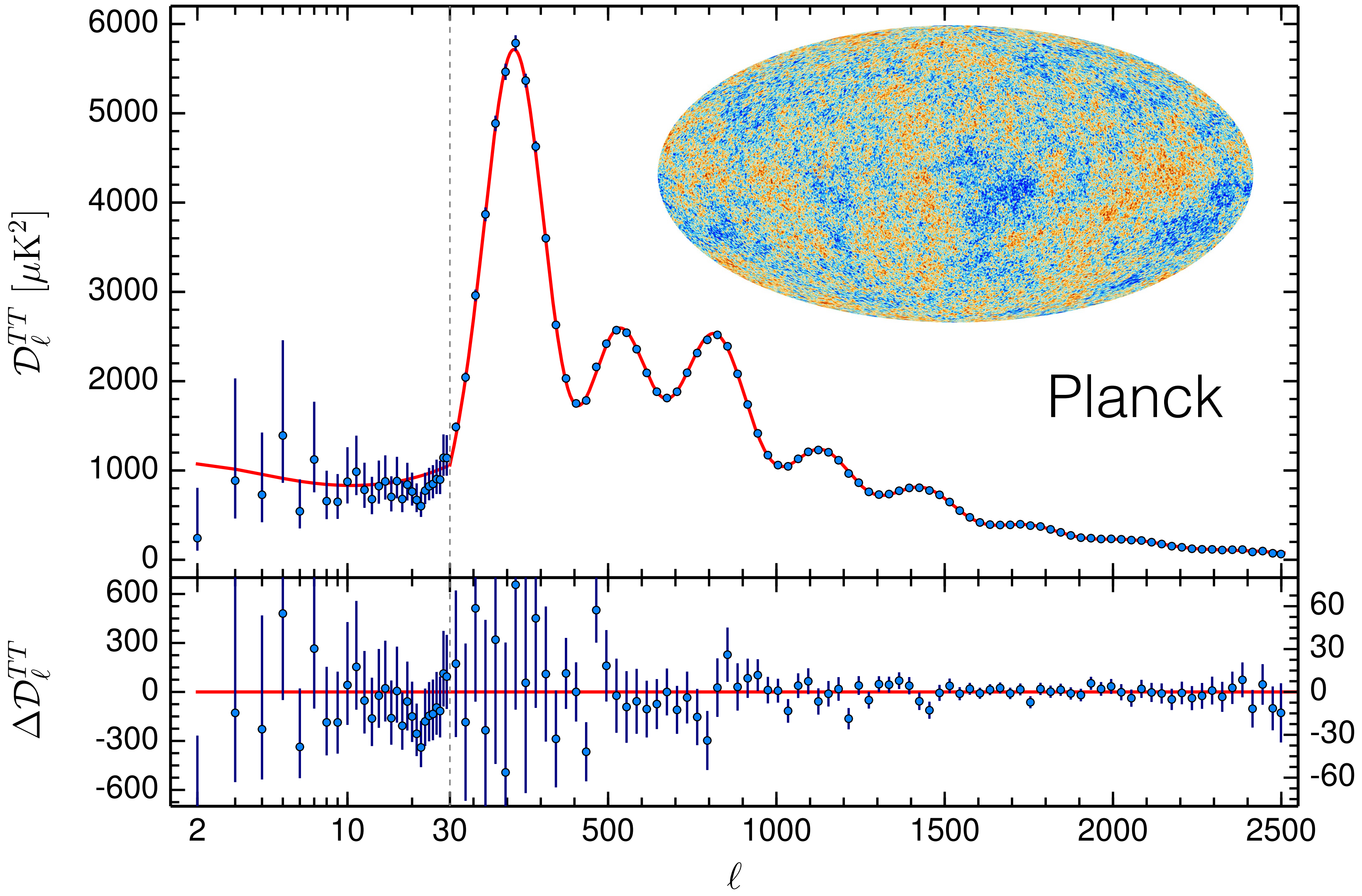
WIMPs and dark sector models

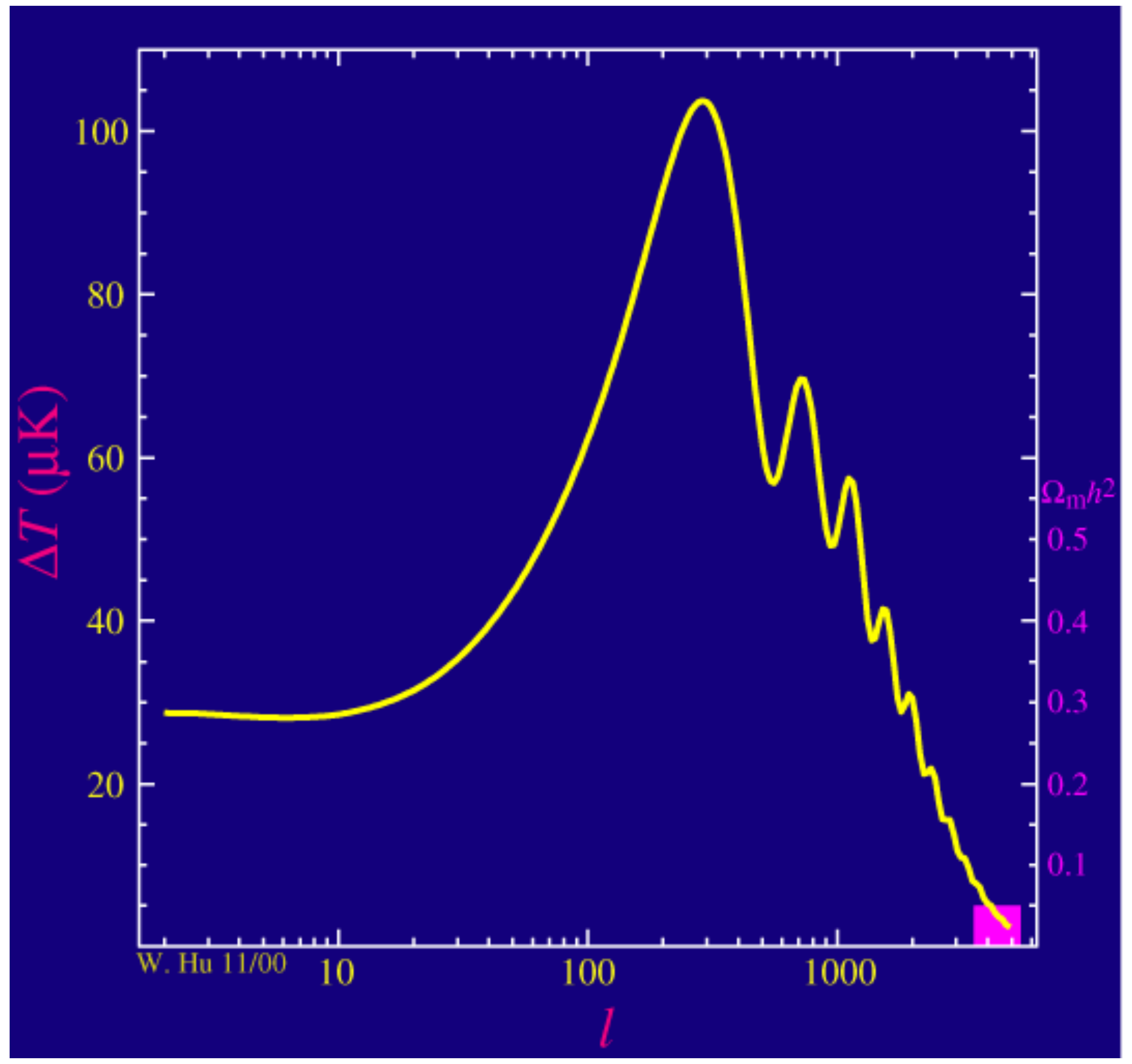
David McKeen

TRIUMF

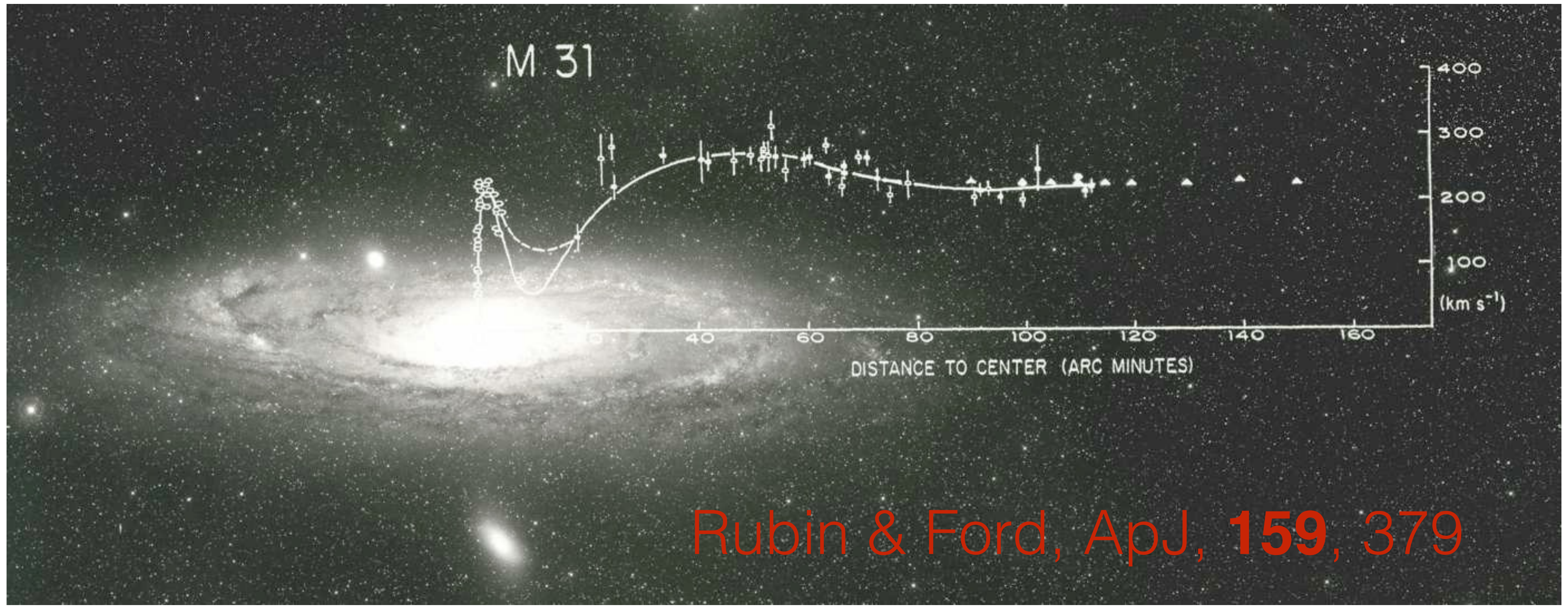
TAUP 2025, 26 August 2025

Evidence for Dark Matter across many scales and epochs





made by Wayne Hu



BBN, …

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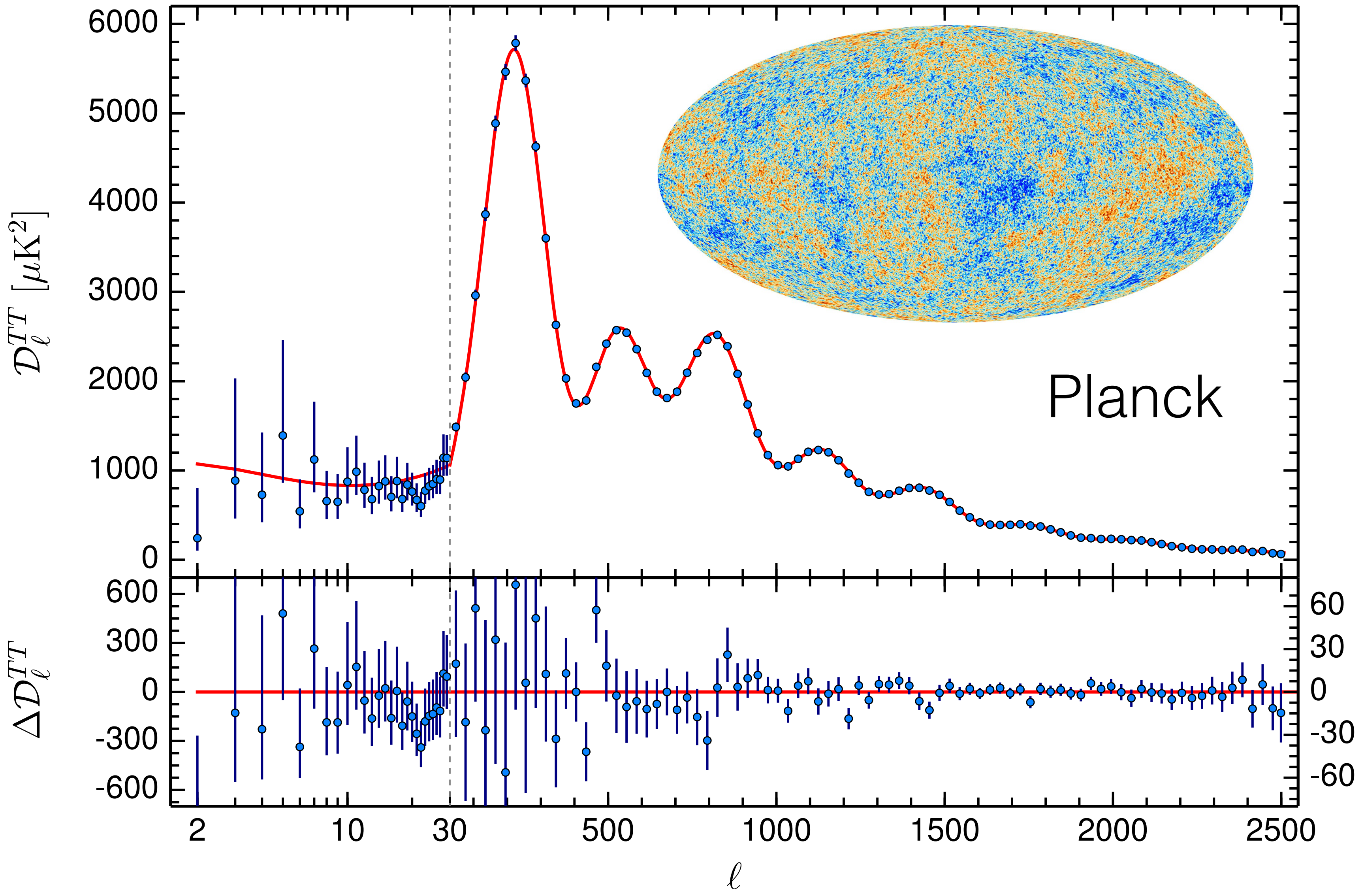

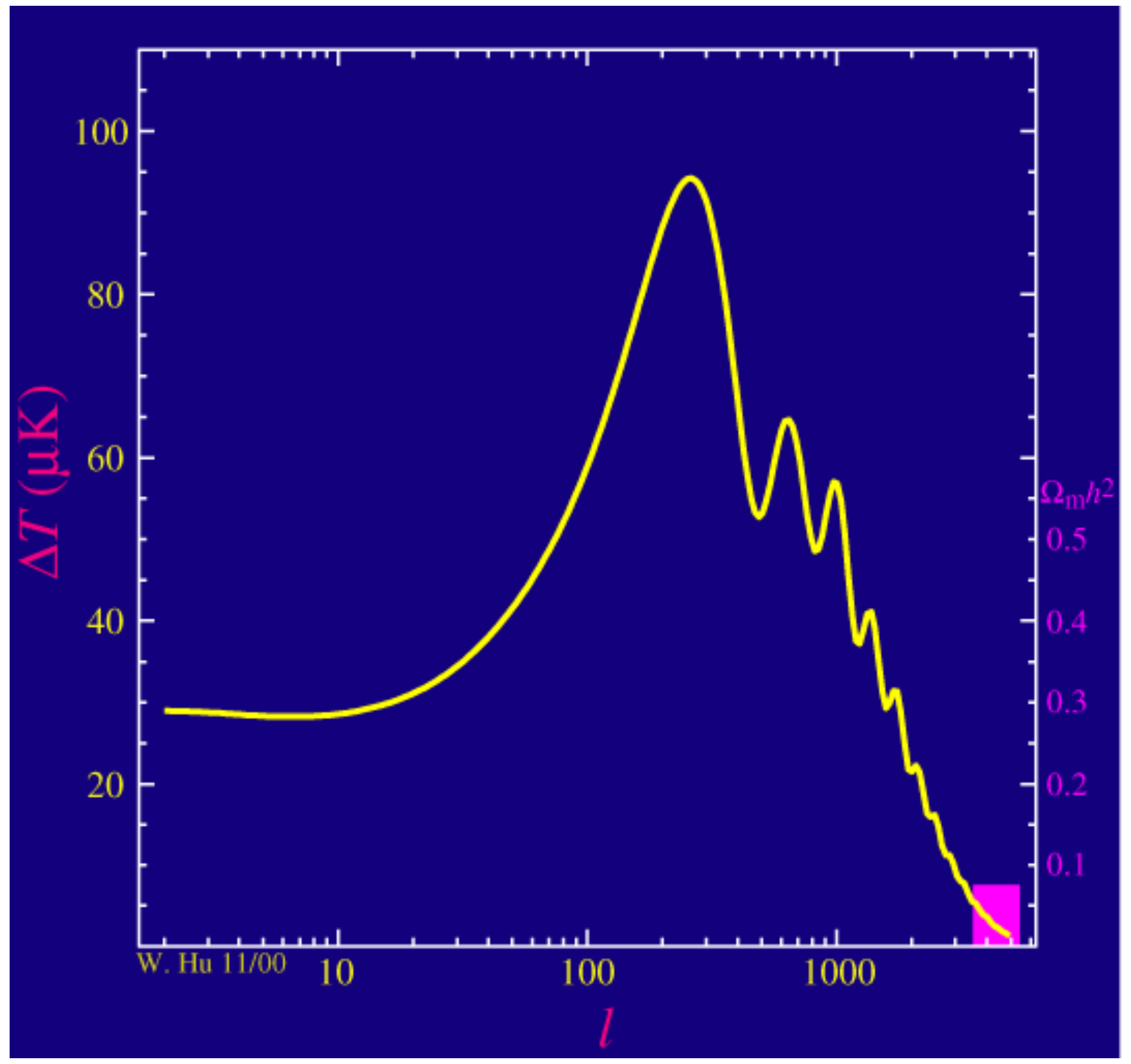

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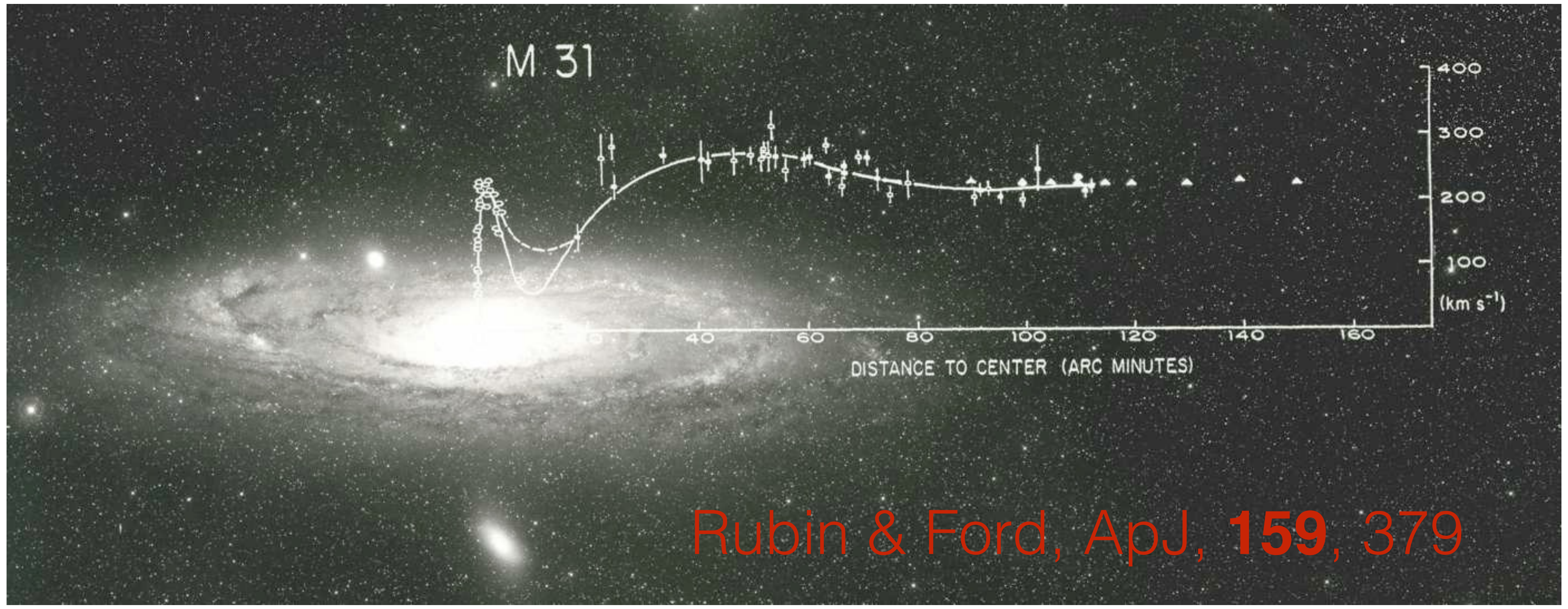

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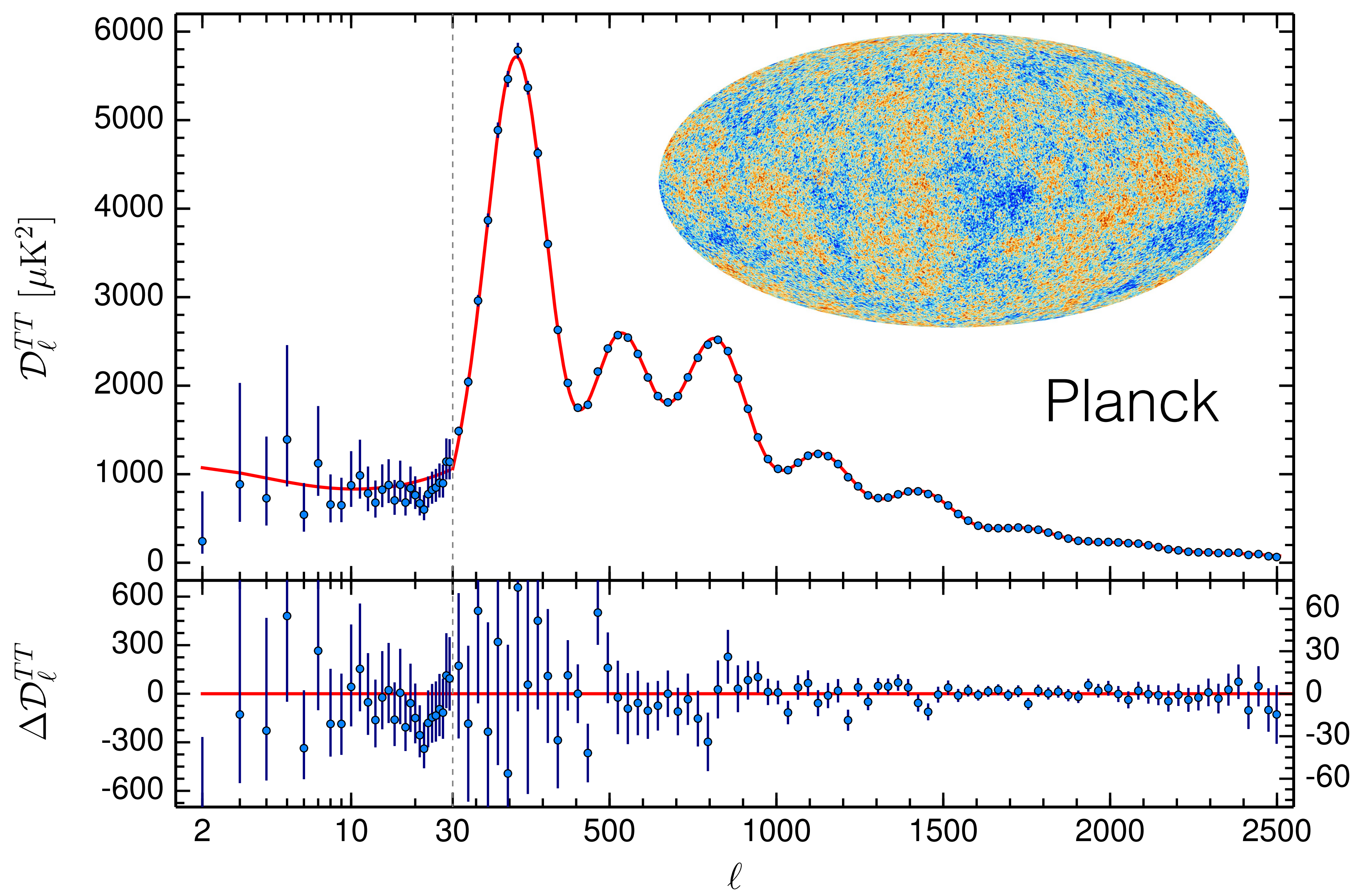

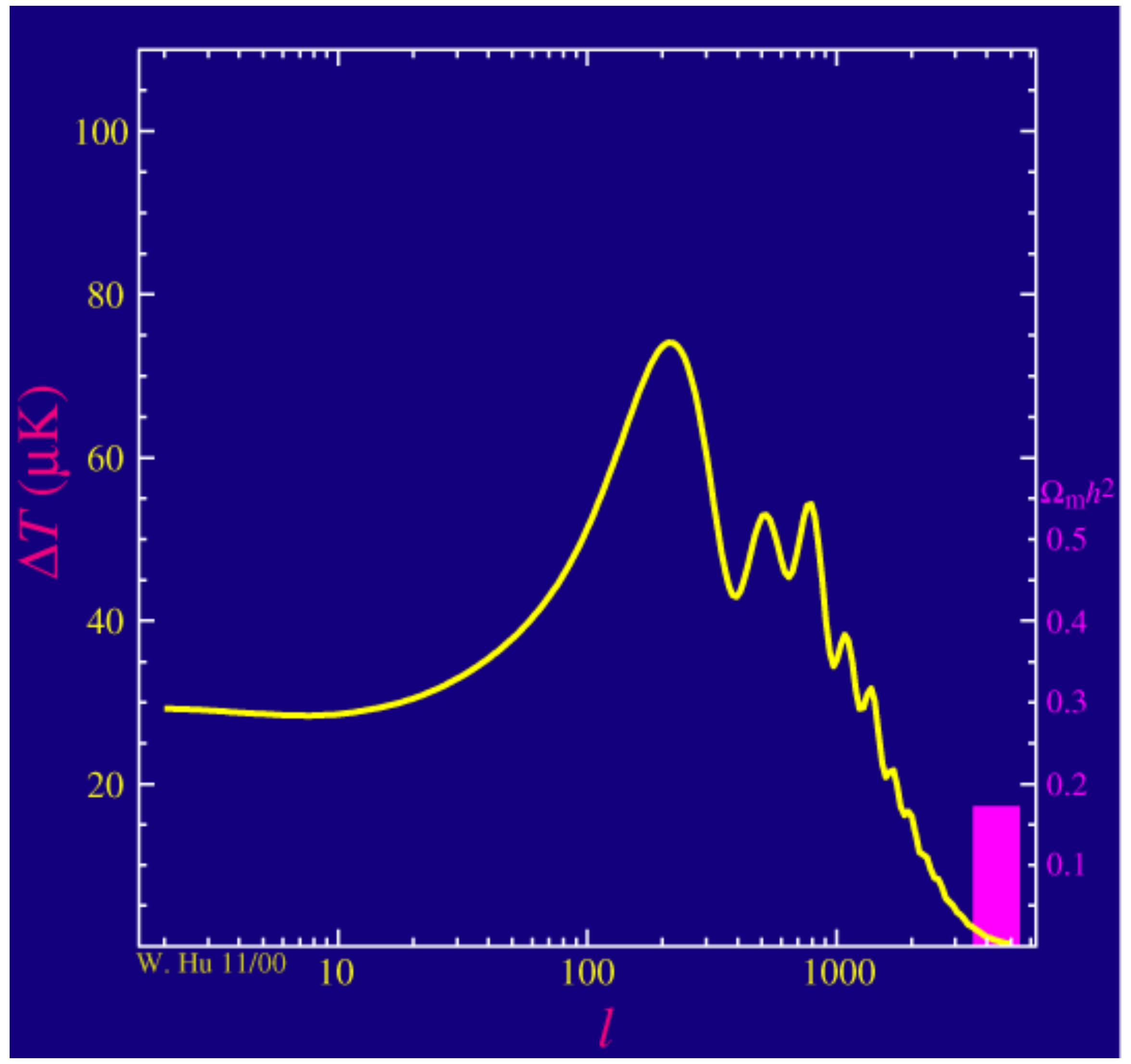

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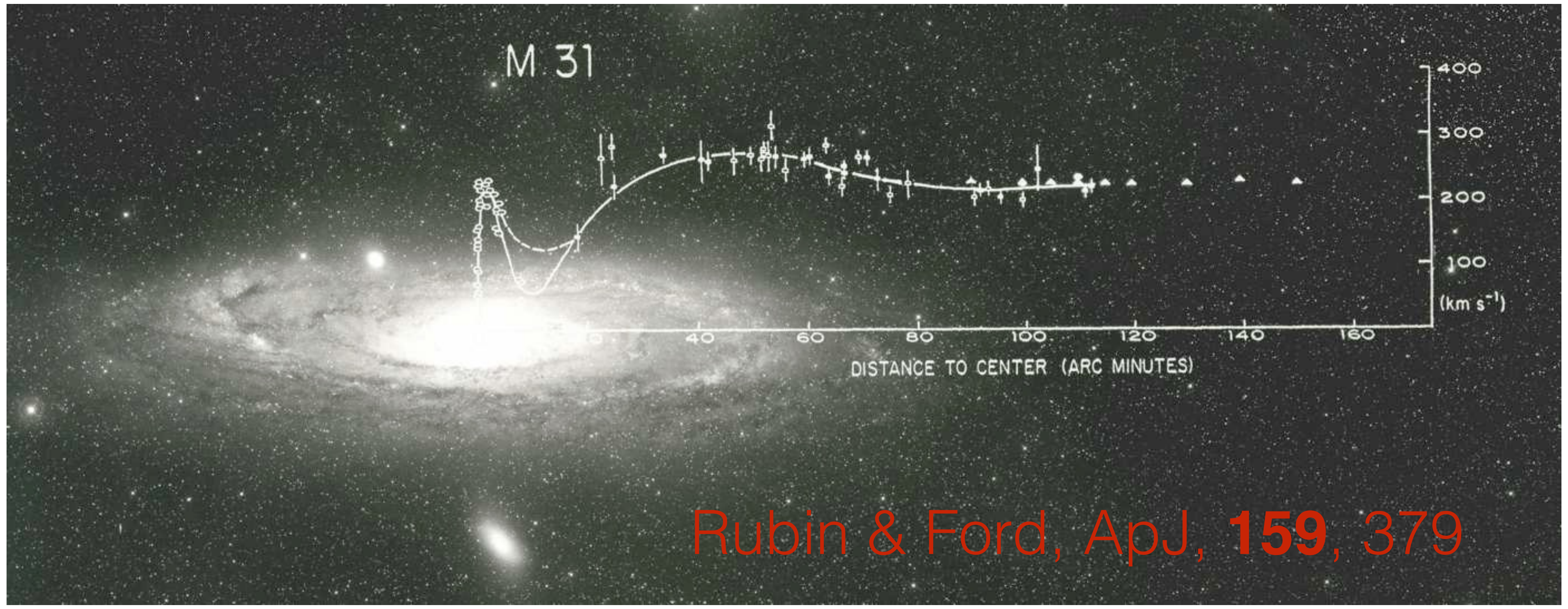

Rubin & Ford, ApJ, **159**, 379

BBN, …

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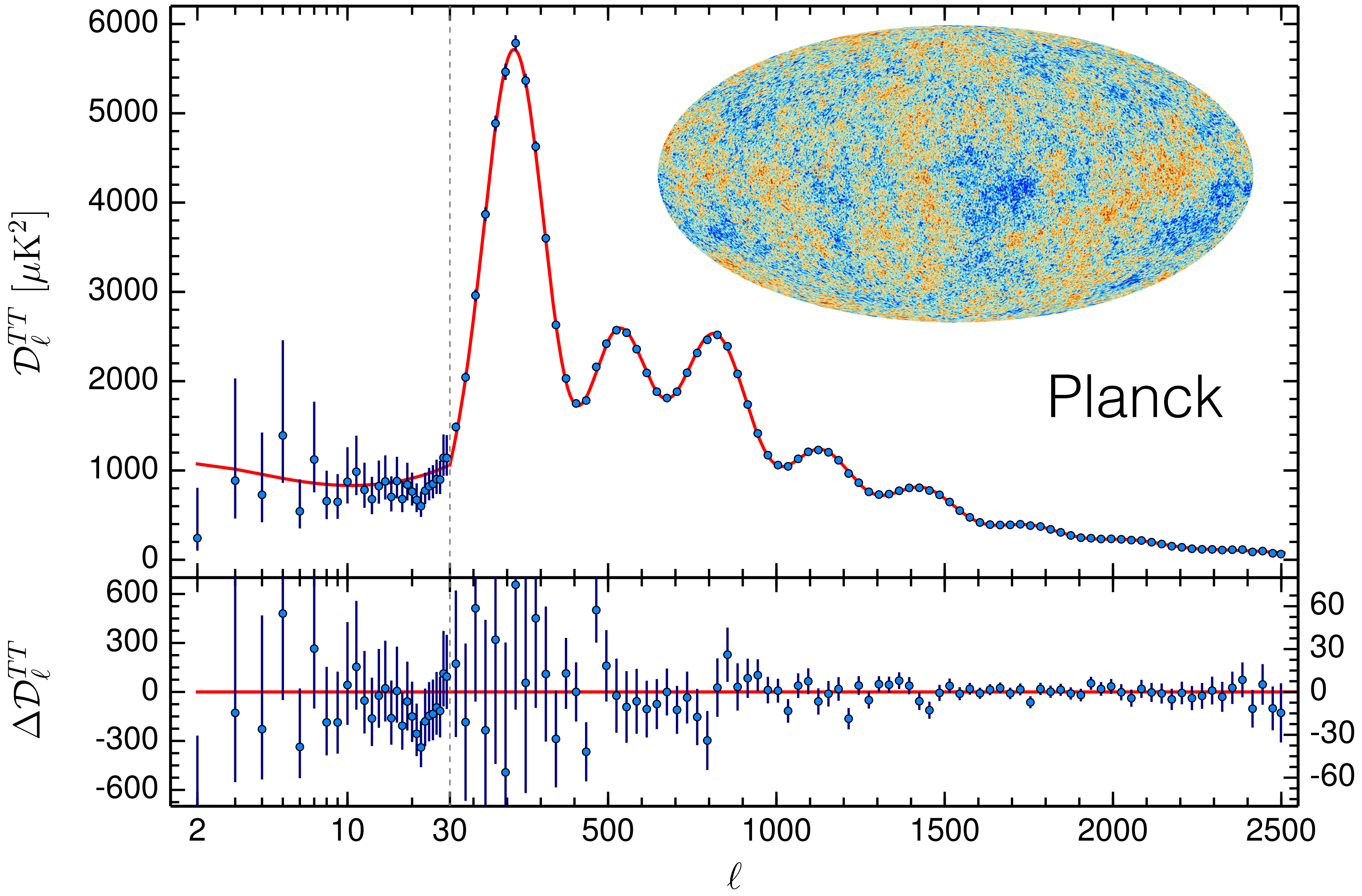

