Prospettive per le particelle da astroparticelle e cosmologia

Alfredo Urbano

INFN, sez. di Trieste

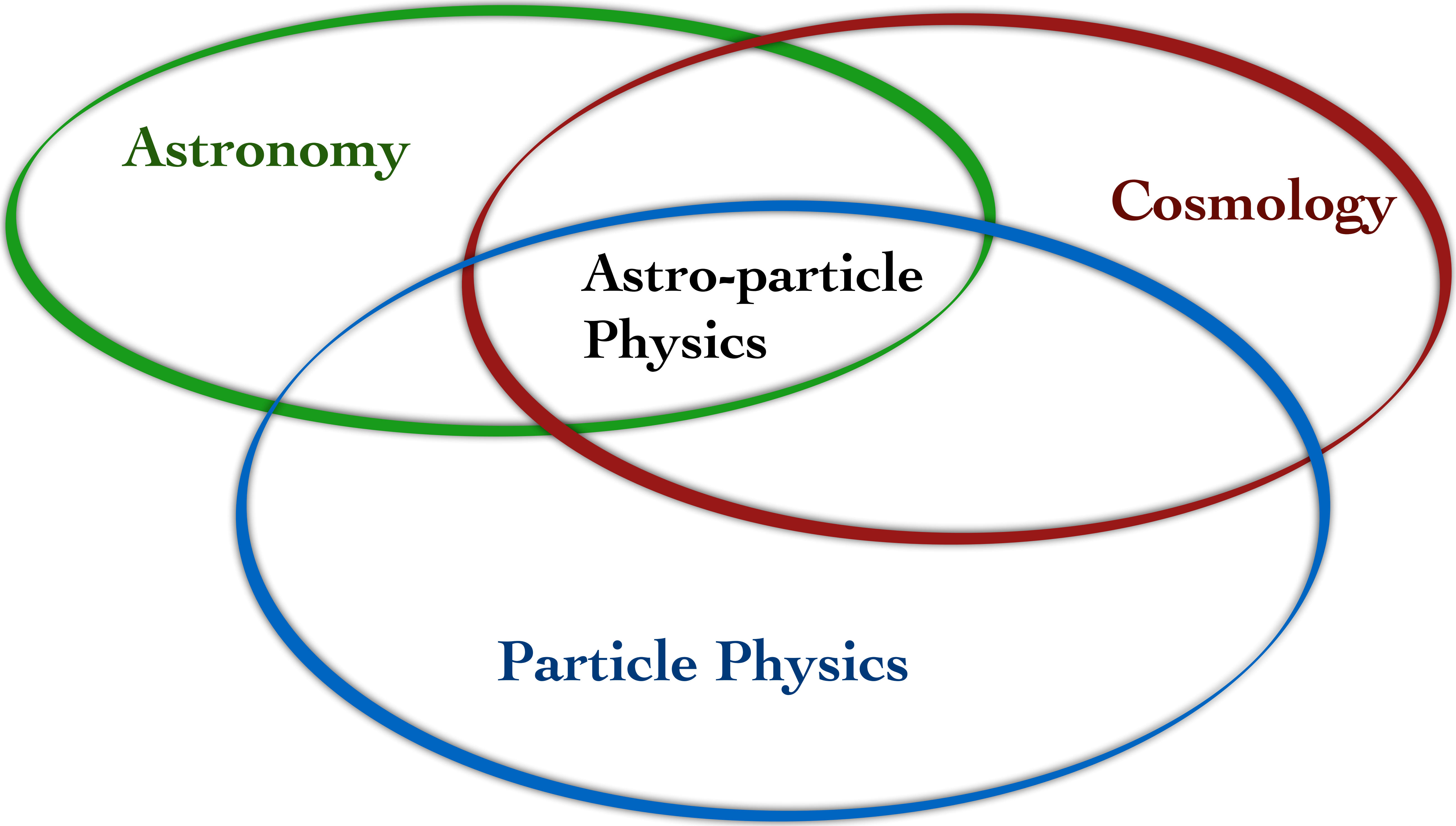
Istituto Nazionale di Fisica Nucleare

Fisica delle Particelle, verso la nuova Strategia Europea

Roma, 7 Settembre 2018

PART I: Introduction

Cosmology / Particle Physics / Astronomy



PART I: Introduction

Cosmology / Particle Physics / Astronomy

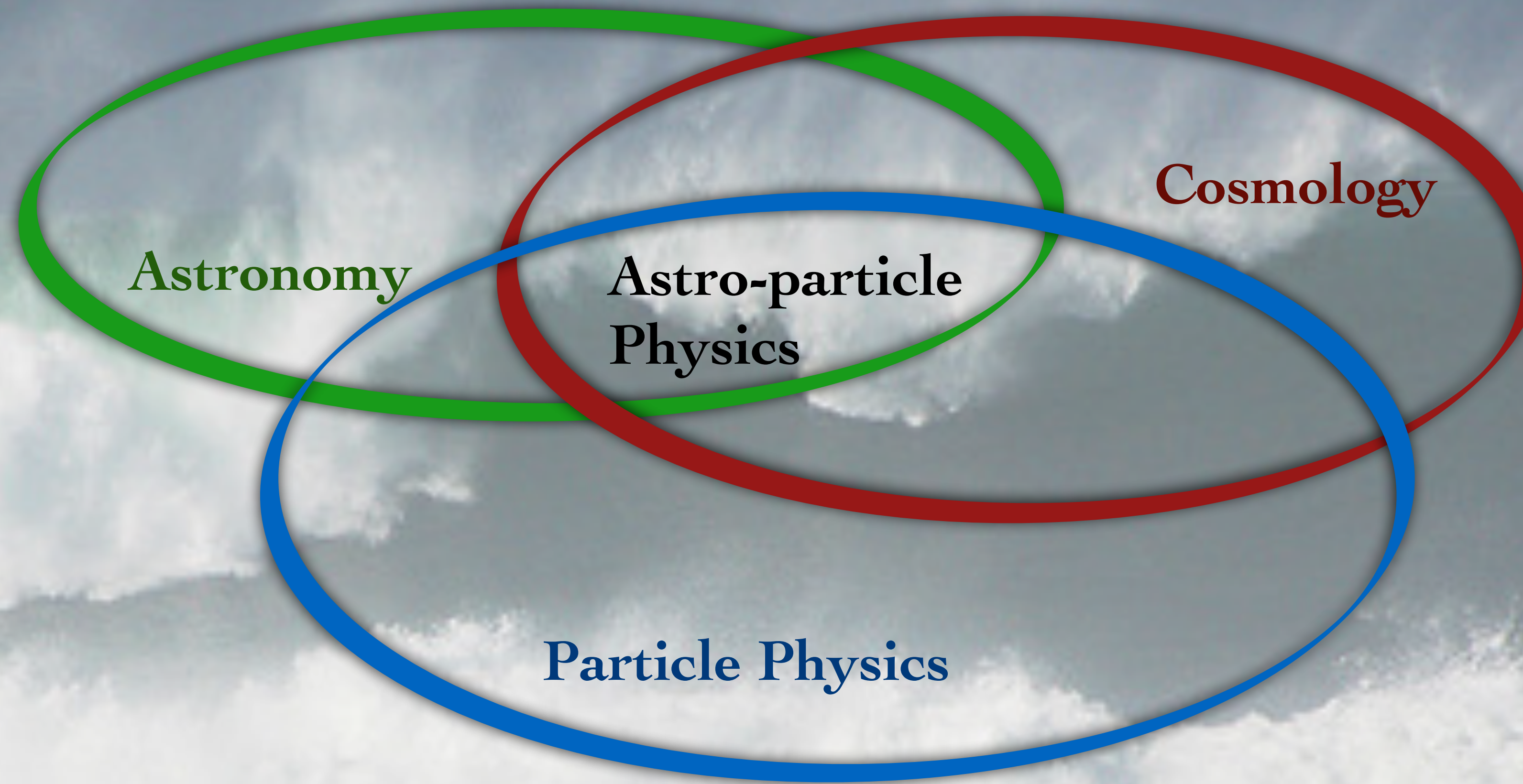
- What is Dark Matter?
- What is Dark Energy?
- What caused our Universe to become dominated by matter and not anti-matter?
- What are the properties of neutrinos?
- Do protons decay?
- What do gravitational waves tell us about General Relativity and Cosmology?

form: "European Astroparticle Physics Strategy 2017-2026"

www.appec.org

PART I: Introduction

Cosmology / Particle Physics / Astronomy

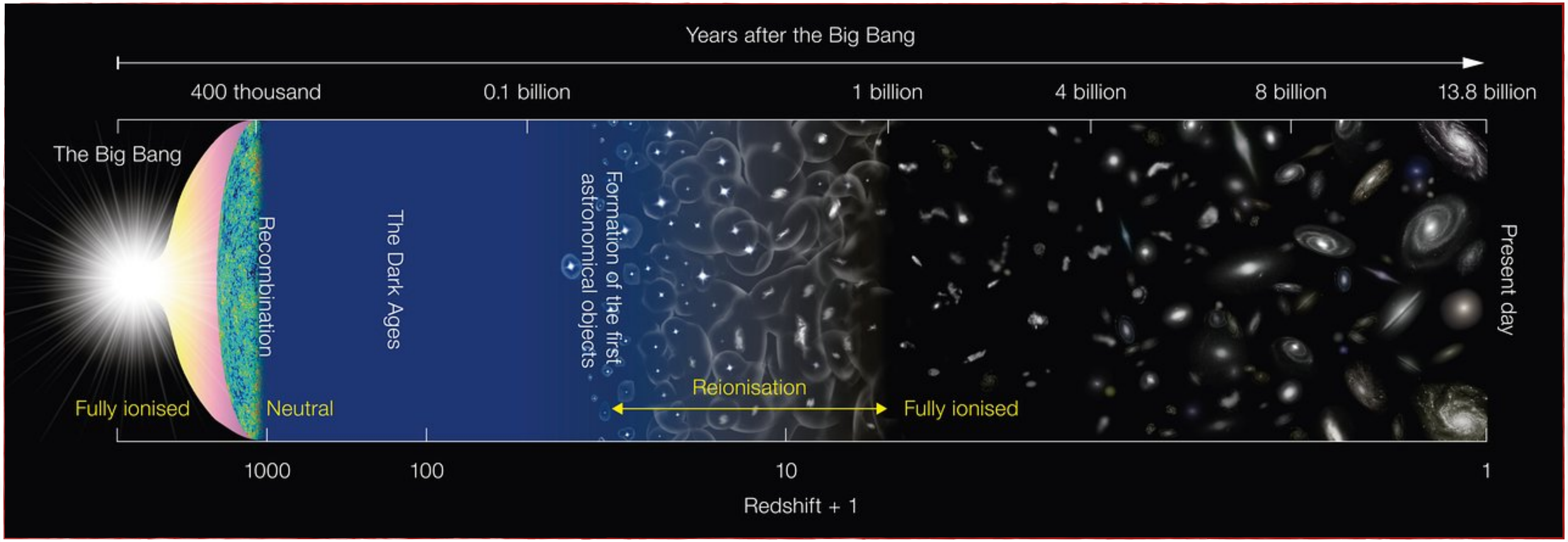


"Science, my lad, is made up of mistakes, but they are mistakes which it is useful to make, because they lead little by little to the truth."

Jules Verne, A journey to the center of the Earth

PART II: Particle physics from Cosmology

PART II: Particle physics from Cosmology



- Very early Universe
- Early Universe
- Late Universe

PART II: Particle physics from Cosmology

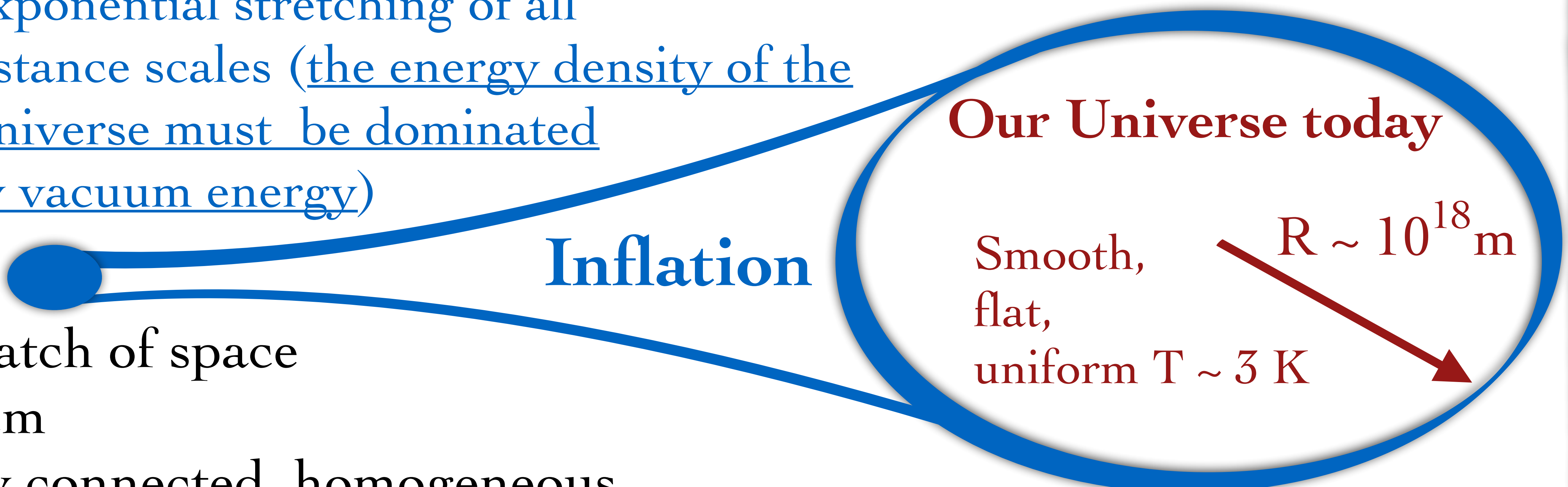
The very early Universe: Inflation

PART II: Particle physics from Cosmology

The very early Universe: Inflation

Inflation is nowadays a well-established paradigm, able to explain the properties of the Universe at large scales and the generation of the primordial density fluctuations seeding structure formation.

Exponential stretching of all distance scales (the energy density of the Universe must be dominated by vacuum energy)



Initial patch of space
R ~ 30 cm
Causally connected, homogeneous
$T \sim 10^{27}$ K

PART II: Particle physics from Cosmology

The very early Universe: Inflation

Inflation is nowadays a well-established paradigm, able to explain the properties of the Universe at large scales and the generation of the primordial density fluctuations seeding structure formation.

Simplest parametrization in terms of a slowly-moving scalar field (inflaton)

The nature (and true dynamics) of the inflaton field remains unknown and its role could be played by any particle physics candidate able to imitate a slowly-moving scalar condensate.

PART II: Particle physics from Cosmology

The very early Universe: Inflation

The Higgs as the inflaton

$$\mathcal{S} = \int d^4x \sqrt{-g} \left[\frac{\bar{M}_{\rm Pl}^2}{2} \mathcal{R} + \xi \mathcal{R} H^\dagger H + \mathcal{L}_{\rm SM} \right]$$

The Higgs field itself could be responsible for inflation if a minimalistic, and at the same time compelling, non-minimal coupling to gravity is added to the Standard Model action.

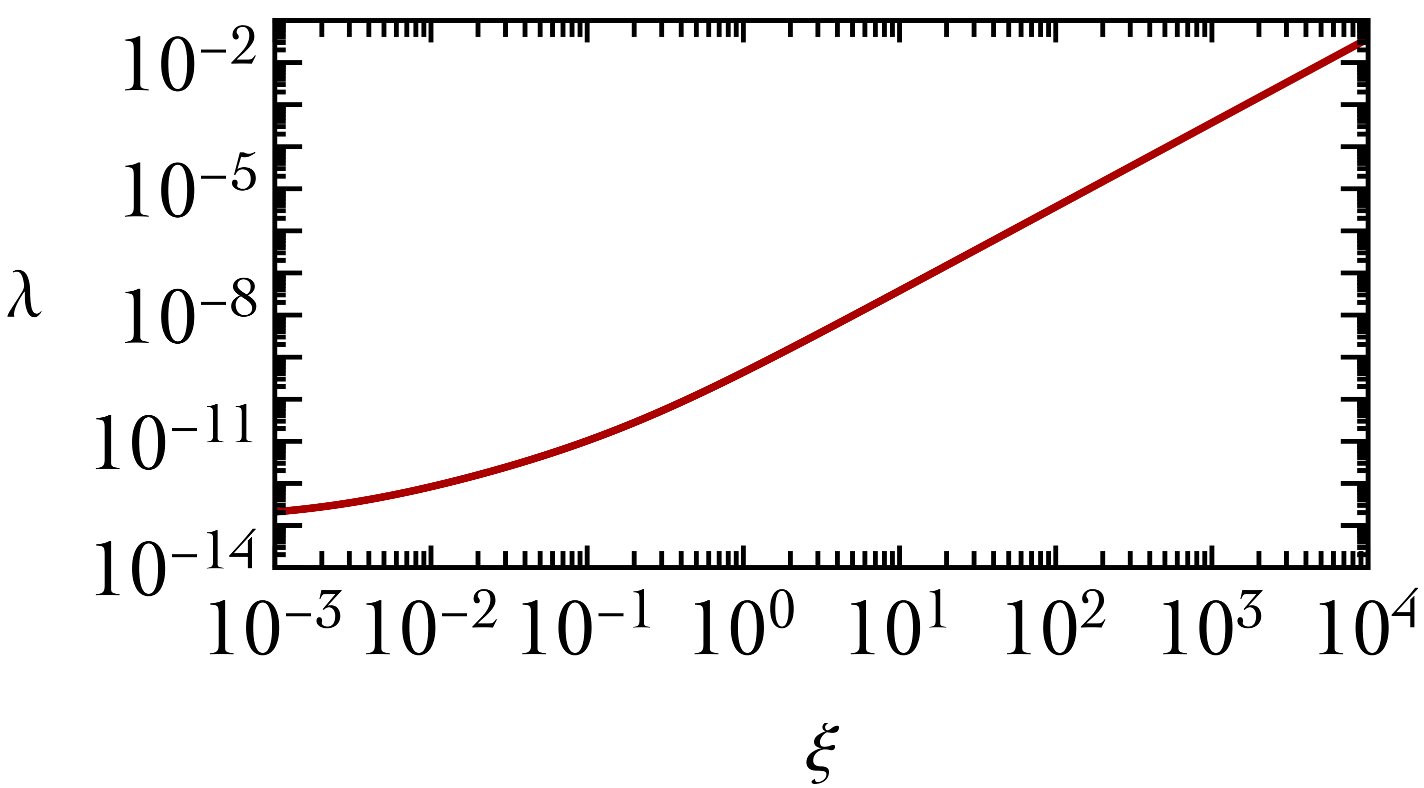
The value of this coupling can be fixed by the normalization of the spectrum of primordial density perturbations, leaving a theory with no free parameters.

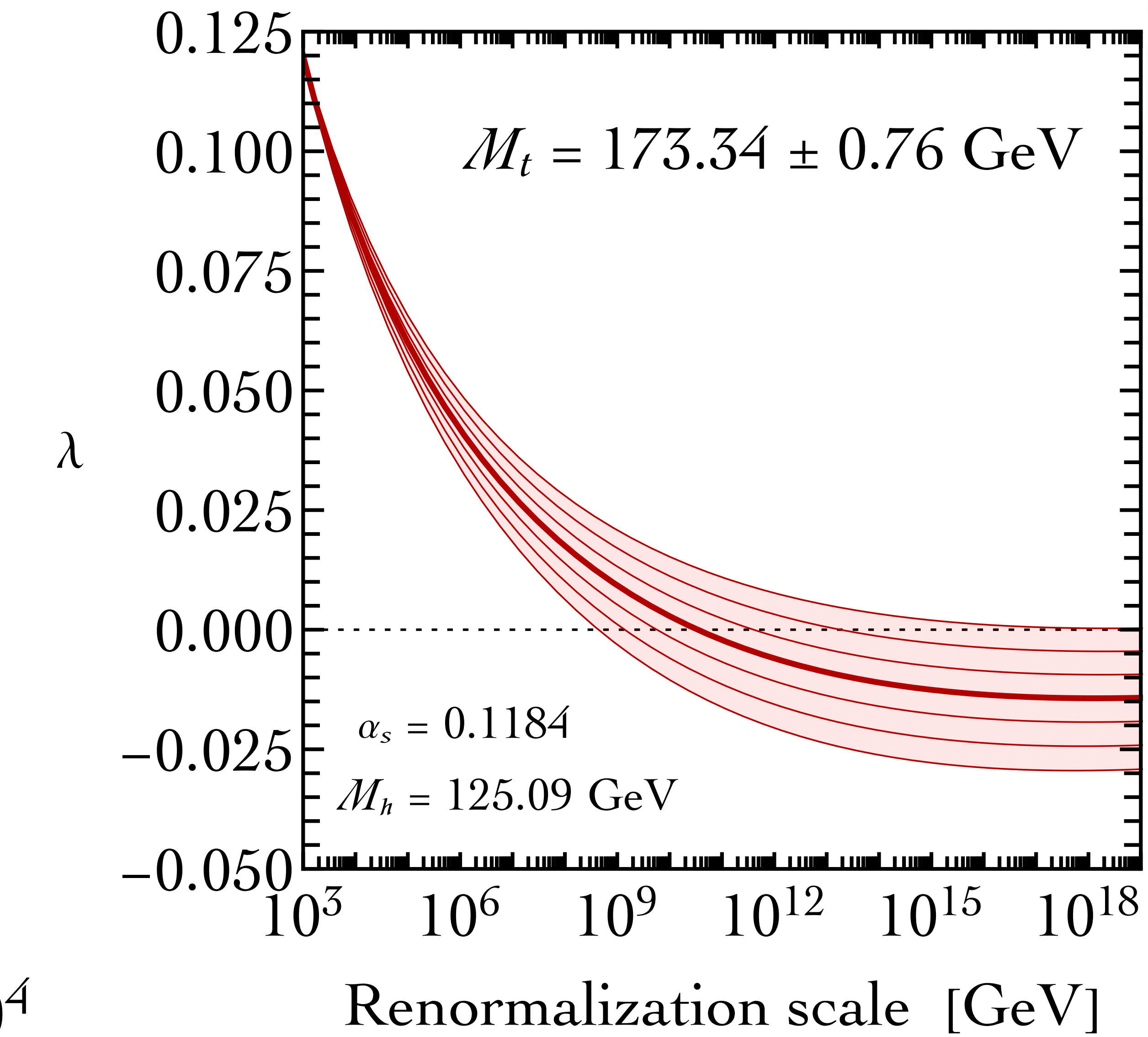
PART II: Particle physics from Cosmology

The very early Universe: Inflation

$$V(h) = \frac{\lambda \bar{M}_{\rm Pl}^4}{4\xi^2}\left(1 - e^{-2\sqrt{|a|}\,h/\bar{M}_{\rm Pl}}\right)^2$$

The Higgs as the inflaton





PART II: Particle physics from Cosmology

The very early Universe: Inflation

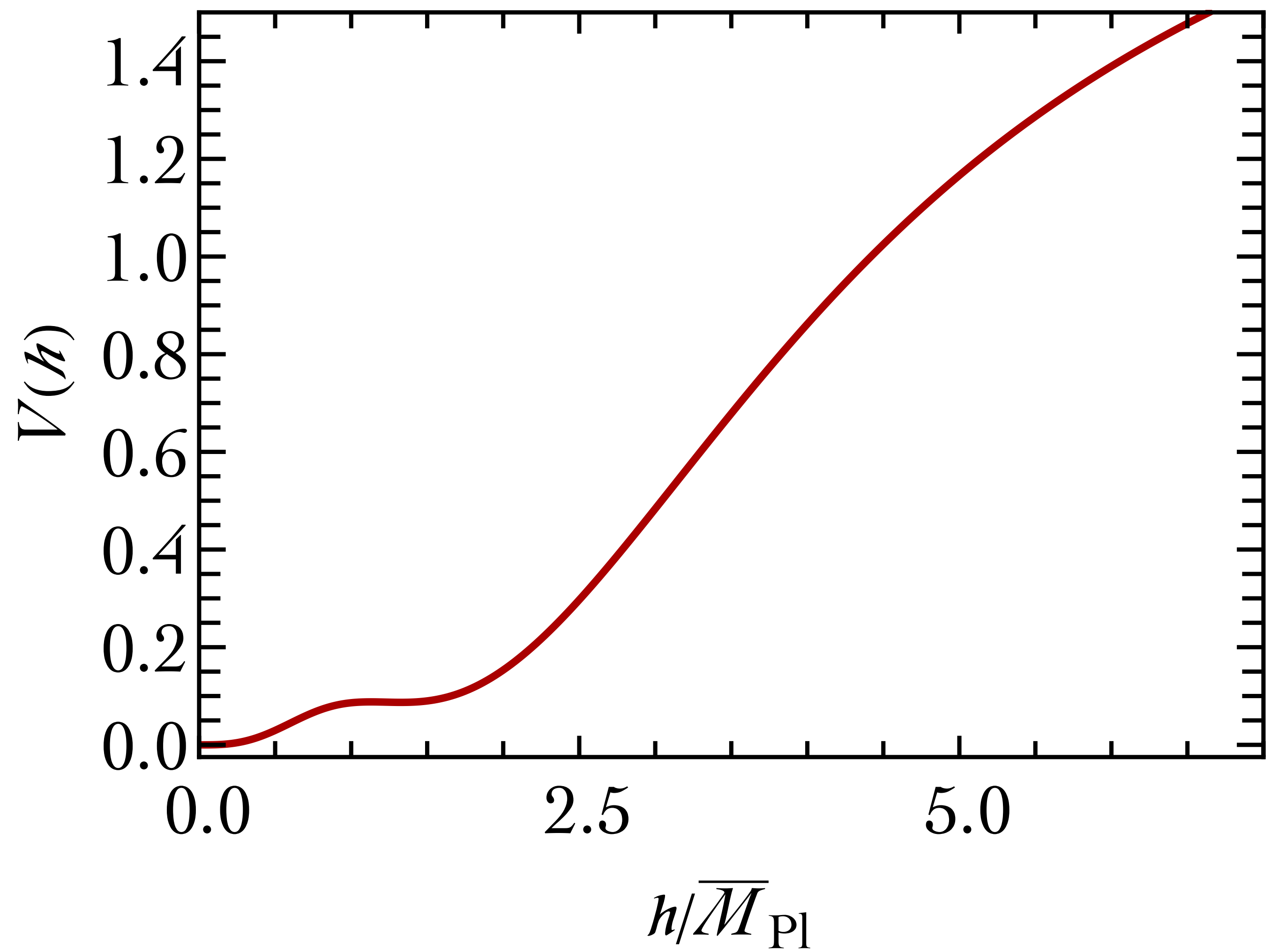
- The role of the inflaton in the SM of particle physics (or beyond it) is an interesting open question
- The SM Higgs boson is still a viable option
- Are there distinctive features ?

PART II: Particle physics from Cosmology

The very early Universe: Inflation

Primordial black holes from Higgs inflation?

critical Higgs inflation
if $M_t \sim 171\,\text{GeV}$

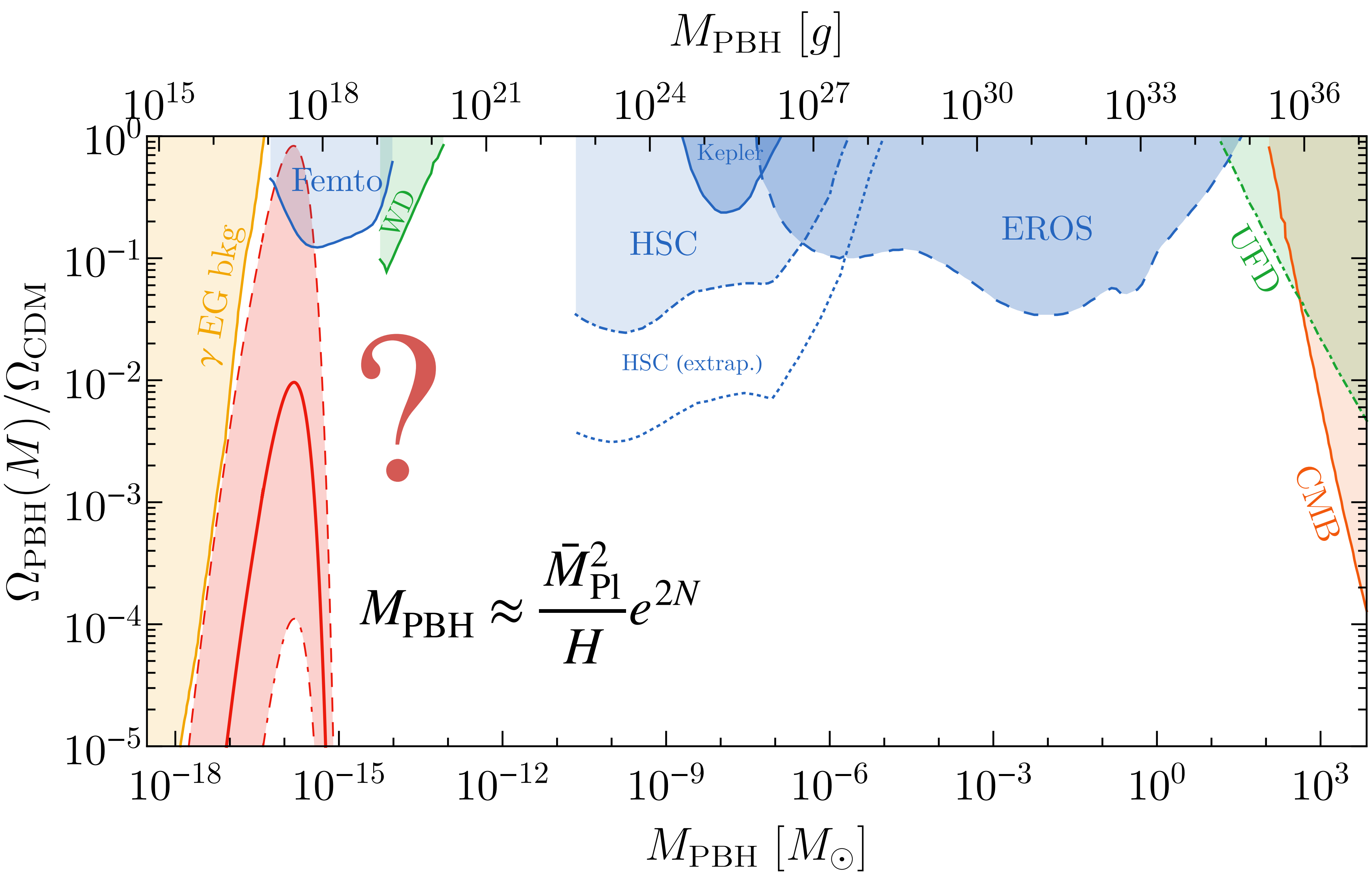


J. Ezquiaga, J. Garcia-Bellido, E. Ruiz Morales, arXiv:1705.04861
F. Bezrukov, M. Pauly, J. Rubio, arXiv:1706.05007
I. Masina, arXiv:1805.02160

PART II: Particle physics from Cosmology

The very early Universe: Inflation

Primordial black holes from Higgs inflation?

