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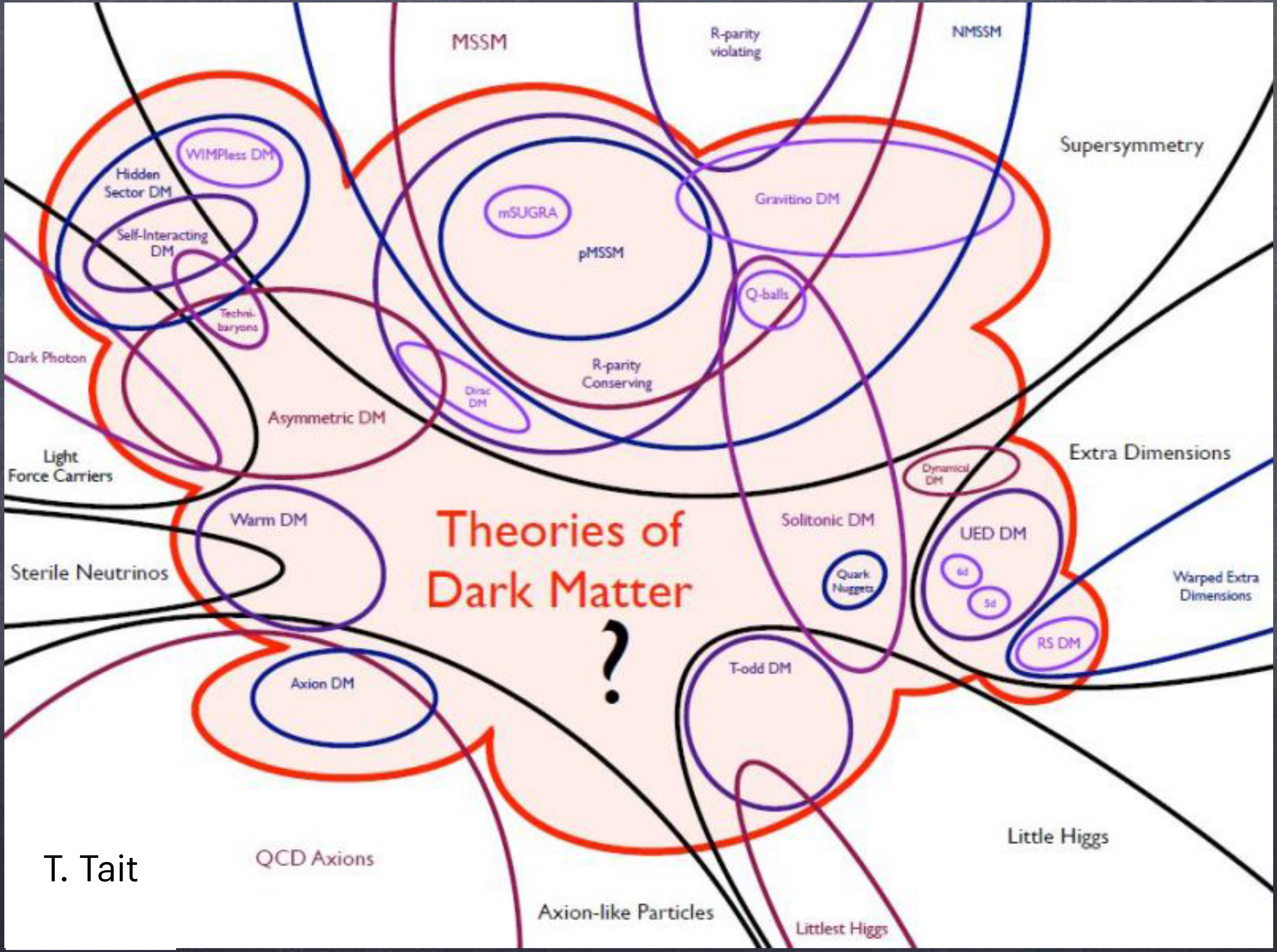
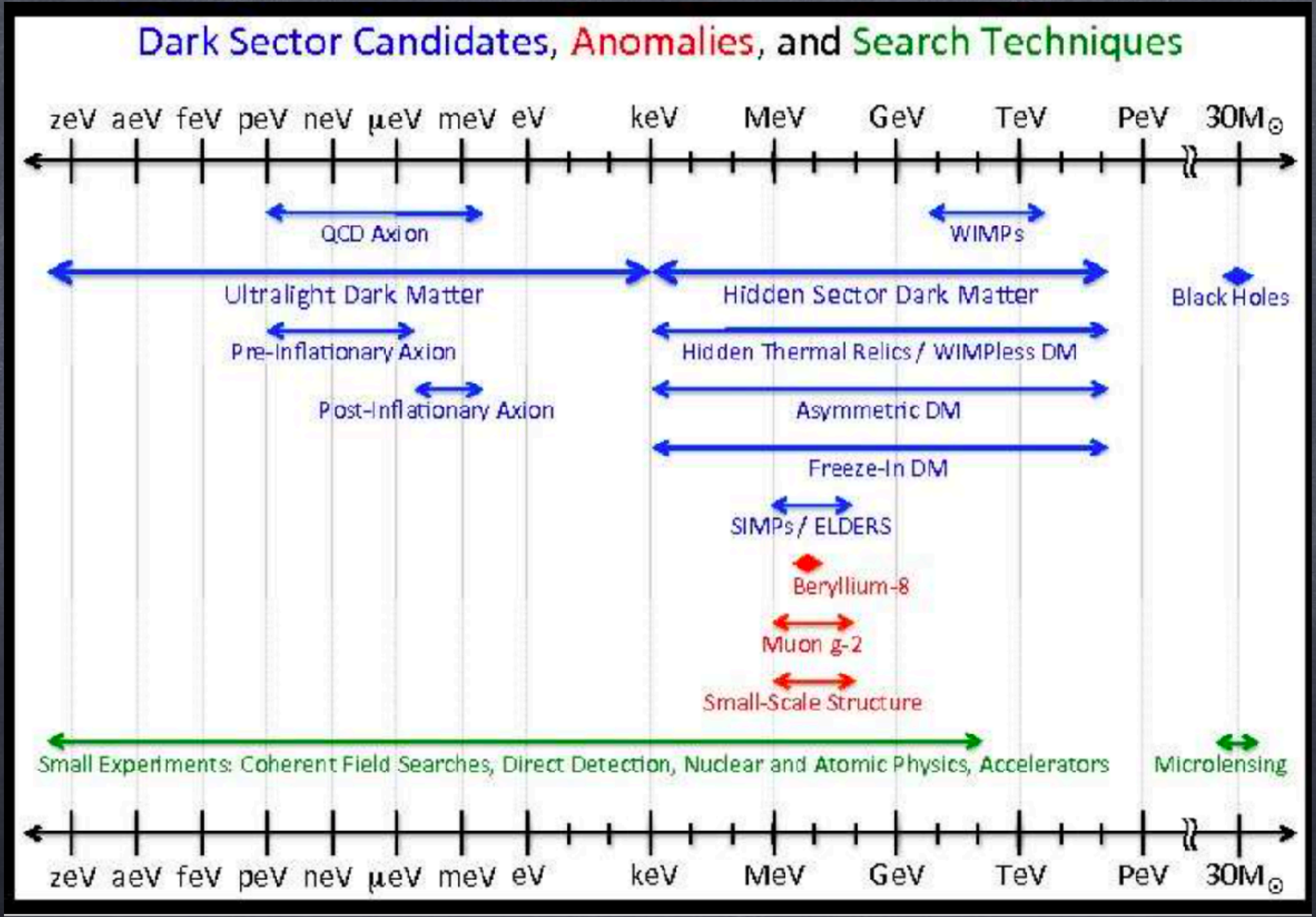
Massive gravitons as Feebly interacting Dark Matter Candidates

