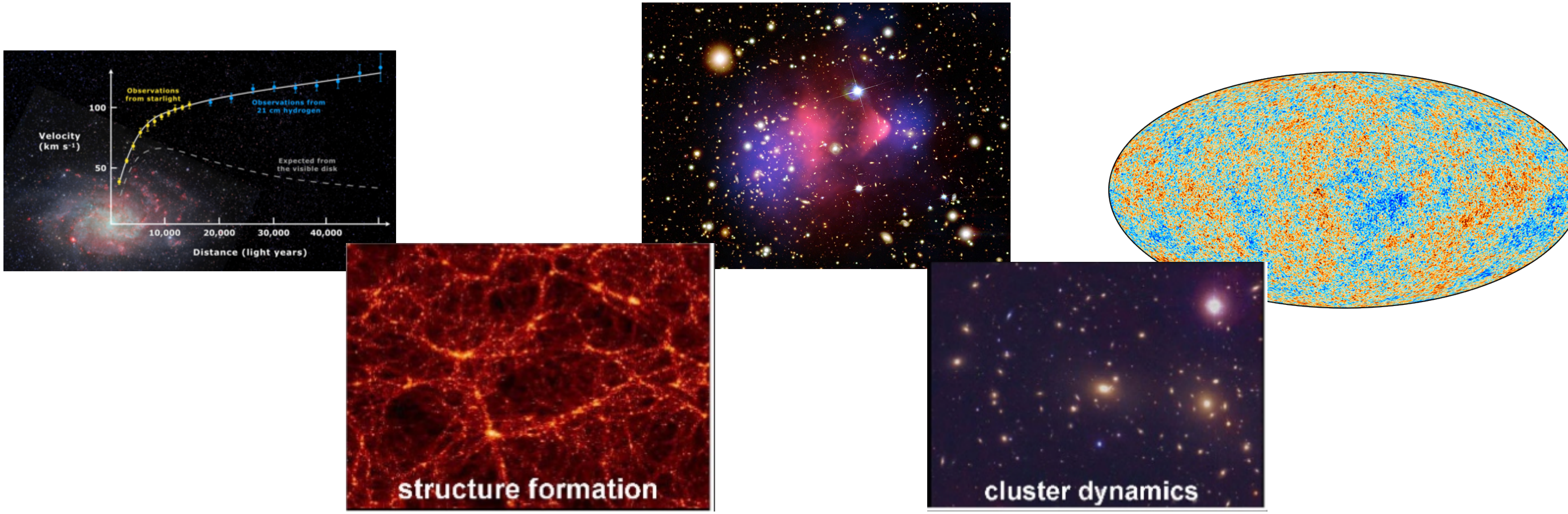
INFN

Gravitational Production of Dark Matter

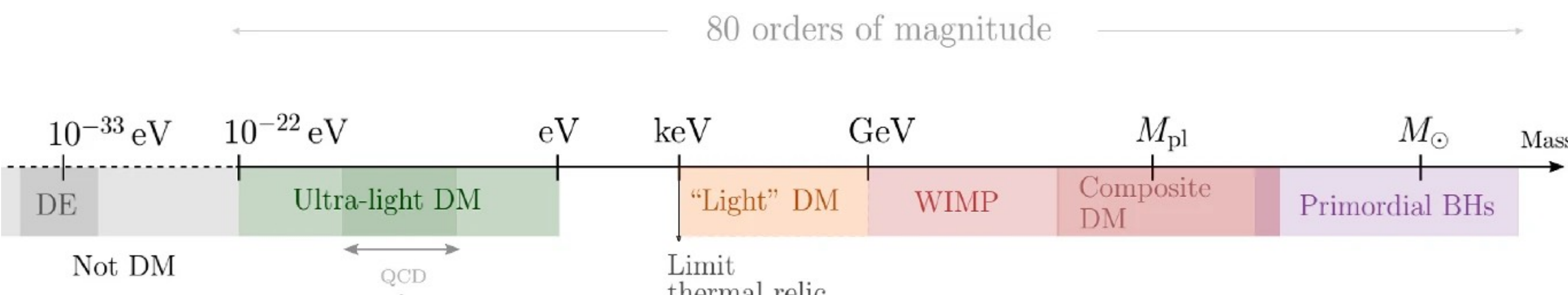
Based on 2011.10565, 2204.14274, 2211.06421
with Andrea Tesi

Pisa - 25 January 2023

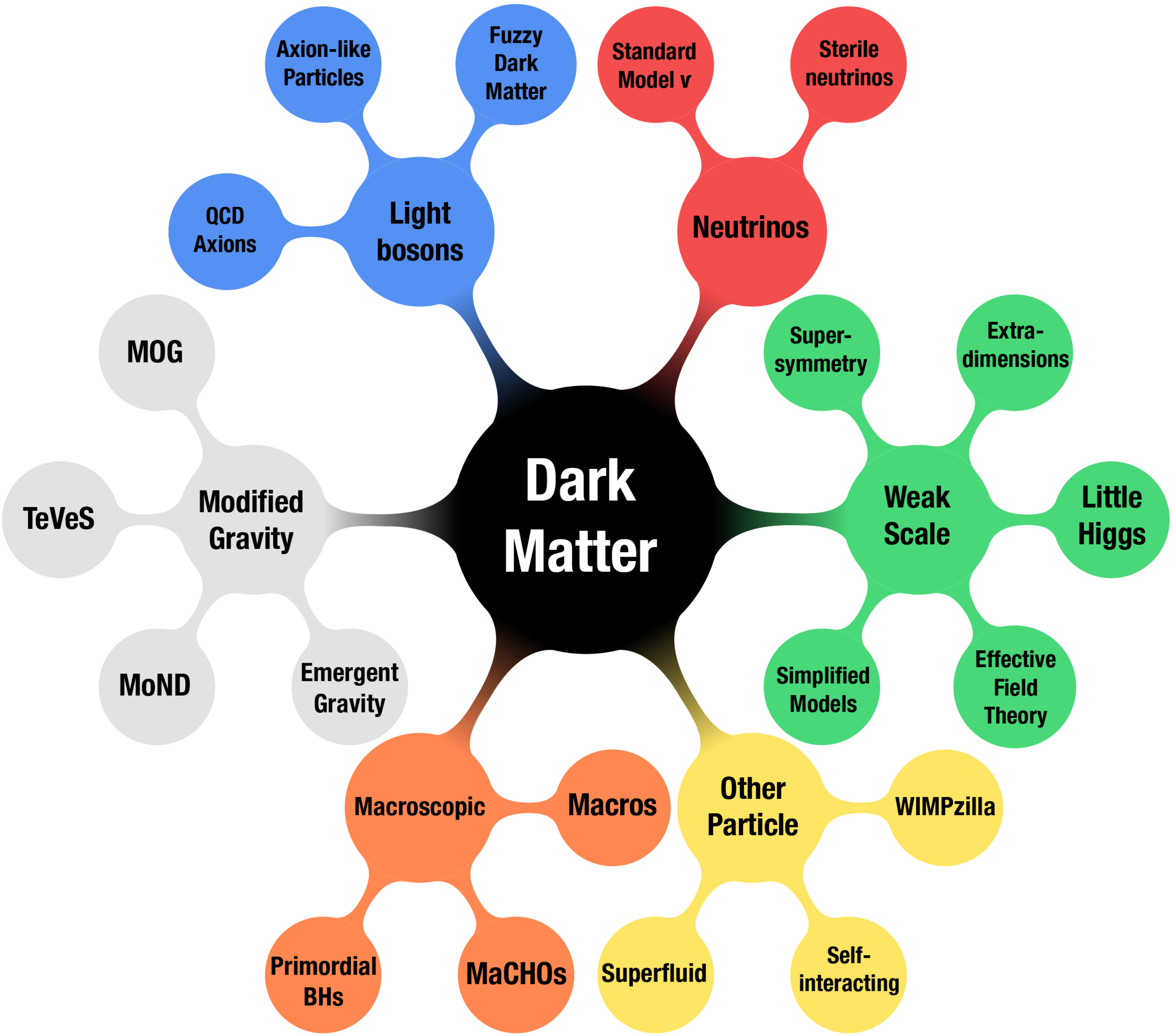


There is extraordinary evidence for the existence of a new non-baryonic cold component of matter — DARK MATTER:

- All evidences are inferred through gravity.
- We don't know what DM is made of and its mass