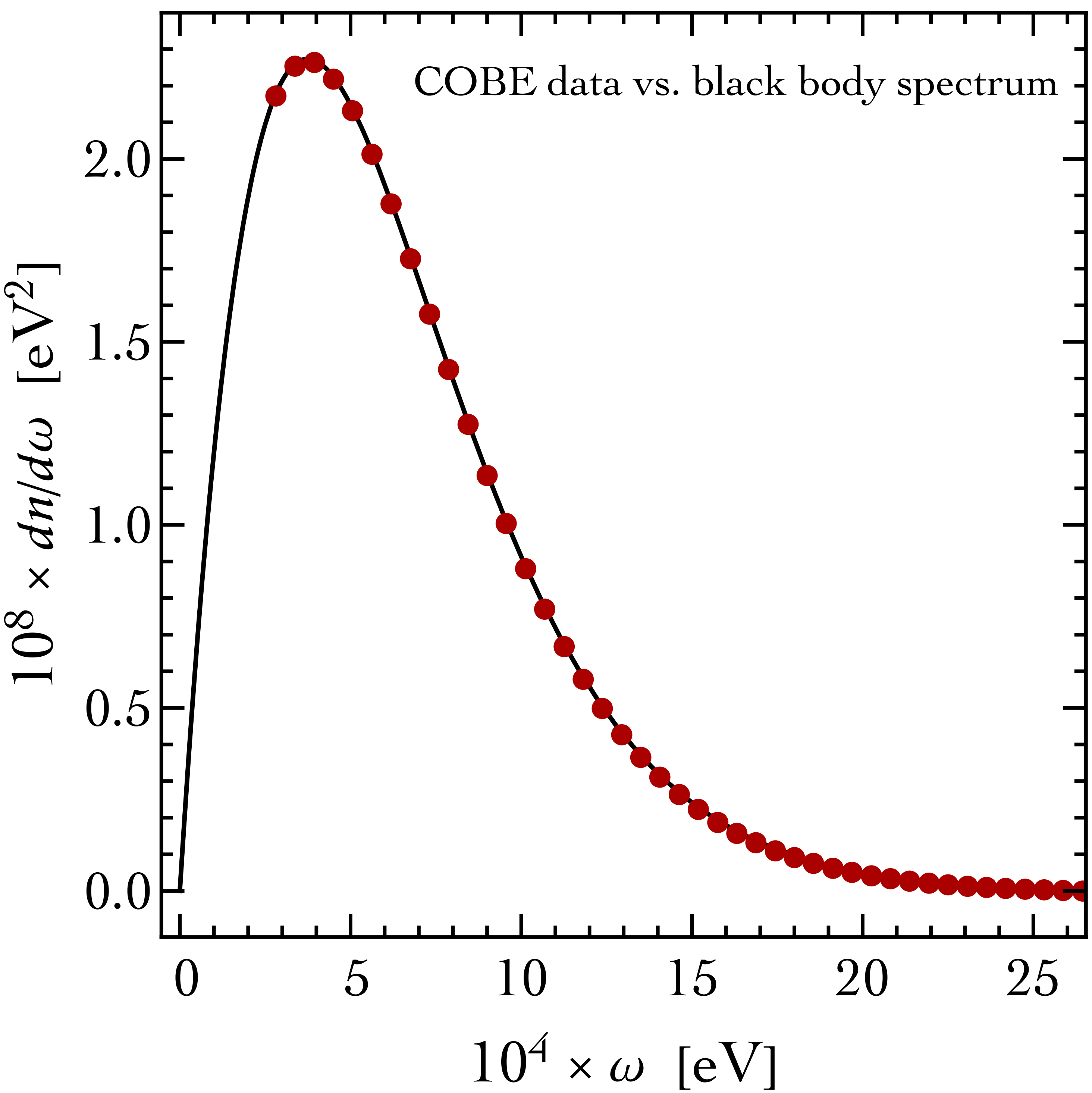


PART II: Particle physics from Cosmology

The late Universe: 21 cm cosmology

PART II: Particle physics from Cosmology

The late Universe: 21 cm cosmology

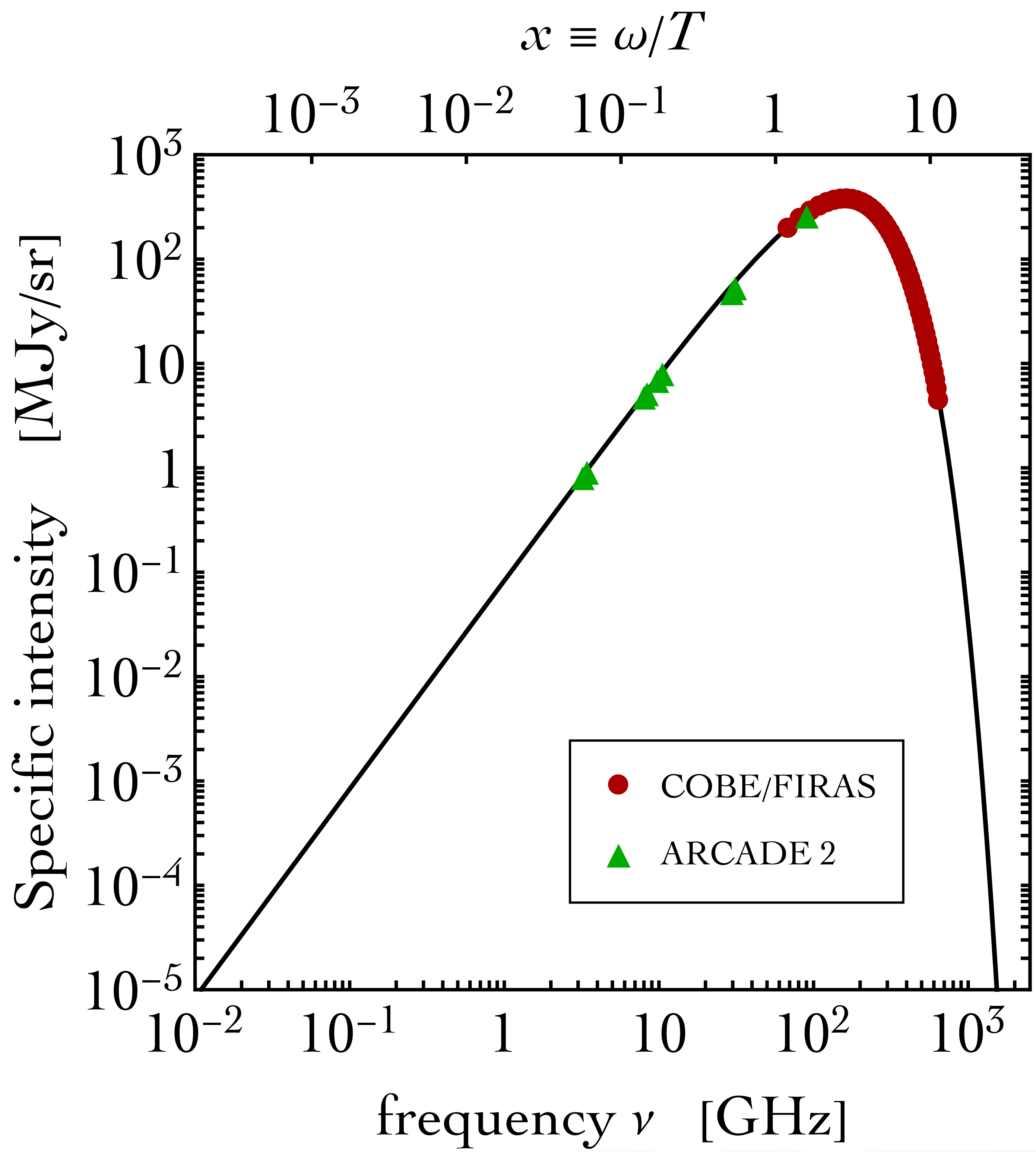


$$\frac{dn}{d\omega} = \frac{\omega^2}{\pi^2 \left(e^{\omega/T_0} - 1\right)}$$

$$T_0 = 2.7255 \quad K$$

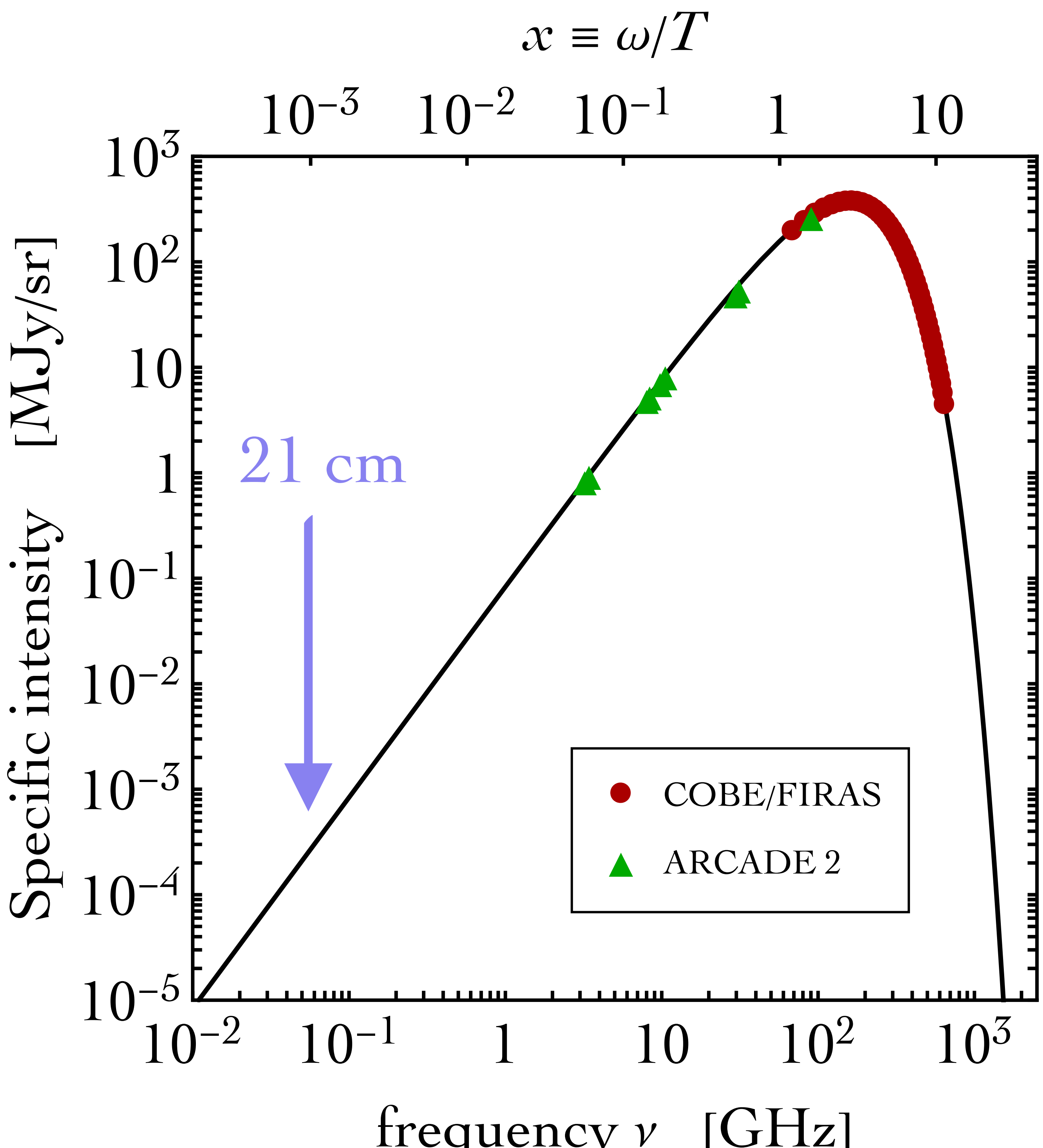
PART II: Particle physics from Cosmology

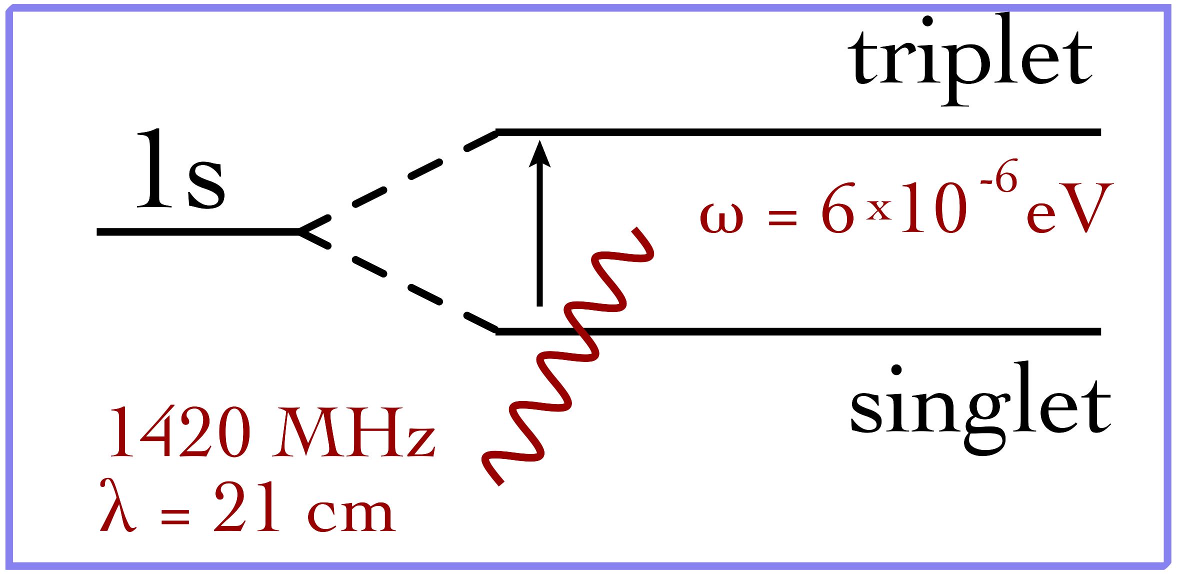
The late Universe: 21 cm cosmology



PART II: Particle physics from Cosmology

The late Universe: 21 cm cosmology





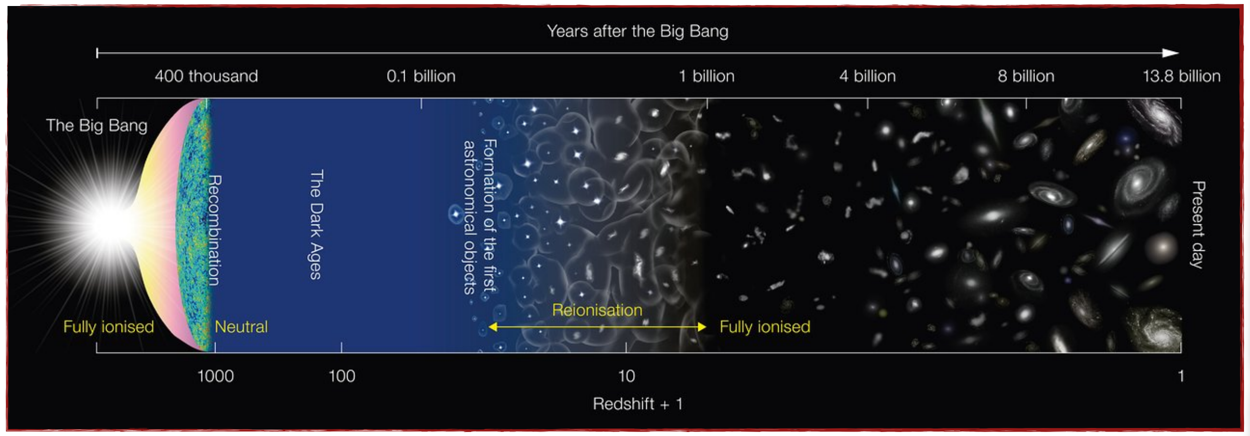
$$\frac{n_1}{n_0} = 3e^{-\Delta E/T_s}$$

High T_s : Mostly in the excited state
Likely to emit 21cm photons

Low T_s : Mostly in the ground state
Likely to absorb 21cm photons

PART II: Particle physics from Cosmology

The late Universe: 21 cm cosmology



After decoupling ($z < 1000$), in the early Universe there is cosmic gas (largely neutral, and made mostly of hydrogen with spin temperature T_s) and CMB photons

Triplet-to-singlet transition of the 1s level of atomic hydrogen

PART II: Particle physics from Cosmology

$$\Delta T_{21} \propto \left(1 - \frac{T_{\rm CMB}}{T_s}\right)$$

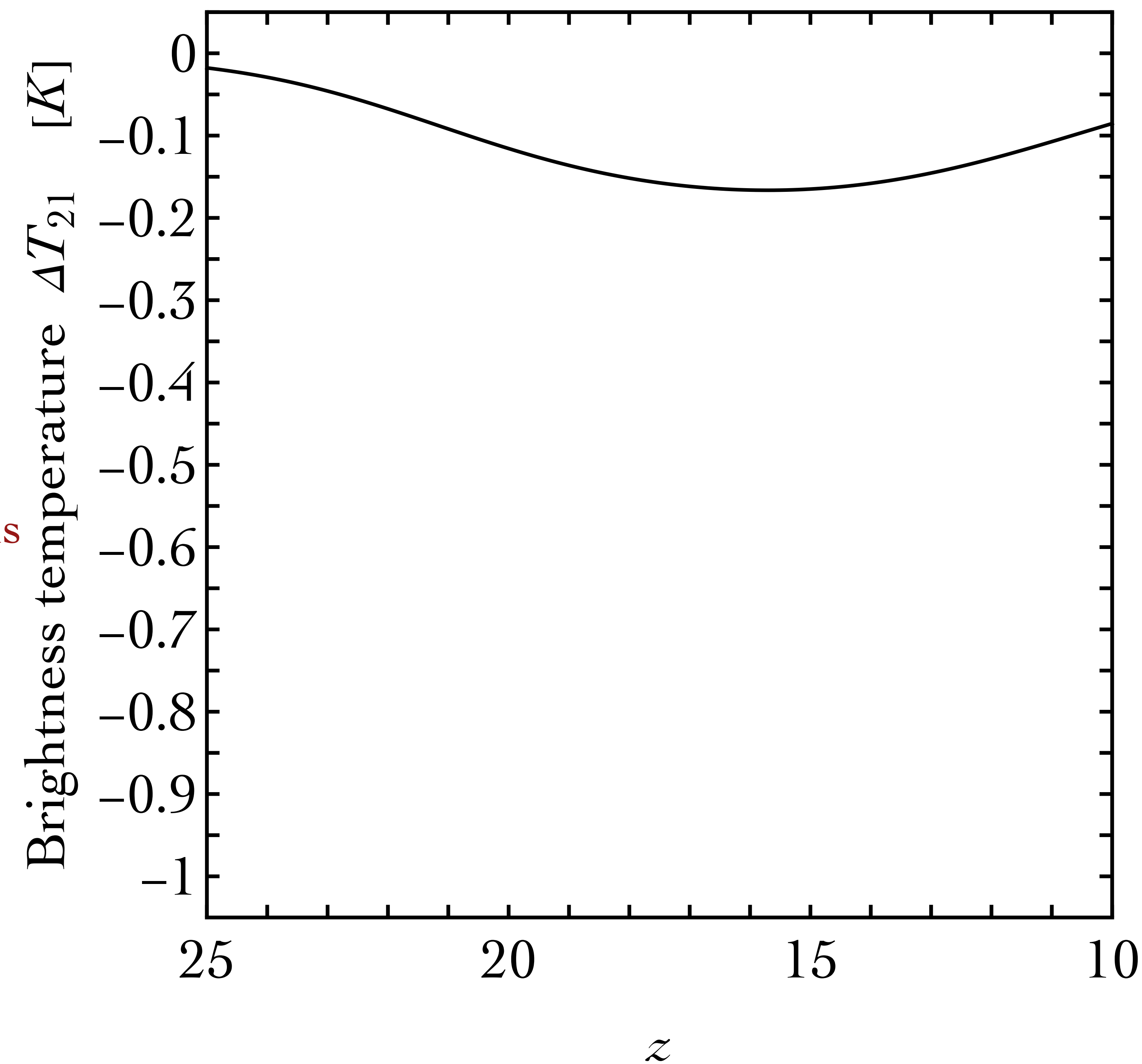
late Universe: 21 cm cosmology

$$T_s \gg T_{\rm CMB} \quad \Rightarrow \quad \Delta T_{21} > 0$$

More emission of 21 cm photons

$$T_s \ll T_{\rm CMB} \quad \Rightarrow \quad \Delta T_{21} < 0$$

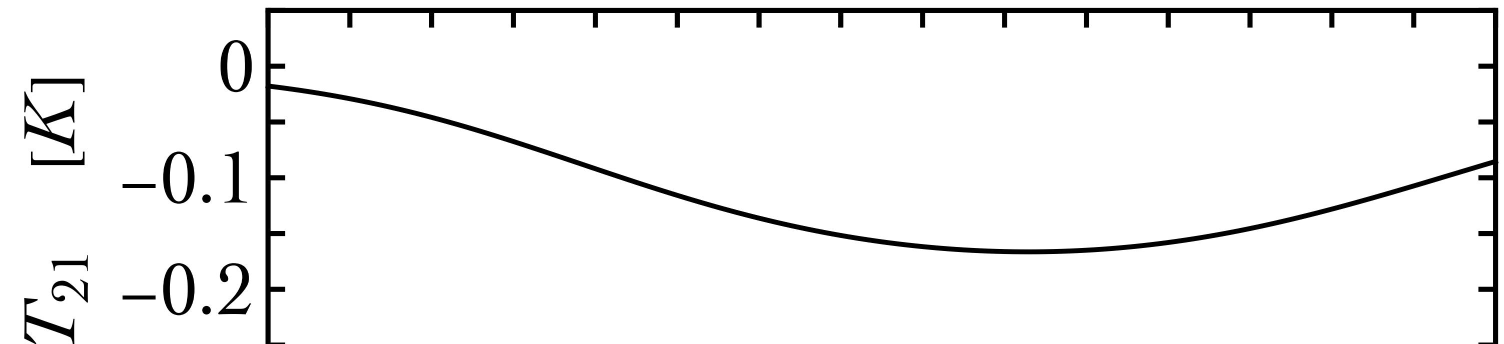
More absorption of 21 cm photons



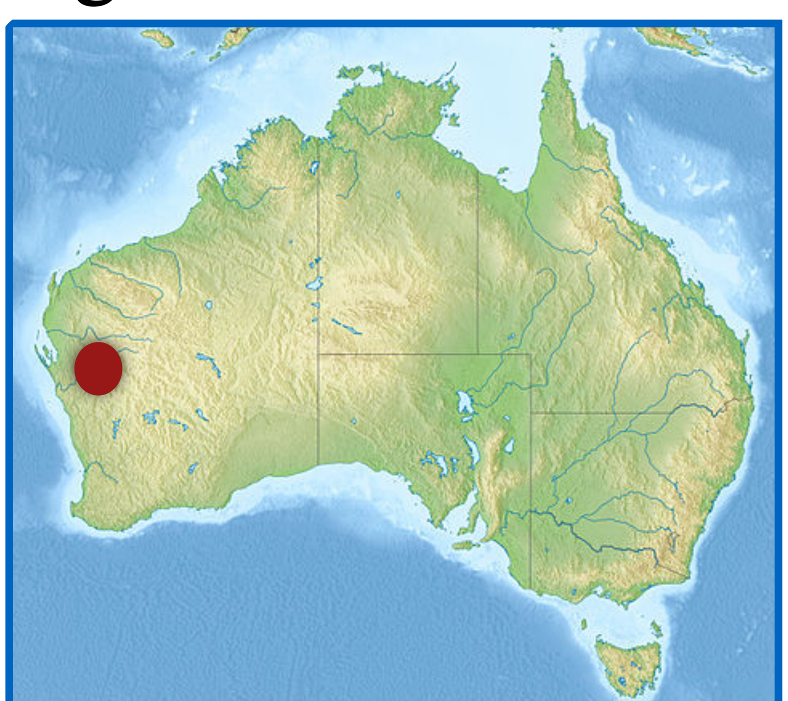
PART II: Particle physics from Cosmology

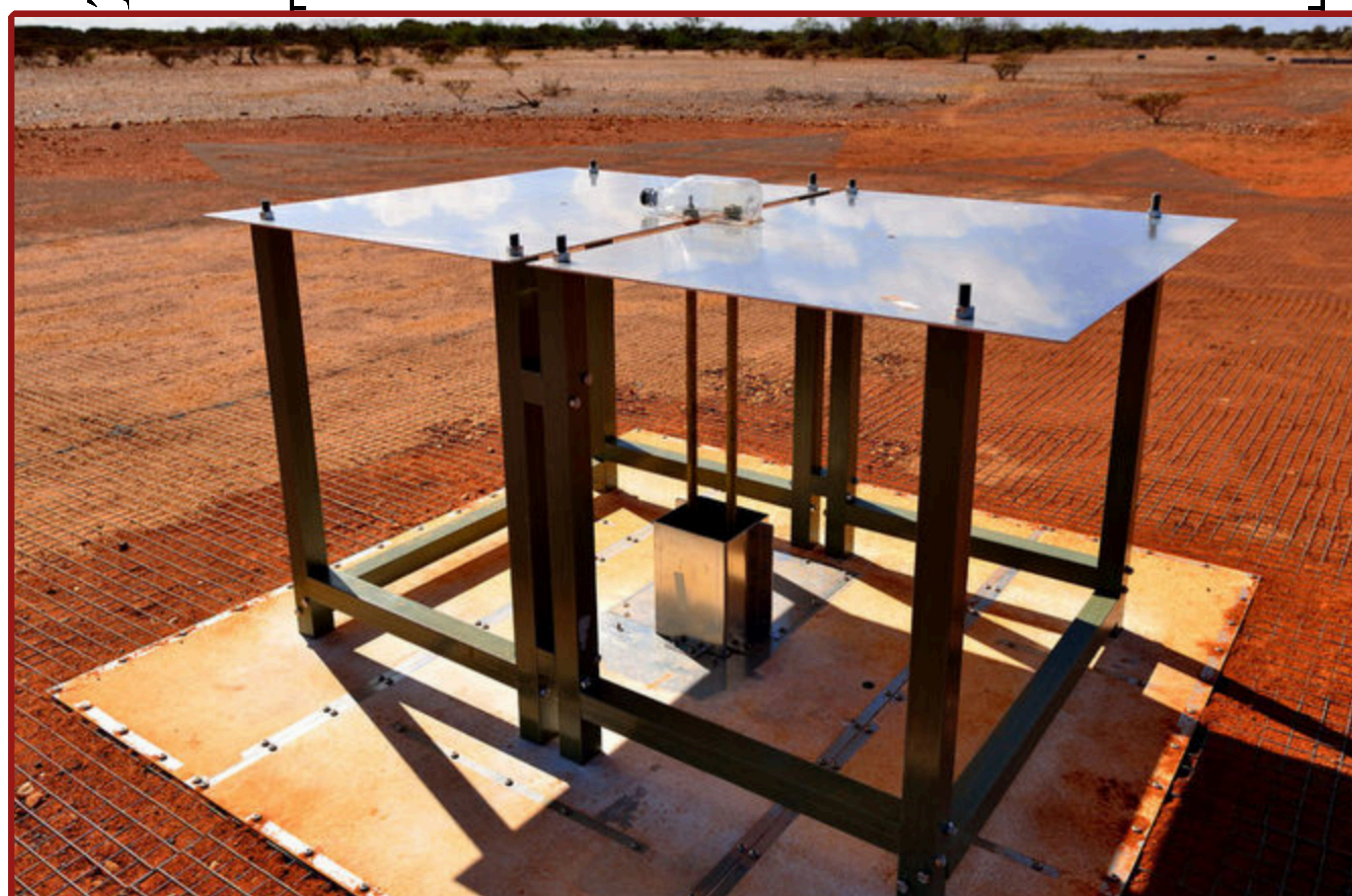
$$\Delta T_{21} \propto \left(1 - \frac{T_{\rm CMB}}{T_s}\right)$$

late Universe: 21 cm cosmology



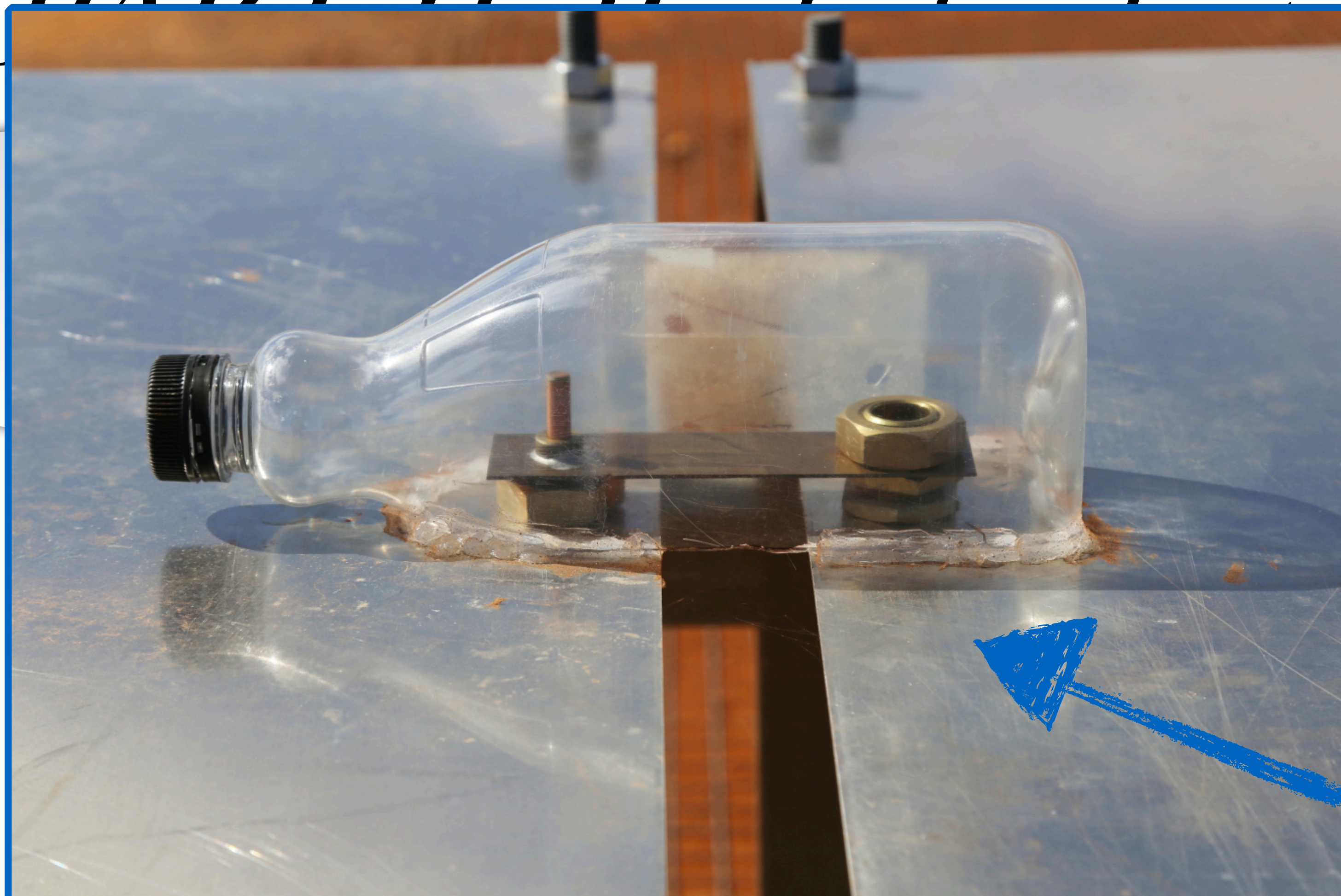
Experiment to
Detect the
Global
Epoch of reionization
Signature

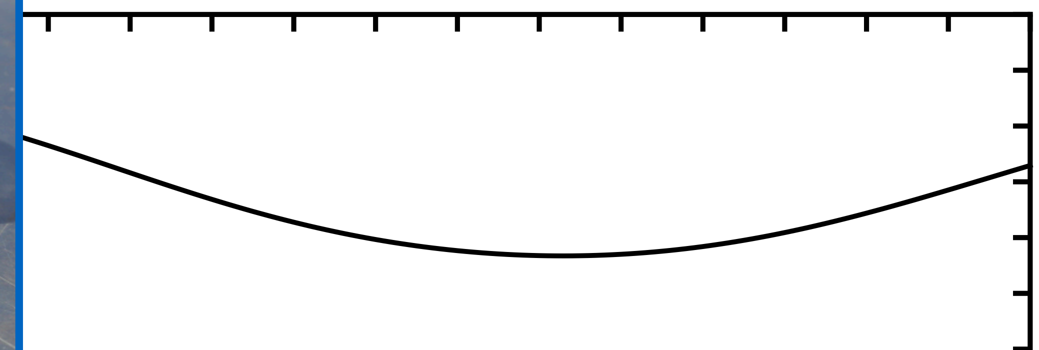


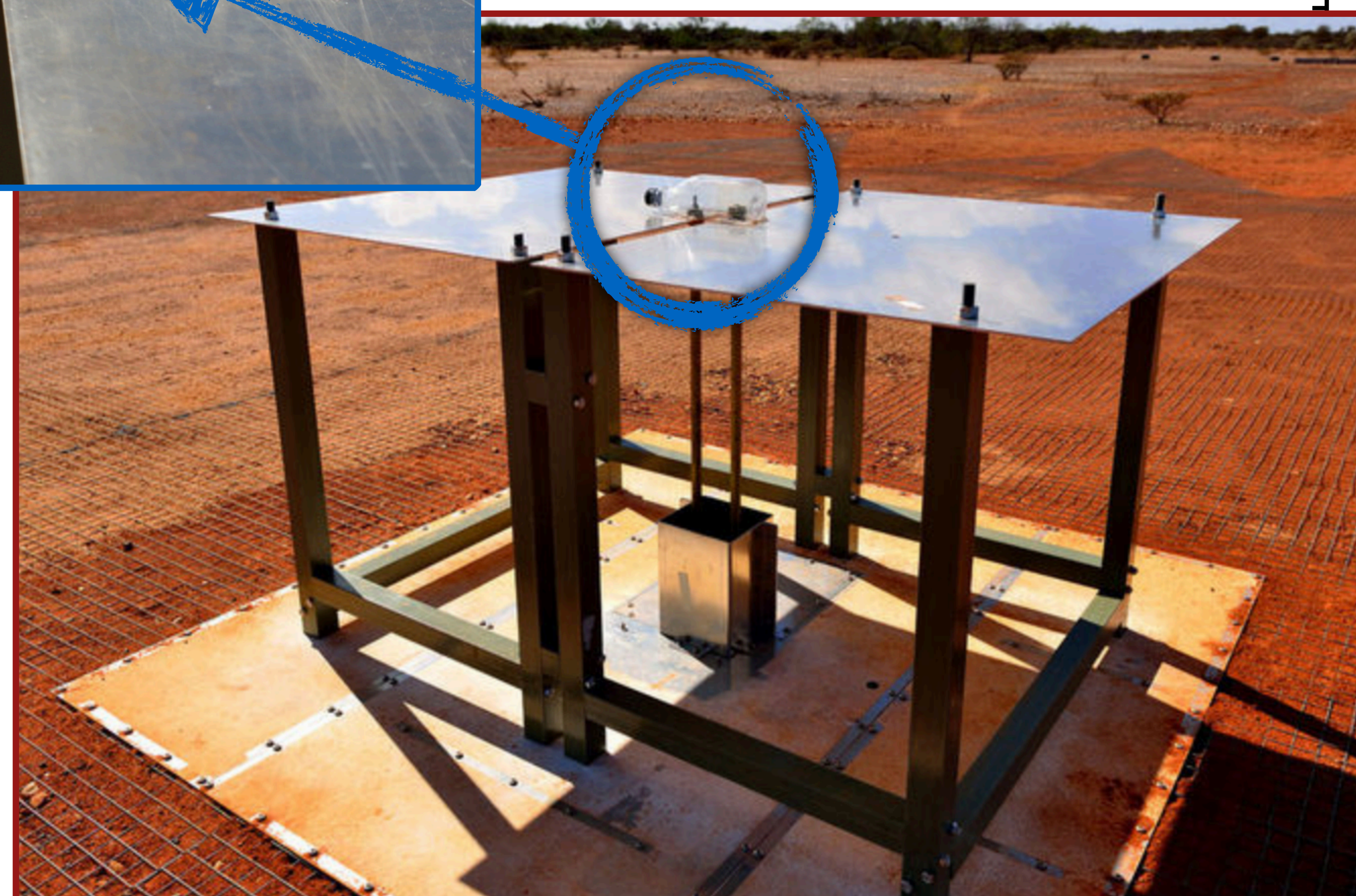


PART II: Particle physics from Cosmology

...e: 21 cm cosmology

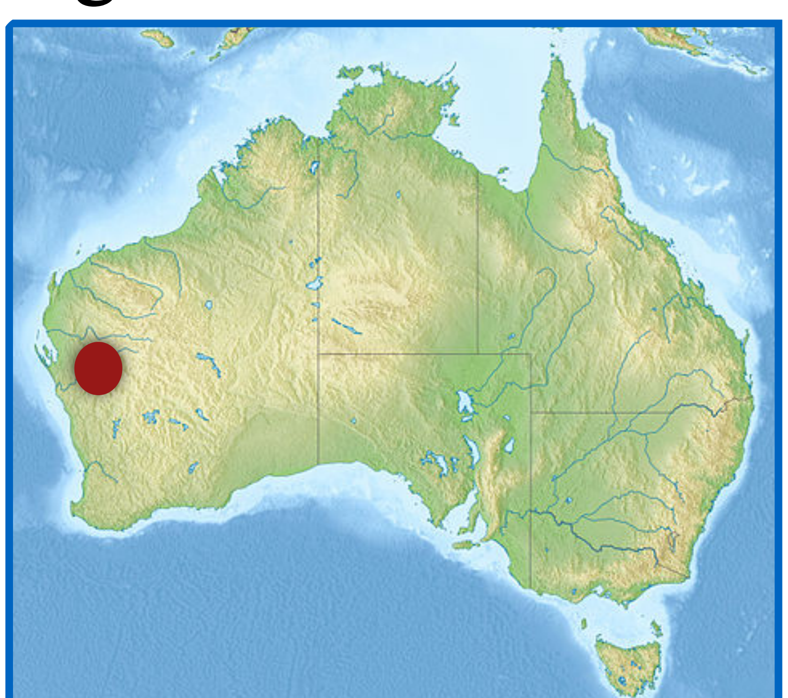






Epoch of reionization

Signature

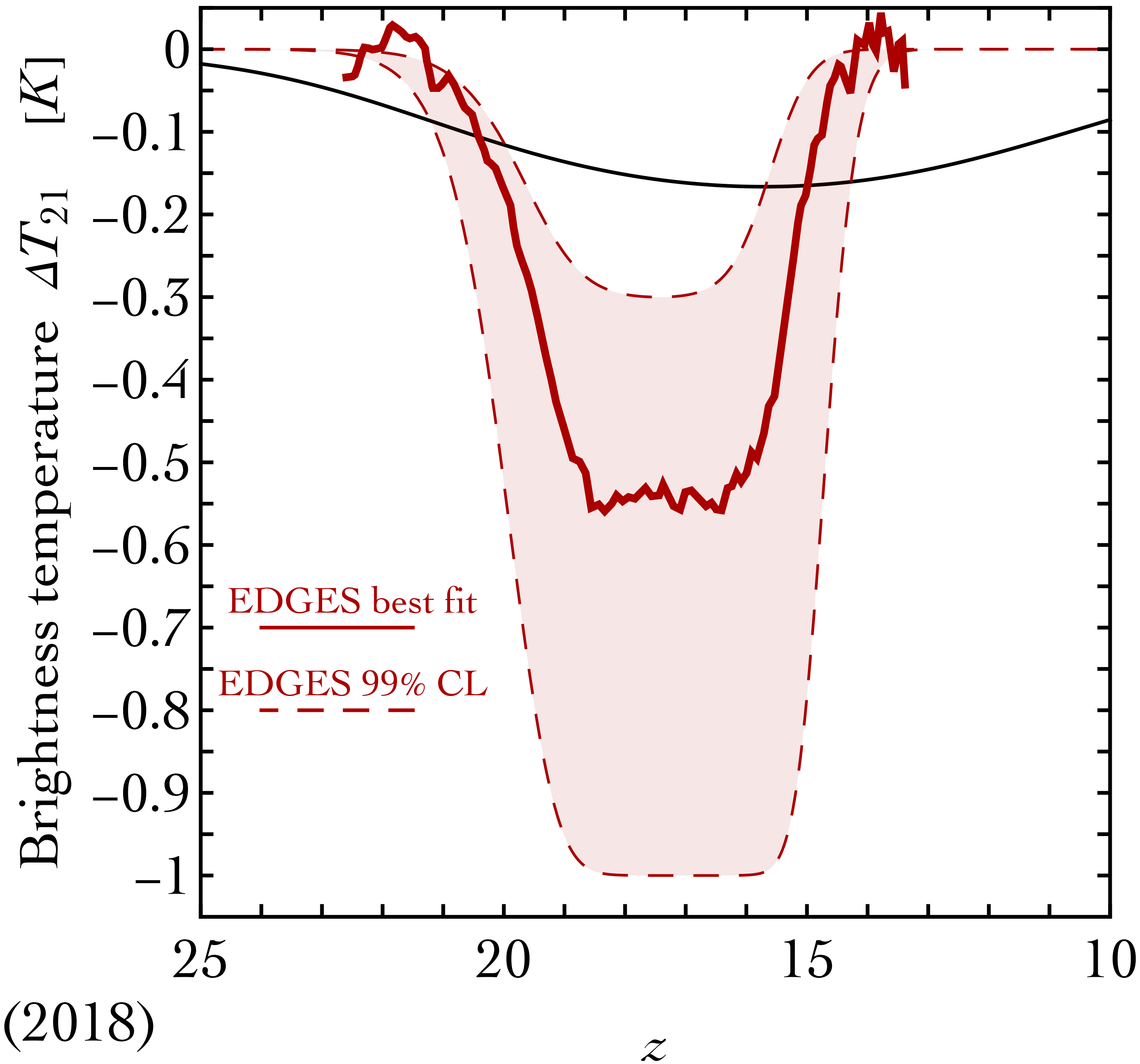


PART II: Particle physics from Cosmology

$$\Delta T_{21} \propto \left(1 - \frac{T_{\mathrm{CMB}}}{T_s}\right)$$

late Universe: 21 cm cosmology

Experiment to
Detect the
Global
Epoch of reionization
Signature

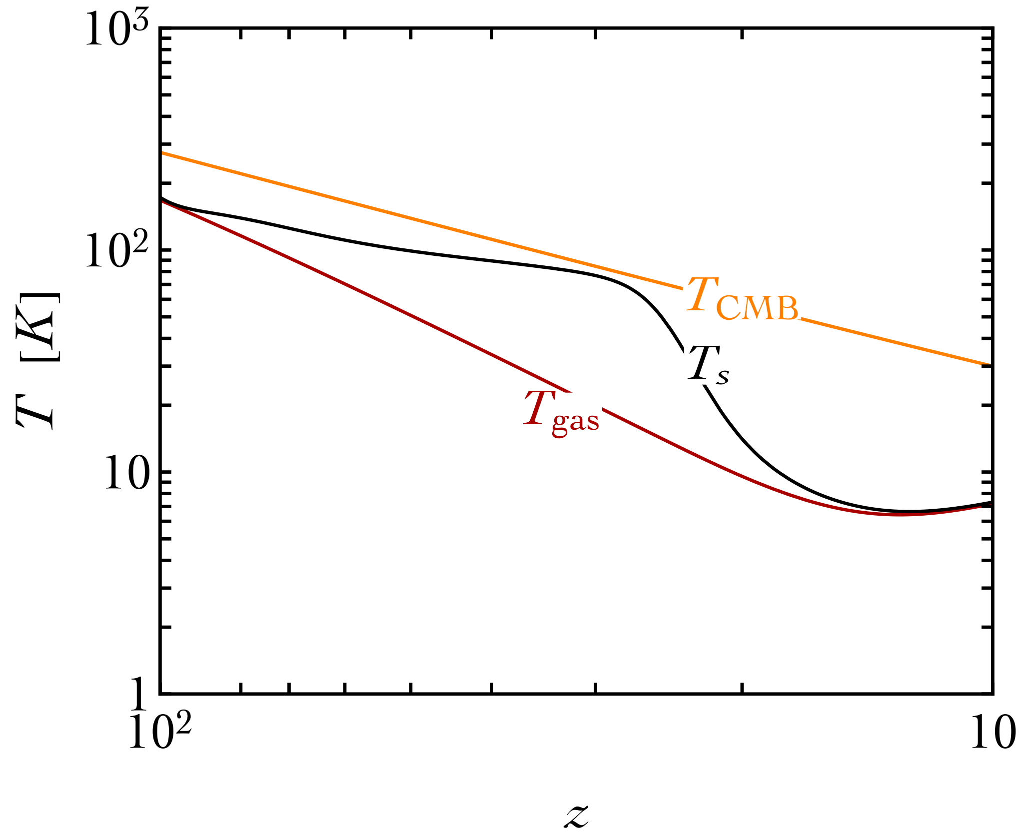


Bowman et. al. Nature **555**, 67 (2018)