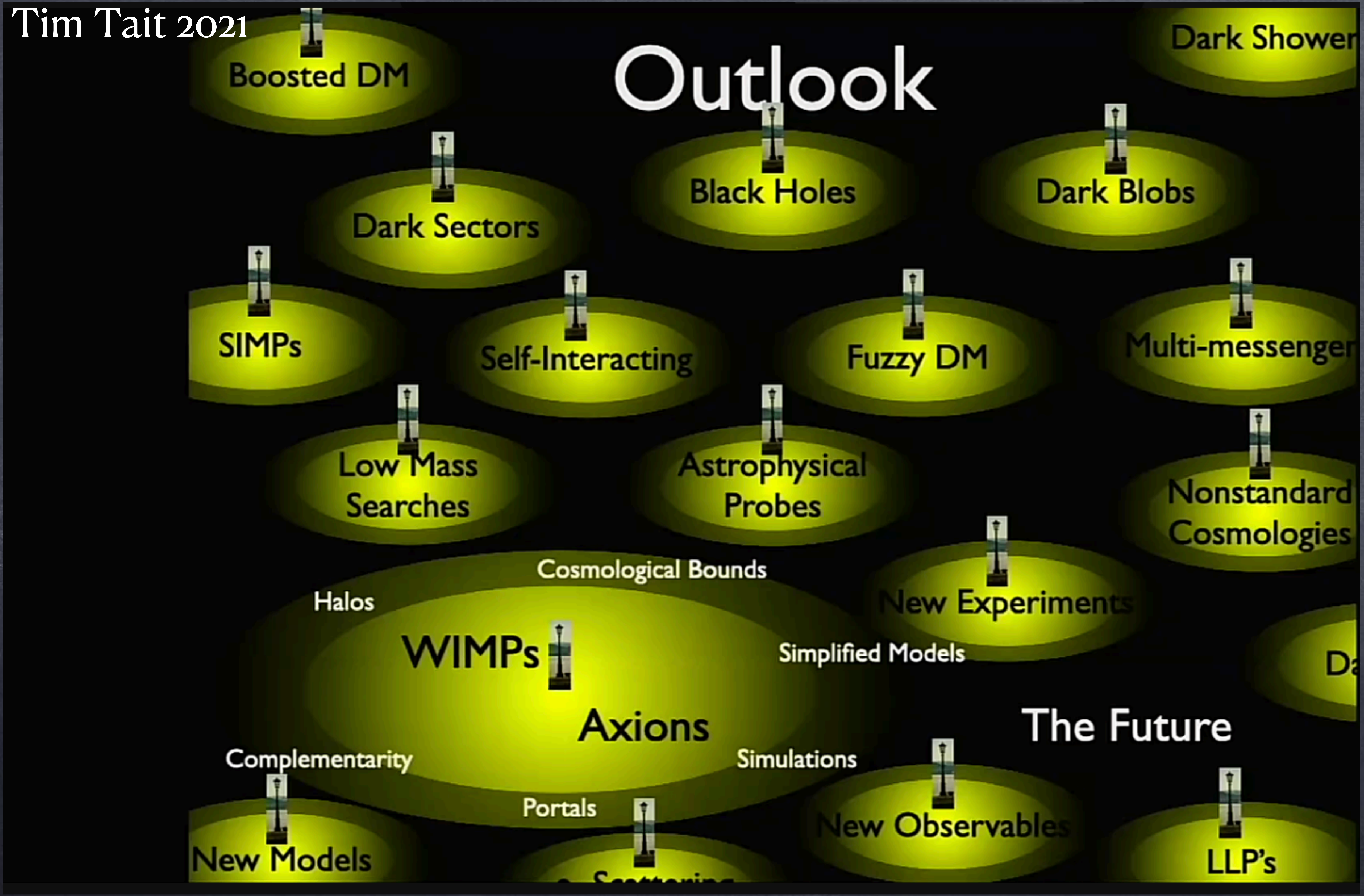
Outlook



Theories of Dark Matter
?
MSSM
R-parity violating
NMSSM
Supersymmetry
WIMPless DM
Hidden Sector DM
Self-Interacting DM
Techni-baryons
mSUGRA
pMSSM
Gravitino DM
Q-balls
R-parity Conserving
Dirac DM
Dark Photon
Asymmetric DM
Light Force Carriers
Extra Dimensions
Dynamical DM
UED DM
6d
5d
RS DM
Warped Extra Dimensions
Warm DM
Sterile Neutrinos
Solitonic DM
Quark Nuggets
Axion DM
T-odd DM
Little Higgs
T. Tait
QCD Axions
Axion-like Particles
Littlest Higgs