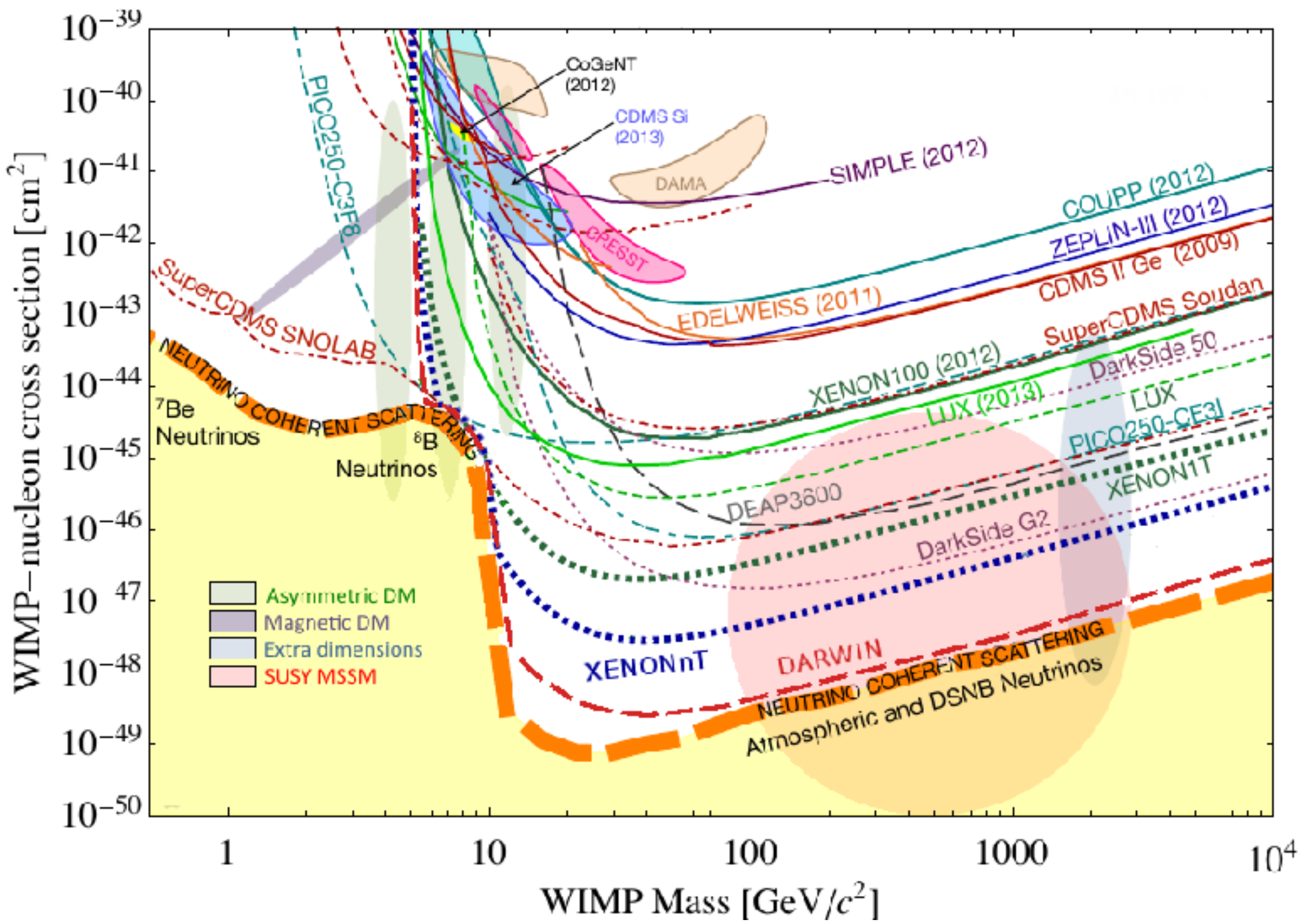


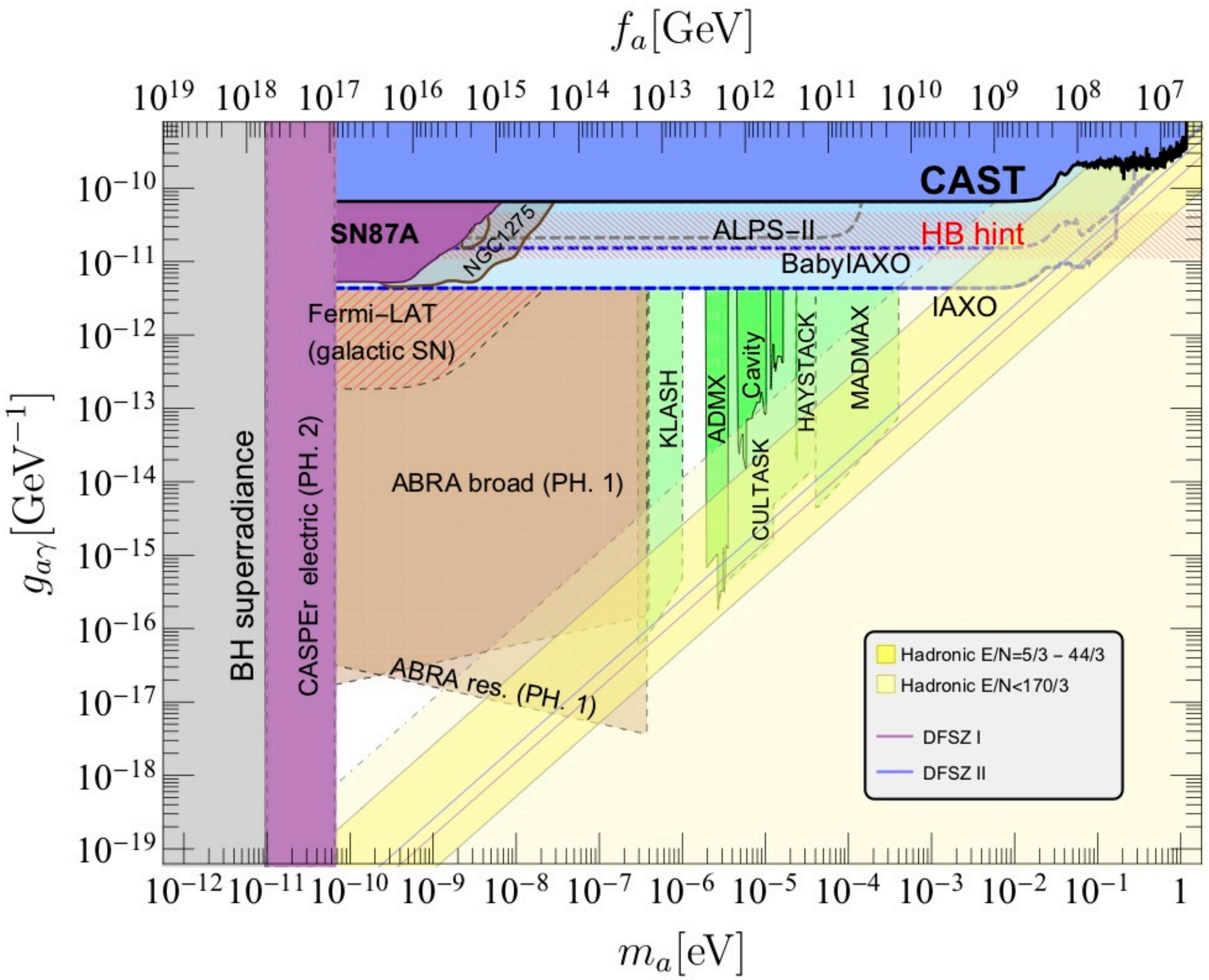
DM LANDSCAPE



Need some guidance!

It would be great if DM had interactions with SM:





Is this wishful thinking?

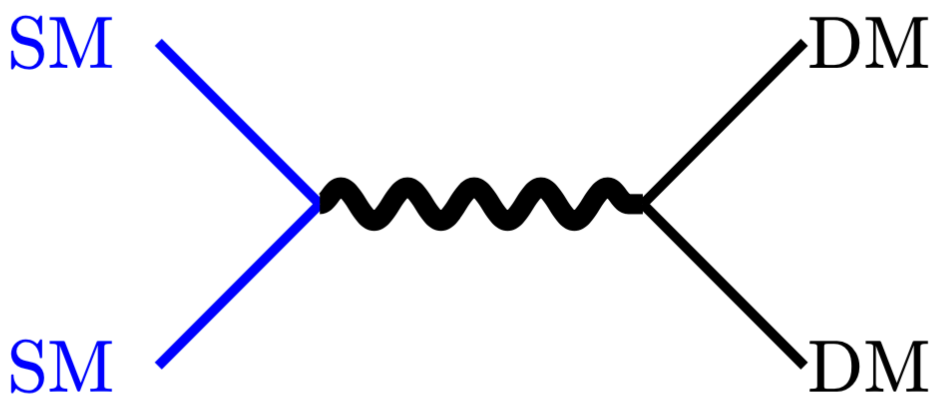
What if DM interacts only gravitationally?

Gravitational freeze-in

- 2011.10565 with A. Tesi

- Tree level gravity:

[Garny-Sandora-Sloth '15]



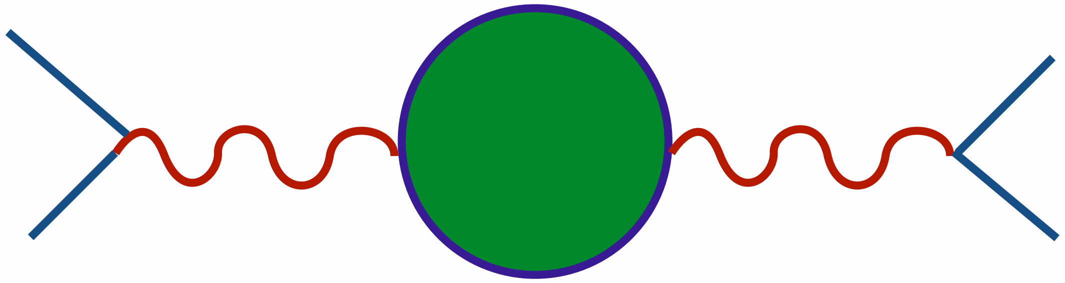
$$\mathcal{A} = \frac{1}{M_p^2 s}\left(T^{\rm SM}_{\mu\nu}T^{\rm DM}_{\alpha\beta}\eta^{\mu\alpha}\eta^{\nu\beta} - \frac{1}{2}T^{\rm SM}T^{\rm DM}\right)$$

$$\frac{dY_D}{dT} = \frac{\langle\sigma v\rangle s(T)}{HT}(Y_D^2 - Y_{\rm eq}^2)$$

$$Y_D(0) = \int_0^{T_R}\frac{dT}{T}\,\frac{\langle\sigma v\rangle s}{H}Y_{\rm eq}^2$$

$$\langle\sigma v\rangle = 4\langle\sigma_0 v\rangle + 45\langle\sigma_{1/2}v\rangle + 12\langle\sigma_1 v\rangle$$

X-sec can be obtained through the optical theorem:



$$\sigma_{tot}(s) = \frac{\mathrm{Im}[\mathcal{A}(s)]_{\mathrm{forward}}}{\sqrt{s(s-4M^2)}}$$

$$\mathcal{A} \sim T_{SM} \frac{1}{p^2} \langle T(p) T(-p) \rangle \frac{1}{p^2} T_{SM}$$

In relativistic regime:

$$\langle T(p) T(-p) \rangle \sim c\, p^4 \log(-p^2)$$

$$\rho_D \approx 5 \cdot 10^{-4}\, c_D \left(\frac{T_R}{M_p} \right)^3 T^4$$

Free theory:

$$\frac{\Omega h^2}{0.12} = \frac{Y_D M}{0.4\,\mathrm{eV}} \approx \frac{c_D M}{2 \cdot 10^6\,\mathrm{GeV}} \left(\frac{T_R}{10^{15}\,\mathrm{GeV}} \right)^3$$

Glueball DM

[see 1710.06447]

A very minimal scenario for DM is a decoupled ``pure glue" gauge theory. Simplest example is $\mathrm{SU}(3)$:

$$\frac{M_{\rm DG}}{\Lambda} \approx 5.5 \qquad\qquad \frac{L_h}{\Lambda^4} \approx 1.4$$

Lightest glueball is an accidentally stable CP even scalar.
It decays at least to gravitons:

$$\tau \sim \frac{M_p^4}{M_{\rm DG}^5} \sim 10^{19}\,{\rm s}\left(\frac{10^6\,{\rm GeV}}{M_{\rm DG}}\right)^5$$

This scenario requires $\mathrm{T}_D \ll T$ to avoid structure formation and self-interaction constraints ($\sigma_{el} \sim \pi/M_{\rm DG}^2$).

Gravitational production automatically produces a very cold dark sector.

For $T_R > \Lambda$ free gluons are produced:

$$c_D = 16 \times 8 \qquad\qquad \frac{n_{\rm gluons}}{s} = 8 \times 10^{-5} \left(\frac{T_R}{M_p}\right)^3$$

- Thermalization:

If interactions are efficient system thermalises:

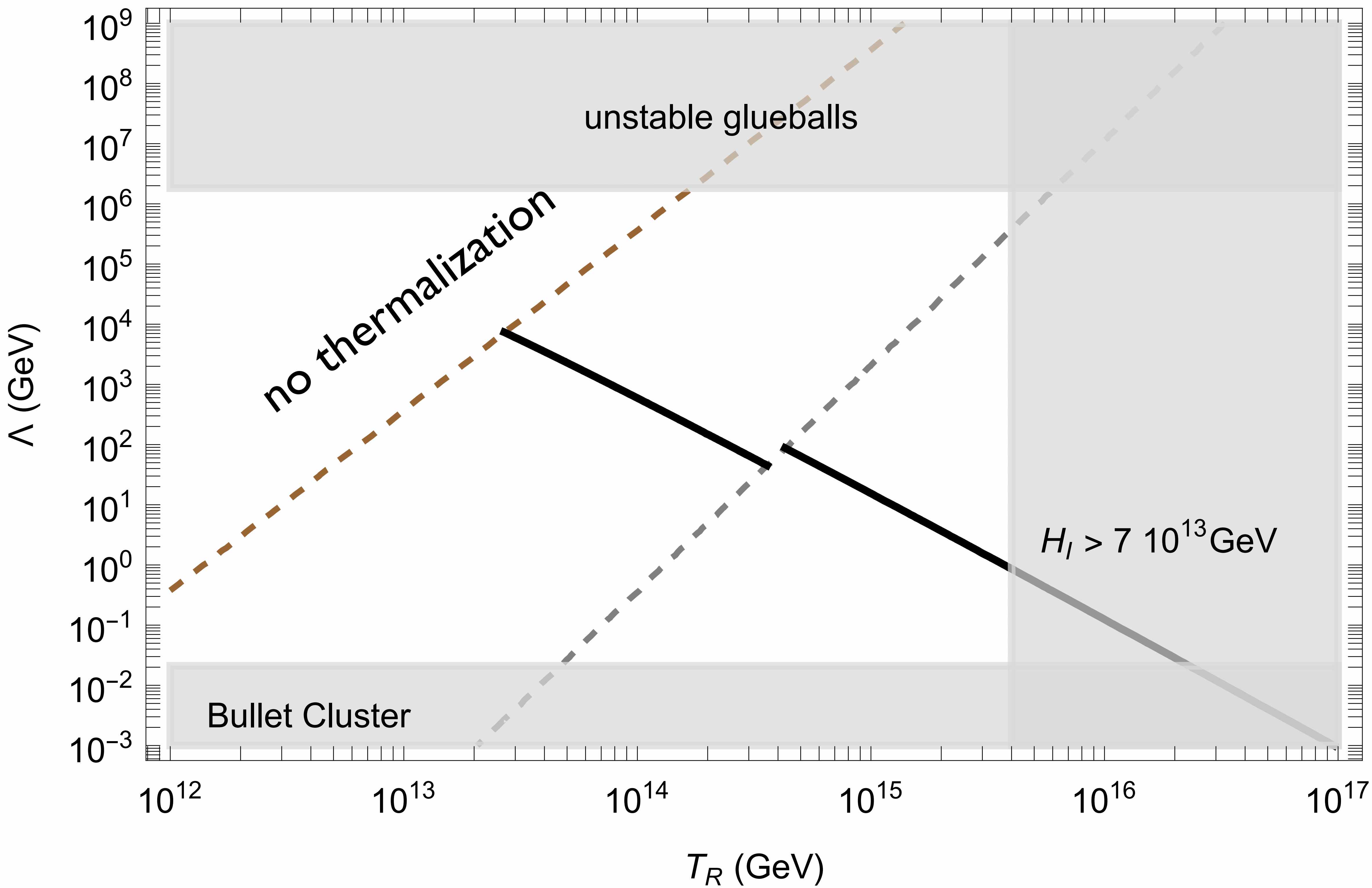
$$\xi \equiv \frac{T_D}{T} \approx 0.4 \left(\frac{T_R}{M_p}\right)^{\frac{3}{4}}$$

When T_D drops below Λ glueballs form:

$$\frac{\rho_{\rm DG}}{s} \approx \left.\frac{\rho_{th}(T) + L_h}{s(T)}\right|_{T_n} \approx 0.01\Lambda \left(\frac{T_R}{M_p}\right)^{9/4}$$

$$\frac{\Omega_{\rm DG} h^2}{0.12} \approx \frac{M_{\rm DG}}{10\,{\rm GeV}} \left(\frac{T_R}{10^{15}\,{\rm GeV}}\right)^{9/4}$$

Glueball Dark Matter



Inflationary production

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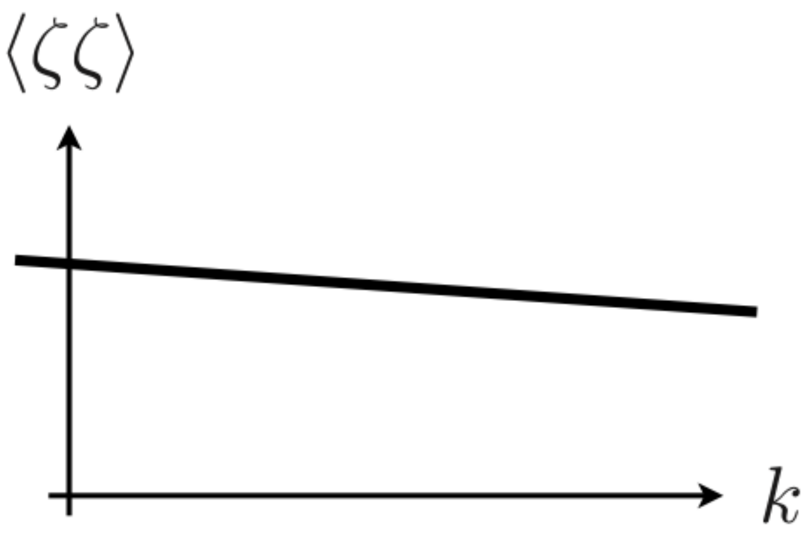
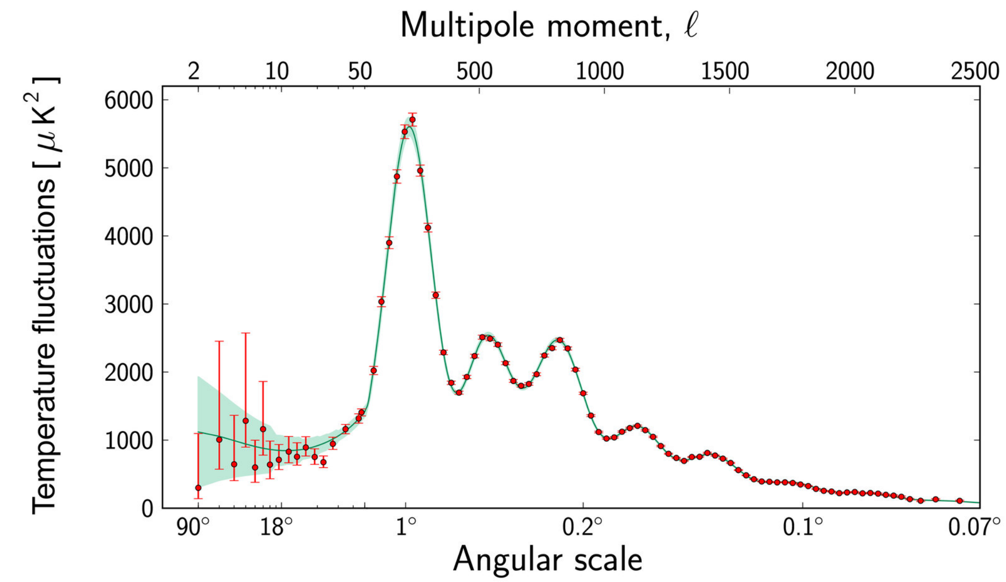




A phase of accelerated expansion — inflation — appears necessary to explain the initial conditions of our universe.
Inflation generates the seeds for the structures:

- Explains smallness and tilt of primordial power spectrum.
- No evidence for isocurvature, non-gaussianity and tensor modes.
- Consistent with slow roll single field inflation.

Could Dark Matter be produced by inflation?

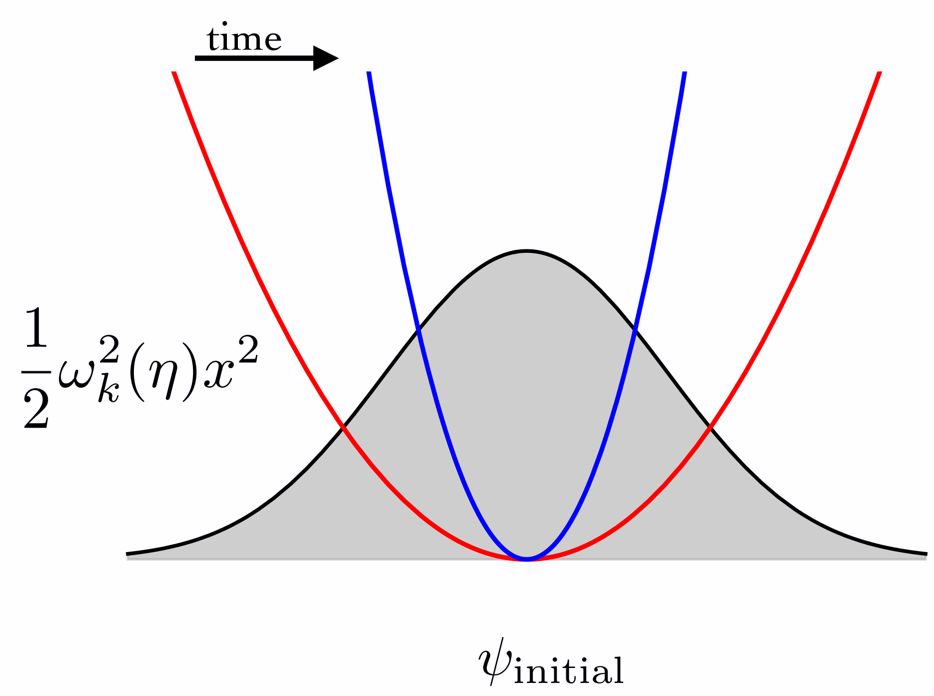
In a time dependent background particles are produced due to the non-adiabatic evolution of the vacuum.

[Schroedinger '39,
Ford '87,
Kolb, Riotto, Giudice '90s
...]

$$L = \frac{1}{2}(\partial\phi)^2 - \frac{M^2}{2}\phi^2 + \frac{\xi}{2}\phi^2 R \qquad a\phi = v$$

$$v_k''(\eta) + \omega_k^2(\eta) v_k(\eta) = 0\,, \mathrm{BD-vacuum}$$

$$\omega_k^2(\eta) = |\vec{k}|^2 + M^2 a^2(\eta) + \frac{a''(\eta)}{a(\eta)}(1-6\xi)$$



Production of conformally coupled scalars $(\xi = 1/6)$ strongly suppressed. This is generic: fermions, gauge fields, strongly coupled CFTs are Weyl invariant ($T_{\mu\nu} = 0$).

Minimally coupled scalare are naturally Nambu-Goldstone bosons.

- Minimal coupling $(\xi = 0)$:

During inflation each mode is produced with an amplitude $H_I/(2\pi)$ that is constant till horizon re-entry. This gives an abundance:

$$\frac{1}{s}\frac{d\rho}{d\log k} \approx \frac{H_I^2}{(2\pi)^2}\frac{\sqrt{M}}{M_{Pl}^{3/2}}\begin{cases}\frac{k_*}{k} & k \gg k_* \\ 1 & k \ll k_*\end{cases}$$

$$k_* = a_{\rm eq}\sqrt{M H_{\rm eq}} \sim 10^{-10}\sqrt{\frac{M}{10^{-5}\rm eV}}\,{\rm km}^{-1}$$

Light non-thermal DM:

$$\frac{\Omega h^2}{0.12} = \frac{\rho/s}{0.44\,\rm eV} \approx \sqrt{\frac{M}{10^{-6}\,\rm eV}}\left(\frac{H_I}{10^{14}\,\rm GeV}\right)^2 \log\frac{k_*}{H_0}$$

Inflationary production generates non-adiabatic perturbations in DM. The flat IR energy spectrum is grossly excluded by isocurvature constraints.

