Dark Sectors and DM Models: from ultralight to ultra heavy

Hitoshi Murayama (Berkeley, Kavli IPMU)

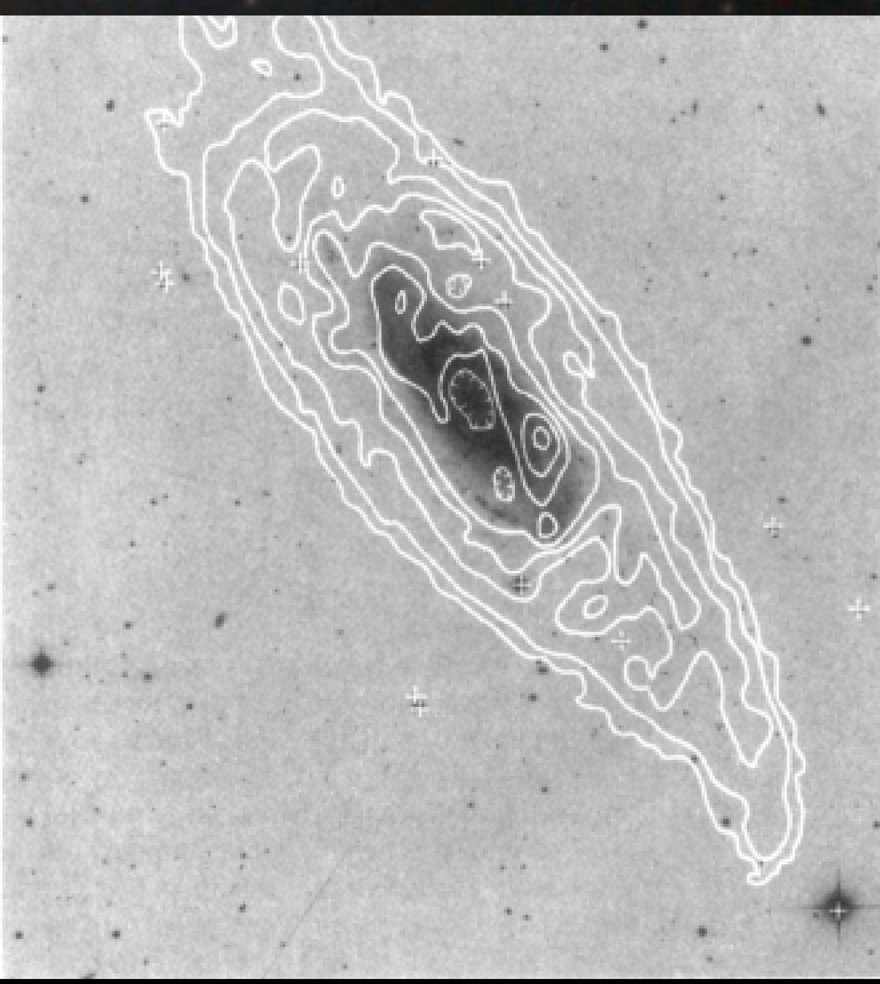
European Strategy Update for Particle Physics
Granada, May 13, 2019

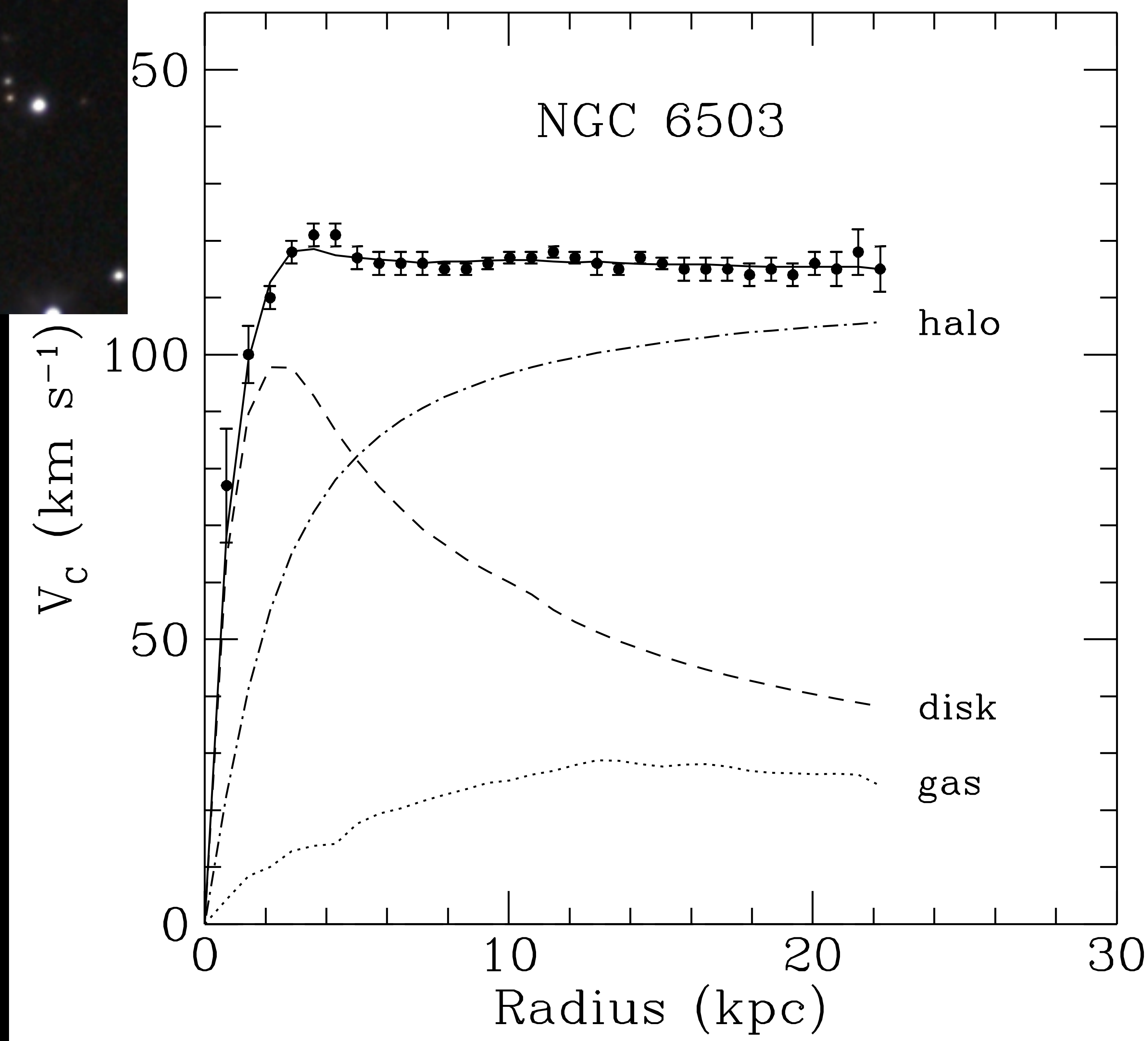
東京大学 THE UNIVERSITY OF TOKYO
UTIAS 東京大学国際高等研究所 THE UNIVERSITY OF TOKYO INSTITUTES FOR ADVANCED STUDY
KAVLI IPMU INSTITUTE FOR THE PHYSICS AND MATHEMATICS OF THE UNIVERSE
BERKELEY CENTER FOR THEORETICAL PHYSICS
BERKELEY LAB

Many submissions

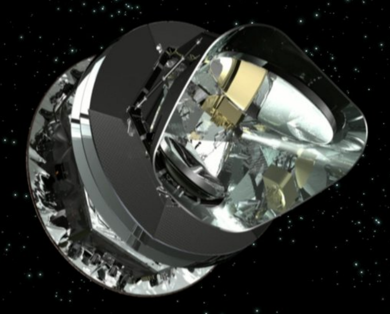
- SHiP
- Darkside
- Darwin
- NA64
- WISP with pulsed magnetic field
- LDMX@eSPS
- IAXO
- MAGIS atom interferometer
- and all the colliders!

galactic rotation curves



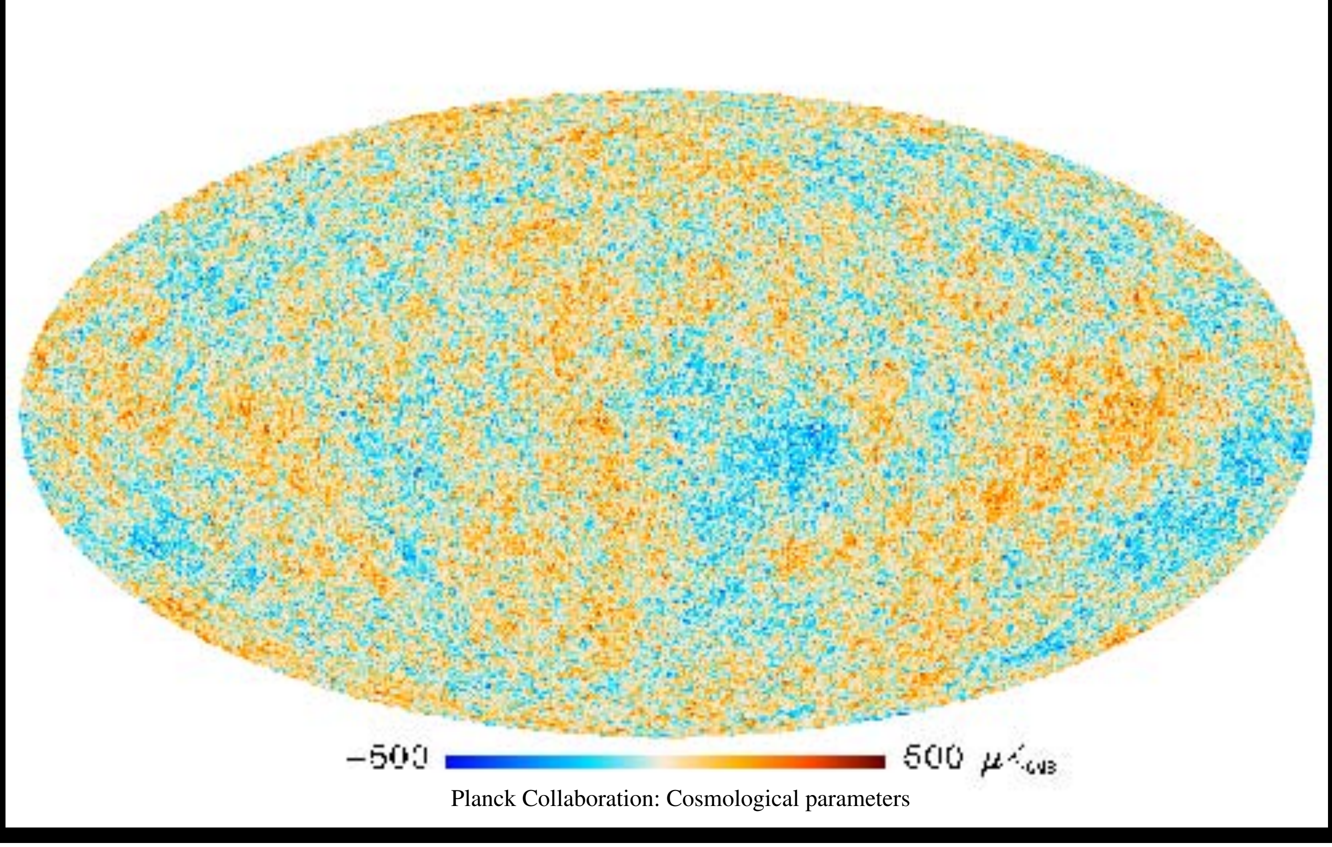



cluster of galaxies
Abell 2218
2.1B lyrs

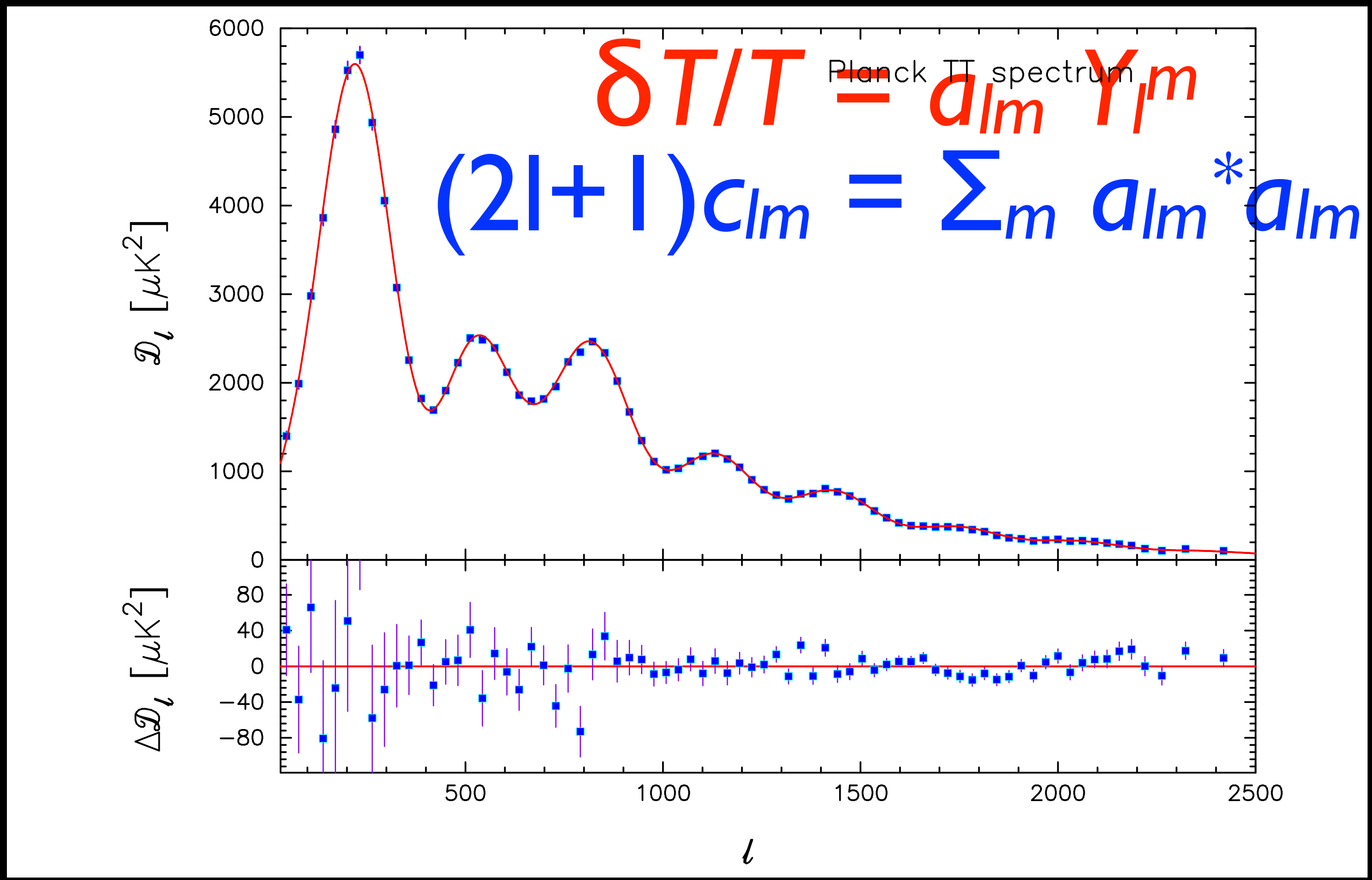


cosmological scales

- a random density fluctuations ~O(10^{-5}) more-or-less scale invariant $P(k) \propto k^{n_s-1}$
- starts acoustic oscillation, amplified by gravitational attraction
- "knows" about everything between 0<z<1300
- $\Omega_{DM}=0.25 \gg \Omega_b=0.05$

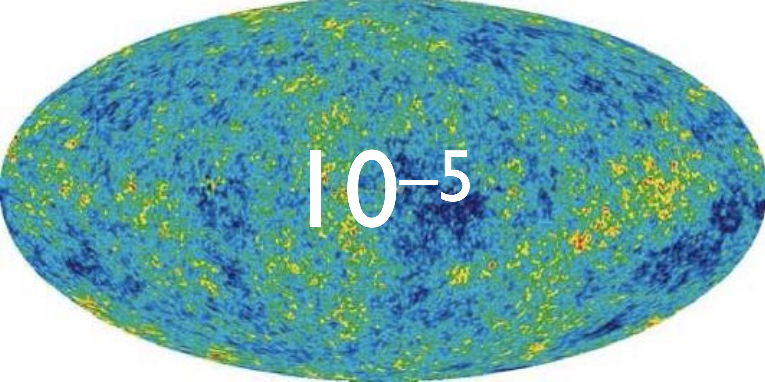


Planck Collaboration: Cosmological parameters

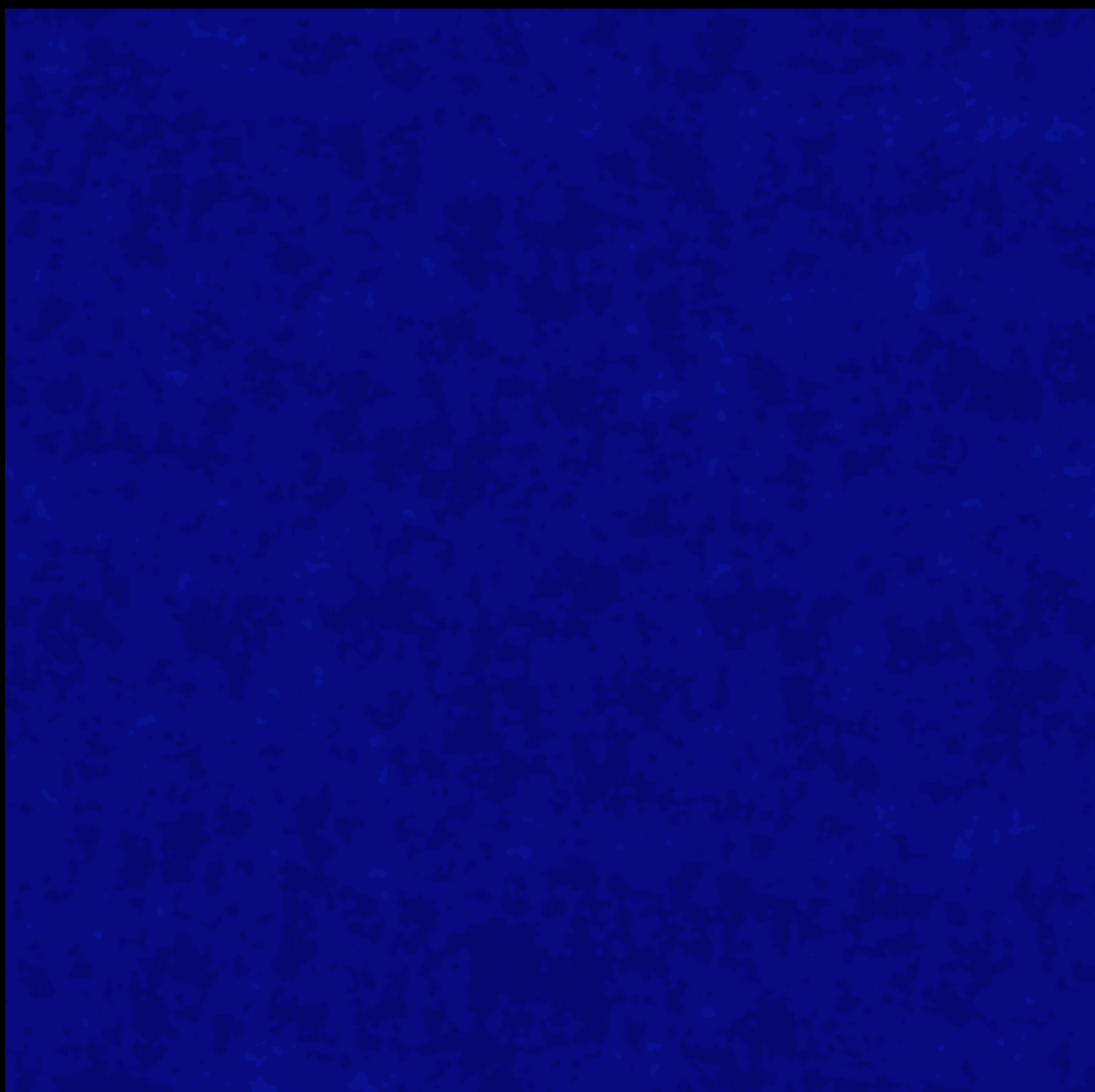


$\delta T/T = a_{lm} Y_l^m$

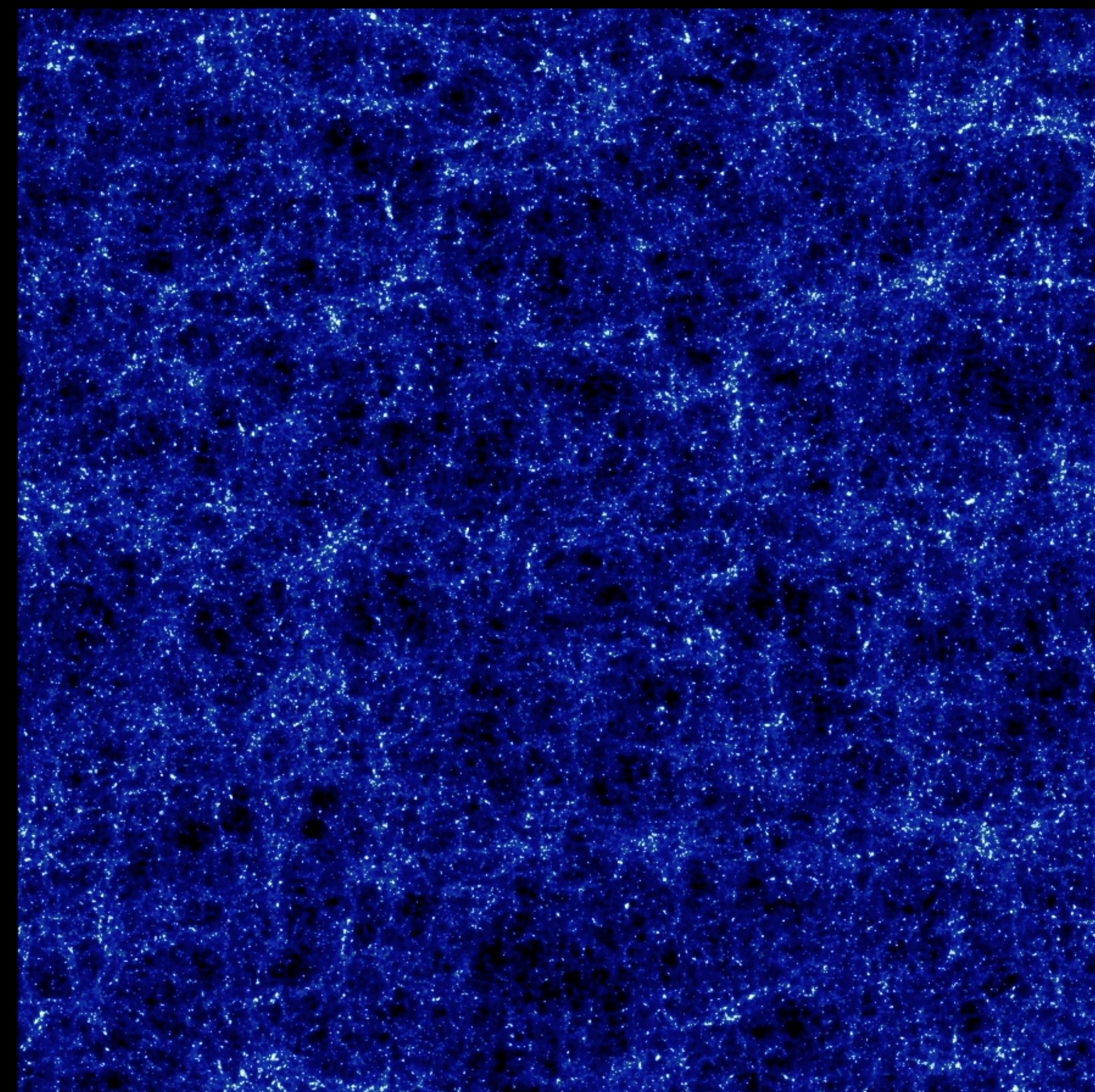
$(2l+1)c_{lm} = \Sigma_m a_{lm}^* a_{lm}$



Dark Matter is our Mom



without dark matter



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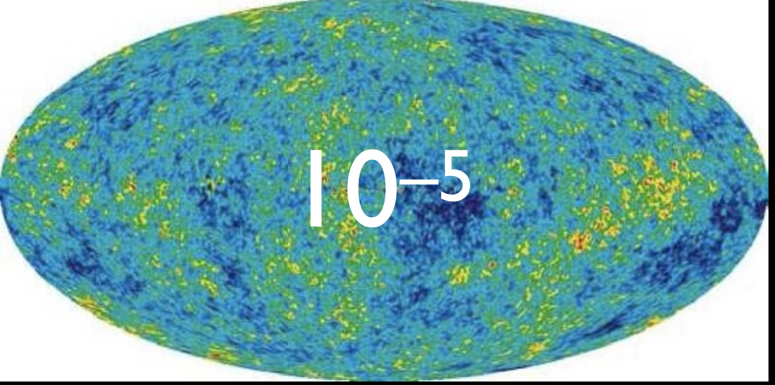

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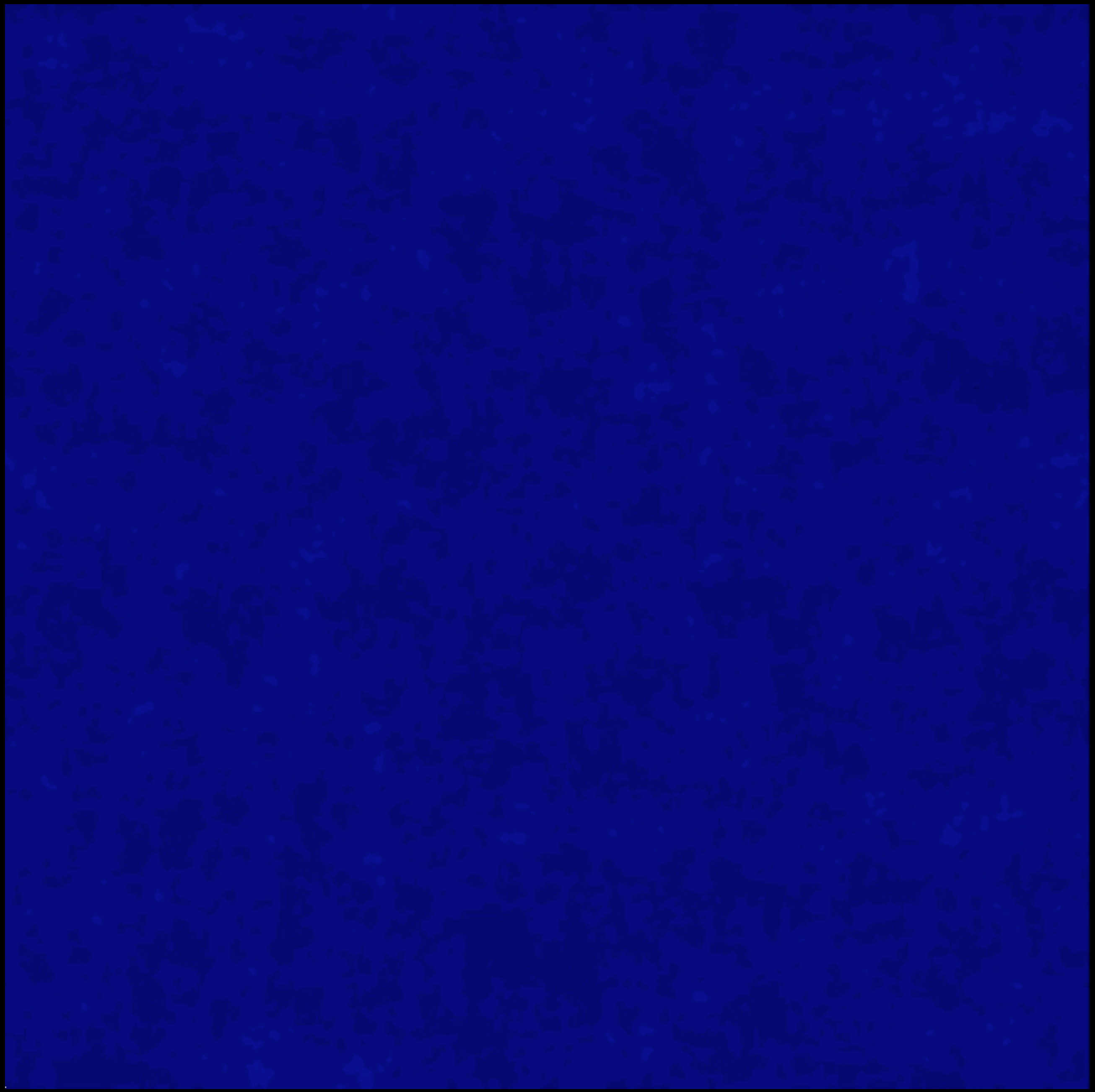

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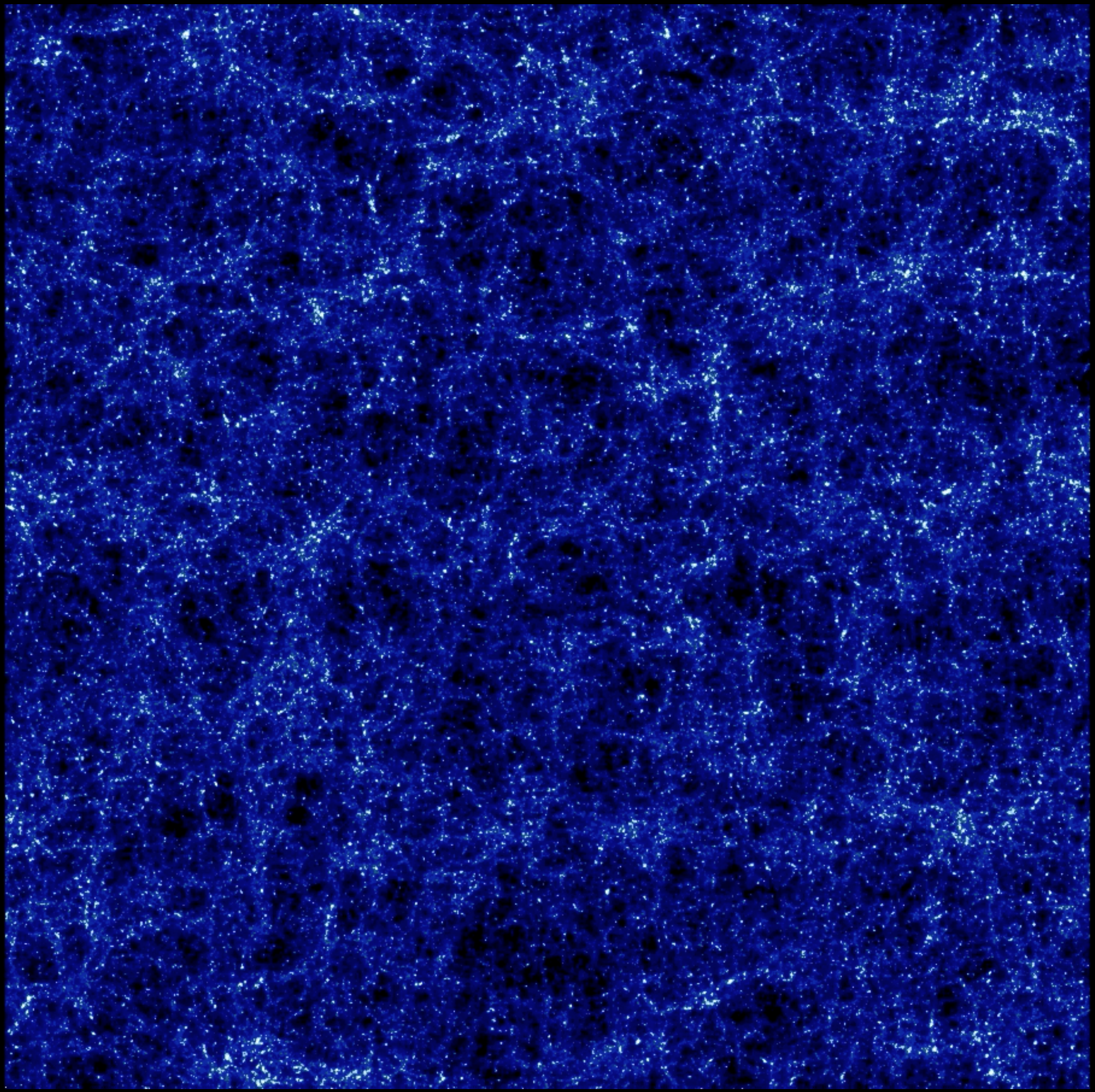
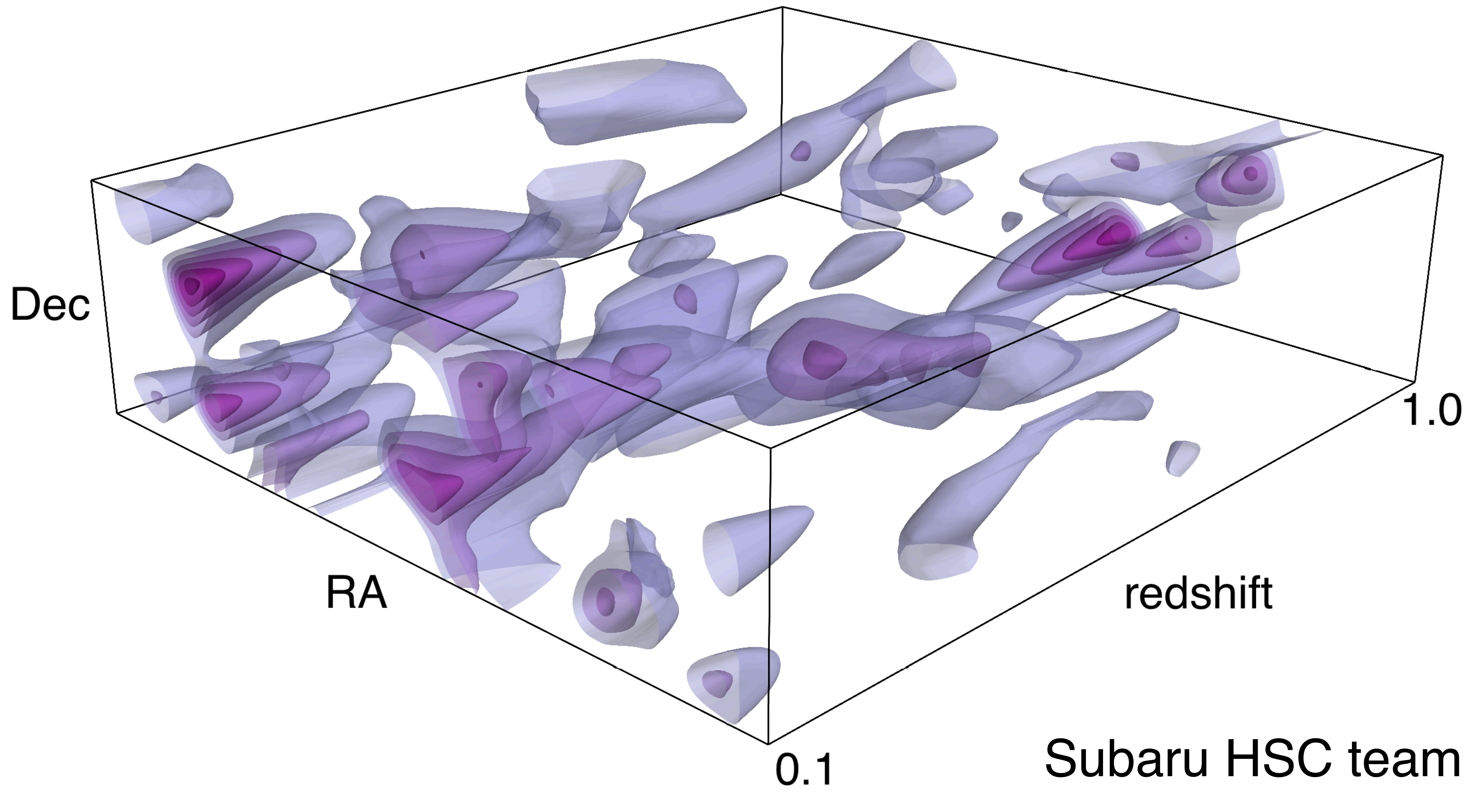
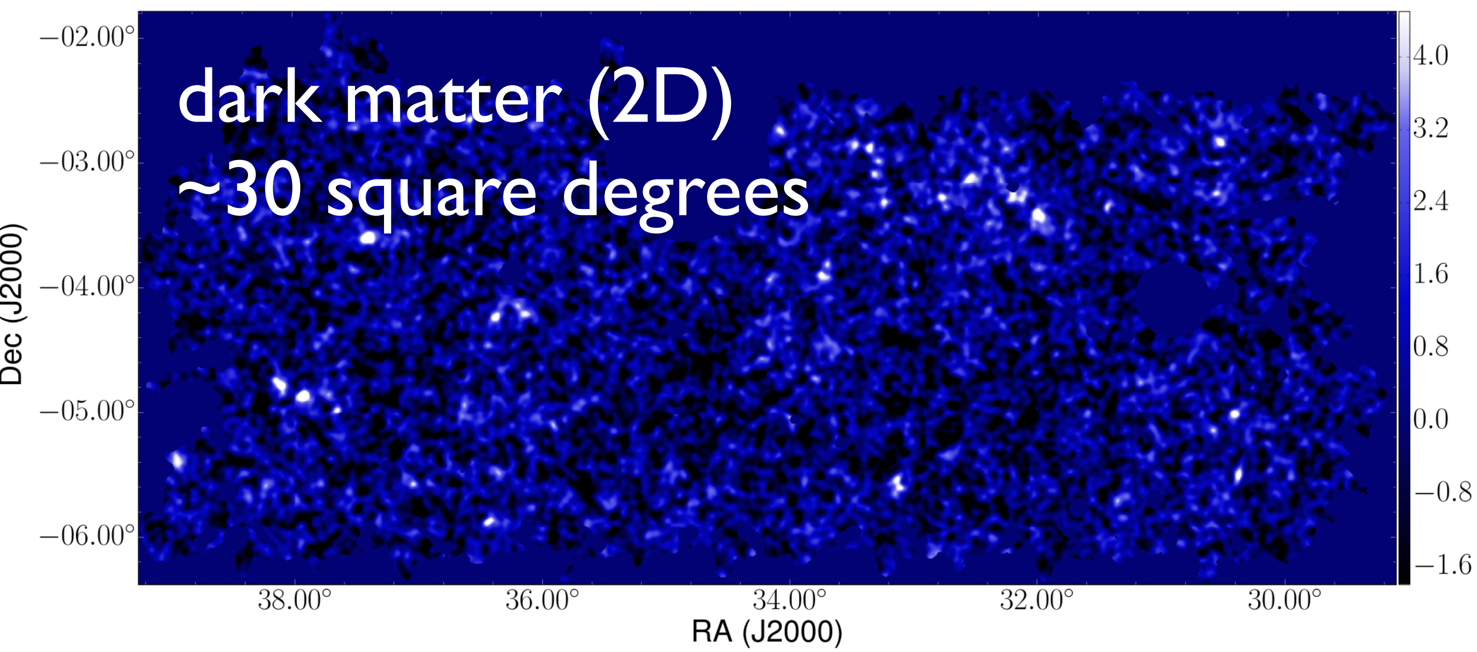


with dark matter

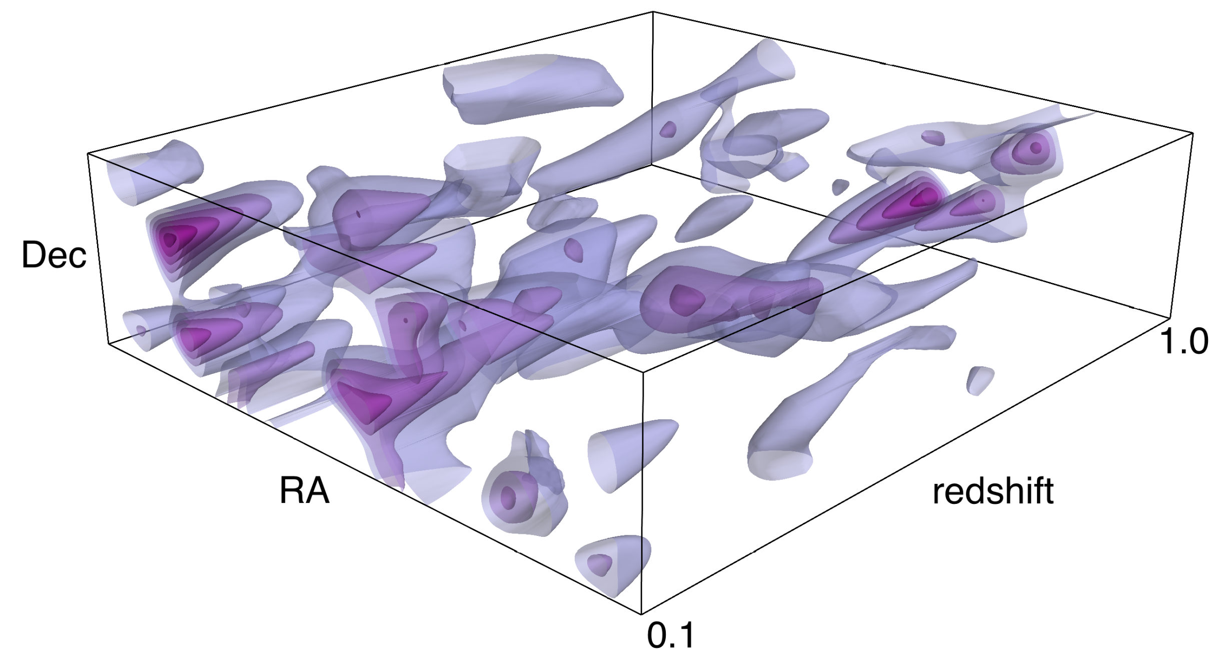
World's largest 3D map of dark matter

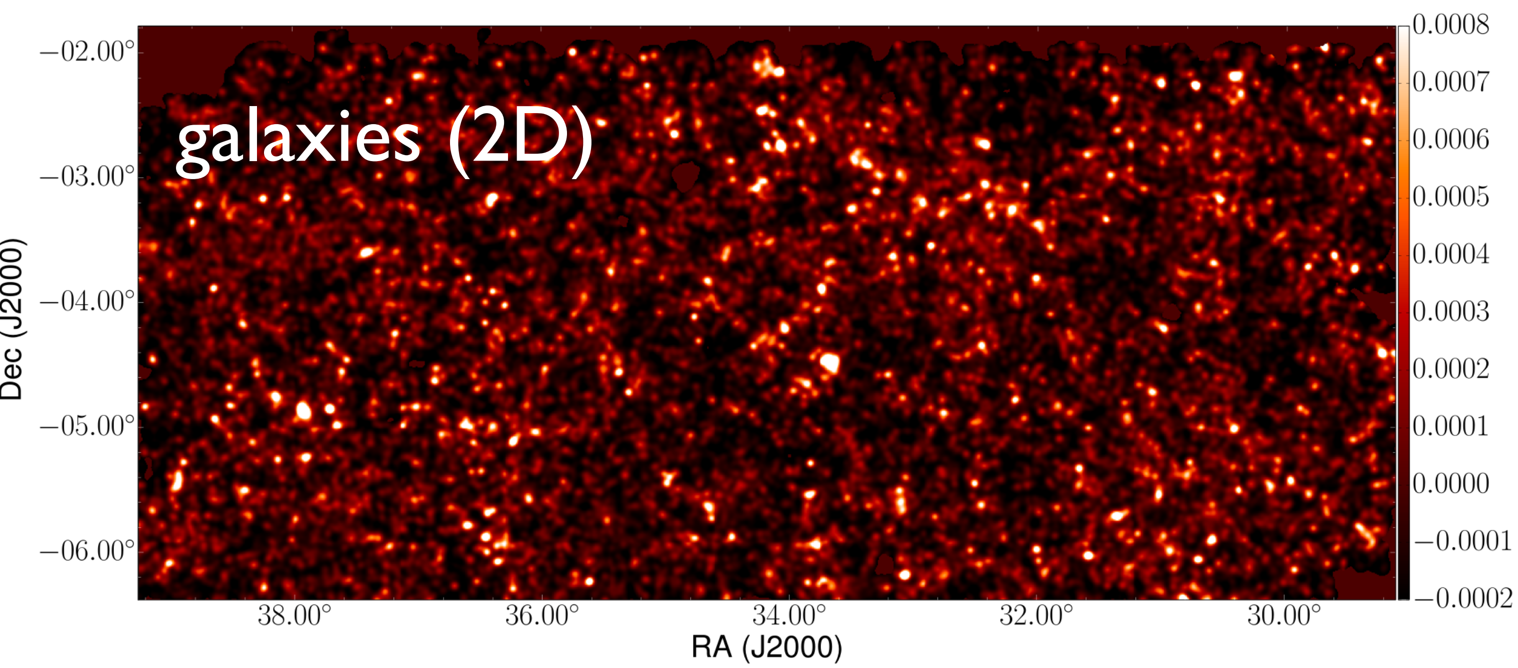


She is our Mom, indeed!