Outlook

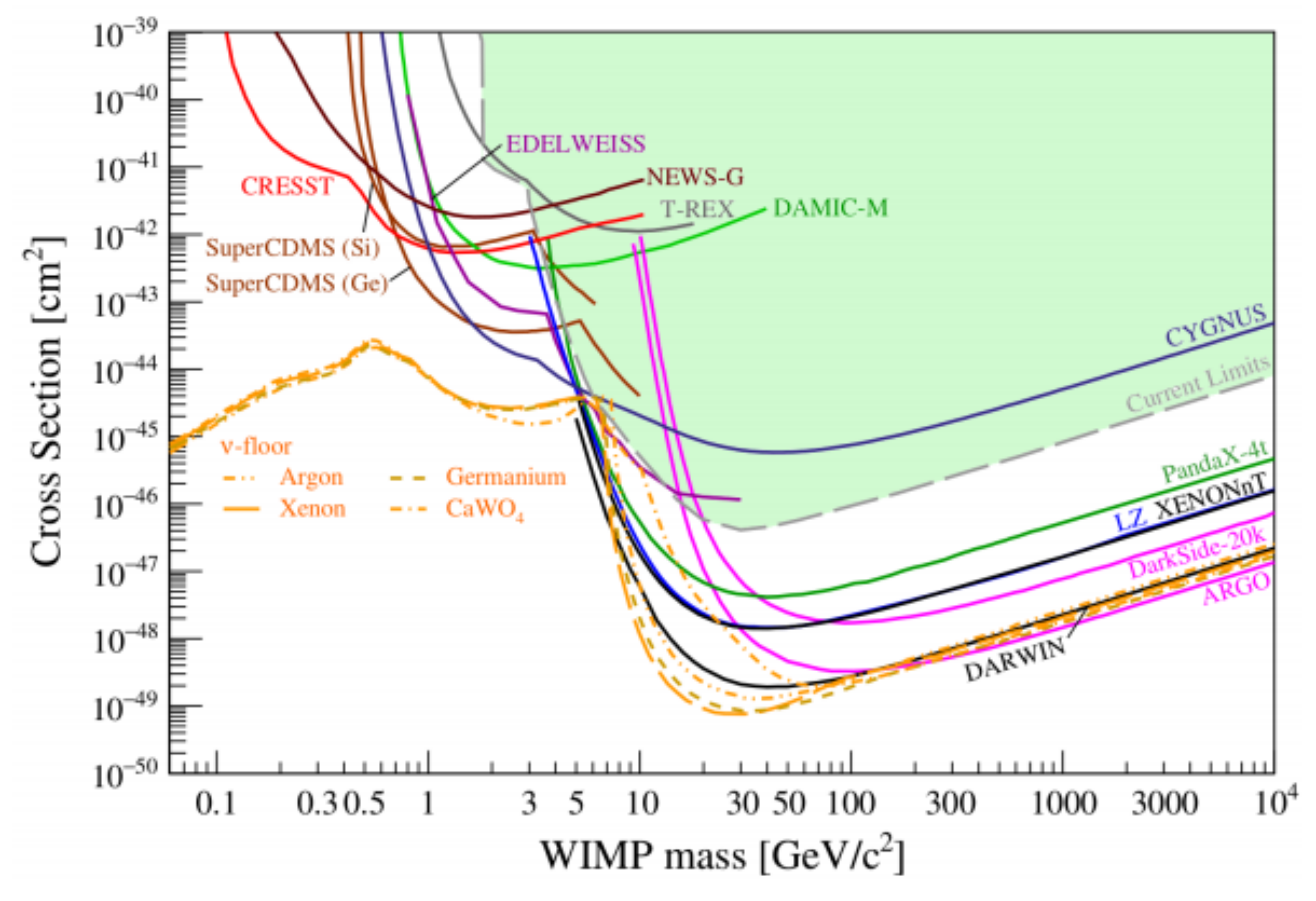

Dark Sector Candidates, Anomalies, and Search Techniques
zeV aeV feV peV neV μeV meV eV keV MeV GeV TeV PeV 30M⊙
QCD Axion
WIMPs
Ultralight Dark Matter
Hidden Sector Dark Matter
Black Holes
Pre-Inflationary Axion
Hidden Thermal Relics / WIMPless DM
Post-Inflationary Axion
Asymmetric DM
Freeze-In DM
SIMPs / ELDERS
Beryllium-8
Muon g-2
Small-Scale Structure
Small Experiments: Coherent Field Searches, Direct Detection, Nuclear and Atomic Physics, Accelerators
Microlensing
zeV aeV feV peV neV μeV meV eV keV MeV GeV TeV PeV 30M⊙



Tim Tait 2021
Outlook
Boosted DM
Dark Shower
Dark Sectors
Black Holes
Dark Blobs
SIMPs
Self-Interacting
Fuzzy DM
Multi-messenger
Low Mass Searches
Astrophysical Probes
Nonstandard Cosmologies
Cosmological Bounds
Halos
New Experiments
WIMPs
Simplified Models
Axions
The Future
Complementarity
Simulations
Portals
New Observables
New Models
LLP's

Dark Matter: where are we?