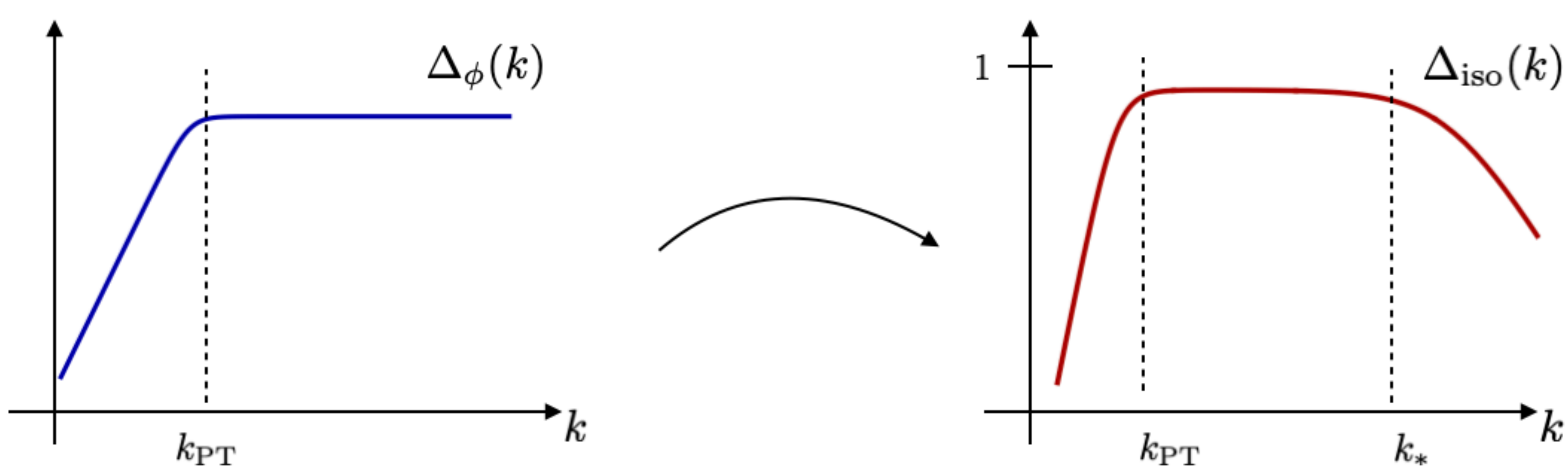
Ways out:

- $H_I \sim M$

$$\Delta(k) = \frac{H_I^2}{(2\pi)^2}\left(\frac{k}{a_e H_I}\right)^{\frac{2M^2}{3H_I^2}}$$

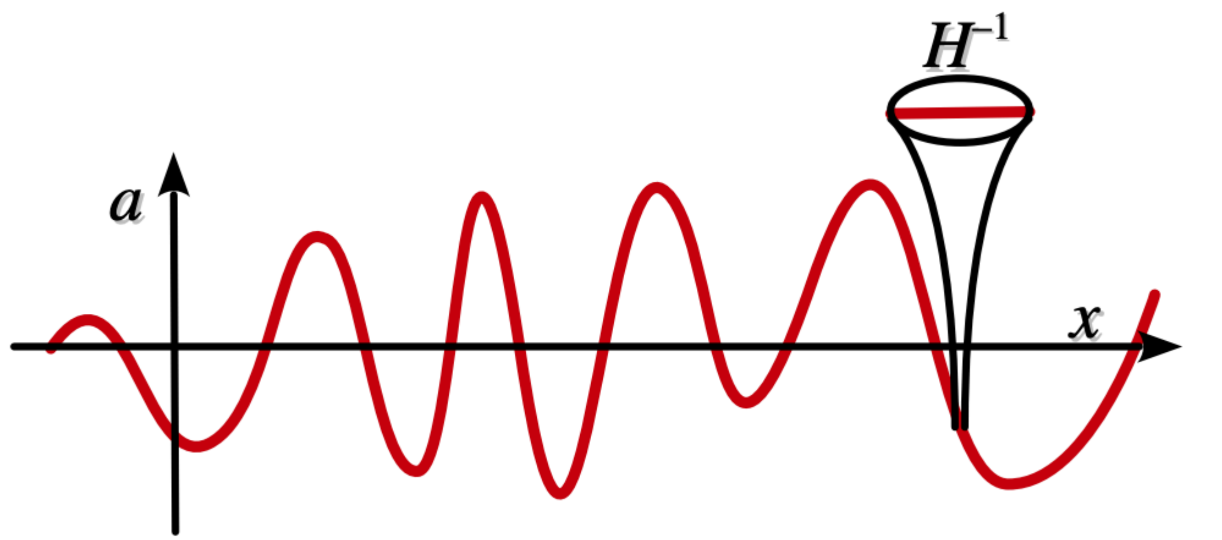
- Scalar emerges during inflation

Modes with $k/a_{PT} > H_I$ are produced.



QCD axion:

- Pre-inflationary $f_a > \mathrm{Max}[H_I, T_{\mathrm{Max}}]$



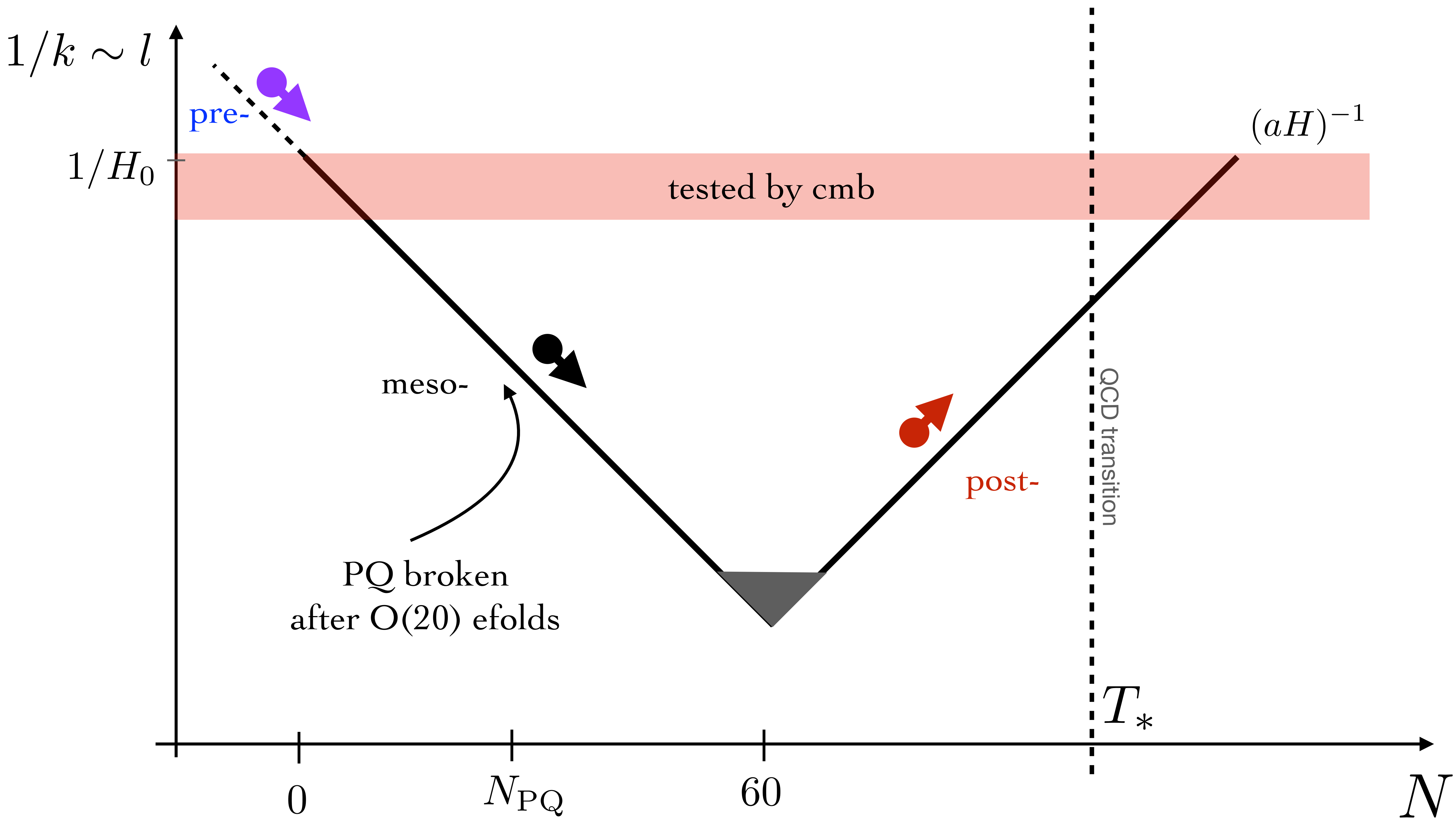
PQ symmetry is broken. Initial misalignment is constant over the visible universe. Strong isocurvature constraints:

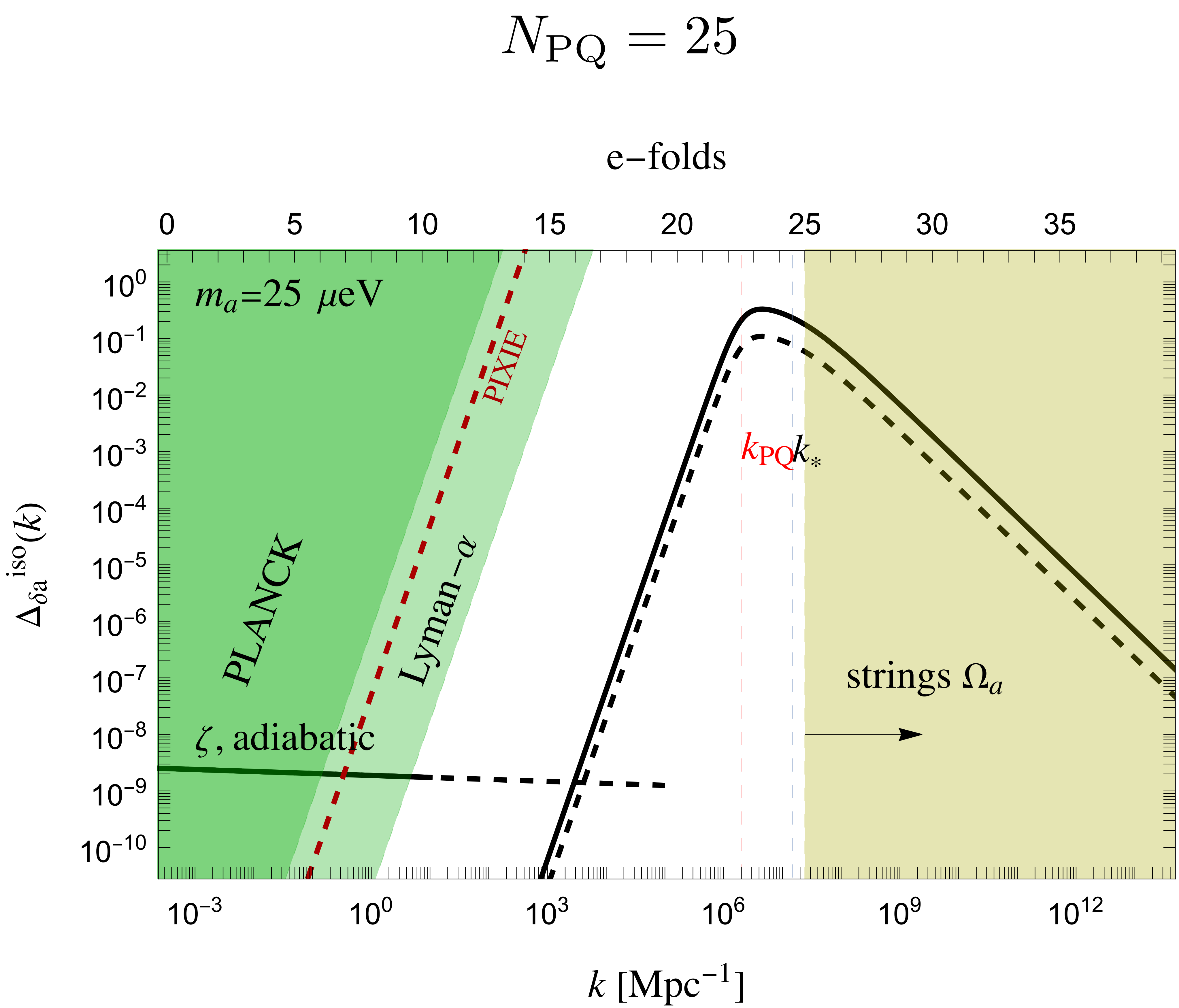
$$H_I \lesssim 10^8\,\mathrm{GeV}\sqrt{\frac{f_a}{10^{12}\,\mathrm{GeV}}}$$

- Post-inflationary $f_a < \mathrm{Max}[H_I, T_{\mathrm{Max}}]$

PQ symmetry is unbroken. Initial misalignment scans over all values so that abundance is predicted in principle.
Allowed if $N_{\mathrm{DW}} = 1$.

