Overview of Theoretical Explanations of Dark Matter

Hitoshi Murayama

290E, September 11, 2019

Five empirical evidences for physics beyond SM

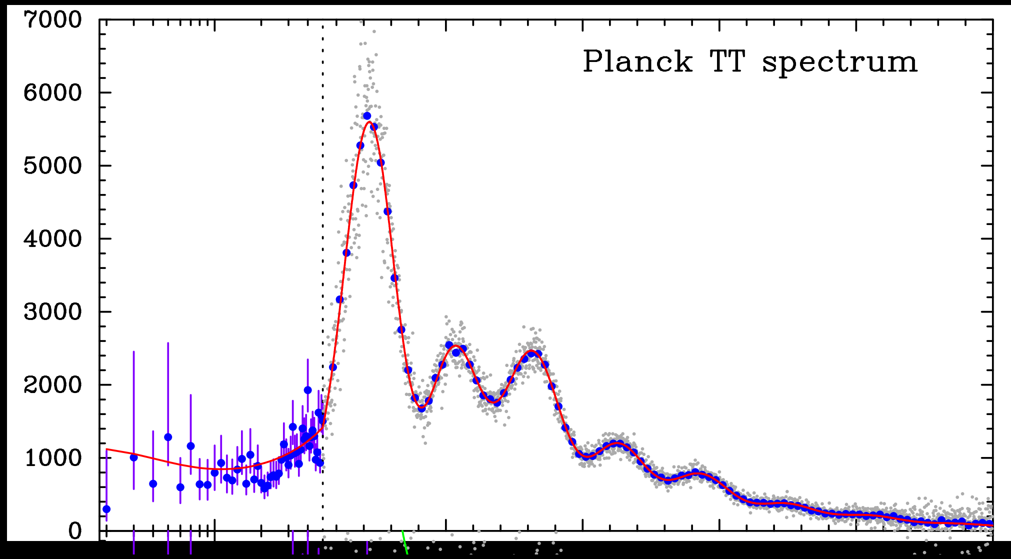
- at least five missing pieces in the SM:
  - dark matter
  - neutrino mass
  - dark energy
  - apparently acausal density fluctuations
  - baryon asymmetry

$0\nu\beta\beta$
gravitational wave

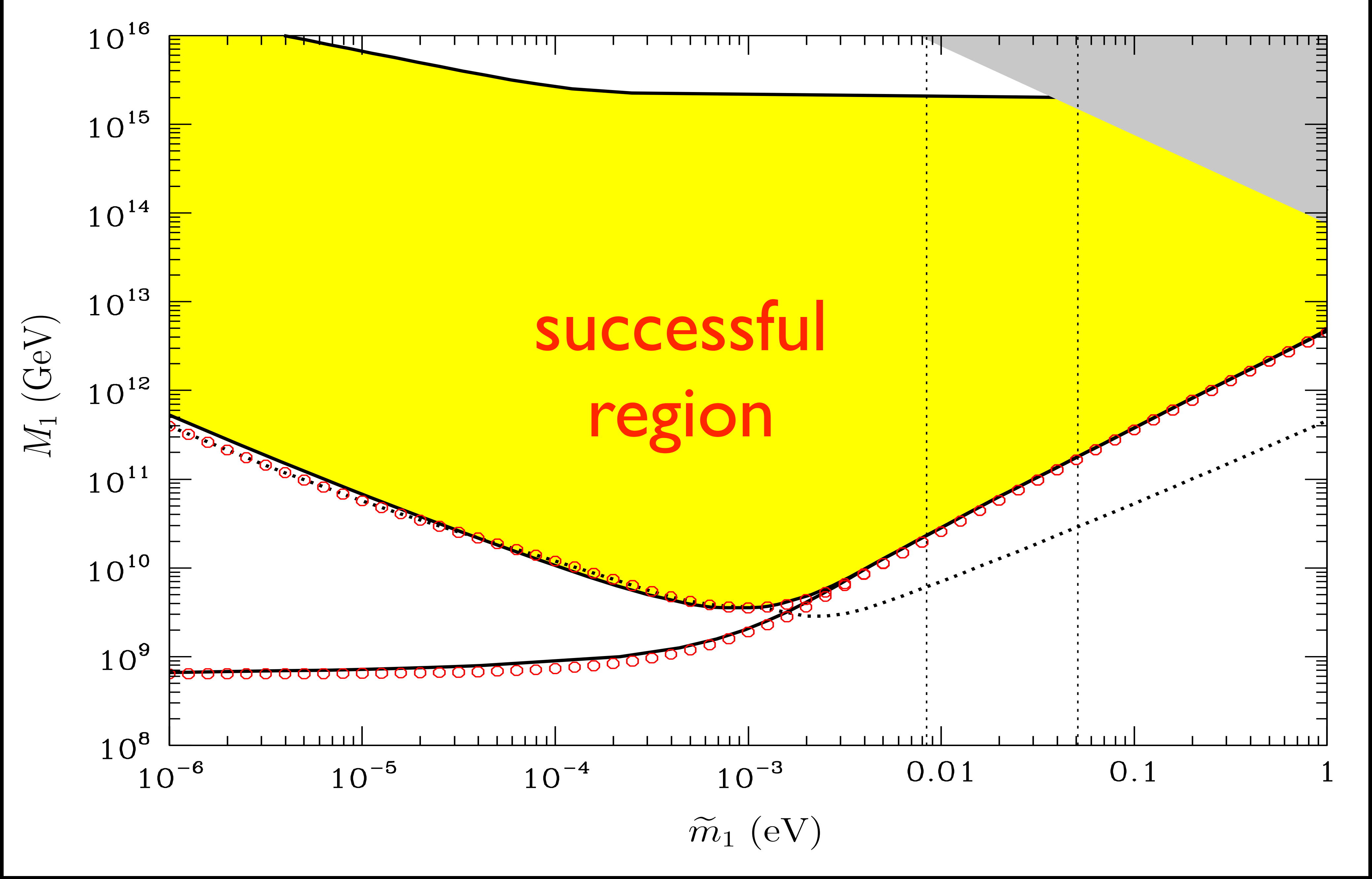
galaxy surveys
DESI, PFS, Euclid,
LSST, WFIRST

Simons Array
CMB S4
LiteBIRD

HyperK, DUNE
LHCb, Belle II



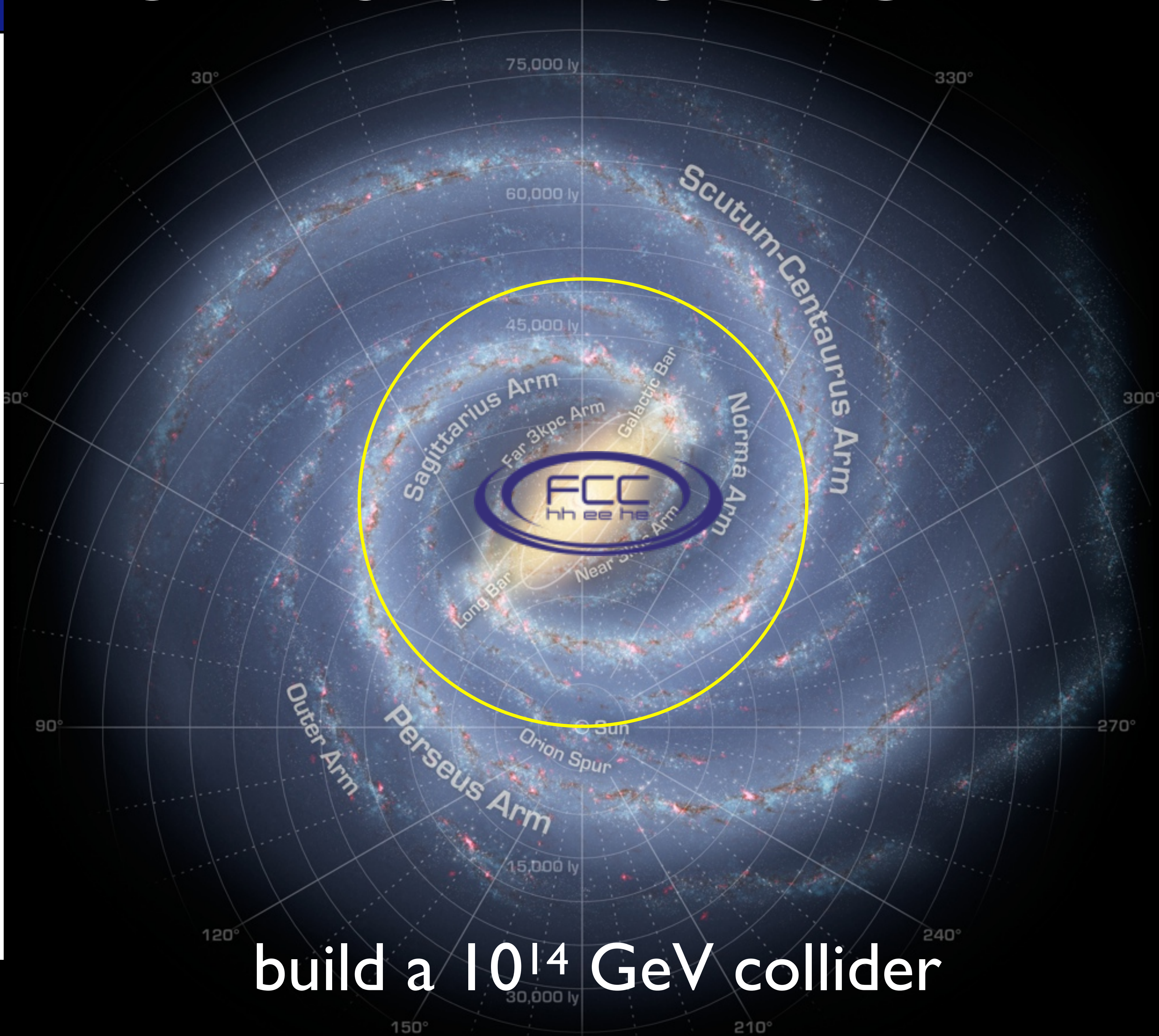
Leptogenesis



$$\tilde{m}_1 = \frac{(m_D^\dagger m_D)_{11}}{M_1}$$

di Bari, Plümacher, Buchmüller

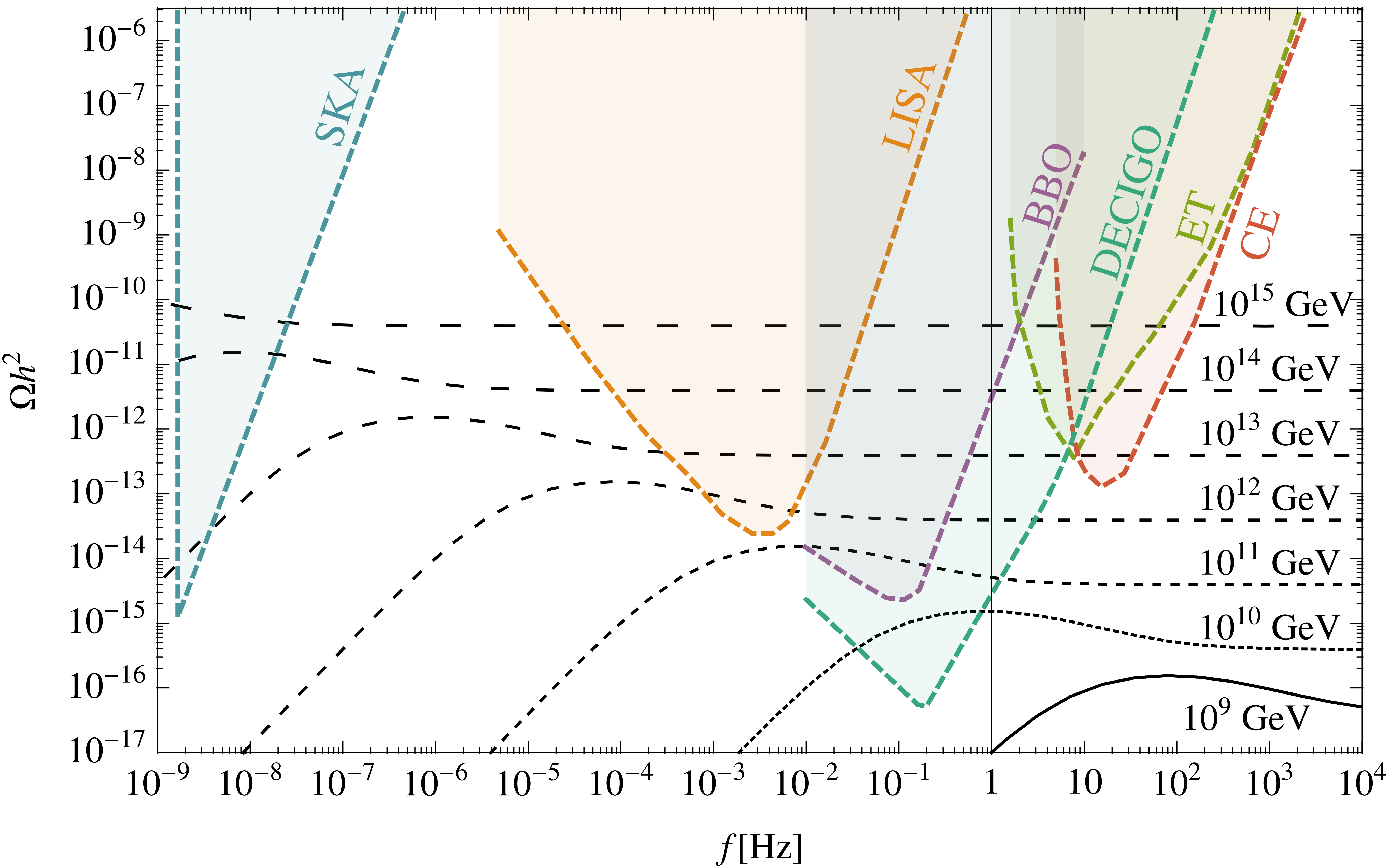
How do we test it?



build a 10^{14} GeV collider

how do we test it?

- possible three circumstantial evidences
  - $0\nu\beta\beta$
  - CP violation in neutrino oscillation
  - other impacts e.g. LFV (requires new particles/interactions < 100 TeV)
- *archeology*
- *any more circumstantial evidences?*



J. Dror, T. Hiramatsu, K. Kohri, HM, G. White, arXiv:1908.03227

covers pretty much the entire range for leptogenesis!

caveat: particle emission from cosmic strings

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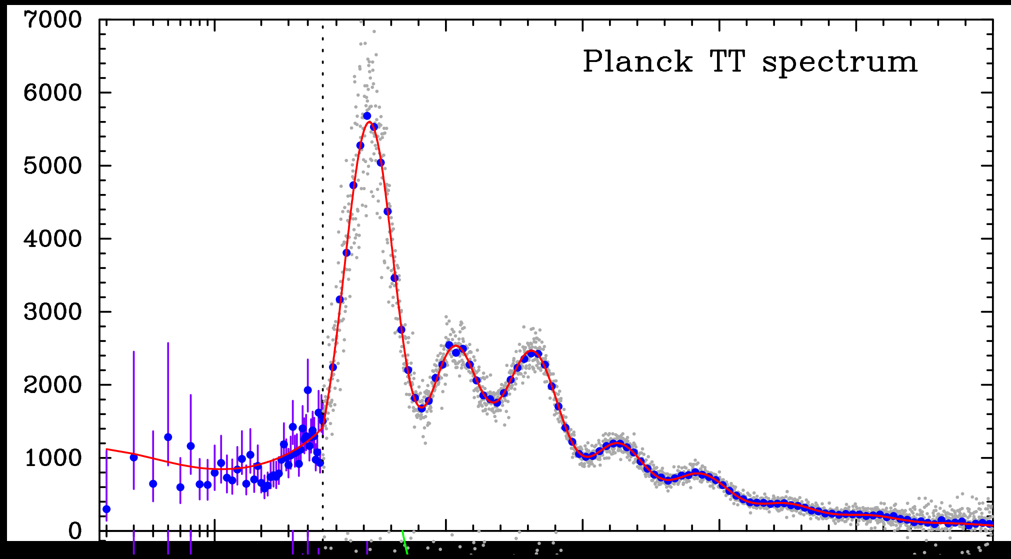
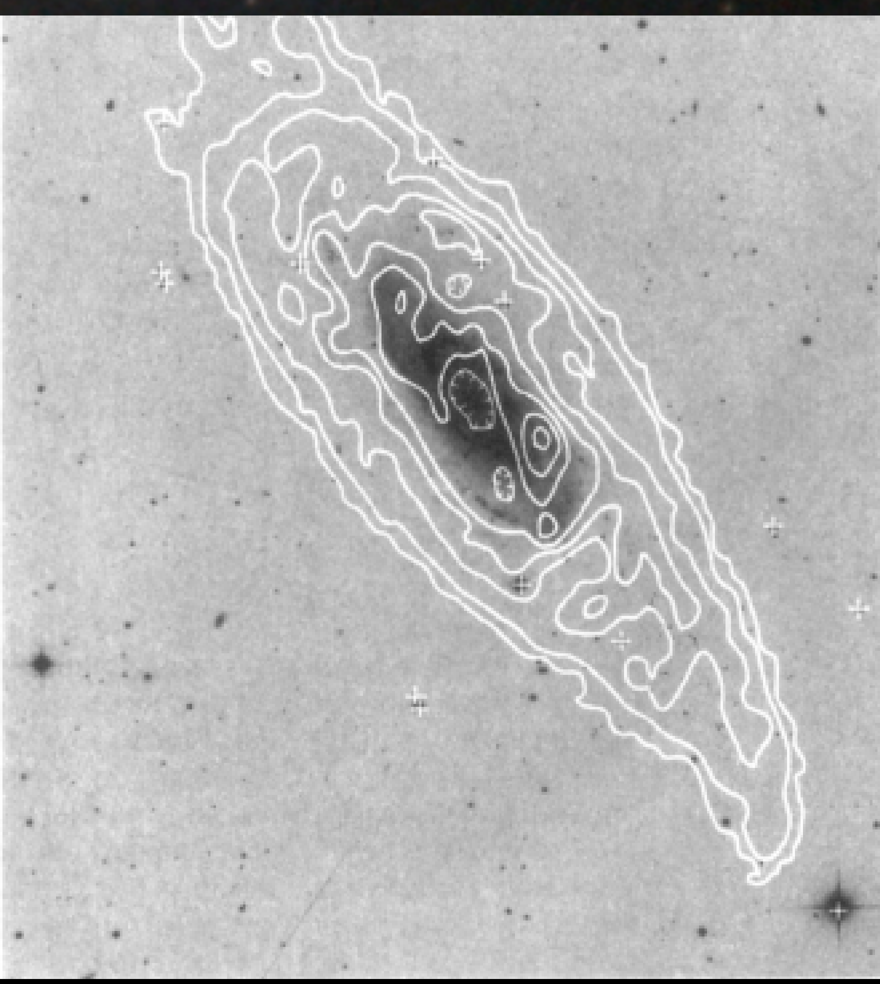
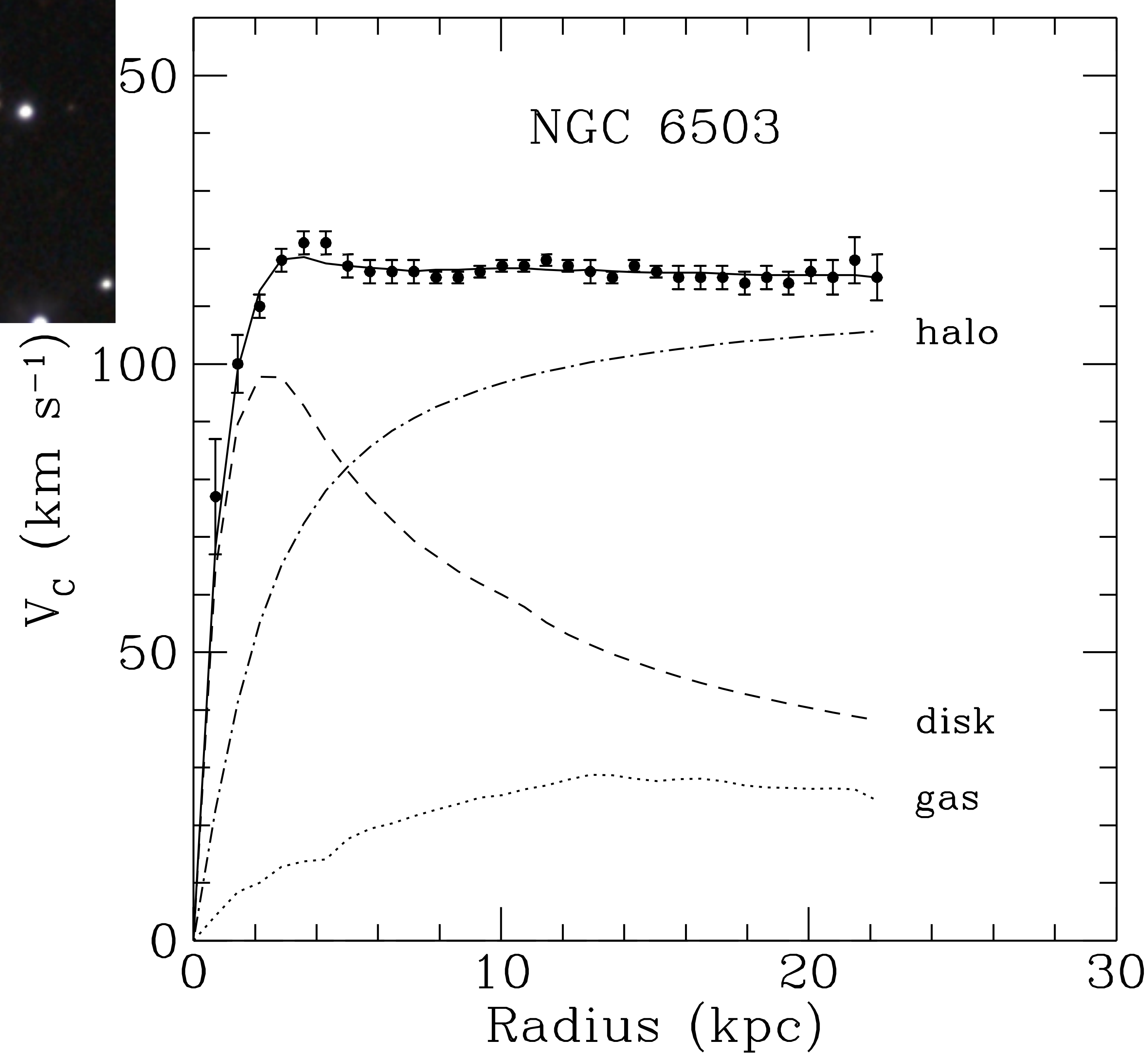
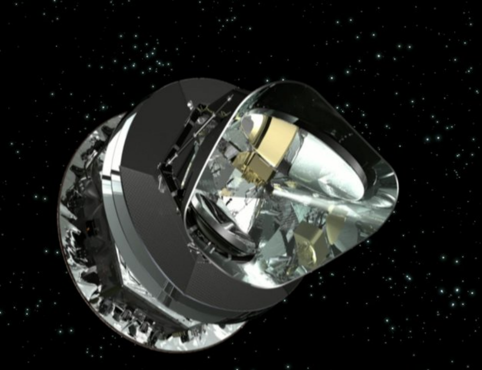