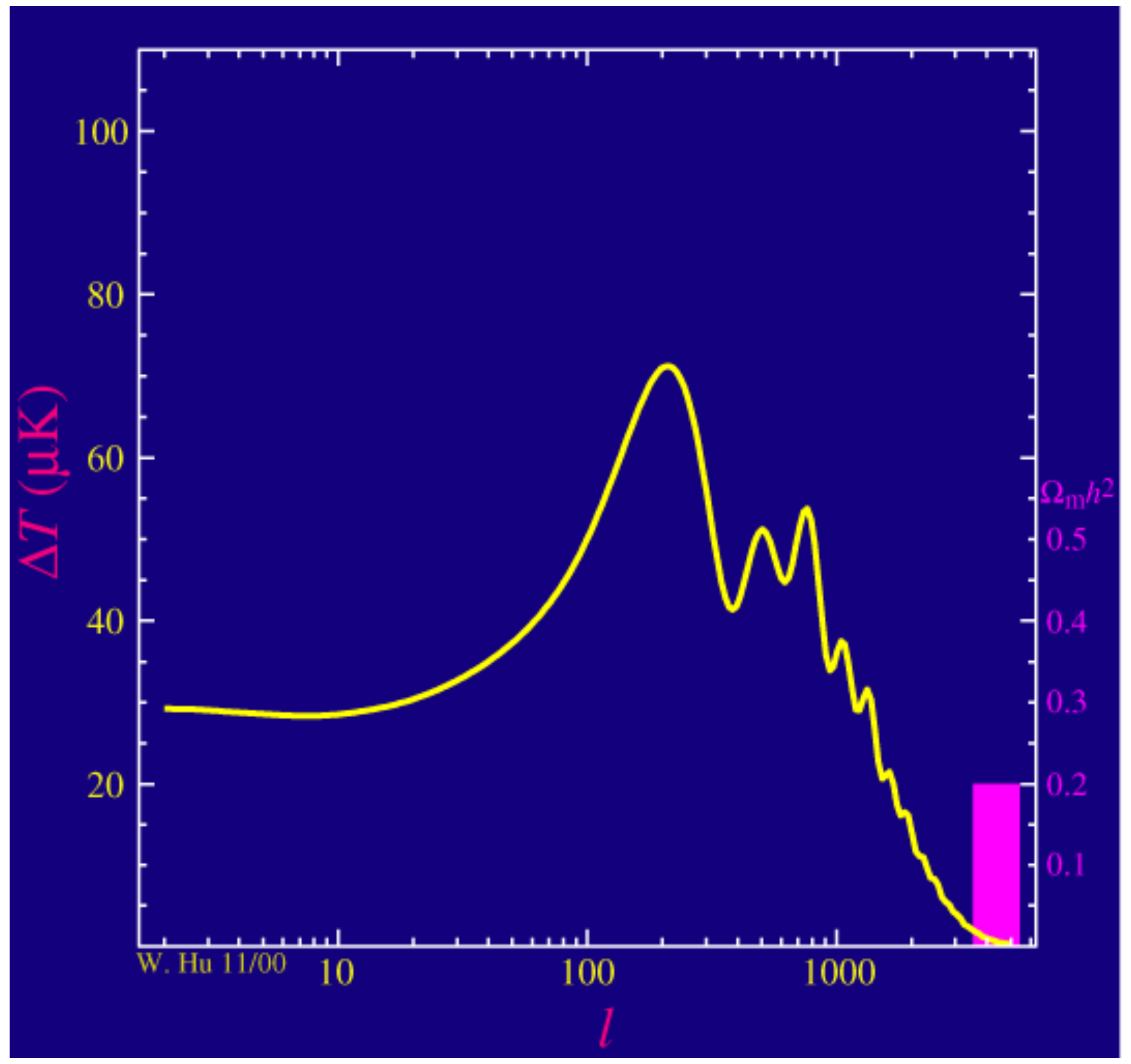

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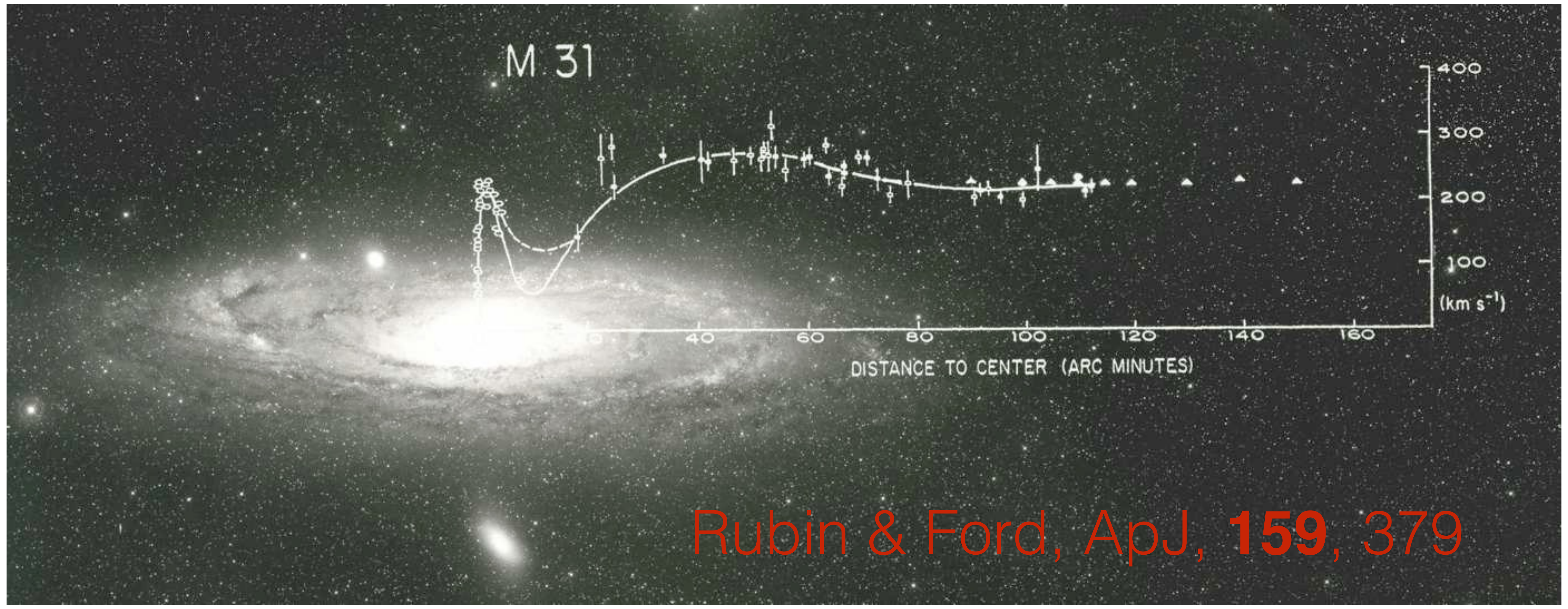

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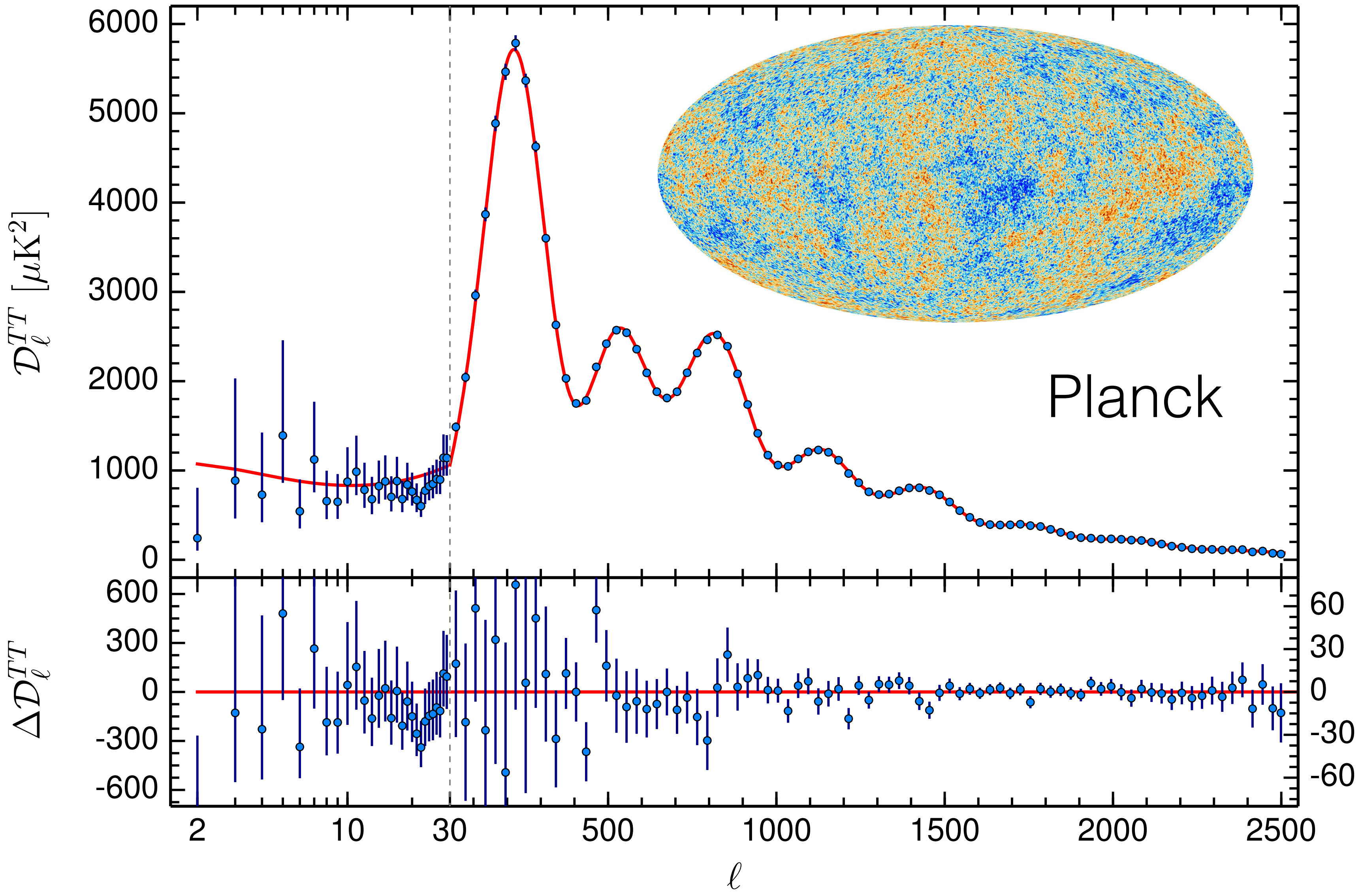

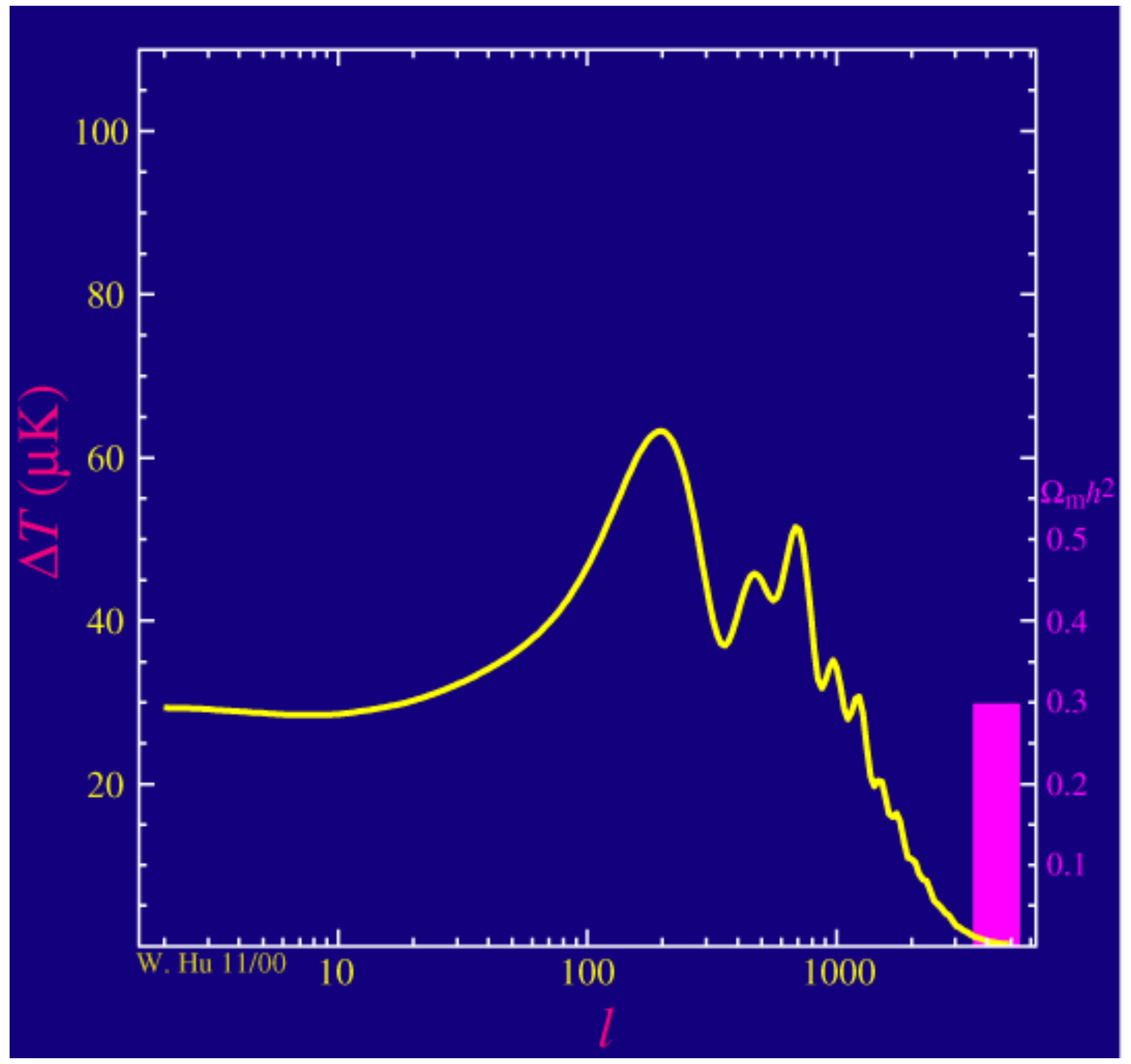

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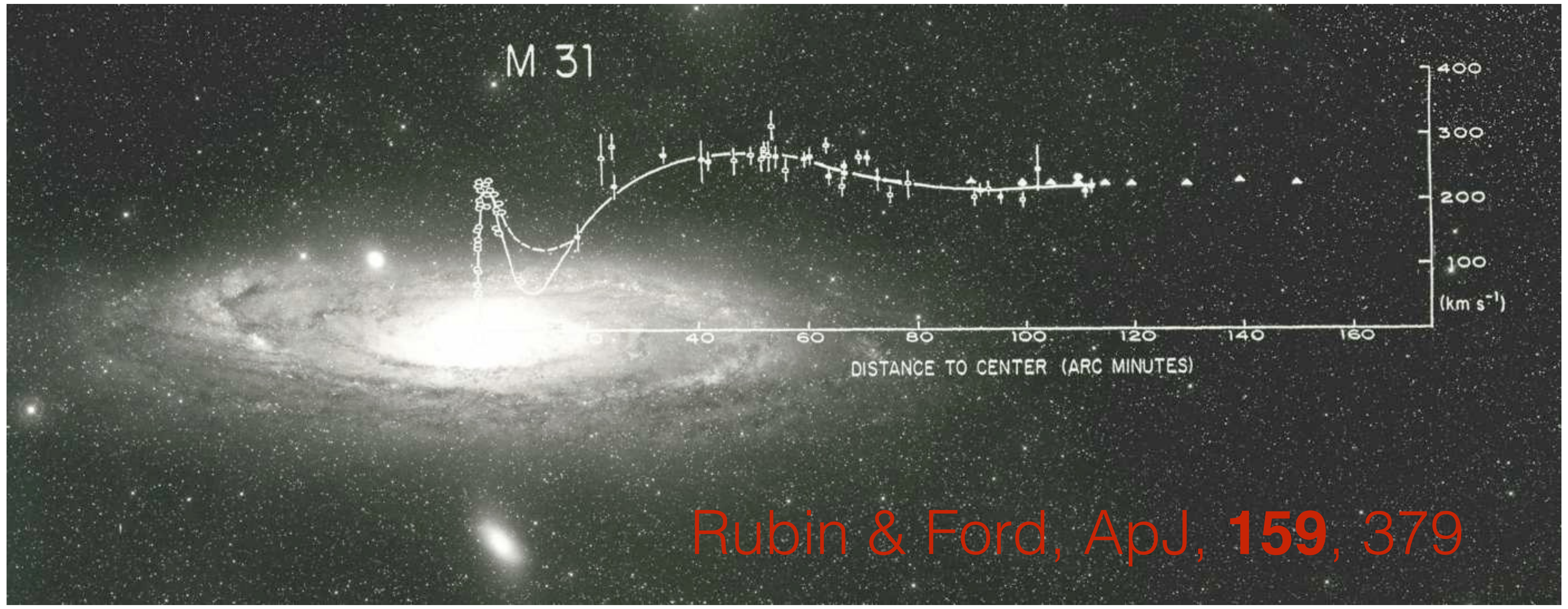

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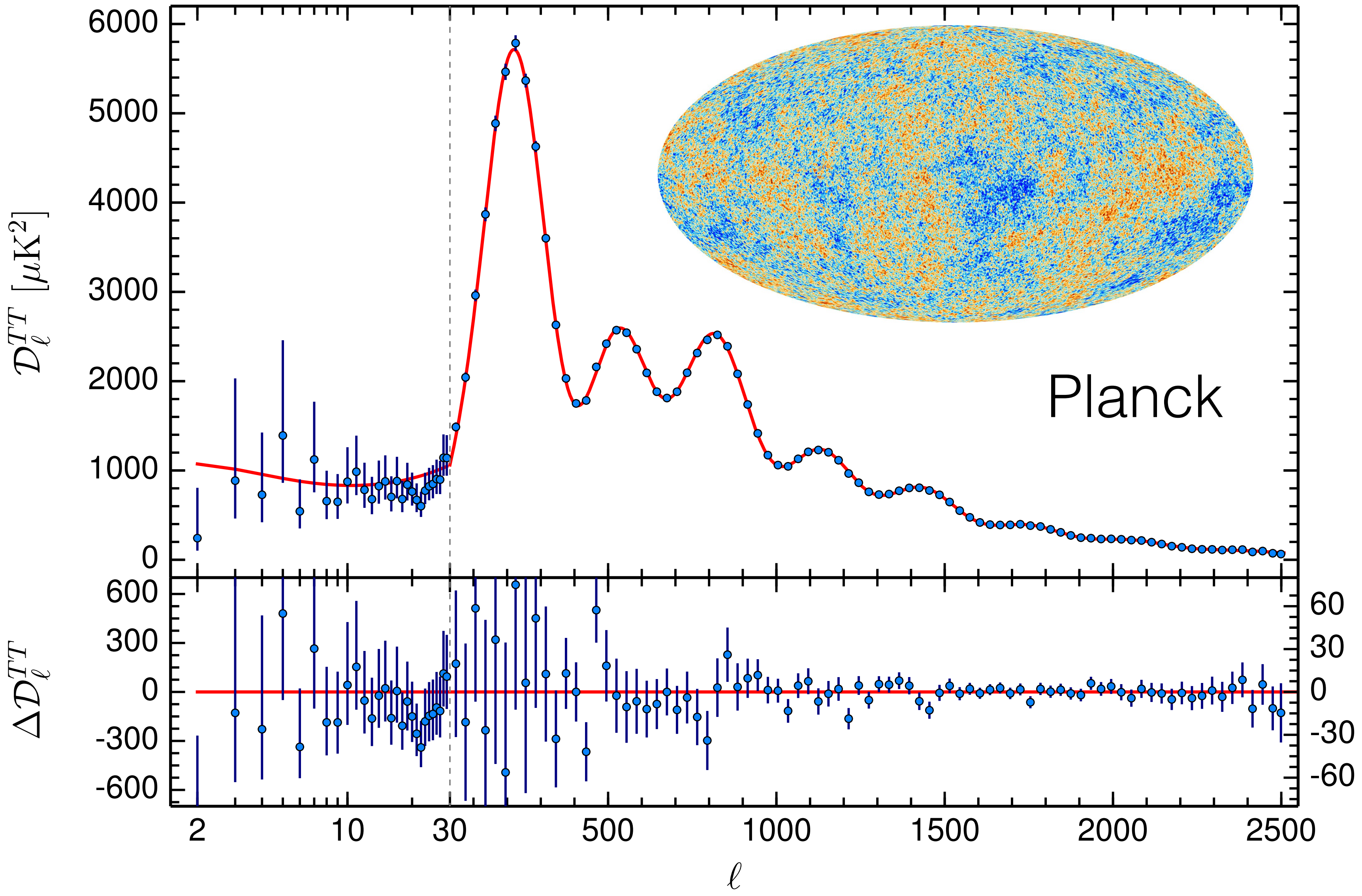

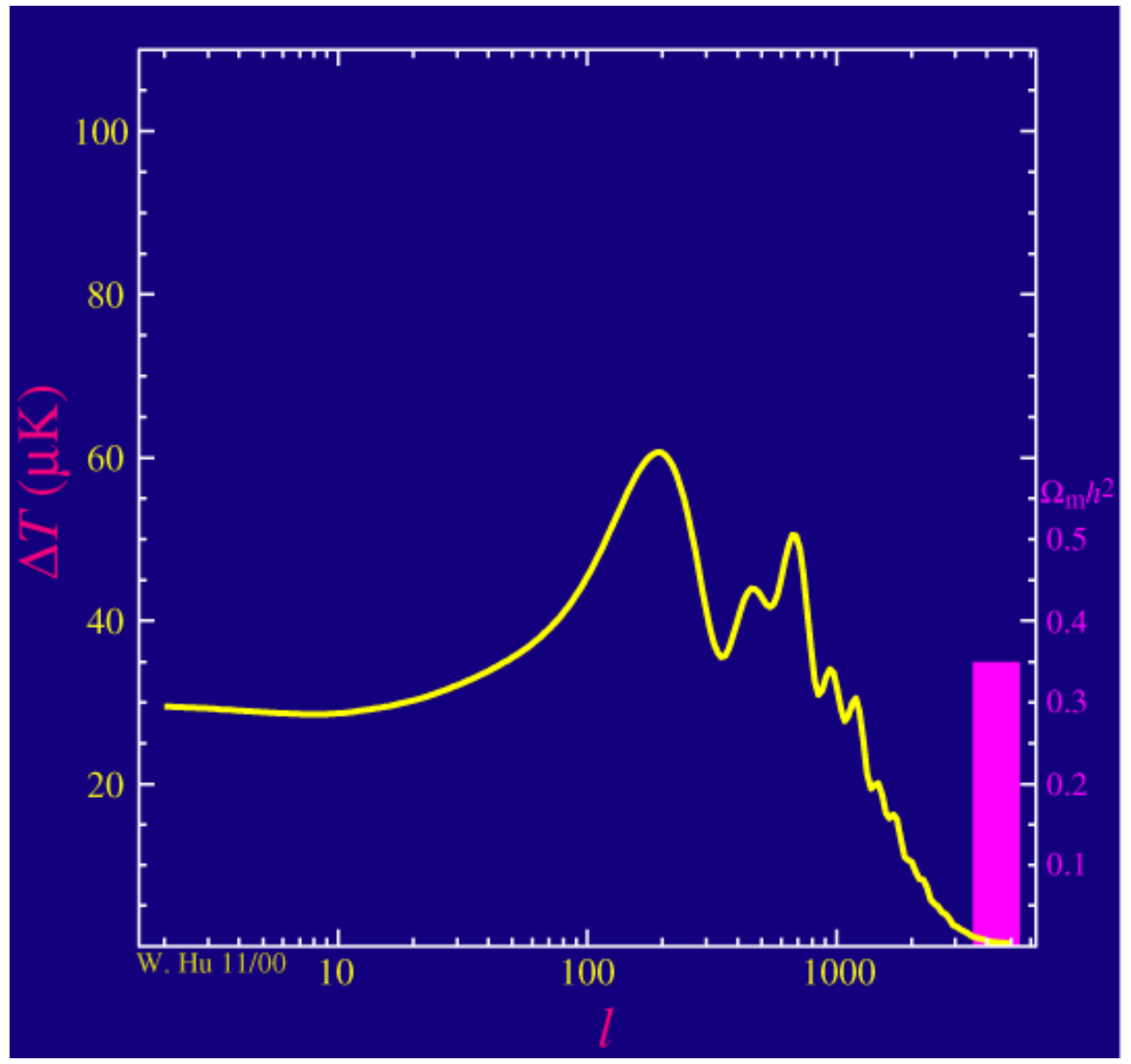

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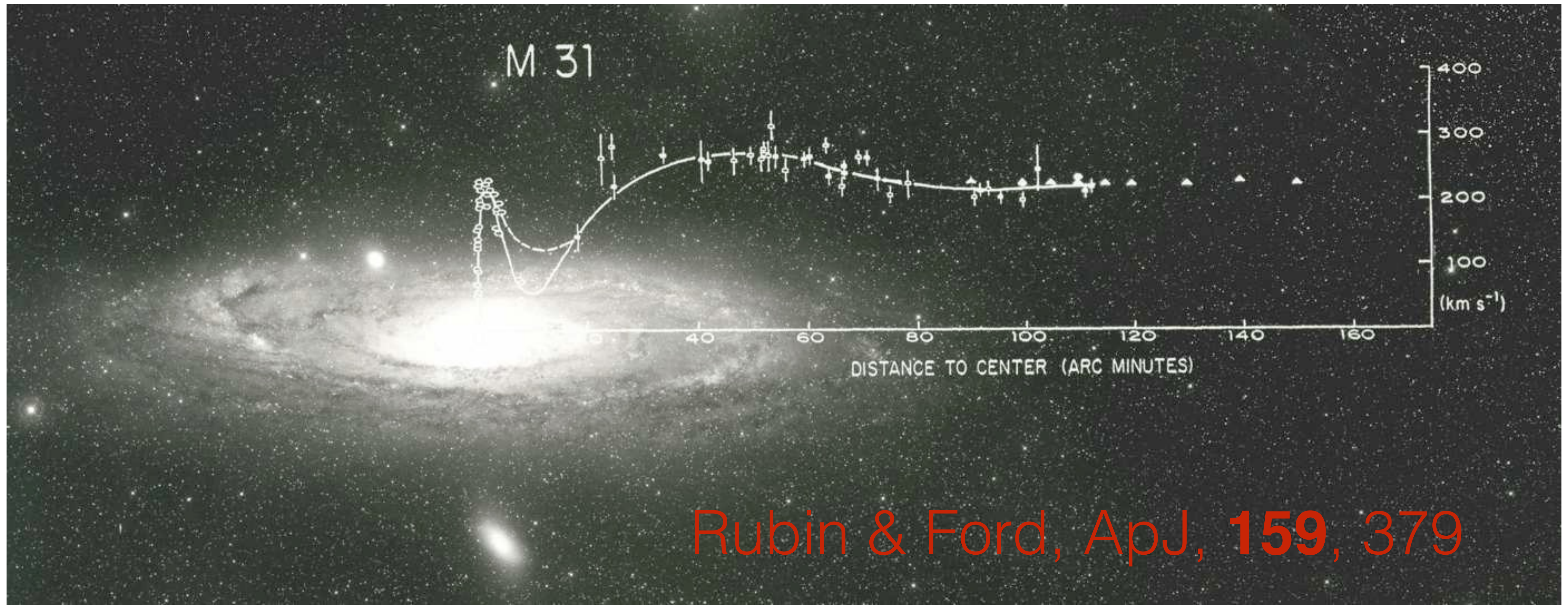

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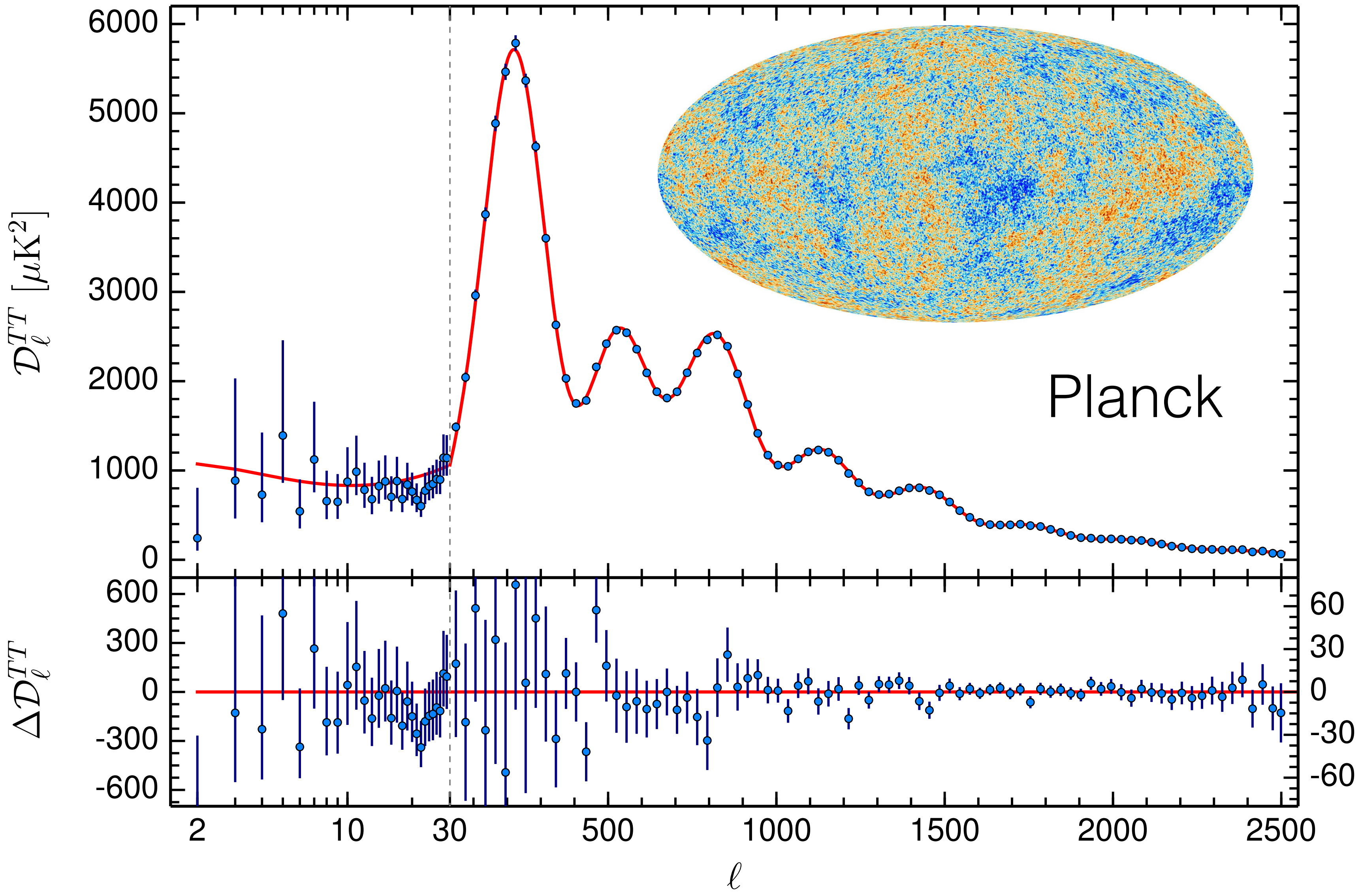

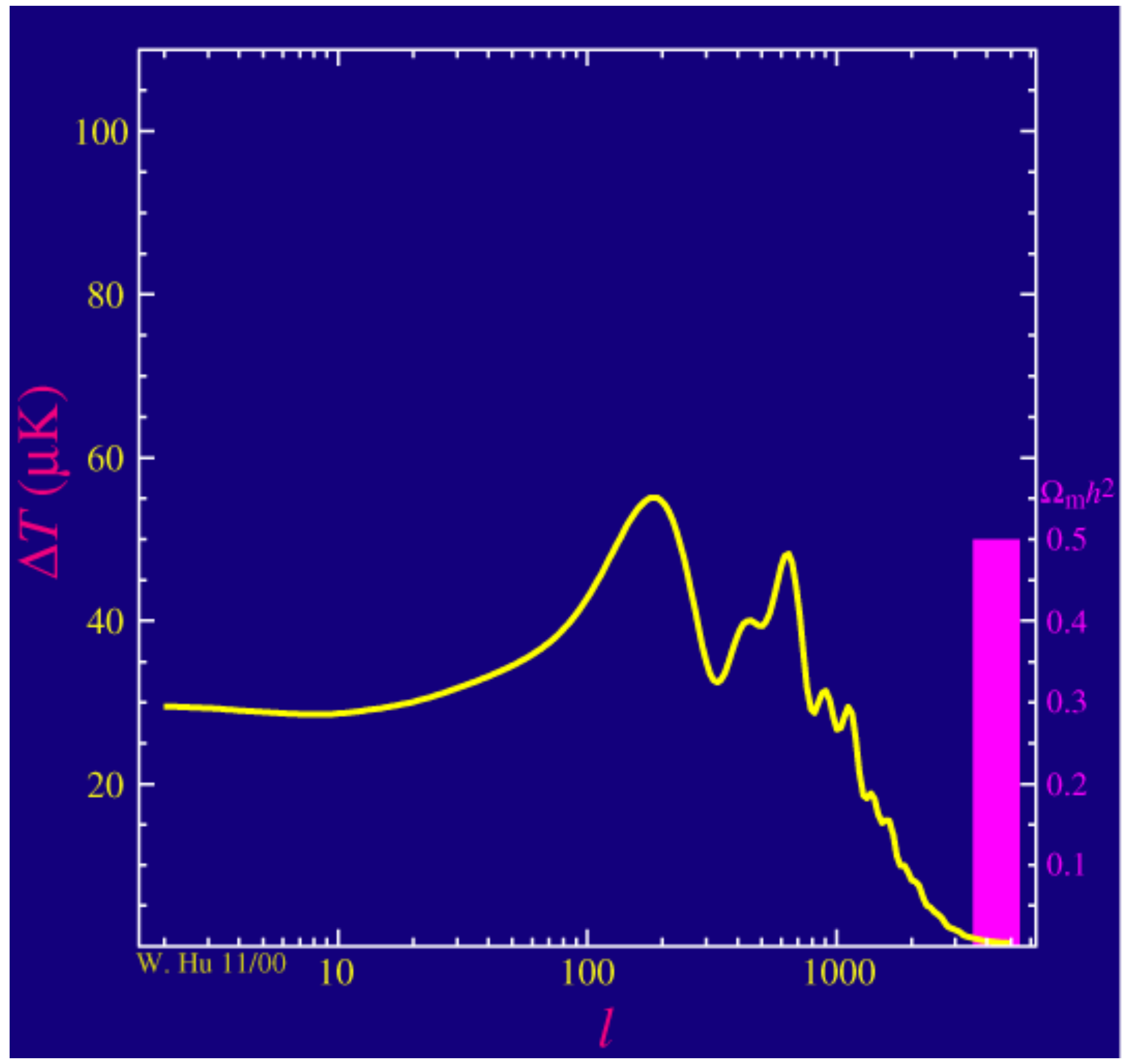

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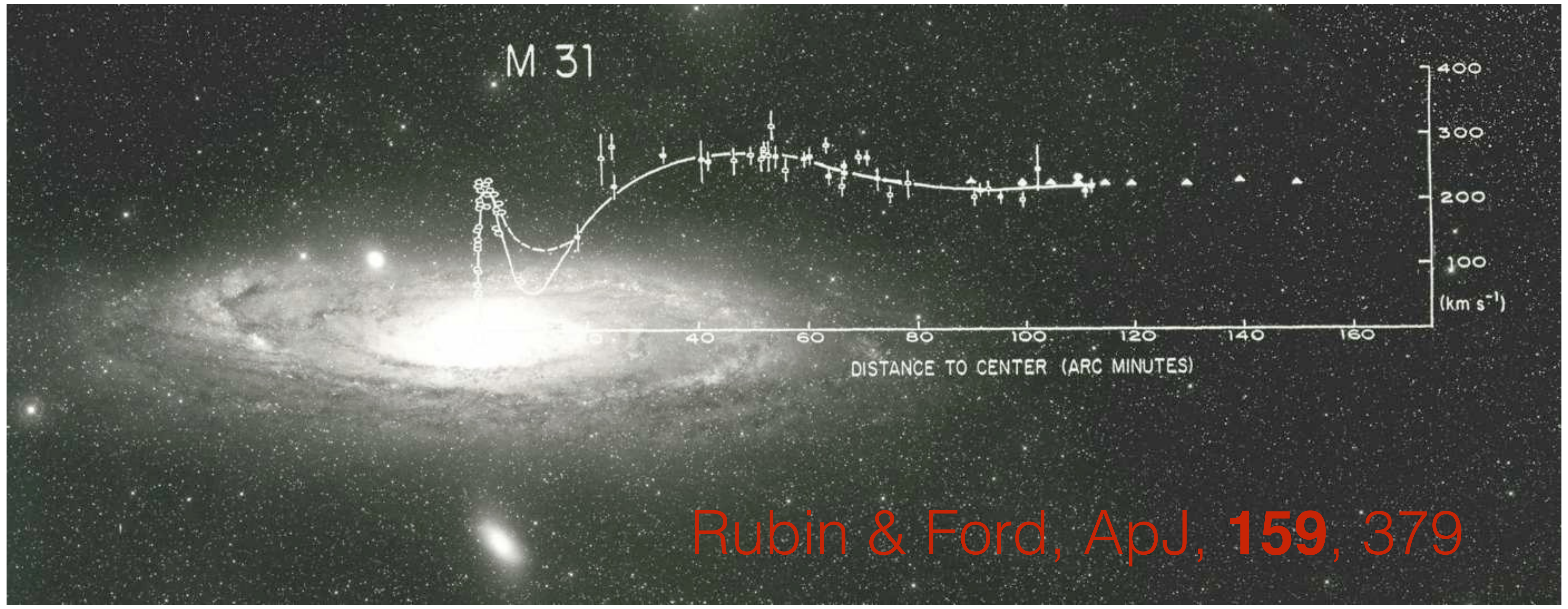
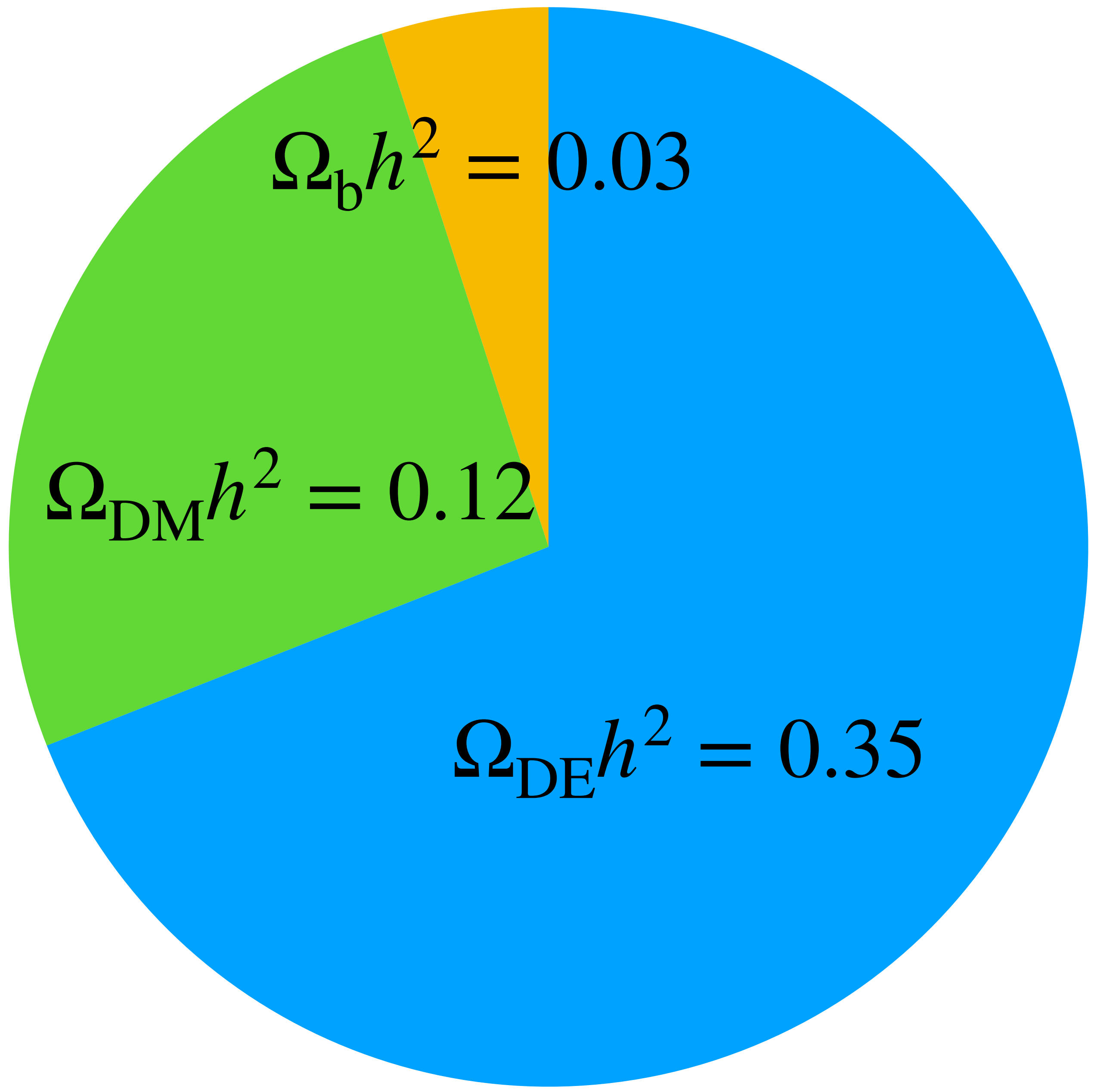
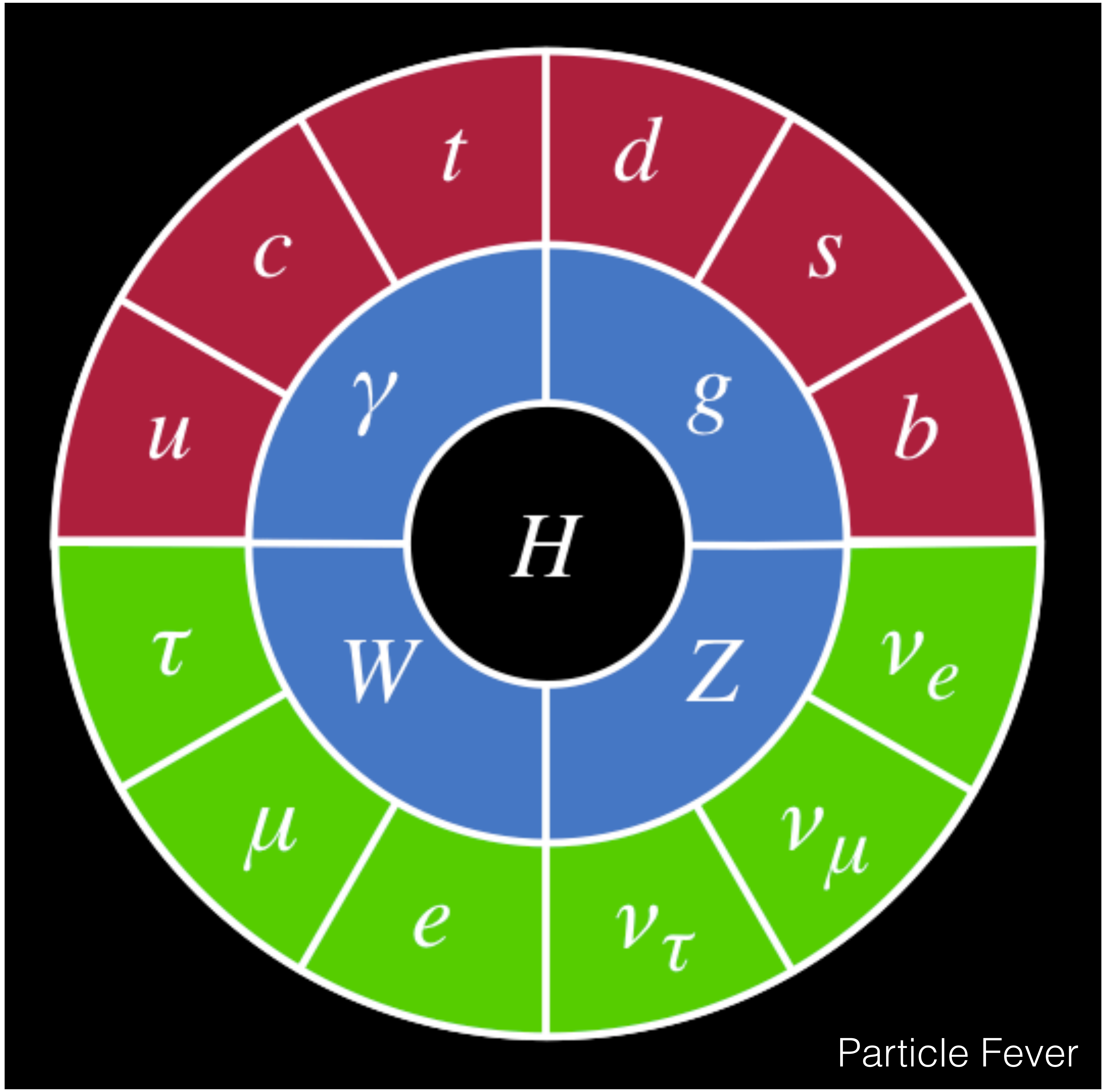


BBN, …


$\Omega_{\mathrm{b}}h^2 = 0.03$
$\Omega_{\mathrm{DM}}h^2 = 0.12$
$\Omega_{\mathrm{DE}}h^2 = 0.35$

So what is it?

