Planckian Interacting Massive Particles as Dark Matter

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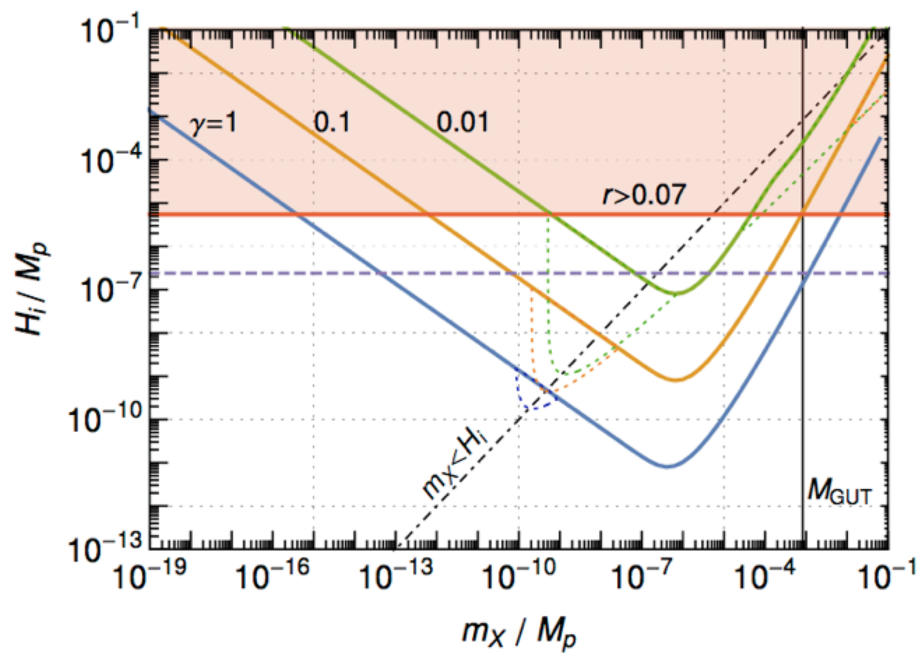


arXiv:1511.03278 w. Mathias Garny and McCullen Sandora
arXiv:1709.09688 and arXiv:1810.01428 w. Mathias Garny, Andrea Palessandro and McCullen Sandora
arXiv:1903.12168 w. Nielsen Palessandro

Evidence for Dark Matter

Galaxy scale

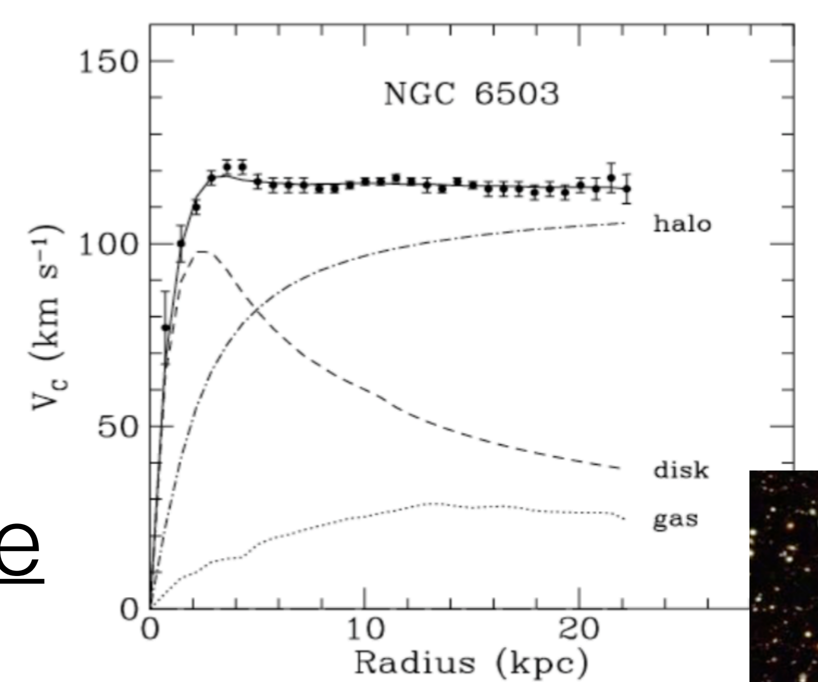
- Rotation curves
- Micro lensing

Clusters of galaxies scale

- Dynamics
- Gravitational lensing

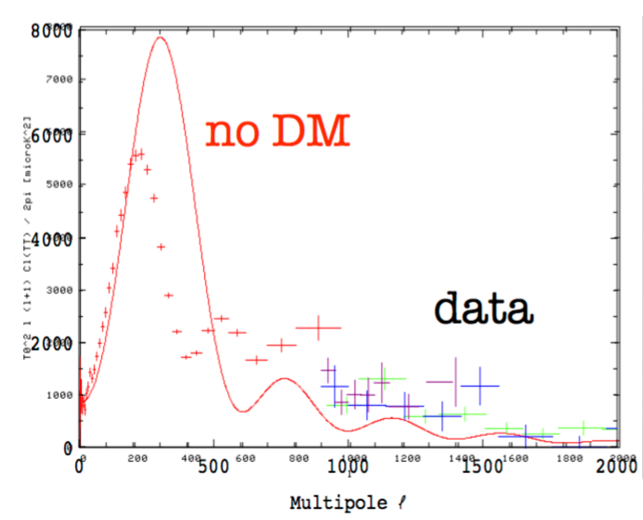
CMB and LSS scale

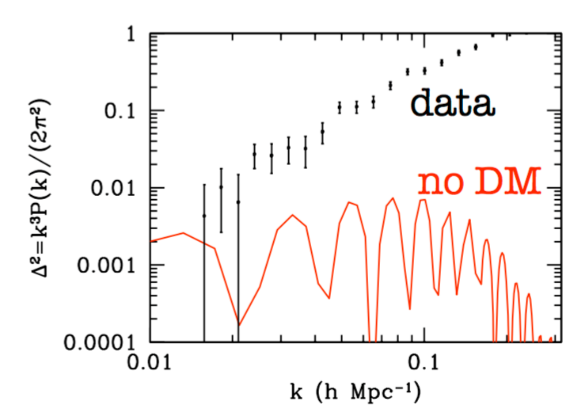
- third peak in CMB
- enough structure



[credit: Begeman et al.]

[Chandra X-ray observatory: Bullet cluster]





[credit: Cirelli]

Occam's razor vs. theoretical bias

What is known about Dark Matter?

So far ΛCDM fits the data, so

- DM has gravitational interactions

- DM looks cold

⇒ A minimal model of Dark Matter:

- DM is a massive particle with only gravitational interaction

(Planckian Interacting Massive Particle as Dark Matter)

The effective model

PIDM

- Assume DM only interacts gravitationally with SM

$$\mathcal{L} = \mathcal{L}_{SM} + \mathcal{L}_{DM} + \mathcal{L}_{EH} + \frac{1}{2} h^{\mu\nu} (T^{SM}_{\mu\nu} + T^{DM}_{\mu\nu})$$

$$\mathcal{L}_{DM} = -\frac{1}{2}\partial_\mu \chi \partial^\mu \chi - \frac{1}{2} m_X^2 \chi^2$$

(scalar case — fermions ok too)

- In absence of any additional scales, the PIDM mass must be close to the Planck scale

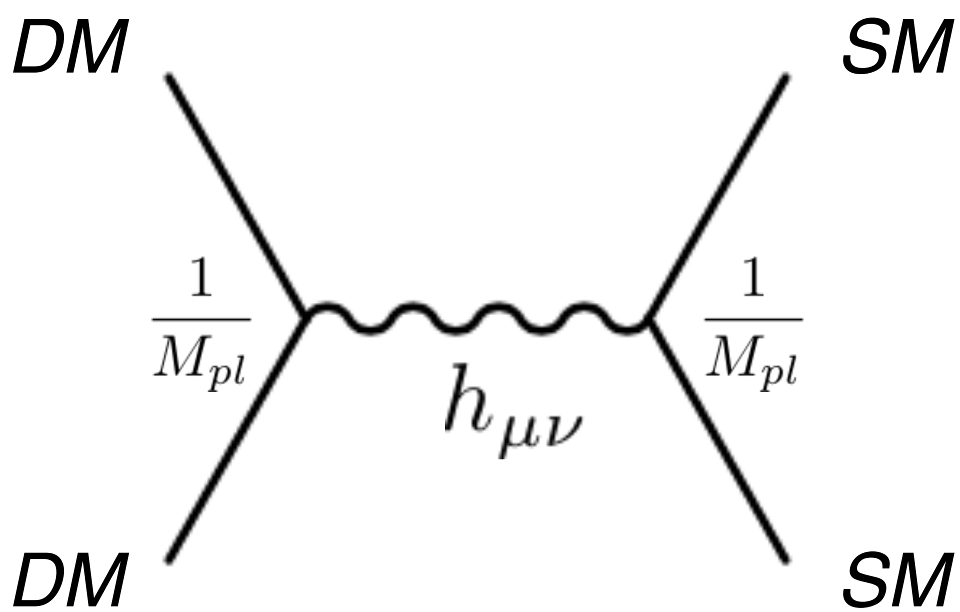
$$m_X \gtrsim M_{GUT}$$

Minimal PIDM

The effective model

PIDM

- DM only talks to SM through gravity



$$|\mathcal{M}|^2 \sim \frac{E^4}{M_{pl}^4} \begin{cases} m_X >> T & \langle \sigma v \rangle \propto \frac{m_X^2}{M_{pl}^4} \\ m_X << T & \langle \sigma v \rangle \propto \frac{T^2}{M_{pl}^4} \end{cases}$$

