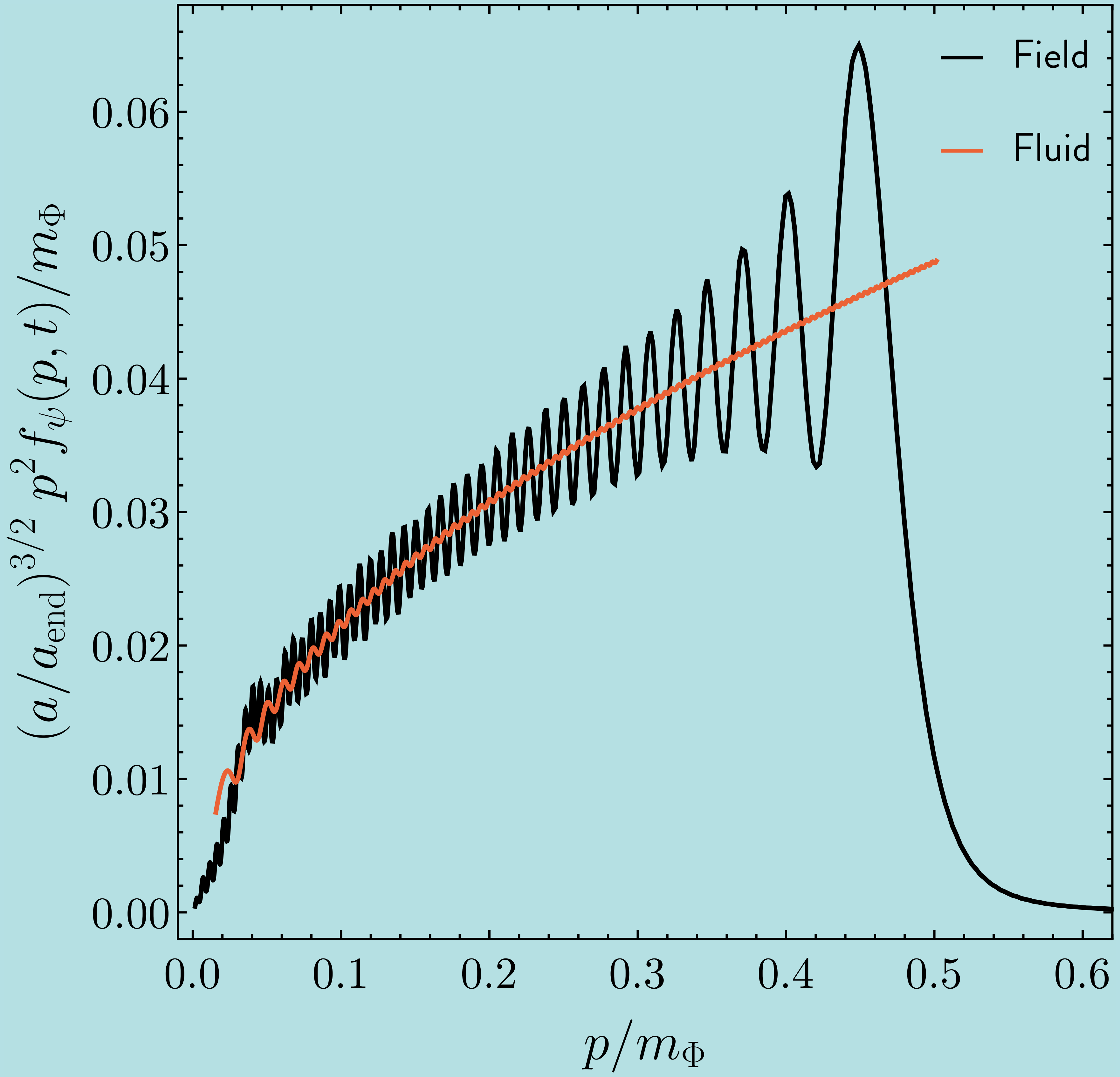
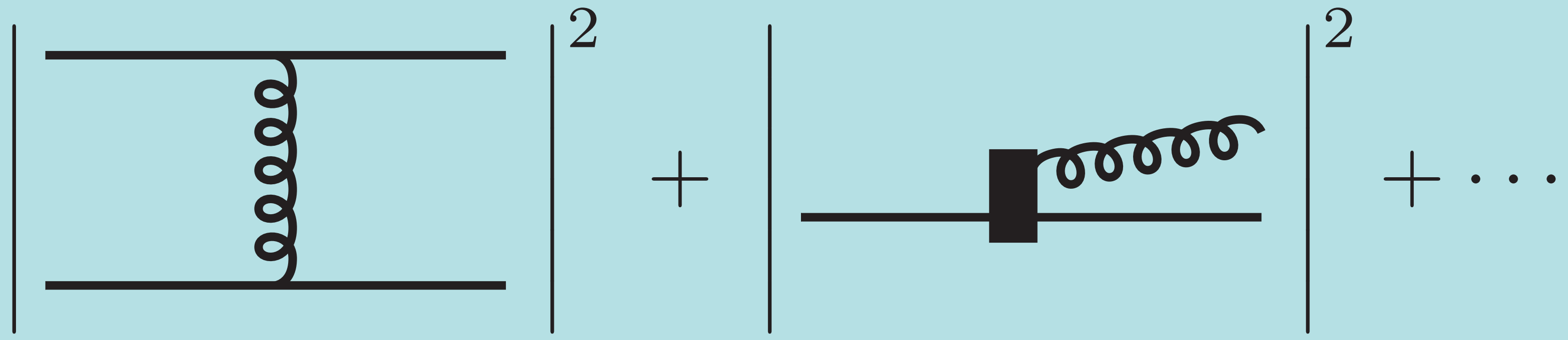
The phase space distribution

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

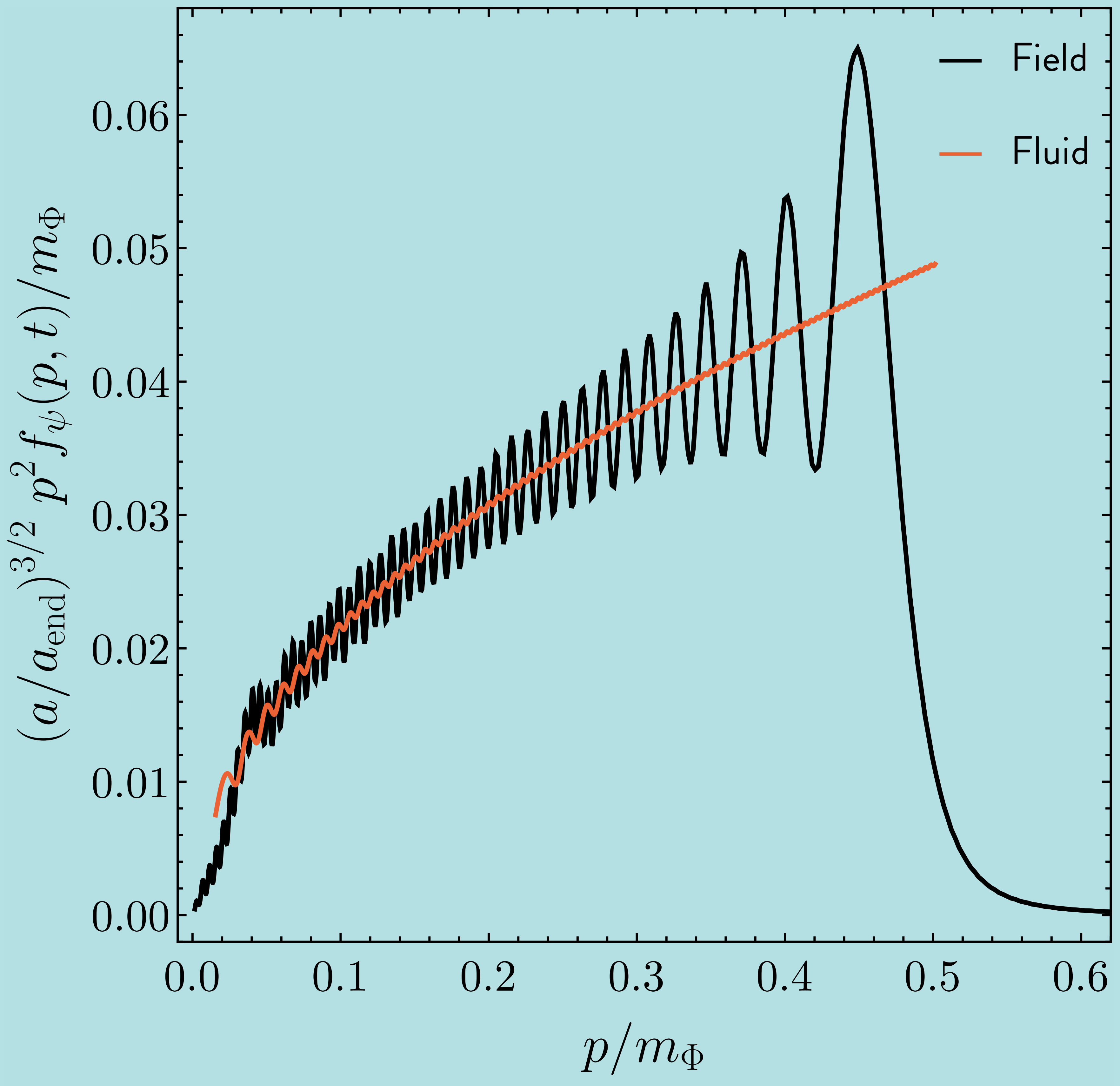


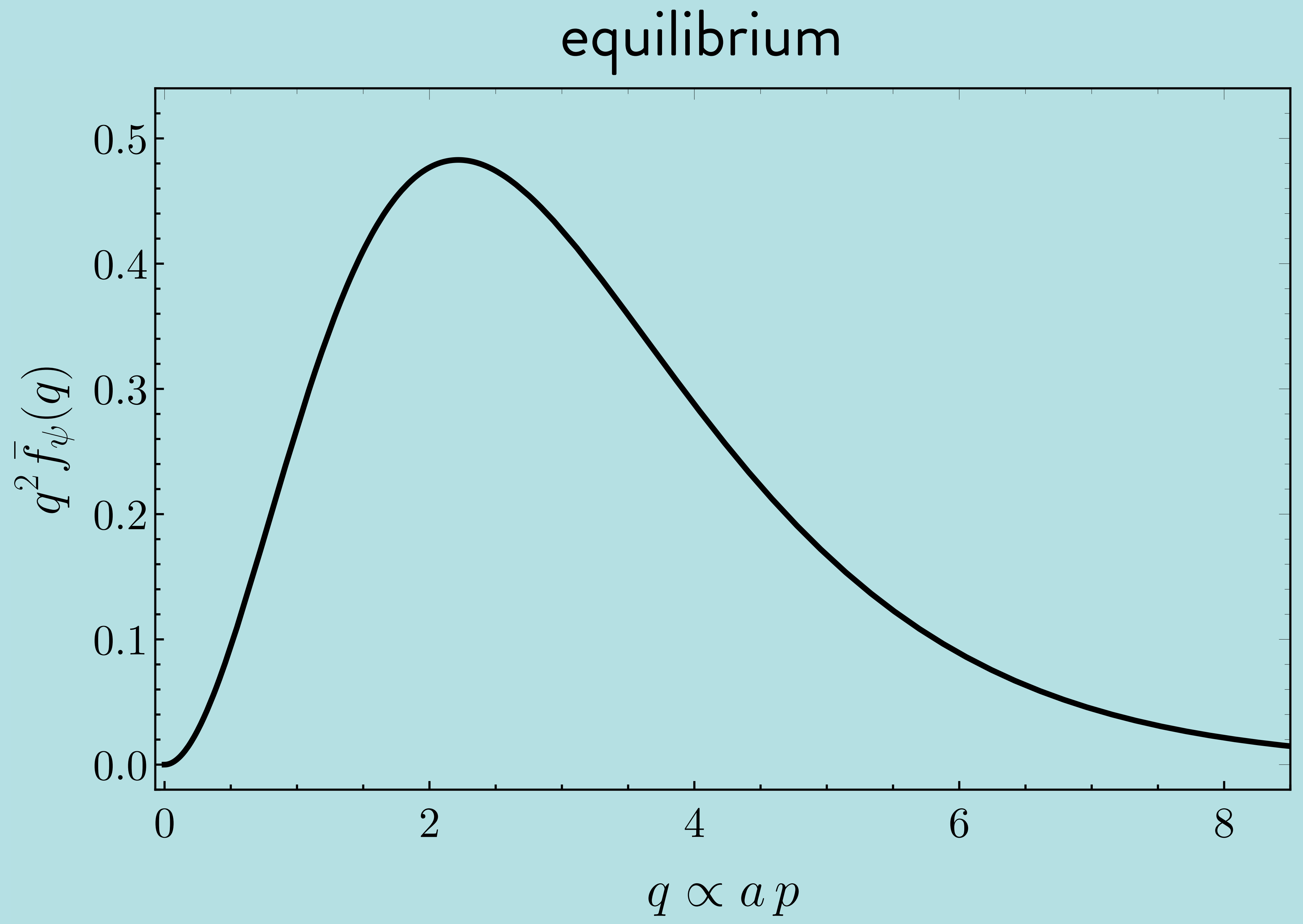
$\mathcal{C}^{\rm int}[f_\psi] =$ 

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

The phase space distribution

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





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

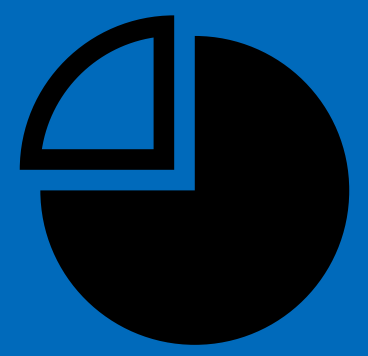
Is a spin-$\frac{3}{2}$ dark matter particle the missing piece in the puzzle?

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

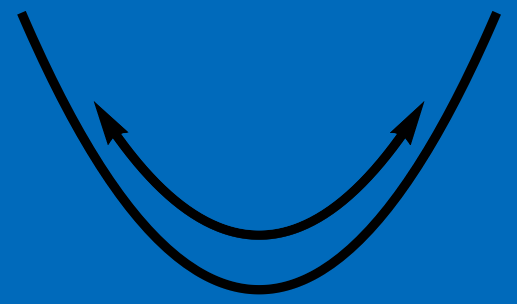
$$\mathcal{L} = -\frac{1}{2}\bar{\Psi}_\mu \left(i\gamma^{[\mu}\gamma^{\nu}\gamma^{\rho]}\partial_\rho + m_{3/2}\gamma^{[\mu}\gamma^{\nu]}\right)\Psi_\nu$$

(Rarita-Schwinger)

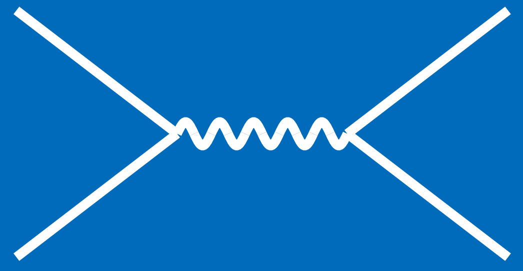
1. Beyond WIMPs



2. Inflation & reheating



3. FIMPs



4. Compact objects

5. Prospects

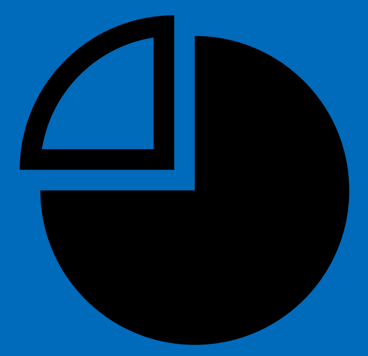
Is a spin-$\frac{3}{2}$ dark matter particle the missing piece in the puzzle?

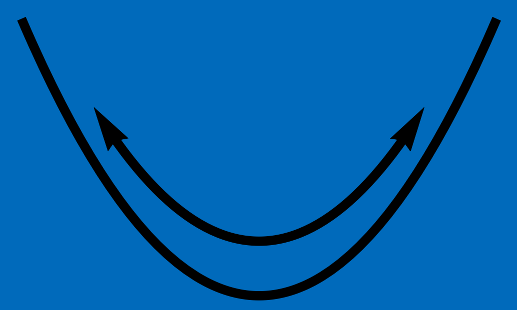
	spin 0	spin 1/2	spin 1	spin 3/2	spin 2
SM+DM:	H	u_L	W^0	Ψ	G
				raritron	
	Φ	ν_R			
	inflaton	R-neutrino			

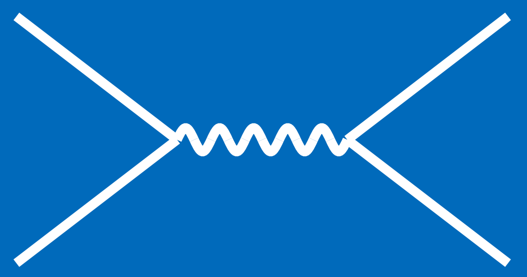
$$\mathcal{L} \;=\; -\tfrac{1}{2}\bar{\Psi}_\mu \left(i\gamma^{[\mu}\gamma^{\nu}\gamma^{\rho]}\partial_\rho + m_{3/2}\gamma^{[\mu}\gamma^{\nu]}\right)\Psi_\nu$$

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

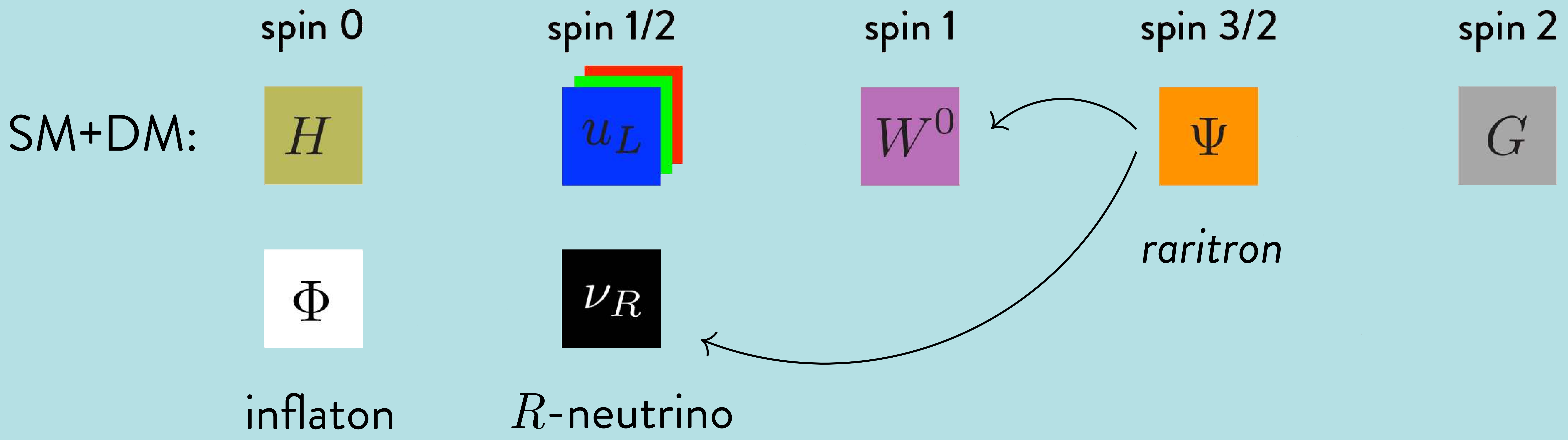
$$+\, y_\nu \Phi\bar{\nu}_R\nu_R \qquad \text{(reheating)}$$







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



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

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			

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

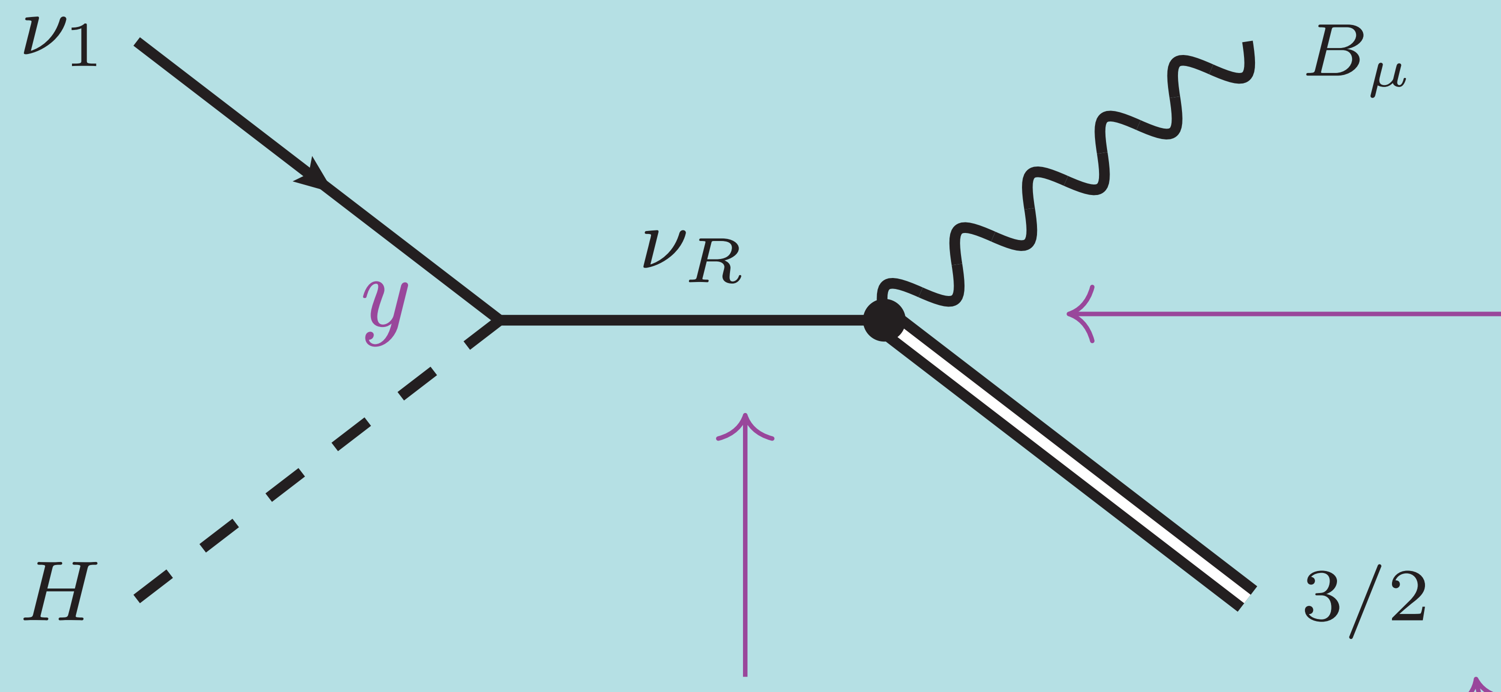
MG, Y. Mambrini, K. A. Olive and S. Verner, PRD 102 (2020), 083533

Scatterings and decays

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

$E_{\mathrm{CM}} = \sqrt{s} \rightarrow$

$E_{\mathrm{CM}} = \sqrt{s} \rightarrow$



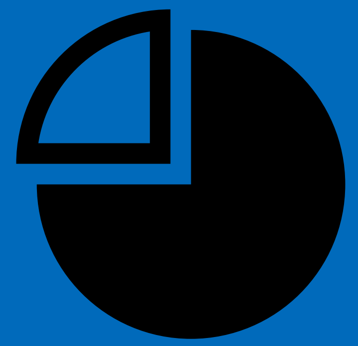
$\leftarrow \dfrac{\alpha_1}{M_P}$

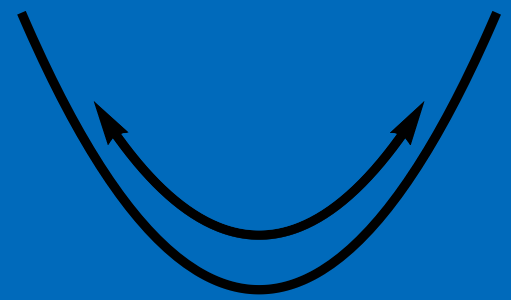
$$\frac{i}{s-M_R^2} \approx -\frac{i}{M_R^2}$$

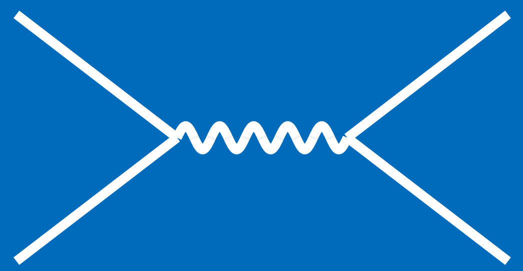
$$\Psi_\mu \sim i\sqrt{\frac{2}{3}}\frac{\partial_\mu\Psi}{m_{3/2}}$$

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

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

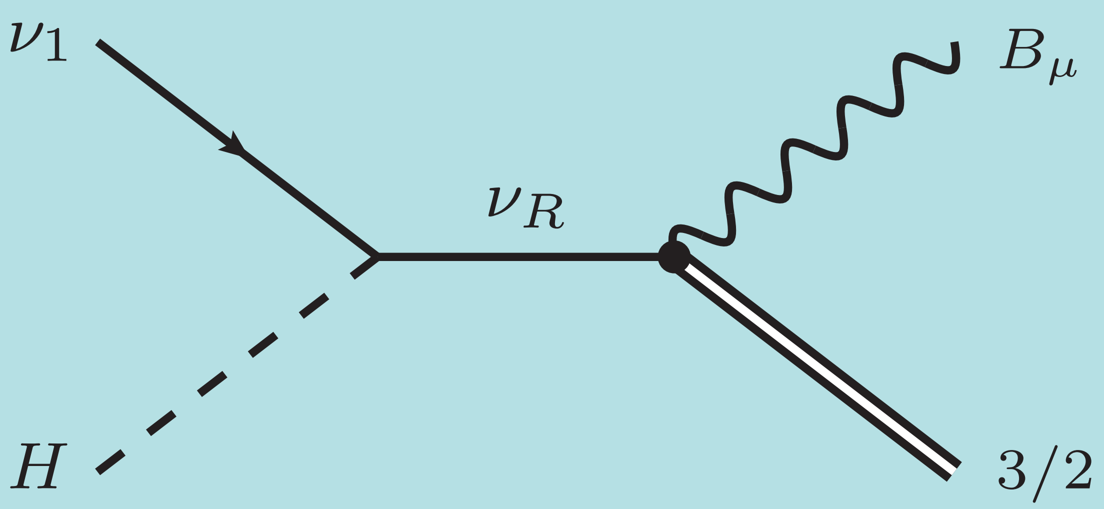




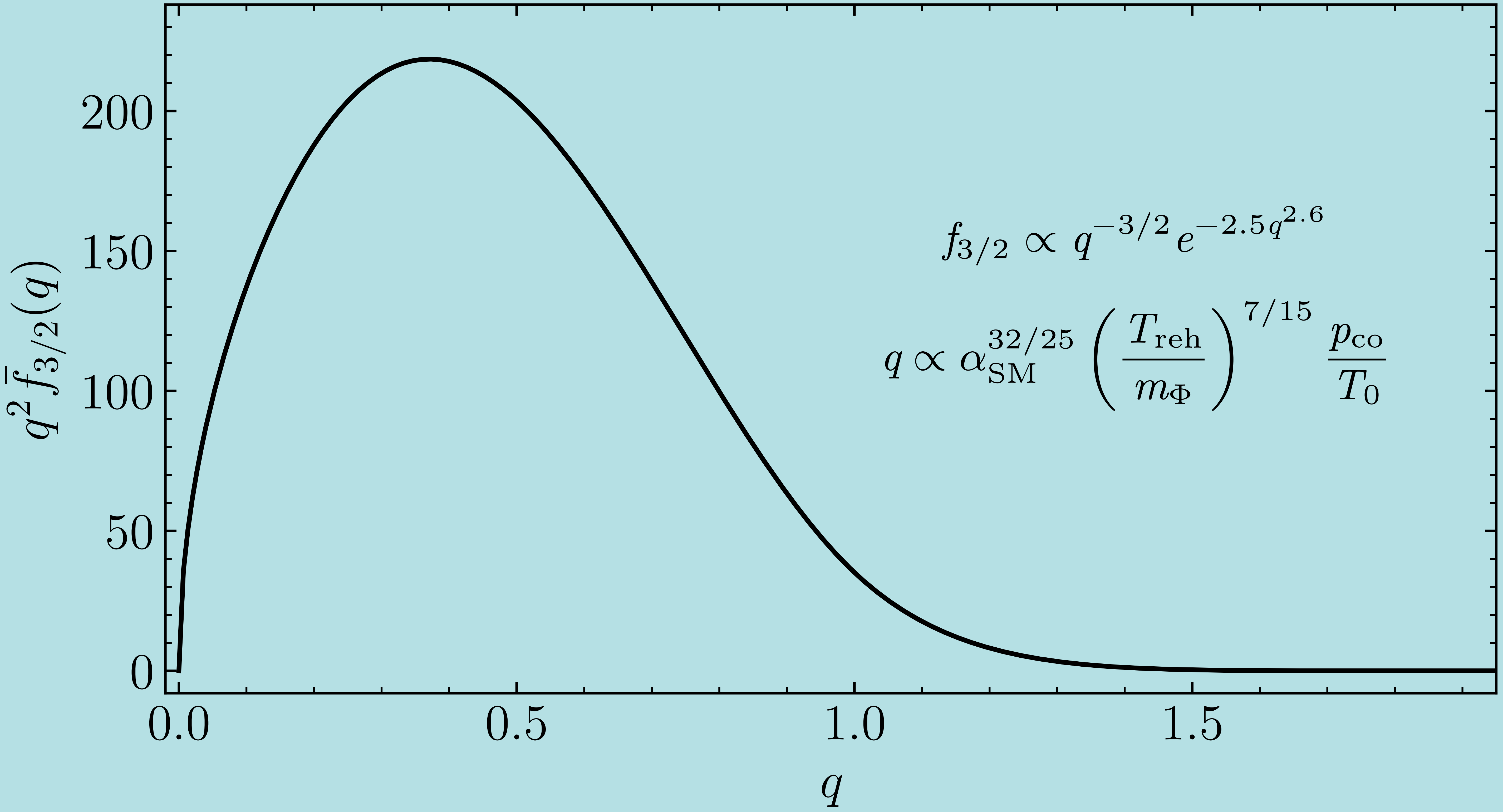


Scatterings and decays

not equilibrated

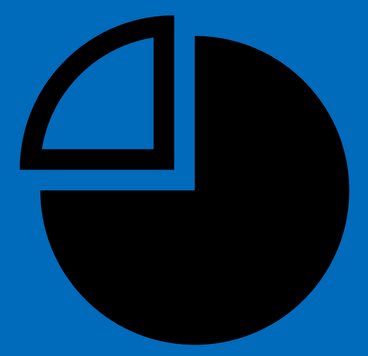


$$\Omega_{3/2} \propto \alpha_1 \frac{m_\nu m_\Phi^2 T_{\rm reh}^3}{m_{3/2} M_R\, t_{\rm therm}}$$