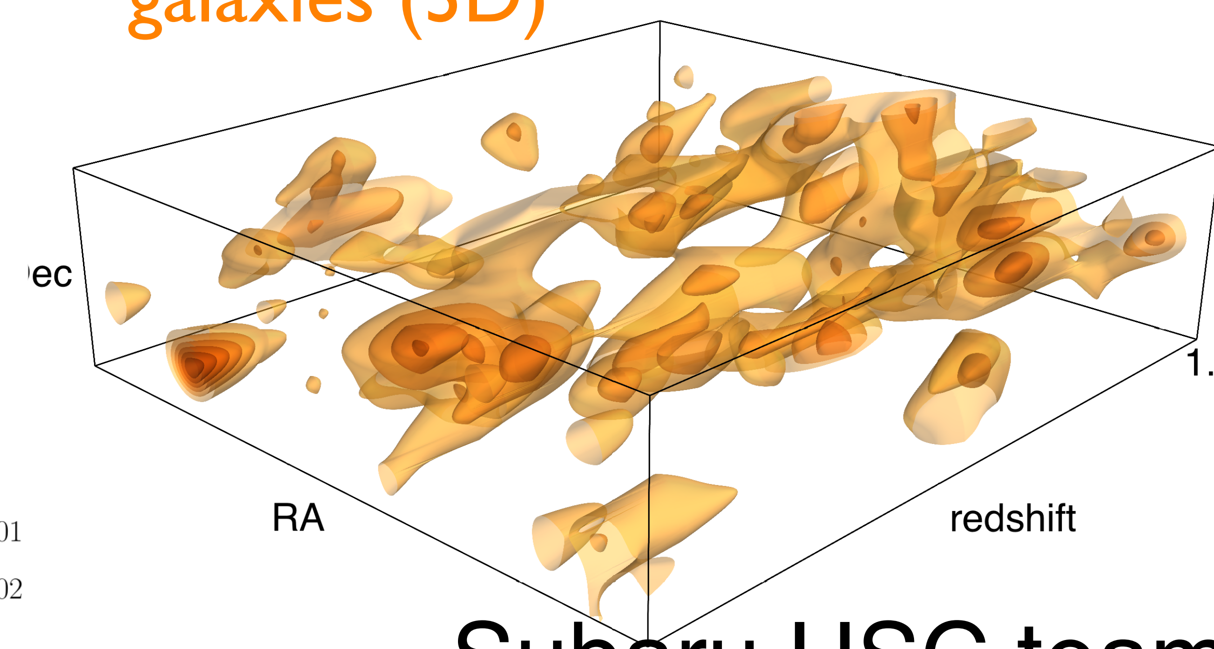


dark matter (3D)





galaxies (3D)



Subaru HSC team

Dim Stars? Black Holes?

Search for MACHOs
(Massive Compact Halo Objects)

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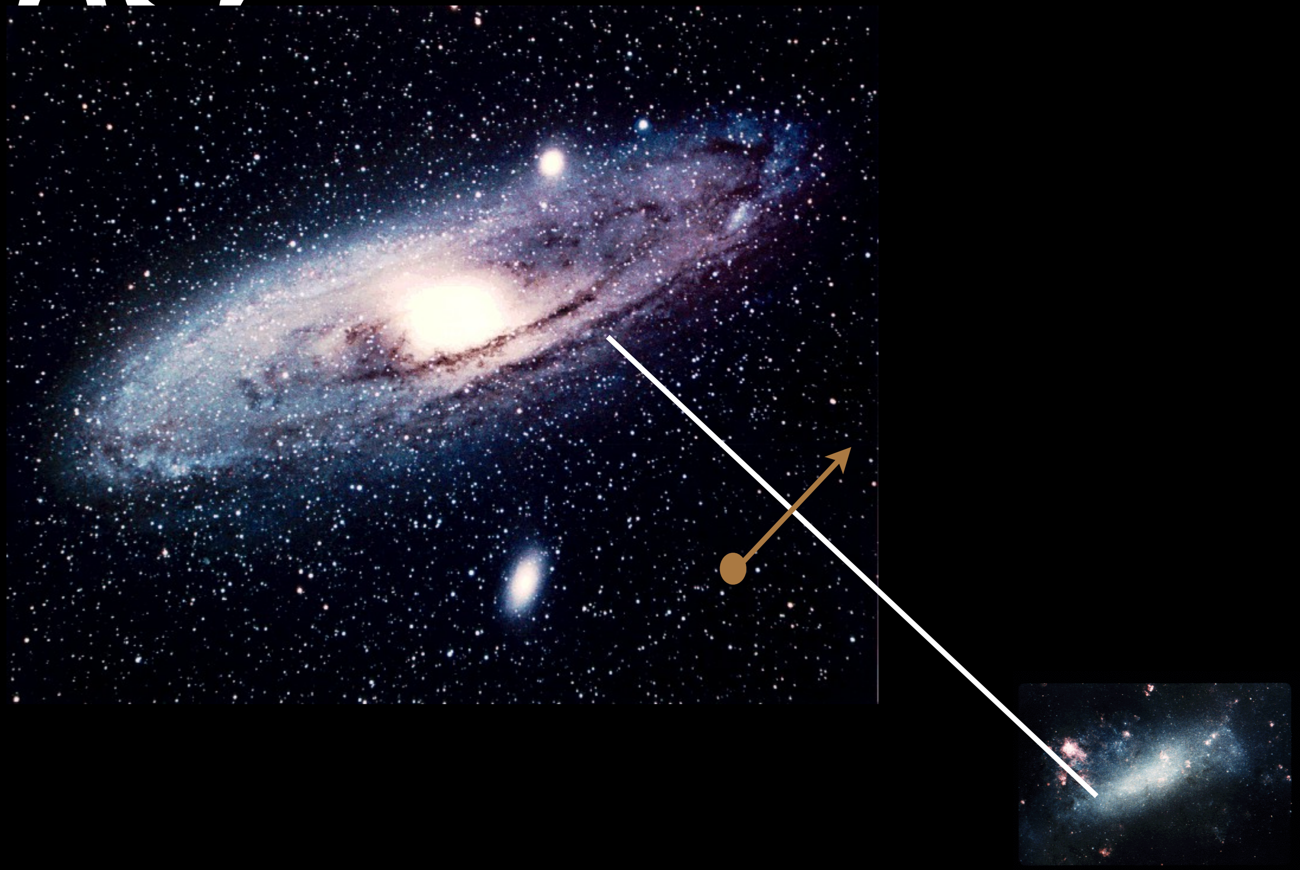

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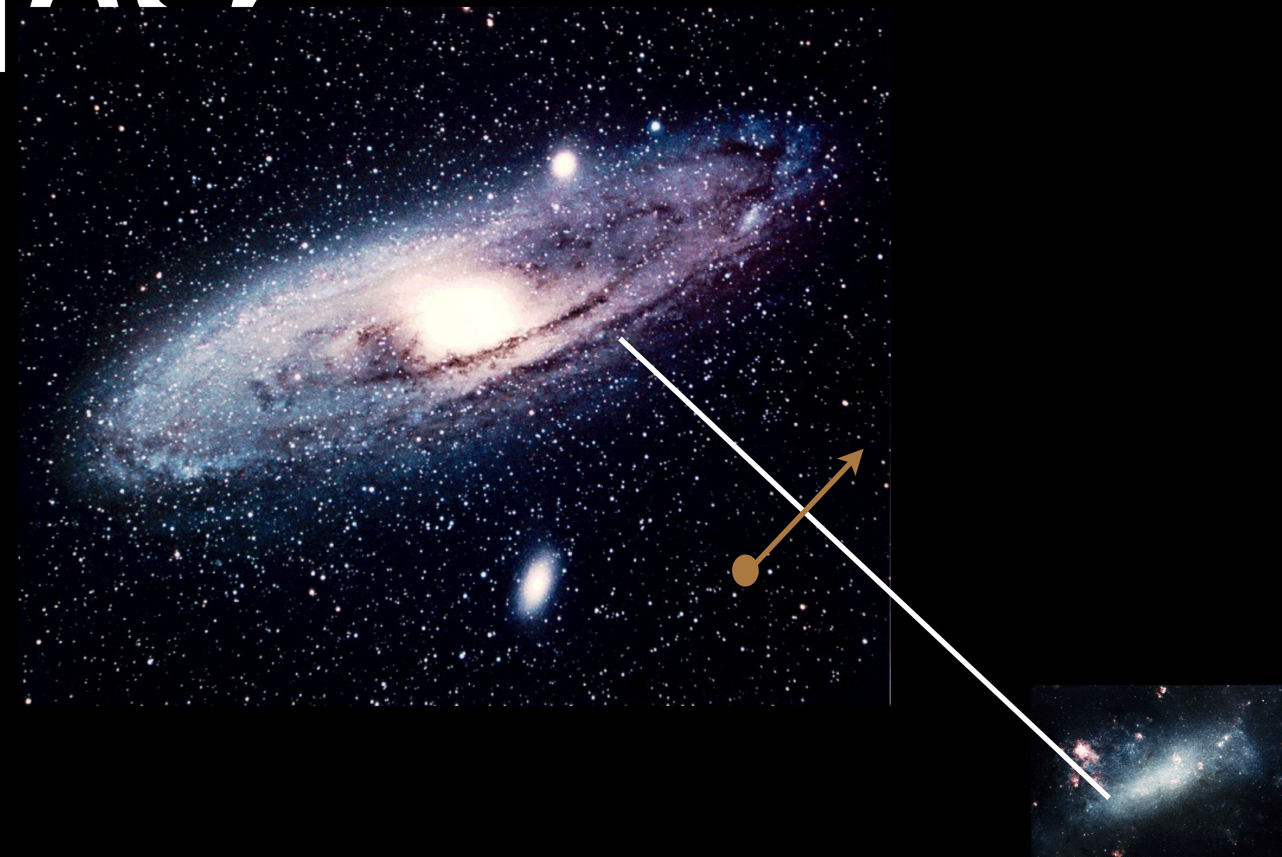

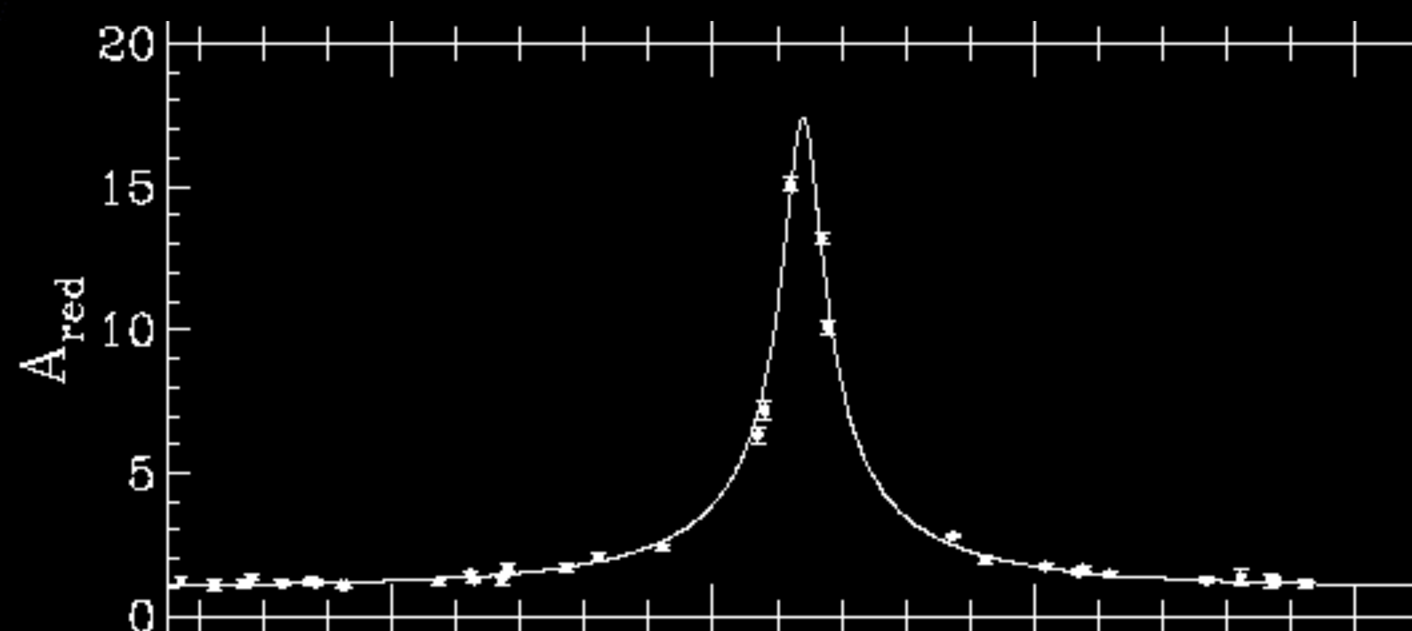

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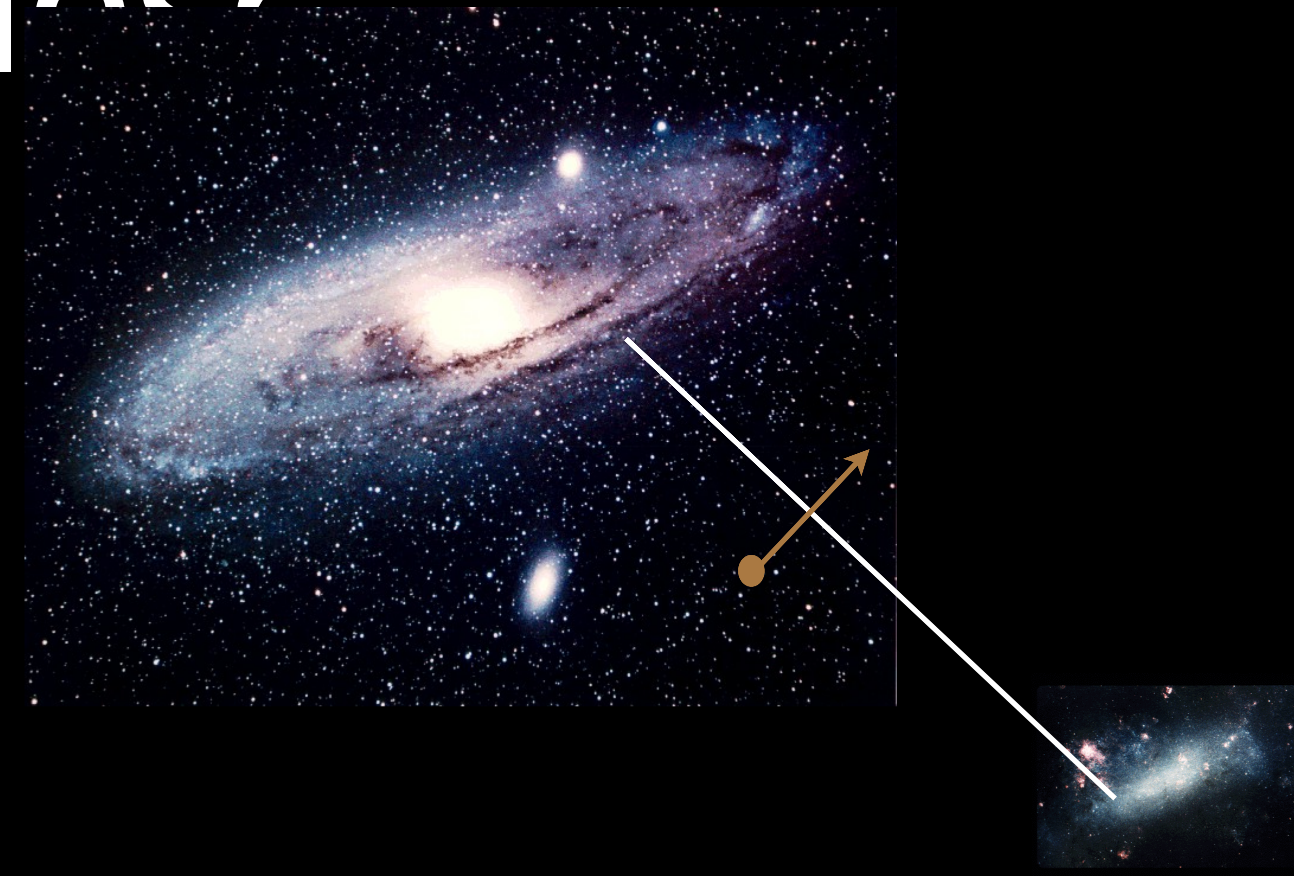

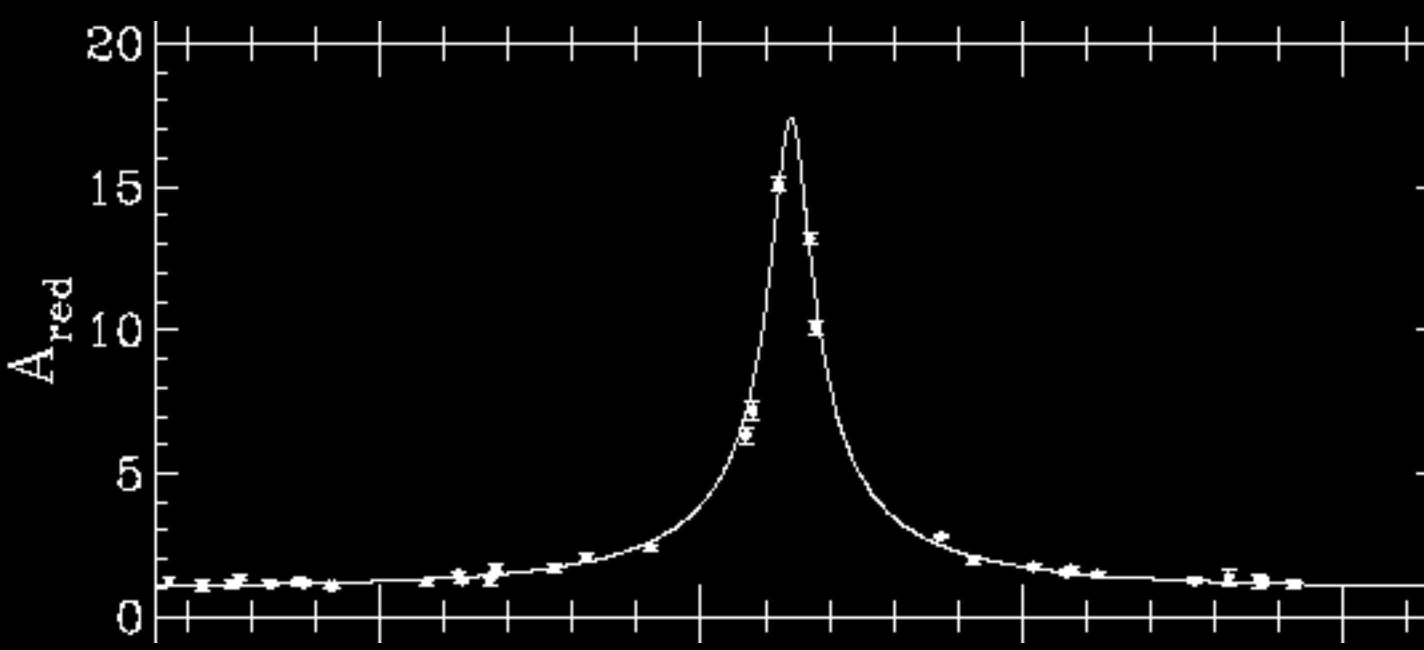

Not enough of them!

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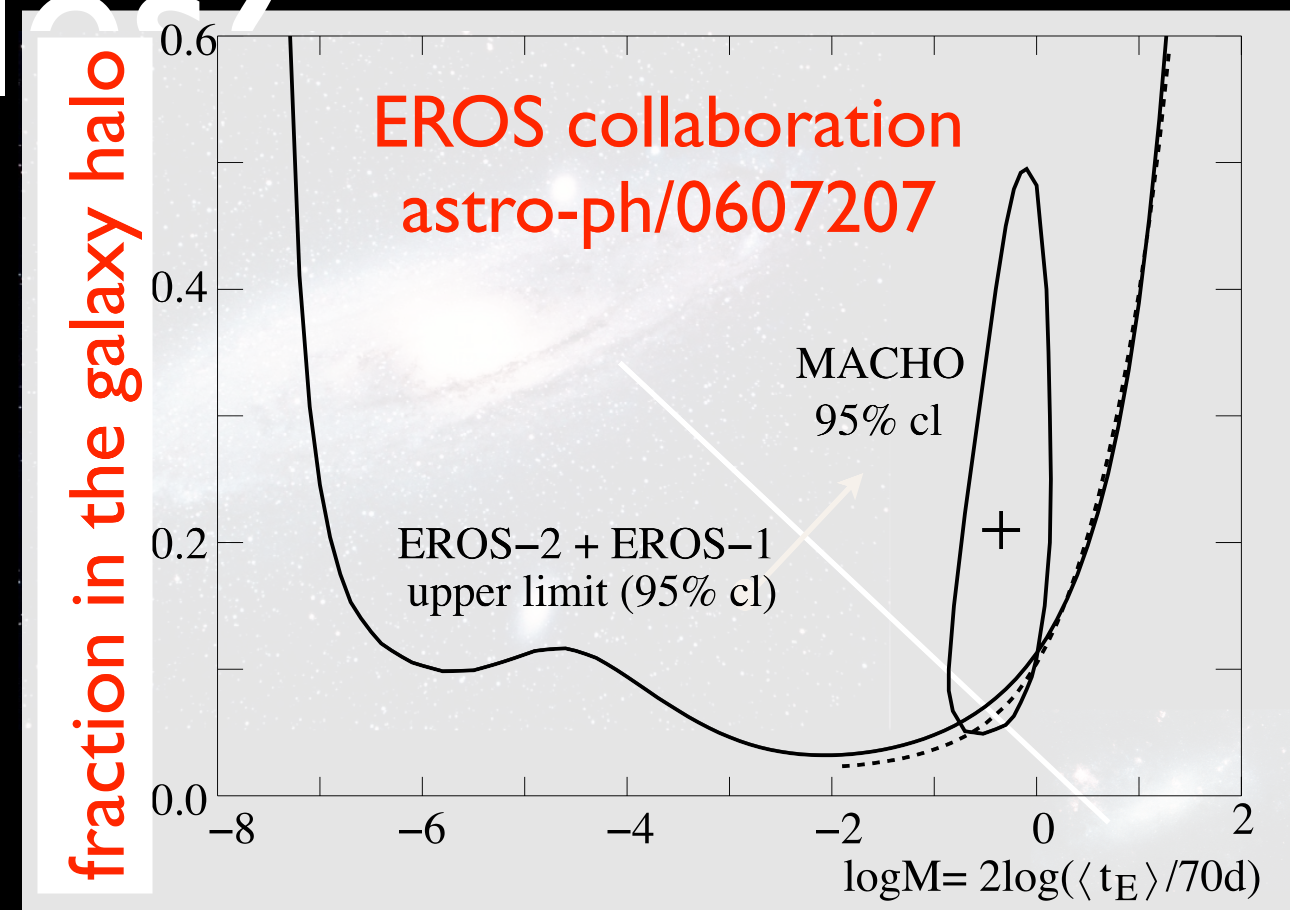

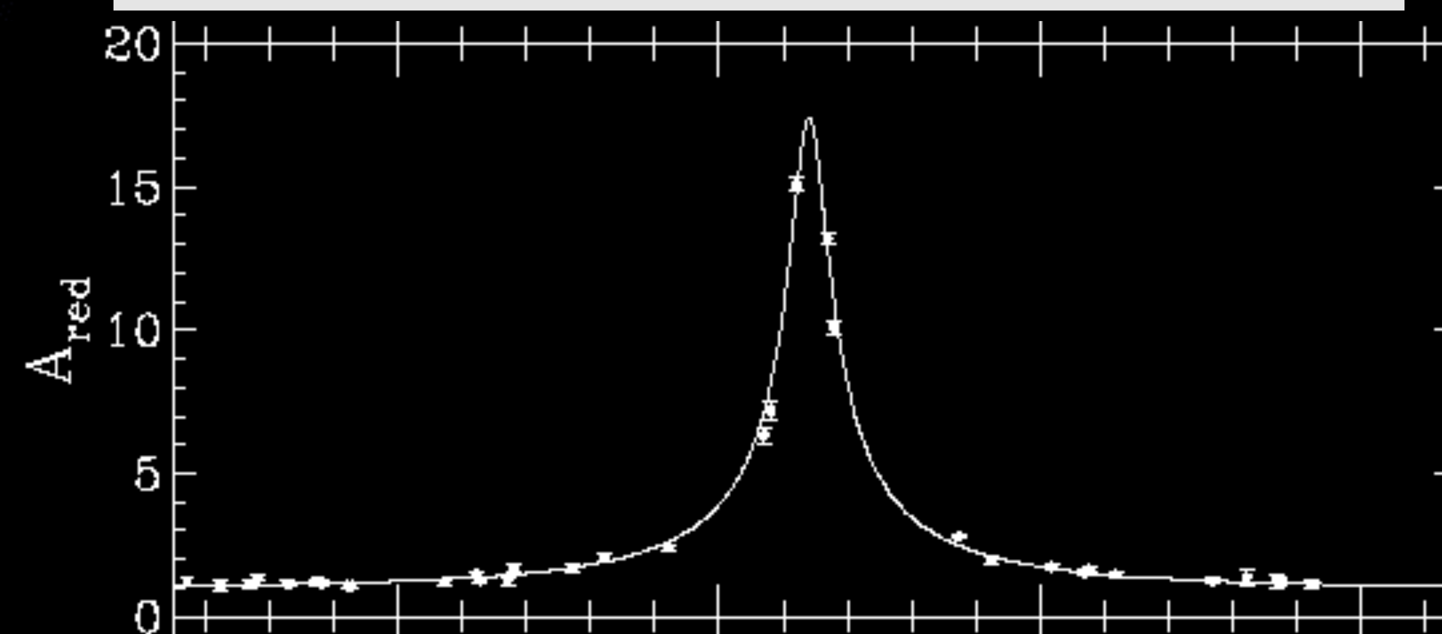

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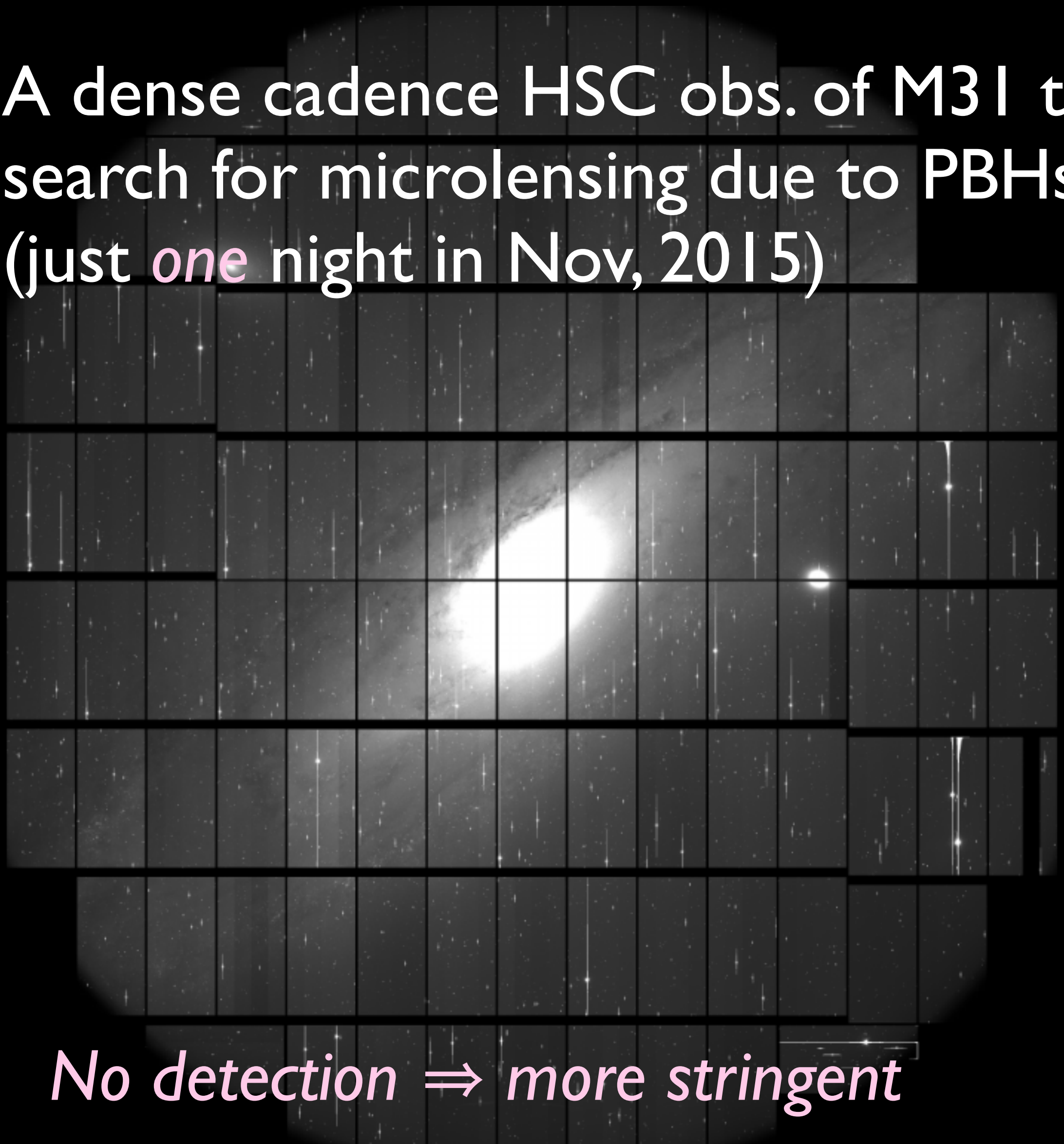
Best limit on Black Hole dark matter

Niikura, Takada et al., to submit soon

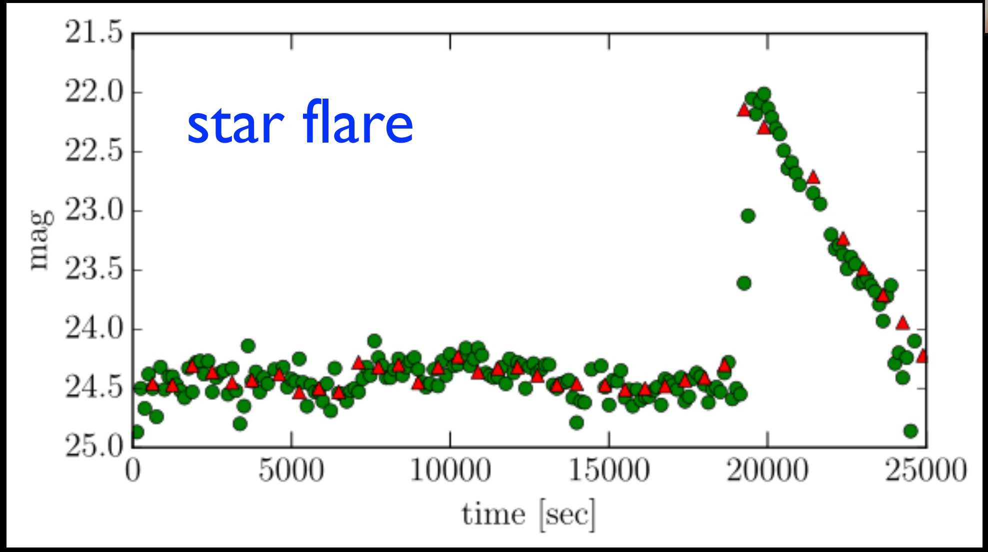
started from conversation between astronomers and particle physicists

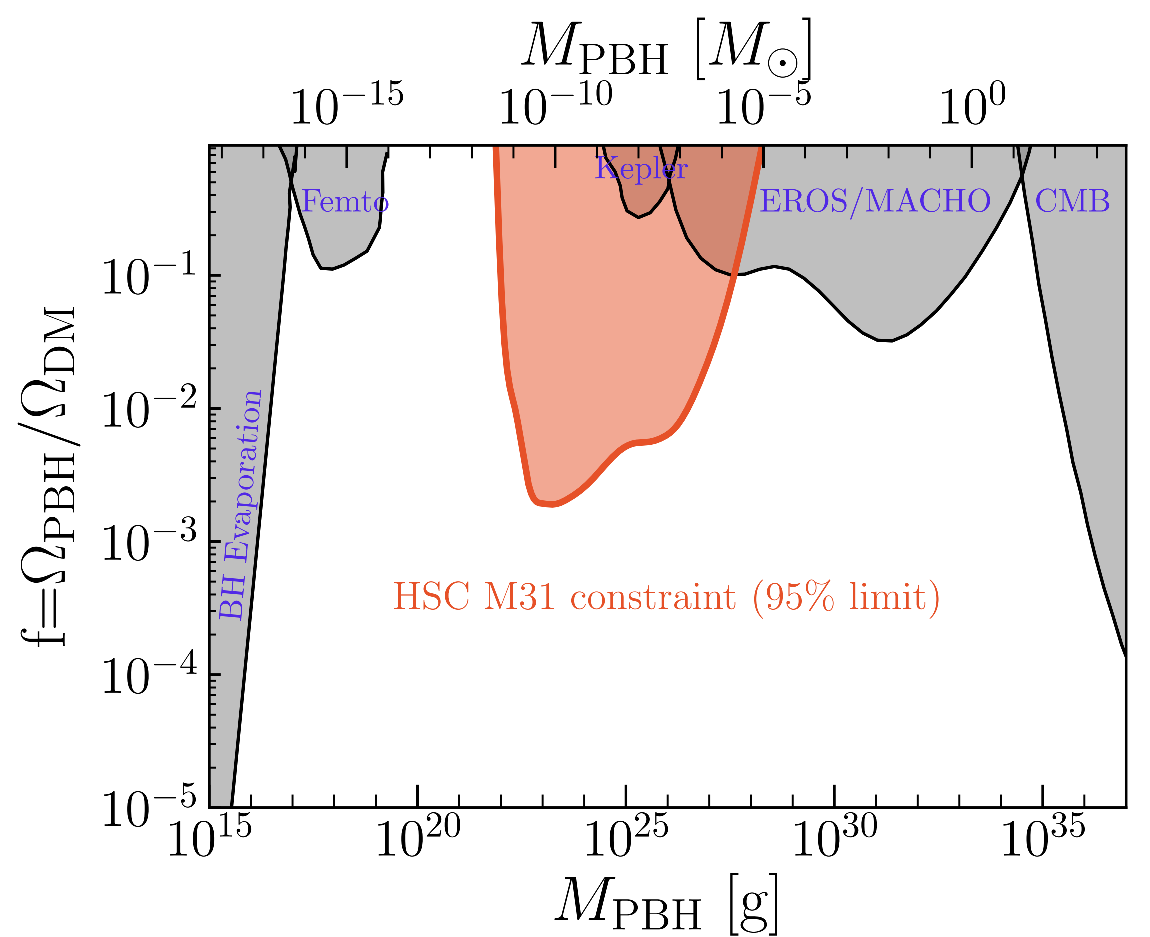
A dense cadence HSC obs. of M31 to search for microlensing due to PBHs (just *one* night in Nov, 2015)



No detection ⇒ more stringent upper bound, than 2yr Kepler data (Griest et al.)

