Strongly Interacting Massive Particles

with Yonit Hochberg and Eric Kuflik

秋の学校「理論と観測から迫るダークマターの正体とその分布」

国立天文台 Nov 9, 2016

Hitoshi Murayama (Berkeley, Kavli IPMU)

arXiv:1411.3727 w/ Tomer Volansky Jay Wacker,
arXiv:1512.07917, many more papers to come

暗黒物質
ゲテモノ候補

秋の学校「理論と観測から迫るダークマターの正体とその分布」

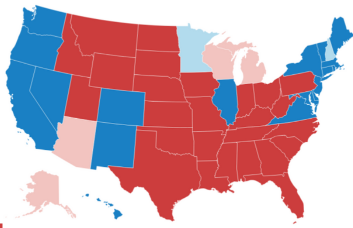
国立天文台 Nov 9, 2016

Hitoshi Murayama (Berkeley, Kavli IPMU)

The New York Times | http://nyti.ms/2ezzlp2

President »

218 **266**



Clinton 270 to win Trump

Full Results 2:33 AM ET

Key States

Electoral votes	Fla. 29	Mich. 16	N.H. 4	N.C. 15	Pa. 20	Wis. 10	Va. 13	Ariz. 11	Colo. 9	Minn. 10
Clinton	48%	47%	48%	47%	48%	46%	50% ✓	45%	48% ✓	47%
Trump	49% ✓	48%	47%	51% ✓	49% ✓	49%	45%	50%	45%	45%
Reporting	100%	94%	91%	100%	99%	99%	98%	83%	76%	92%

Senate »

Dem.	Rep.
47	51

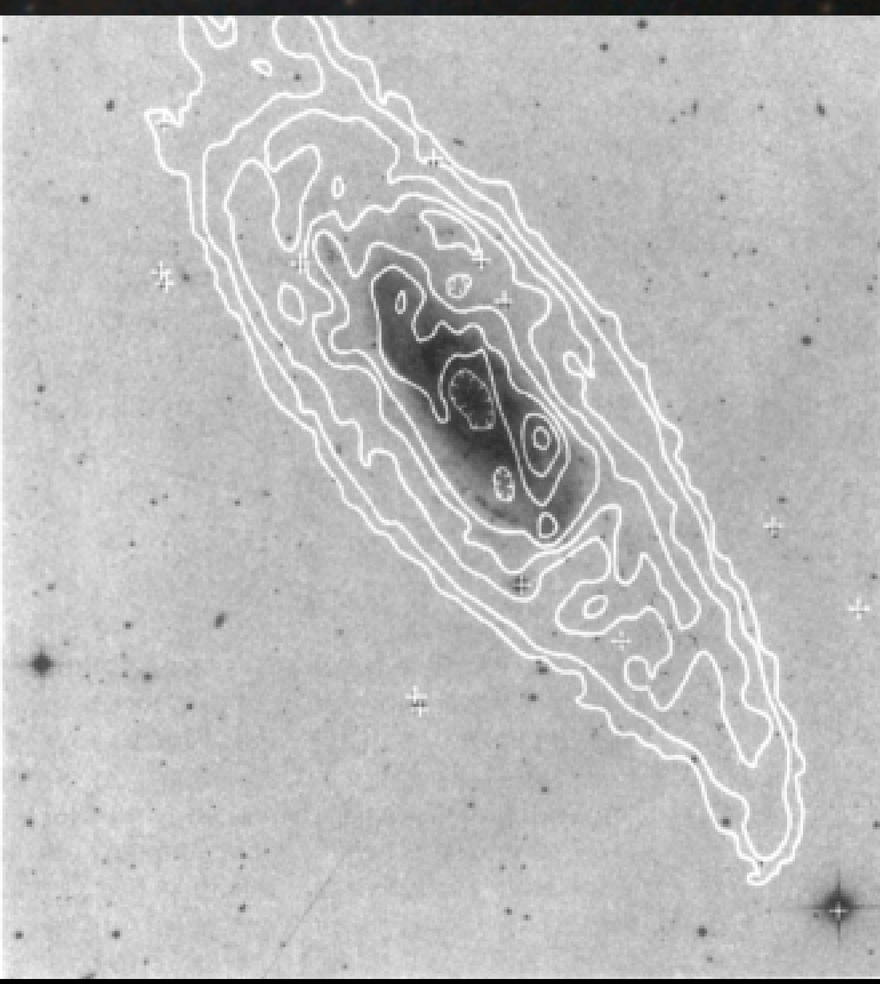
House »