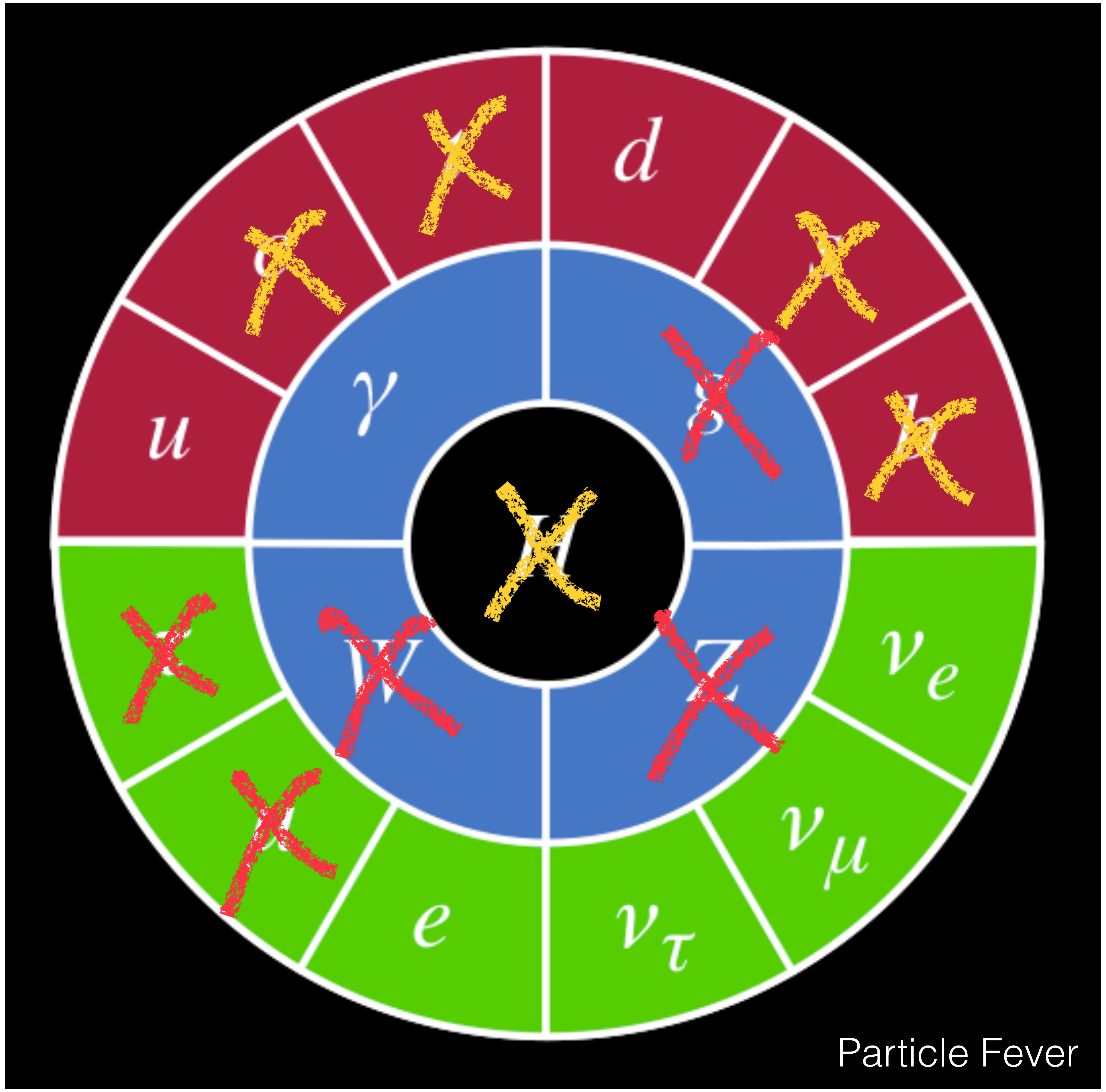
Standard Model particle content



So what is it?

Long-lived

Standard Model particle content

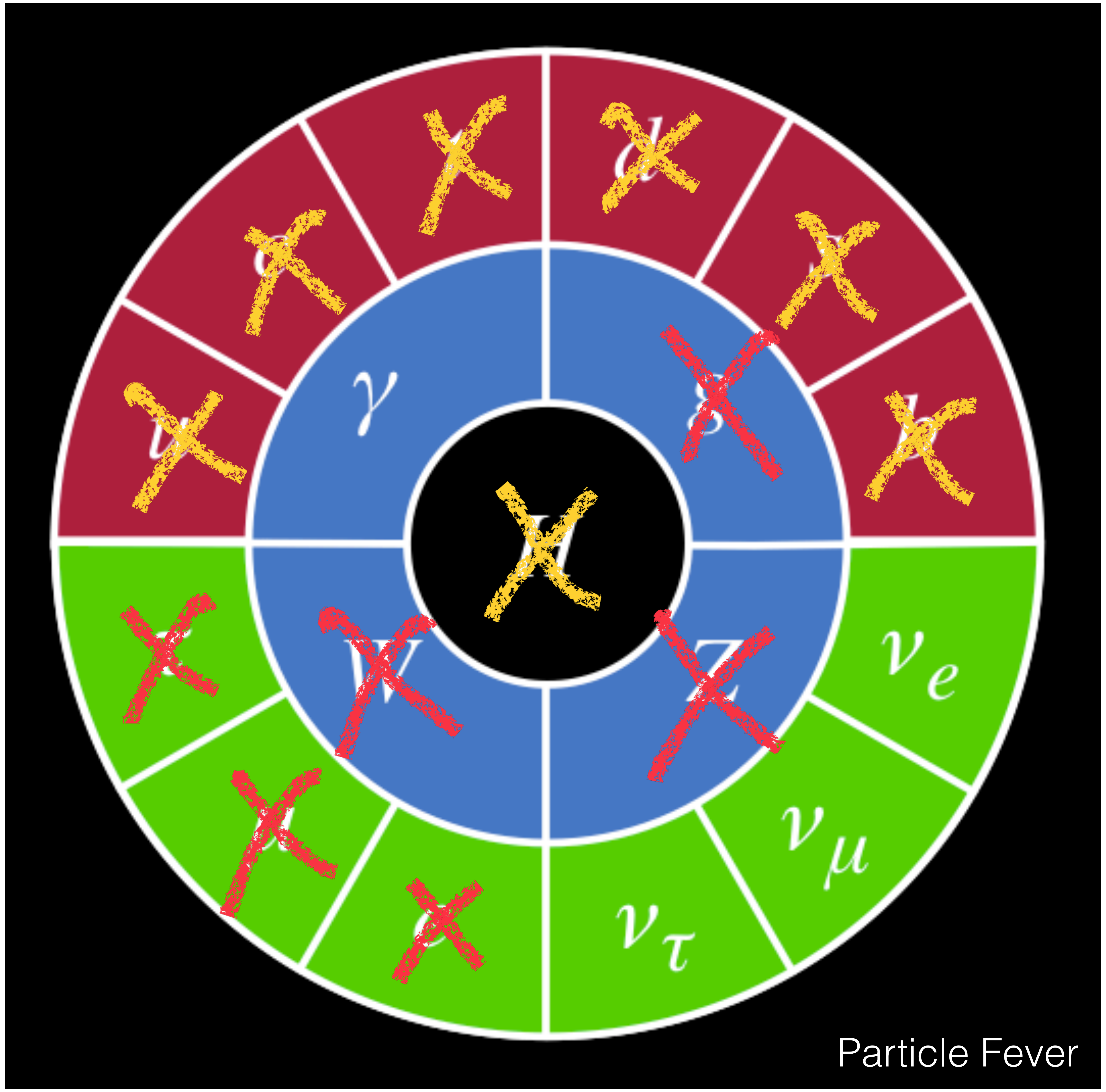


So what is it?

Long-lived

Electrically neutral

Standard Model particle content



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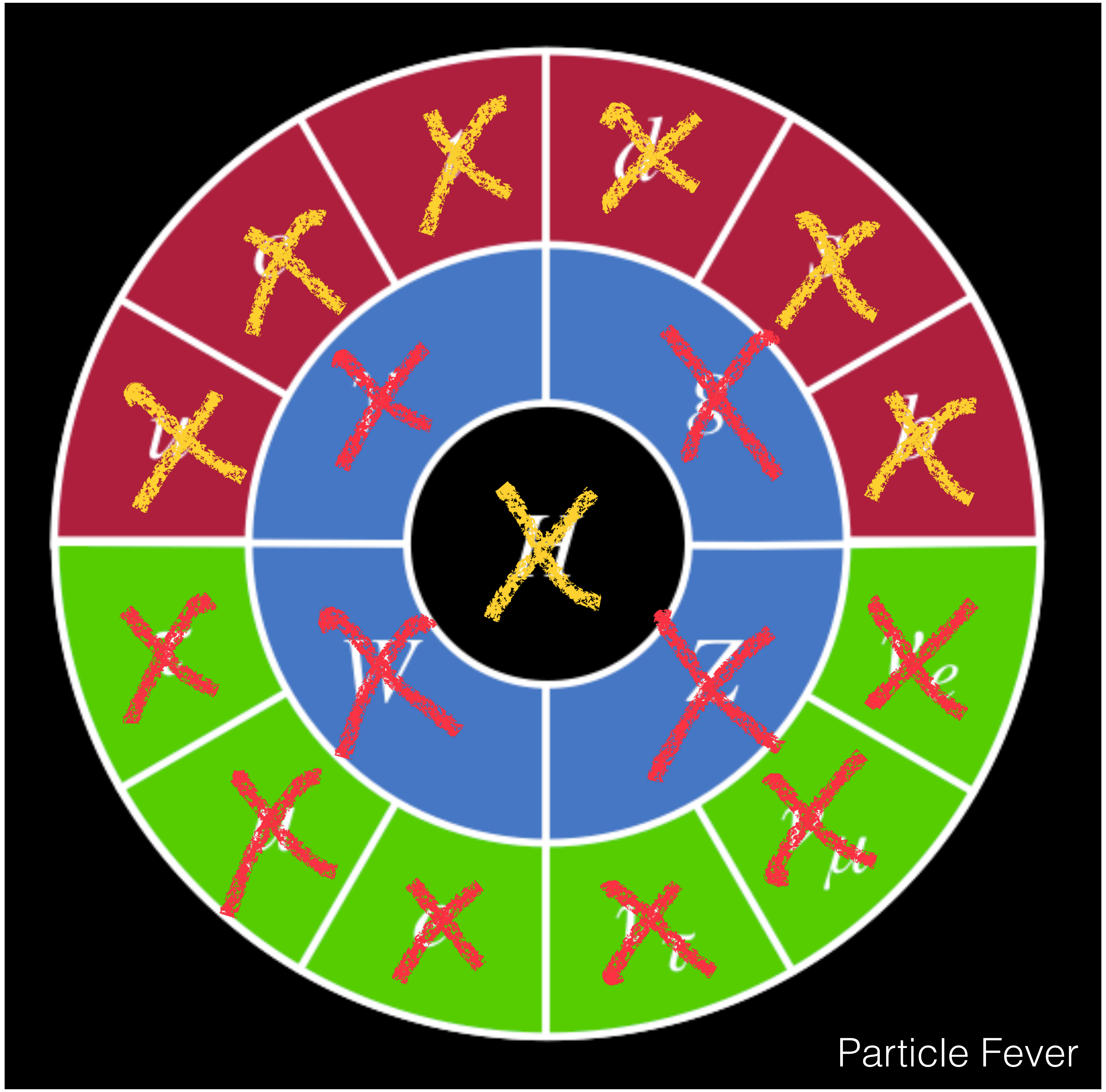
Long-lived

Electrically neutral

"Matter"

Standard Model particle content



So what is it?

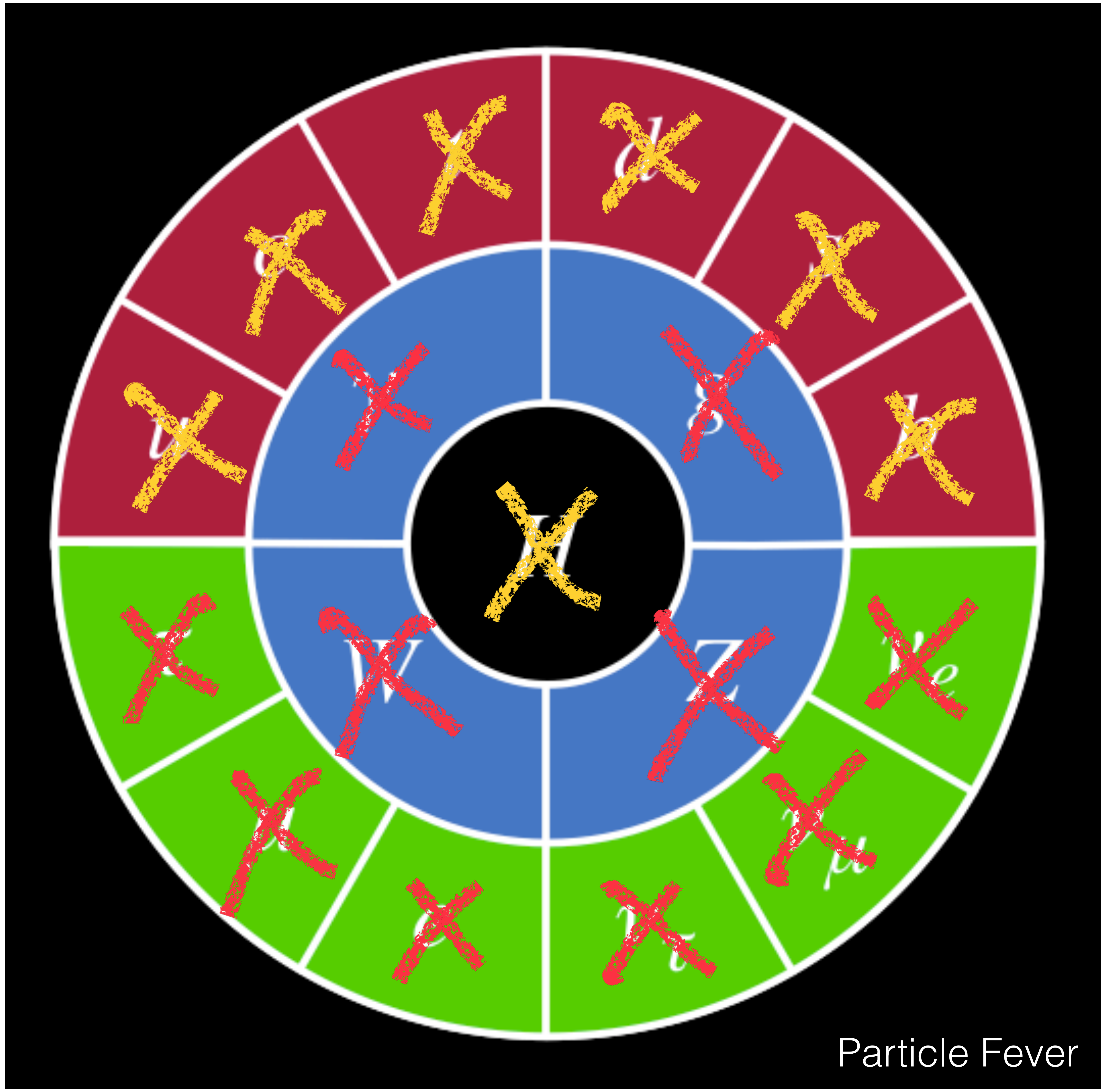
Long-lived

Electrically neutral

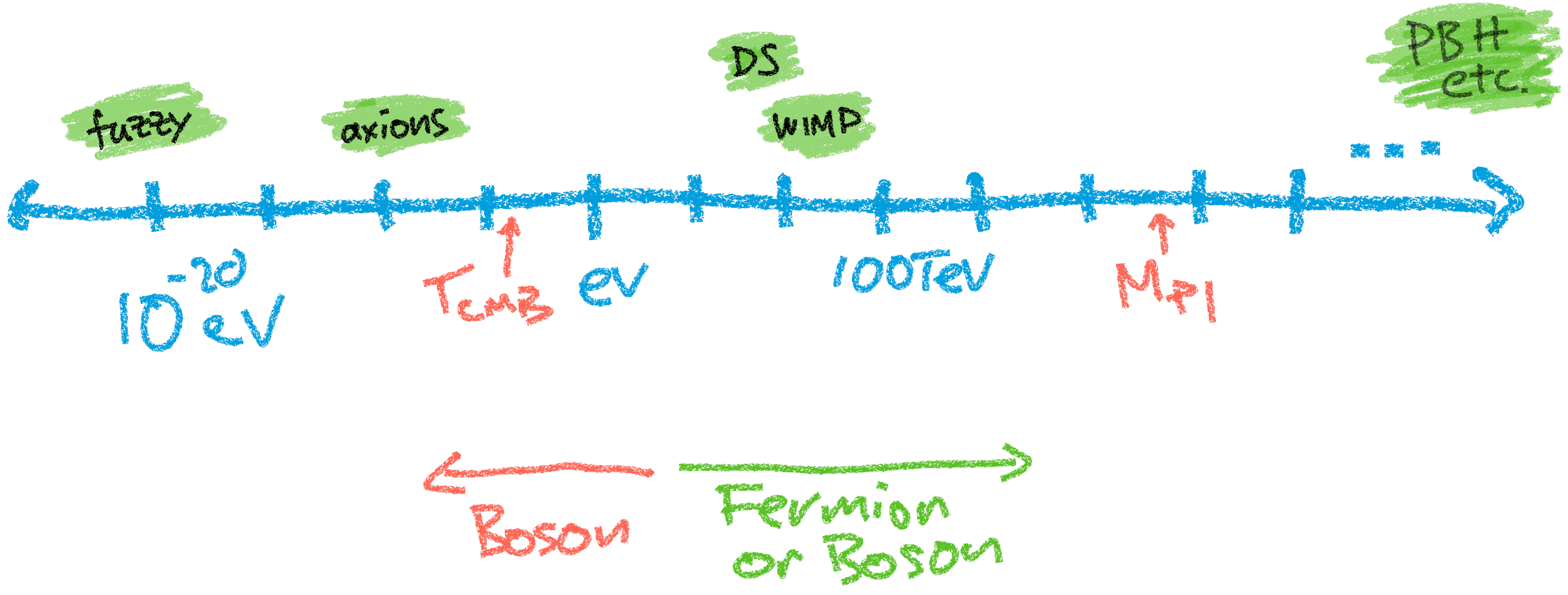
"Matter"

Something new

Standard Model particle content

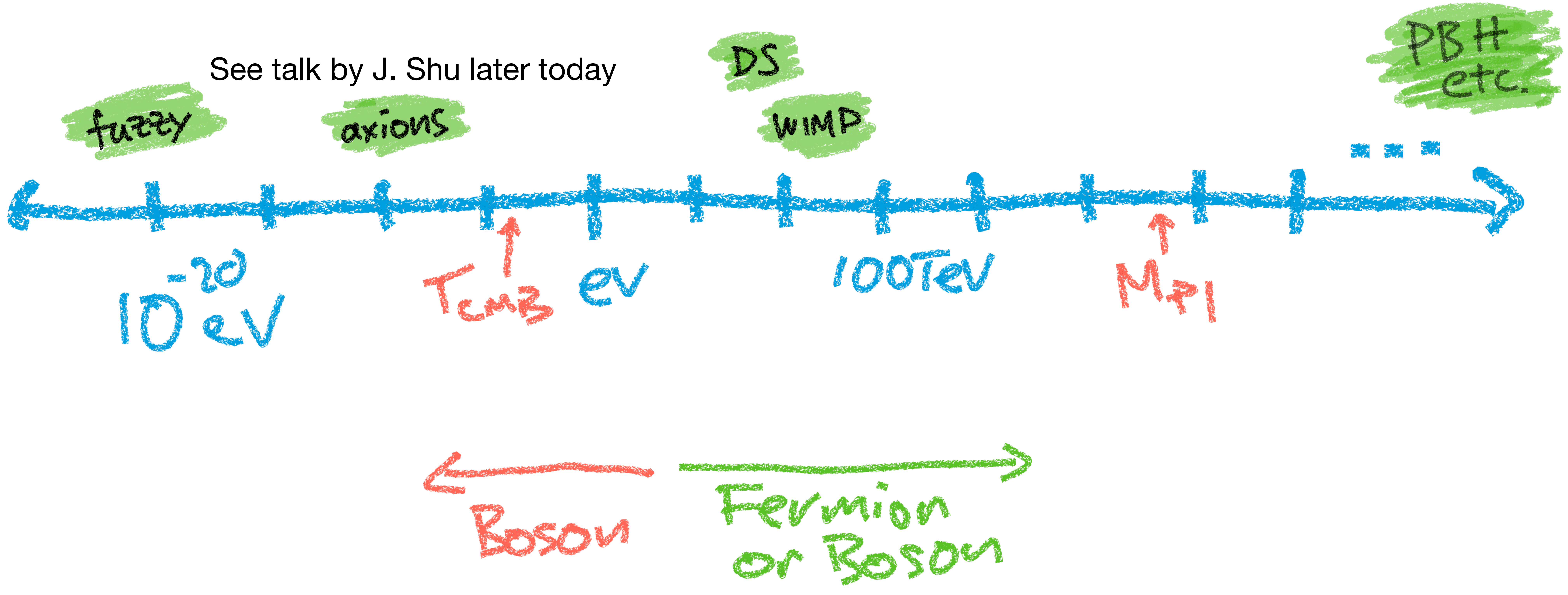


DM Landscape



DM Landscape

See talk by J. Shu later today



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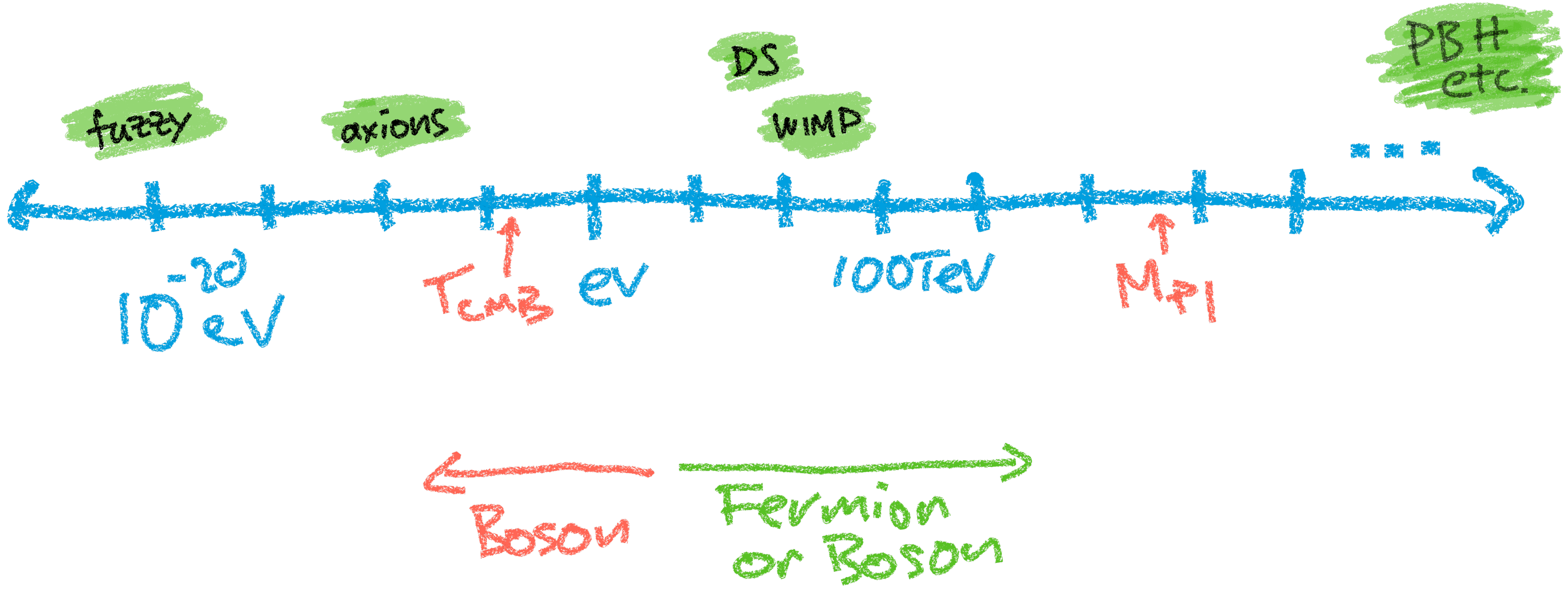

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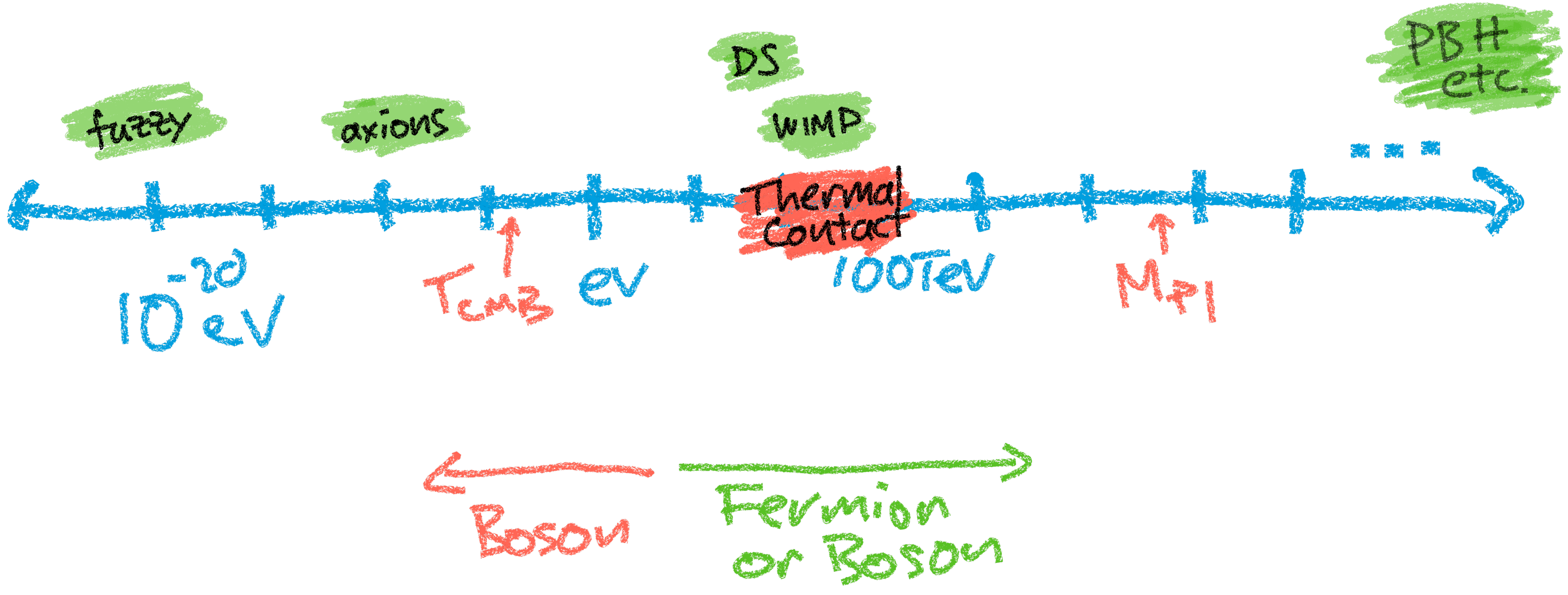

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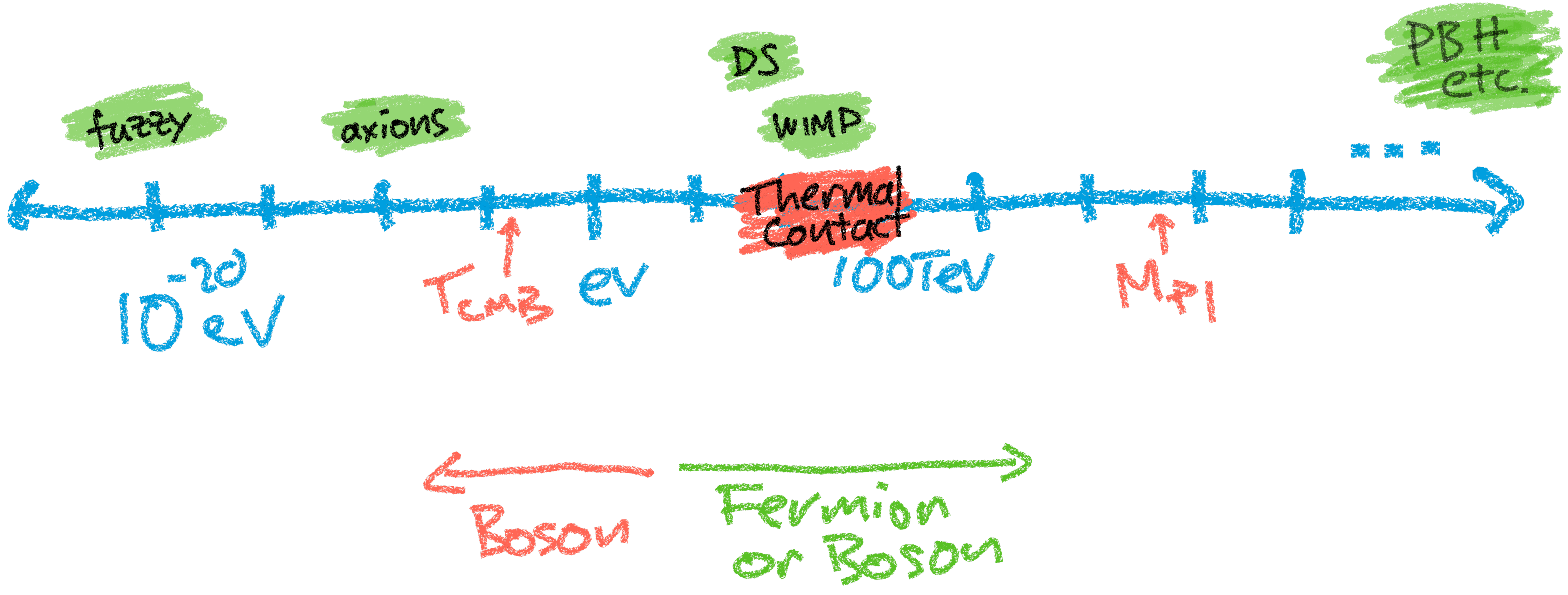
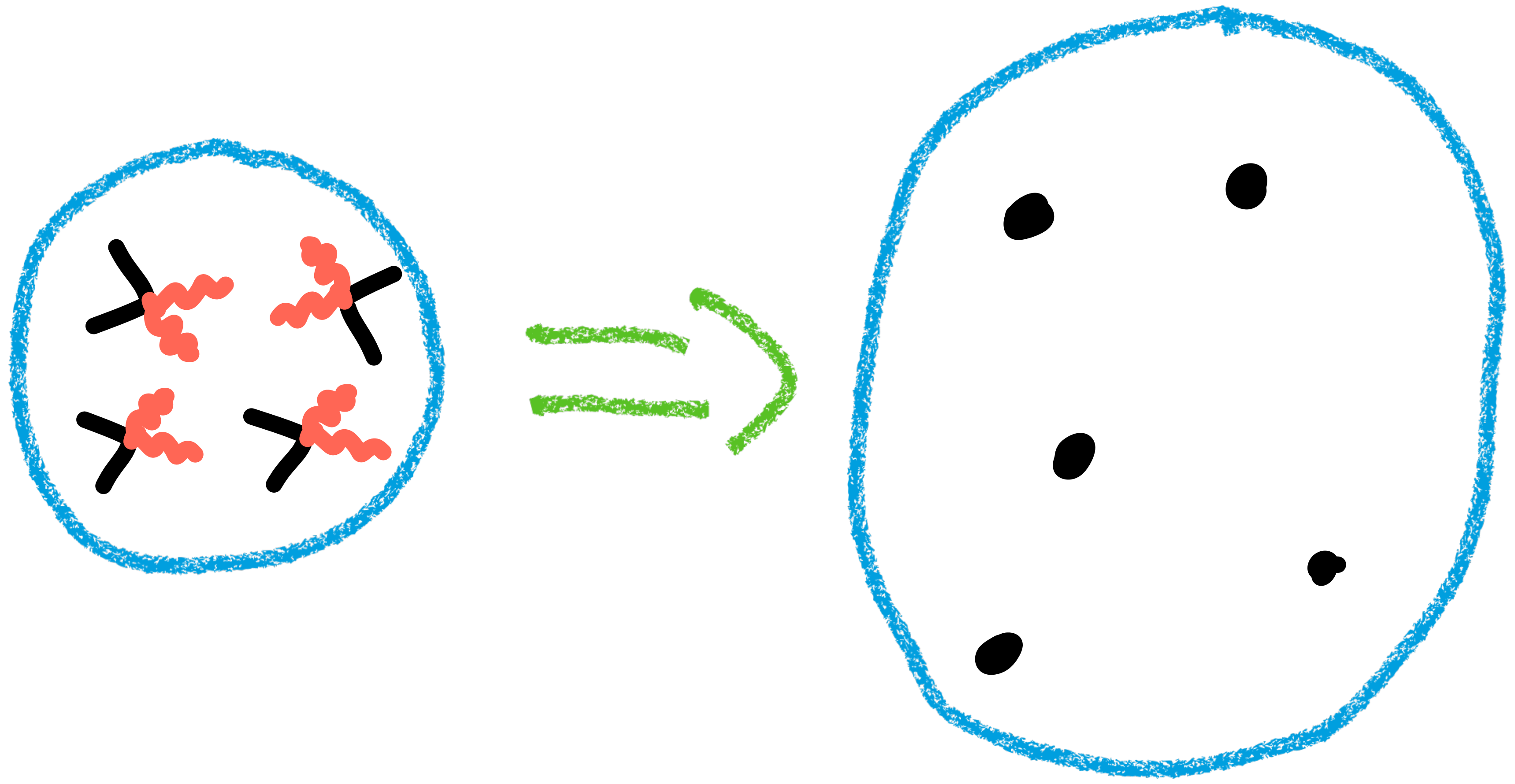