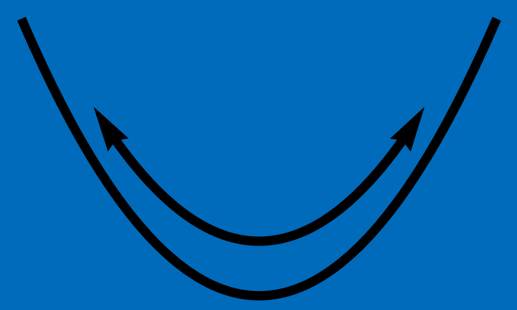


MG and M. A. Amin, PRD 98 (2018), 103504; G. Ballesteros, MG and M. Pierre, JCAP 03 (2021), 101

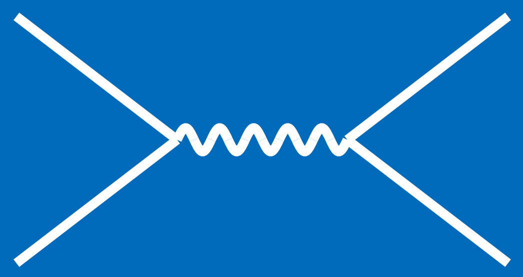
1. Beyond WIMPs



2. Inflation & reheating



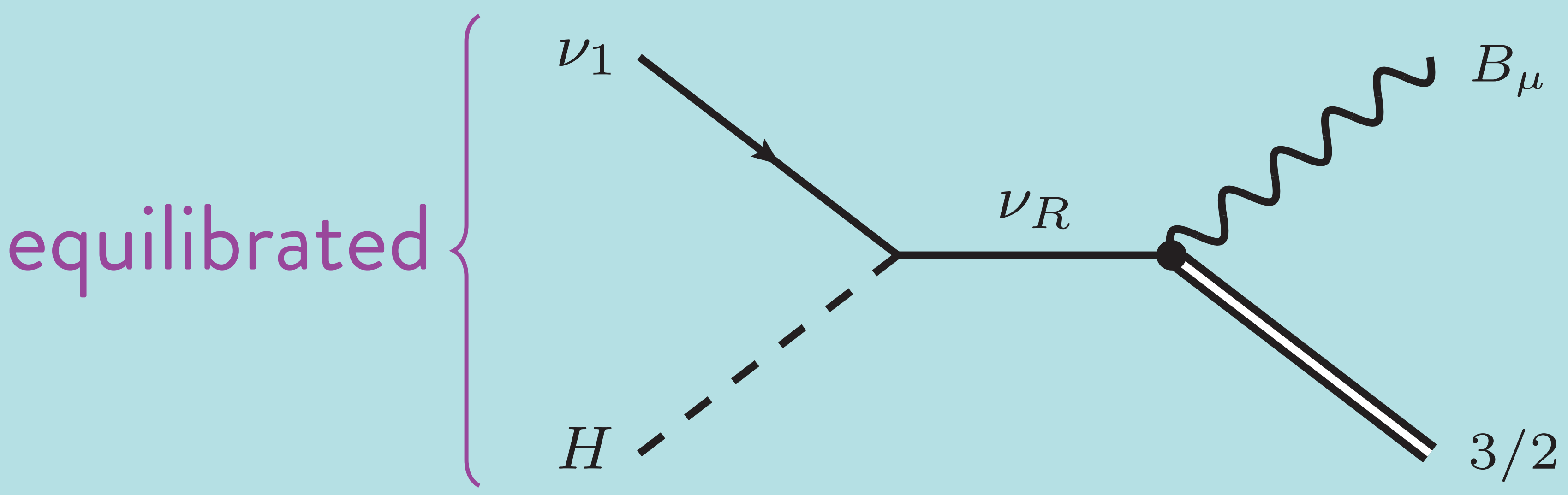
3. FIMPs



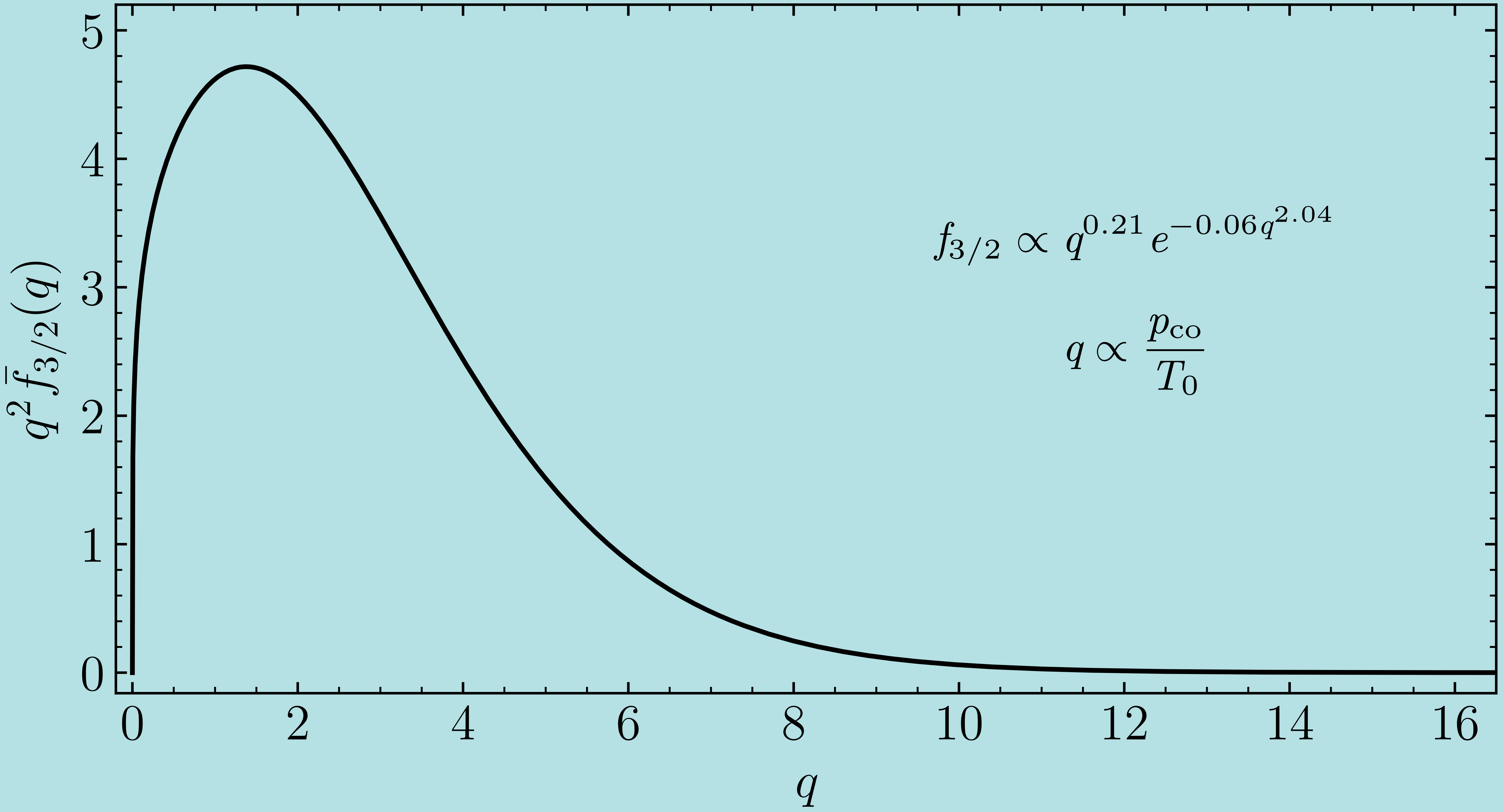
4. Compact objects

5. Prospects

Scatterings and decays



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



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

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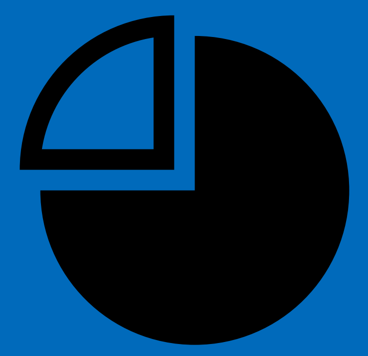

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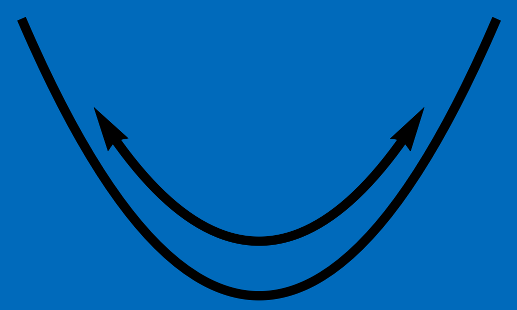

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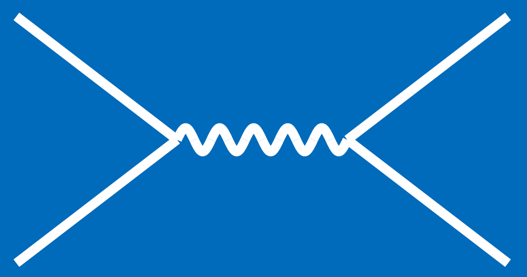
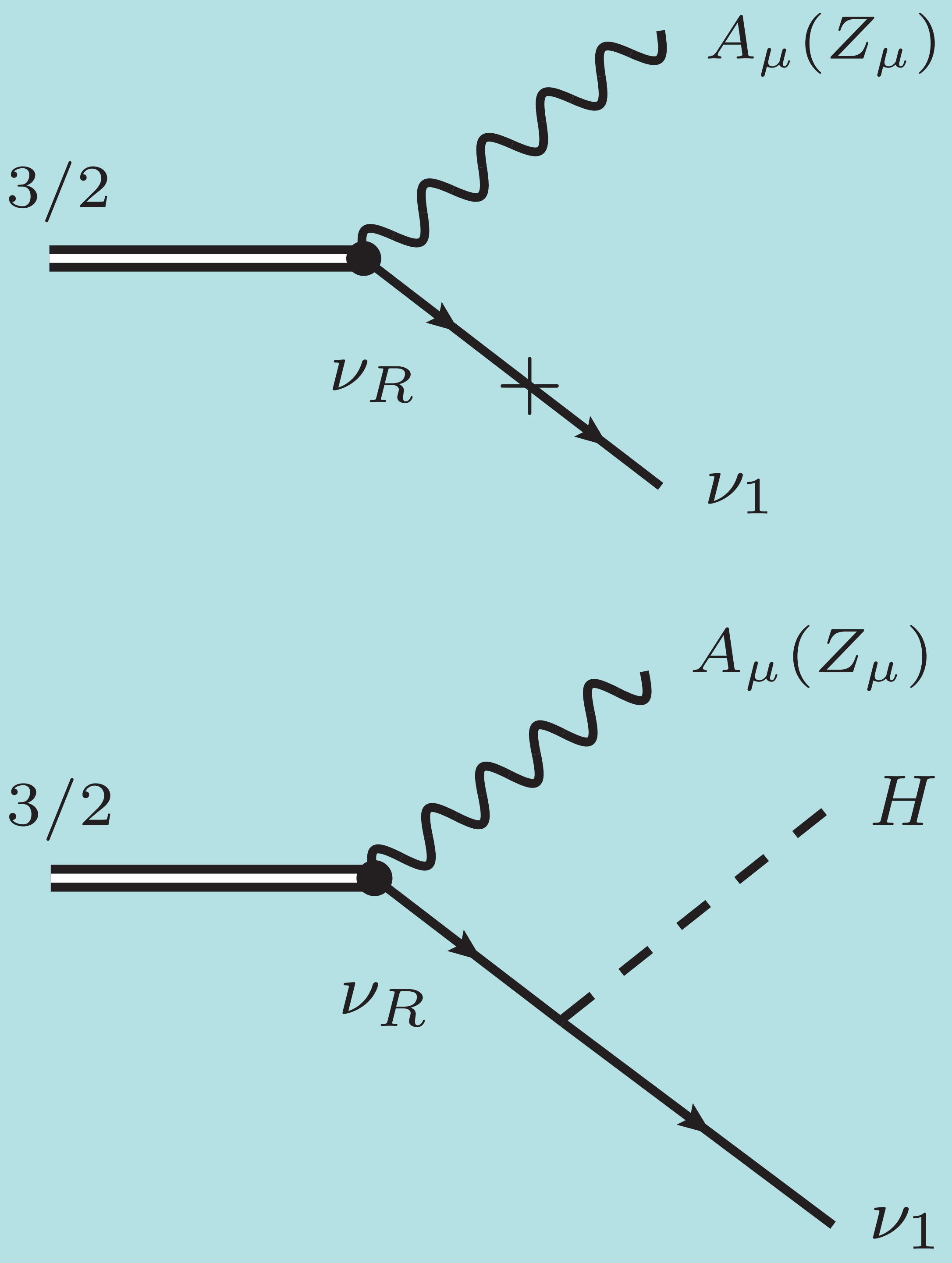


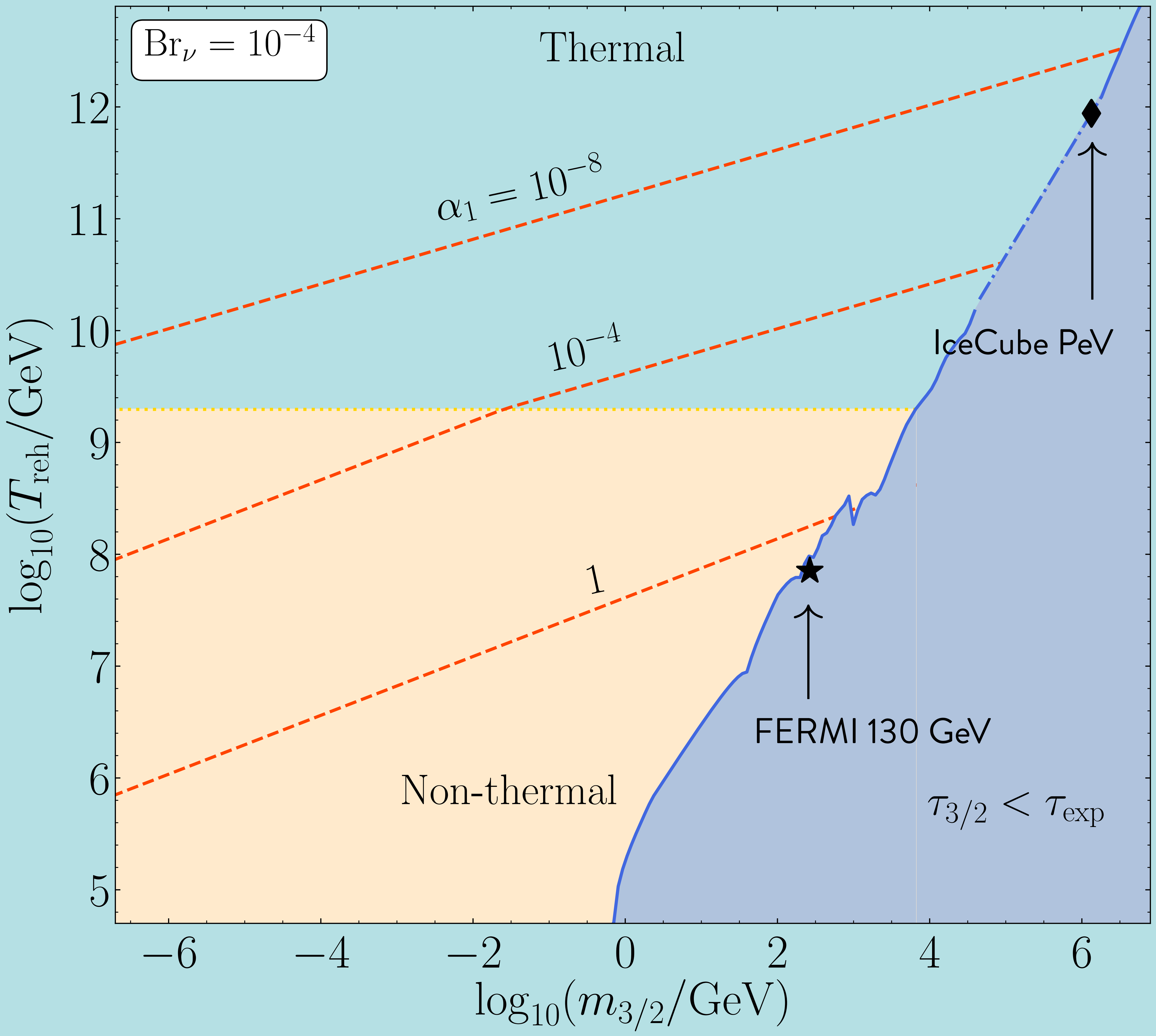
4. Compact objects

5. Prospects

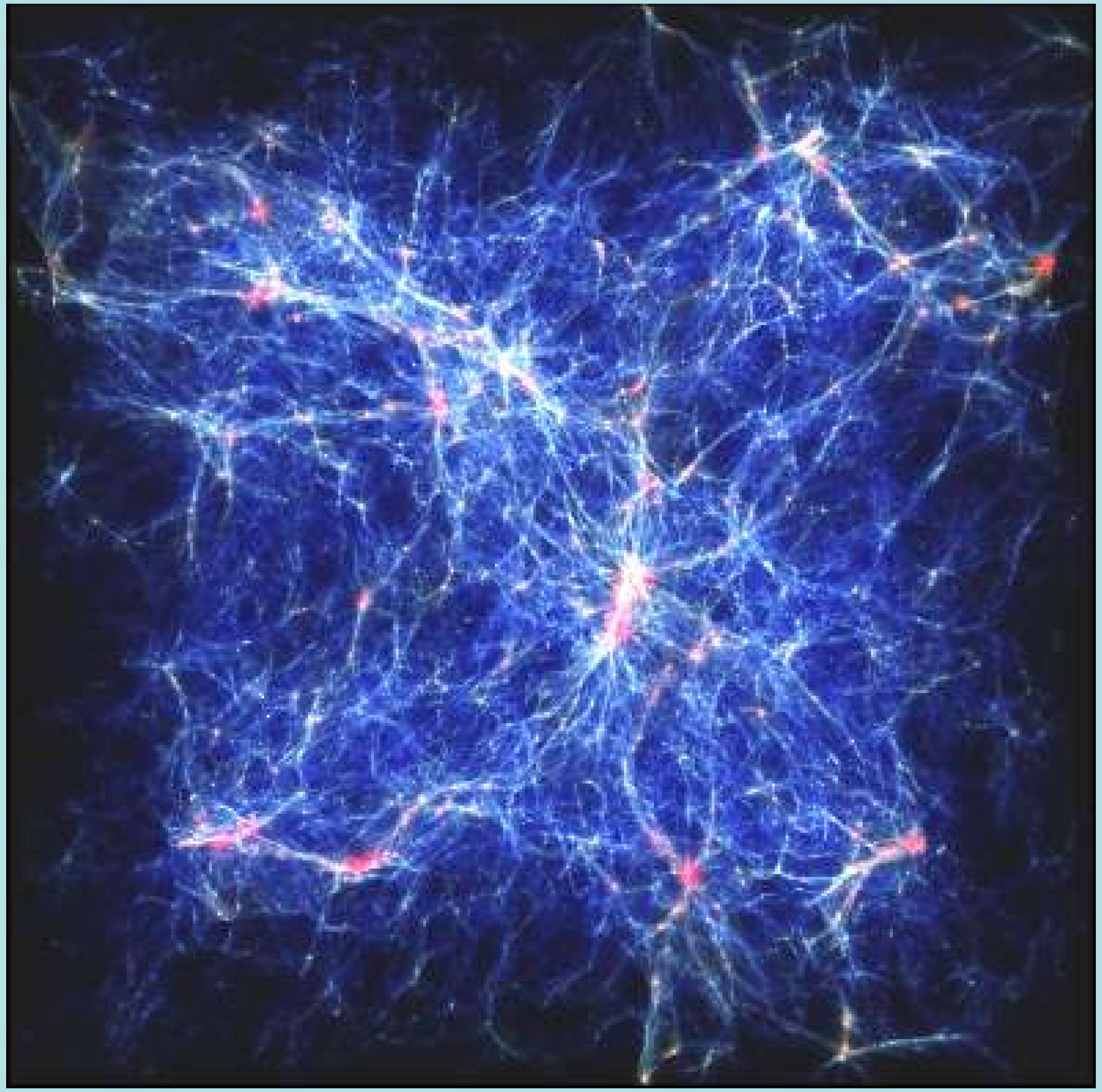
Scatterings and decays



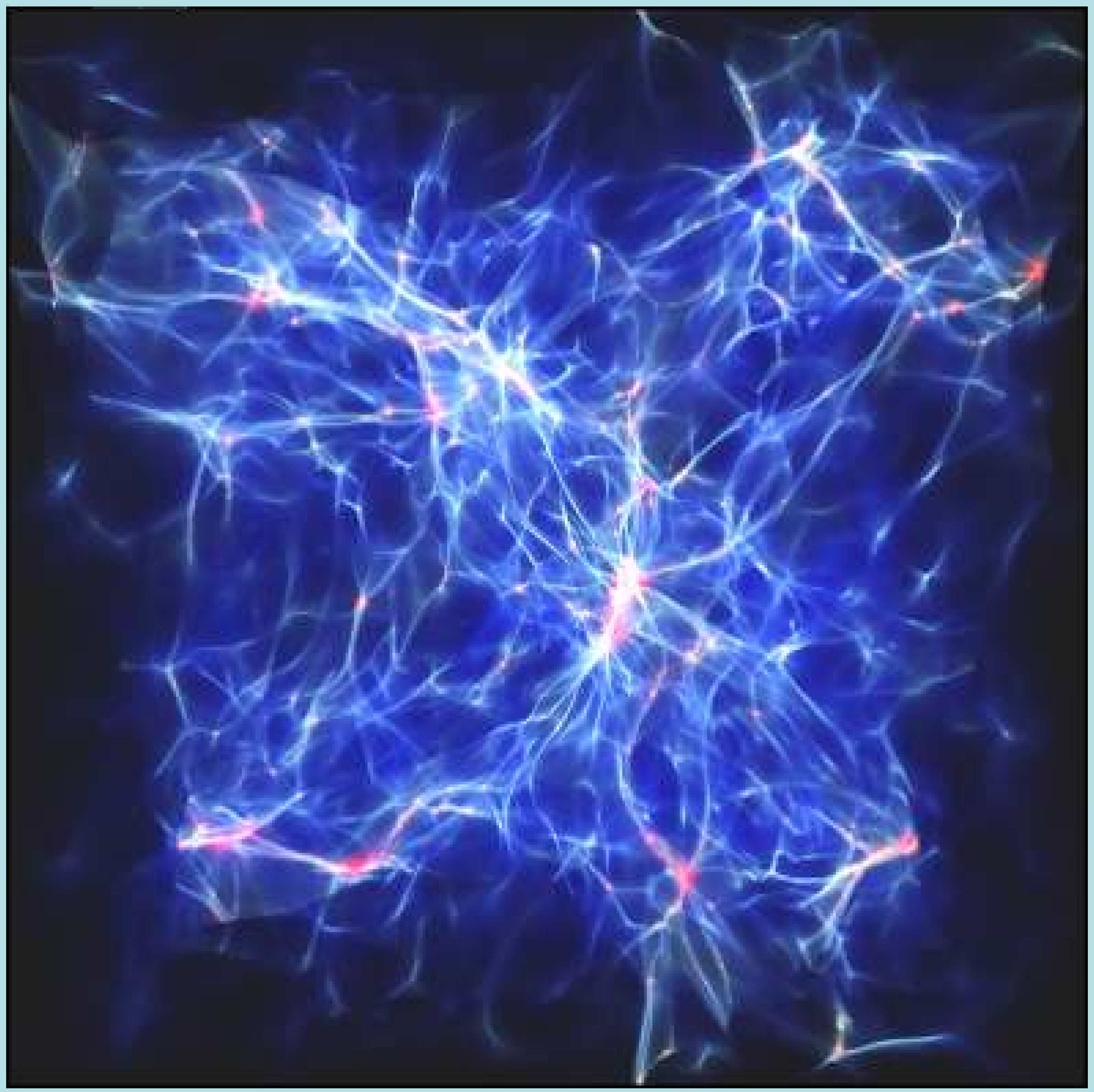
Scattering



How warm is out-of-equilibrium dark matter?



CDM



WDM (0.5 keV)

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

1. Beyond WIMPs

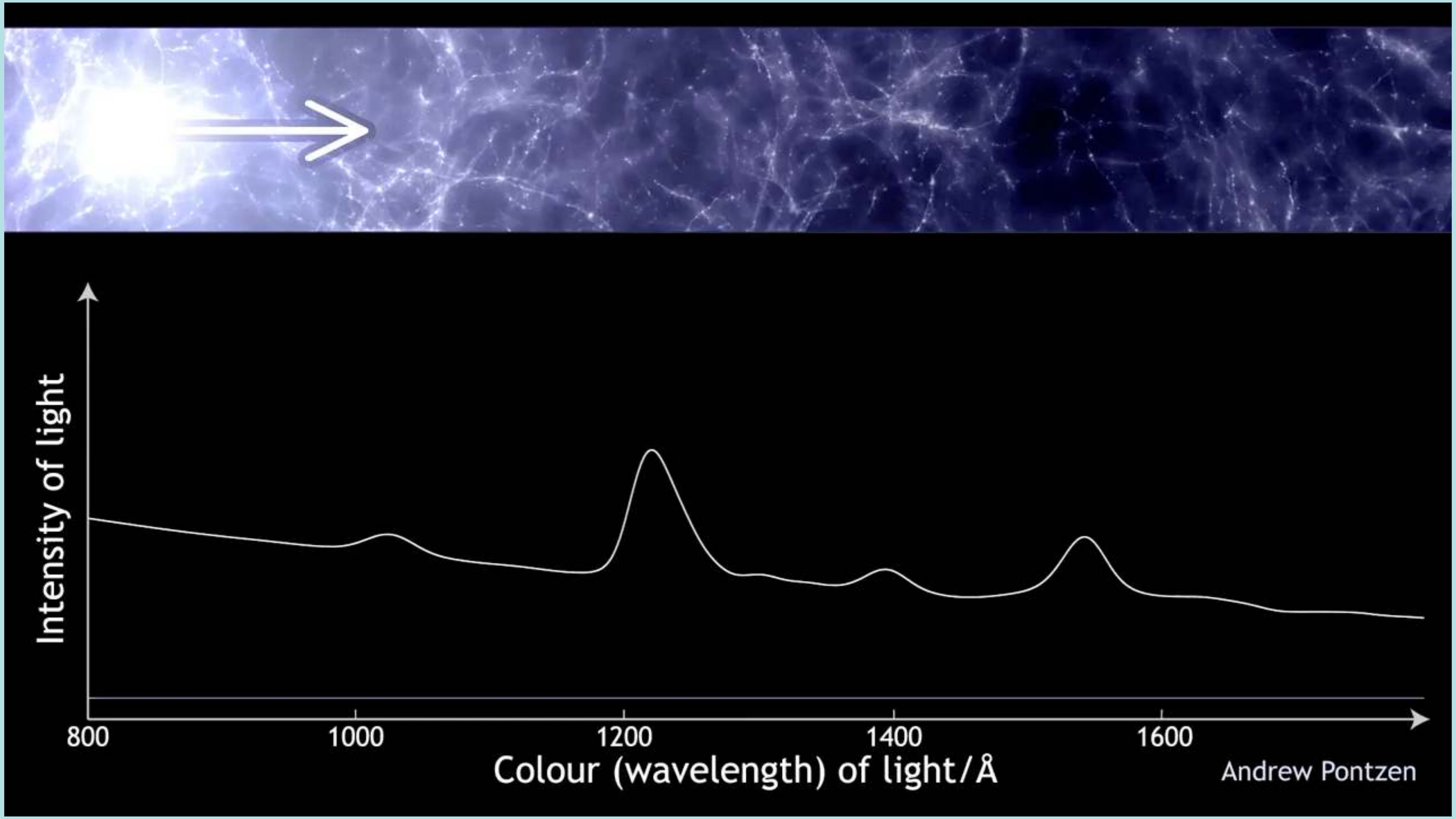
2. Inflation & reheating

3. FIMPs

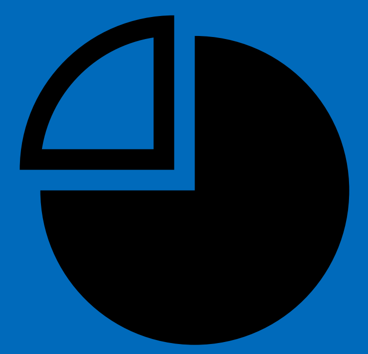
4. Compact objects

5. Prospects

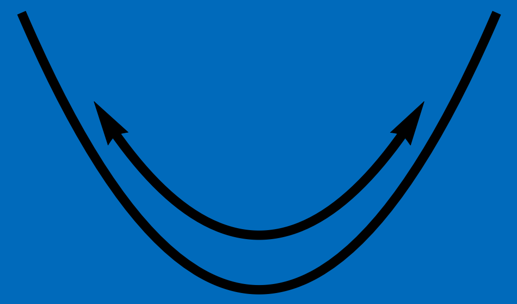
How warm is out-of-equilibrium dark matter?