PART II: Particle physics from Cosmology

The late Universe: 21 cm cosmology

21 cm probes new particle physics

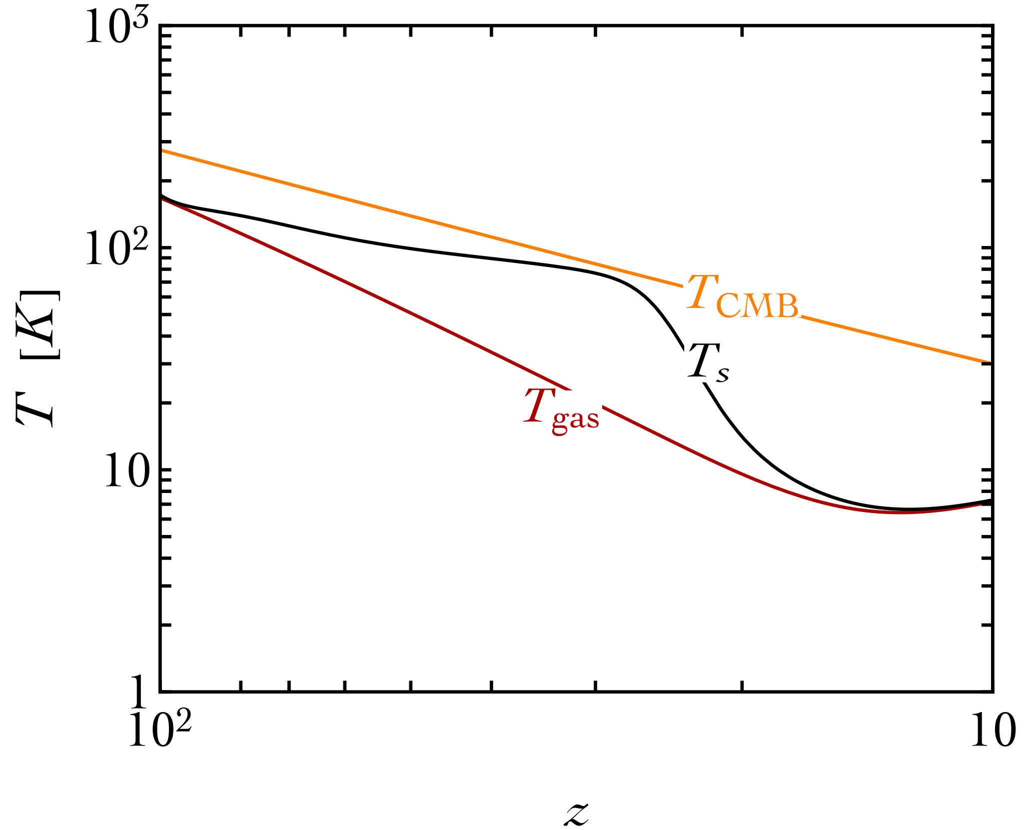


$$\Delta T_{21} \propto \left(1 - \frac{T_{\rm CMB}}{T_s}\right)$$

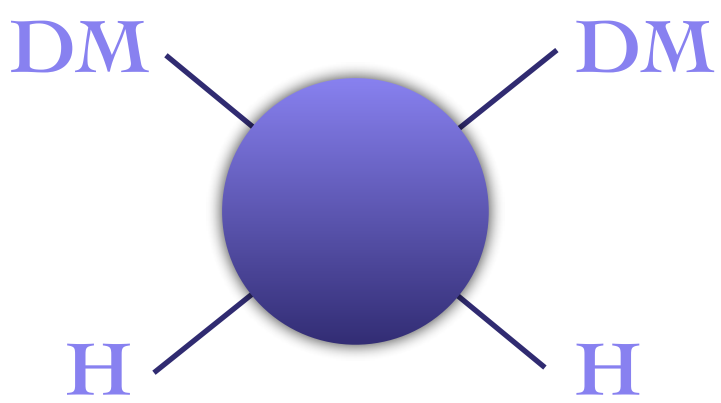
PART II: Particle physics from Cosmology

The late Universe: 21 cm cosmology

21 cm probes new particle physics



Cool baryons (very hard!)

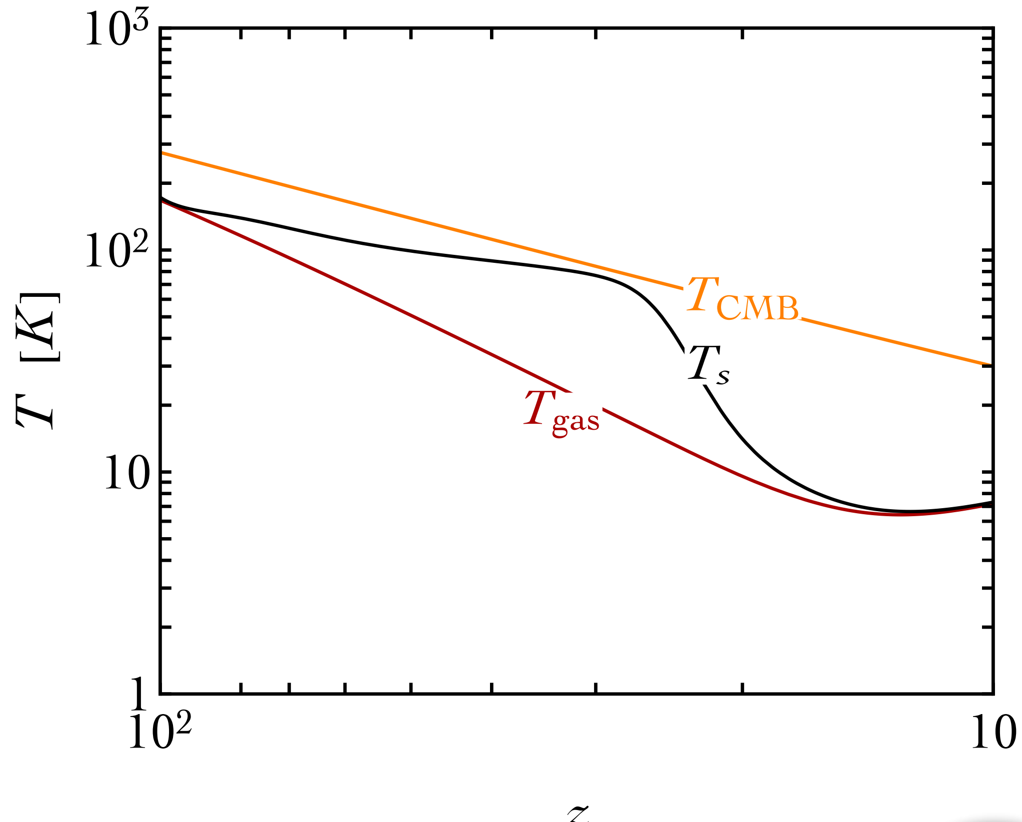


$$\Delta T_{21} \propto \left(1 - \frac{T_{\rm CMB}}{T_s}\right)$$

PART II: Particle physics from Cosmology

The late Universe: 21 cm cosmology

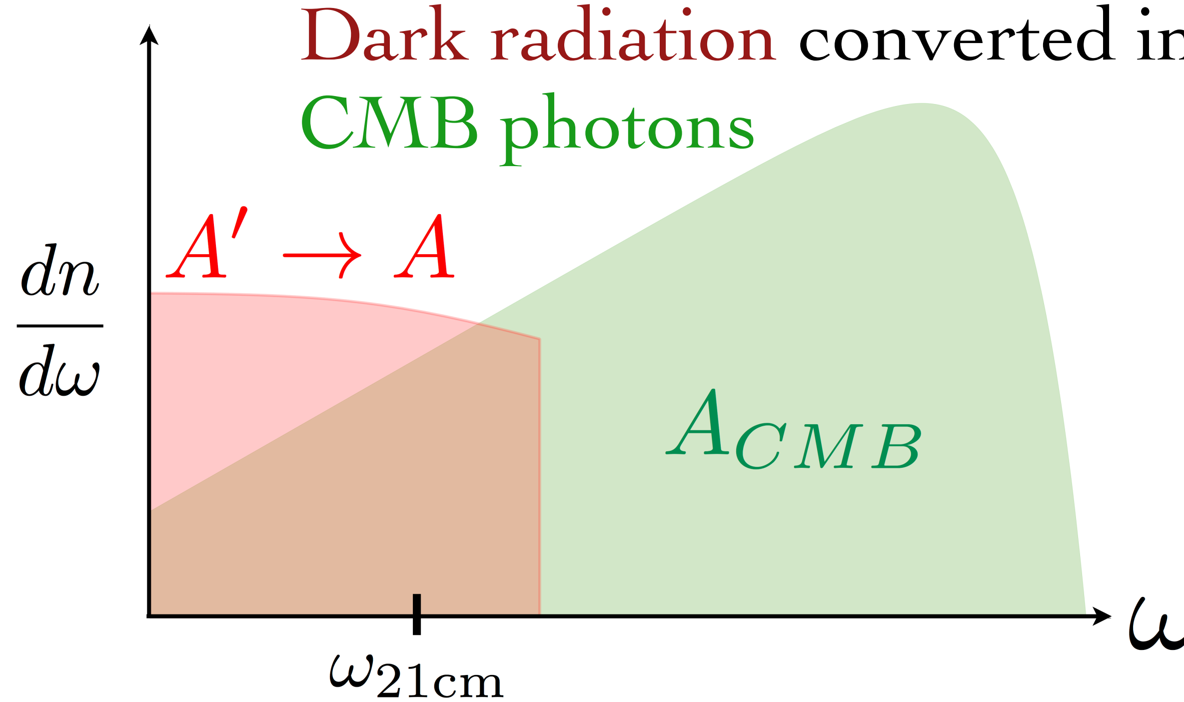
21 cm probes new particle physics



Add photons (very easy!)

$$T_\gamma > T_{\rm CMB}$$

$$\Delta T_{21} \propto \left(1 - \frac{T_\gamma}{T_s}\right)$$



PART II: Particle physics from Cosmology

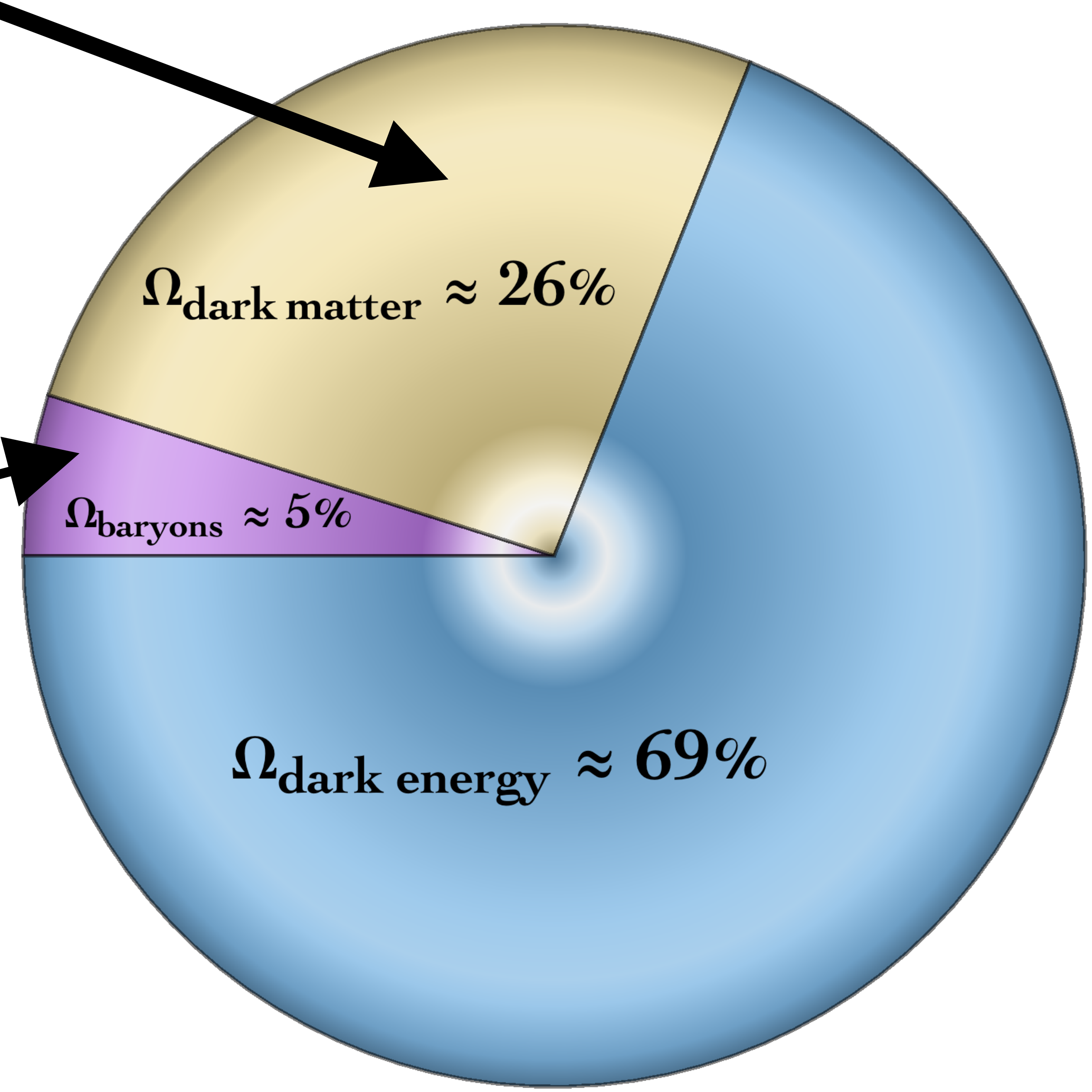
The late Universe: 21 cm cosmology

- We have started probing the Universe by 21cm
- 21 cm cosmological signal provides the key test for models with beyond SM sectors with dark radiation (without any tension with bounds on $\Delta N_{\rm eff}$)
- Exciting detection prospects!

PART III: Particle physics from Astroparticle

PART III: Particle physics from Astroparticle

Not charged under $U(1)_{em}$ and $SU(3)_C$
Stable on cosmological time-scale
Not in the SM particle list



Mostly intergalactic gas +
Stars, stuff, … $\approx 0.4\ \%$
Neutrinos $\approx 0.1\ \%$
Photons $\approx 0.01\ \%$
Black holes $\approx 0.005\ \%$

Planck cosmological parameters, 2018

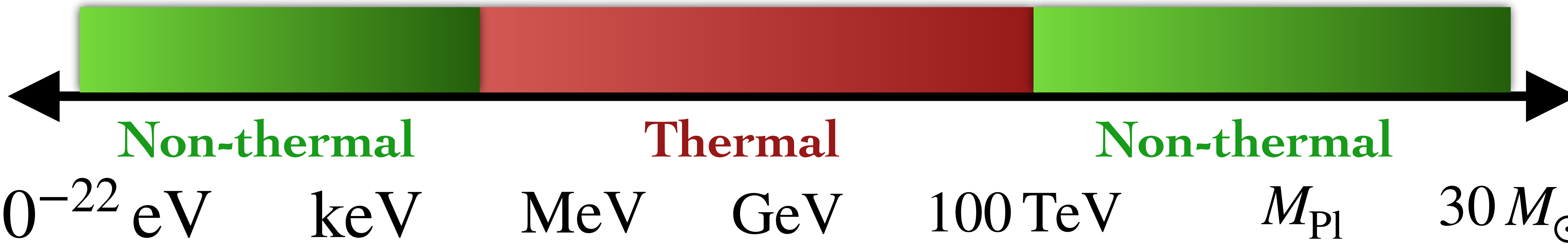
PART III: Particle physics from Astroparticle

What could dark matter be?

PART III: Particle physics from Astroparticle

What could dark matter be?

Classify models according to their thermal history

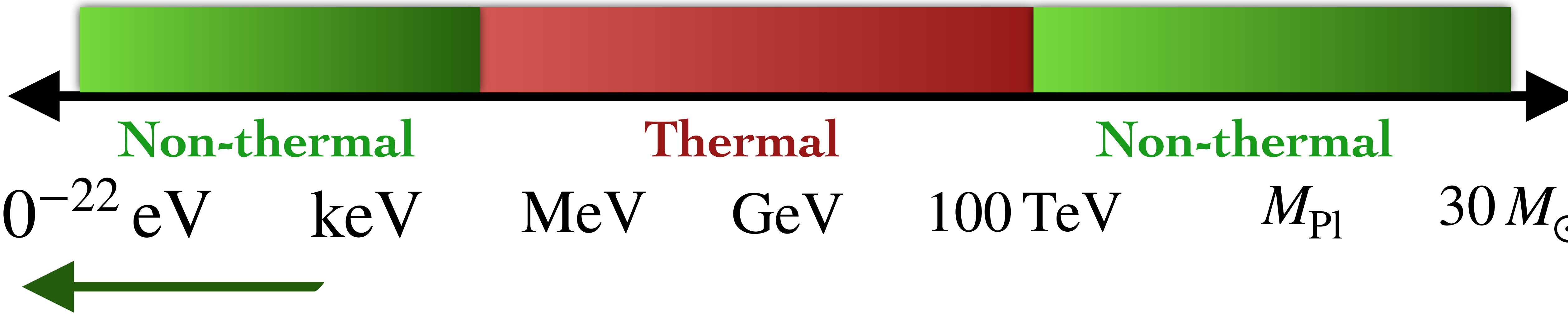


89 orders of magnitude of possibilities…

PART III: Particle physics from Astroparticle

What could dark matter be?

Classify models according to their thermal history

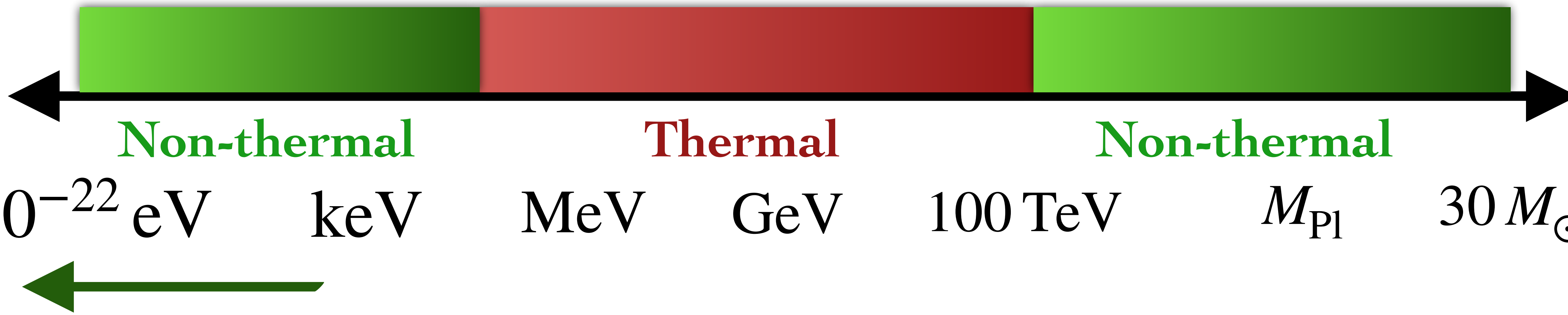


Only bosons below ~1keV (-ish)
(Tremaine-Gunn bound for fermions)

PART III: Particle physics from Astroparticle

What could dark matter be?

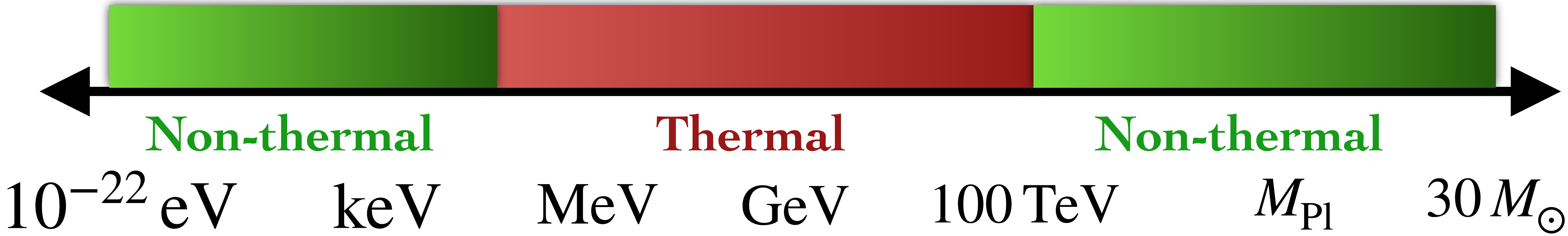
Classify models according to their thermal history



Only bosons below ~1keV (-ish)
(Tremaine-Gunn bound for fermions)

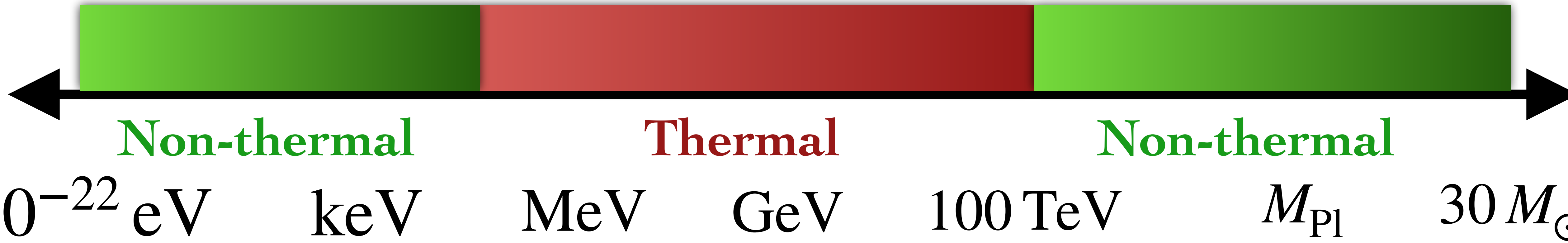
$m_b \gtrsim 10^{-22}\,\mathrm{eV}$ otherwise no Galaxy formation below a Jeans scale of $10^{8}\,M_{\odot}$

PART III: Particle physics from Astroparticle



Ultra-light dark matter (ULDM)

PART III: Particle physics from Astroparticle



Ultra-light dark matter (ULDM)

Interesting theoretical motivations: an axion-like particles from string theory

- Goldstone ϕ of U(1) symmetry spontaneously broken at some high scale f_a
- 4D axions appear as zero modes of gauge fields compactified in extra dimensions
- Periodic potential generated by non-perturbative effects

$$\Lambda = M_s \qquad \mathcal{S}_{\rm inst} = \frac{8\pi^2}{g_s^2}$$

$$V(\phi) = \Lambda^4 e^{-\mathcal{S}_{\rm inst}} \left[1 - \cos\left(\frac{\phi}{f_a}\right)\right]$$

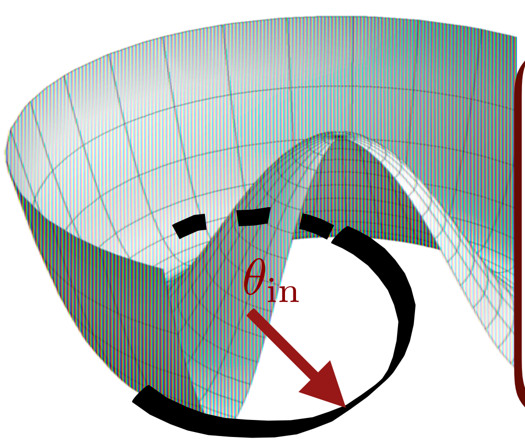
PART III: Particle physics from Astroparticle

Non-thermal	Thermal	Non-thermal

$10^{-22}\,\mathrm{eV}$ keV MeV GeV $100\,\mathrm{TeV}$ $M_{\rm Pl}$ $30\,M_\odot$

Ultra-light dark matter (ULDM)

Three parameters: axion mass m_a, axion decay constant f_a, and initial value $\theta_{\rm in} \equiv \phi_{\rm in}/f_a$

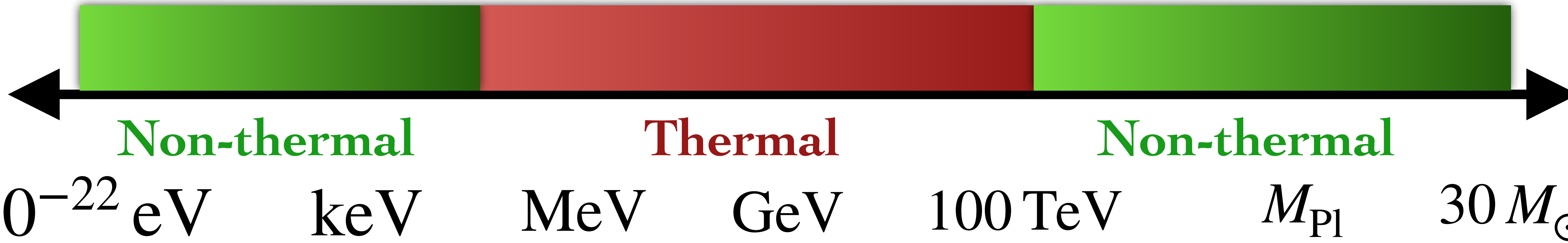


$$\Omega_a h^2 \approx 0.1\,\theta_{\rm in}^2 \left(\frac{f_a}{10^{17}\,\mathrm{GeV}}\right)^2 \left(\frac{m_a}{10^{-22}\,\mathrm{eV}}\right)^{1/2}$$

Relic density sets by the <u>misalignment mechanism</u>

[Energy density today is initial value, redshifted from start of oscillation]

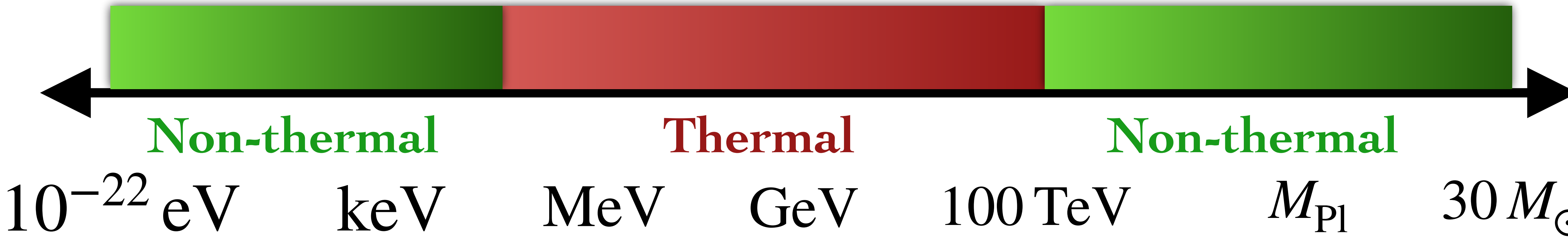
PART III: Particle physics from Astroparticle



Ultra-light dark matter (ULDM)

<u>Interesting phenomenology</u>

PART III: Particle physics from Astroparticle



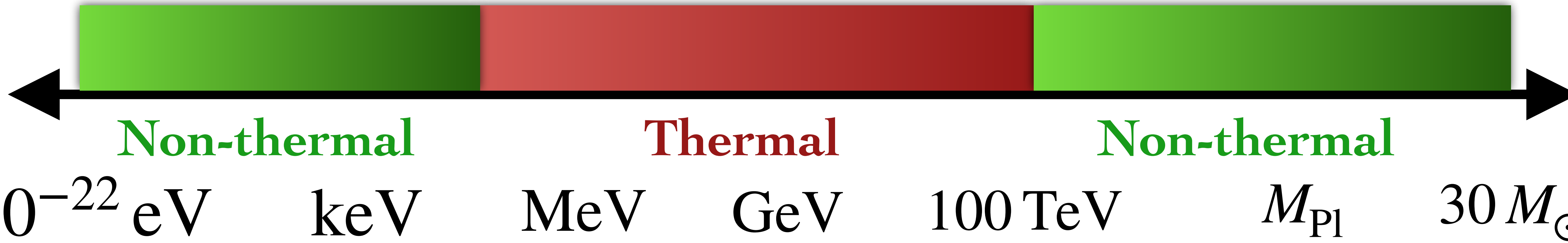
Ultra-light dark matter (ULDM)

A possibile solutions of the "small scales CDM issues":

- Cusp-core problem — DM profile at the center of DphS, no NFW peak
- Too big to fail problem — The observed satellites of the Milky Way are not massive enough to be consistent with predictions from CDM
- Missing satellites problem — 1000's of satellites predicted. Only dozens seen

[But… are they really problems?
All of the predictions that lead to the small scale crises
are based on dark matter-only simulations. What about baryons?]

PART III: Particle physics from Astroparticle



Ultra-light dark matter (ULDM)

Bounds from Ly-α forest*analysis $m_a \gtrsim 10^{-21}$ eV

B. Bozek, D. J. E. Marsh, J. Silk, and R. F. G. Wyse, arXiv:1409.3544
V. Irsic, M. Viel, M. G. Haehnelt, J. S. Bolton, and G. D. Becker, arXiv:1703.04683
T. Kobayashi, R. Murgia, A. De Simone, V. Irsic, and M. Viel, arXiv:1708.00015

[However, the strongest Ly-α bound constraints come from the smallest and most non-linear scales, where systematic effects are challenging…]

* Absorption feature by neutral hydrogen at $\lambda = 1216$ Å at different redshifts in the spectra of distant quasars.

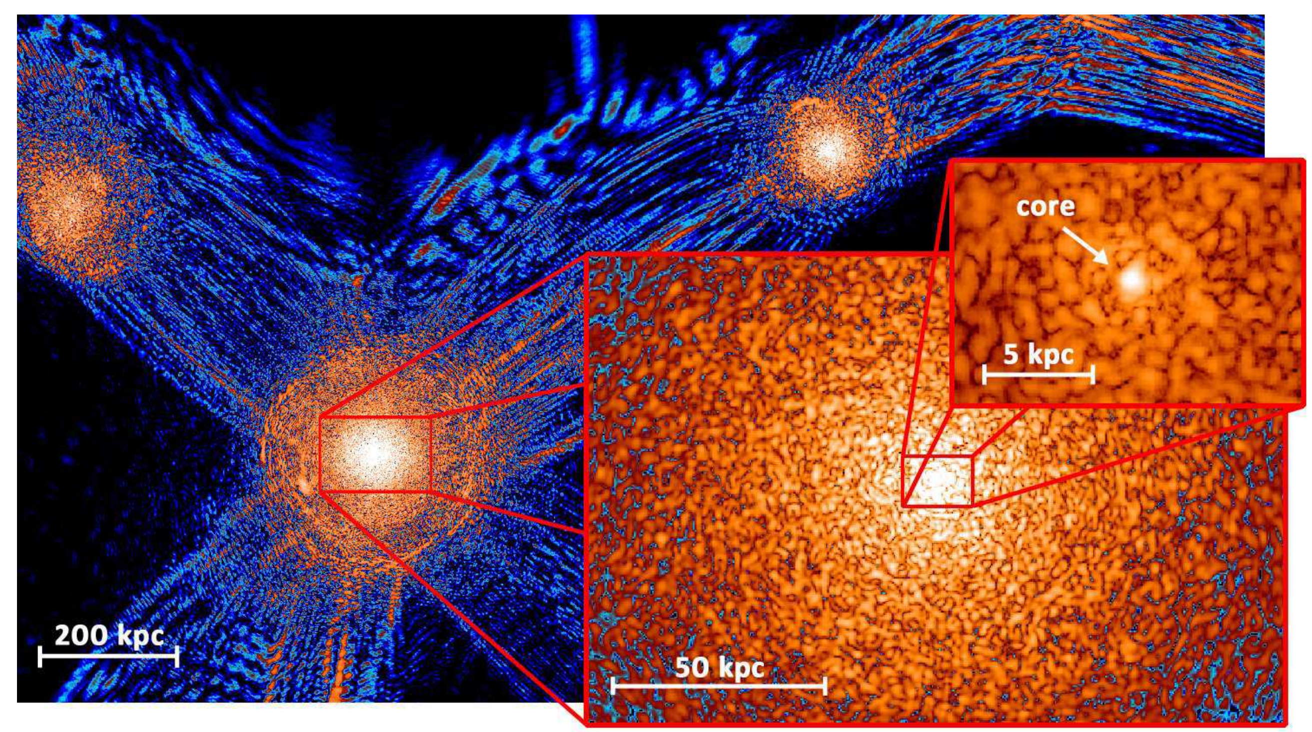
PART III: Particle physics from Astroparticle

Non-thermal | Thermal | Non-thermal

$10^{-22}\,\mathrm{eV}$ keV MeV GeV 100 TeV $M_{\rm Pl}$ $30\,M_\odot$

Ultra-light dark matter (ULDM)

In the last ~ 5 years, numerical structure formation simulations with ULDM have become available.