- Couplings uniquely fixed by equivalence principle

➡ Only one free parameter — the DM mass

Beyond WIMP

Stronger	X	X	MACHO
Weak	X	WIMP	WIMPZILLA
Super Weak	Axion/ Sterile	Gravitino/ FIMP	?
	Super Light	Light	Heavy

Beyond WIMP

Stronger	X	X	MACHO
Weak	X	WIMP	WIMPZILLA
Super Weak	Axion/ Sterile	Gravitino/ FIMP	PIDM
	Super Light	Light	Heavy

Production mechanism

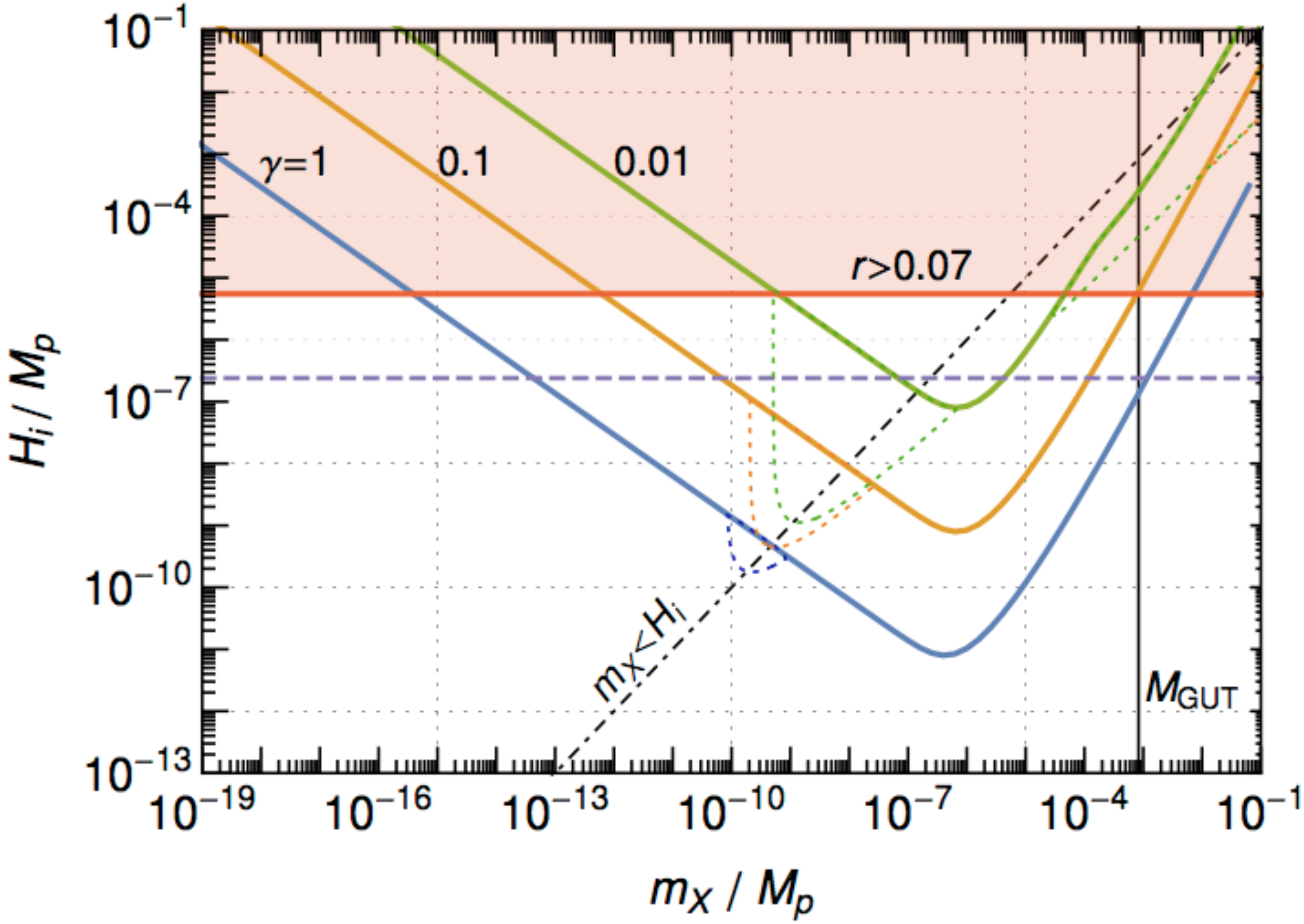
PIDM production requires very high temperatures

➡ We consider three contributions

1. Shortly after reheating by gravitational scattering of SM particles in the hot plasma
2. During reheating by gravitational scattering
3. At the end of inflation from change in background