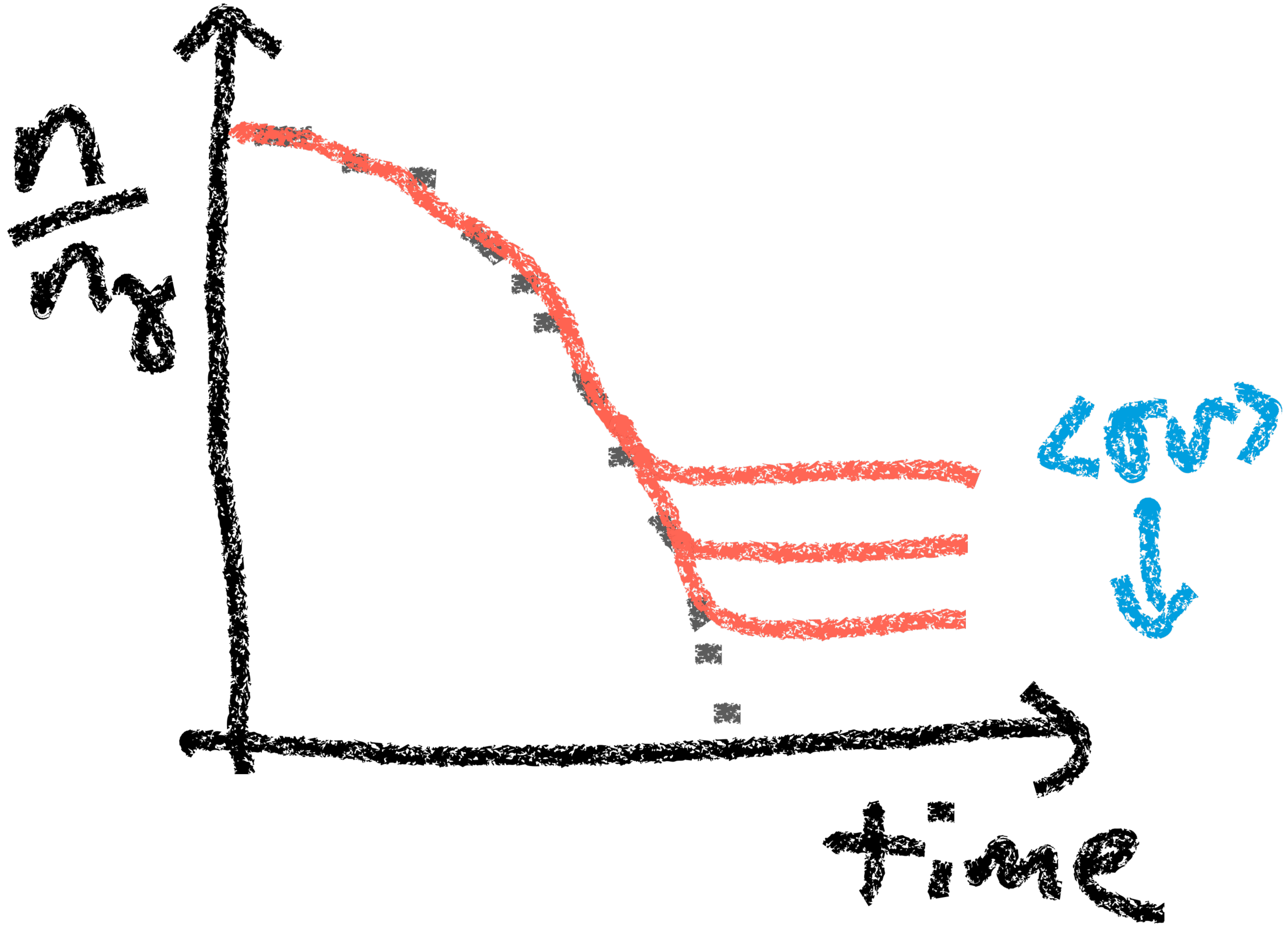
Thermal production offers a nice (predictive) story

Thermally produced DM

$$\frac{dn}{dt} + 3Hn = -\langle \sigma v \rangle \left(n^2 - n_{\mathrm{eq}}^2 \right)$$

Competition between
expansion and microphysics



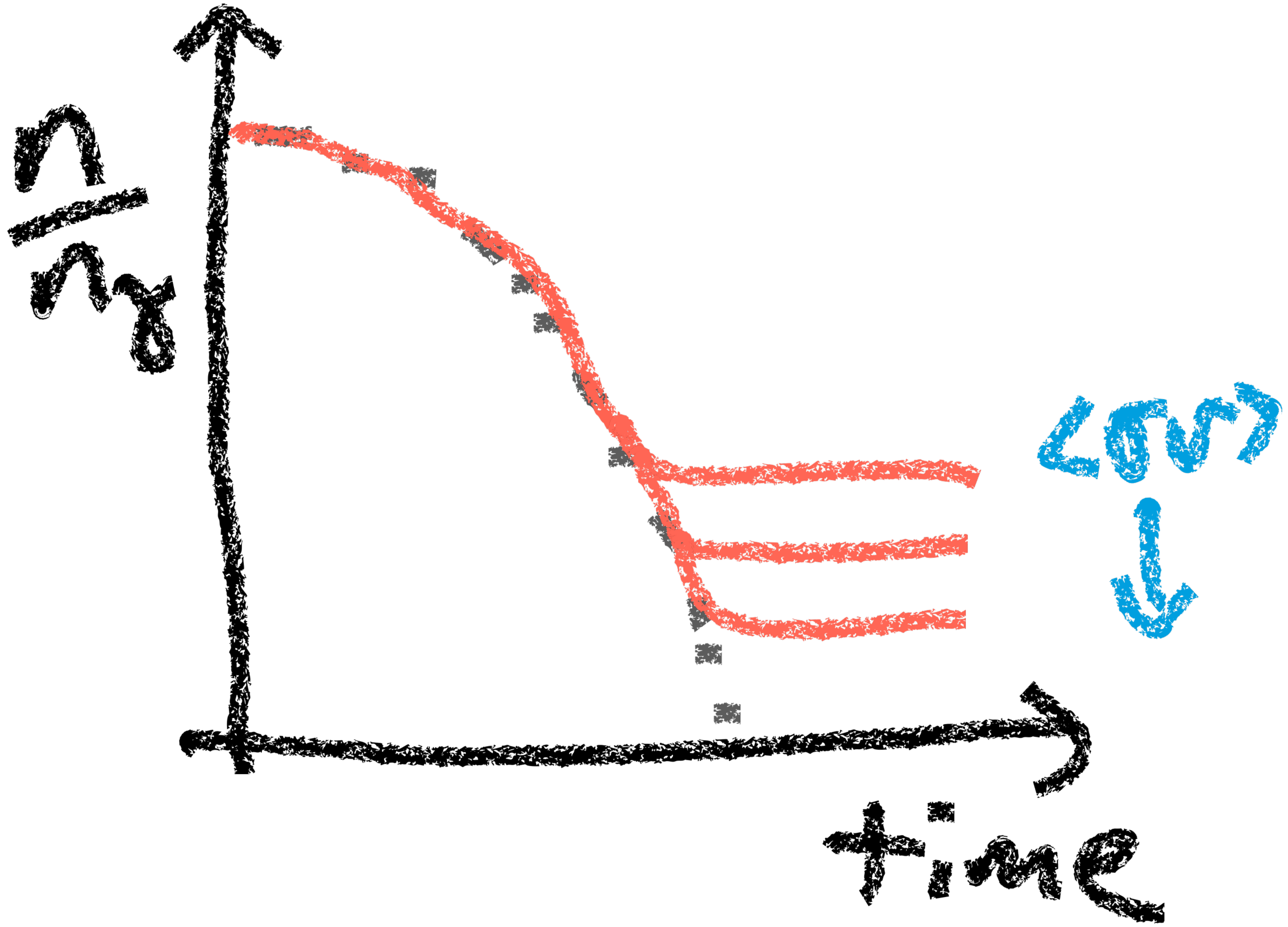


Thermally produced DM

$$\frac{dn}{dt} + 3Hn = -\langle\sigma v\rangle\left(n^2 - n_{\rm eq}^2\right)$$

$$\Rightarrow \Omega h^2 \sim \frac{\Omega_\gamma h^2}{\text{few} \times T_{\rm CMB} M_{\rm Pl}\langle\sigma v\rangle} \sim \frac{1}{10^3\ \text{TeV}^2\langle\sigma v\rangle}$$

$$\langle\sigma v\rangle = \text{const} \times \frac{g^4}{\Lambda^2} \Rightarrow \frac{\Lambda}{g^2} \sim 10\ \text{TeV}\sqrt{\frac{\Omega h^2}{0.1}}$$



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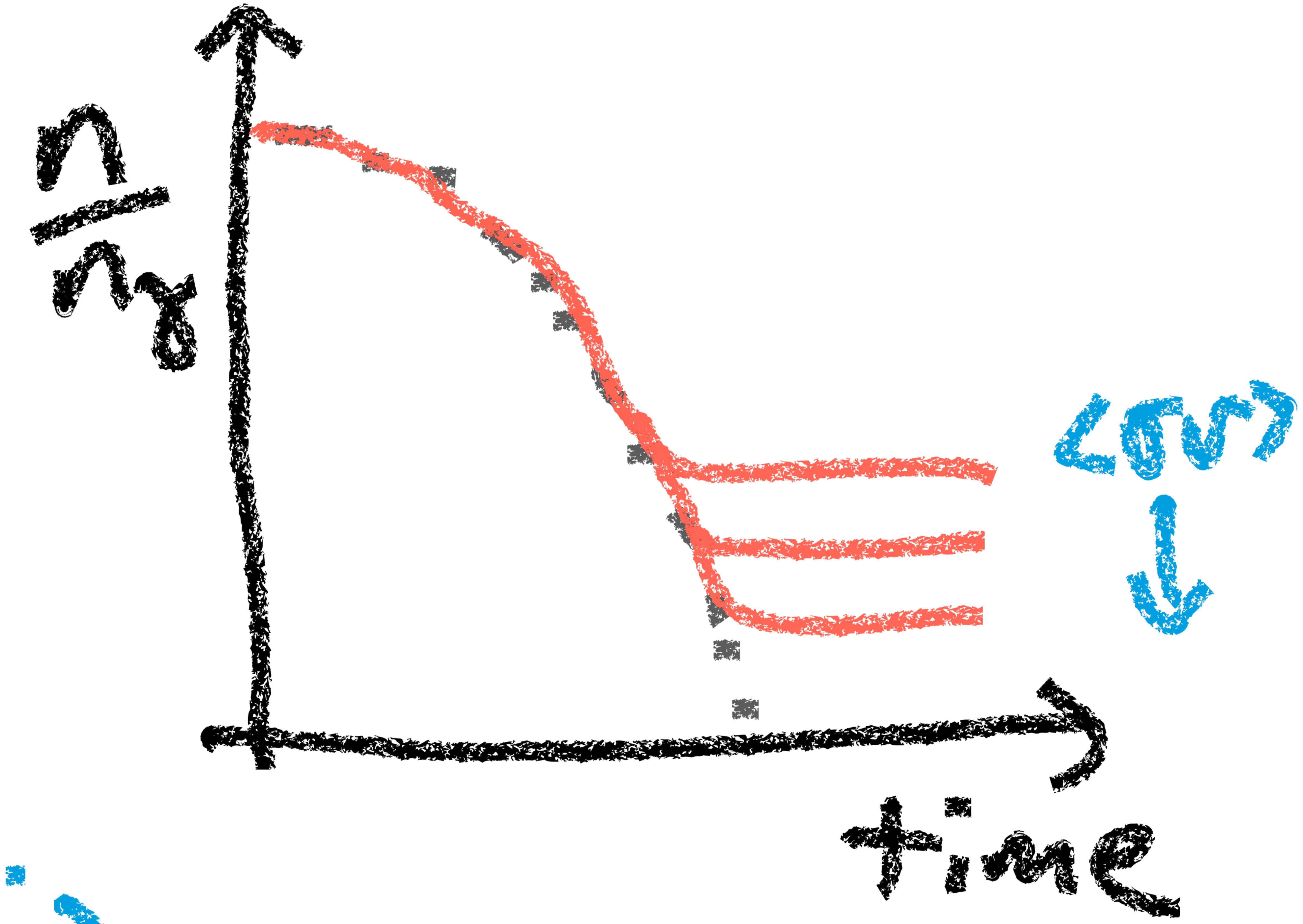
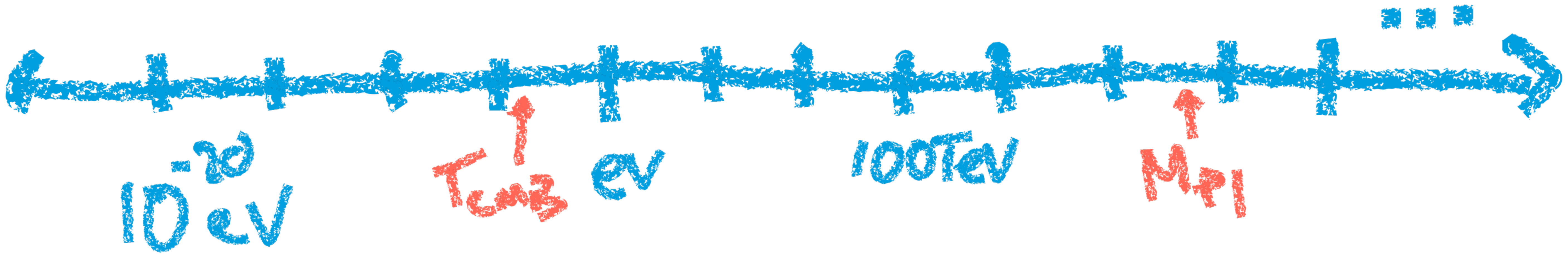




cf. Dimopoulos PLB **246**, 347 (1990)

WIMP "Miracle"

$$\Lambda \sim 100 \text{ GeV} \left(\frac{g}{0.1}\right)^2 \sqrt{\frac{\Omega h^2}{0.1}}$$

Something with weak scale mass and coupling (hence WIMP) can obtain correct DM density

Weak scale is a very interesting scale

Could be connected to deep puzzles concerning electroweak symmetry breaking

e.g. SUSY: $H_{u,d}$ B W

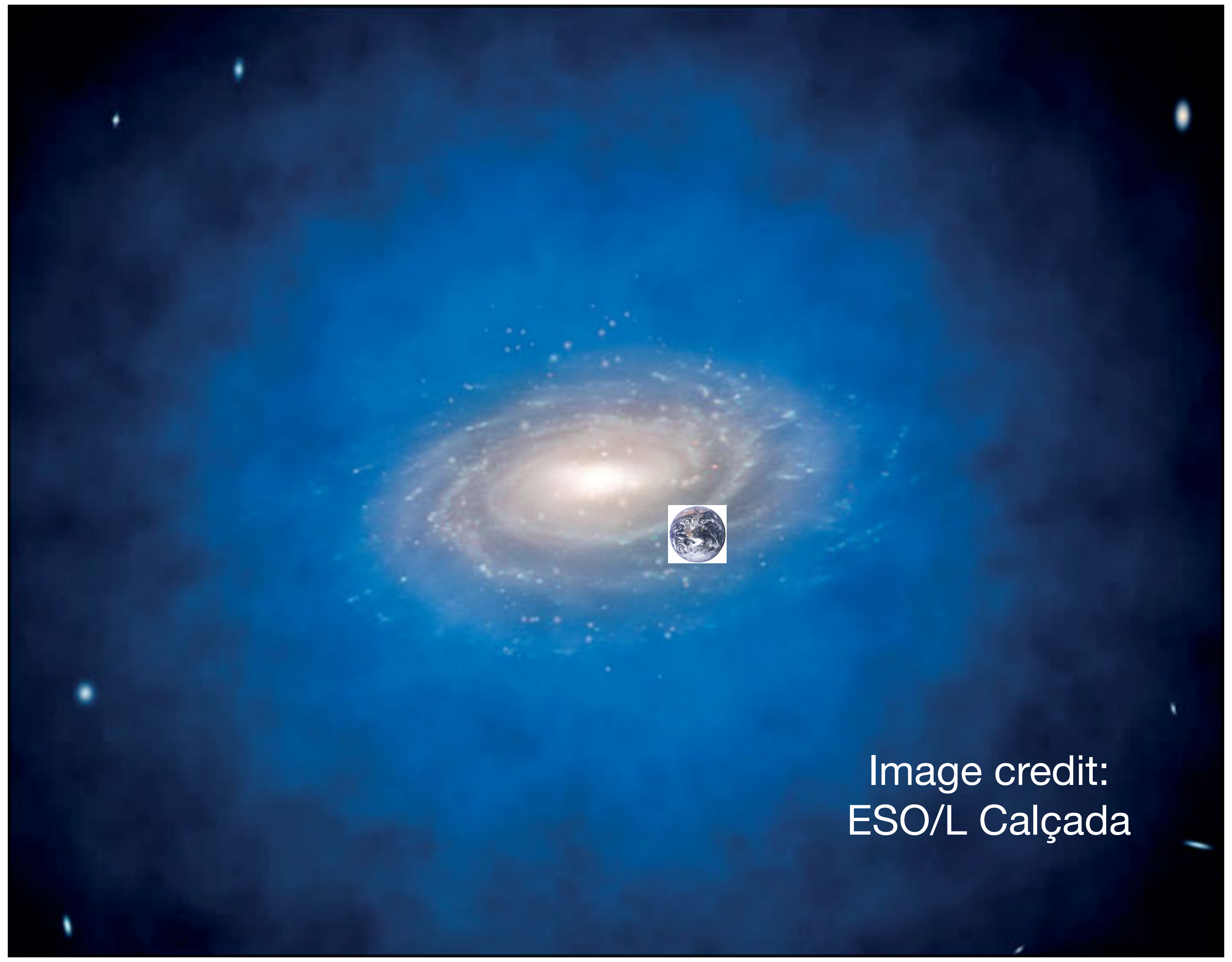
$\tilde{H}_{u,d}$ $\tilde{B}$ $\tilde{W}$

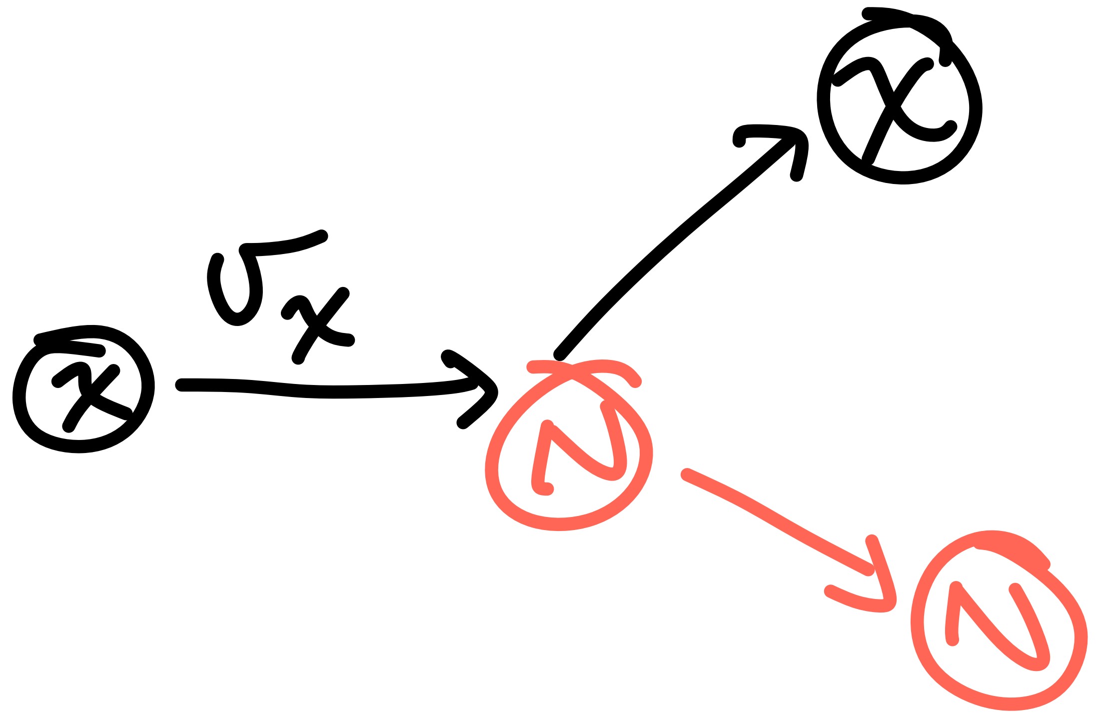
Proton stability⇒Lightest of these is stable⇒DM candidate!

(See also extra-dims., Little Higgs, …)

Connection to other mysteries is a very nice feature

Searching for WIMPs



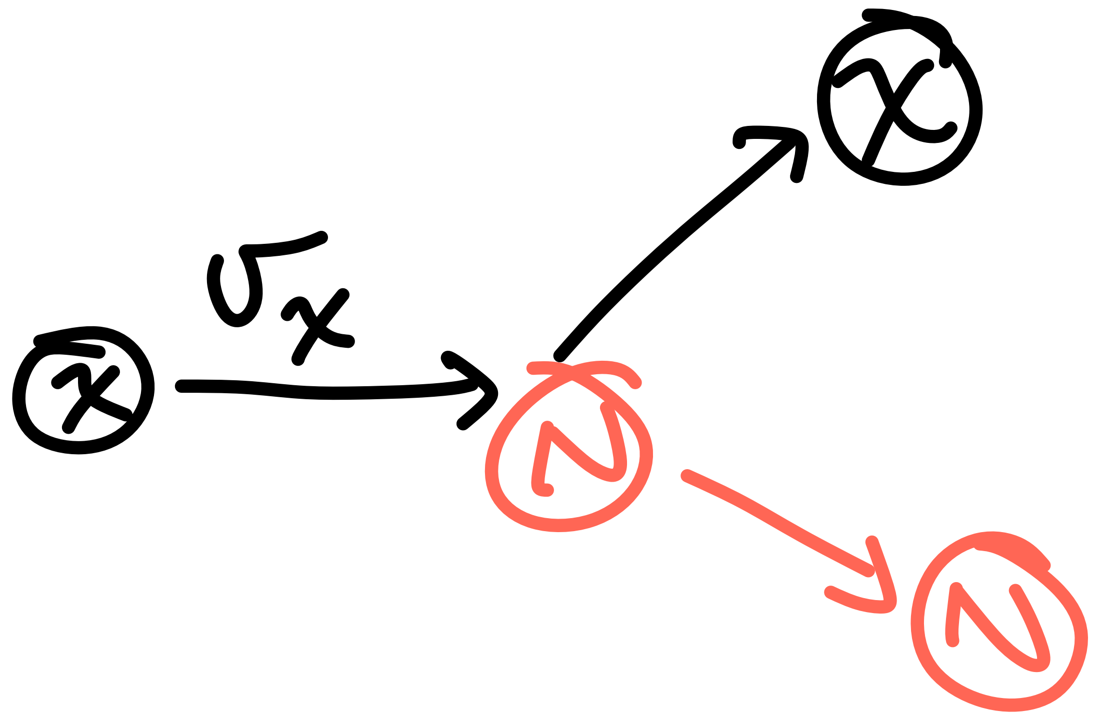


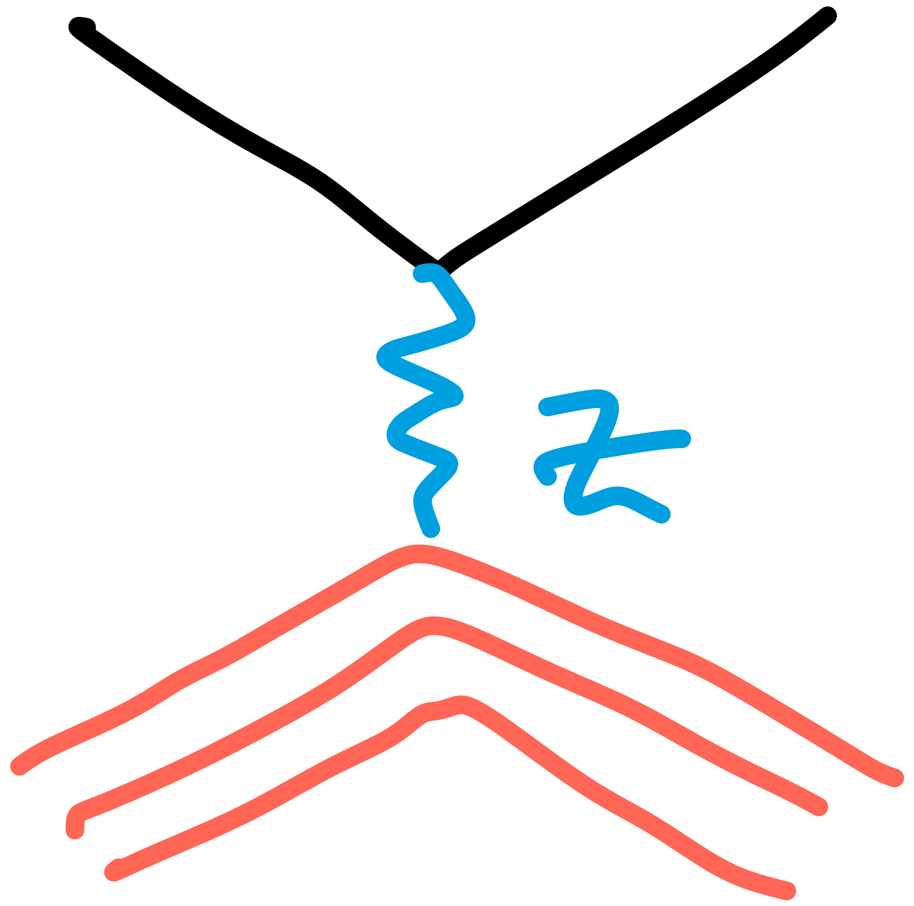
Detect recoil

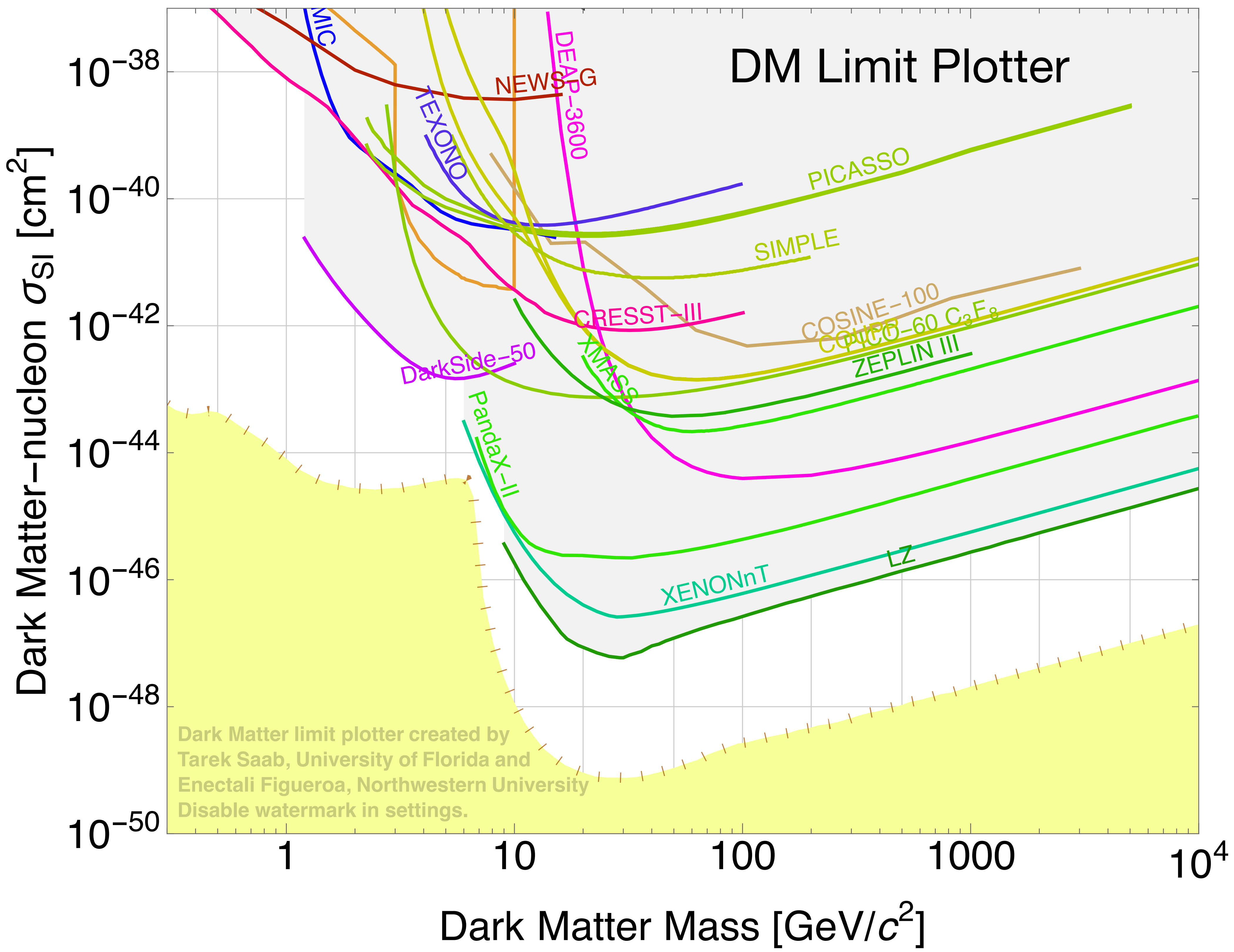
$$E_{\mathrm{recoil}} \leq \frac{2\mu_{\chi N}^2 v_\chi^2}{m_N} \sim \mathcal{O}(10\ \mathrm{keV})\ \text{for}\ v_\chi \sim 10^{-3}c$$

Goodman & Witten (1985)

Searching for WIMPs





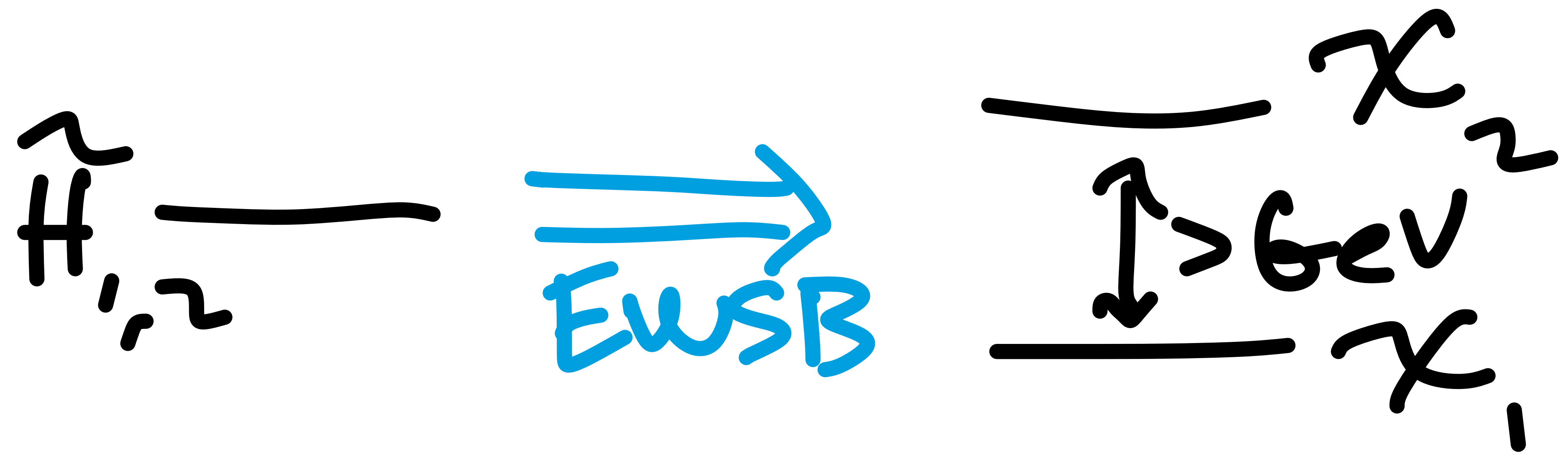


$$\sigma_N \simeq \frac{G_F^2 \mu_{N\chi}^2}{2\pi} Y^2 \sim 10^{-38} Y^2 \text{ cm}^2$$

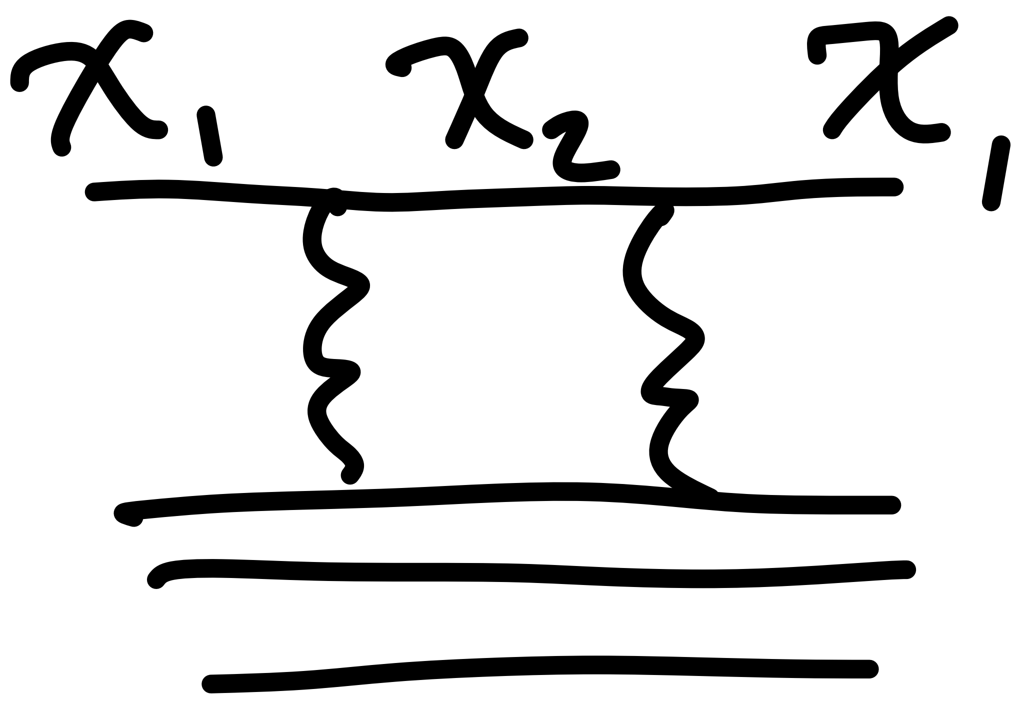
Vanilla WIMPs are dead

The “WIMPiest” WIMPs

Top down models lead to not-so-vanilla WIMPs…



e.g. Higgsino DM is inelastic



The "WIMPiest" WIMPs

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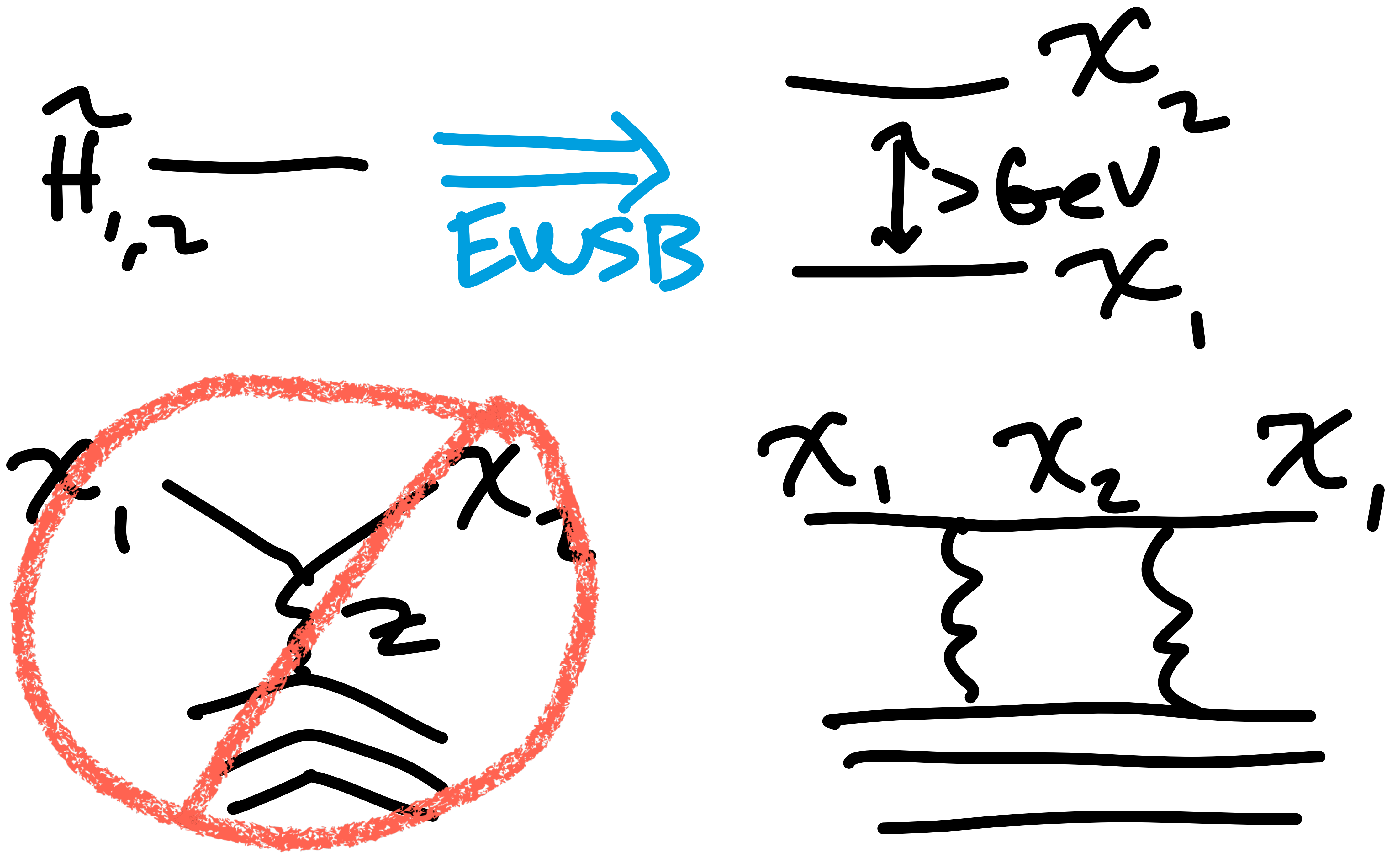