Found many variable stars





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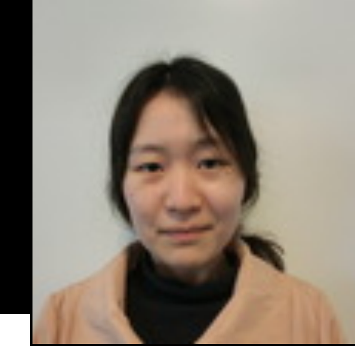

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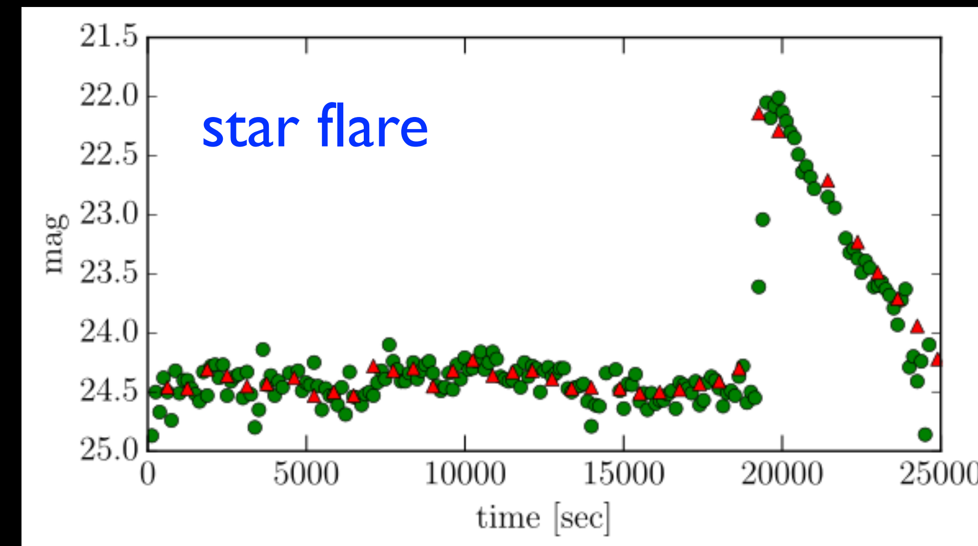

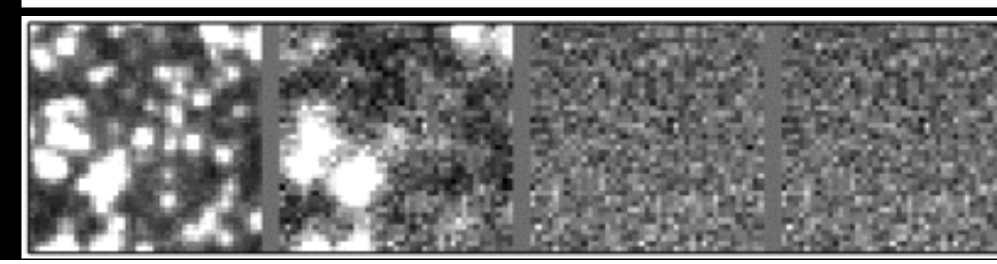

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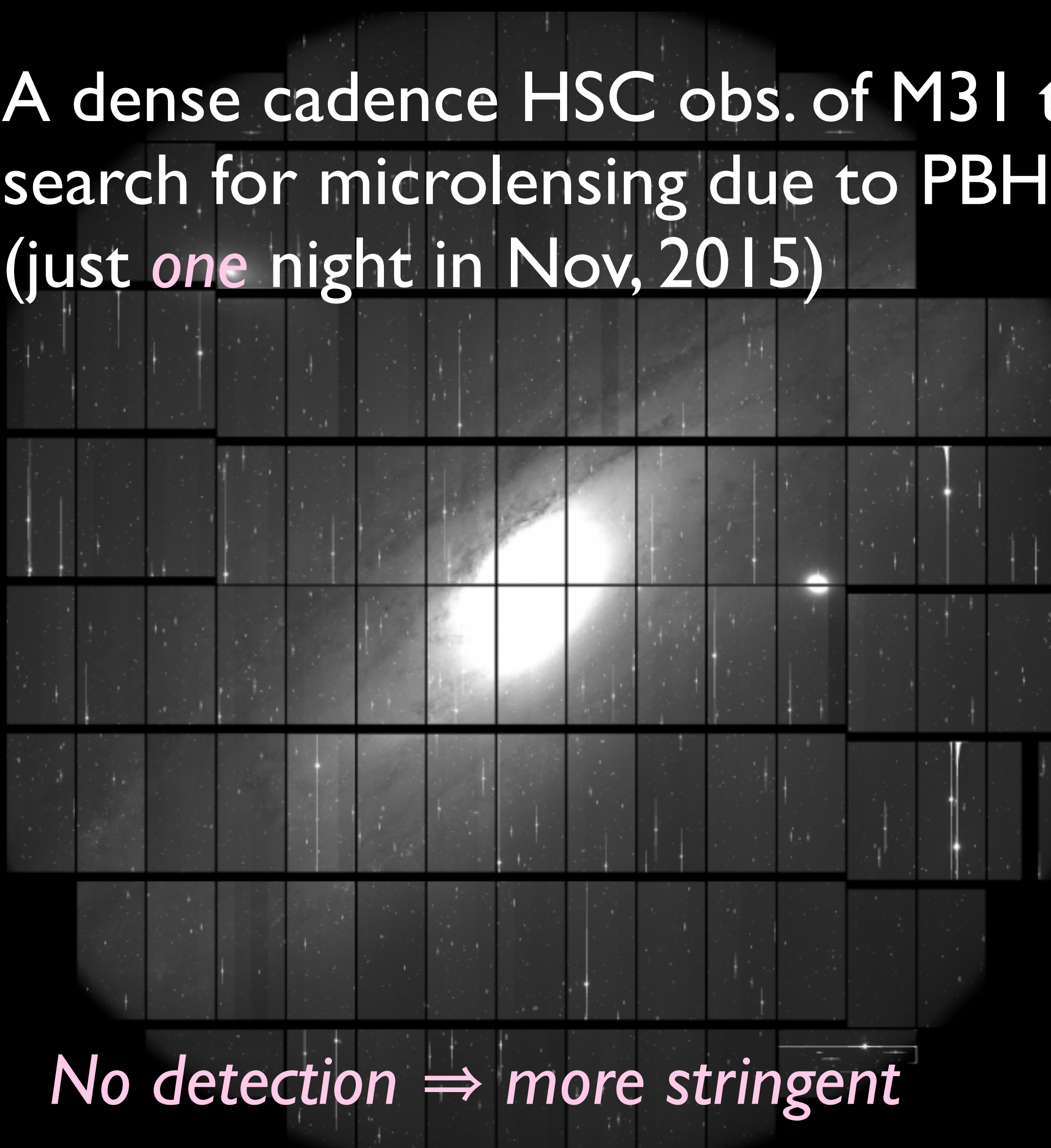

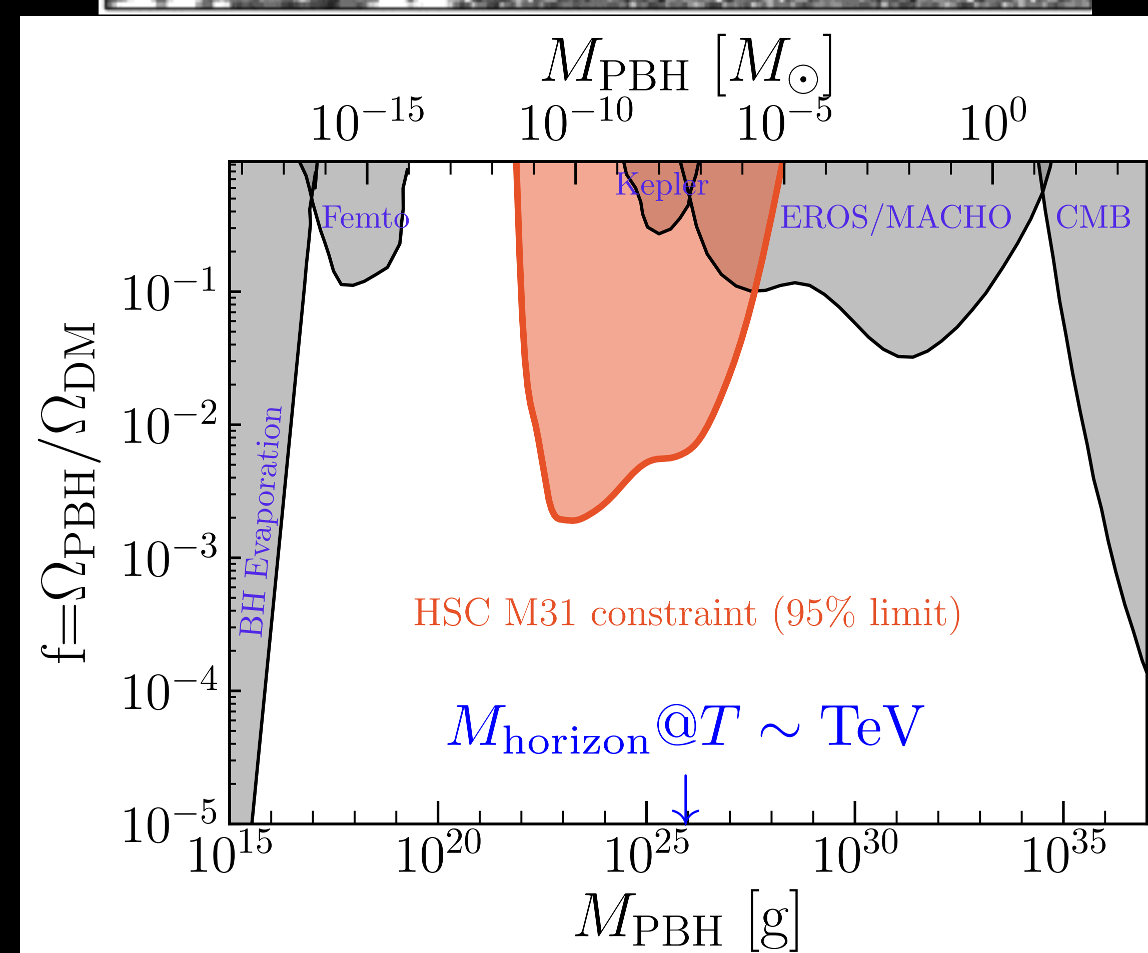

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Mass Limits
"Uncertainty Principle"

- Clumps to form structure
- imagine $V = G_N \frac{Mm}{r}$
- "Bohr radius": $r_B = \frac{\hbar^2}{G_N M m^2}$
- too small m ⇒ won't "fit" in a galaxy!
- m >10^{-22} eV "uncertainty principle" bound
  (modified from Hu, Barkana, Gruzinov, astro-ph/0003365)

sociology

- We used to think

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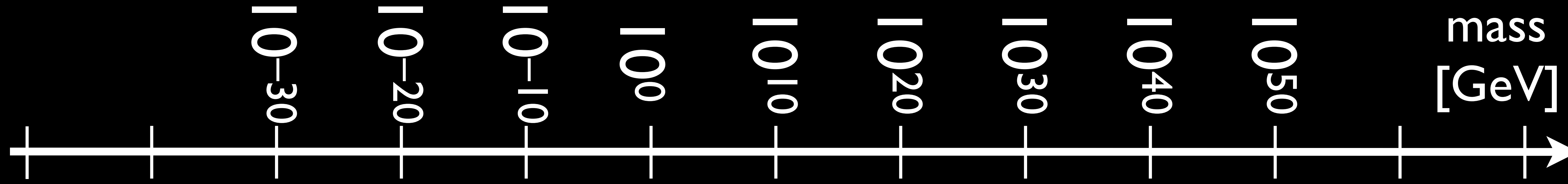
  - need to solve problems with the SM
  - hierarchy problem, strong CP, etc
  - it is great if a solution also gives dark matter candidate as an *option*
  - big ideas: supersymmetry, extra dim
  - probably because dark matter problem was not so established in 80's



10^{-30}
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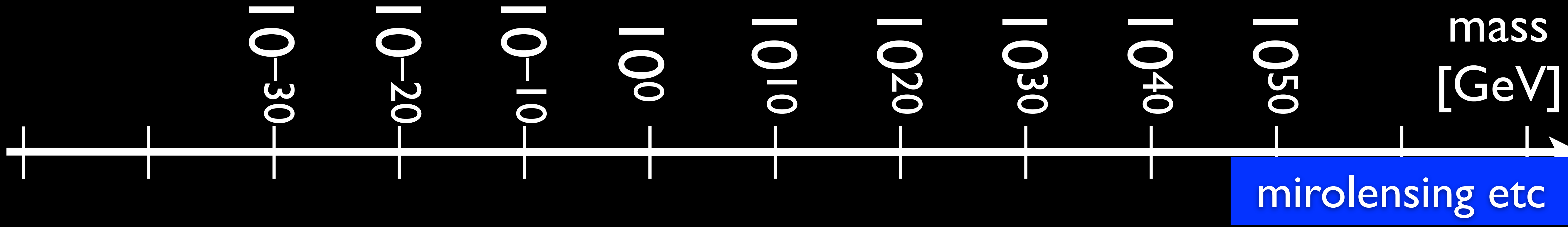

mass [GeV]
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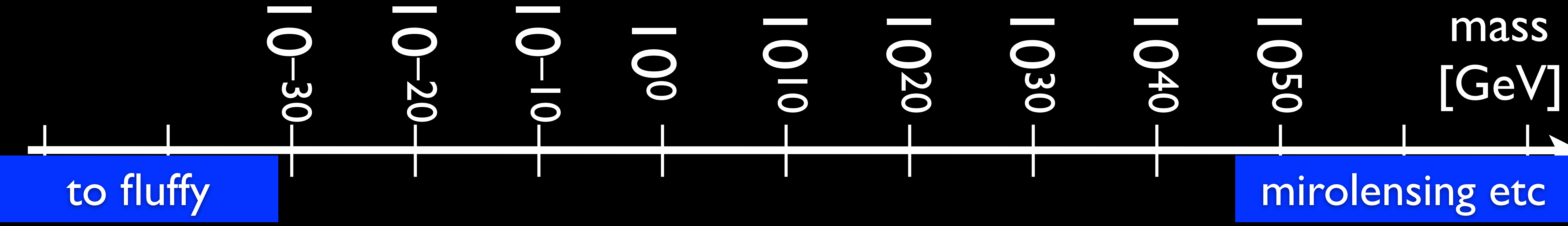
mirolensing etc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to fluffy
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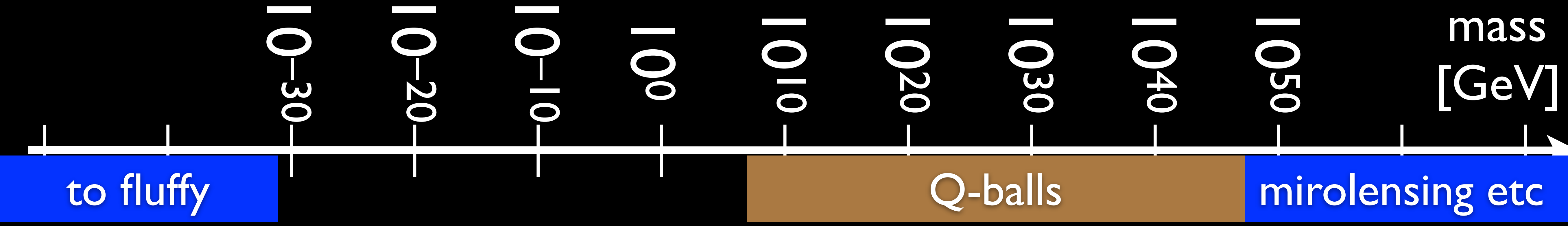
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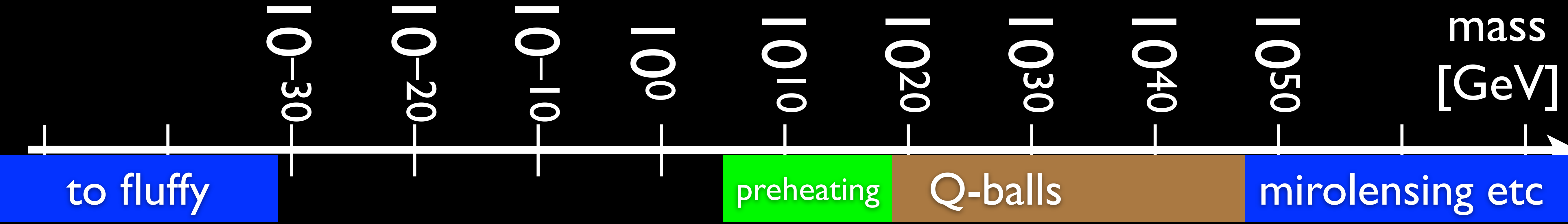
to fluffy
Q-balls
mirolensing etc



mass
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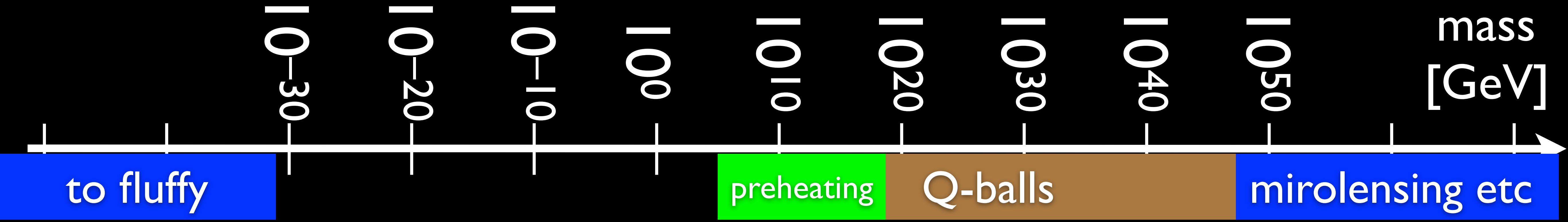
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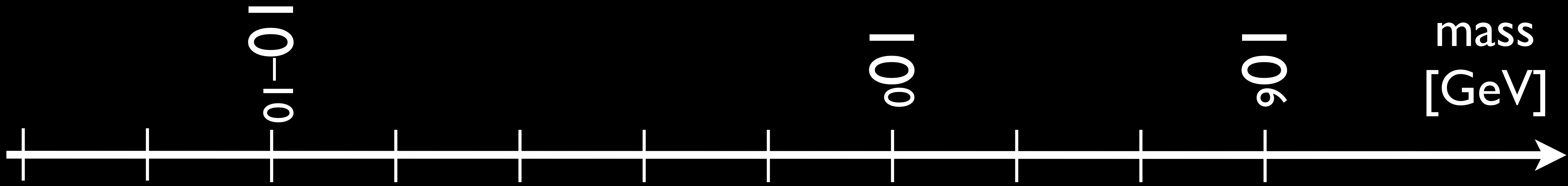
mass [GeV]
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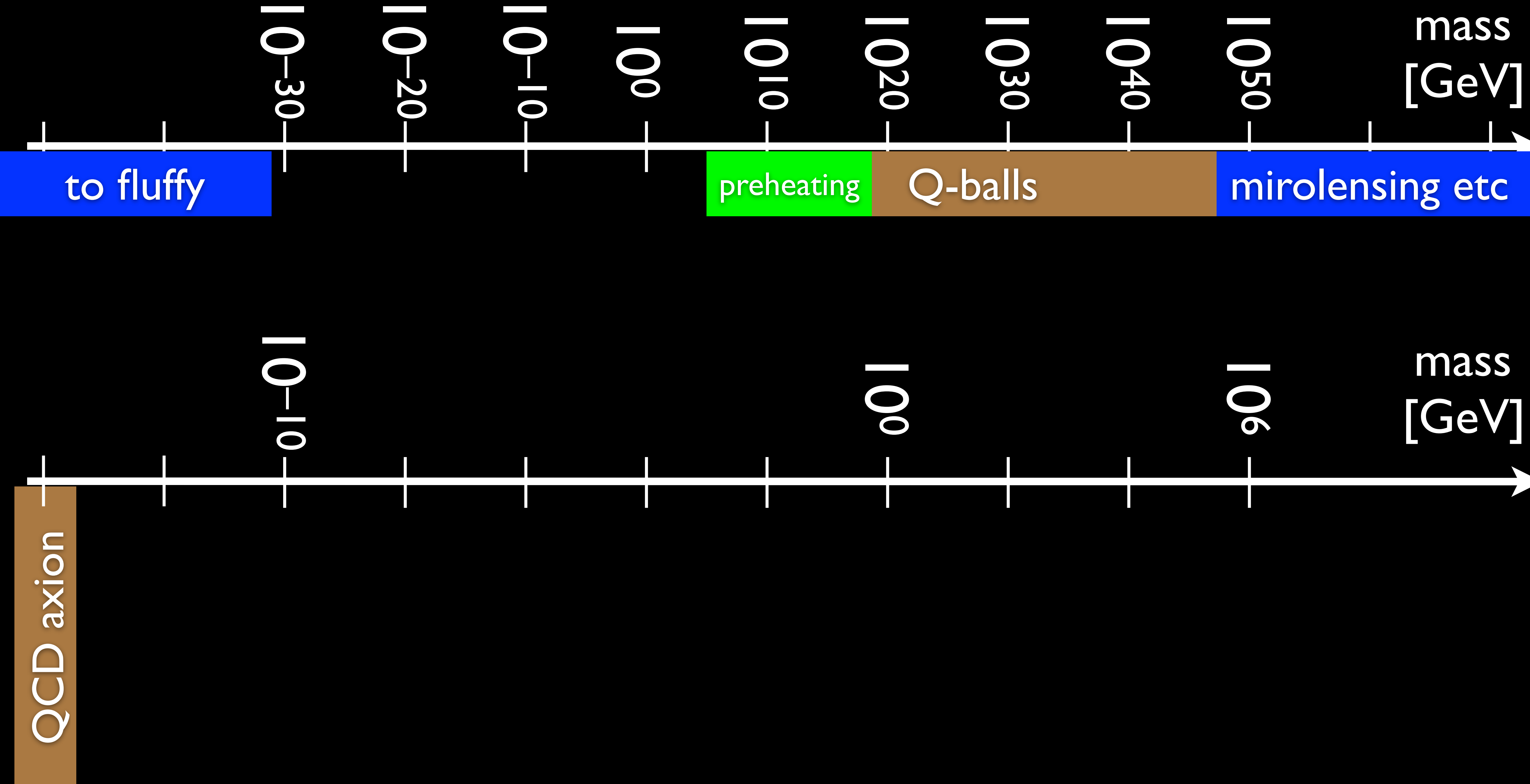

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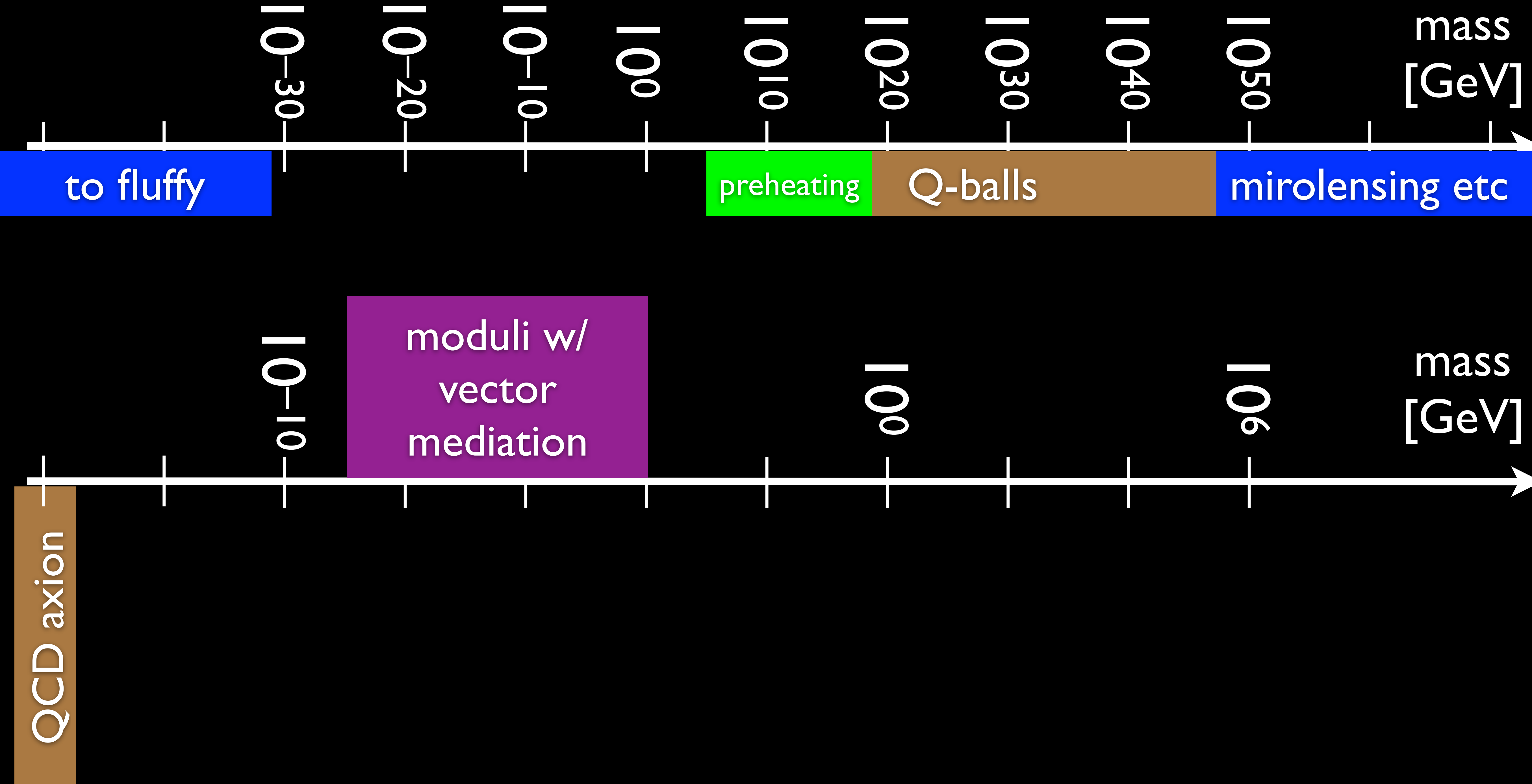

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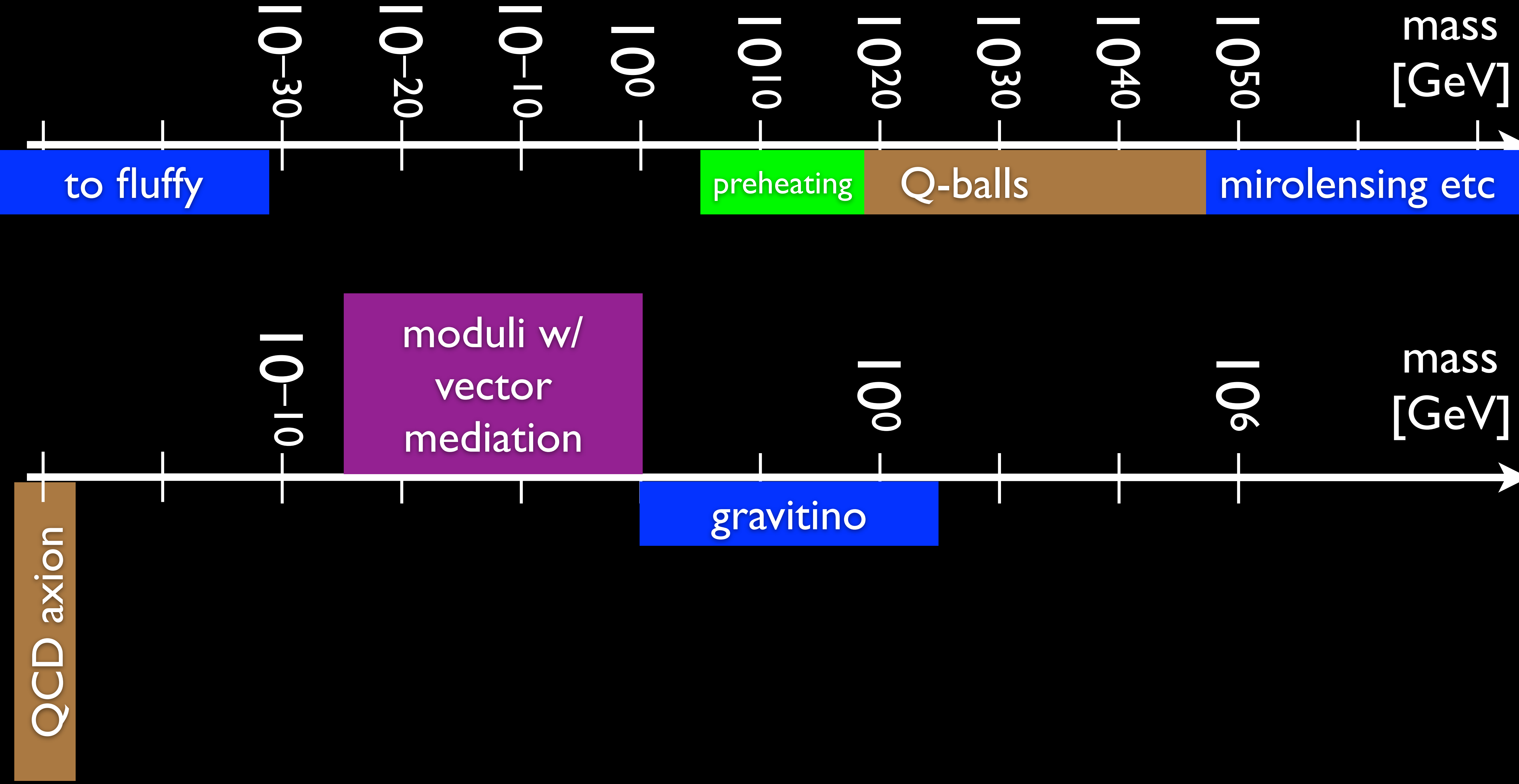
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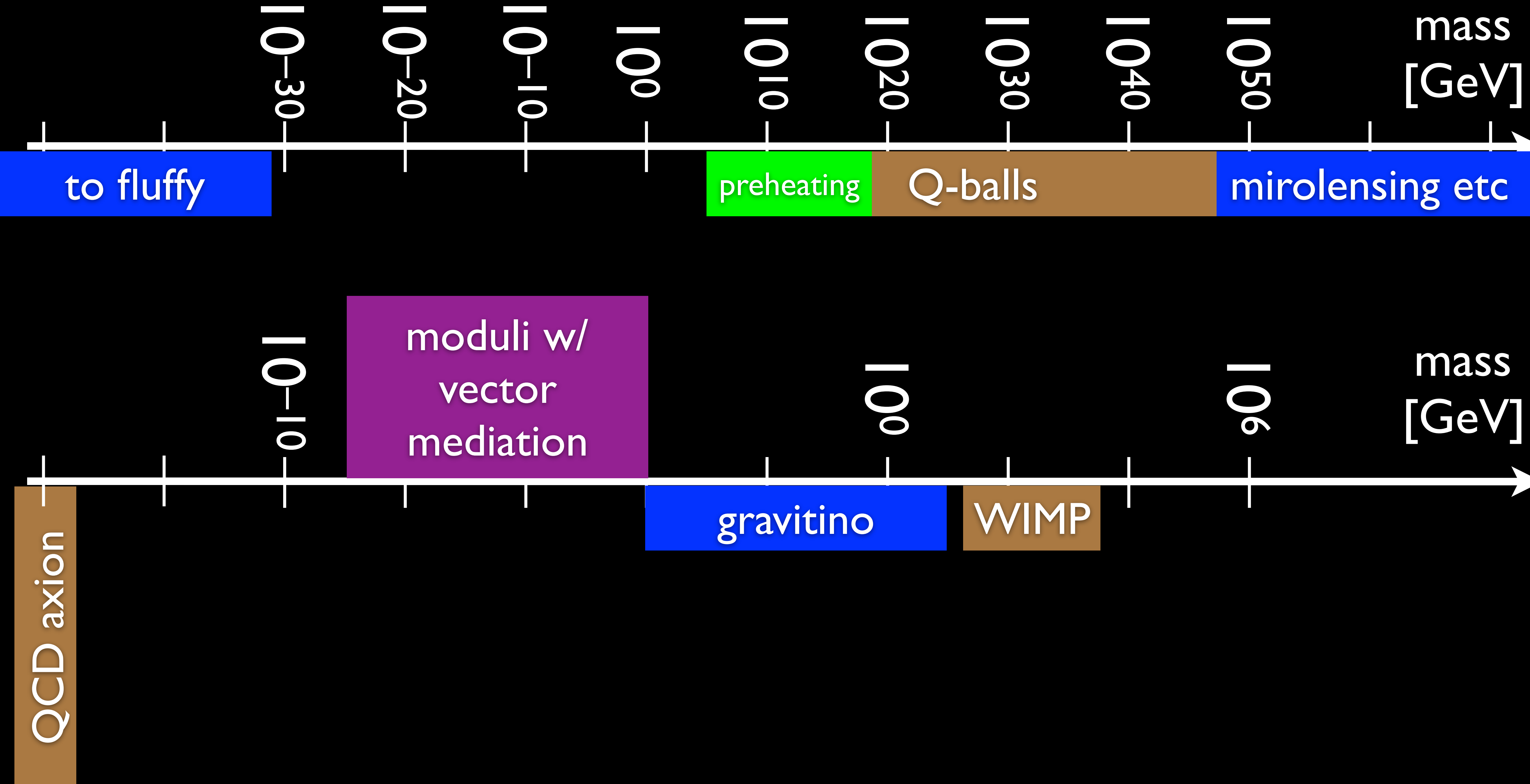

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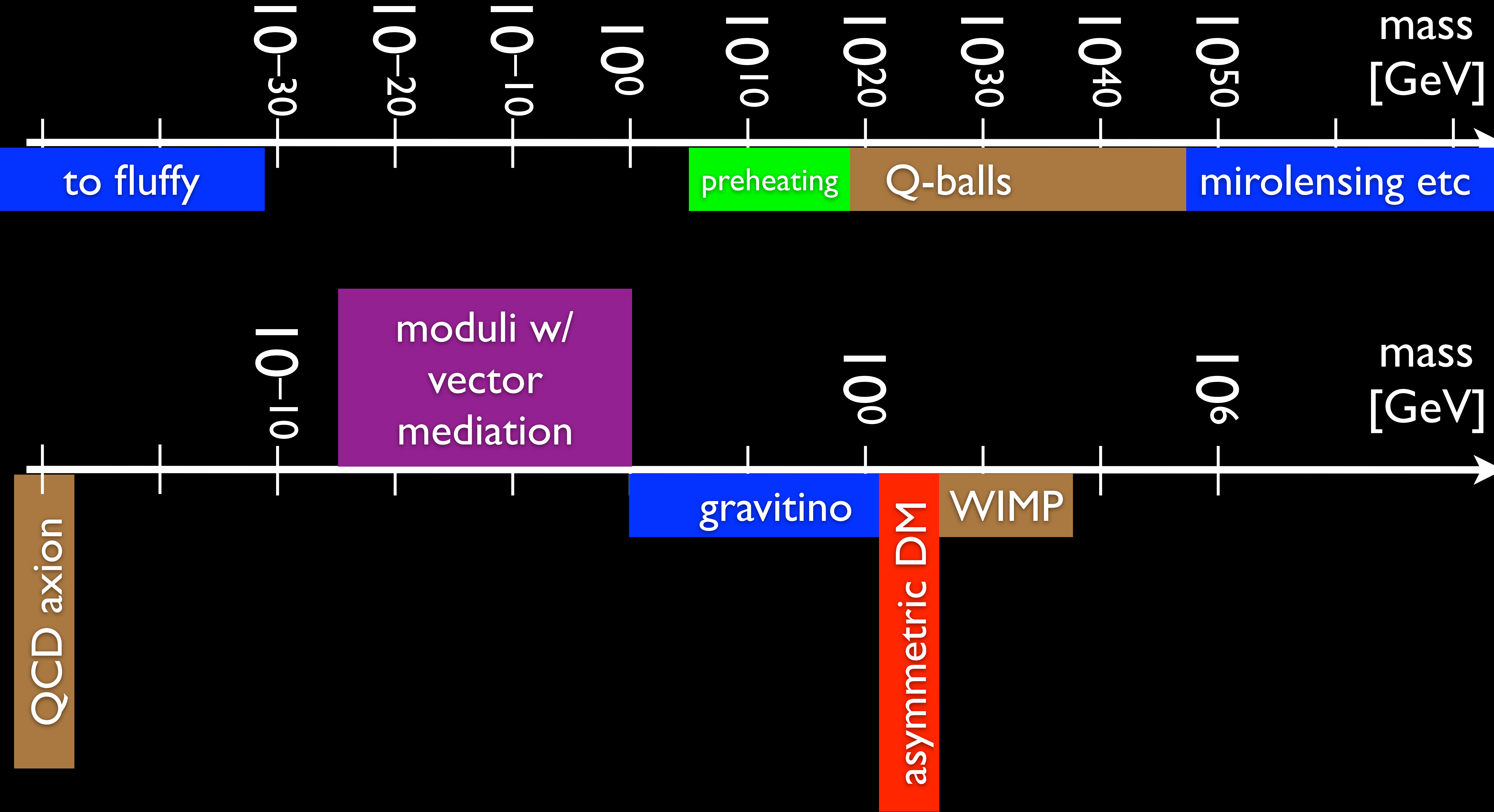

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asymmetric DM
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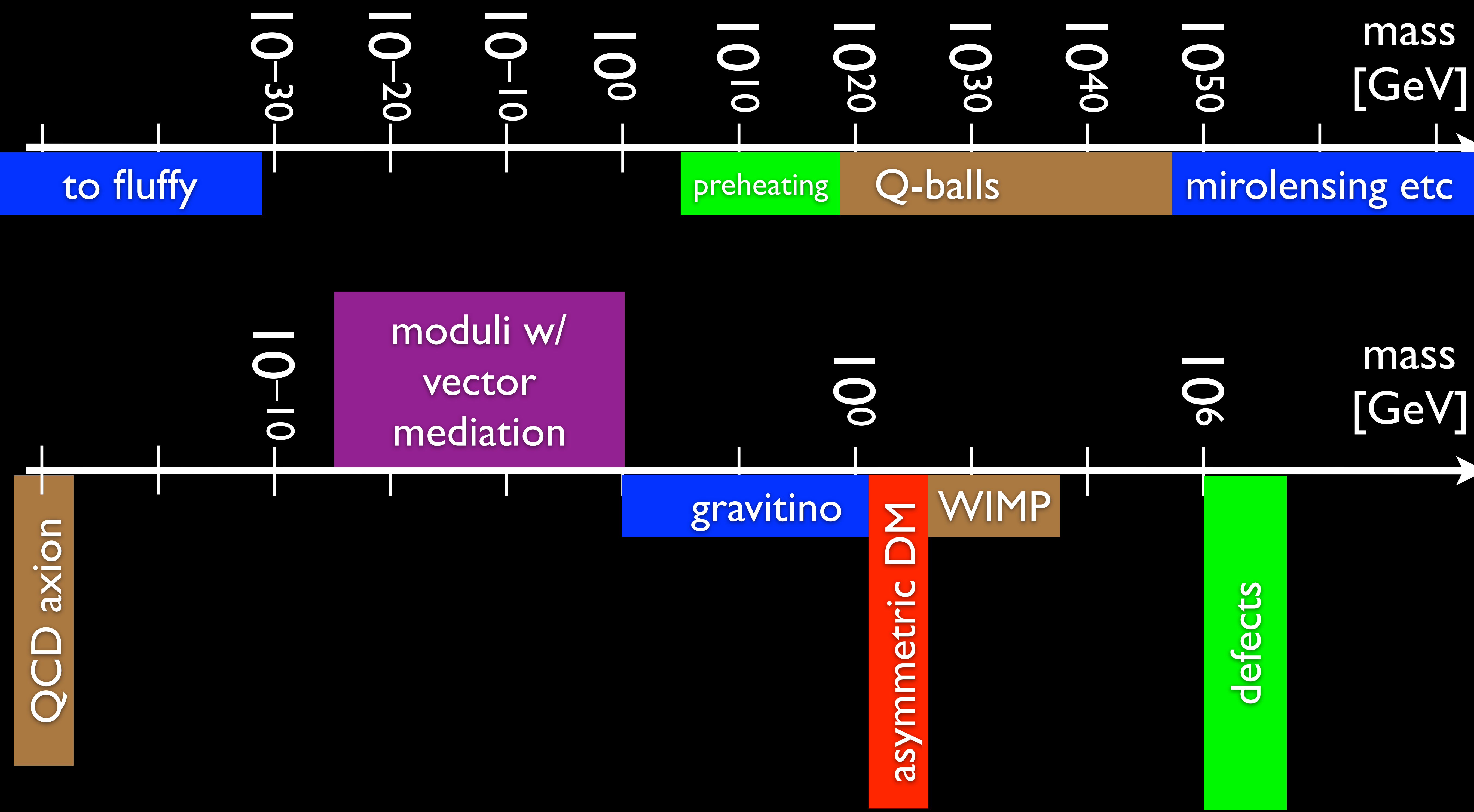