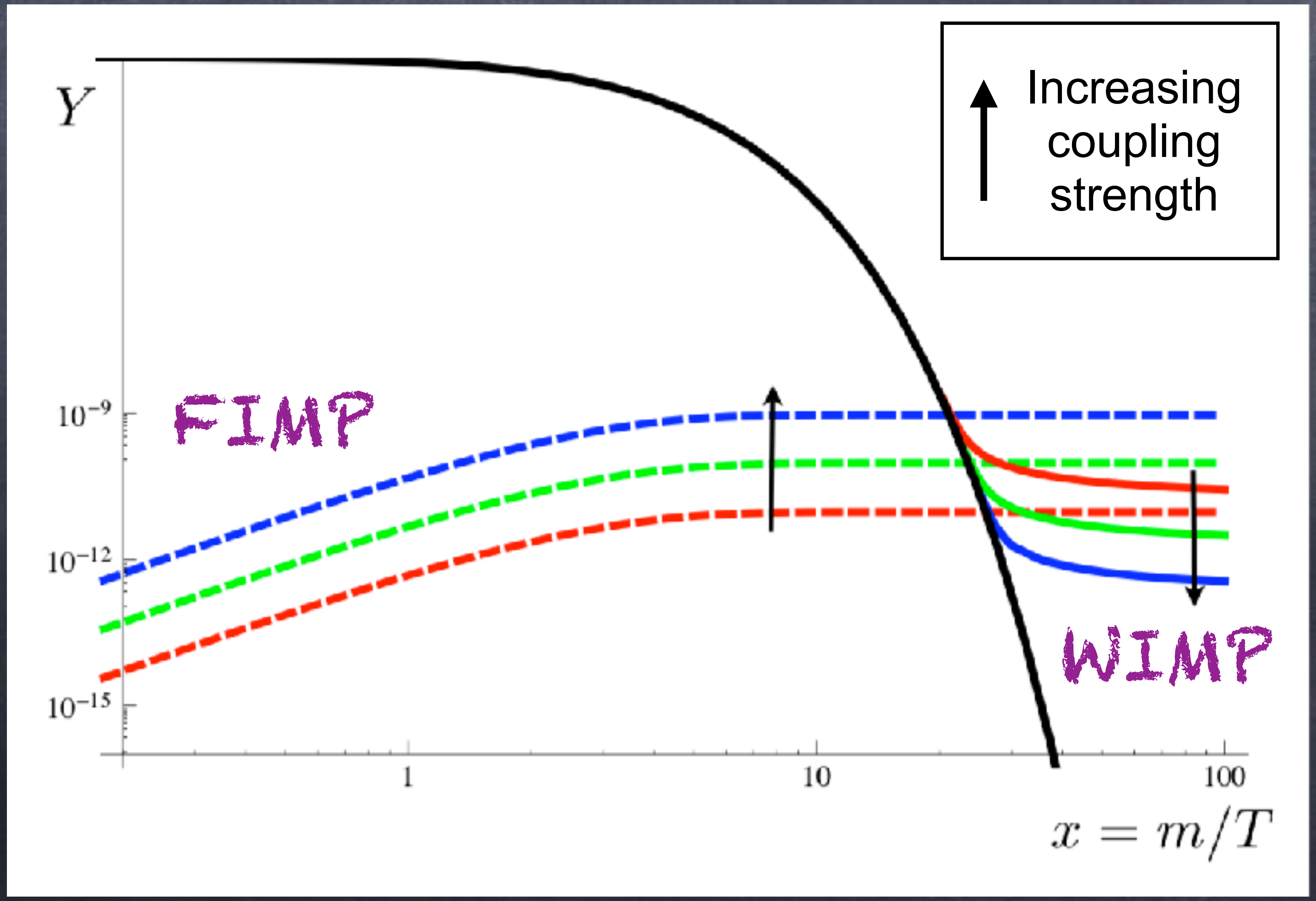
- Strong constraints from Direct Detection:



From the APPEC DM report

FIMPs

- Very weak interactions avoid detection bounds
- Produced non-thermally via scattering or decays.



Renormalisable int.:
IR dominated!

$$\mathcal{A} \sim g^2$$

Non-renorm. int.:
UV dominated!

$$\mathcal{A} \sim \frac{1}{\Lambda^2} s$$

Gravity-interacting massive particles as FIMPs?

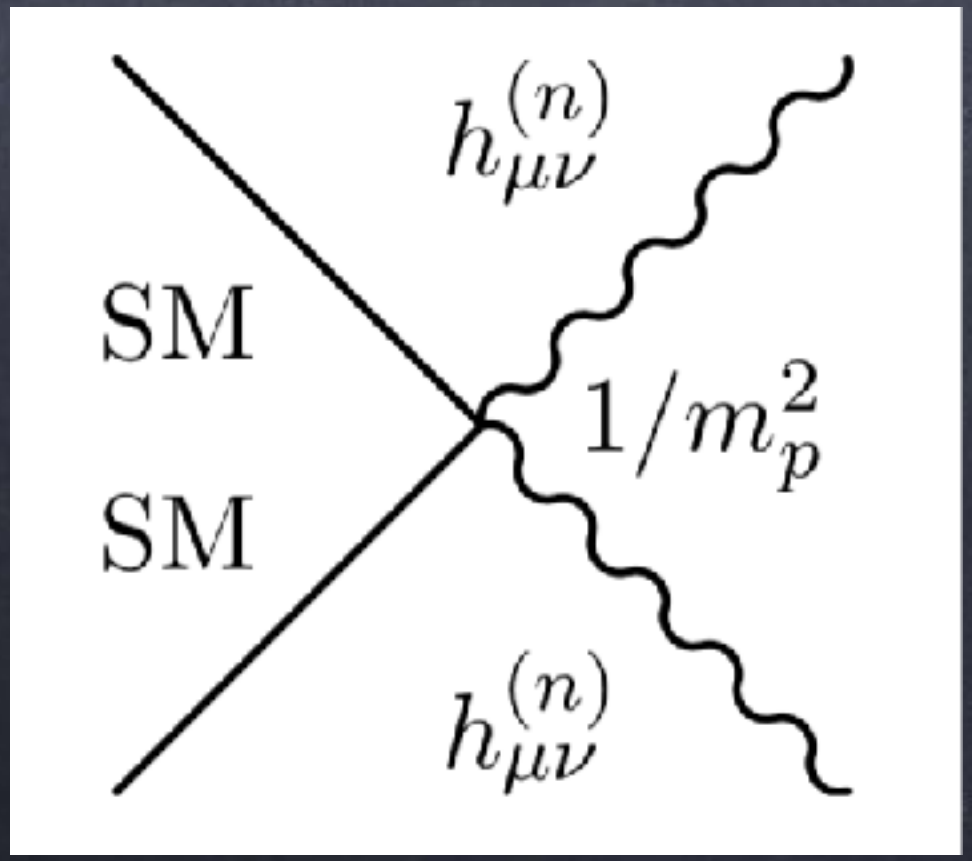
$$\mathcal{L}_{eff} = C_H \, G^{\mu\nu}_{(n)} \; T^{\rm SM}_{\mu\nu} \qquad C_H \sim \frac{1}{M_{\rm Pl}}$$