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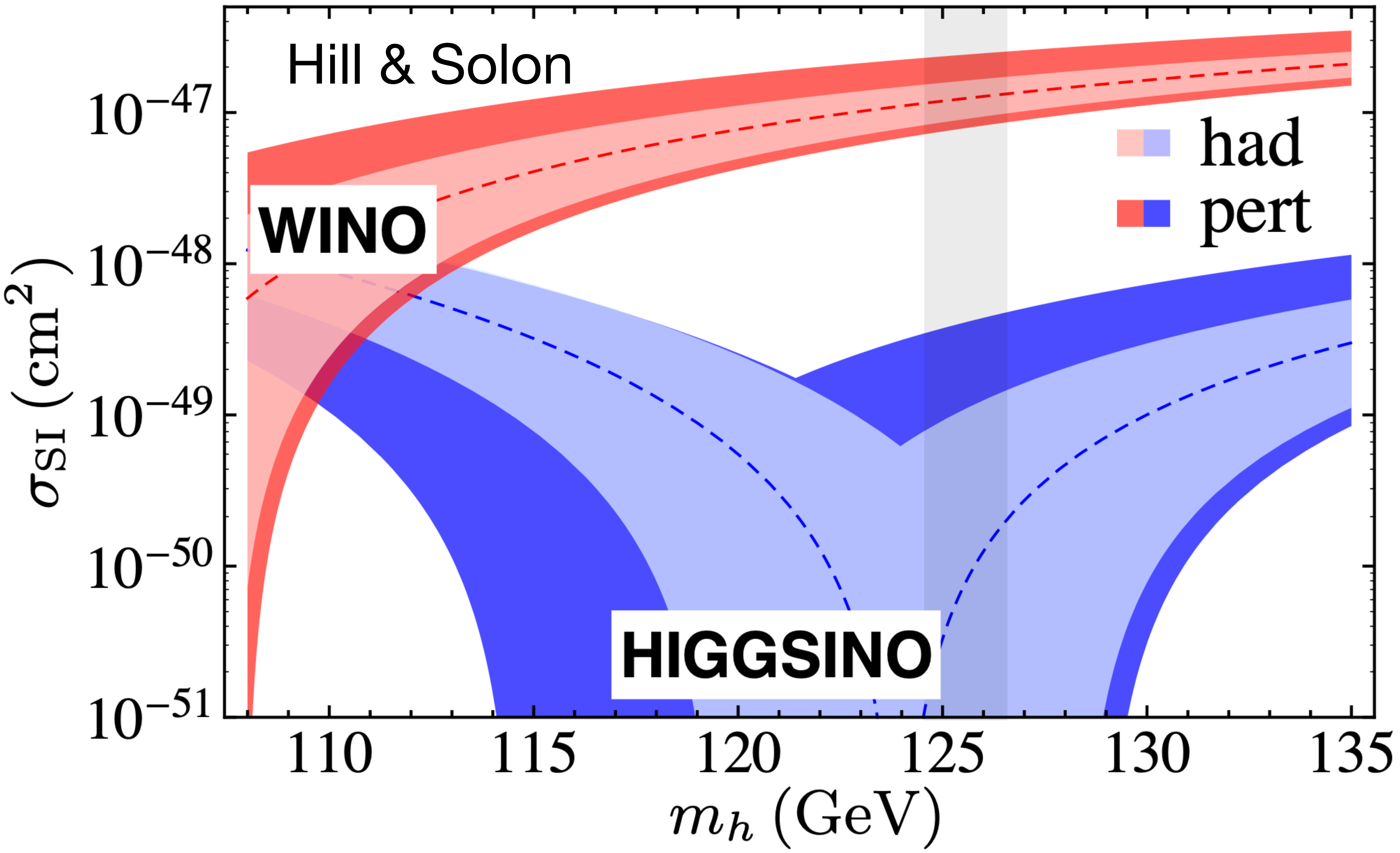
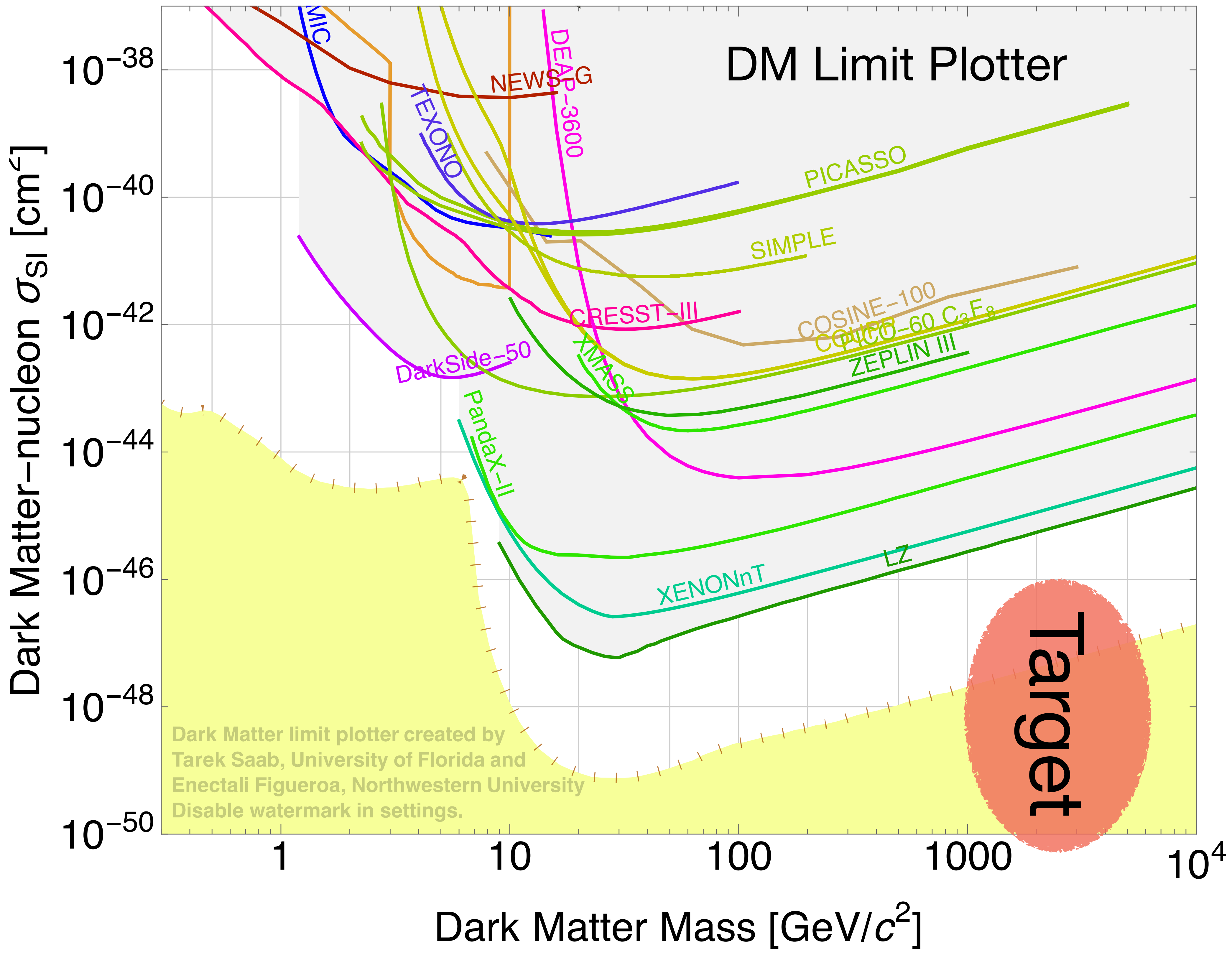
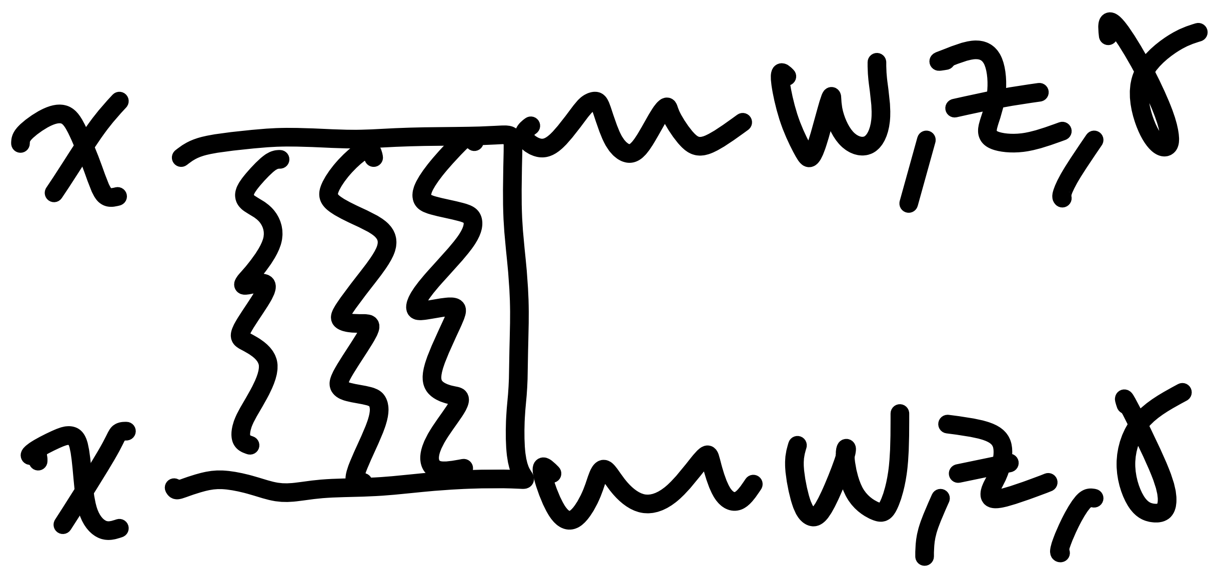




See also Hisano et al., Cirelli et al., …

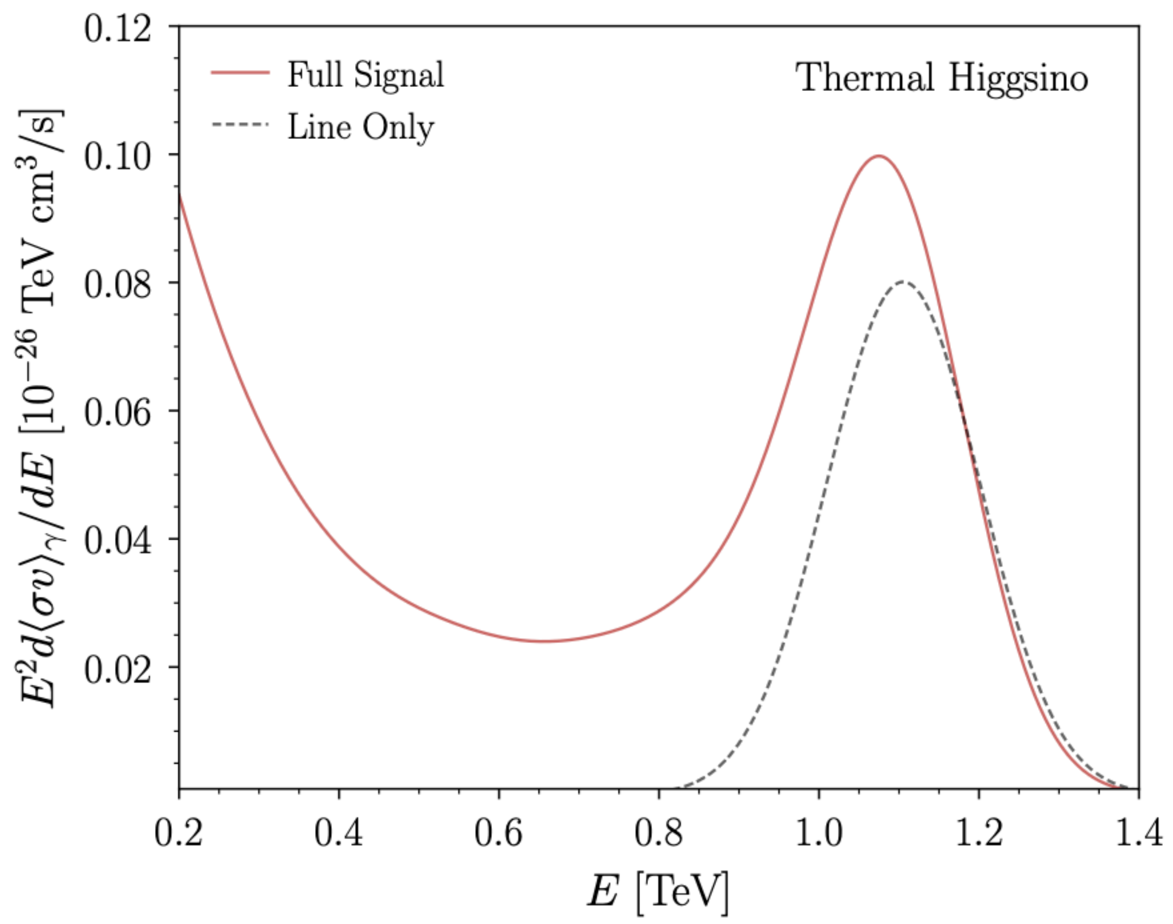
The “WIMPiest” WIMPs

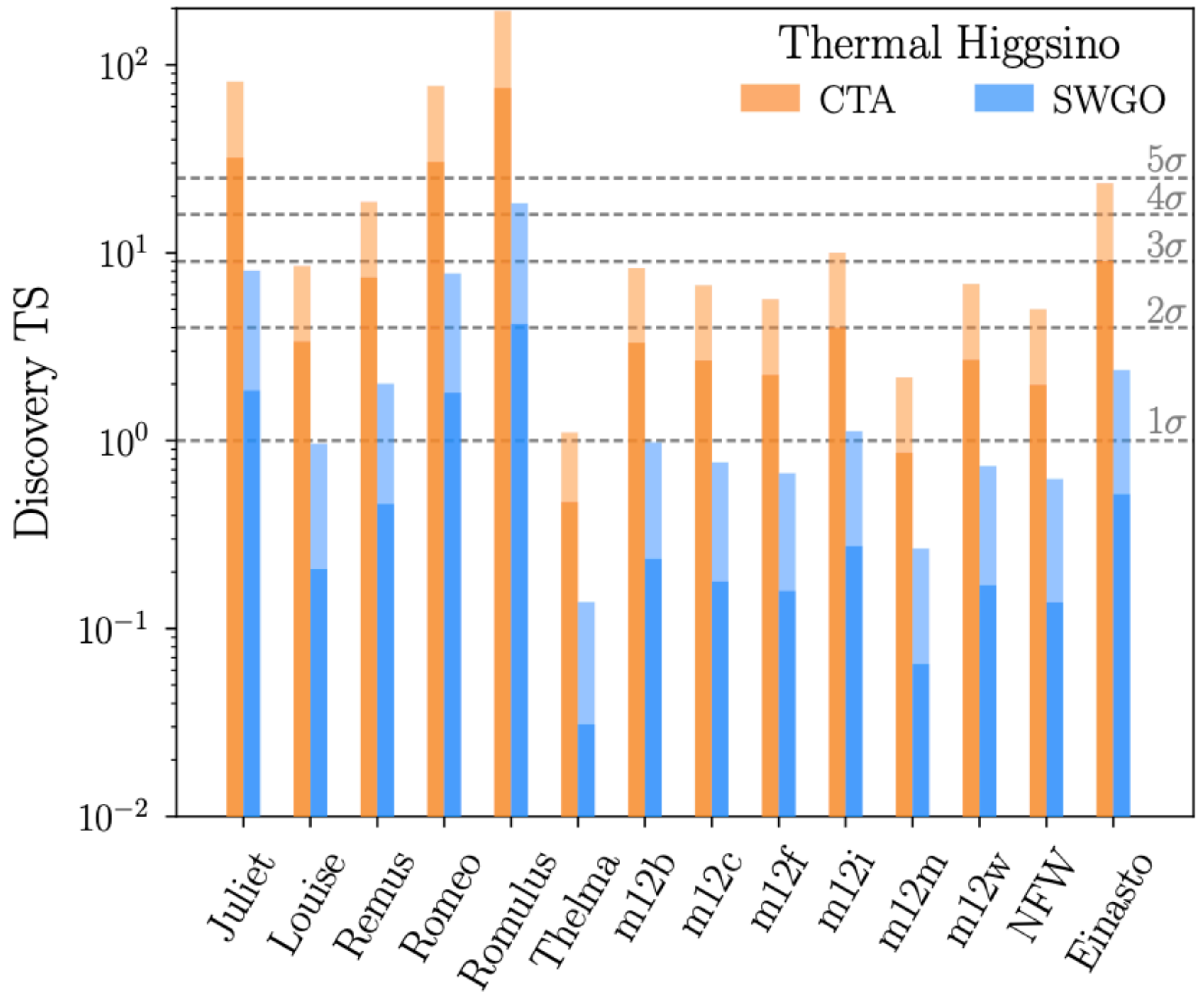
Pure $\mathrm{SU}(2)_L$ doublet (Higgsino) or triplet (Wino)



Pure Higgsino at $1.1\ \mathrm{TeV}$ gives correct abundance

Gamma rays from galactic center good way to constrain



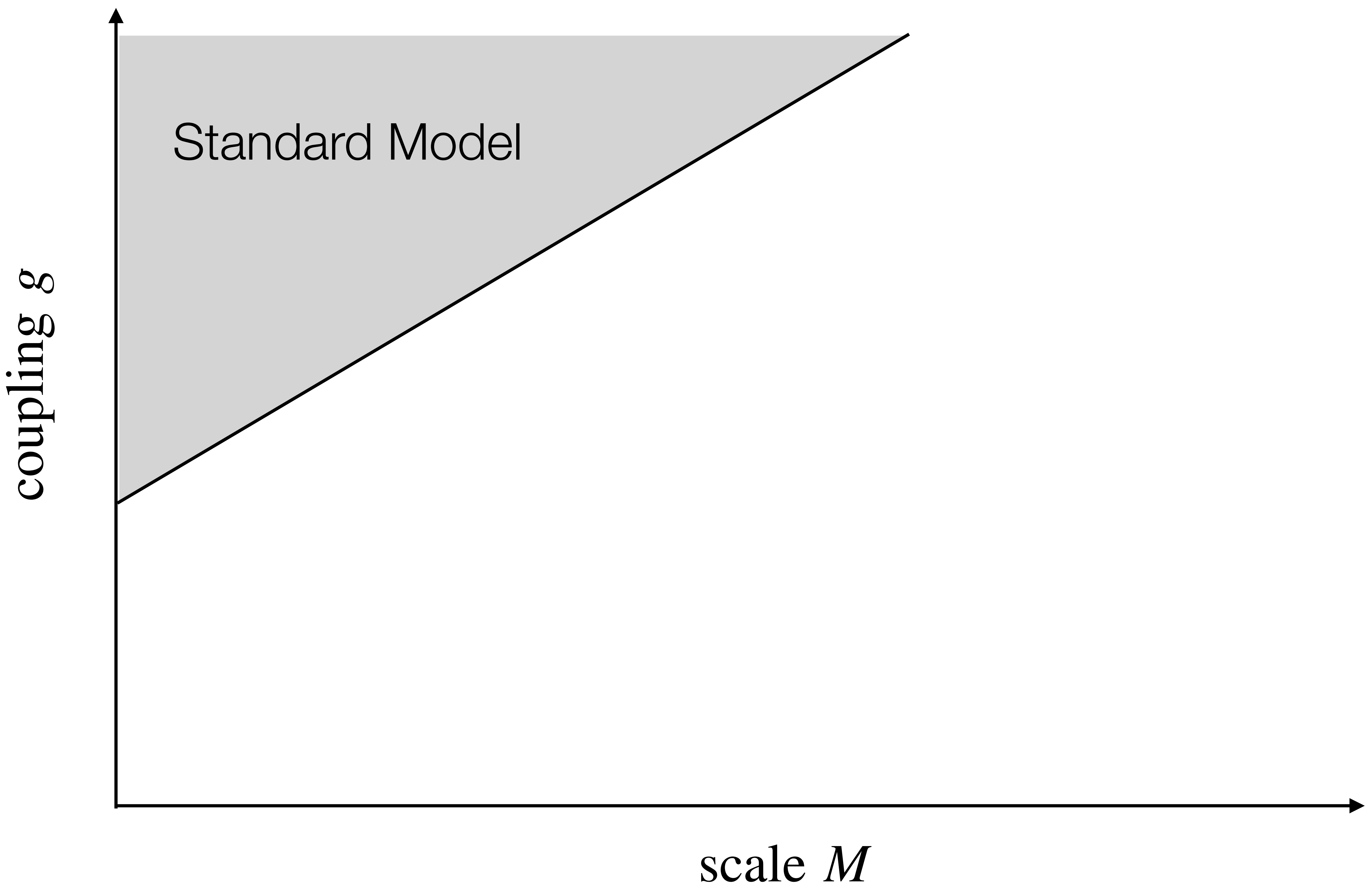


Rodd, Safdi, & Xu
2405.13104

Winos & larger reps: Baumgart et al. 2507.15937; Safdi & Xu 2507.15934—Pure Winos excluded

Changing gears a bit…

~~WIMP~~ “Miracle”



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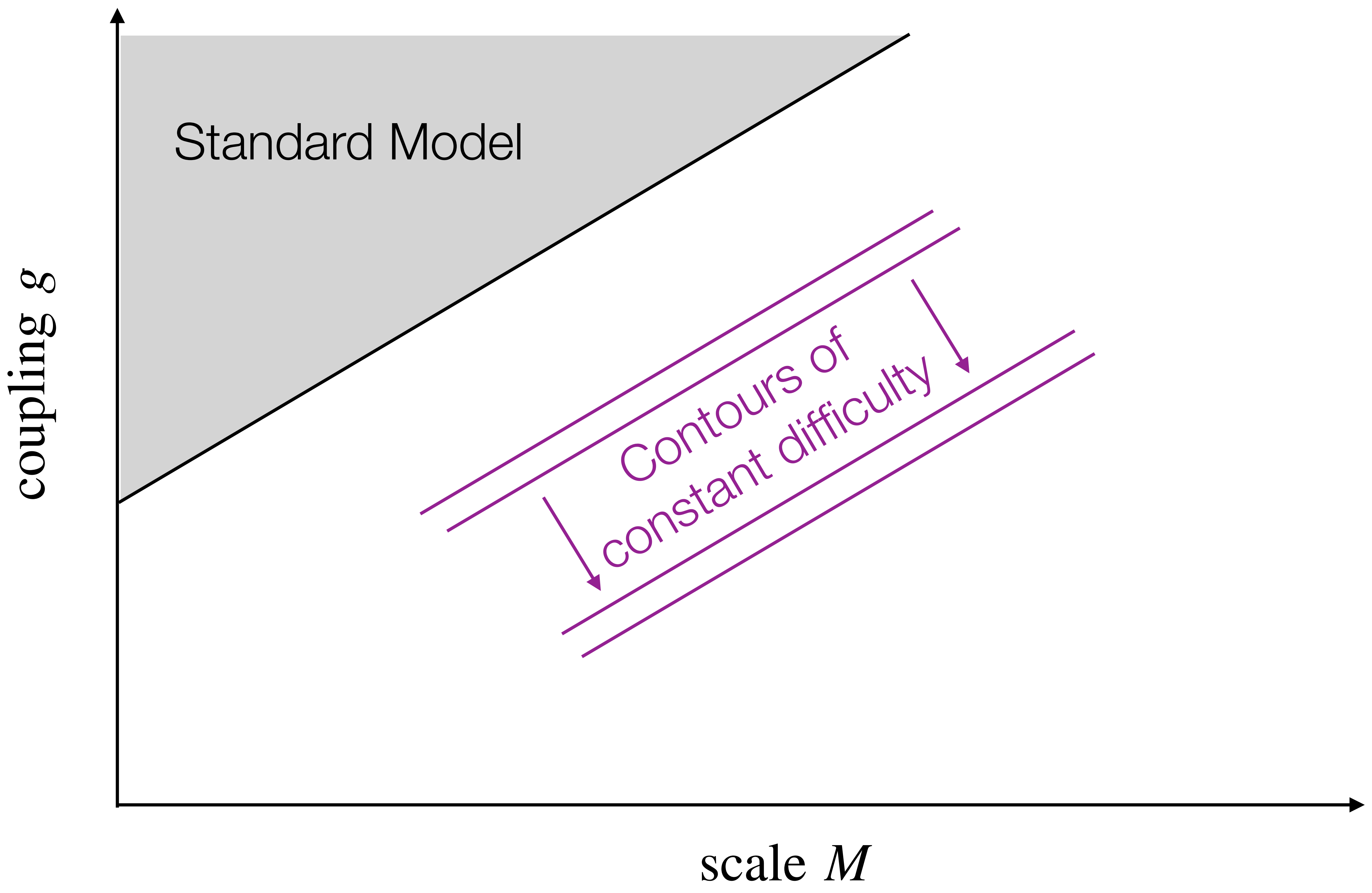

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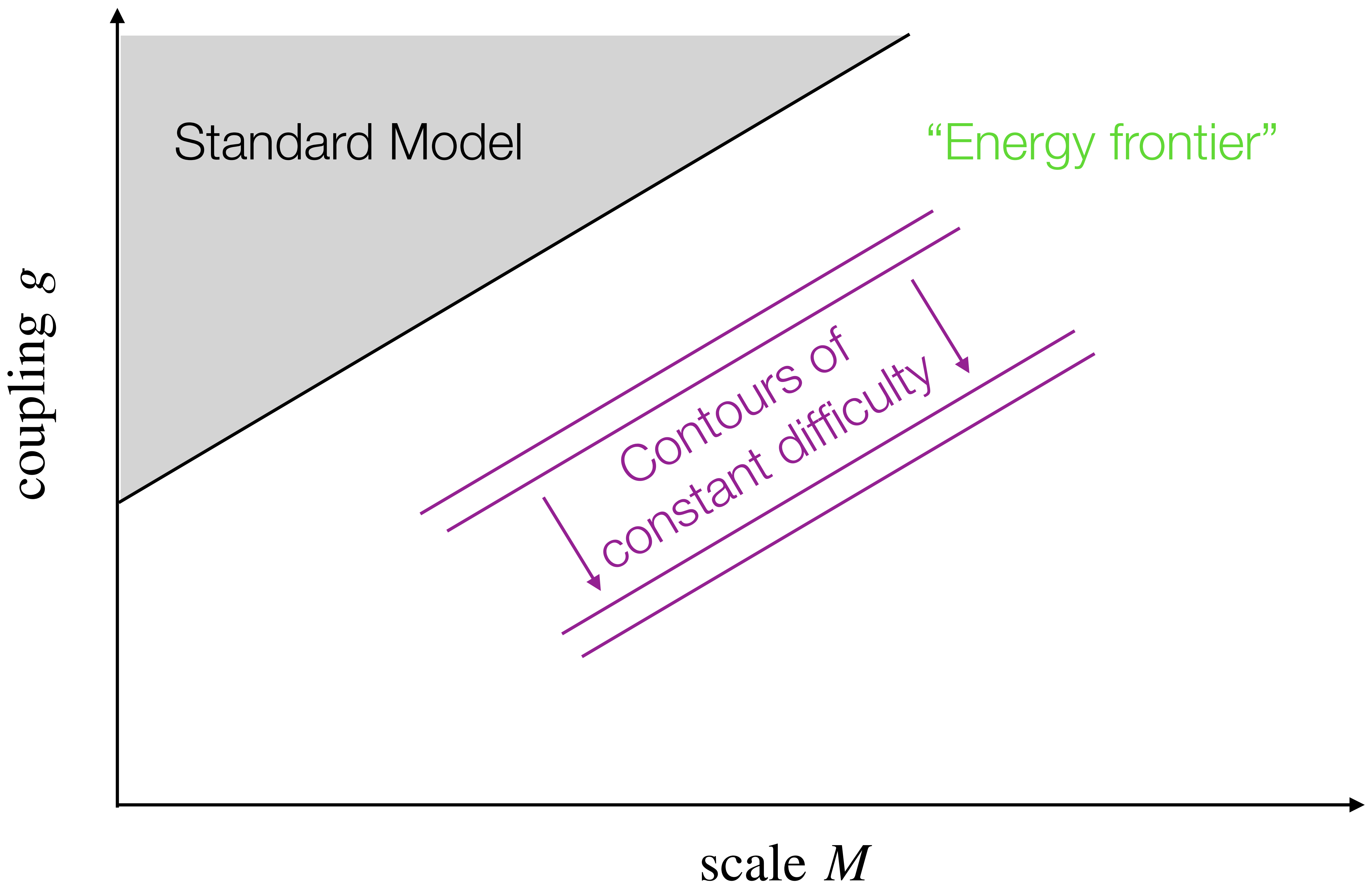

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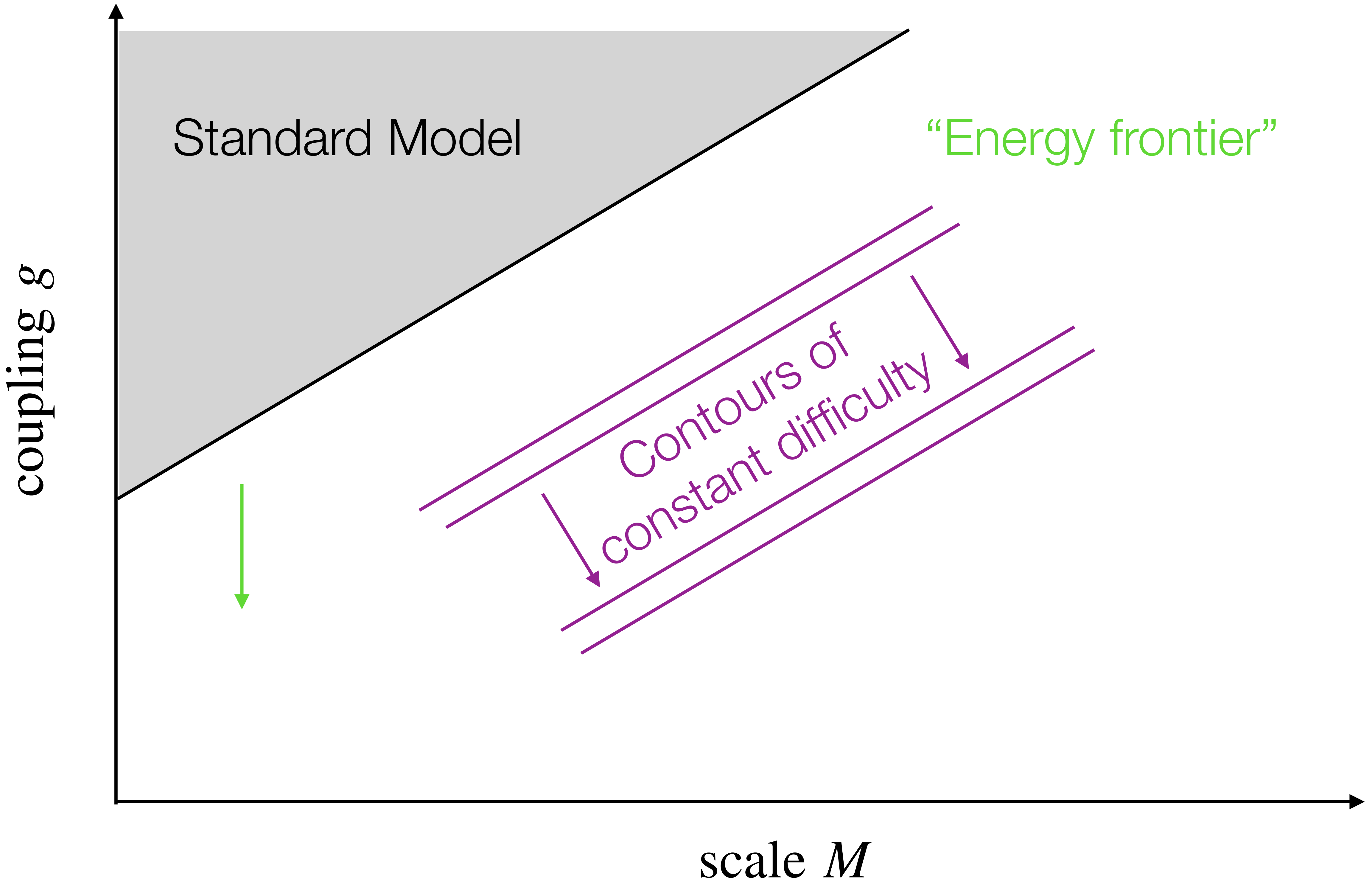

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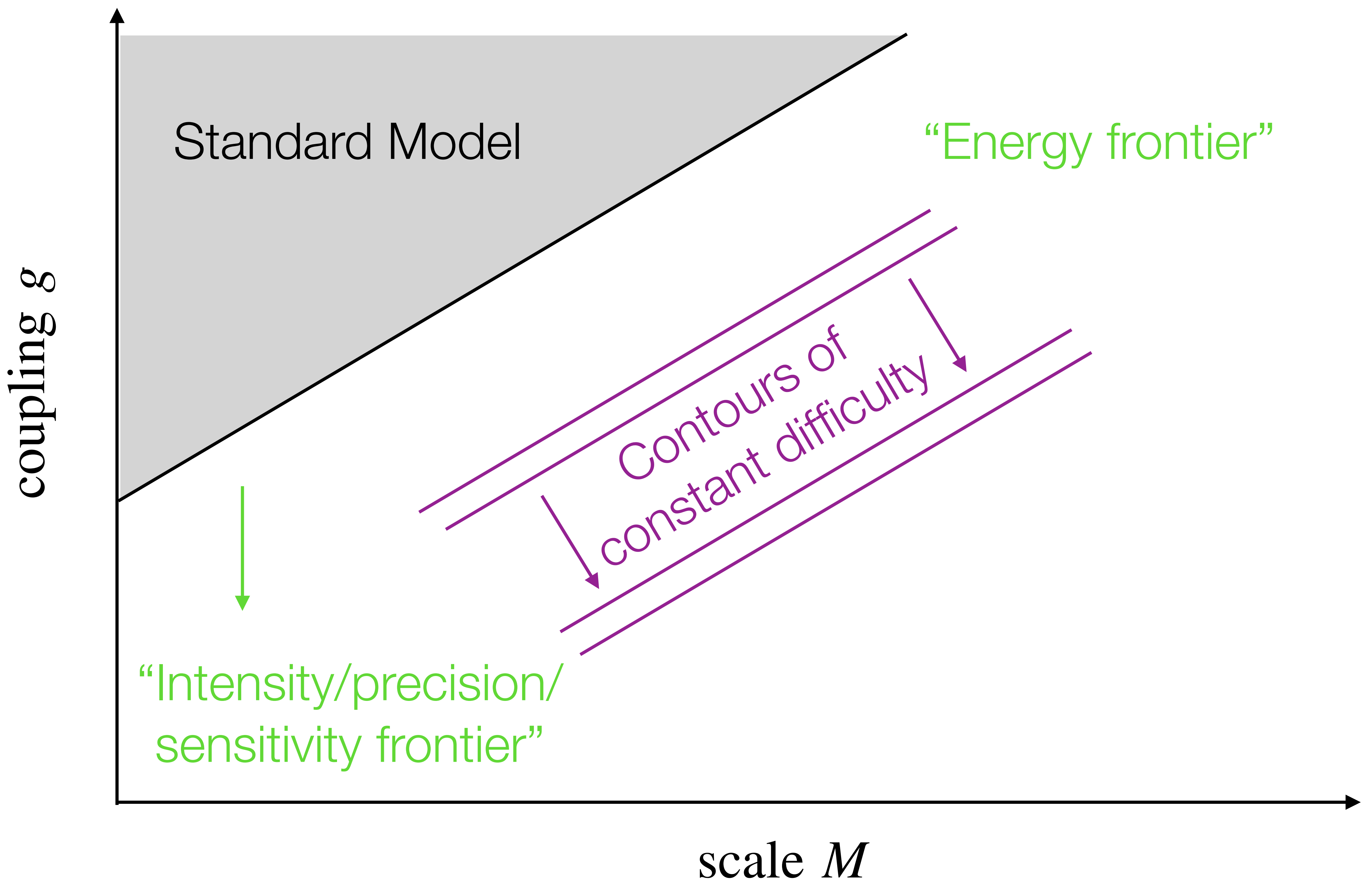