galactic rotation curves



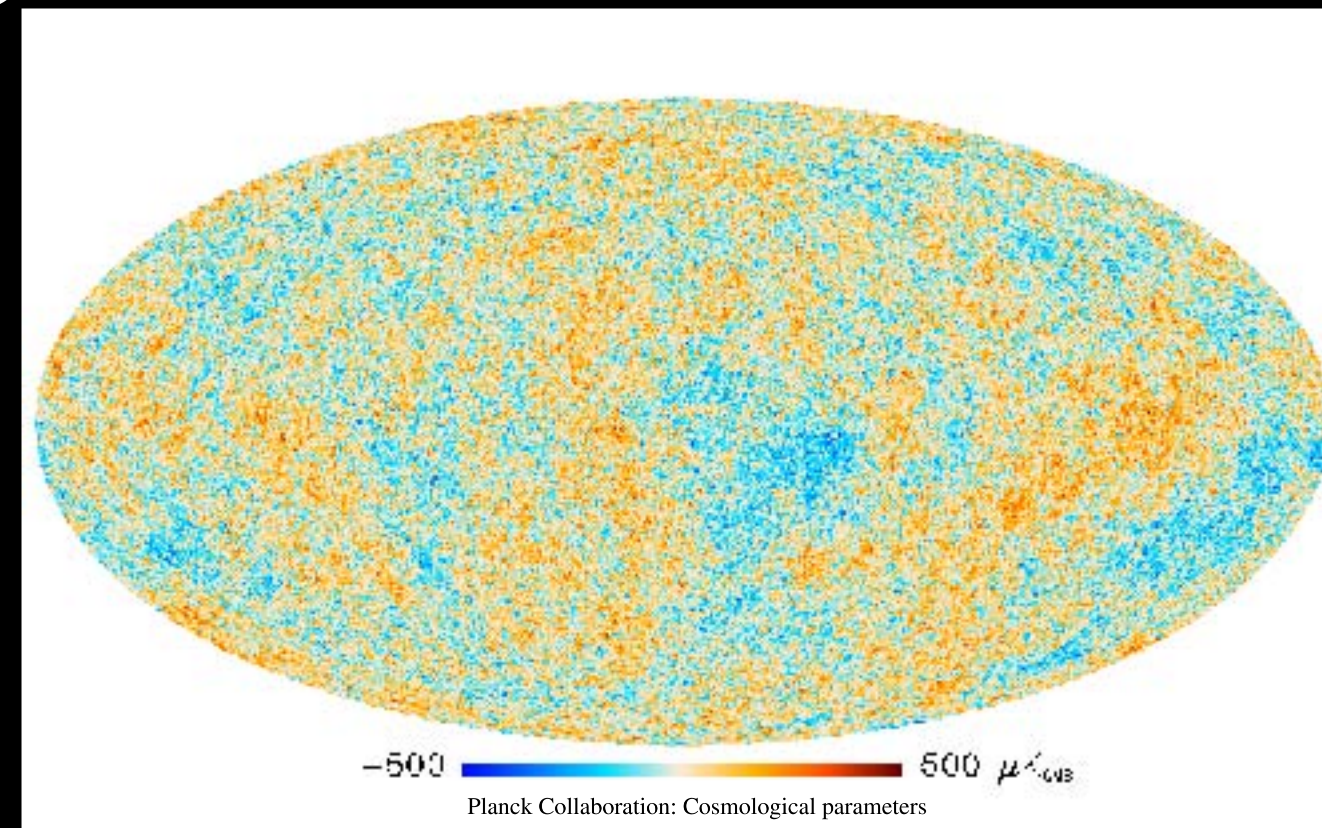


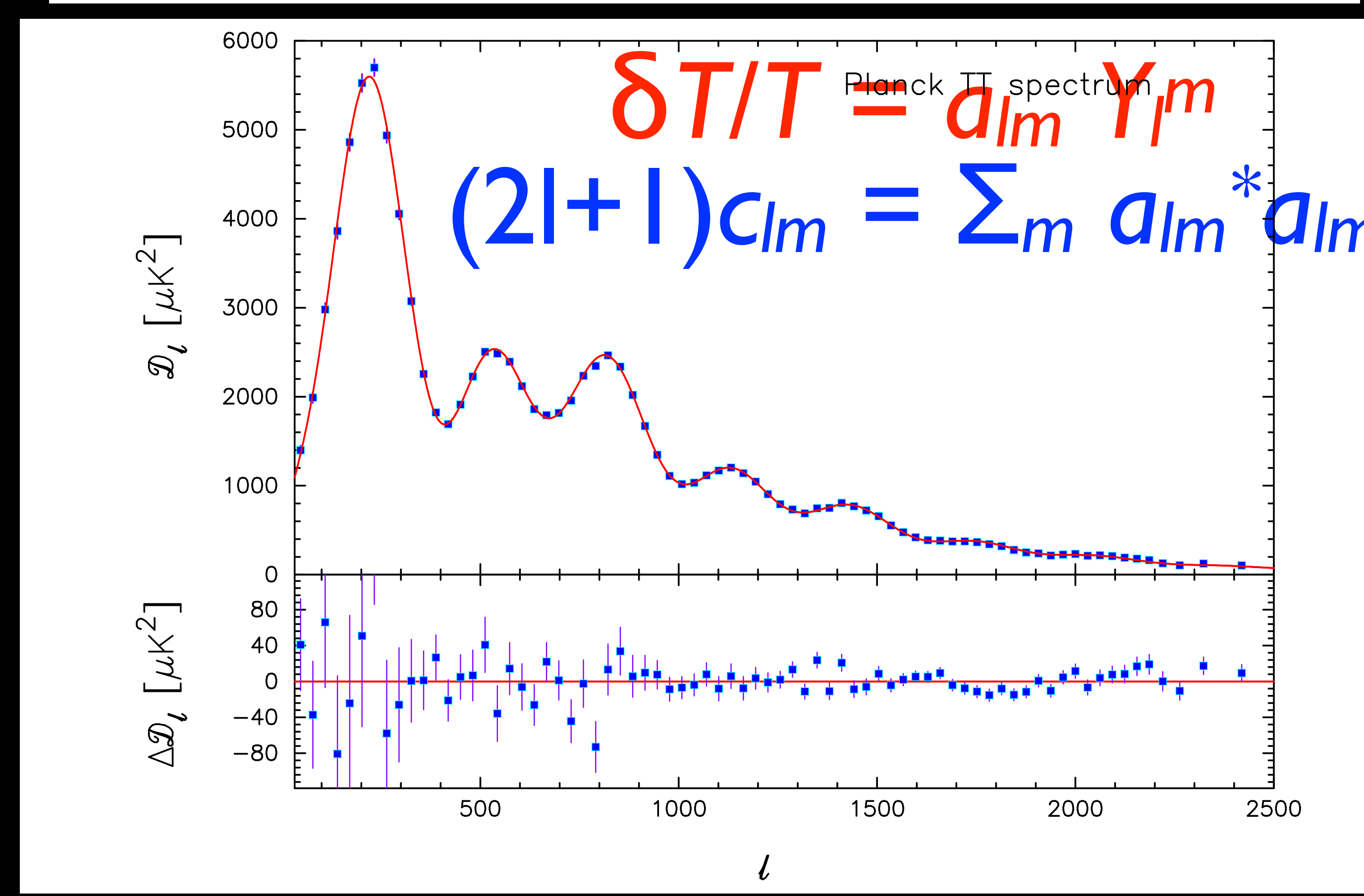

cluster of galaxies
Abell 2218
2.1B lyrs

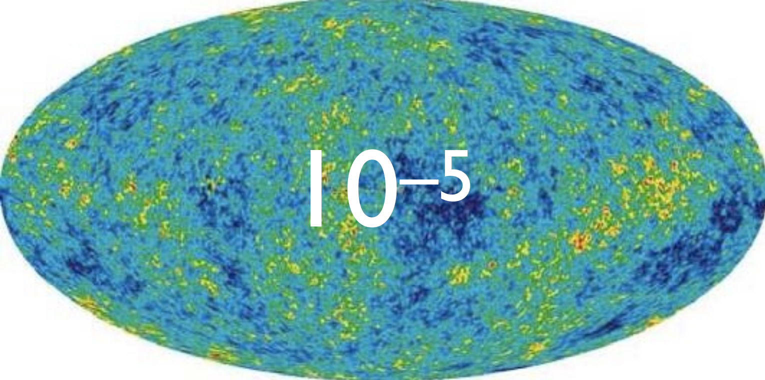


cosmological scales

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

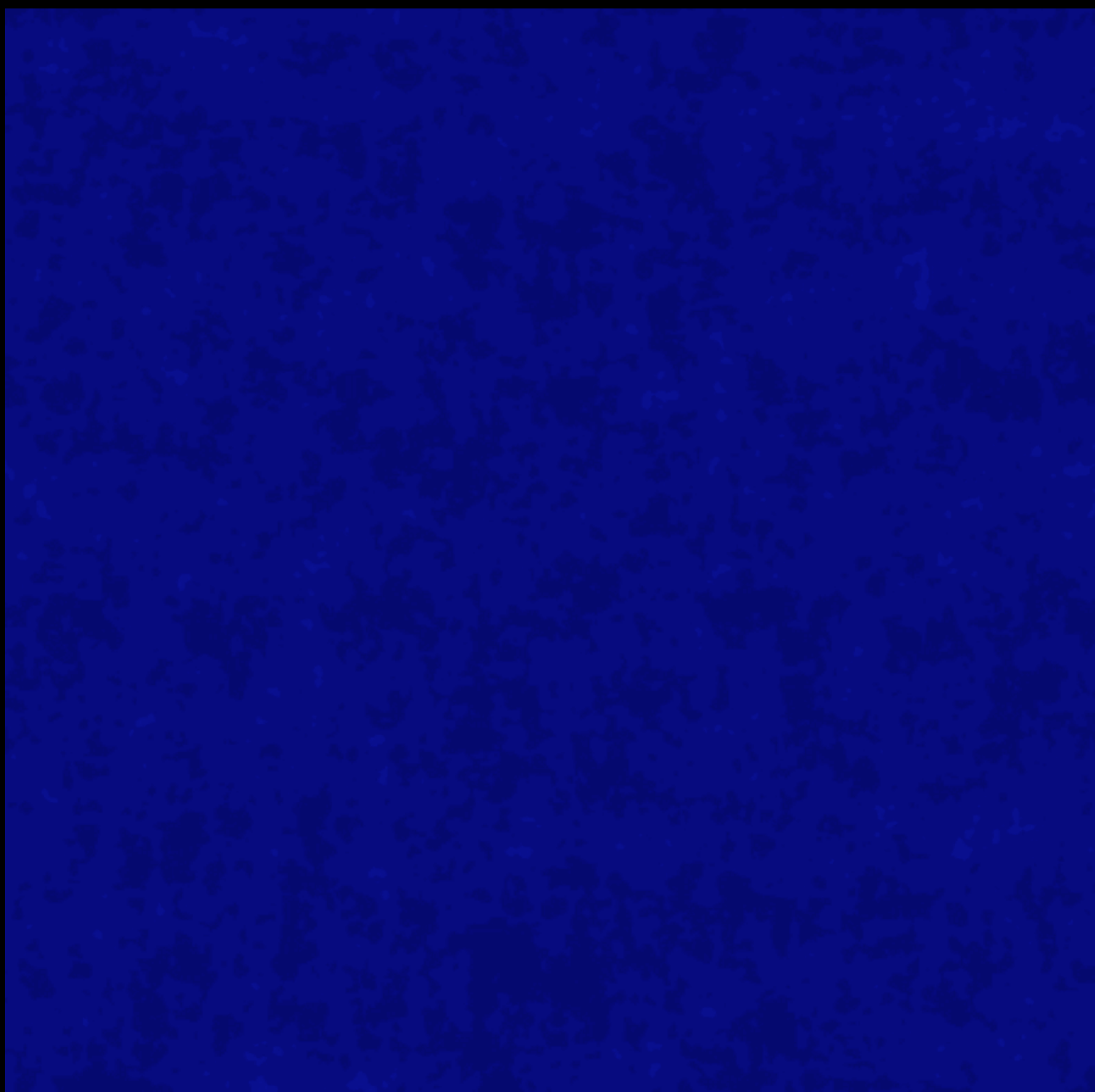




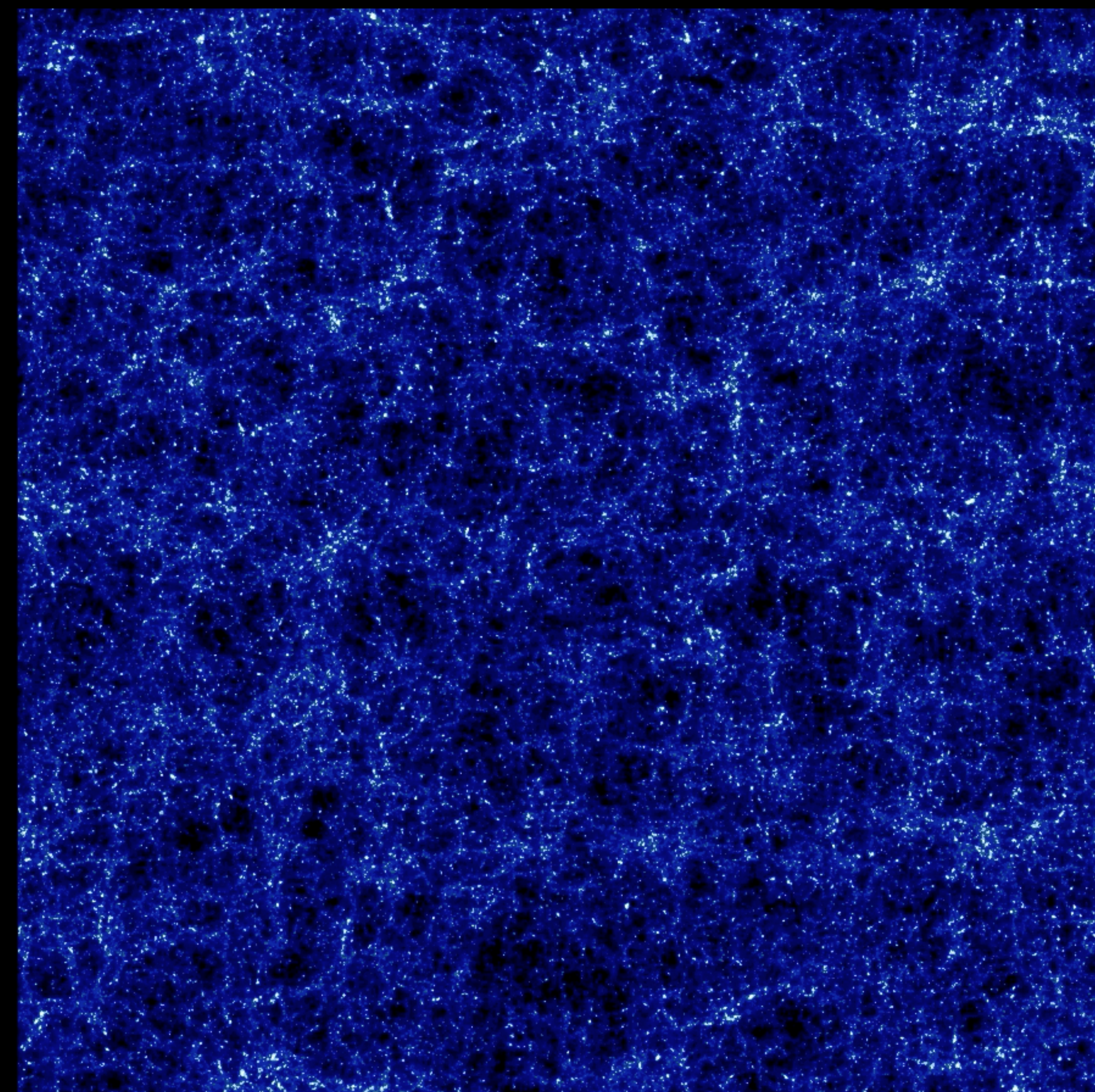


Dark Matter is our Mom

Naoki Yoshida



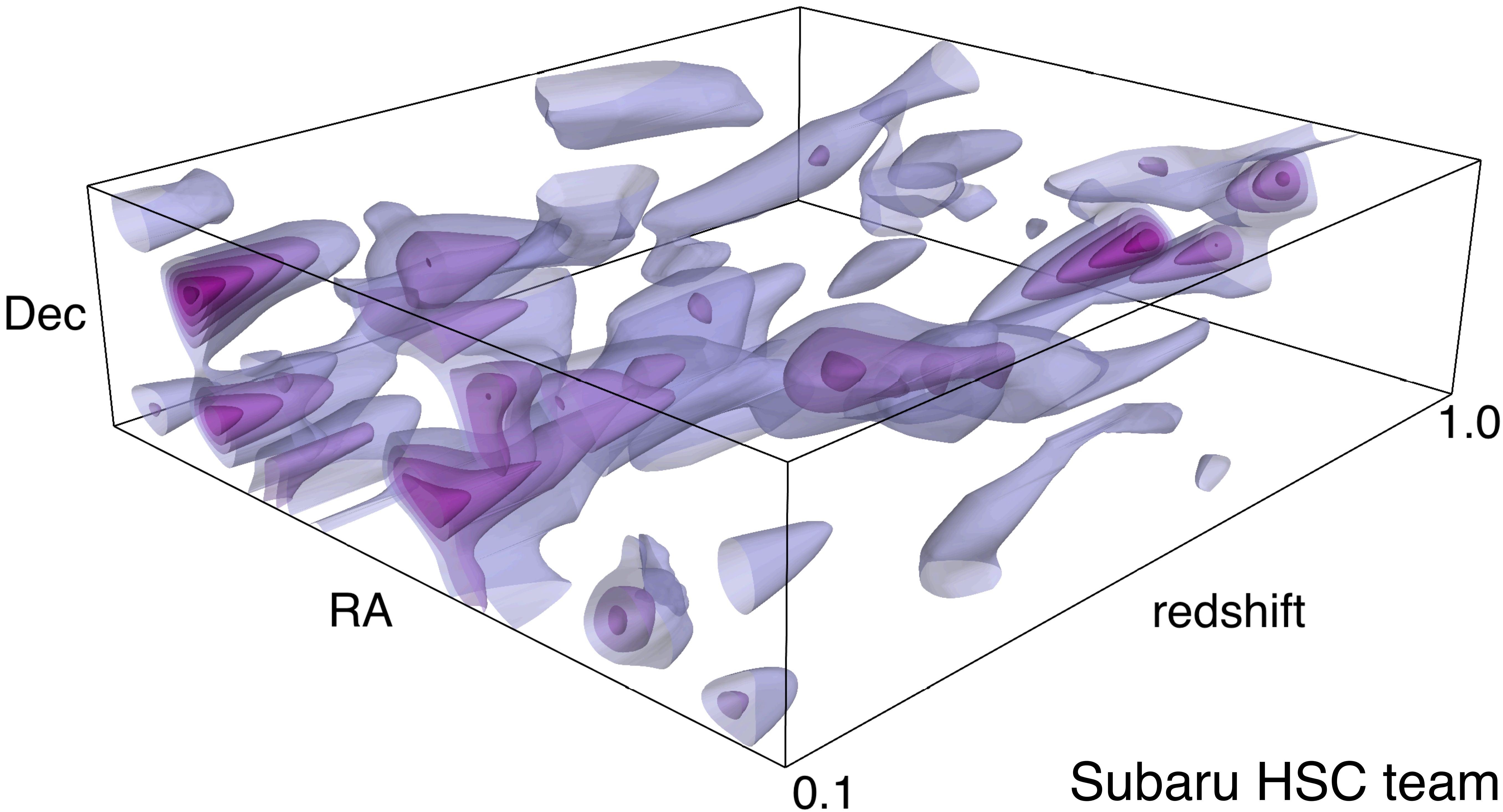
without dark matter



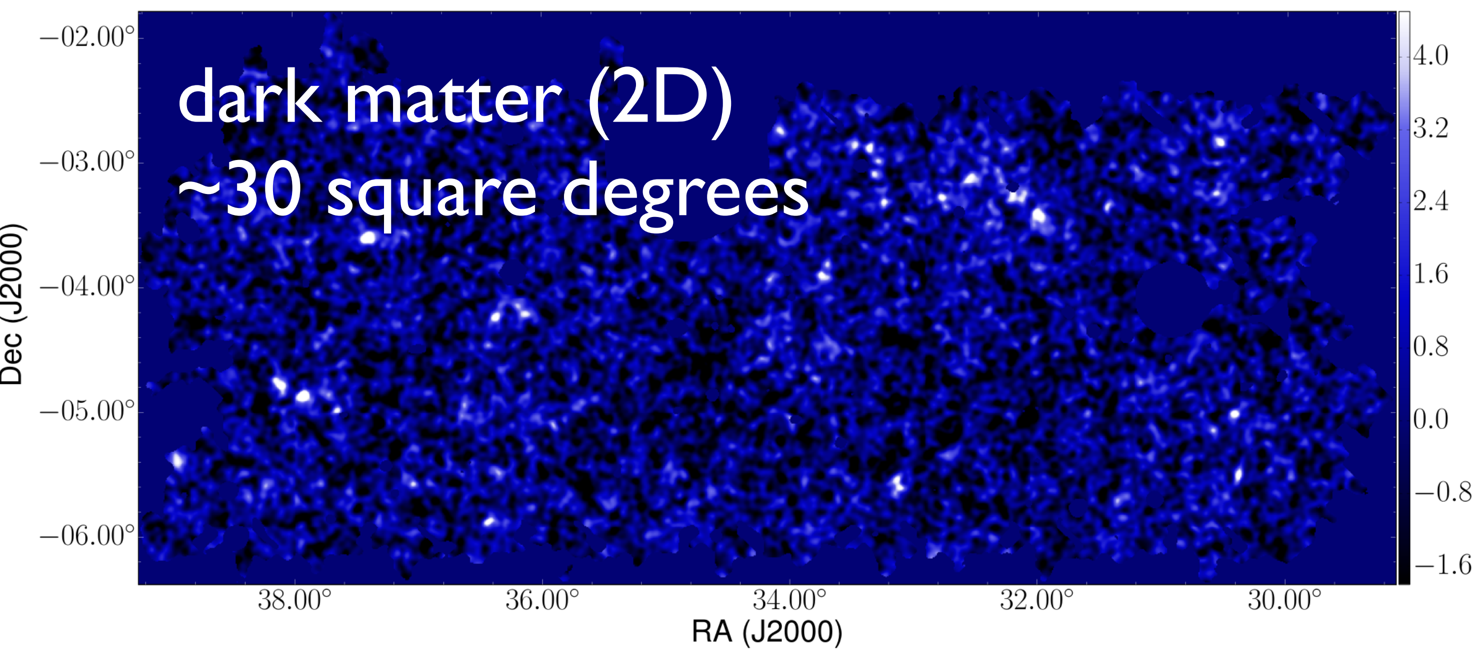
with dark matter

Reenacting the Big Bang with Cal Marching Band

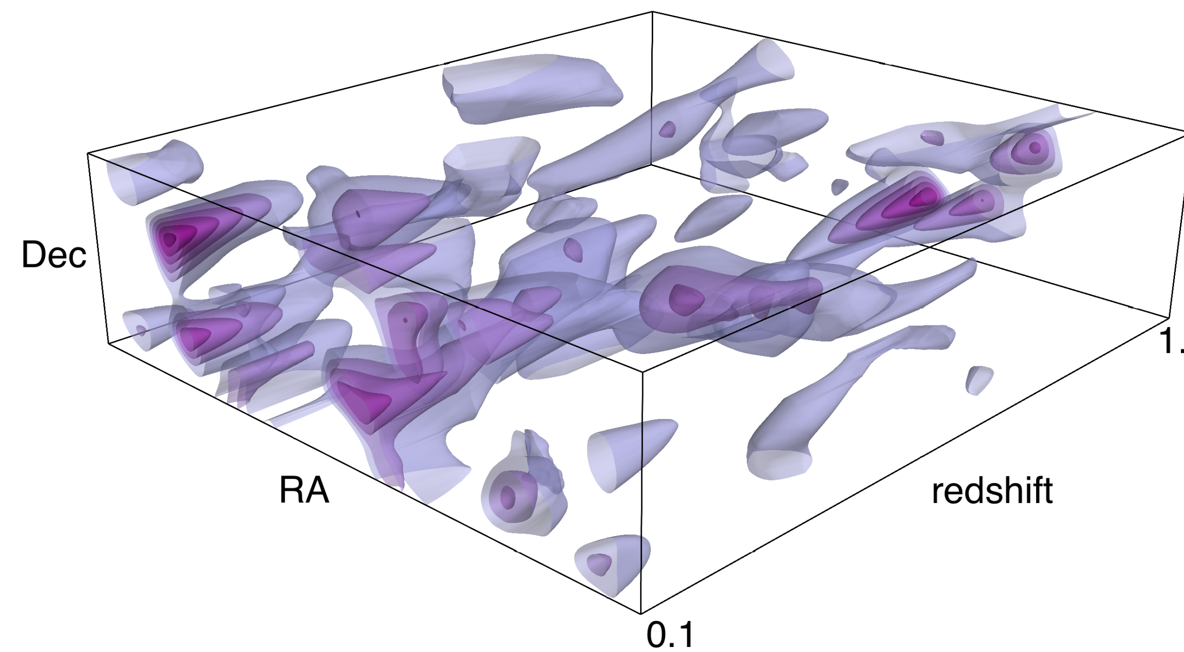
World's largest 3D map of dark matter

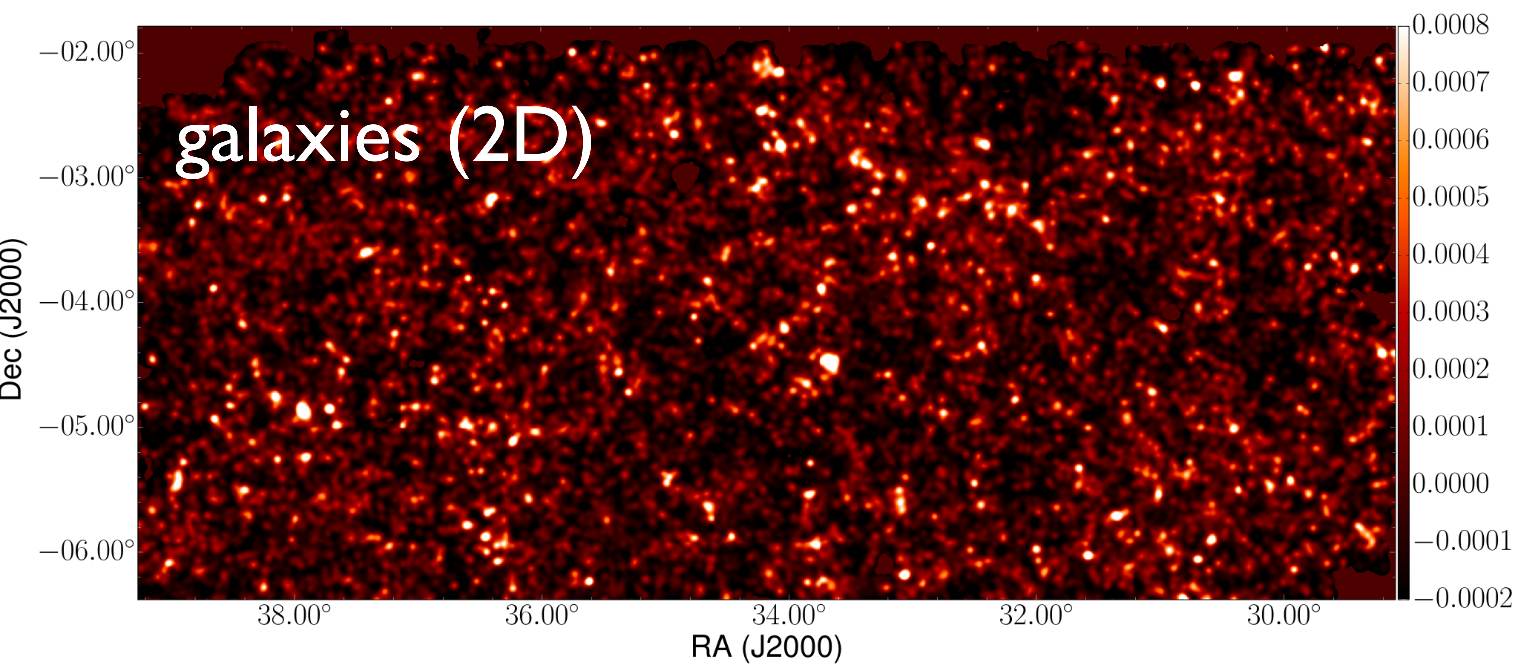


dark matter made us

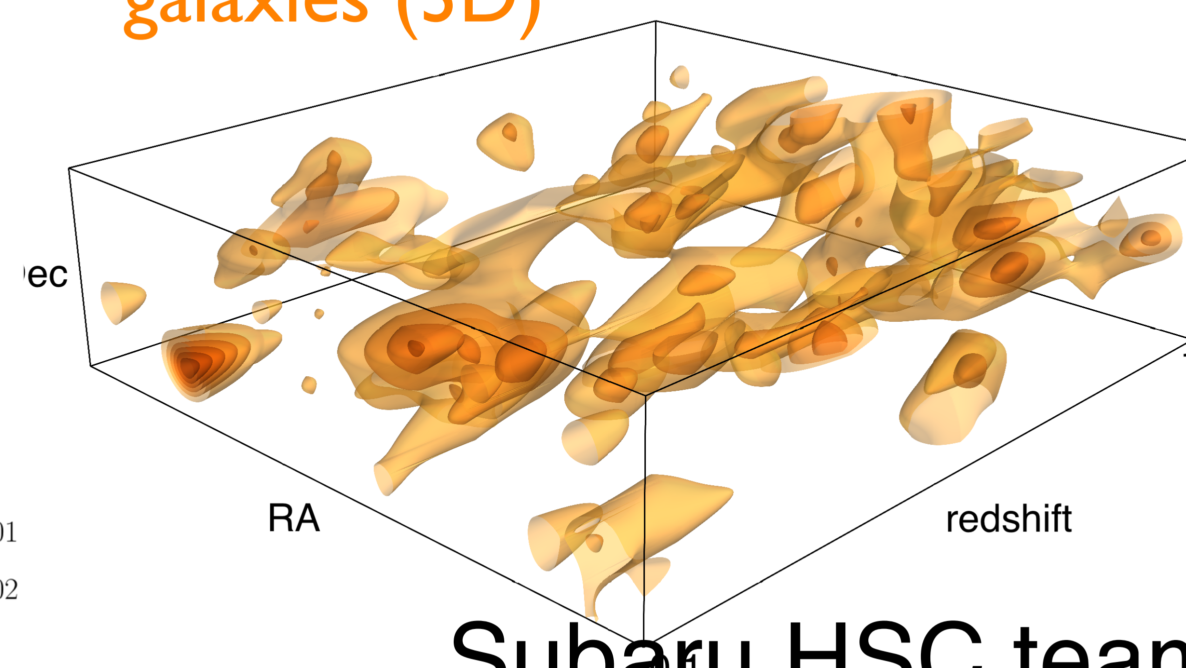


dark matter (3D)





galaxies (3D)



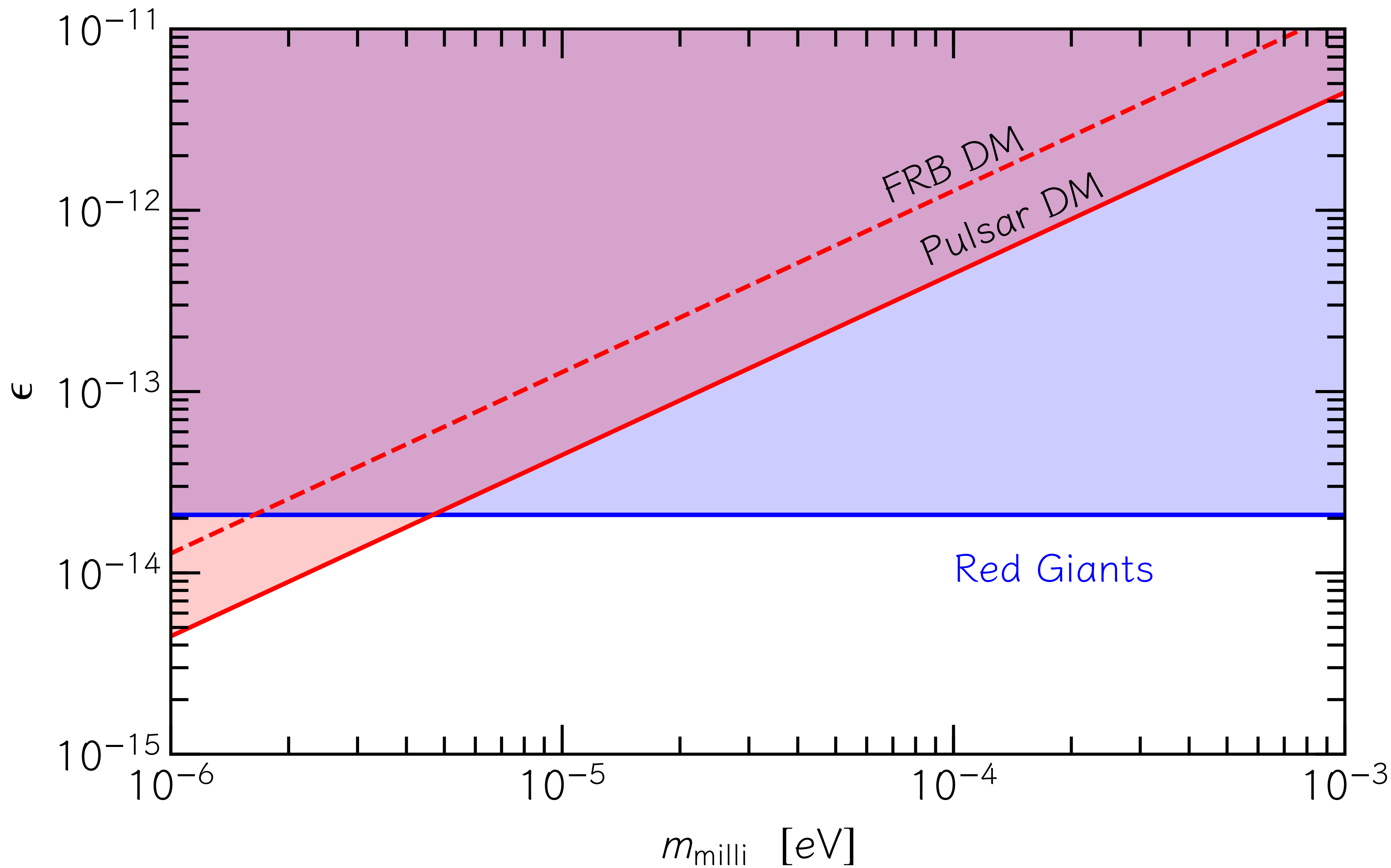
Subaru HSC team

What do we know?

- basic properties of a particle:
  - mass
  - quantum number
  - spin
  - lifetime
  - interaction

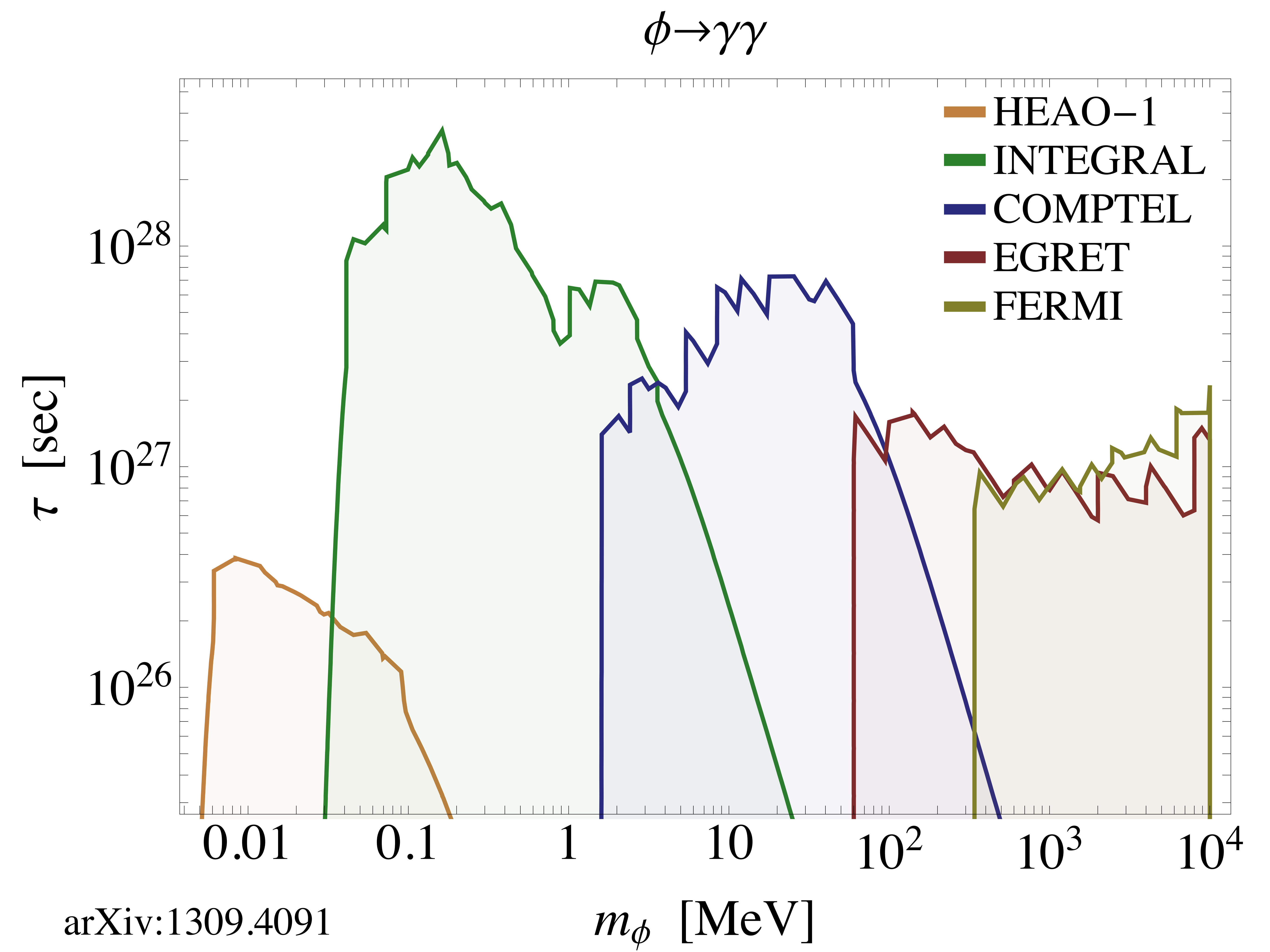
Cold and Neutral

- it must be moving slowly (cold)
- it must be electrically neutral
  - people discuss milli-charged dark matter
- it must be long-lived (at least 13.8Byrs)
  - stronger limit if decay products visible



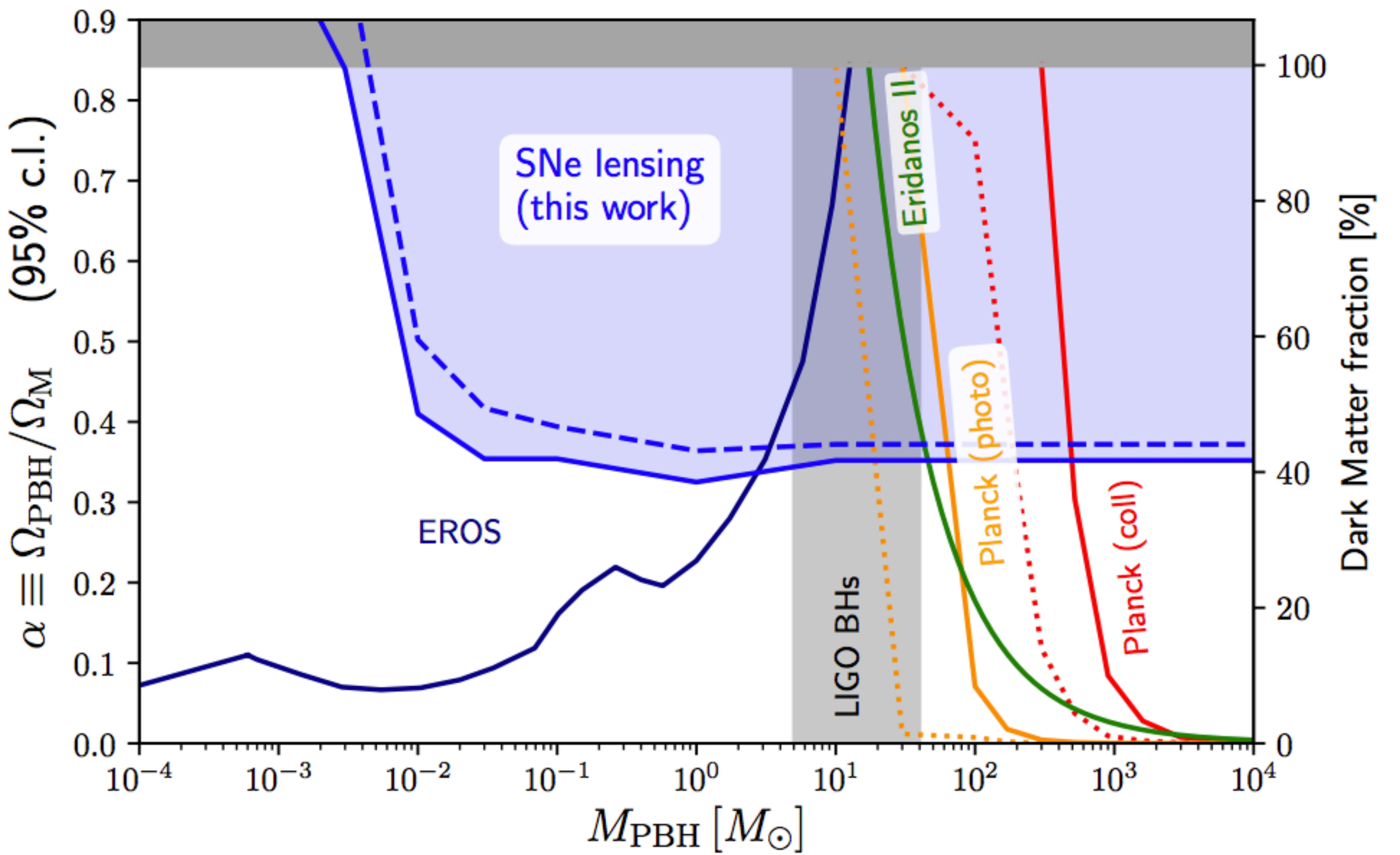
arXiv:1902.02695

FIG. 1. *Constraint on millicharged DMa in the* $\epsilon - m_{\rm milli}$ *space from pulsar (solid red line) and FRB 121102 (dashed red line) DM at 95% confidence level. Solid blue line indicates the bound from Red Giants [15]. We assume a homogeneous DMa density* $\rho_{\rm dm} = \rho_{\rm milli} \approx 0.3\,{\rm GeV/cm^3}$. *The bound scales as* $\rho_{\rm milli}^{-1/2}$ *for fractional components.*



$\phi \to \gamma\gamma$
HEAO−1
INTEGRAL
COMPTEL
EGRET
FERMI
10^{28}
10^{27}
10^{26}
τ [sec]
0.01
0.1
1
10
10^2
10^3
10^4
m_ϕ [MeV]
arXiv:1309.4091

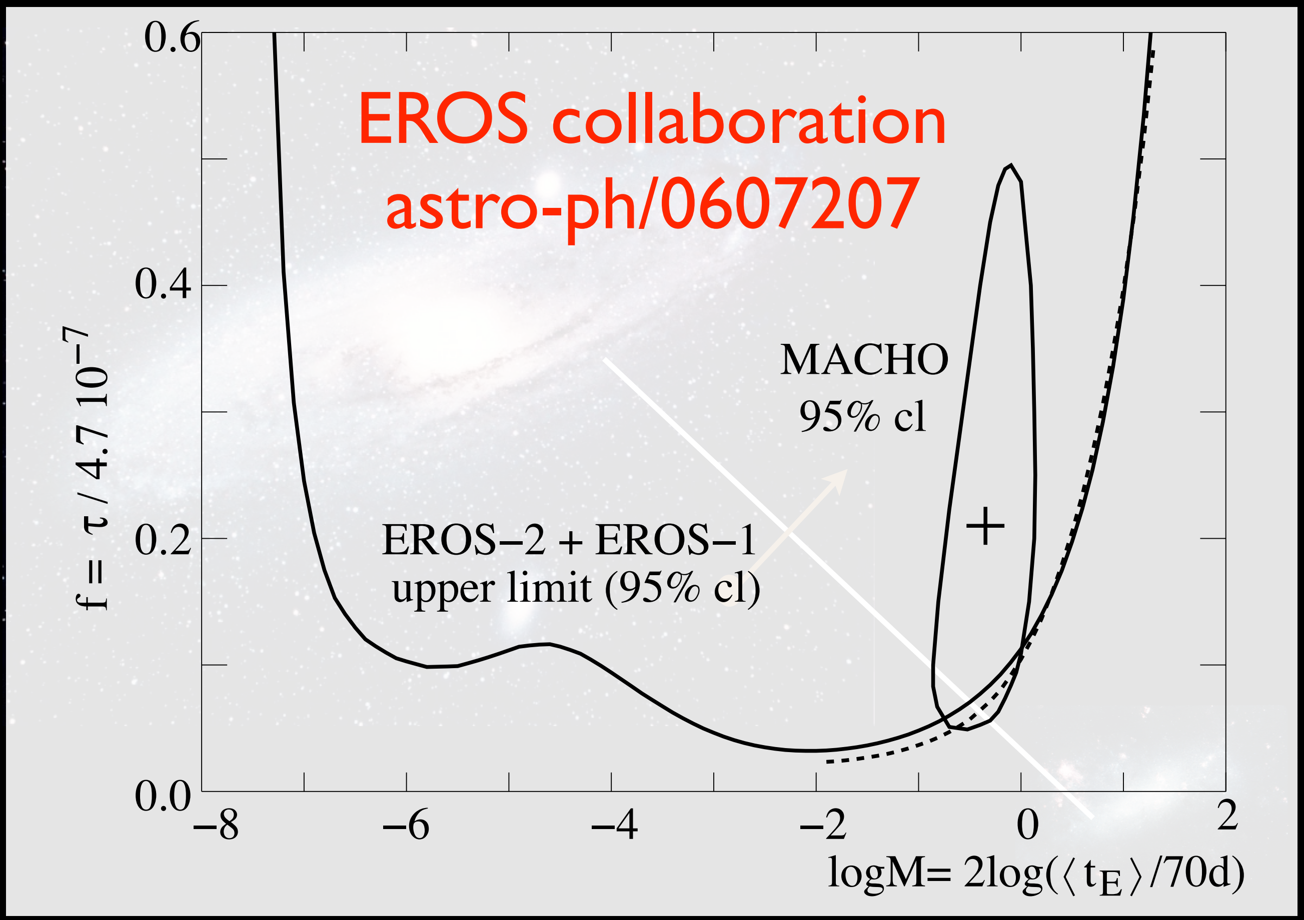
Current bounds on MACHOs

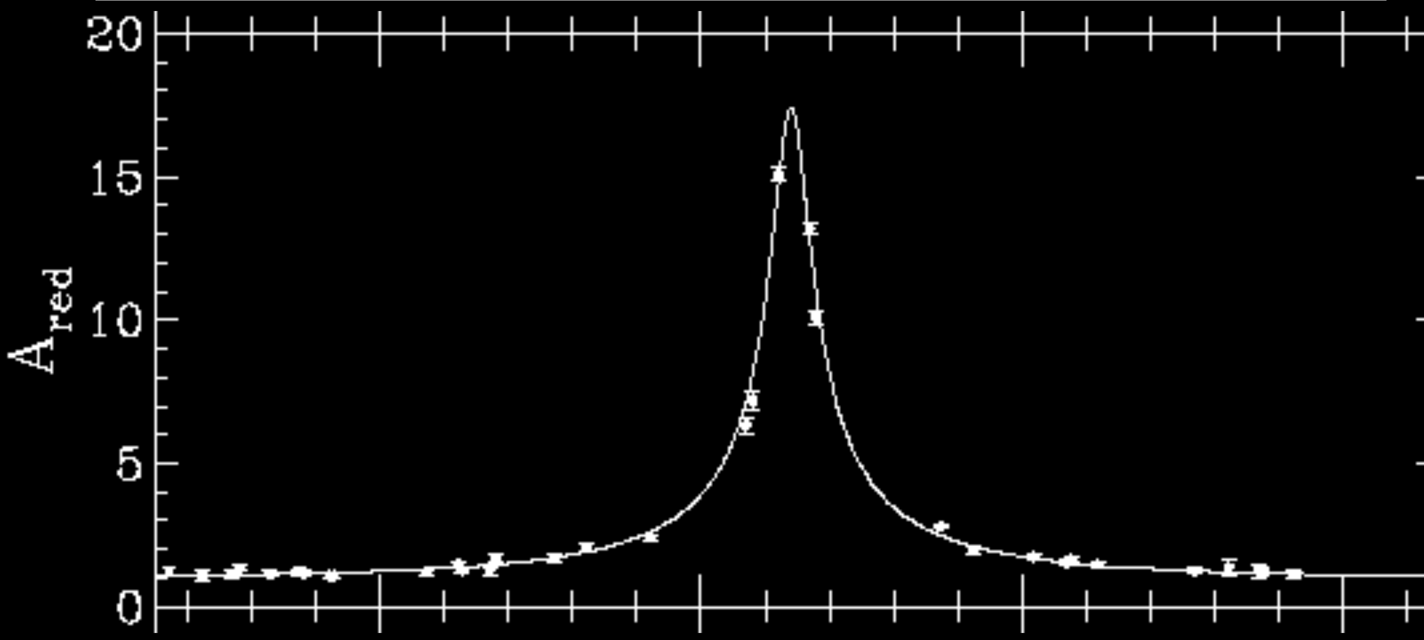


Zumalacarregui, Seljak (2018)

Dim Stars?