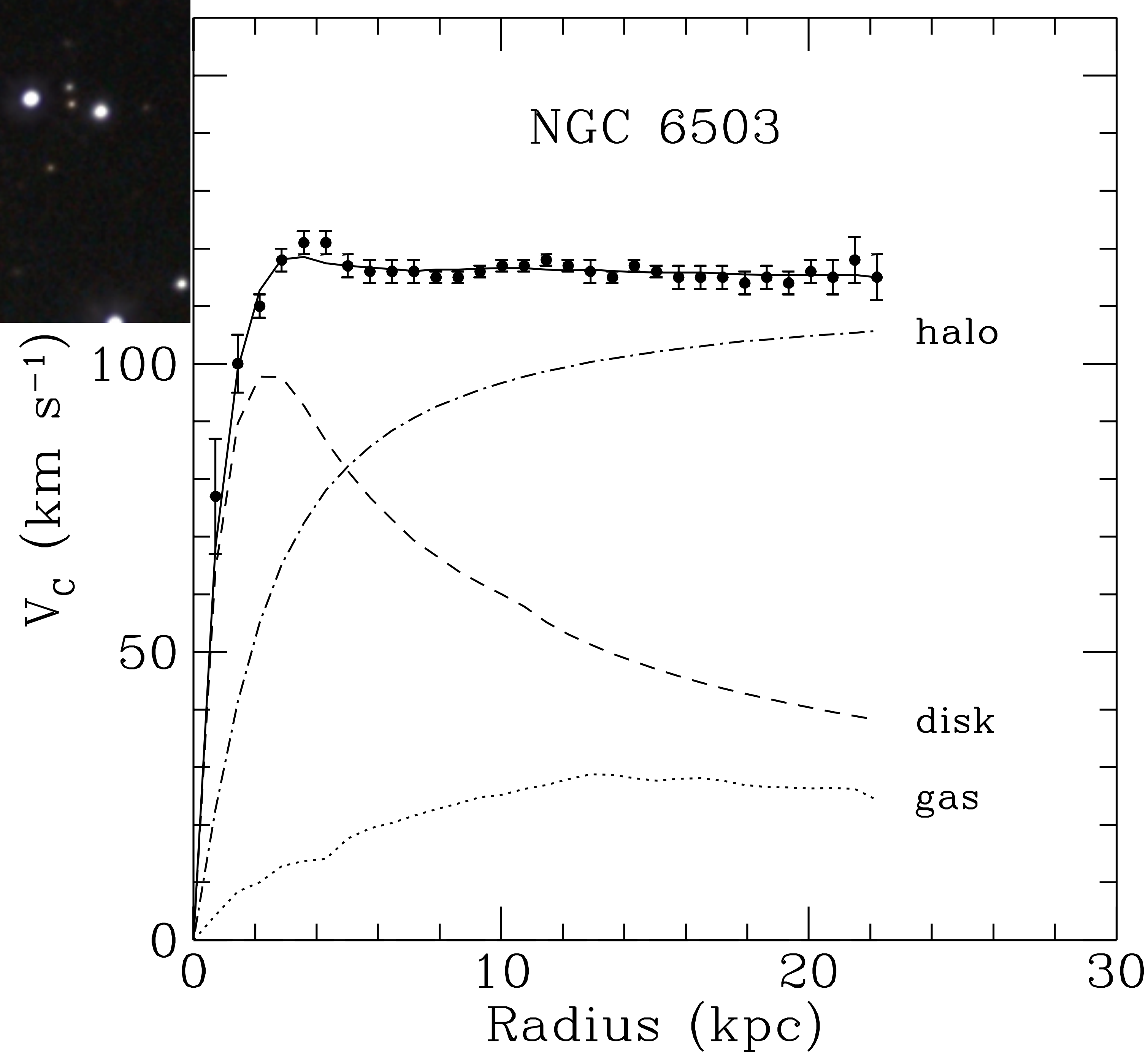
Dem.	Rep.
174	234

ELECTION 2016 Results | Live Presidential Forecast | Live Coverage

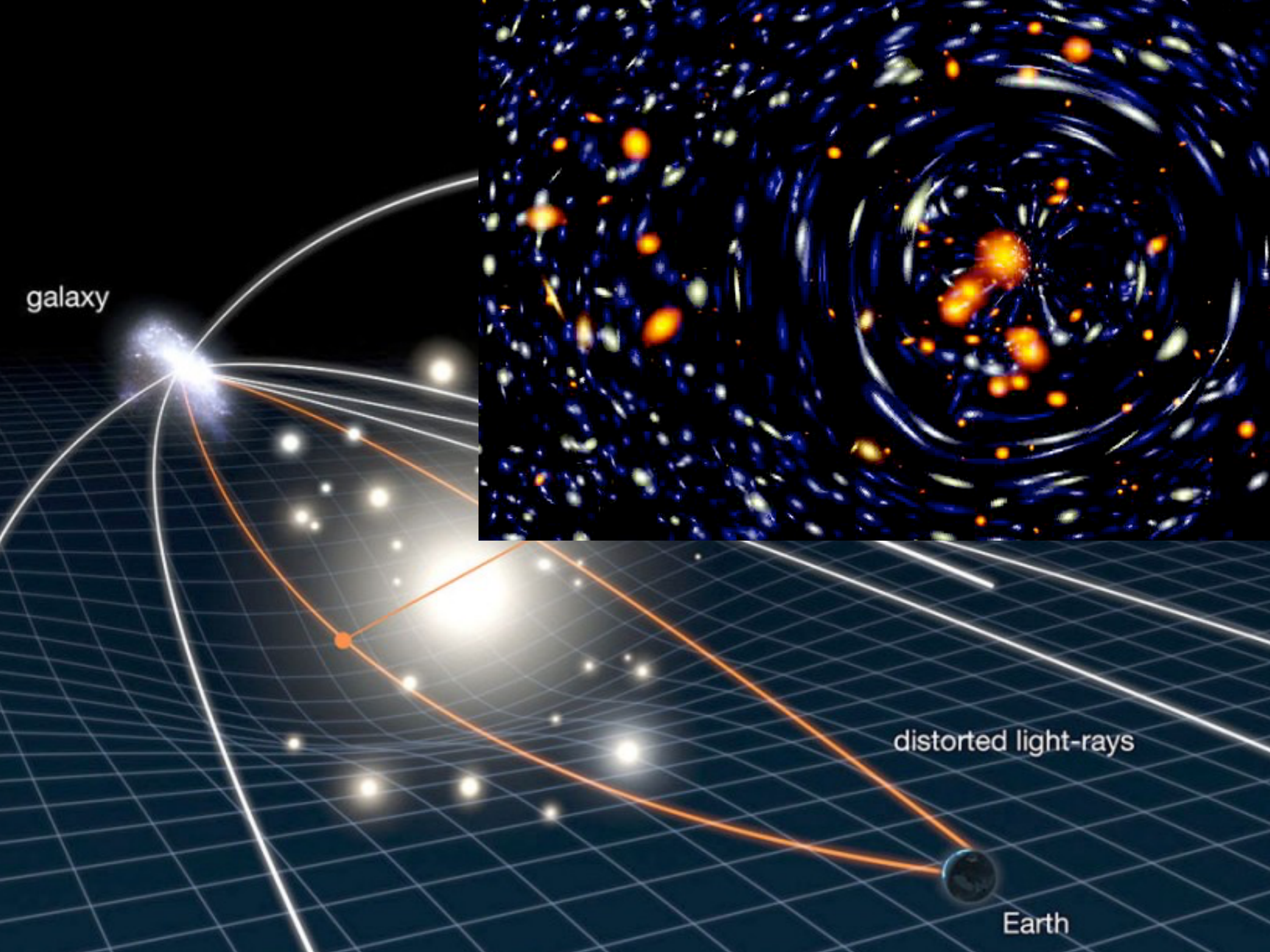
Live Briefing

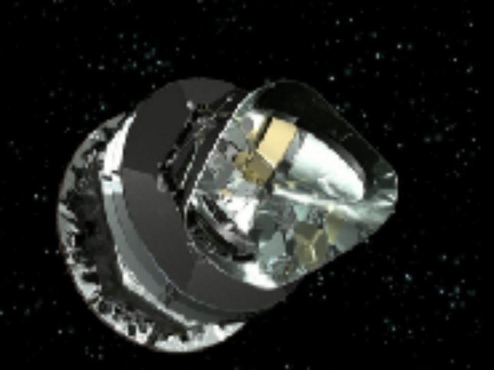
Presidential Election Live: Donald Trump Nears Victory, but Hillary Clinton Refuses to Concede




NGC 6503
halo
disk
gas
Vc (km s^-1)
Radius (kpc)
0
50
100
0
10
20
30


cluster of galaxies
Abell 2218
2.1B lyrs


galaxy
distorted light-rays
Earth

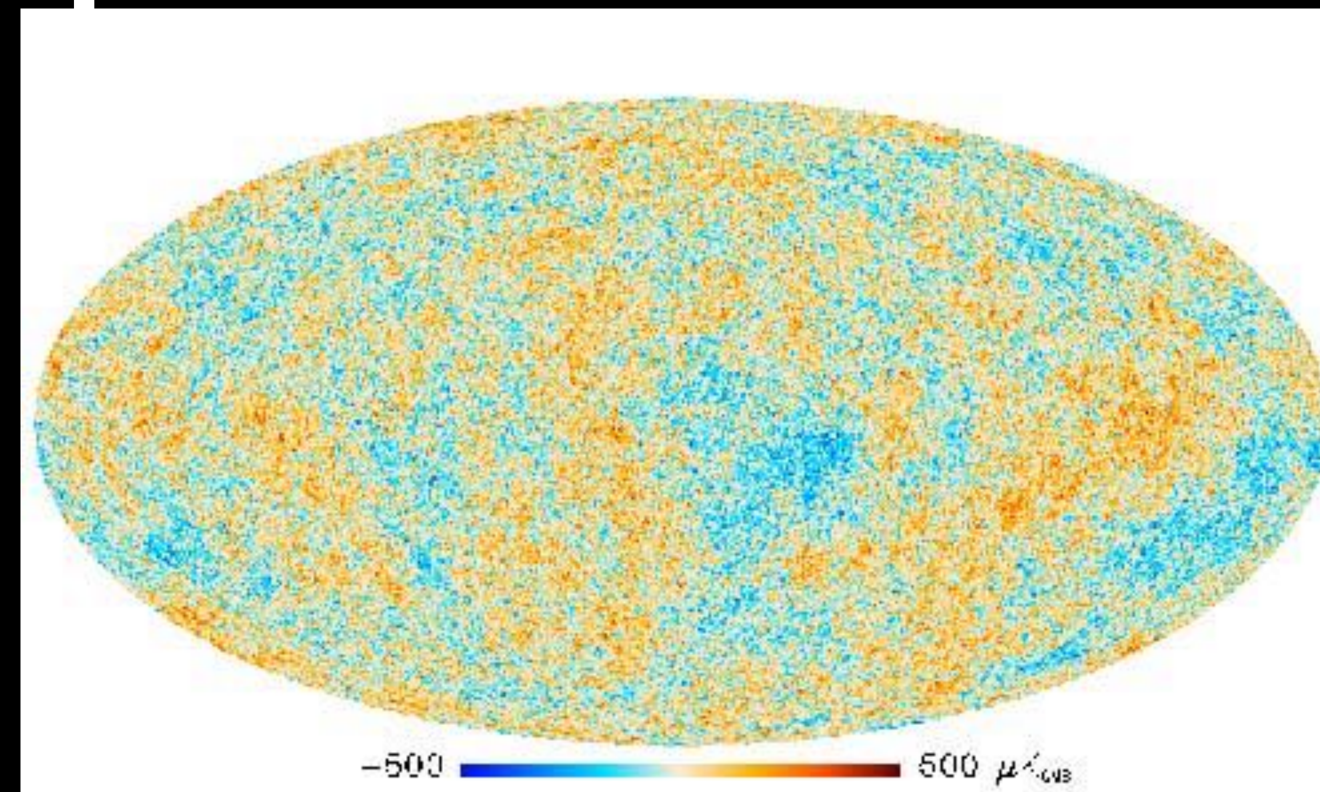


assumption

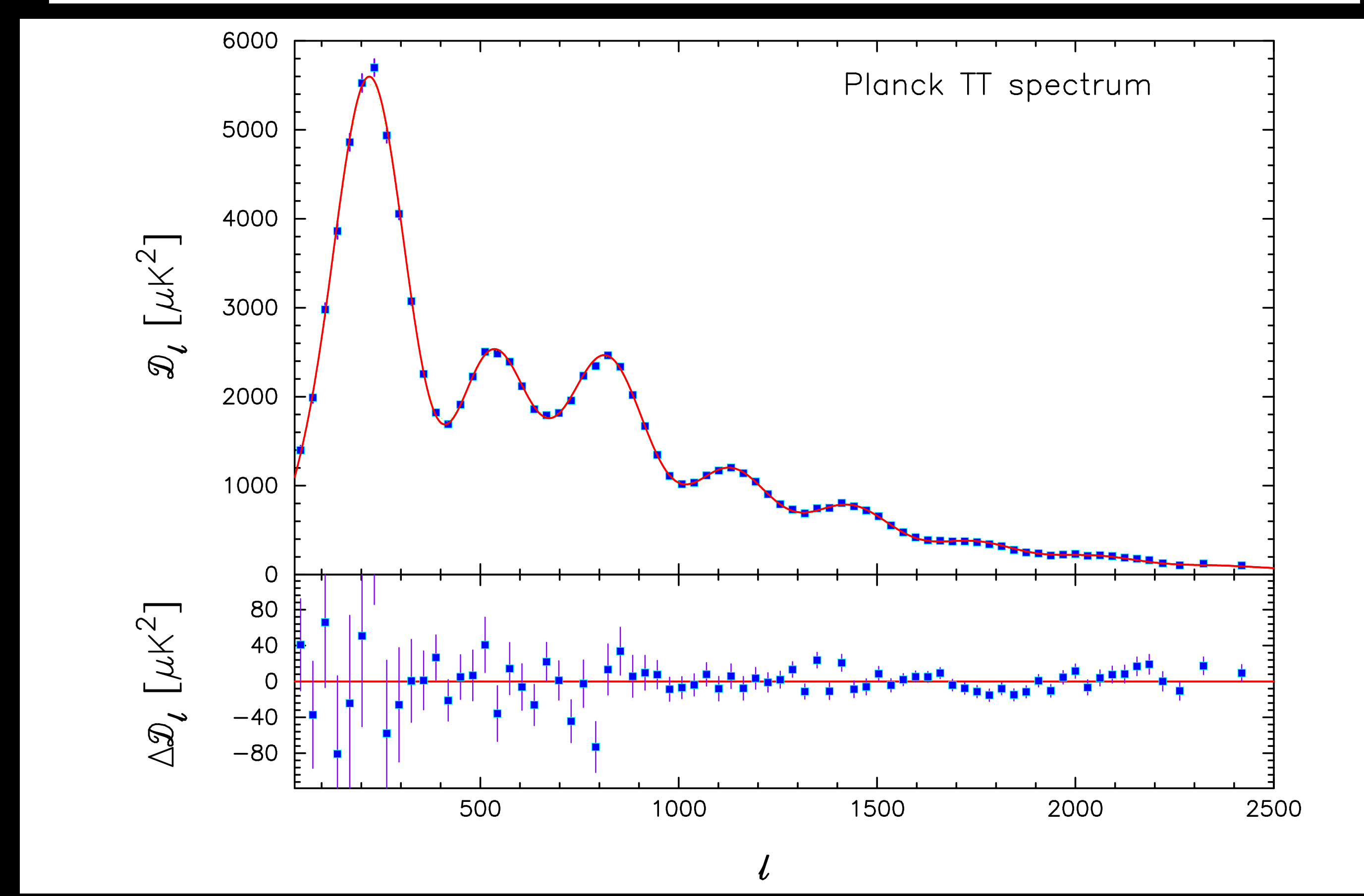
- a random density fluctuations ~$O(10^{-5})$ more-or-less scale invariant $P(k) \propto k^{n_s-1}$
- starts acoustic oscillation, amplified by gravitational attraction
- "knows" about everything between $0<z<1300$