Meso-inflationary axion

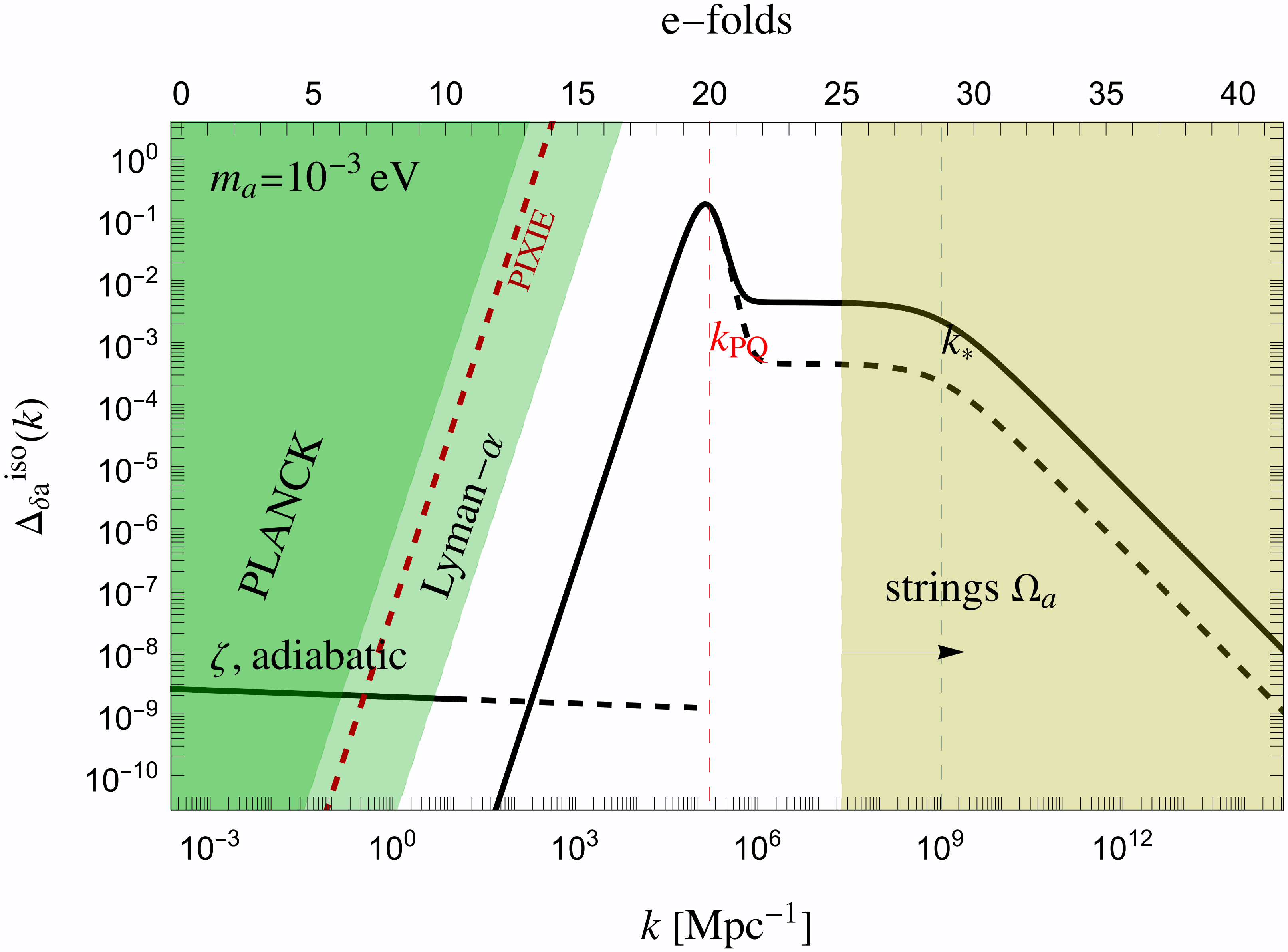




$N_{\rm PQ} = 25$
e−folds
0
5
10
15
20
25
30
35
m_a=25 μeV
PIXIE
PLANCK
Lyman−α
$k_{\rm PQ}$
k_*
strings Ω_a
ζ, adiabatic
$\Delta_{\delta a}{}^{\rm iso}(k)$
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-3}
10^{0}
10^{3}
10^{6}
10^{9}
10^{12}
k [Mpc^{-1}]

For $N_{\rm PQ} \lesssim 23$ string/domain wall network annihilates after QCD phase transition. Abundance is drastically enhanced:

$$\rho_{\rm dw} \approx \sigma H \approx 9 m_a f^2 H \longrightarrow \Omega_a^{\rm dw} \sim \Omega_a^{\rm mis} \frac{\Lambda_{\rm QCD}}{T_{\rm net}}$$

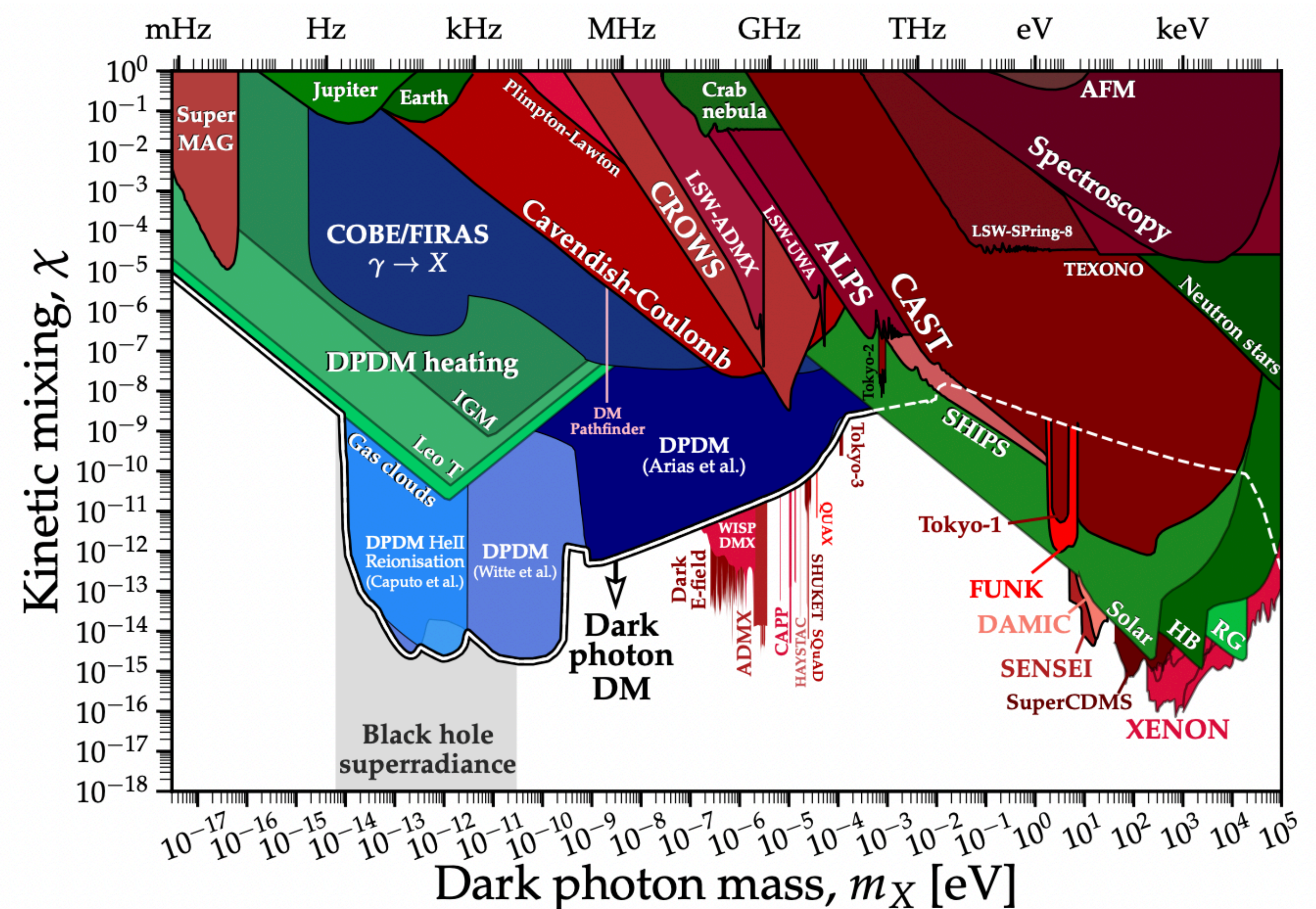


$$N_{\rm PQ} = 20$$

DM abundance is reproduced for smaller f_a.

Axion miniclusters larger than in standard scenario predicted.

Dark photons

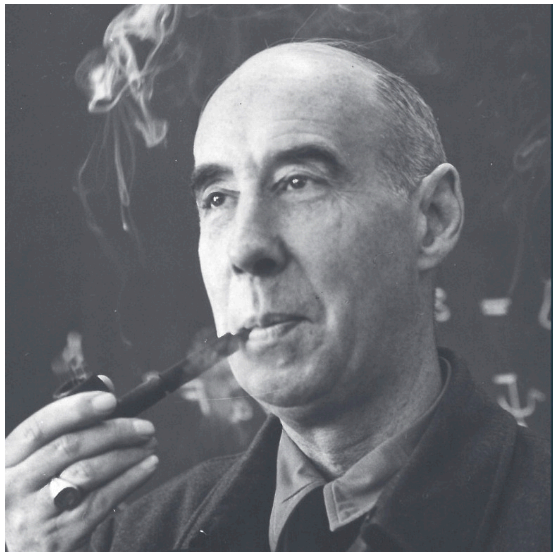


[Caputo et al '21]

Great interest in (Stueckelberg) dark photons!

- Stueckelberg:

Massive spin-1 field described by the Proca lagrangian:



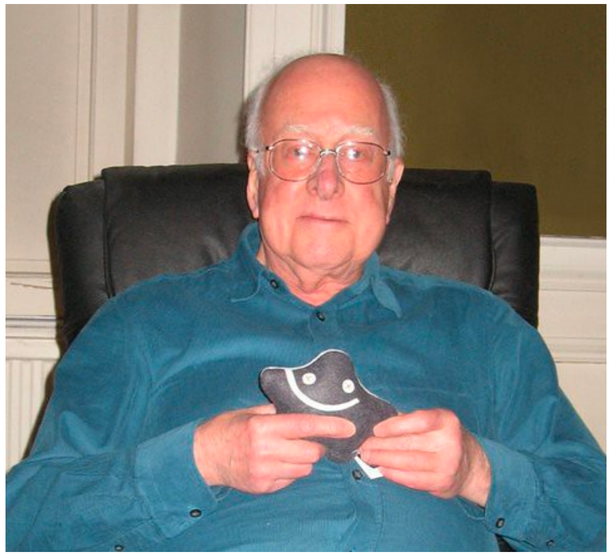
$$L = -\frac{1}{4}F_{\mu\nu}^2 + \frac{f^2}{2}(\partial_\mu\theta - gA_\mu)^2$$

3 = 2 + 1

free theory

- Higgs:

Massive spin-1 particle arise from the Higgs mechanism:



$$\mathscr{L}_D = -\frac{1}{4}F_{\mu\nu}^2 + |D_\mu\Phi|^2 - \lambda\left(|\Phi|^2 - \frac{f^2}{2}\right)^2 + \xi|\Phi|^2 R$$