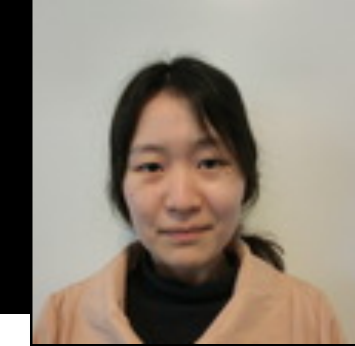
Search for MACHOs
(Massive Compact Halo Objects)





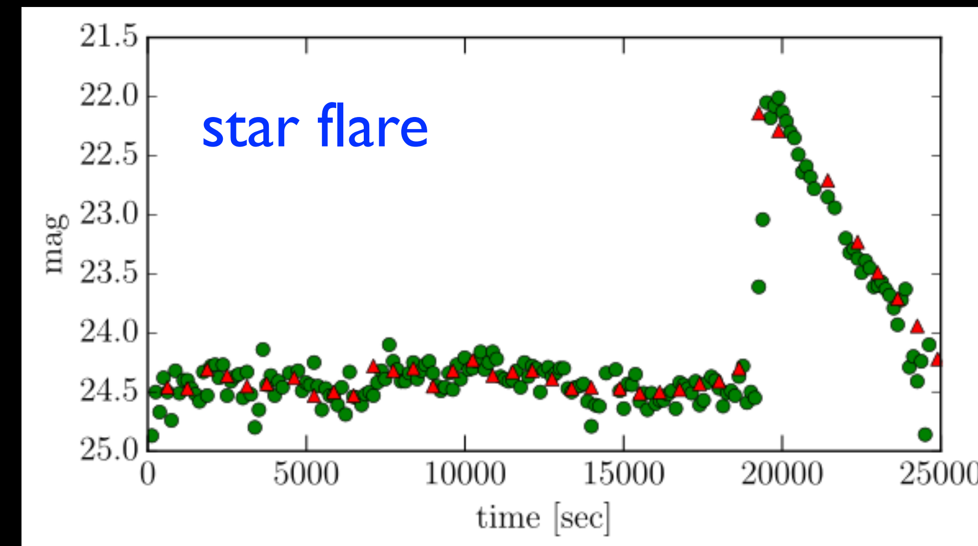
Not enough of them!

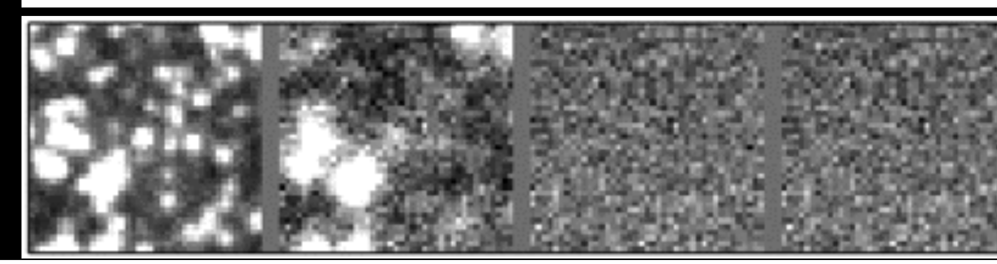
Best limit on Black Hole dark matter



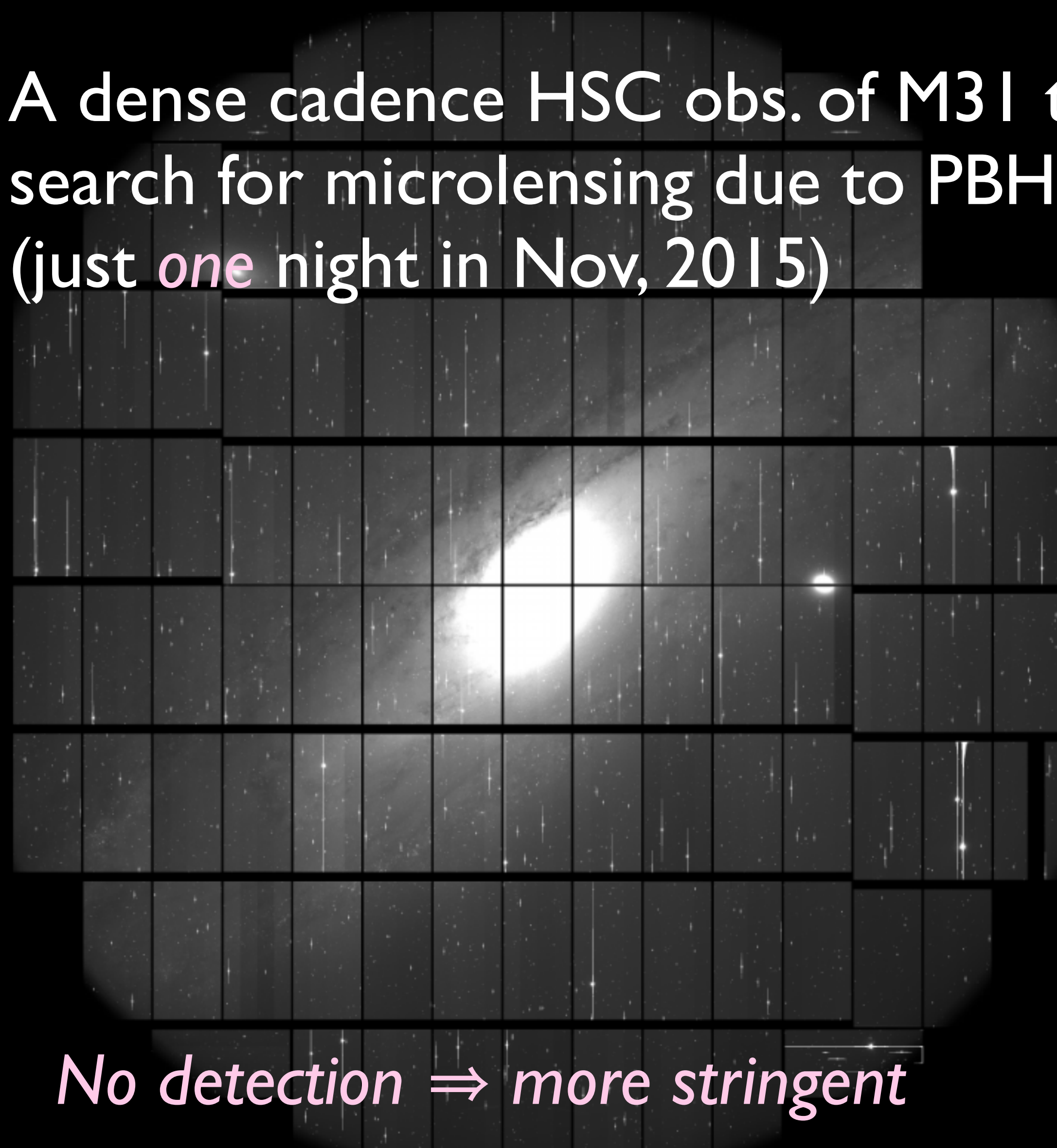
Niikura, Takada et al., *Nature Astronomy*

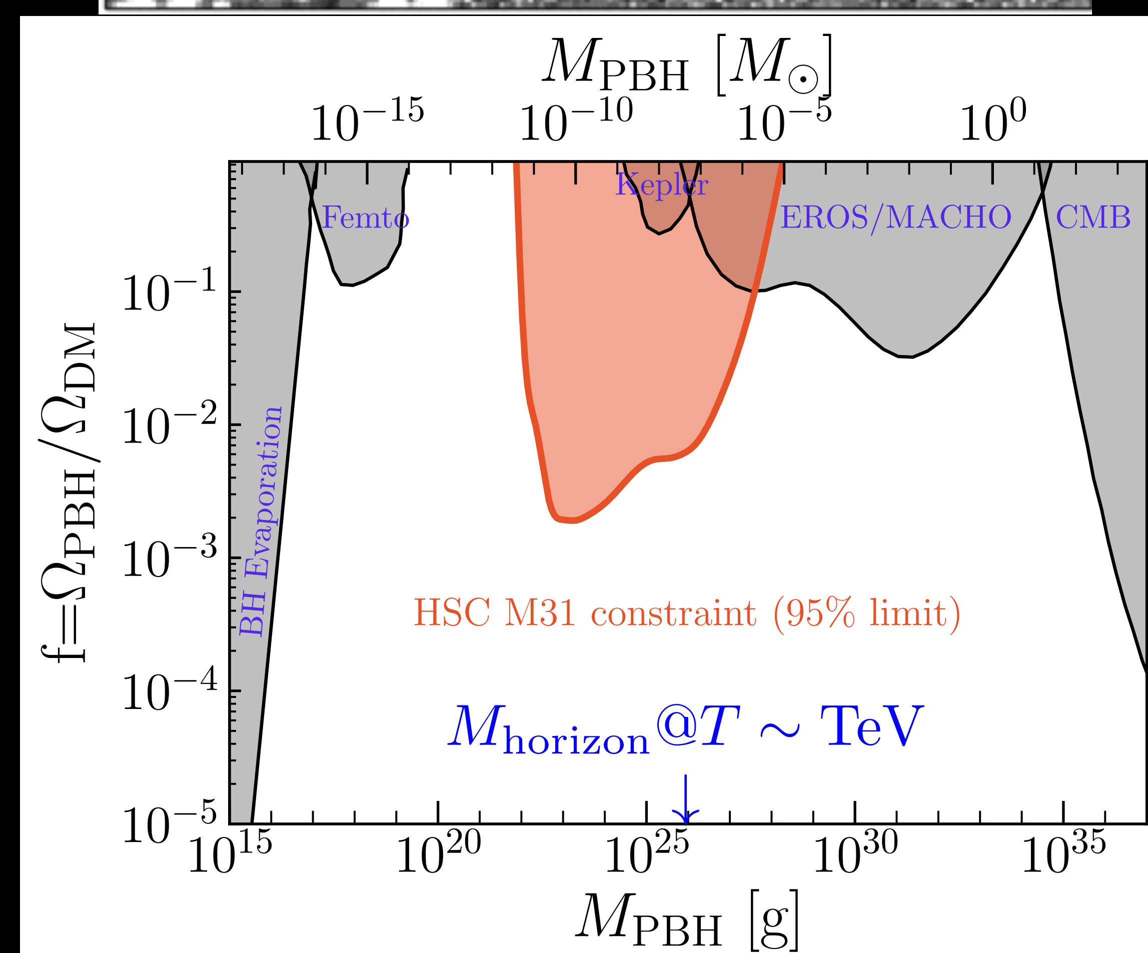
Found many variable stars





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





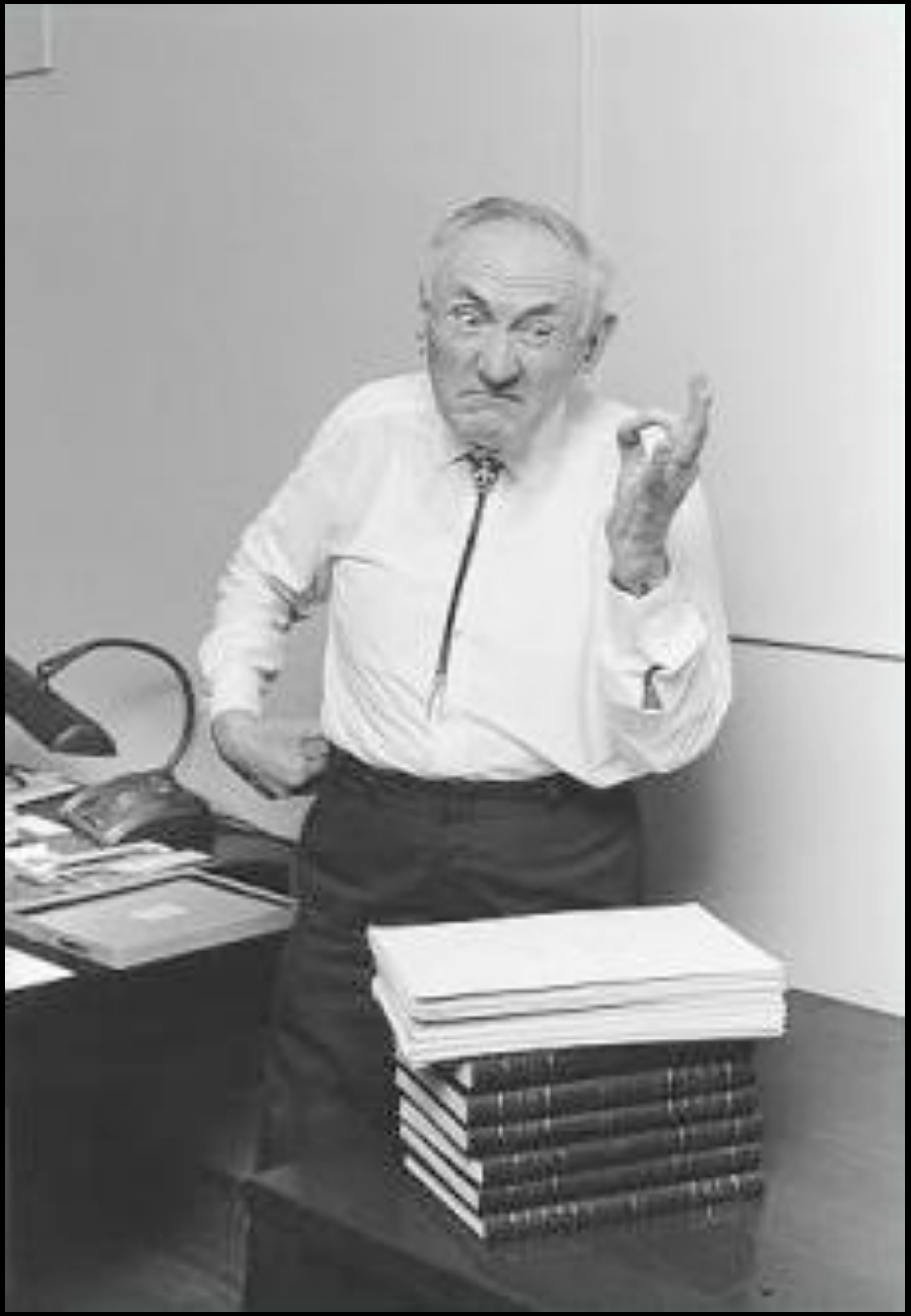
No detection ⇒ more stringent upper bound, than 2yr Kepler data (Griest et al.)

Mass Limits
"Uncertainty Principle"

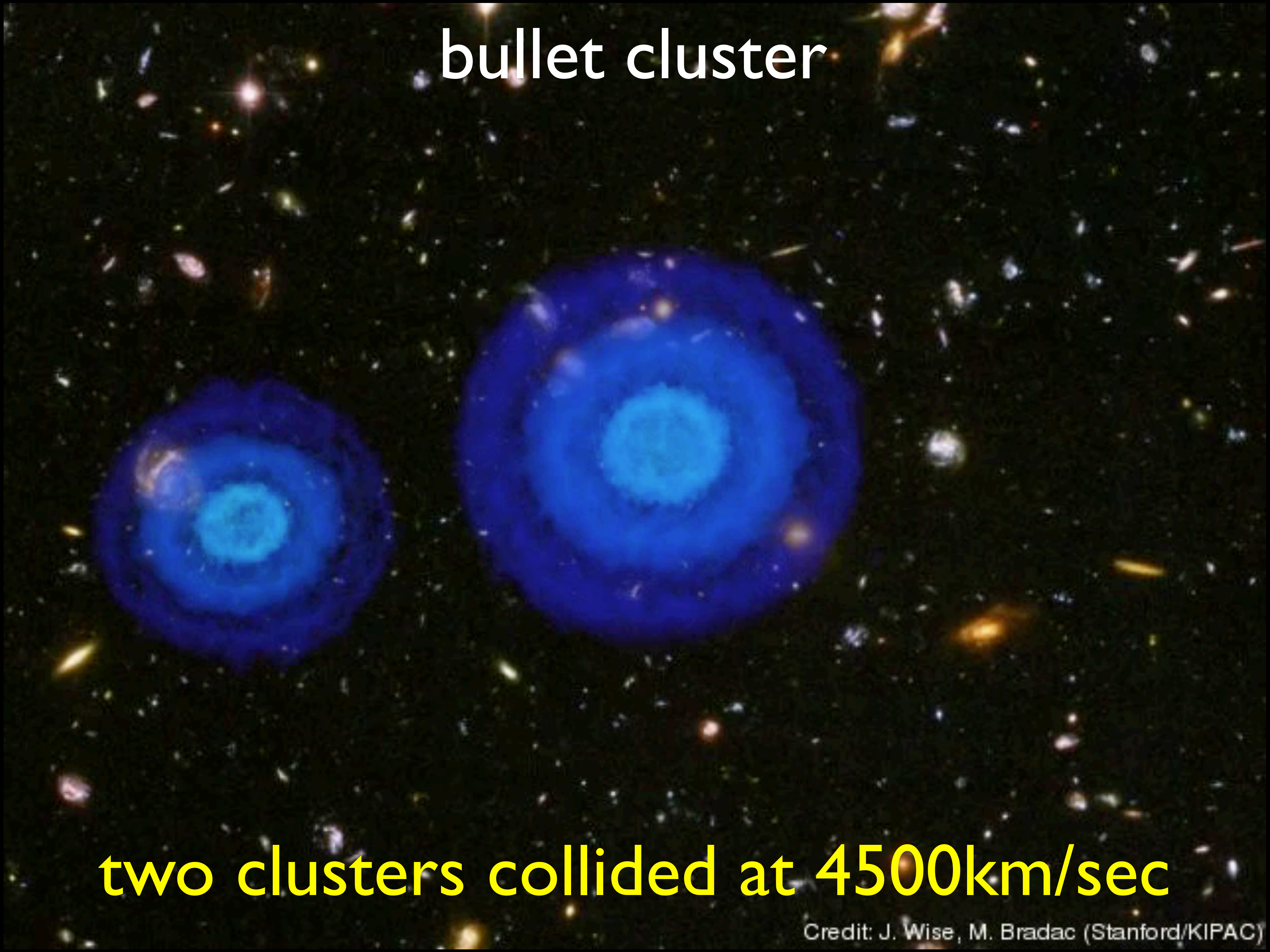
- Clumps to form structure
- imagine $V = G_N \frac{Mm}{r}$
- "Bohr radius": $r_B = \frac{\hbar^2}{G_N M m^2}$
- too small m ⇒ won't "fit" in a galaxy!
- m >10^{-22} eV "uncertainty principle" bound
  (modified from Hu, Barkana, Gruzinov, astro-ph/0003365)

Summary
Mass Limits

- 10^{-31} GeV to 10^{46} GeV
- narrowed it down to within 77 orders of magnitude
- a *big progress* in 70 years since Zwicky



Good not to be here



4B lyrs away

Self-Coupl

- if self-coupling too big, will "smooth out" cuspy profile at the galactic center
- some people want it

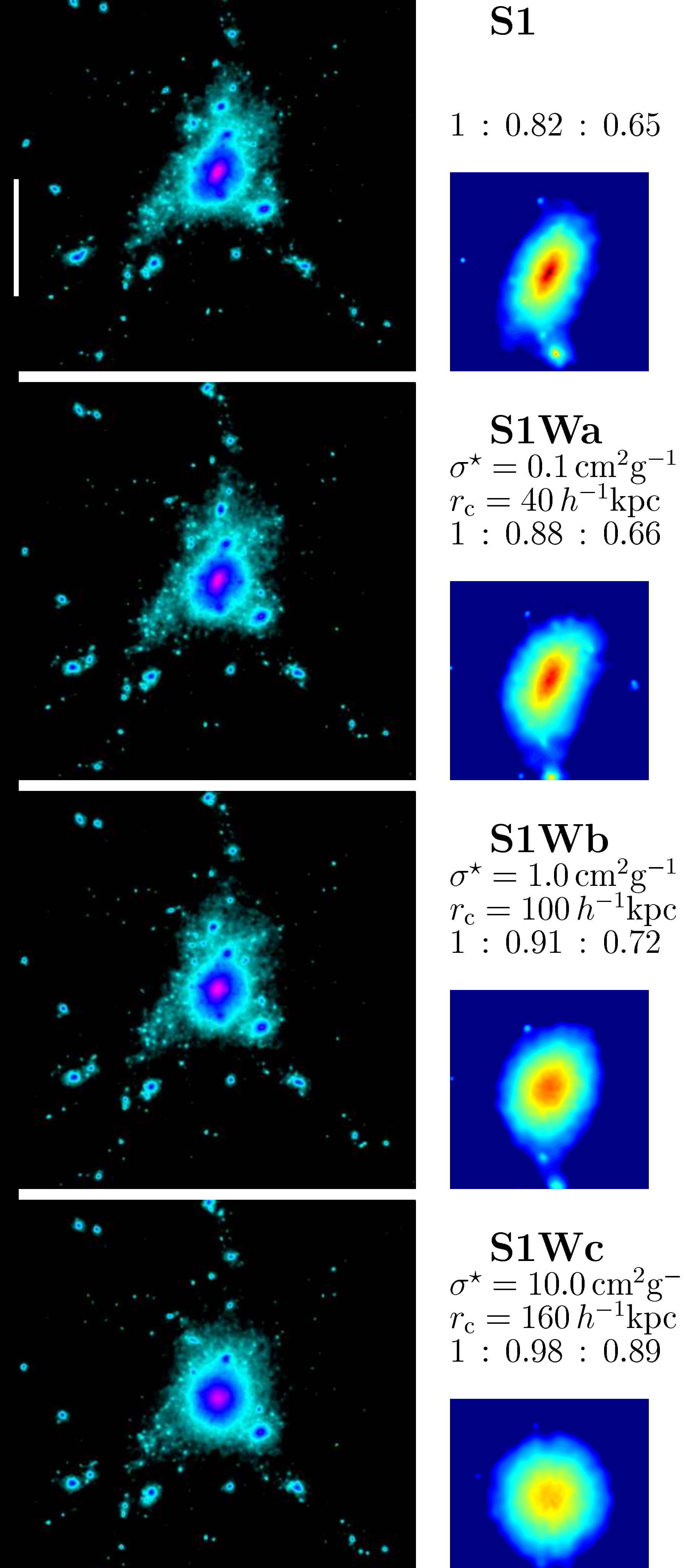
  (Spergel and Steinhardt, astro-ph/9909386)
- need core < 35 kpc/h from data

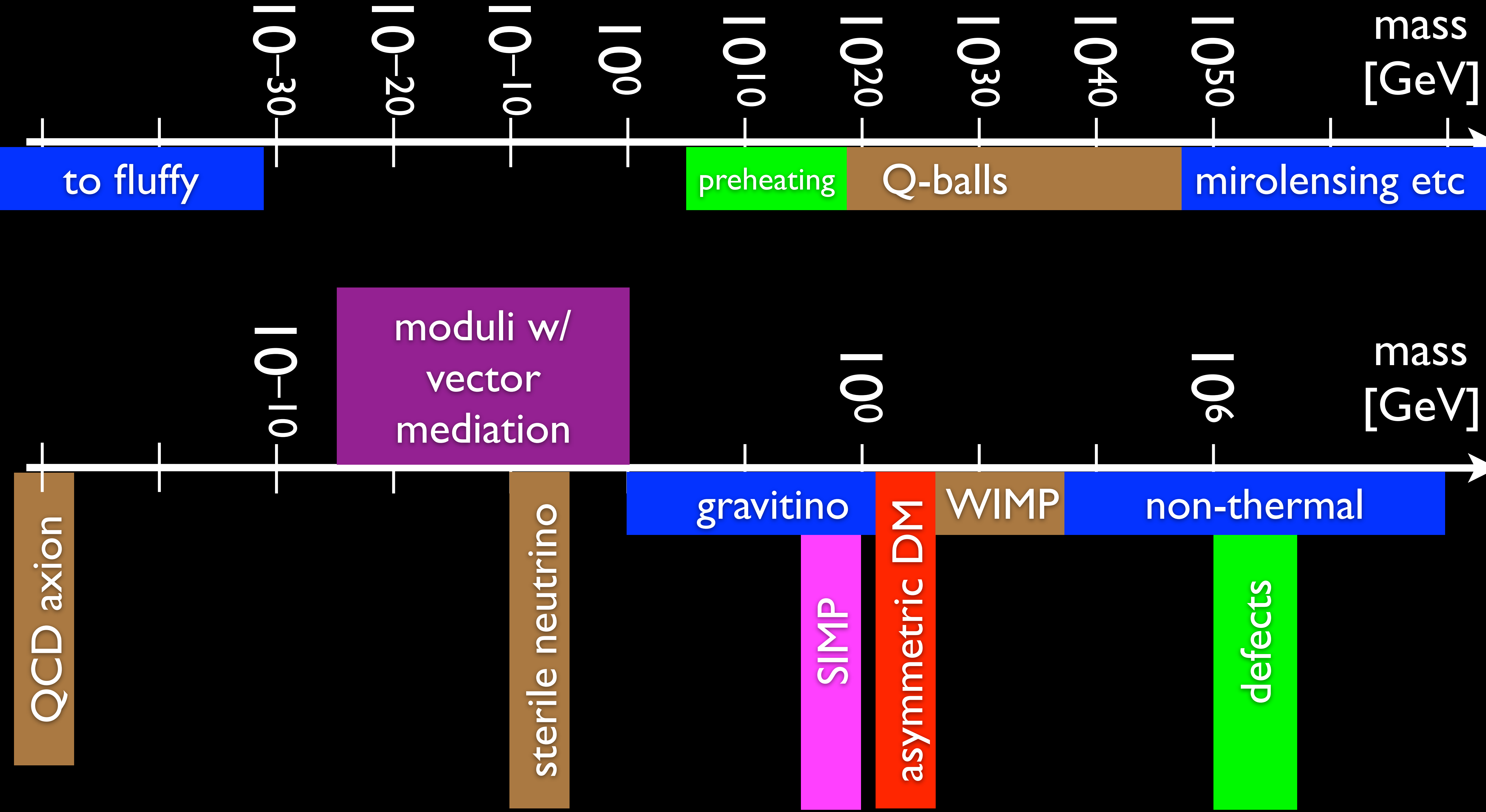
  $\sigma < 1.7 \times 10^{-25}$ cm^2 (m/GeV)

  (Yoshida, Springel, White, astro-ph/0006134)
- bullet cluster:

  $\sigma < 1.7\text{x}10^{-24}$ cm^2 (m/GeV)

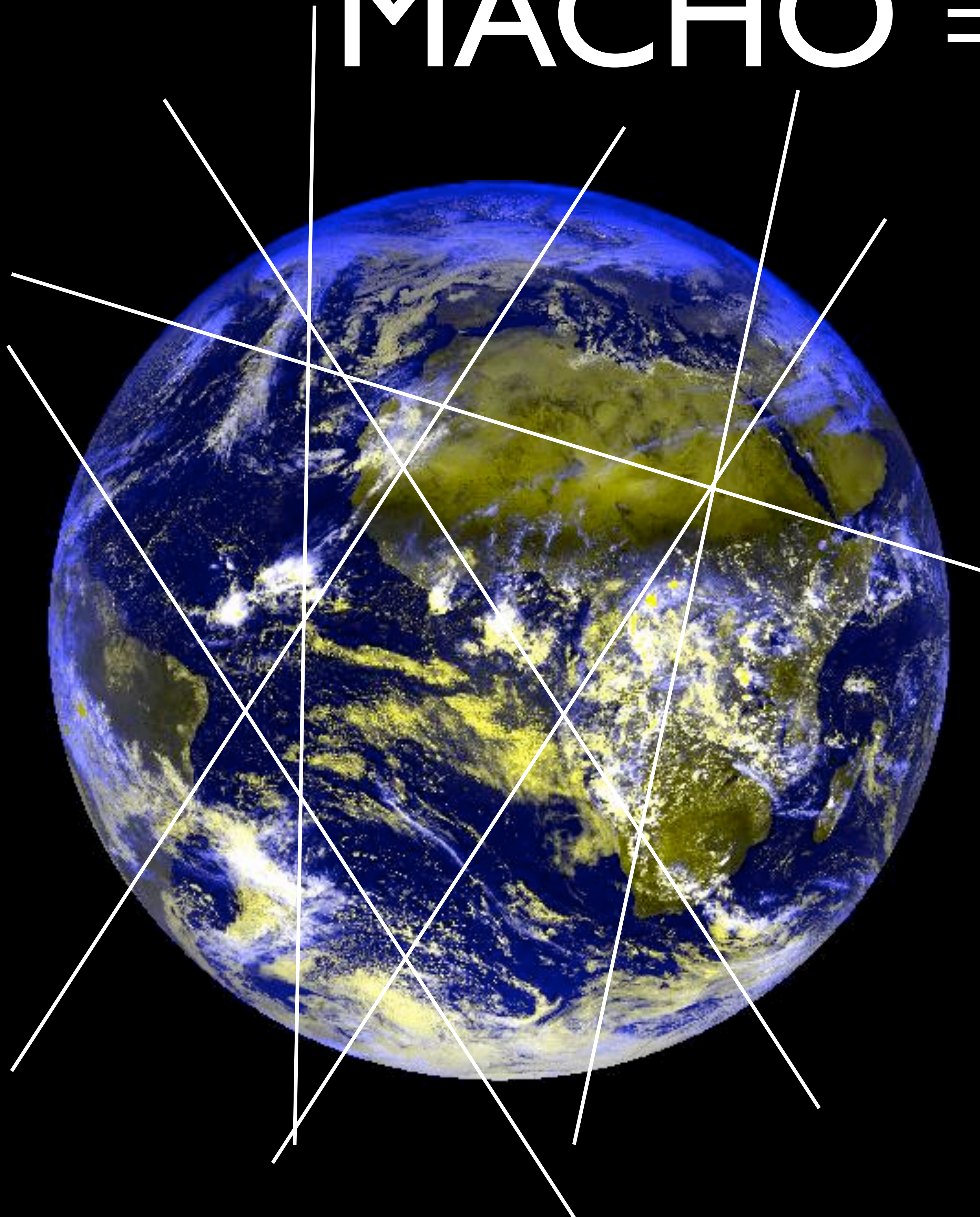
  (Markevitch et al, astro-ph/0309303)





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

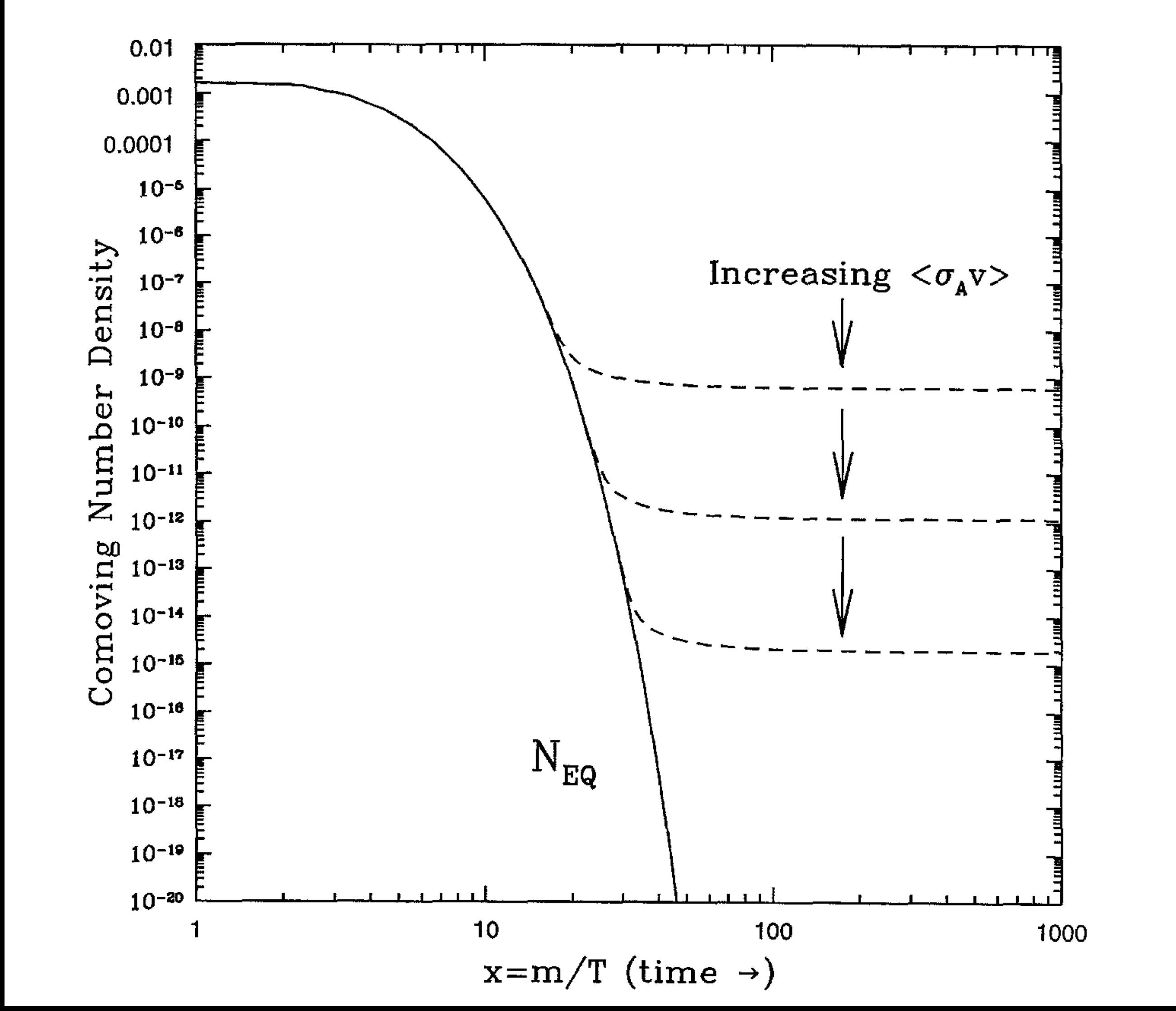
MACHO ⇒ WIMP



- It is probably WIMP (Weakly Interacting Massive Particle)
- Stable heavy particle produced in early Universe, left-over from near-complete annihilation
- Will focus on WIMPs for the rest or the lecture

thermal relic

- thermal equilibrium when $kT > m_\chi c^2$
- Once $kT < m_\chi c^2$, no more χ created
- if stable, only way to lose them is annihilation
- but universe expands and χ get dilute
- at some point they can't find each other
- their number in comoving volume "frozen"