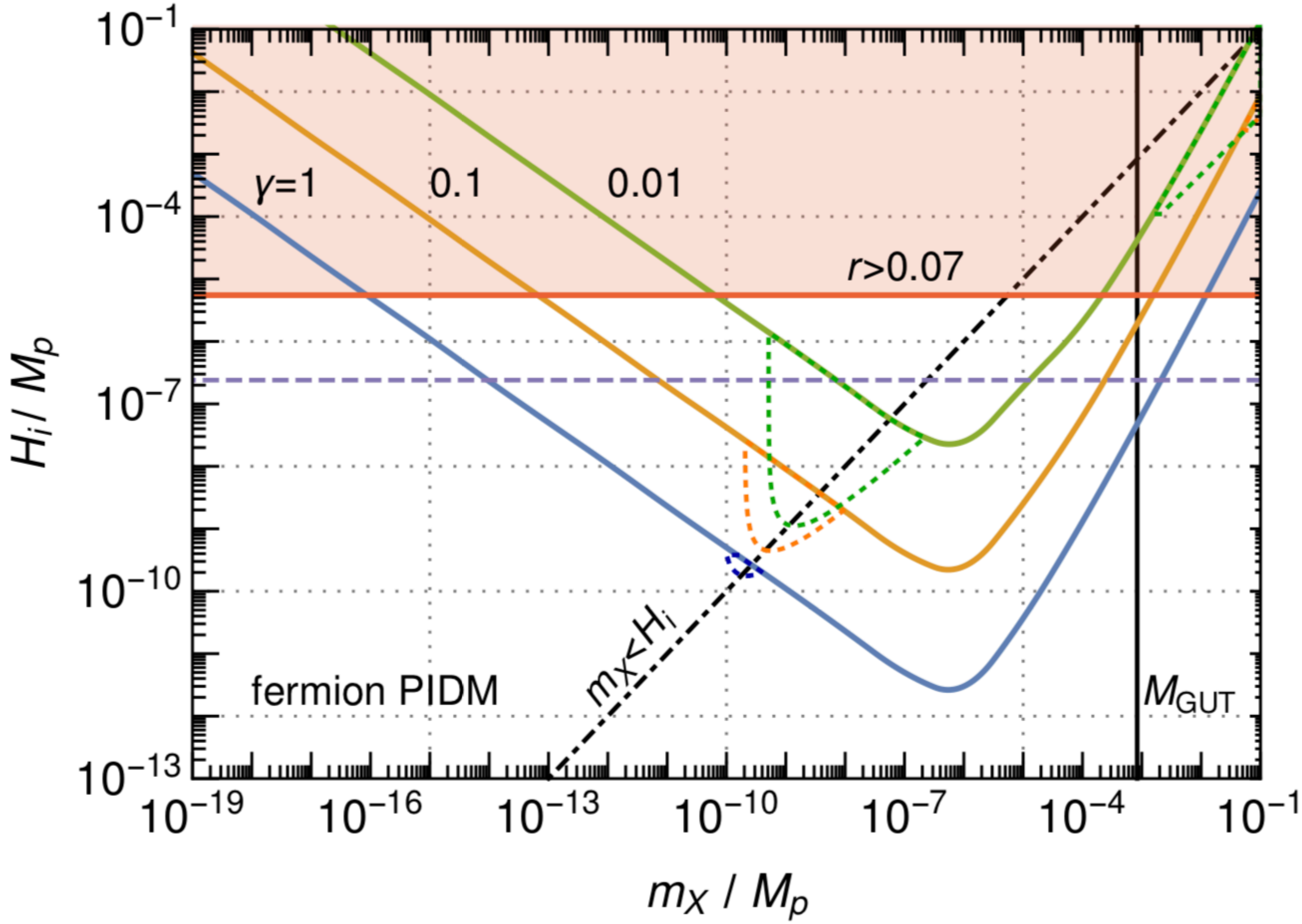
Results

Scalar PIDM



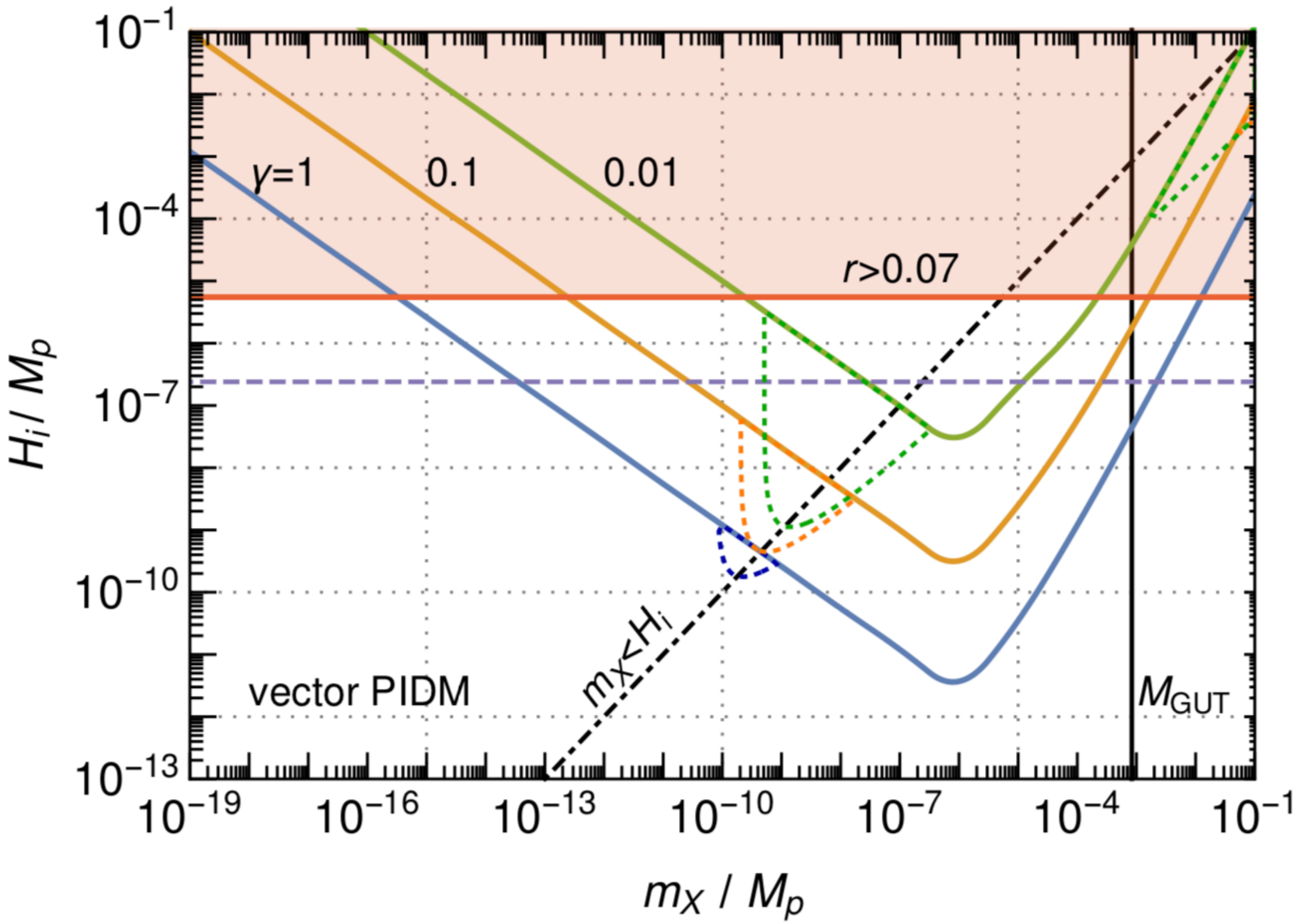
Results

Fermion PIDM



Results

Vector PIDM



Results

Minimal PIDM paradigm

$$m_X \gtrsim M_{GUT}$$

- Current constraint from no observation of tensor modes

$$r < 0.07 \;\; \Rightarrow m_X < 0.01 M_{pl}$$

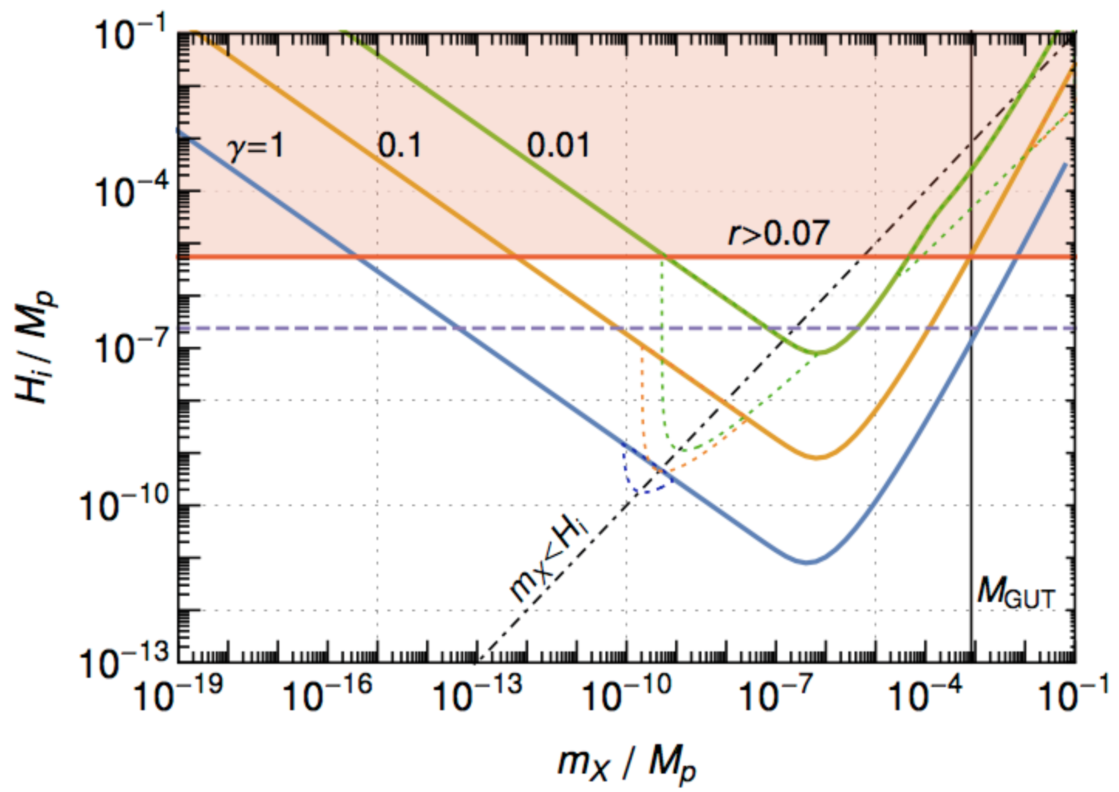
- Most optimistic future sensitivity

$$r \sim 10^{-4}$$

- Entire parameter space

$$m_X \gtrsim M_{GUT}$$

can be probed in the future



Results

Comparison with axion DM

- Anthropic window of axion:
  possible connection to GUT or Planck scale

$$f_a \gtrsim 10^{16}\mathrm{GeV} \quad \Rightarrow \quad E_{\mathrm{infl.}} \lesssim 4 \cdot 10^{14}\mathrm{GeV} \quad \Rightarrow \quad r \lesssim 2 \cdot 10^{-9}$$

➡ No tensor modes!