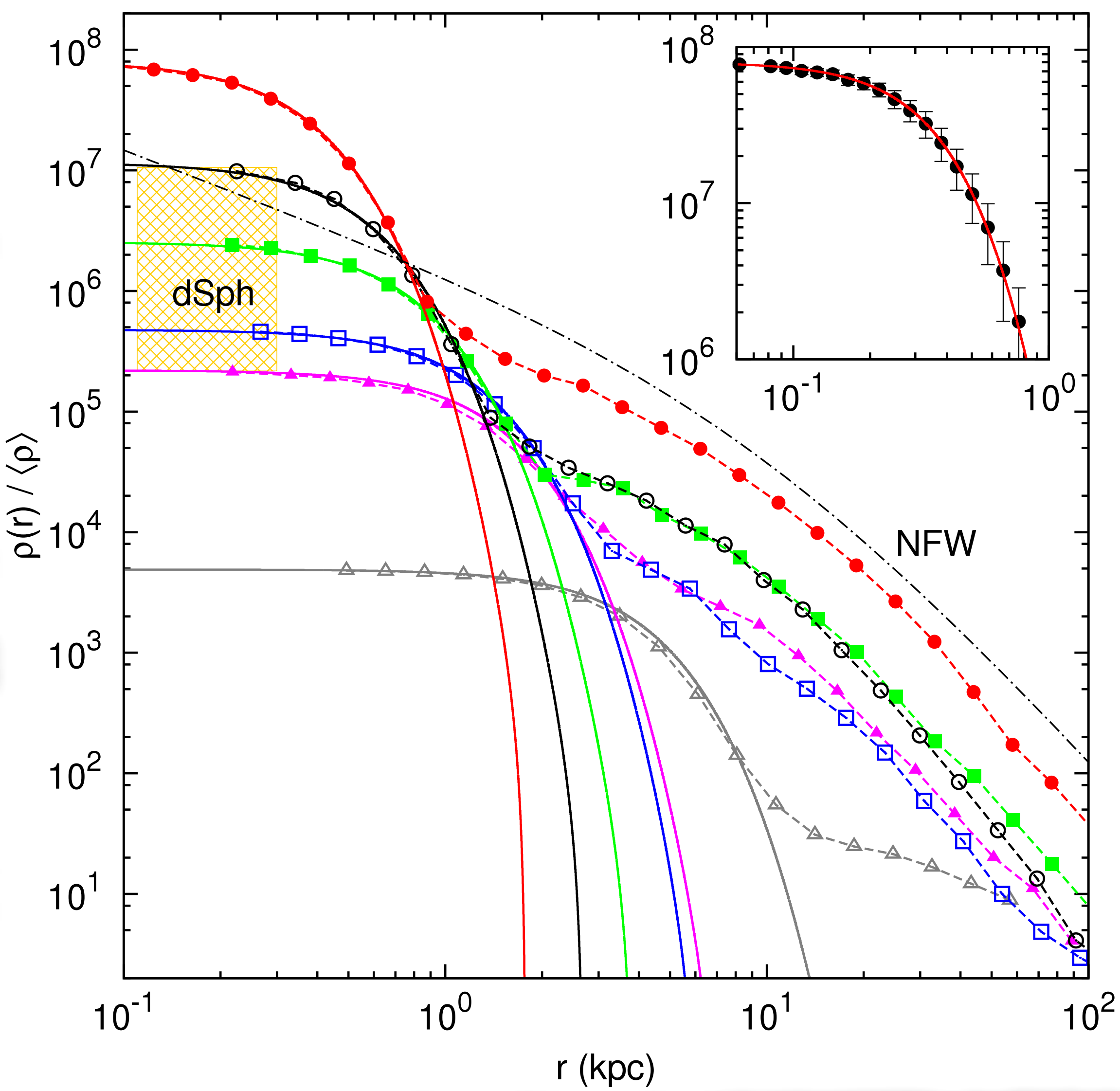
H.-Y. Schive, T. Chiueh, T. Broadhurst, arXiv:1406.6586

PART III: Particle physics from Astroparticle

Non-thermal | **Thermal** | **Non-thermal**

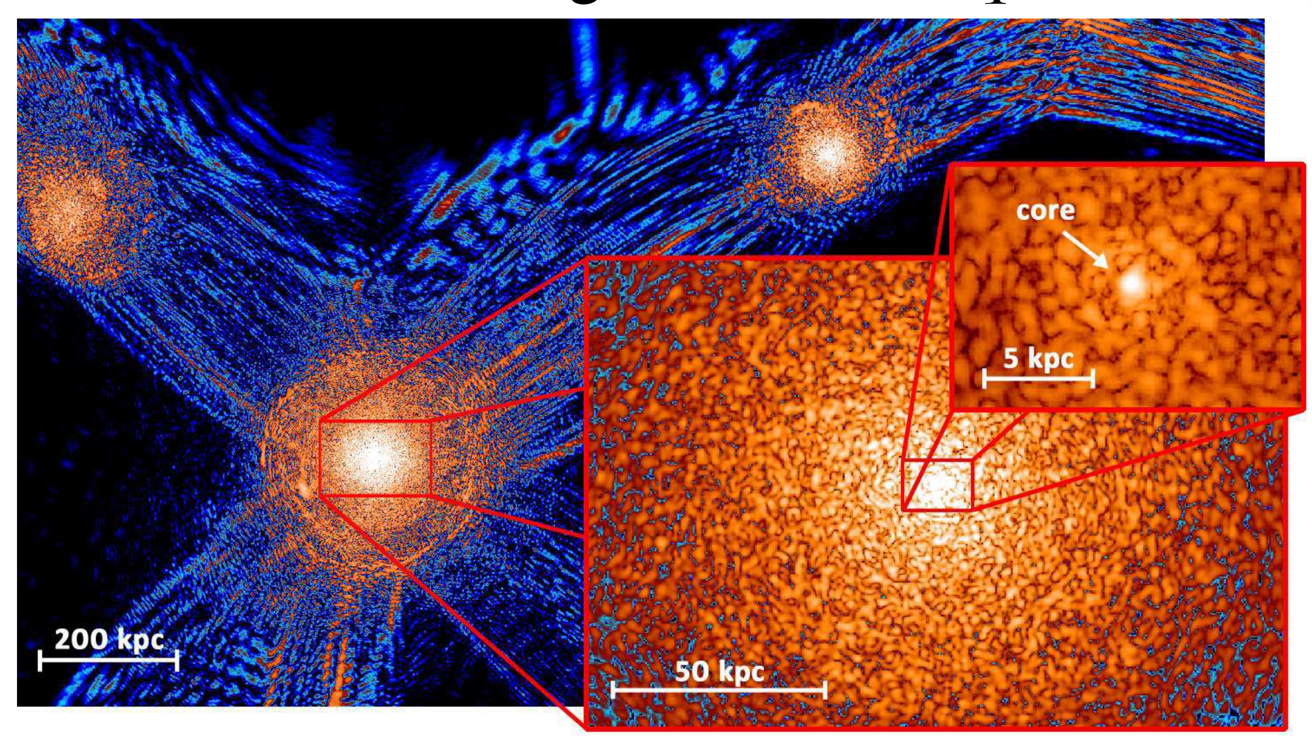
10^{-22} eV — keV — MeV — GeV — 100 TeV — $M_{\rm Pl}$ — $30\,M_\odot$

Ultra-light dark matter (ULDM)



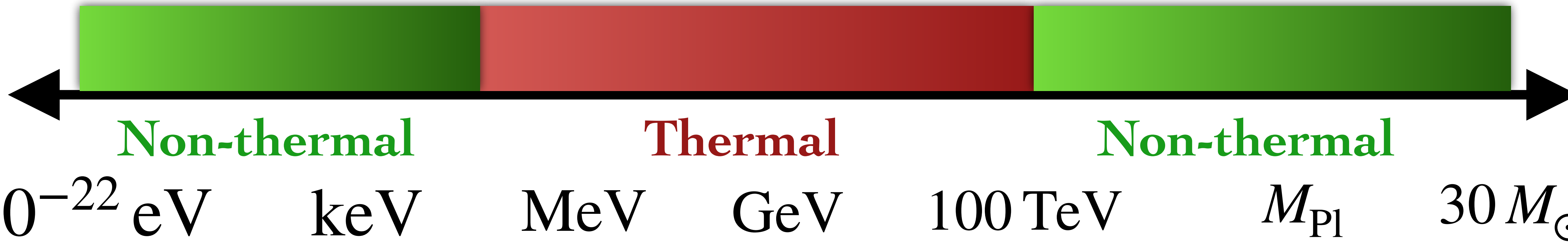
Key prediction: a solitonic core

The core is the lowest energy bound state solution of the Schroedinger-Poisson equations



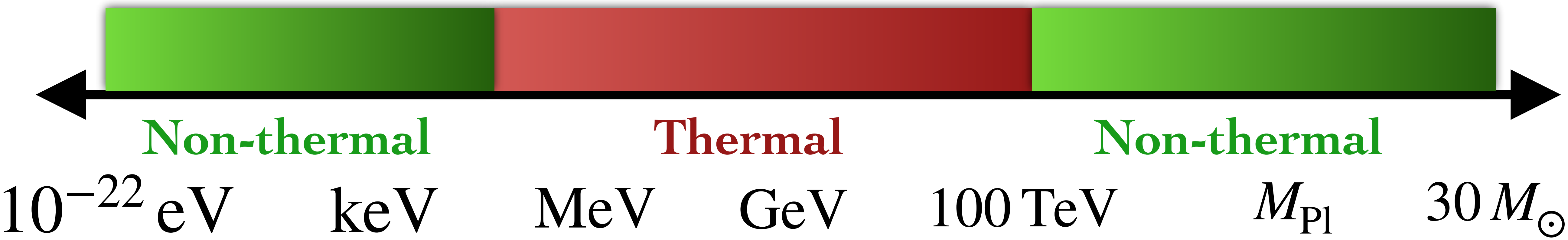
H.-Y. Schive, T. Chiueh, T. Broadhurst, arXiv:1406.6586

PART III: Particle physics from Astroparticle



QCD axion dark matter

PART III: Particle physics from Astroparticle

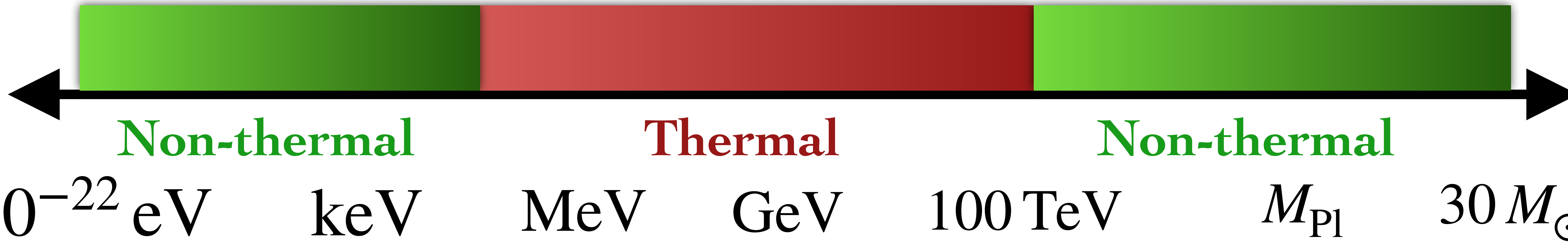


QCD axion dark matter

- Strongest theoretical motivations: The QCD axion solves the strong CP problem
- Periodic potential generated from non-perturbative QCD effects

$$V(a) = \Lambda_{\mathrm{QCD}}^4 \left[1 - \cos\left(\frac{a}{f_a}\right)\right]$$

PART III: Particle physics from Astroparticle

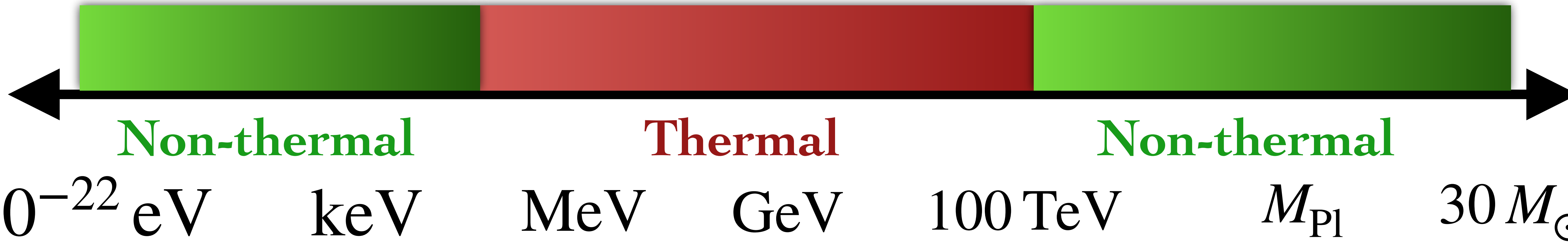


QCD axion dark matter

Relation between the axion mass and the axion decay constant

$$m_a = 5.70 \times 10^{-6} \left(\frac{10^{12}\,\mathrm{GeV}}{f_a} \right) \mathrm{eV}$$

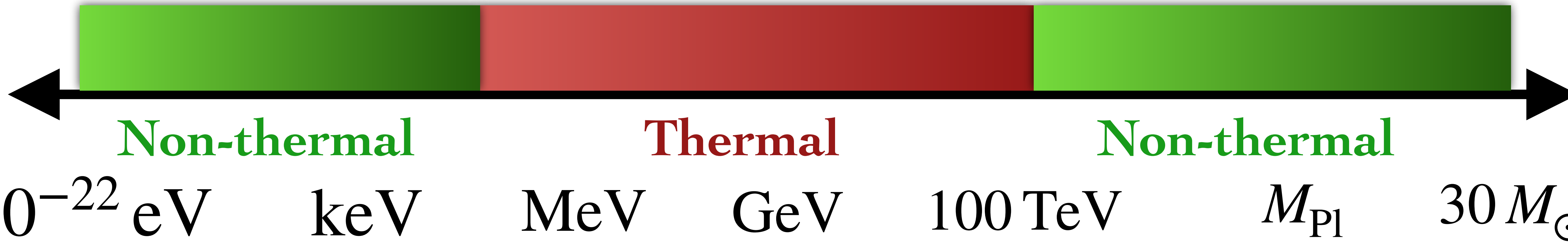
PART III: Particle physics from Astroparticle



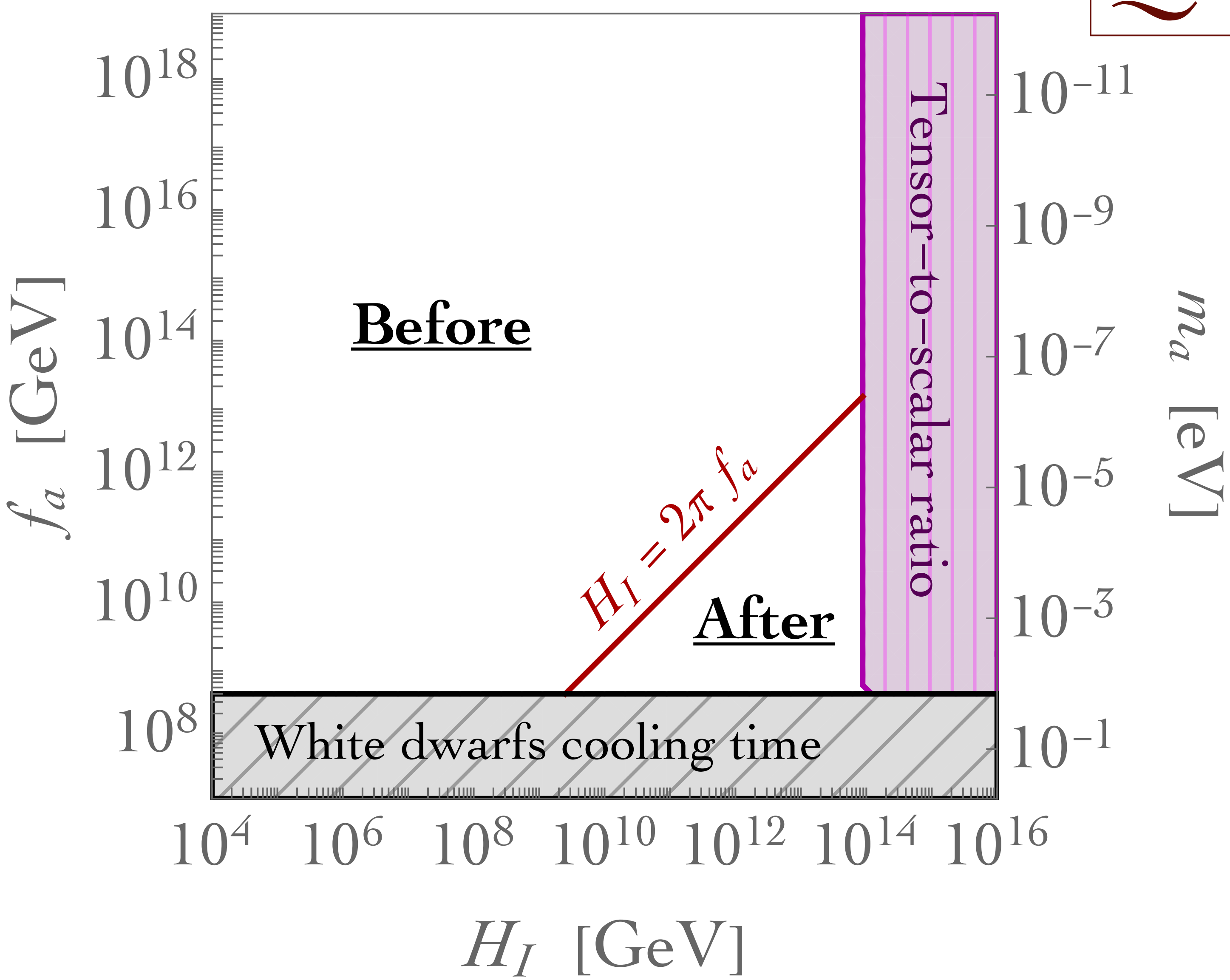
QCD axion dark matter

Crucial interplay with inflation

PART III: Particle physics from Astroparticle



QCD axion dark matter



Crucial interplay with inflation

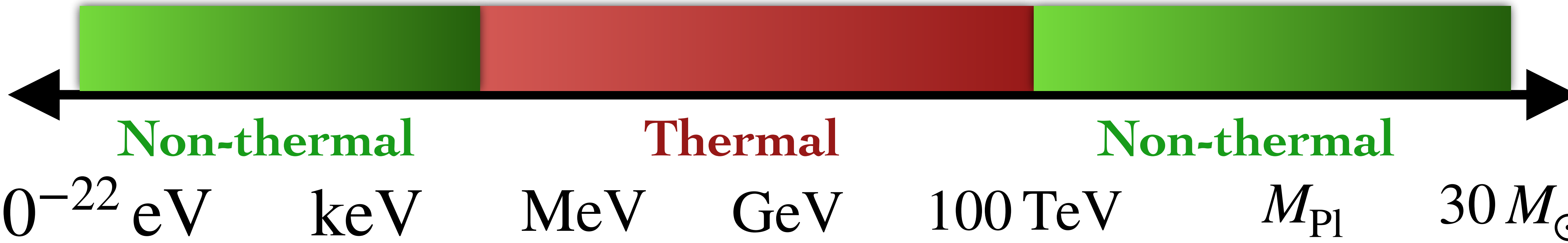
$$\frac{H_I}{2\pi} > f_a$$

After the end of inflation

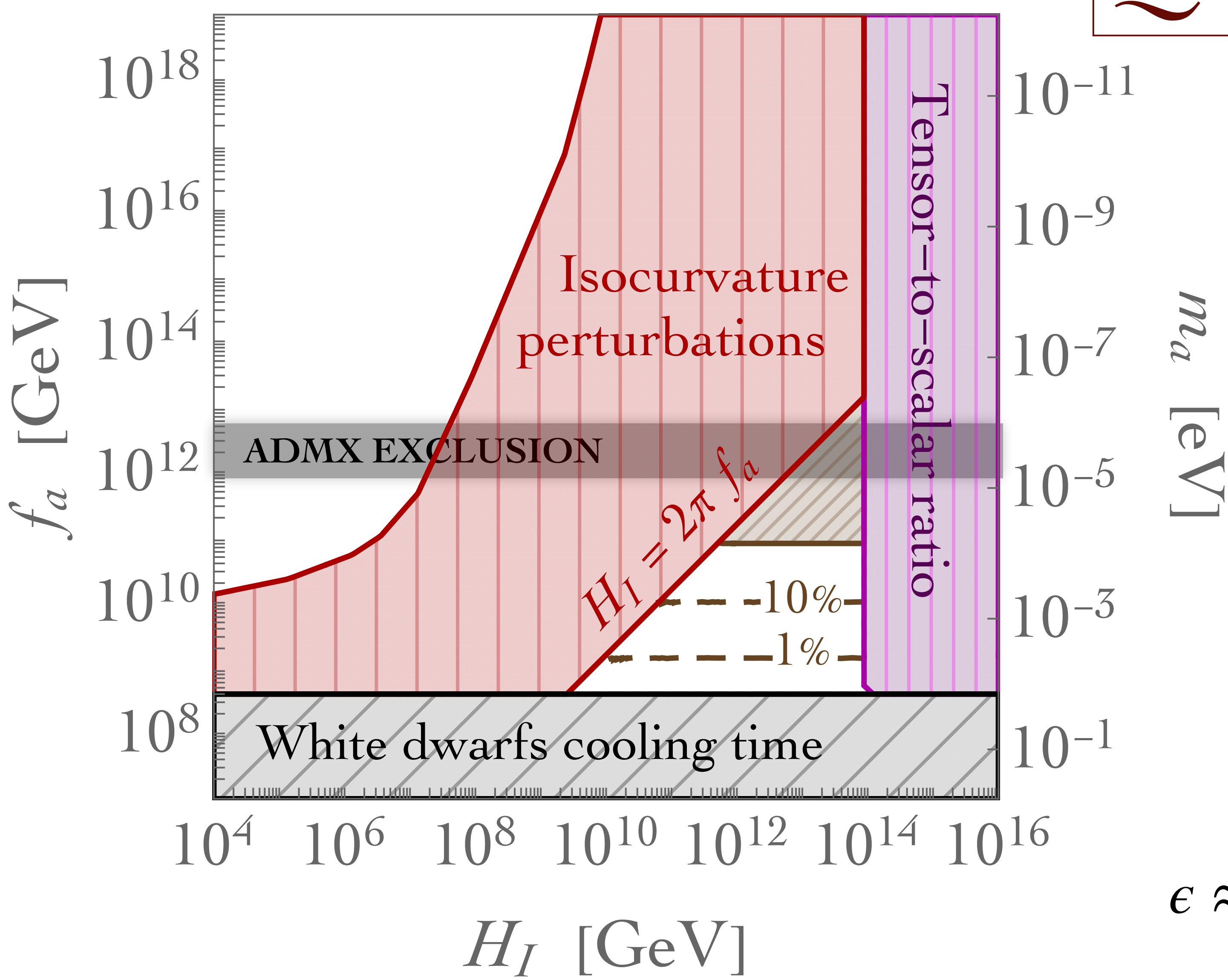
$$\frac{H_I}{2\pi} < f_a$$

Before the end of inflation

PART III: Particle physics from Astroparticle



QCD axion dark matter



Crucial interplay with inflation

$$\frac{H_I}{2\pi} > f_a$$

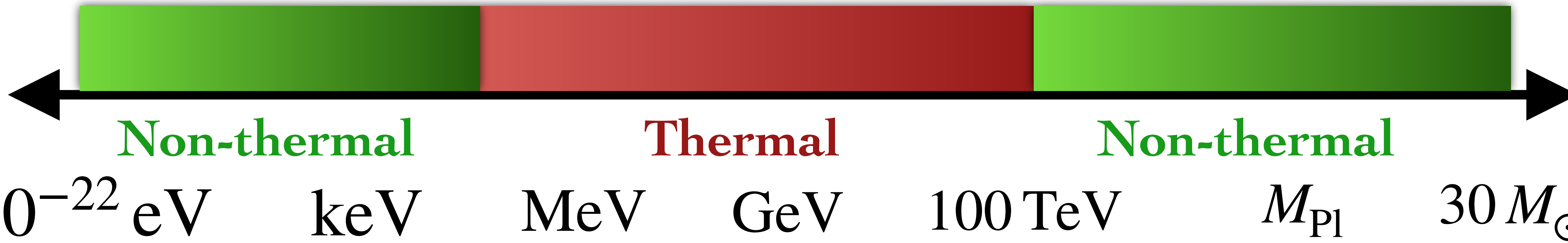
After the end of inflation

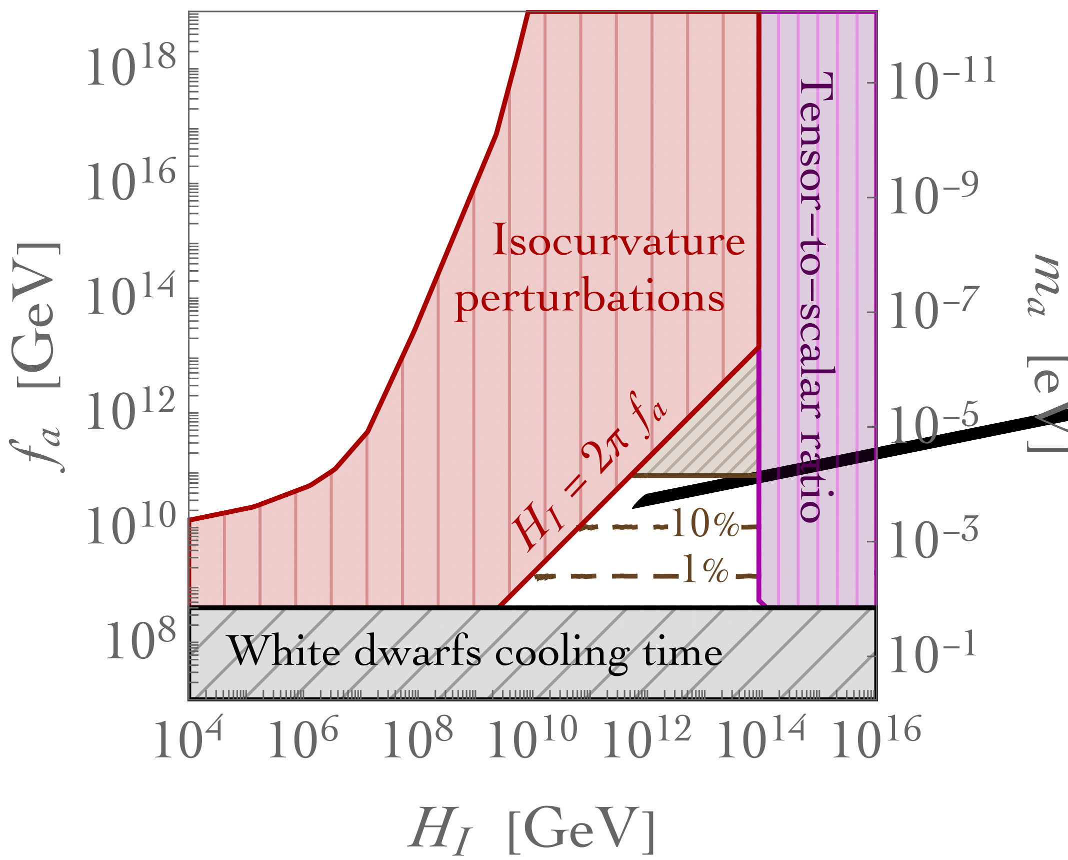
$$\frac{H_I}{2\pi} < f_a$$

Before the end of inflation

$$\epsilon \approx 9 \times 10^{-27} \left(\frac{H_I}{100\,\mathrm{GeV}}\right)^2$$

PART III: Particle physics from Astroparticle



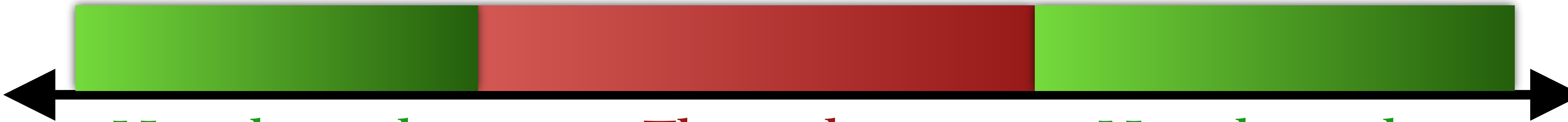


QCD axion dark matter

Contributions to energy density from decays of strings and domain walls if U(1) broken after inflation. Potentially dominant, difficult to compute, and we do not know yet the final answer.

M. Gorghetto, E. Hardy, G. Villadoro, arXiv:1806.04677

PART III: Particle physics from Astroparticle



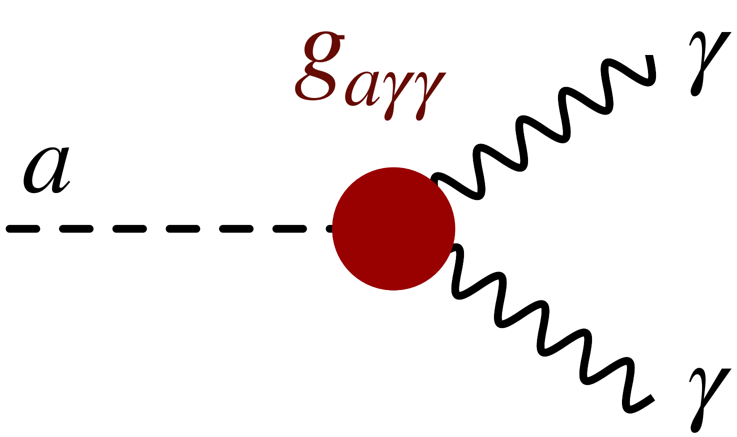
Non-thermal | Thermal | Non-thermal

$10^{-22}\,\mathrm{eV}$ keV MeV GeV 100 TeV M_{Pl} $30\,M_\odot$

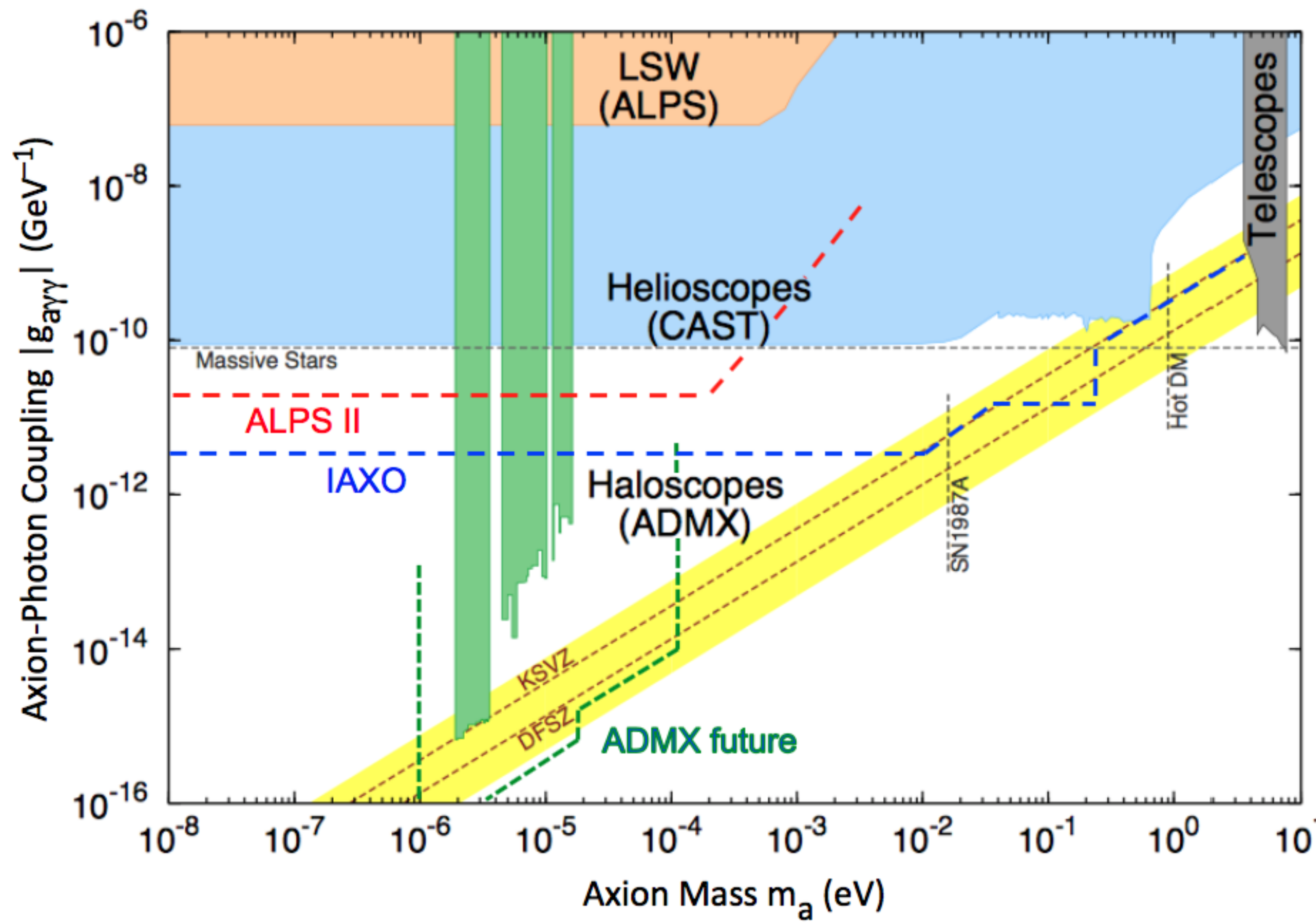
QCD axion searches

QCD axion dark matter

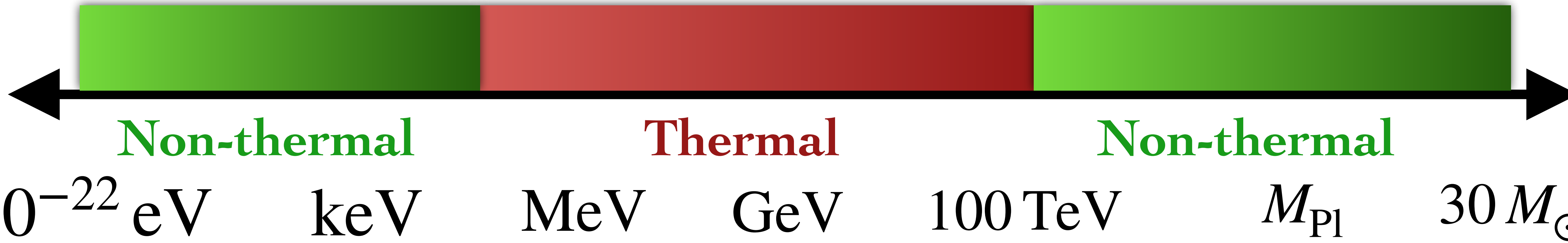
Mostly base on the <u>axion coupling with photons</u>



$$g_{a\gamma\gamma} \sim \frac{\alpha_{\mathrm{em}}}{2\pi f_a}$$



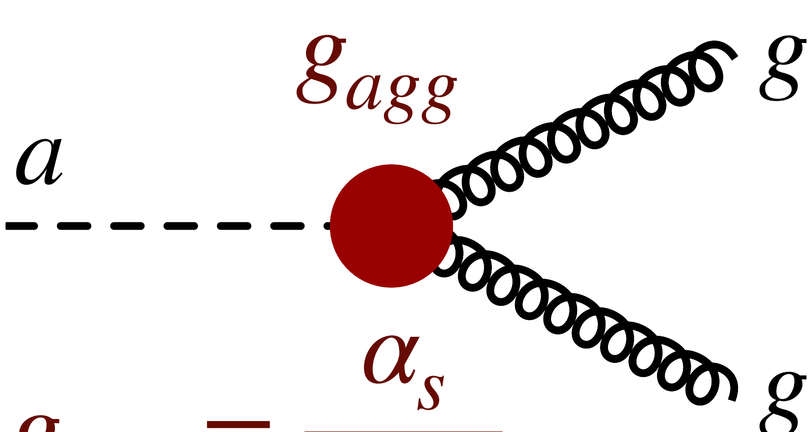
PART III: Particle physics from Astroparticle



QCD axion searches

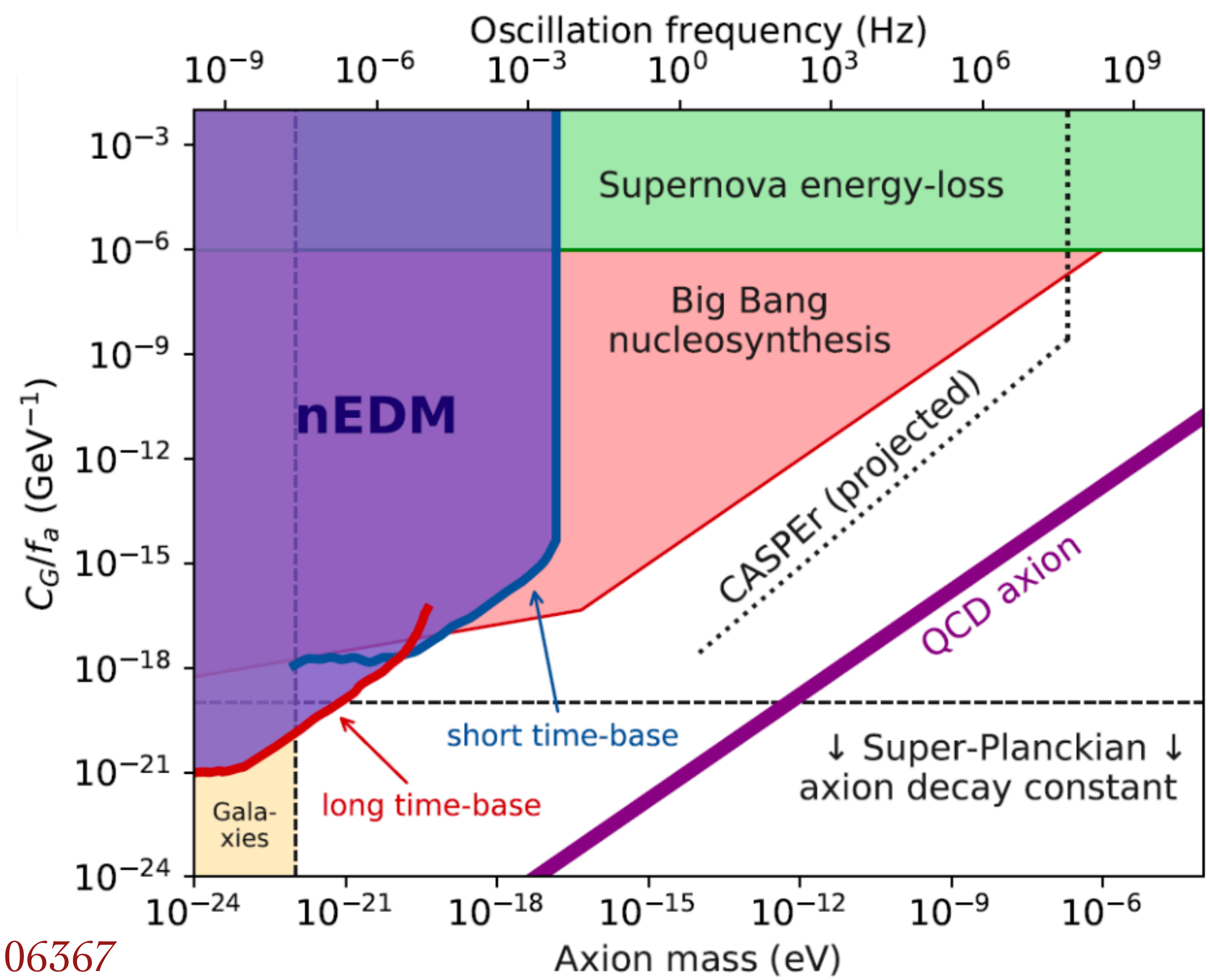
First experimental limits
on axion coupling with gluons

$$d_n(t) \approx 2.4 \times 10^{-16} \frac{C_G a_0}{f_a} \cos(m_a t) \;\; e\,\mathrm{cm}$$



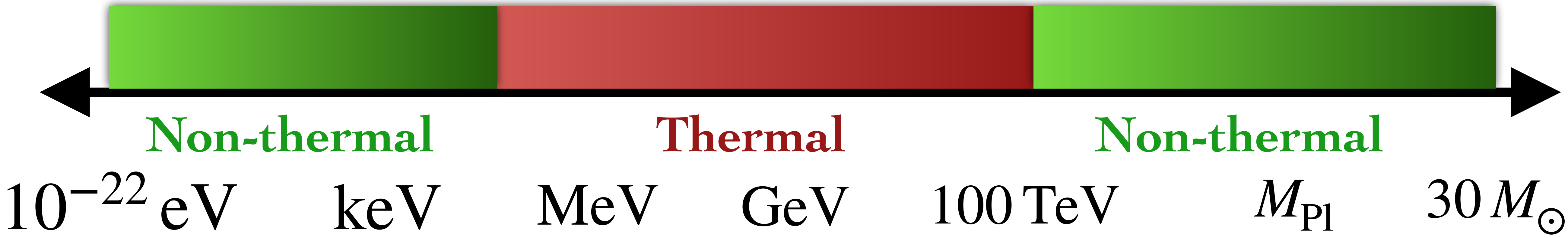
$$g_{agg} = \frac{\alpha_s}{8\pi f_a}$$

QCD axion dark matter



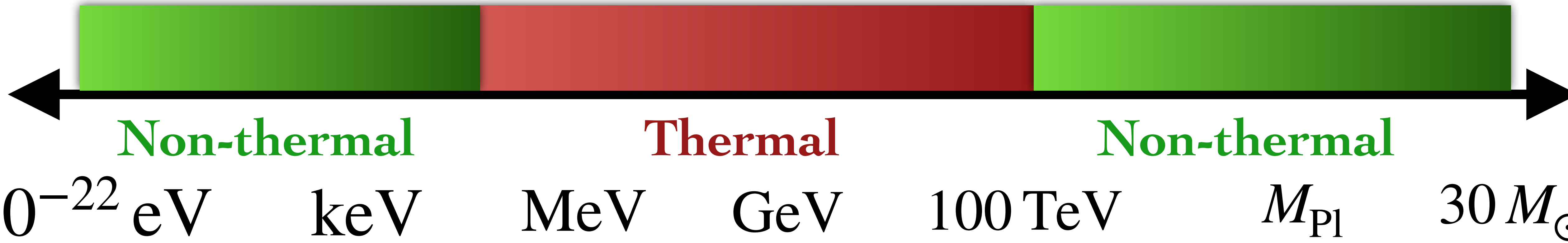
C. Abel et al., arXiv:1708.06367

PART III: Particle physics from Astroparticle



keV dark matter: the case of sterile neutrinos

PART III: Particle physics from Astroparticle



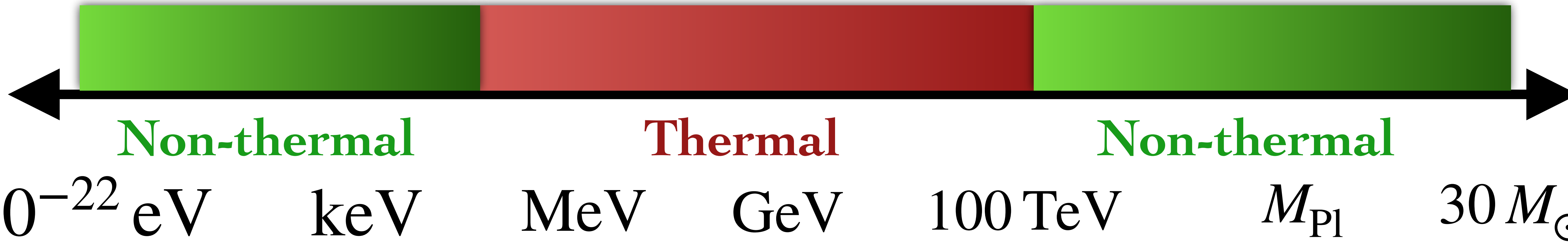
keV dark matter: the case of sterile neutrinos

- Sterile neutrino is a right-chiral counterpart of the left-chiral neutrinos of the SM (called "active" neutrinos in this context).