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

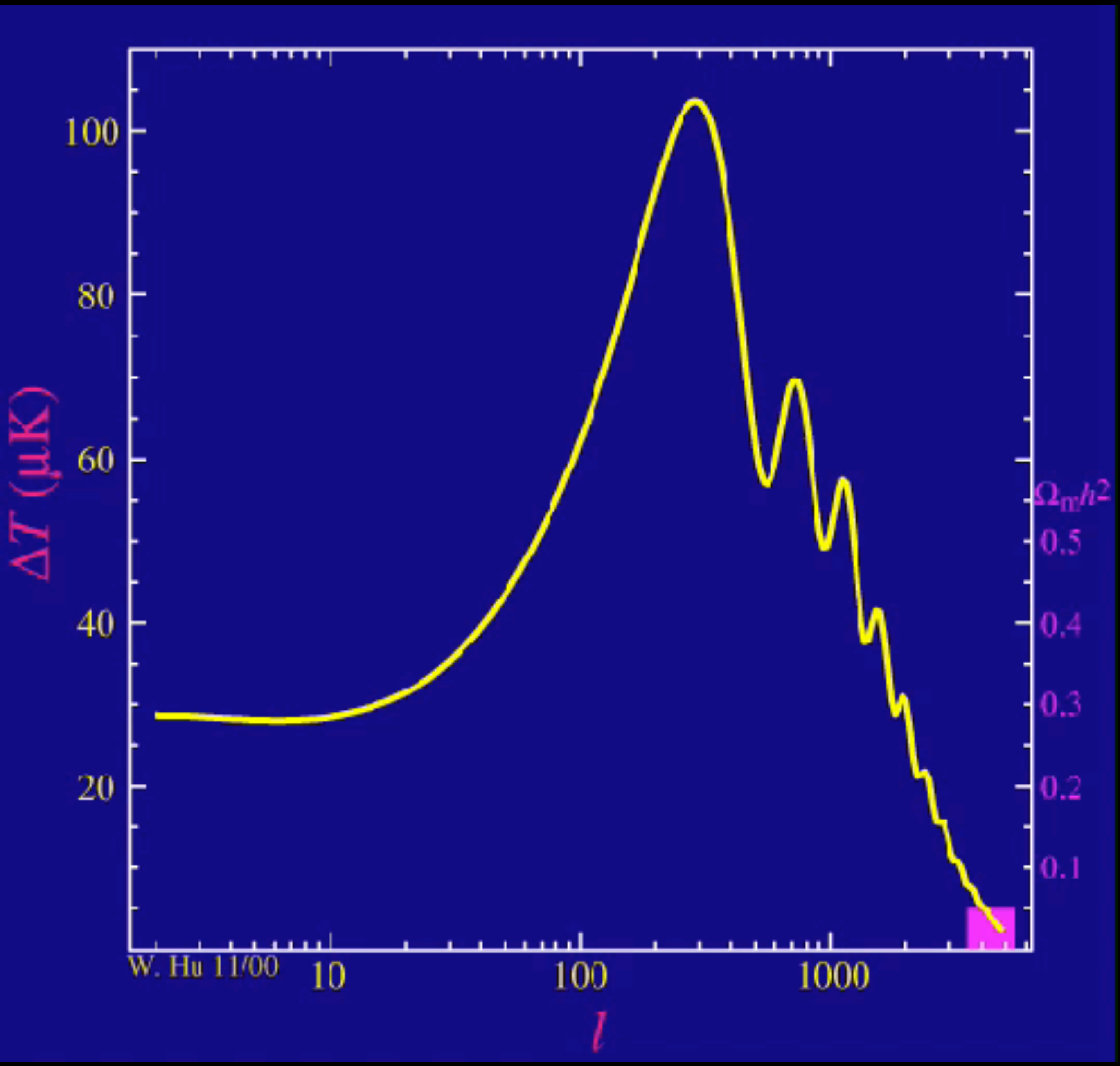
$$(2l+1)c_{lm} = \Sigma_m\, a_{lm}^* a_{lm}$$