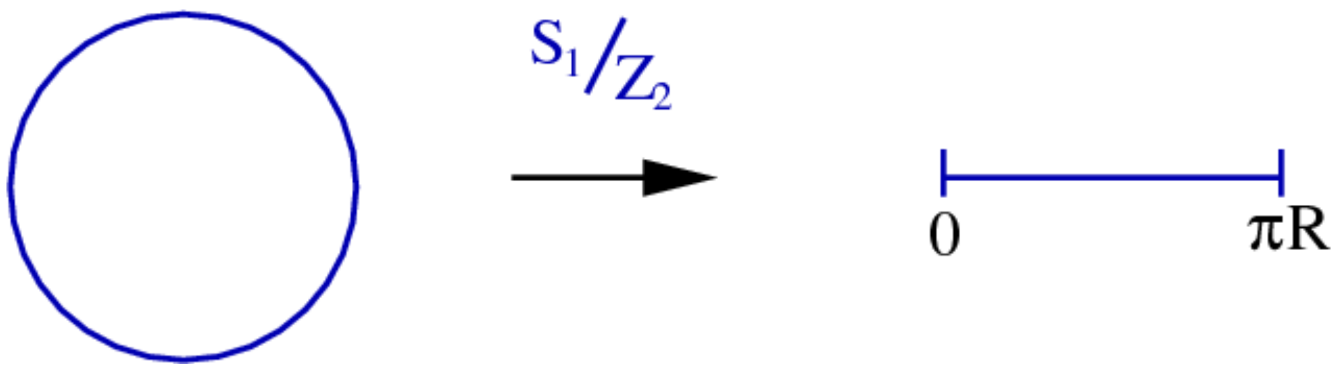
- Minimal PIDM paradigm

$$m_X \gtrsim M_{GUT} \quad \Rightarrow \quad r \gtrsim 10^{-4}$$

➡ Tensor modes!

Specific models

KK-mode of graviton



- Z_2 breaks KK-number but KK-parity is conserved
- Lightest KK-mode stable
- If lightest KK-mode is the graviton — it could be a PIDM

[Garny, Palessandro, Sandora, MSS, 2017]

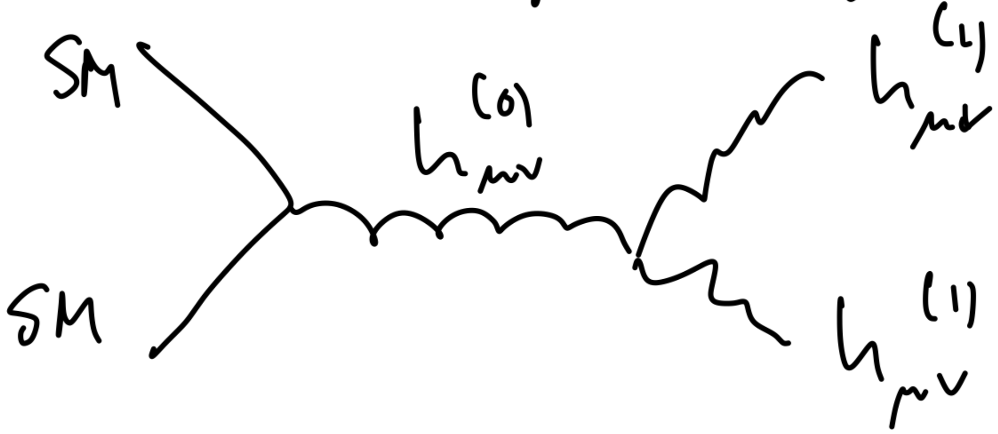
Massive KK graviton PIDM

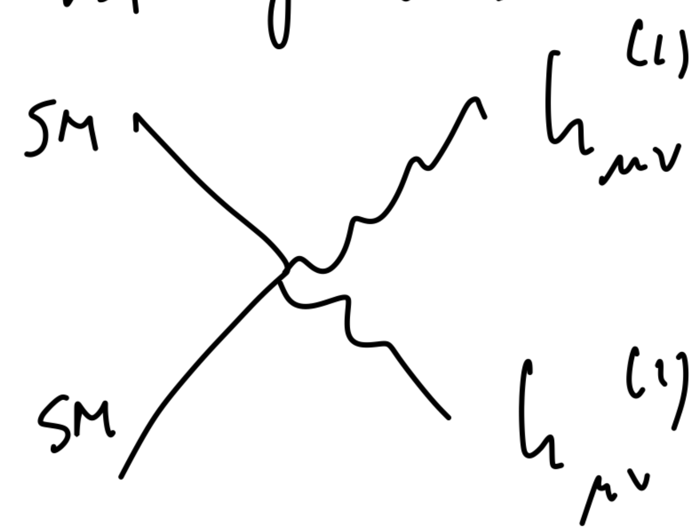
- Lagrangian for KK mode of graviton has Fierz-Pauli form

$$\mathcal{L}^n = \frac{1}{2}\Big[\partial_\lambda h^{\mu\nu,n}\partial^\lambda h^n_{\mu\nu} - \partial_\lambda h^{\mu,n}_\mu \partial^\lambda h^{\nu,n}_\nu - 2\,\partial_\lambda h^{\lambda\nu,n}\partial^\mu h^n_{\mu\nu} + 2\,\partial^\nu h^{\lambda,n}_\lambda \partial^\mu h^n_{\mu\nu}$$
$$+ m_n^2\big(h^{\mu,n}_\mu h^{\nu,n}_\nu - h^{\mu\nu,n} - h^{\mu\nu,n} h^n_{\mu\nu}\big)\Big]$$

- Lightest KK has odd parity while SM even

→ can only be produced in pairs





Massive KK graviton PIDM

→ the amplitudes scales as

$$|M|^2 \sim E^{12}/(m^8 m_p^4)$$

- EFT description is valid up to cutoff

$$\Lambda = (m^2 m_p)^{1/3}$$

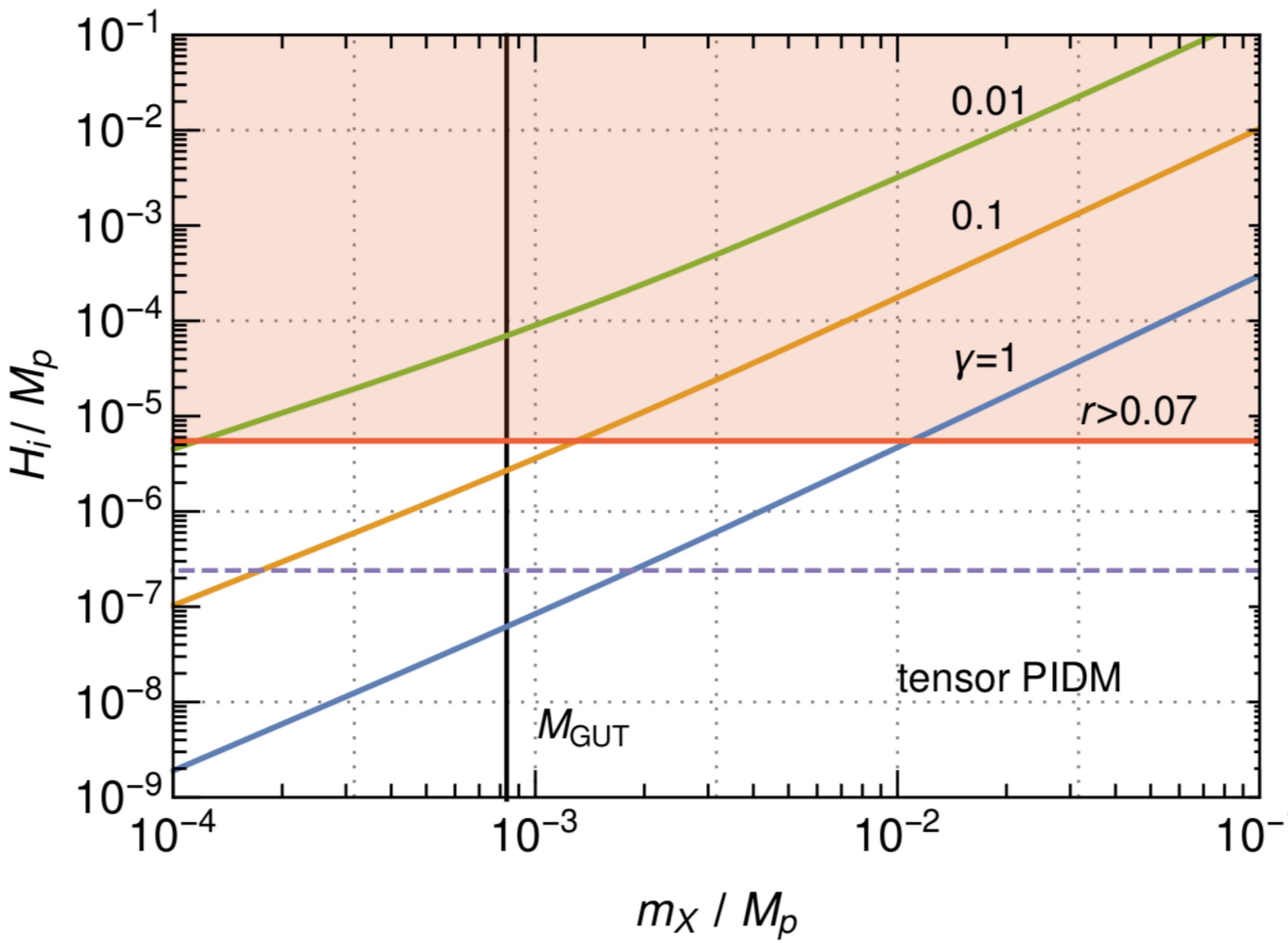
where $|M|^2 \sim 1$ ⇒ Unitarity lost

→ above this scale one needs to include full KK tower (go to 5D)

$$E < \Lambda \quad \text{is sufficent for us}$$

Results

KK graviton PIDM



[Garny, Palessandro, Sandora, MSS, 2017]

Other observables

- If stability of PIDM protected by global symmetry

➡ Quantum grav./string theory breaks it through non-pert. grav. instanton effects

➡ Decay rate suppressed by the Euclidian action

$$\propto e^{-S}$$

➡ Flux of ultrahigh energy cosmic rays to be seen in observations?