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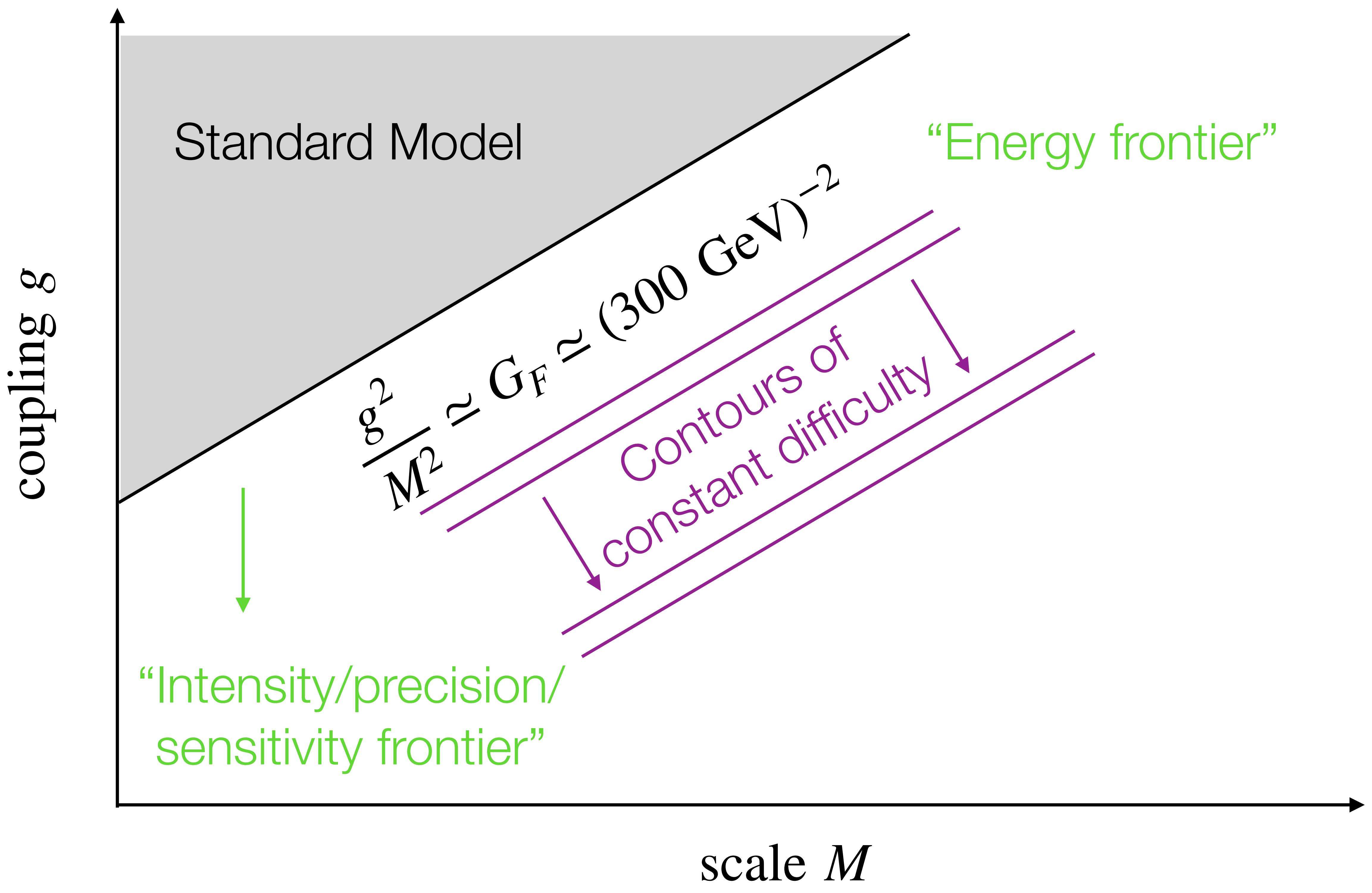

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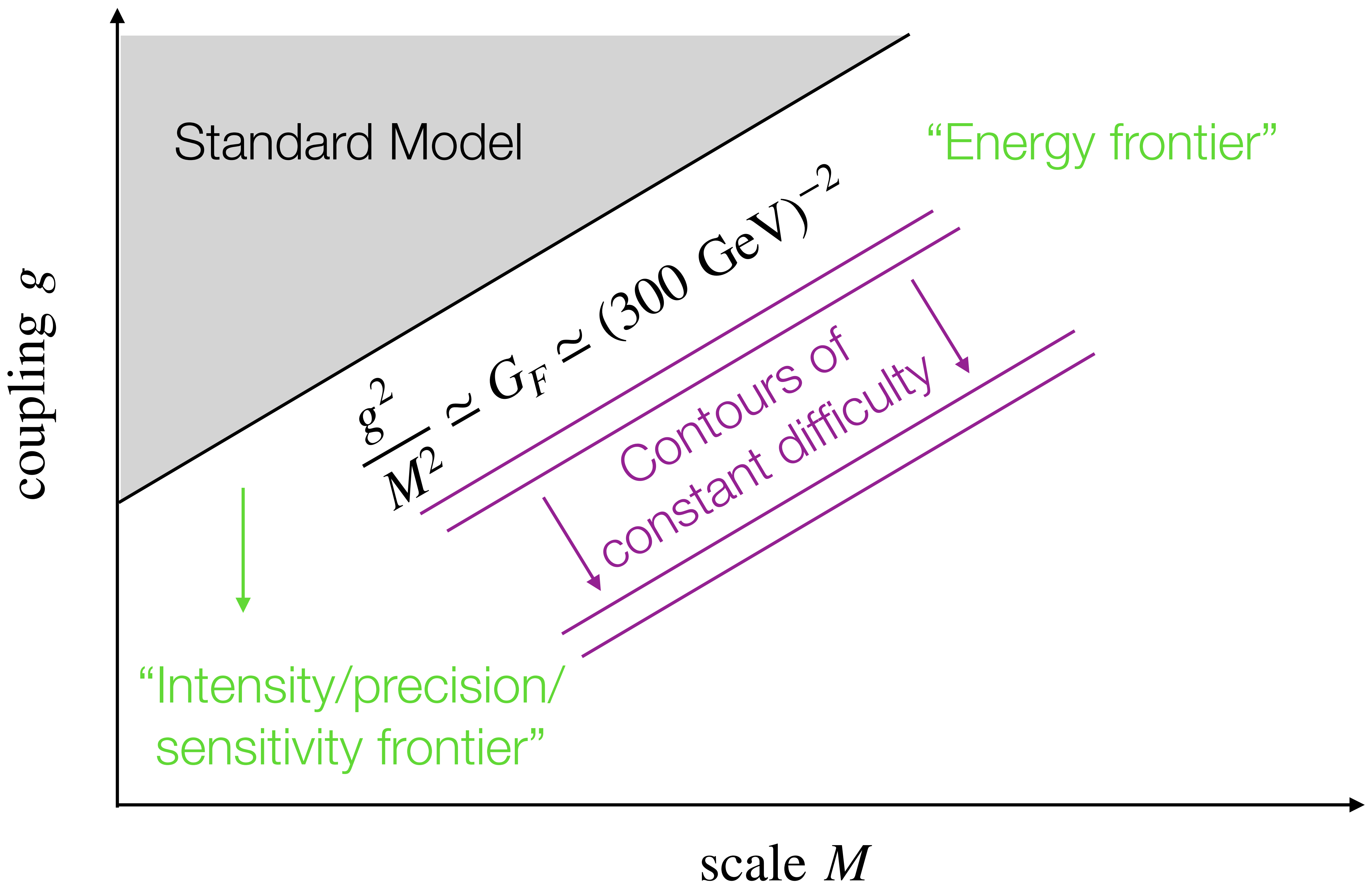
$$\frac{\Lambda}{g^2} \sim 10\ \mathrm{TeV}\sqrt{\frac{\Omega h^2}{0.1}} \sim \mathcal{O}\left(G_F^{-1/2}\right)$$



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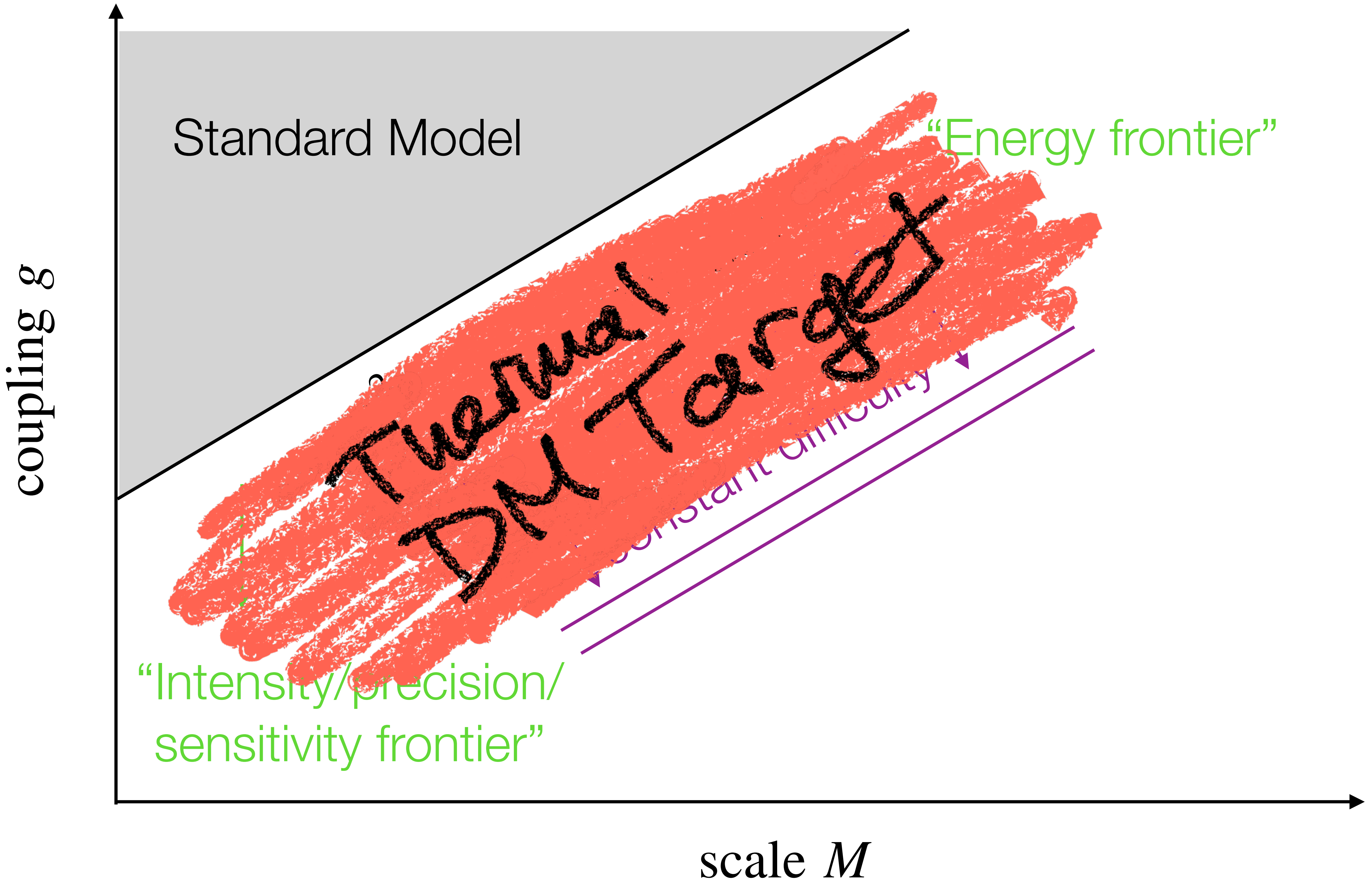

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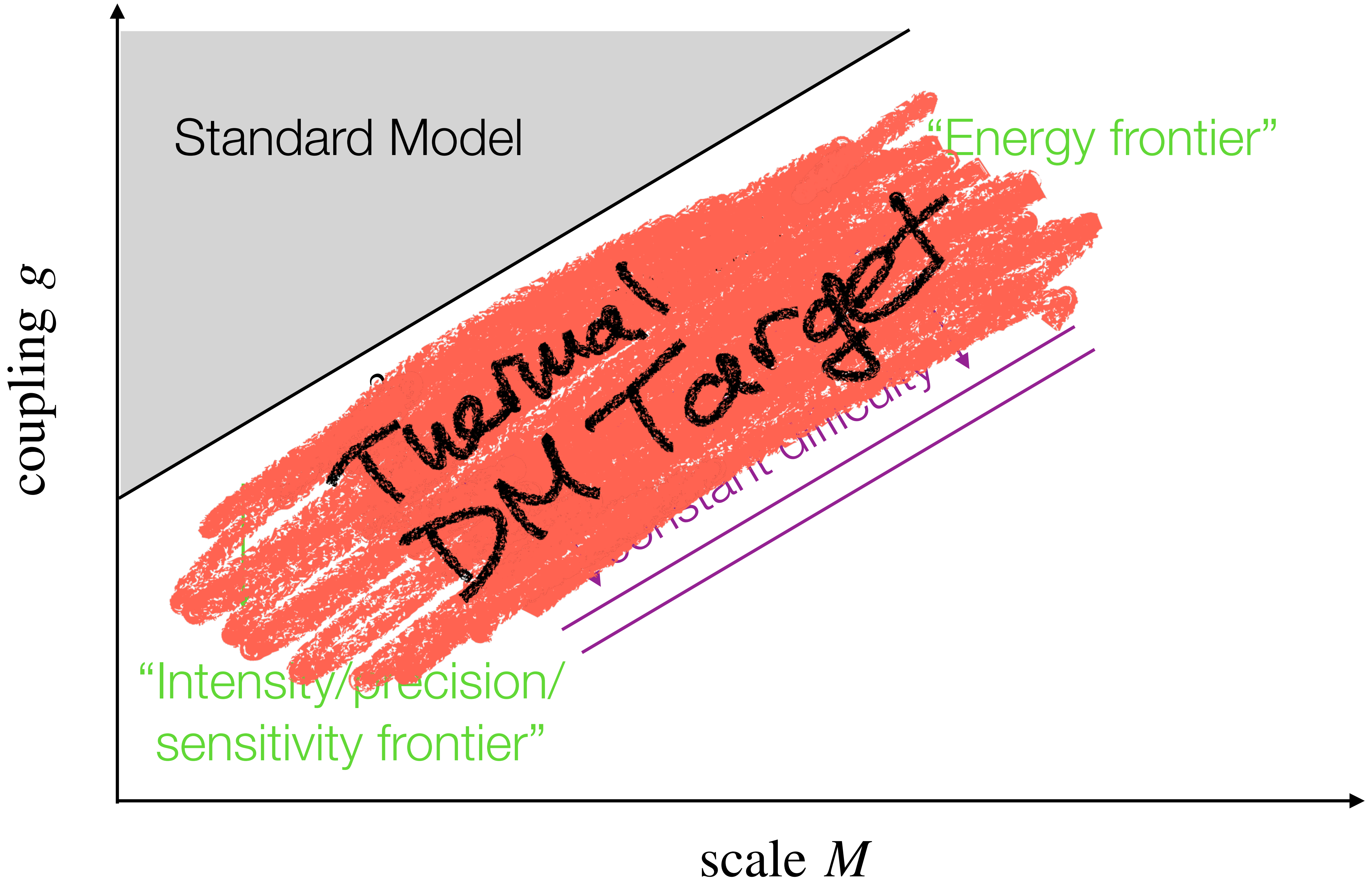
Need not be tied to weak scale



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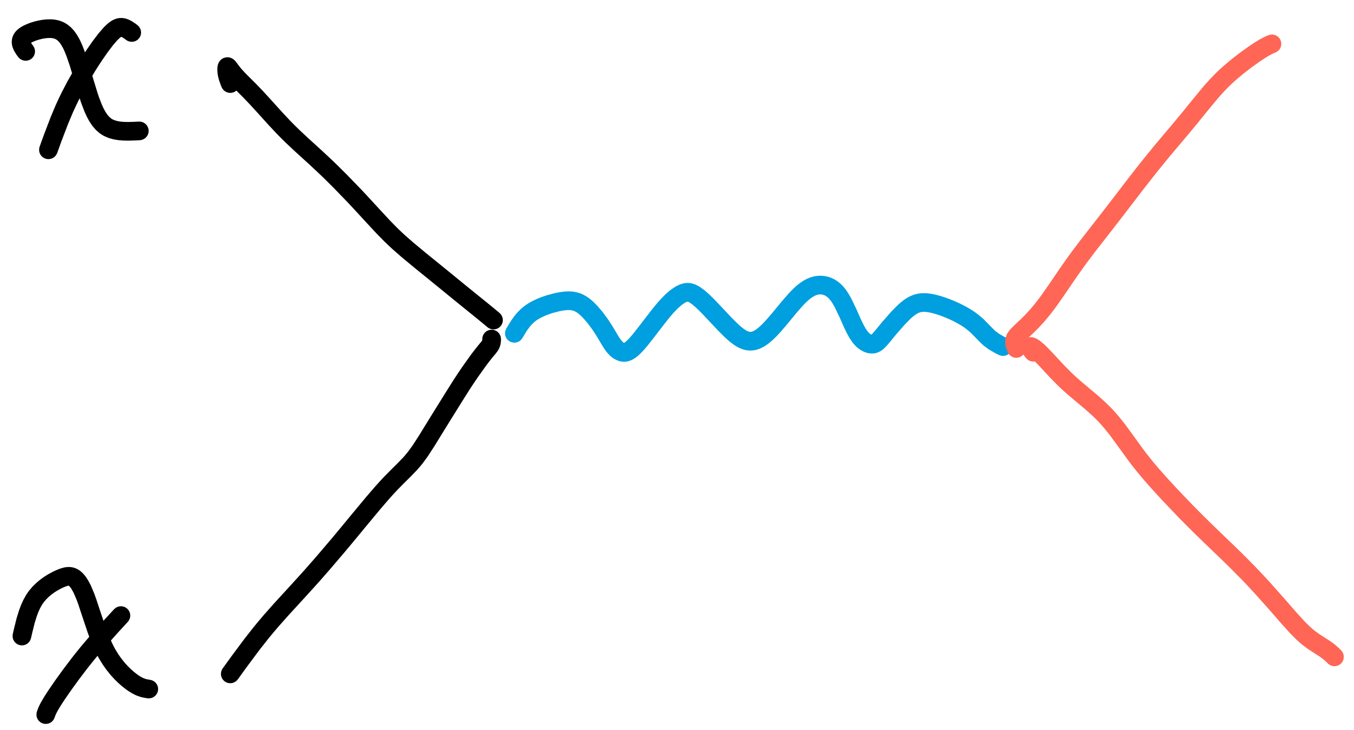
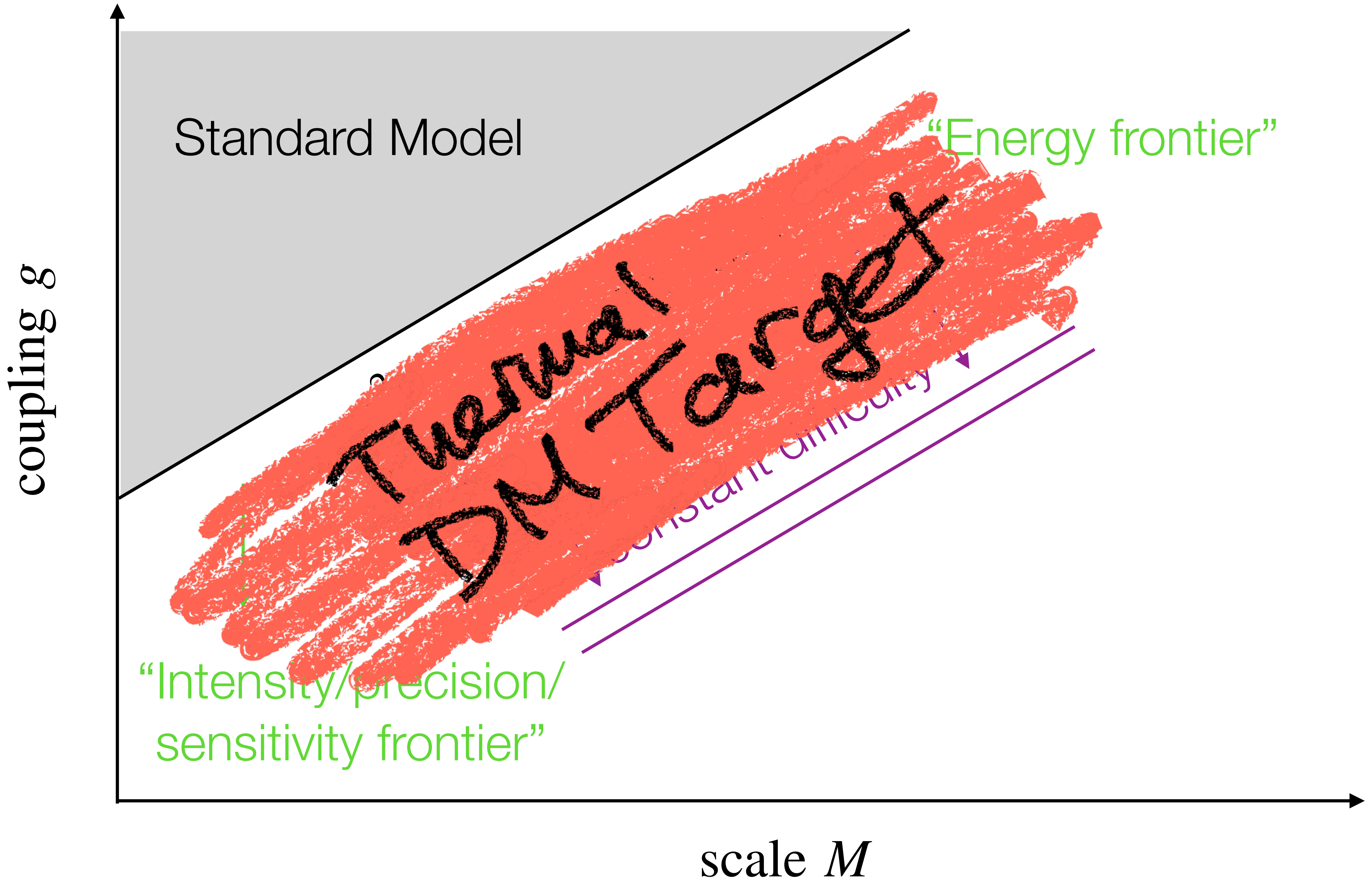
Need not be tied to weak scale

Feng, Kumar (2008)





But if we want to push the scale down we **need new light mediators**

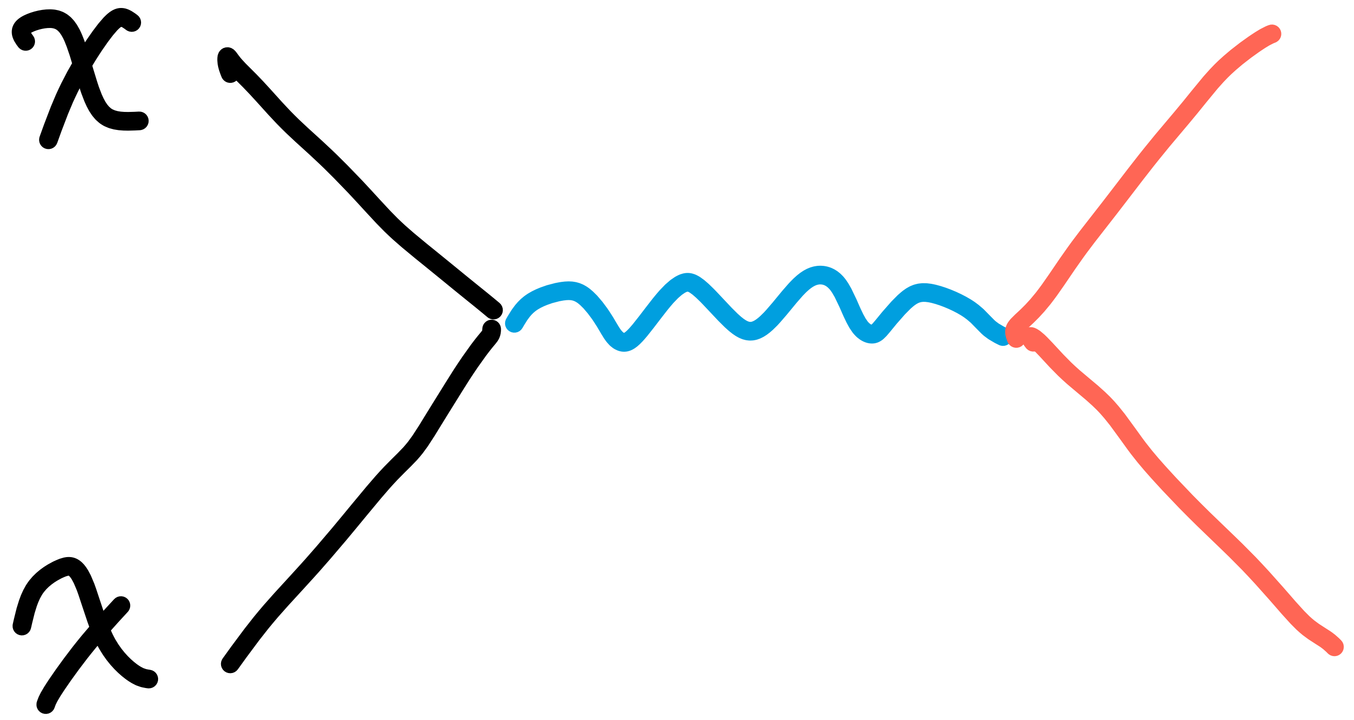
Lee, Weinberg (1977)

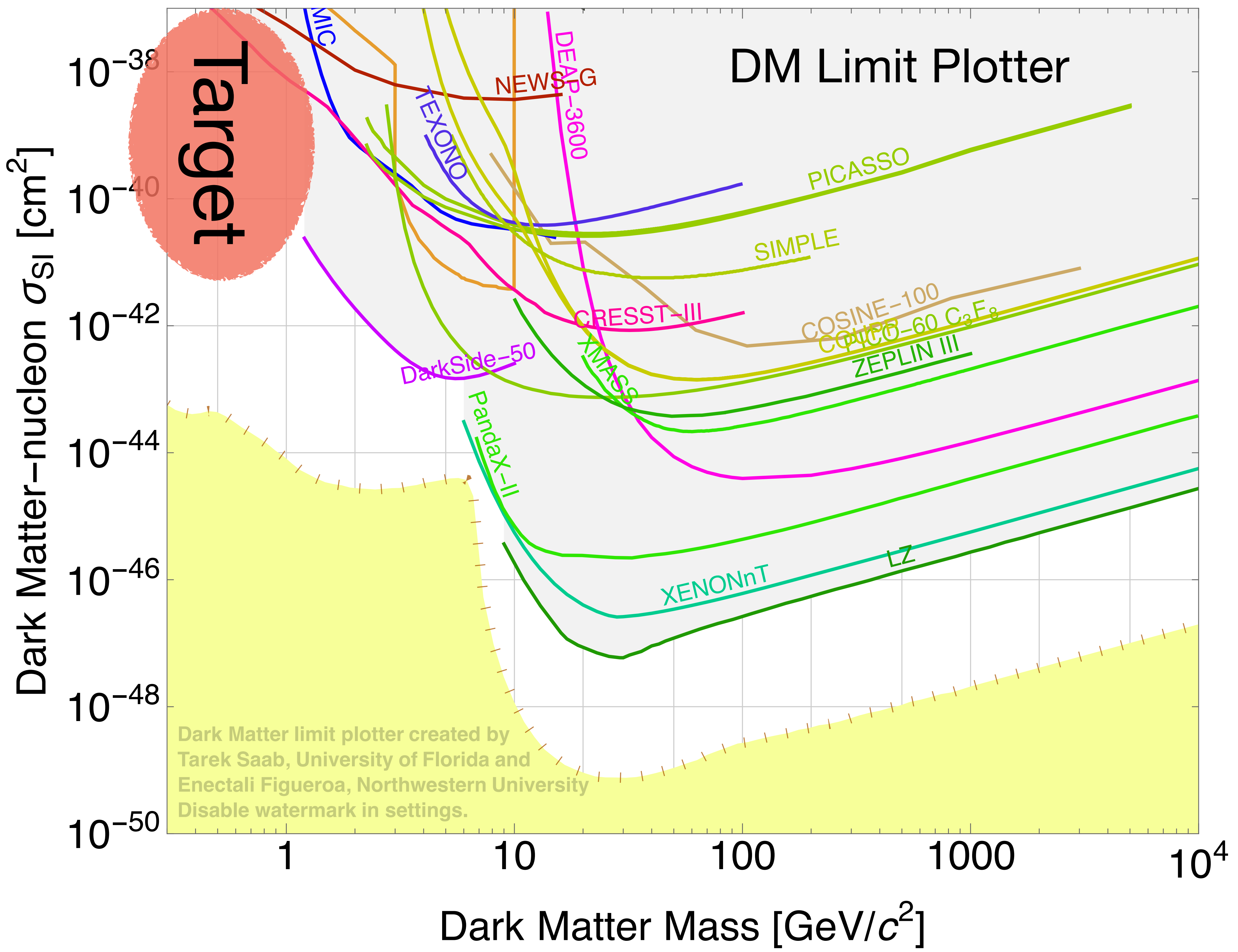
~~WIMP~~ “Miracle”

$$\frac{\Lambda}{g^2} \sim 10\ \text{TeV}\sqrt{\frac{\Omega h^2}{0.1}} \sim \mathcal{O}\left(G_F^{-1/2}\right)$$

Need not be tied to weak scale

Feng, Kumar (2008)



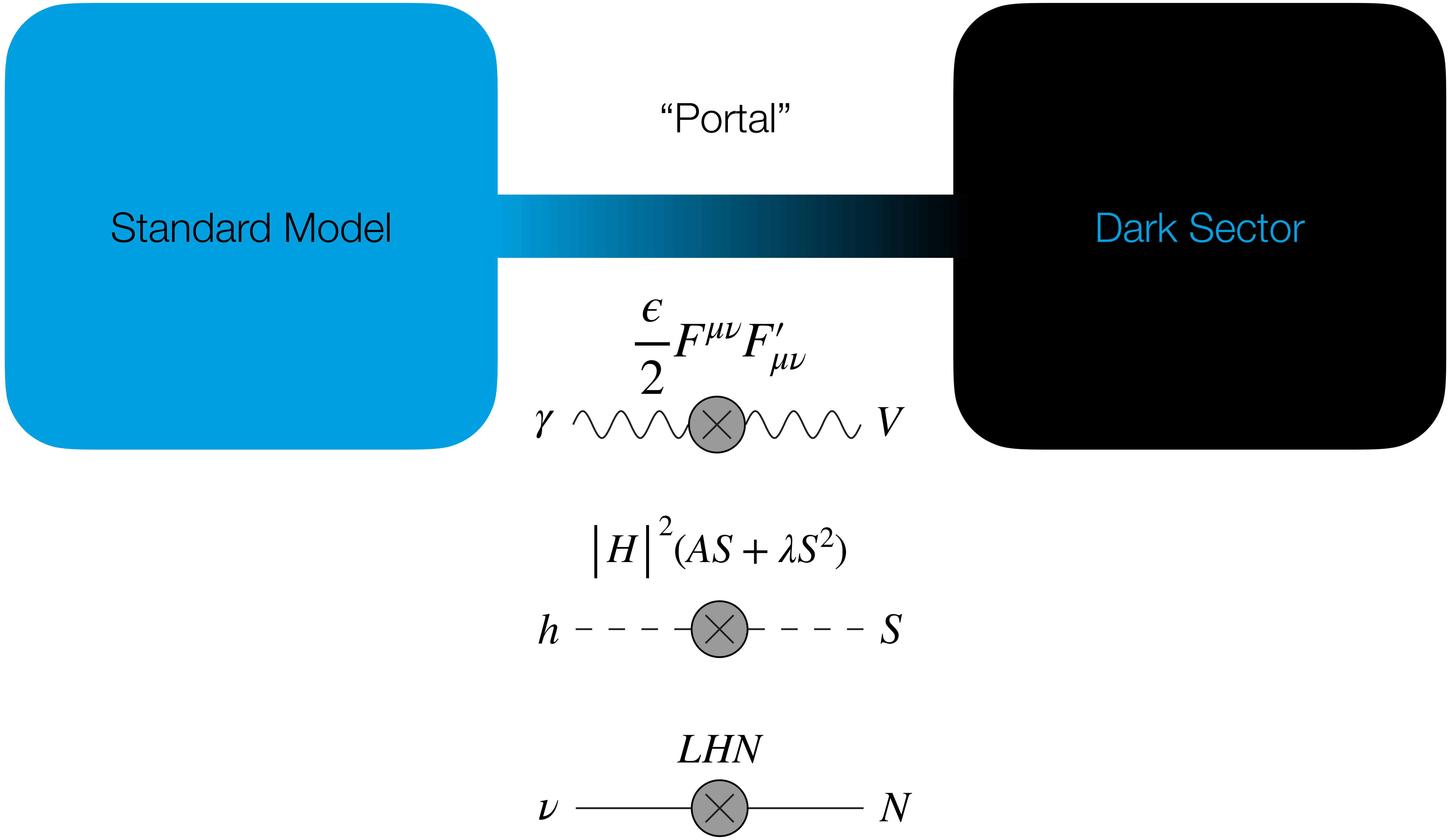


But if we want to push the scale down we **need new light mediators**

Lee, Weinberg (1977)

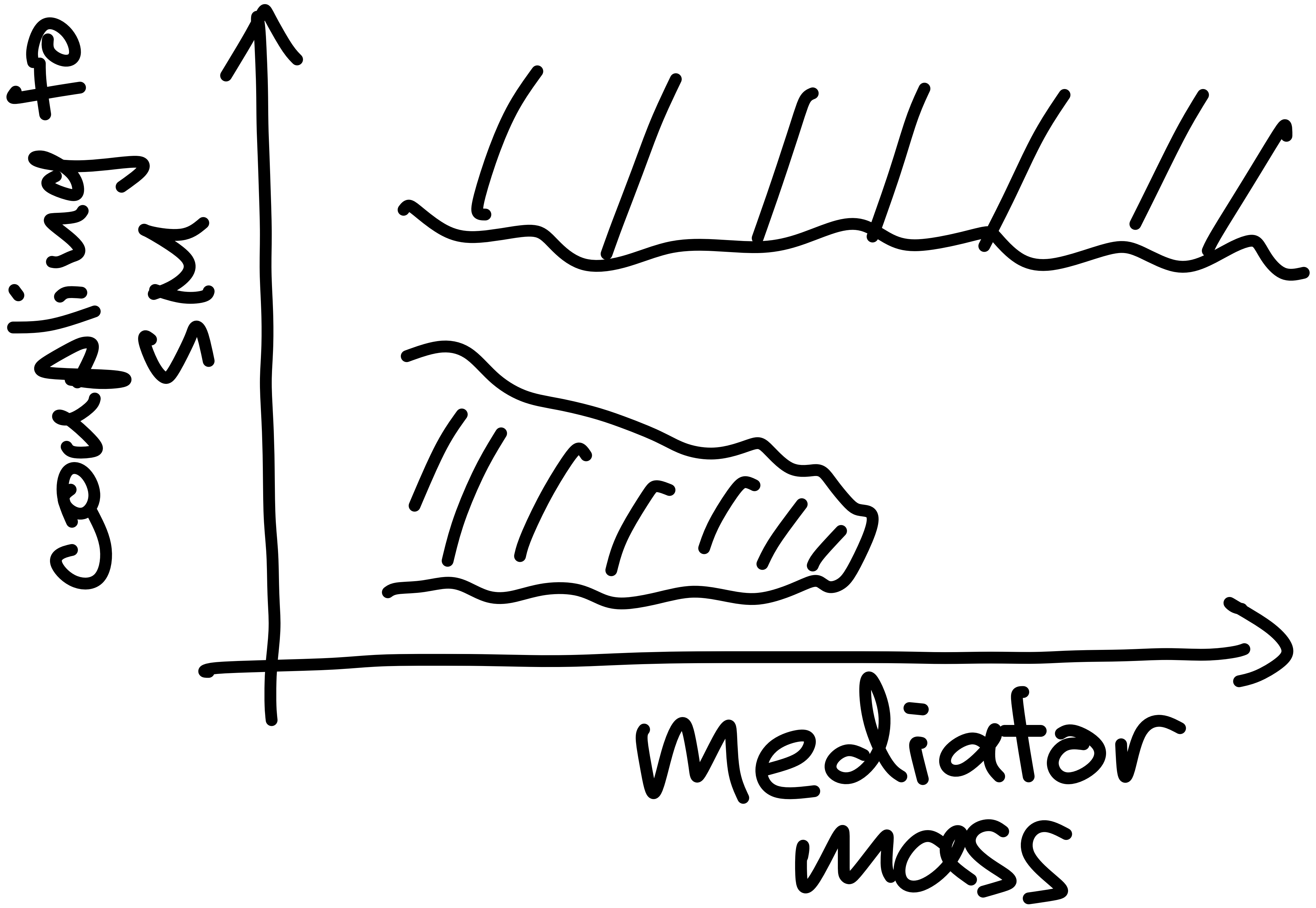
Dark Sector Models

A dark sector is uncharged under SM forces: strong, weak, E&M



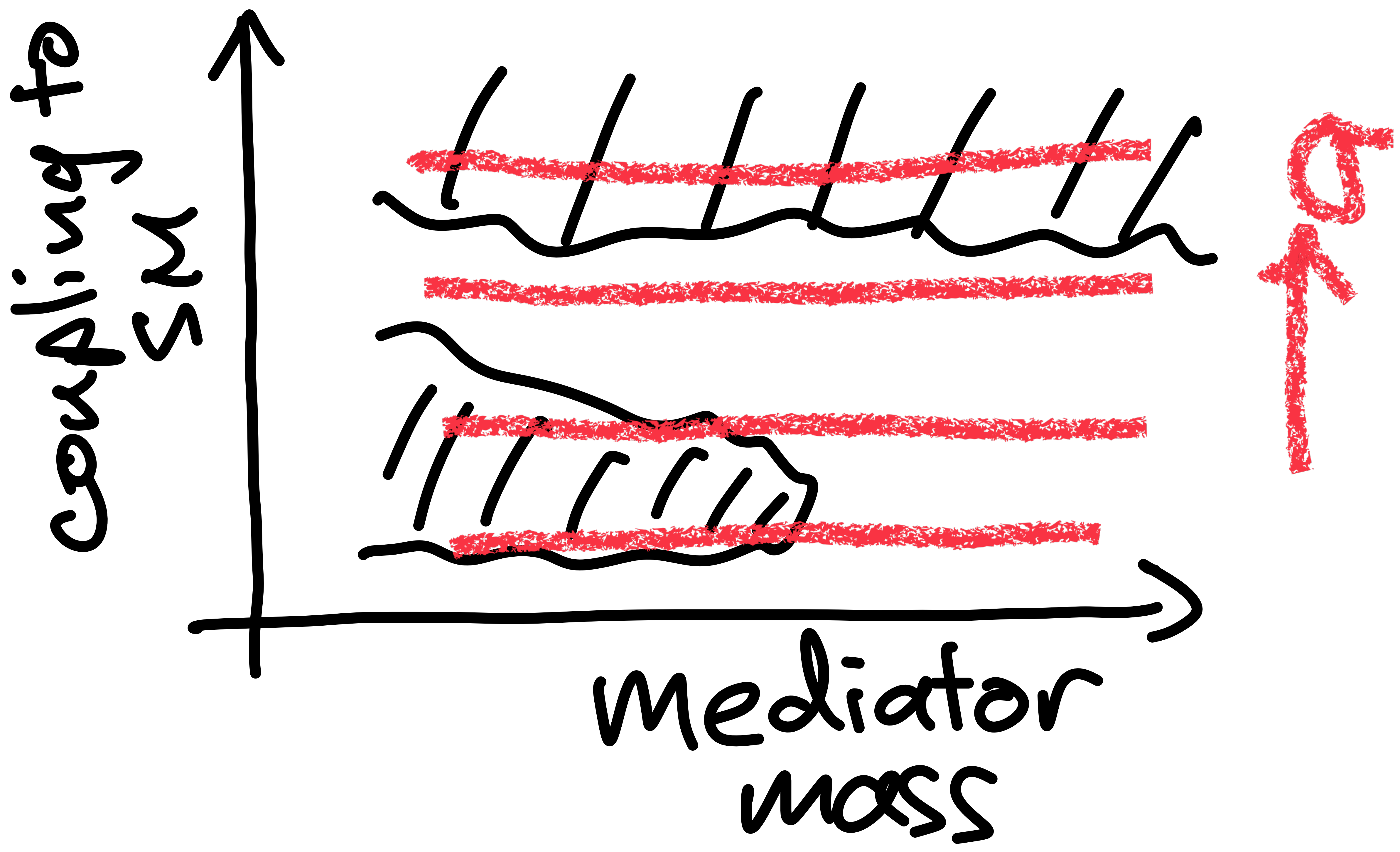
But can be connected via a "portal"—mixing with SM particles. Especially useful for GeV-ish new stuff

Dark Sector Models: searching for the mediator



Can make intuitive plots to benchmark different search strategies, scenarios, etc.