Freeze-out

- WIMP freezes out when the annihilation rate drops below the expansion rate
- Yield Y=n/s constant under expansion
- stronger annihilation ⇒ less abundance

$$H \approx g_*^{1/2} \frac{T^2}{M_{Pl}}$$

$$\Gamma_{\rm ann} \approx \langle \sigma_{\rm ann} v \rangle n$$

$$H(T_f) = \Gamma_{\rm ann}$$

$$n \approx g_*^{1/2} \frac{T_f^2}{M_{Pl} \langle \sigma_{\rm ann} v \rangle}$$

$$s \approx g_* T^3$$

$$Y = \frac{n}{s} \approx g_*^{-1/2} \frac{1}{M_{Pl} T_f \langle \sigma_{\rm ann} v \rangle}$$

$$\Omega_\chi = \frac{m_\chi Y s_0}{\rho_c}$$

$$\approx g_*^{-1/2} \frac{x_f}{M_{Pl}^3 \langle \sigma_{\rm ann} v \rangle} \frac{s_0}{H_0^2}$$

Order of magnitude

- "Known" Ω_χ=0.23 determines the WIMP annihilation cross section
- simple estimate of the annihilation cross section
- within the range at LHC!!!

$$\Omega_\chi \approx g_*^{-1/2} \frac{x_f}{M_{Pl}^3 \langle \sigma_{\rm ann} v \rangle} \frac{s_0}{H_0^2}$$

$$\langle \sigma_{\rm ann} v \rangle \approx \frac{1.12 \times 10^{-10} {\rm GeV}^{-2} x_f}{g_*^{1/2} \Omega_\chi h^2}$$

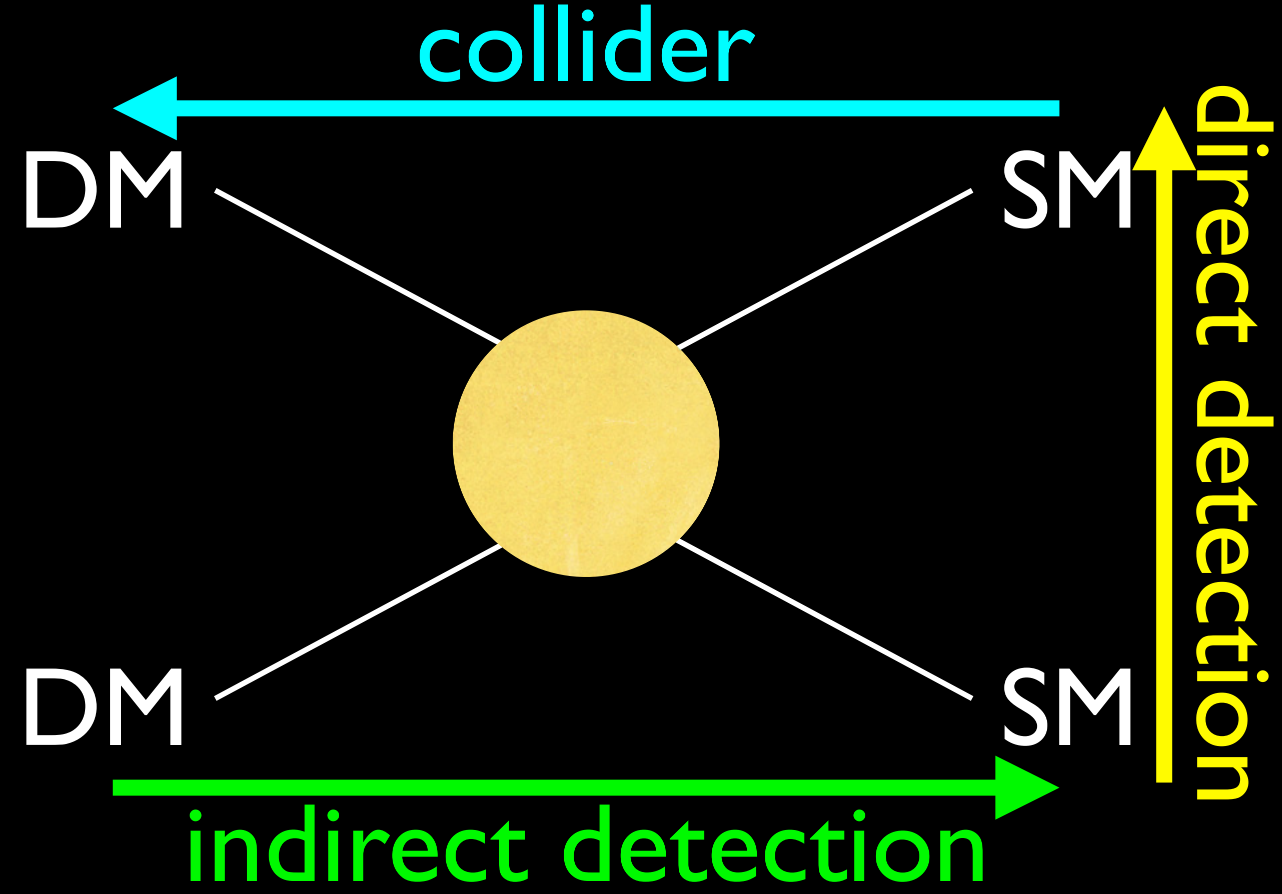
$$\sim 10^{-9} {\rm GeV}^{-2}$$

$$\langle \sigma_{\rm ann} v \rangle \approx \frac{\pi \alpha^2}{m_\chi^2}$$

$$m_\chi \approx 300 \text{ GeV}$$

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

WIMP Miracle



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

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

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

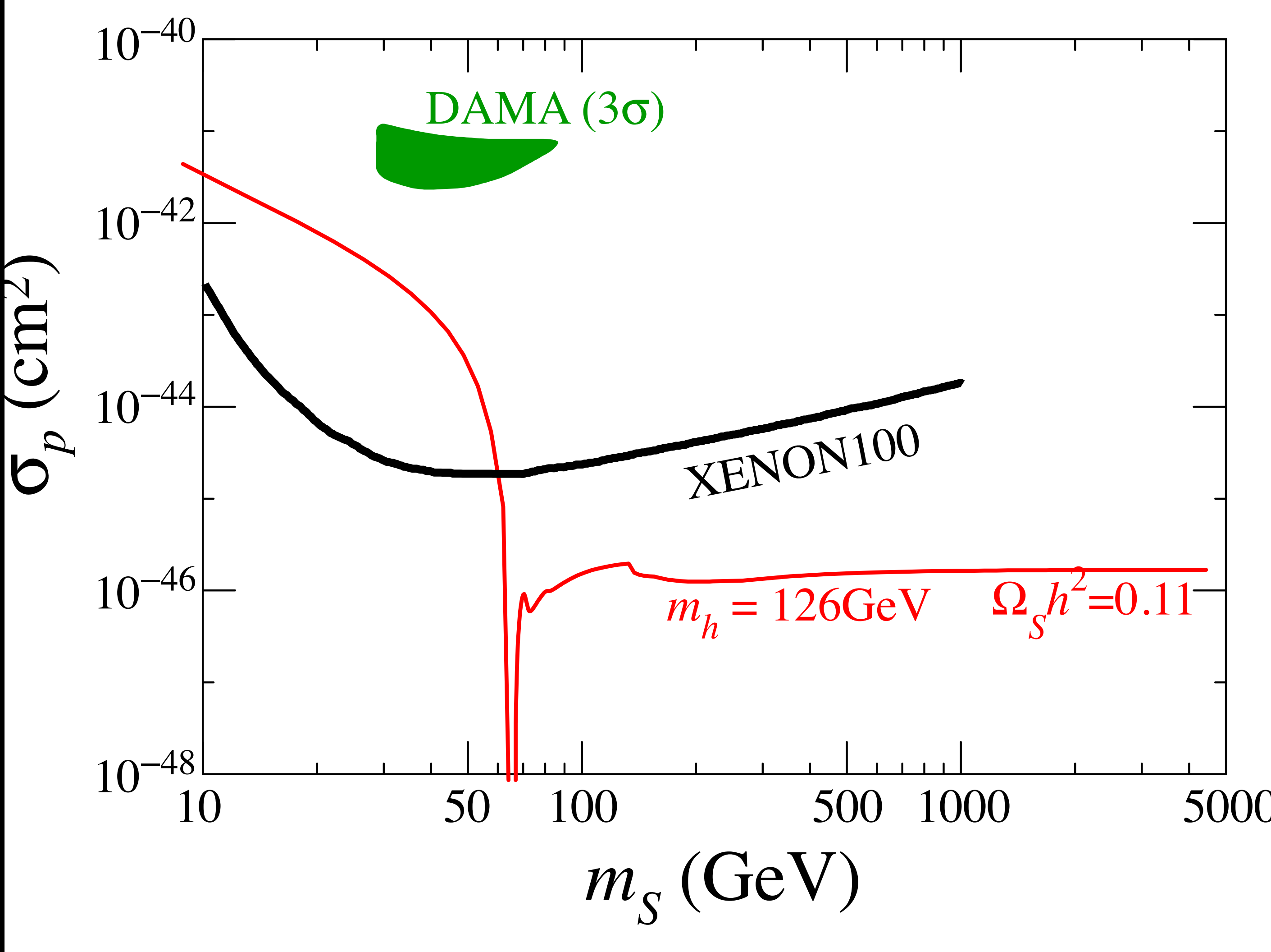
"weak" coupling
"weak" mass scale → correct abundance

We want new particles for naturalness anyway

Miracle²

Littlest Dark Matter

- dark matter clearly a new degree of freedom
- The smallest dof you can add to the SM is a real Klein-Gordon field *S*: dof=1
- assign odd Z_2 parity to S, everything else even



$$L_S = \frac{1}{2}\partial_\mu S \partial^\mu S - \frac{1}{2} m_S^2 S^2 - \frac{k}{2}|H|^2 S^2 - \frac{h}{4!} S^4.$$

Electron mass is natural by doubling #particles

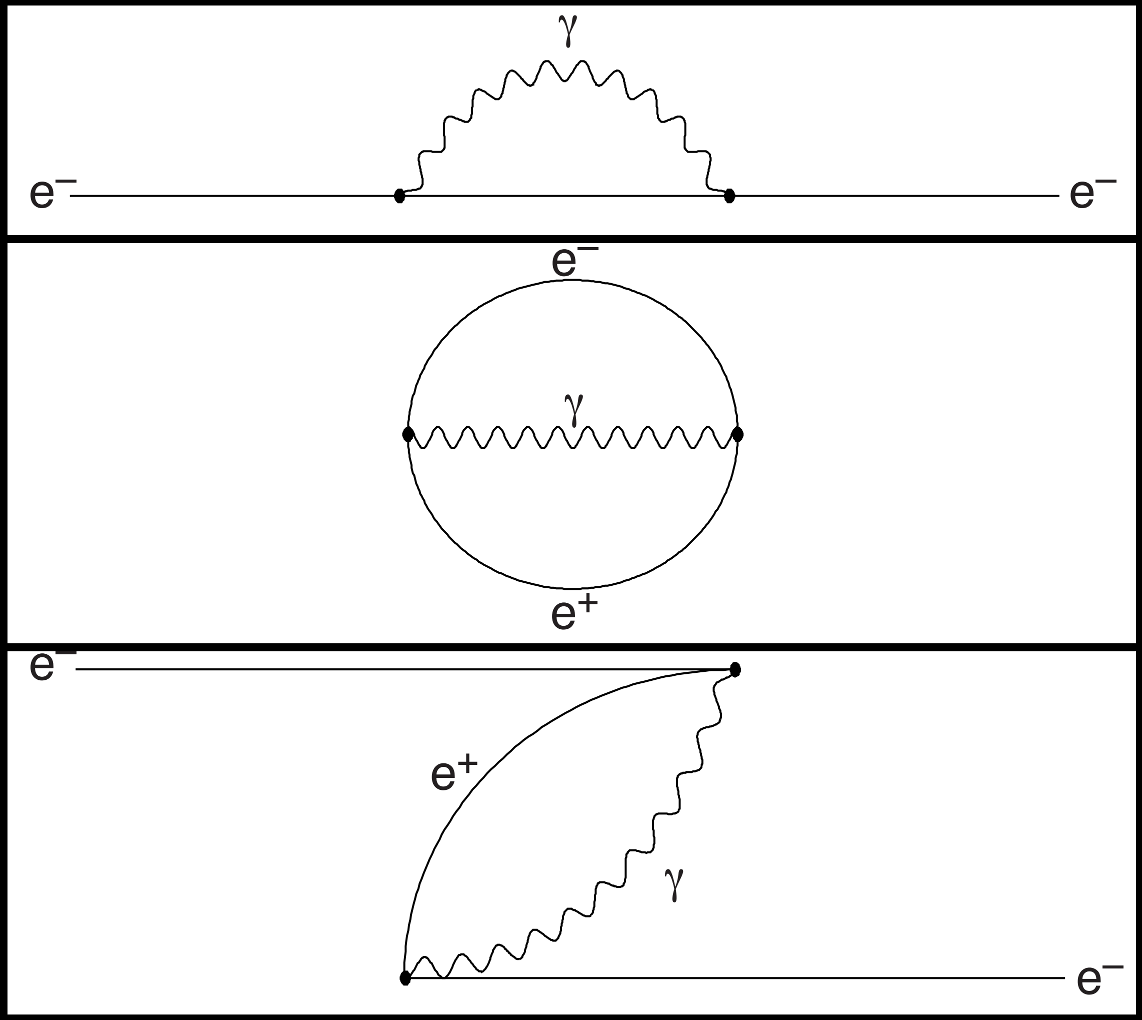
- Electron creates a force to repel itself

$$\Delta m_e c^2 \sim \frac{e^2}{r_e} \sim \mathrm{GeV}\frac{10^{-17}\mathrm{cm}}{r_e}$$

- quantum mechanics and anti-matter

⇒ only 10% of mass even

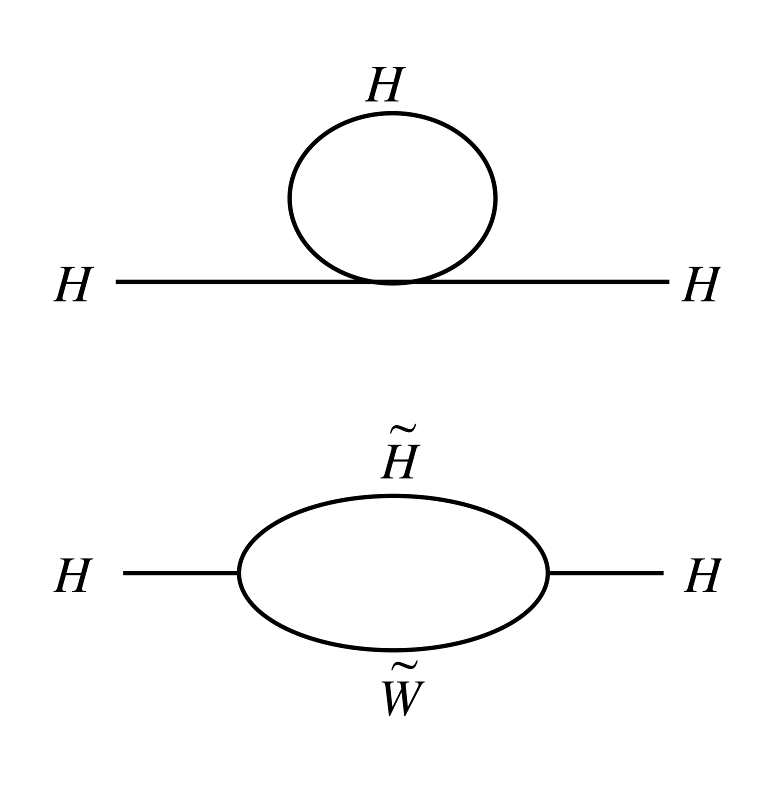
for Planck-size $r_e \sim 10^{-33}$cm



$$\Delta m_e \sim m_e \frac{\alpha}{4\pi} \log(m_e r_e)$$

Higgs mass is natural by doubling #particles?

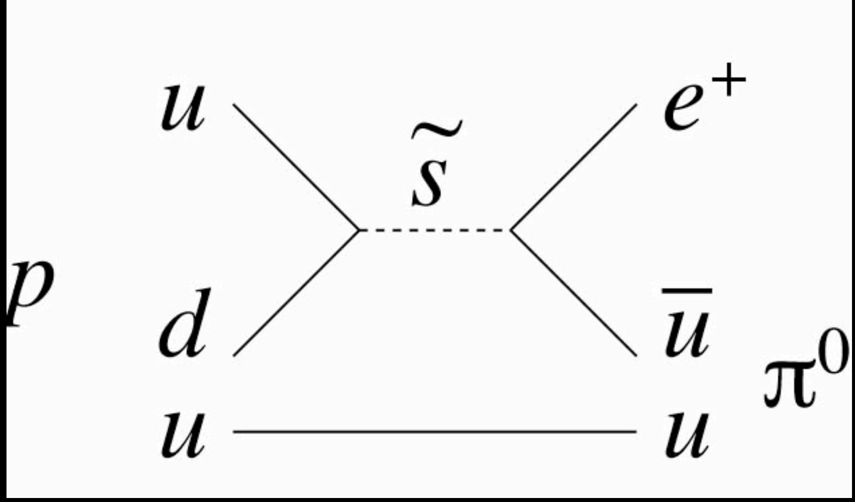
- Higgs also repels itself
- Double #particles again
  ⇒ superpartners
- only log sensitivity to UV
- Standard Model made consistent up to higher energies



$$\Delta m_H^2 \sim \frac{\alpha}{4\pi} m_{SUSY}^2 \log(m_H r_H)$$

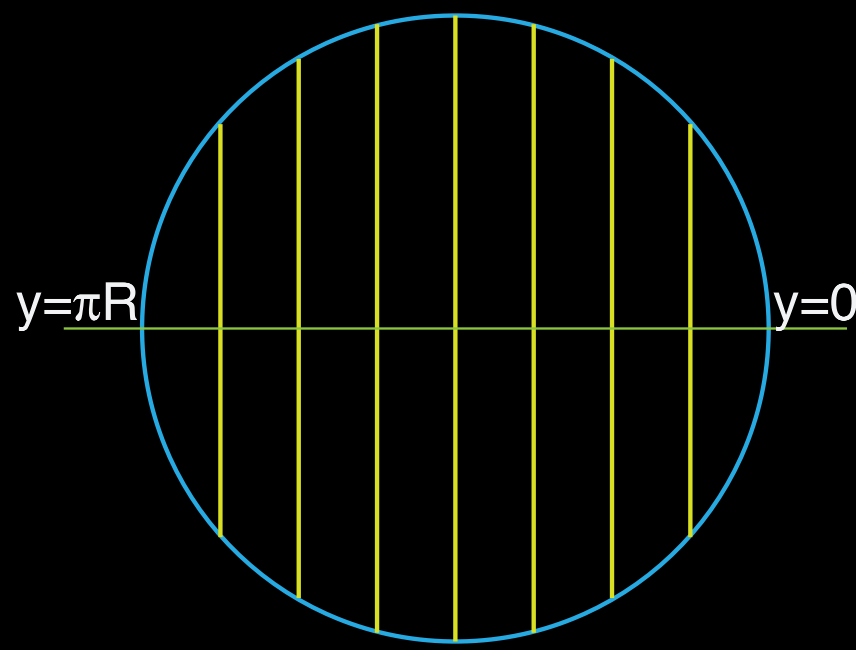
⇒ I still take it seriously

R-parity



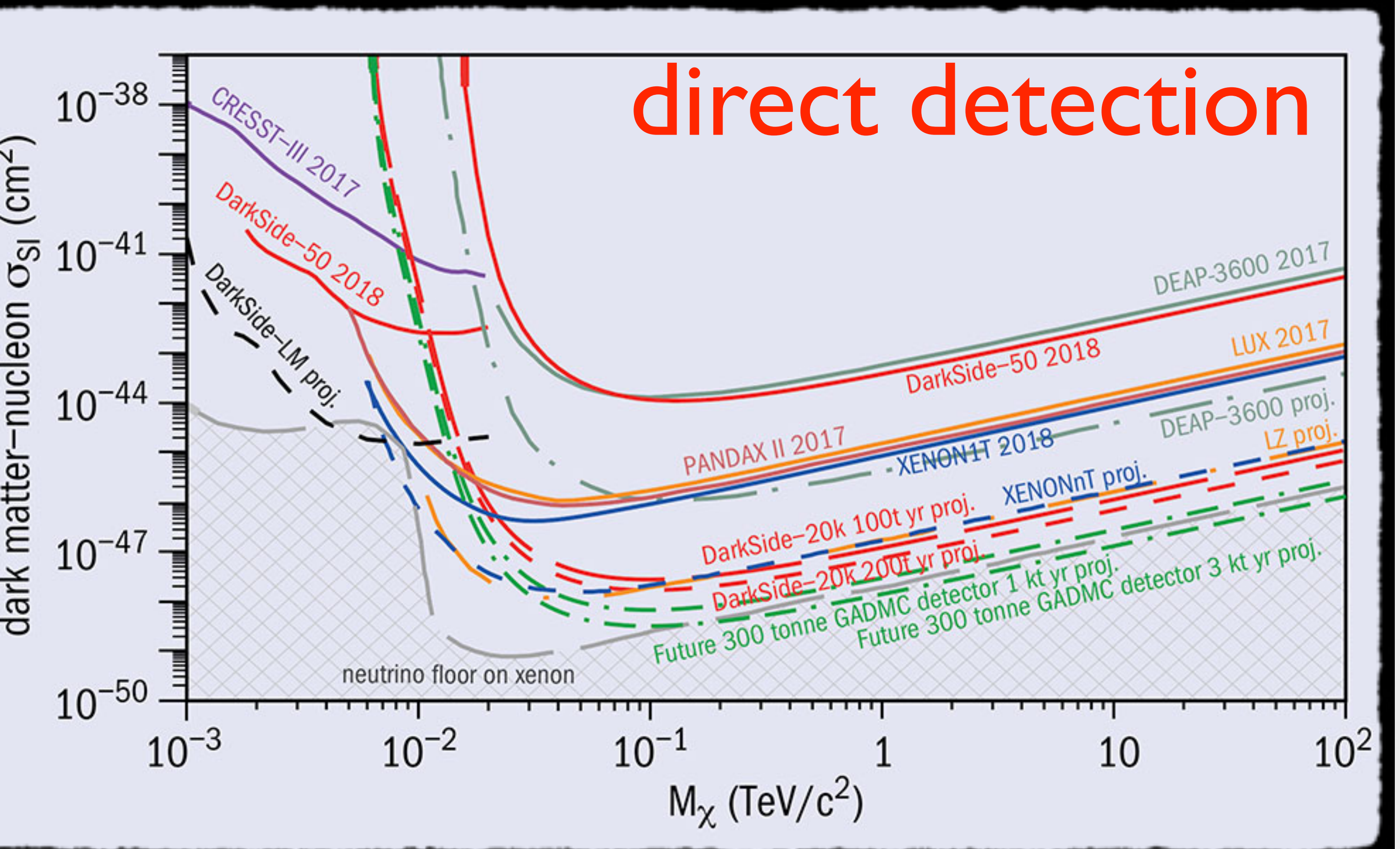
- B, L-conservation not automatic
- $W = udd + QdL + LLe + LH_u$
- If they exist with $O(1)$ couplings:
- $\tau_p \sim m_{sq}^4 / m_p^5 \sim 10^{-12}$ sec!
- Product of two couplings $< 10^{-26}$
- Impose R-parity $= (-1)^{3B+L+2s}$
- Forbids B and L number violation
- R-parity is non-anomalous; may be gauged
- Stable Lightest Supersymmetric Particle
  $\Rightarrow$ Cold Dark Matter
- SUSY particles always pair-produced and decay into the LSP: missing energy signal

UED

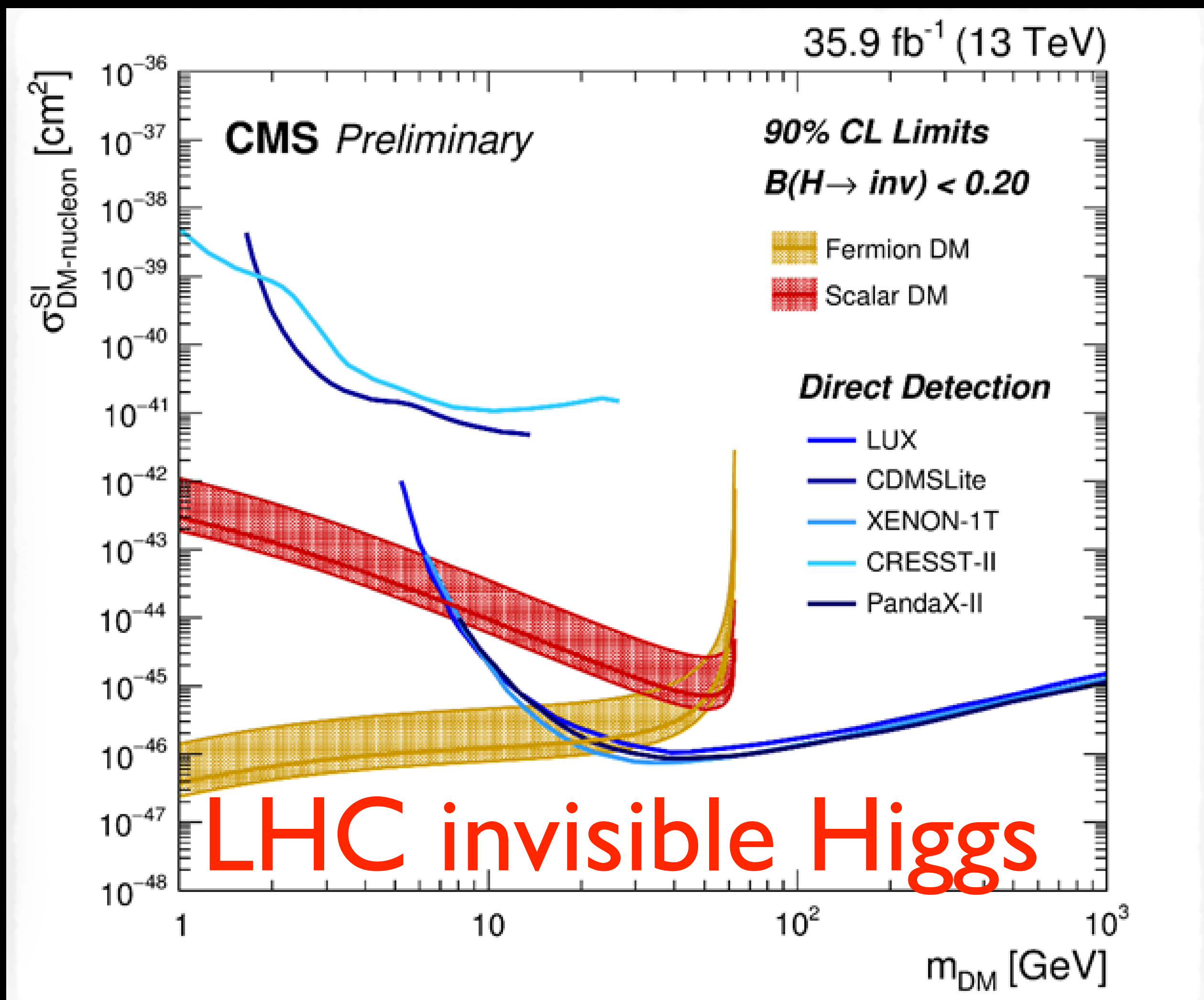


- one extra dimension (S^1/Z_2)
  - mod out by parity in 5D
- Lightest state with odd parity is stable
- typically KK state of U(1)Y gauge boson