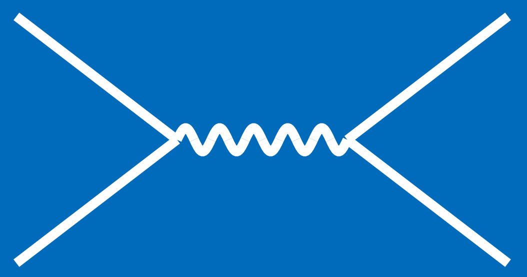
1. Beyond WIMPs



2. Inflation & reheating



3. FIMPs

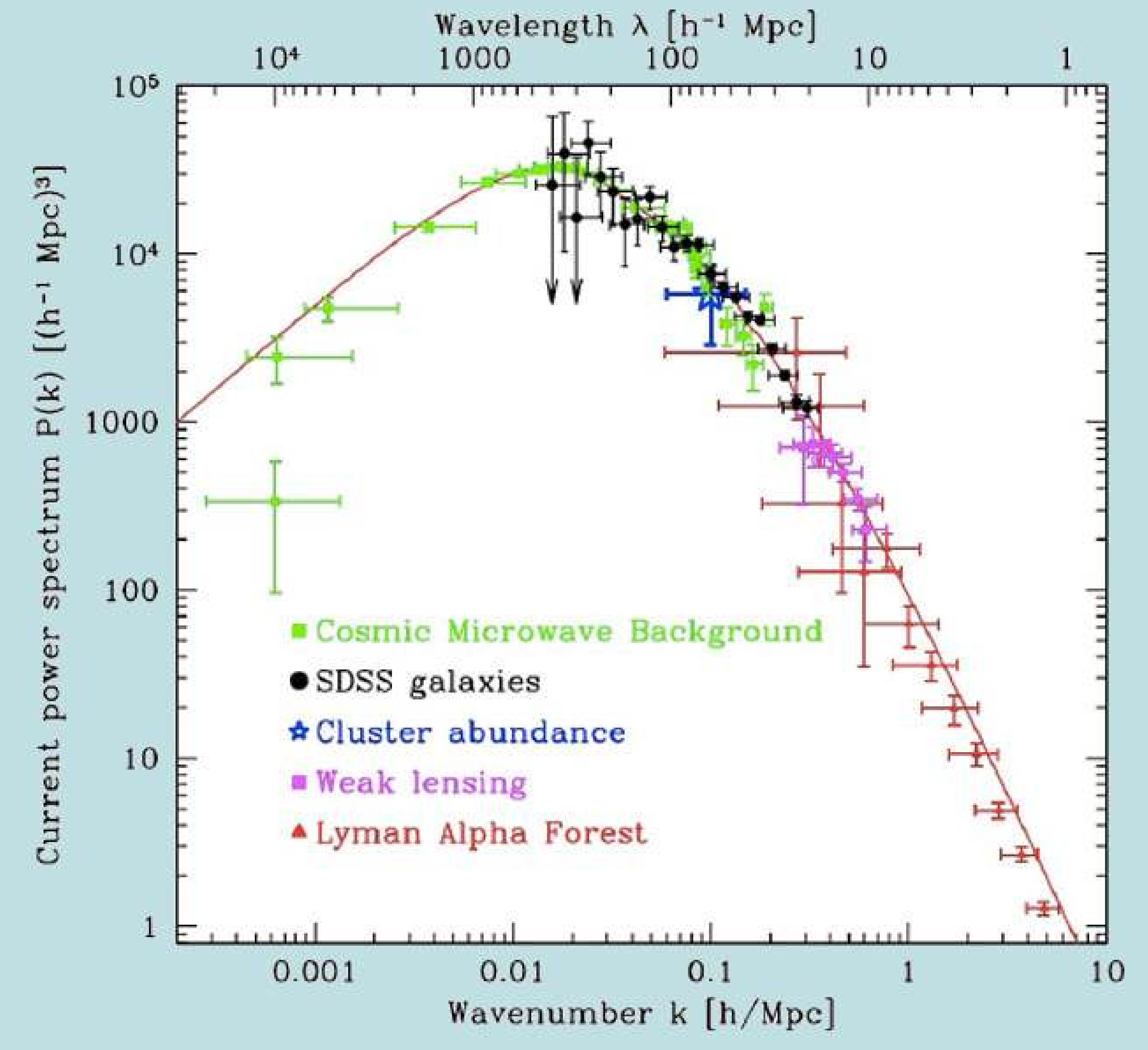


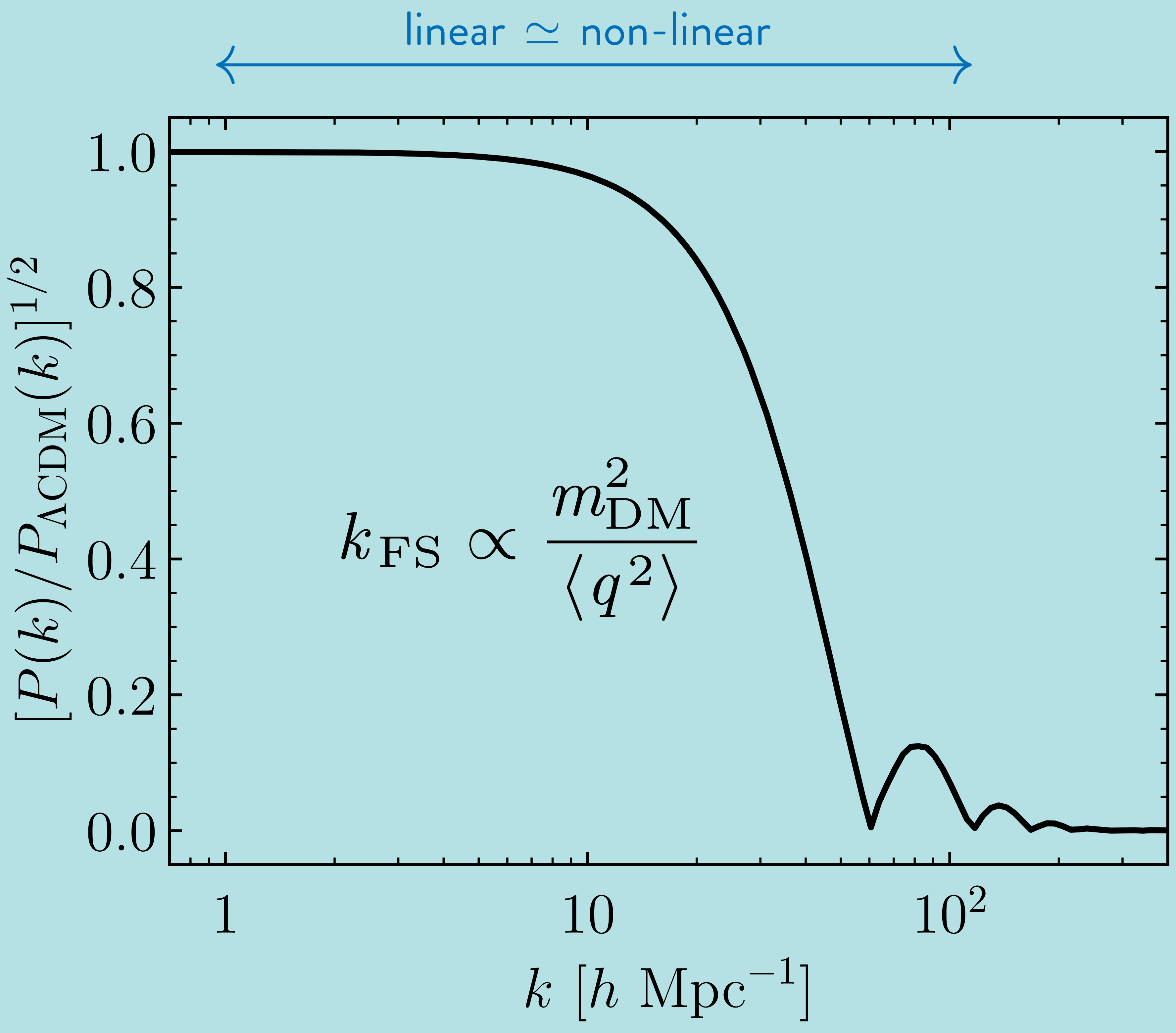
4. Compact objects

5. Prospects

How warm is out-of-equilibrium dark matter?

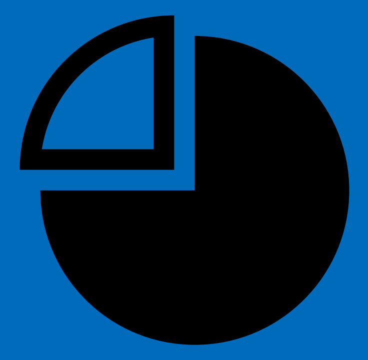
R. Murgia, V. Iršič and M. Viel, PRD 98 (2018), 083540





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

1. Beyond WIMPs



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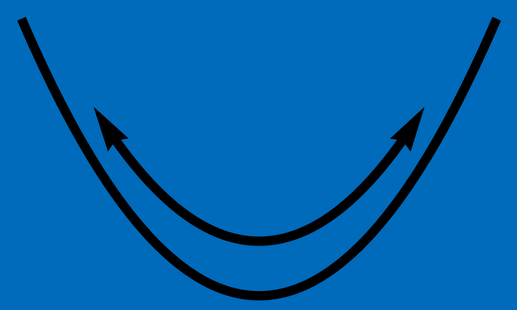
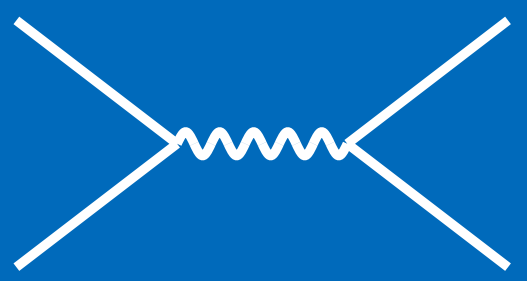


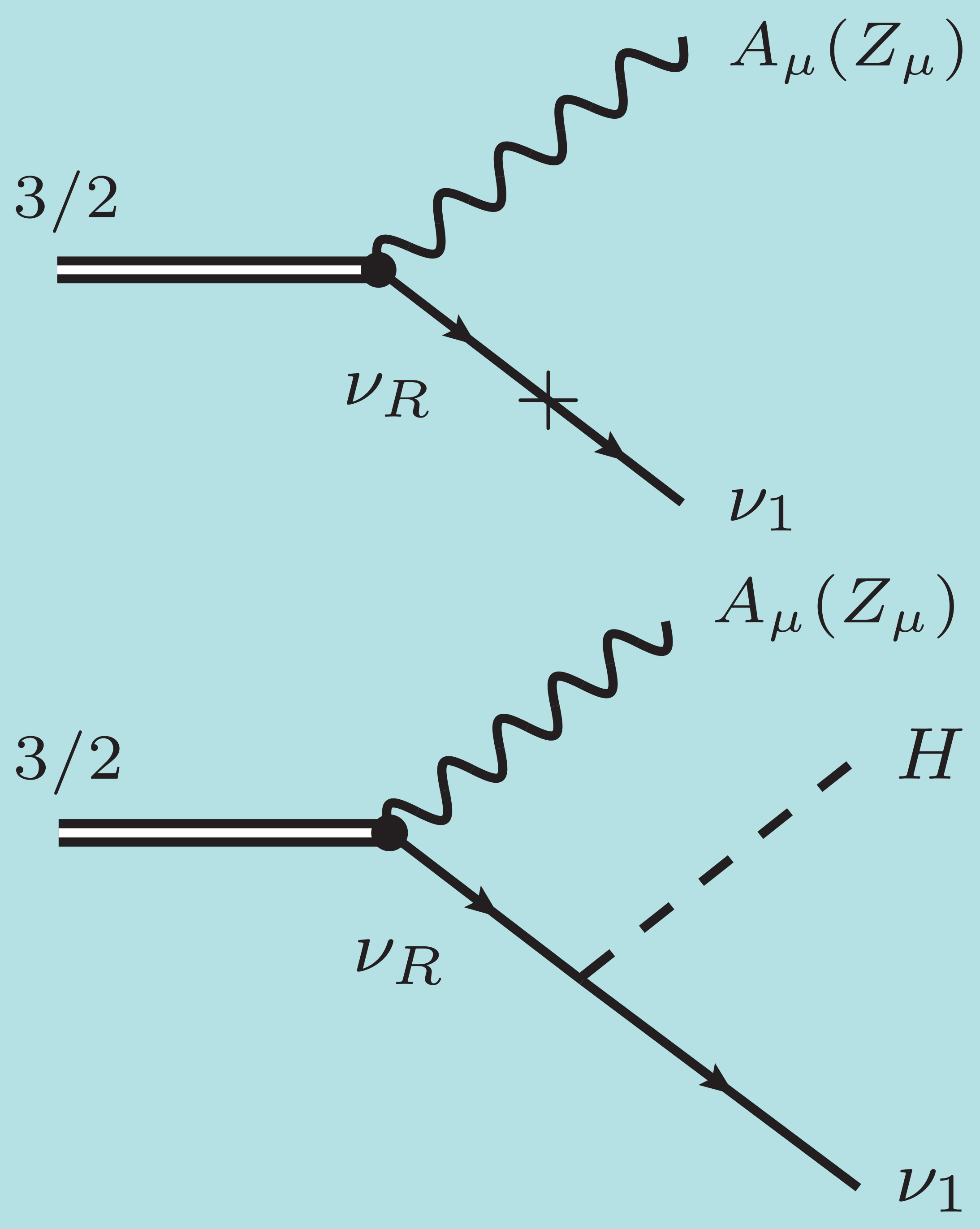
3. FIMPs

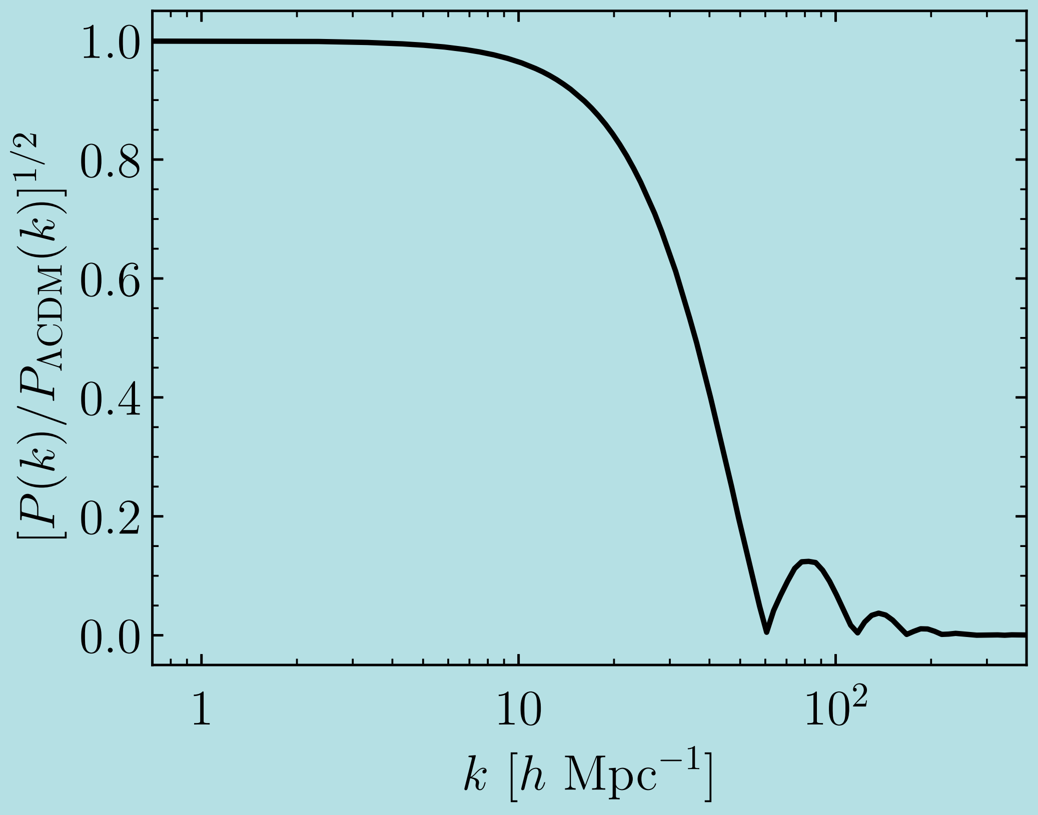


4. Compact objects

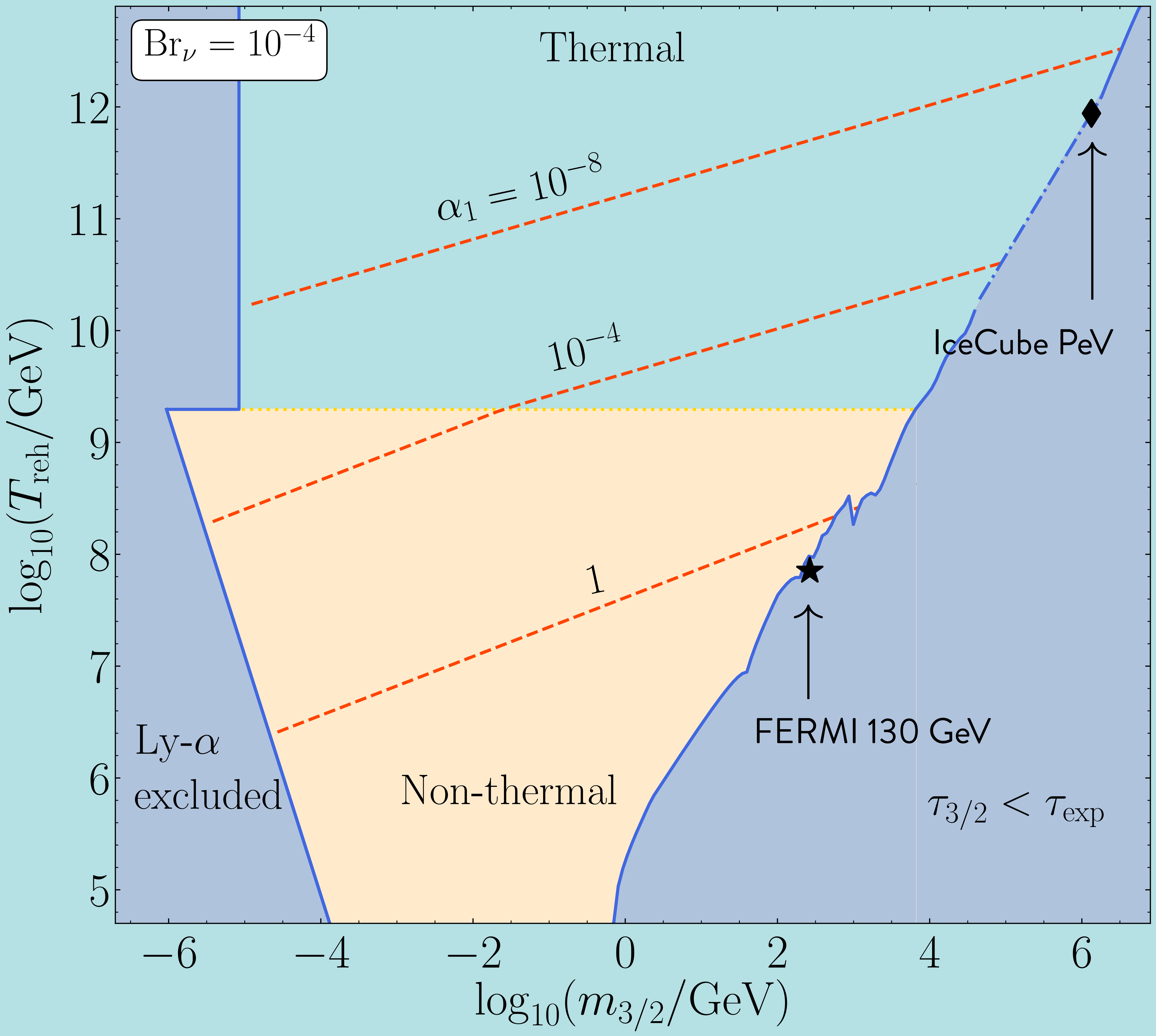
5. Prospects

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





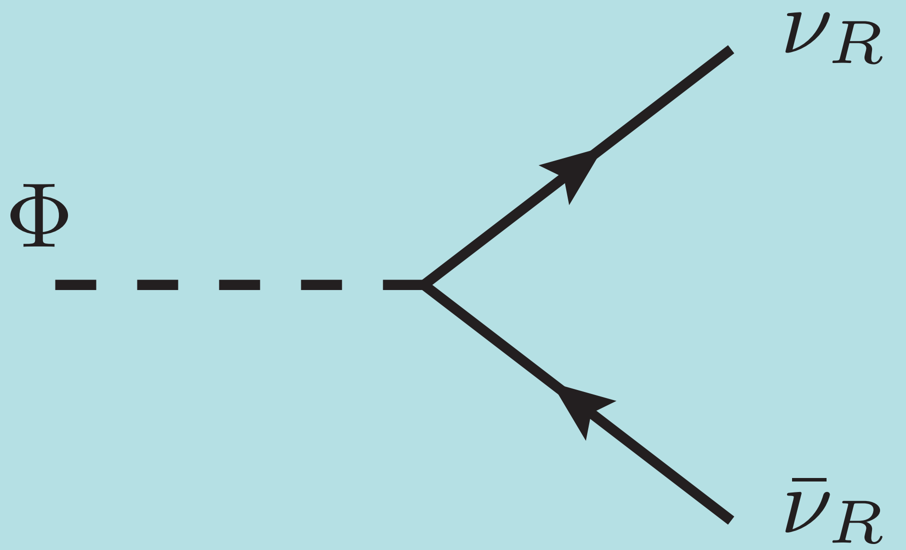
Scattering

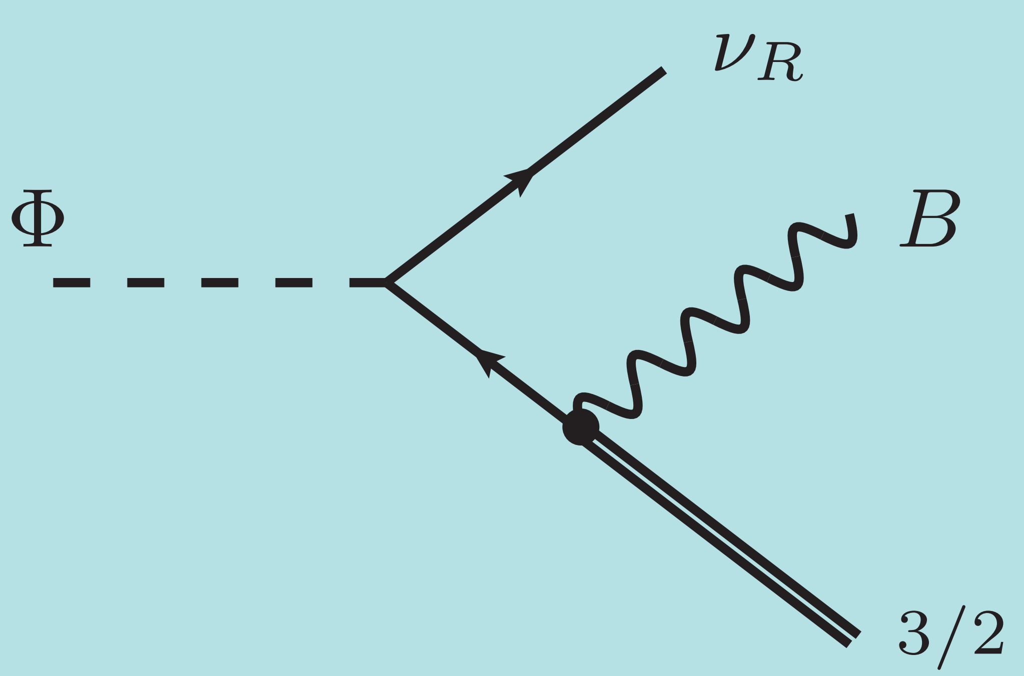


Production (via inflaton decay)

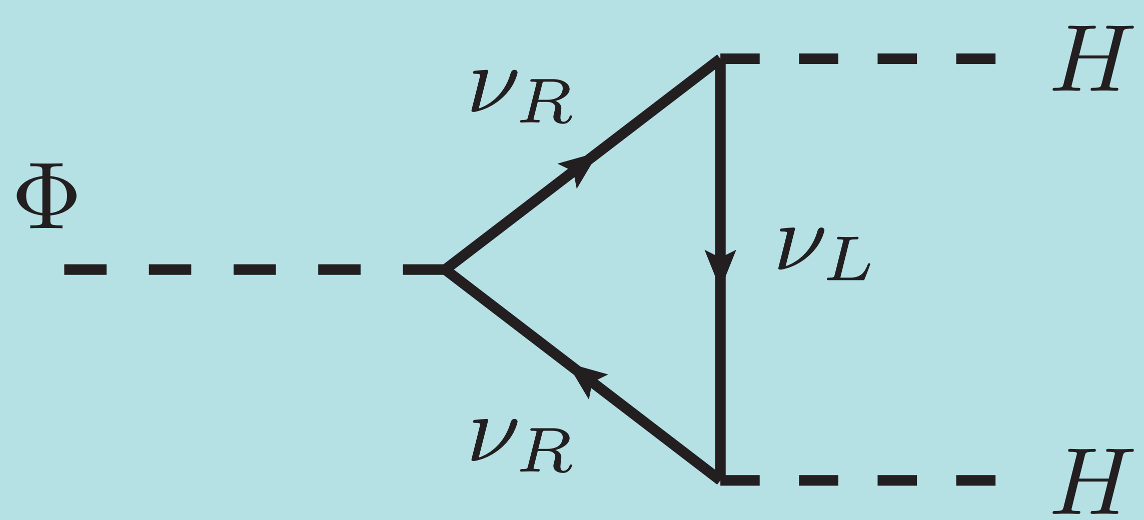
Via α_1,

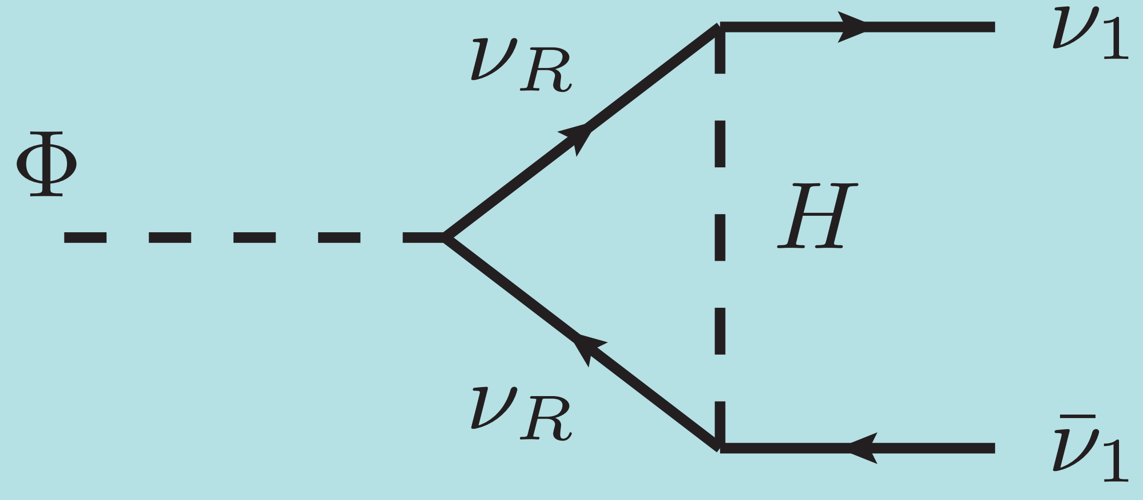
$M_R \ll m_\Phi$:

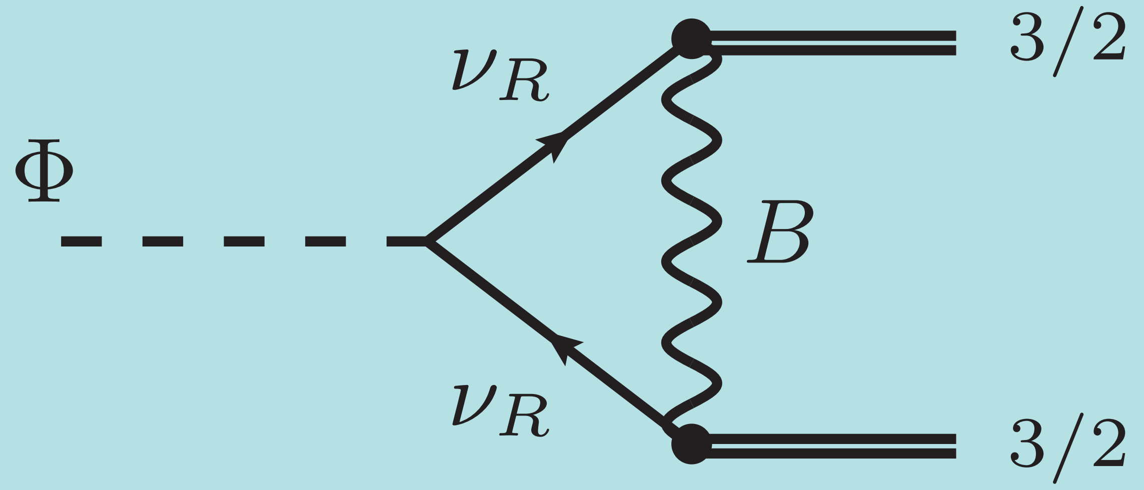




$M_R \gg m_\Phi$:

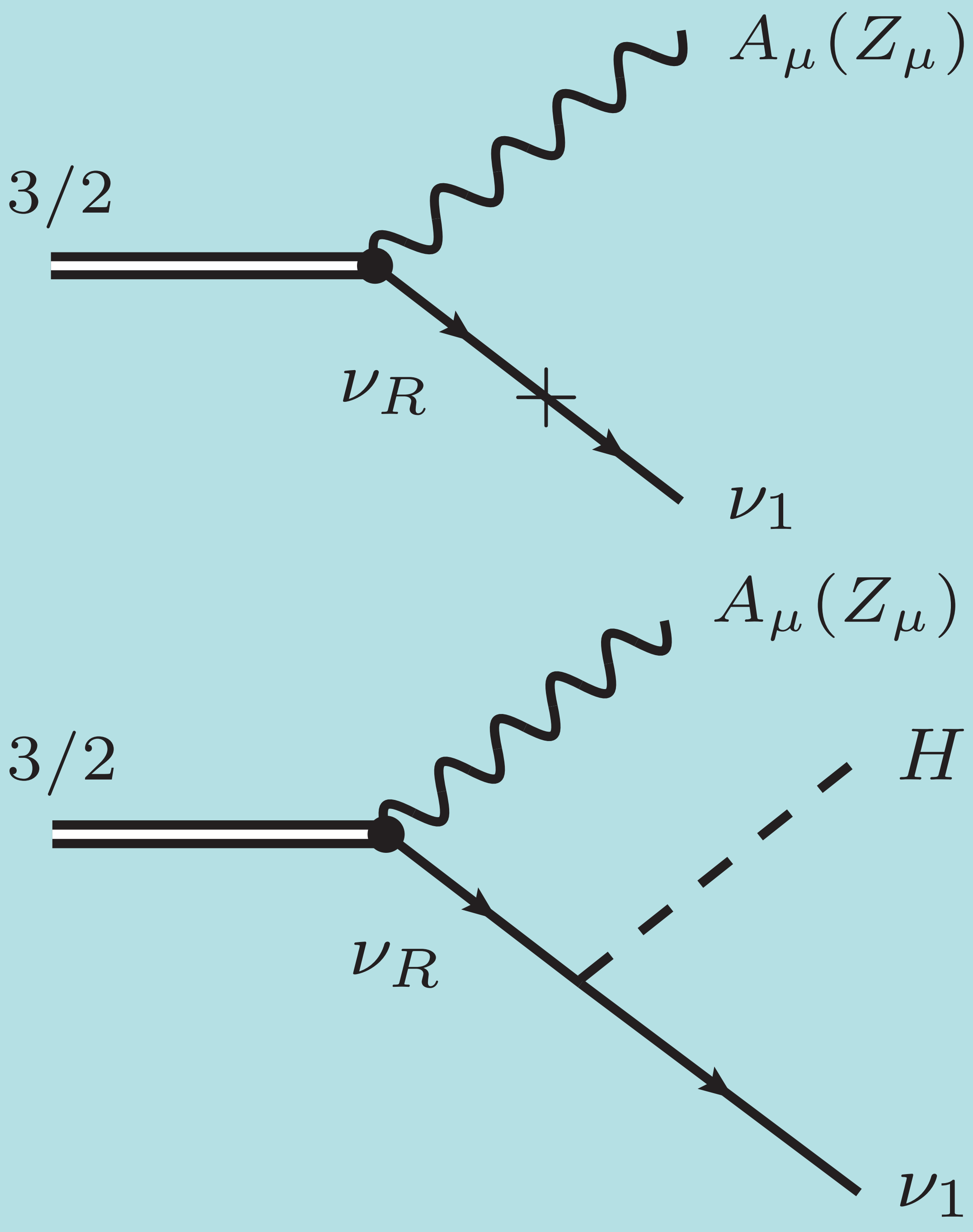


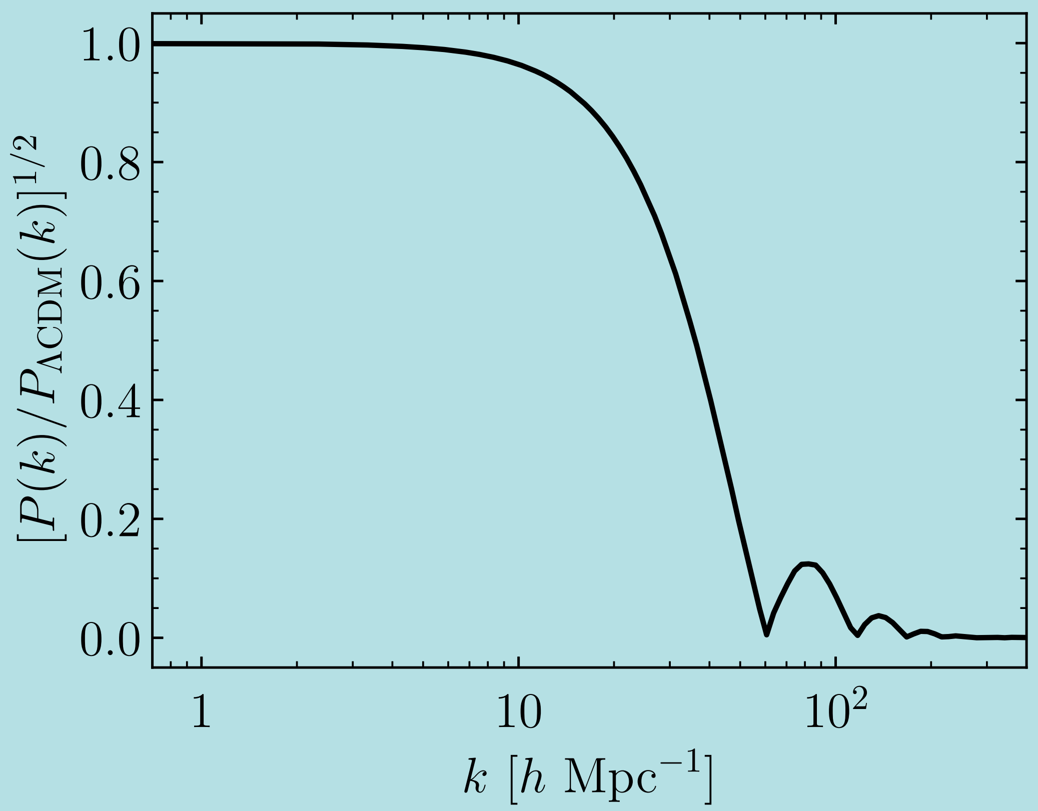




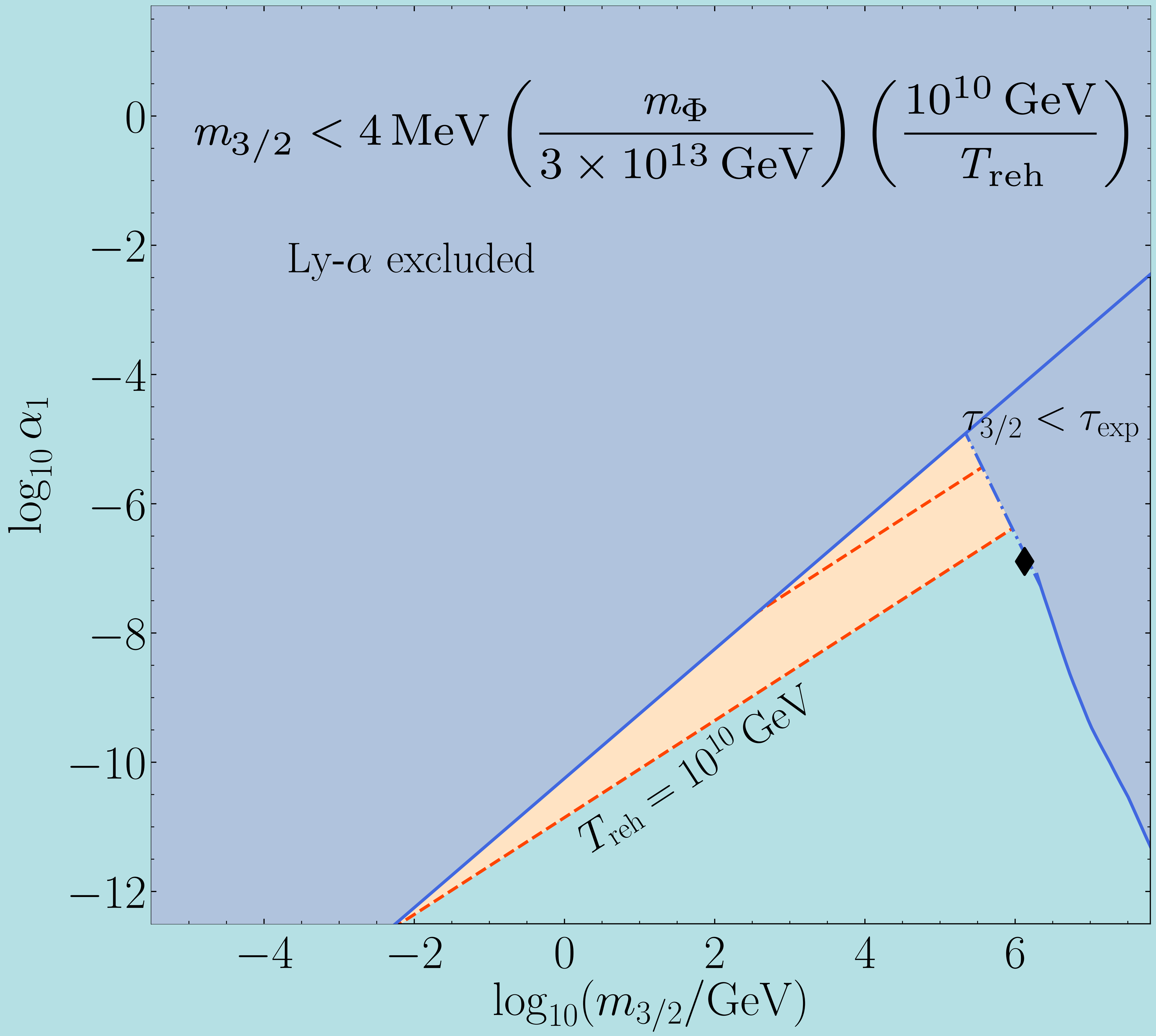
(via α_2 are 2-loop suppressed)

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

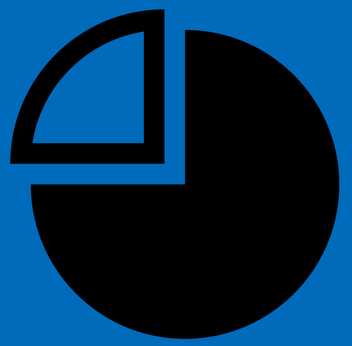




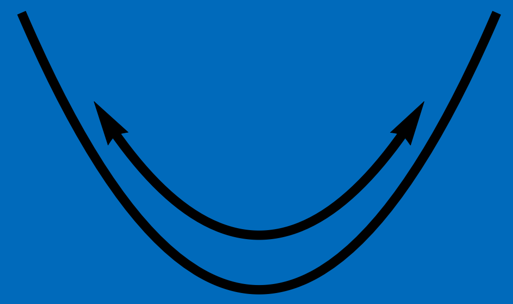
Inflaton decay



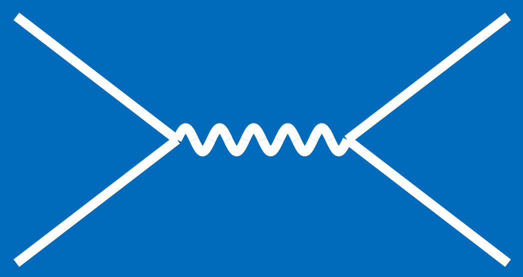
1. Beyond WIMPs



2. Inflation & reheating



3. FIMPs



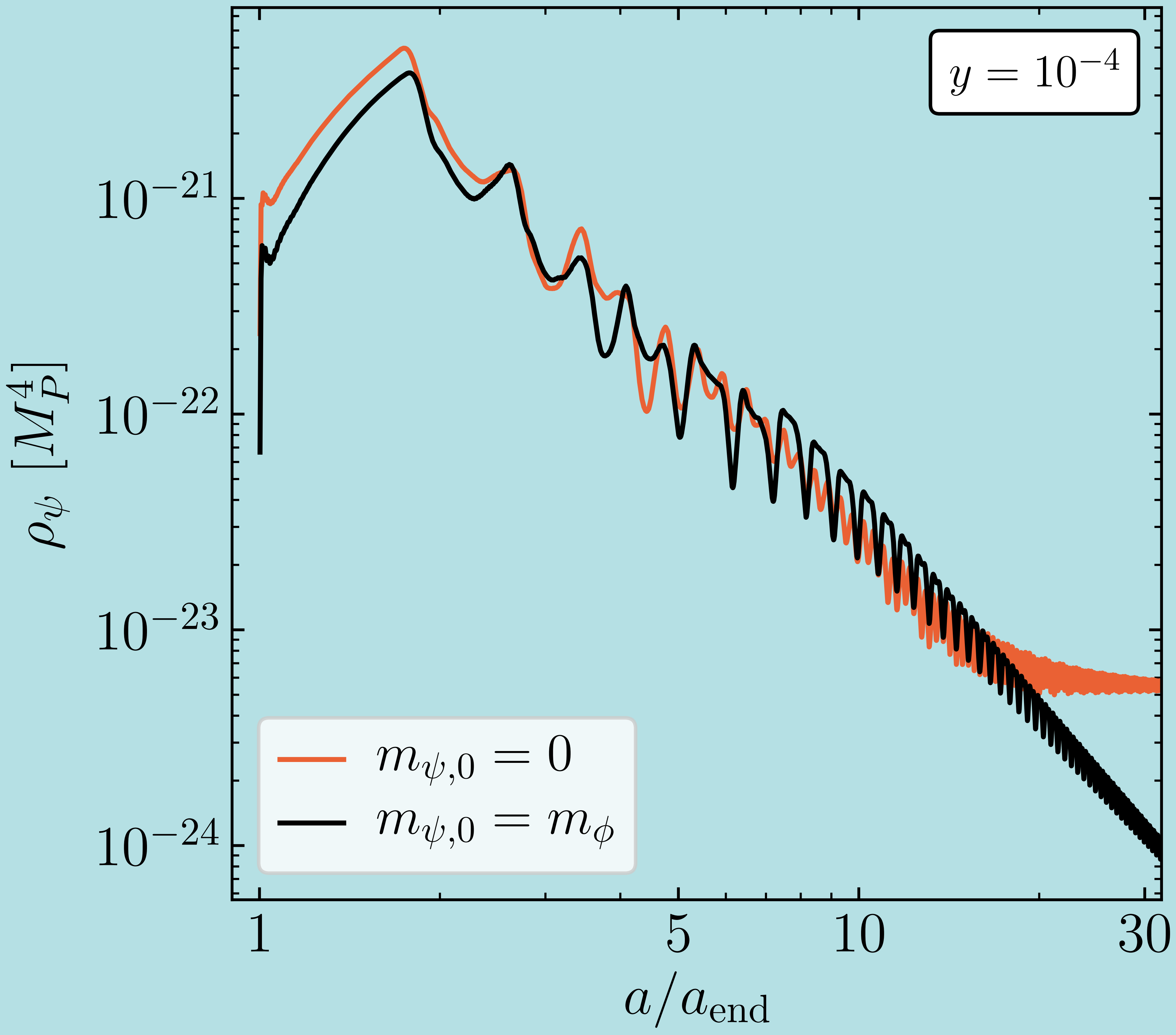
4. Compact objects

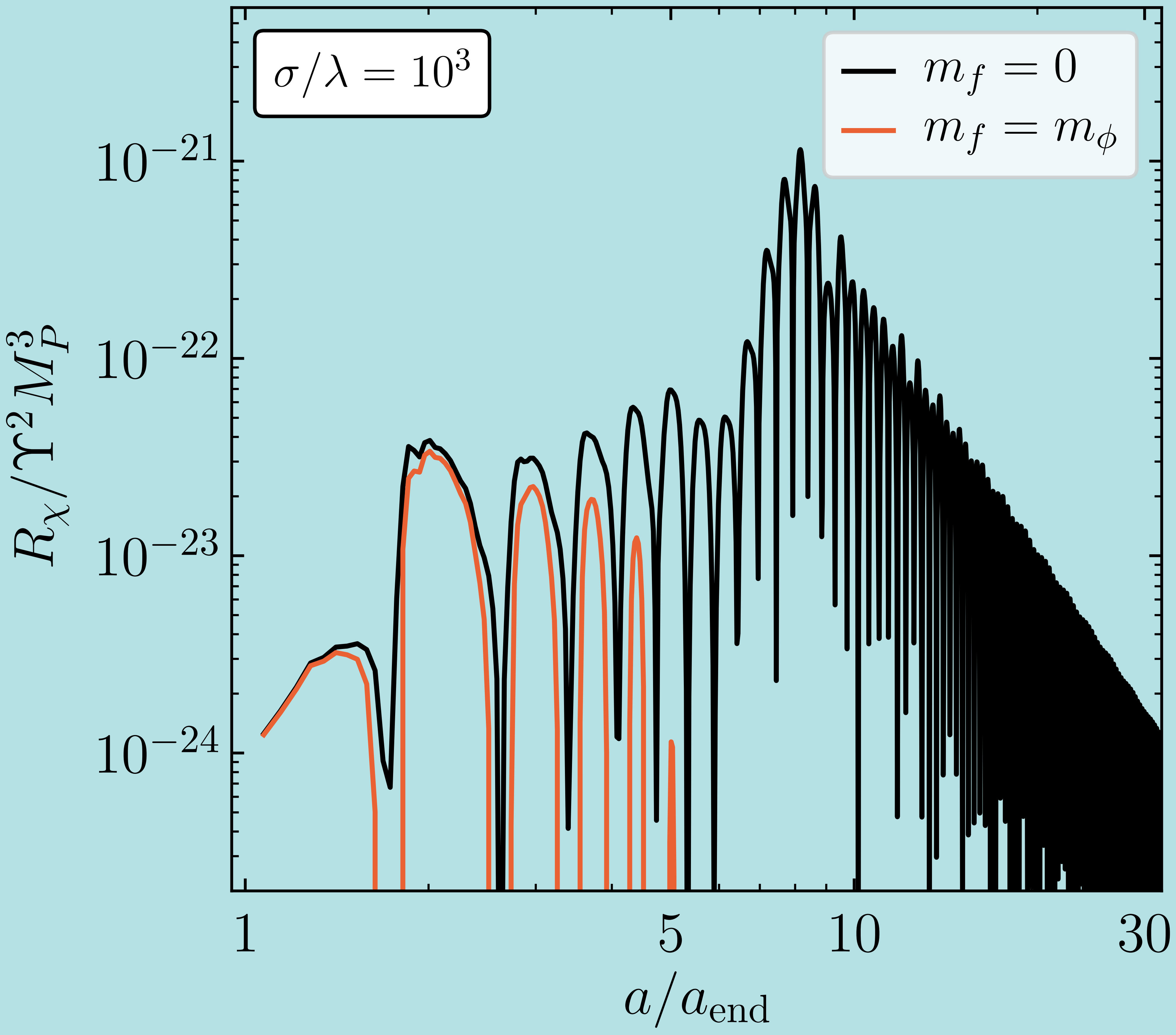
5. Prospects

Beyond perturbation theory

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

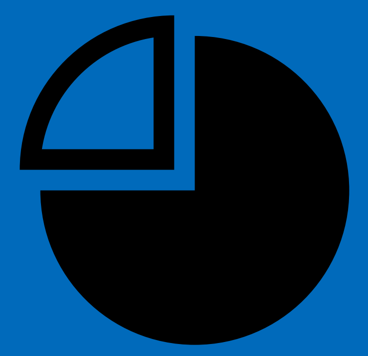
E. Kolb, D. Chung and A. Riotto, AIP Conf. Proc. 484 (1999), 91

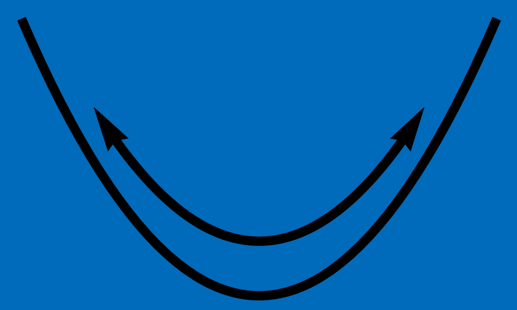


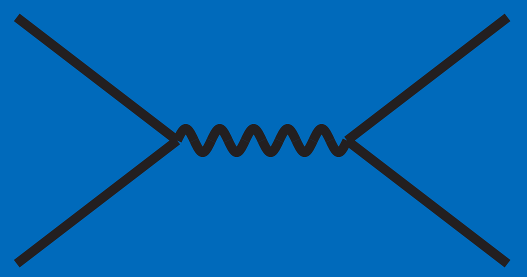


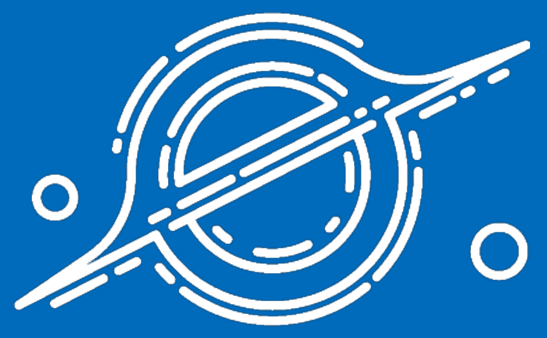
(but not thermally though)

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

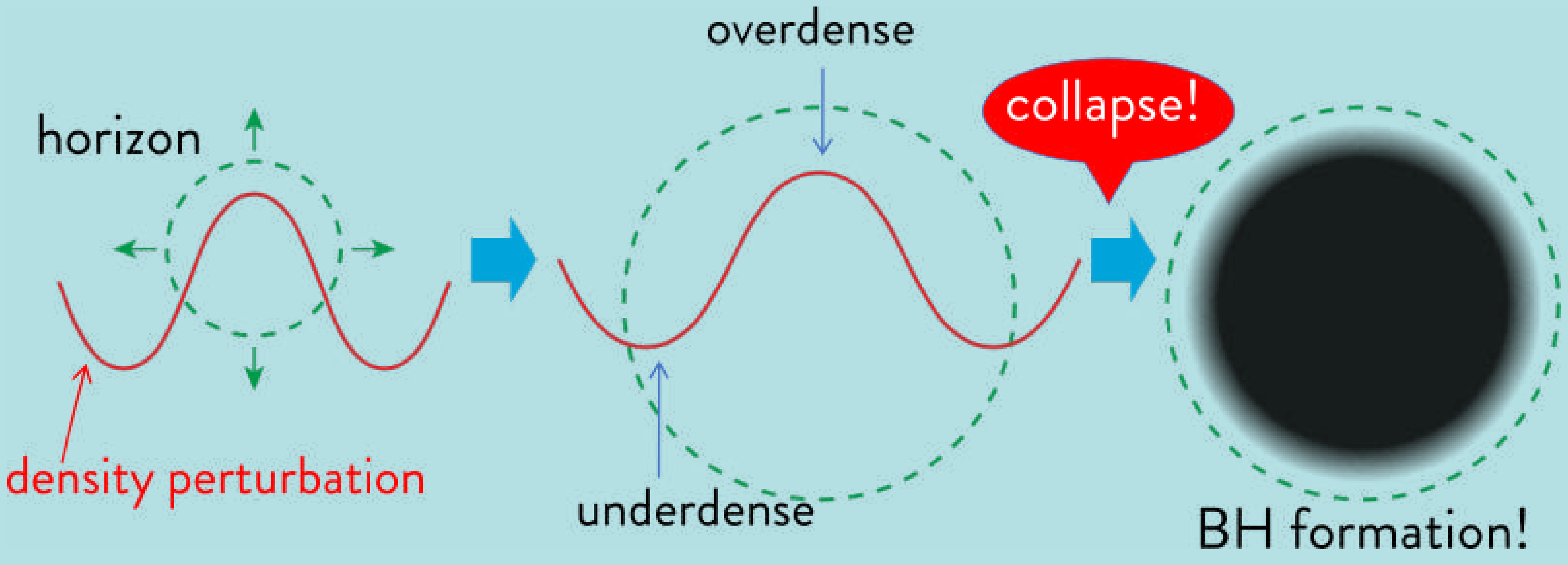








Large metric fluctuations?



Credit: Naoya Kitajima

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

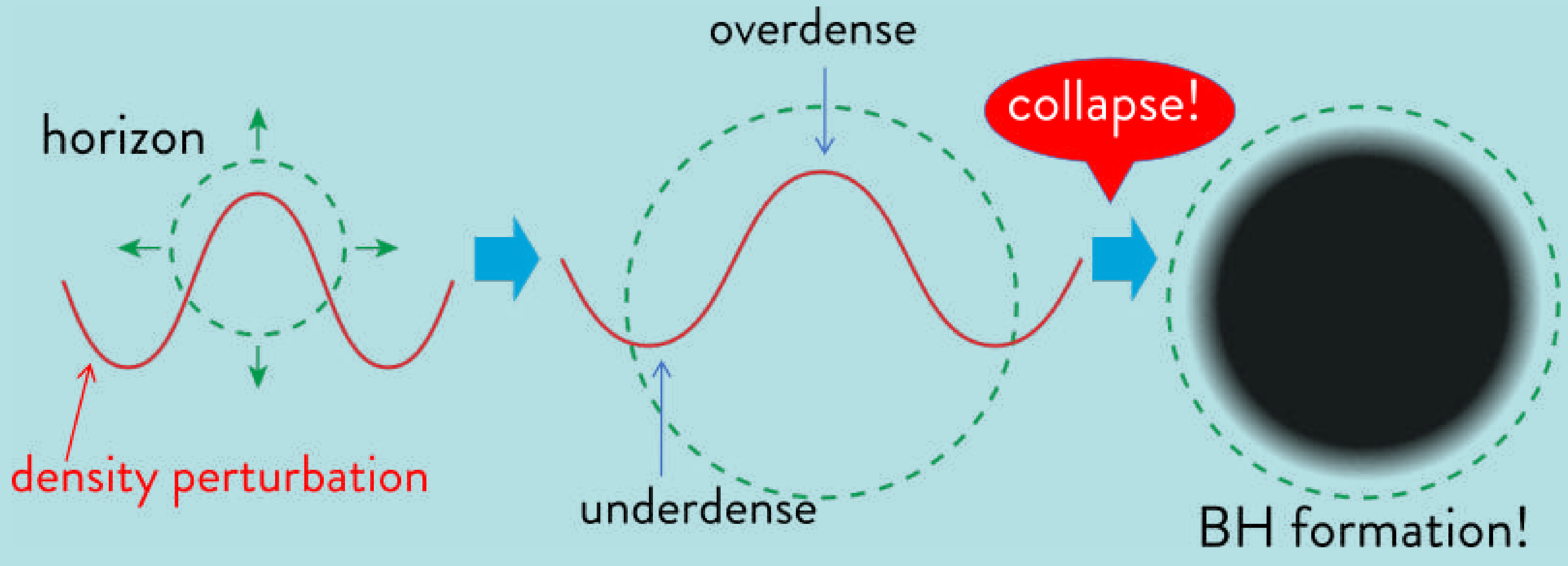
$M_{\rm BH}$	$\tau_{\rm BH}$
A man	10^{-12} s
10^{15} g	10^{10} y
Earth	10^{49} y
Sun	10^{66} y
Milky Way	10^{99} y

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

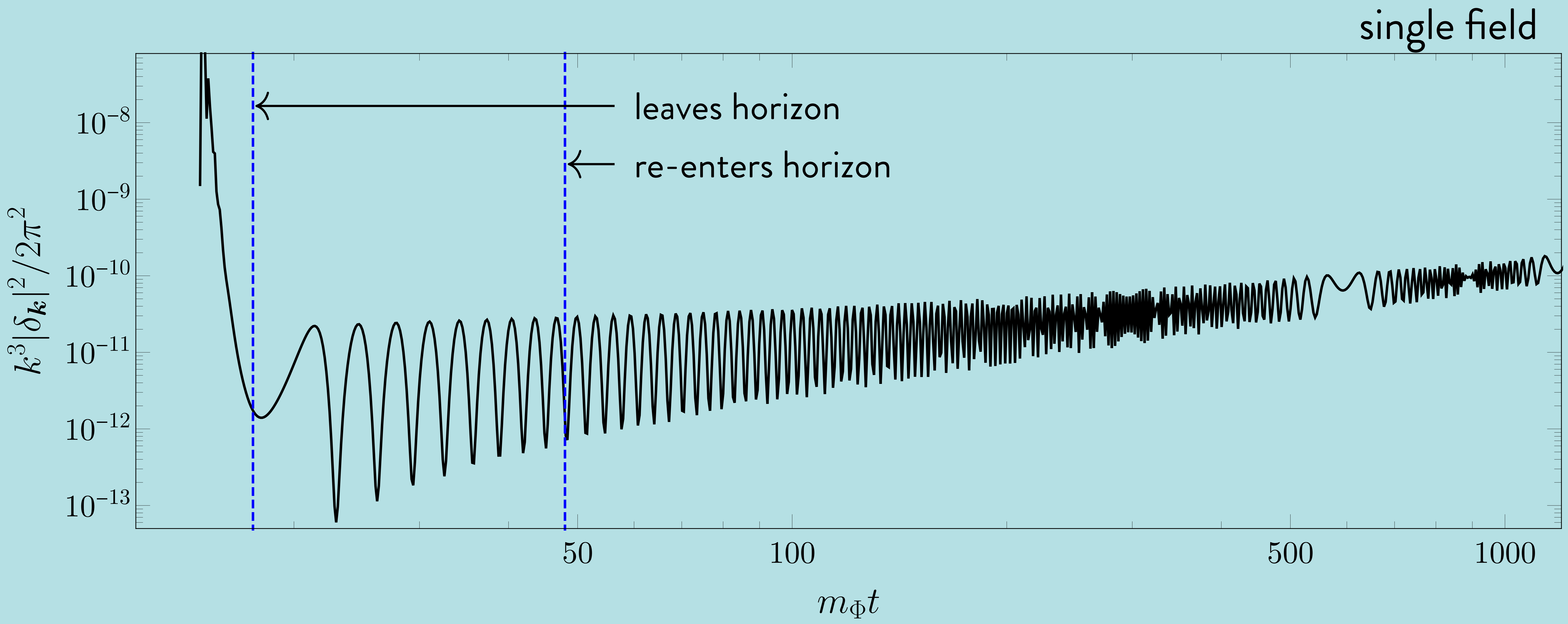
$$M_{\rm BH} \propto \rho_{\rm form}/H^3_{\rm form} < 10^9 \text{ g}$$

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

Large metric fluctuations?