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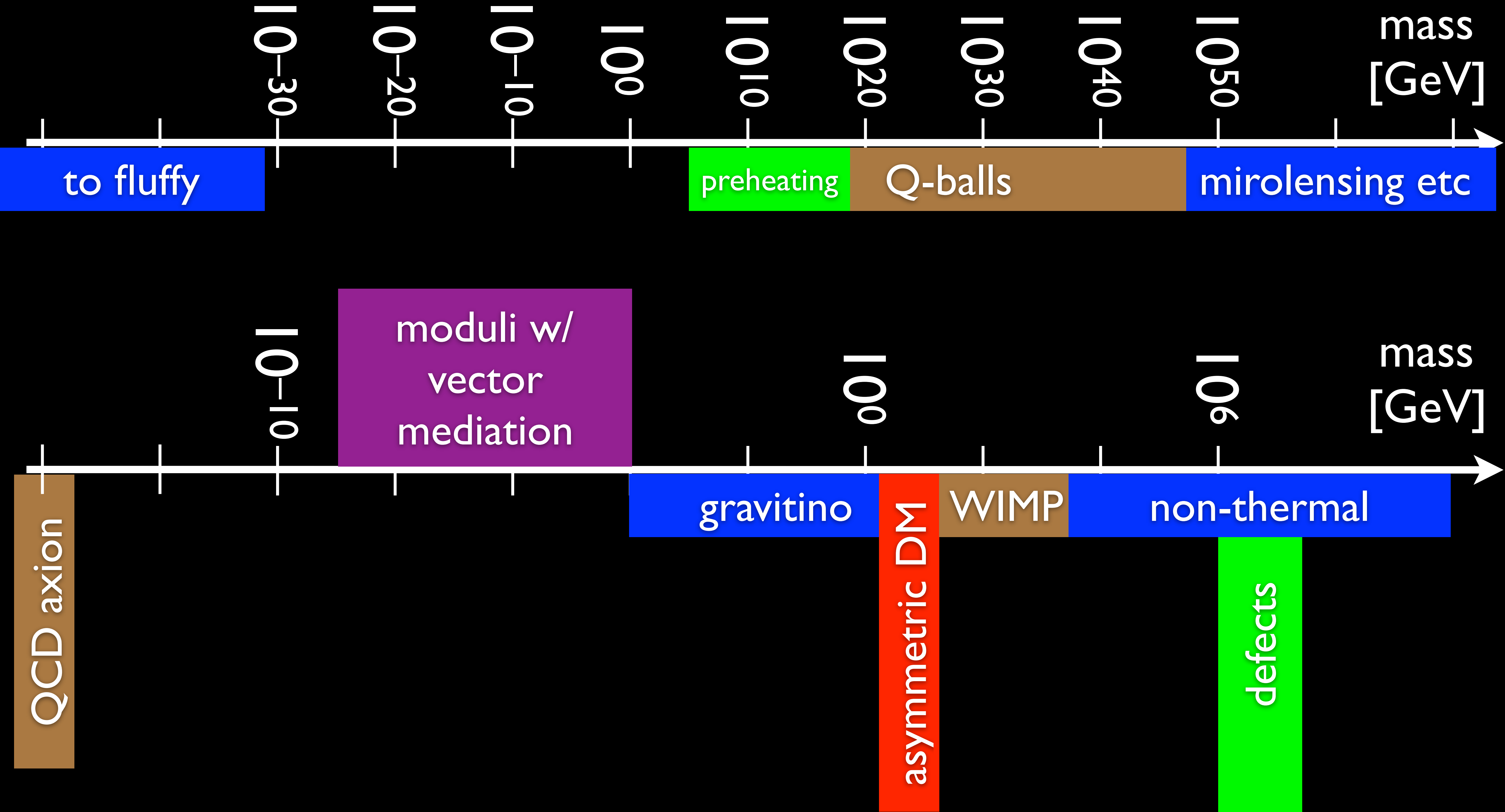

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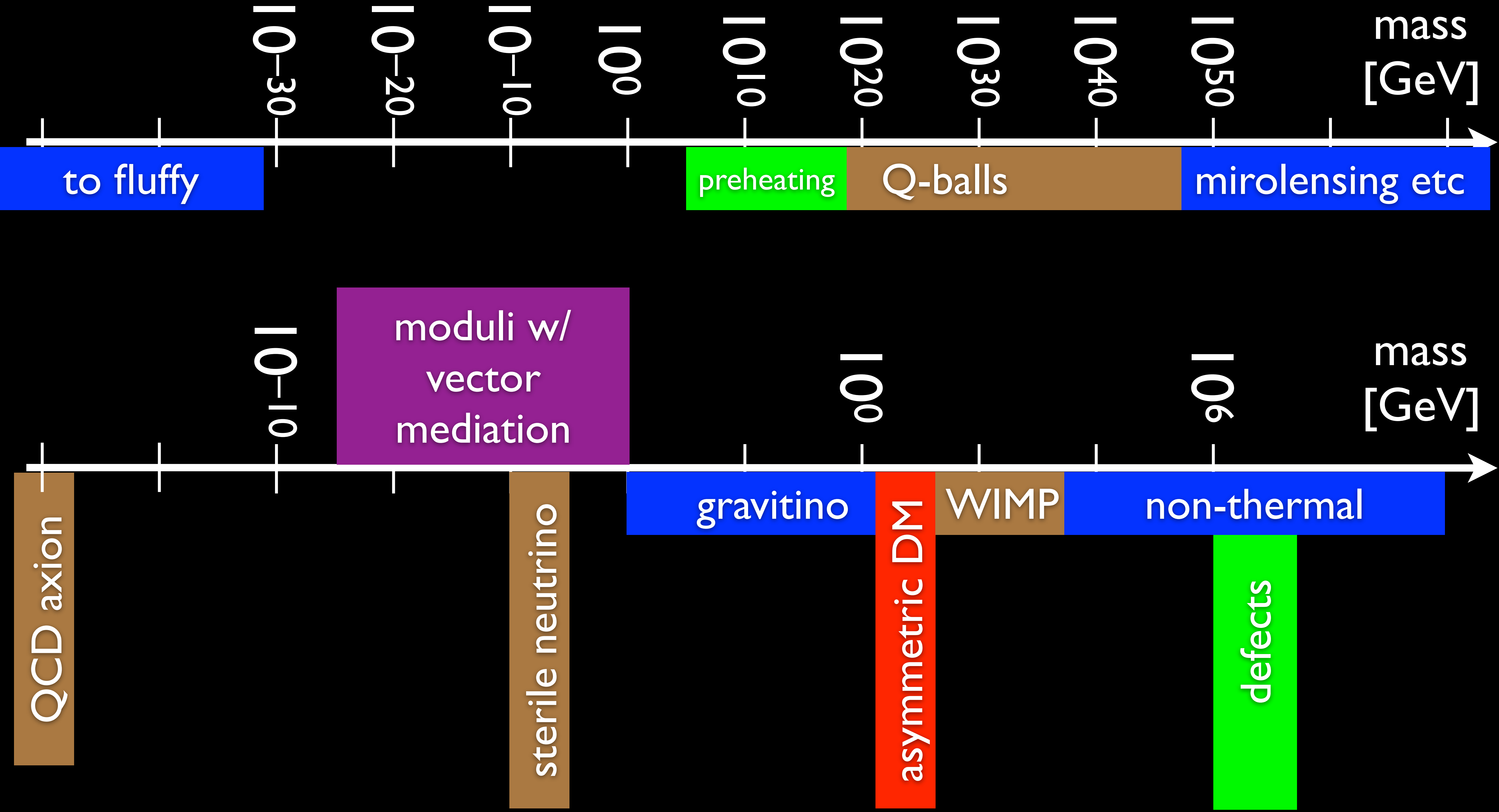
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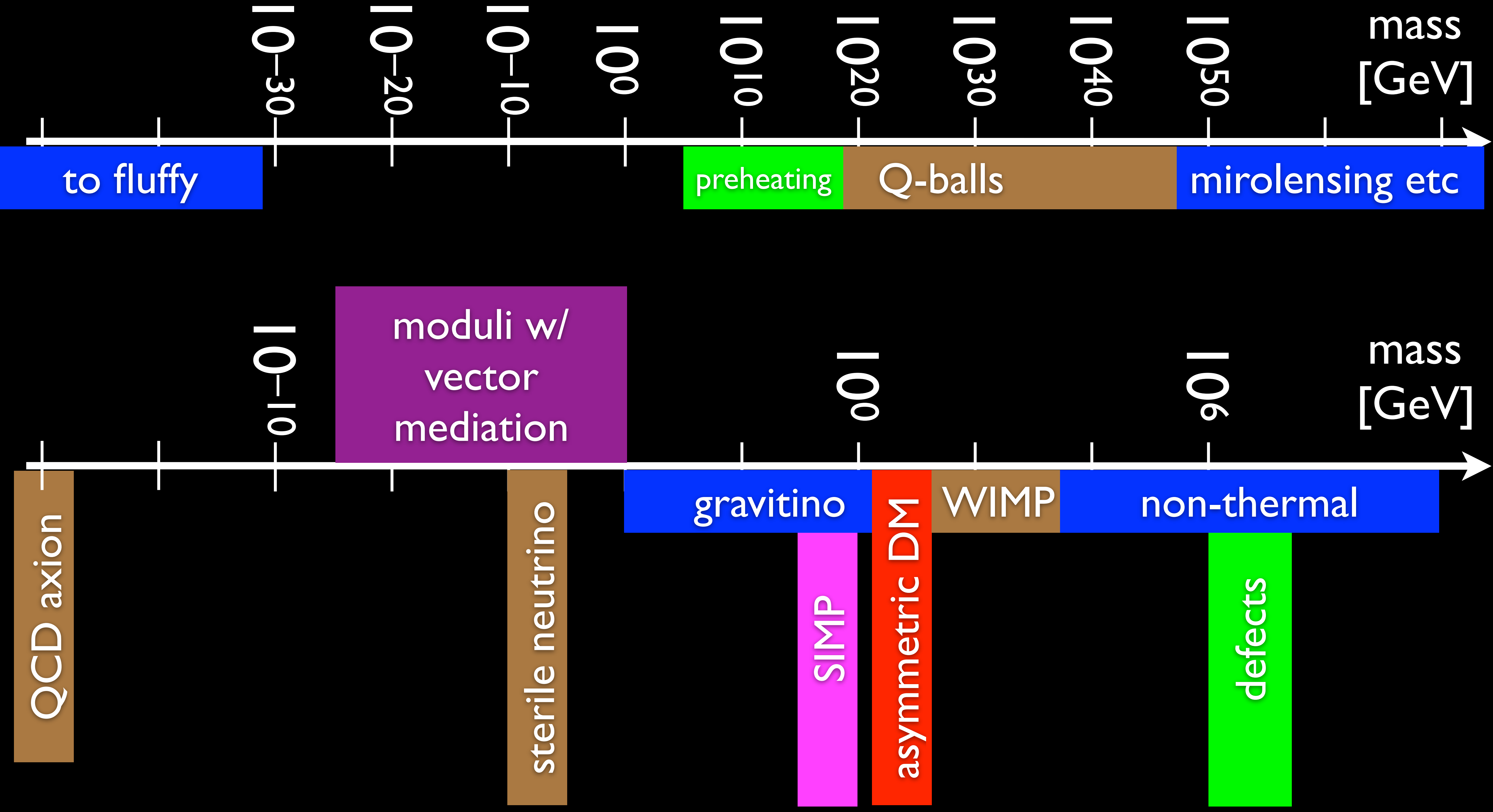
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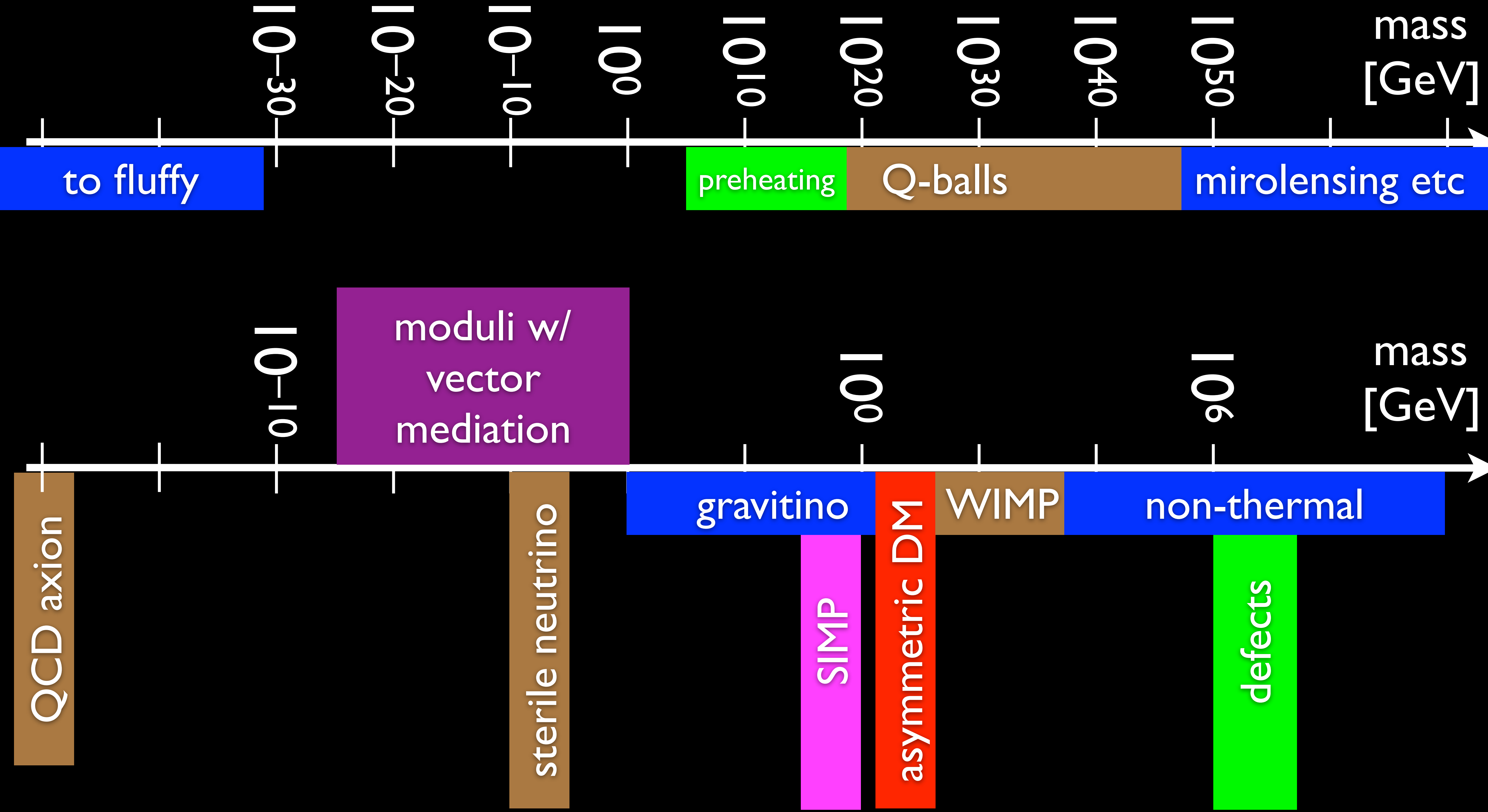
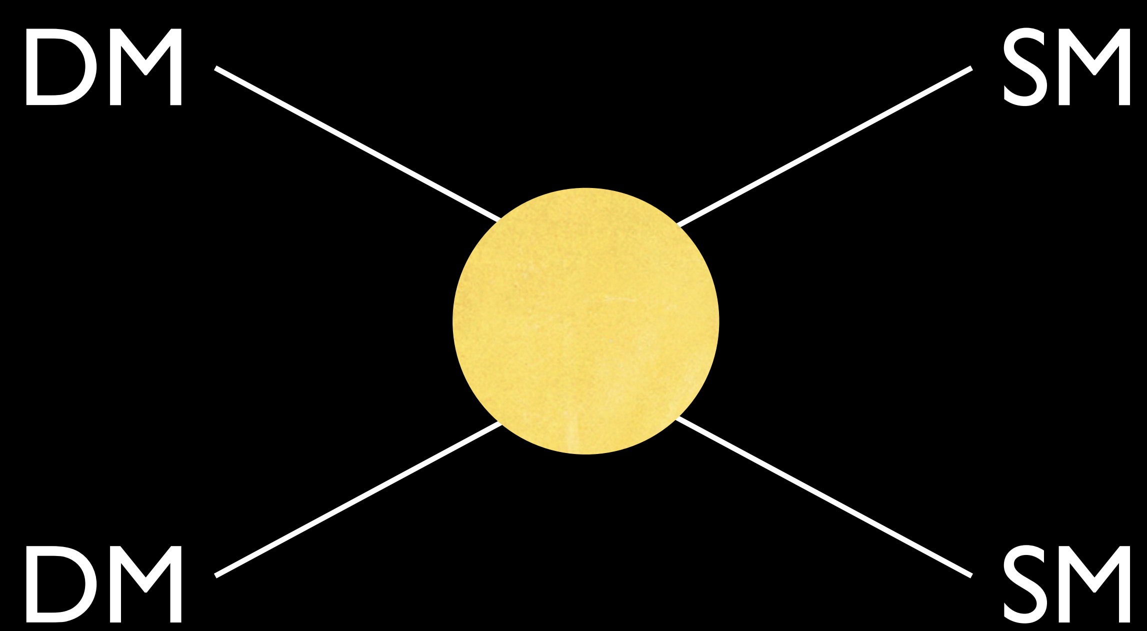


Can't do justice to many many ideas in the literature!

$$\frac{n_{\rm DM}}{s} = 4.4 \times 10^{-10} \frac{\rm GeV}{m_{\rm DM}}$$

WIMP Miracle



"weak" coupling
"weak" mass scale → correct abundance

We want new particles for naturalness anyway

Miracle^2

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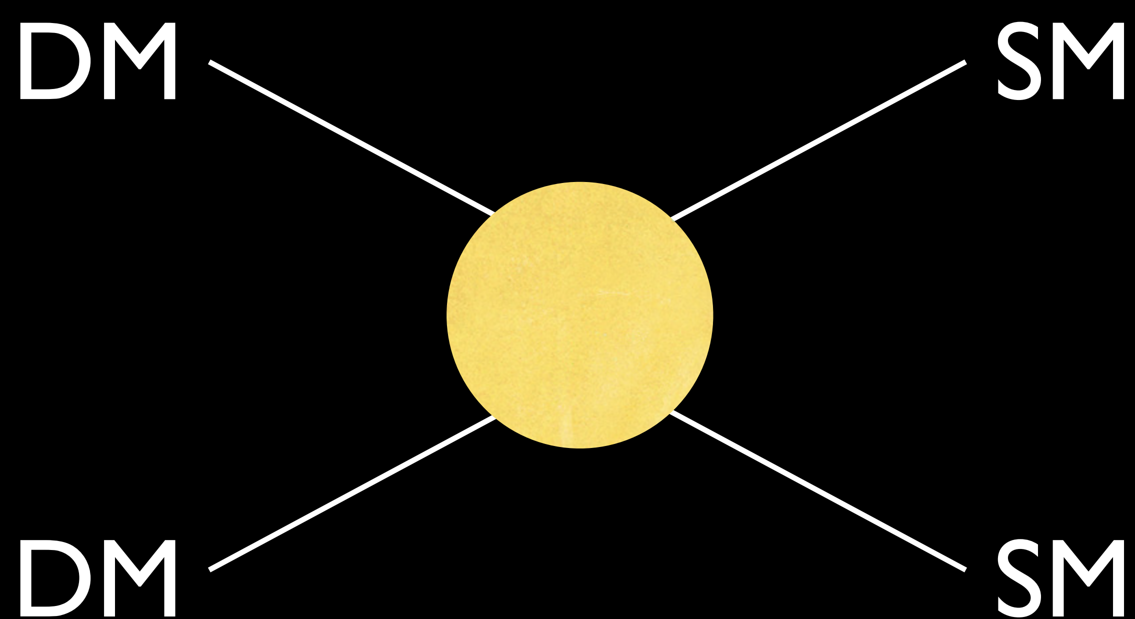

$$\langle \sigma_{2\to 2} v \rangle \approx \frac{\alpha^2}{m^2}$$

$$\alpha \approx 10^{-2}$$

$$m \approx 300 \ \mathrm{GeV}$$

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"weak" mass scale
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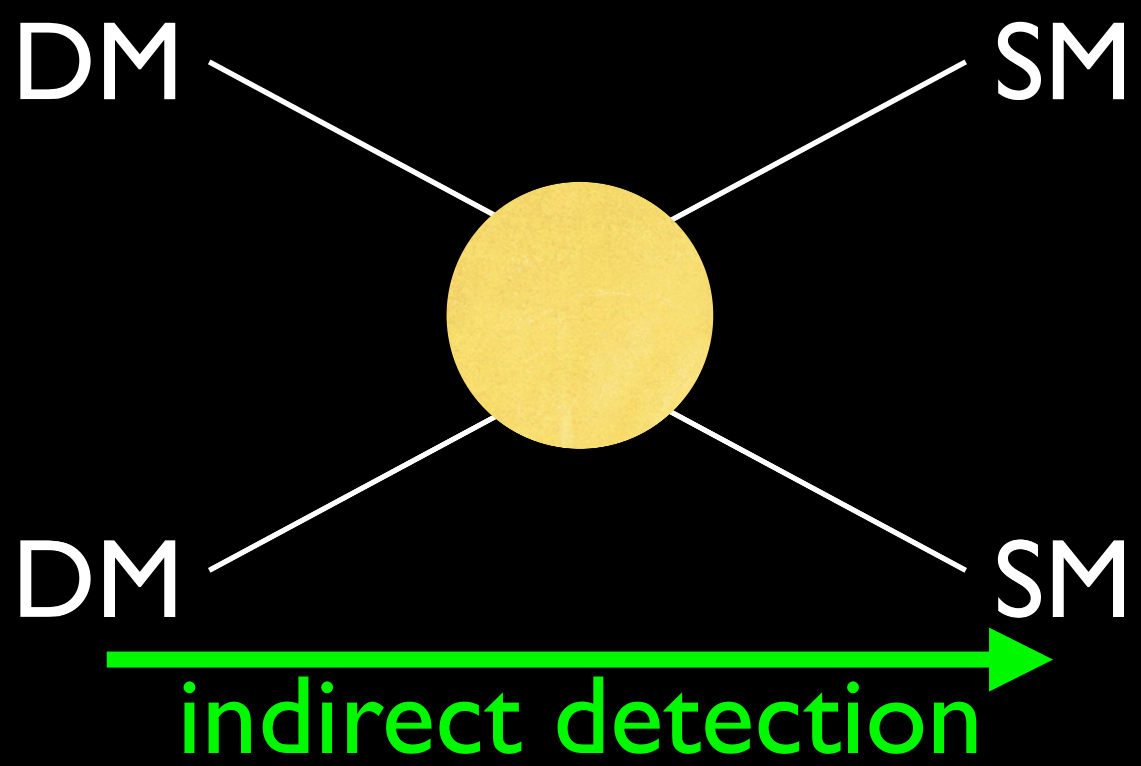
We want new particles for naturalness anyway

Miracle^2

$$\frac{n_{\rm DM}}{s} = 4.4 \times 10^{-10} \frac{\rm GeV}{m_{\rm DM}}$$

WIMP Miracle



$$\langle \sigma_{2\to 2} v \rangle \approx \frac{\alpha^2}{m^2}$$

$$\alpha \approx 10^{-2}$$

$$m \approx 300 \text{ GeV}$$

"weak" coupling
"weak" mass scale → correct abundance

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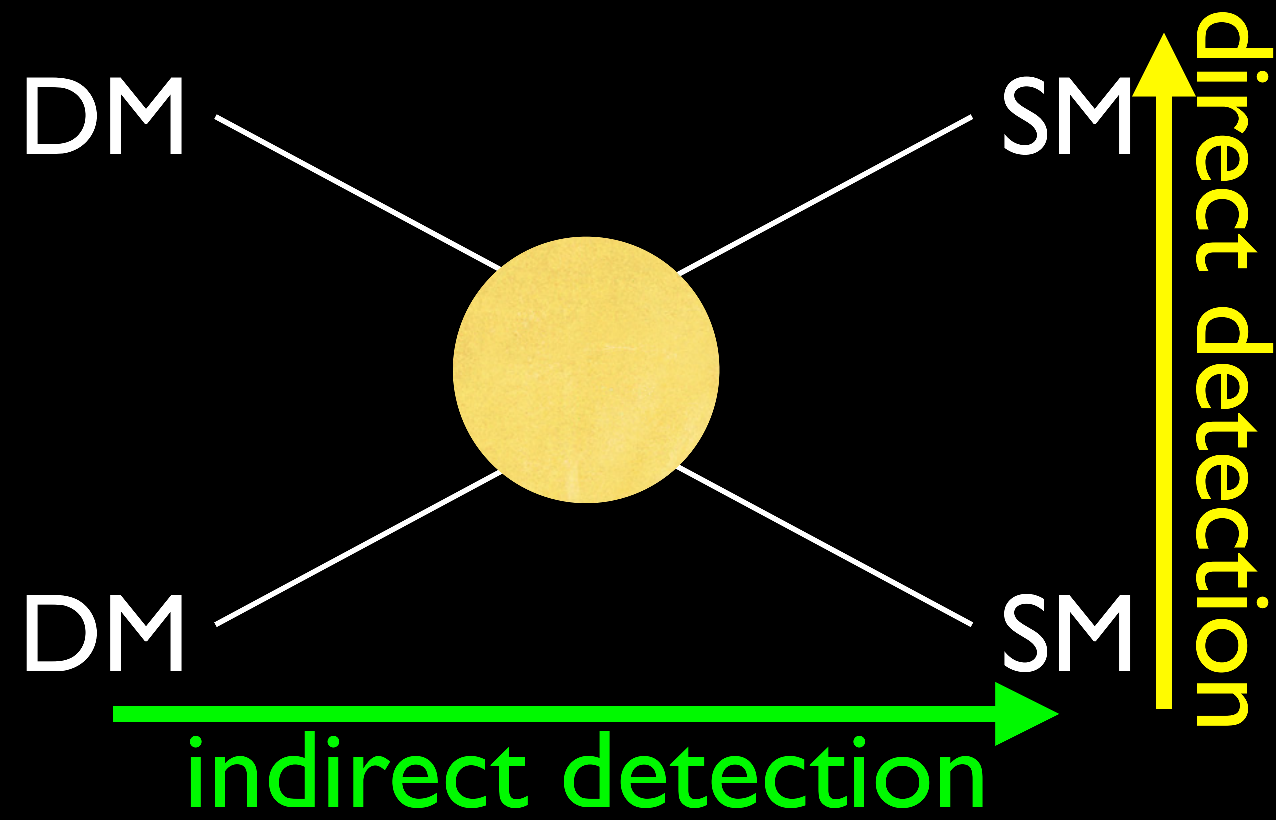

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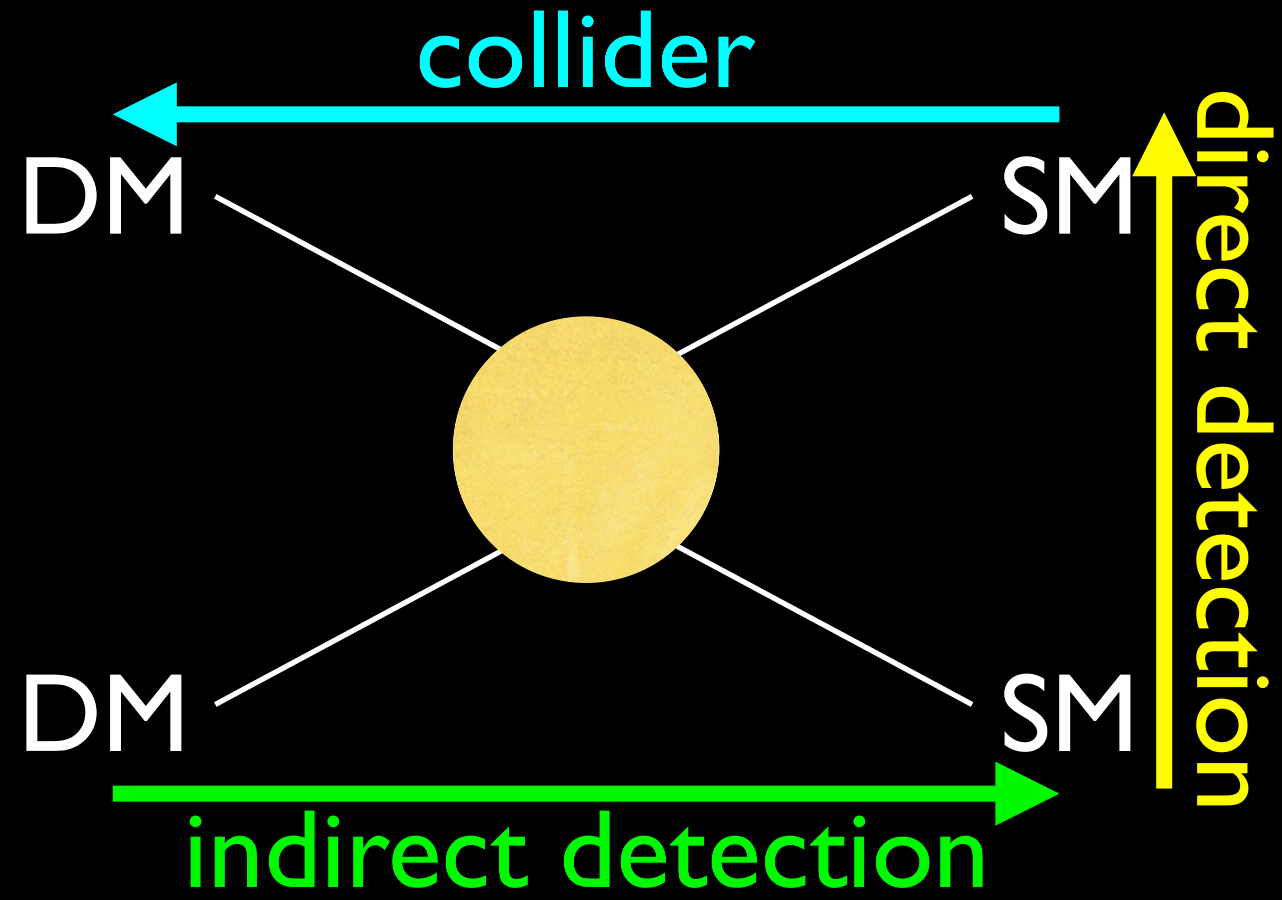