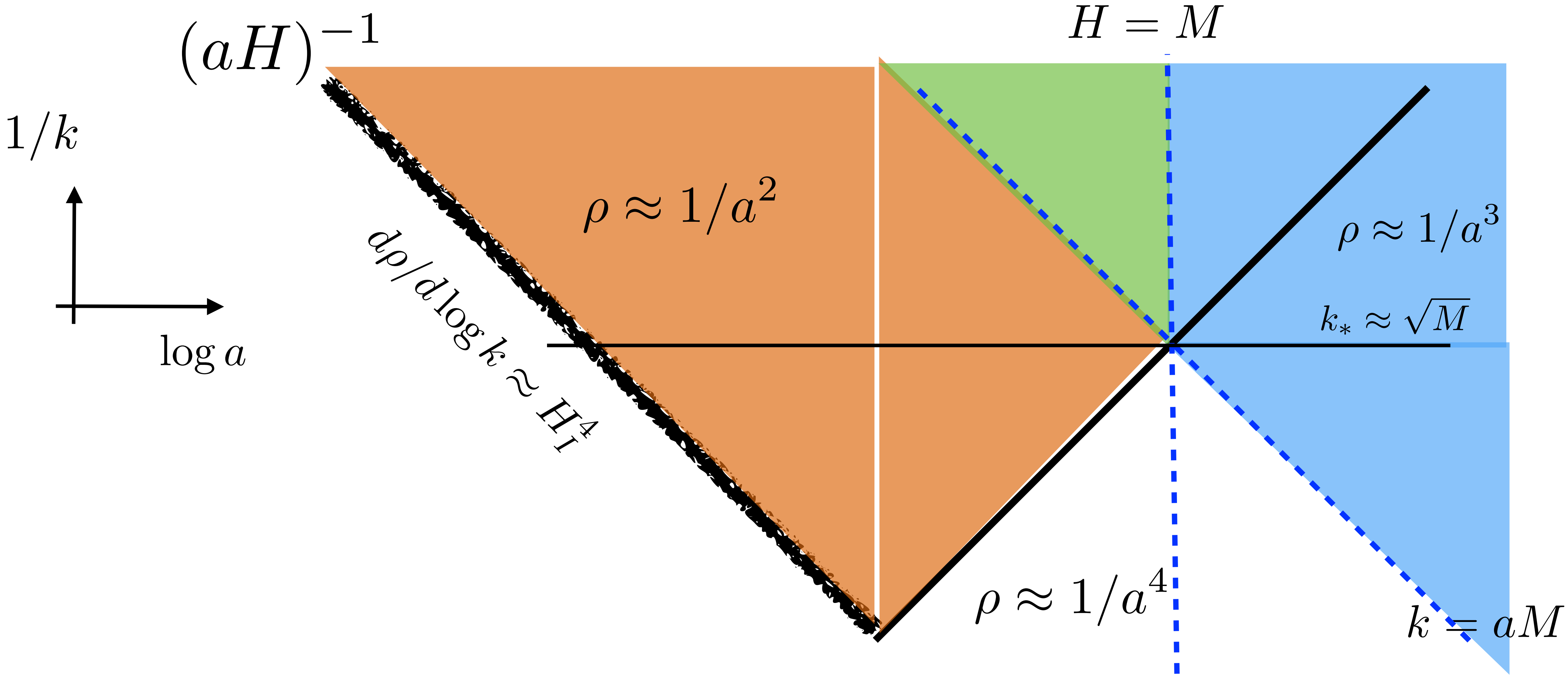
$$L = -\frac{1}{4}F_{\mu\nu}^2 + \frac{1}{2}(\partial\chi)^2 + \frac{(f+\chi)^2}{2}(\partial_\mu\theta - gA_\mu)^2 - \frac{\lambda}{4}\chi^2(2f+\chi)^2$$

4 = 3 + 1

- Stueckelberg:

At high energies a Stueckelberg vector is equivalent to a minimally coupled scalar + massless gauge field. Scalar is produced during inflation but evolution is different:

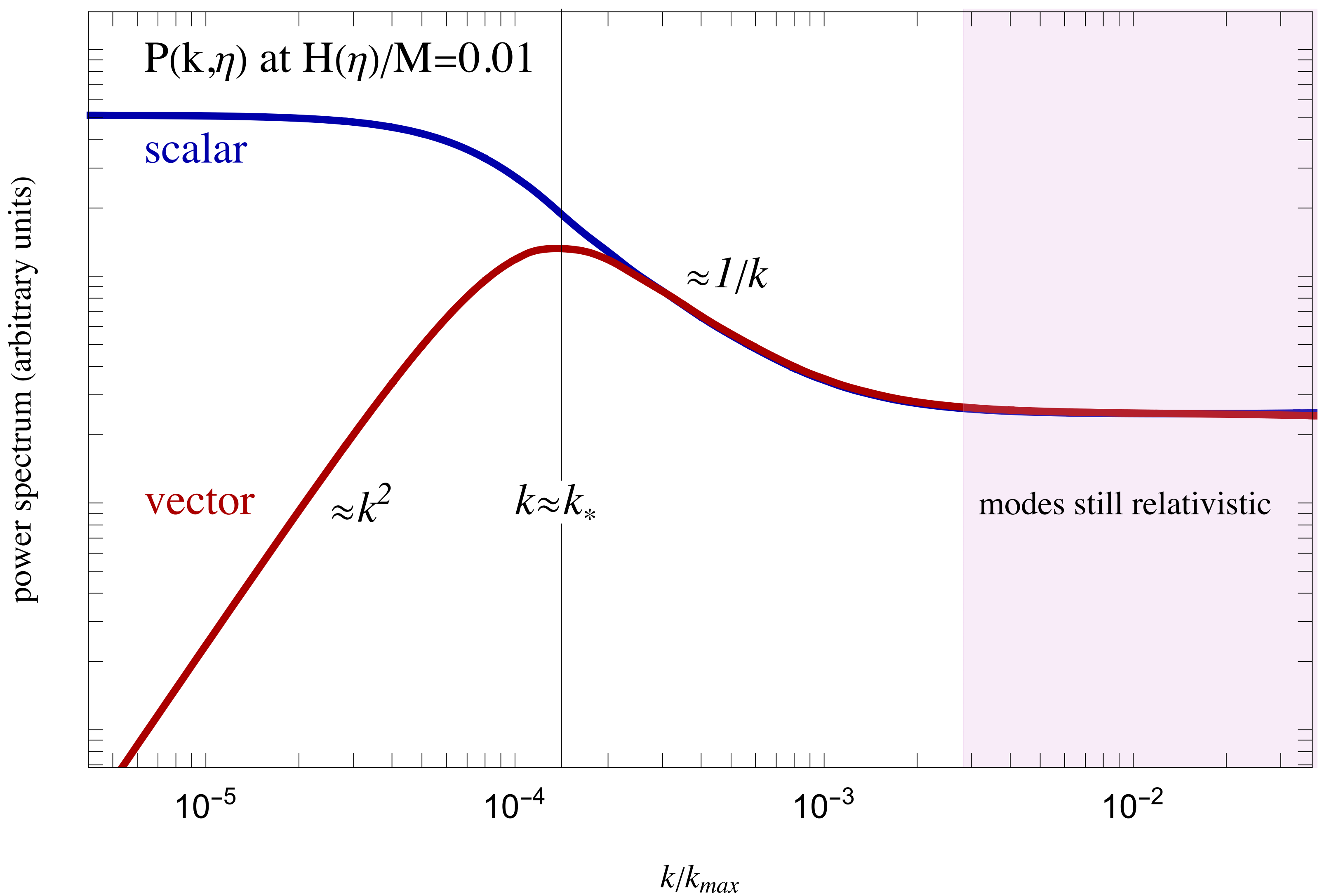
$$\ddot{A}_L + H\left(1 + \frac{2k^2}{k^2 + a^2 M^2}\right)\dot{A}_L + \frac{k^2}{a^2}A_L + M^2 A_L = 0$$



[Graham, Mardon, Rajendran '16]

Power spectrum of massive spin-1 is suppressed at large scales:

$$\frac{1}{s}\frac{d\rho_A}{d\log k}\bigg|_L \approx \frac{H_I^2}{(2\pi)^2}\frac{\sqrt{M}}{M_{pl}^{3/2}}\begin{cases} k_*/k & k \gg k_* \\ 1 & k \approx k_* \\ k^2/k_*^2 & k \ll k_* \end{cases}$$



scalar vs vector

Dangerous isocurvature perturbations eliminated!

- Higgs Dark Photon:

$$M_A = g f\,, \quad M_\phi = \sqrt{2\lambda} f$$

- $M_A < H_I < M_\phi$

Stueckelberg dark photon is recovered:

$$\frac{\Omega_A^{\rm GMR} h^2}{0.12} \approx \sqrt{\frac{M_A}{6\times 10^{-6}\,{\rm eV}}} \left(\frac{H_I}{10^{14}\,{\rm GeV}}\right)^2$$

Light dark photon requires tiny couplings:

$$g < 6\cdot 10^{-29} \left(\frac{10^{14}\,{\rm GeV}}{H_I}\right)^5 = 3\cdot 10^{-11}\left(\frac{M_A}{\rm GeV}\right)^{5/4}$$

	$M_\phi \gg H_I \gg M_A$	$H_I \gg M_\phi \gg M_A$	$H_I \gg M_A \gg M_\phi$
$f > H_I$	GMR	GMR + ϕ-decay + (iso) $\xi = 0$	GMR + thermal-FO + (iso) $\xi = 0$
$f < H_I, \xi = \frac{1}{6}$	–	string network	string network
$f < H_I, \xi = 0$	–	string net.+ ϕ-decay +(iso)	string net. + thermal-PT +(iso)

DM from a Phase Transition

- 2210.03108 with A. Tesi

Michele Redi, INFN Florence

Consider an interacting Weyl invariant dark sector.

$$H_I \gg M$$

- Conformally coupled scalar:

$$L = \frac{(\partial_\mu \phi)^2}{2} - \frac{1}{2}\mu^2\phi^2 + \frac{1}{12}\phi^2 R - \frac{\lambda}{4}\phi^4$$