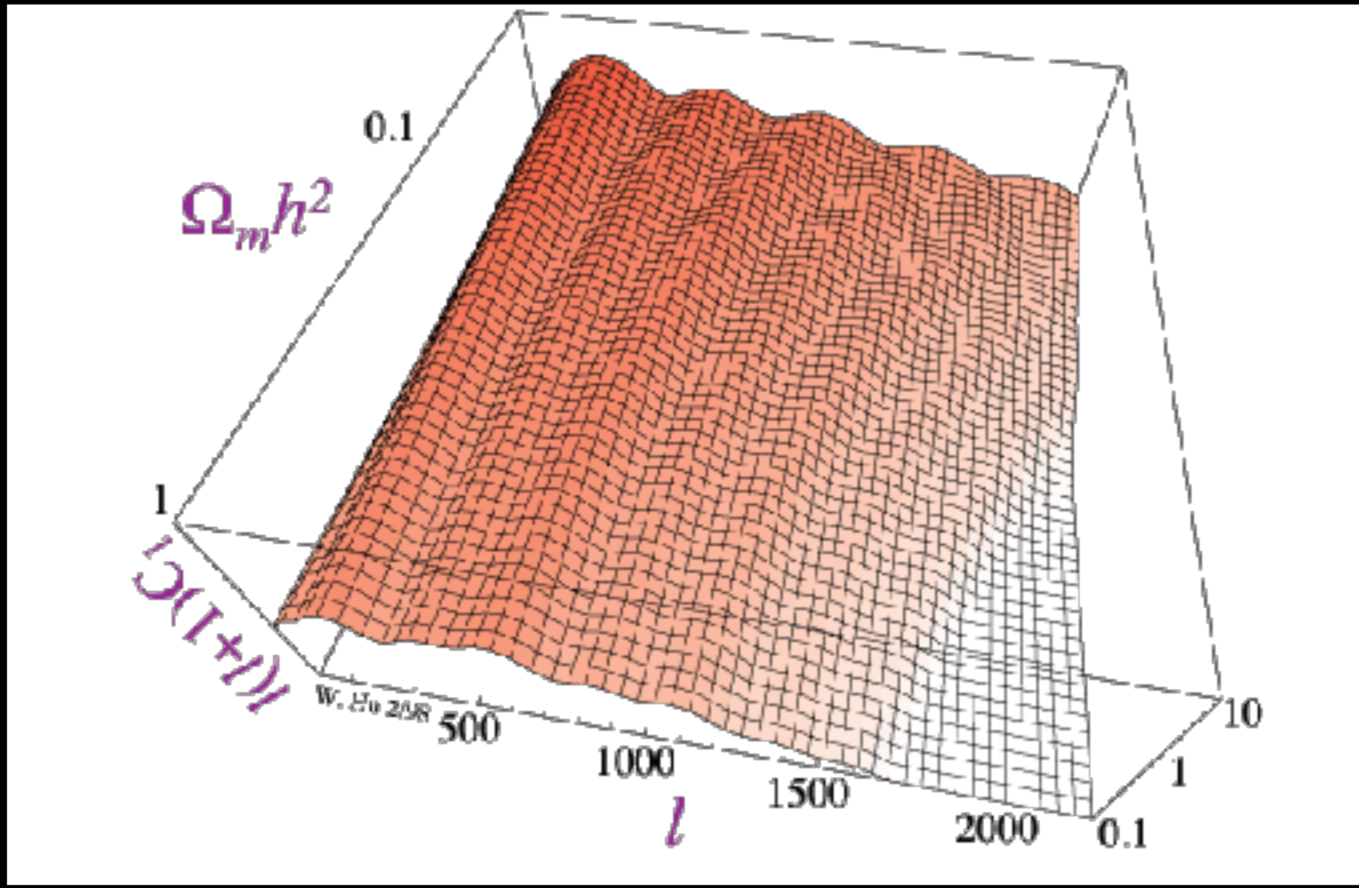


Planck Collaboration: Cosmological parameters



dark matter





Ω_m changes overall power

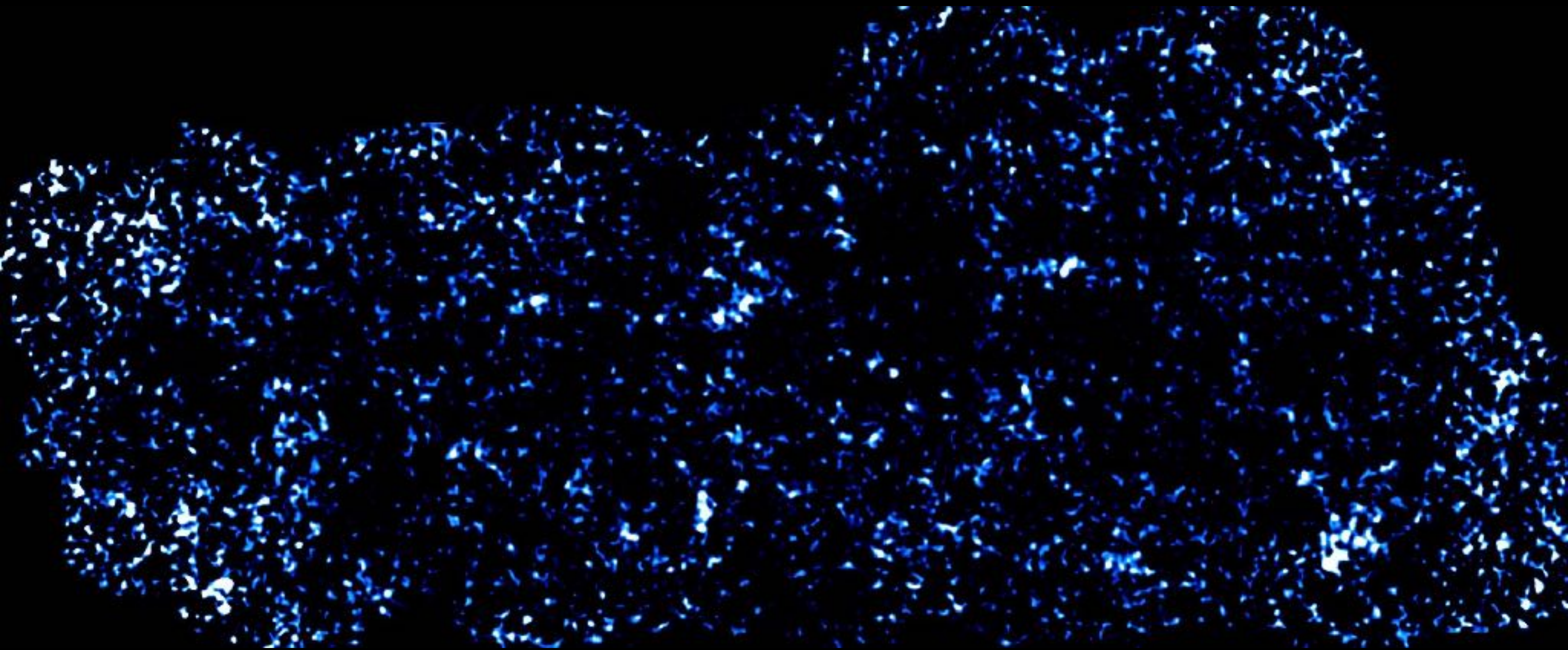
HSC performance

HSC: riz in 2.5 hours

COSMOS HST (640 orbits: ~500hrs)

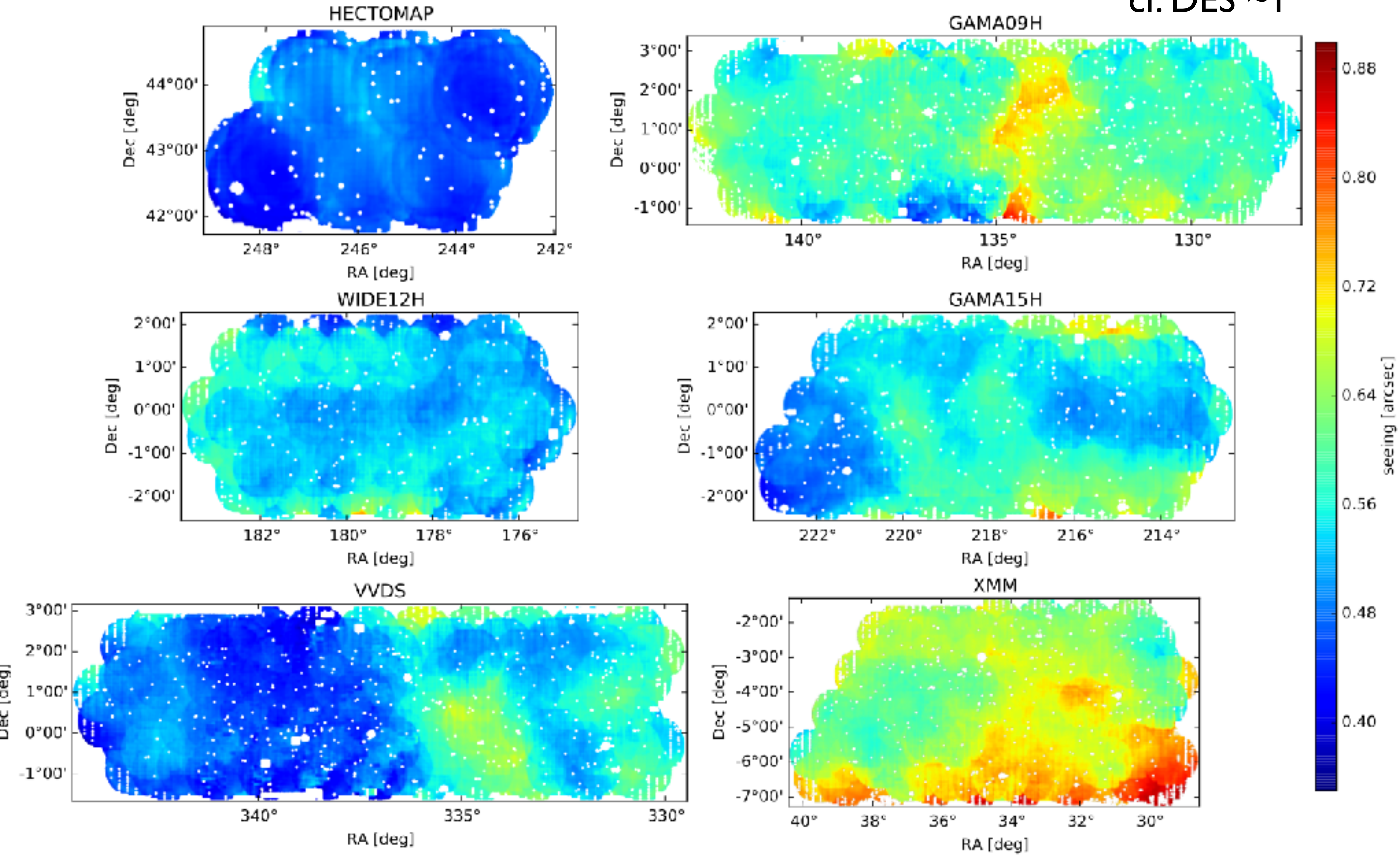
Conducting a major survey for 300 nights! First data release Feb 2017

dark matter map ~20 square degrees (2 hours of observation)

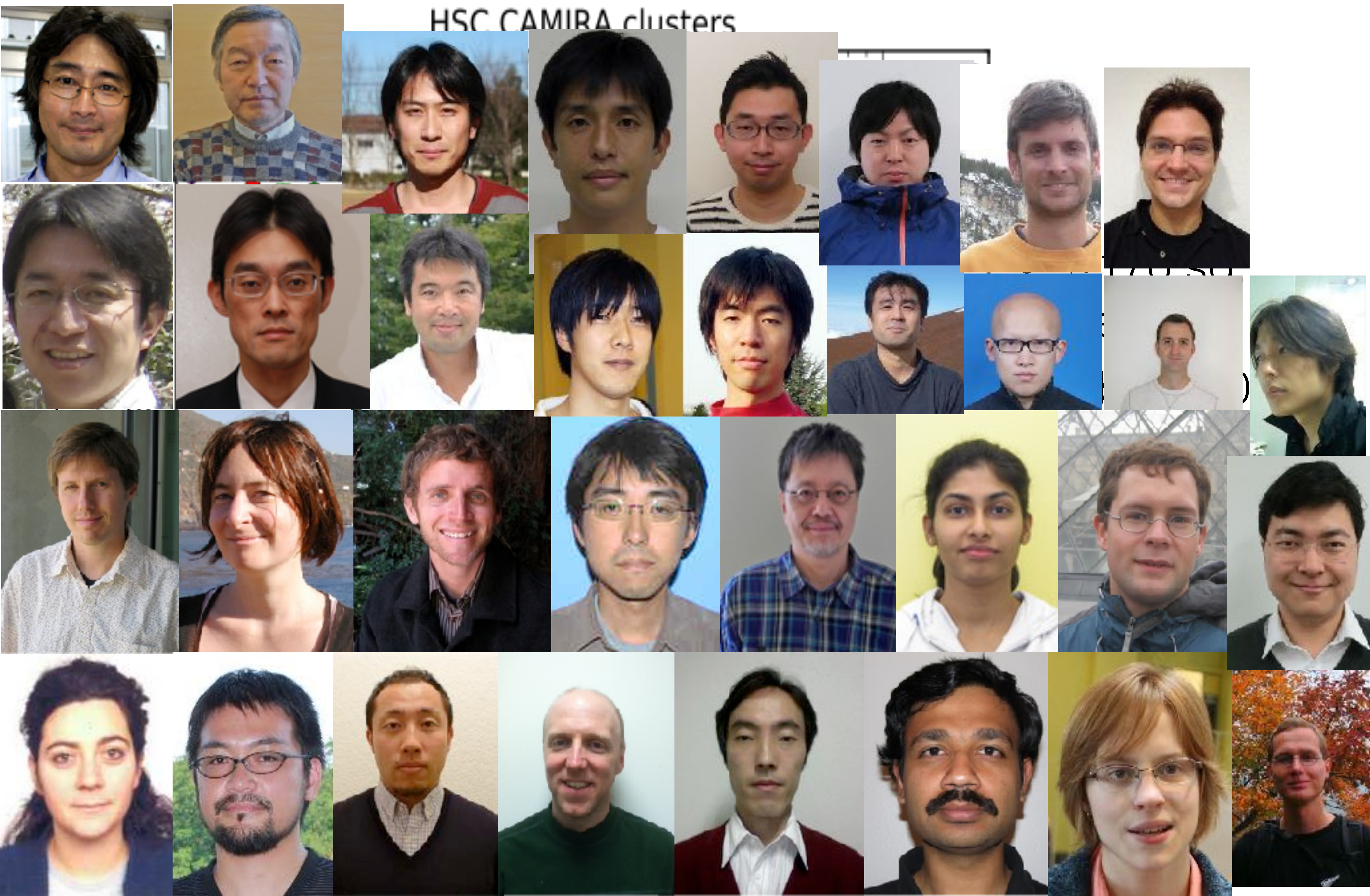


Now move forward to writing the 1st-year science papers with about 170 sq. degs. (full color, full depth, typical seeing ~0.6", so far 100 nights)

cf. DES ~1"