- Adding these particles to the SM Lagrangian makes neutrinos massive. Their existence provides a simple and natural explanation of the observed neutrino flavor oscillations.

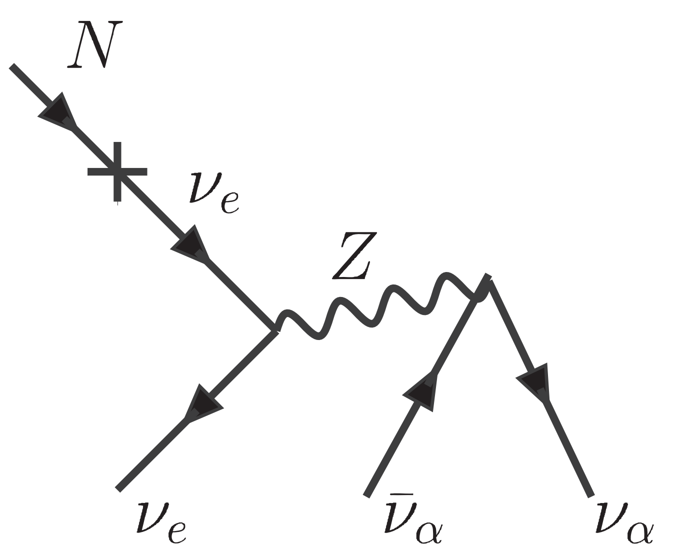
- These particles are SM singlet. Along with their Yukawa interaction with the active neutrinos (="Dirac mass") they can have a Majorana mass term.

PART III: Particle physics from Astroparticle



keV dark matter: the case of sterile neutrinos

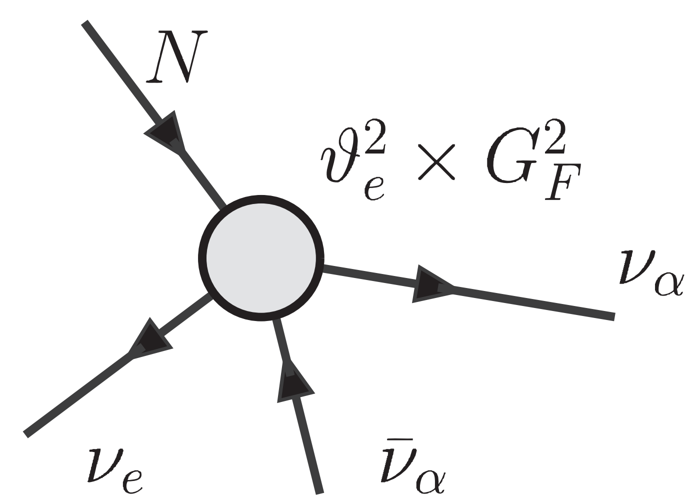
They interact with the matter via creation of virtual active neutrino (quadratic mixing) and in this way they effectively participate in weak interactions.



$$\theta^2_{\alpha N} = \left| \frac{(m_{\rm Dirac})_{\alpha N}}{M_{\rm Majorana}} \right|^2$$

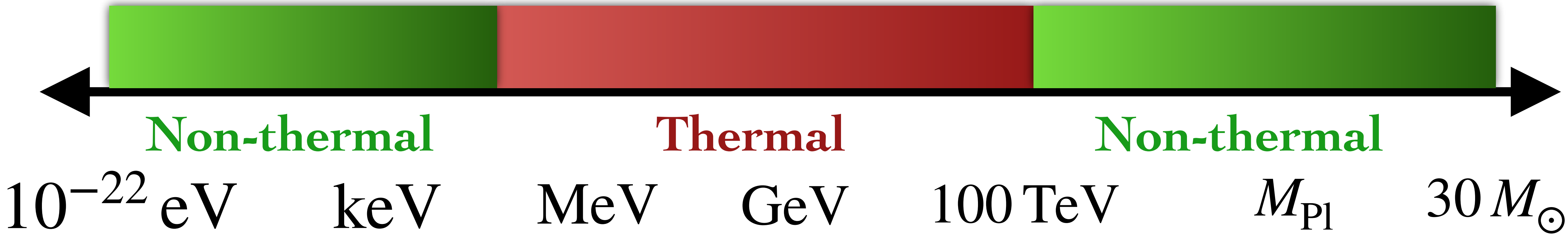
$$\Longrightarrow$$

$$E_N \ll M_Z$$



At energies much below the masses of the W and Z-bosons, their interaction can be described by the analog of the Fermi theory with the Fermi coupling constant suppressed by the active-sterile neutrino mixing angle.

PART III: Particle physics from Astroparticle



keV dark matter: the case of sterile neutrinos

To account for dark matter and neutrino masses and oscillations, **three sterile neutrinos are needed**.

Sterile neutrino dark matter can be produced in the early Universe through mixing with active neutrinos and have a correct relic density.

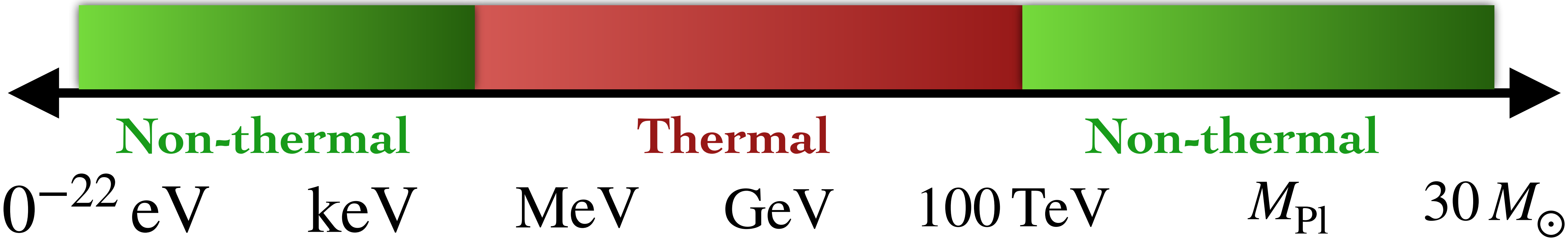
S. Dodelson, L.M. Widrow, hep-ph/9303287

The simplest possibility is the νSM (Neutrino Minimal Standard Model)

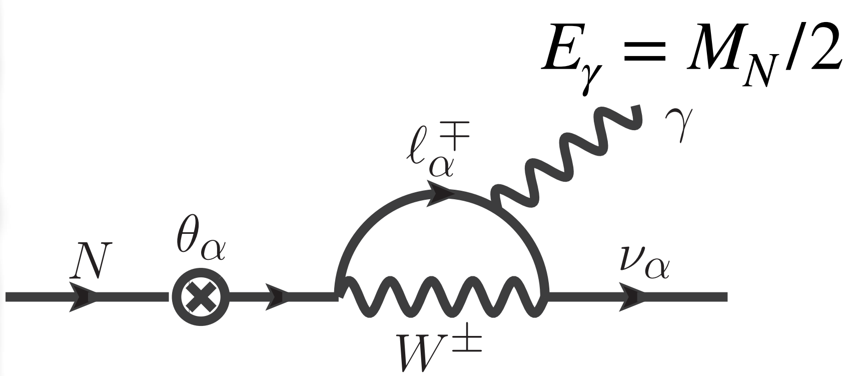
For a review, A. Boyarsky, O. Ruchayskiy, M. Shaposhnikov, arXiv:0901.0011

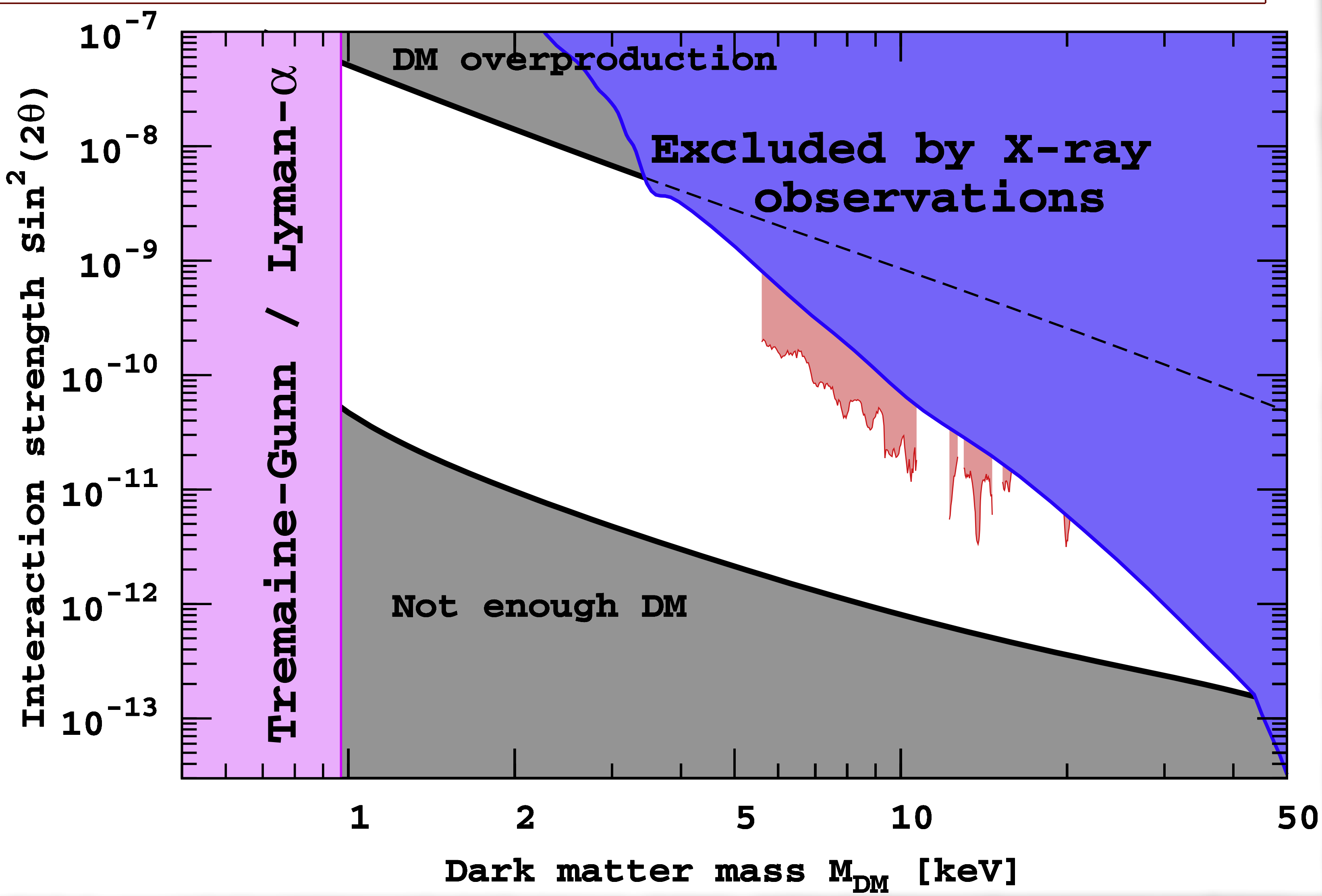
[Out-of equilibrium reactions are capable of generating the observed matter–anti- matter asymmetry of the Universe (baryogenesis)]

PART III: Particle physics from Astroparticle



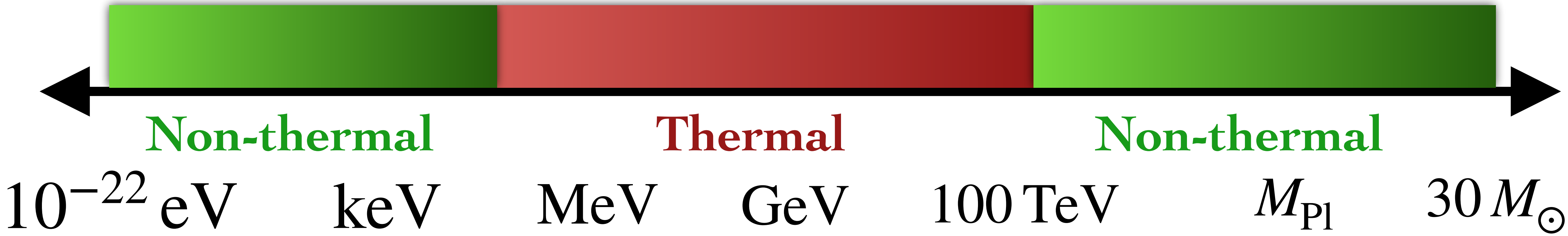
keV dark matter: the case of sterile neutrinos



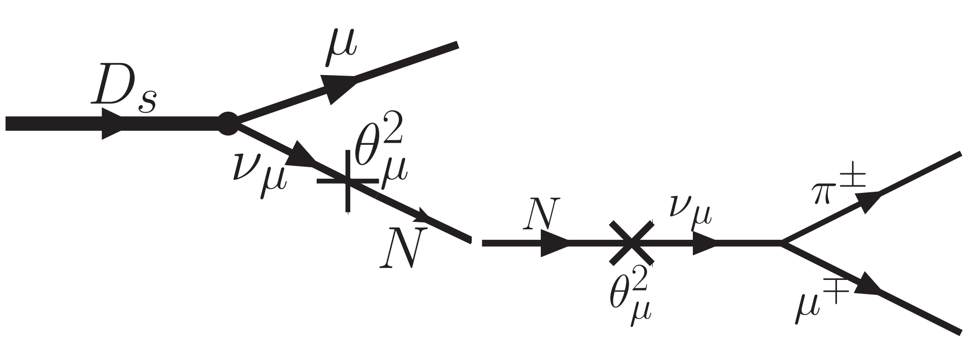


The combination of X-ray bounds and computations of primordial abundance shows that **the parameter space of sterile neutrino DM is bounded on all sides**.

PART III: Particle physics from Astroparticle

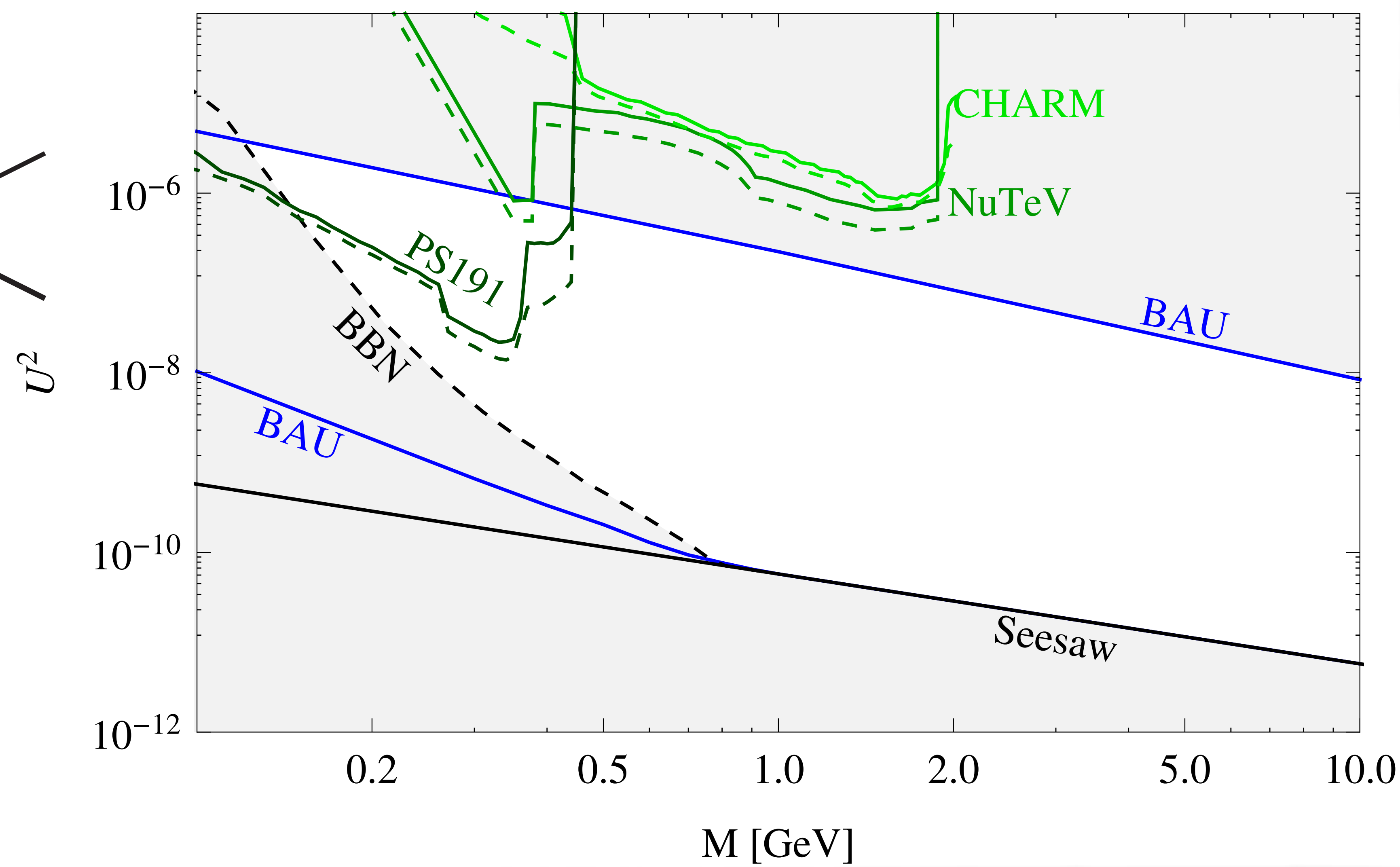


keV dark matter: the case of sterile neutrinos

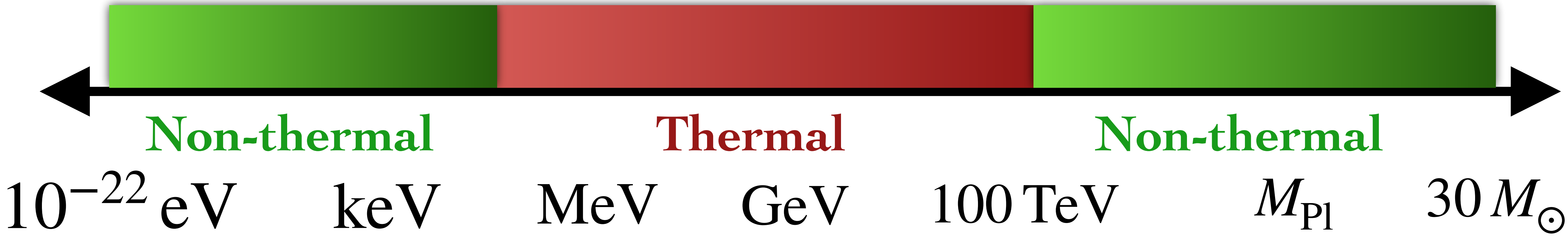


Search for
Hidden
Particles

NA62

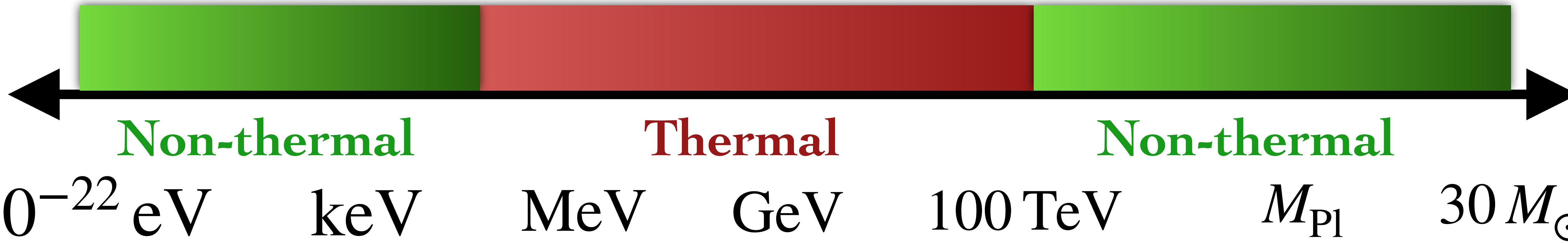


PART III: Particle physics from Astroparticle



WIMP dark matter

PART III: Particle physics from Astroparticle



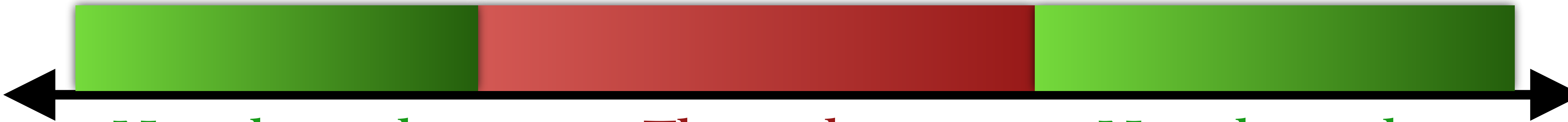
WIMP dark matter

Weakly Interacting Massive Particles (WIMPs) have long reigned as one of the leading classes of dark matter candidates.

$$\langle \sigma v \rangle \sim \frac{\alpha_W^2}{M_{\rm DM}^2} \sim 10^{-26} \times \left(\frac{\alpha_W}{0.003}\right)^2 \times \left(\frac{100\,\mathrm{GeV}}{M_{\rm DM}}\right)^2 \mathrm{cm}^3/\mathrm{s}$$

However, **no (convincing) signals has been observed so far in either “direct” or ”indirect” searches.**

PART III: Particle physics from Astroparticle

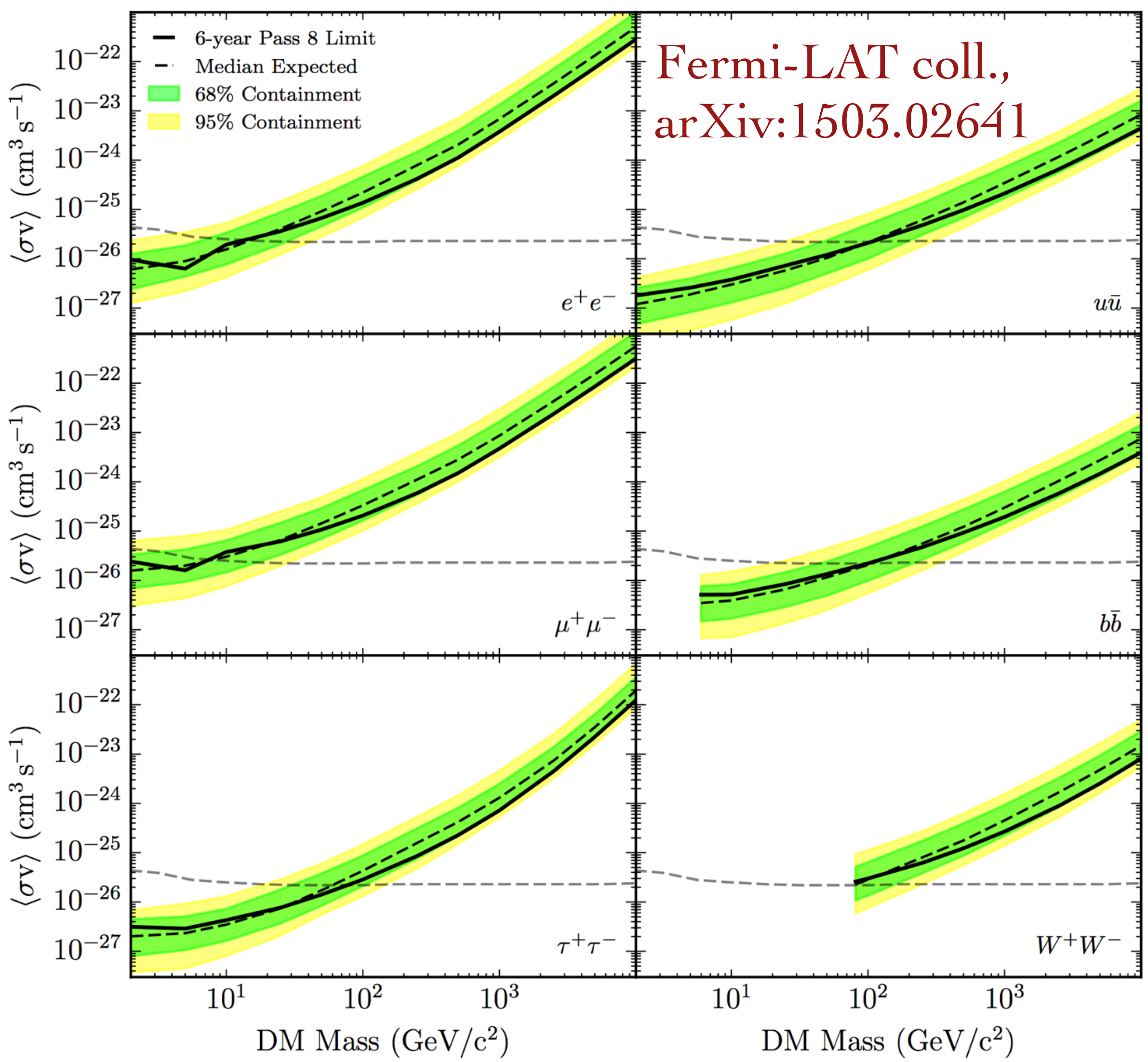


Non-thermal | Thermal | Non-thermal

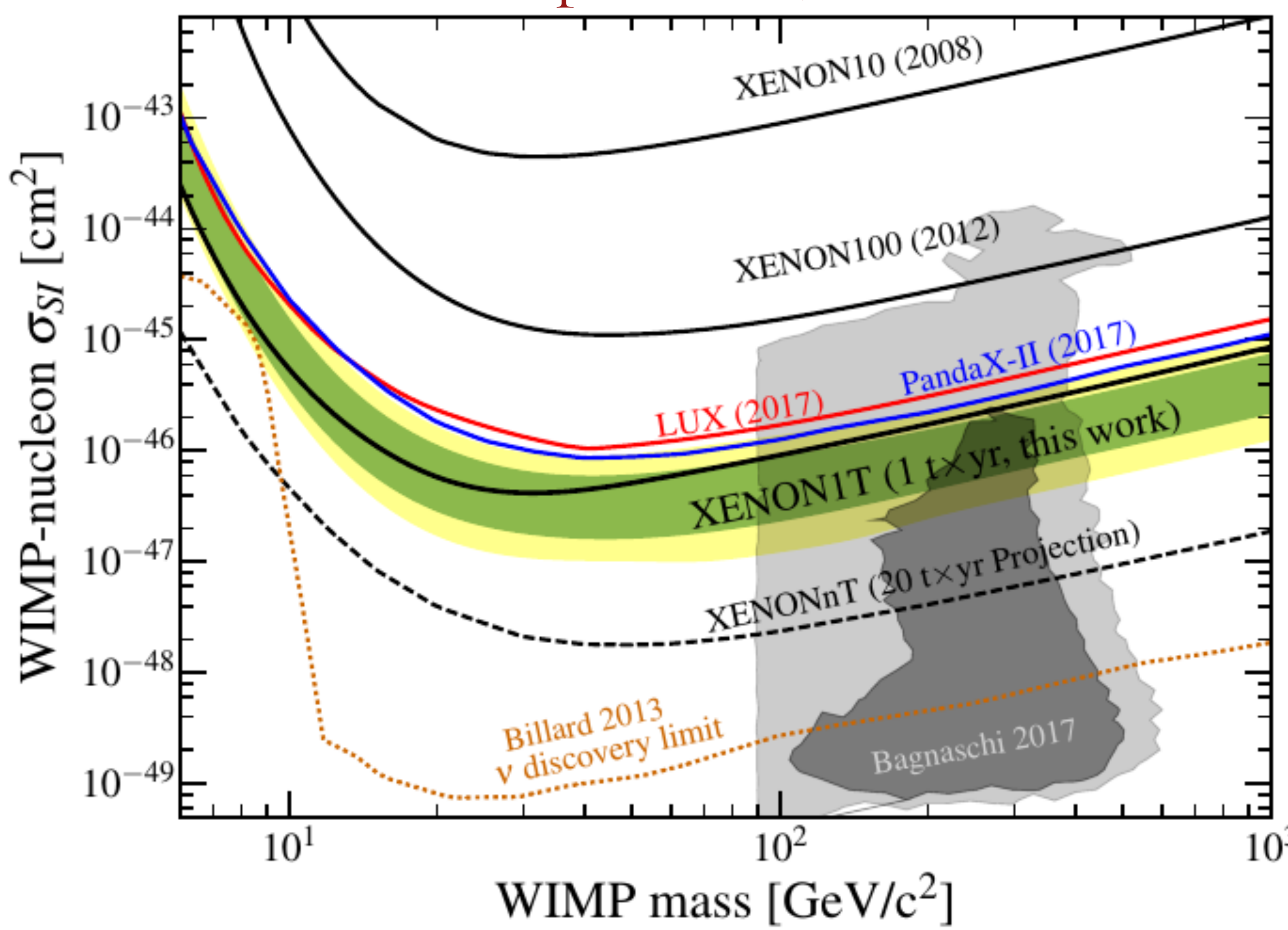
10^{-22} eV | keV | MeV | GeV | 100 TeV | $M_{\rm Pl}$ | $30\,M_{\odot}$