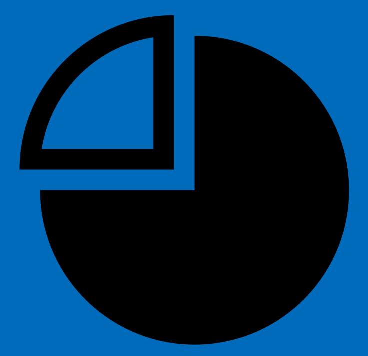


Credit: Naoya Kitajima



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

1. Beyond WIMPs



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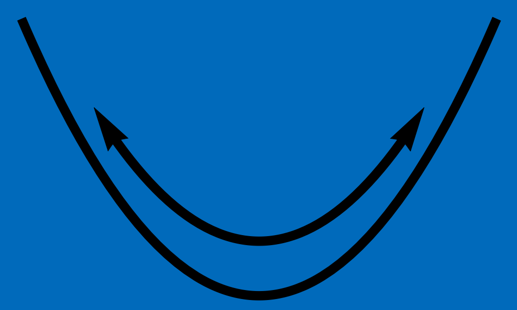
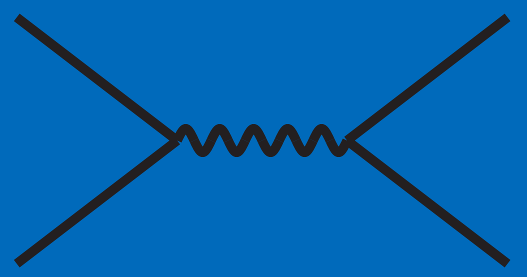


3. FIMPs



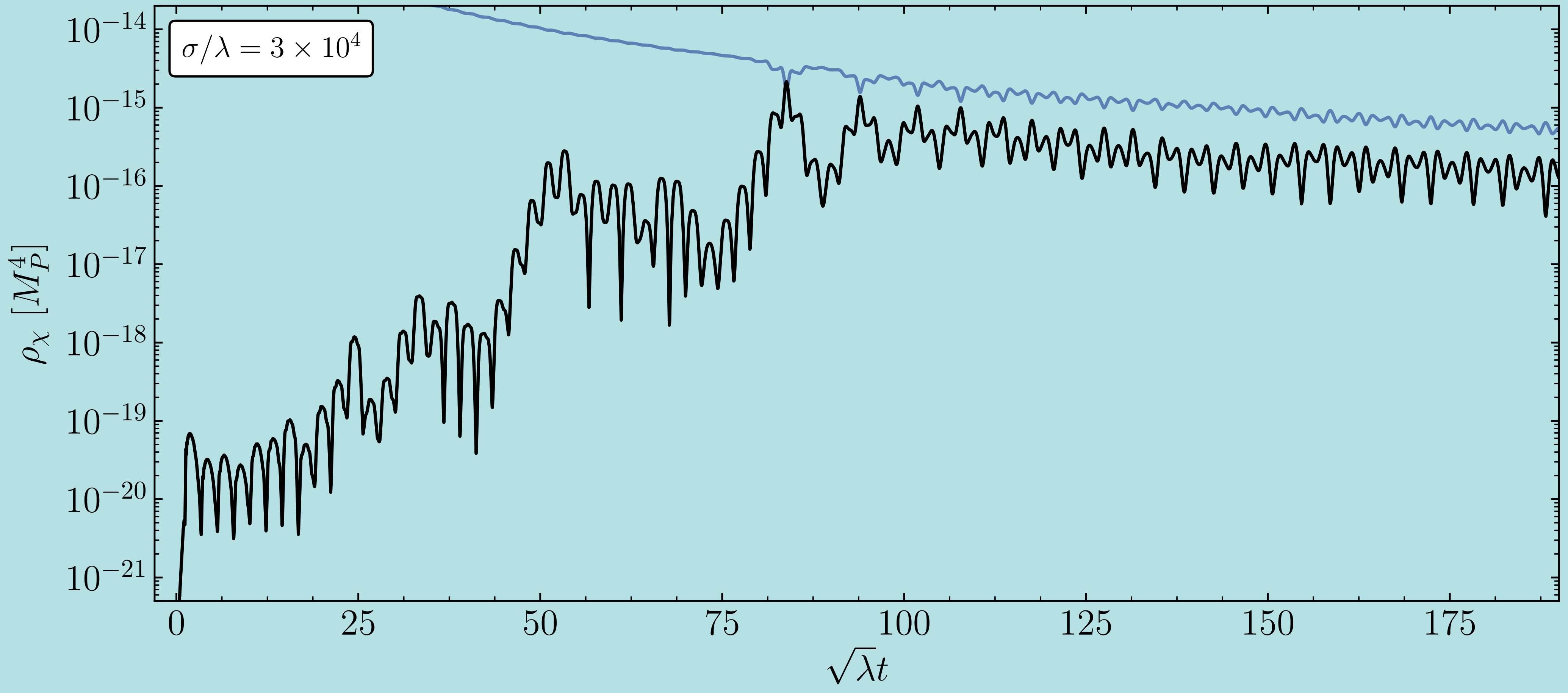
4. Compact objects

5. Prospects

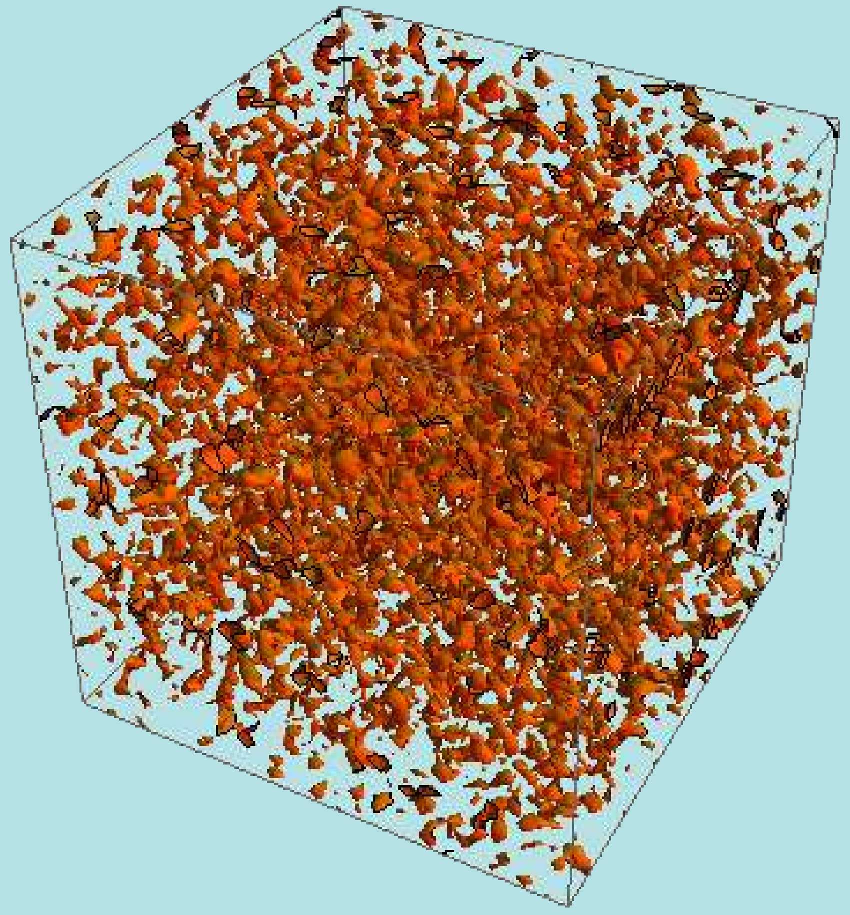
Fragmenting the condensate

Backreaction

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

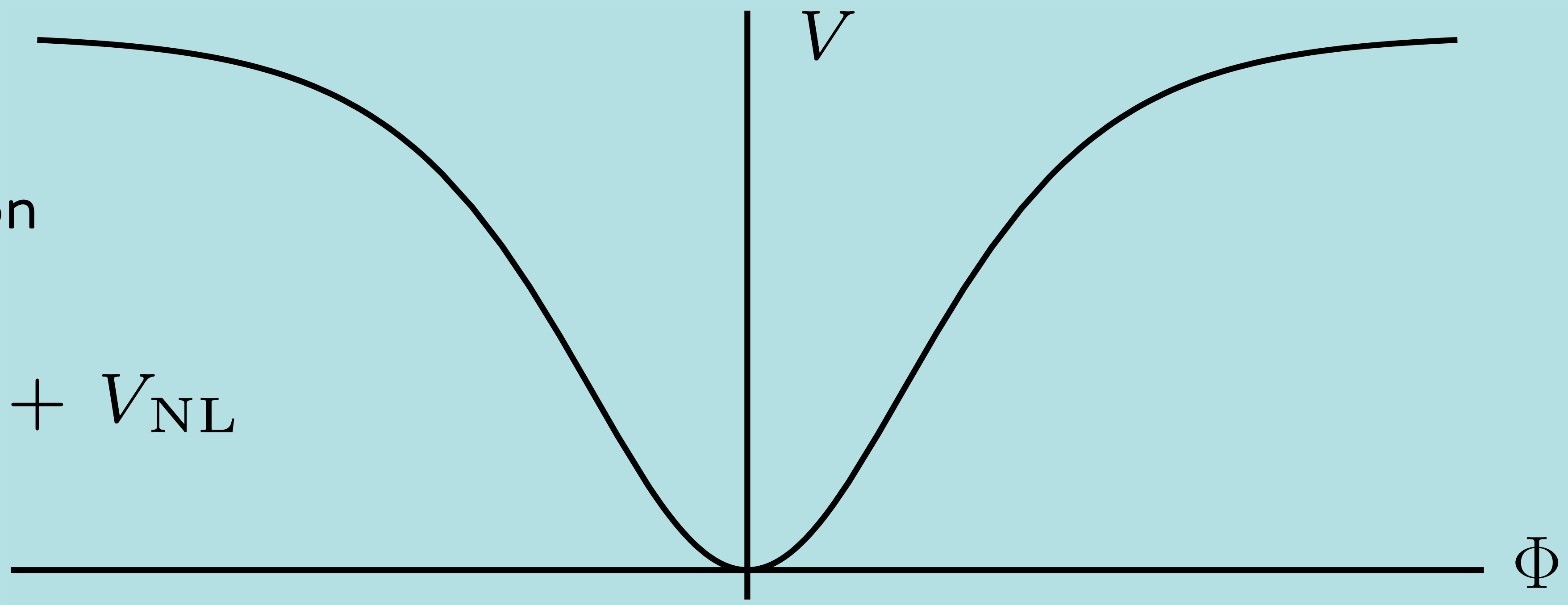


$\longrightarrow$

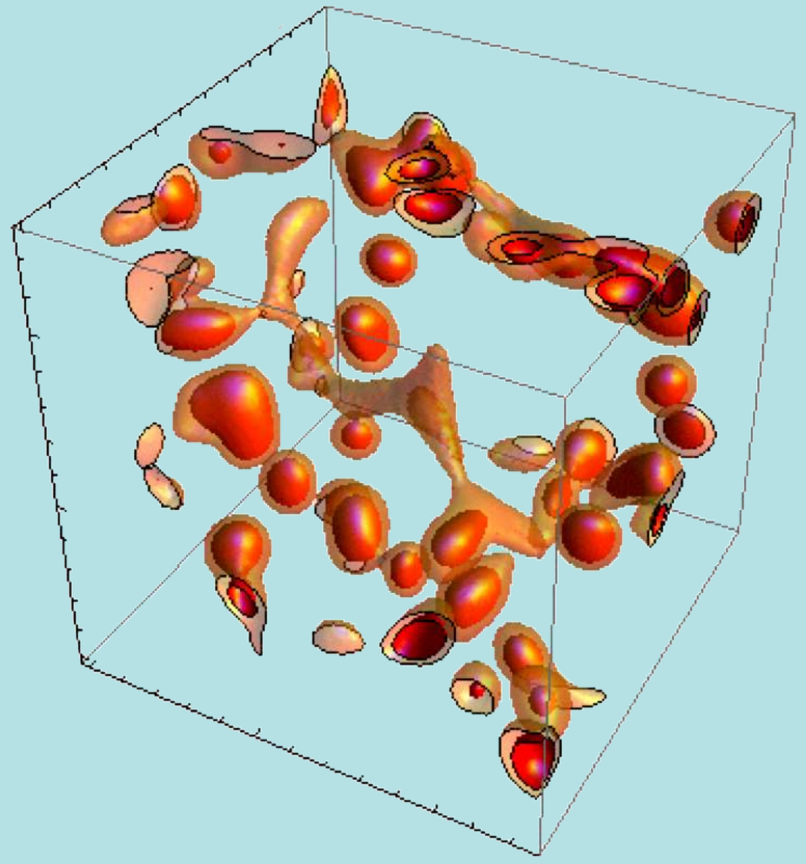


"opening up" =
attractive interaction

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



$\longrightarrow$



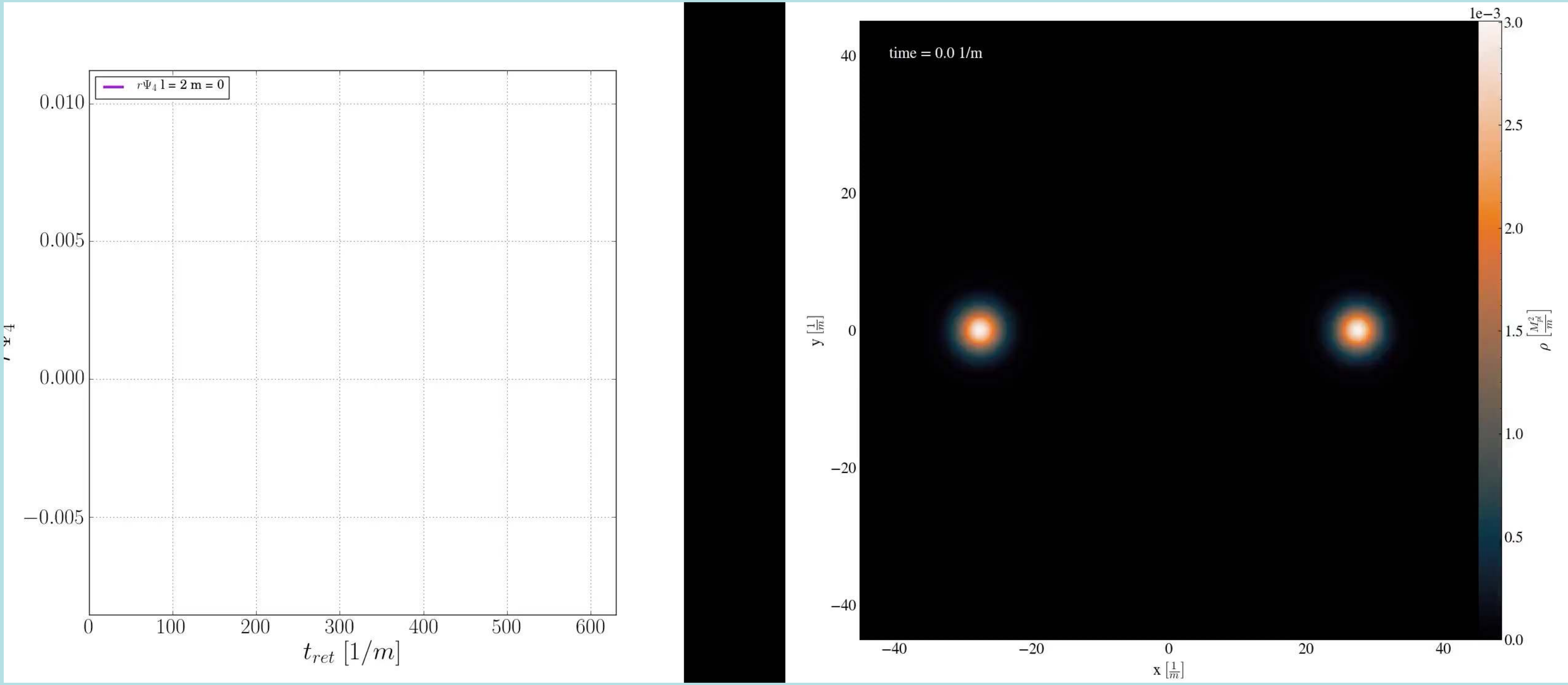
gravity $\longrightarrow$

self-interaction $\longleftarrow$

Complex, U(1): Q-Balls — Boson stars

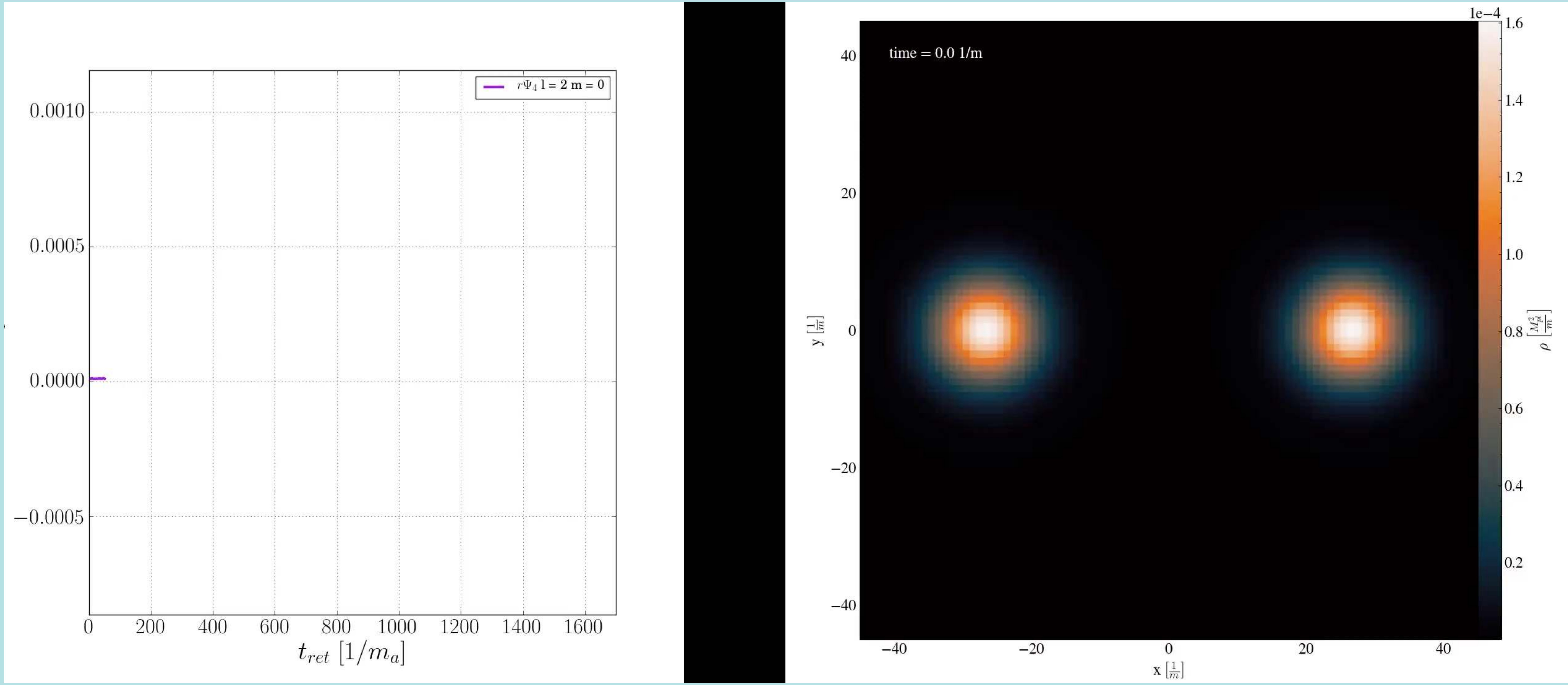
Real: Oscillons — Oscillatons

Oscillaton collisions



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

Oscillaton collisions



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

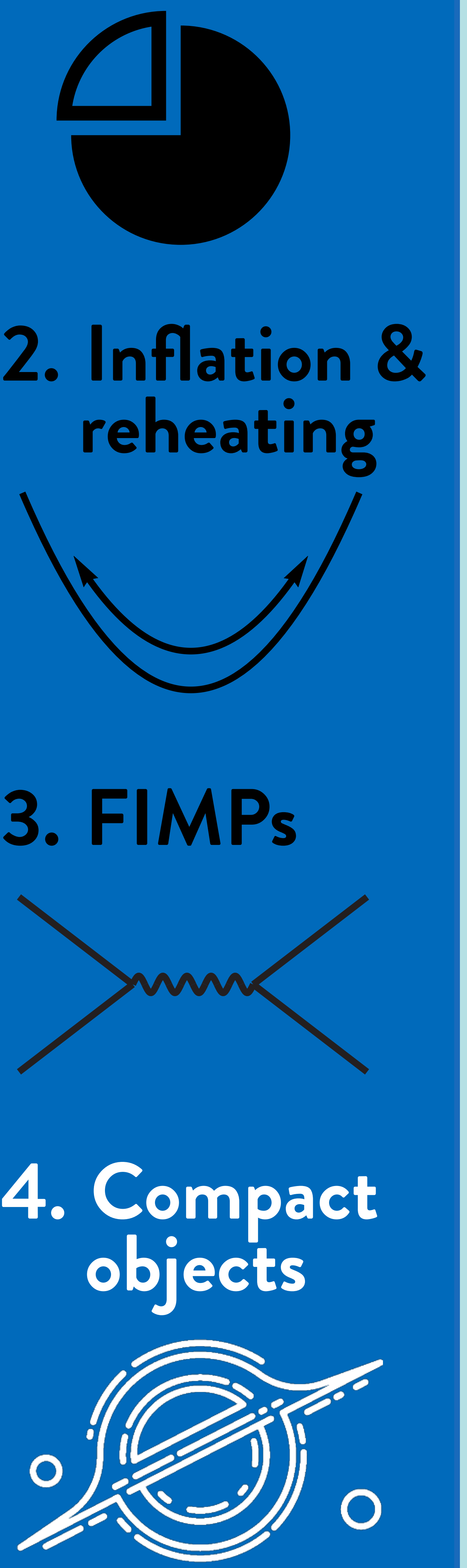
1. Beyond WIMPs

2. Inflation & reheating

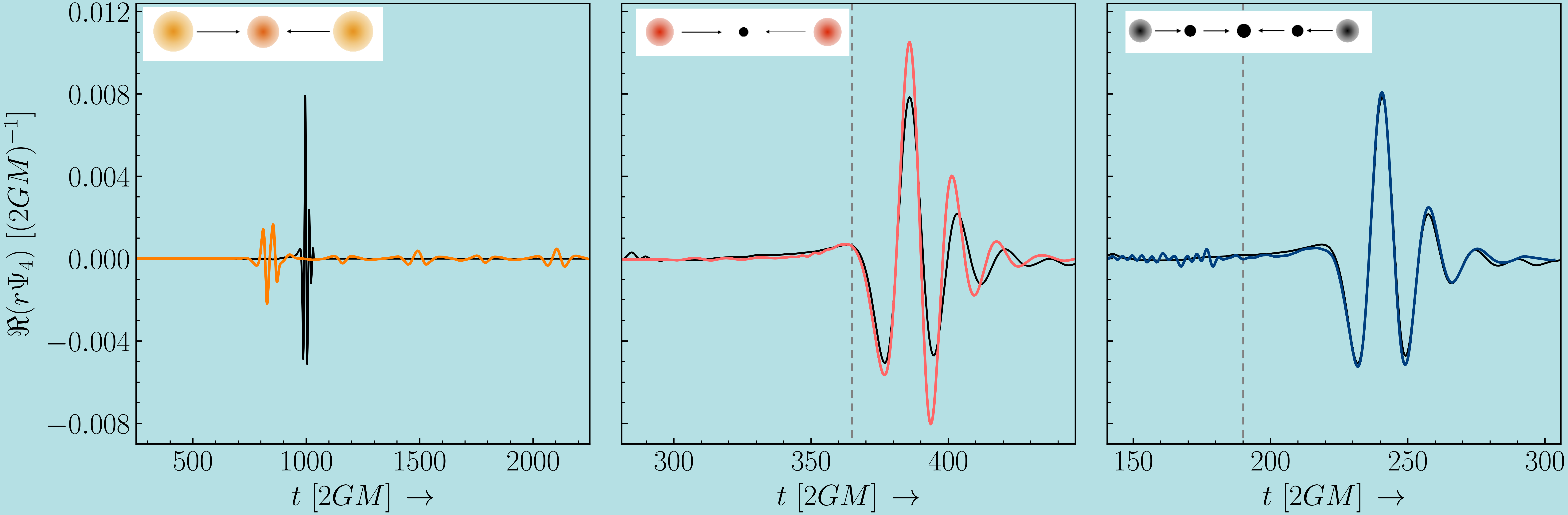
3. FIMPs

4. Compact objects

5. Prospects



Oscillaton collisions



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

1. Beyond WIMPs
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Dark matter from inflation

ON THE CONCENTRATION OF RELIC MAGNETIC MONOPOLES IN THE UNIVERSE

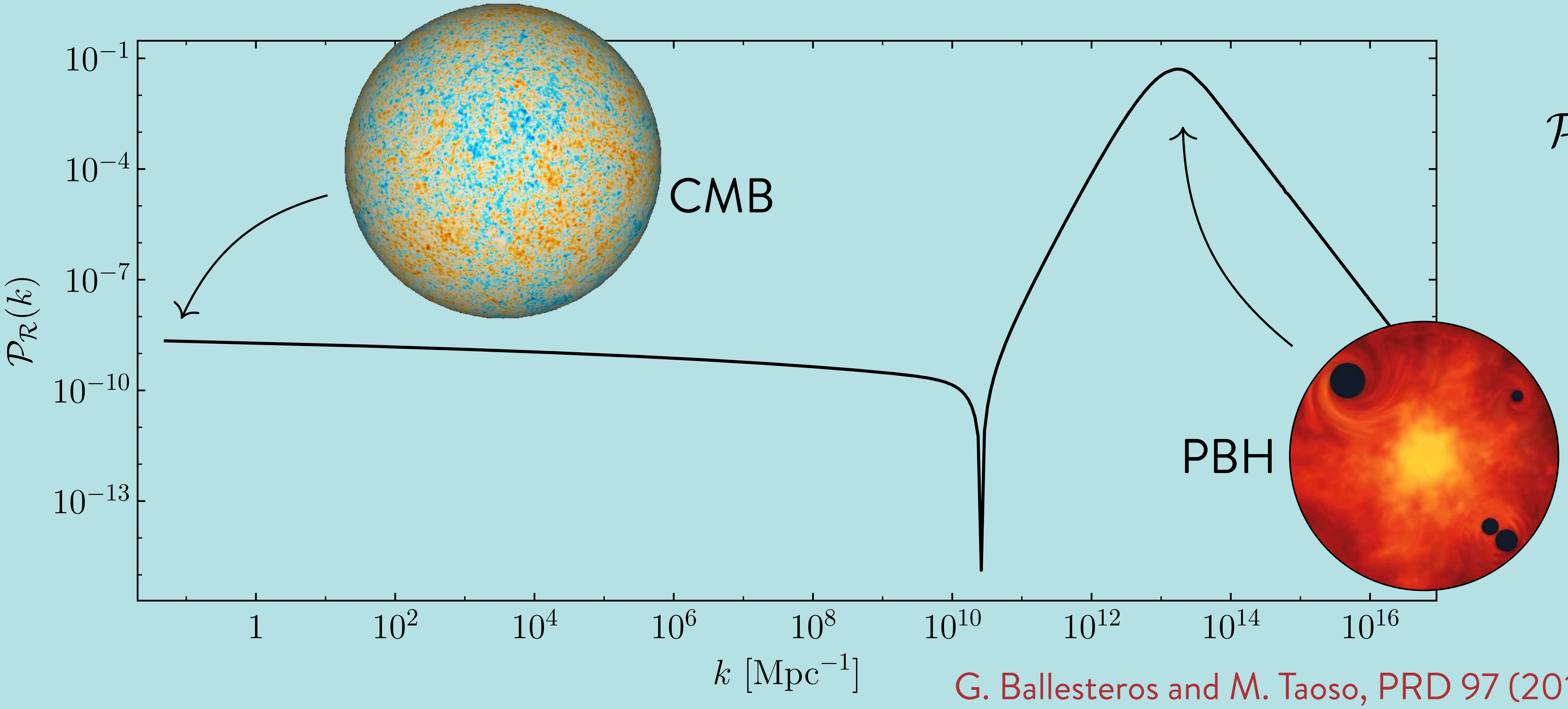
Ya.B. ZELDOVICH and M.Yu. KHLOPOV

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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PLB 79 (1978), 239