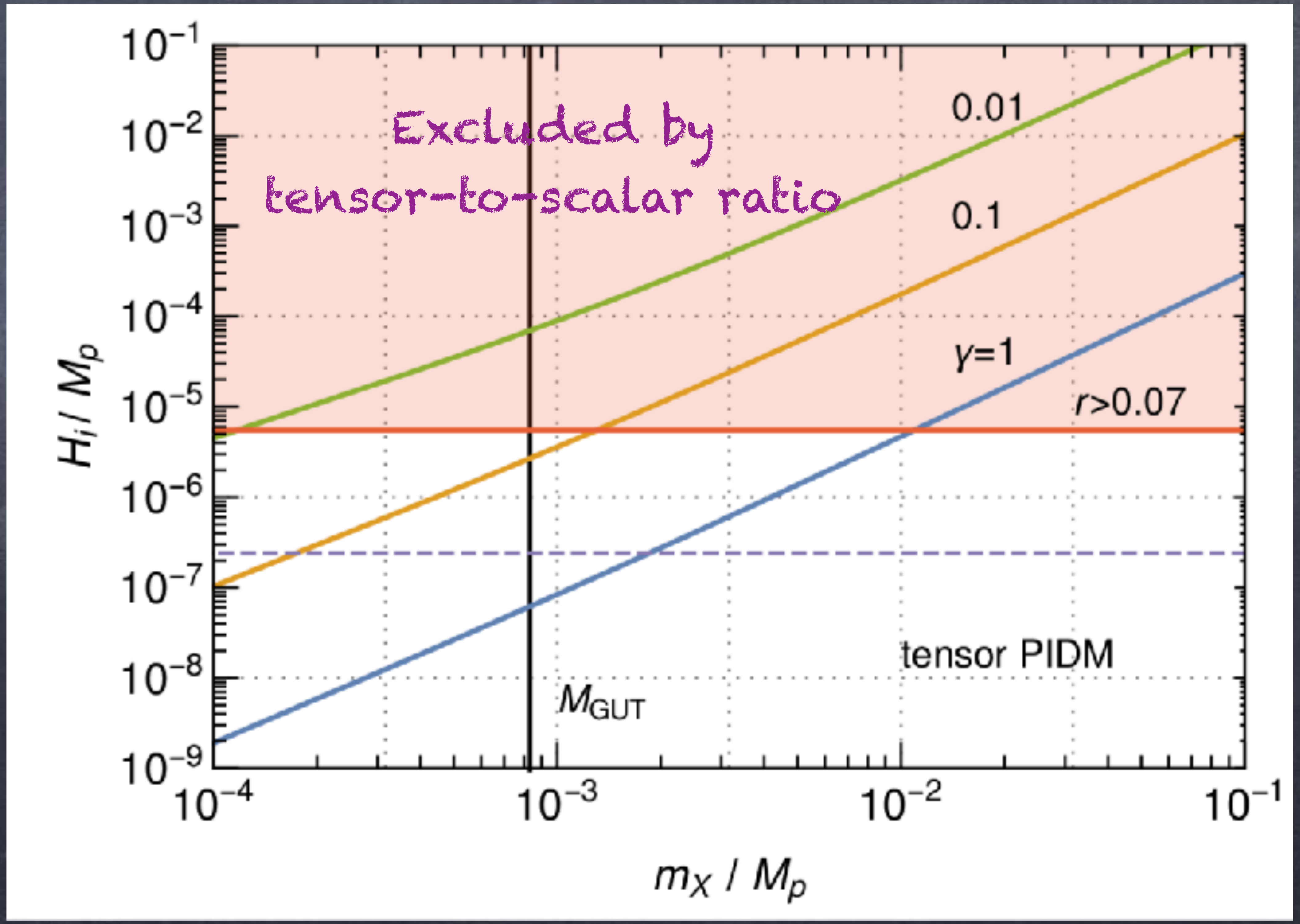
- The freeze-in process will be inevitably UV dominated, hence depend crucially on the reheating temperature.
- The coupling is very weak -> (very) large masses required!

Gravity-interacting massive particles as FIMPs?

$$\mathcal{L}_{eff} = C_H \, G^{\mu\nu}_{(n)} \, T^{\rm SM}_{\mu\nu} \qquad C_H \sim \frac{1}{M_{\rm Pl}}$$

KK gravitons from a flat Xdim (stable by KK parity)





M.Sloth et al, 1709.09688

Chiral enhancement on the rescue

- What happens for light gravitons?
- We consider a general case, one massive graviton and no parity.

$$\mathcal{L}_{eff} = C_H \, G^{\mu\nu}_{(n)} \, T^{\rm SM}_{\mu\nu} \qquad C_H \sim \frac{1}{M_{\rm Pl}}$$

- Let's consider the process: $q + \bar{q} \to \text{gluon} + G$

For massless fermion:

$$\mathcal{A}^0_{\bar{q}q} = \frac{128\pi}{3} C_H^2 g_s^2 s$$

(in line with the naive expectation)

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For massive fermion:

$$\mathcal{A}_{\bar{q}q} = \frac{256\pi C_H^2 g_s^2 m_q^2 s\left(s + 2m_q^2\right)}{9M_G^4}$$

(applies below the EW phase transition)

Chiral enhancement on the rescue

For massive fermion:

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Huge enhancement!

$$\longrightarrow \left(\frac{m_b}{M_G \sim 2\ \text{MeV}}\right)^4 \sim 10^{12}$$

- Easy to understand: it comes from the longitudinal mode of the massive graviton

Sum over graviton polarisations:

$$P_{\mu\nu,\alpha\beta} = \frac{1}{2}\left(P_{\mu\alpha}P_{\nu\beta} + P_{\nu\alpha}P_{\mu\beta} - \frac{2}{3}P_{\mu\nu}P_{\alpha\beta}\right),$$

$$P_{\mu\nu} = \eta_{\mu\nu} - \frac{k_\mu k_\nu}{M_G^2}$$

$$M \sim \frac{m_q^2}{M_G^2}$$

Chiral enhancement on the rescue

For massive fermion:

$$\mathcal{A}_{\bar{q}q} = \frac{256\pi C_H^2 g_s^2 m_q^2 s\left(s+2m_q^2\right)}{9M_G^4}$$

$$\mathcal{A}_{qg} = \mathcal{A}_{\bar{q}g} = \frac{256\pi C_H^2 g_s^2 m_q^2 \left(s-m_q^2\right)^2\left(s+m_q^2\right)}{3sM_G^4}$$

Huge enhancement!

$$\longrightarrow \left(\frac{m_b}{M_G \sim 2\ \mathrm{MeV}}\right)^4 \sim 10^{12}$$

Similar processes with the photon smaller by the electromagnetic coupling.
Heavier quarks contribute: bottom and charm.
(the top is not in thermal equilibrium)

Chiral enhancement on the rescue

- Computing the relic density

$$\mathcal{A}_{\bar{q}q} = \frac{256\pi C_H^2 g_s^2 m_q^2 s\,(s+2m_q^2)}{9M_G^4}$$

$$Y_{\rm IR} \simeq \frac{1}{2048\pi^6}\int_{T_{QCD}}^{T_C}\frac{dT}{SH}\left(\int_{4m_q^2}^{\infty} ds(s-4m_q^2)^{1/2}A_{\bar{q}q}\right.$$
$$\left. K_1\left(\frac{\sqrt{s}}{T}\right) + 2\int_{m_q^2}^{\infty} ds\frac{(s-m_q^2)^2}{s^{3/2}}A_{qg}K_1\left(\frac{\sqrt{s}}{T}\right)\right), \quad (8)$$

Integral starts at the EW phase transition temperature!