[AUGER, Telescope Array, JEM-EUSO or ARA]

[Garny, Palessandro, Sandora, MSS, 2017]

Other observables

<u>Coldest and darkest Dark Matter</u>

- Very large mass and very early decoupling

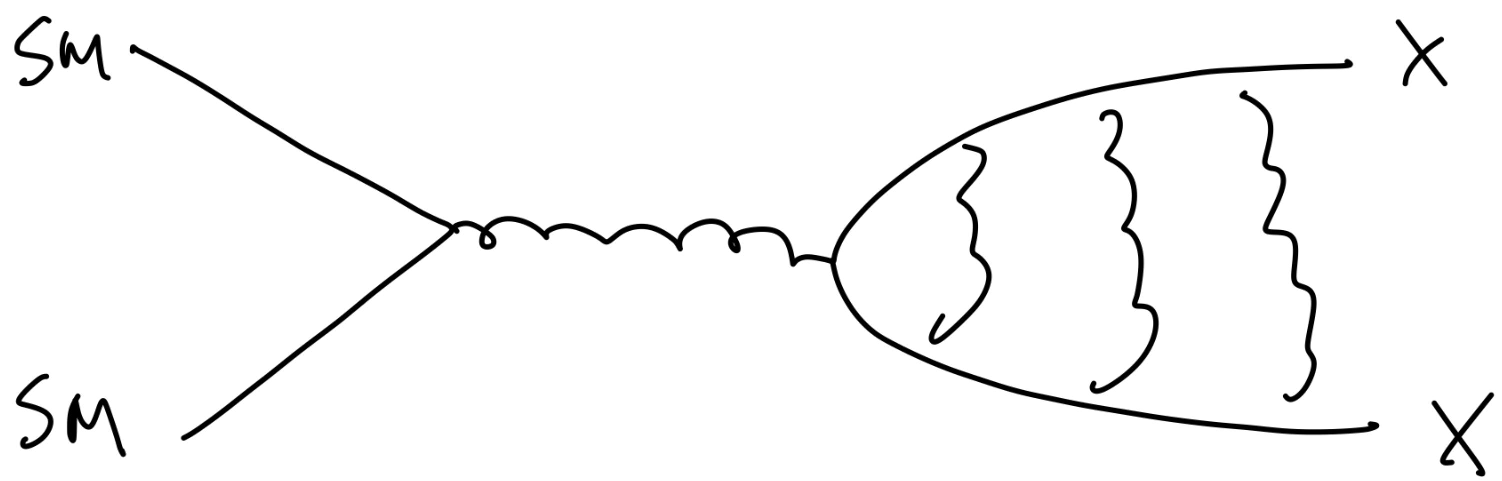
➡ Practically zero free-streaming length

➡ Extremely cold and could form structures down to microphysical scales

Other observables

<u>Gravitational atoms</u> [Nielsen, Palessandro, MSS 2019]

- Two particle PIDM (quantum) gravitational bound states can be formed in small fraction at freeze-in



➡ Unstable gravitational atoms will decay to gravitational waves (and SM sector w. similar branching ratios)

Gravitational atoms

- The Bohr-radius of two identical particles held together by a central inverse square law potential

$$V(r) = \alpha/r$$

is

$$r_B = (\mu\alpha)^{-1}$$

$\mu = m_1 m_2/(m_1 + m_2)$
is the reduced mass of the system

- For Gravitational atoms $(m_1 = m_2 \equiv m_X)$

$$\alpha_G = m_X^2/m_p^2 \qquad \mu = m_X/2$$

➡ Will not be disrupted by Hubble expansion if

$$m_X \gtrsim (H m_p^2)^{1/3}$$

Gravitational atoms

- Number density of gravitational atoms suppressed by $\sim \alpha_G^3$ relative to free PIDM particles

$$n_B = \alpha_G^3 \sqrt{\frac{\pi m_X^3}{T_{rh}^3}} n_X$$

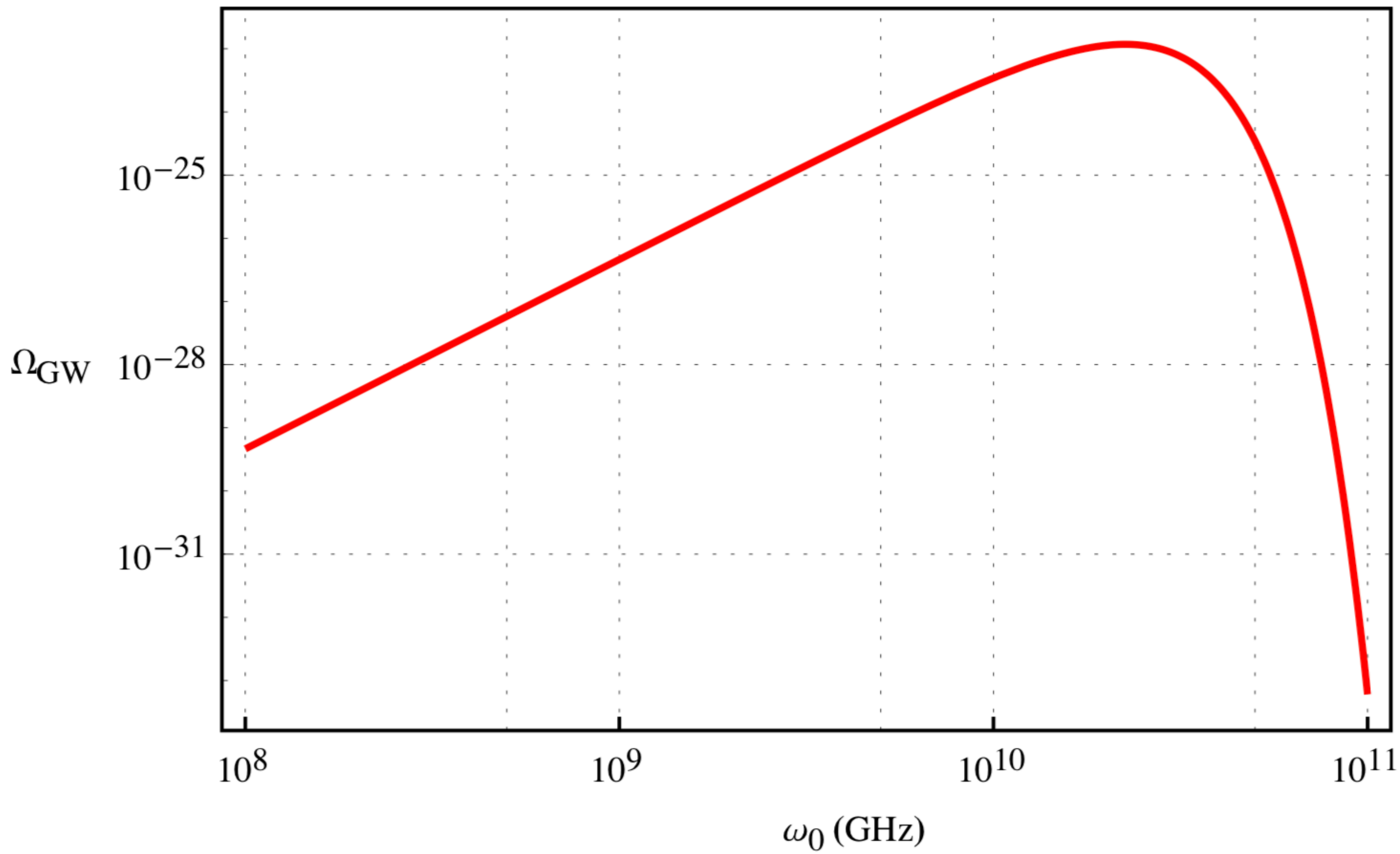
$n_X =$ dark matter abundance

- The decay rate can be computed similarly to bound state formation cross section

$$\Gamma_G = \frac{41 m_X}{128\pi^2} \left(\frac{m_X}{m_p}\right)^{10} \equiv \frac{41 \alpha_G^5 m_X}{128\pi^2}$$