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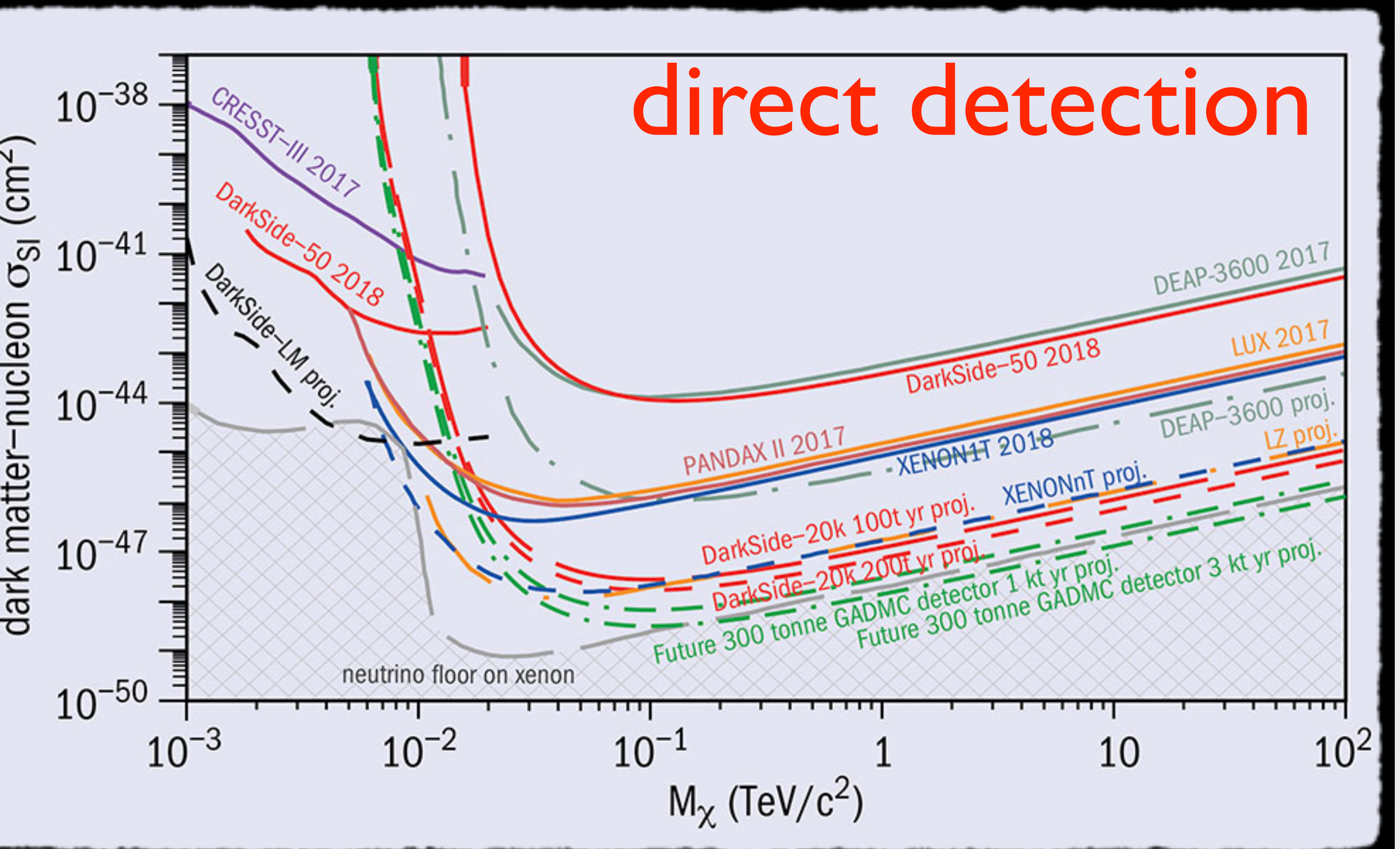
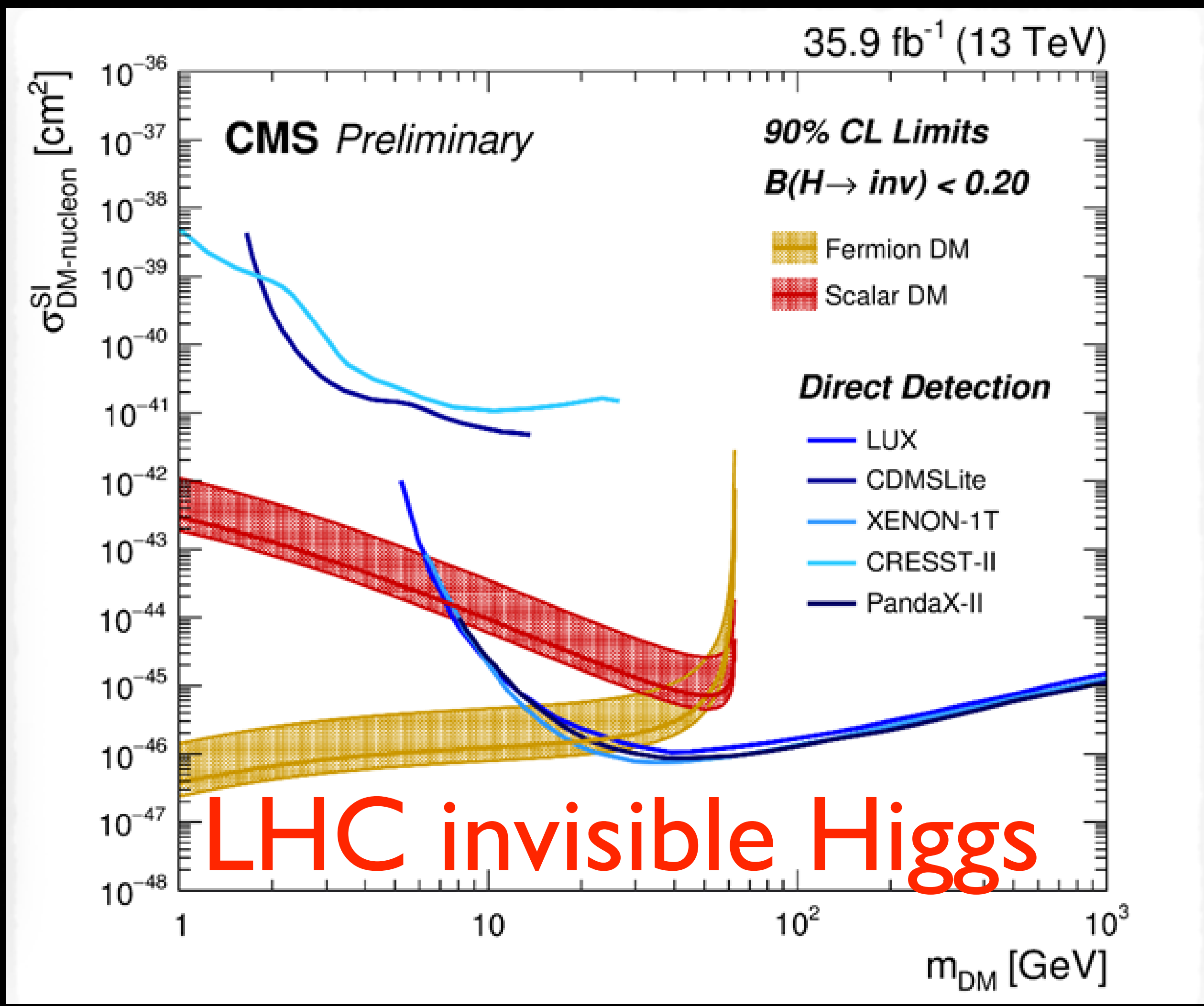
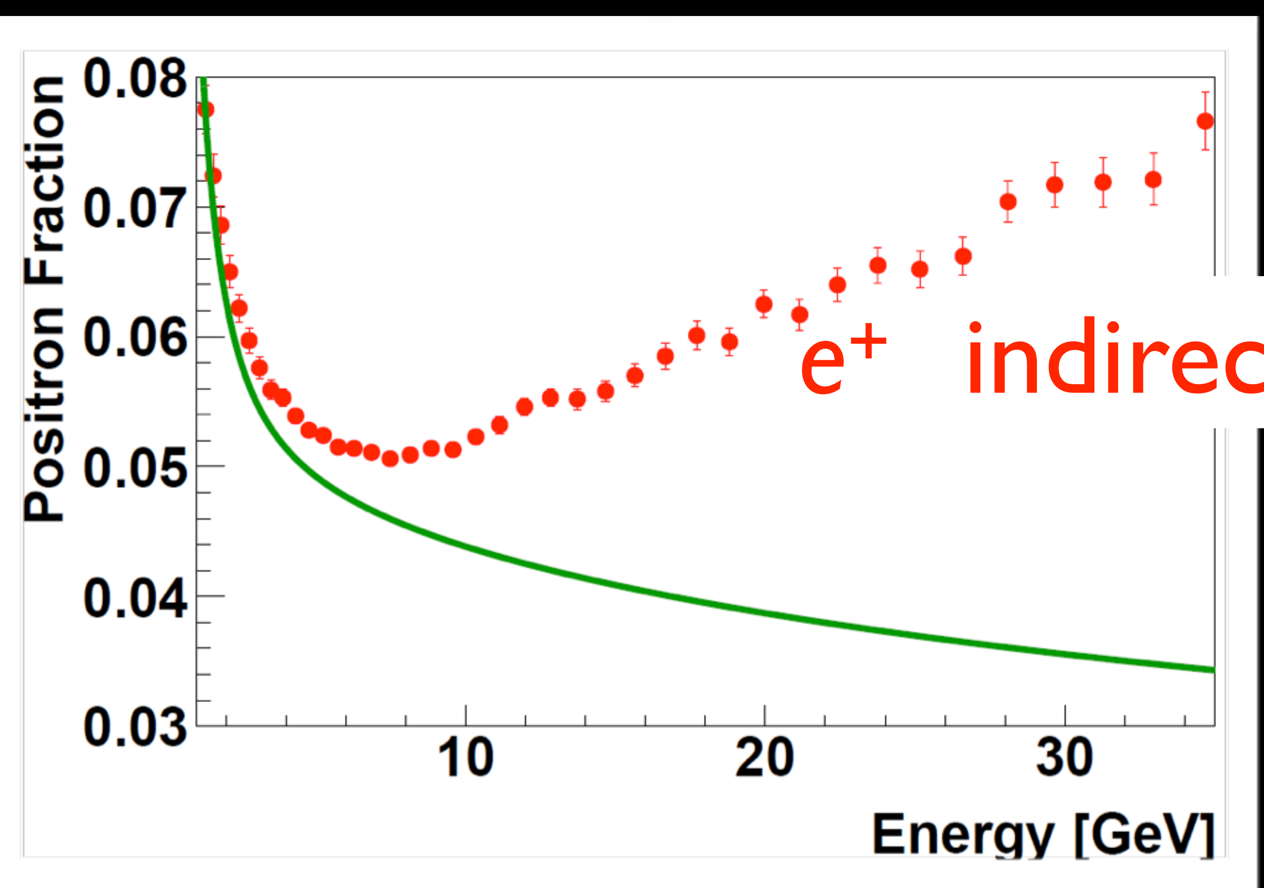
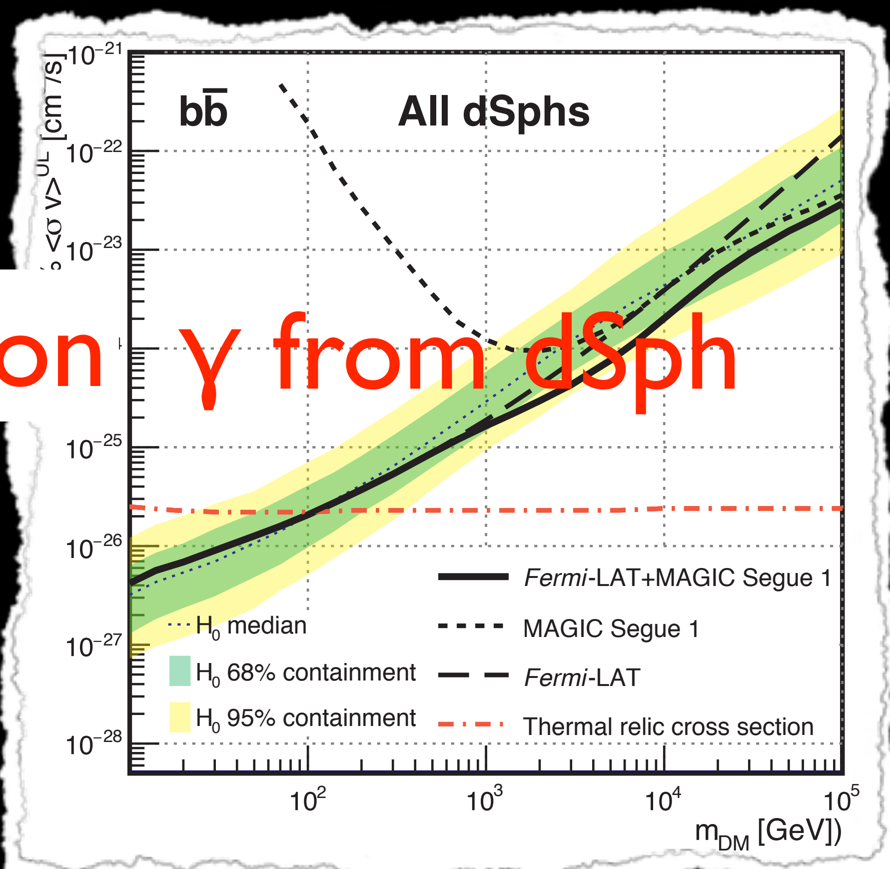
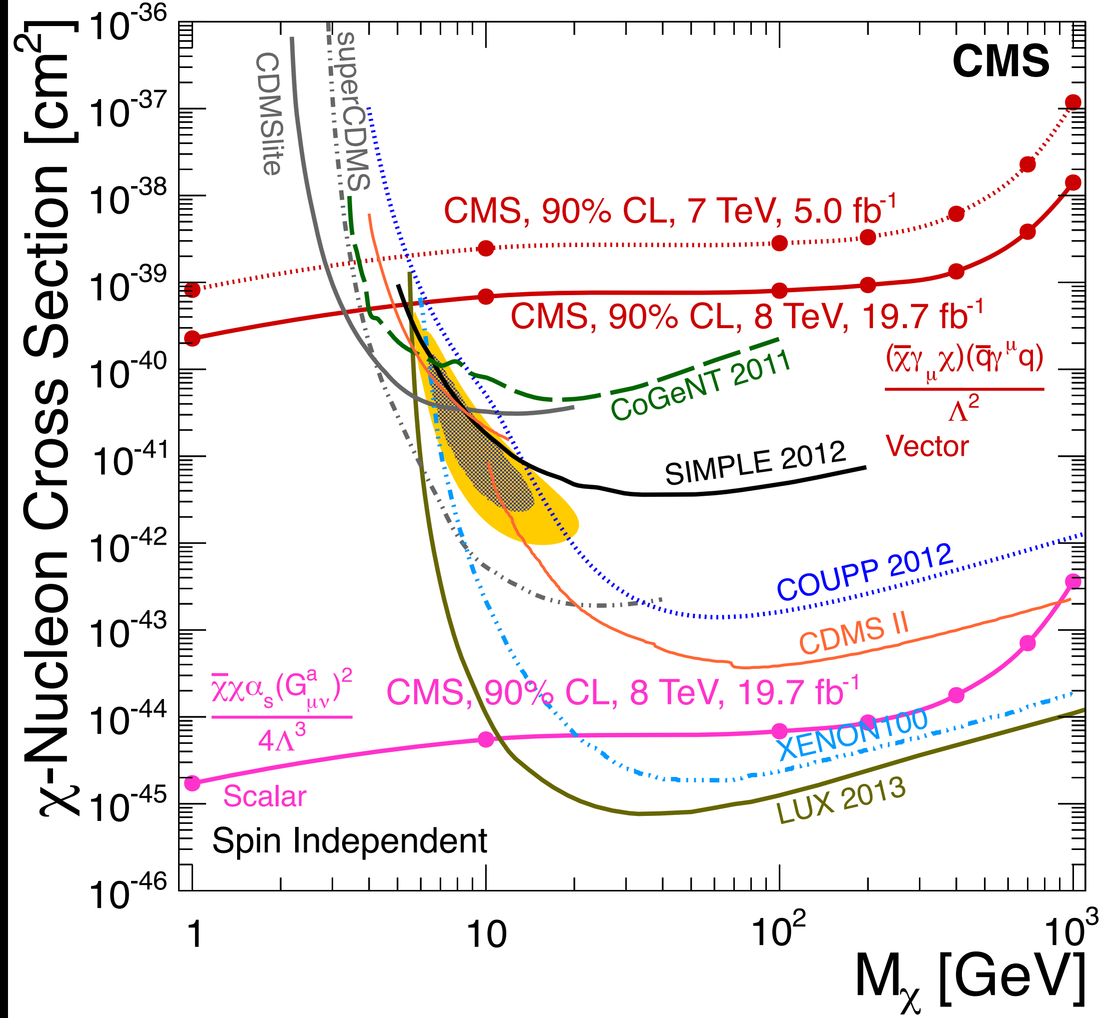
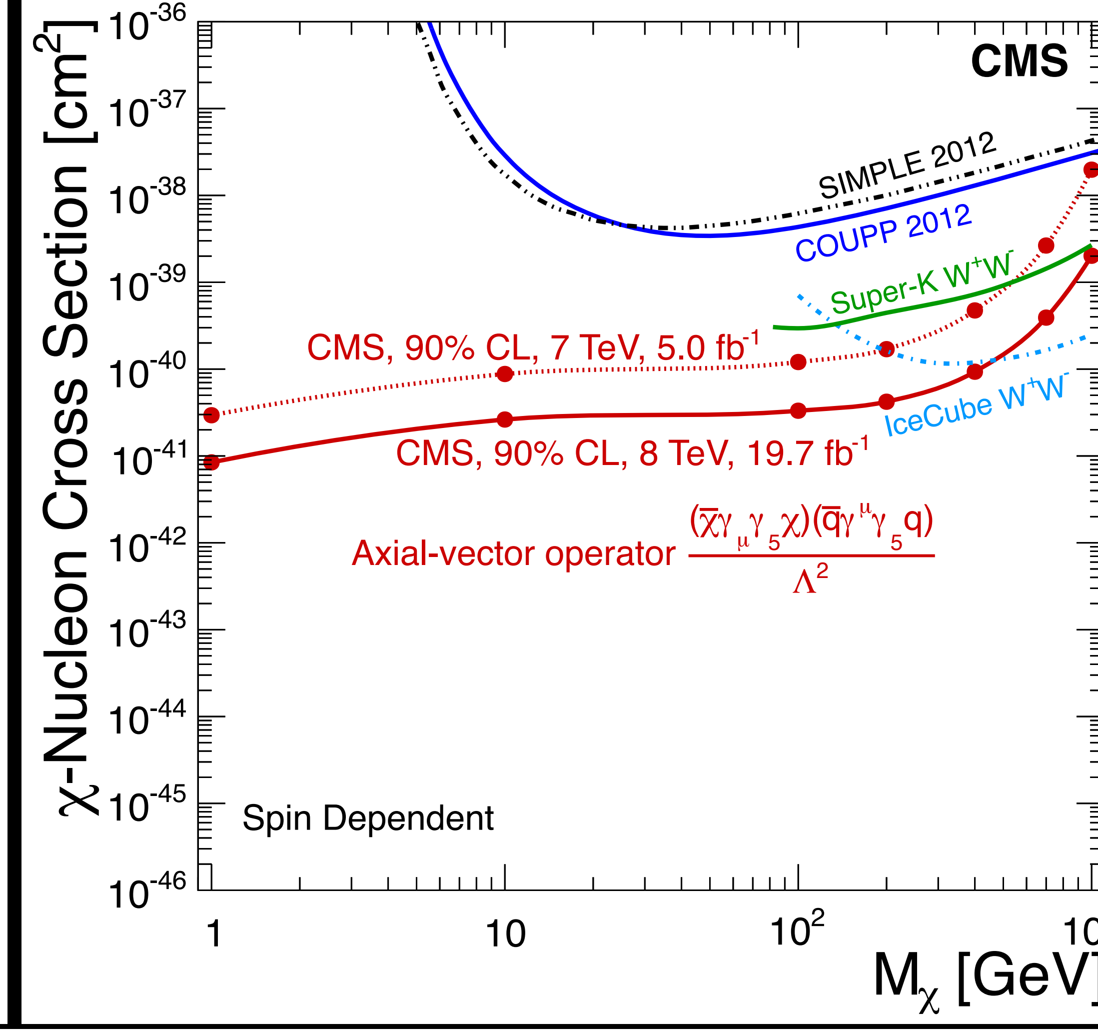

direct detection
dark matter–nucleon σSI (cm²)
Mχ (TeV/c²)
CRESST–III 2017
DarkSide–50 2018
DarkSide–LM proj.
DEAP-3600 2017
LUX 2017
PANDAX II 2017
XENON1T 2018
DEAP–3600 proj.
LZ proj.
XENONnT proj.
DarkSide–20k 100t yr proj.
DarkSide–20k 200t yr proj.
Future 300 tonne GADMC detector 1 kt yr proj.
Future 300 tonne GADMC detector 3 kt yr proj.
neutrino floor on xenon

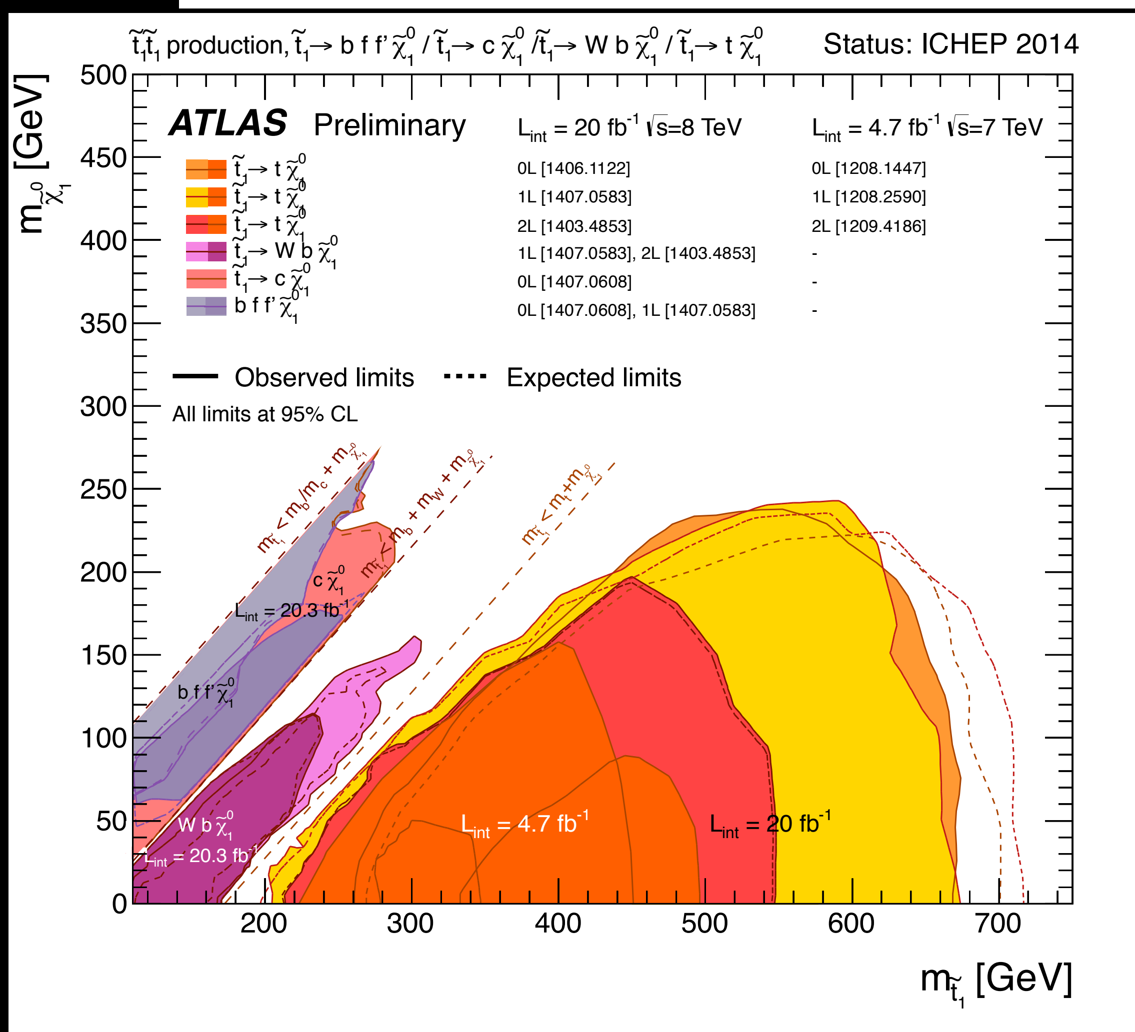

35.9 fb⁻¹ (13 TeV)
CMS Preliminary
90% CL Limits
B(H→ inv) < 0.20
Fermion DM
Scalar DM
Direct Detection
LUX
CDMSLite
XENON-1T
CRESST-II
PandaX-II
σSI DM-nucleon [cm²]
mDM [GeV]
LHC invisible Higgs

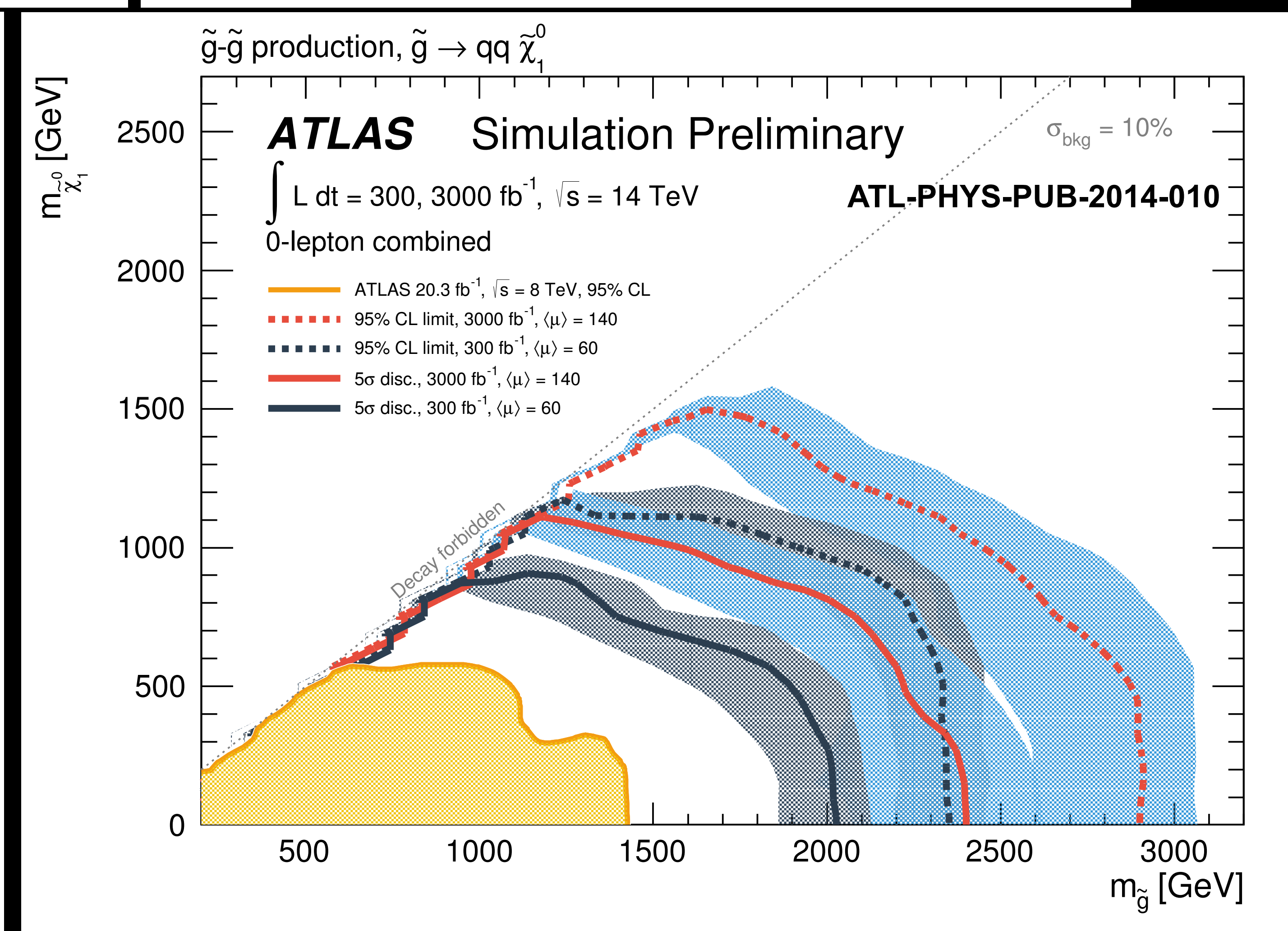

Positron Fraction
Energy [GeV]
e⁺ indirect detection


bb̄
All dSphs
γ from dSph
H0 median
H0 68% containment
H0 95% containment
Fermi-LAT+MAGIC Segue 1
MAGIC Segue 1
Fermi-LAT
Thermal relic cross section
mDM [GeV])


CMS
χ-Nucleon Cross Section [cm²]
M_χ [GeV]
CDMSlite
superCDMS
CMS, 90% CL, 7 TeV, 5.0 fb⁻¹
CMS, 90% CL, 8 TeV, 19.7 fb⁻¹
CoGeNT 2011
SIMPLE 2012
Vector
COUPP 2012
CDMS II
CMS, 90% CL, 8 TeV, 19.7 fb⁻¹
XENON100
LUX 2013
Scalar
Spin Independent


CMS
χ-Nucleon Cross Section [cm²]
M_χ [GeV]
SIMPLE 2012
COUPP 2012
Super-K W⁺W⁻
CMS, 90% CL, 7 TeV, 5.0 fb⁻¹
IceCube W⁺W⁻
CMS, 90% CL, 8 TeV, 19.7 fb⁻¹
Axial-vector operator
Spin Dependent


t̃₁t̃₁ production, t̃₁→ b f f' χ̃⁰₁ / t̃₁→ c χ̃⁰₁ / t̃₁→ W b χ̃⁰₁ / t̃₁→ t χ̃⁰₁
Status: ICHEP 2014
ATLAS Preliminary
L_int = 20 fb⁻¹ √s=8 TeV
L_int = 4.7 fb⁻¹ √s=7 TeV
0L [1406.1122]
1L [1407.0583]
2L [1403.4853]
1L [1407.0583], 2L [1403.4853]
0L [1407.0608]
0L [1407.0608], 1L [1407.0583]
0L [1208.1447]
1L [1208.2590]
2L [1209.4186]
Observed limits
Expected limits
All limits at 95% CL
L_int = 20.3 fb⁻¹
L_int = 4.7 fb⁻¹
L_int = 20 fb⁻¹
m_t̃₁ [GeV]


g̃-g̃ production, g̃ → qq χ̃⁰₁
ATLAS Simulation Preliminary
σ_bkg = 10%
∫ L dt = 300, 3000 fb⁻¹, √s = 14 TeV
ATL-PHYS-PUB-2014-010
0-lepton combined
ATLAS 20.3 fb⁻¹, √s = 8 TeV, 95% CL
95% CL limit, 3000 fb⁻¹, ⟨μ⟩ = 140
95% CL limit, 300 fb⁻¹, ⟨μ⟩ = 60
5σ disc., 3000 fb⁻¹, ⟨μ⟩ = 140
5σ disc., 300 fb⁻¹, ⟨μ⟩ = 60
Decay forbidden
m_g̃ [GeV]

new sociology

new sociology

- WIMP should be explored at least down to the neutrino floor

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  - heavier? e.g., wino @ 3TeV

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- dark matter definitely exists
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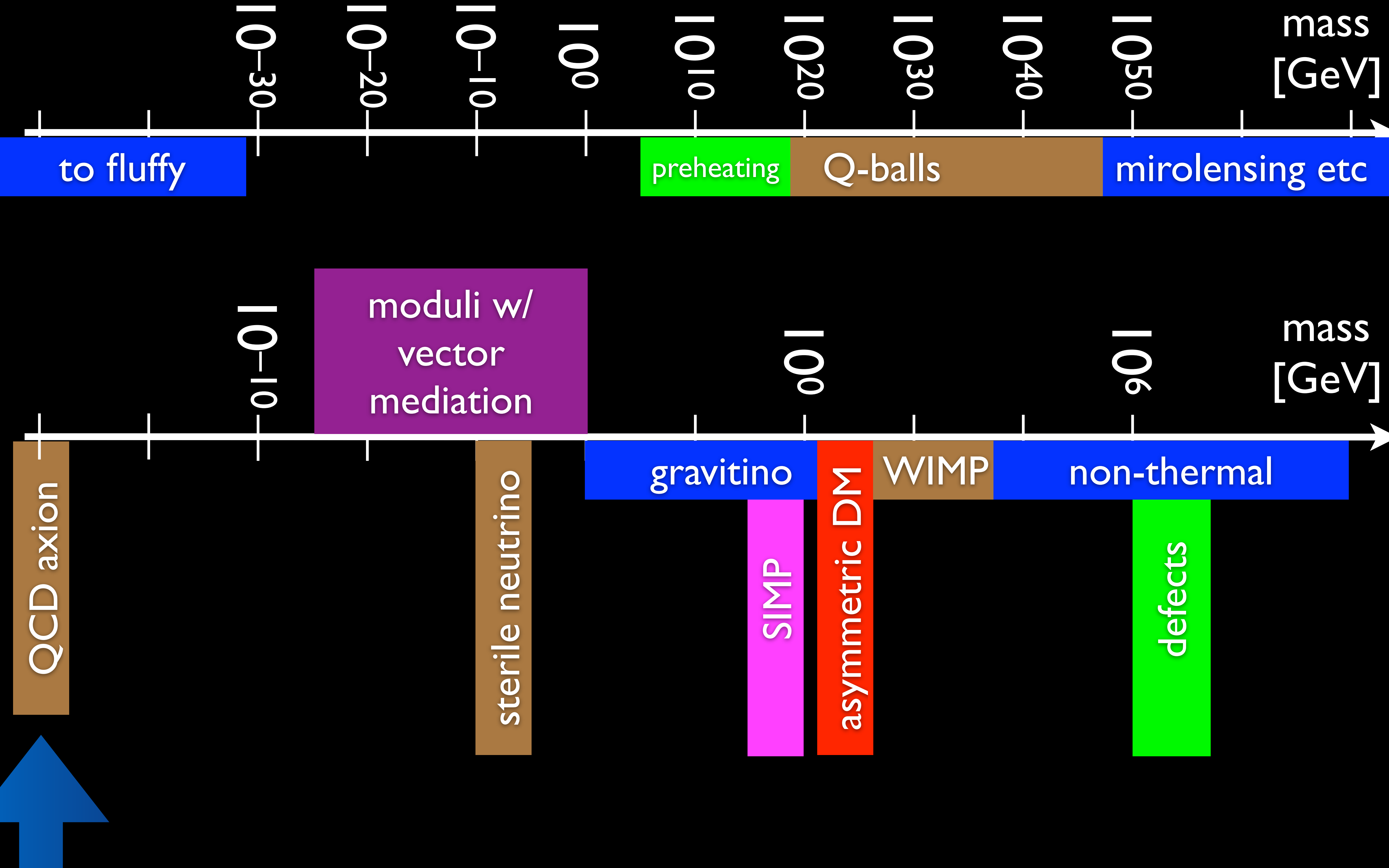
- need to explain dark matter on its own
- perhaps we should decouple these two
- do we really need big ideas like SUSY?
- perhaps not necessarily heavier but rather lighter and weaker coupling?


10^{-30}
10^{-20}
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10^{0}
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10^{30}
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mass [GeV]
to fluffy
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QCD axion
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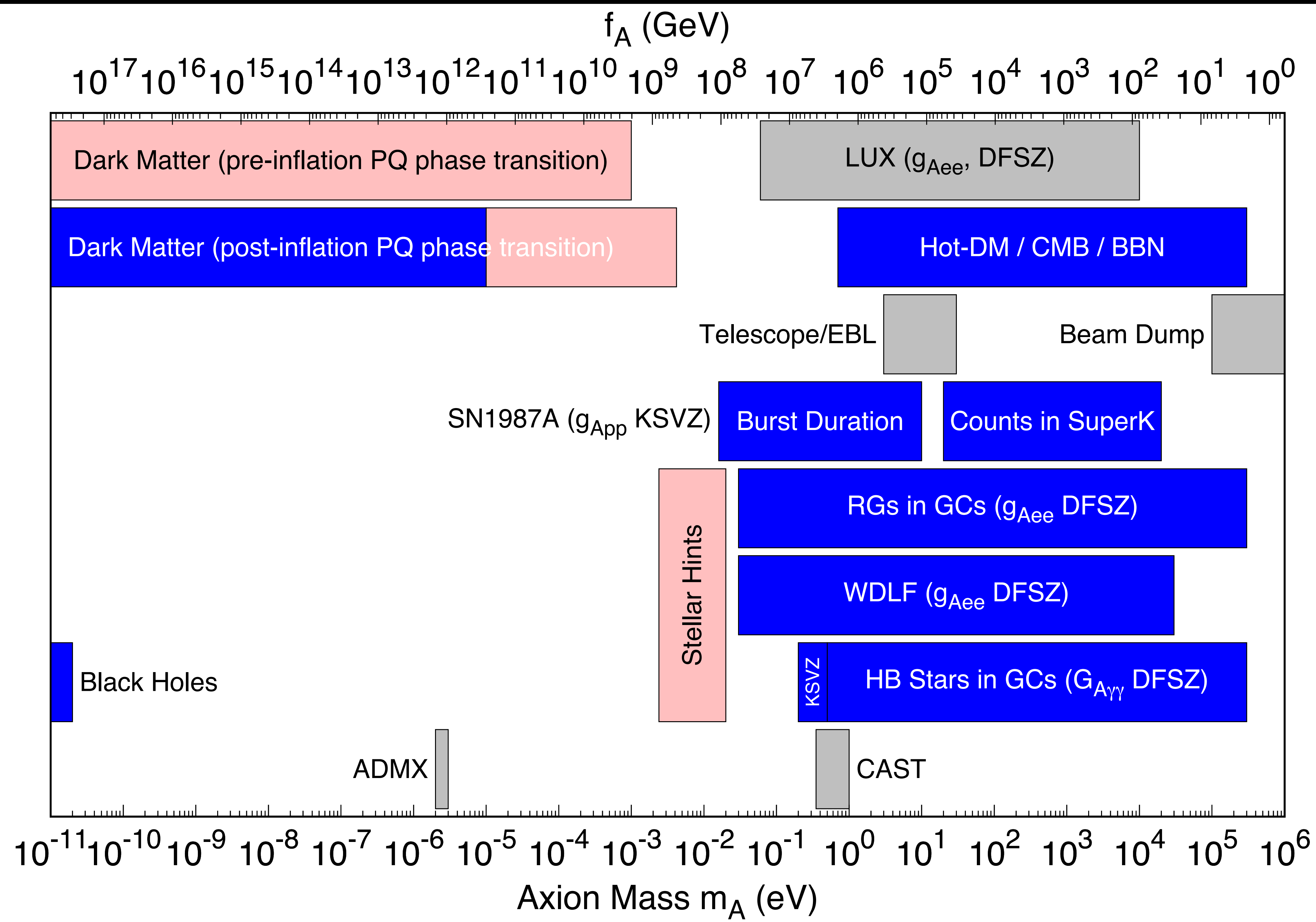
QCD axion

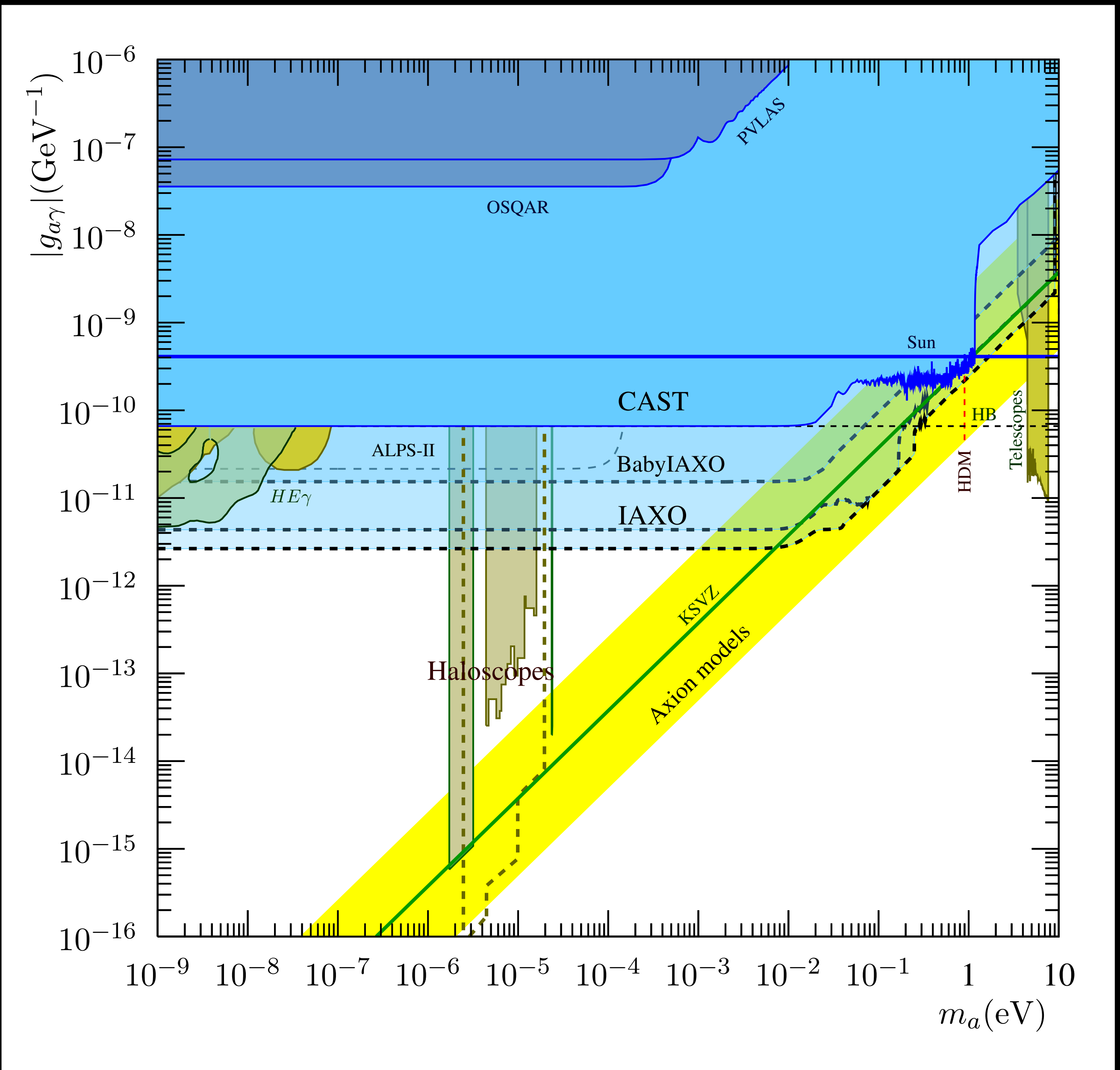


$$m_a = m_\pi f_\pi / f_a \ [\mathrm{eV}]$$

$$a \times B \rightarrow \gamma$$

Use the effective coupling

$$\mathcal{L}_{eff} \sim \frac{e^2}{4\pi^2}\frac{a}{f_a}\vec{E}\cdot\vec{B}$$

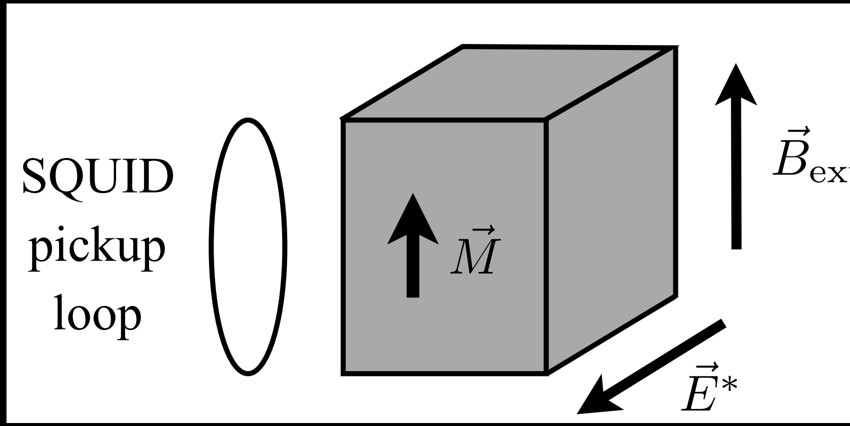


Cosmic Axion Spin Precession

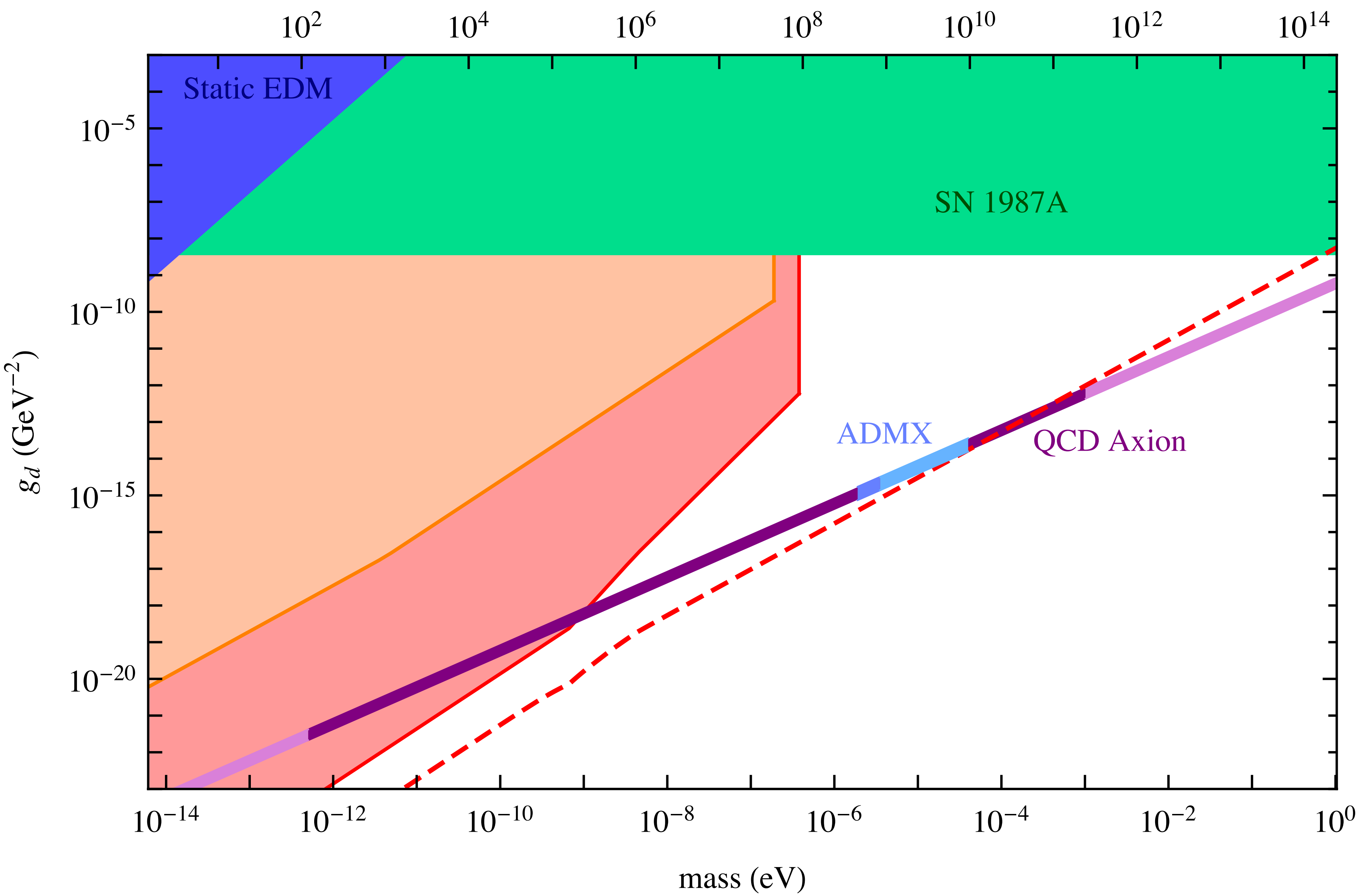
$$H_{eff}(t) = -\vec{\mu}\cdot\vec{B} - \frac{m_u}{m_{\mathrm{const}}^2}\sin(m_a t)\times\vec{s}_n\cdot\vec{E}$$

coherent $a(t)=a_0 \sin m_a t$

resonance @ $\mu B = m_a$



Budker et al
arXiv:1306.6089

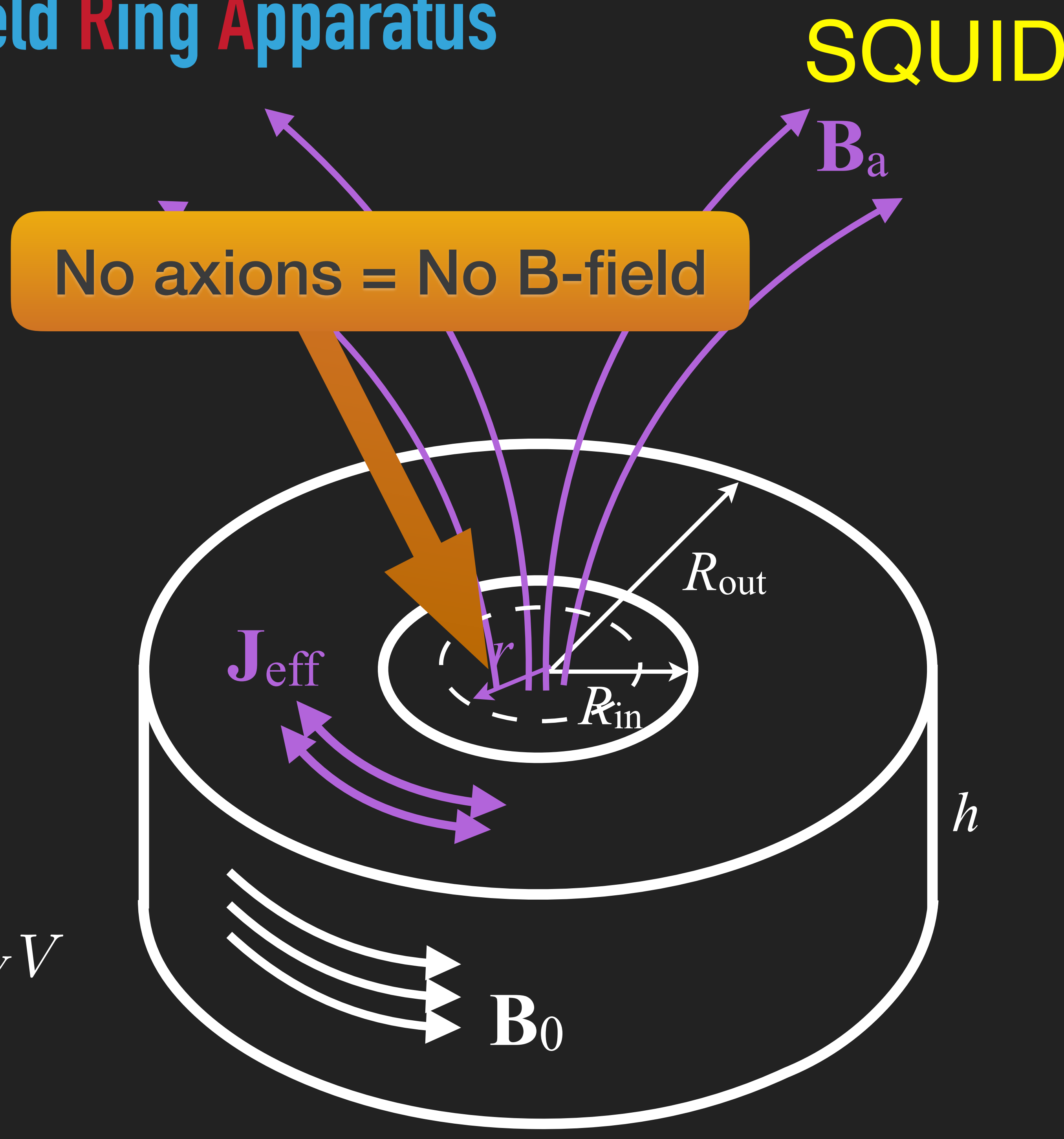


coherent $a(t)$

A Broadband/Resonant Approach to Cosmic Axion Detection with an Amplifying B-Field Ring Apparatus