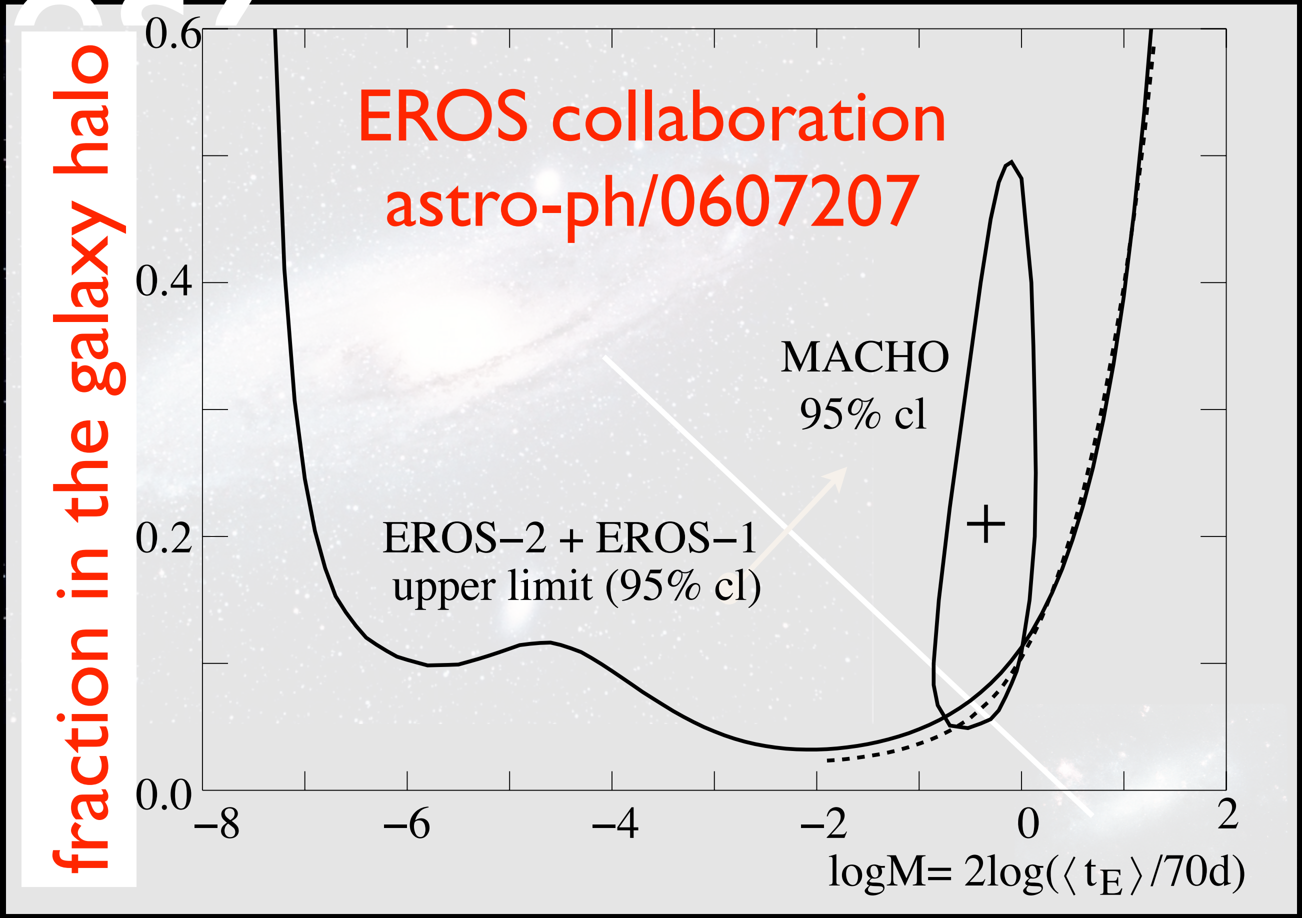


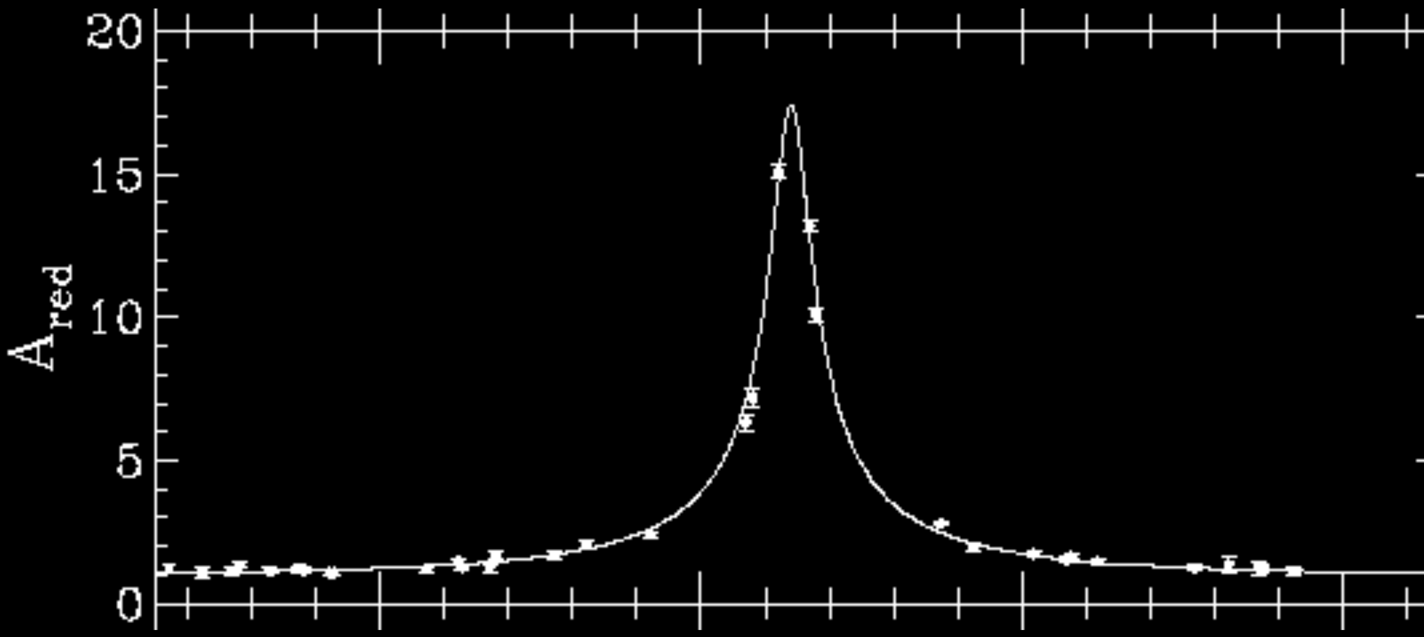
Cluster weak lensing



Dim Stars? Black Holes?

Search for *MACHOs*
(Massive Compact Halo Objects)