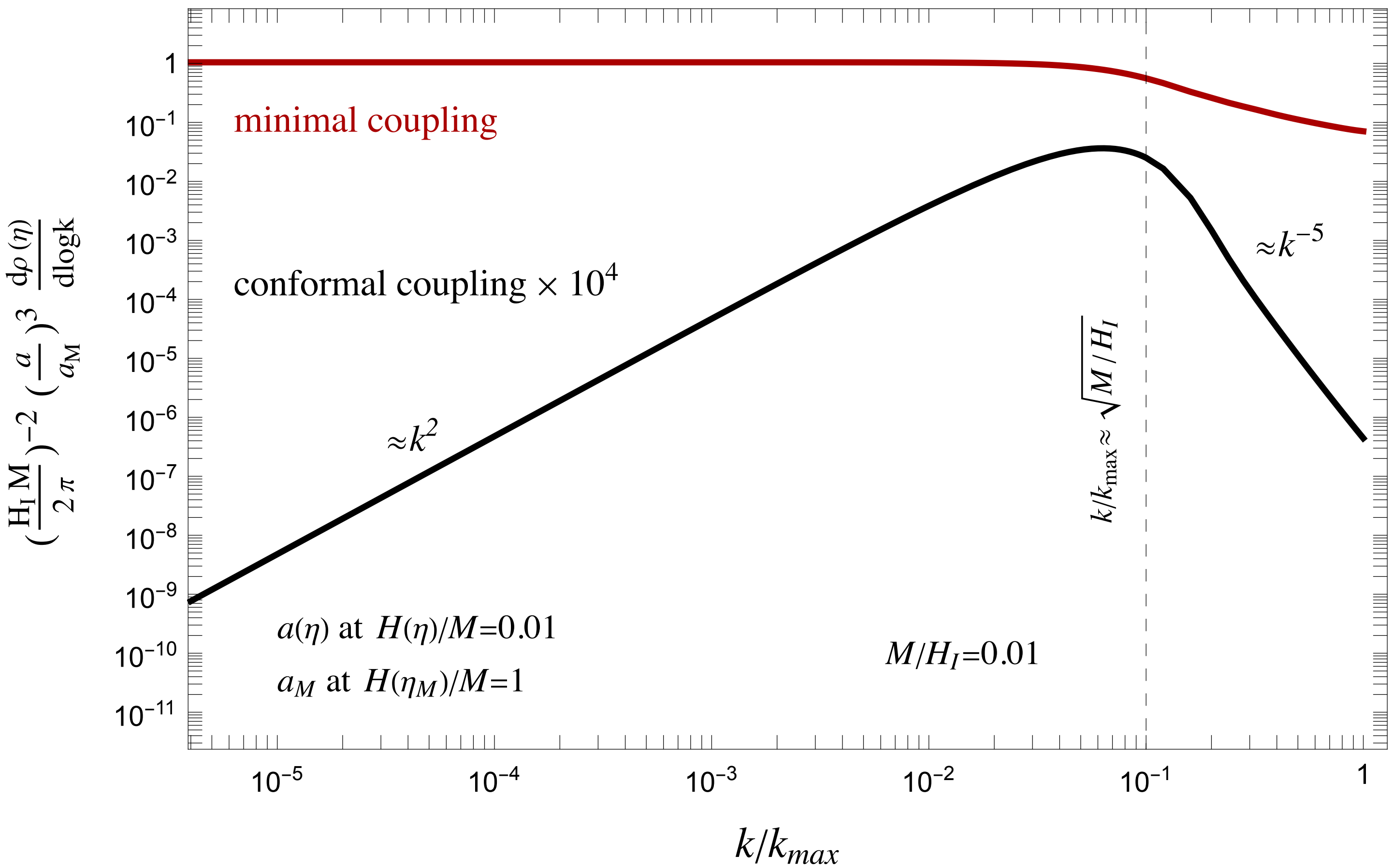
- $\mu^2 > 0$

$$v = a\phi \qquad\qquad v'' + k^2 v + \mu^2 a^2 v = 0$$

Particle production peaked at:

$$H = M = \frac{k}{a} \qquad\qquad k_{\rm peak} = \begin{cases} a_{\rm eq}\sqrt{H_{\rm eq} M} & T_R > \sqrt{M M_p} \\ a_{\rm eq}\sqrt{H_{\rm eq} M}\left(\frac{H_R}{M}\right)^{1/3} & T_R < \sqrt{M M_p} \end{cases}$$

@ radiation:



$$\left.\frac{\rho}{s}\right|_{\text{quantum}} = 0.0002\, M \left(\frac{M}{M_p}\right)^{\frac{3}{2}}$$

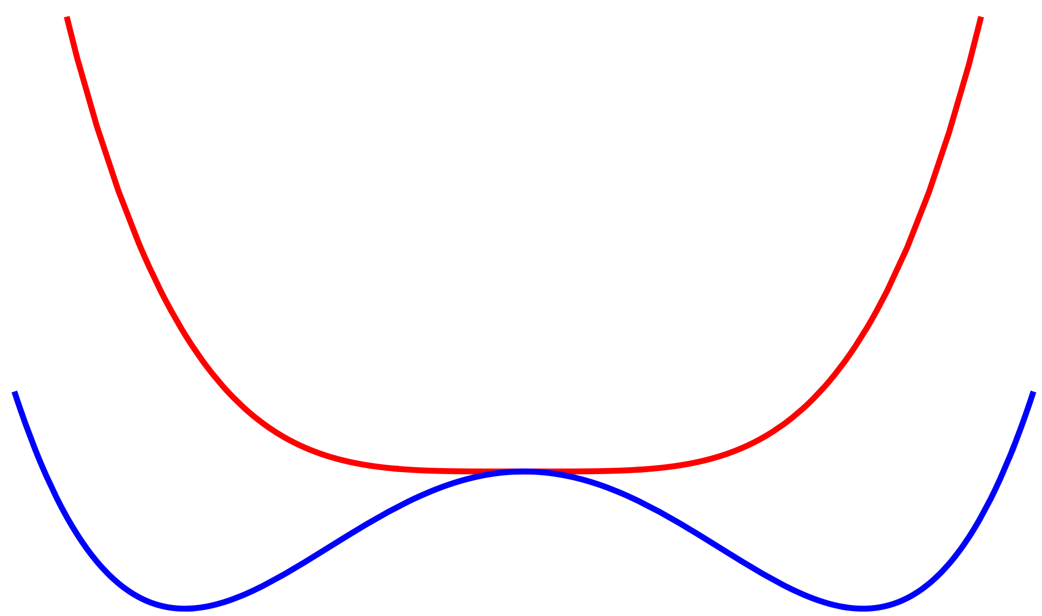
DM abundance reproduced for $M_{\rm DM} = 5.7 \times 10^8\, \rm GeV$

@ reheating:

$$\left.\frac{\rho}{s}\right|_{\text{quantum}} \approx 10^{-4}\, T_R \frac{M^2}{M_p^2}$$

- $\mu^2 < 0$

In flat space the minimum is at $\phi = -\mu^2/\lambda$. During inflation the conformal coupling produces a positive mass $2H_I^2$ so that the symmetry is restored. A phase transition takes place during radiation or reheating releasing the latent heat:



$$\Delta V = \frac{M^4}{16\lambda} \qquad @ \qquad H \sim M$$

The abundance is:

radiation:

$$\left.\frac{\rho_\phi}{s}\right|_{\rm PT} = \frac{\Delta V}{s(T_*)} \approx 0.1 \frac{M}{\lambda} \frac{M^{3/2}}{M_p^{3/2}}$$

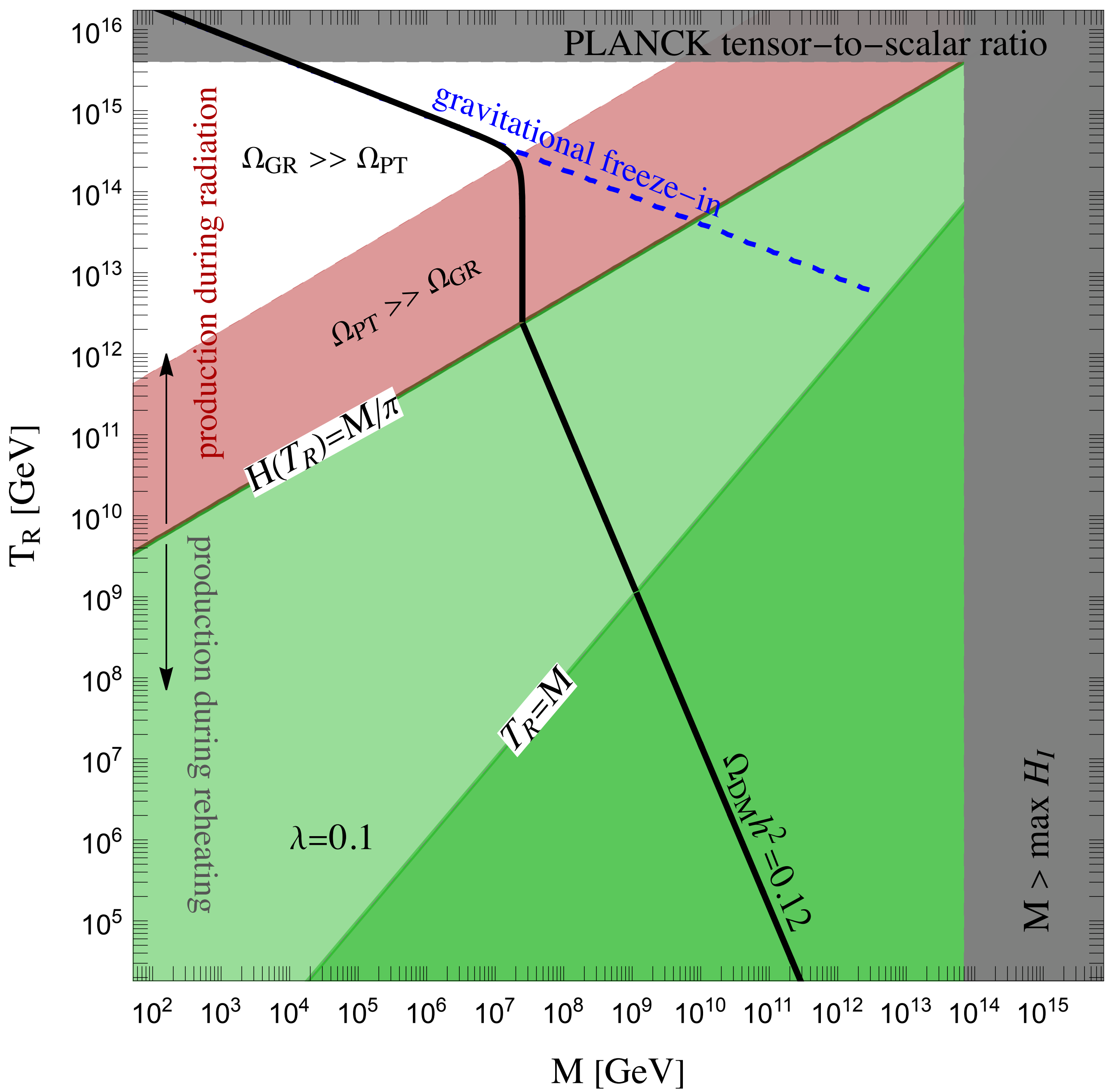
reheating:

$$\left.\frac{\rho_\phi}{s}\right|_{\rm PT} = \frac{\Delta V}{s(T_R)} \left(\frac{a_*}{a_R}\right)^3 \approx 0.5 \frac{T_R}{\lambda} \frac{M^2}{M_p^2}$$

Gravitational freeze-in:

$$\left.\frac{\rho}{s}\right|_{\mathrm{GR}} = 8\times10^{-6} M \left(\frac{T_R}{M_p}\right)^3$$