WIMP dark matter

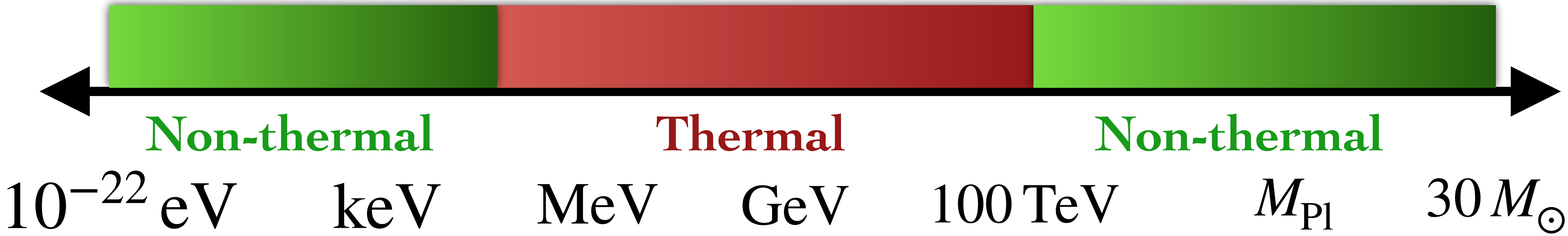
Fermi-LAT coll., arXiv:1503.02641



E. Aprile et al., arXiv:1805.12562

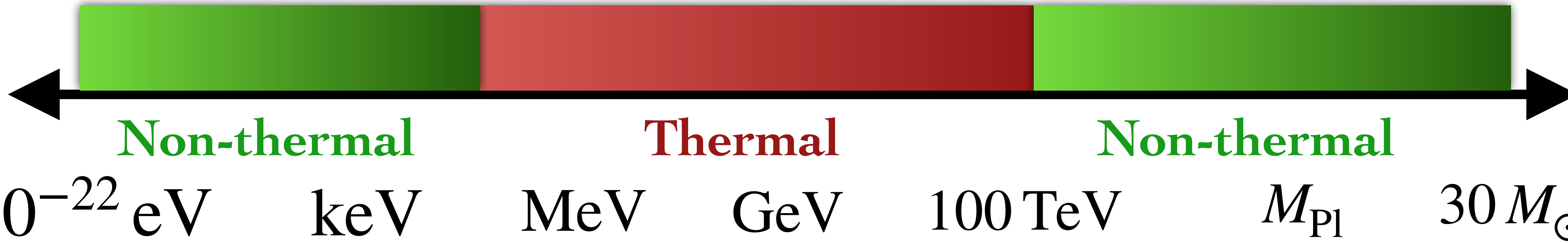


PART III: Particle physics from Astroparticle

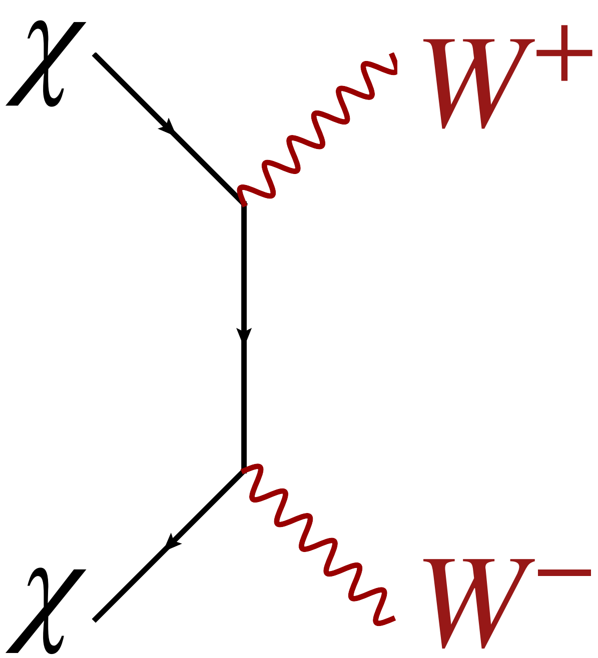


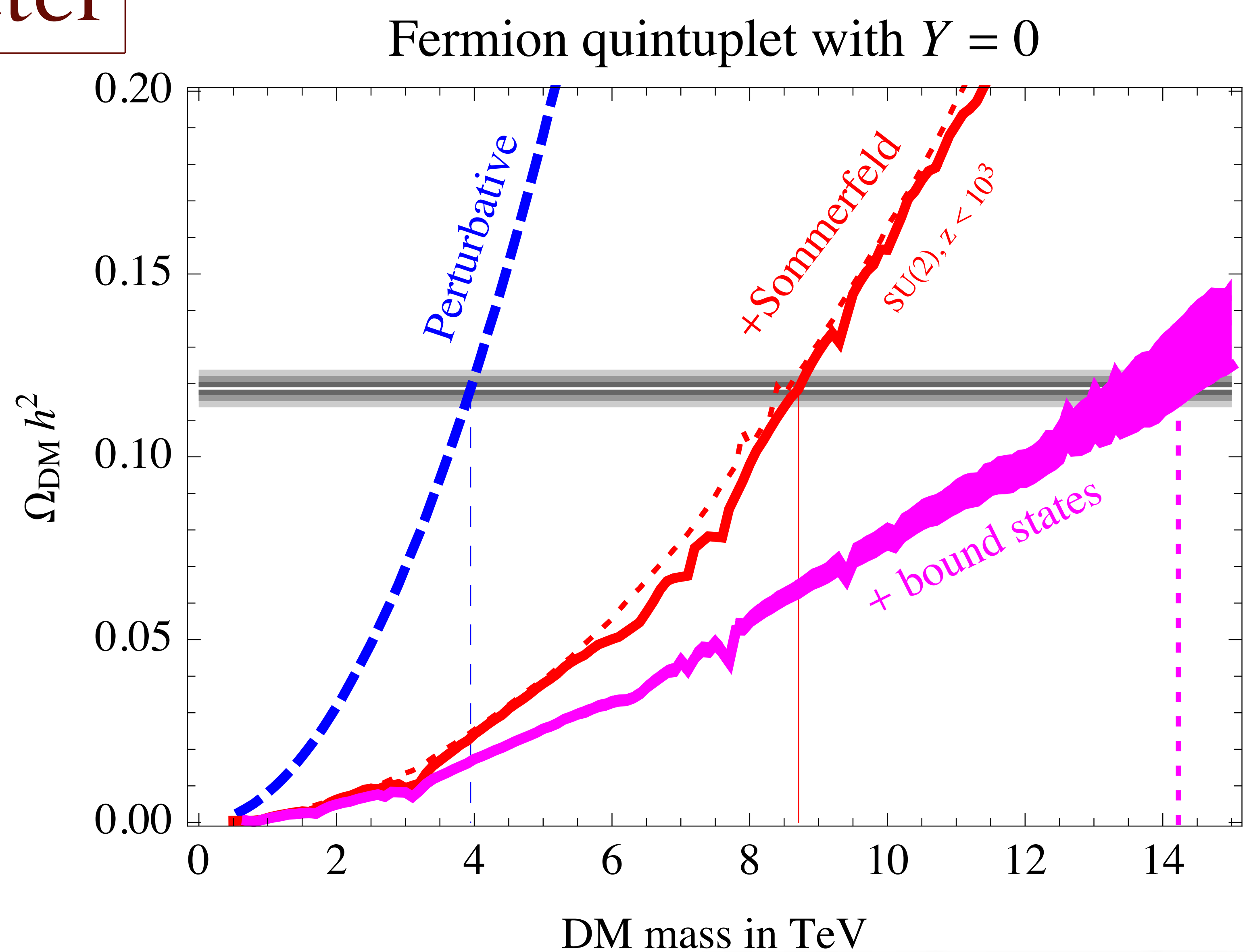
TeV thermal dark matter

PART III: Particle physics from Astroparticle

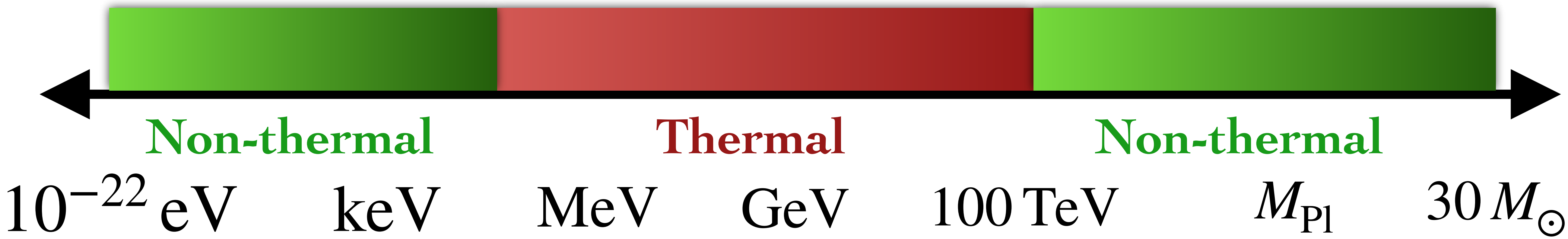


TeV thermal dark matter



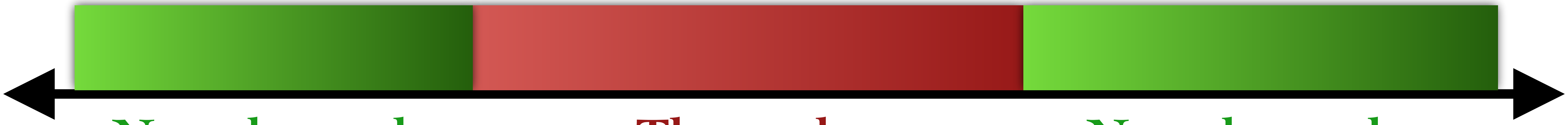


PART III: Particle physics from Astroparticle



MeV thermal dark matter

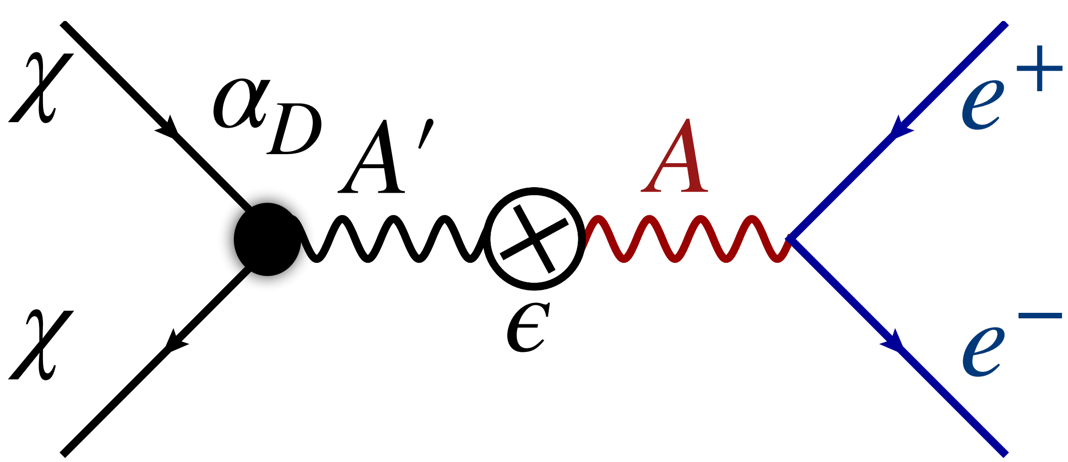
PART III: Particle physics from Astroparticle



MeV thermal dark matter

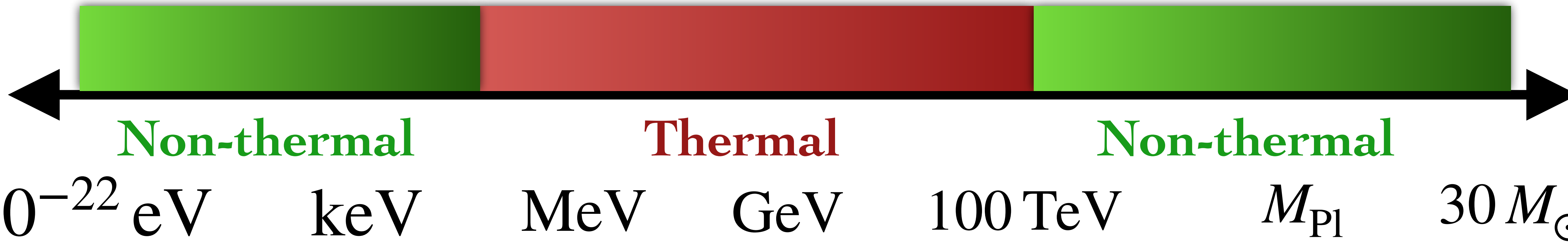
Representative benchmark model: Dark Photon A'

- Vector mediator
- Kinetically mixed with QED photon A
- Annihilation cross section into SM states:



$$\sigma v \sim \alpha_D \epsilon^2 \frac{m_\chi^2}{m_{A'}^4} \sim \left(\alpha_D \epsilon^2 \frac{m_\chi^4}{m_{A'}^4} \right) \frac{1}{m_\chi^2} \equiv \frac{Y}{m_\chi^2}$$

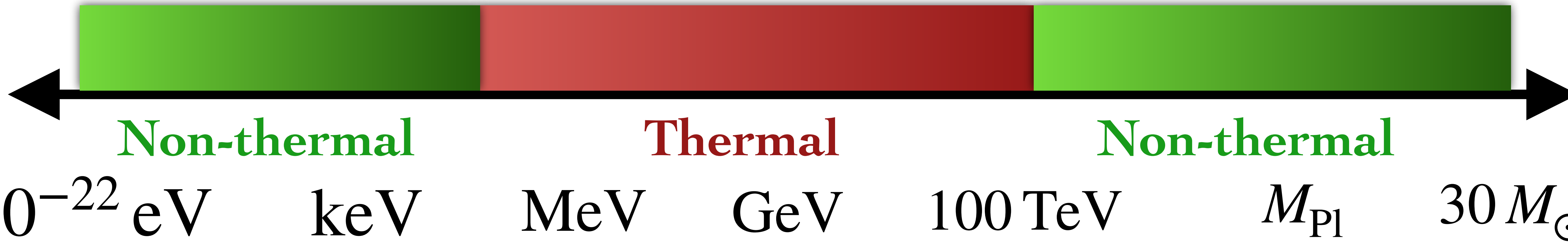
PART III: Particle physics from Astroparticle



MeV thermal dark matter

Simple model but rich phenomenology

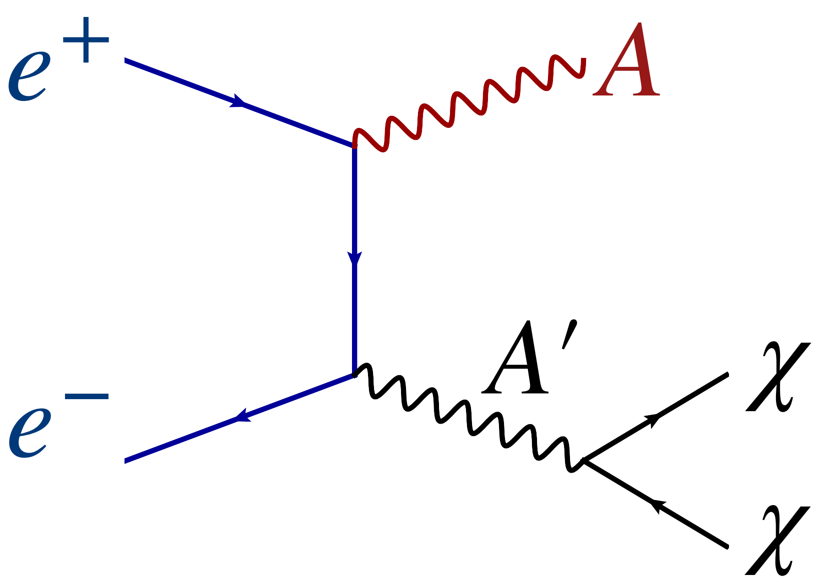
PART III: Particle physics from Astroparticle



MeV thermal dark matter

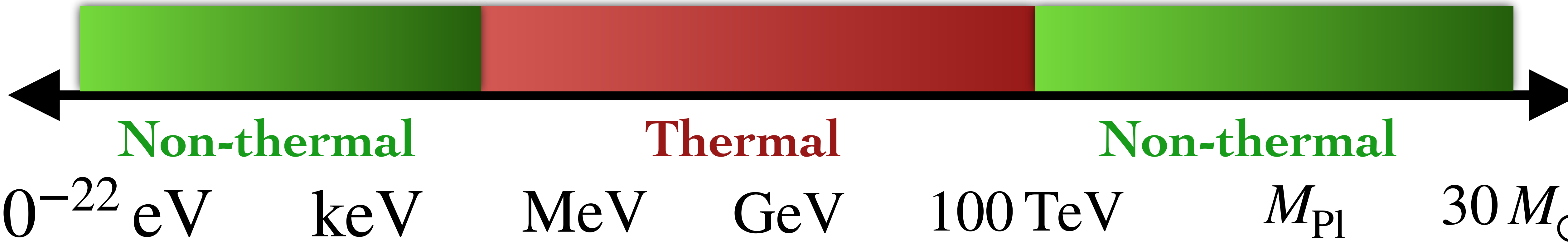
Simple model but rich phenomenology

Collider physics (BaBar, Belle II, LHC)



Need single photon trigger

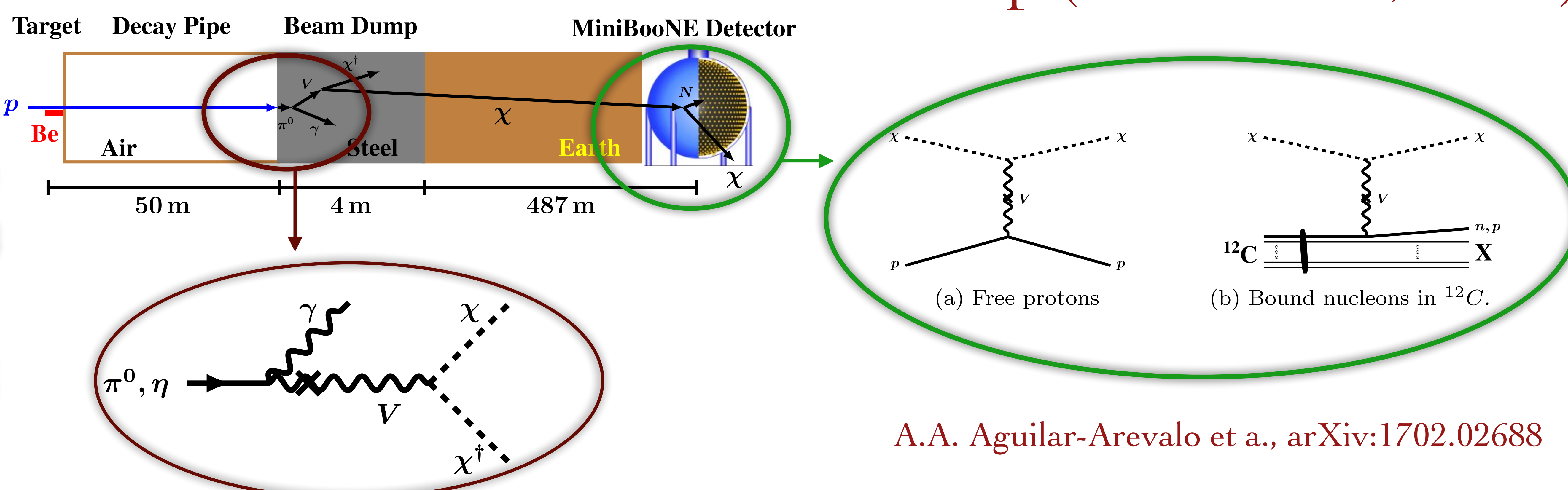
PART III: Particle physics from Astroparticle



MeV thermal dark matter

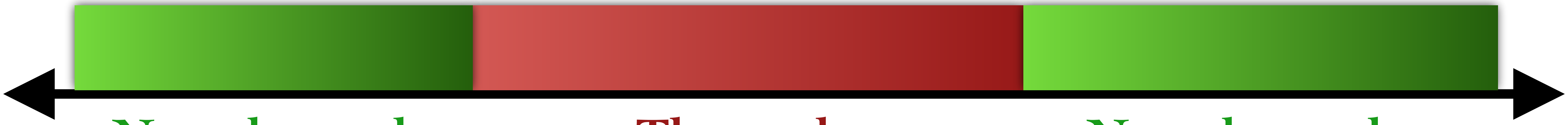
Simple model but rich phenomenology

Proton beam dump (MiniBooNE, SHiP)



A.A. Aguilar-Arevalo et a., arXiv:1702.02688

PART III: Particle physics from Astroparticle

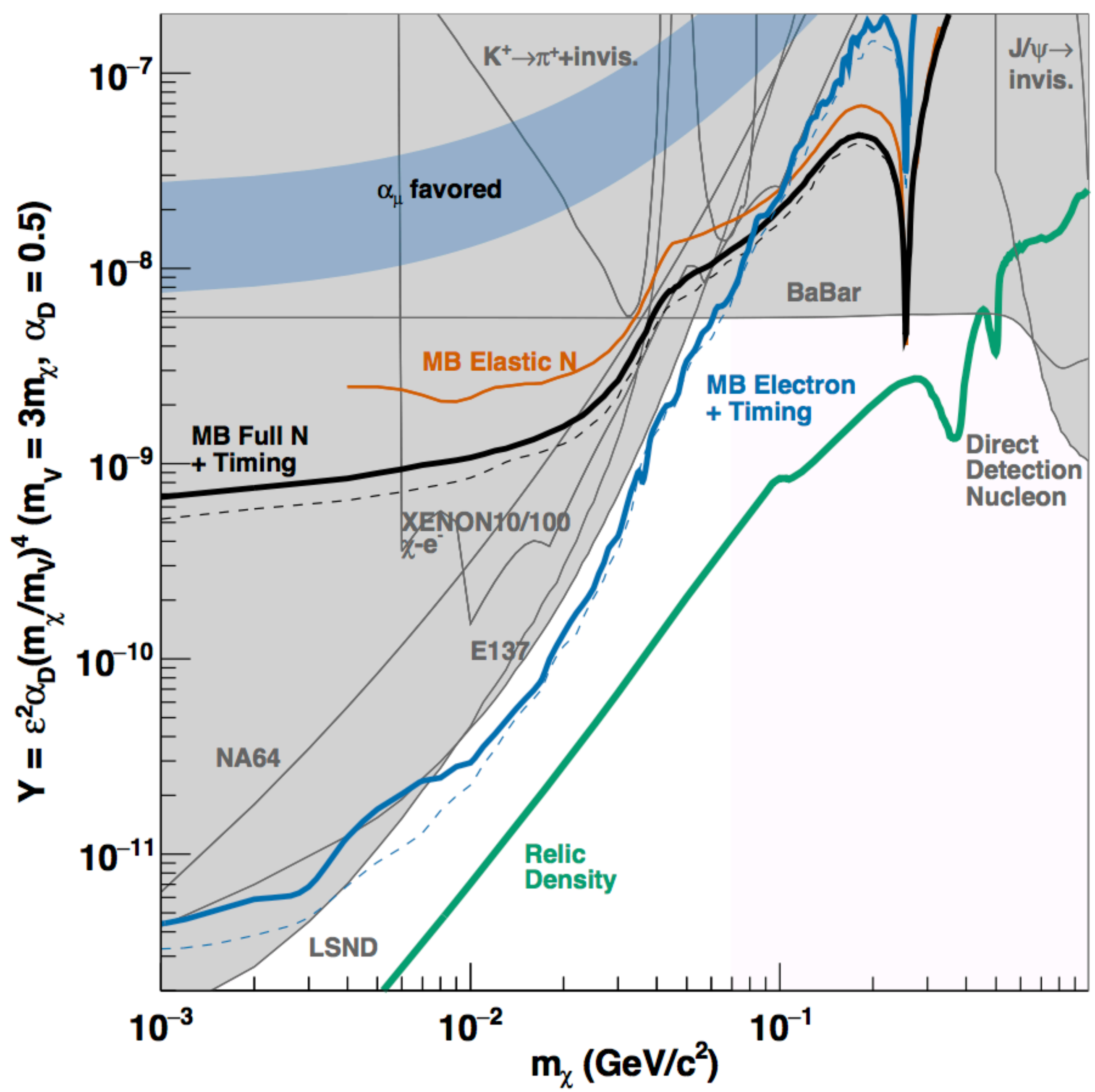


Non-thermal | Thermal | Non-thermal

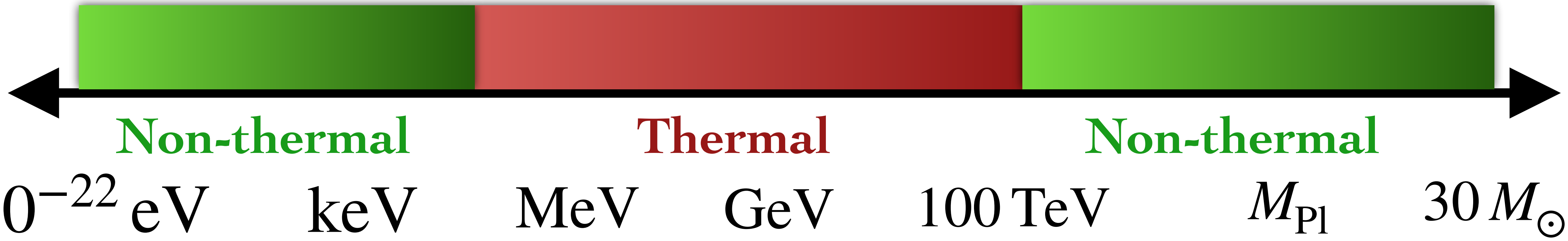
$10^{-22}\,\mathrm{eV}$ keV MeV GeV 100 TeV M_{Pl} $30\,M_{\odot}$

MeV thermal dark matter

Simple prototype for a "Dark Sector". Rich, and mostly new, phenomenology.

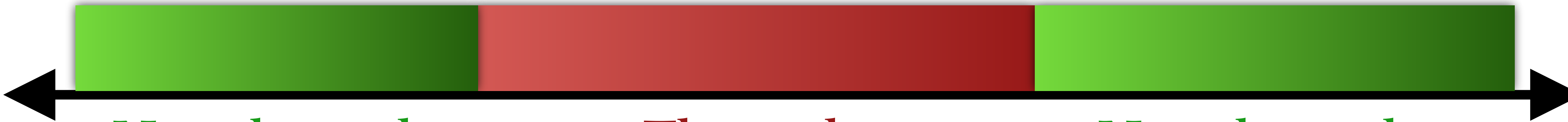


PART III: Particle physics from Astroparticle



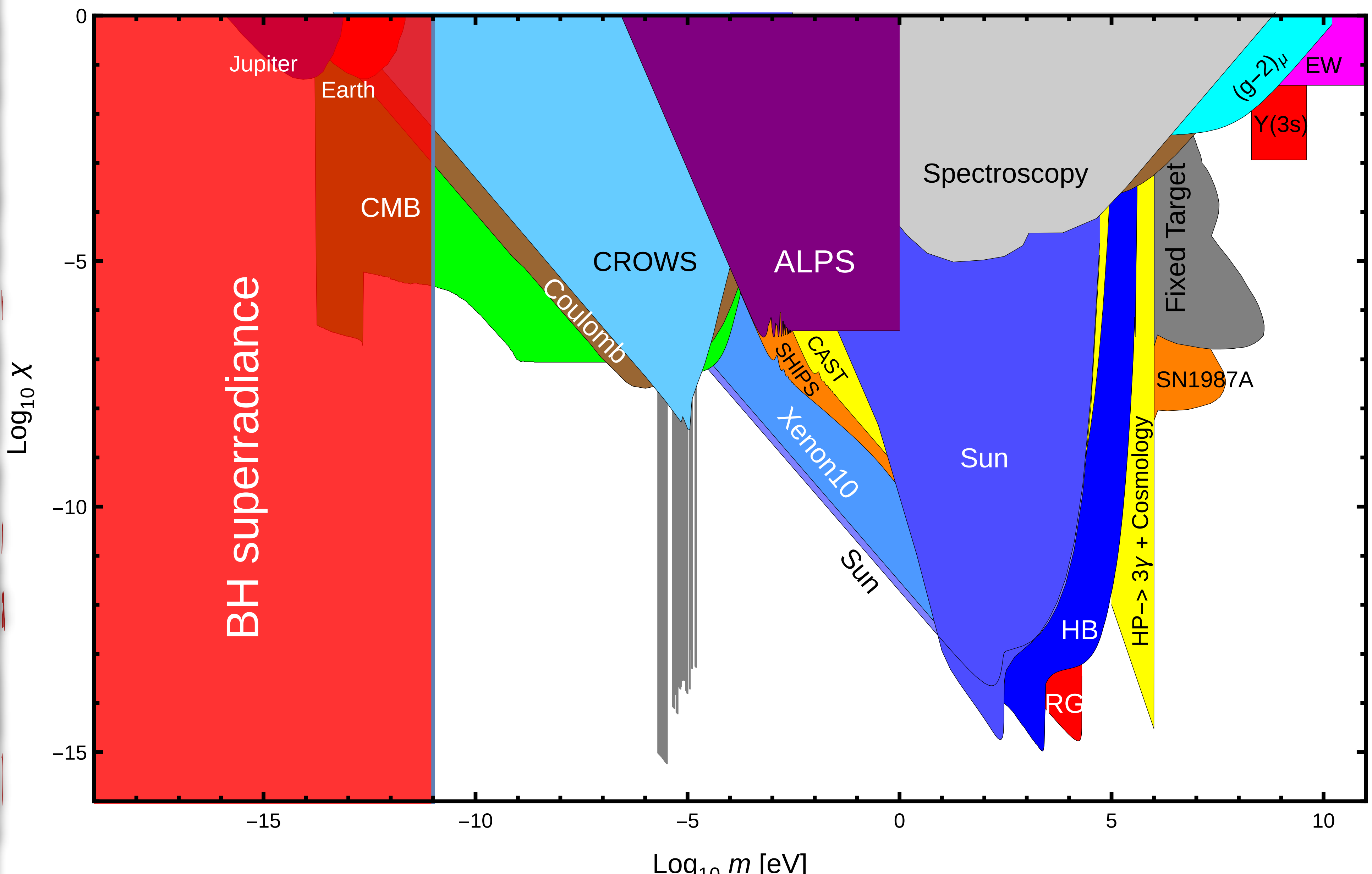
Dark photon

PART III: Particle physics from Astroparticle



Non-thermal Thermal Non-thermal

$10^{-22}\,\mathrm{eV}$ keV MeV GeV 100 TeV M_{Pl} $30\,M_{\odot}$

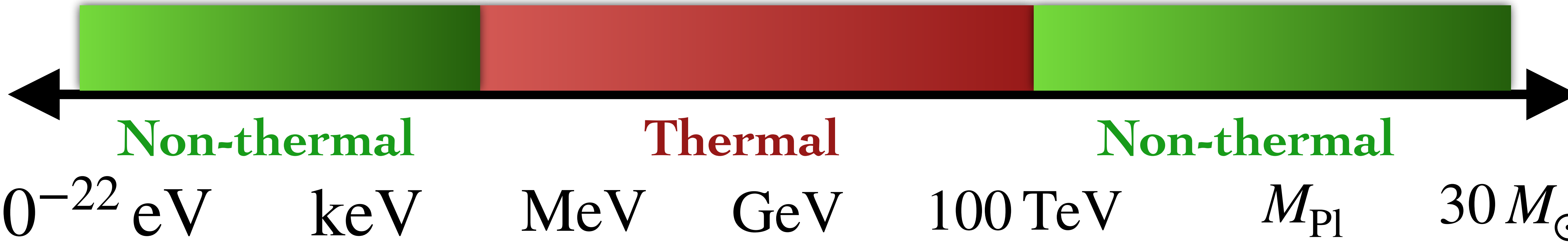


V. Cardoso et al., arXiv:1801.01420

Dark photon

However, it looks like a blind search

PART III: Particle physics from Astroparticle

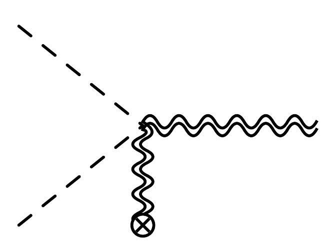


Remarkable connection with gravitational wave physics

Dark photon

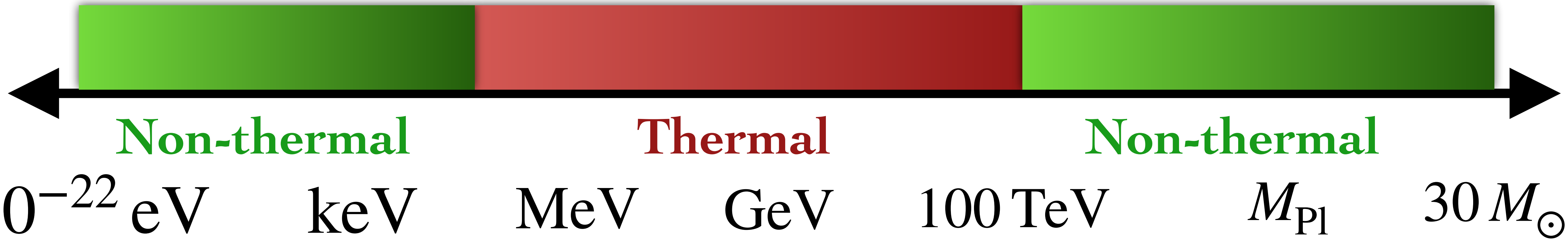
There are two main experimental signatures of BH superradiance

Monochromatic emission of gravitational wave from the scalar cloud (with frequency set by the scalar field mass)



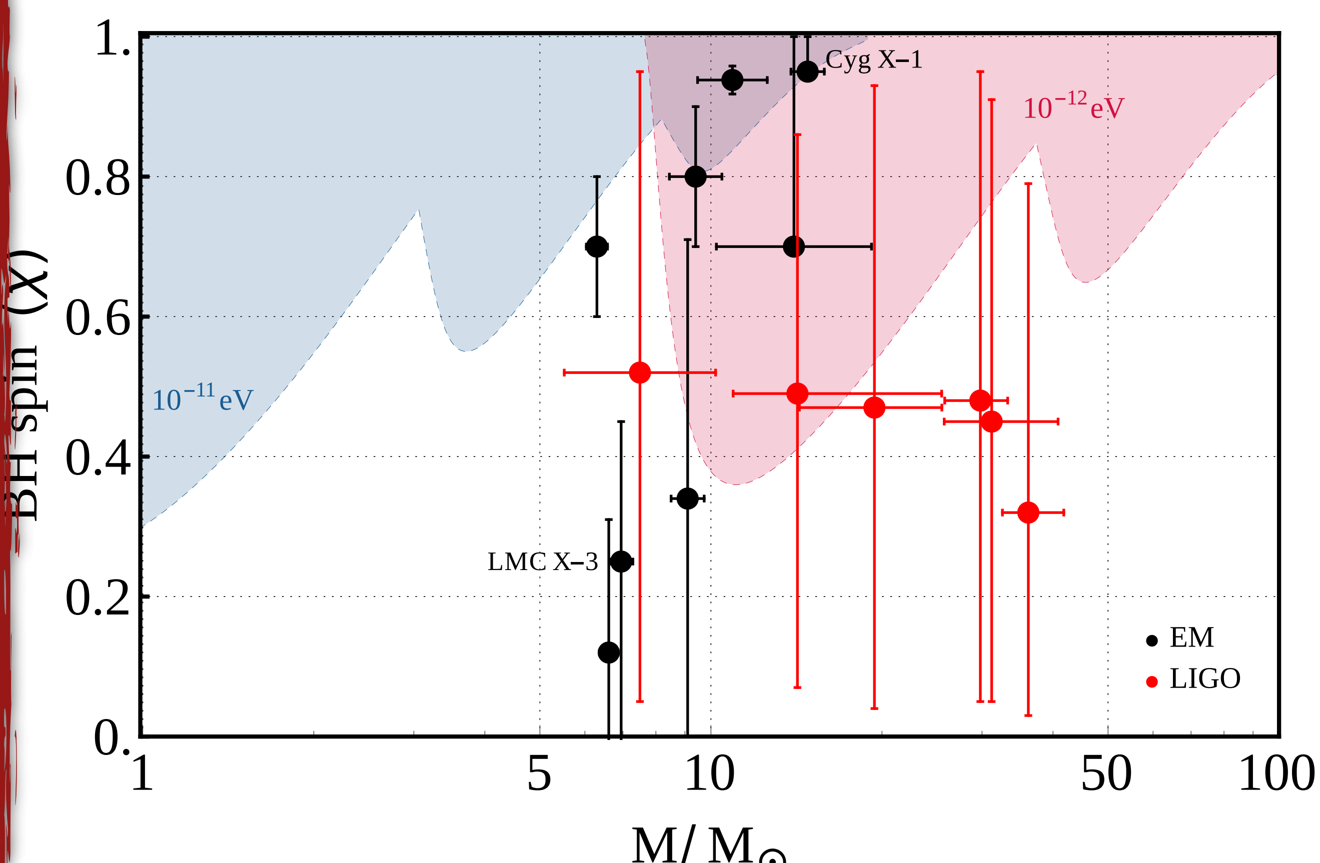
We should not observe rapidly-spinning black holes

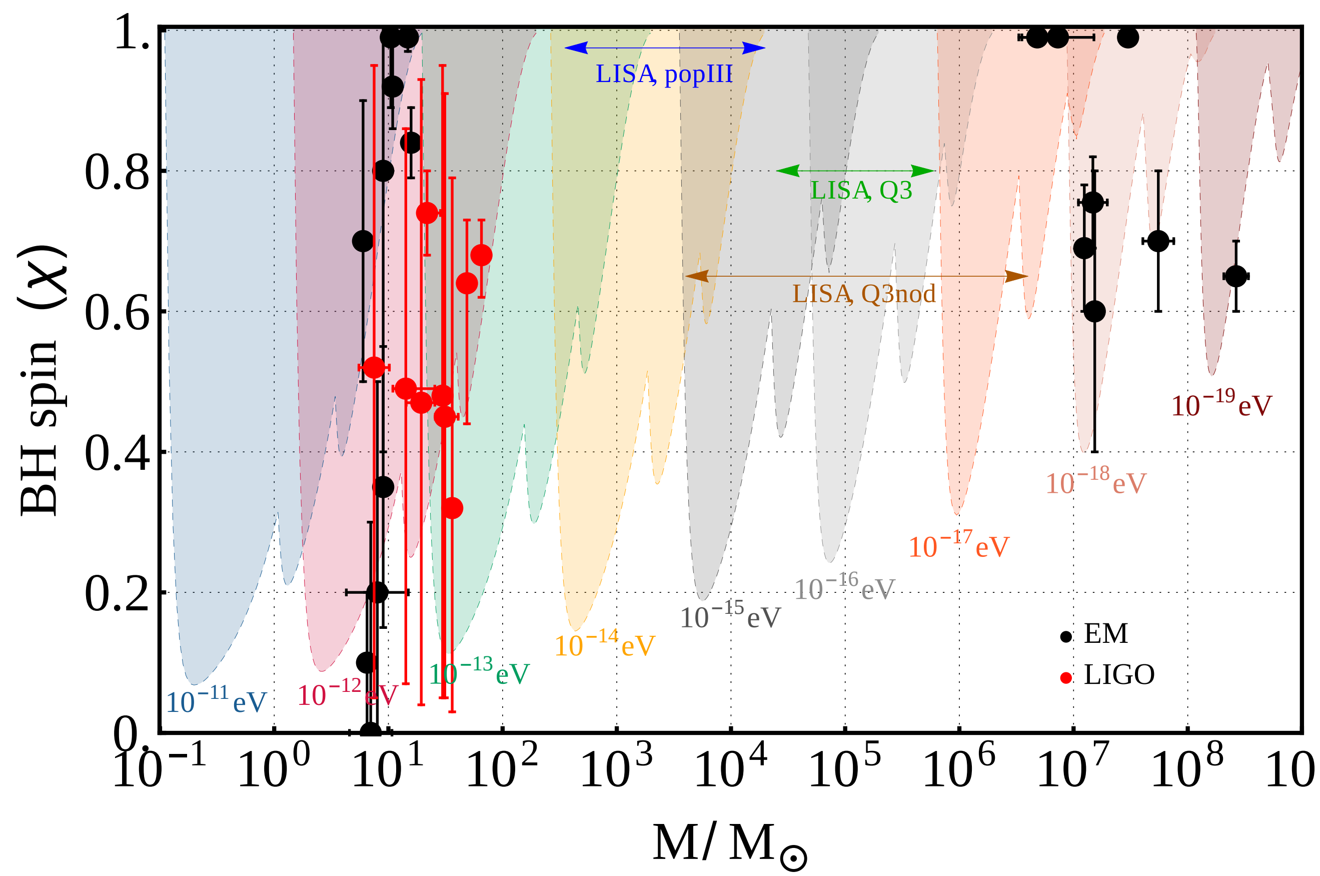
PART III: Particle physics from Astroparticle