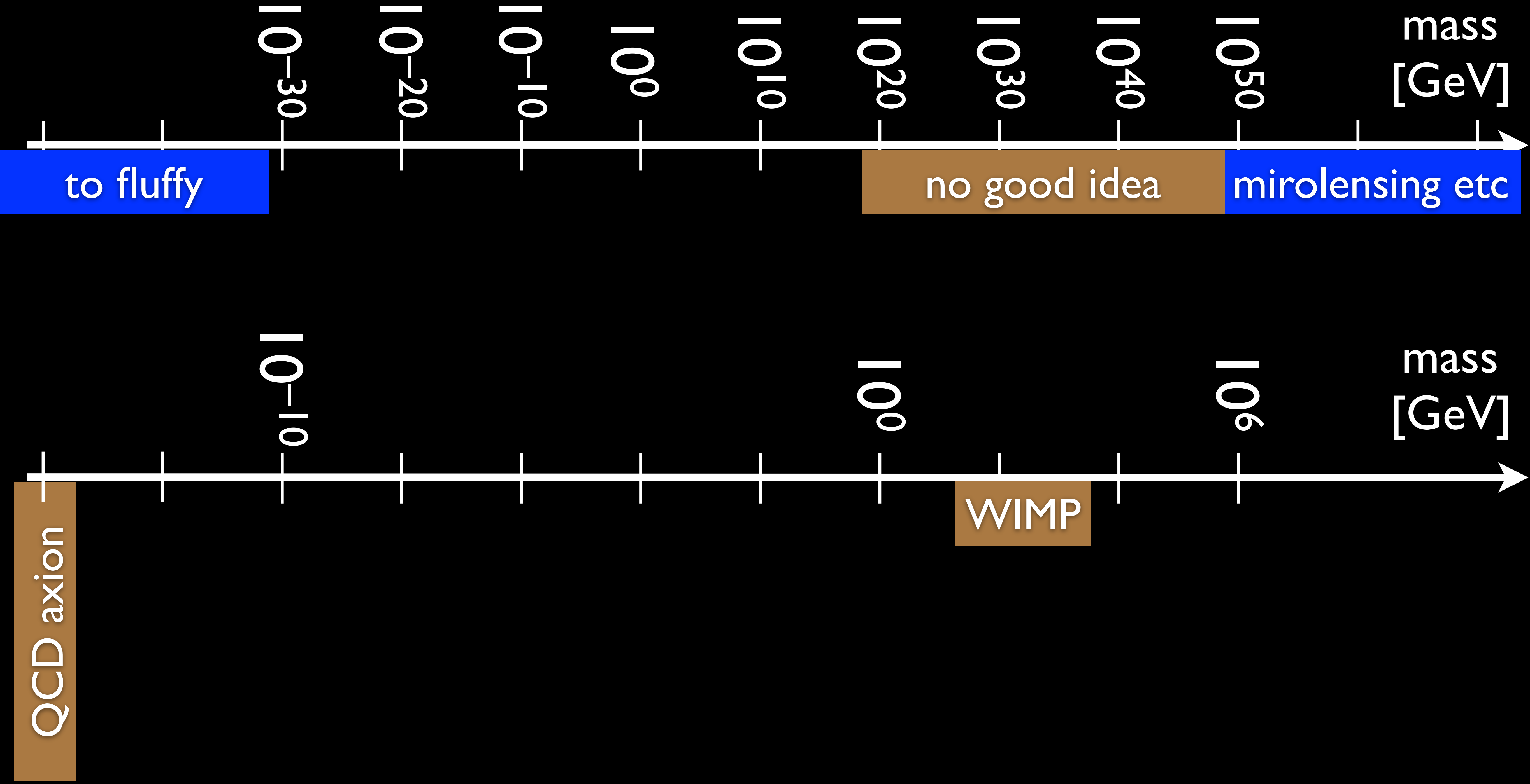
Not enough of them!

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)

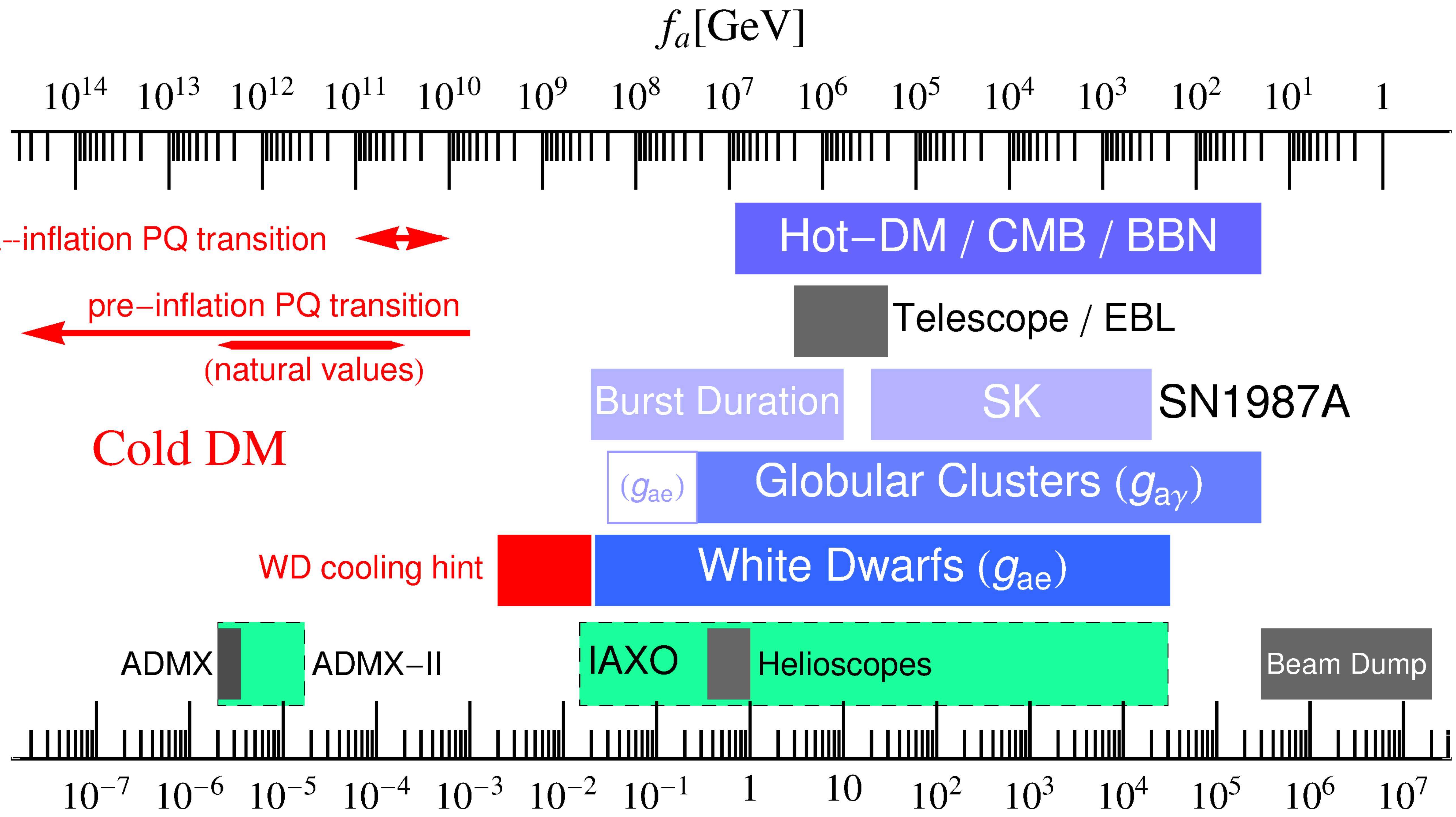
sociology

- We used to think
  - 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} 10^{-20} 10^{-10} 10^{0} 10^{10} 10^{20} 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
WIMP