PT vs. freeze-in

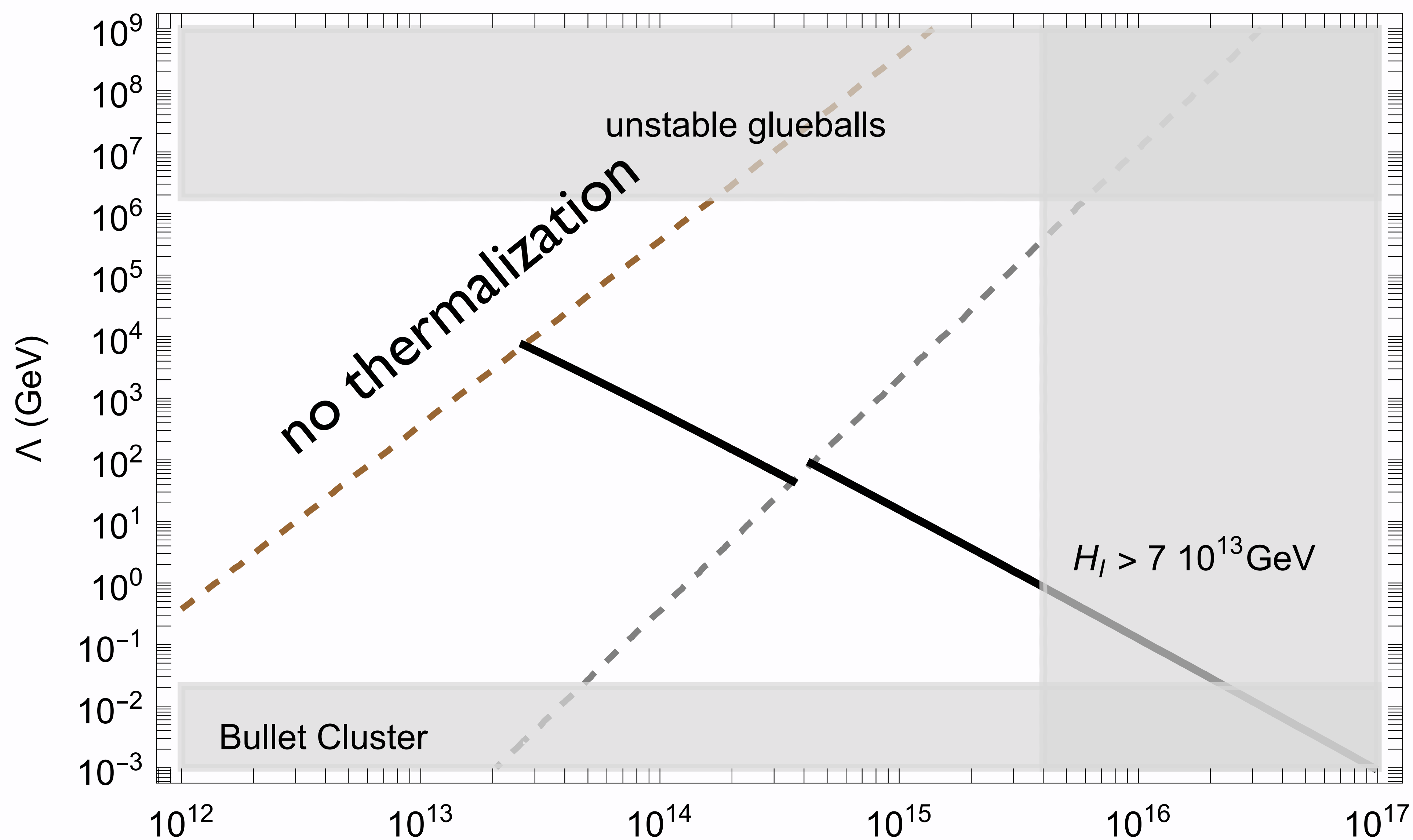


Glueball DM

[MR, Tesi, Tillim '20]

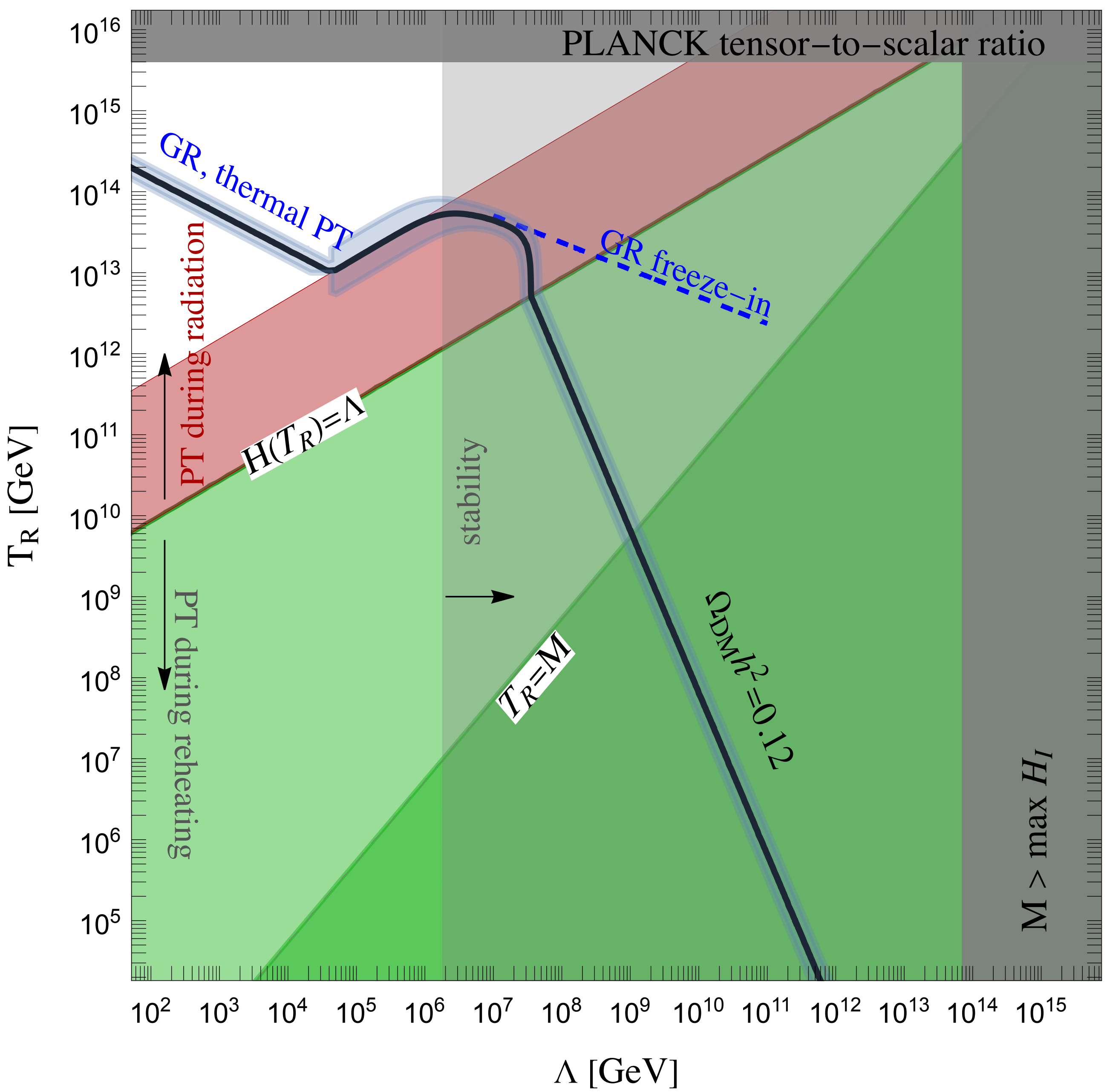
- thermal scenario

$$\frac{\rho}{s} \approx \frac{g_D}{g^*} \Lambda\, \xi^3 \qquad \xi = 0.4 \left(\frac{T_R}{M_p} \right)^{3/4} \qquad T_R > 10^{13}\text{GeV}$$



- No thermalization:

Gluons are deconfined during inflation for $H_I > \Lambda$.
Inflation prepares the system in an empty false vacuum state.
As for the scalar an energy Λ^4 will be released @ $H \sim \Lambda$:



$$\frac{\rho_{\rm DG}}{s} \sim 0.1\,\Lambda\,{\rm Min}\left[\left(\frac{\Lambda}{M_p}\right)^{3/2}, \frac{\Lambda T_R}{M_p^2}\right]$$

SUMMARY

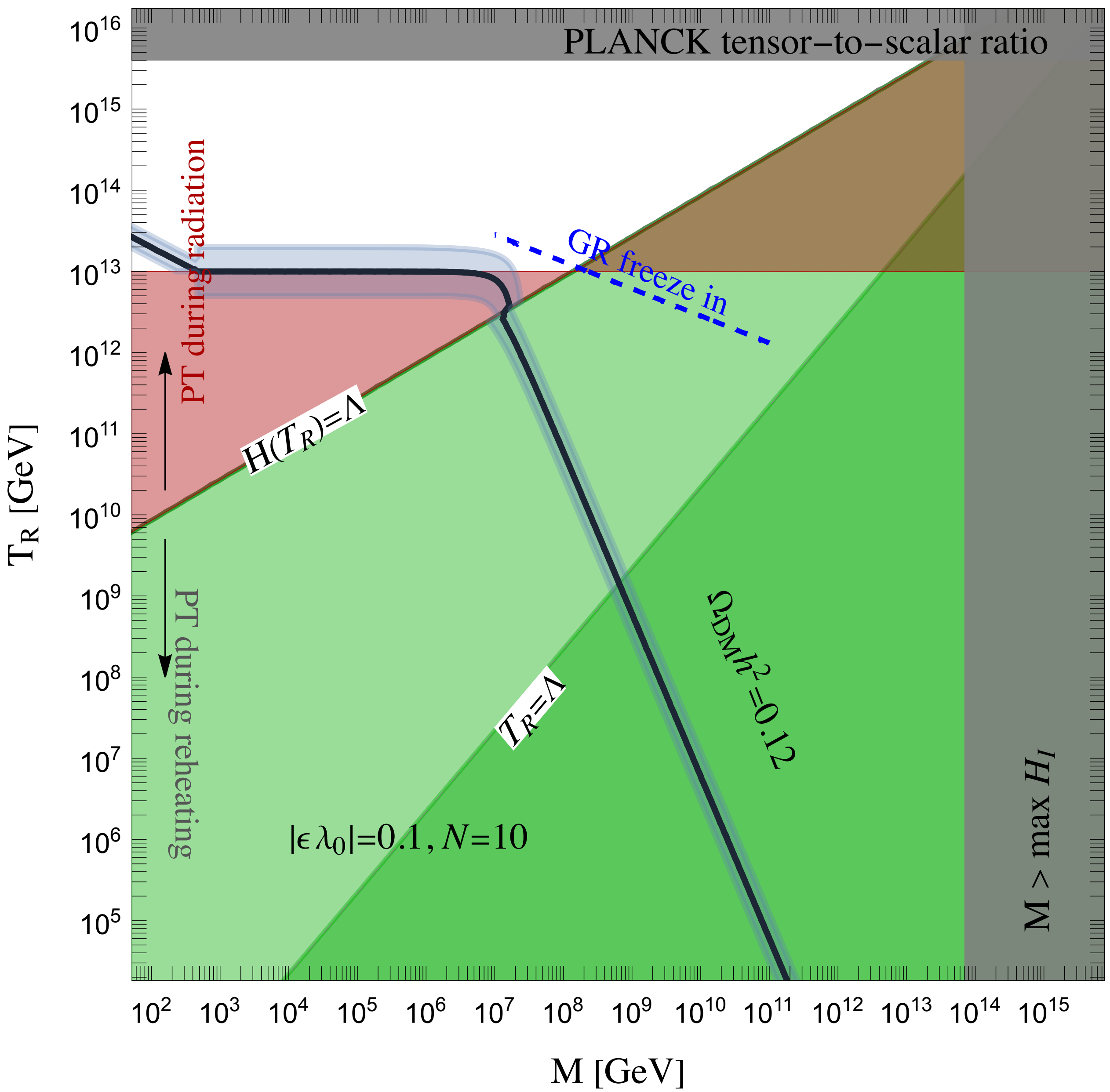
- Any dark sector is unavoidably populated through gravitational interactions or inflationary fluctuations.

- Gravitational freeze-in leads to very heavy DM and necessarily requires a large reheating temperature. If the system undergoes a phase transition dark sector can be populated from "nothing".

- Inflationary fluctuation of Nambu-Goldstone bosons lead to light dark matter. Isocurvature constraints can be solved if the minimally coupled scalar emerge during inflation or if it becomes the longitudinal degree of freedom of a vector.

- Dilaton Dark Matter:

Very similar conclusions in strongly coupled scenarios described by their holographic Randall-Sundrum dual (with light dilaton).



$$\Delta V \sim \frac{N^2}{64\pi^2}\epsilon\Lambda^4$$

$$M^2 \sim \epsilon\Lambda^2$$

$$\left.\frac{\rho_{\rm dilaton}}{s}\right|_{\rm PT} = \frac{N^2}{64\pi^2}\frac{1}{|\epsilon\lambda_0|}\min\left[0.5\frac{M^{5/2}}{M_p^{3/2}}, \frac{T_R M^2}{M_p^2}\right]$$