- Start with a toroidal magnet with a fixed magnetic field B_0
- ADM generates an oscillating effective current around the ring (MQS approx: λ≫R)
- … this generates an oscillating magnetic field through the center of the toroid
- Insert a pickup loop in the center and measure the induced current in the loop read out by a SQUID based readout

$$\Phi(t) = g_{a\gamma\gamma} B_{\max} \sqrt{2\rho_{\rm DM}} \cos(m_a t) \mathcal{G}_V V$$



Jonathan Ouellet

Phys. Rev. Lett. 117, 141801 (2016)

Ultralight scalar dark matter

Ultralight dilaton DM acts as a background field (e.g., mass ~10^{-15} eV)

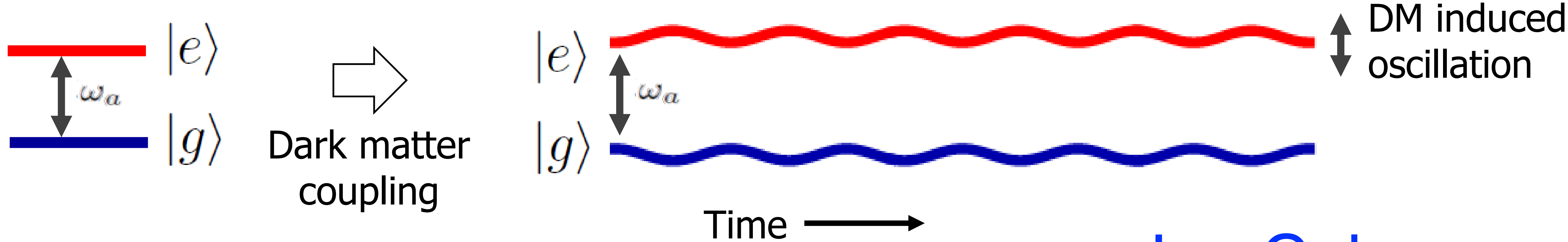
$$\mathcal{L} = +\frac{1}{2}\partial_\mu\phi\partial^\mu\phi - \frac{1}{2}m_\phi^2\phi^2 - \sqrt{4\pi G_N}\phi\left[d_{m_e}m_e\bar{e}e - \frac{d_e}{4}F_{\mu\nu}F^{\mu\nu}\right] + \ldots$$

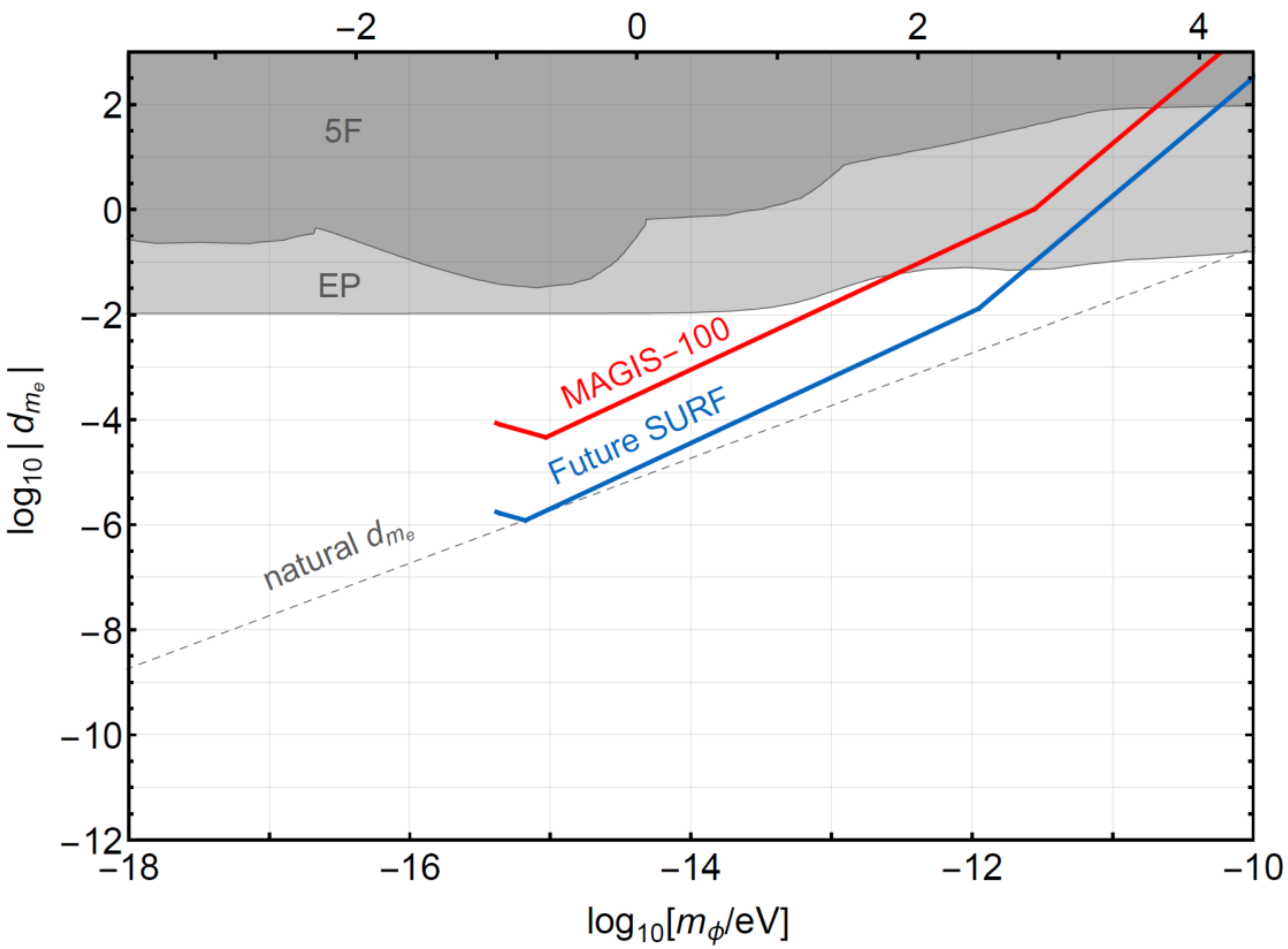
DM scalar field — Electron coupling — Photon coupling — e.g., QCD

$$\phi(t,\mathbf{x}) = \phi_0\cos\left[m_\phi(t - \mathbf{v}\cdot\mathbf{x}) + \beta\right] + \mathcal{O}\left(|\mathbf{v}|^2\right)$$

$$\phi_0 \propto \sqrt{\rho_{\mathrm{DM}}}$$ DM mass density

DM coupling causes time-varying atomic energy levels:





dark matter

l field (e.g., mass ~10^{-15} eV)

$$\left[d_{m_e} m_e \bar{e} e - \frac{d_e}{4} F_{\mu\nu} F^{\mu\nu}\right] + \ldots$$

Electron coupling

Photon coupling

e.g., QCD

$|\mathbf{v}|^2)$

$\phi_0 \propto \sqrt{\rho_{\mathrm{DM}}}$ DM mass density

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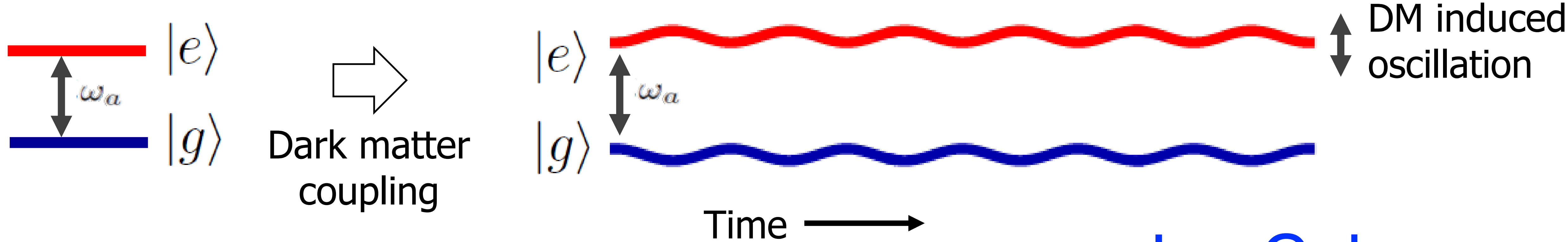
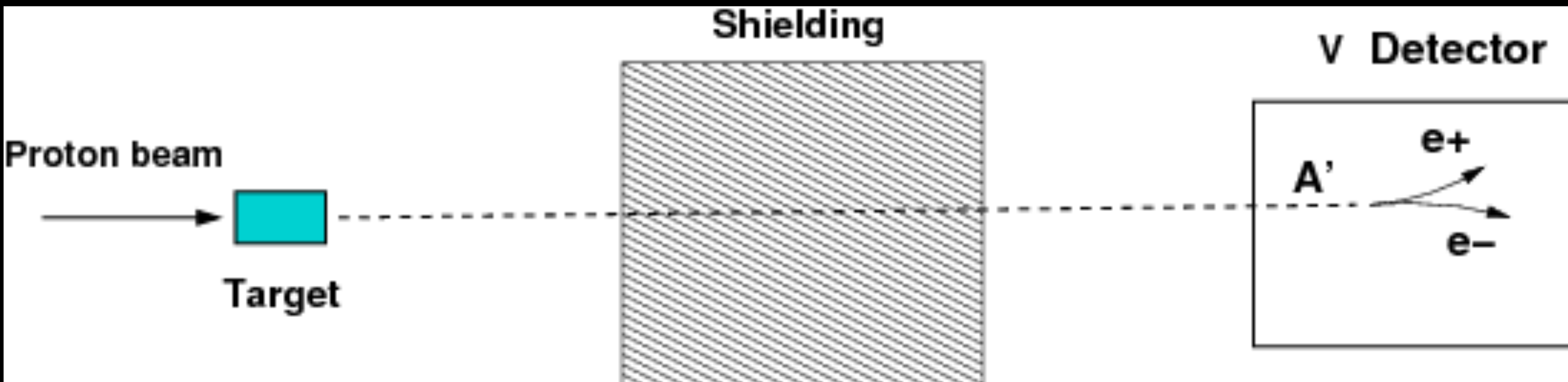
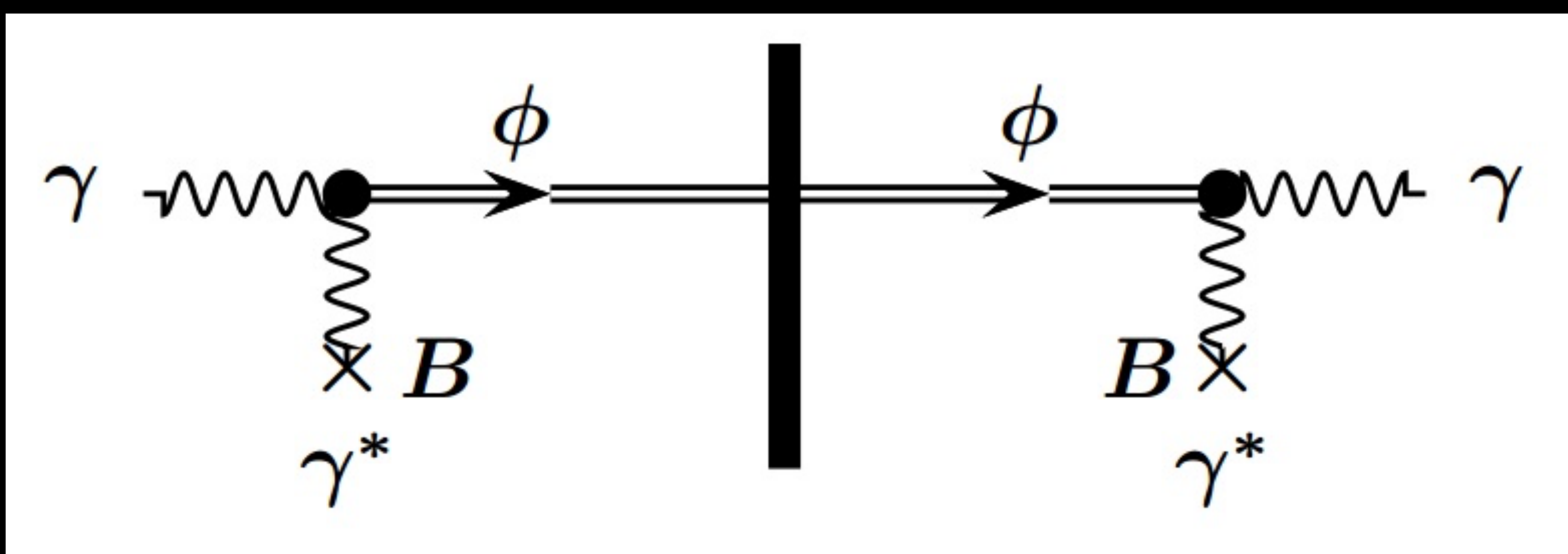
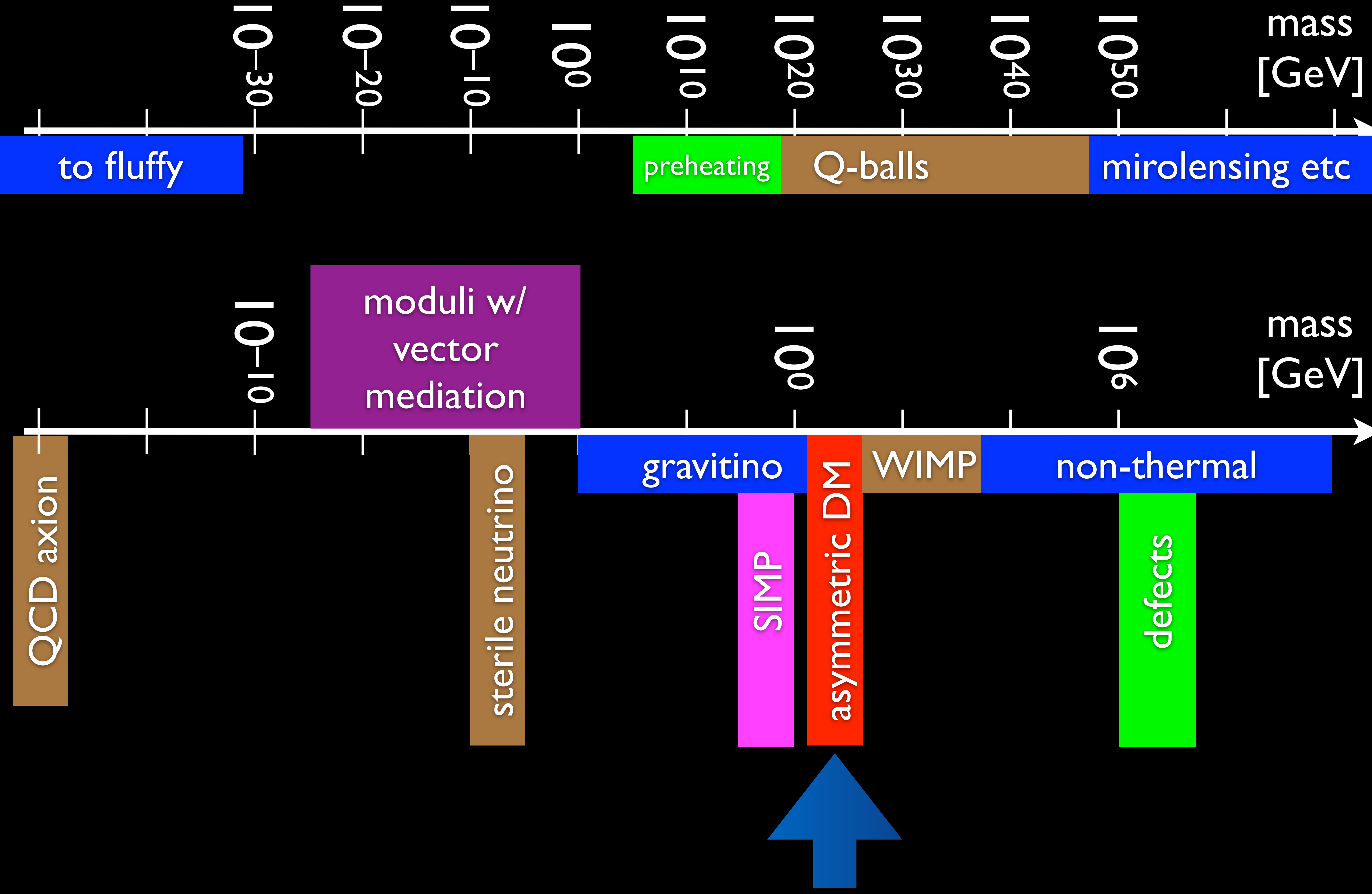


Search for ALPS







10^{-30}
10^{-20}
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to fluffy
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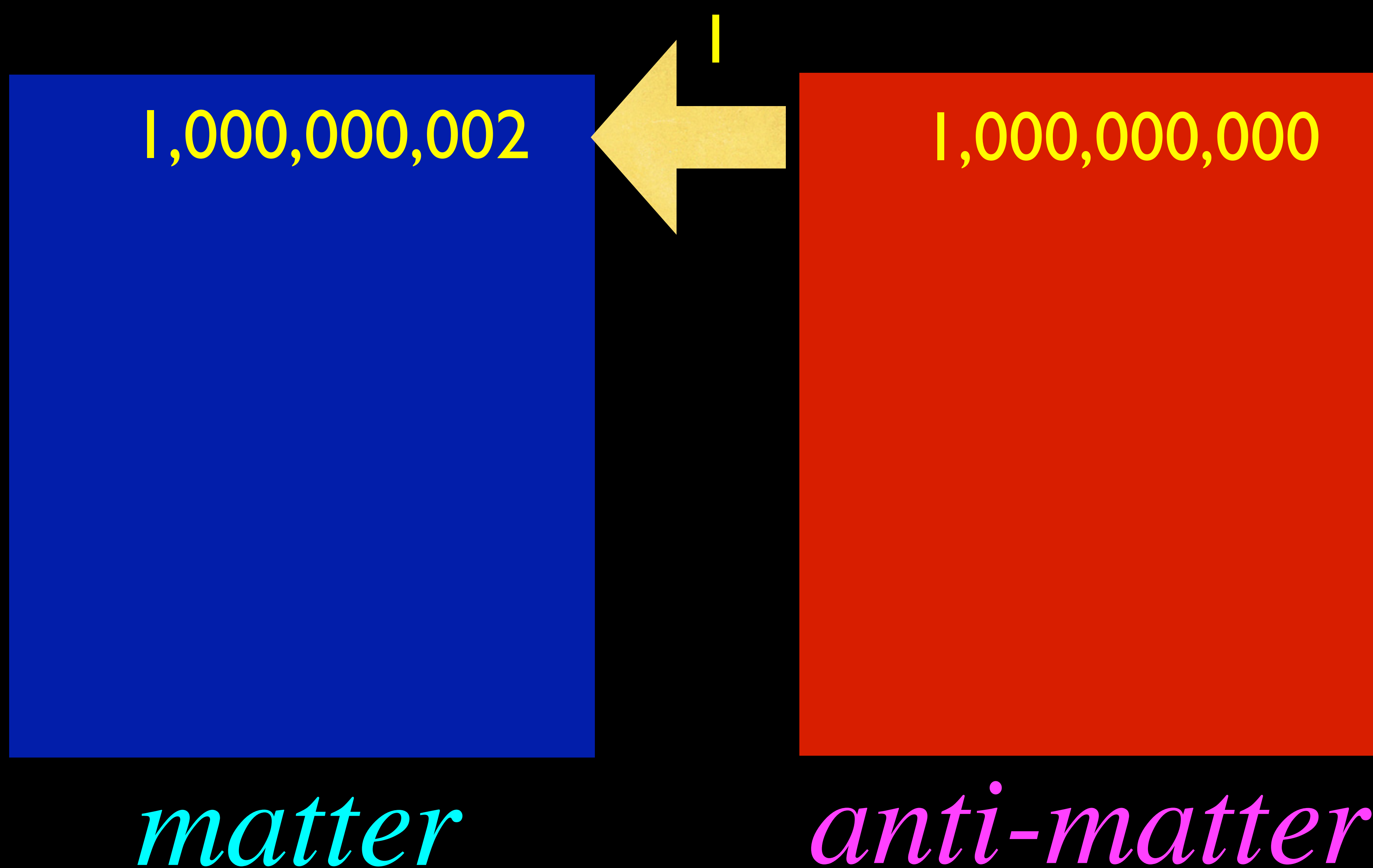
mass [GeV]
QCD axion
sterile neutrino
gravitino
SIMP
asymmetric DM
WIMP
non-thermal
defects

After Inflation

1,000,000,001	1,000,000,001
matter	*anti-matter*

fraction of second later



turned a billionth of anti-matter to matter

Universe Now

2

•

us

matter *anti-matter*

This must be how we survived the Big Bang!

Universe Now

2

•

us

Gelmini, Hall, Lin (1987)
Kaplan, Luty, Zurek, 0901.4117

dark matter *dark anti-matter*

This must be how we survived the Big Bang!
they

Universe Now

$$m_{\rm DM} = \frac{n_b}{n_{\rm DM}} \frac{\Omega_{\rm DM}}{\Omega_b} m_p \approx 6 \text{ GeV} \times \frac{\eta_b}{\eta_{\rm DM}}$$

2

•

us

Gelmini, Hall, Lin (1987)
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2

us

- motivation for 1–10 GeV dark matter
- signal depends on portal; new medium

Gelmini, Hall, Lin (1987)
Kaplan, Luty, Zurek, 0901.4117

dark matter *dark anti-matter*

This must be how we survived the Big Bang!

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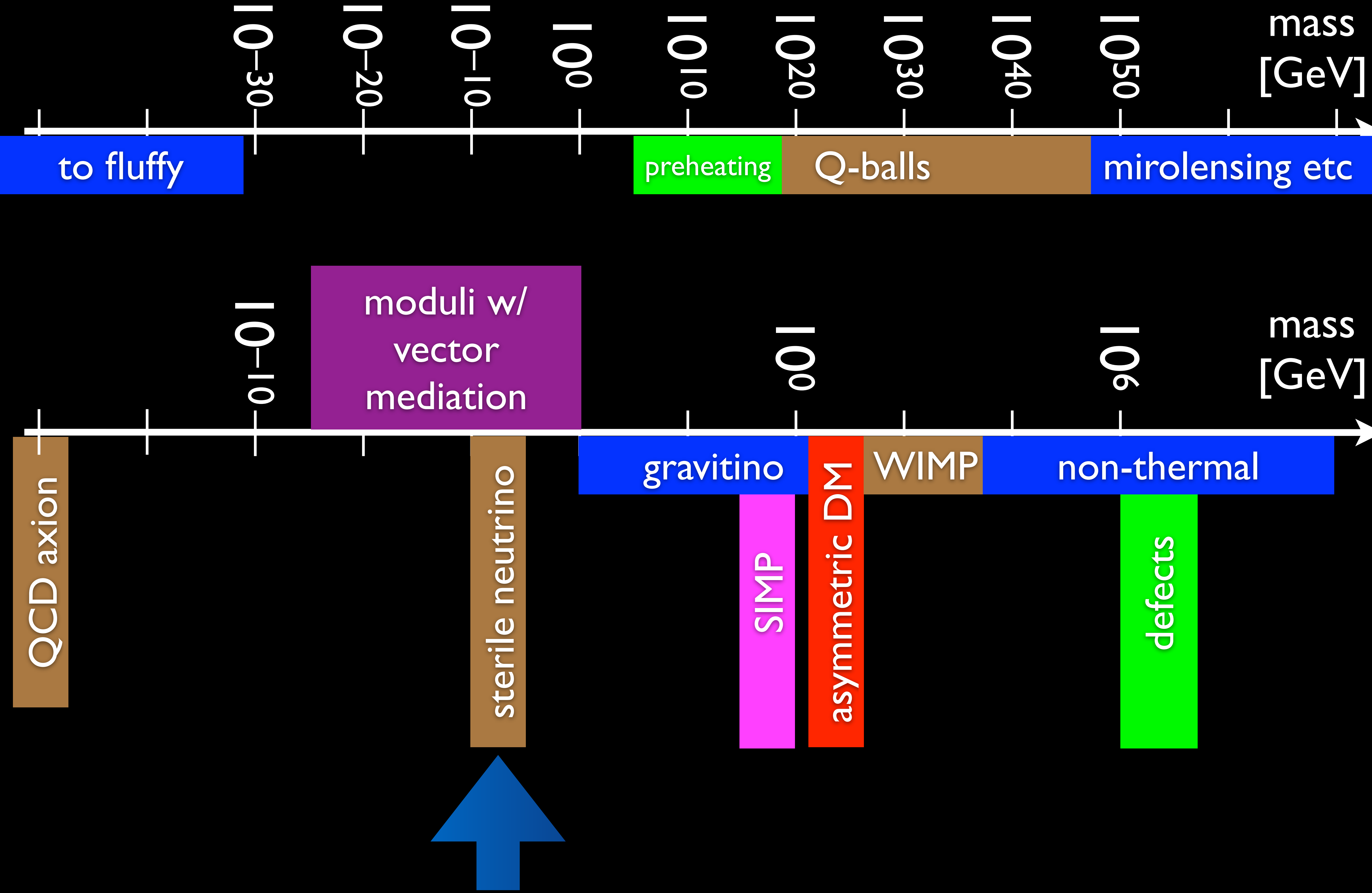

10−30
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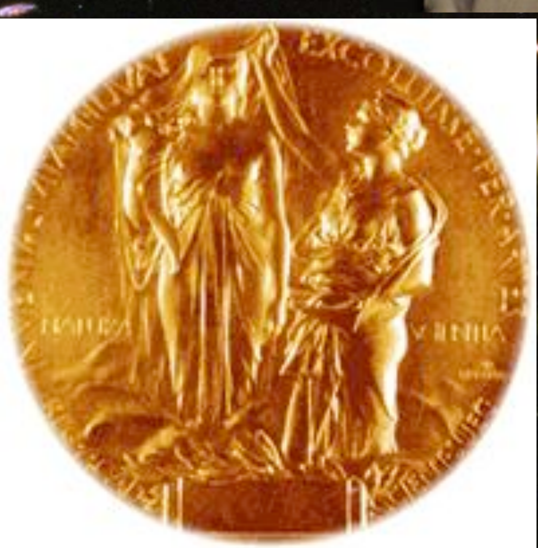
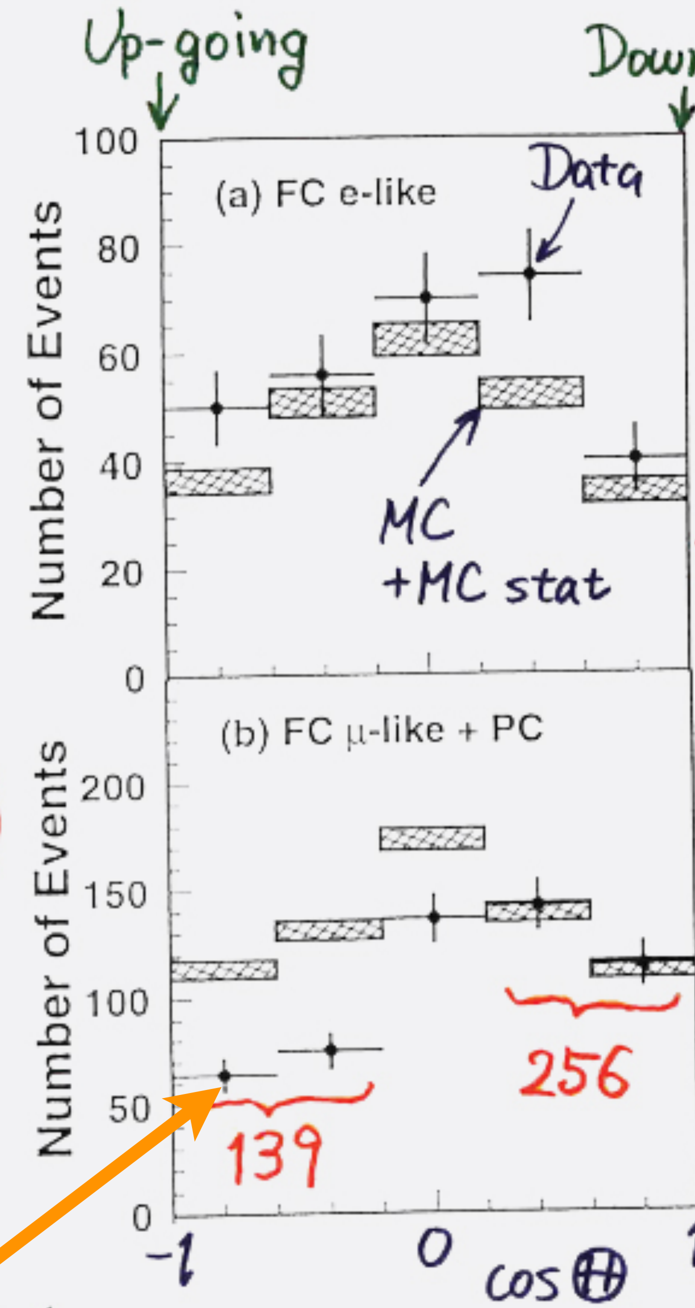


1998

a half of expected

Zenith angle dependence (Multi-GeV)



(e): χ^2(shape) $= 2.8/4$ dof

$\frac{\text{Up}}{\text{Down}} = 0.93^{+0.13}_{-0.12}$

(μ): χ^2(shape) $= 30/4$ dof

$\frac{\text{Up}}{\text{Down}} = 0.54^{+0.06}_{-0.05}$

(**6.2σ !!**)

※ Up/Down syst. error for μ-like

Prediction (flux calculation …… $\lesssim 1\%$; 1km rock above SK …. 1.5%) 1.8%

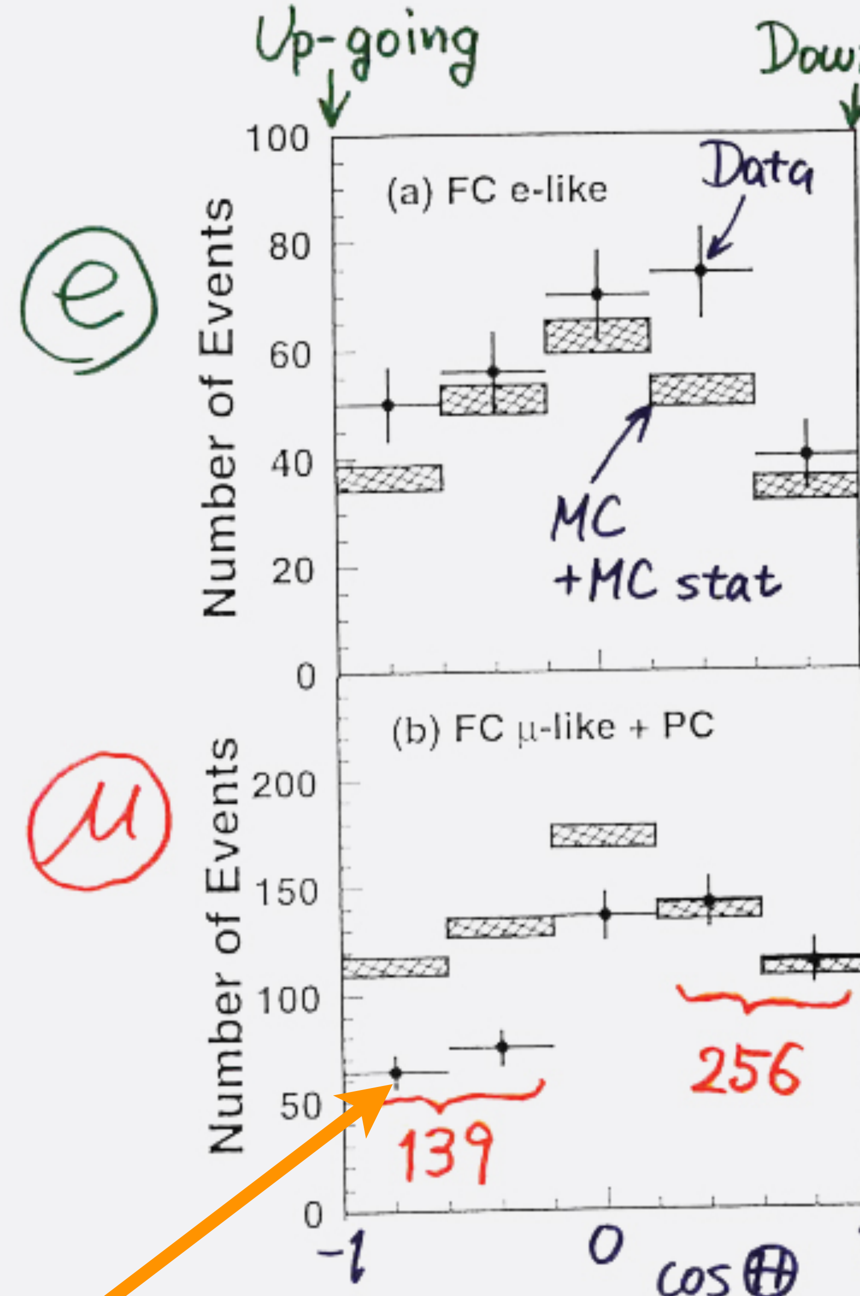
Data (Energy calib. for ↑↓ …. 0.7%; Non ν Background …. < 2%) 2.1%

neutrino mass too light for dark matter

1998

a half of expected

Zenith angle dependence (Multi-GeV)



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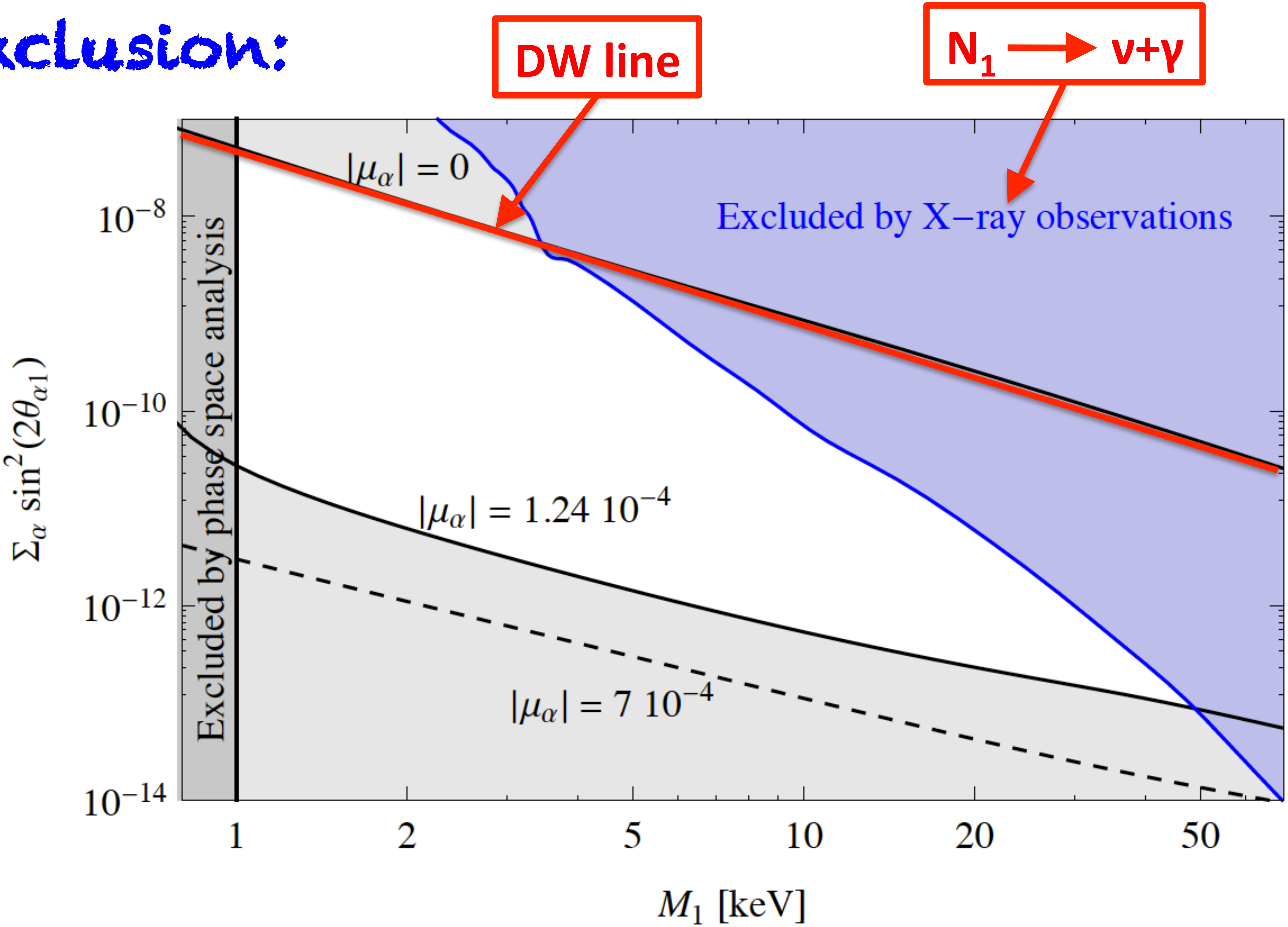
2. Production Mechanisms