Gravitational atoms

PIDM w. instant reheating (no early matter domination, minimal coupling)



$$T_{rh} \sim 10^{-3} m_p, \text{ and } m_X \sim 0.01 m_p.$$

[Nielsen, Palessandro, MSS 2019]

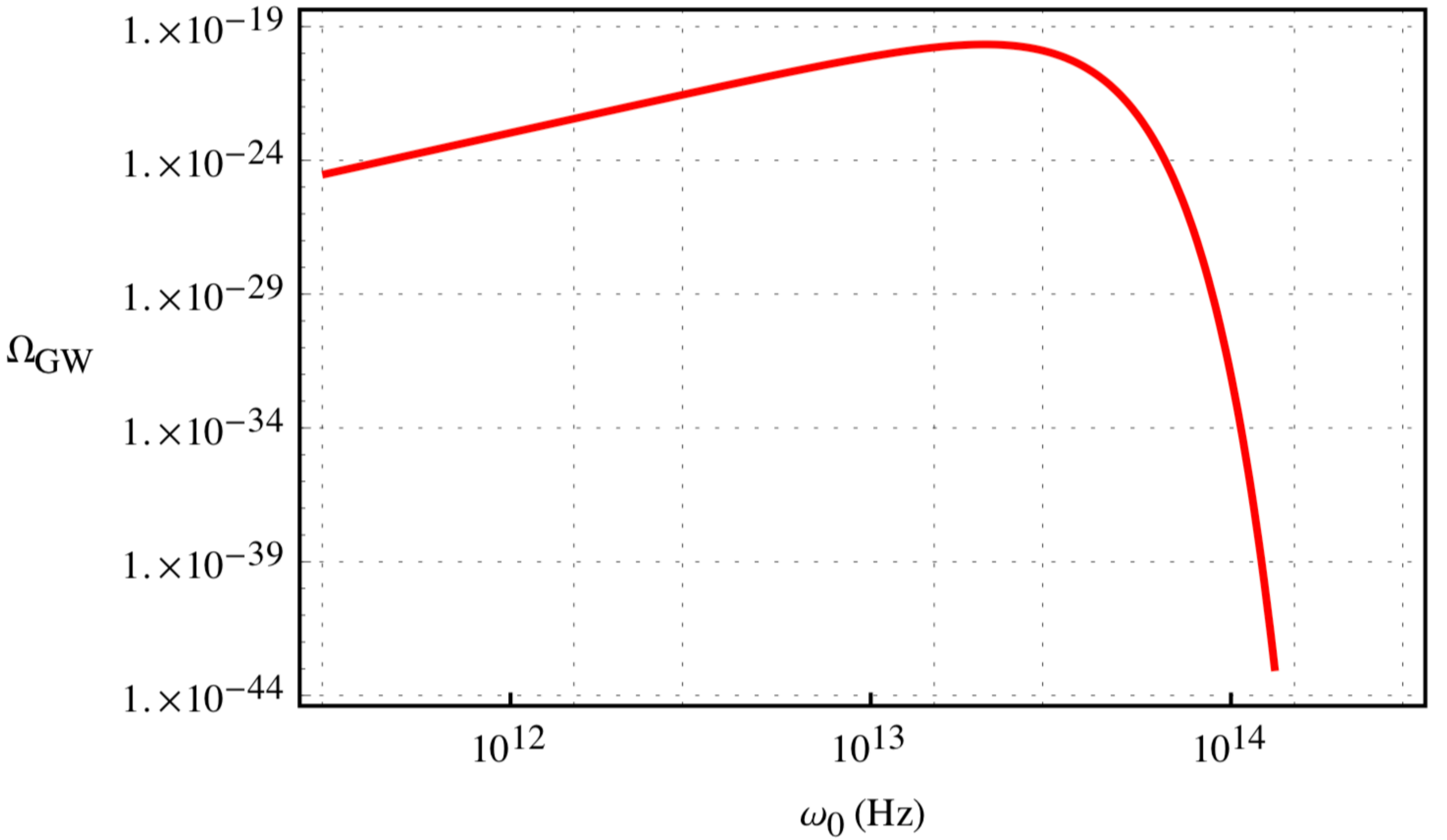
Gravitational atoms

- Minimal scenario extremely constrained with only one free parameter (PIDM mass)
- However sensitive to near Planckian modification of gravity and cosmology

➡ Non-minimal toy-models with larger/lower frequency gravitational wave signal

Gravitational atoms

PIDM w. non-minimal coupling $\mathcal{L}_{NM} = \frac{1}{2}\xi_X X^2 R$



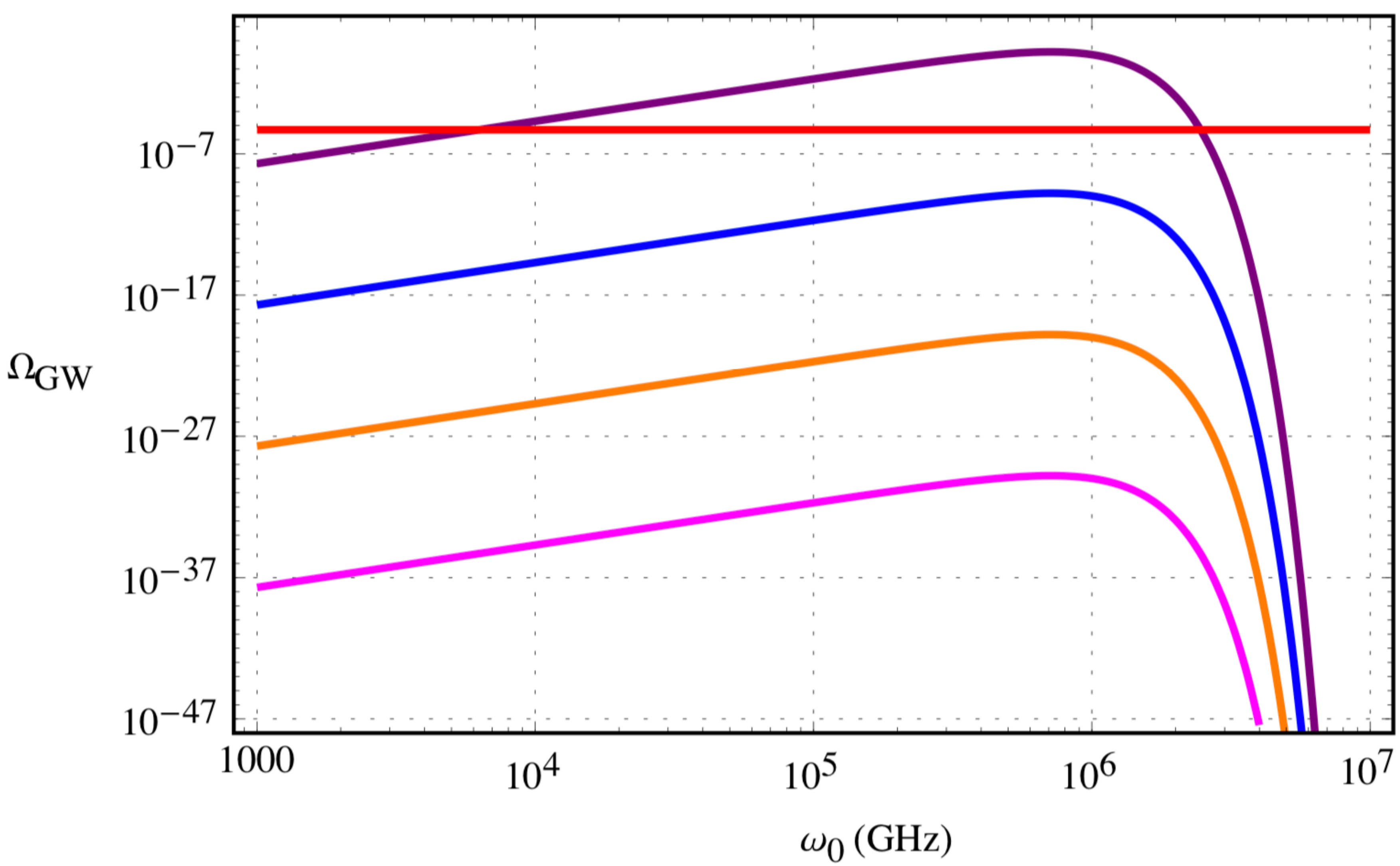
$T_{rh} \sim 10^{-3} m_p$, and $m_X \sim 0.01 m_p$.