Numerically:

$$\Omega_{\rm IR}h^2 = \frac{M_G}{3.6\times10^{-9}\ \text{GeV}}Y_{\rm IR}$$
$$\simeq 3.0\times10^{31}\ \text{GeV}^5\ \frac{C_H^2}{M_G^3}$$

For Planck couplings,
this indicates MeV graviton mass.

This is not the end of the game...

- The graviton can decay:

For MeV masses: $$\Gamma(G \to e^+e^- + \nu_i\bar{\nu}_i + \gamma\gamma) \simeq \frac{9C_H^2 M_G^3}{320\pi}$$

- Lifetime bounded by CMB and indirect detection:

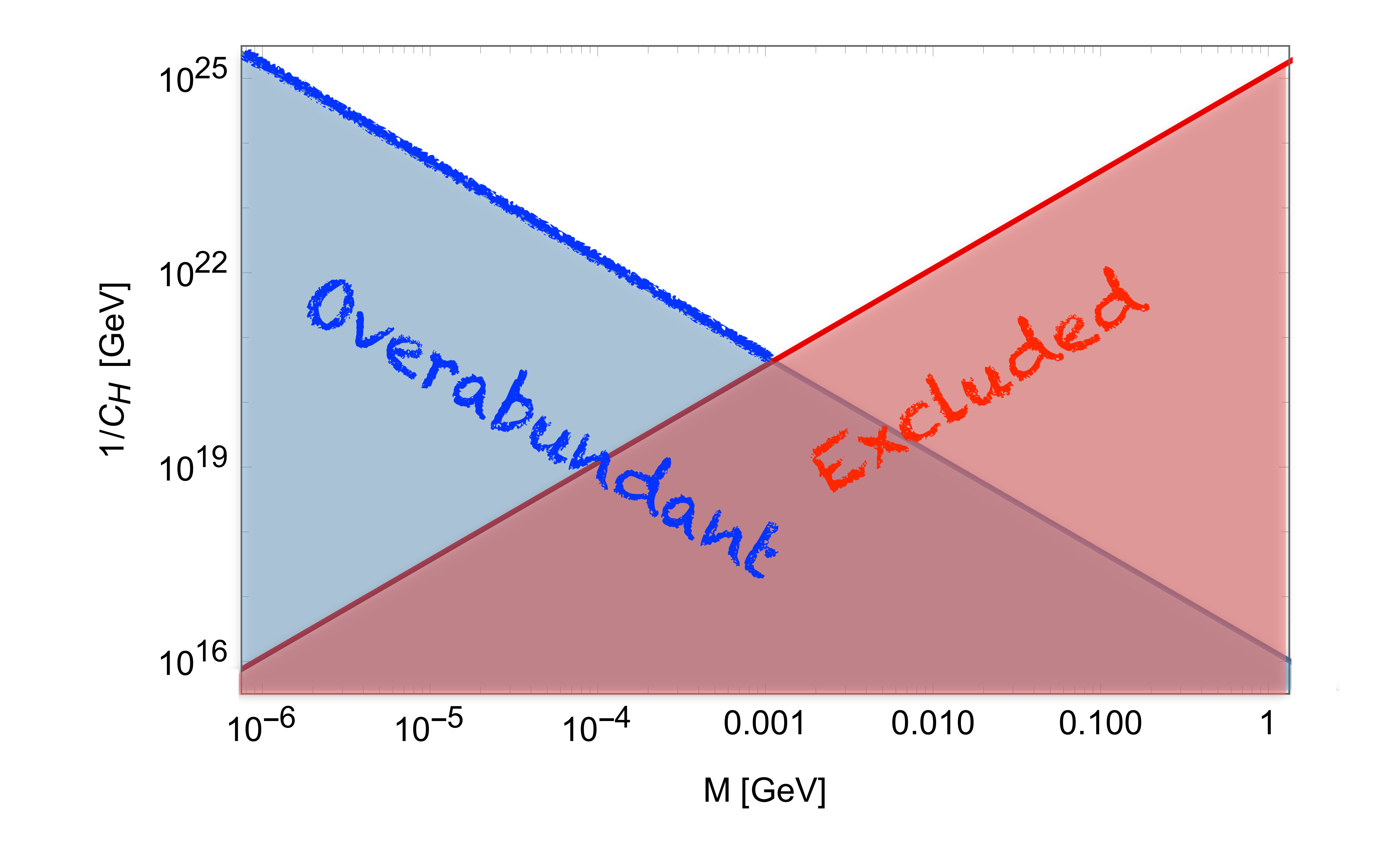
$$\tau_G > 10^{27}\ \text{sec}$$

1309.4091, 1610.10051

- Hence:

$$\Omega_{\rm IR}h^2 \lesssim 0.12 \times \left(\frac{1.6\ \text{MeV}}{M_G}\right)^6 \frac{10^{27}\ \text{Sec}}{\tau_G}$$

This is not the end of the game...