Exclusion:



[Canetti *et al.*: Phys. Rev. **D87** (2013) 093006]

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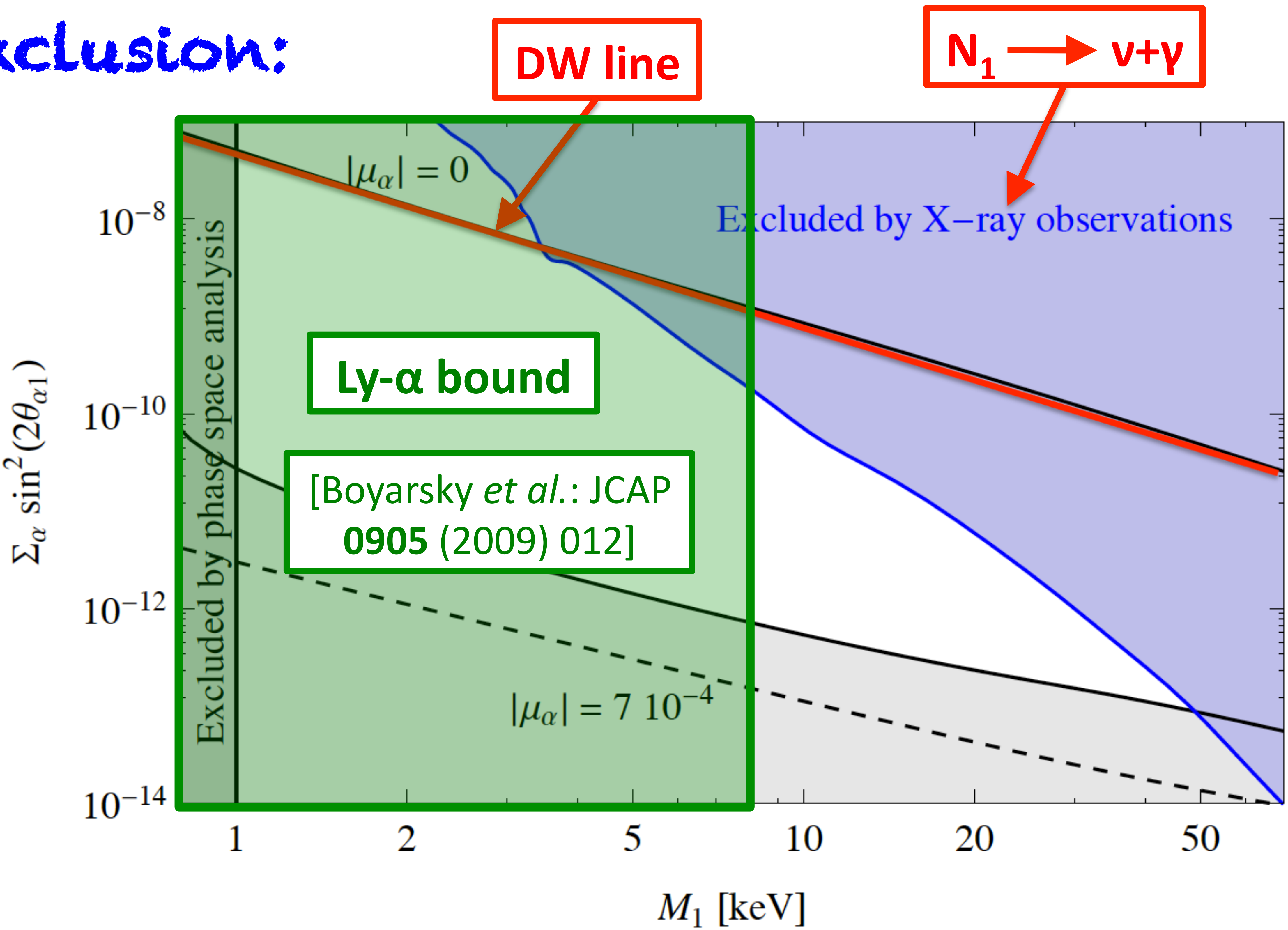
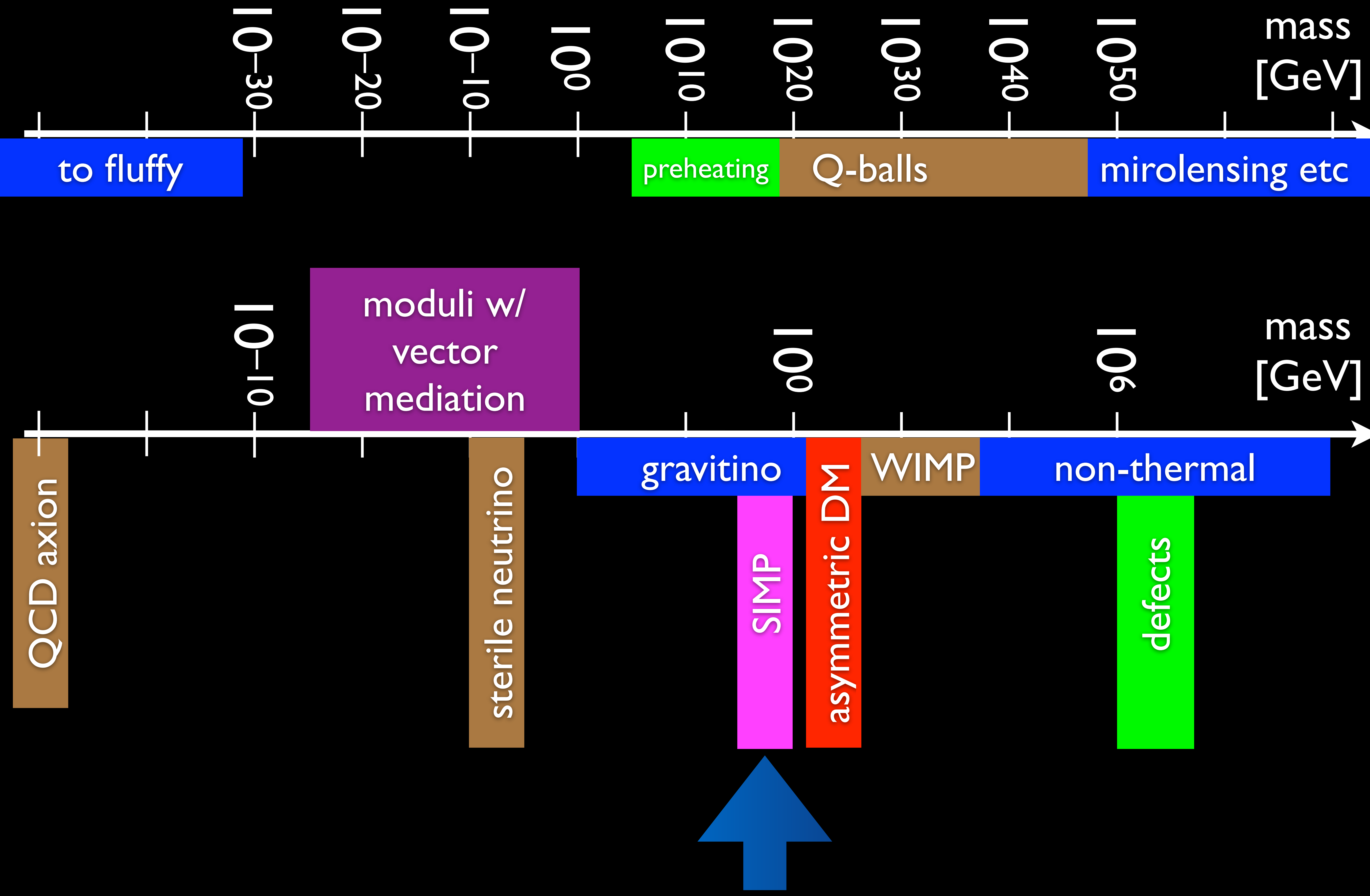


[Canetti *et al.*: Phys. Rev. **D87** (2013) 093006]

Alexander Merle



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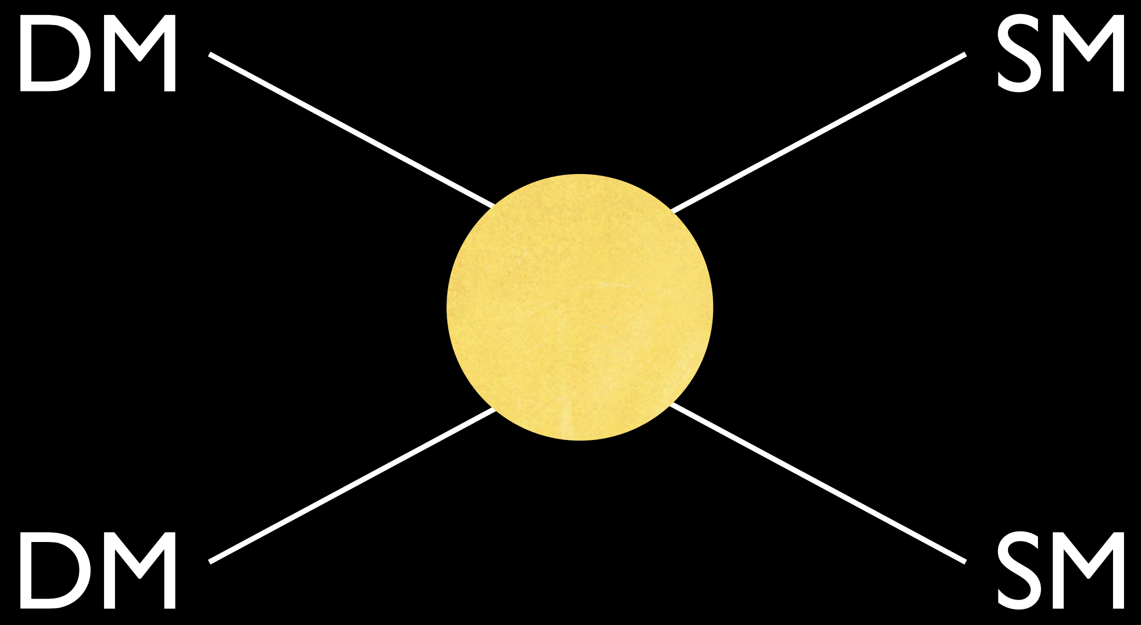
$$\frac{n_{\rm DM}}{s} = 4.4 \times 10^{-10} \frac{\rm GeV}{m_{\rm DM}}$$

Miracles



$$\langle \sigma_{2\to 2} v \rangle \approx \frac{\alpha^2}{m^2}$$

$$\alpha \approx 10^{-2}$$

$$m \approx 300 \ {\rm GeV}$$

WIMP miracle!

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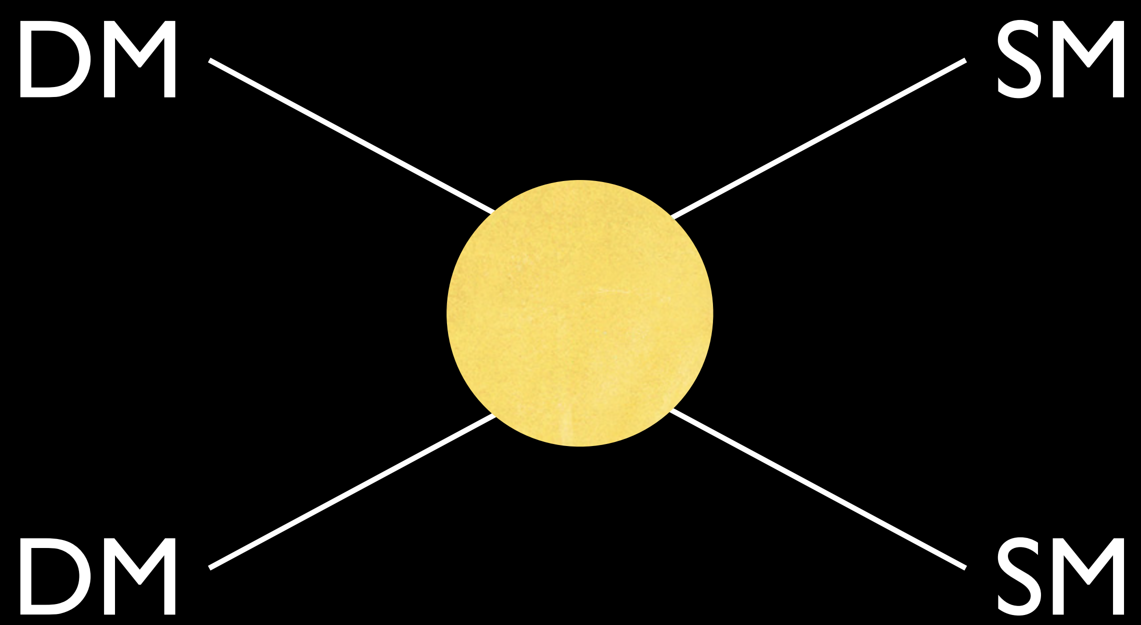
Miracles



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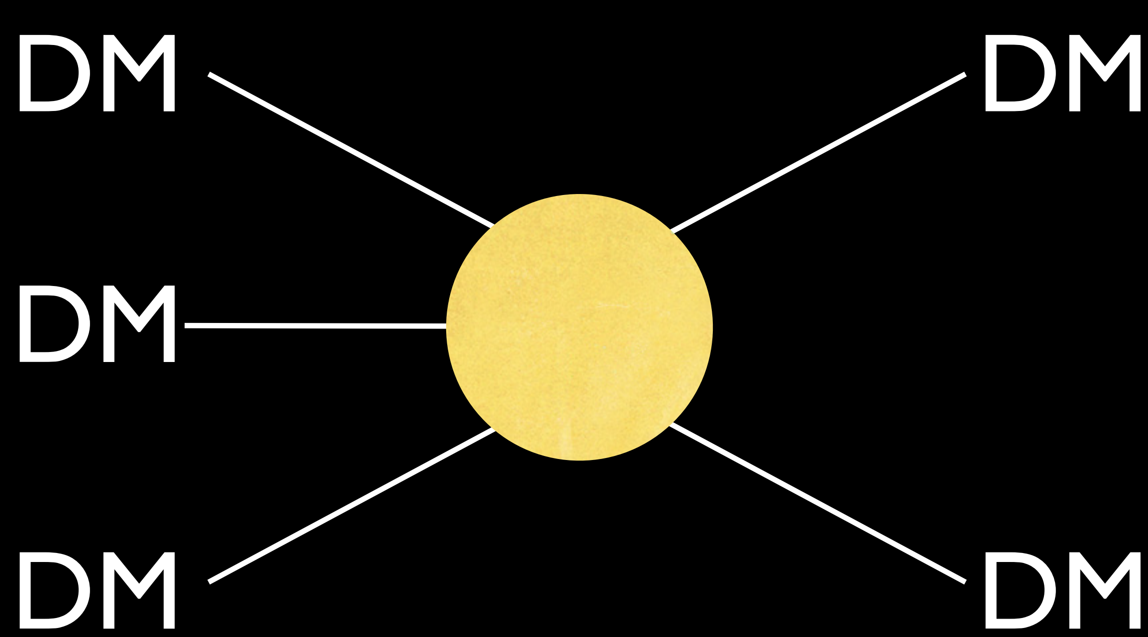

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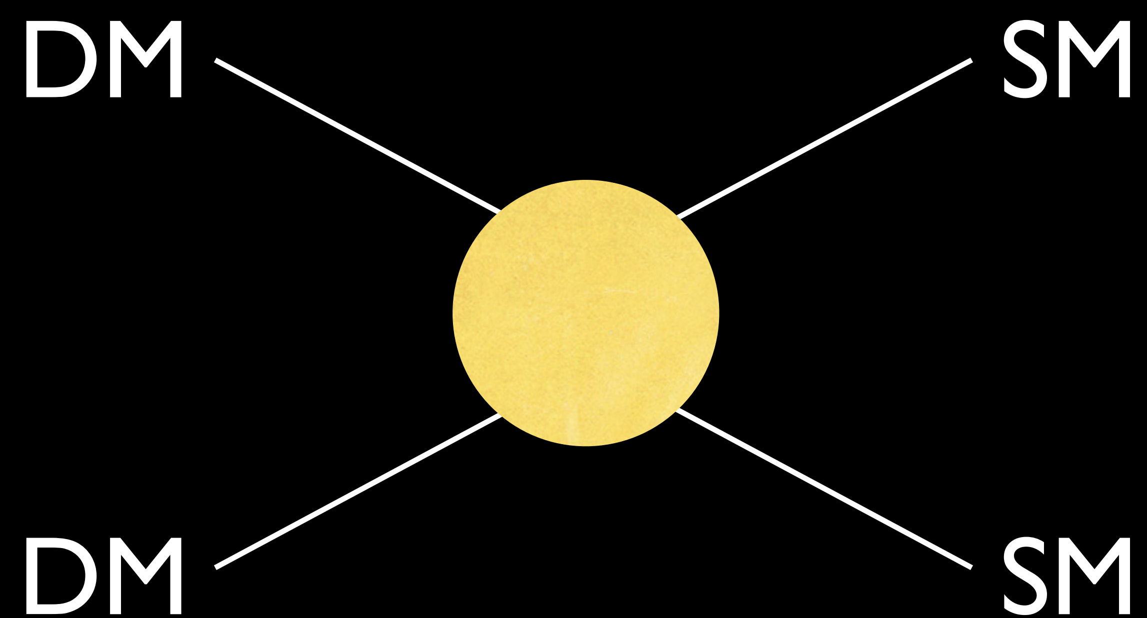
Miracles



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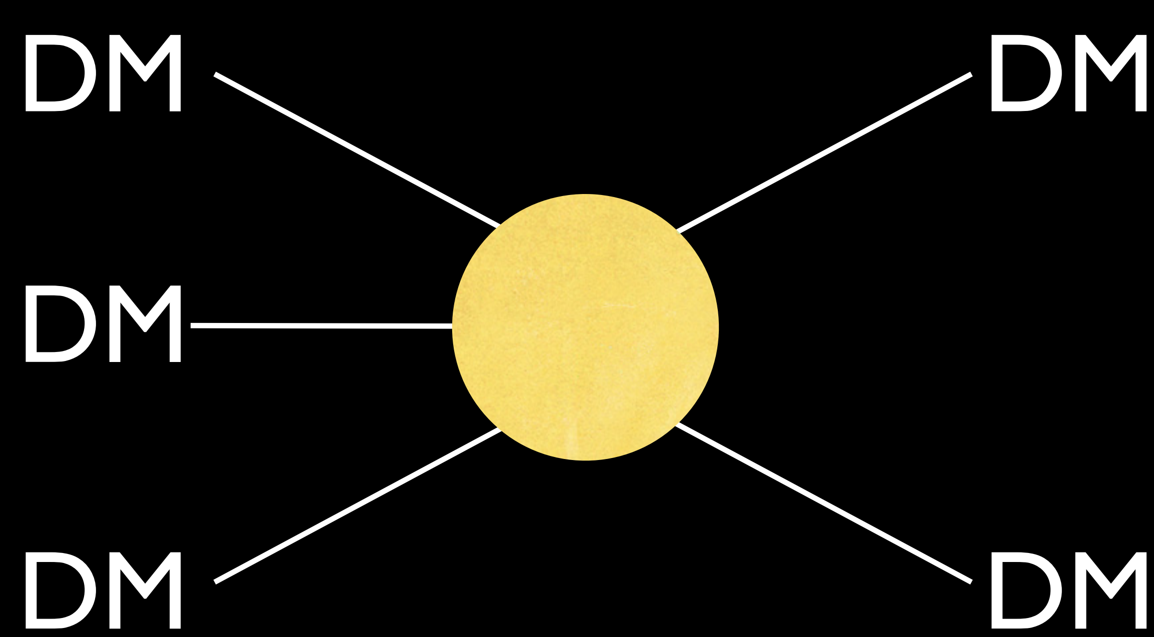

$$\langle \sigma_{3\to 2} v^2 \rangle \approx \frac{\alpha^3}{m^5}$$

$$\alpha \approx 4\pi$$

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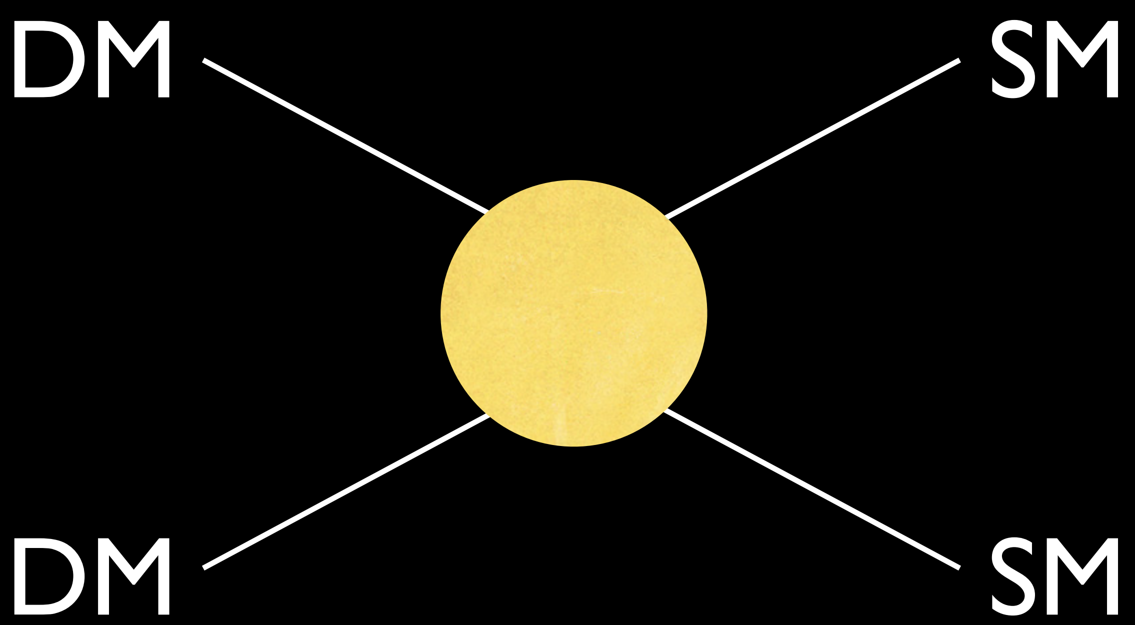
$$\frac{n_{\rm DM}}{s} = 4.4 \times 10^{-10} \frac{\rm GeV}{m_{\rm DM}}$$

Miracles



$$\langle \sigma_{2\to 2} v \rangle \approx \frac{\alpha^2}{m^2}$$

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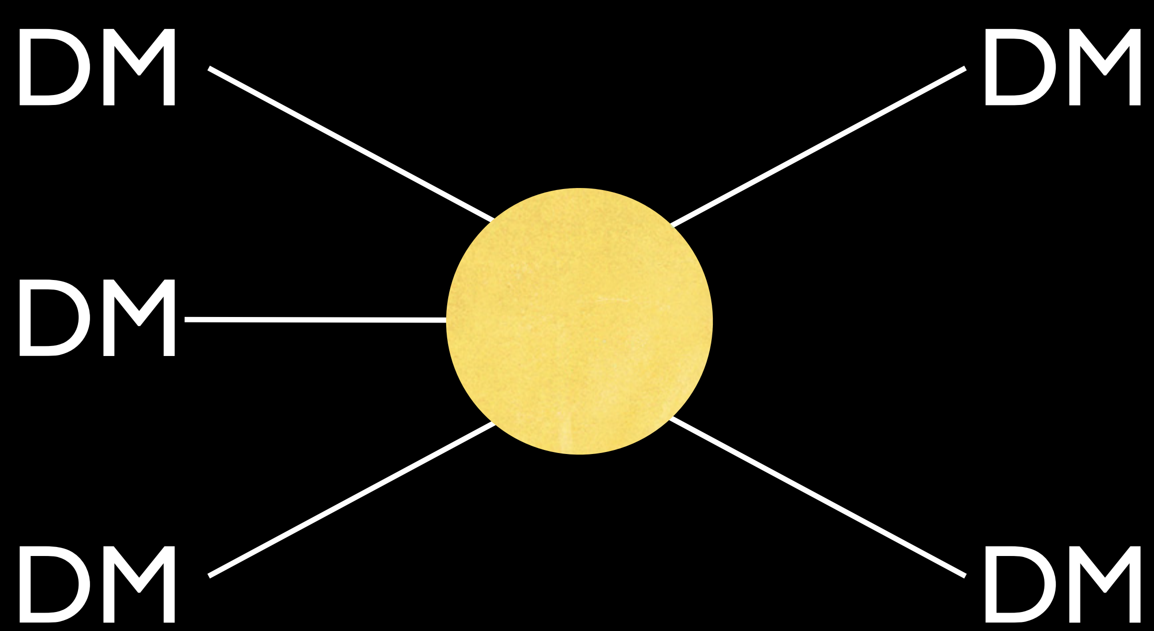

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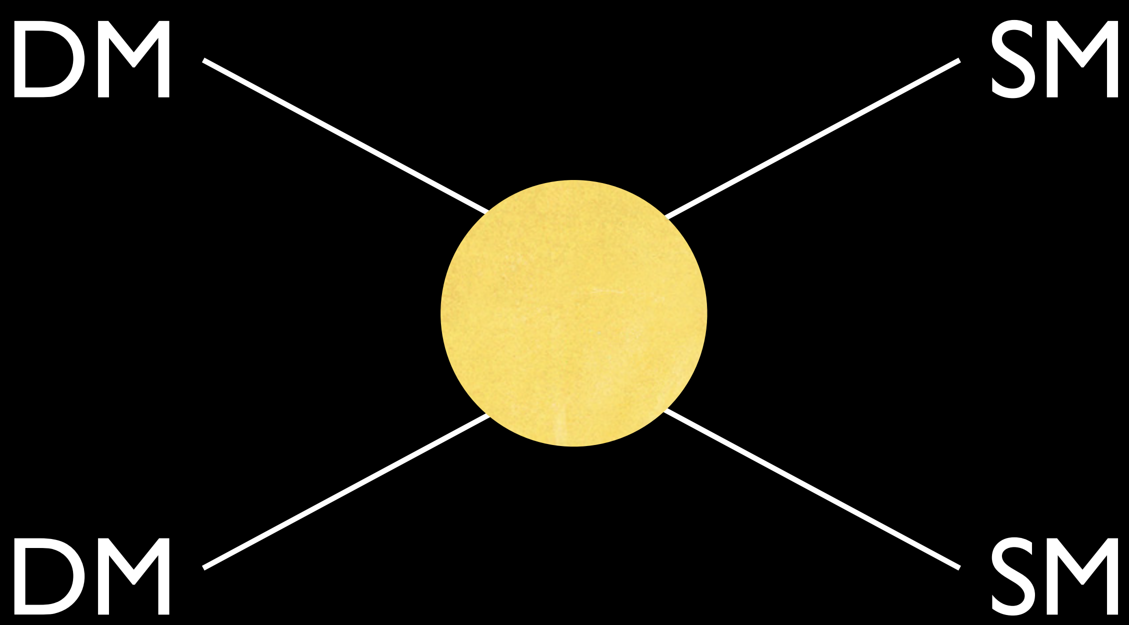

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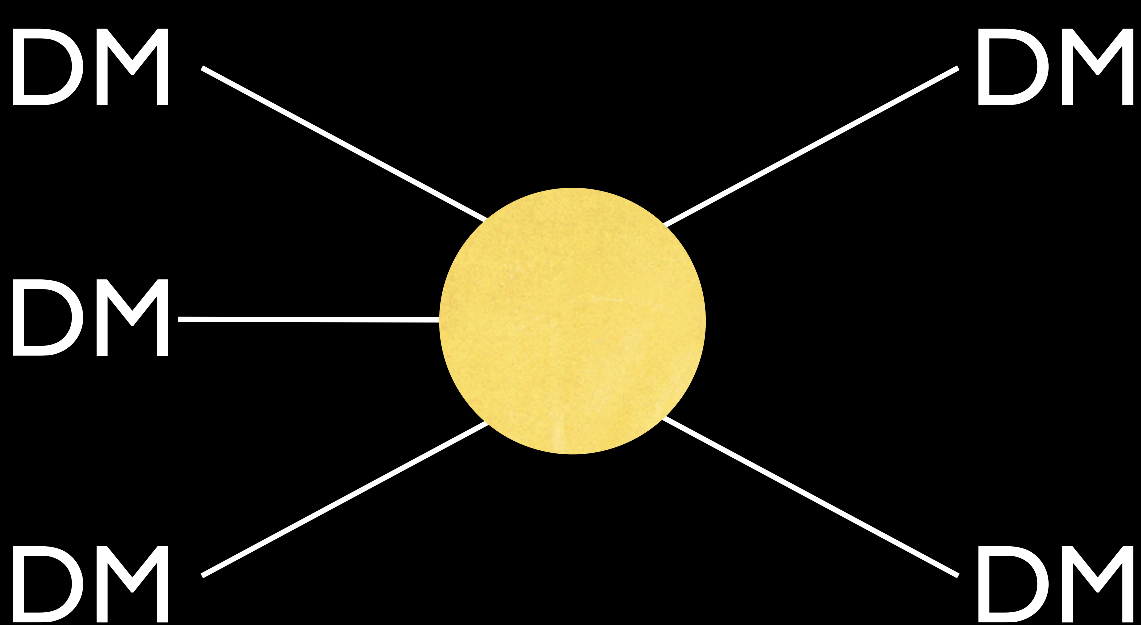

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Hochberg, Kuflik, Volansky, Wacker arXiv:1402.5143

SIMP miracle!

SIMPle

- Most gauge theories, $SU(N_C)$, $SO(N_C)$, $Sp(N_C)$ lead to Wess-Zumino term if $N_f \geq 2,3$
- $\mathcal{L}_{WZ} = \varepsilon_{abcde}\, \varepsilon^{\mu\nu\rho\sigma}\, \pi^a \partial_\mu \pi^b \partial_\nu \pi^c \partial_\rho \pi^d \partial_\sigma \pi^e$
- 3to2 interaction automatically there
- strongly-coupled theory
- rich with resonances

DDO 154 dwarf galaxy

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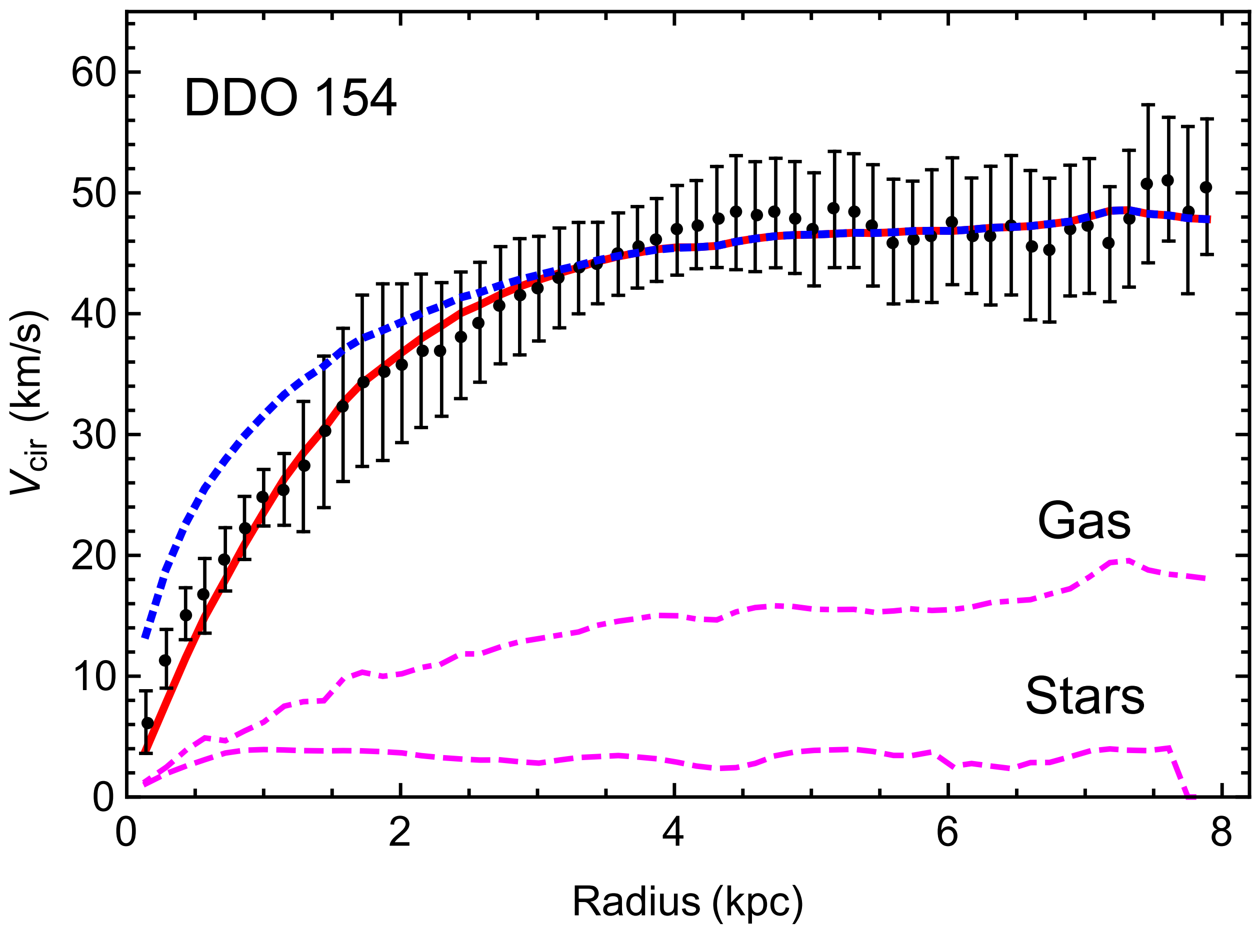
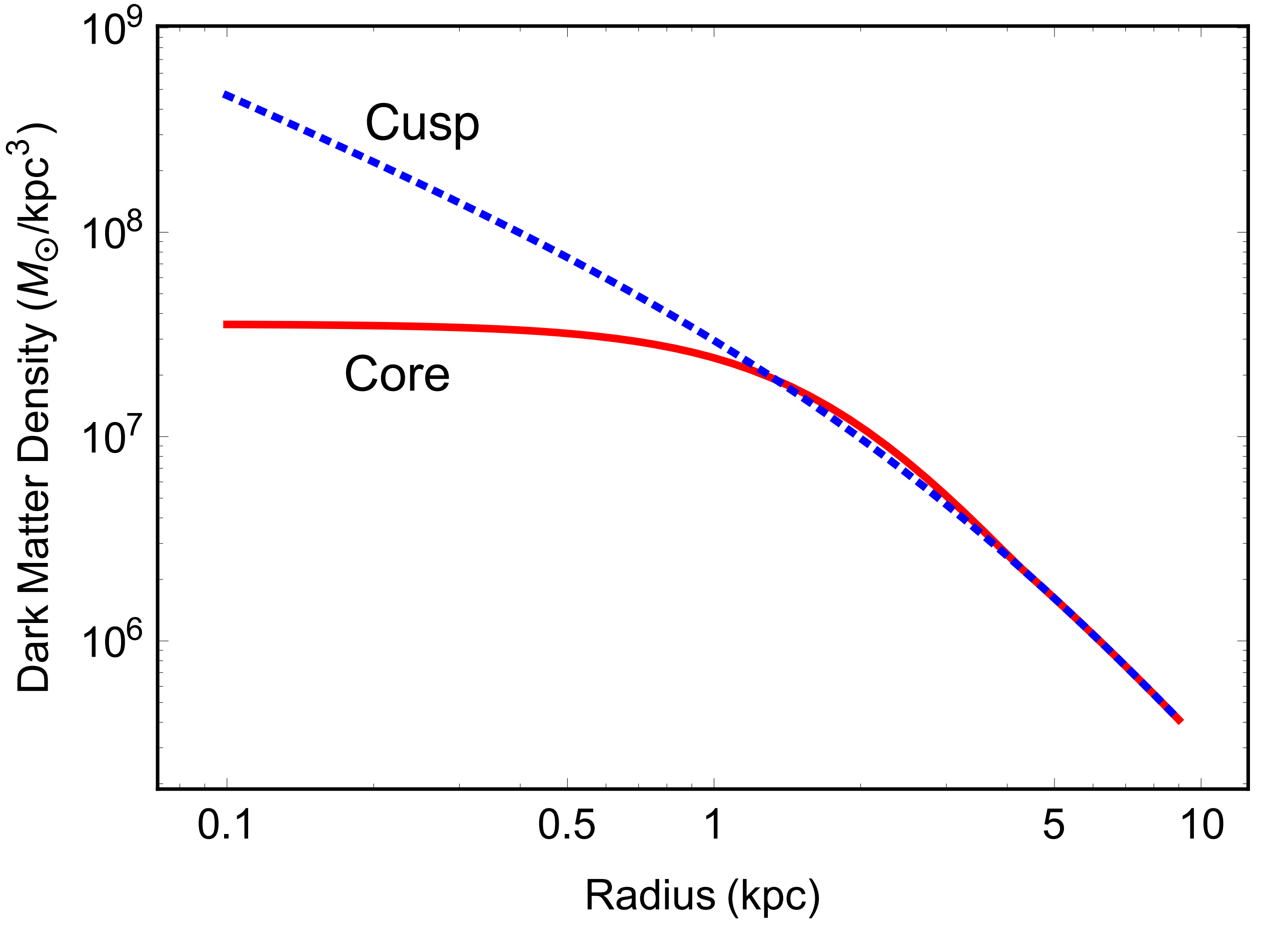




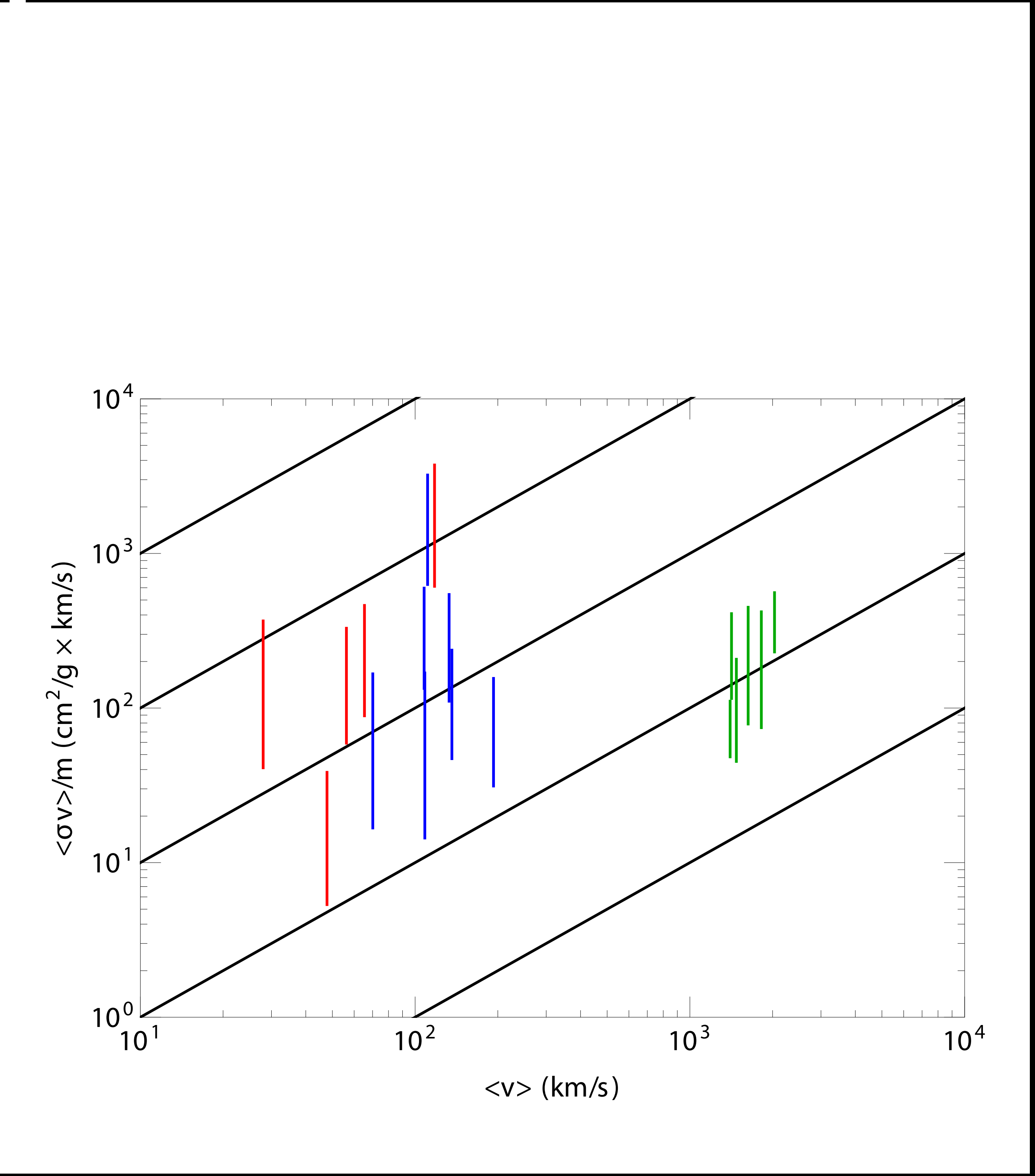
can be explained if dark matter scatters against itself

Need $\sigma/m \sim$ 1b / GeV

only astrophysical information beyond gravity

velocity dependence?