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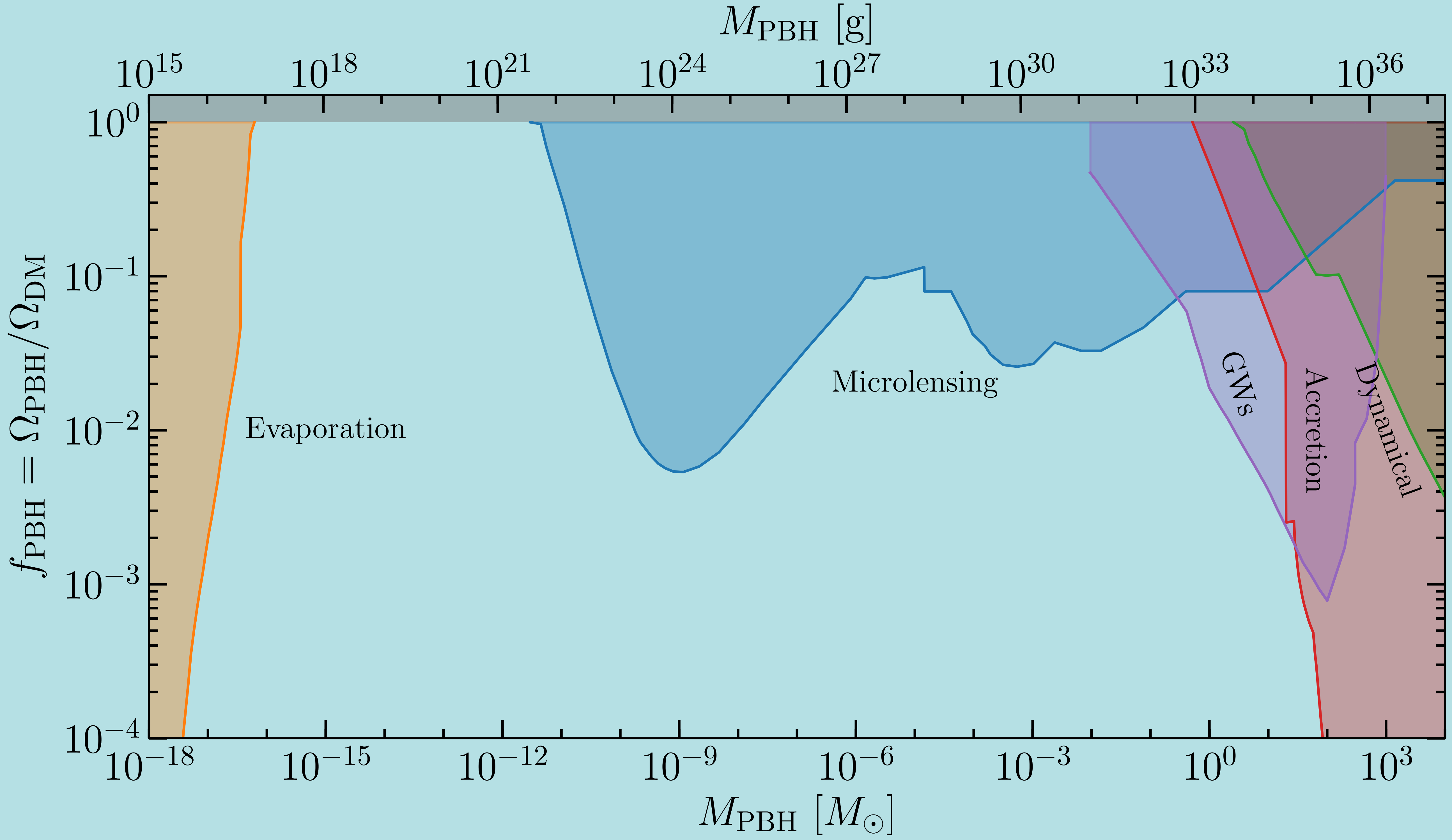
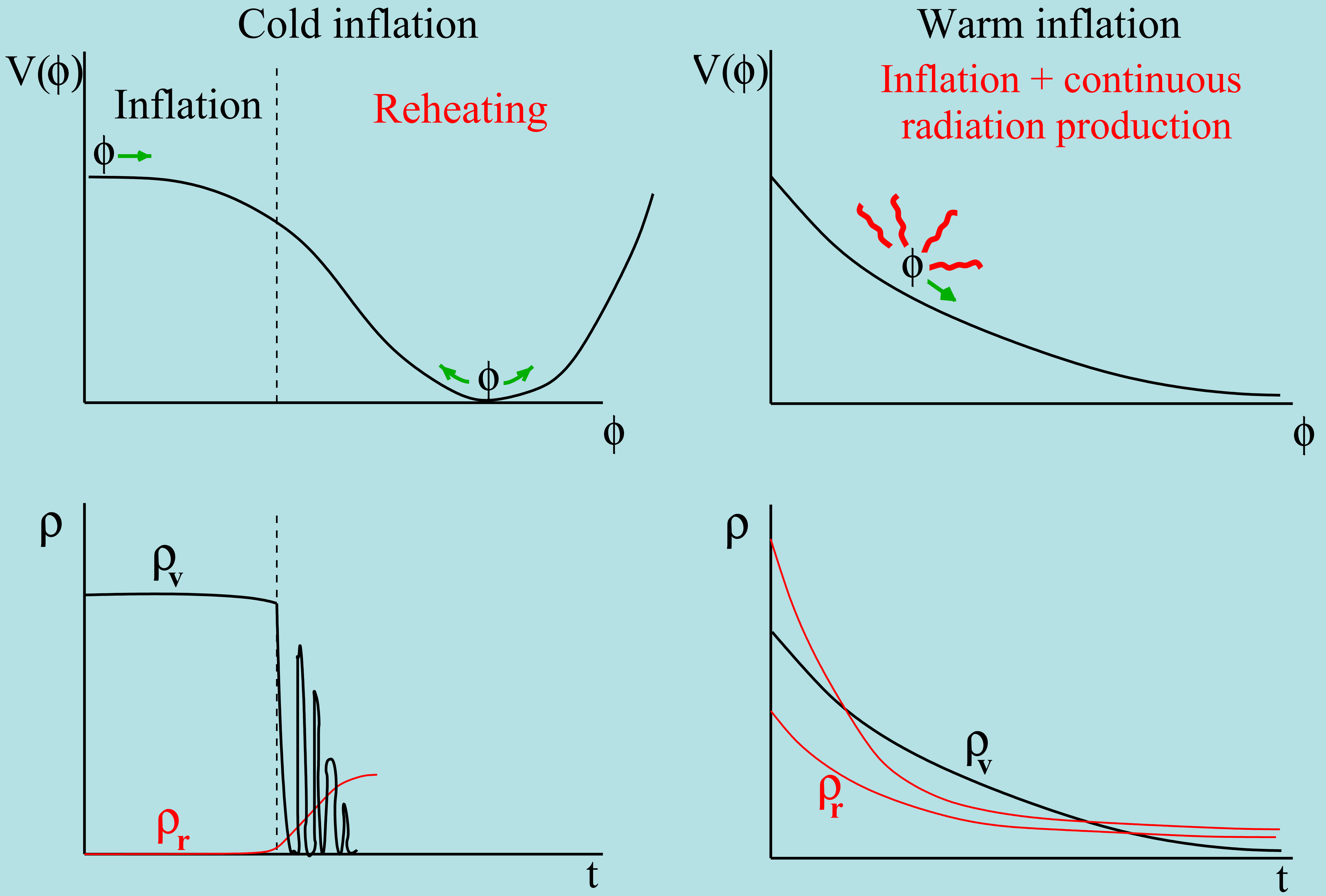


github.com/bradkav/PBHbounds

Warm inflation?

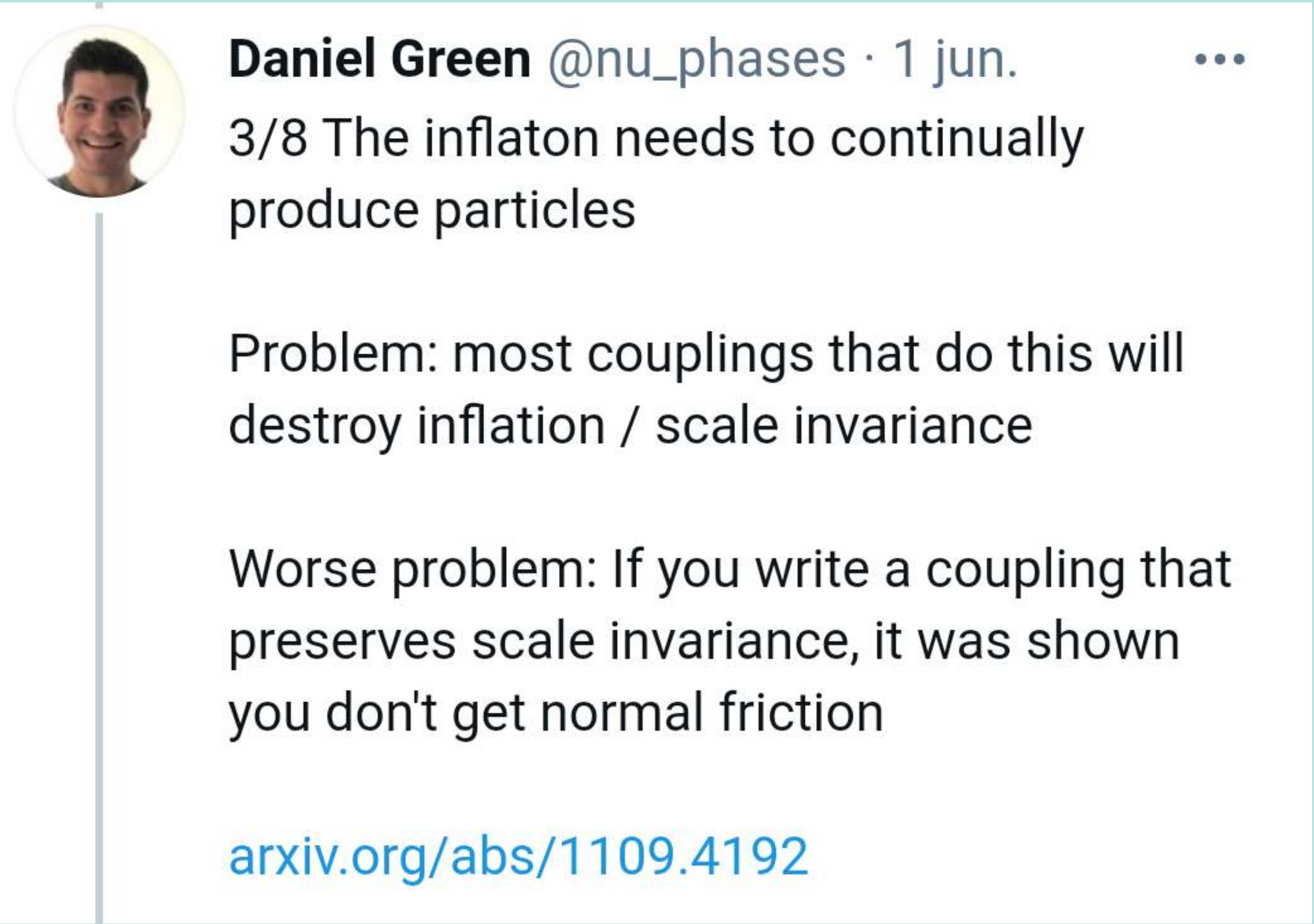


Inflaton slows down by thermal friction

$$\ddot{\Phi} + (3H + \Gamma)\dot{\Phi} + V_\Phi = 0$$
$$\dot{\rho}_r + 4H\rho_r - \Gamma\dot{\Phi}^2 = 0$$

Thermal noise is an extra source of density fluctuations

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



A. Berera, PRL 75 (1995), 3218

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

1. Beyond WIMPs

2. Inflation & reheating

3. FIMPs

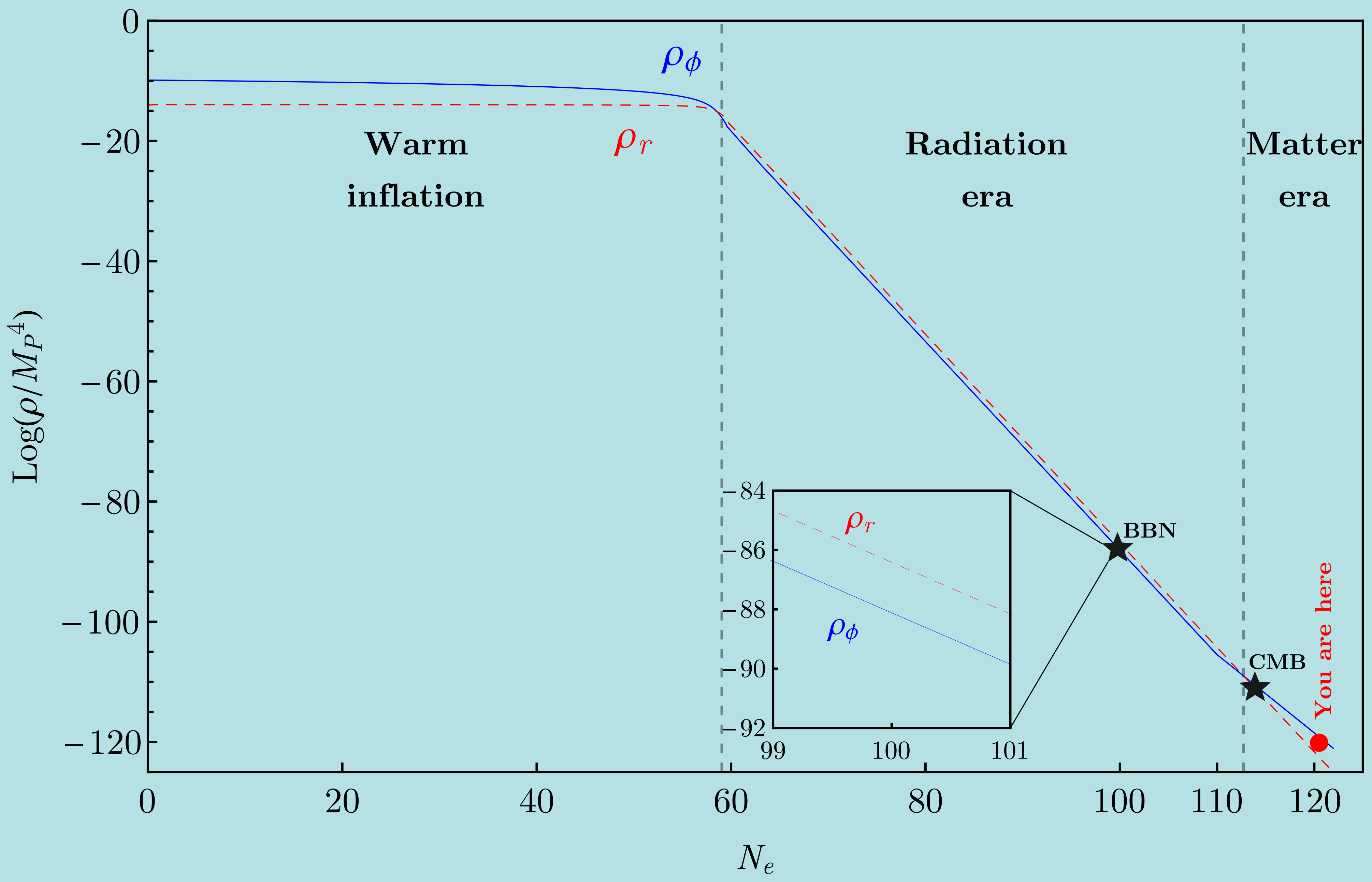
4. Compact objects

5. Prospects

Warm inflation?

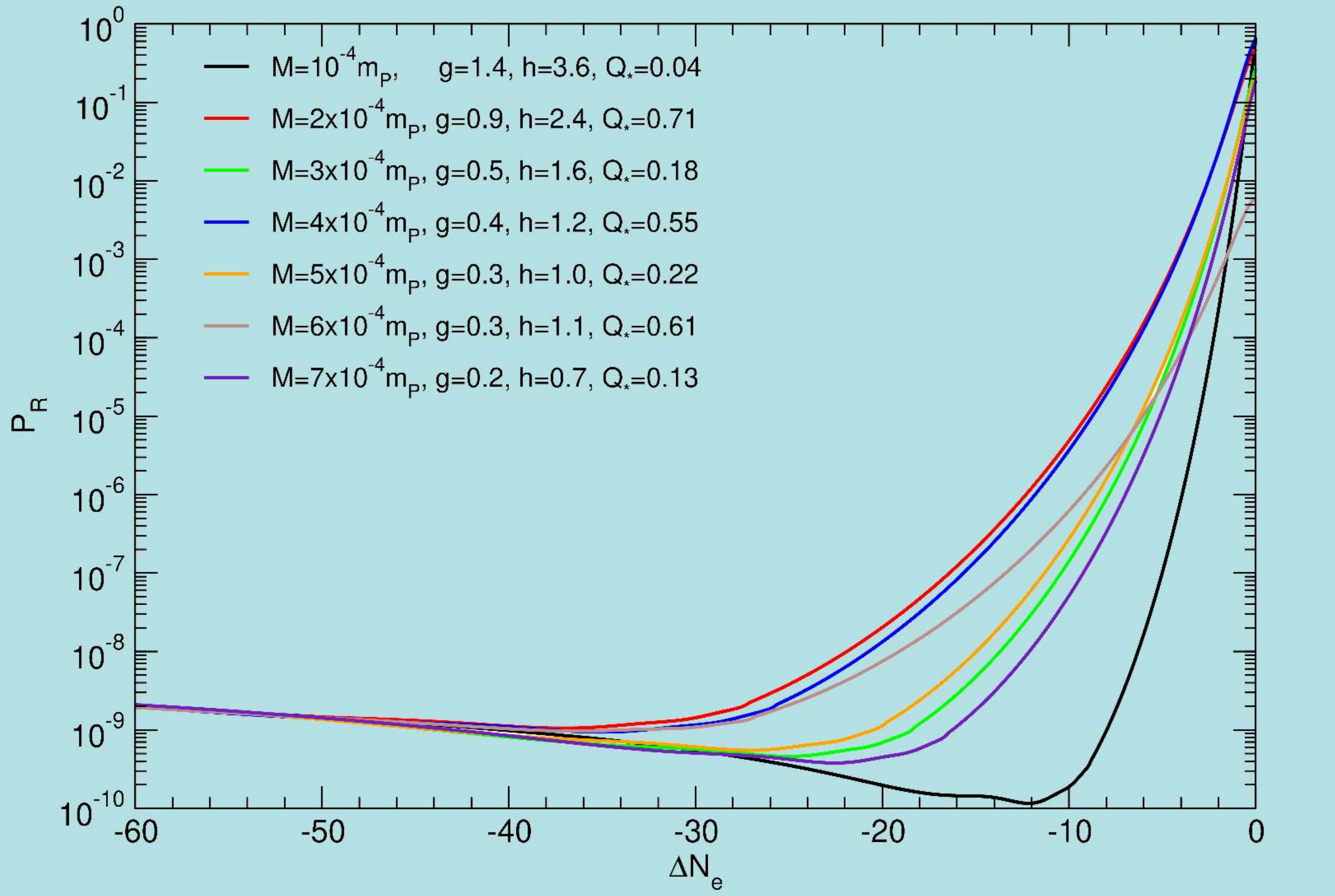
A way around? Warm Little Inflation (Φ as a pseudo-Nambu-Goldstone boson)

Leftover Φ as DM



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

PBH from WLI



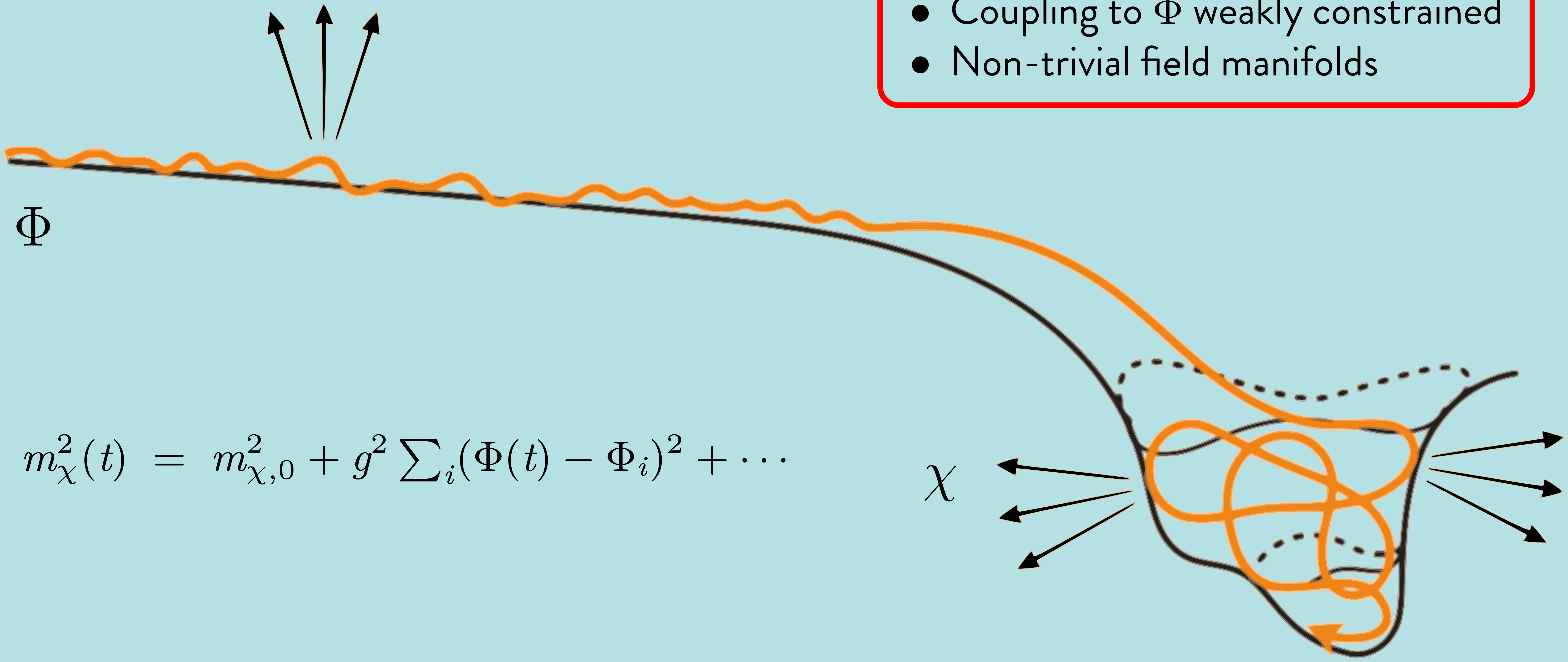
M. Bastero-Gil and M. Díaz-Blanco, arXiv:2105.08045 [hep-ph]

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

Complexity in the early Universe

Particle theory

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



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

1. Beyond WIMPs

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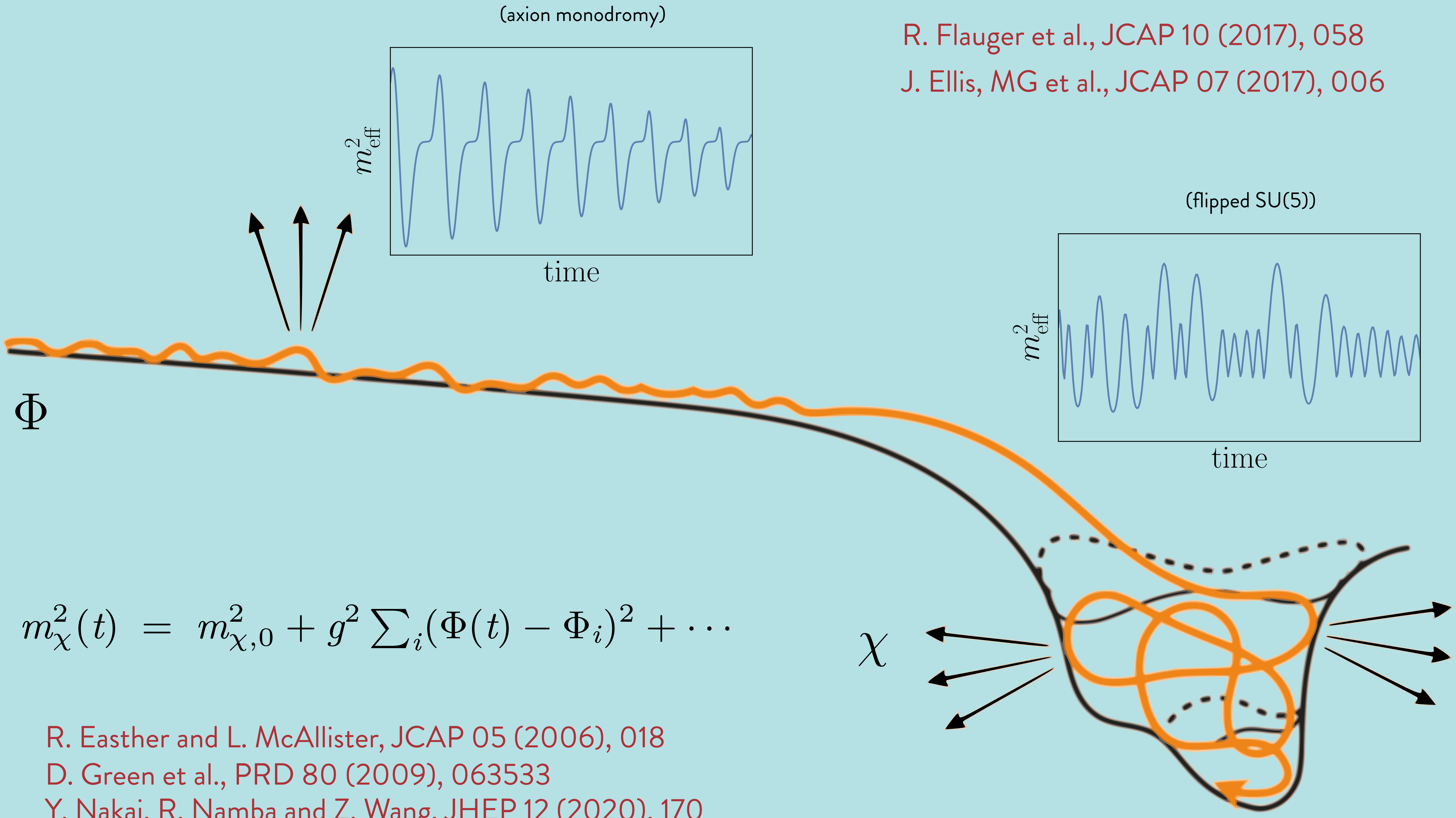
3. FIMPs

4. Compact objects

5. Prospects

Complexity in the early Universe

R. Flauger et al., JCAP 10 (2017), 058
J. Ellis, MG et al., JCAP 07 (2017), 006



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

R. Easther and L. McAllister, JCAP 05 (2006), 018
D. Green et al., PRD 80 (2009), 063533
Y. Nakai, R. Namba and Z. Wang, JHEP 12 (2020), 170