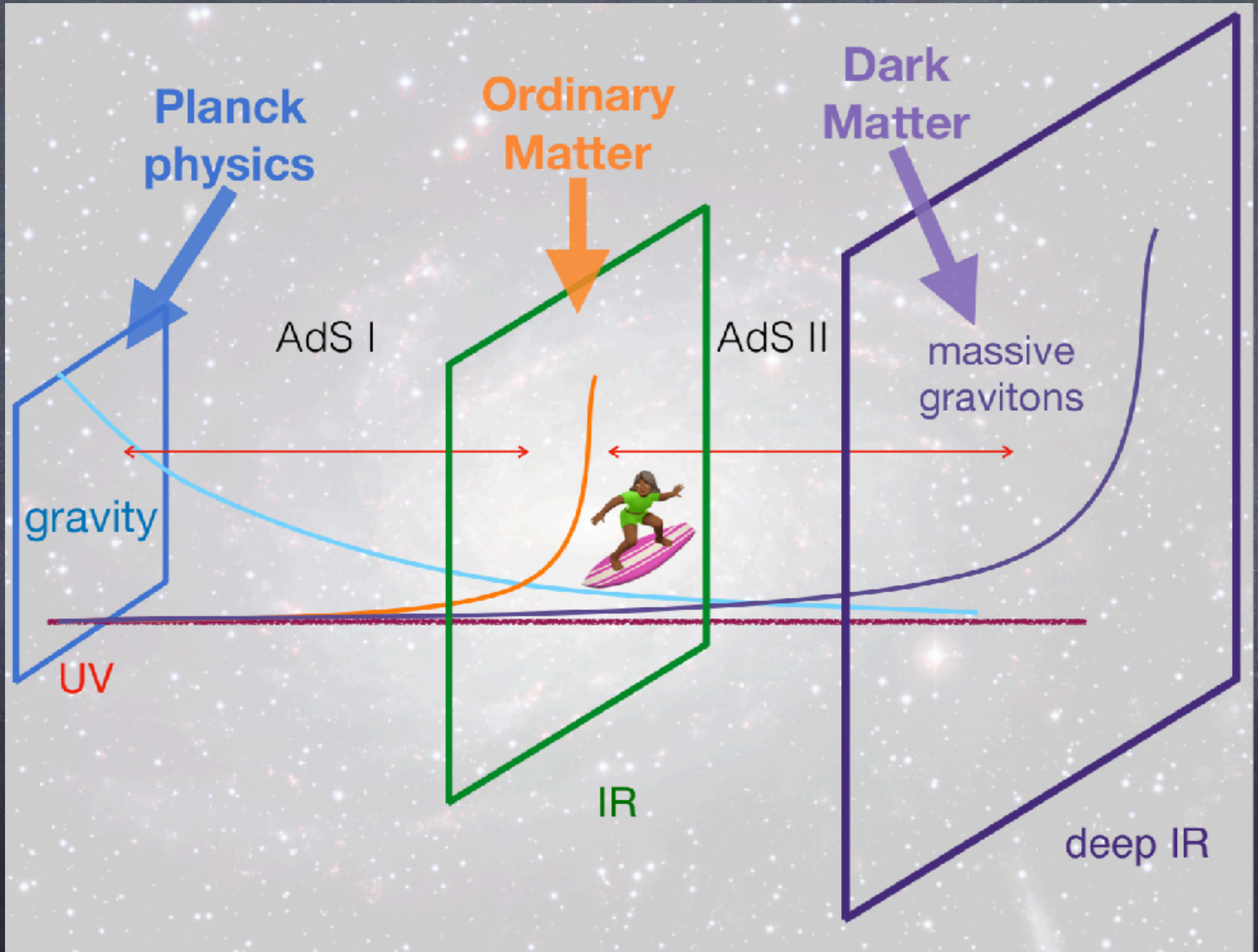
$$\Omega_{\rm IR} h^2 \lesssim 0.12 \times \left(\frac{1.6\ \rm MeV}{M_G}\right)^6 \frac{10^{27}\ \rm Sec}{\tau_G}$$

Summary so far:

- We discovered a chiral enhancement in processes involving SM fermions (and one massless gauge boson).
- The FIMP relic becomes IR-dominated, even though generated via non-renorm interactions.
- A massive graviton below 1.6 MeV can saturate the DM relic density.
- Can we embed this graviton in a complete model?

Example: three-brane warped extra dimension

Agashe et al, 1608.00526
Lee et al, 2109.10938



Warped extra dimension model

Here enters the radion

- The theory features many KK massive gravitons. Hence multi-component DM may be allowed.

- A light radion r is also present:

$$\mathcal{L}_{eff} = C_H \sum_i G^{(n)\mu\nu} T^i_{\mu\nu} + d_V \, r V_{\mu\nu} V^{\mu\nu} + C_r \left(2 G^{(n)\mu\nu} G^0_{\mu\nu} - G^{(n)\mu}_{\mu} G^{0\nu}_{\nu} \right) \Box r + C_Q \mathcal{Q}(G^3, G^2 r, G r^2, r^3) \,,$$

$$C_H = \frac{1}{\Lambda_H} \frac{x_n^2}{4\sqrt{2} \; J_2(x_n)} \,, \qquad C_r = \frac{1}{M_{pl}} \frac{\sqrt{6}(1 - J_0(x_n))}{x_n^2 J_2(x_n)} \,,$$

$$C_H \sim C_r \sim \frac{1}{M_{\rm Pl}} \qquad\qquad C_Q \sim \frac{1}{\Lambda_{IR}} \gg \frac{1}{M_{\rm Pl}}$$

Here enters the radion

- Lifetime of the KK gravitons:

1) $2m_r < M_{G1}$

Prompt decays of KK gravitons in radions.