Dark Sector Models: searching for the mediator



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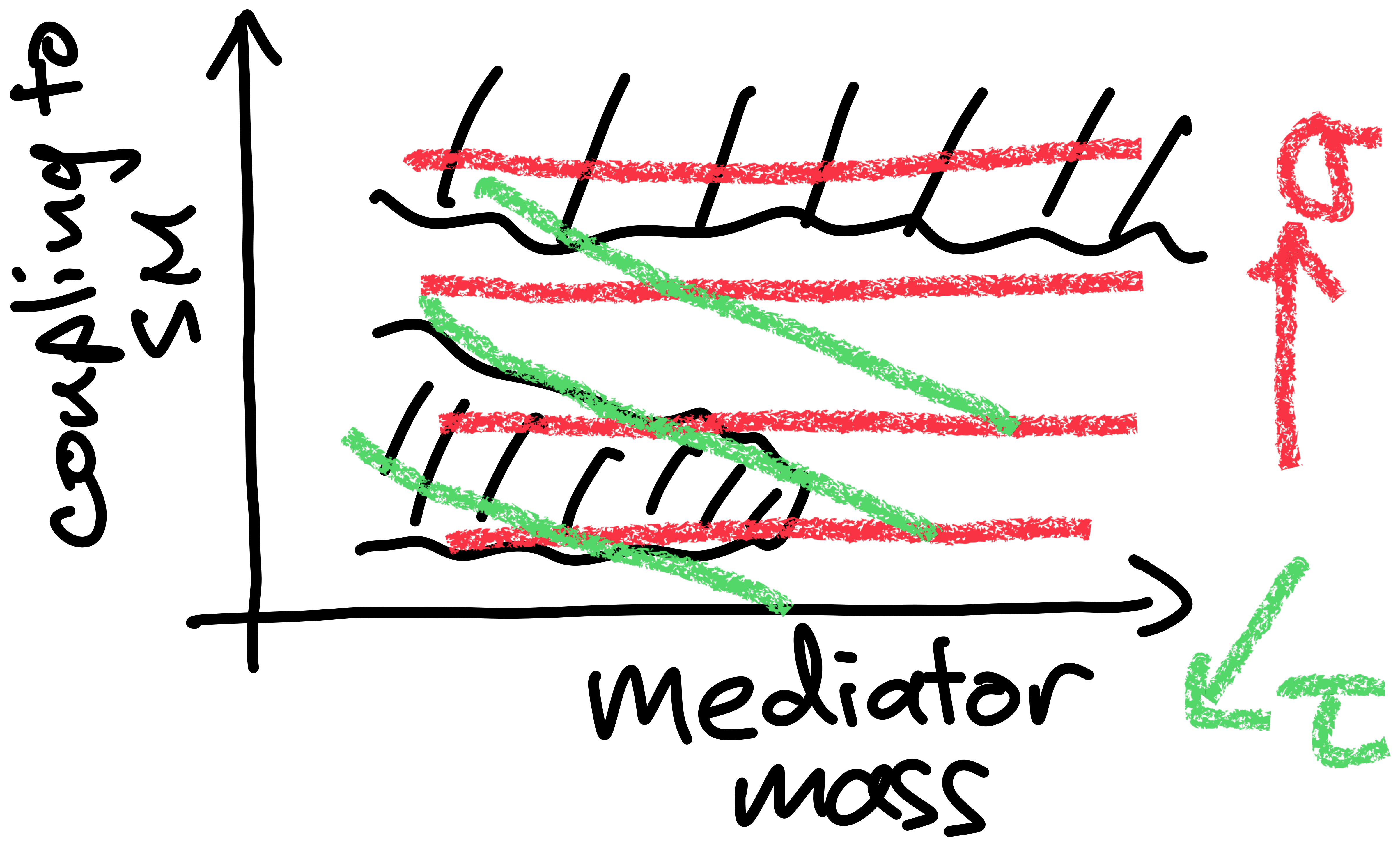
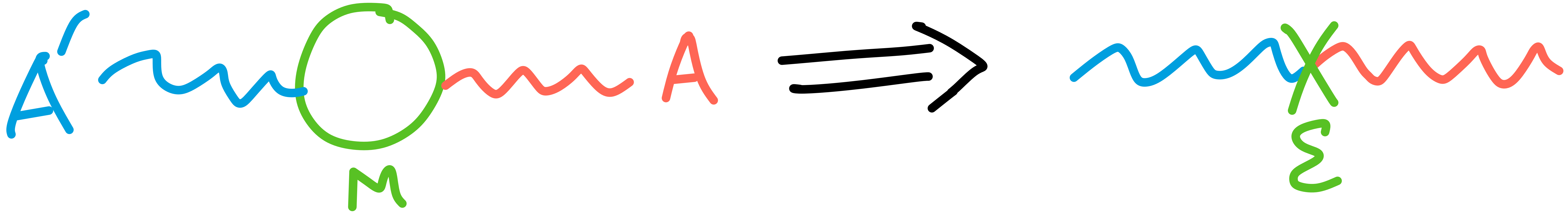


Can make intuitive plots to benchmark different search strategies, scenarios, etc.

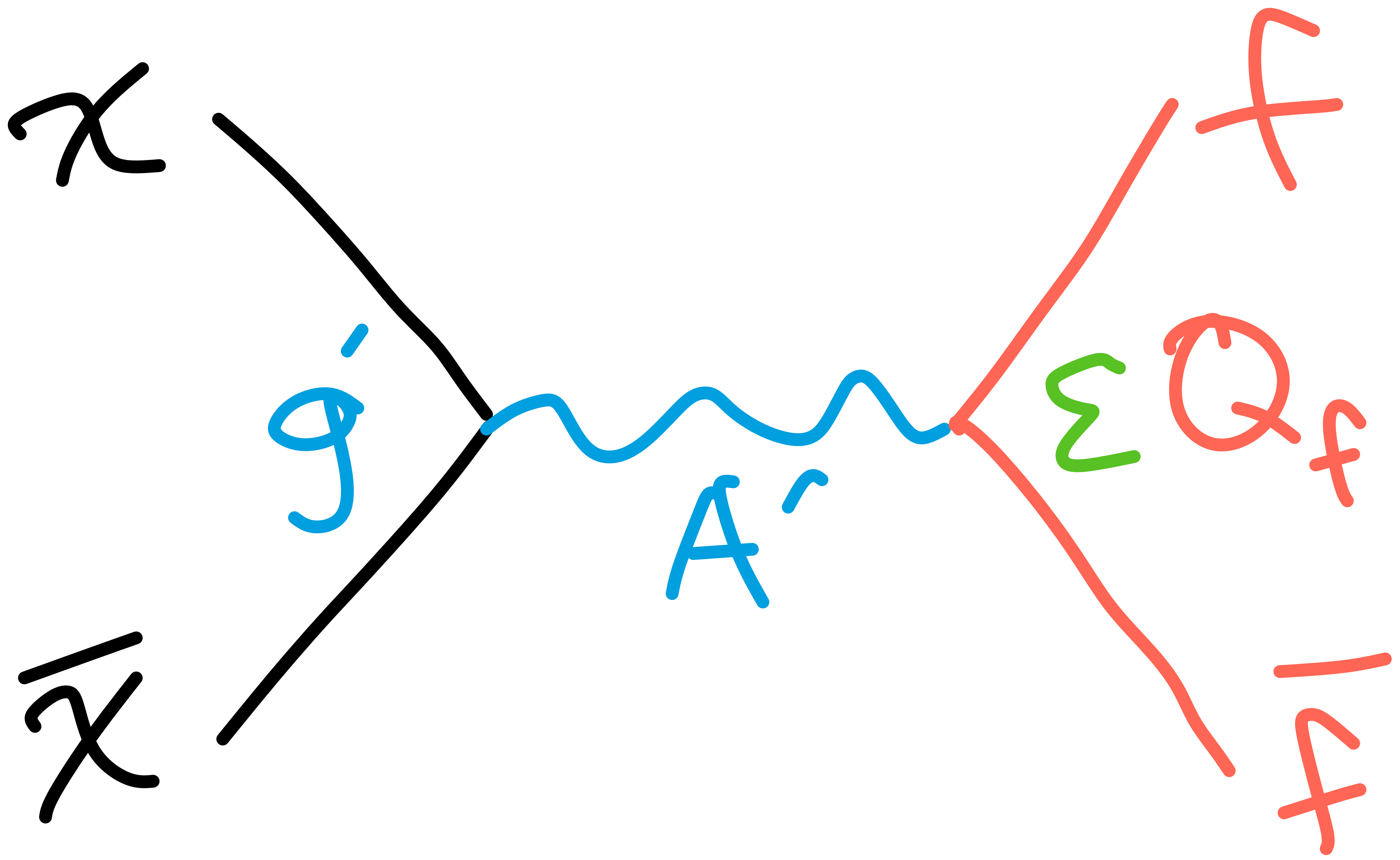
The dark photon



$$\mathscr{L} \supset \frac{\epsilon}{2} F^{\mu\nu} F'_{\mu\nu} \qquad \epsilon \sim \frac{eg'}{16\pi^2} \log \frac{\mu}{M}$$

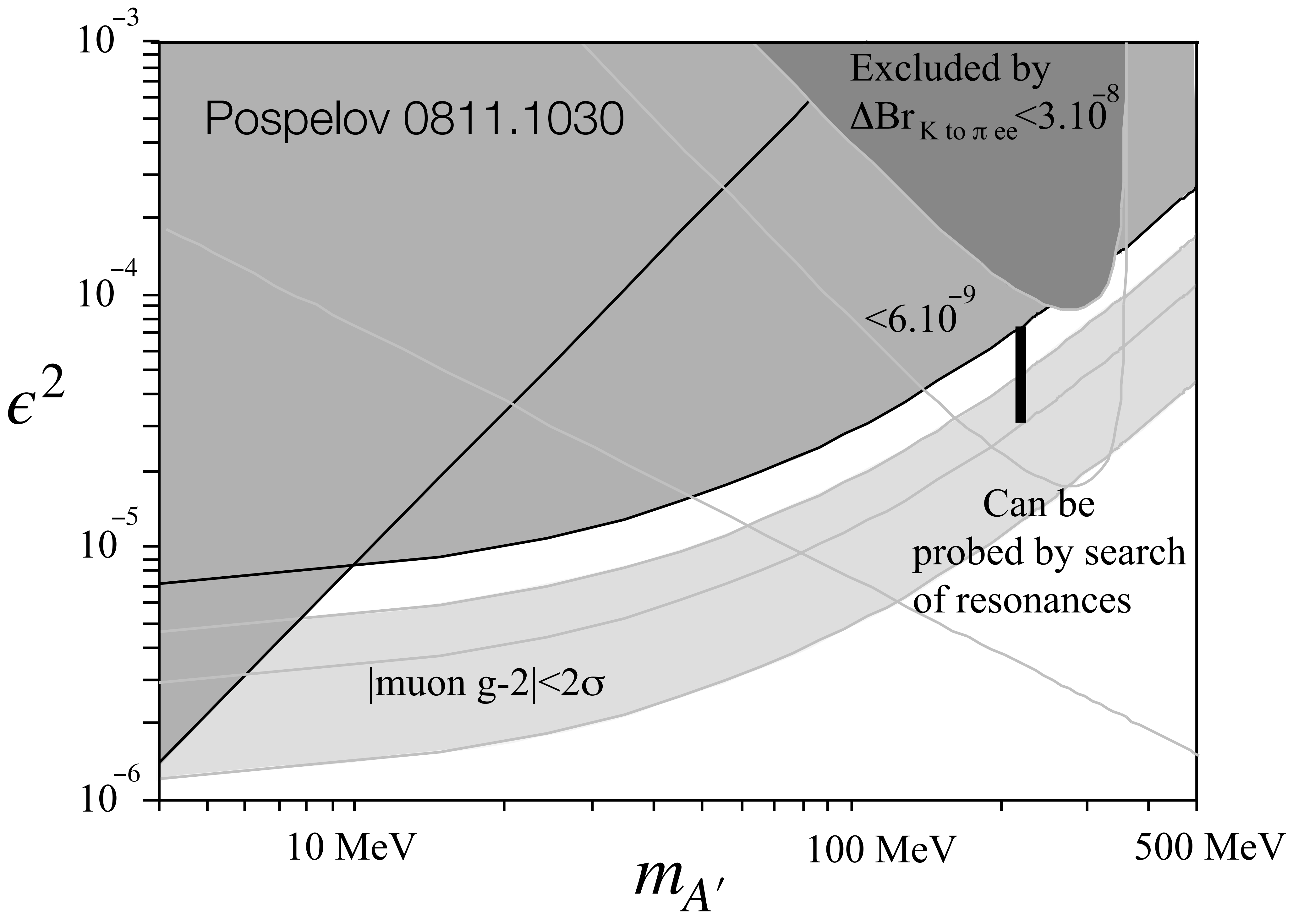
Okun; Holdom; Gallison & Manohar

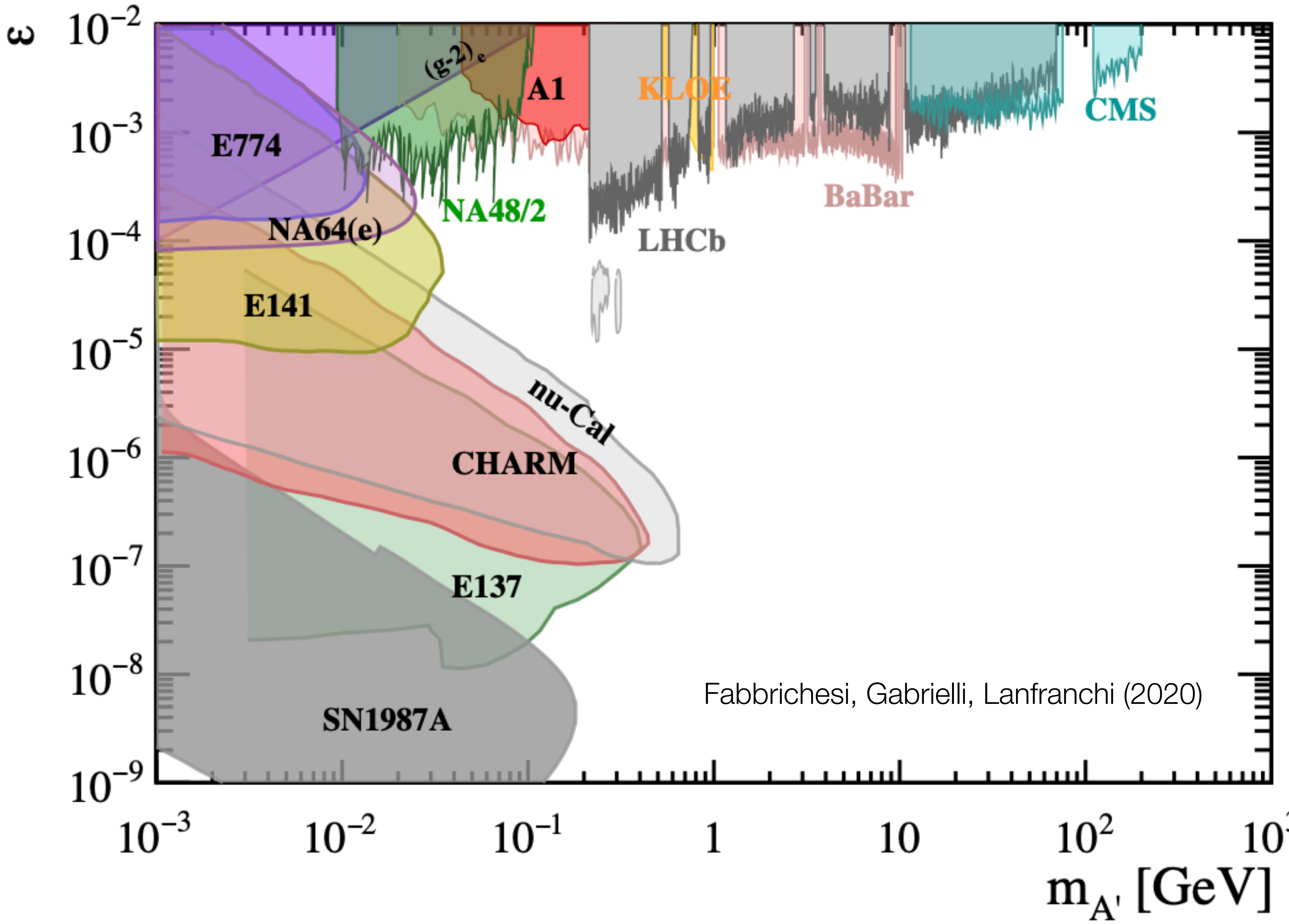
The dark photon



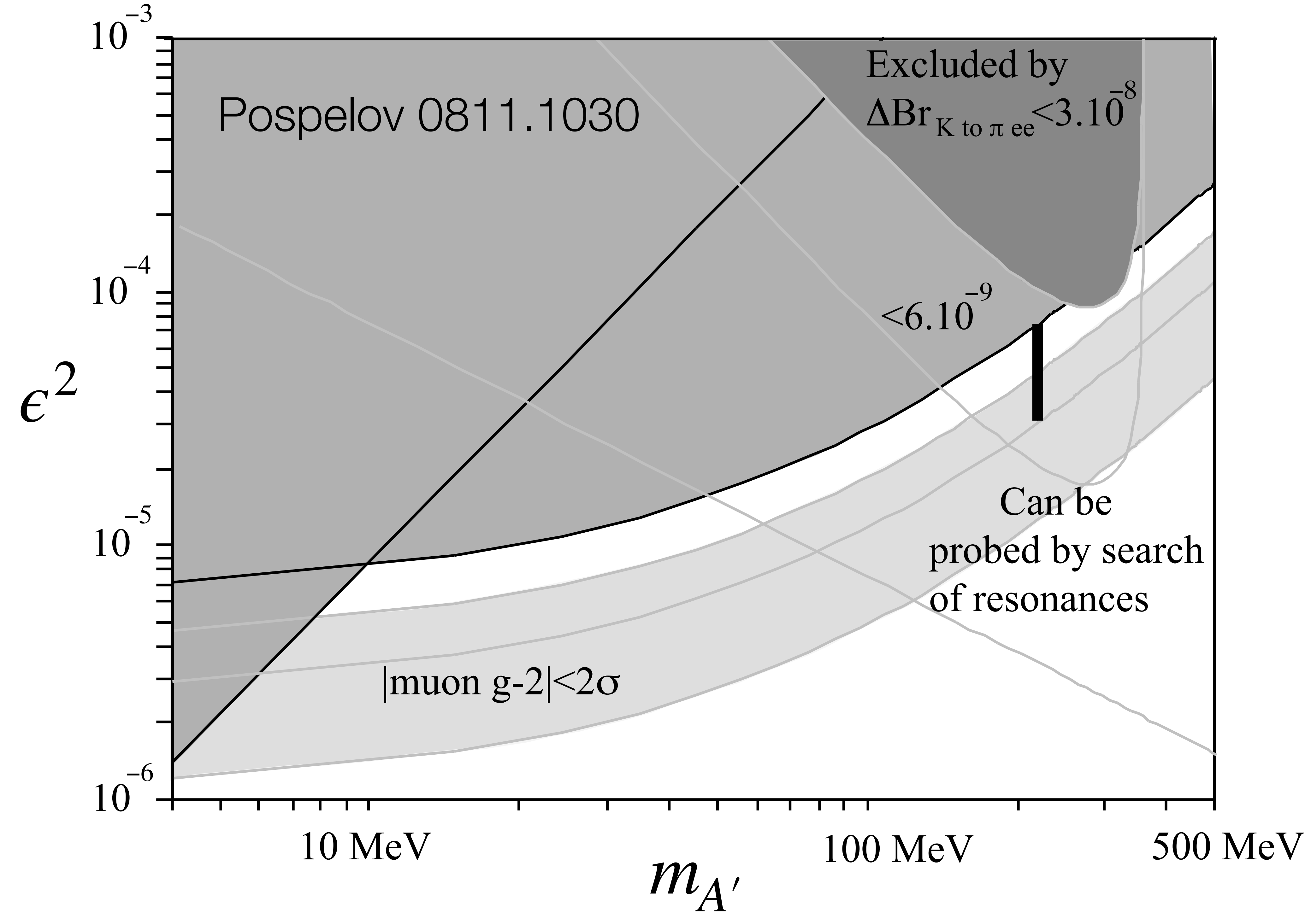
Can act as a mediator for DM-SM interactions

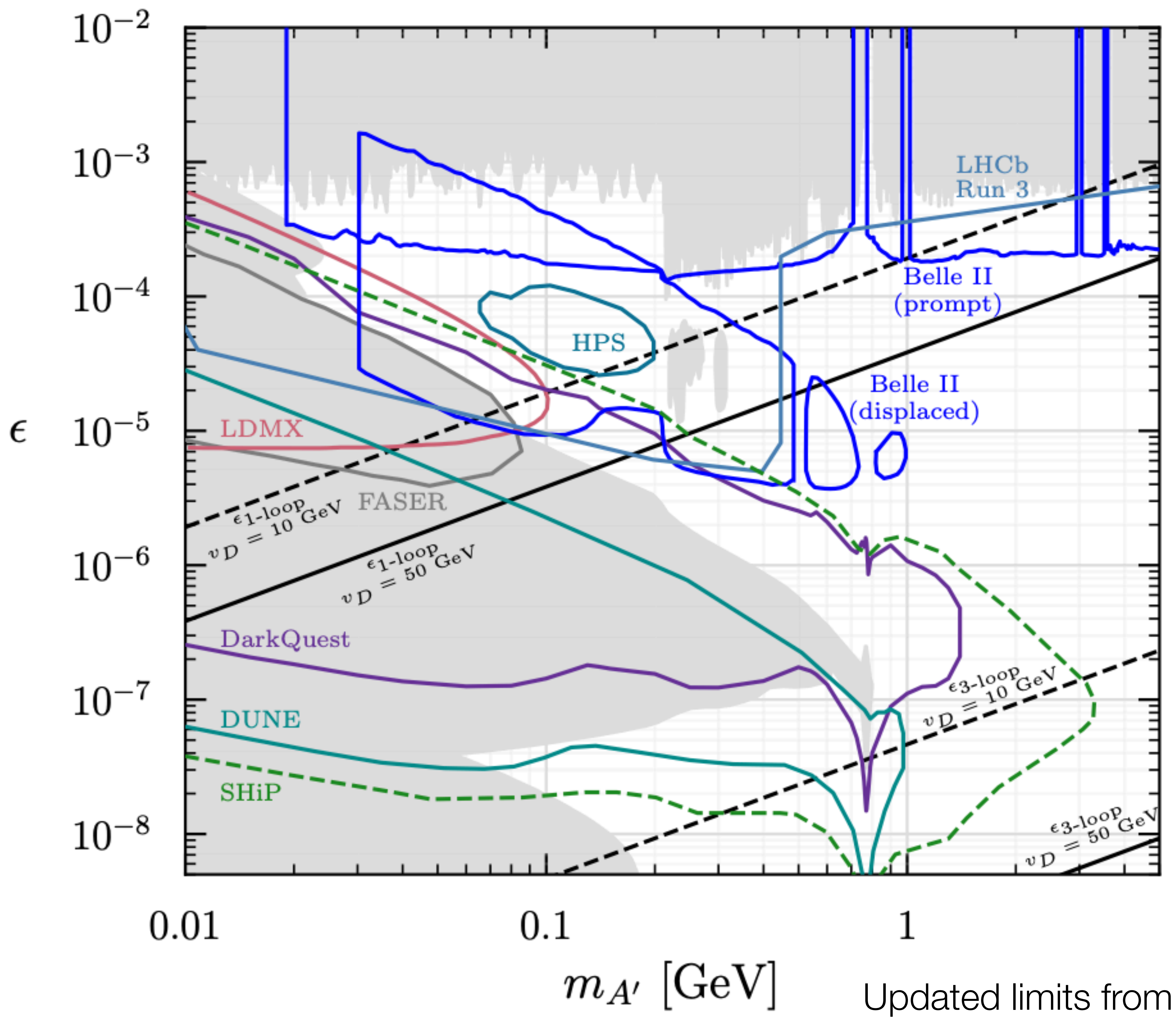
Dark Sector Models: searching for the mediator





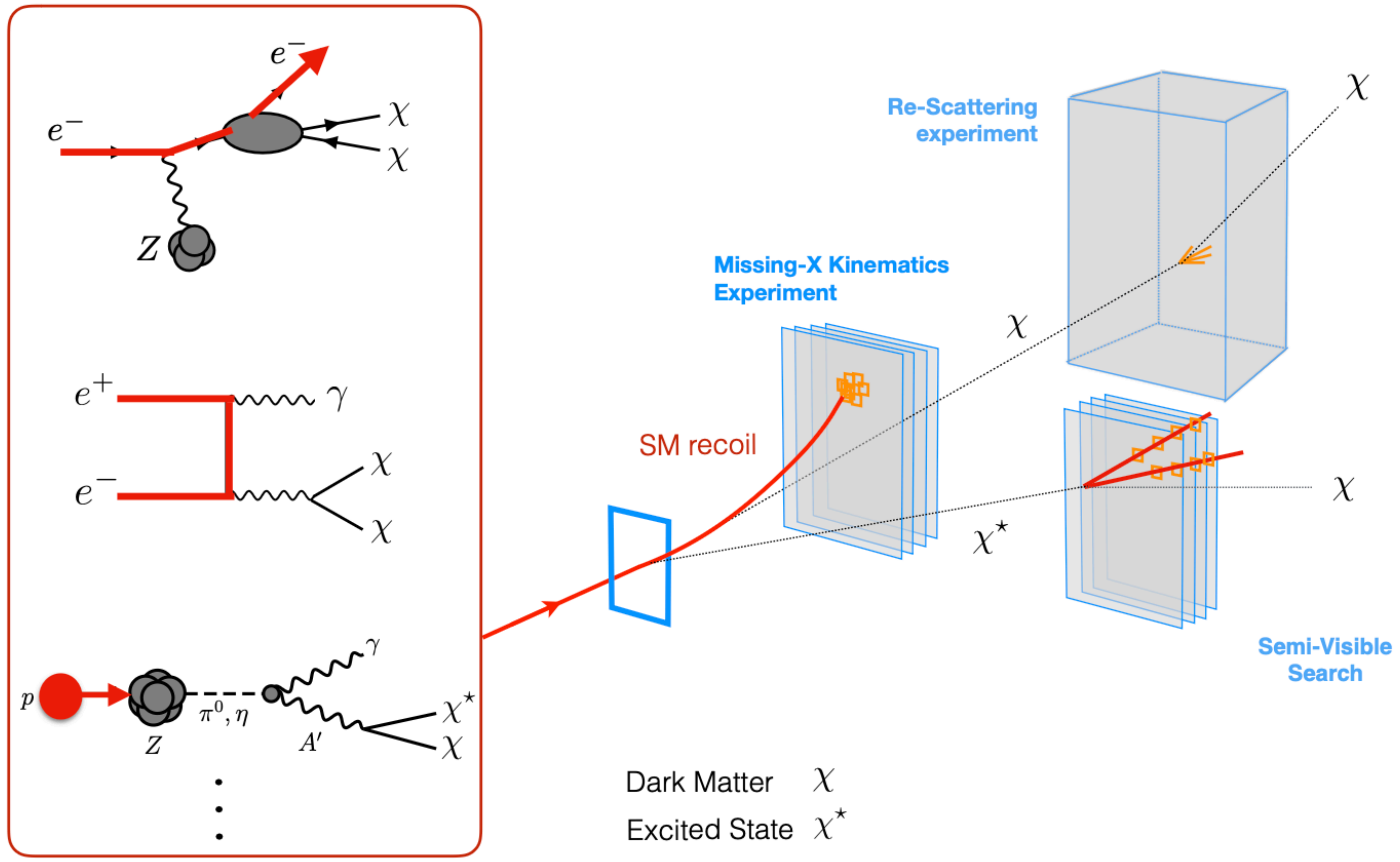
Dark Sector Models: searching for the mediator

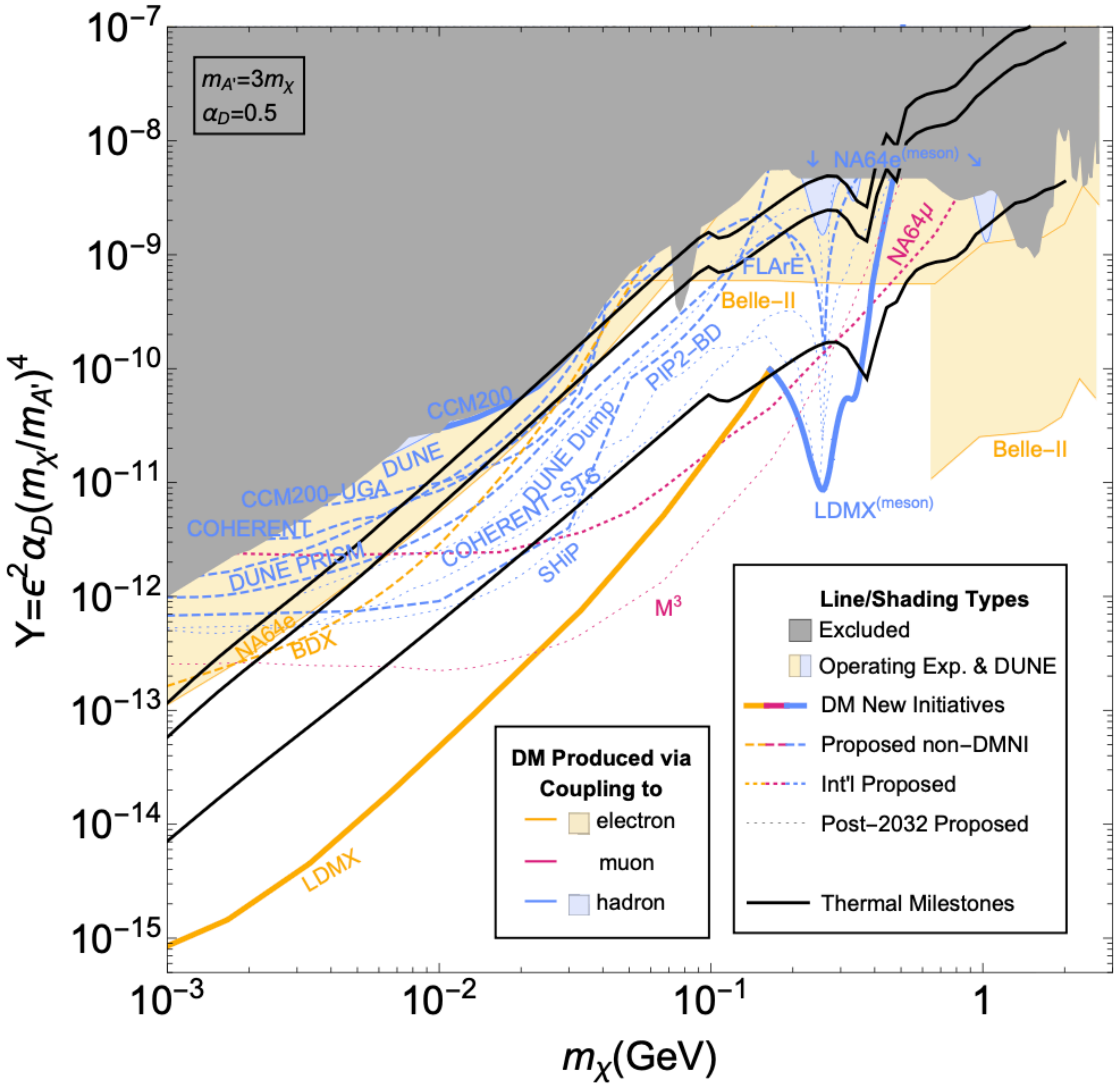




Updated limits from Darkcast

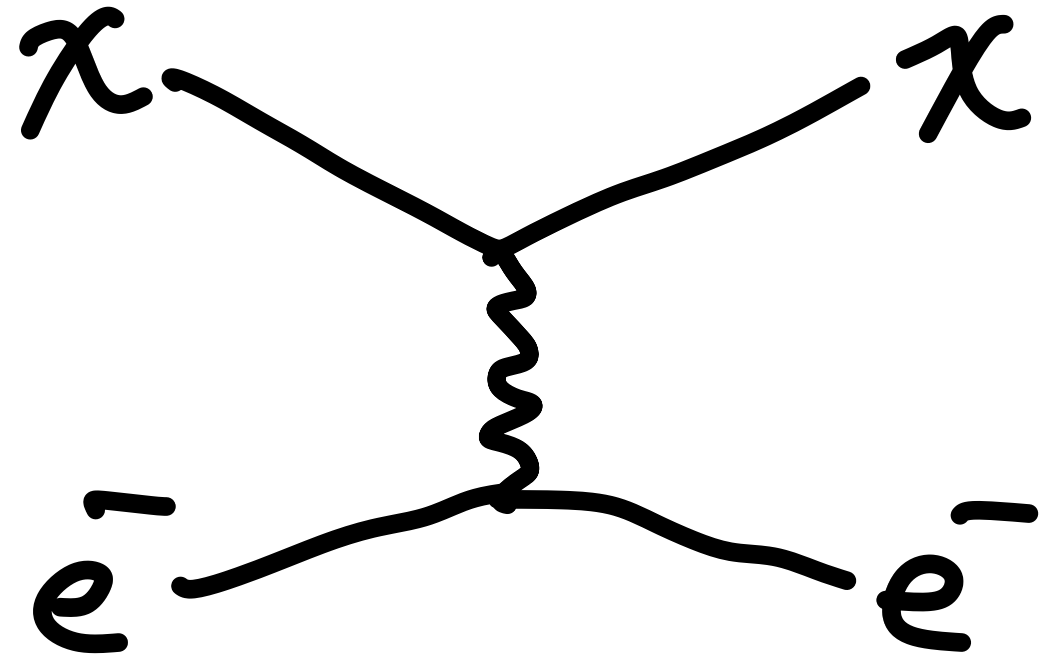
Searches for light DM with beams





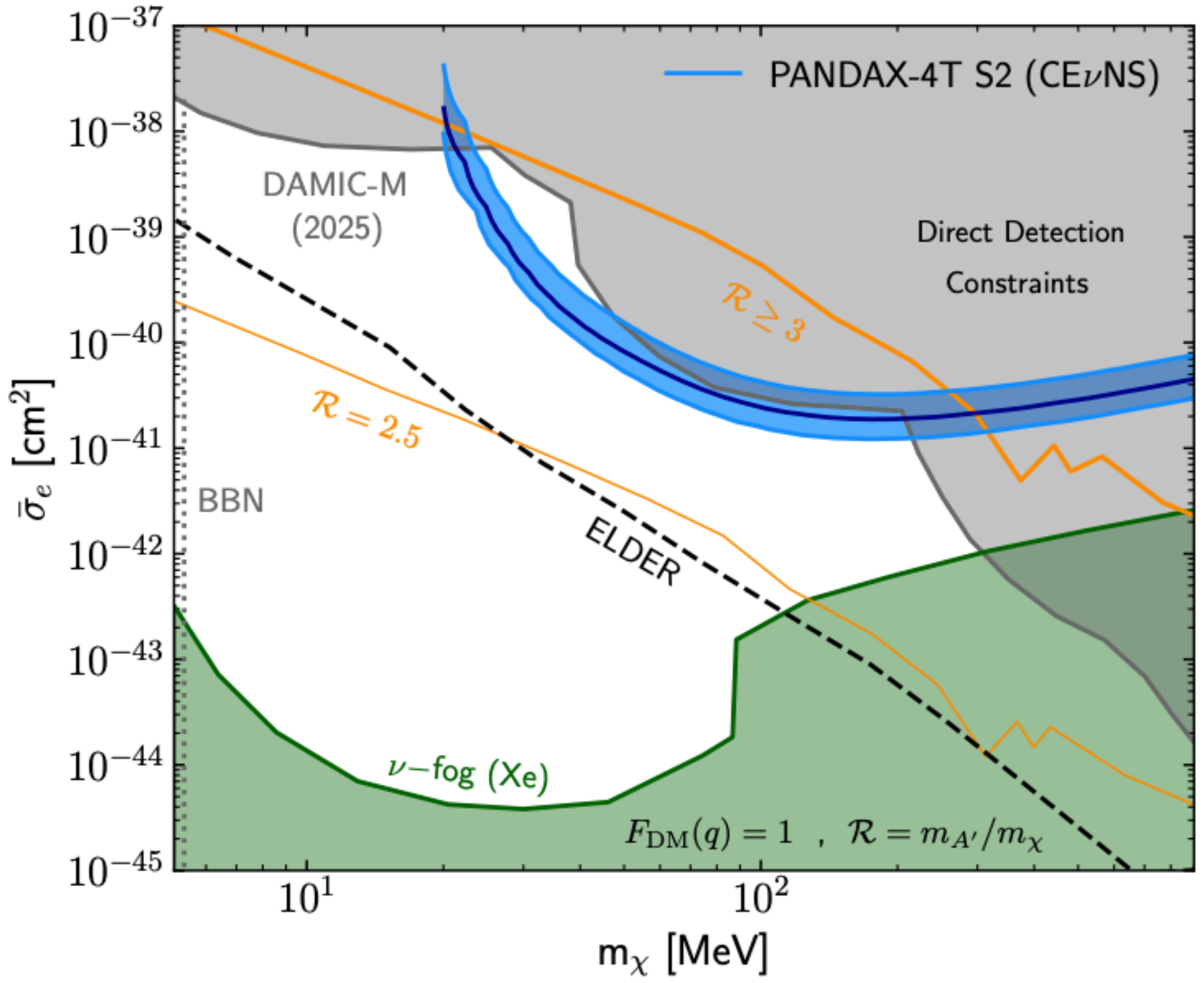
Snowmass Whitepaper: Dark Matter Production at Intensity-Frontier Experiments (2207.00597)