$\xi_X \sim 100$

[Nielsen, Palessandro, MSS 2019]

Gravitational atoms

Other production mechanisms of bound states
(leaving initial bound state number density as free parameter)



$$T_{rh} \sim 10^{-3} m_p \quad m_X \sim 0.1 m_p \quad n_{B,i} = \alpha T_{rh}^3$$

$\alpha = 1$ (purple), $\alpha = 10^{-10}$ (blue), $\alpha = 10^{-20}$ (orange) [Nielsen, Palessandro, MSS 2019]

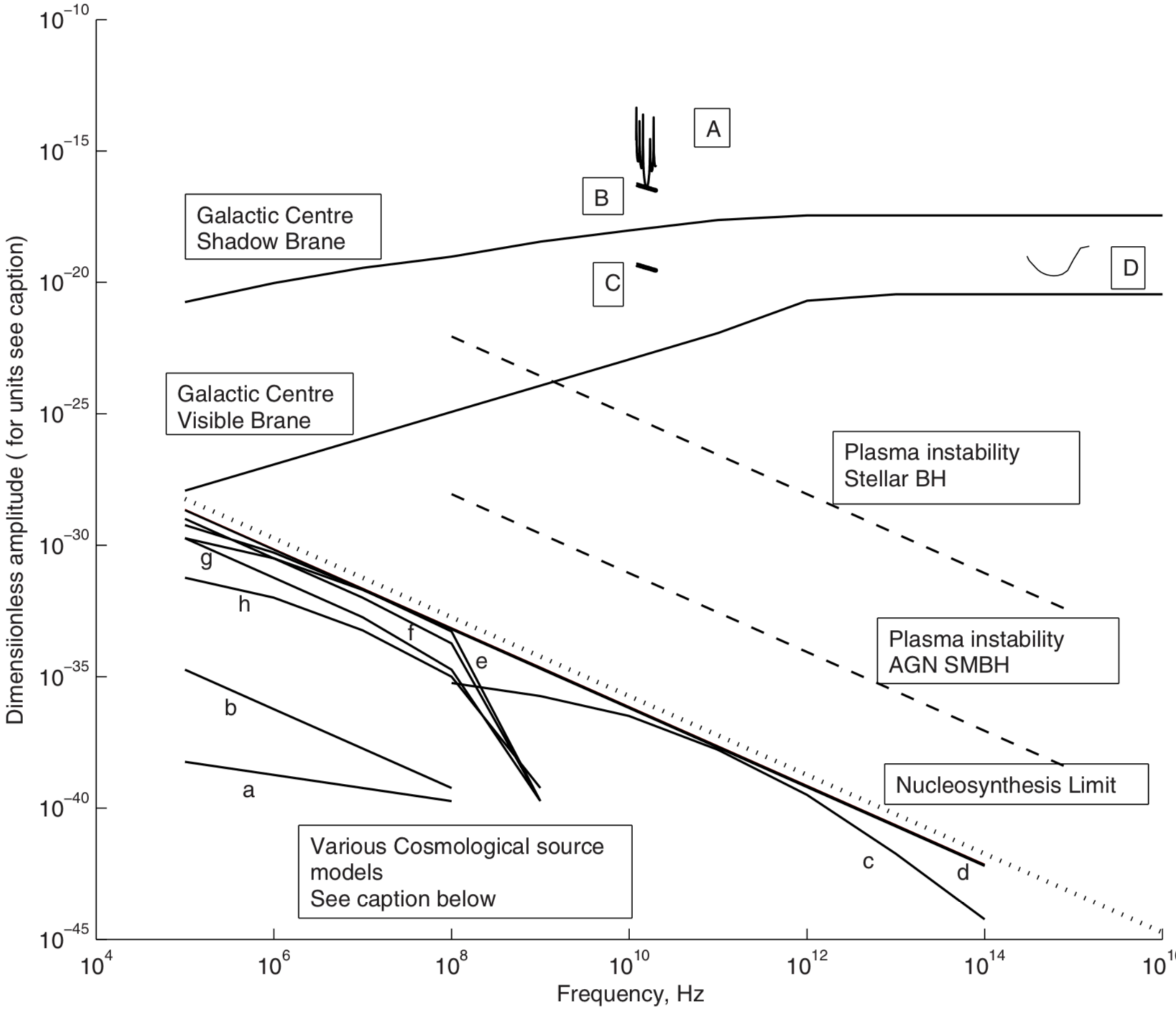
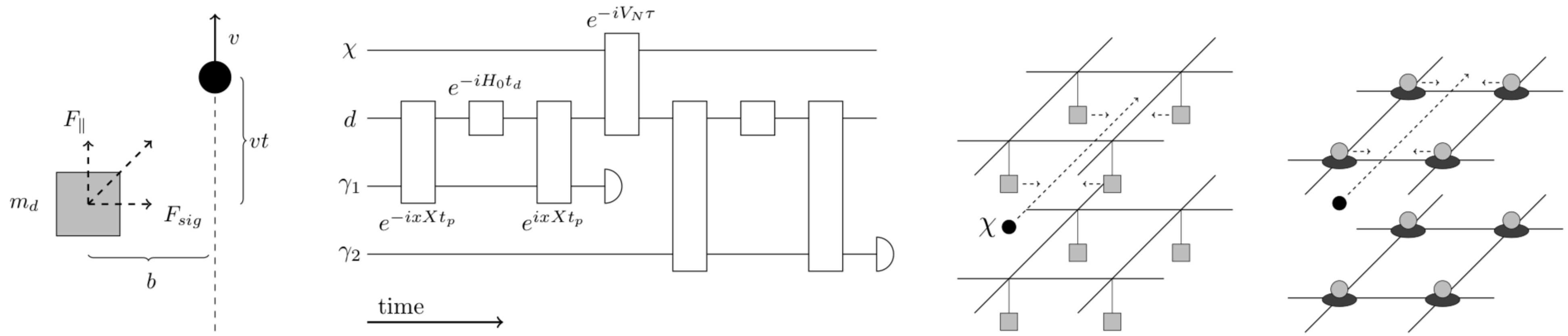


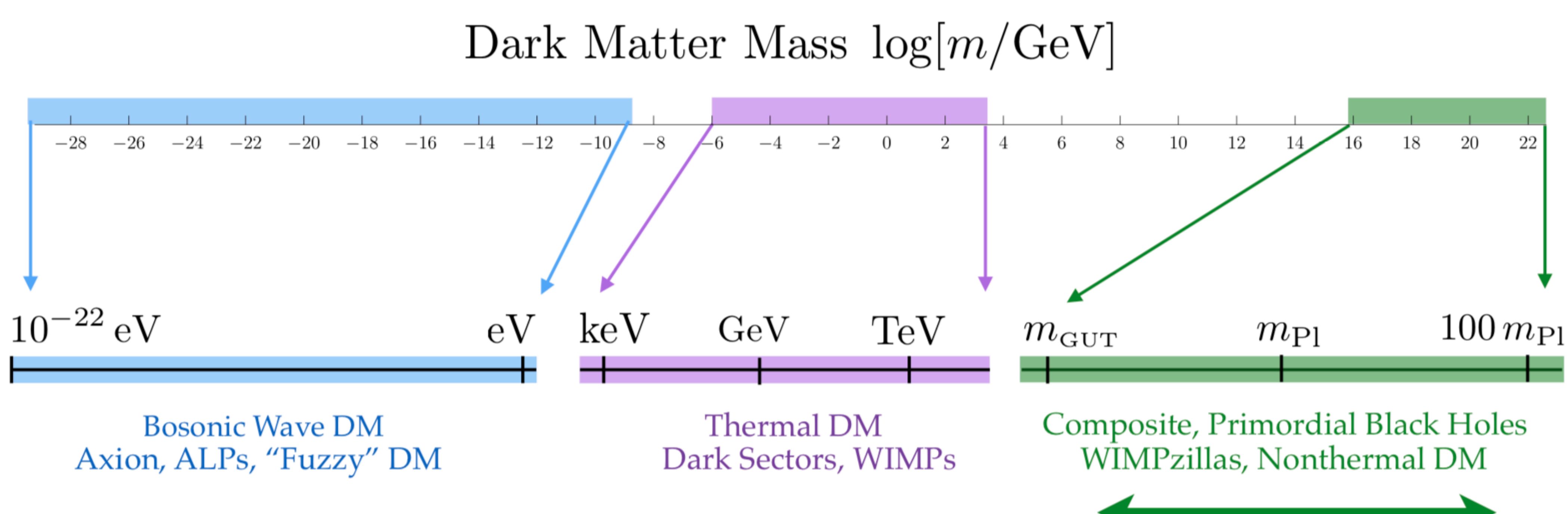
Figure 1. Signal amplitudes and sensitivities. Approximate dimensionless amplitudes expected in detectors with bandwidth approximately equal to the operating frequency from stochastic signal models and KK modes generated in the galactic centre branes. (*a*), (*b*) Copeland *et al*, (*c*), (*d*) Leblond *et al* for various string tensions, (*e*) Giovannini *et al*, (*f*) Veniziano *et al*, (*g*) Battye *et al* and (*h*) Bellido-Garcia *et al*. See referenced works for precise predictions and underlying

Direct PIDM detection?