1. Beyond WIMPs

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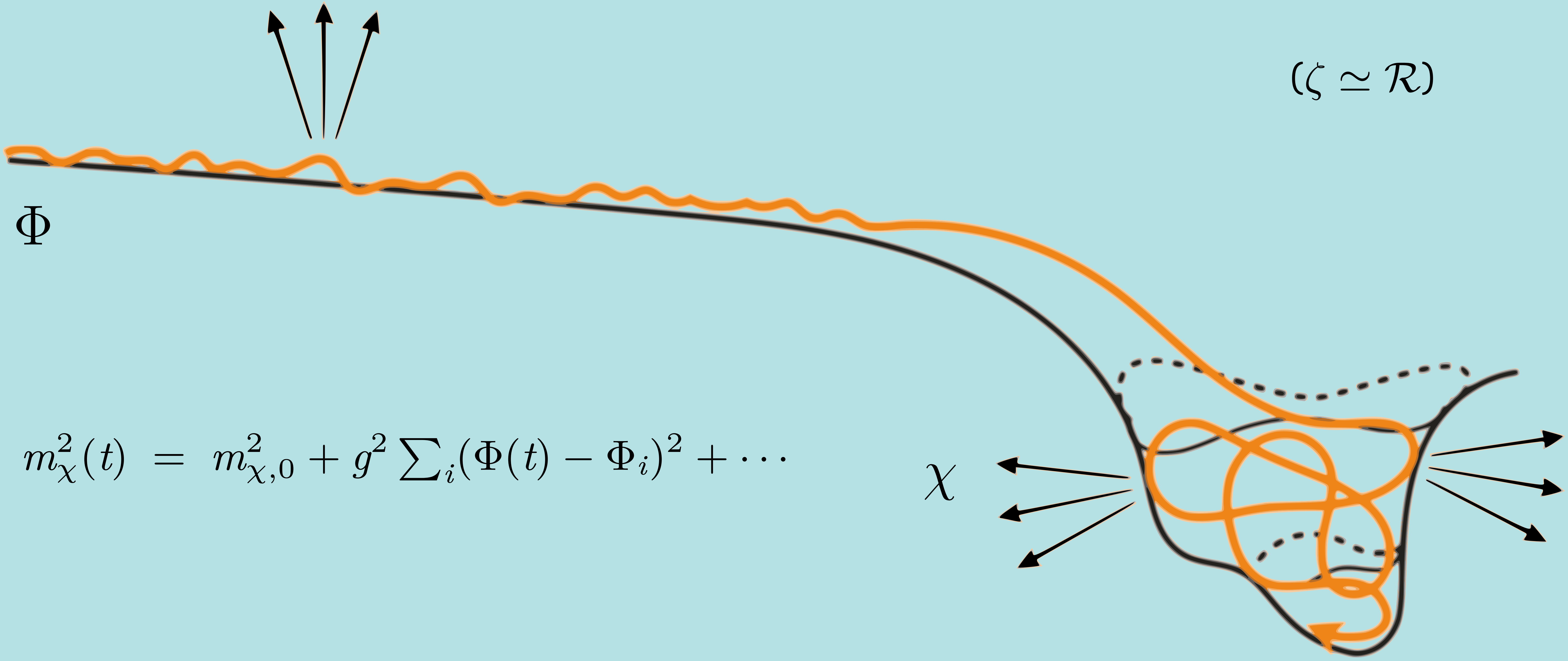
Complexity in the early Universe

background dynamics $\longrightarrow$ particle production $\langle \chi_{\boldsymbol{k}_1} \chi_{\boldsymbol{k}_2} \cdots \rangle$ $\longleftrightarrow$ curvature fluctuations $\langle \zeta_{\boldsymbol{k}_1} \zeta_{\boldsymbol{k}_2} \cdots \rangle$

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



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

1. Beyond WIMPs

2. Inflation & reheating

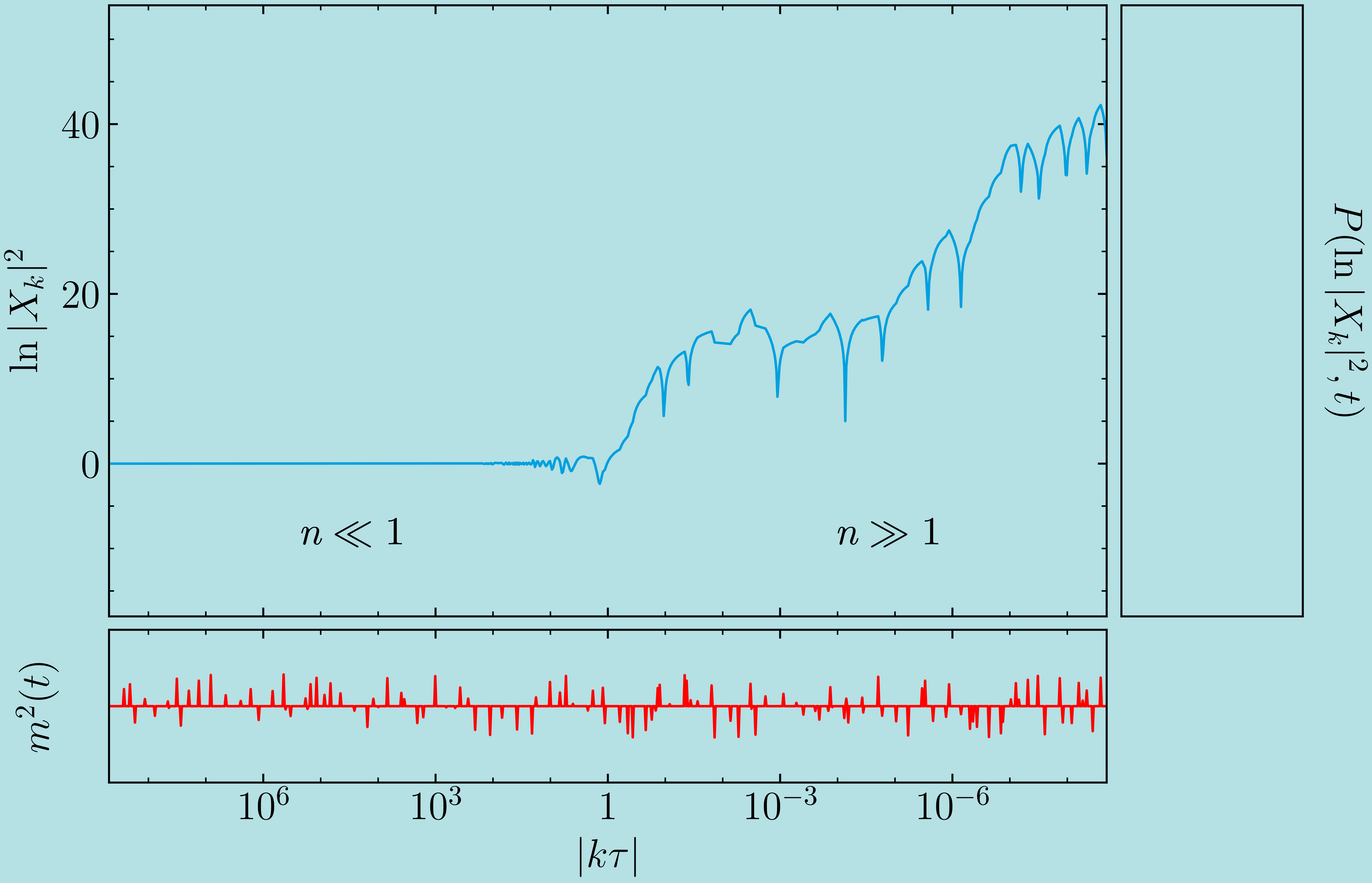
3. FIMPs

4. Compact objects

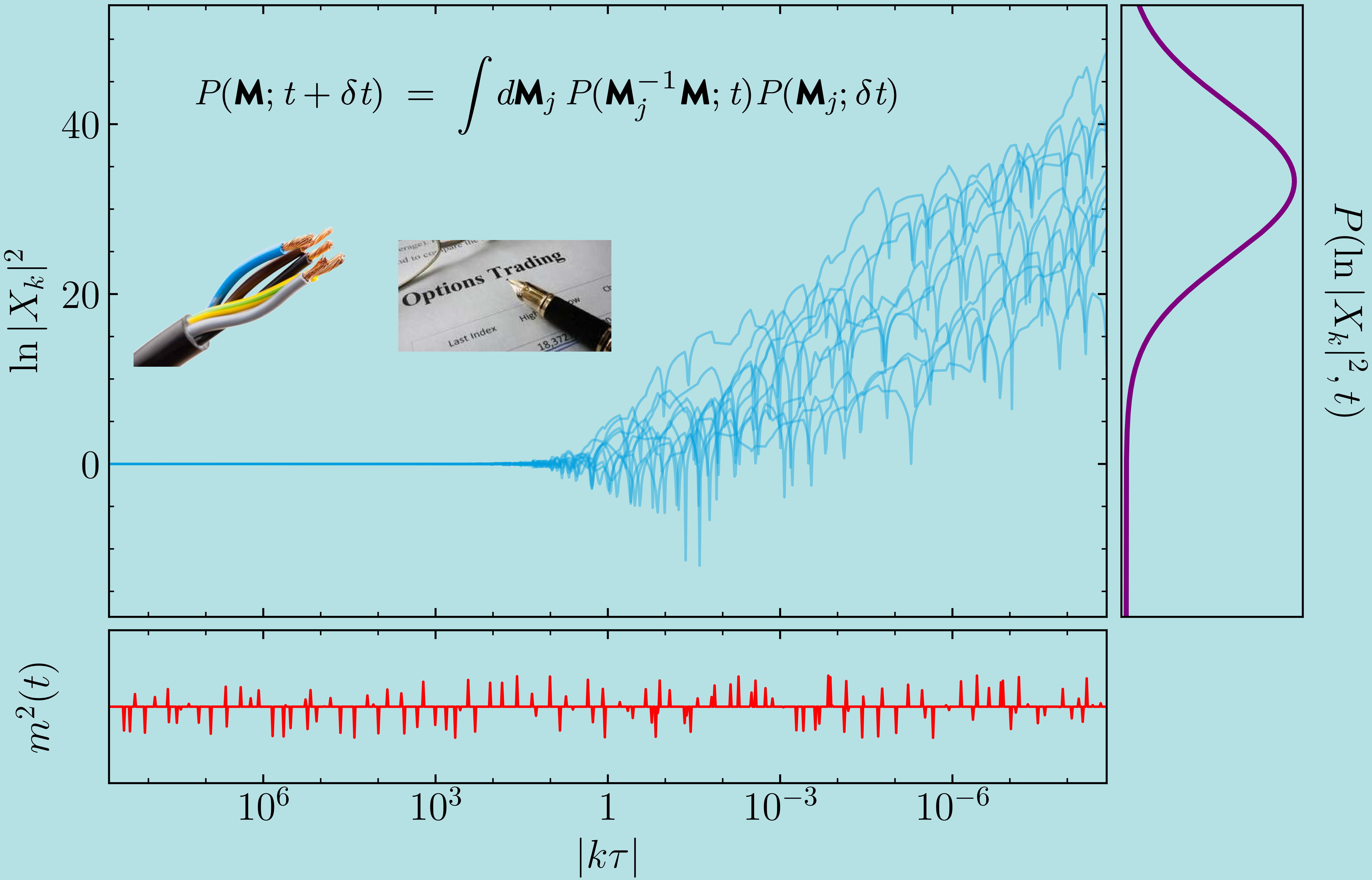
5. Prospects

A (conformal) spectator in dS

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



A (conformal) spectator in dS



1. Beyond WIMPs

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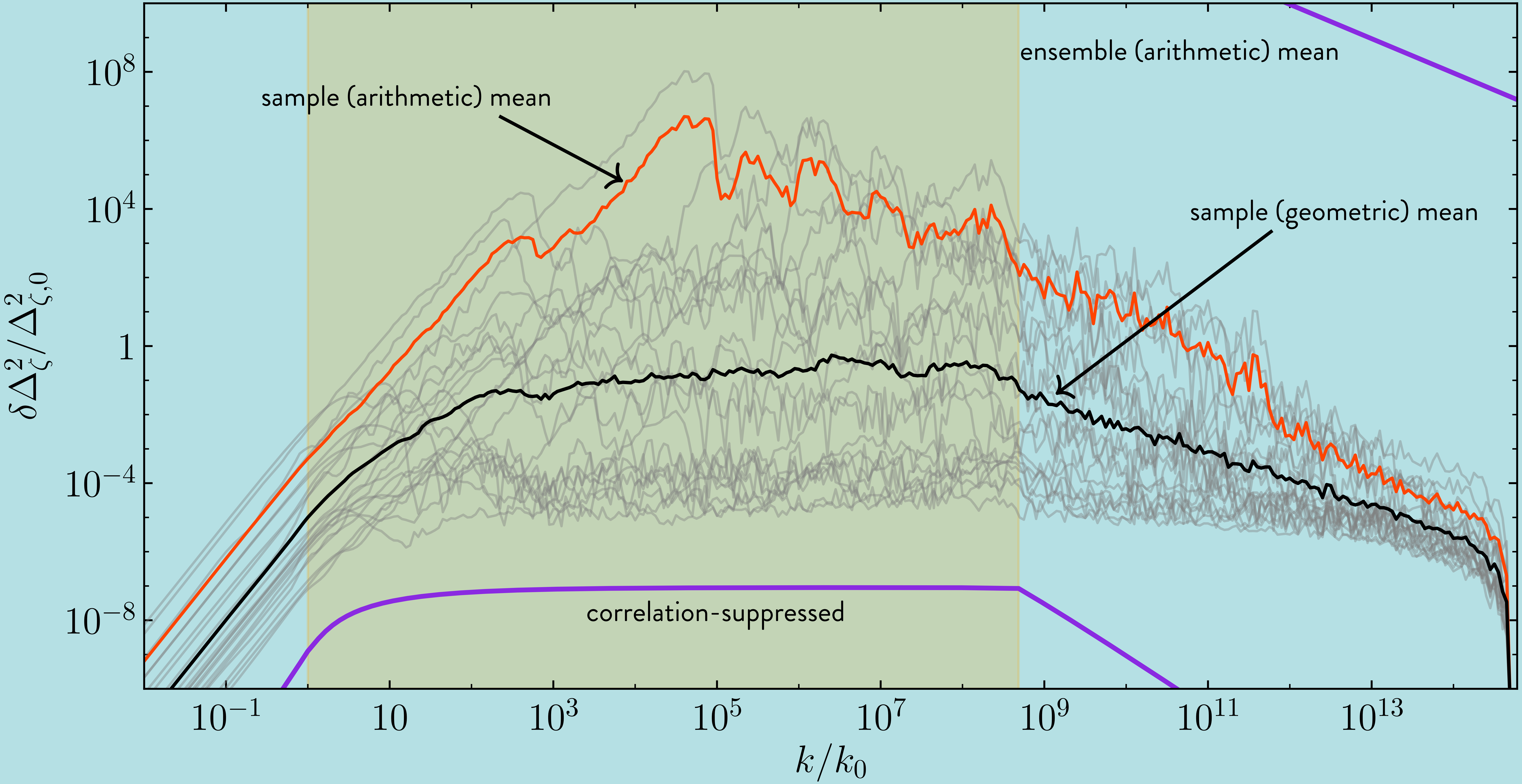
5. Prospects

A stochastically sourced power spectrum

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



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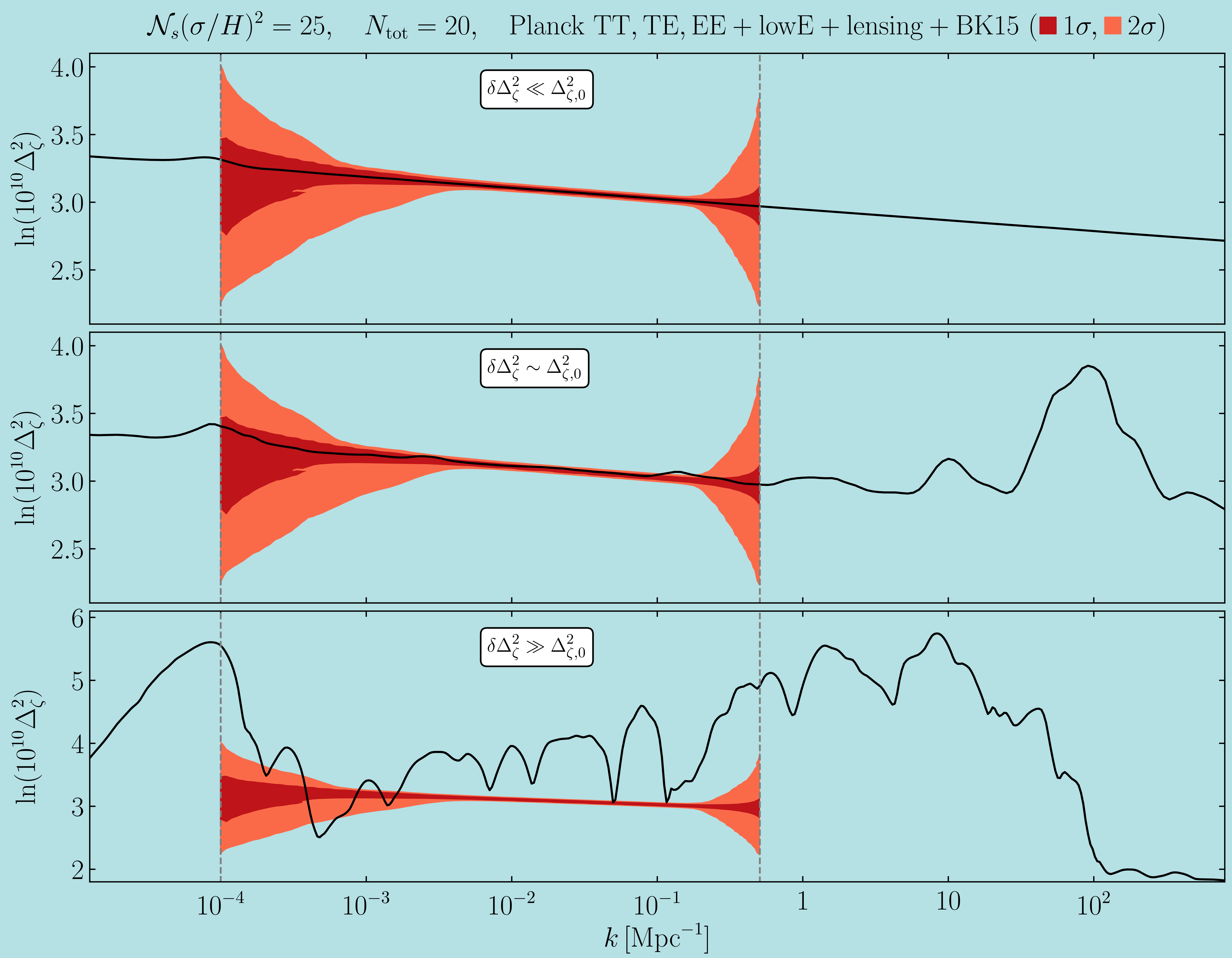

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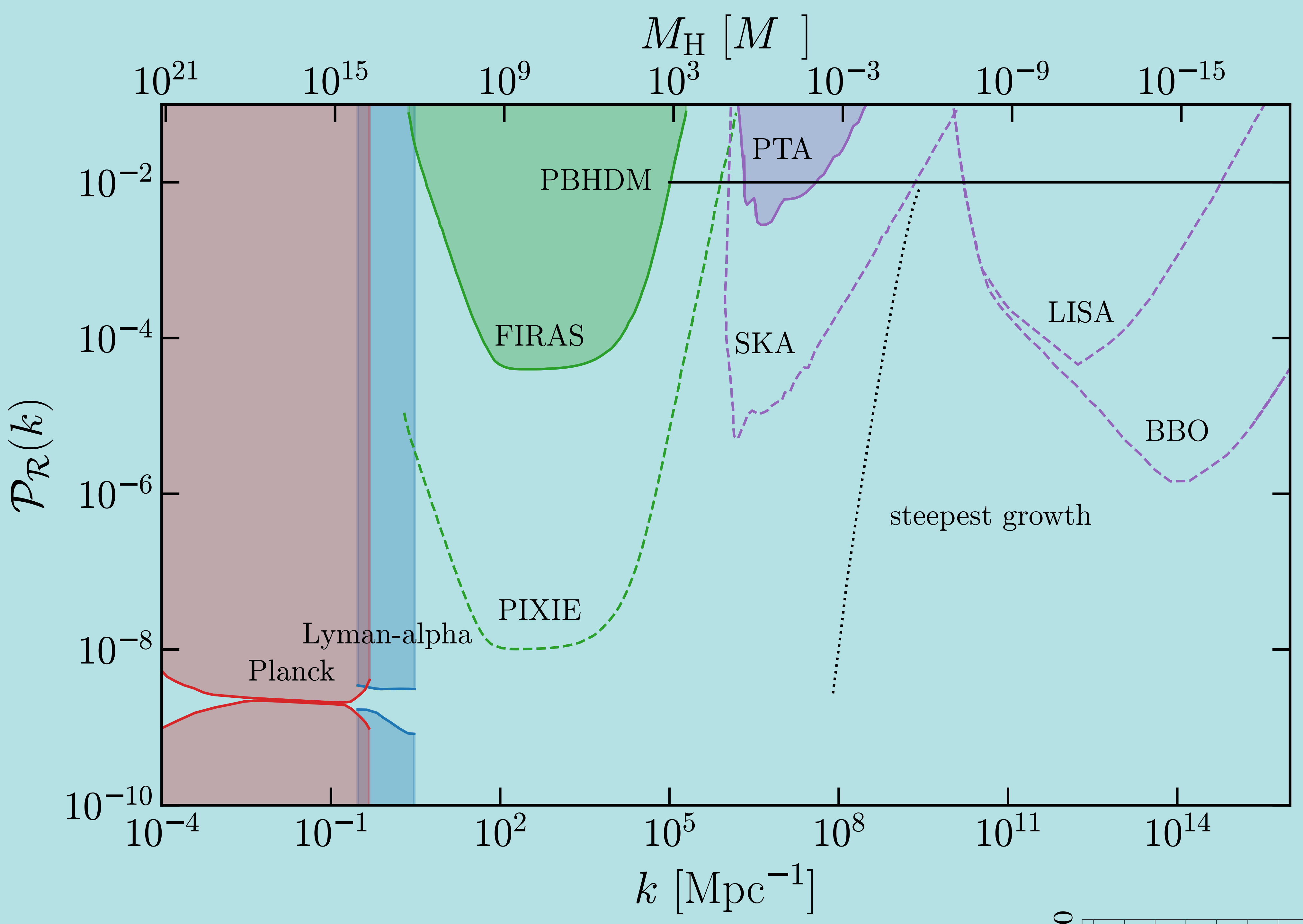
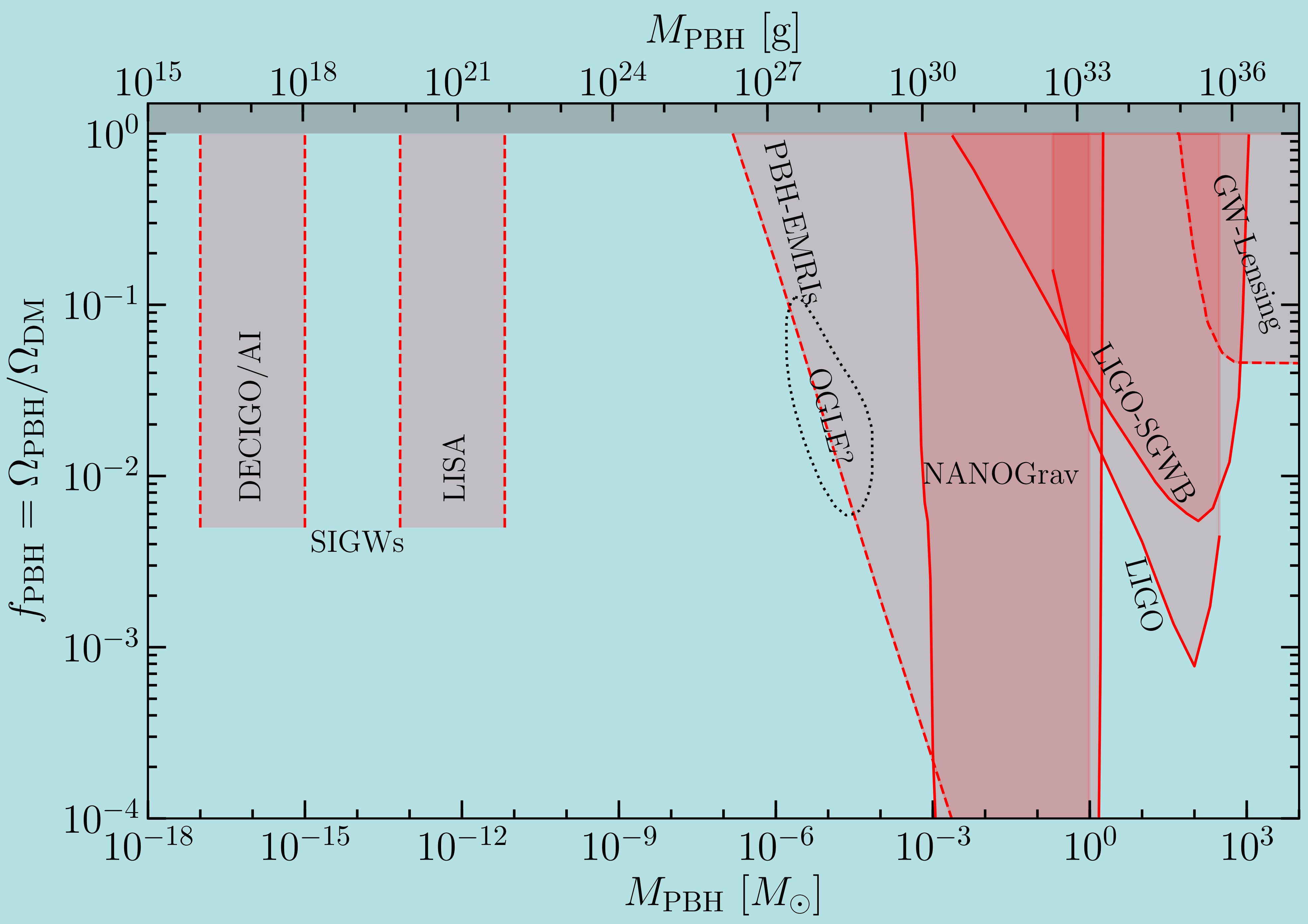
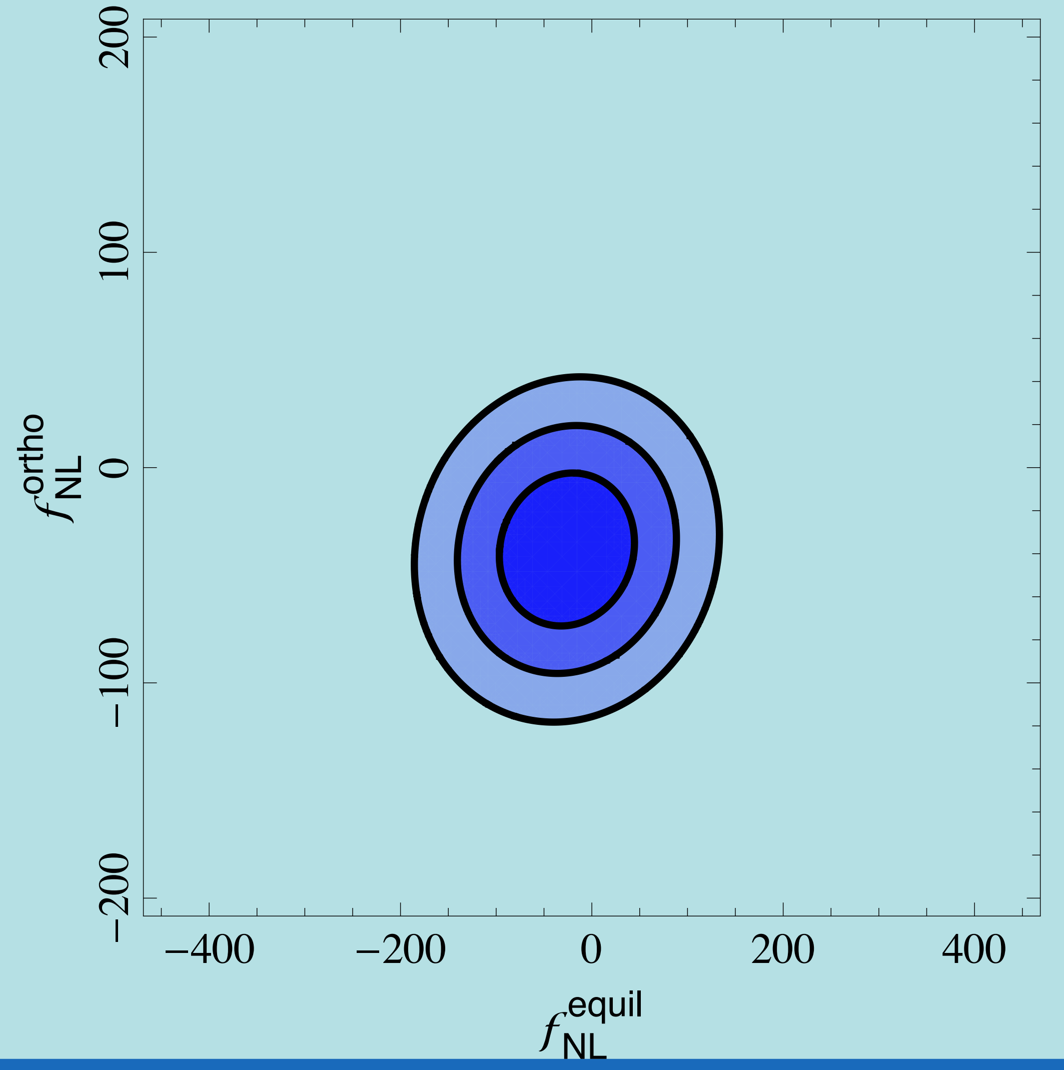
Prospects