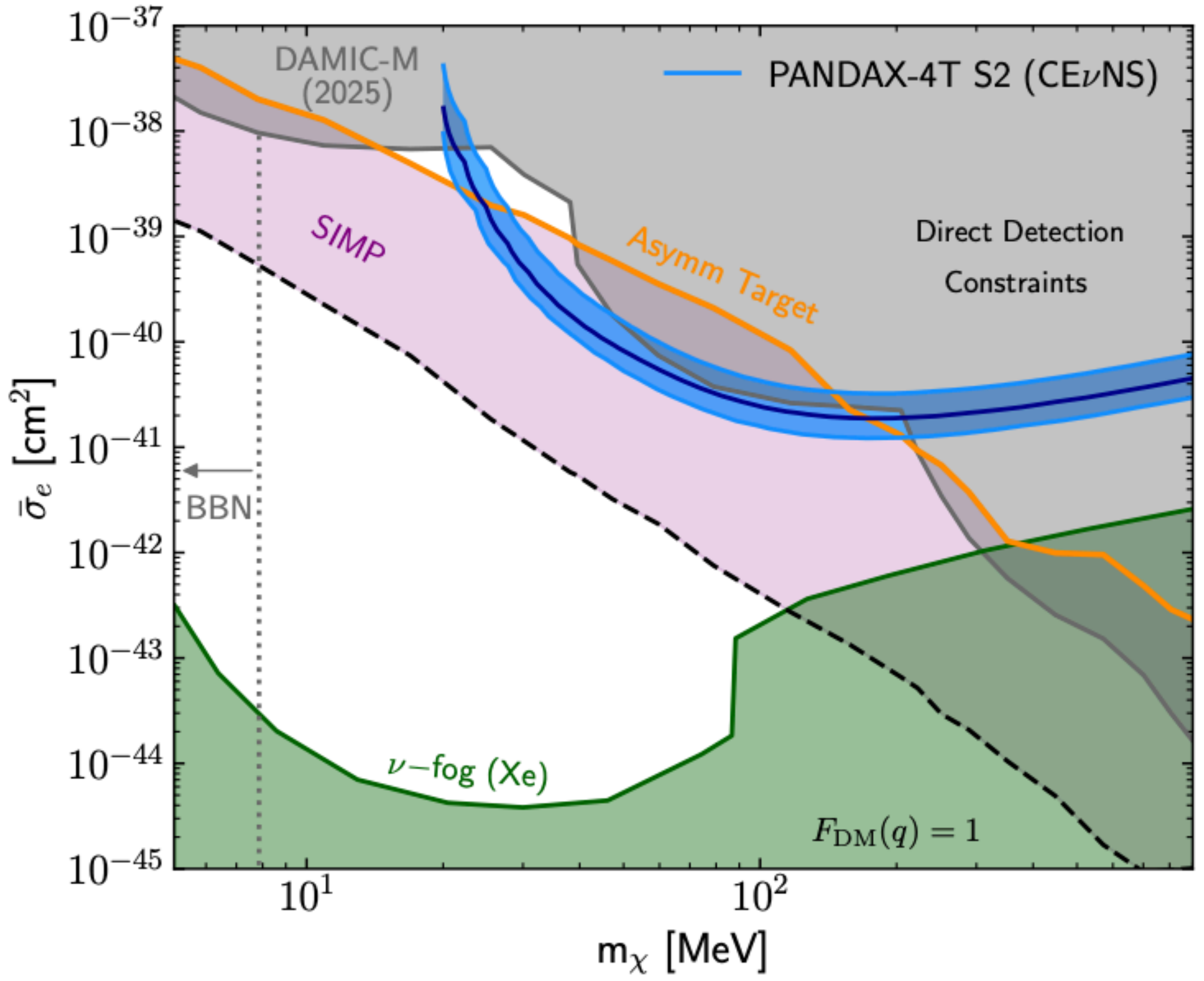
Light DM direct detection



Different kinematics allows access to light DM

Cheek et al. 2507.15956





Detector response generally more complicated

See parallel talk by C.-P. Liu on computing response yesterday

Thermal freeze-out story under stress

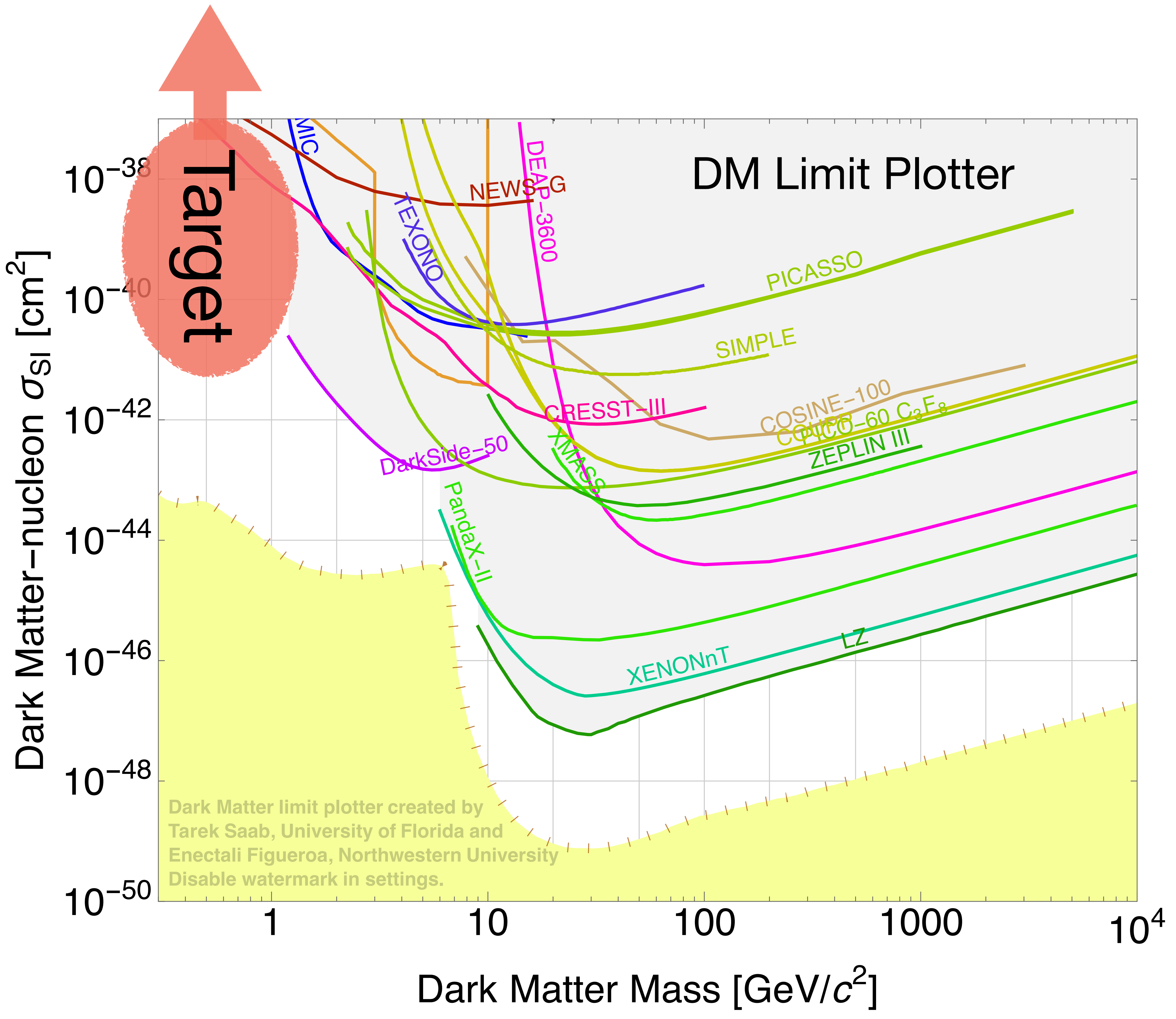
Freeze-in through ultralight A' viable

Lots of activity considering novel target materials

Changing gears a bit…

DM, Moore, Morrissey, Pospelov, Ramani ('22)

Application: Strongly* interacting DM



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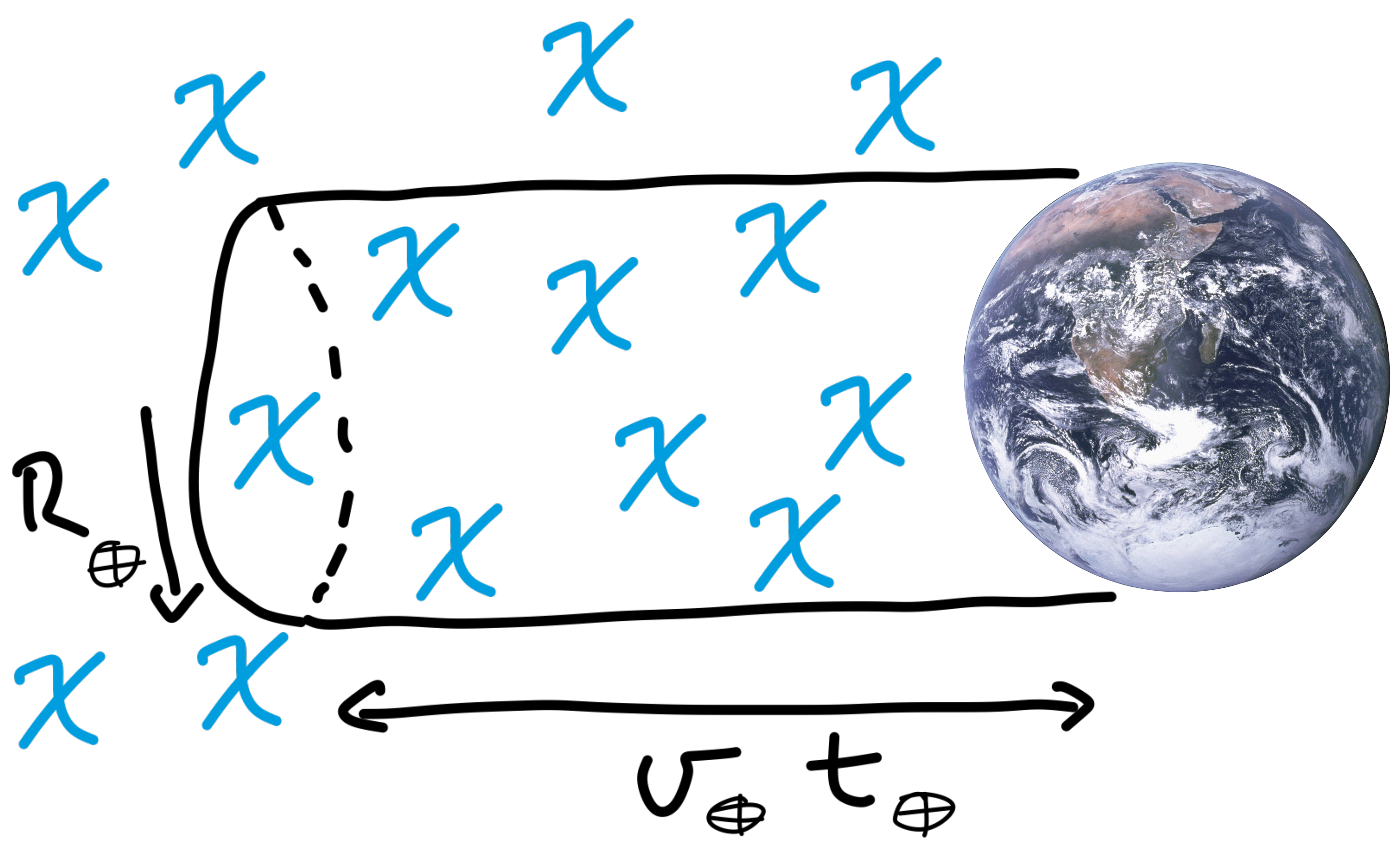

Strongly-interacting DM scatters efficiently in atmosphere/earth & thermalizes

$$v_\chi \sim \sqrt{T/m_\chi} \sim 10^{-6} c \sqrt{\mathrm{GeV}/m_\chi} < v_{\mathrm{esc},\oplus} \text{ for } m_\chi \gtrsim 100 \text{ MeV}$$

Assuming uniformly distributed in Earth

$$\Rightarrow \rho_{\chi,\oplus} \sim 10^{15} \frac{\mathrm{GeV}}{\mathrm{cm}^3} \times f_\chi$$

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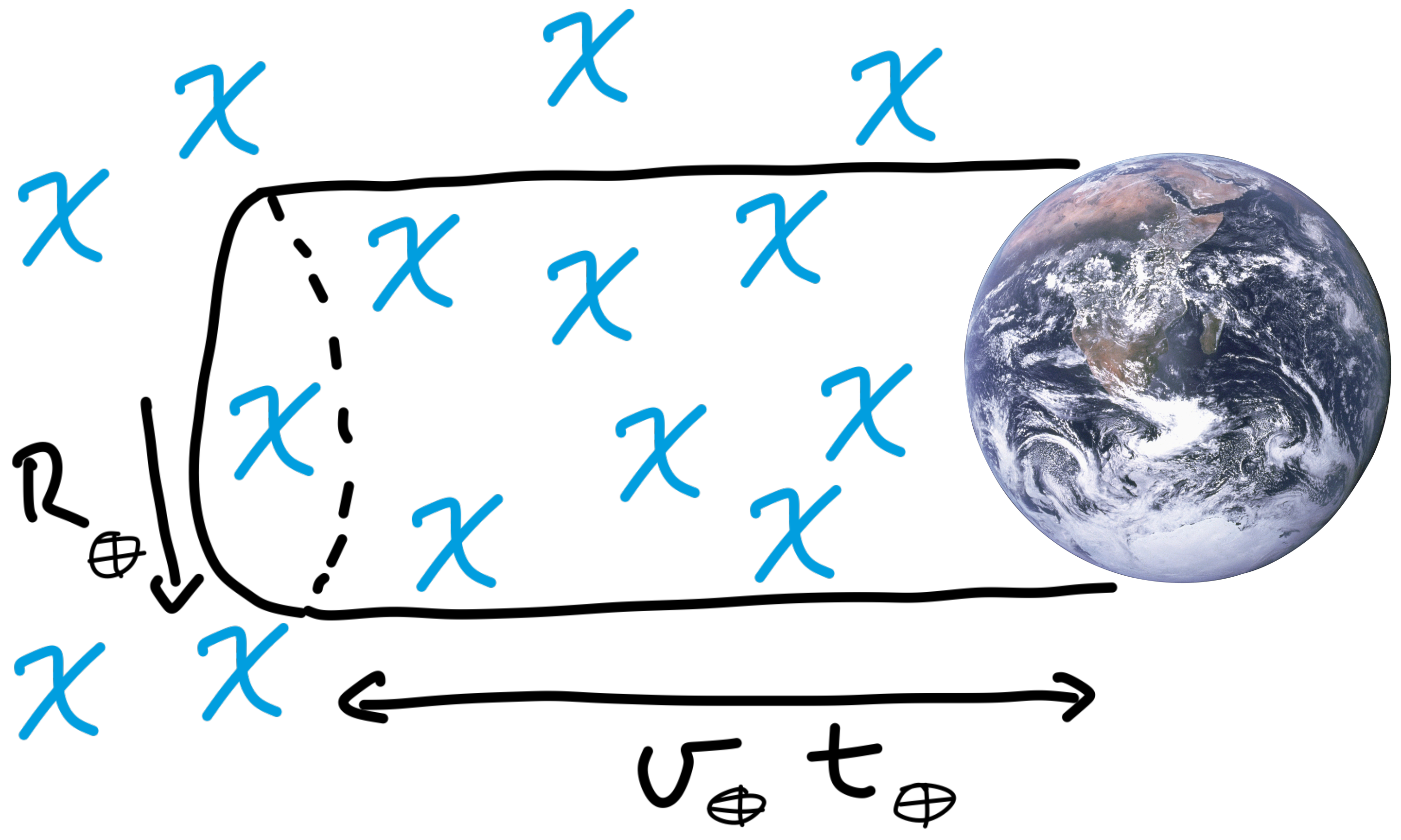

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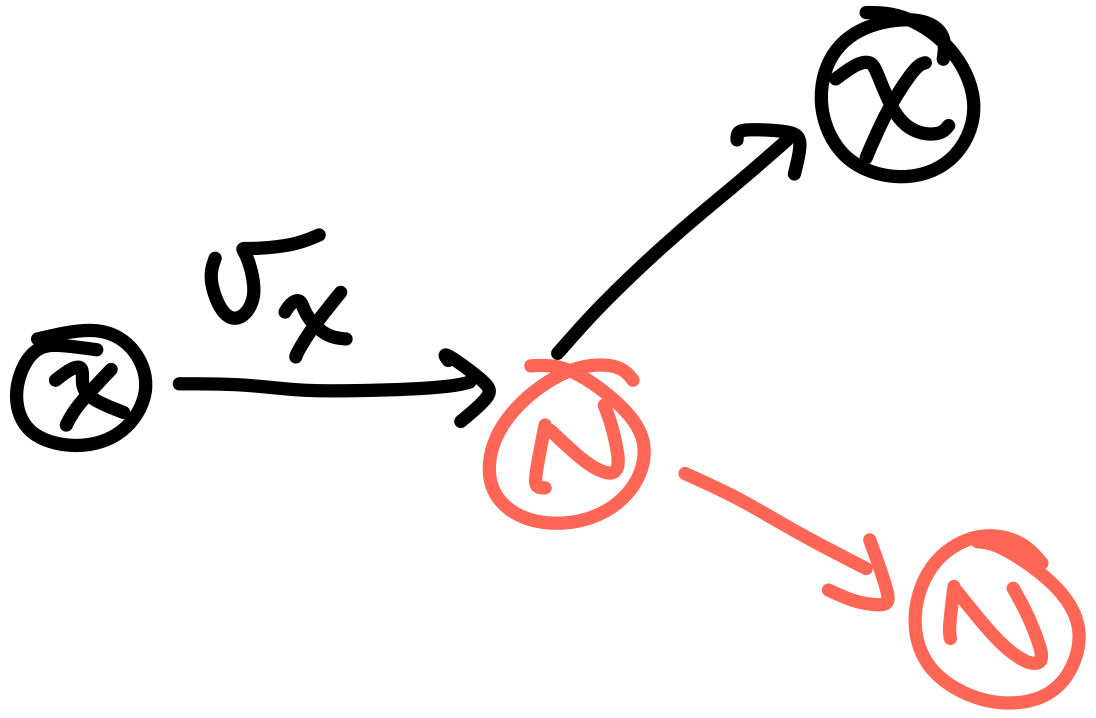
Assuming uniformly distributed in Earth

$$\Rightarrow \rho_{\chi,\oplus} \sim 10^{15} \frac{\mathrm{GeV}}{\mathrm{cm}^3} \times f_\chi$$

But hard to detect

$$E_{\mathrm{recoil}} \leq \frac{2\mu_{\chi N}^2 v_\chi^2}{m_N} \lesssim \mathcal{O}(\mathrm{eV}) \text{ for } v_\chi \sim 10^{-6} c$$



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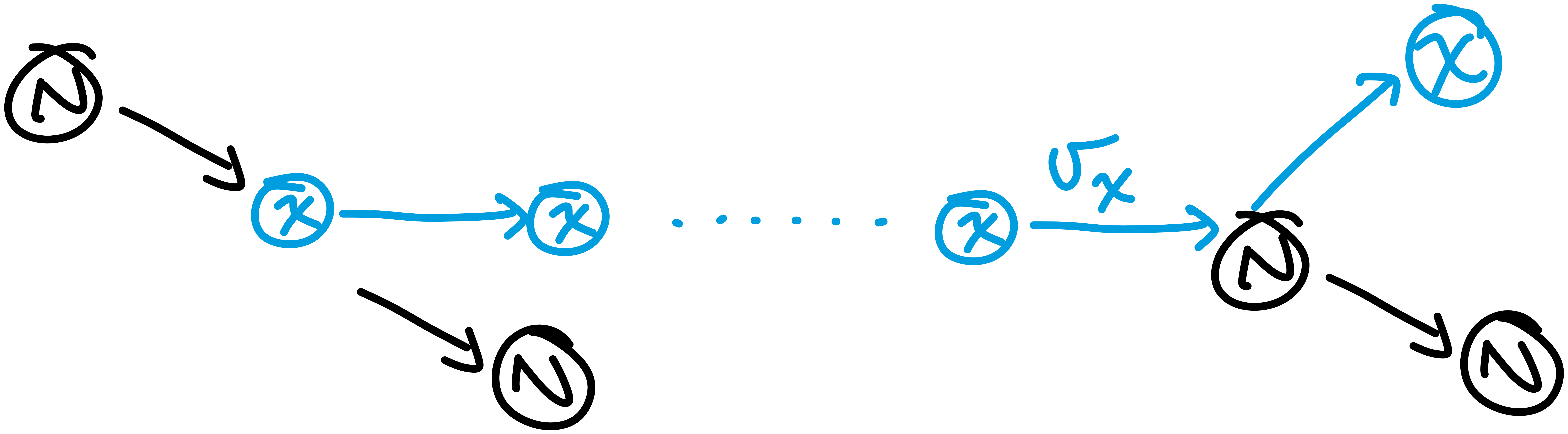
There can be a lot of strongly-interacting DM locally but it is slow. How do we detect it?

Speed it up!



"(direct detection)^2"

DM, Moore, Morrissey, Pospelov, Ramani ('22)

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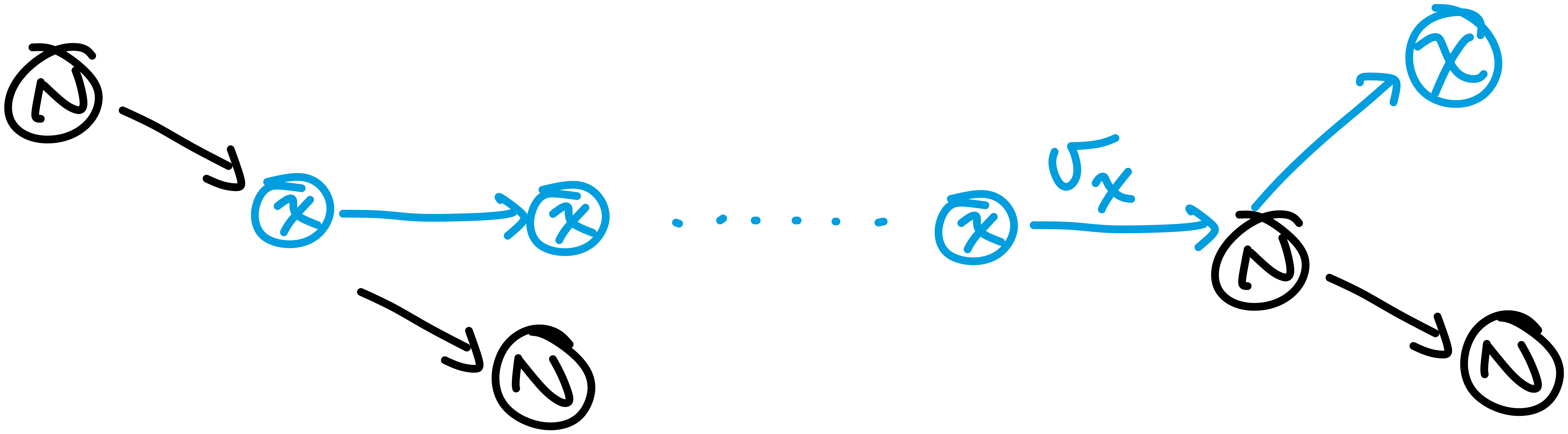

"(direct detection)^2"

See parallel talk by H. Nie on speeding up DM yesterday

DM, Moore, Morrissey, Pospelov, Ramani ('22)

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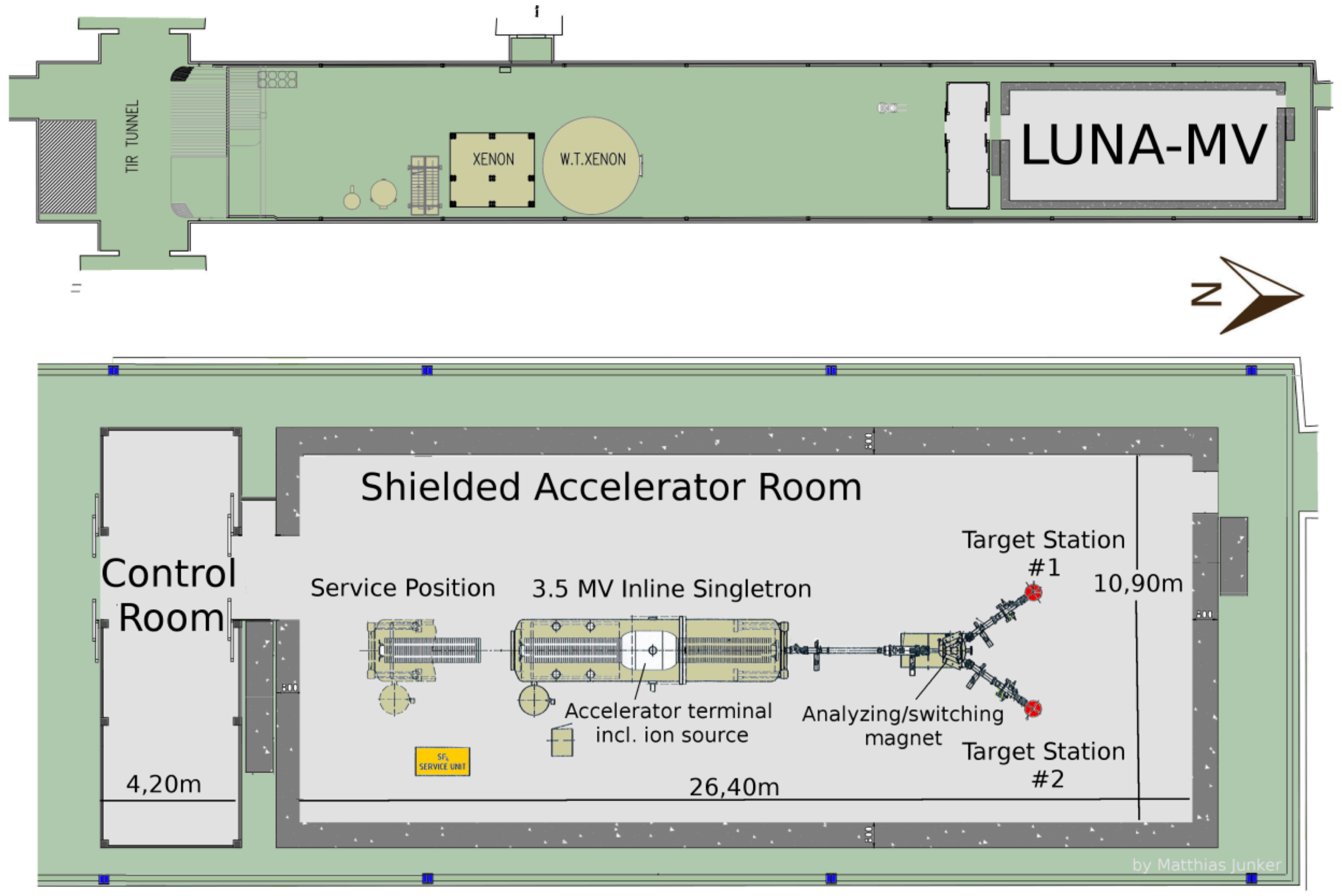

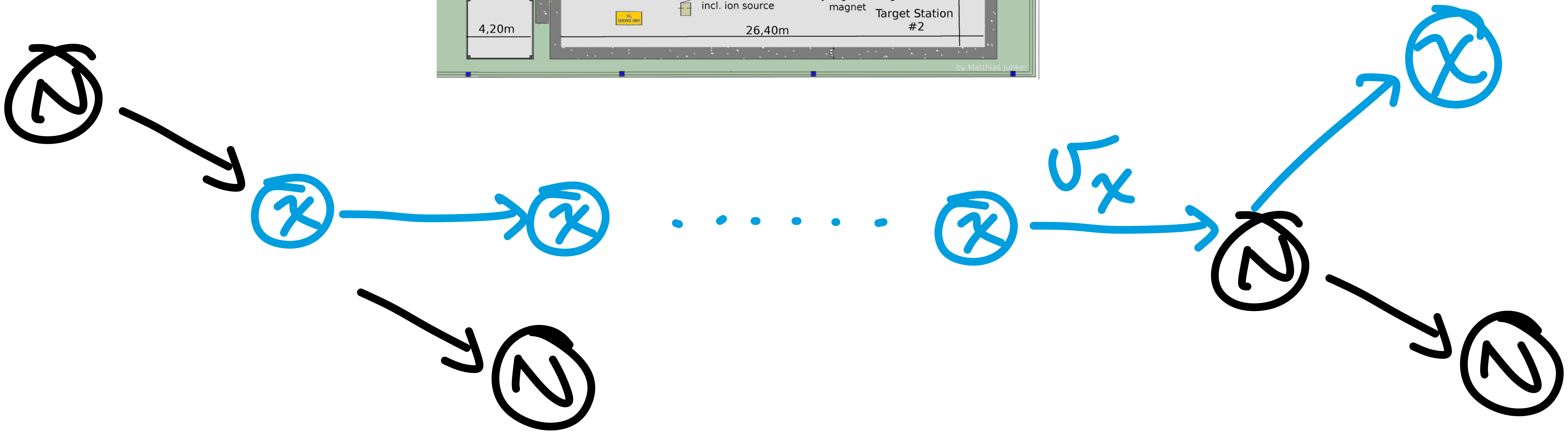

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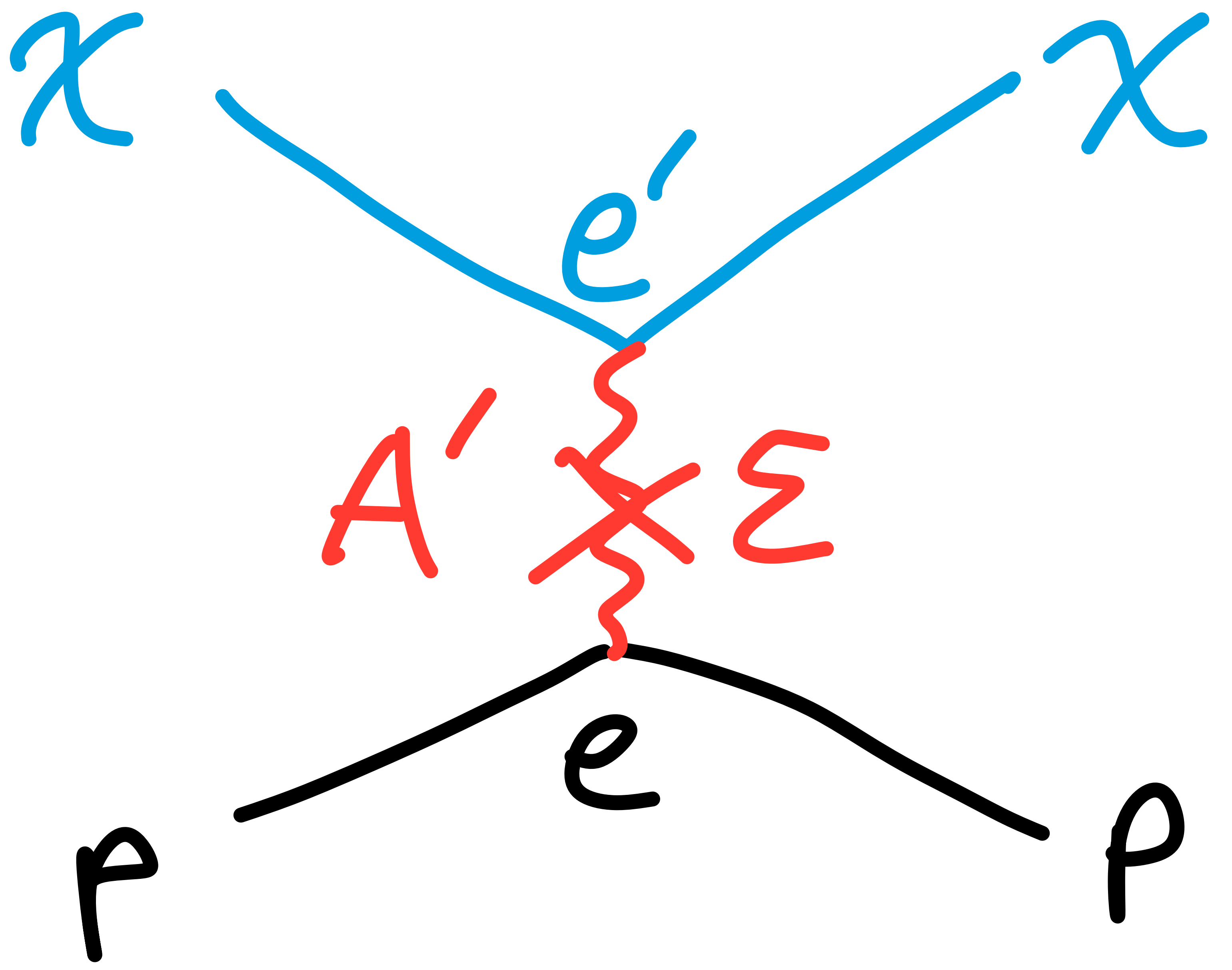
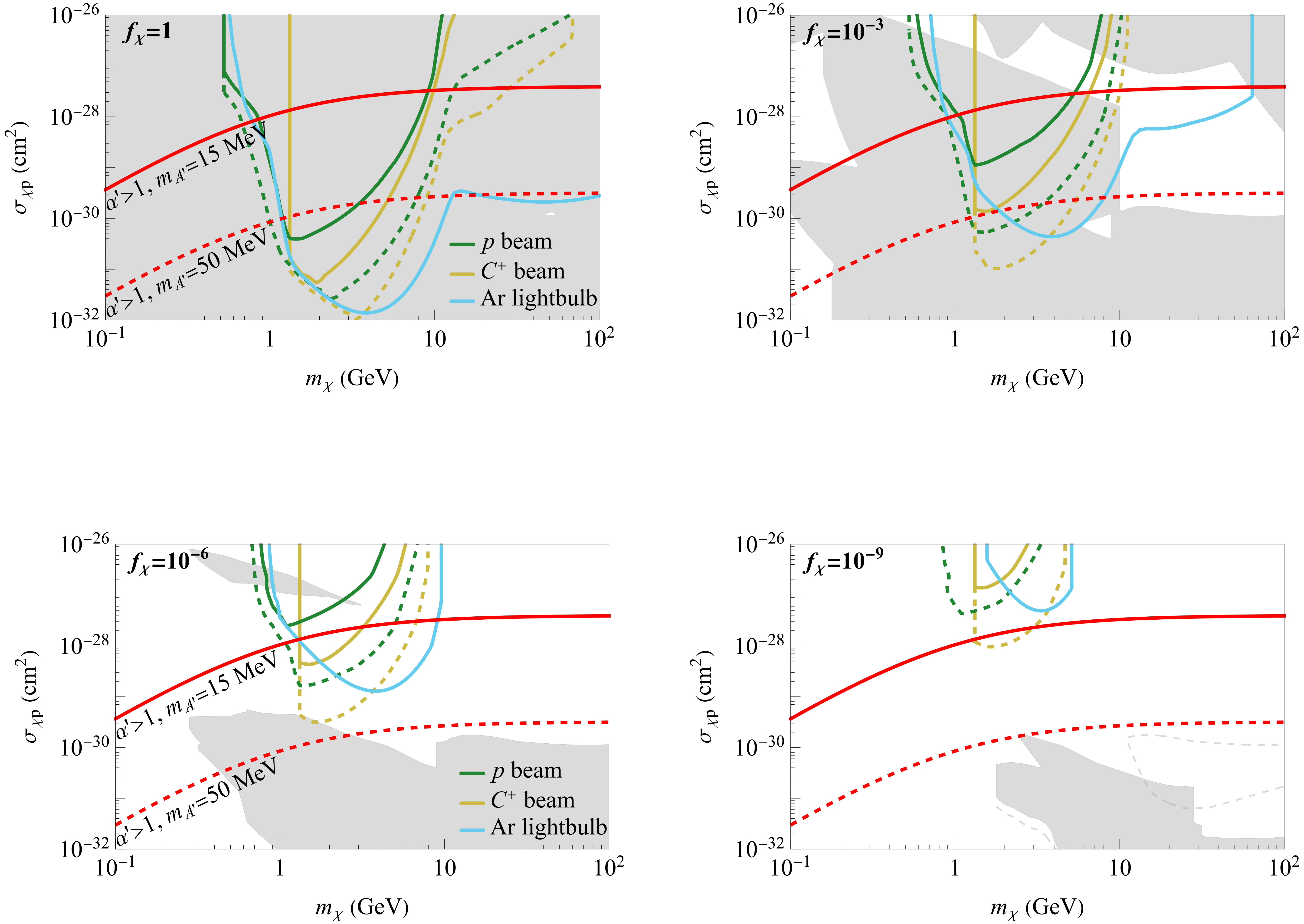


$$\sigma_{\chi p} = 16\pi\,\epsilon^2\,\alpha\,\alpha'\,\frac{\mu_p^2}{m_{A'}^4}$$



See parallel talk by P. Du on strongly interacting DM yesterday

Wrap up

Unraveling the nature of dark matter is a pressing problem in fundamental physics

Assumption of thermal contact in the early universe provides for motivated physics targets

Despite null results over past 30+ years WIMPs are a very well motivated DM candidate and there are parts of parameter space we need to explore

Dark sectors allow for some model building freedom and can accommodate a large number of benchmark possibilities and motivate novel strategies

Lots of other possibilities—way too much for 30 minutes

Still lots to do!