Proposal to measure PIDM by displacement of test masses in array
[Carney, Gosh, Krnjaic and Taylor 2019]
(with their futuristic design order one detection per year)



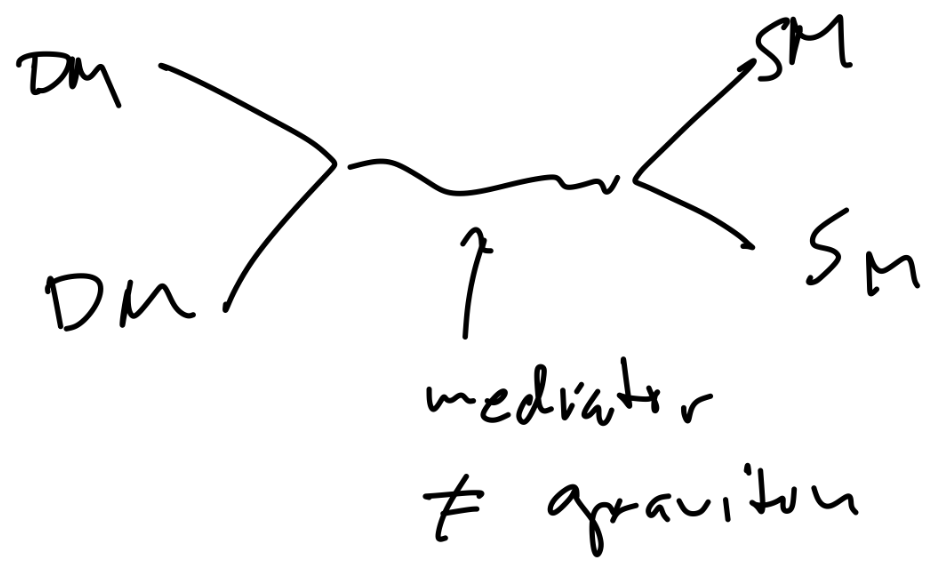
(figures from [Carney, Gosh, Krnjaic and Taylor 2019])



Beyond PIDM?

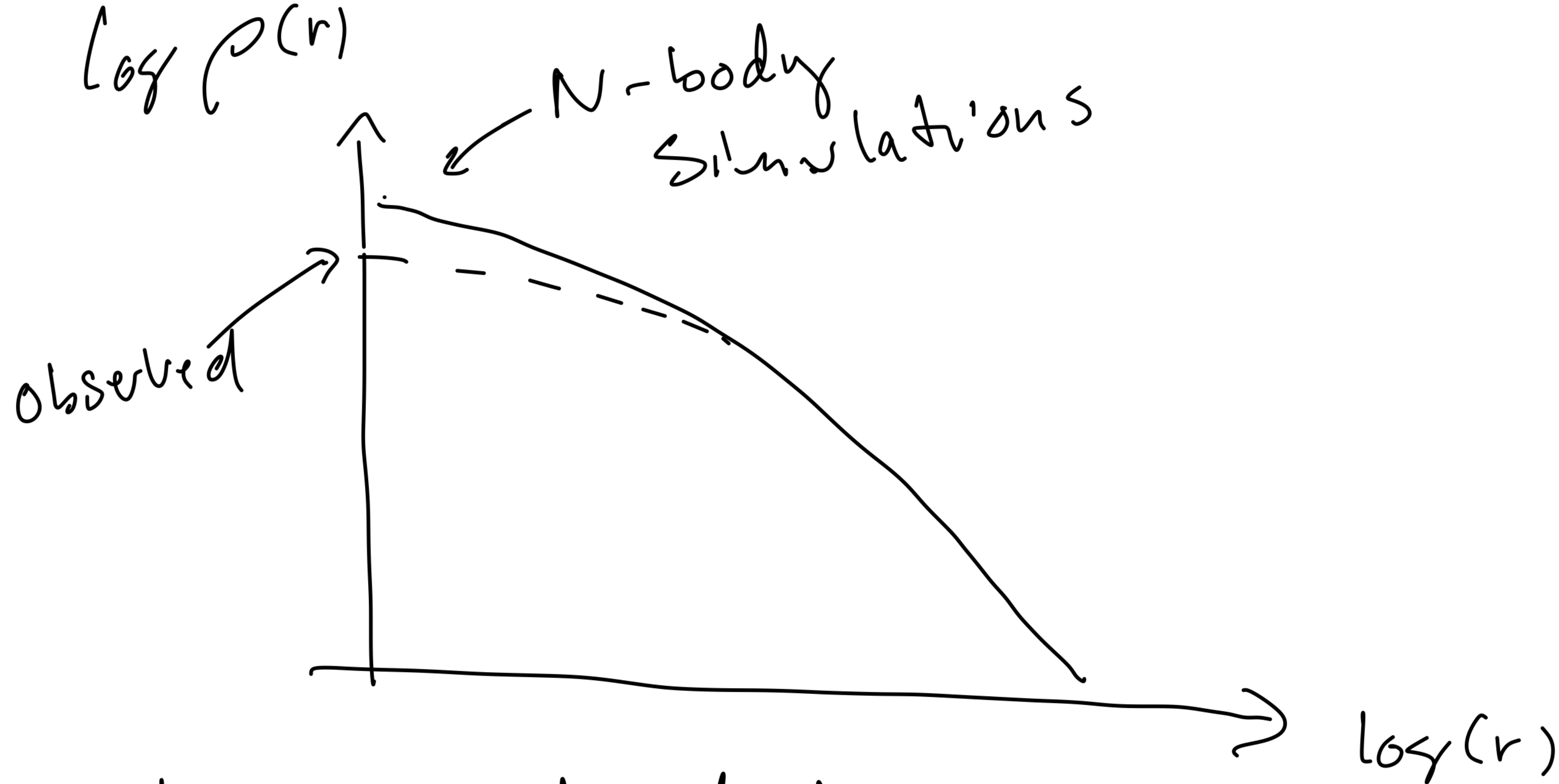
Stronger	X	X	MACHO
Weak	X	WIMP	WIMPZILLA
Super Weak	Axion/ Sterile	Gravitino/ FIMP	PIDM
	Super Light	Light	Heavy

- All these models has non-gravitational mediators



- Any evidence for interactions beyond gravitational ?

Core-Cusp problem



Could be explained by

- Baryonic feedback
- DM self-interactions

} neither requires non-gravitational SM-DM mediators

Charged PIMP

What about small scale problems of structure formation?

- Let the PIMP be a fermion charged under its own *U(1)*

$$\mathcal{L}_{DM} = -\frac{1}{4}V_{\mu\nu}V^{\mu\nu} + \bar{X}i\not{D}X - m_X\bar{X}X$$

$$D_\mu = \partial_\mu + ig_D V_\mu \qquad 4\pi\alpha_D \equiv g_D^2 \qquad V_{\mu\nu} \equiv \partial_\mu V_\nu - \partial_\nu V_\mu$$

- The charged PIMP might explain the small-scale structure tensions with CDM predictions with

$$m_X \sim 100\,\mathrm{GeV} \qquad \alpha_D \sim 10^{-2}$$

- Can be discriminated from other “hidden charged dark matter due to different thermal leading to a different N_{eff}
- Thermalization in dark sector reduces sensitivity on reheat temp.

[Garny, Palessandro, Sandora, MSS, 2018]

Conclusions

- Dark Matter requires only gravitational interactions
- PIMP is a one parameter model of DM
- The minimal model connects with Planck/GUT scale physics
- Unlike axion in anthropic window, it requires observable tensors in the minimal paradigm

- Interesting phenomenology :
  - ★ Connection with inflation models in particular preheat/reheating part
  - ★ Explicit models
  - ★ Non-Perturbative instanton induced decay
  - ★ Properties of structure formation
  - ★ Gravitational atoms
  - ★ Direct detection?