Limits

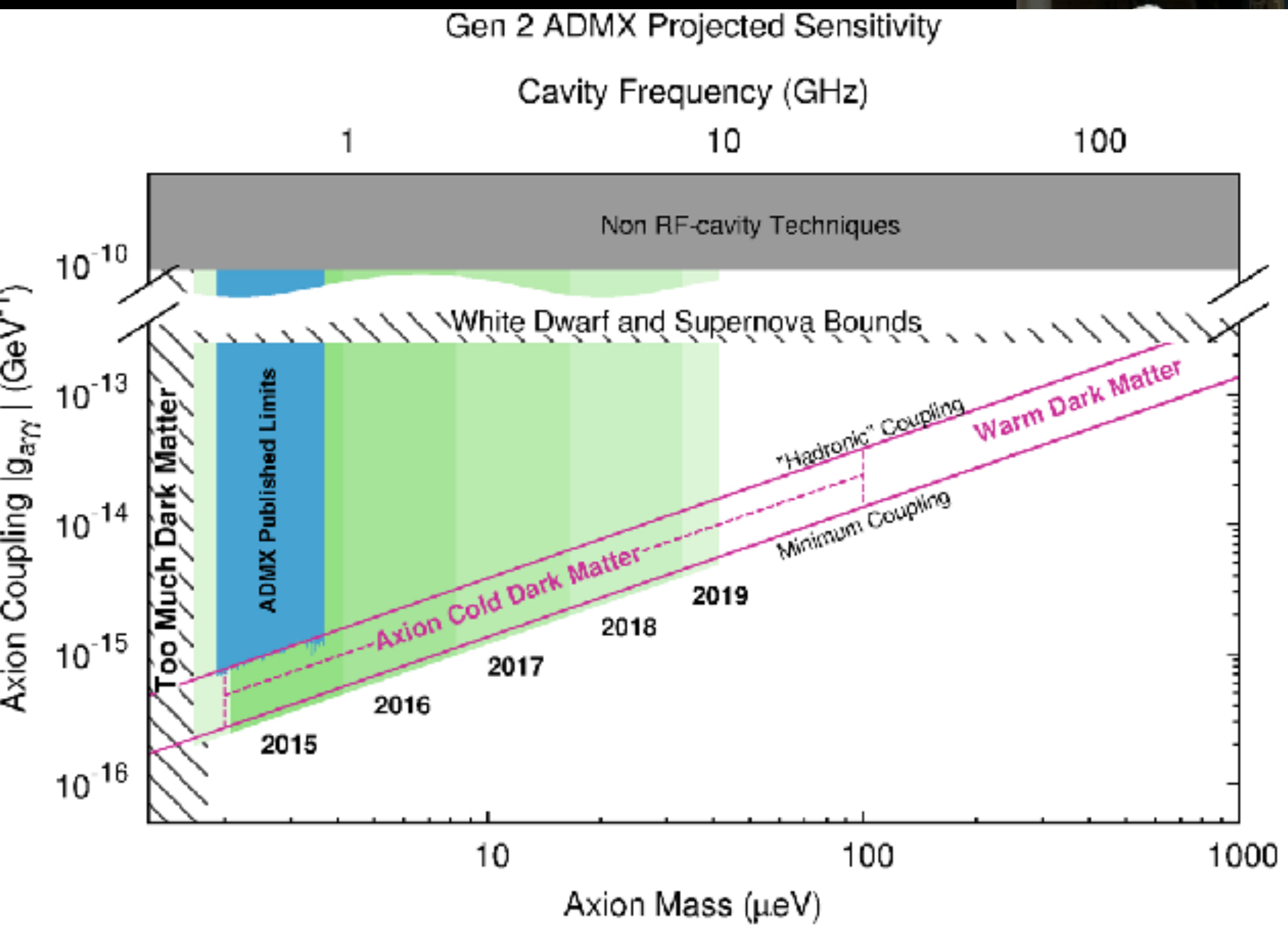


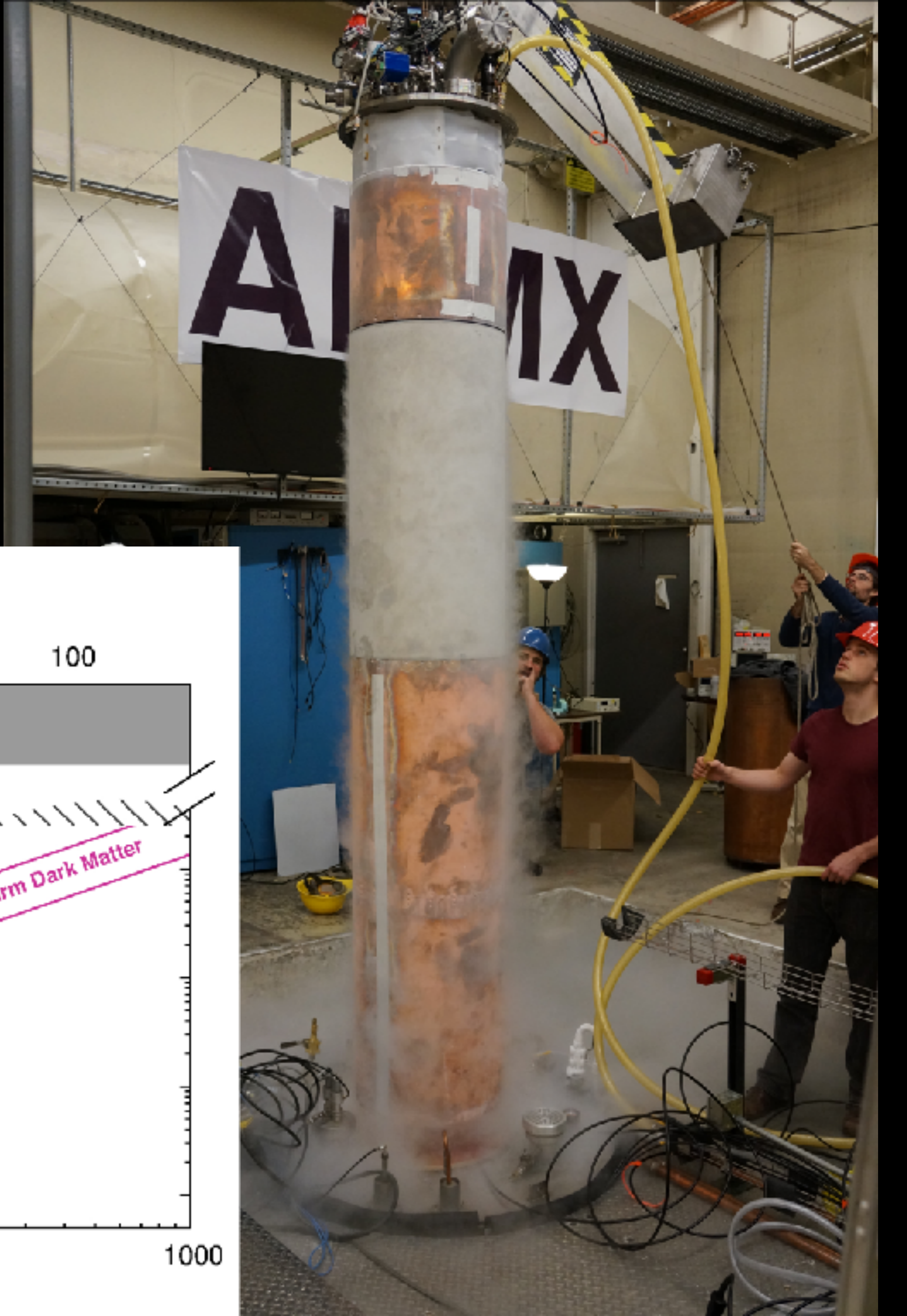
$m_a = m_\pi f_\pi / f_a$ [eV]

ADMX

Use the effective coupling

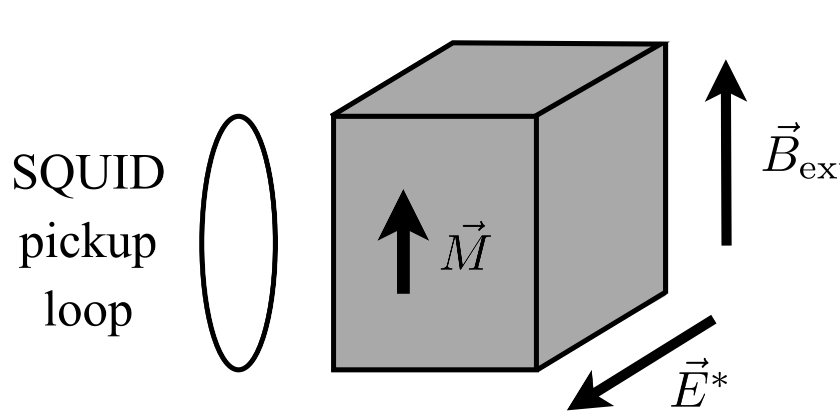
$$\mathcal{L}_{eff} \sim \frac{e^2}{4\pi^2}\frac{a}{f_a}\vec{E}\cdot\vec{B}$$