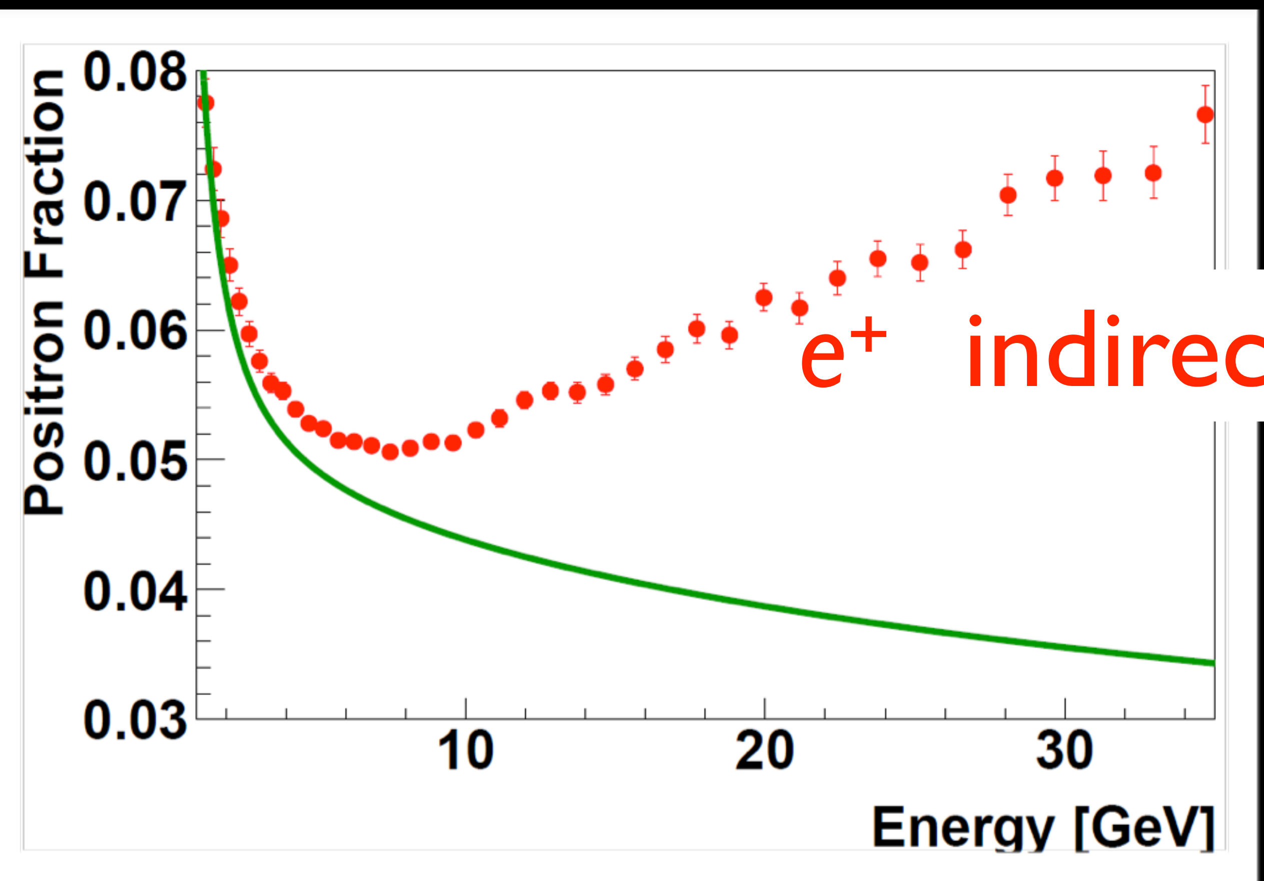
direct detection

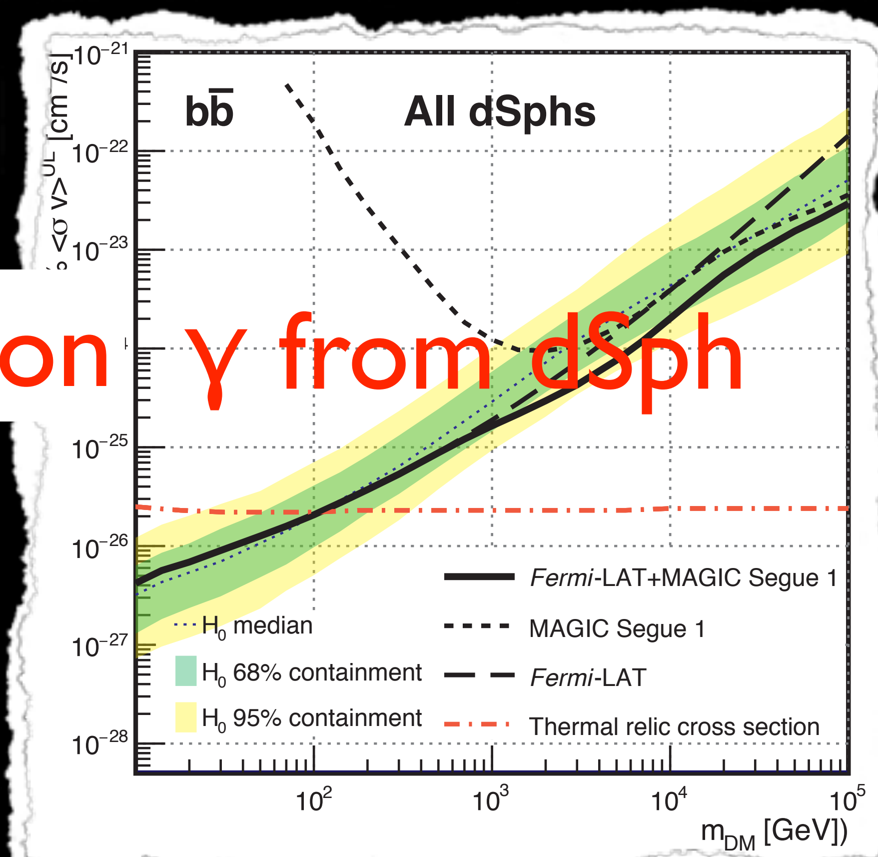


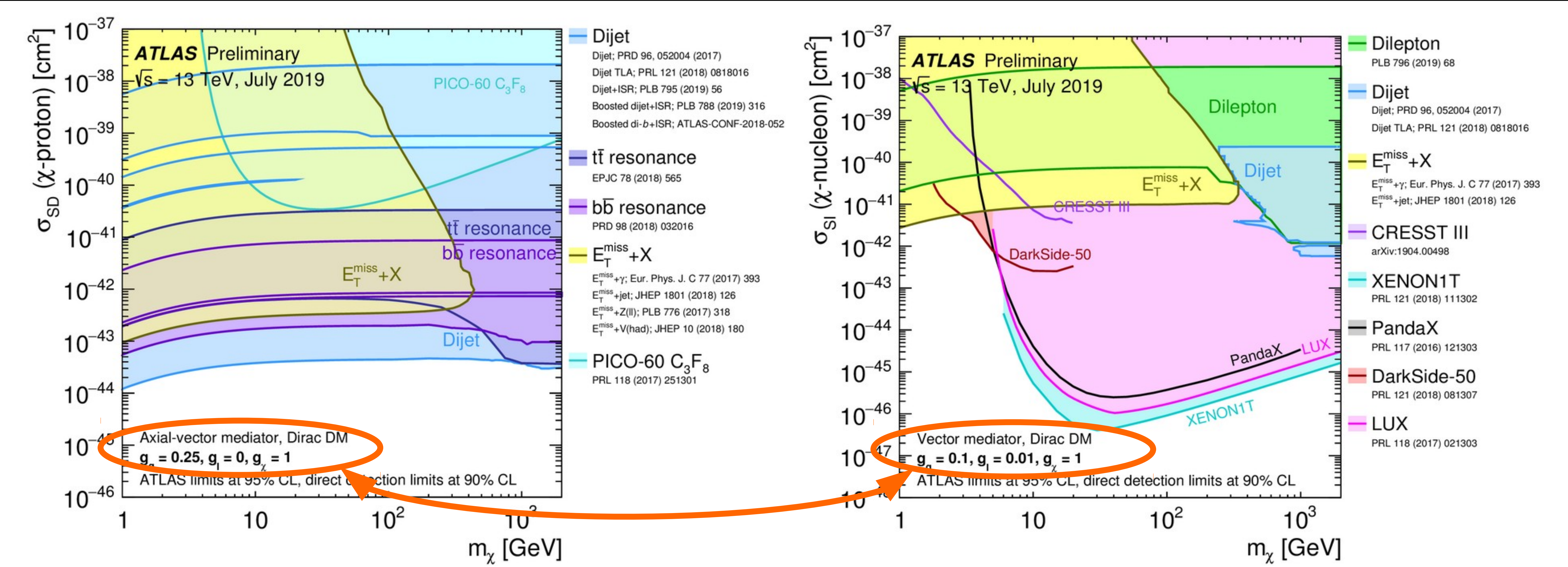
LHC invisible Higgs

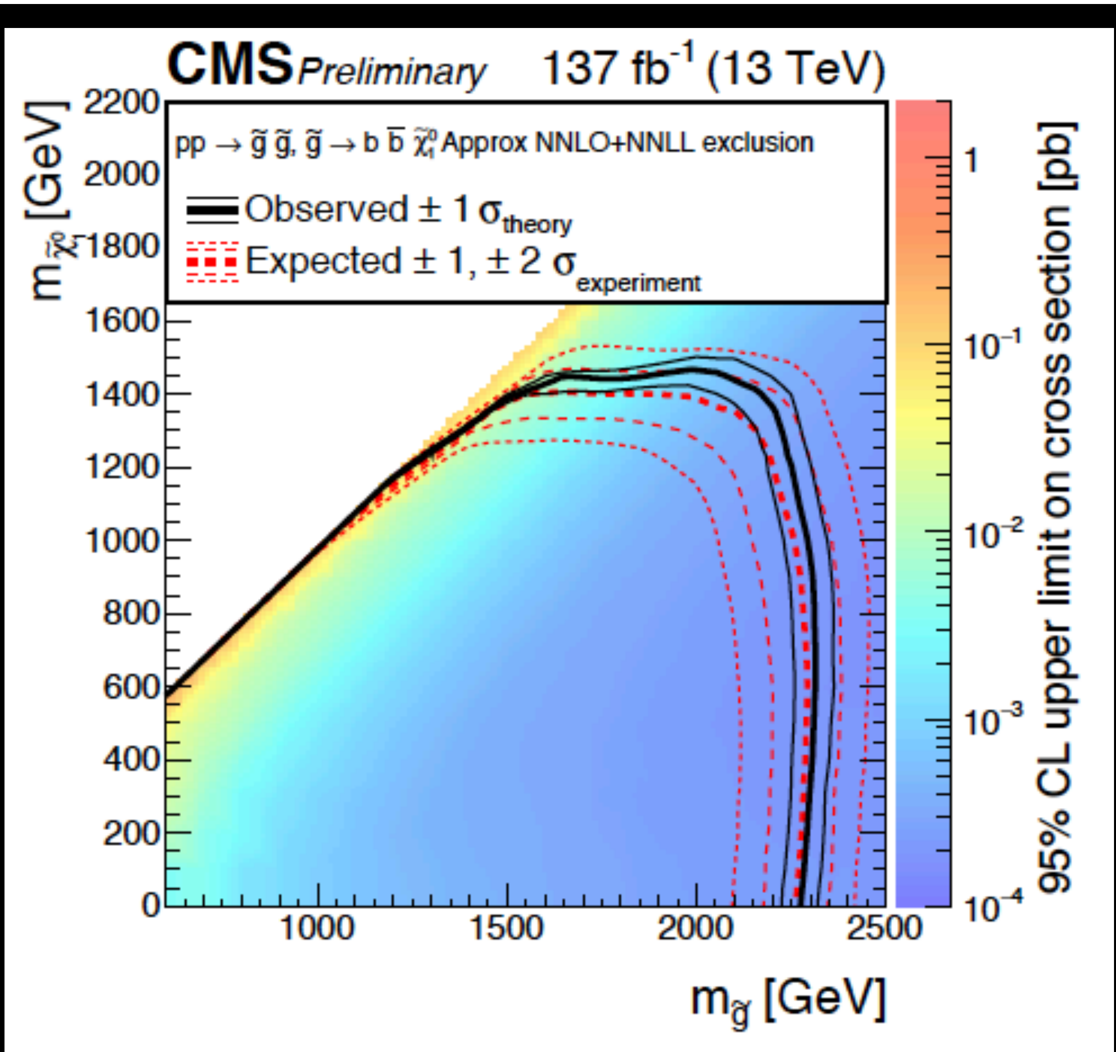


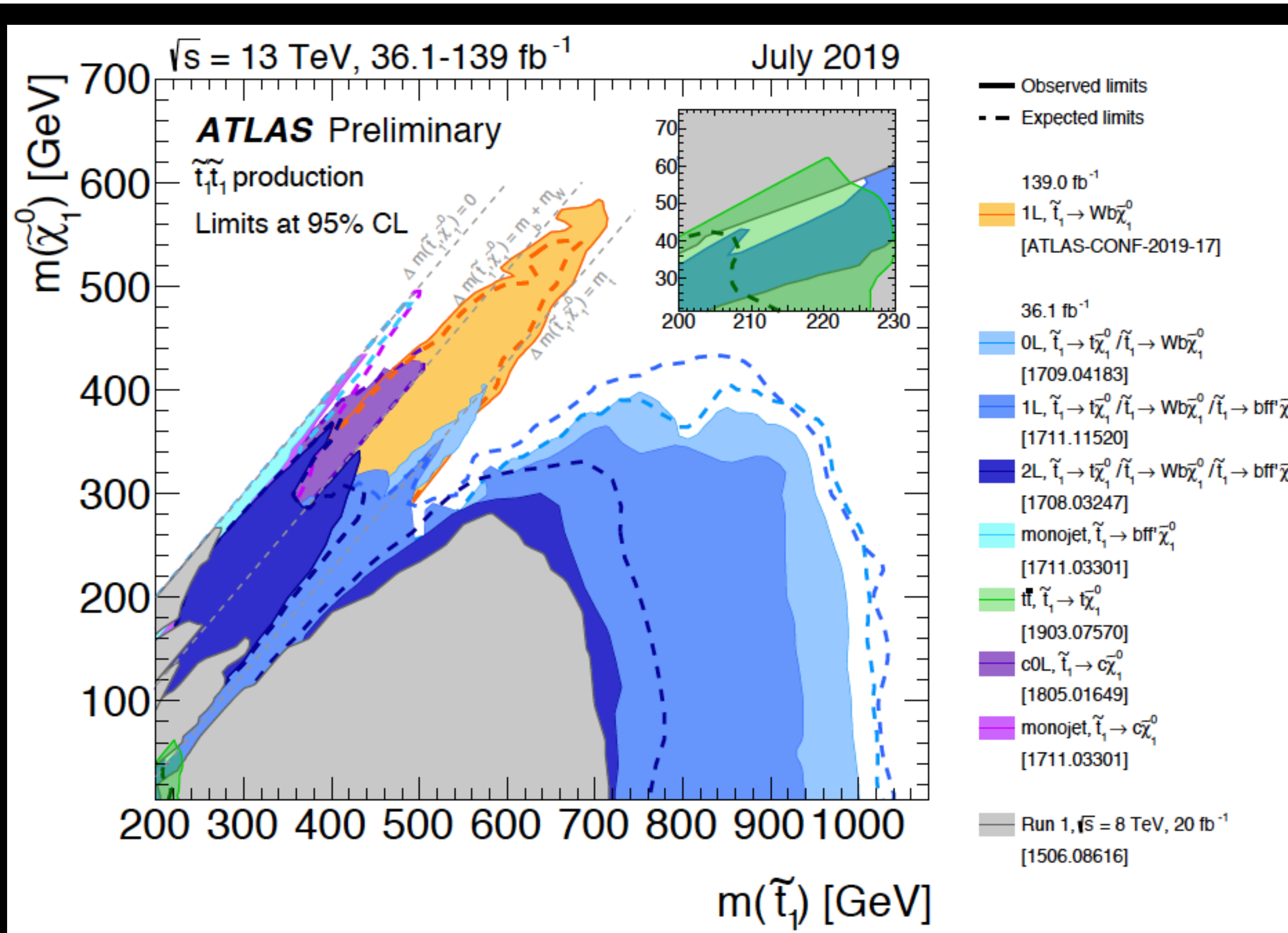
e^+ indirect detection γ from dSph






ATLAS Preliminary
√s = 13 TeV, July 2019
σ_{SD} (χ-proton) [cm²]
m_χ [GeV]
PICO-60 C3F8
tt̄ resonance
bb̄ resonance
E_T^{miss}+X
Dijet
Axial-vector mediator, Dirac DM
g_q = 0.25, g_l = 0, g_χ = 1
ATLAS limits at 95% CL, direct detection limits at 90% CL
Dijet
Dijet; PRD 96, 052004 (2017)
Dijet TLA; PRL 121 (2018) 0818016
Dijet+ISR; PLB 795 (2019) 56
Boosted dijet+ISR; PLB 788 (2019) 316
Boosted di-b+ISR; ATLAS-CONF-2018-052
tt̄ resonance
EPJC 78 (2018) 565
bb̄ resonance
PRD 98 (2018) 032016
E_T^{miss}+X
E_T^{miss}+γ; Eur. Phys. J. C 77 (2017) 393
E_T^{miss}+jet; JHEP 1801 (2018) 126
E_T^{miss}+Z(ll); PLB 776 (2017) 318
E_T^{miss}+V(had); JHEP 10 (2018) 180
PICO-60 C3F8
PRL 118 (2017) 251301
ATLAS Preliminary
√s = 13 TeV, July 2019
σ_{SI} (χ-nucleon) [cm²]
m_χ [GeV]
Dilepton
Dijet
E_T^{miss}+X
CRESST III
DarkSide-50
PandaX
LUX
XENON1T
Vector mediator, Dirac DM
g_q = 0.1, g_l = 0.01, g_χ = 1
ATLAS limits at 95% CL, direct detection limits at 90% CL
Dilepton
PLB 796 (2019) 68
Dijet
Dijet; PRD 96, 052004 (2017)
Dijet TLA; PRL 121 (2018) 0818016
E_T^{miss}+X
E_T^{miss}+γ; Eur. Phys. J. C 77 (2017) 393
E_T^{miss}+jet; JHEP 1801 (2018) 126
CRESST III
arXiv:1904.00498
XENON1T
PRL 121 (2018) 111302
PandaX
PRL 117 (2016) 121303
DarkSide-50
PRL 121 (2018) 081307
LUX
PRL 118 (2017) 021303


CMS Preliminary
137 fb⁻¹ (13 TeV)
pp → g̃ g̃, g̃ → b b̄ χ̃⁰₁ Approx NNLO+NNLL exclusion
Observed ± 1 σ_{theory}
Expected ± 1, ± 2 $\sigma_{experiment}$
$m_{\tilde{\chi}^0_1}$ [GeV]
$m_{\tilde{g}}$ [GeV]
95% CL upper limit on cross section [pb]


√s = 13 TeV, 36.1-139 fb⁻¹
July 2019
ATLAS Preliminary
t̃₁t̃₁ production
Limits at 95% CL
m(χ̃⁰₁) [GeV]
m(t̃₁) [GeV]
Observed limits
Expected limits
139.0 fb⁻¹
1L, t̃₁→ Wbχ̃⁰₁
[ATLAS-CONF-2019-17]
36.1 fb⁻¹
0L, t̃₁→ tχ̃⁰₁ / t̃₁→ Wbχ̃⁰₁
[1709.04183]
1L, t̃₁→ tχ̃⁰₁ / t̃₁→ Wbχ̃⁰₁ / t̃₁→ bff'χ̃⁰₁
[1711.11520]
2L, t̃₁→ tχ̃⁰₁ / t̃₁→ Wbχ̃⁰₁ / t̃₁→ bff'χ̃⁰₁
[1708.03247]
monojet, t̃₁→ bff'χ̃⁰₁
[1711.03301]
tt̄, t̃₁→ tχ̃⁰₁
[1903.07570]
c0L, t̃₁→ cχ̃⁰₁
[1805.01649]
monojet, t̃₁→ cχ̃⁰₁
[1711.03301]
Run 1, √s = 8 TeV, 20 fb⁻¹
[1506.08616]

Galactic center

Daylan et al, arXiv:1402.6703

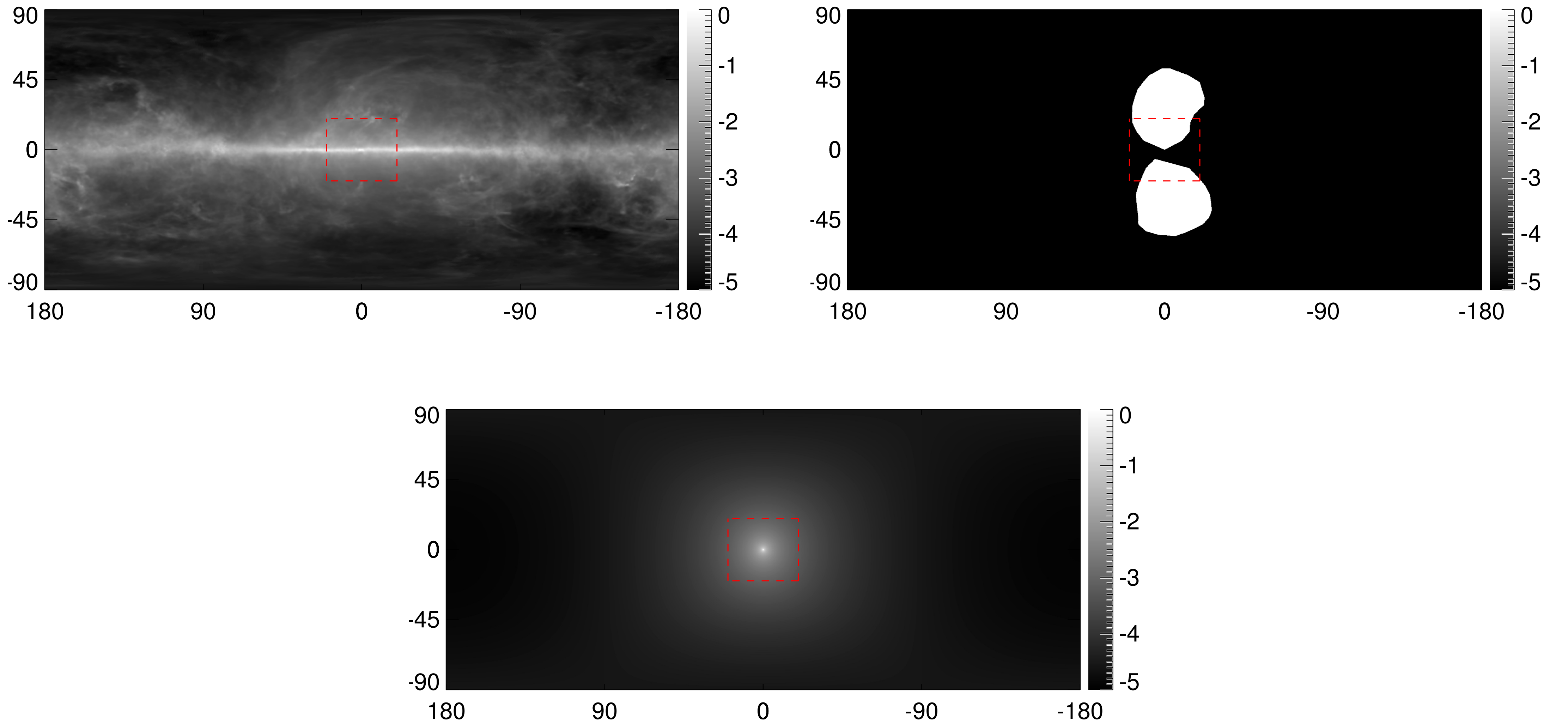
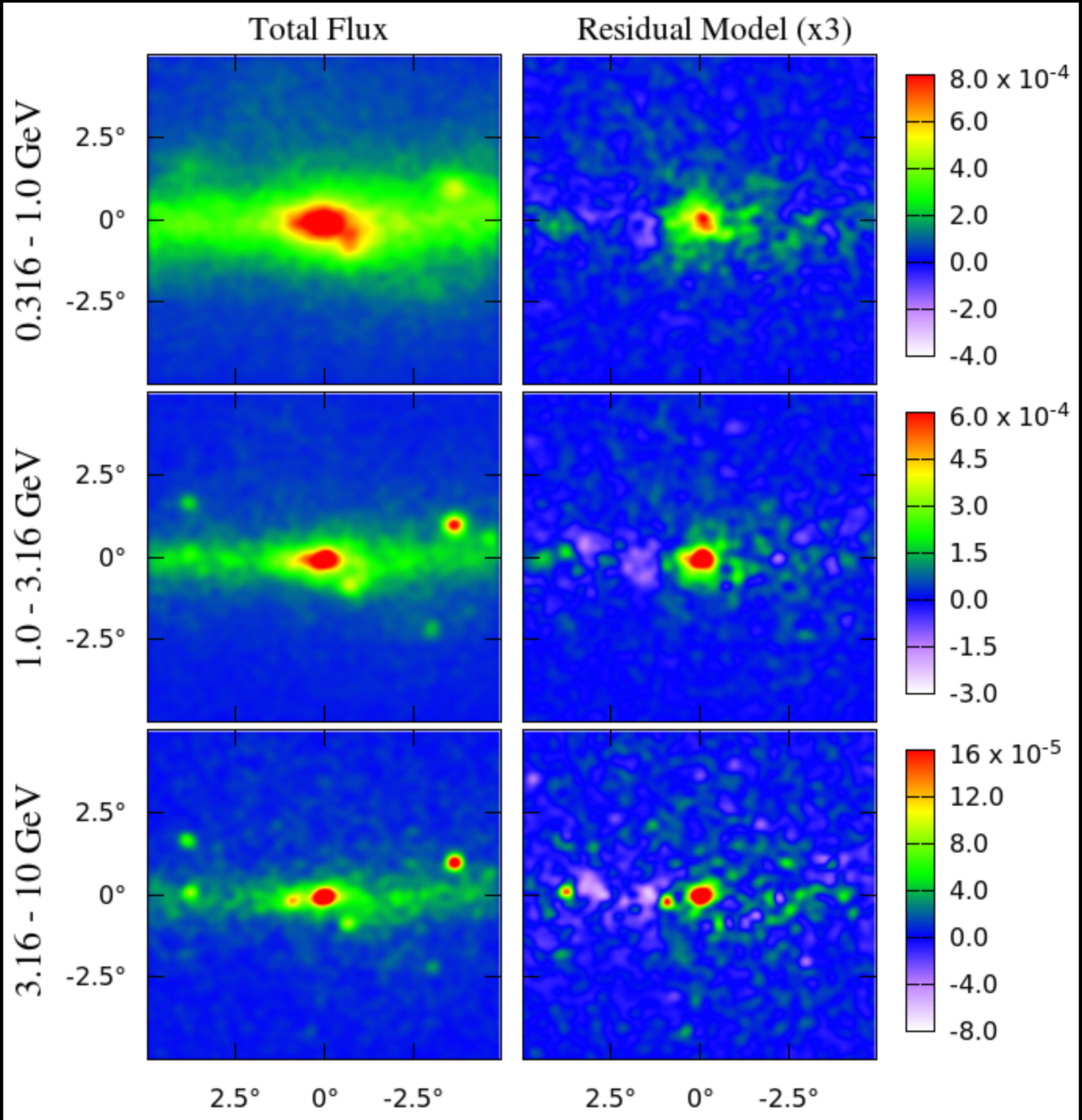
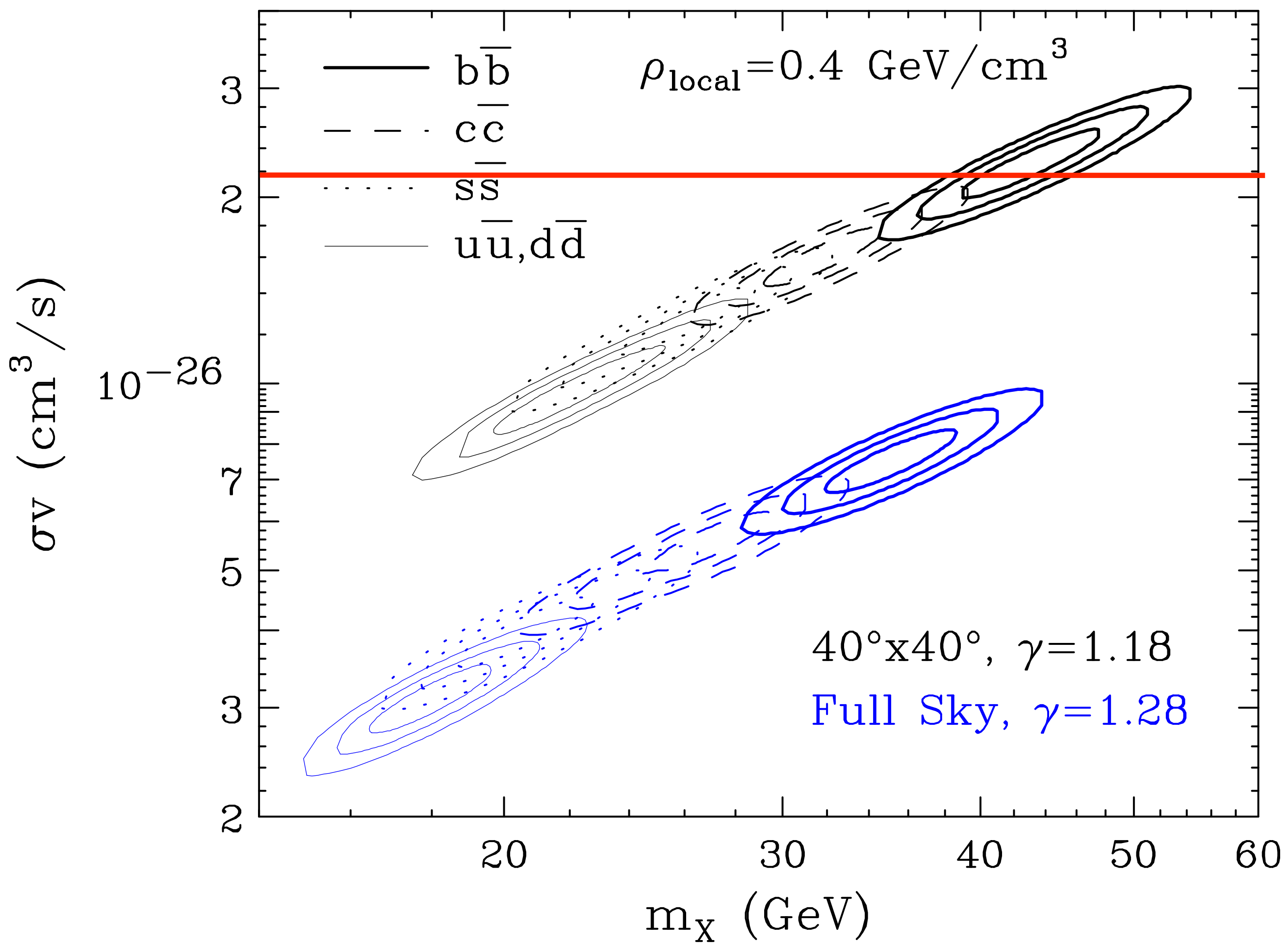


FIG. 4: The spatial templates (in galactic coordinates) for the Galactic diffuse model (upper left), the *Fermi* bubbles (upper right), and dark matter annihilation products (lower), as used in our Inner Galaxy analysis. The scale is logarithmic (base 10), normalized to the brightest point in each map. The diffuse model template is shown as evaluated at 1 GeV, and the dark matter template corresponds to a generalized NFW profile with an inner slope of $\gamma = 1.18$. Red dashed lines indicate the boundaries of our standard Region of Interest (we also mask bright point sources and the region of the Galactic plane with $|b| < 1^\circ$).


Total Flux
Residual Model (x3)
0.316 - 1.0 GeV
1.0 - 3.16 GeV
3.16 - 10 GeV
2.5°
0°
-2.5°
8.0 x 10-4
6.0
4.0
2.0
0.0
-2.0
-4.0
6.0 x 10-4
4.5
3.0
1.5
0.0
-1.5
-3.0
16 x 10-5
12.0
8.0
4.0
0.0
-4.0
-8.0

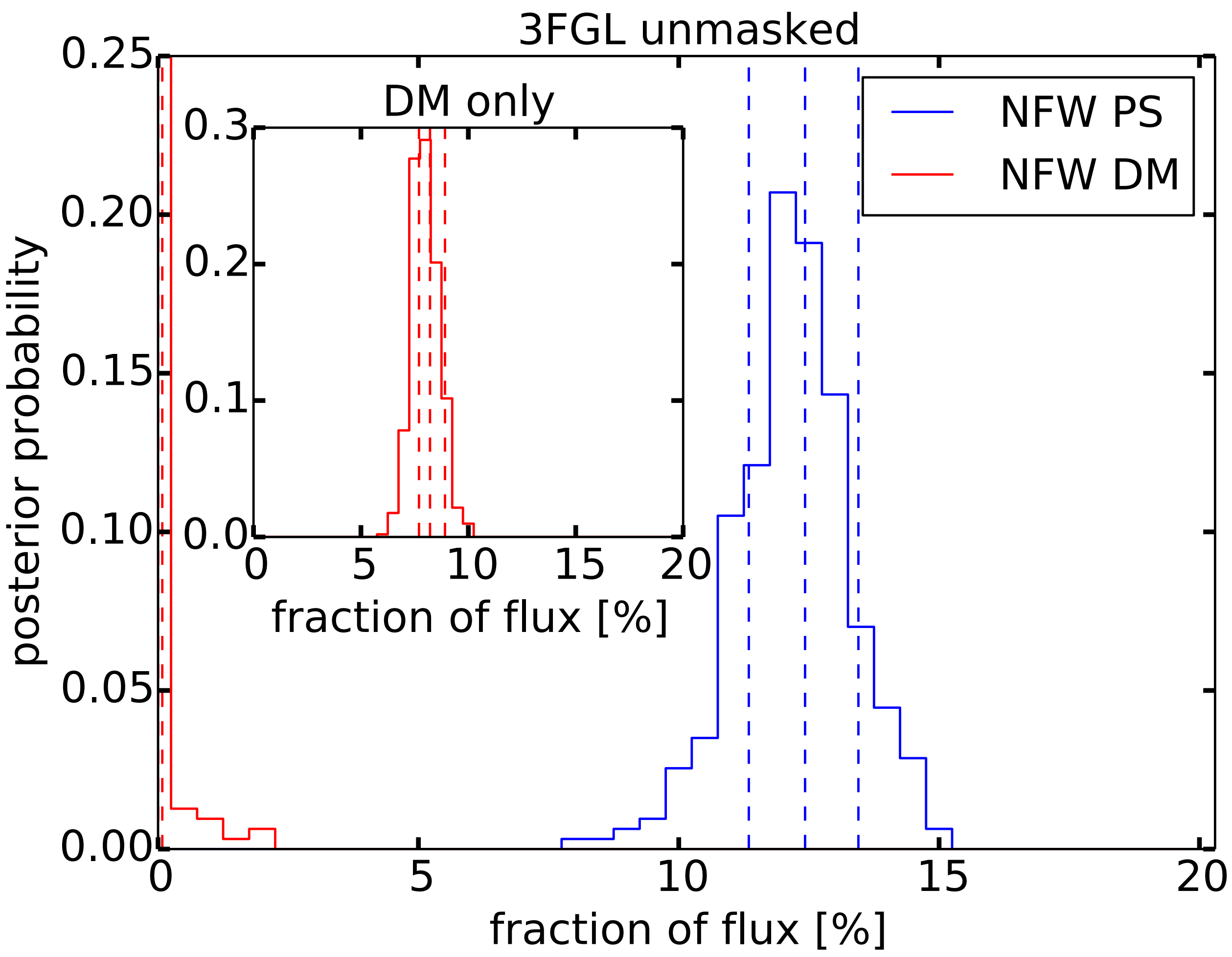
dark matter annihilation?

Daylan et al, arXiv:1402.6703



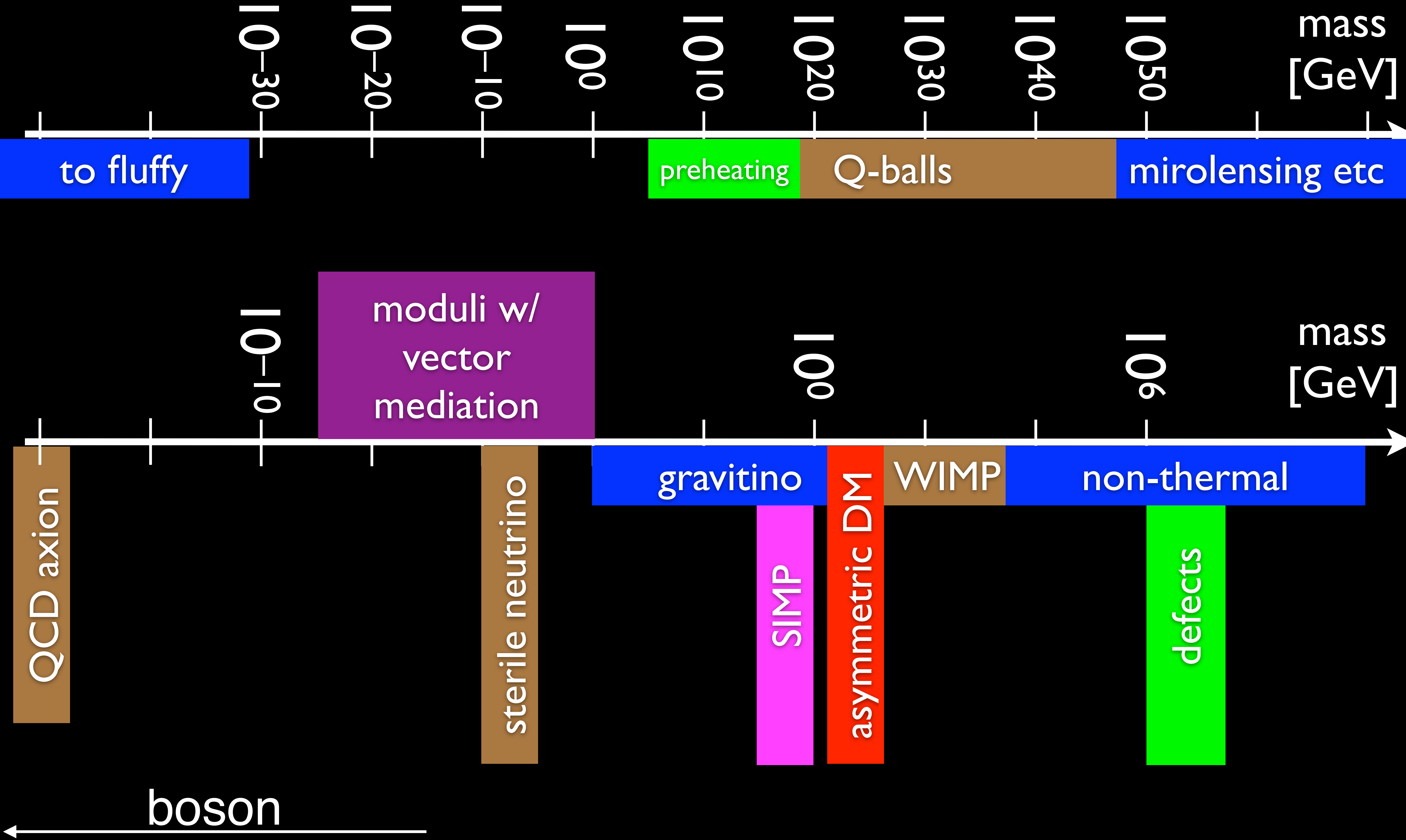
or unresolved point sources?