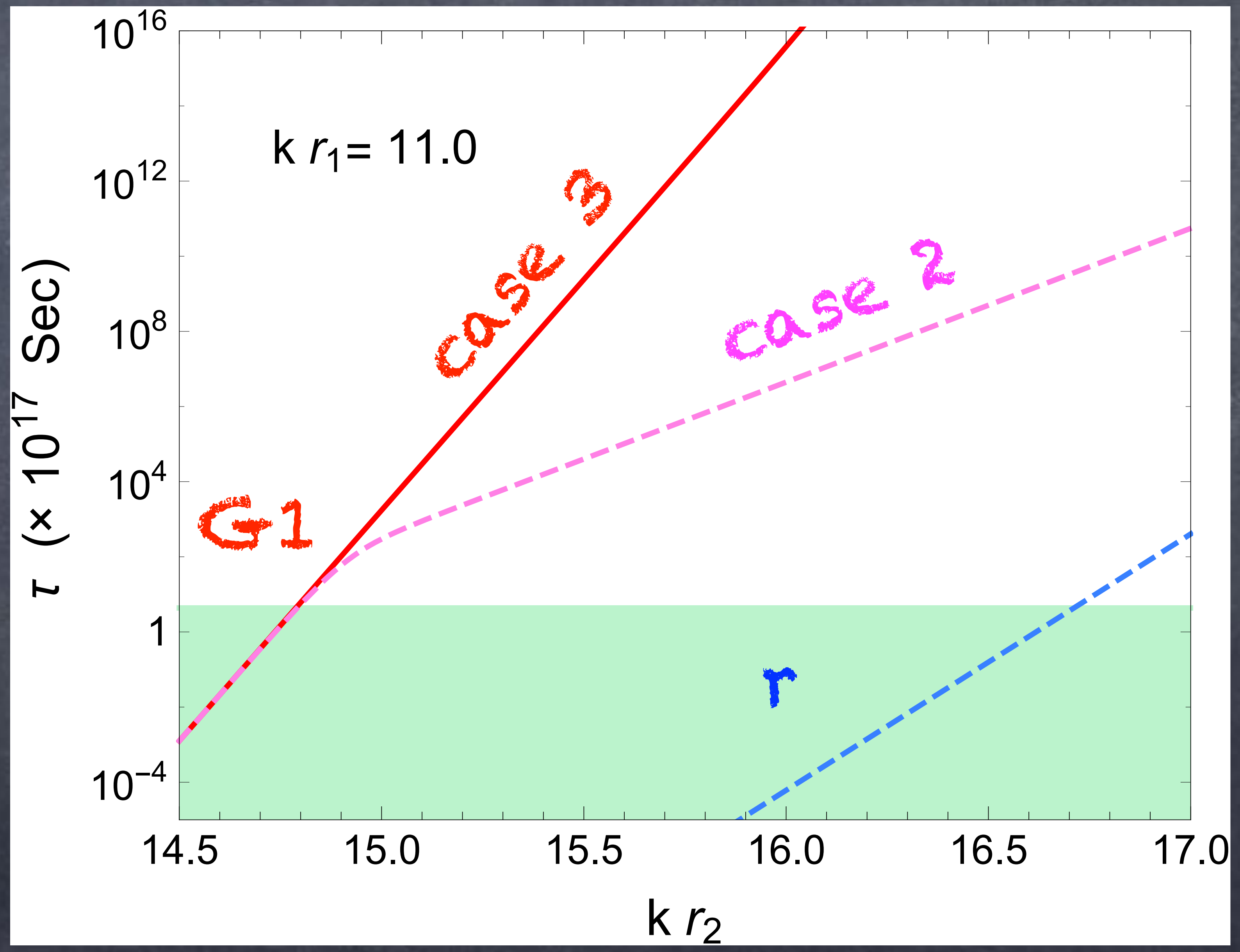
2) $M_{G1} < 2m_r < M_{G2}$

$G_1 \to G_0 + r$ Planck-suppressed

$G_2 \to 2r$ Prompt

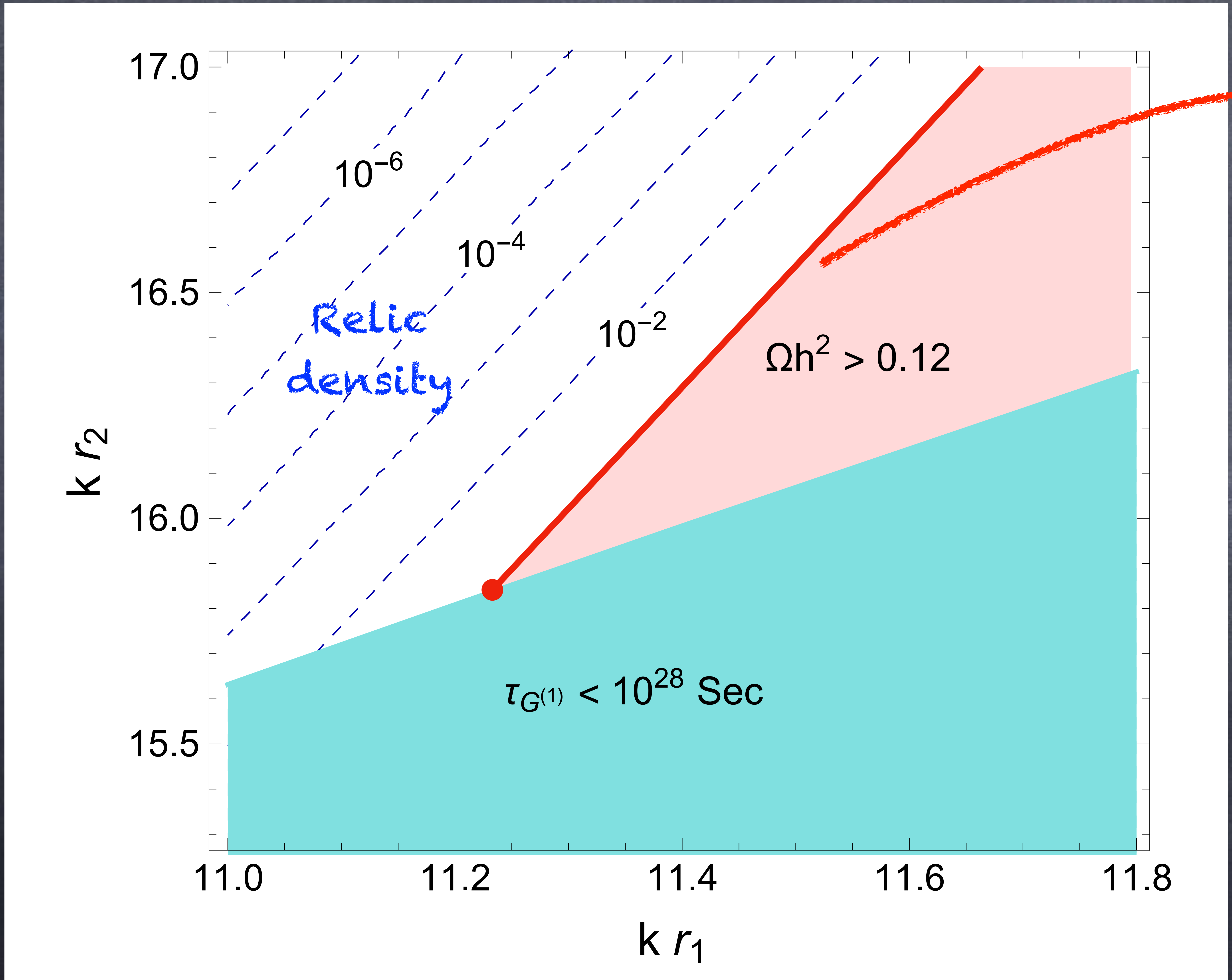
3) $2m_r > M_{G2}$

$G_{3+} \to 2G_1$ while G2 stable



Case 3 is safer, as it leads to longer lifetimes for G1.
G2 remains also long-lived.

Final result



$M_G \lesssim 2$ MeV

Conclusions

- Massive graviton production enhanced below the EW breaking scale (chiral enhancement)
- Freeze-in dominated by the EW scale
- For masses below 2 MeV, the correct relic can be obtained
- This applied to a general class of spin-2 models