Remarkable connection with gravitational wave physics

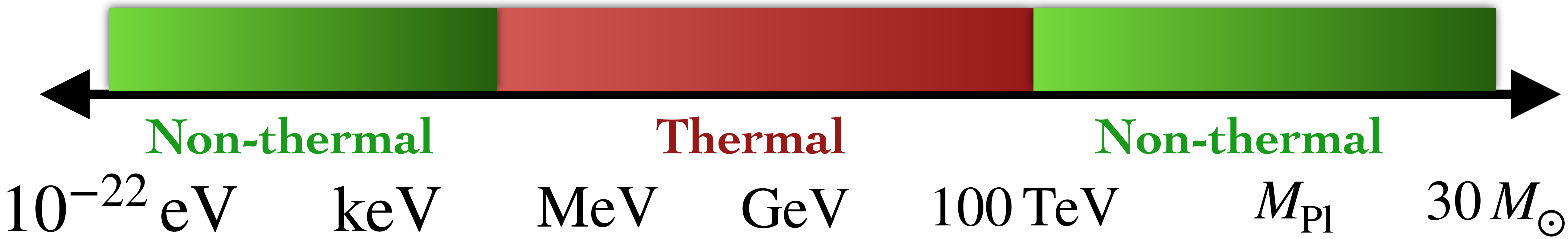
Dark photon





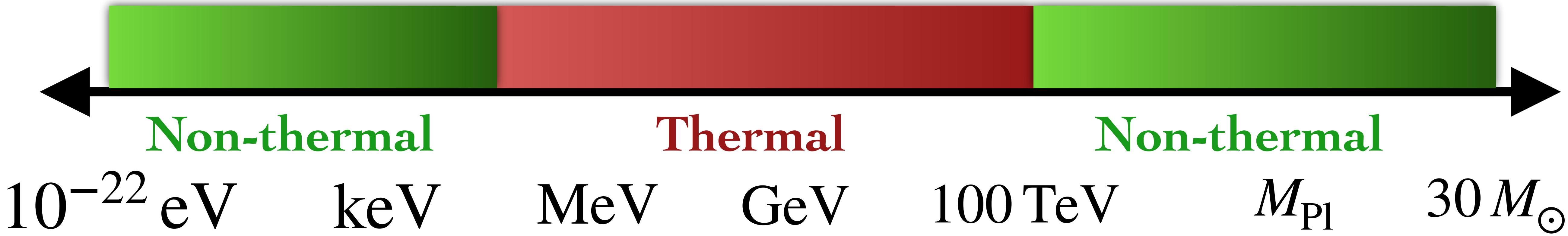
V. Cardoso et al., arXiv:1801.01420

PART III: Particle physics from Astroparticle



Primordial black holes as dark matter

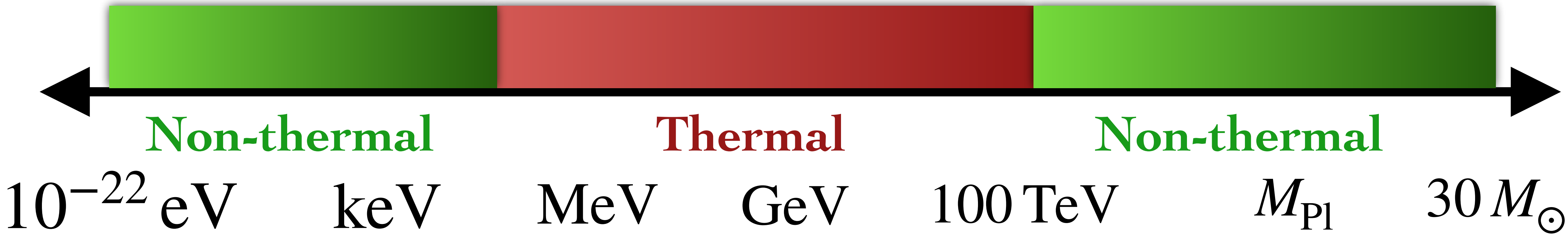
PART III: Particle physics from Astroparticle



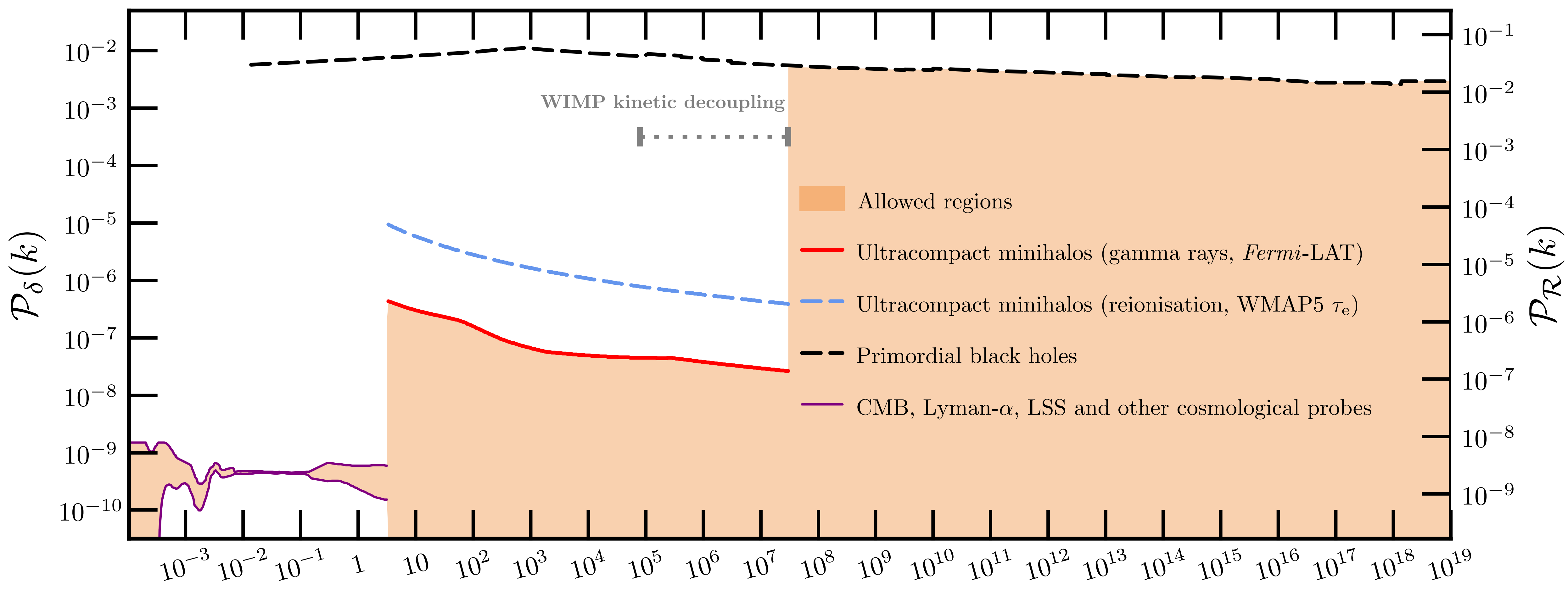
Primordial black holes as dark matter

- The only exception to new physics beyond the Standard Model if dark matter is made out of primordial black holes.
- Old idea, but LIGO/Virgo discoveries generated new excitement
- In order for such compact objects to form, the primordial power spectrum needs to be boosted by about *7* orders of magnitude above the value observed on large scales

PART III: Particle physics from Astroparticle

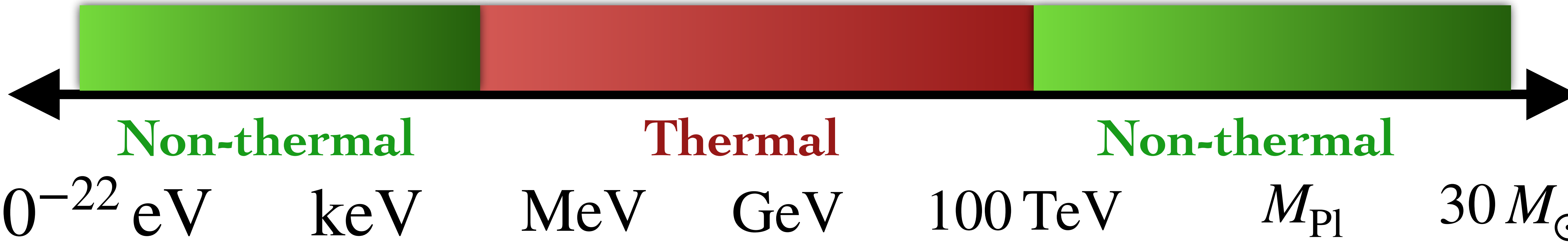


Primordial black holes as dark matter



T. Bringmann, P. Scott, Y. Akrami, arXiv:1110.2484

PART III: Particle physics from Astroparticle



Primordial black holes as dark matter

The BHs LIGO detected might be astrophysical or primordial

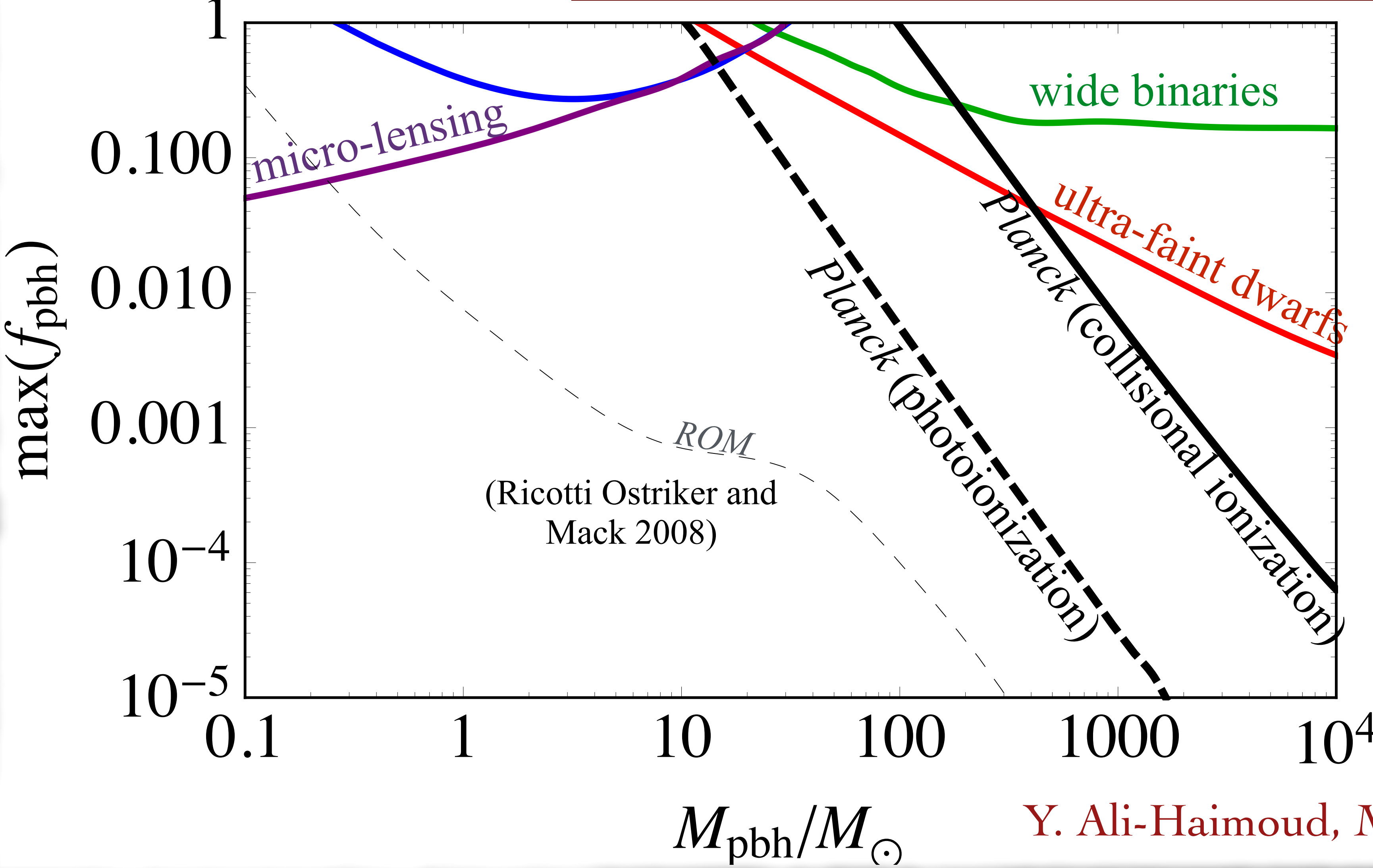
Clear-cut tests:

Astrophysical	**Primordial**
$M \gtrsim 1\,M_\odot$	$\frac{dN}{dM} =$ your favorite distribution
do not exist at $z \gtrsim 30$	already exist at $z \gg 10^3$
high spin	low spin

PART III: Particle physics from Astroparticle

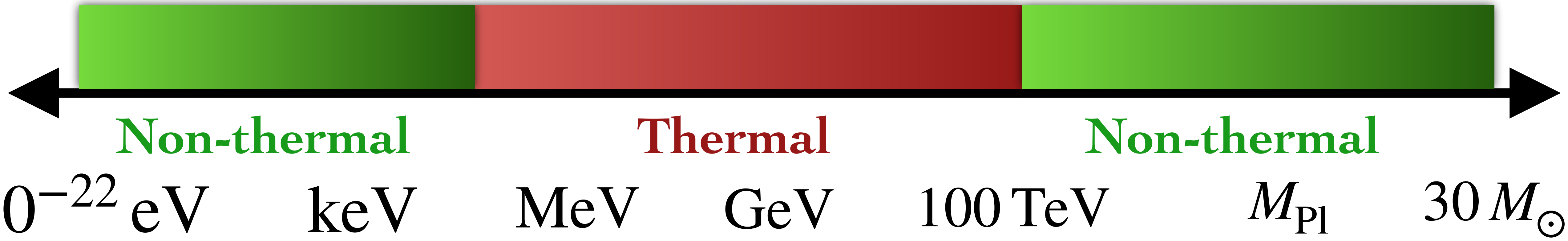
Non-thermal		Thermal			Non-thermal	
10^{-22} eV	keV	MeV	GeV	100 TeV	M_{Pl}	$30\,M_\odot$

Primordial black holes as dark matter

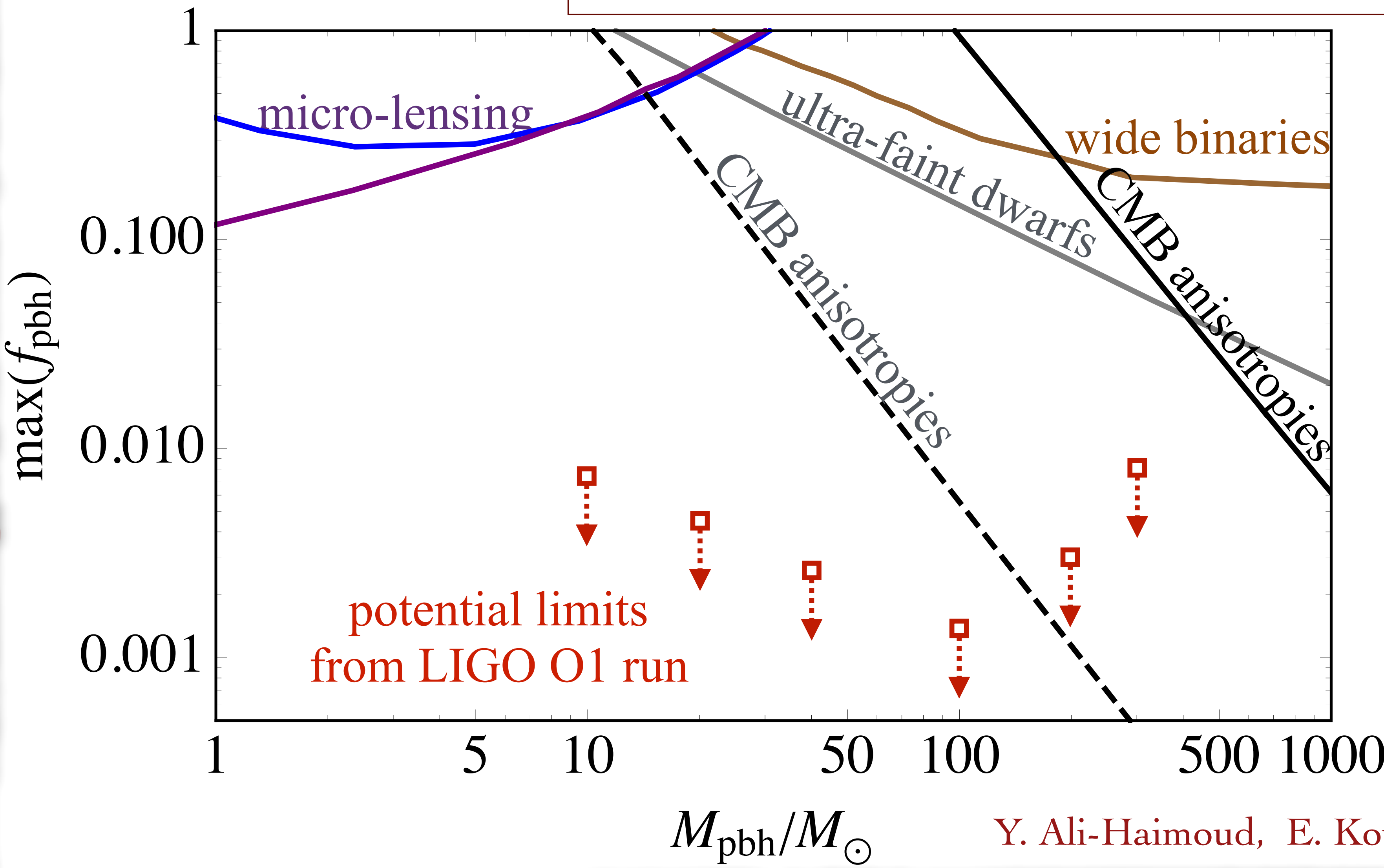


Y. Ali-Haimoud, M. Kamionkowski, arXiv:1612.05644

PART III: Particle physics from Astroparticle



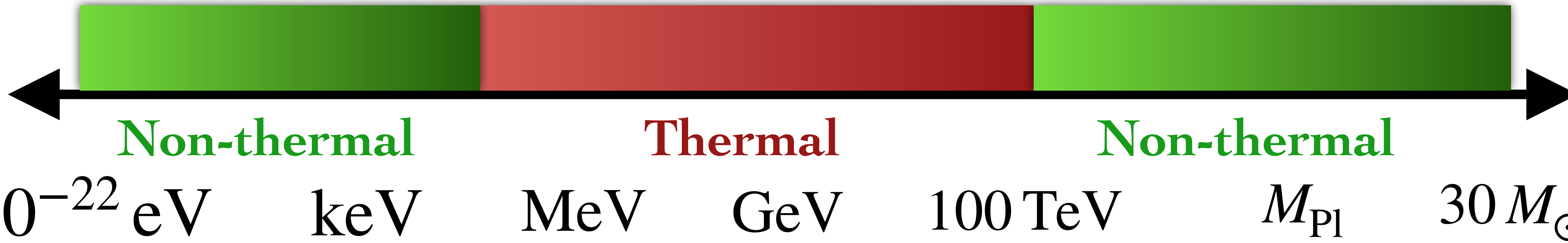
Primordial black holes as dark matter



More checks are needed

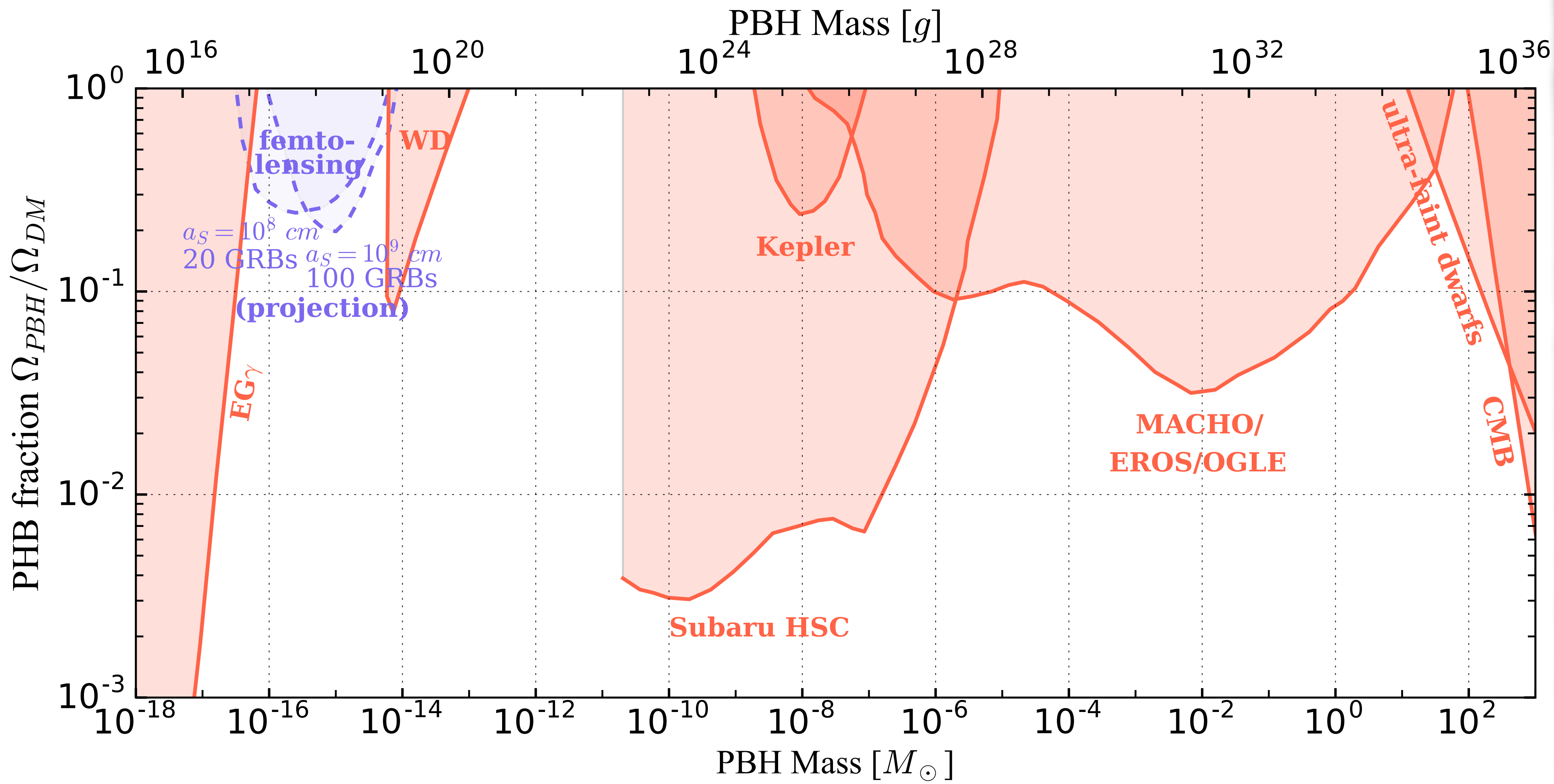
Y. Ali-Haimoud, E. Kovetz, M. Kamionkowski, arXiv:1709.06576

PART III: Particle physics from Astroparticle



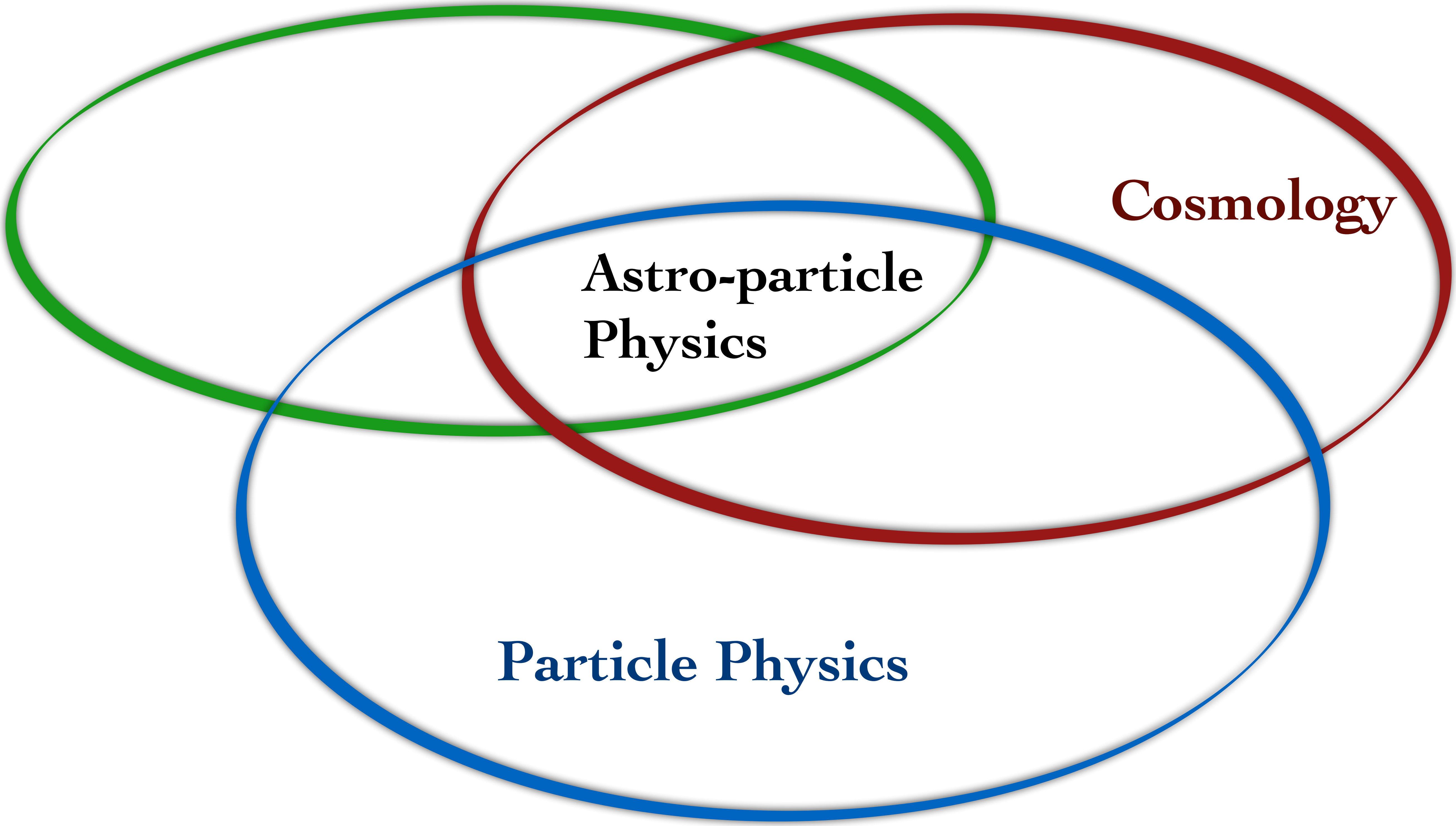
Primordial black holes as dark matter

A. Katz, J. Kopp, S. Sibiryakov, W. Xue, arXiv: 1807.11495



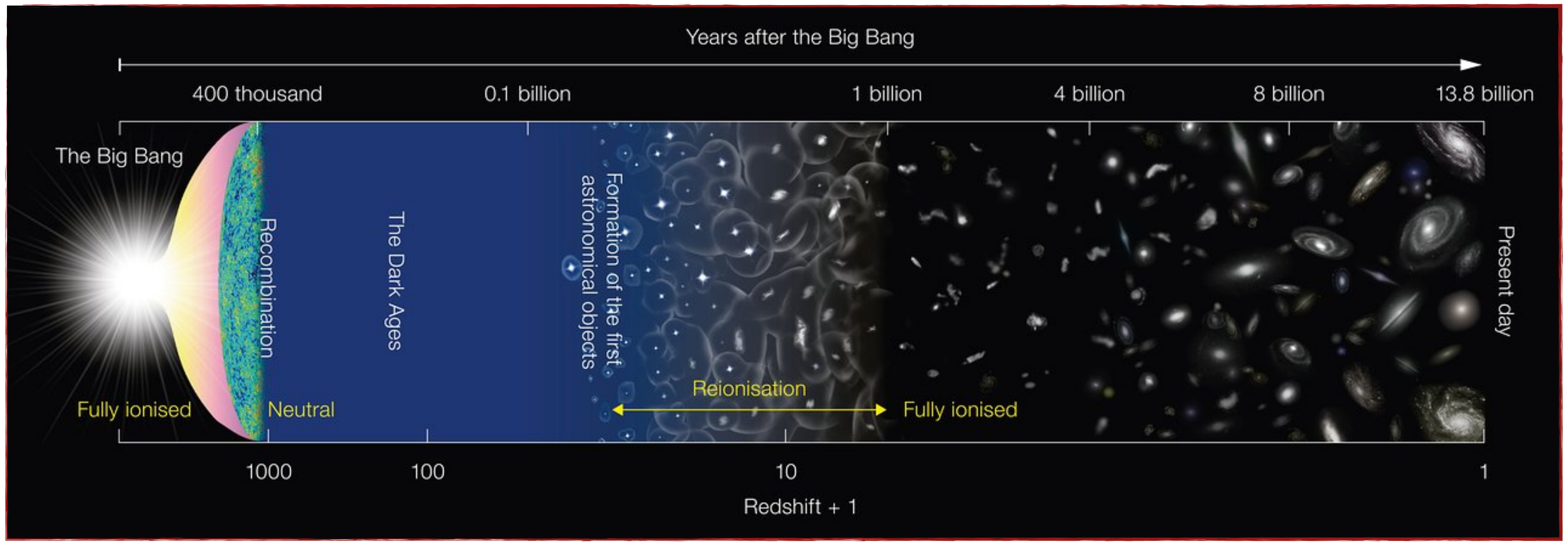
PART IV: Summary

Cosmology Particle Physics Astronomy



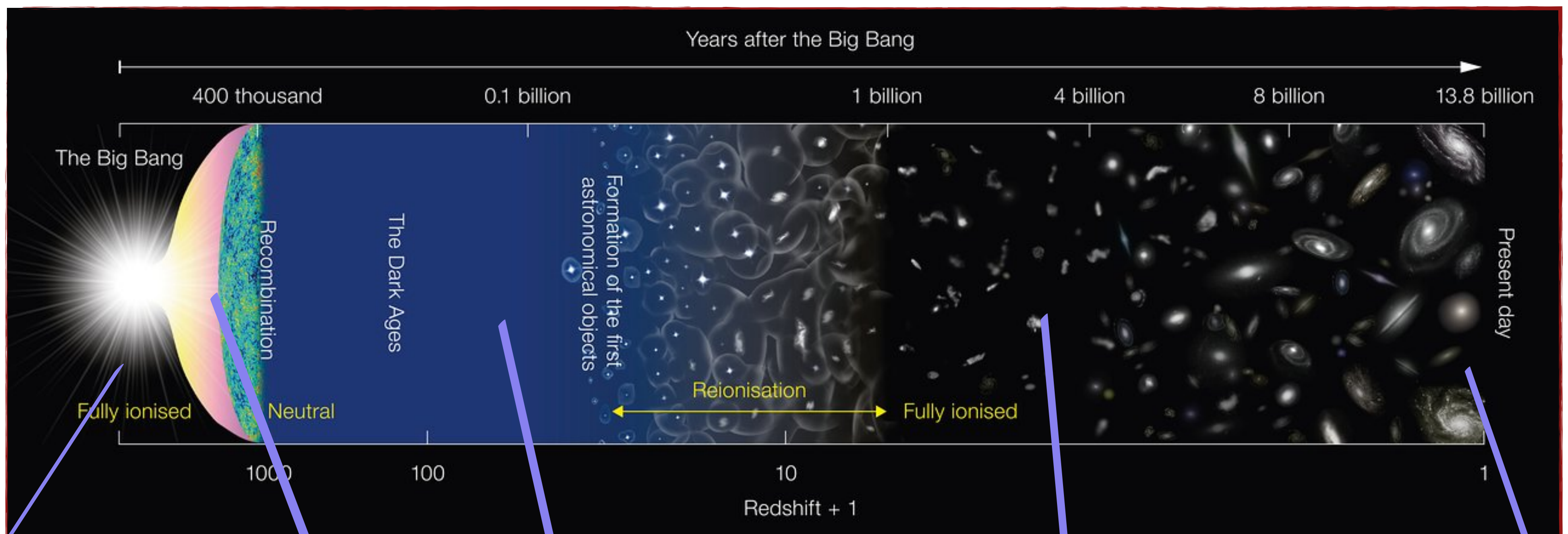
PART IV: Summary

We need to look back to move forward



PART IV: Summary

We need to look back to move forward



Inflation

Dark matter

21-cm cosmology

Structure formation

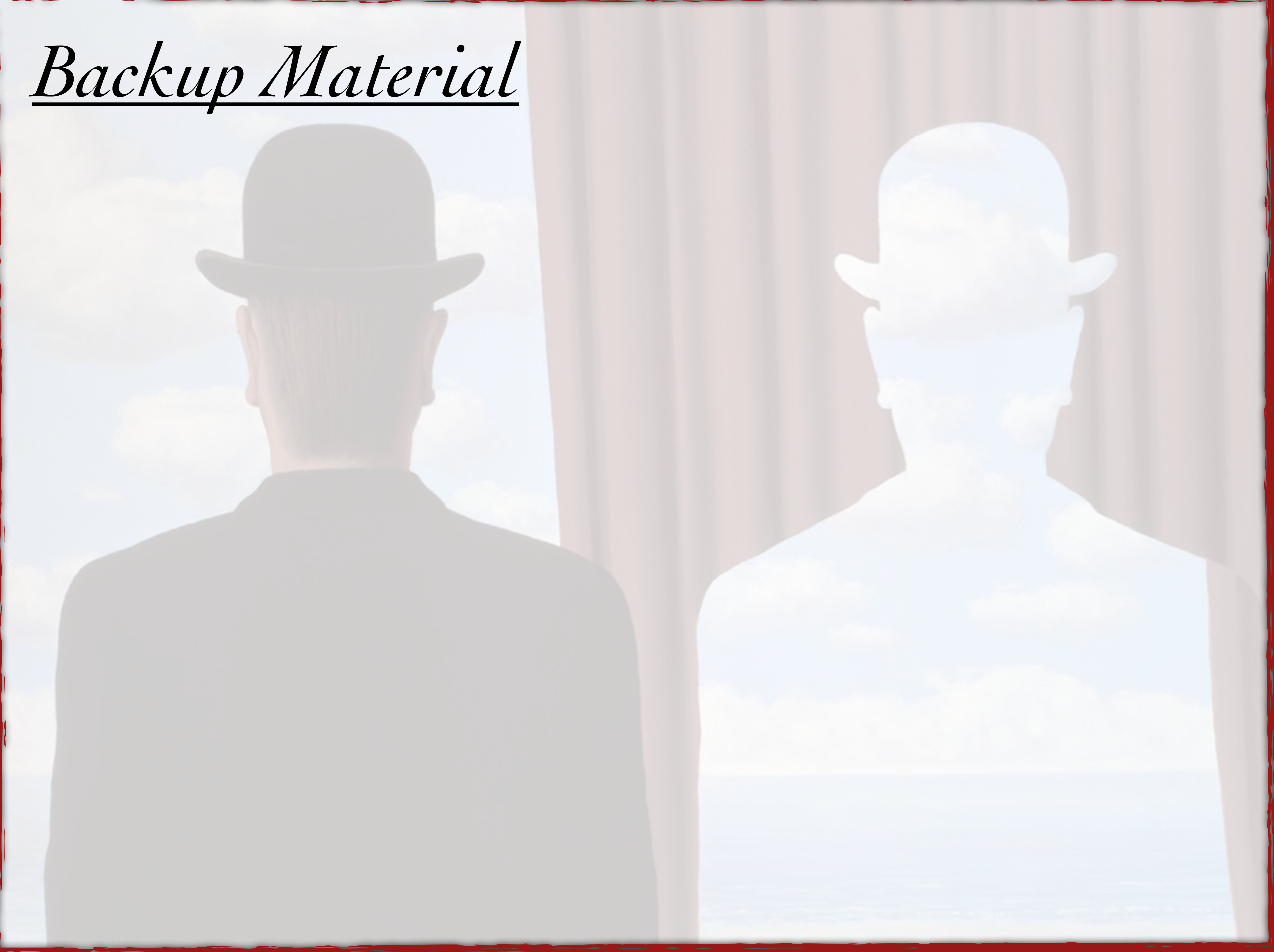
Gravitational waves

"…pronaque cum spectent animalia cetera terram,
os homini sublime dedit
caelumque videre iussit
et erectos ad sidera tollere vultus."