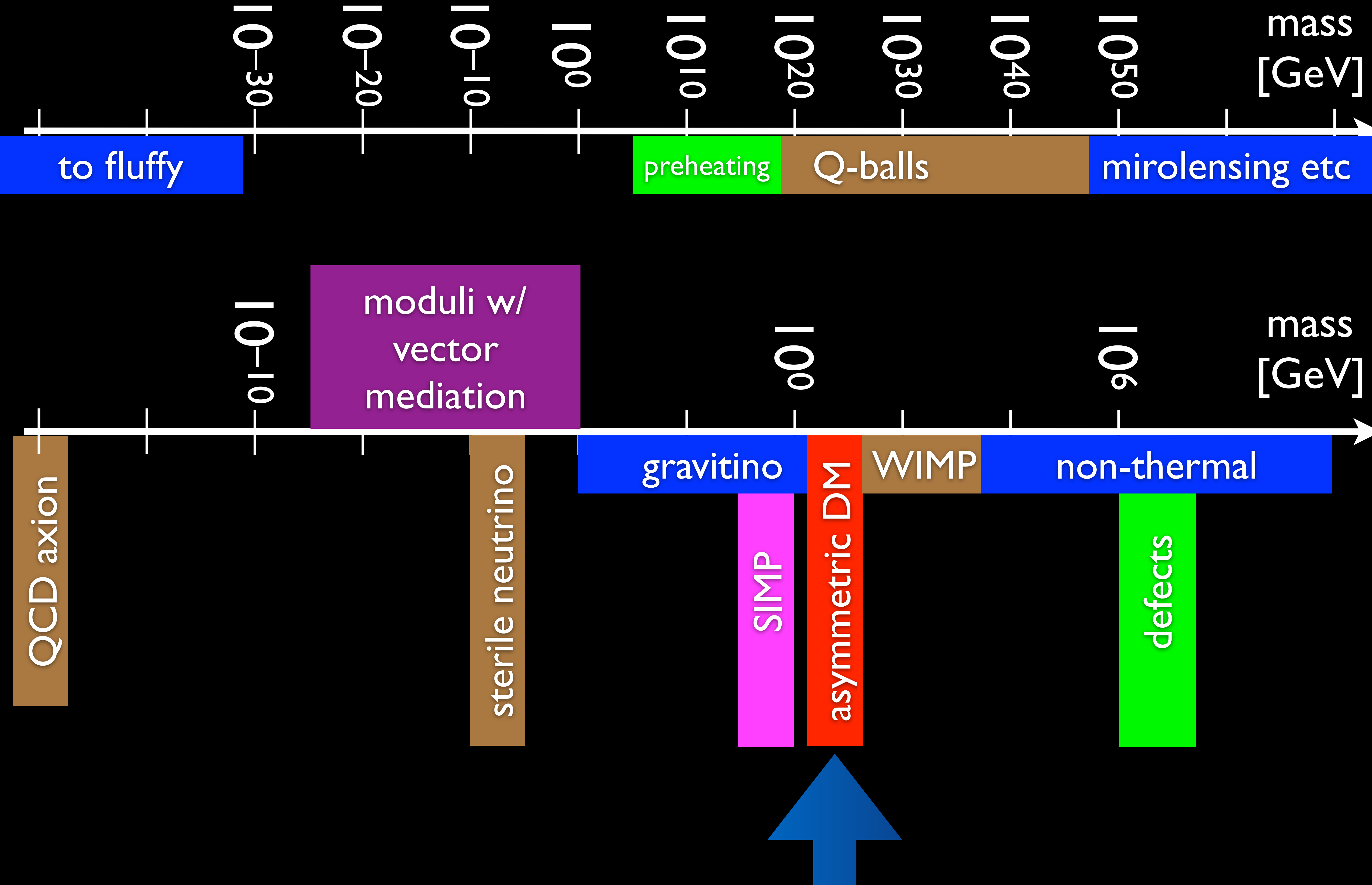
S. Lett et al, arXiv:1506.05124v1



new sociology

- WIMP should be explored at least down to the neutrino floor
  - heavier? e.g., wino @ 3TeV ⟹CTA
- dark matter definitely exists
  - hierarchy problem may be optional?
- 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}
10^{-10}
10^{0}
10^{10}
10^{20}
10^{30}
10^{40}
10^{50}
mass [GeV]
to fluffy
preheating
Q-balls
mirolensing etc
moduli w/ vector mediation
10^{-10}
10^{0}
10^{6}
mass [GeV]
QCD axion
sterile neutrino
gravitino
SIMP
asymmetric DM
WIMP
non-thermal
defects
boson


10−30
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1030
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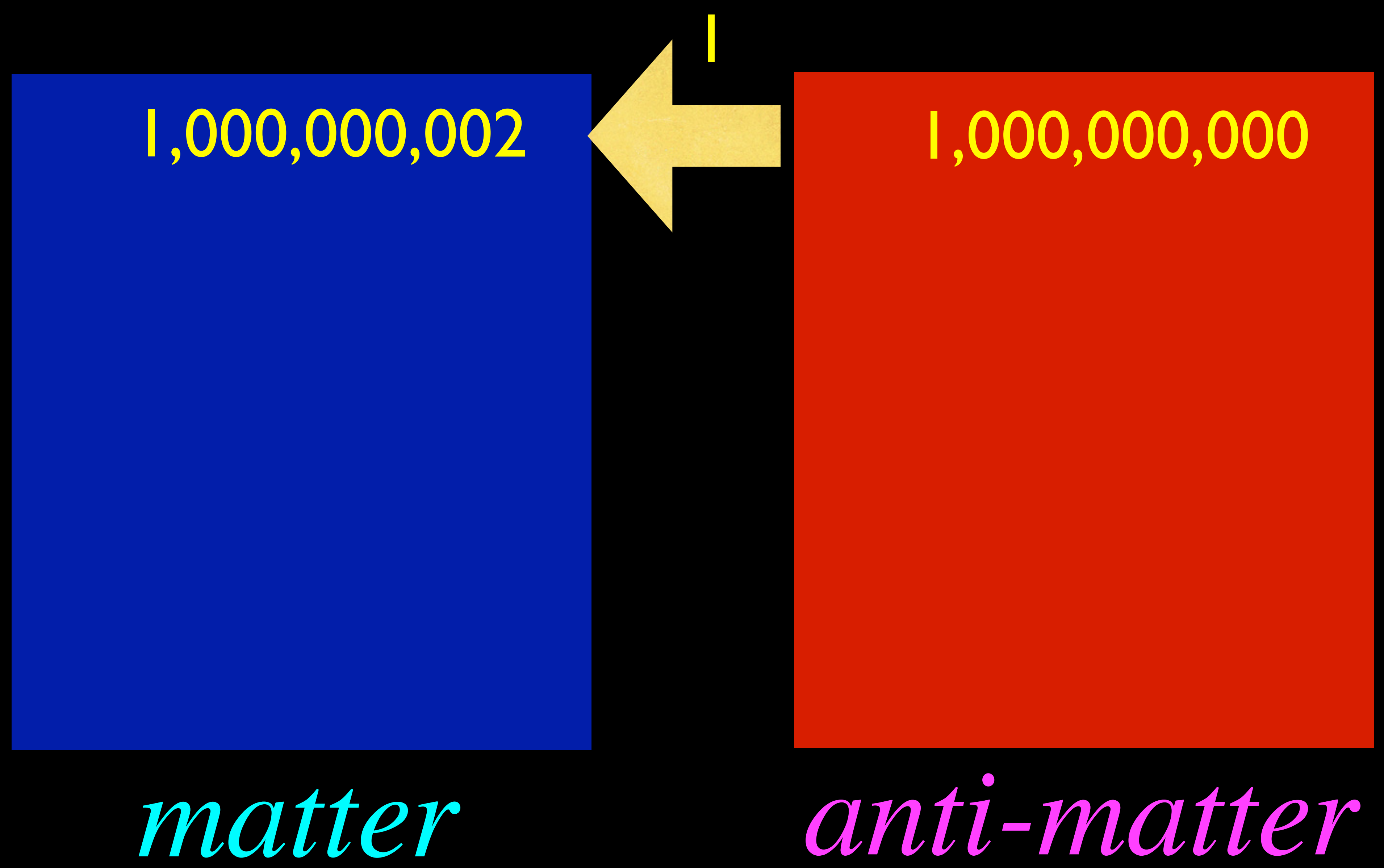
1050
mass [GeV]
to fluffy
preheating
Q-balls
mirolensing etc
moduli w/ vector mediation
10−10
100
106
mass [GeV]
QCD axion
sterile neutrino
gravitino
SIMP
asymmetric DM
WIMP
non-thermal
defects

After Inflation

matter	anti-matter
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

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

2

•

us

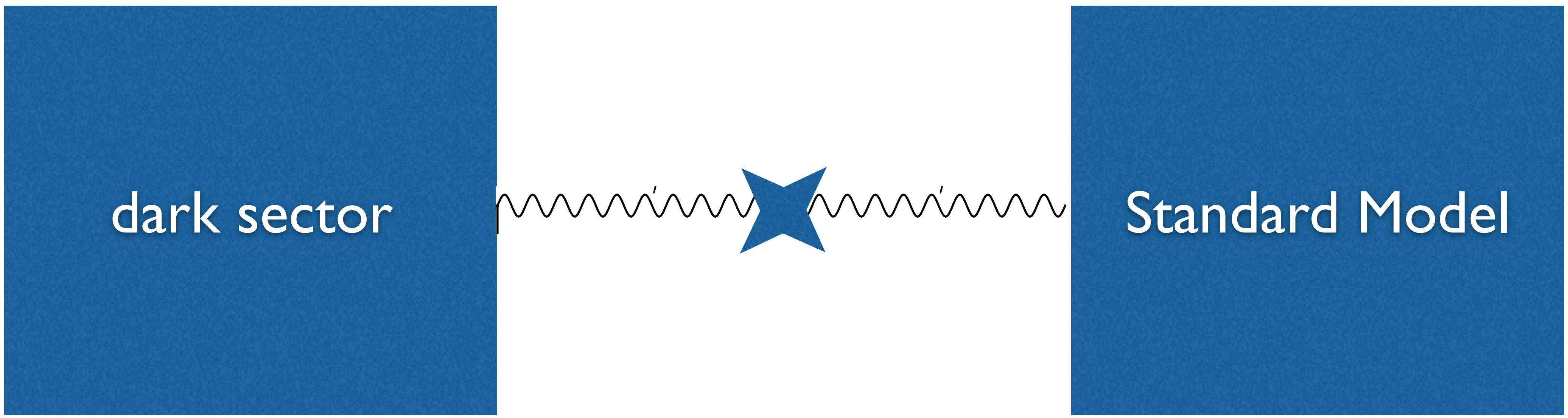
- motivation for 1–10 GeV dark matter
- challenge: get rid of symmetric component
- signal depends on portal; new medium

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

dark matter *dark anti-matter*

This must be how we survived the Big Bang!
they

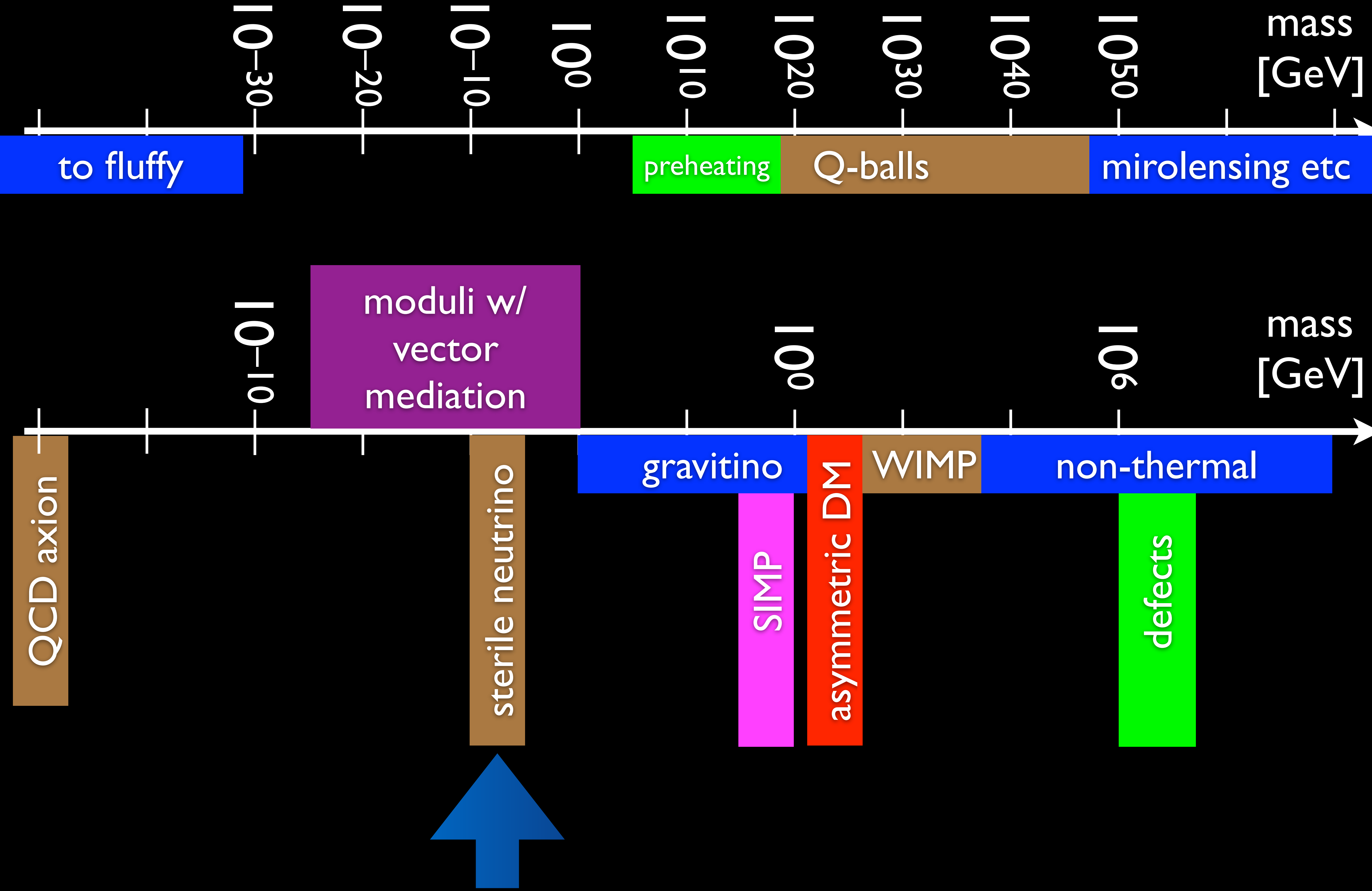
portals



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→invisible, couplings

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



10^{-30}
10^{-20}
10^{-10}
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10^{10}
10^{20}
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10^{40}
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10^{-10}
10^{0}
10^{6}
mass [GeV]
QCD axion
sterile neutrino
gravitino
SIMP
asymmetric DM
WIMP
non-thermal
defects

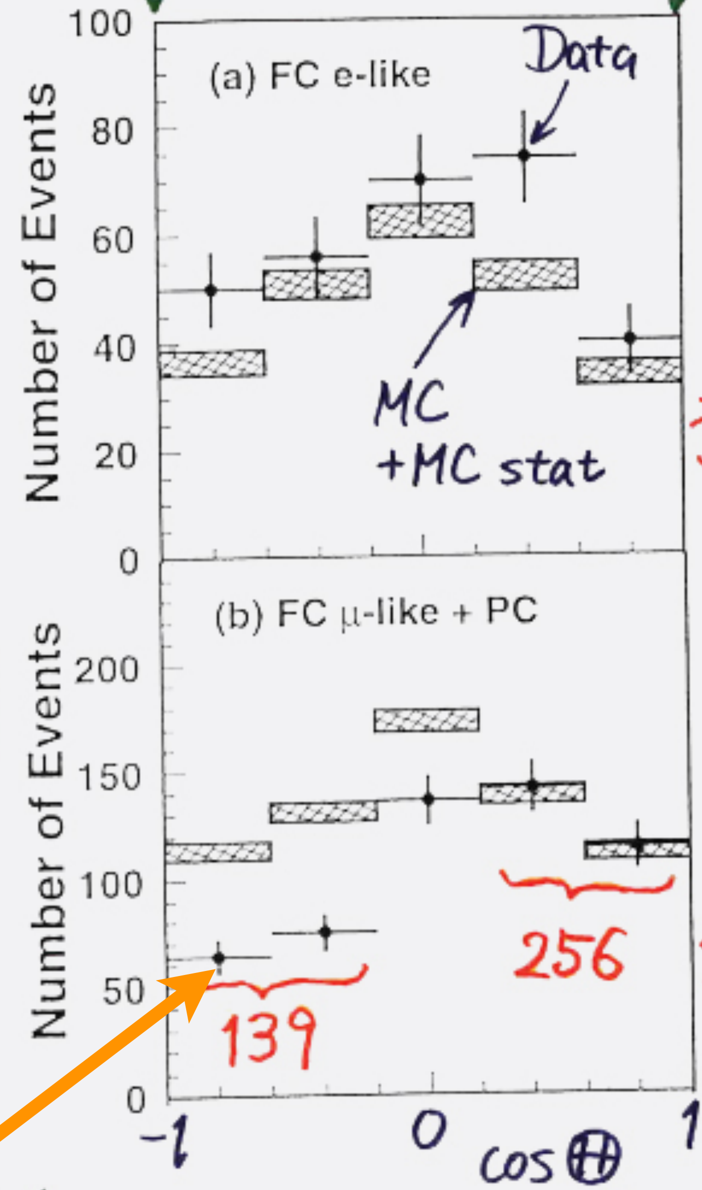
neutrino mass too light for dark matter

1998

a half of expected

Zenith angle dependence (Multi-GeV)

Up-going — Down-going



(e): χ^2(shape) $= 2.8/4$ dof

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

(μ): χ^2(shape) $= 30/4$ dof

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

(6.2σ!!)

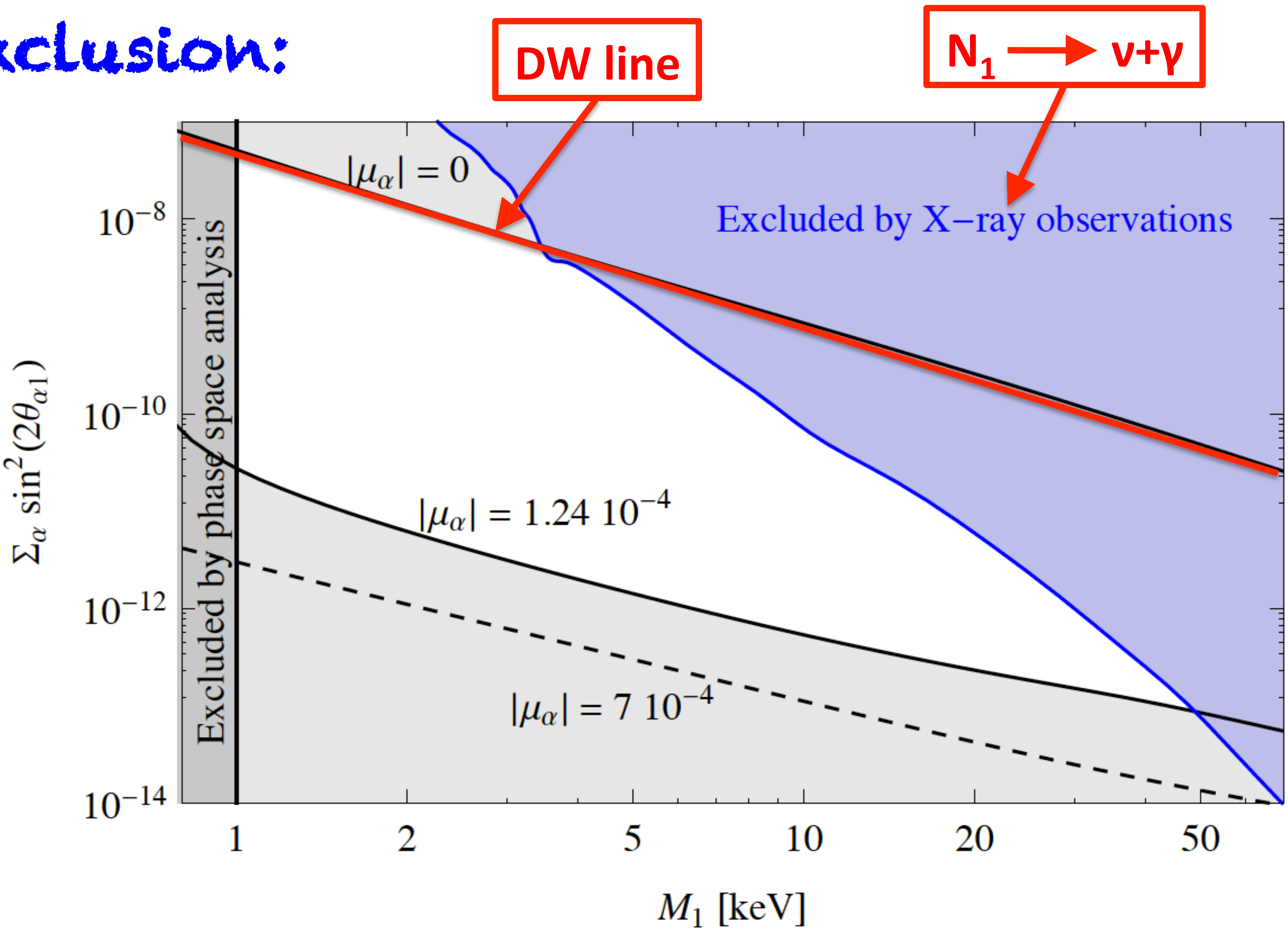
※ Up/Down syst. error for μ-like

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

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

2. Production Mechanisms

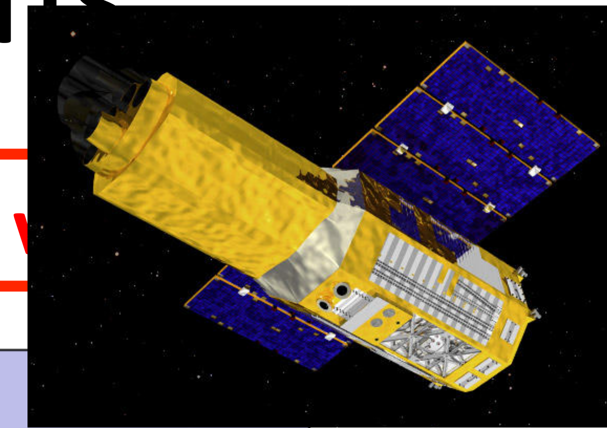
Exclusion:



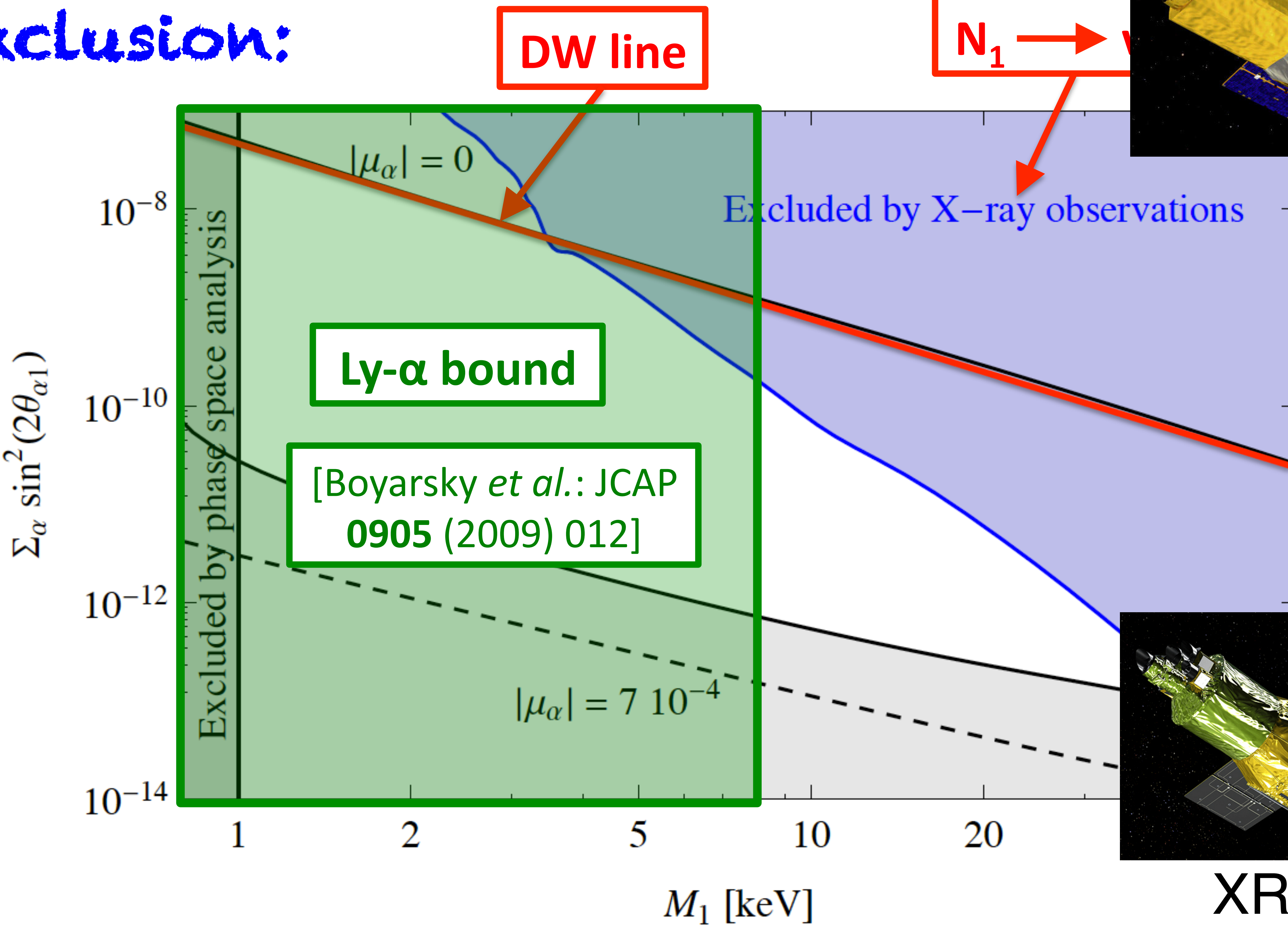
[Canetti *et al.*: Phys. Rev. **D87** (2013) 093006]

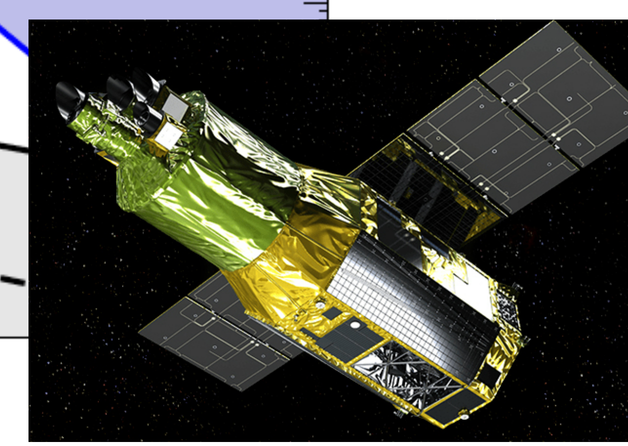
2. Production Mechanisms

Suzaku



Exclusion:

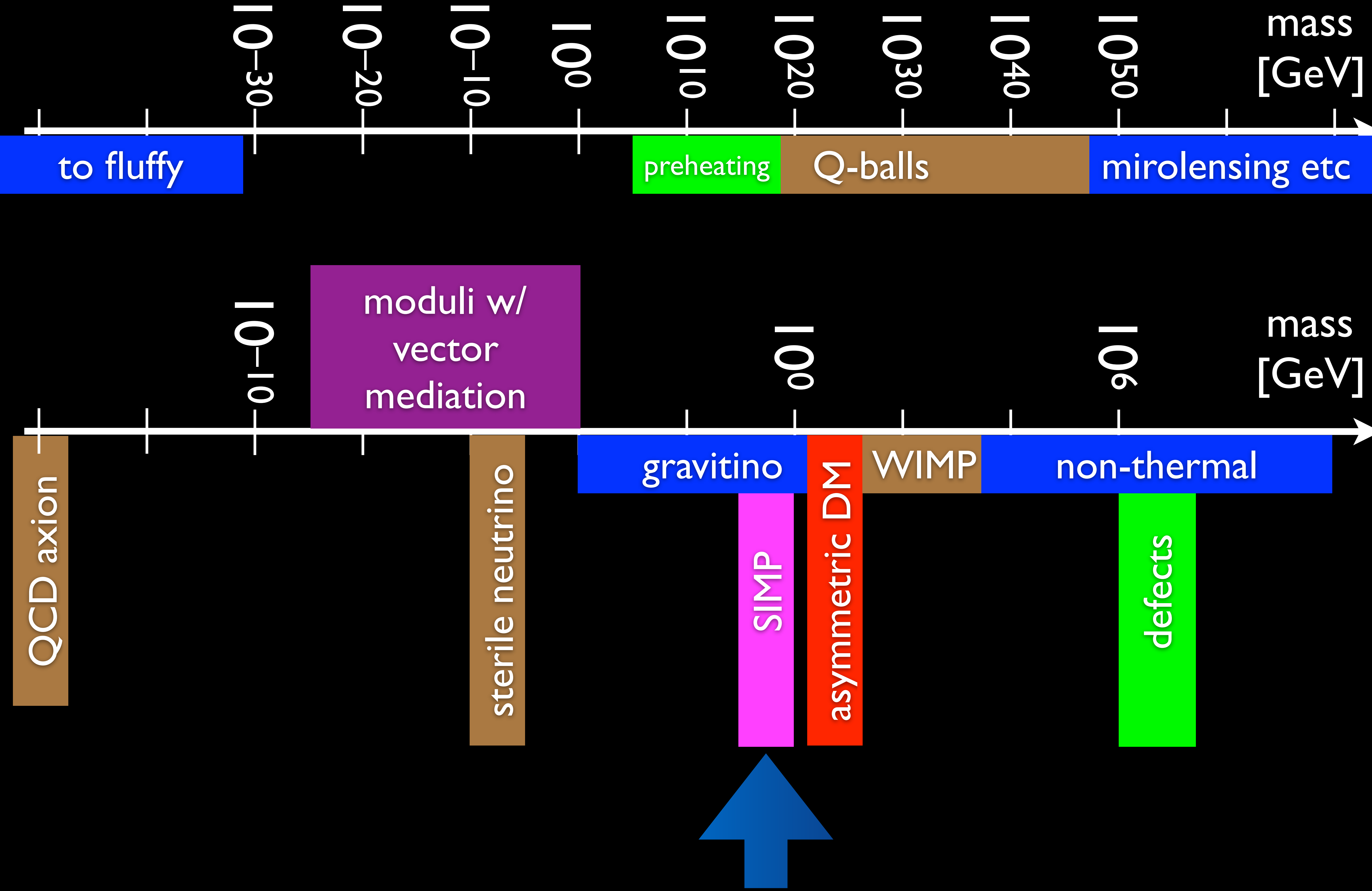




XRISM

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

Alexander Merle


10^{-30}
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10^{6}
mass [GeV]
QCD axion
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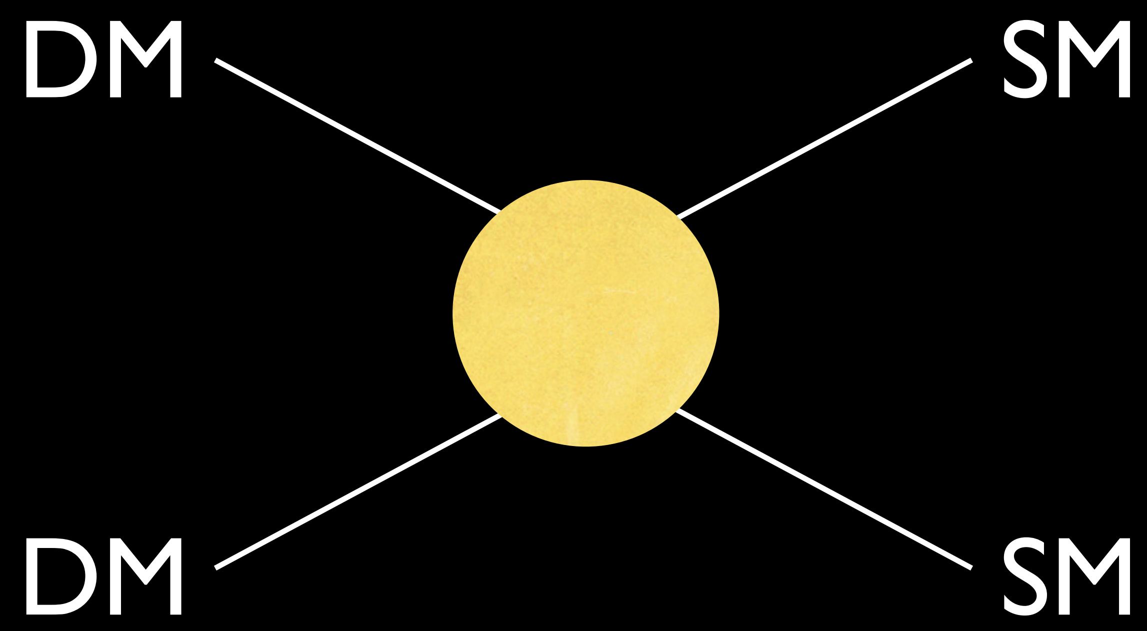
SIMP
asymmetric DM
WIMP
non-thermal
defects

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

Miracles

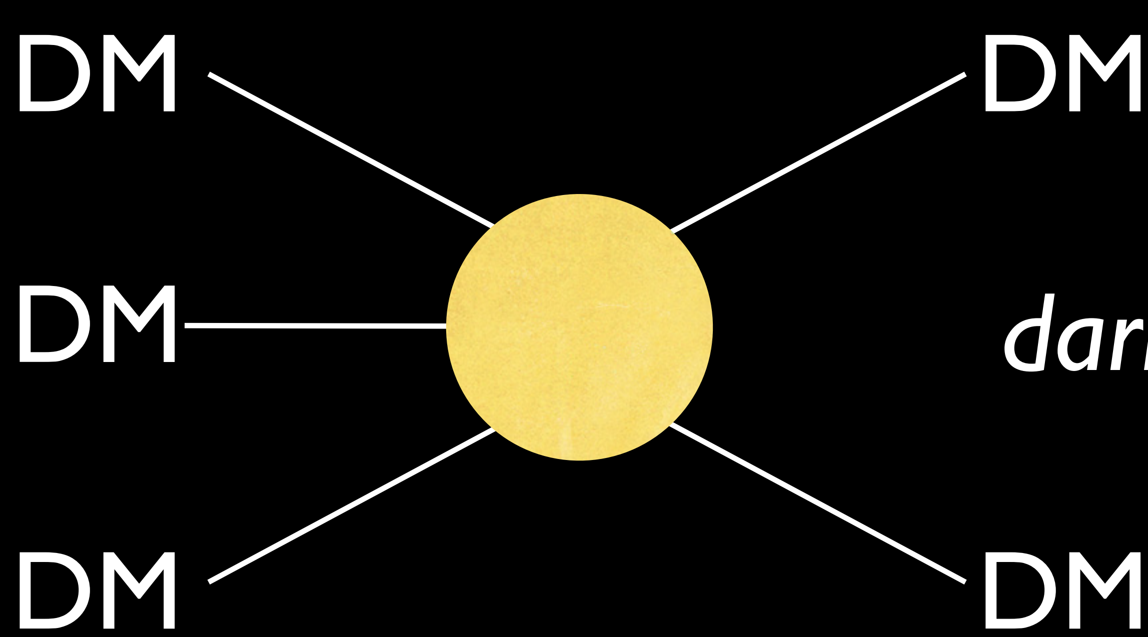


$$\langle \sigma_{2\to 2} v \rangle \approx \frac{\alpha^2}{m^2}$$

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

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

WIMP miracle!



dark pions

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

$$\alpha \approx 4\pi$$

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

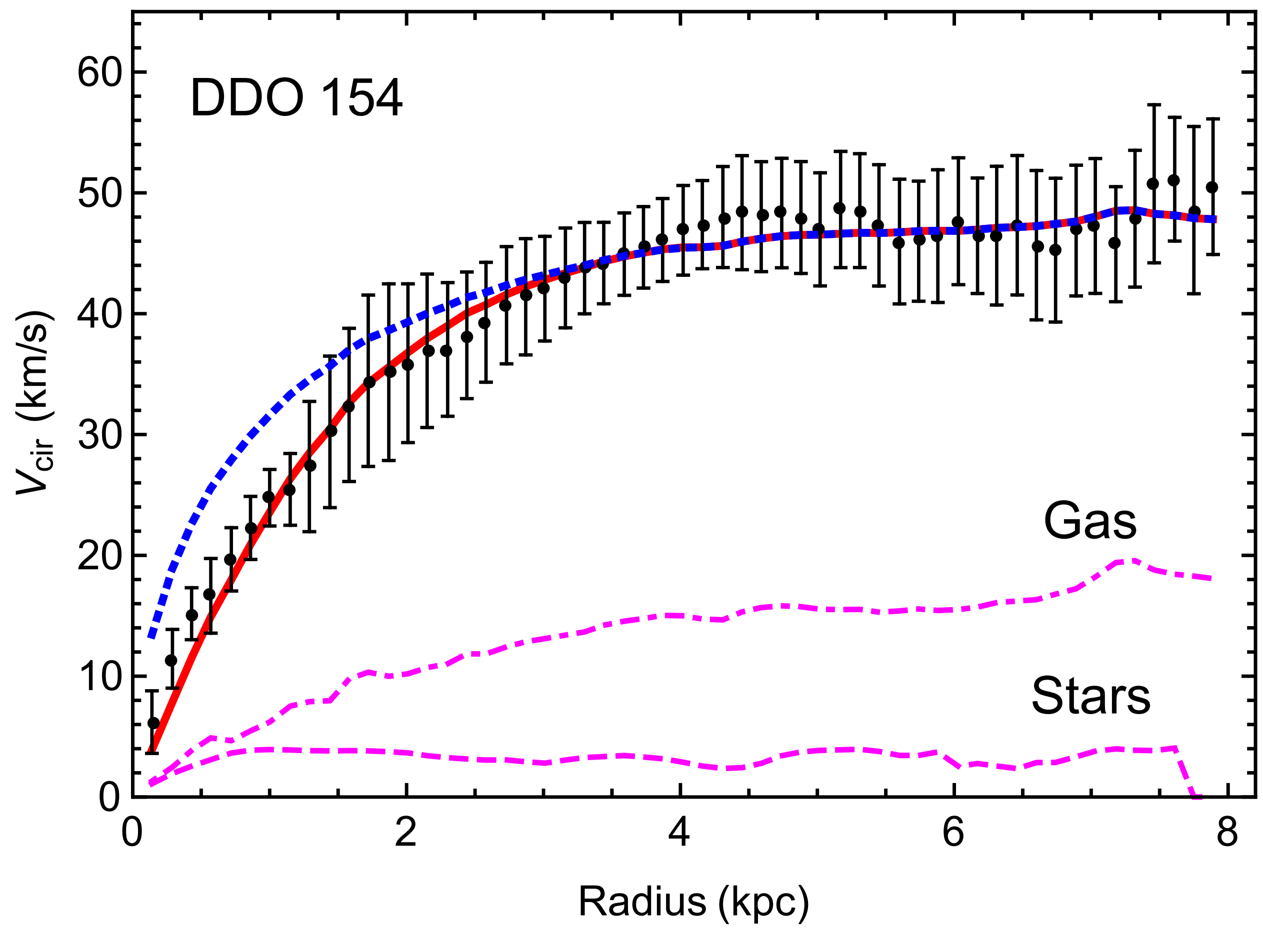
SIMP miracle!