- cluster data prefer smaller σ?
- near constant ⟨σ*v*⟩?
- Sommerfeld effect (S. Tulin, H.-B. Yu, and K.M. Zurek, arXiv:1302.3898)
  - requires light mediator
- near-threshold resonance can "fit" the data
- *i.e.*, $\pi\pi \rightarrow \sigma \rightarrow \pi\pi$
  - (Xiaoyong Chu, Camilo Garcia-Cely, Yonit Hochberg, Eric Kuik, HM)



M. Kaplinghat, S. Tulin, and H.-B. Yu, arXiv:1508.03339.

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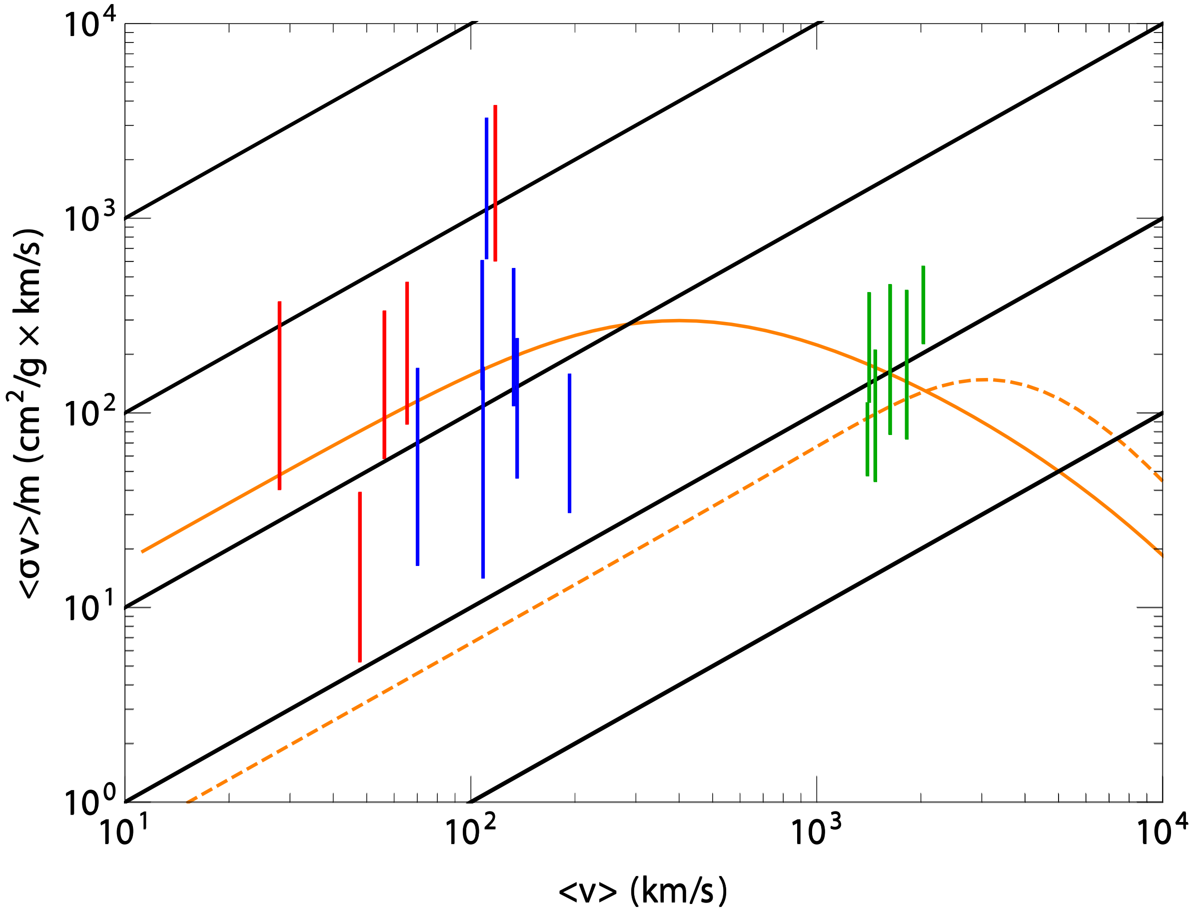
$$\mathcal{L} = m_R g \, \text{RDM}^2 \, .$$

n	a	b	γ_0	v_R (km/s)	m_R (GeV)	χ^2/d.o.f.
0	24	32	$10^{-4.3}$	1829	26	2.1



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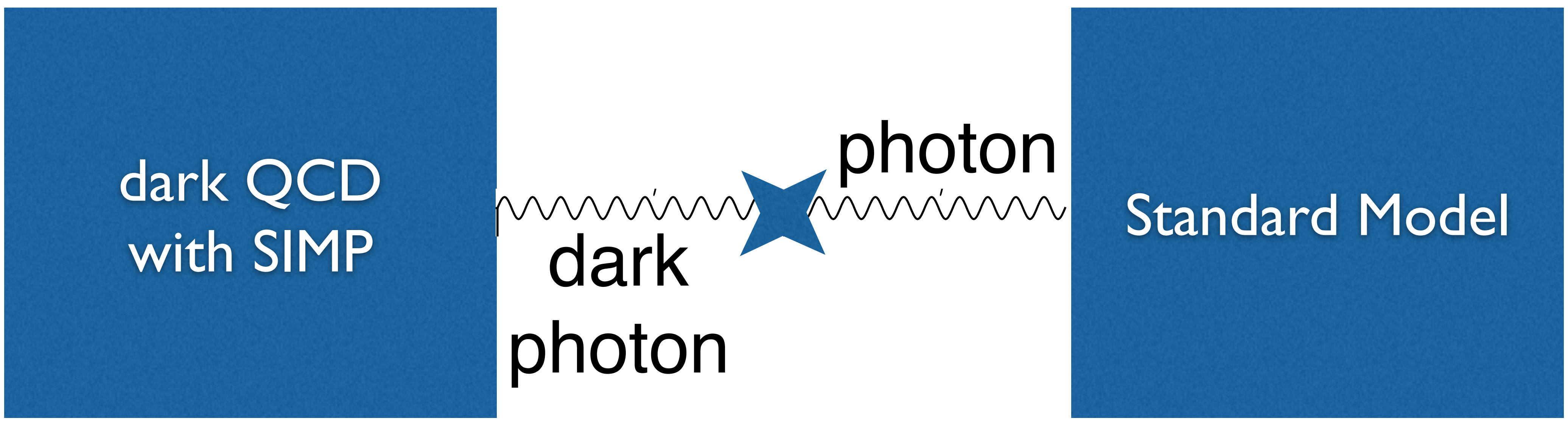
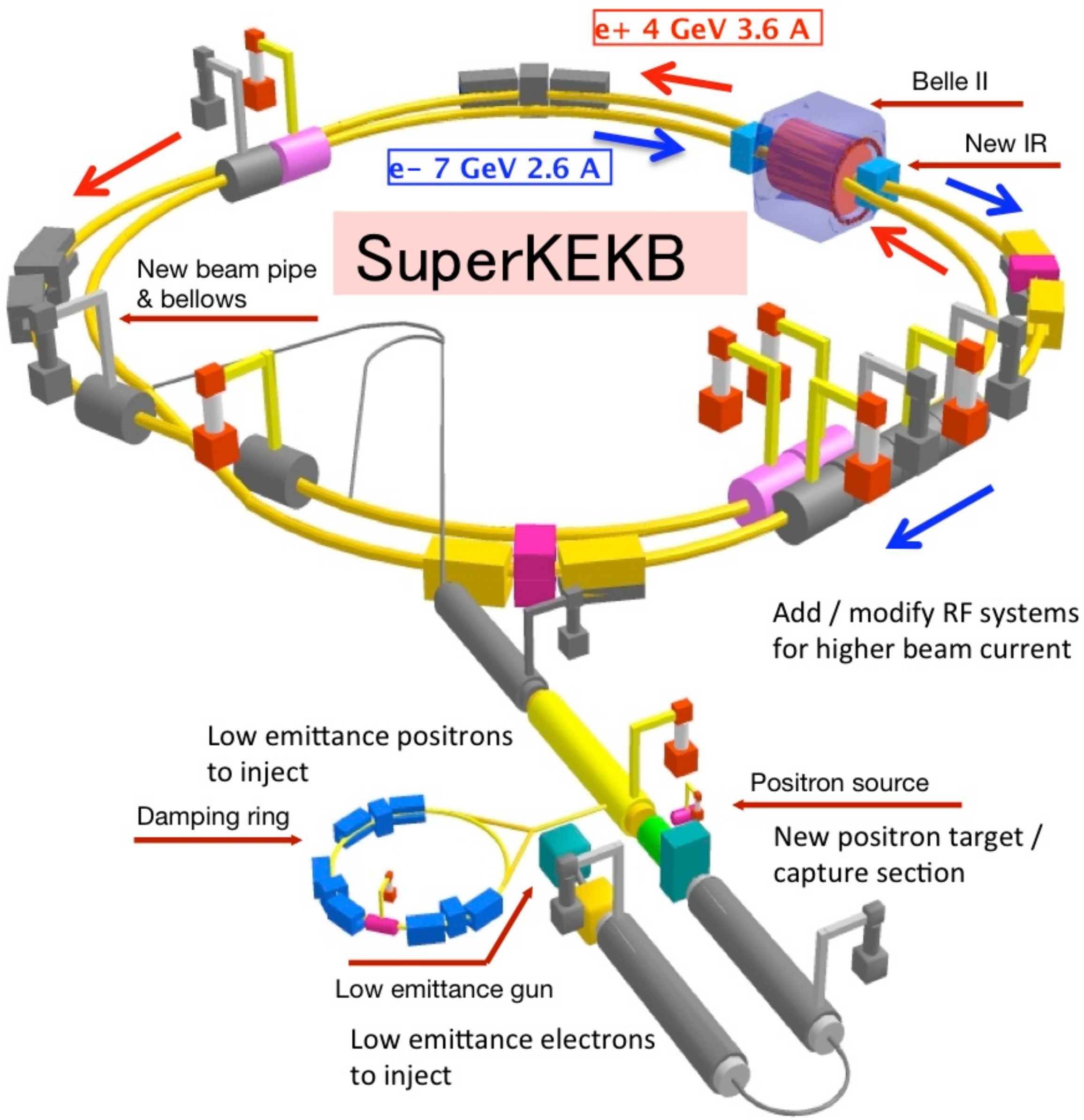
vector portal

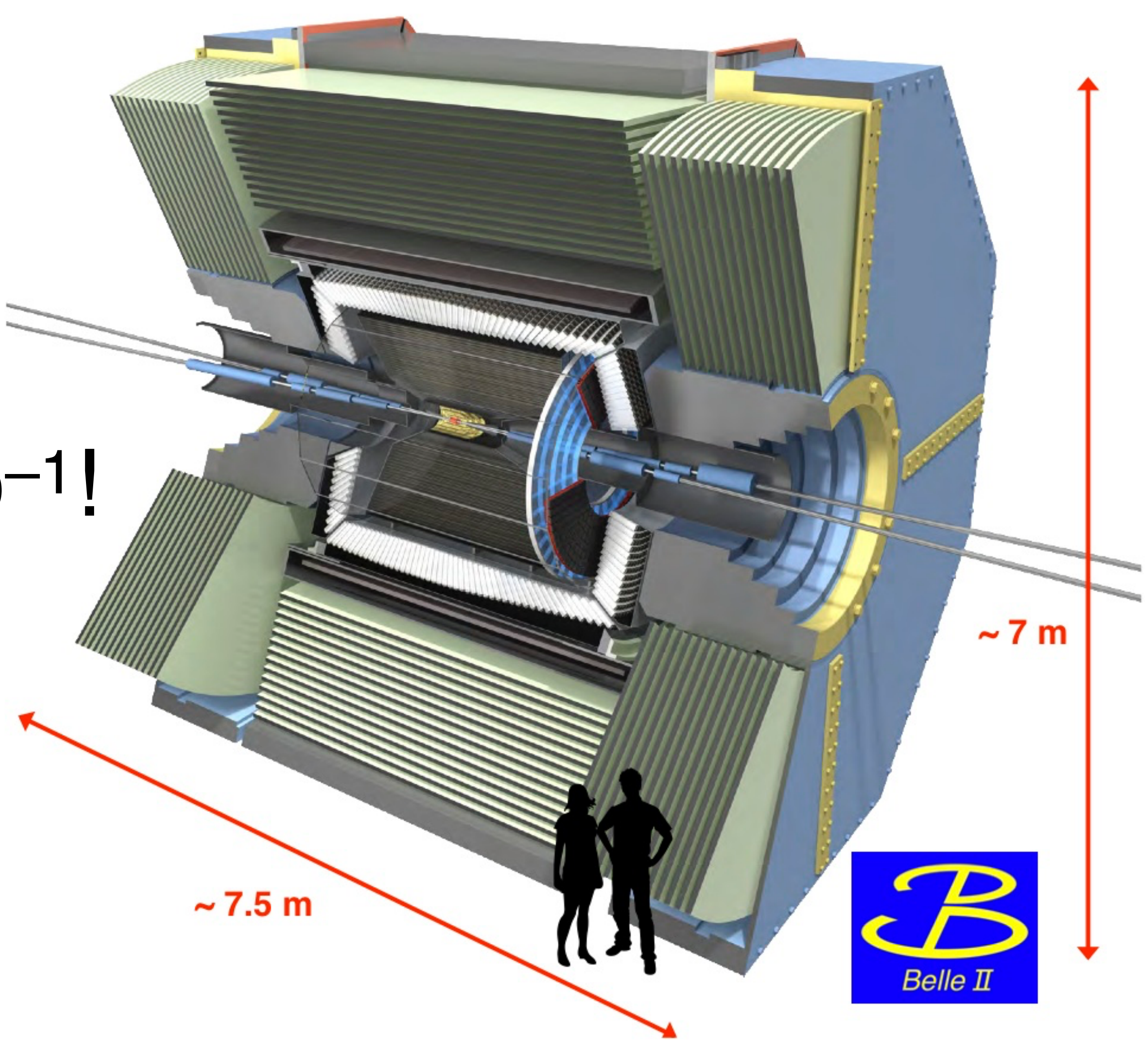


$$\frac{\epsilon_\gamma}{2c_W} B_{\mu\nu} F_D^{\mu\nu}$$

high-lumi e^+e^-



50 ab^{-1}!



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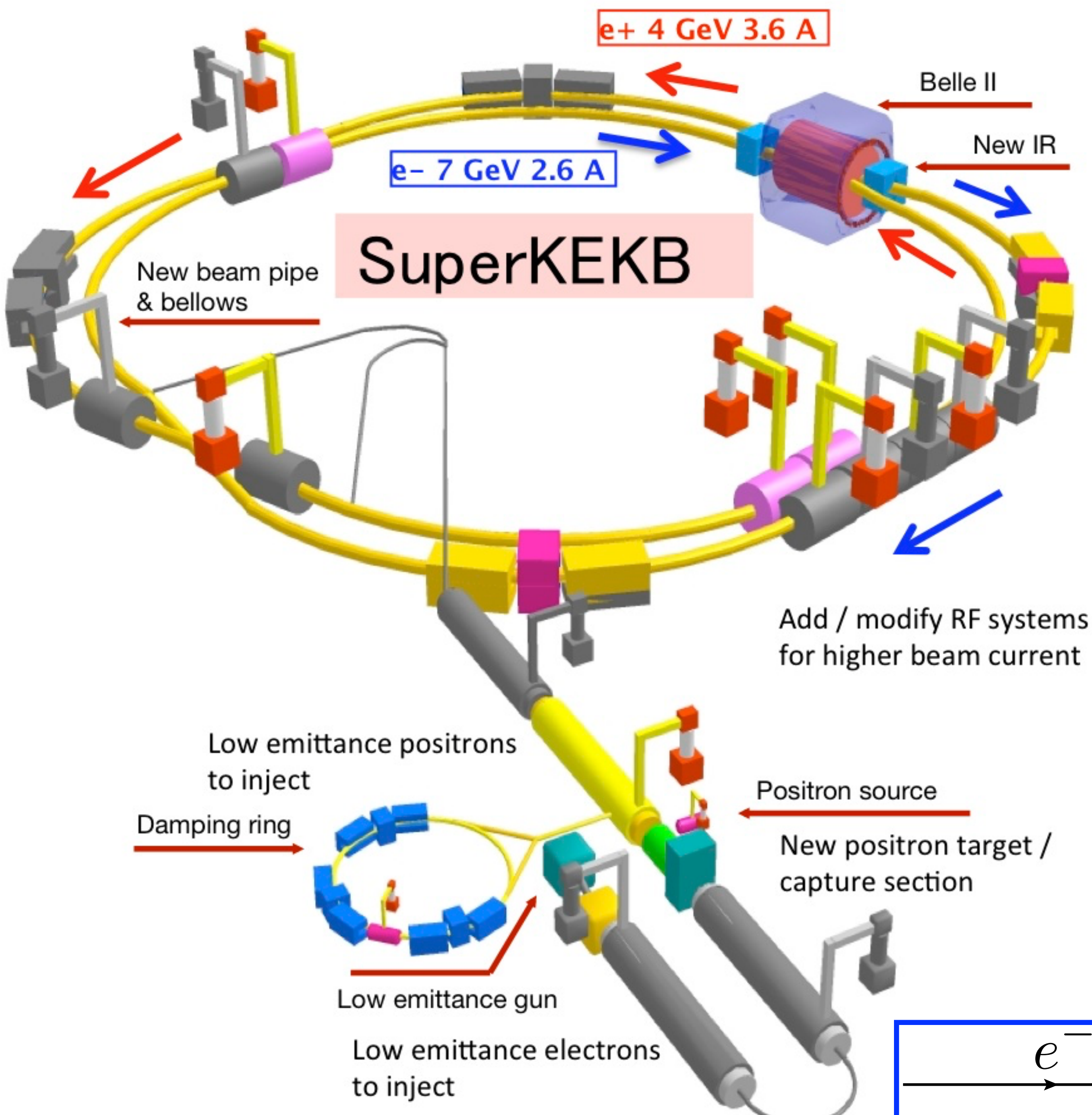

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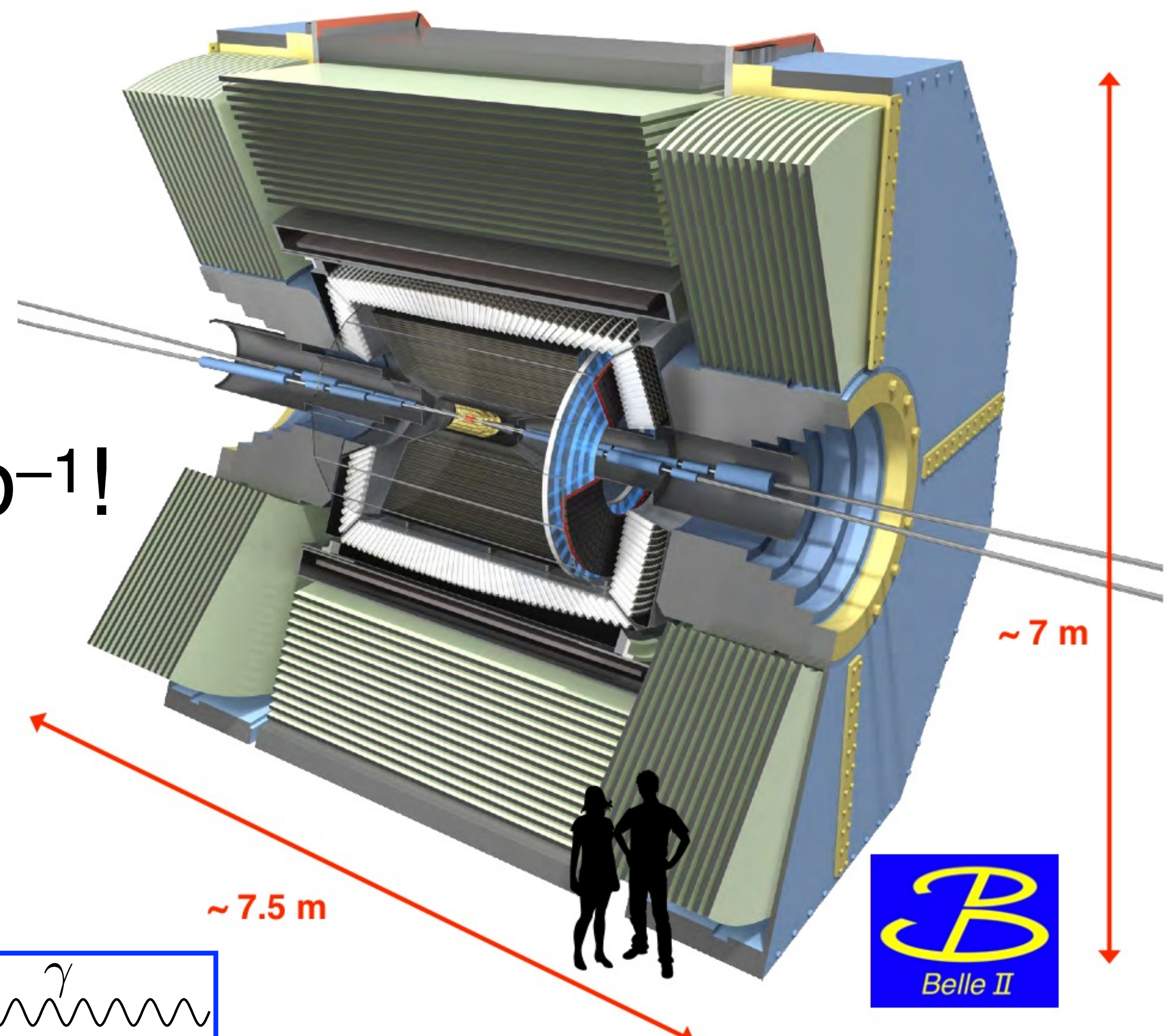

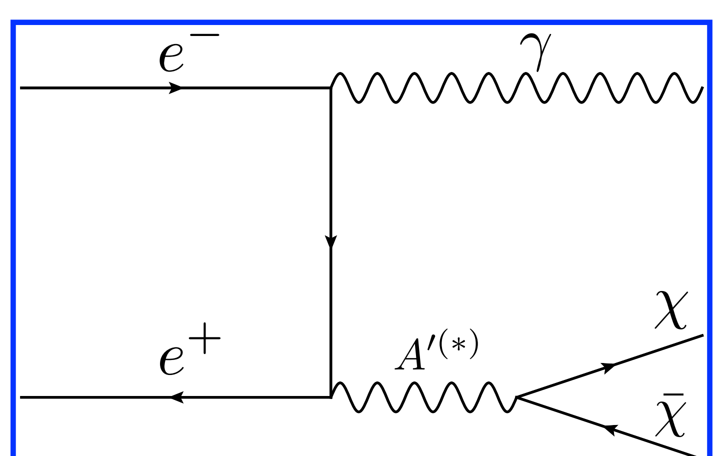

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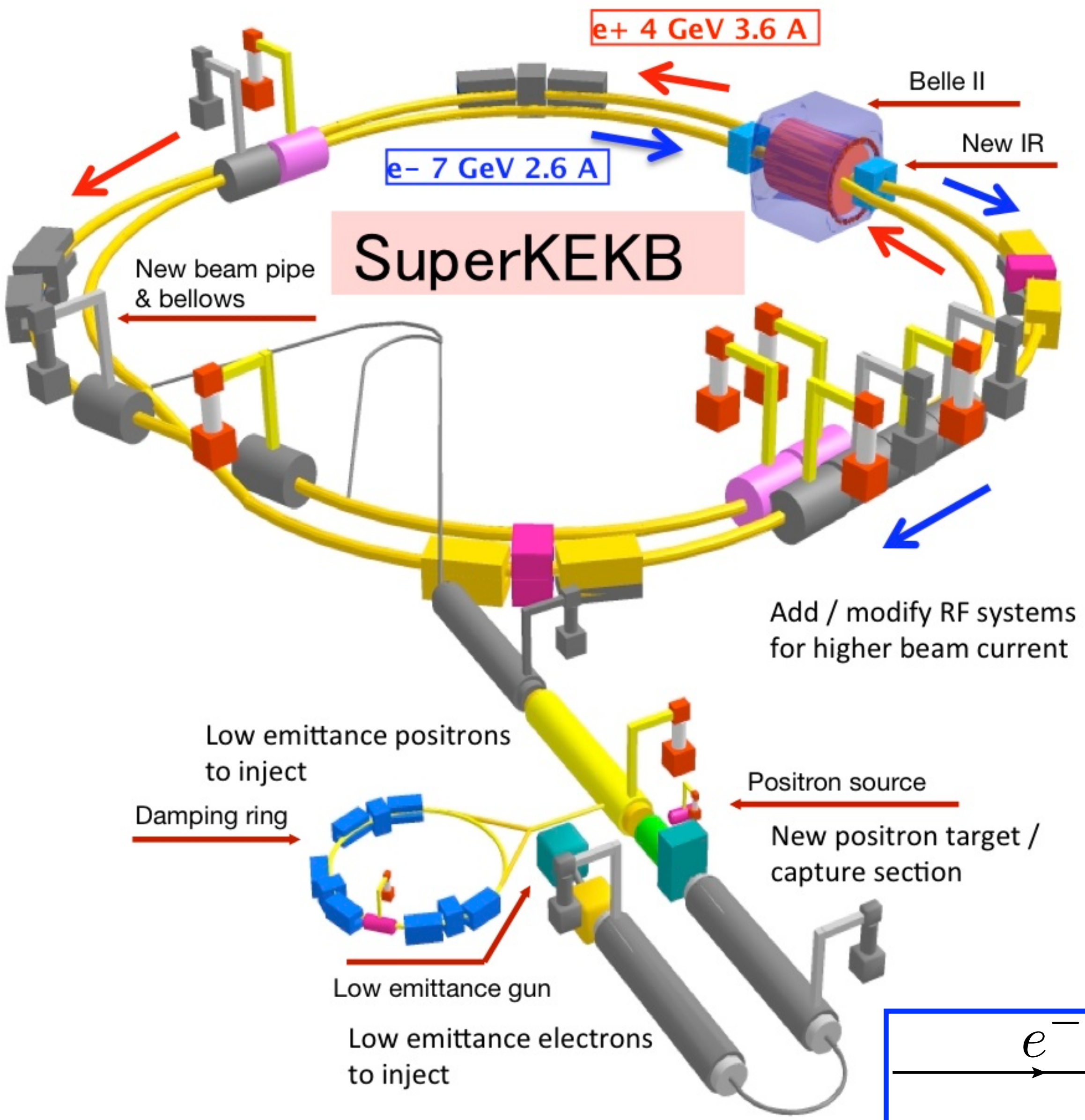

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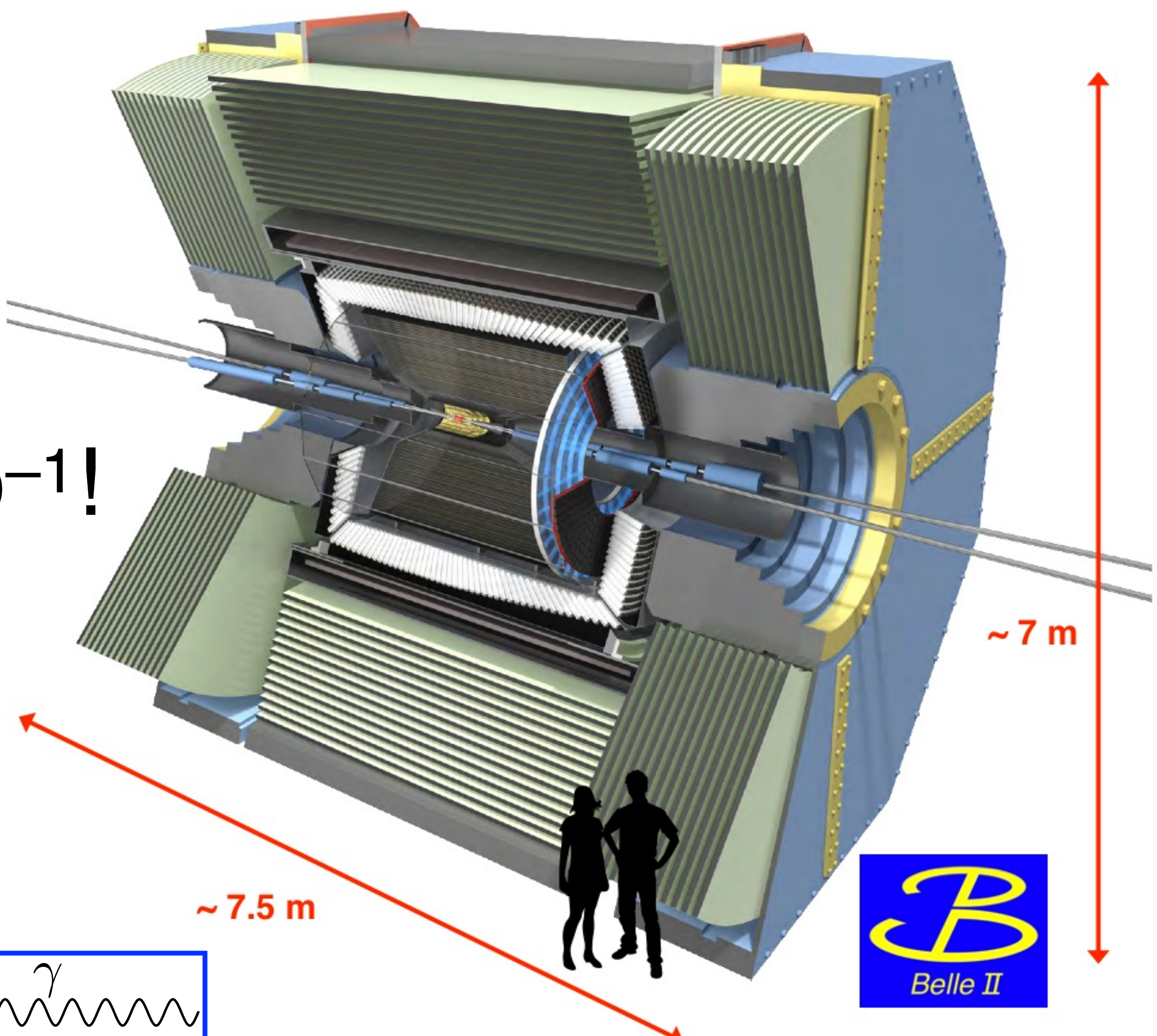
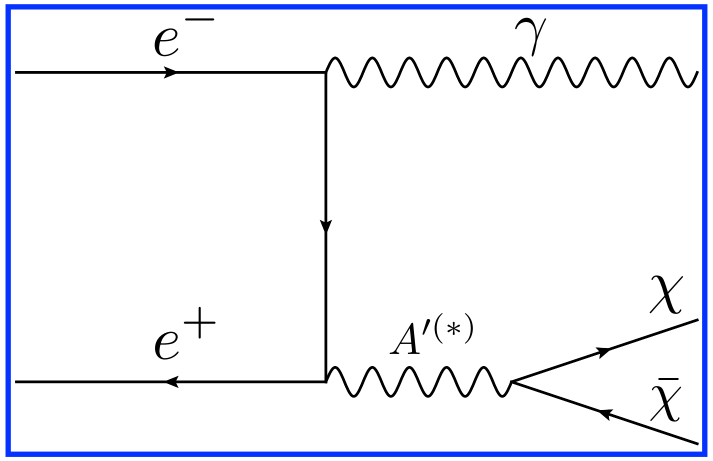
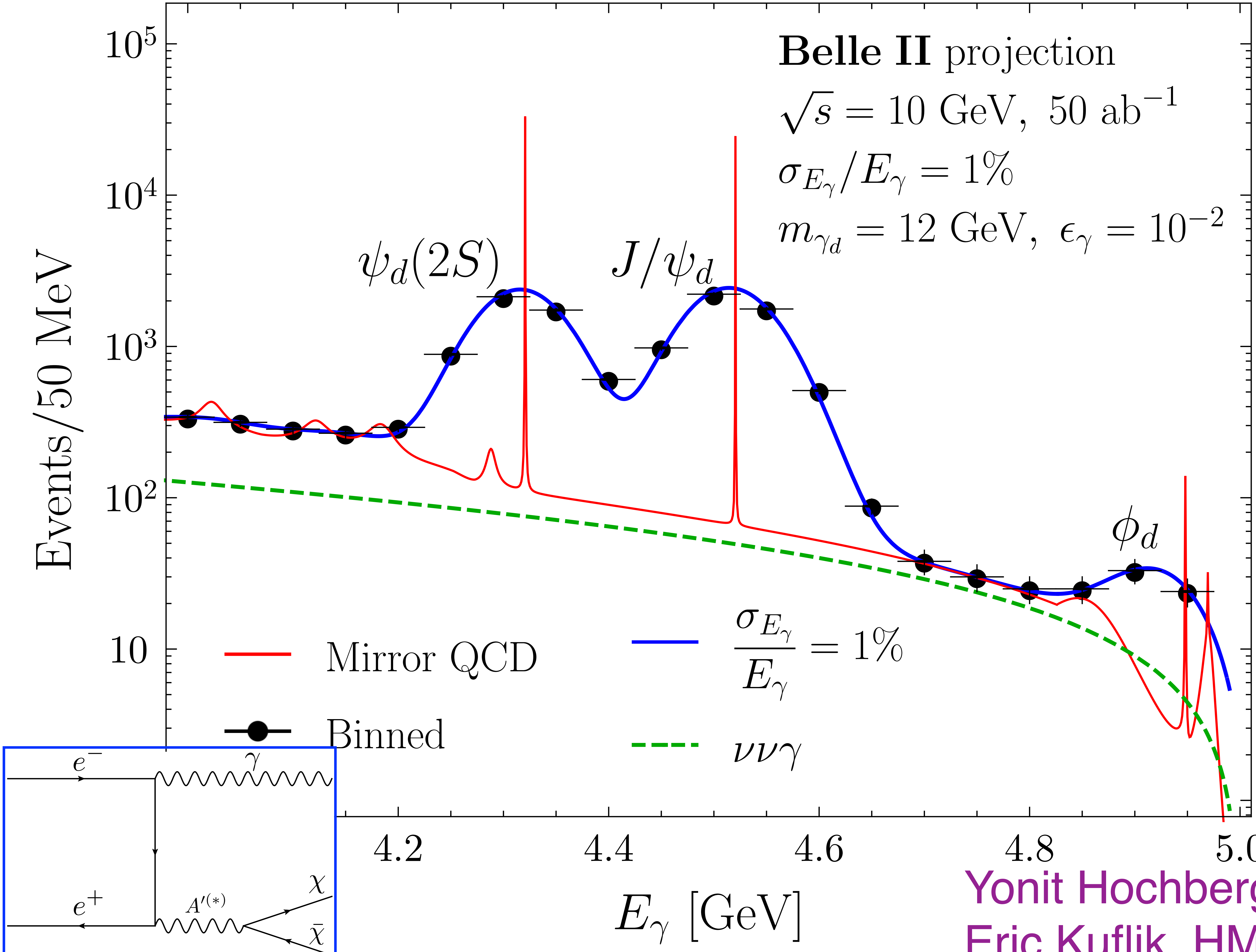


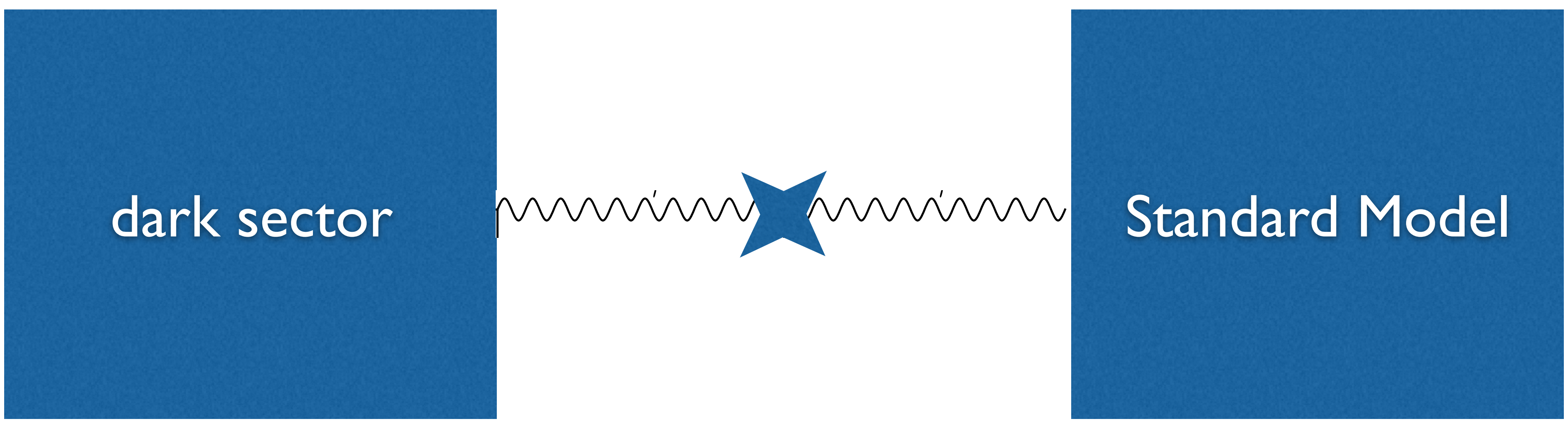


$$E_\gamma = \frac{\sqrt{s}}{2}\left(1 - \frac{M_{\rm inv}^2}{s}\right)$$



Yonit Hochberg, Eric Kuflik, HM

portals



vector portal $\frac{\epsilon_\gamma}{2c_W} B_{\mu\nu} F_D^{\mu\nu}$ → collider, beam dump

scalar portal $\mu S H^\dagger H, S^2 H^\dagger H$ → $H \to$ invisible, couplings

neutrino portal $\bar{L} N H$ → neutrino exp, dump

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- vibrant area and need more data!

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- R&D on magnets, LC, future technologies