Ovidio, Metamorphoses I

"…whereas other animals look grovelling at the ground,
to man he gave an upturned aspect, and ordered him to look
at the sky, and to raise his face to the stars."

Backup Material



PART II: Particle physics from Cosmology

The very early Universe: Inflation

Inflation is nowadays a well-established paradigm, able to explain the properties of the Universe at large scales and the generation of the primordial density fluctuations seeding structure formation.

$$\mathcal{S} = \int d^4x\sqrt{-g}\left[\frac{\bar{M}_{\rm Pl}^2}{2}\mathscr{R} - \frac{g^{\mu\nu}}{2}\left(\partial_\mu\phi\right)\left(\partial_\nu\phi\right) - V(\phi)\right]$$

$$T_{00} = \rho_\phi = \frac{\dot{\phi}^2}{2} + V(\phi)$$

$$\frac{T^i{}_i}{3} = P_\phi = \frac{\dot{\phi}^2}{2} - V(\phi)$$

PART II: Particle physics from Cosmology

The very early Universe: Inflation

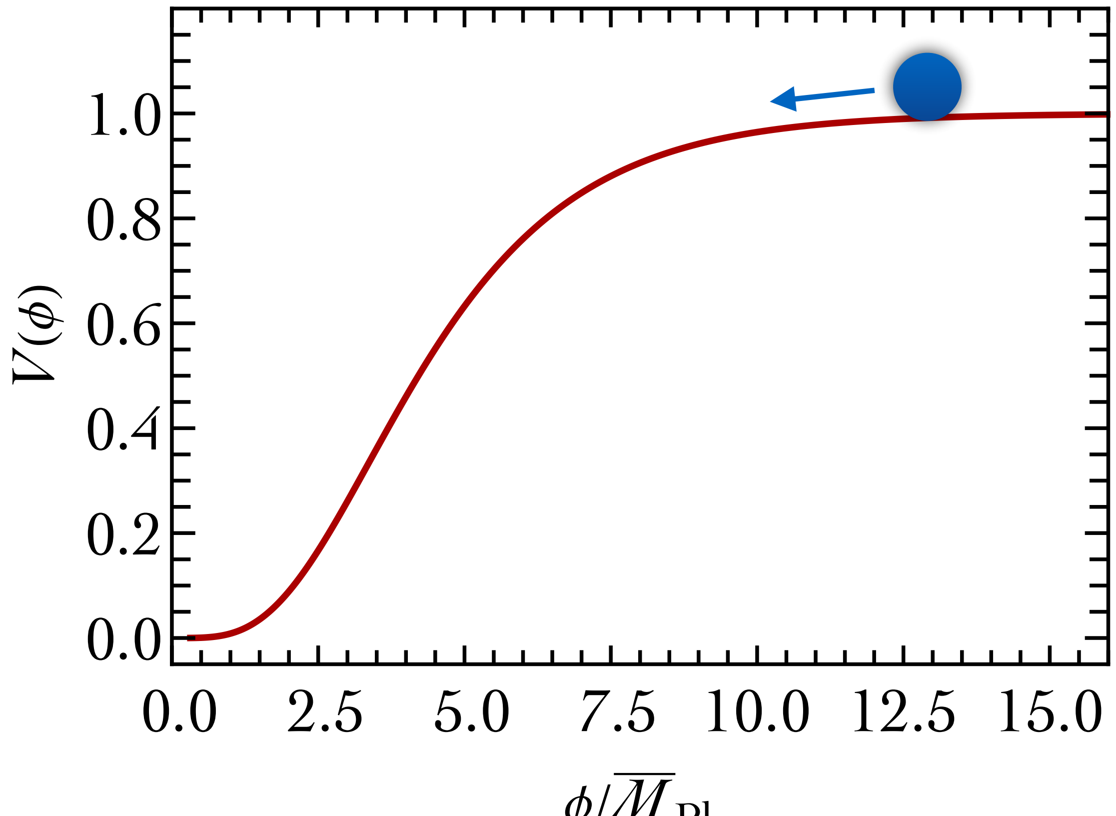
Inflation is nowadays a well-established paradigm, able to explain the properties of the Universe at large scales and the generation of the primordial density fluctuations seeding structure formation.

$$\mathcal{S} = \int d^4x \sqrt{-g} \left[\frac{\bar{M}_{\rm Pl}^2}{2} \mathcal{R} - \frac{g^{\mu\nu}}{2} \left(\partial_\mu \phi\right) \left(\partial_\nu \phi\right) - V(\phi) \right]$$

if $V(\phi) \gg \dot{\phi}^2$

$$T_{00} = \rho_\phi = V(\phi) = -P_\phi$$

$$\frac{T^i{}_i}{3} = P_\phi = -V(\phi)$$



PART II: Particle physics from Cosmology

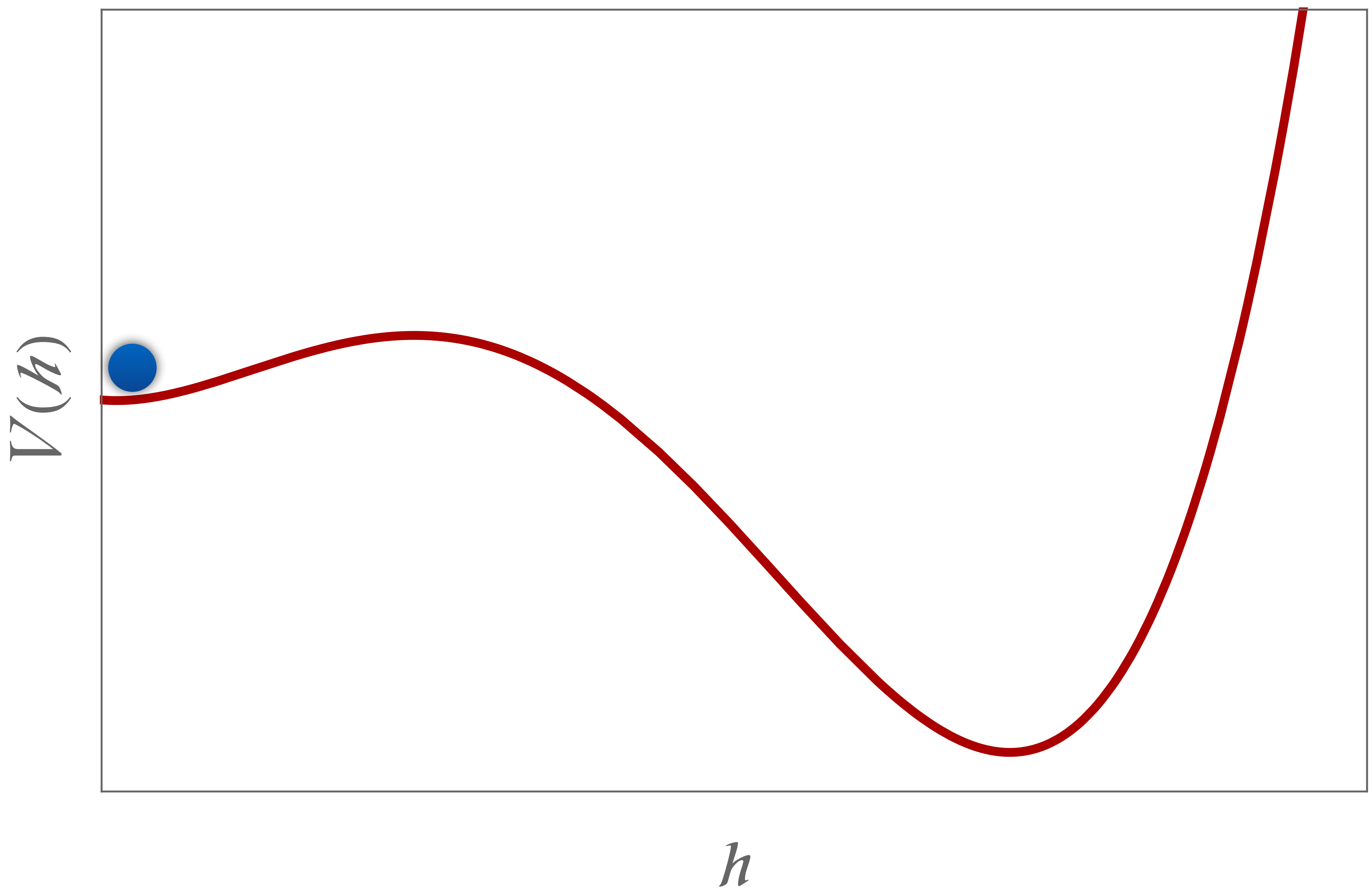
The very early Universe: Inflation

The Higgs + the inflaton

PART II: Particle physics from Cosmology

The very early Universe: Inflation

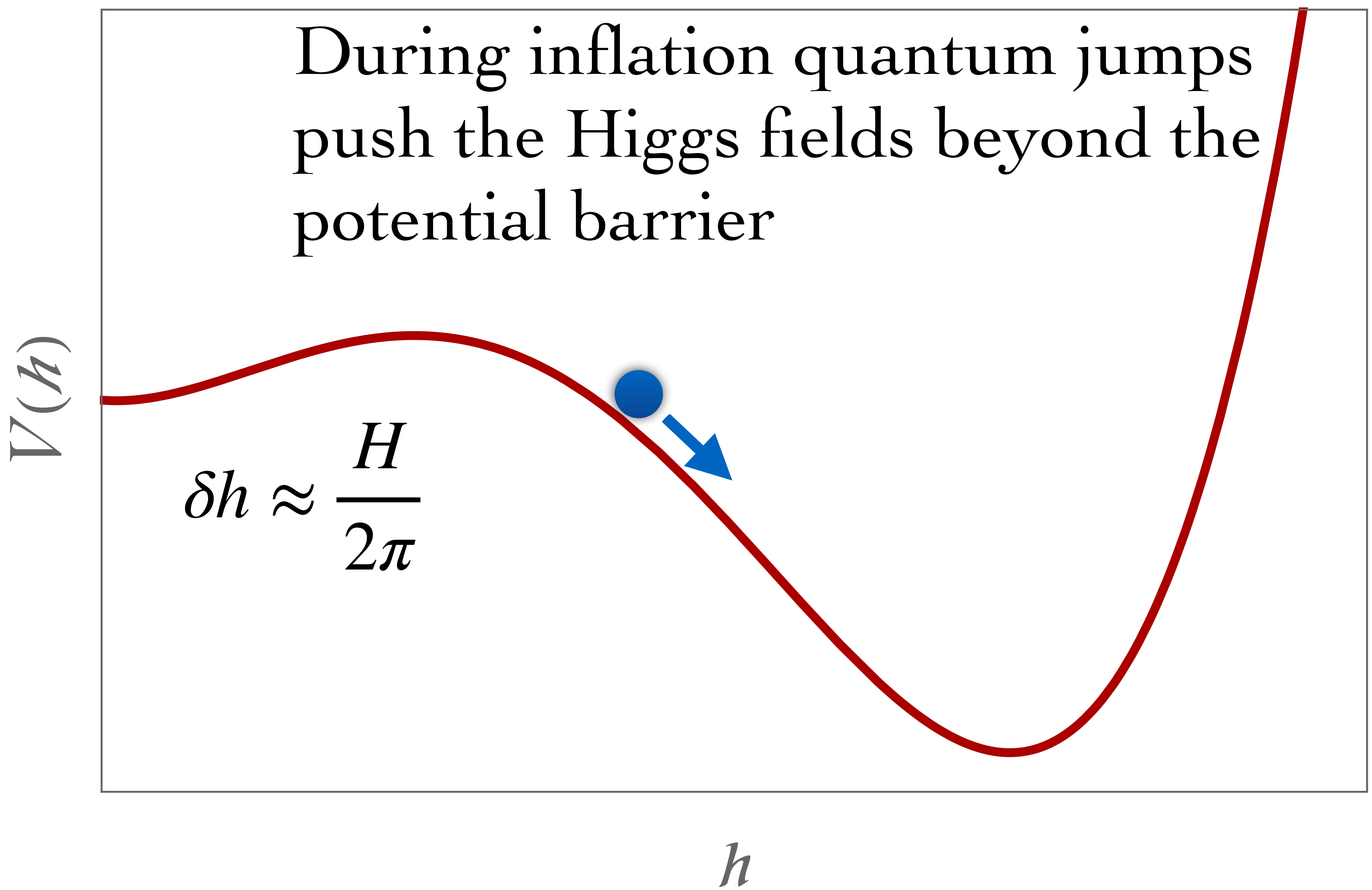
The Higgs + the inflaton



PART II: Particle physics from Cosmology

The very early Universe: Inflation

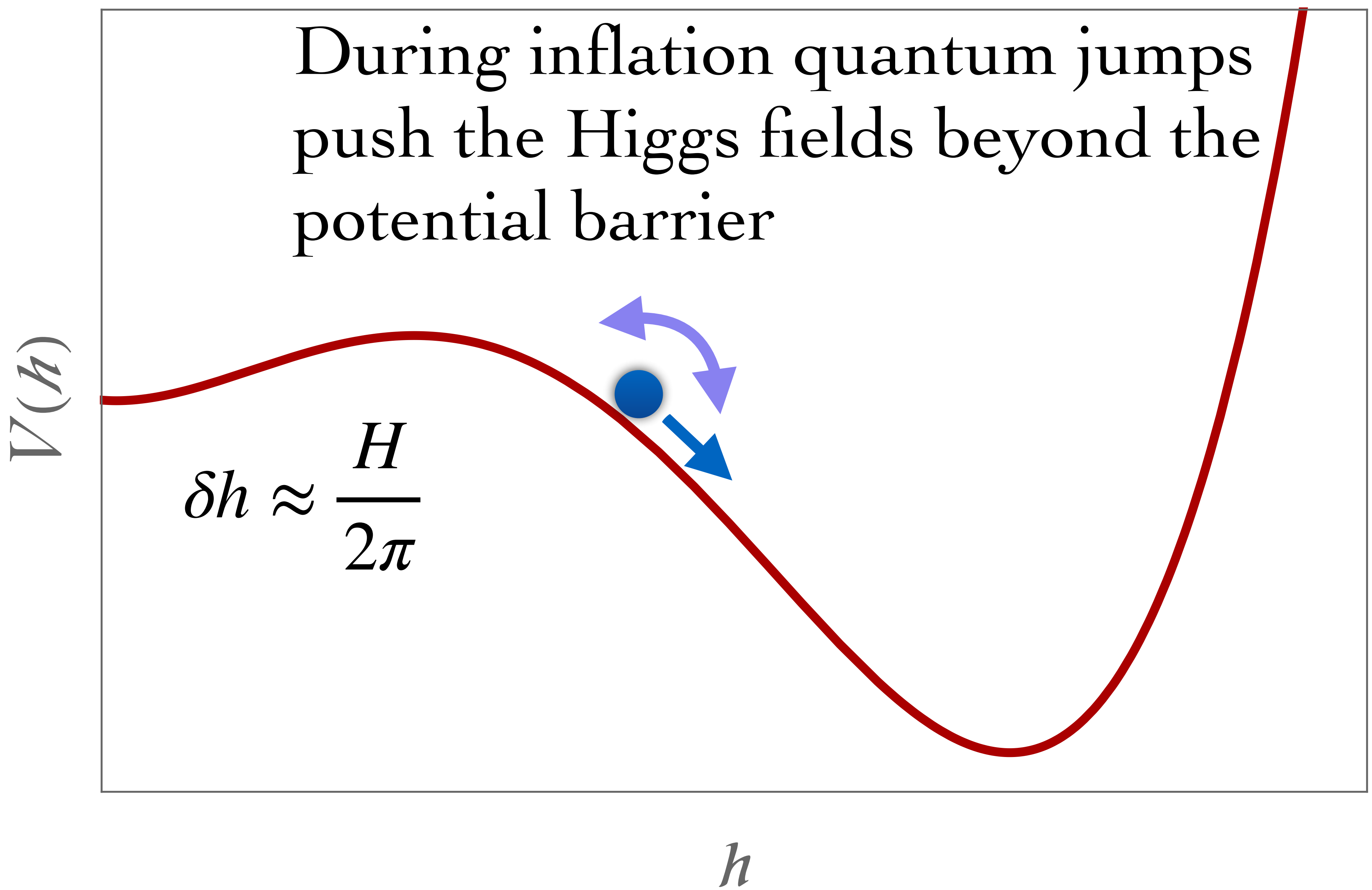
The Higgs + the inflaton



PART II: Particle physics from Cosmology

The very early Universe: Inflation

The Higgs + the inflaton

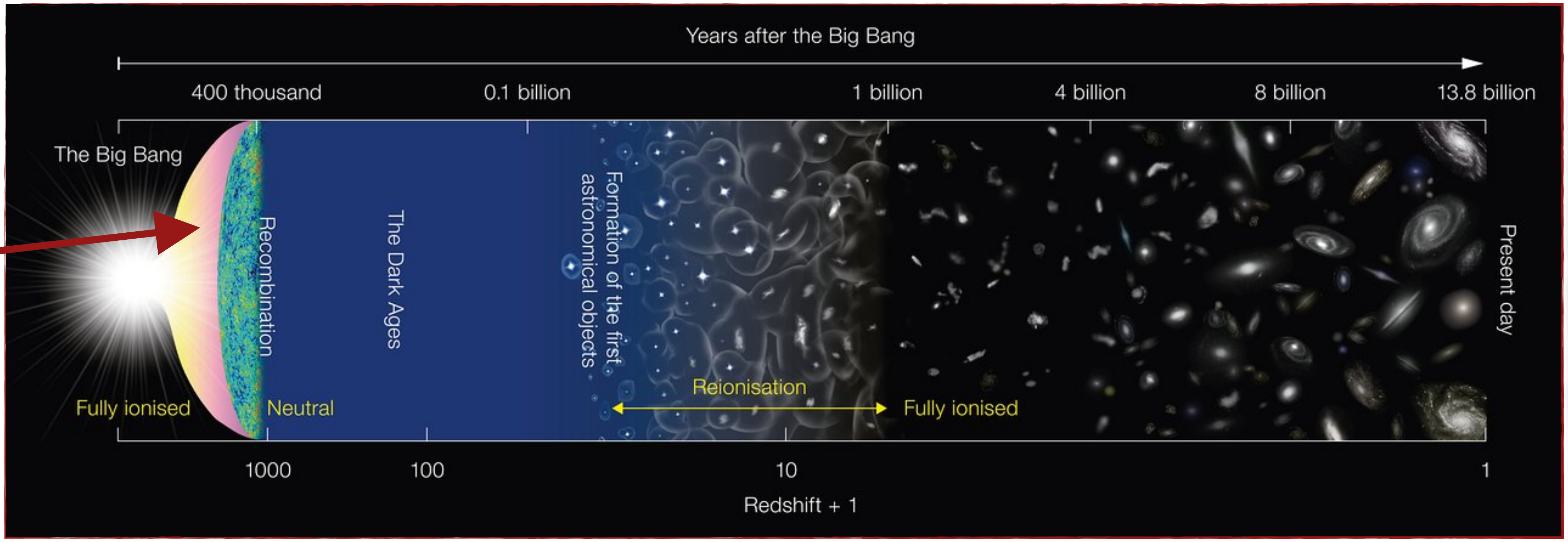


Higgs field rescued after the end of inflation by thermal corrections

PART II: Particle physics from Cosmology

The late Universe: 21 cm cosmology

Mostly protons, electrons and photons



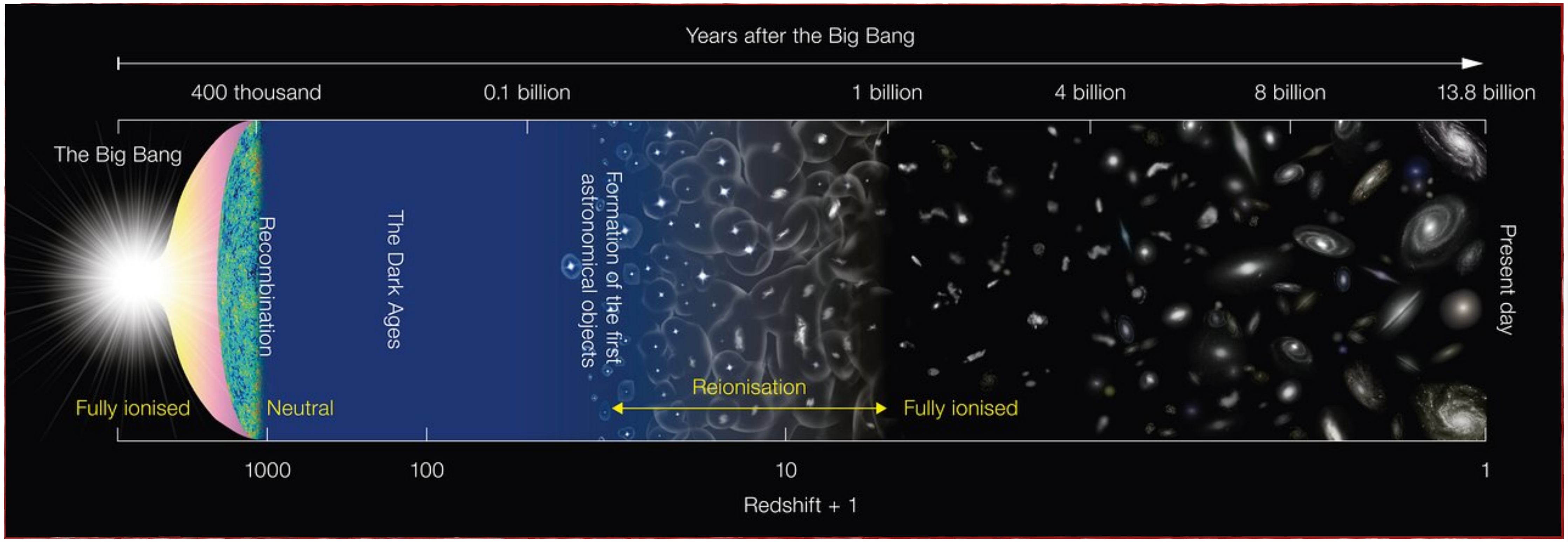
Recombination and photon decoupling

Neutral hydrogen forms through the reaction $e^- + p \to \mathrm{H} + \gamma$ when the
temperature has become low enough that the reverse reaction
is energetically disfavored

$(T_{\rm rec} = 0.26 - 0.33\,\mathrm{eV} = 3000 - 3800\,^\circ\mathrm{K})$

PART II: Particle physics from Cosmology

The late Universe: 21 cm cosmology



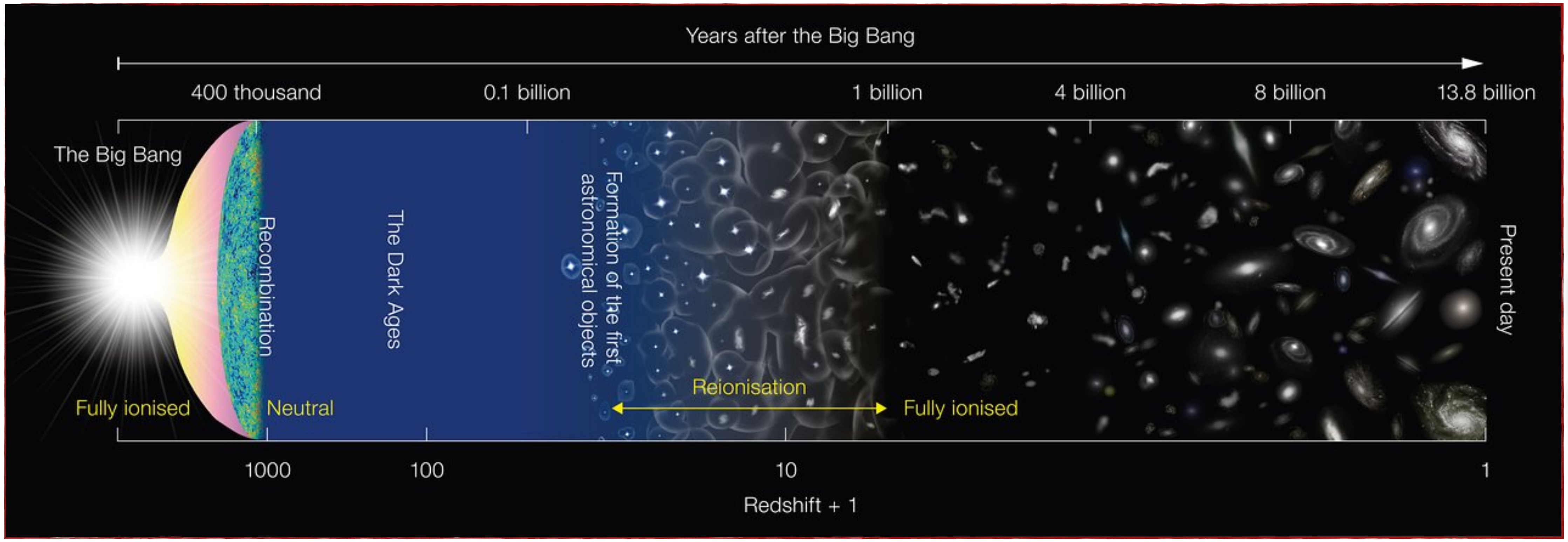
Recombination and photon decoupling

Before recombination the strongest coupling between the photons and the rest of the plasma is through Thomson scattering $e^- + \gamma \to e^- + \gamma$

The sharp drop in the free electron density after recombination means that this process becomes inefficient and the photons decouple.

PART II: Particle physics from Cosmology

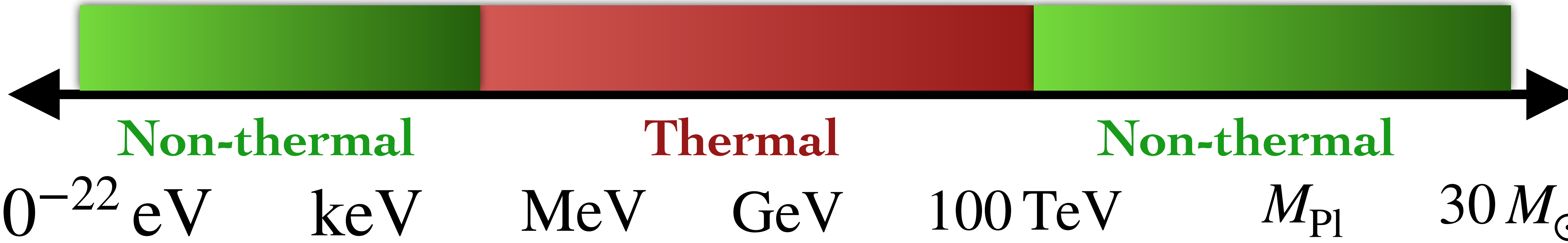
The late Universe: 21 cm cosmology



Recombination and photon decoupling

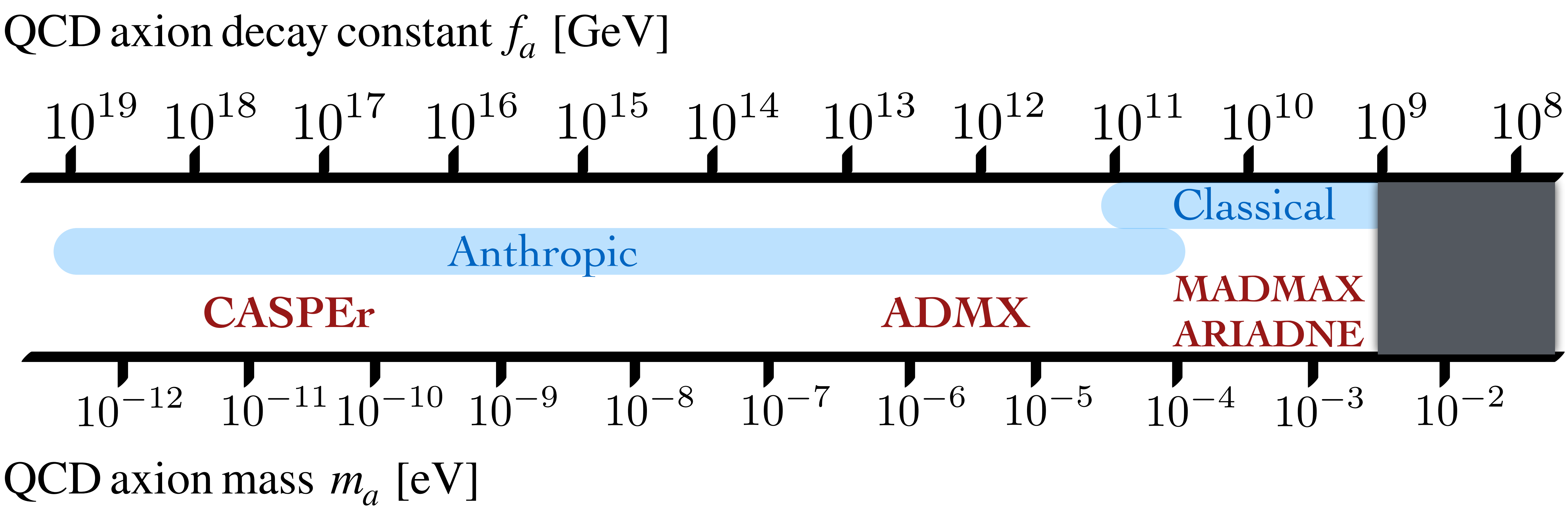
The decoupled photons can stream freely for the entire future history of the Universe without ever being absorbed or scattered, and are today observed as the cosmic microwave background (CMB).

PART III: Particle physics from Astroparticle

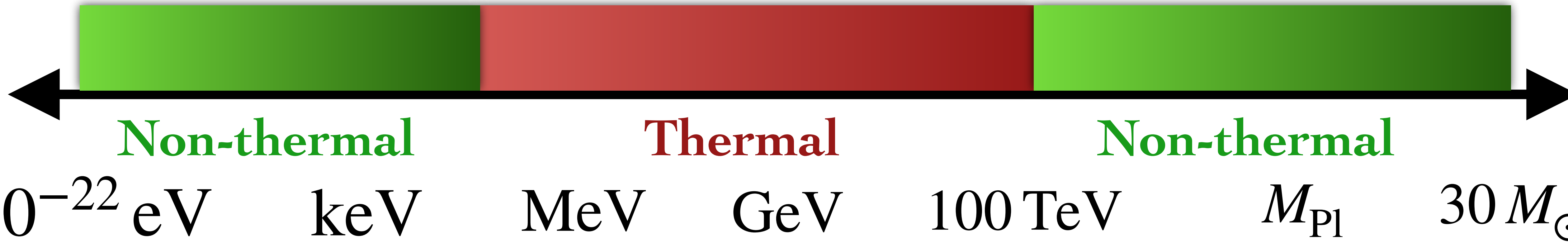


QCD axion searches

QCD axion dark matter

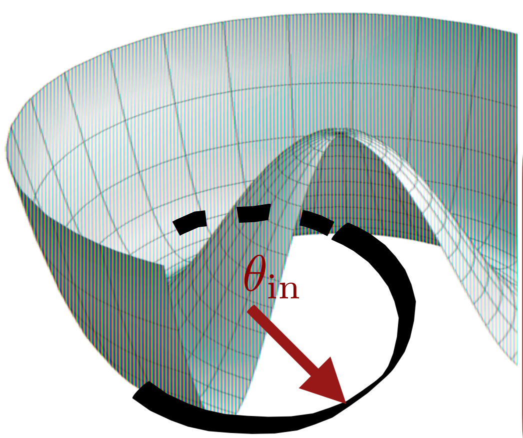


PART III: Particle physics from Astroparticle



QCD axion dark matter

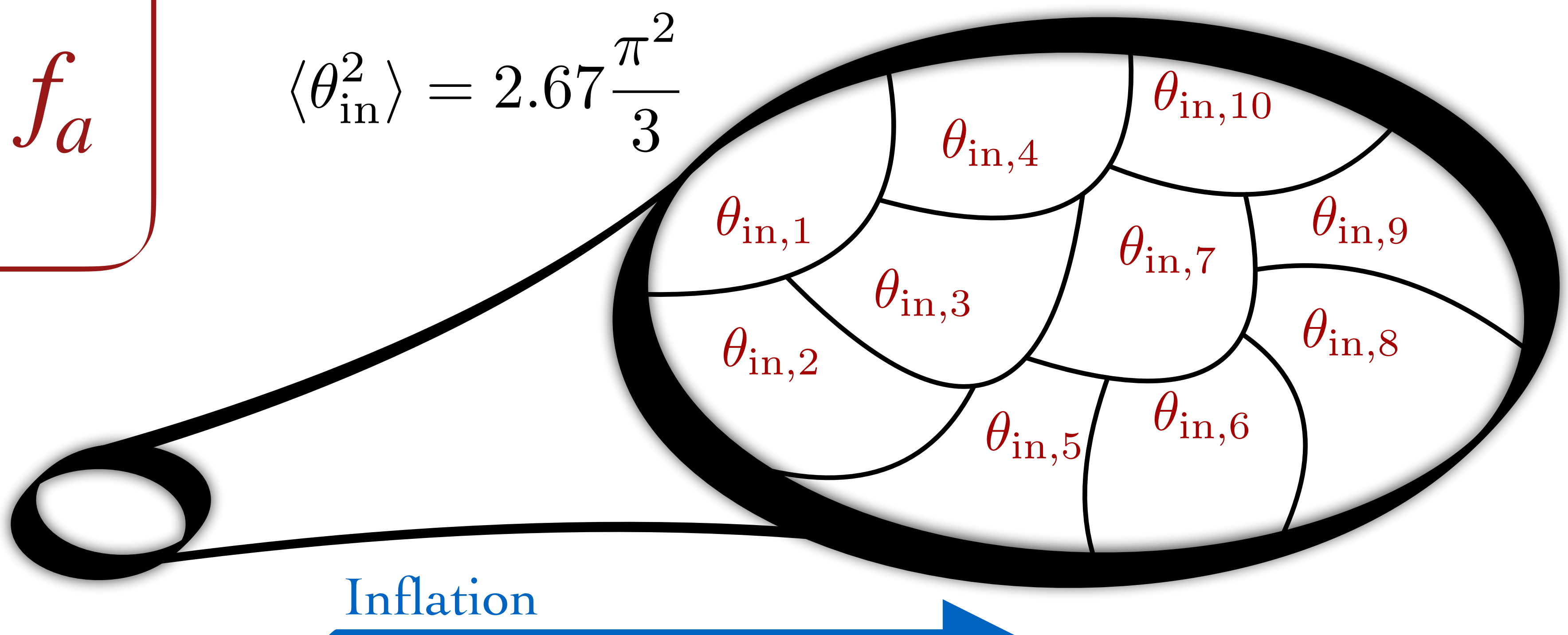
$$m_a = 5.70 \times 10^{-6} \left(\frac{10^{12}\,\mathrm{GeV}}{f_a} \right) \mathrm{eV}$$



$$\frac{H_I}{2\pi} > f_a$$

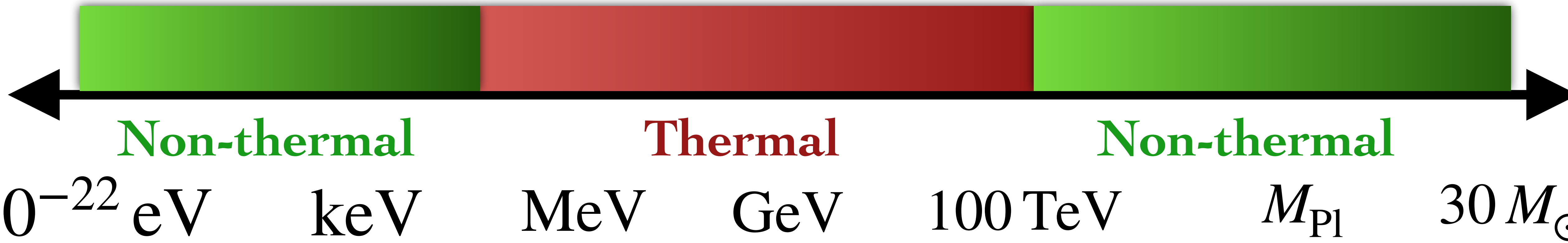
Crucial interplay with inflation

$$\langle \theta_{\rm in}^2 \rangle = 2.67 \frac{\pi^2}{3}$$



The U(1) symmetry broken
after the end of inflation

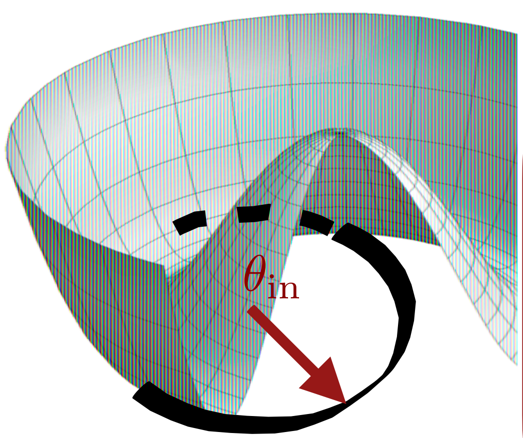
PART III: Particle physics from Astroparticle



QCD axion dark matter

$$m_a = 5.70 \times 10^{-6} \left(\frac{10^{12}\,\mathrm{GeV}}{f_a} \right) \mathrm{eV}$$

Crucial interplay with inflation



$$\frac{H_I}{2\pi} < f_a$$

The U(1) symmetry broken before the end of inflation