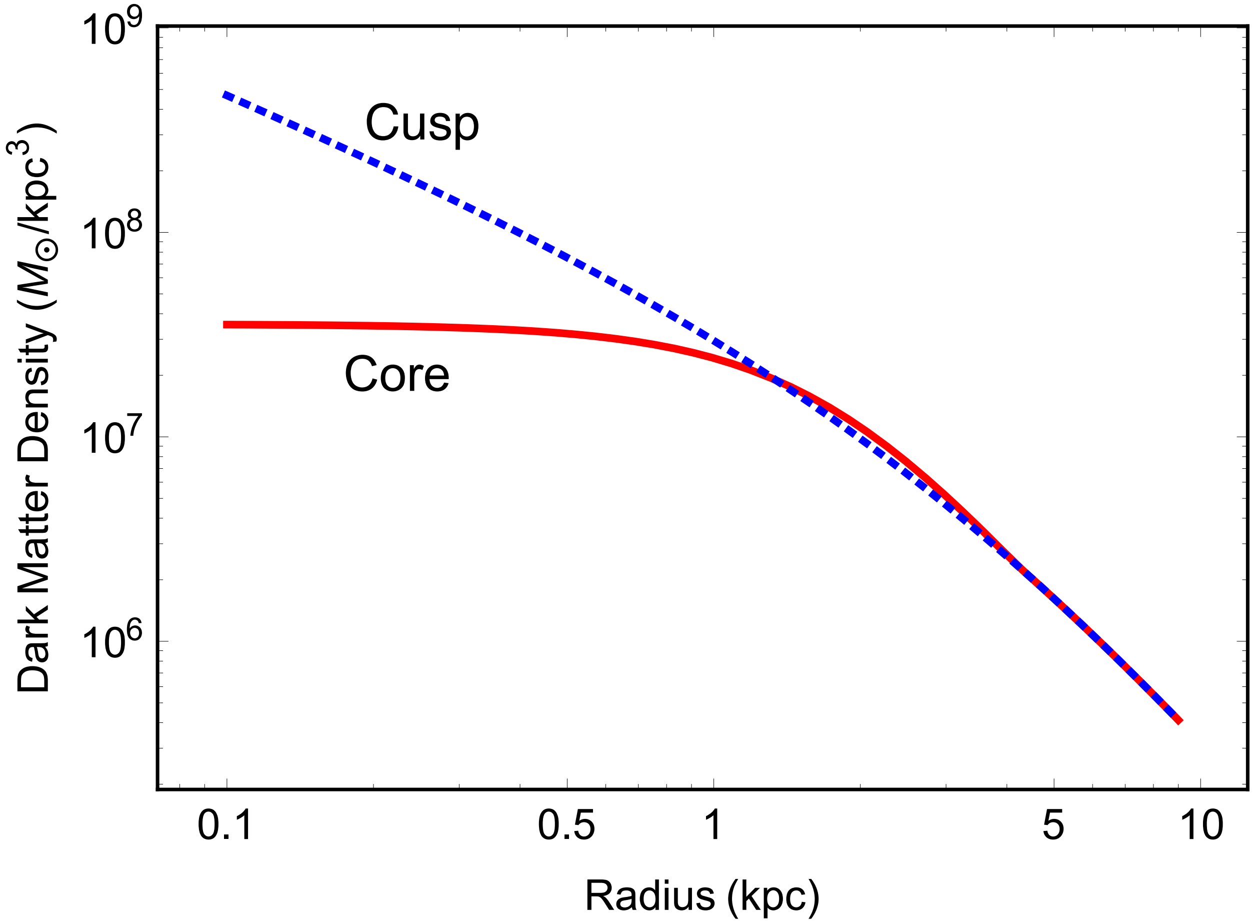
SIMPle

- 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

DDO 154 dwarf galaxy



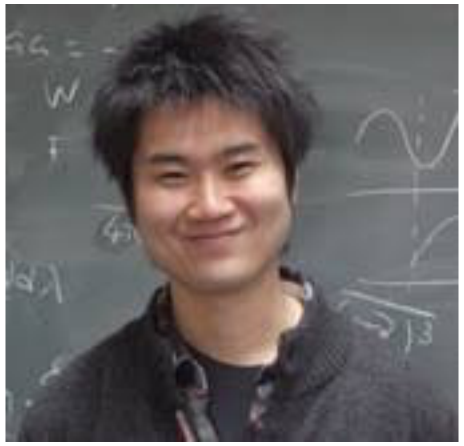


can be explained if dark matter scatters against itself

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

only astrophysical information beyond gravity

Diversity in stellar distribution

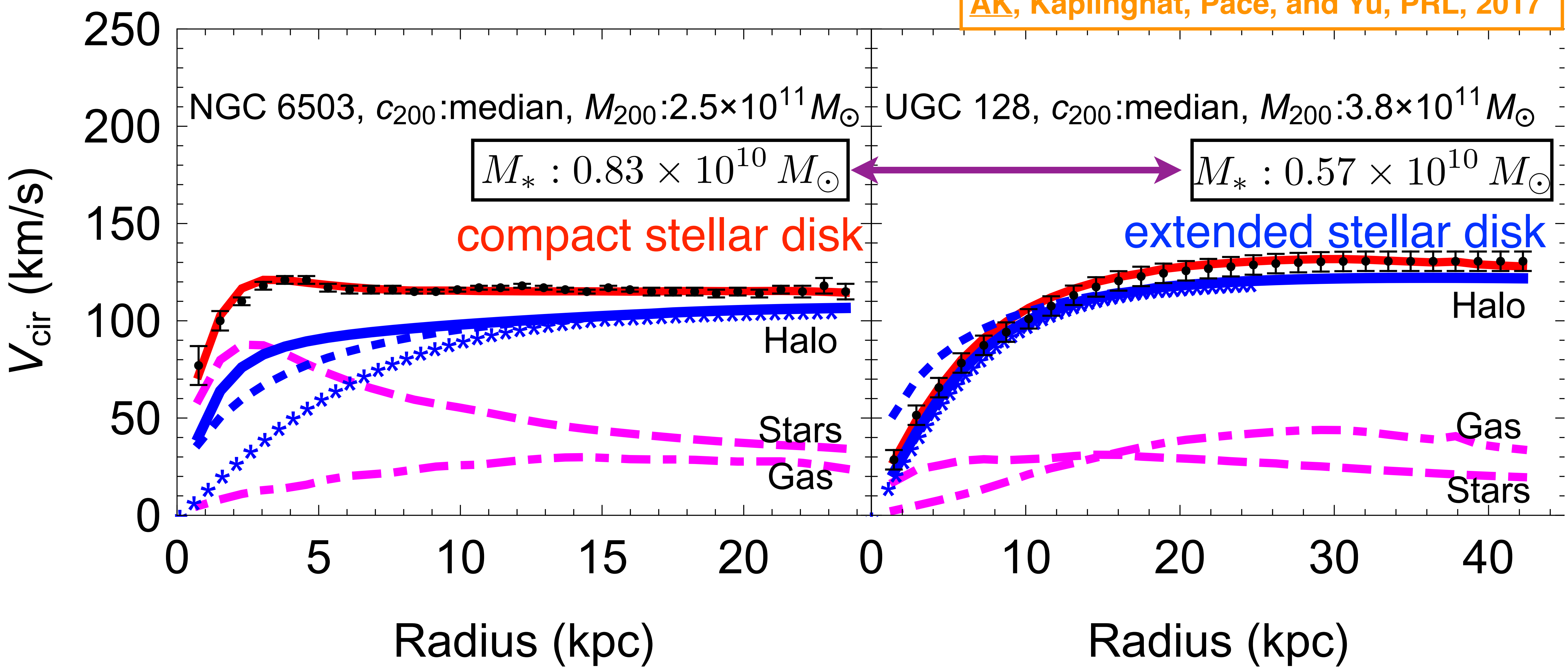


Ayuki Kamada

Similar outer circular velocity and stellar mass, but different stellar distribution

- compact → redistribute SIDM significantly
- extended → unchange SIDM distribution

AK, Kaplinghat, Pace, and Yu, PRL, 2017

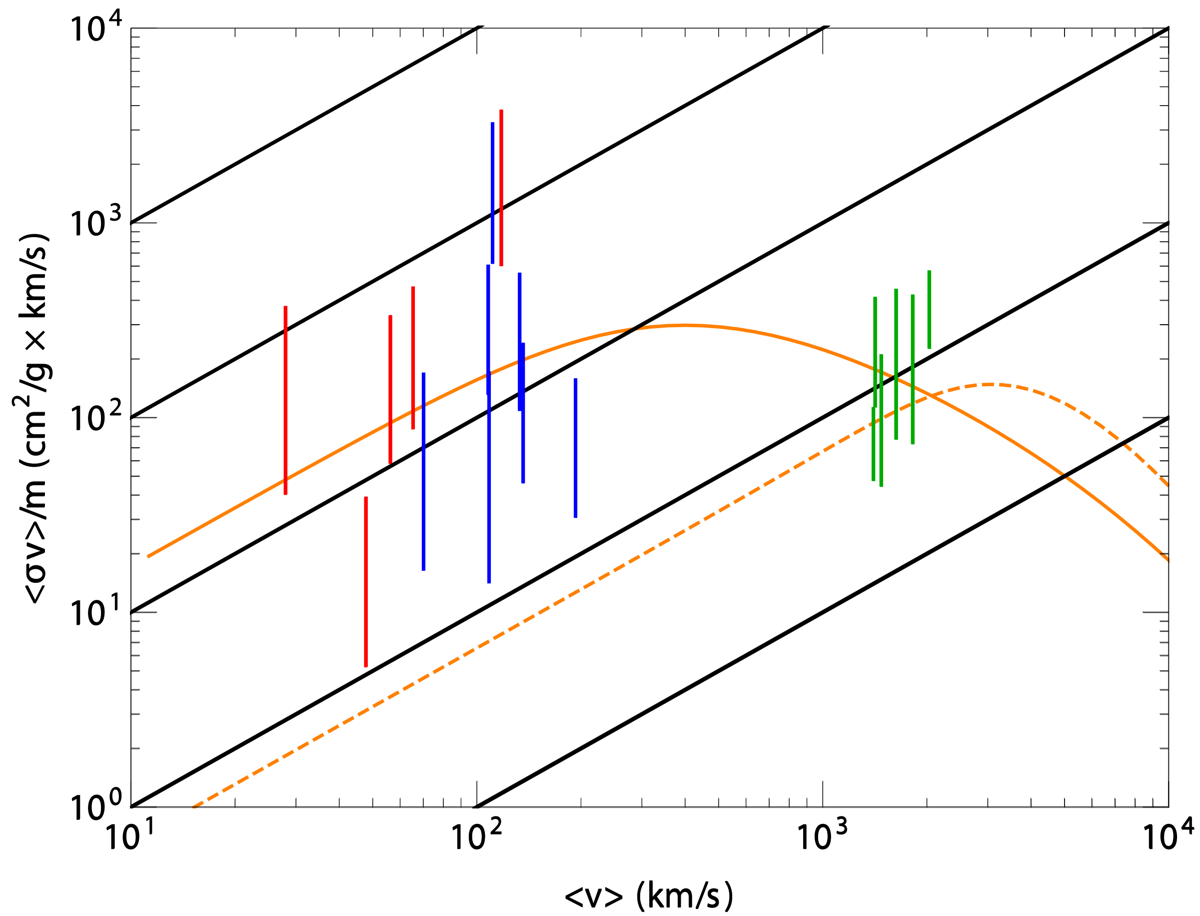


velocity dependence?

- cluster data prefer smaller σ?
- near-threshold resonance can "fit" the data
- *i.e.*, ππ→σ→ππ
  - (Xiaoyong Chu, Camilo Garcia-Cely, HM)
  - useful description by Effective Range Theory (Hans Bethe 1949)

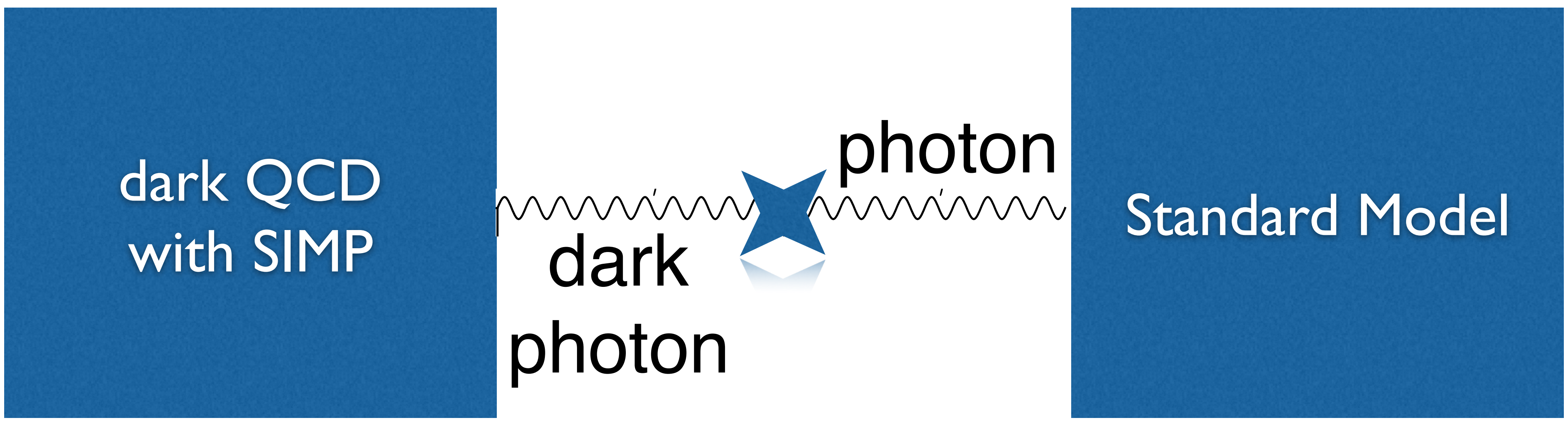
$$\mathcal{L} = m_R g \, \mathrm{RDM}^2 \, .$$

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



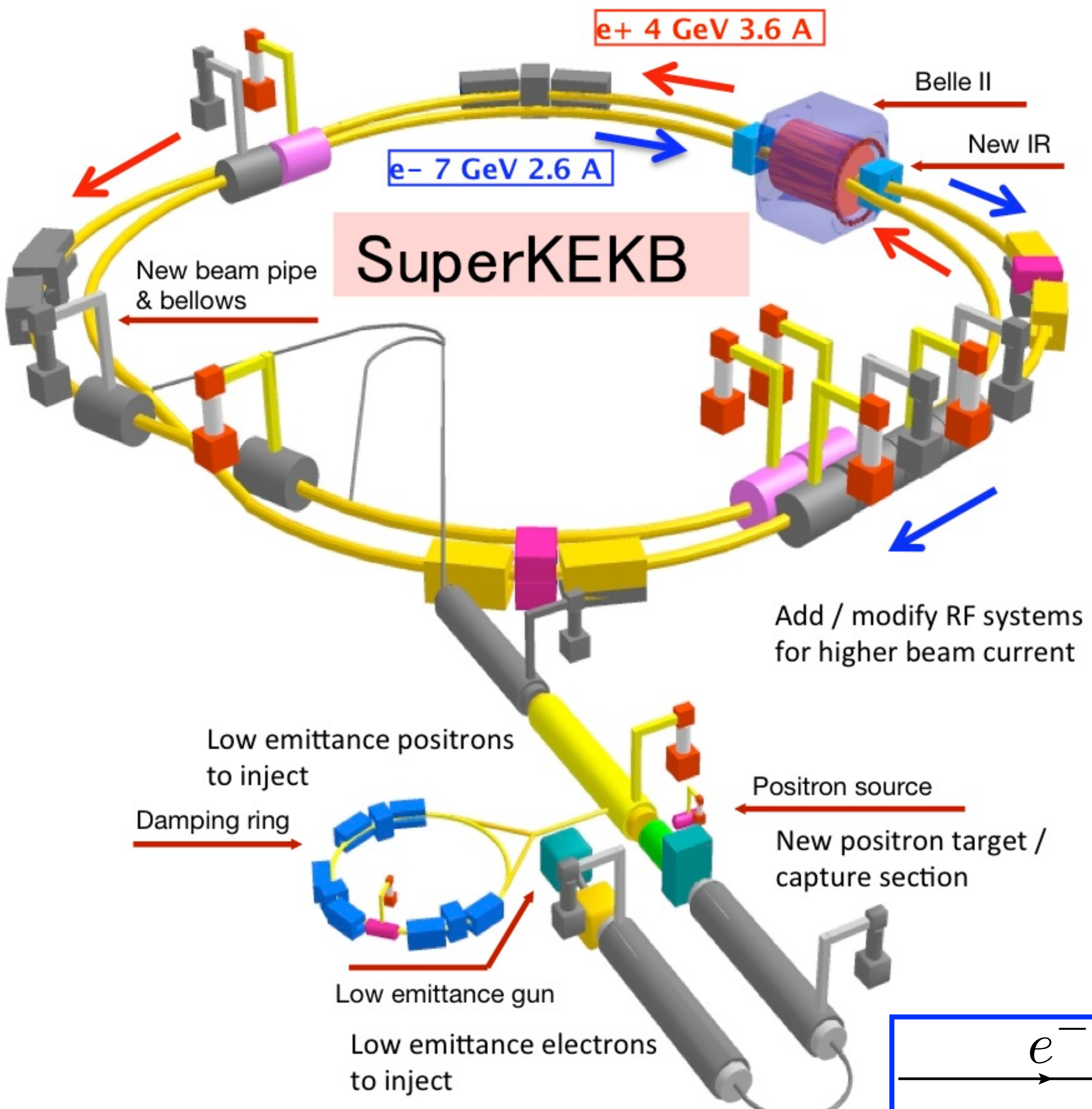
M. Kaplinghat, S. Tulin, and H.-B. Yu, arXiv:1508.03339.

vector portal

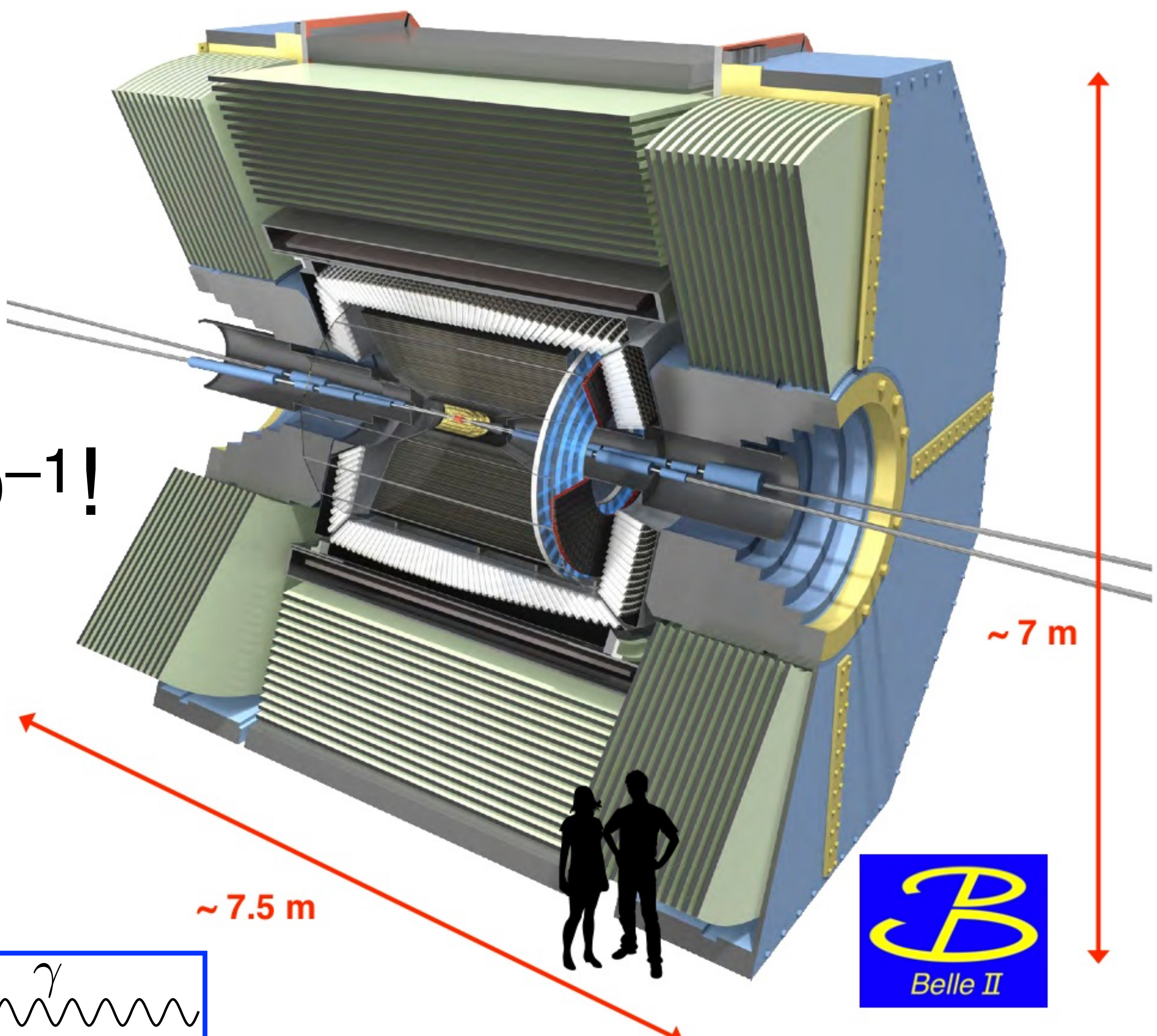


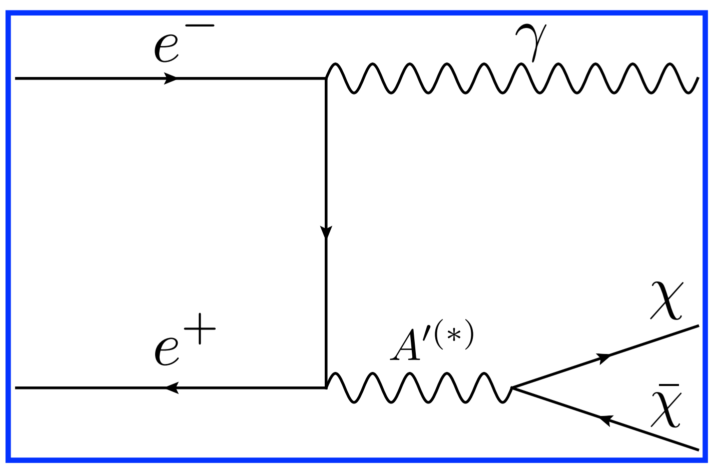
$$\frac{\epsilon_\gamma}{2c_W} B_{\mu\nu} F_D^{\mu\nu}$$

high-lumi e^+e^-

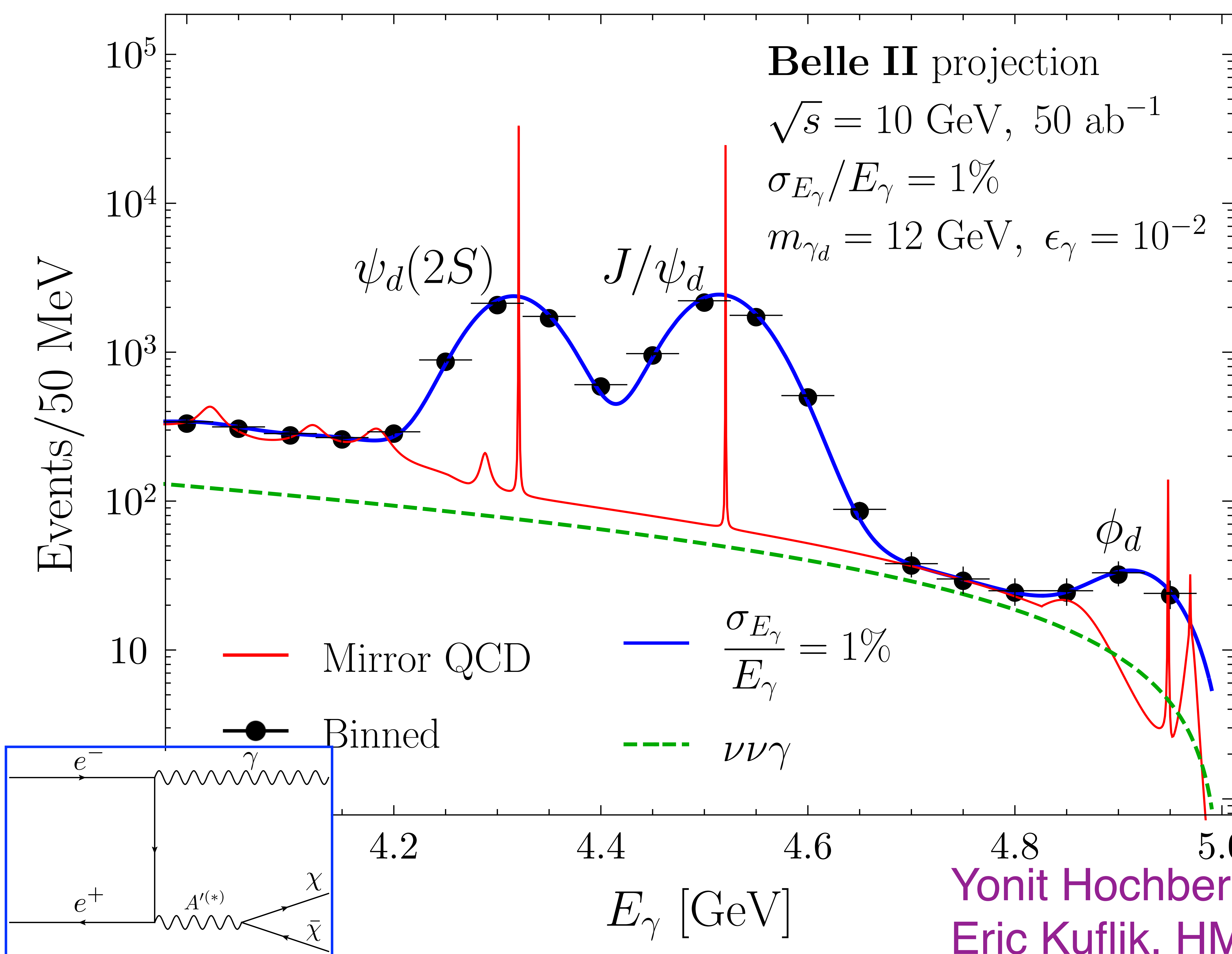


50 ab^{-1}!



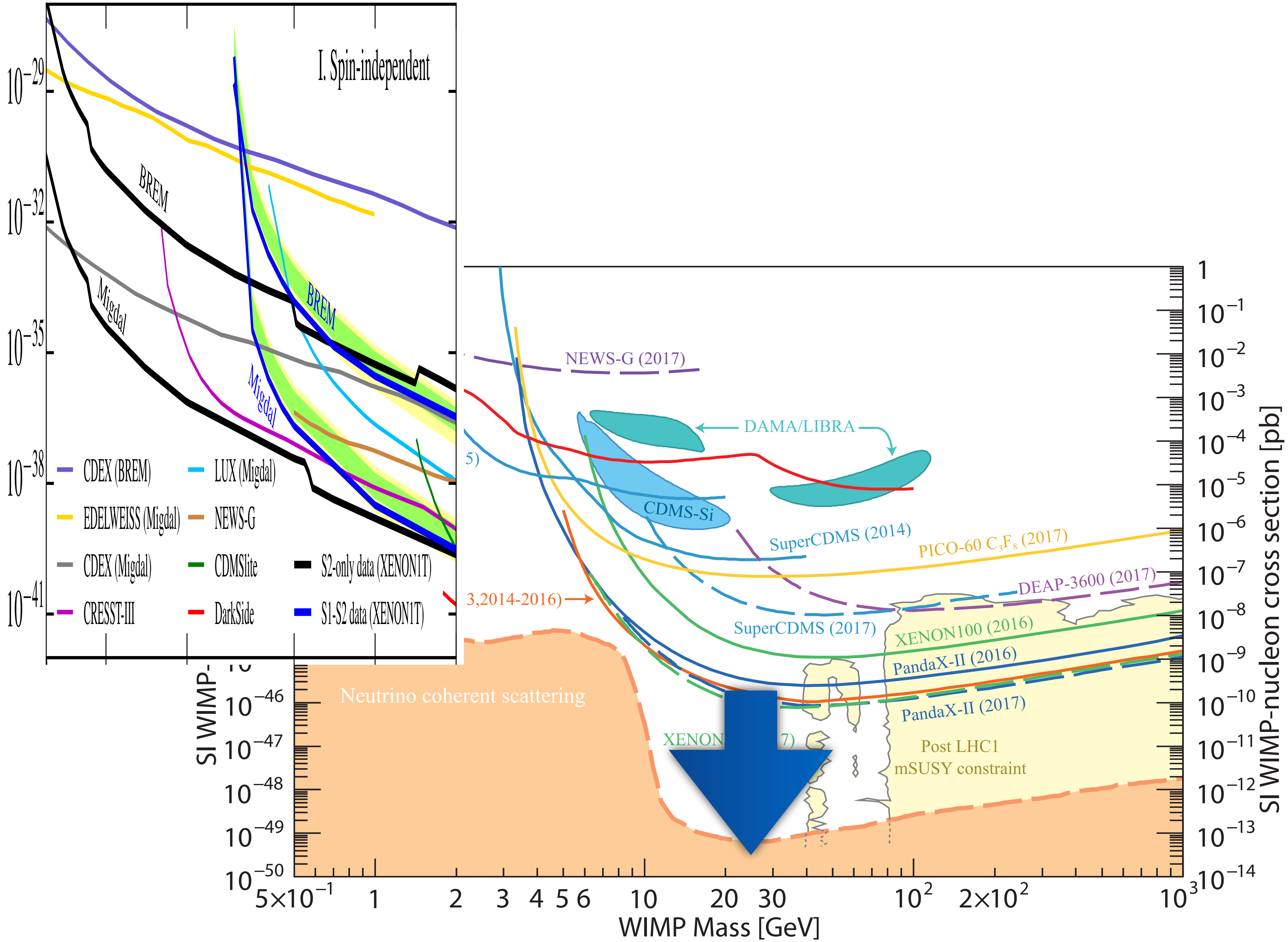


$$E_\gamma = \frac{\sqrt{s}}{2}\left(1 - \frac{M_{\text{inv}}^2}{s}\right)$$



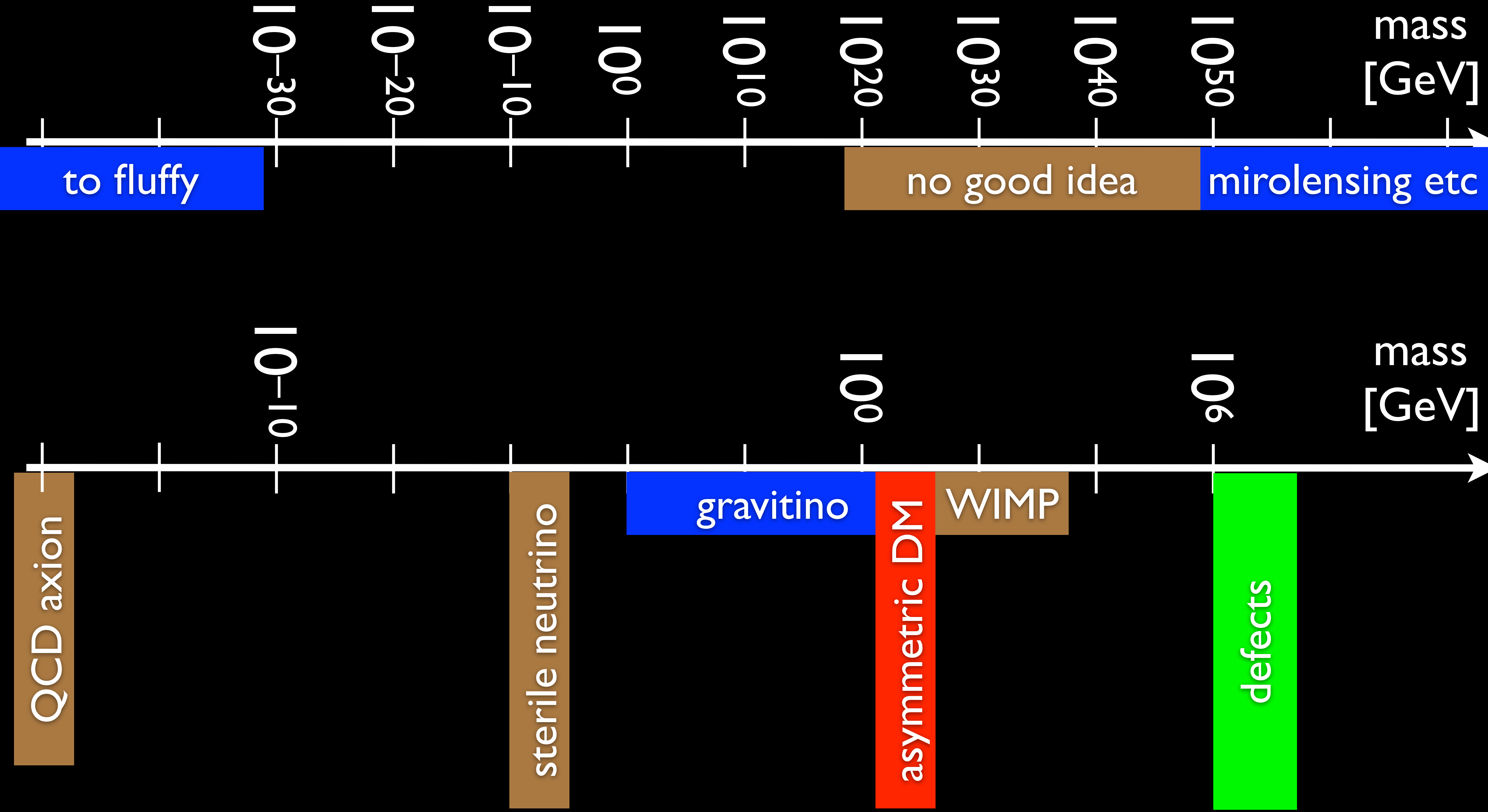
Yonit Hochberg, Eric Kuflik, HM

XENON1t
arXiv:1907.12771



PDG 2018

Migdal effect
M. Ibe et al, arXiv:1707.07258


10^{-30}
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10^{0}
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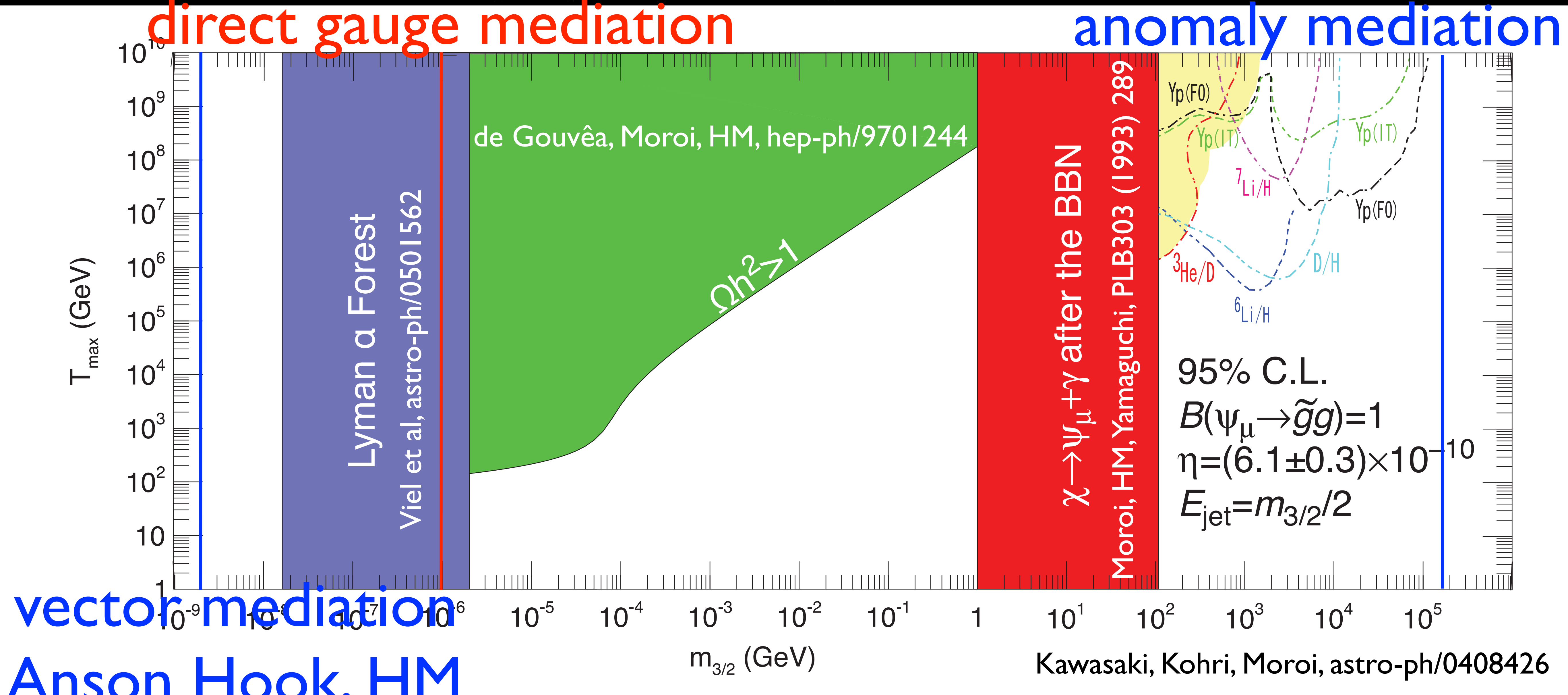
10^{30}
10^{40}
10^{50}
mass [GeV]
to fluffy
no good idea
mirolensing etc
10^{-10}
10^{0}
10^{6}
mass [GeV]
QCD axion
sterile neutrino
gravitino
asymmetric DM
WIMP
defects