1. Beyond WIMPs

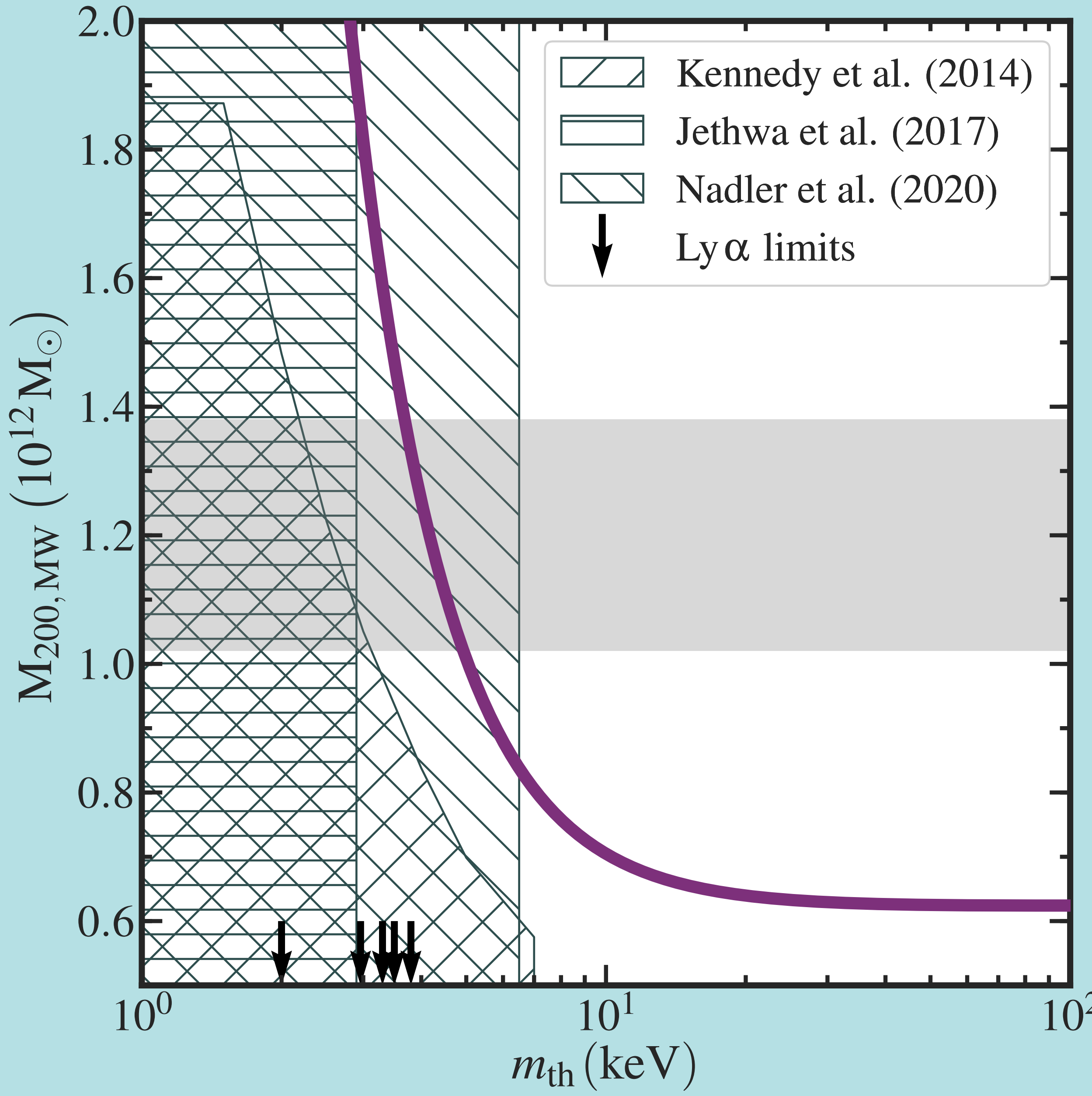
2. Inflation & reheating

3. FIMPs

4. Compact objects

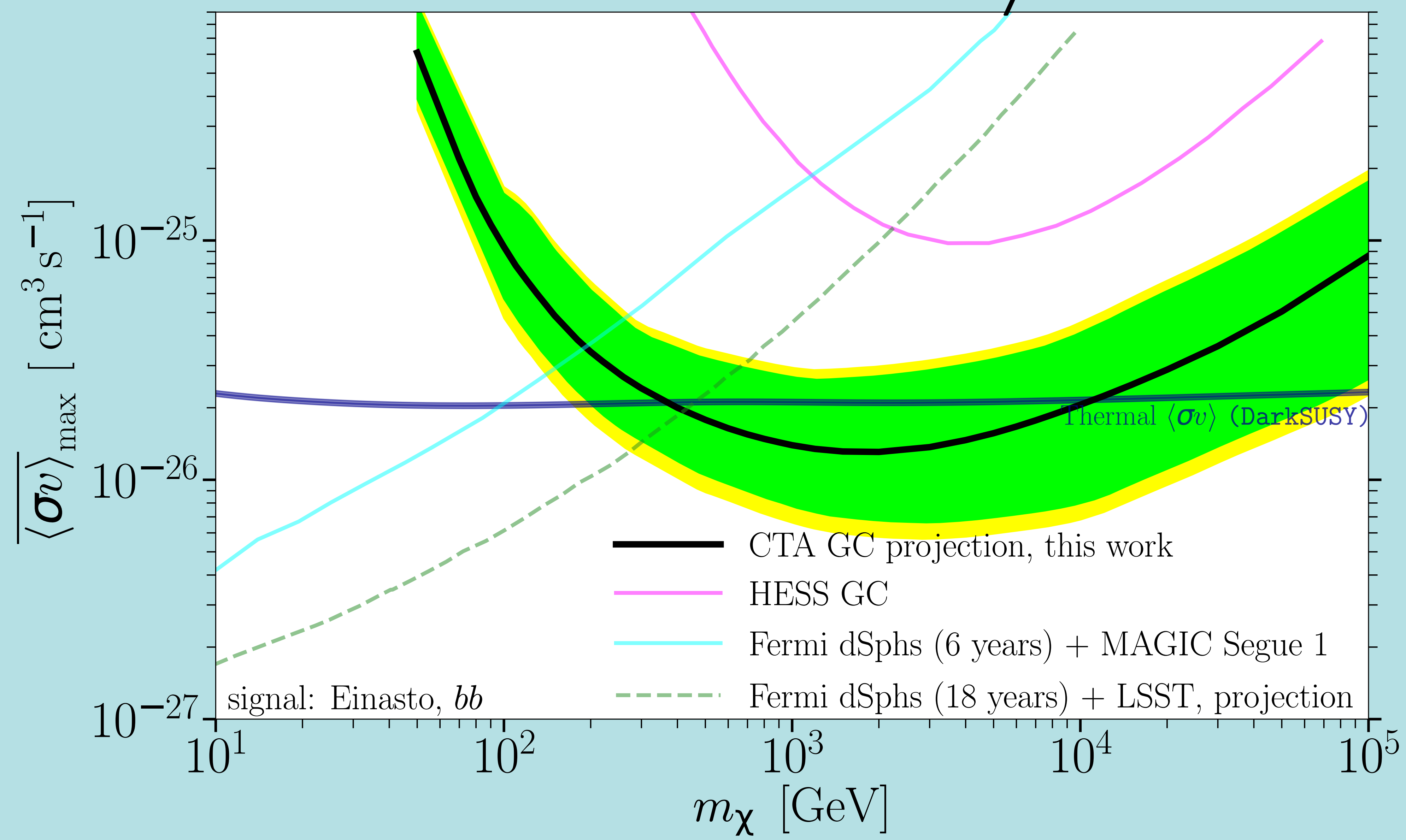
5. Prospects

MW satellites



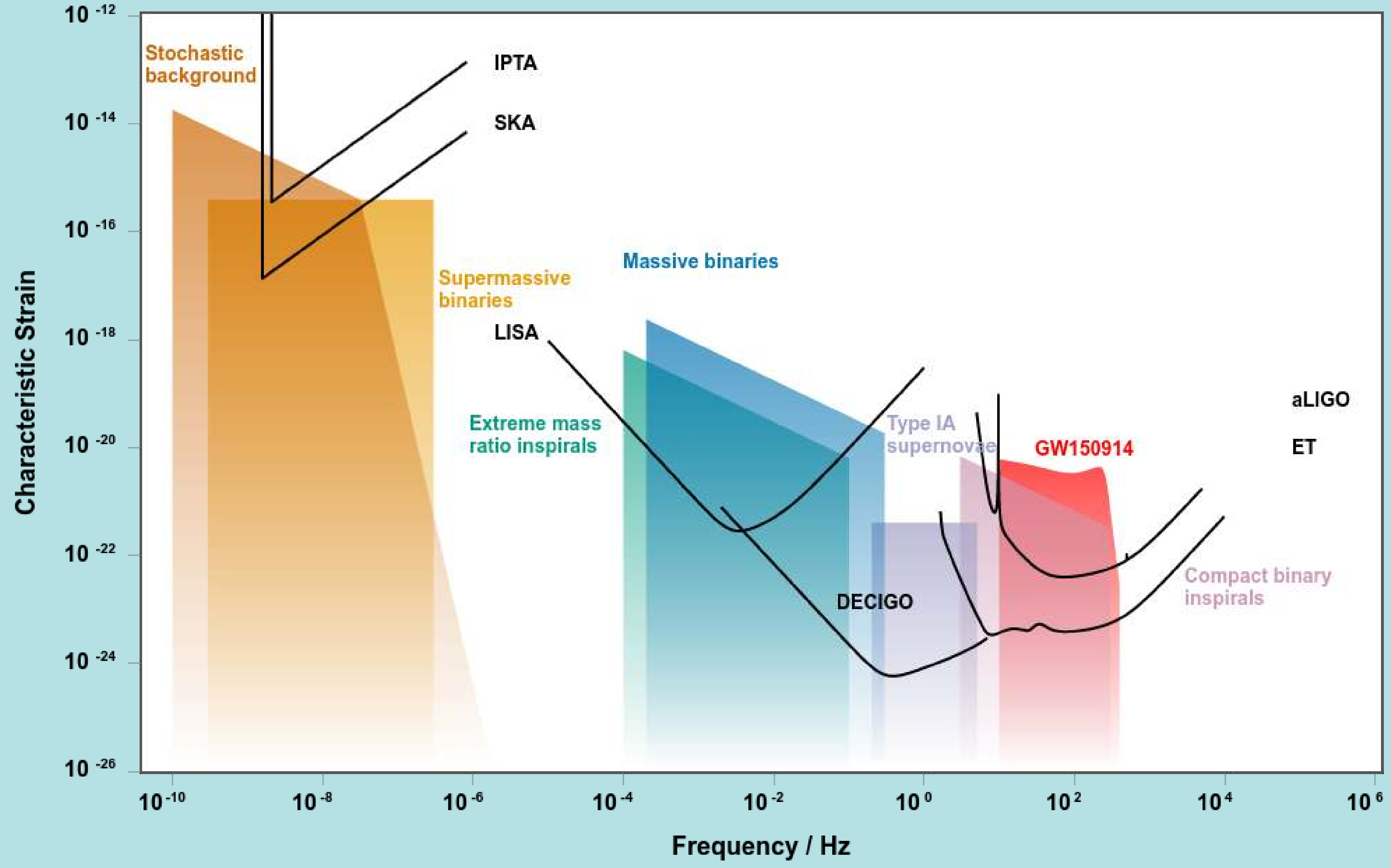
O. Newton et al., arXiv:2011.08865

Annihilation/decay



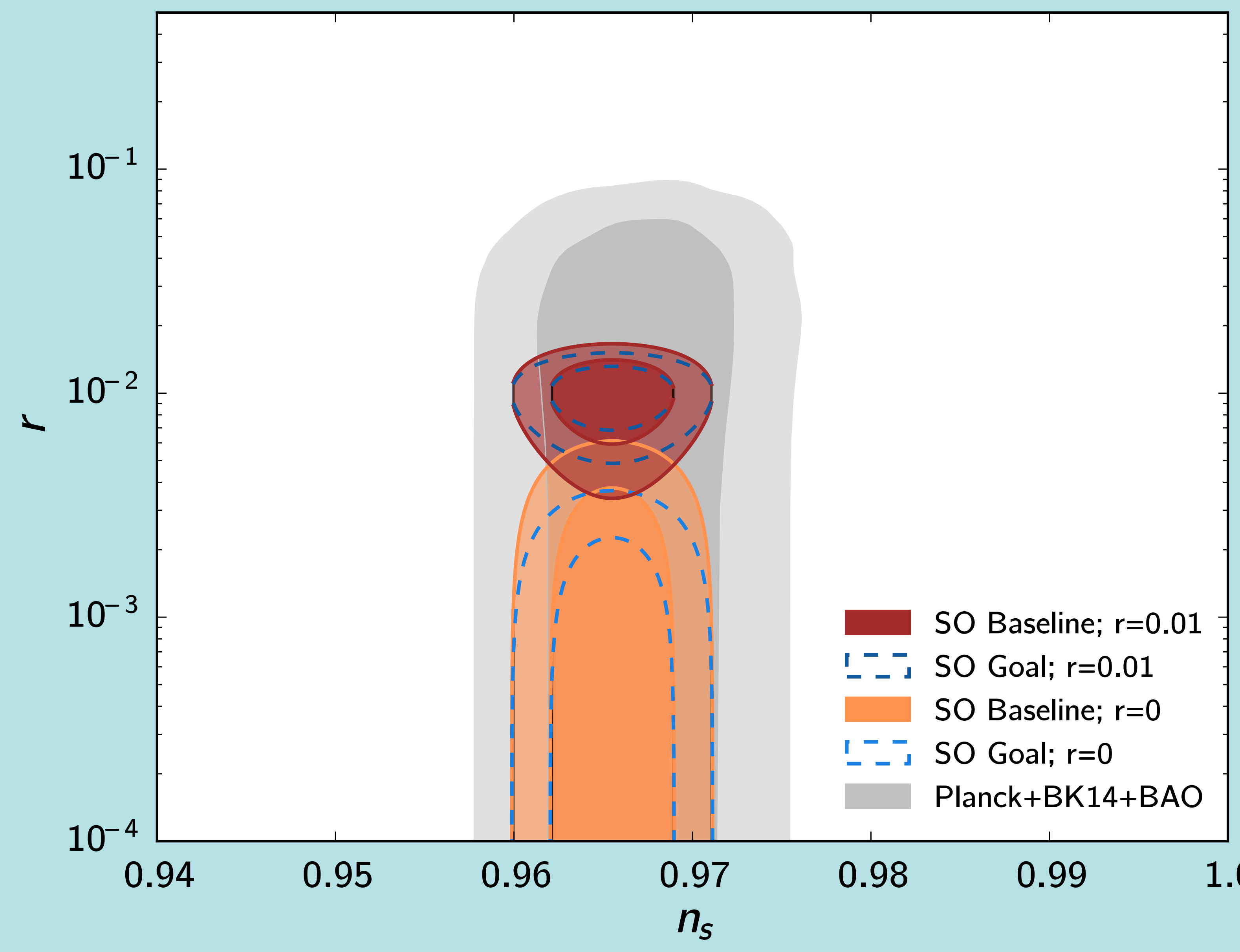
CTA, JCAP 01 (2021), 057

GWs



gwplotter.com

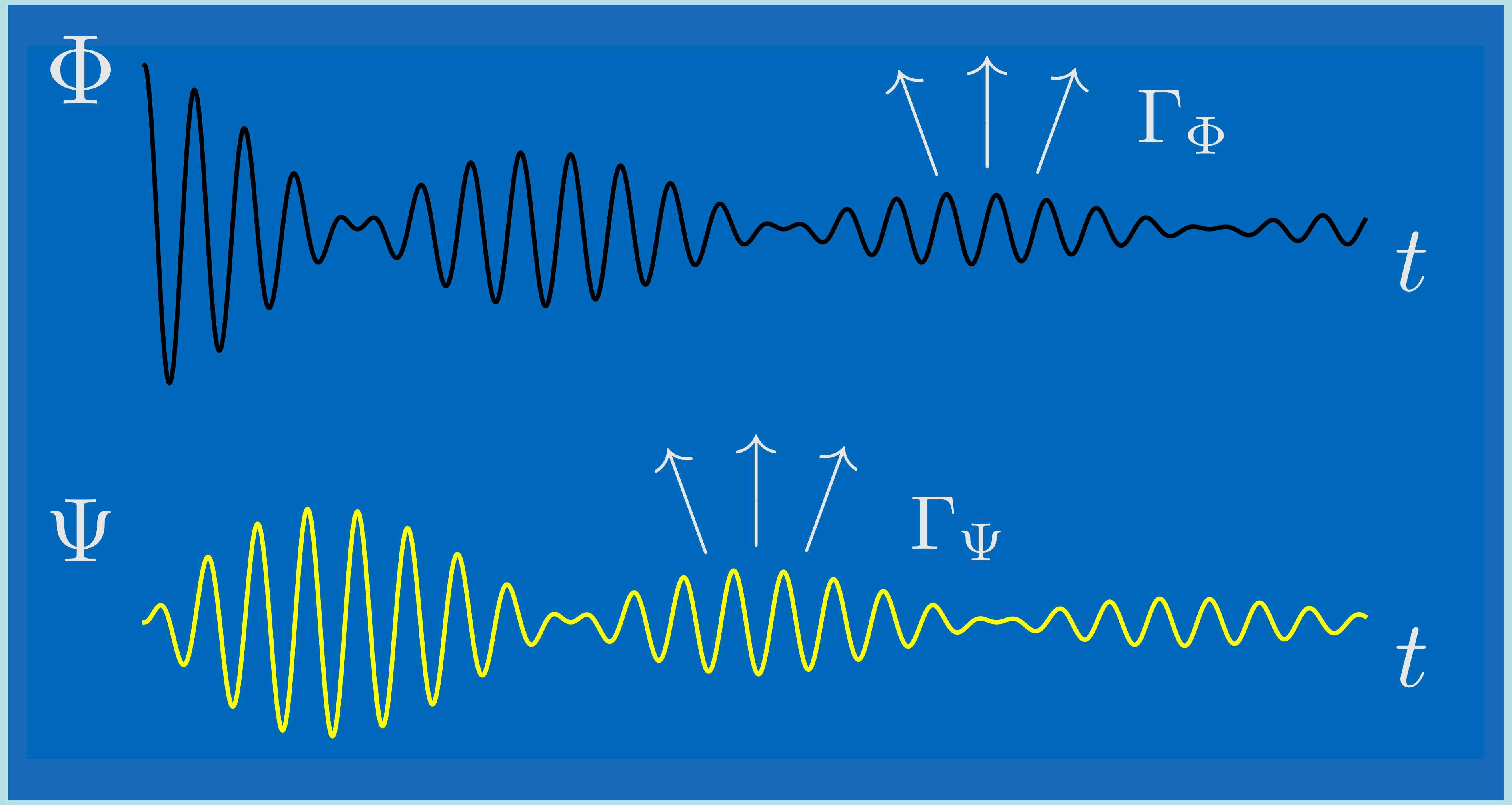
CMB



Simons Observatory, JCAP 02 (2019), 056

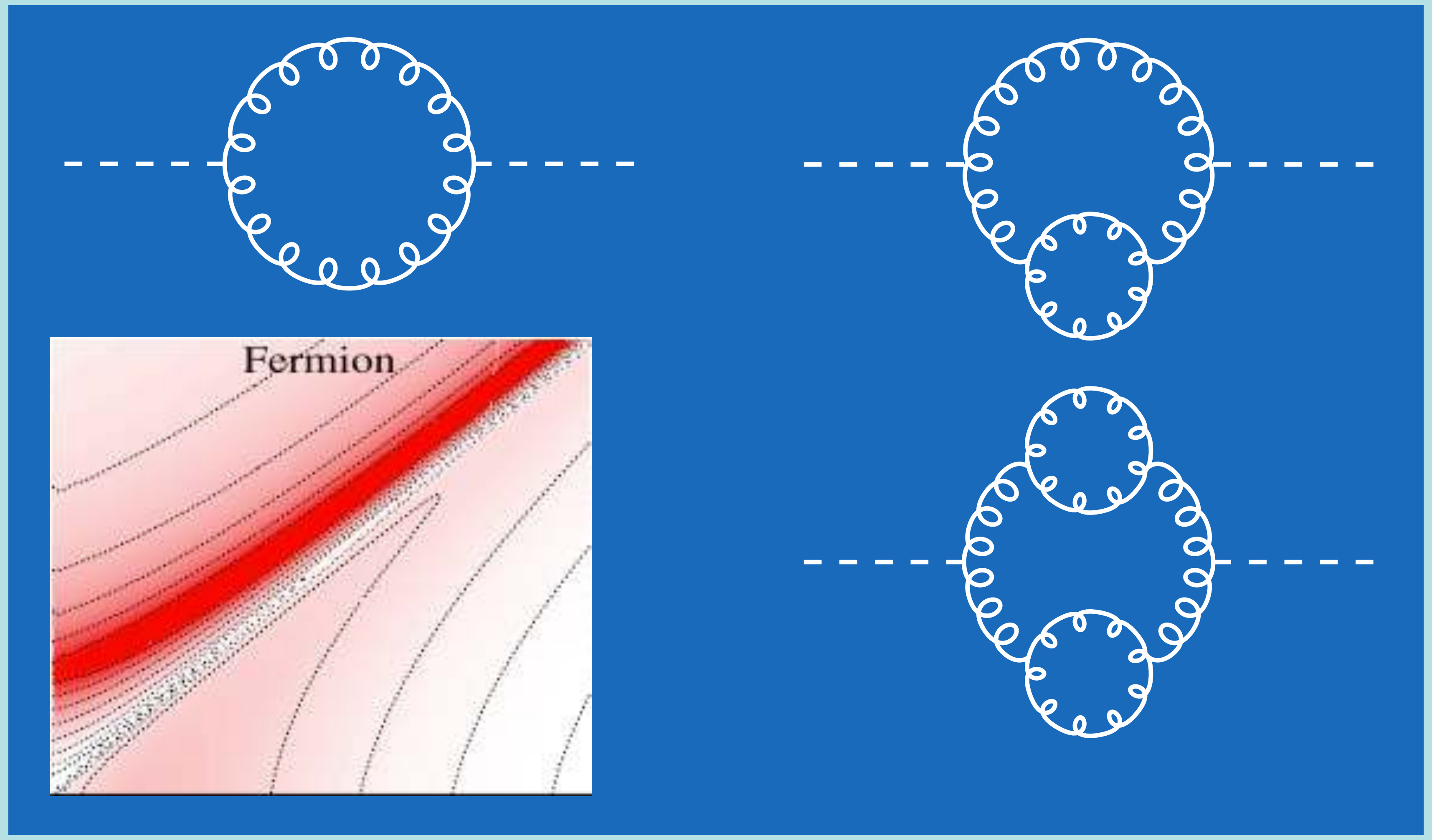
Reheating + BSM is not always simple

Multifield effects



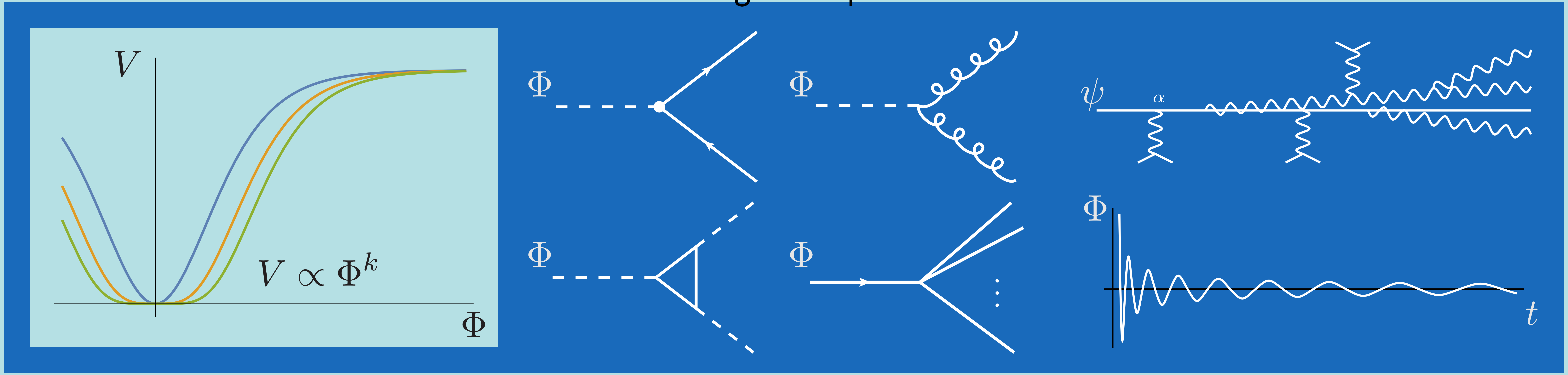
J. Ellis, MG, N. Nagata, D. Nanopoulos and K. Olive, JCAP 07 (2017), 006

In-medium effects



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

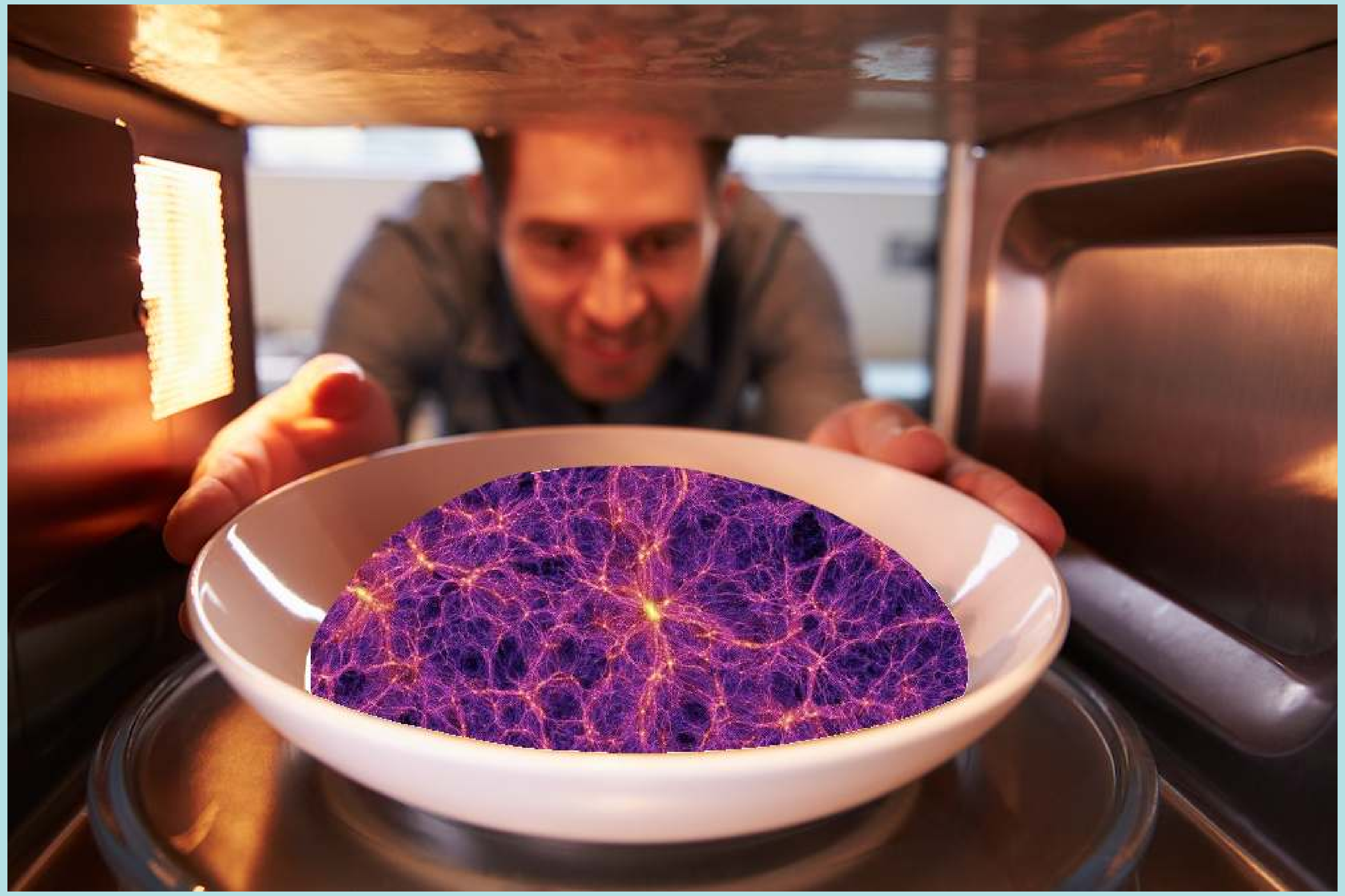
More general potentials



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

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, …)



谢谢!