Gravitino problem

- Gravitinos produced thermally
- If decays after the BBN, dissociates synthesized light elements
- Hadronic decays particularly bad

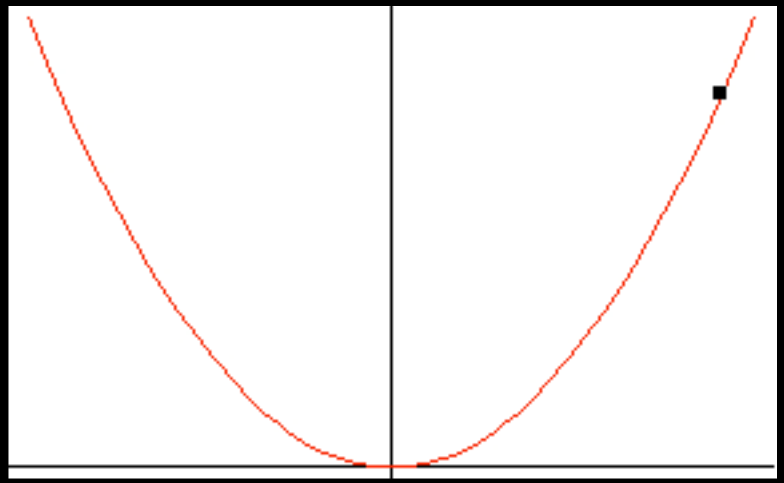
$$\frac{n_{3/2}}{s} \sim 10^{-12} \frac{T_{RH}}{10^{10}\text{GeV}}$$

$$m_{3/2}^2 = \frac{1}{3M_{Pl}^2}\left(|F|^2 + \frac{1}{2}D^2\right)$$



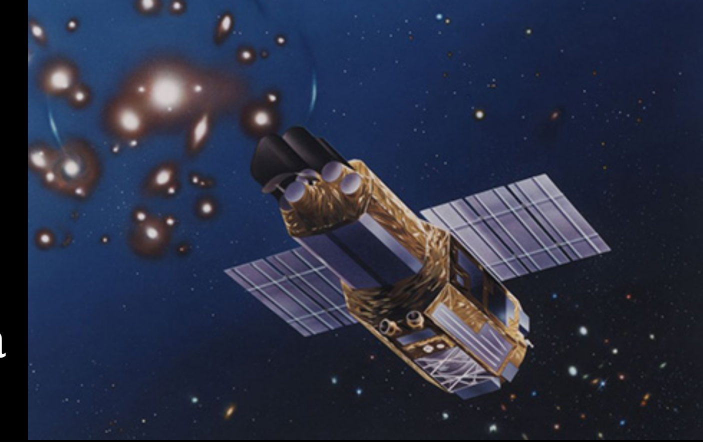
coherent oscillation

- any scalar field with initial displacement can in principle be dark matter



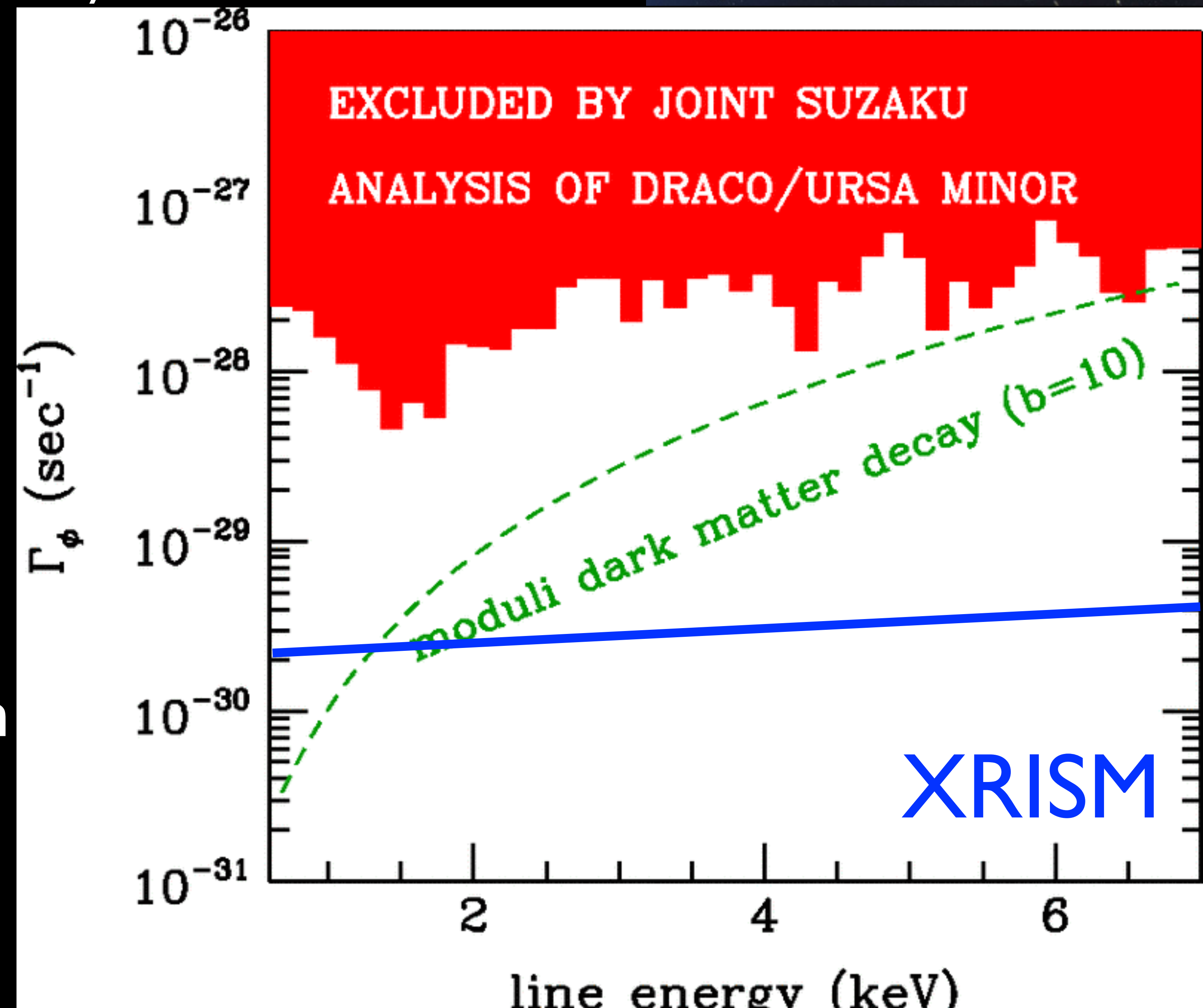
$$\phi_0 \approx \left(\frac{T_{eq}^2 M_{Pl}^3}{m_\phi} \right)^{1/4} = (3 \times 10^{11} \mathrm{GeV}) \left(\frac{\mathrm{eV}}{m_\phi} \right)^{1/4}$$

$$\tau(\phi \to \gamma\gamma) \sim 10^{28}\text{sec}\left(\frac{m_\phi}{10\text{keV}}\right)^{-3}$$



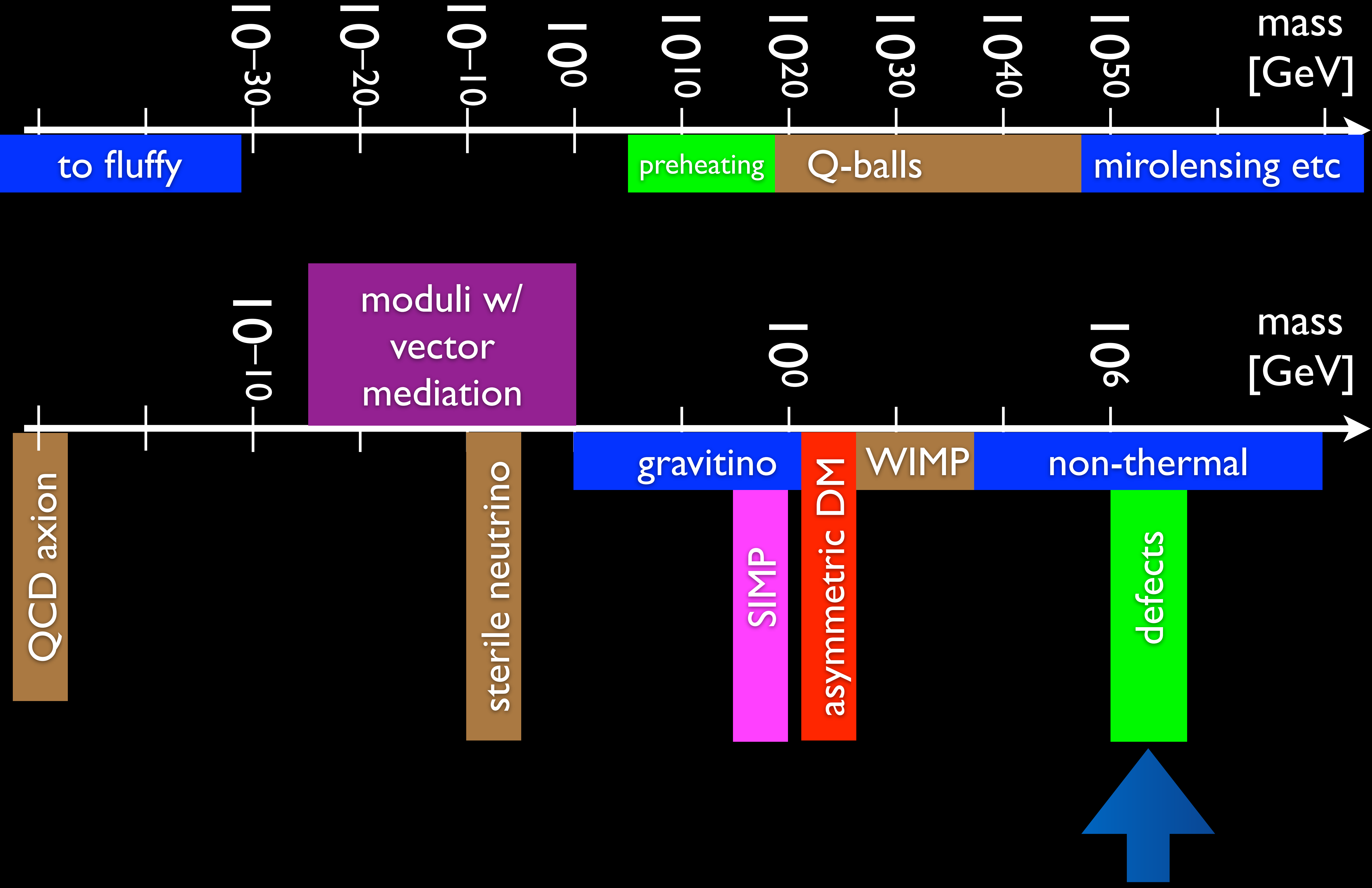
moduli

Kusenko, Lowenstein, Yanagida
Phys. Rev. D 87, 043508



- If stabilized by low-energy SUSY breaking (~TeV), modulus may be very light
- moduli mass expected to be comparable to the gravitino mass
- modulus coherent oscillation can be dark matter (de Gouvêa, HM, Moroi, hep-ph/9701244)

$$\phi_0 \approx \left(\frac{T_{eq}^2 M_{Pl}^3}{m_\phi}\right)^{1/4} = (3\times 10^{11}\text{GeV})\left(\frac{\text{eV}}{m_\phi}\right)^{1/4}$$



mass [GeV]
10^{-30}
10^{-20}
10^{-10}
10^{0}
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defects

Topological defects

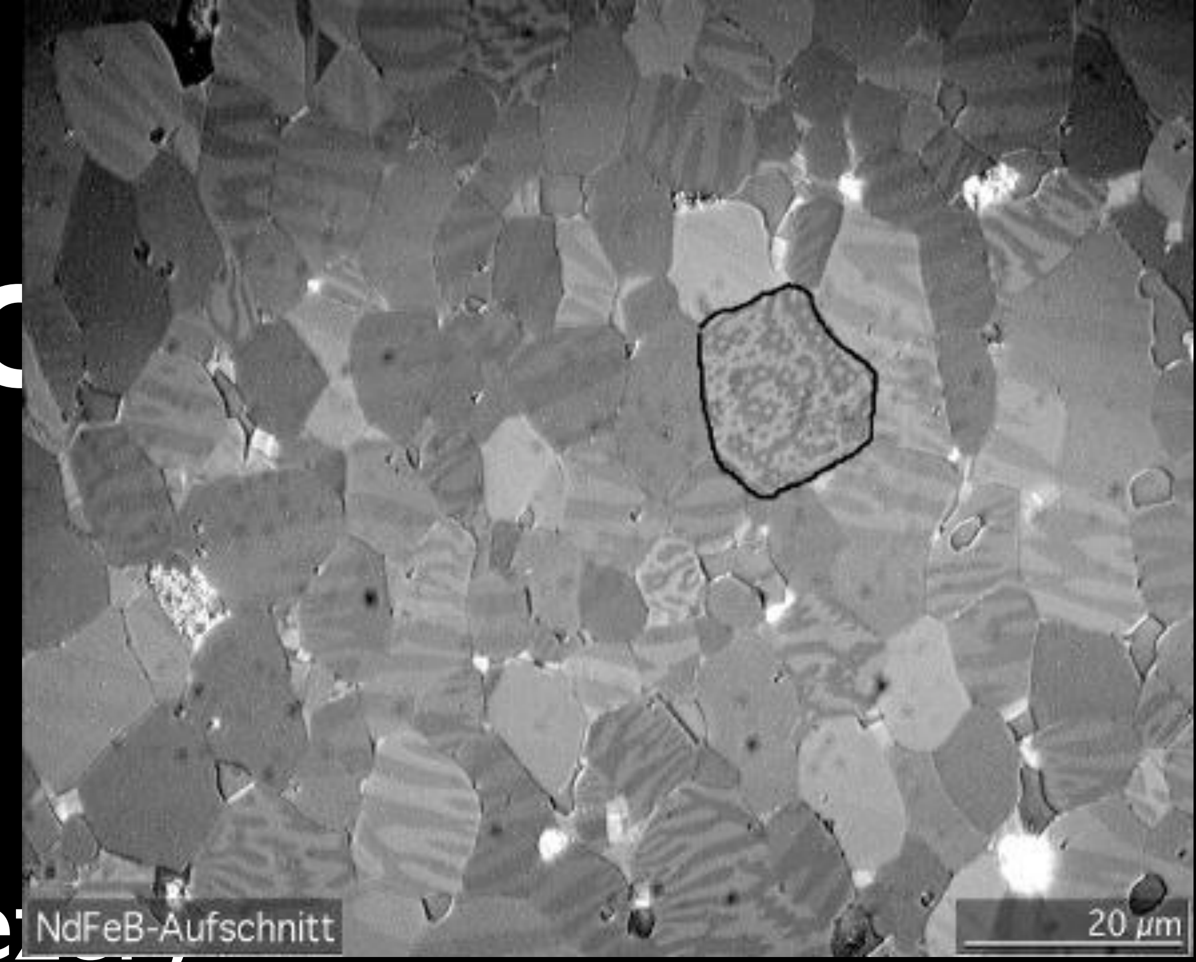
- common interest among AMO, condensed matter, particle physics, algebraic geometry
- symmetry breaking $G \to H$
- coset space G/H describes vacua
- can the space be mapped non-trivially into the coset space?
- $\pi_0(G/H) \neq 0$: domain walls
- $\pi_1(G/H) \neq 0$: string (vortex)
- $\pi_2(G/H) \neq 0$: monopole
- $\pi_3(G/H) \neq 0$: skyrmion

Abrikosov
2003 Nobel

Kibble mechanism

- Kibble (1976) argued that phase transitions in expanding universe produce defects
- second-order phase transitions have infinite correlation length $\xi \propto |T - T_c|^{-\nu}$
- Therefore, all regions of causally connected space choose the same vacuum on G/H
- However, there is a finite horizon size $H^{-1} \approx M_{Pl}/T^2$
- Kibble: about one defect per horizon

Time sc



- We know that we need
  material slowly to grow
  (e.g. clear ice in the free
- How does time scale come into the discussion?
- It takes time for things to line up!
  relaxation
- *quench*ed phase transition
- general discussion by Zurek (1985)

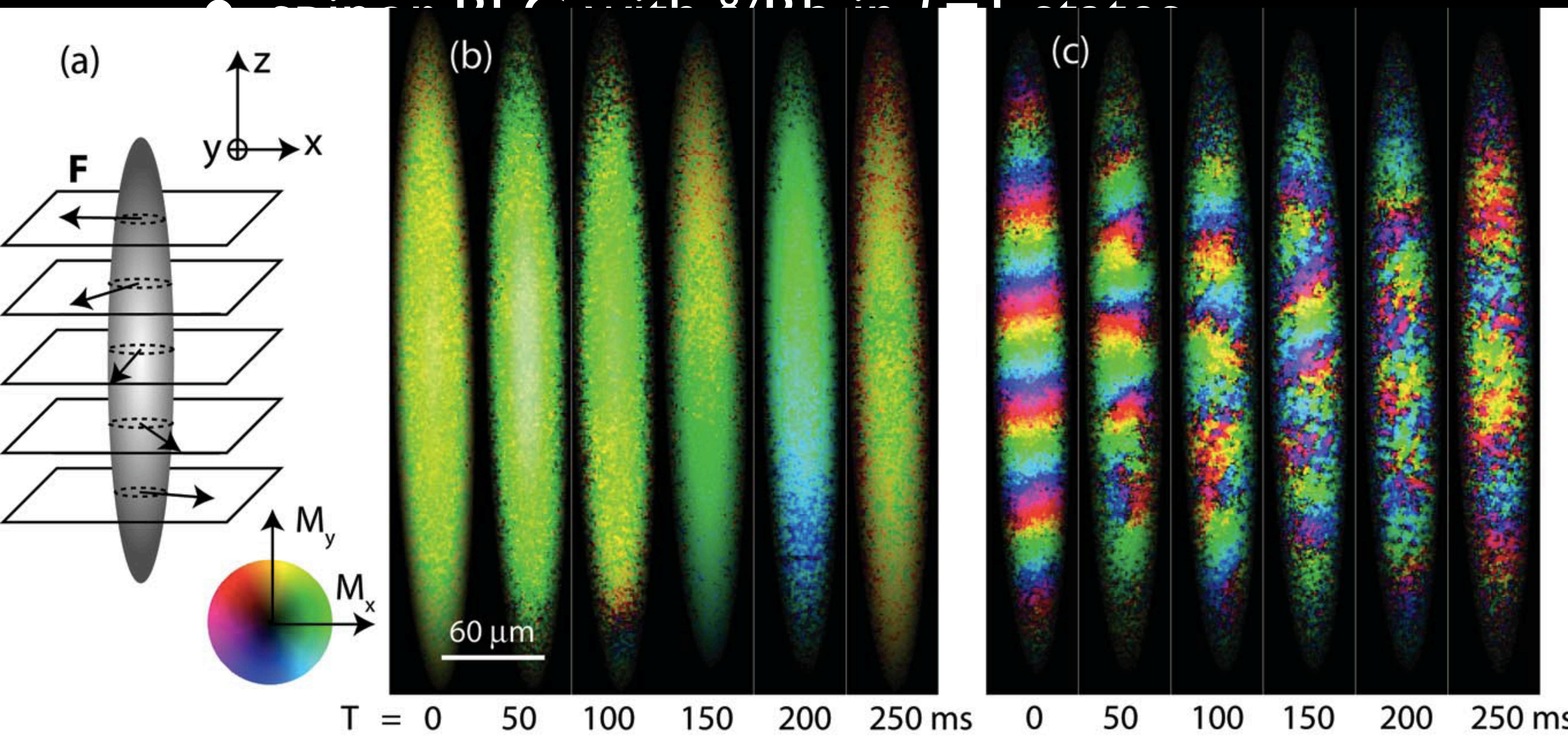
"Cosmological Experiments in Superfluid Helium?"

Phase transition revisited

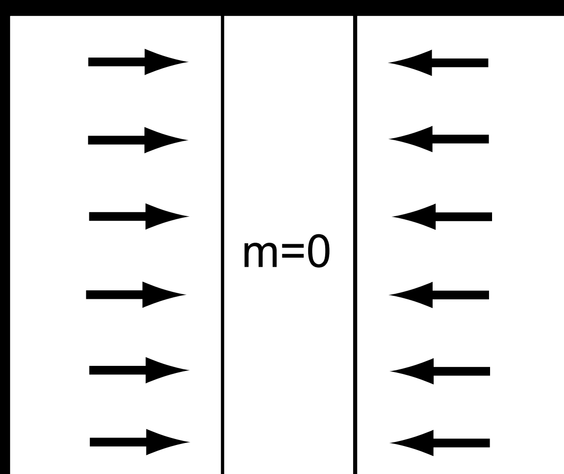
- correlation length: $\xi \propto |T - T_c|^{-\nu}$
- relaxation time: $\tau \propto |T - T_c|^{-\mu}$
- It takes an infinite amount of time for the system to "line up" at T_c
- If the system cools too quickly, it won't line up even within a causally connected region

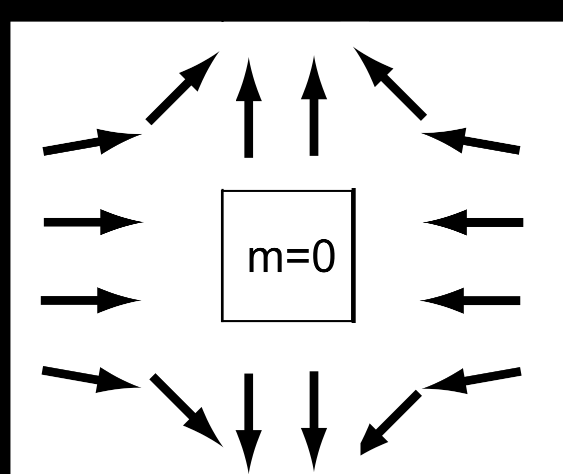
Experimental tests

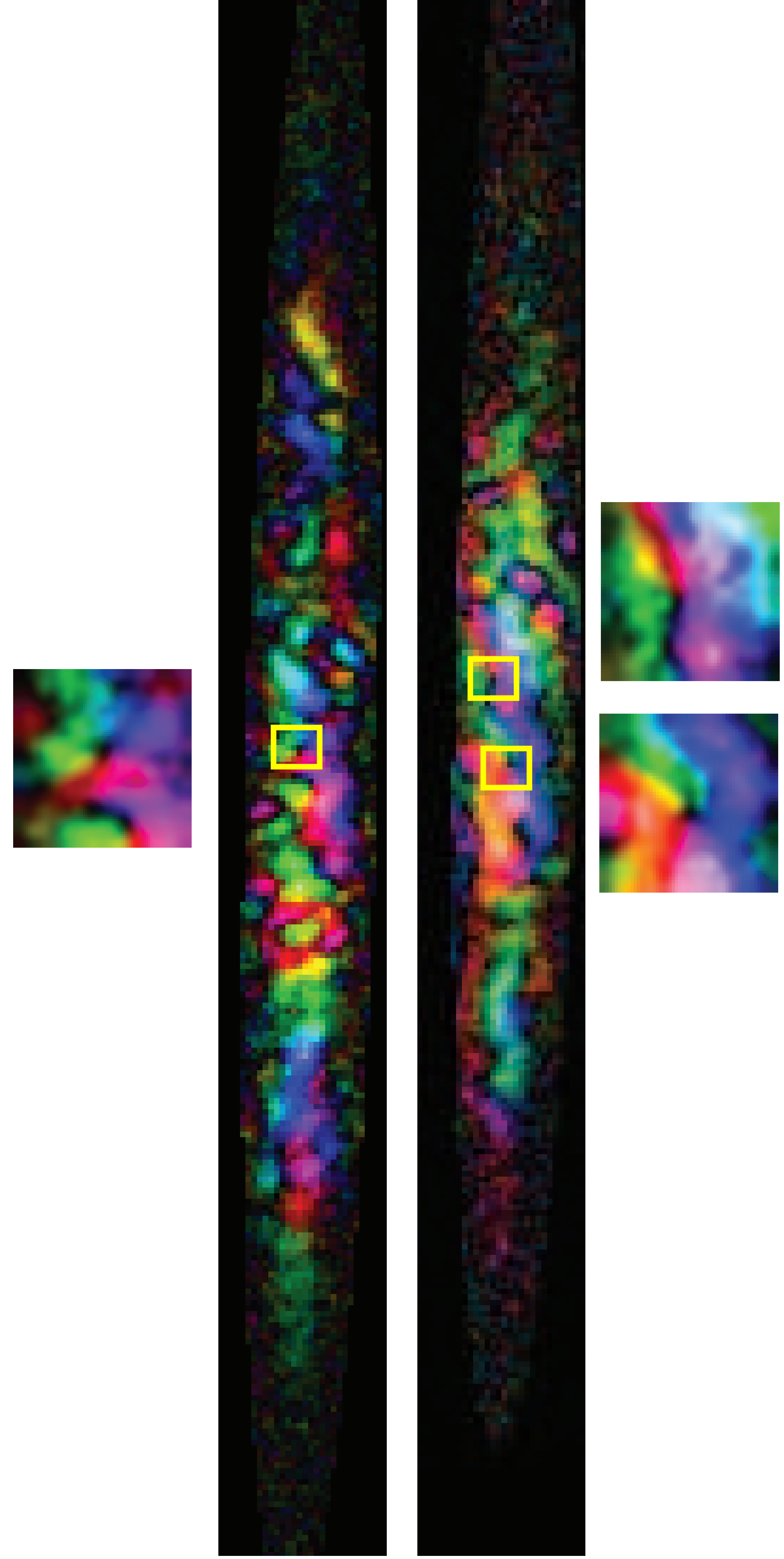
- D. Stamper-Kurn group (Berkeley)
- spinor BEC with ^{87}Rb in F=1 states



Vortex formation

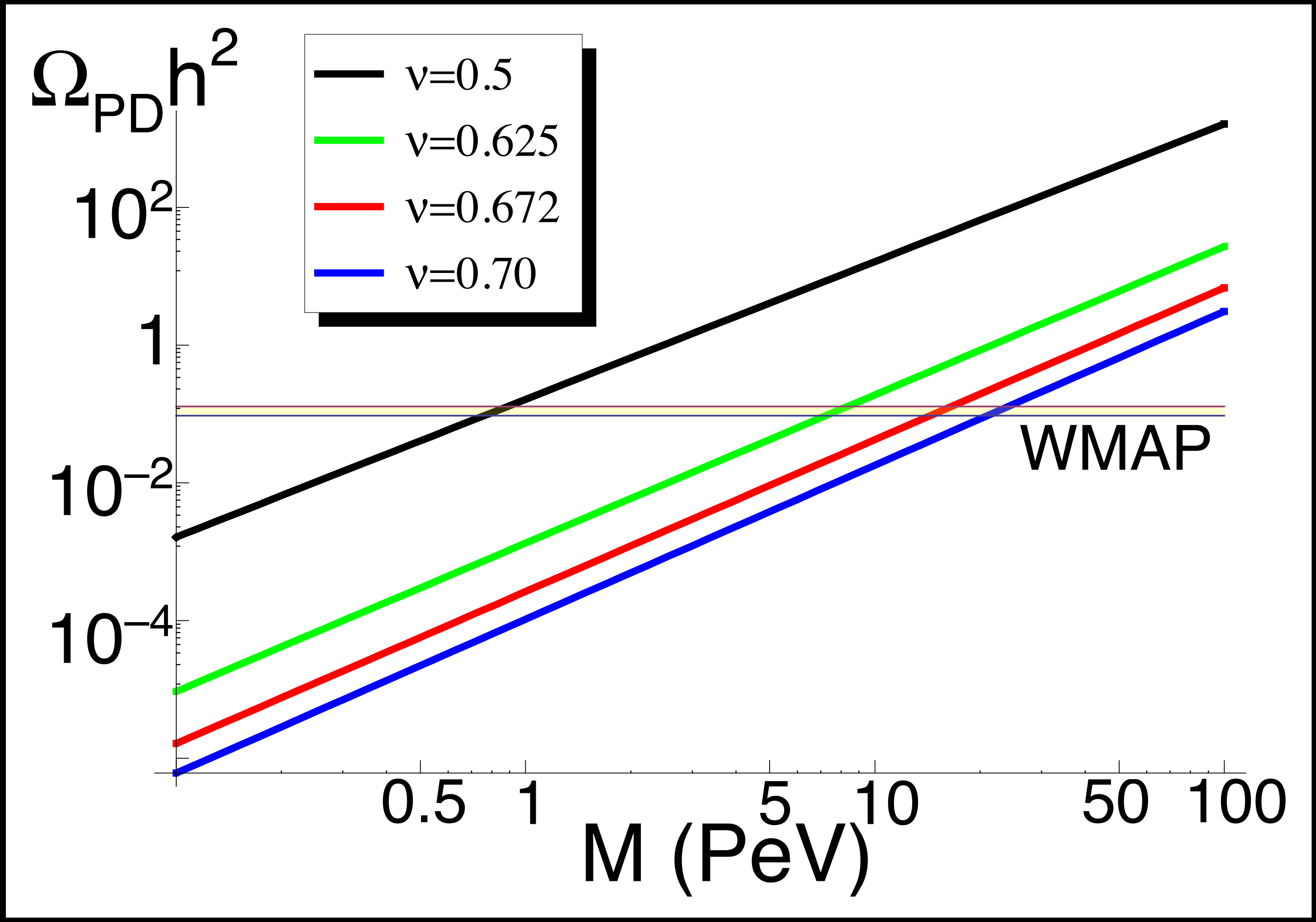






topological dark matter

- point-like defect
- Kibble estimate: one per $H^{-1} \approx T_c^{-1} |M_{Pl}/T_c|$
- Then it could well be dark matter!
- Zurek estimate: one per $\xi \approx T_c^{-1} |M_{Pl}/T_c|^{1/3}$
- new "long-range force" among dark matter
- explain dwarf galaxies?



HM, Jing Shu

Conclusion

- Dark Matter exists, awaiting for discovery
  - In general, Dark Sector may exist, too
- Very little clue on mass scales now
  - wide parameter space: *opportunity!*
- WIMP still main paradigm, reach ν floor
- many new ideas on lighter dark matter
- colliders, beam dump, underground, cosmic rays, cavity, new technologies
- strategy: *look wherever we can!*