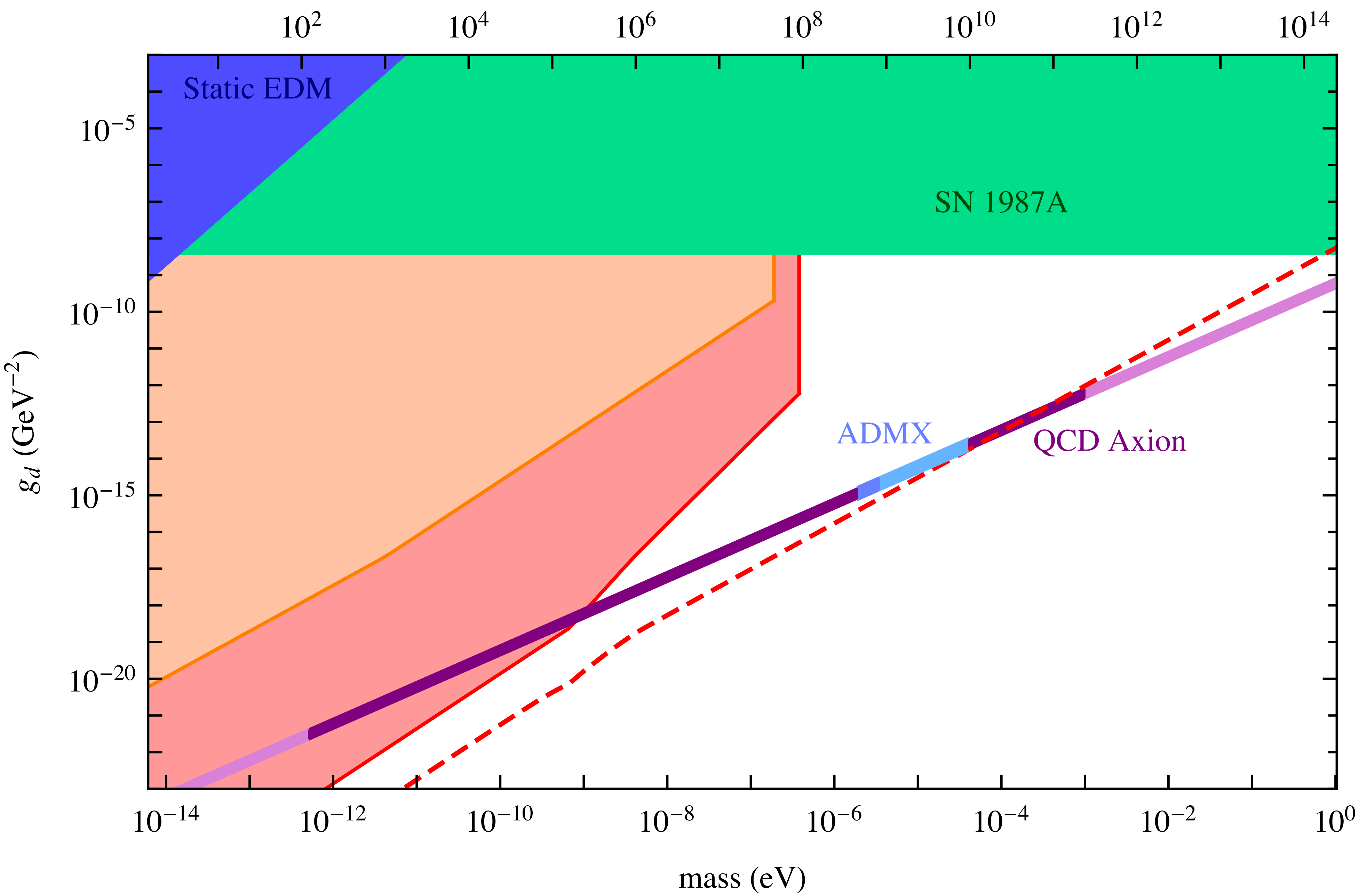
Cosmic Axion Spin Precession

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



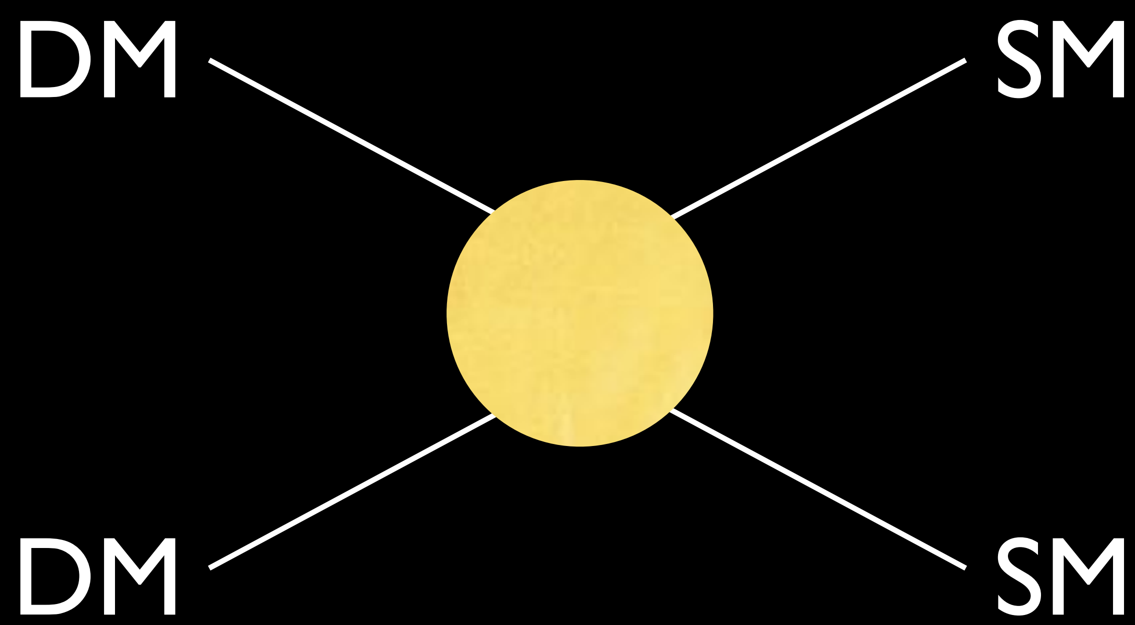
resonance @ $\mu B = m_a$

Budker et al
arXiv:1306.6089



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

WIMP Miracle



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

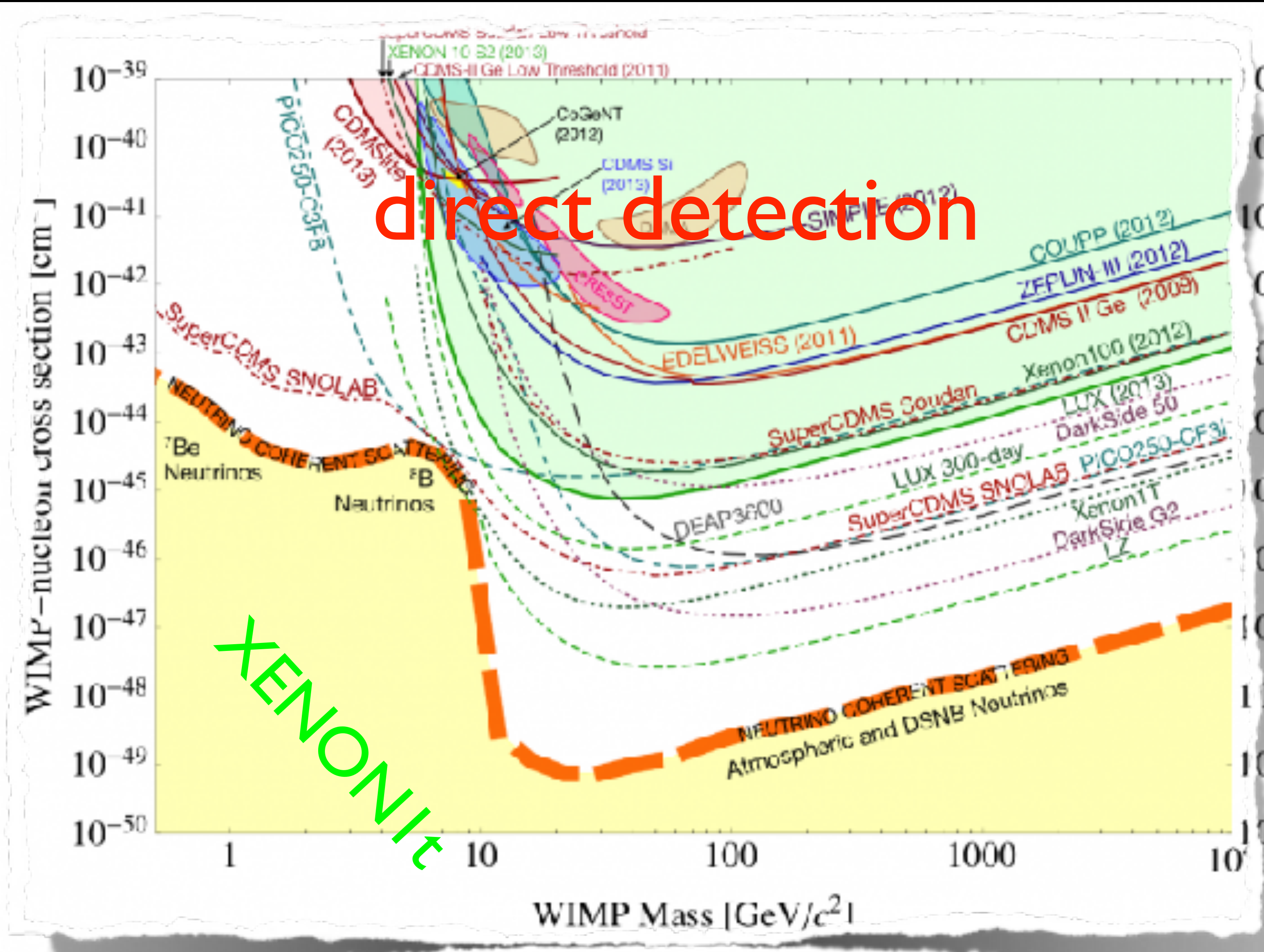
$$\alpha \approx 10^{-2}$$

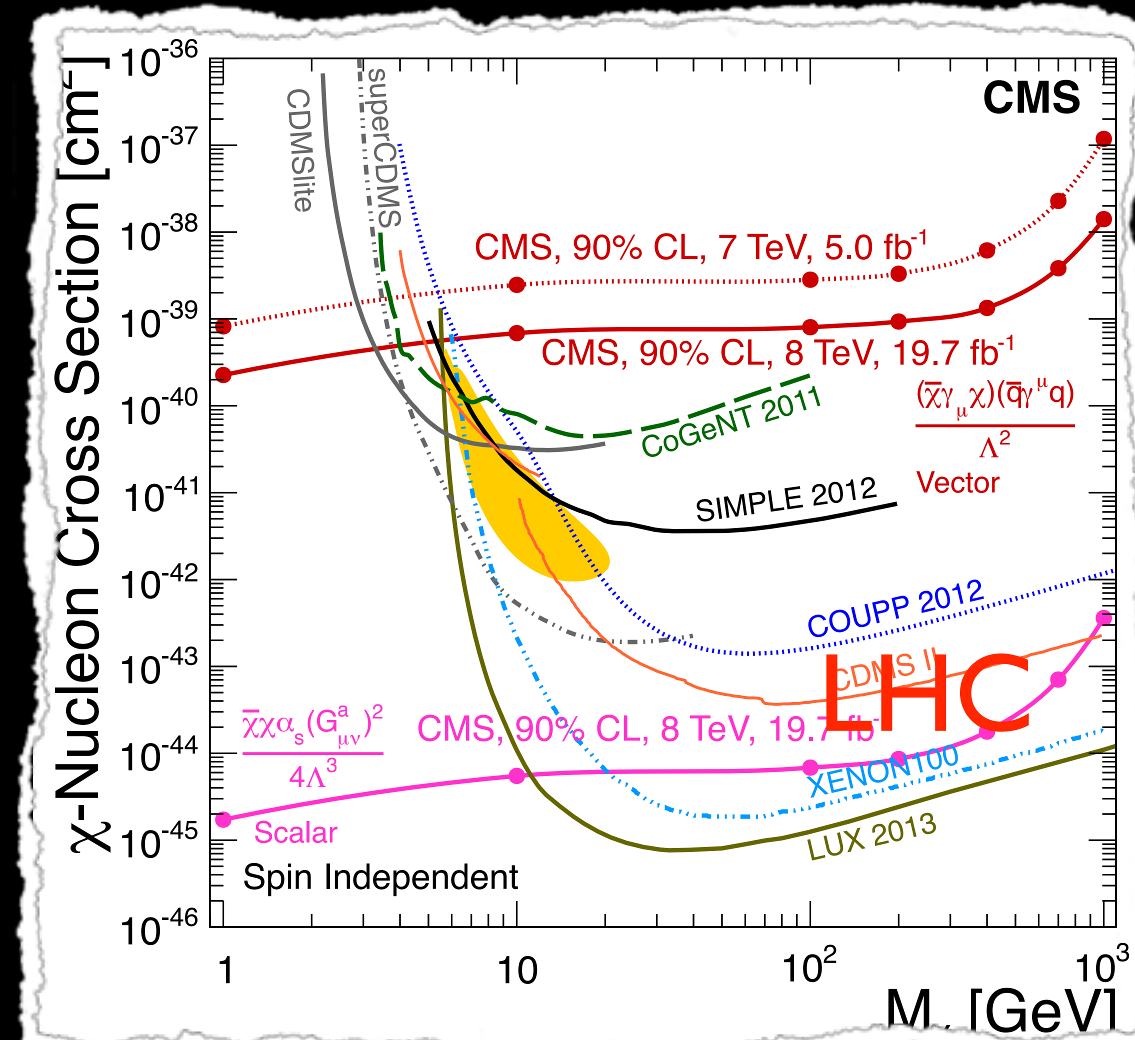
$$m \approx 300 \ \text{GeV}$$

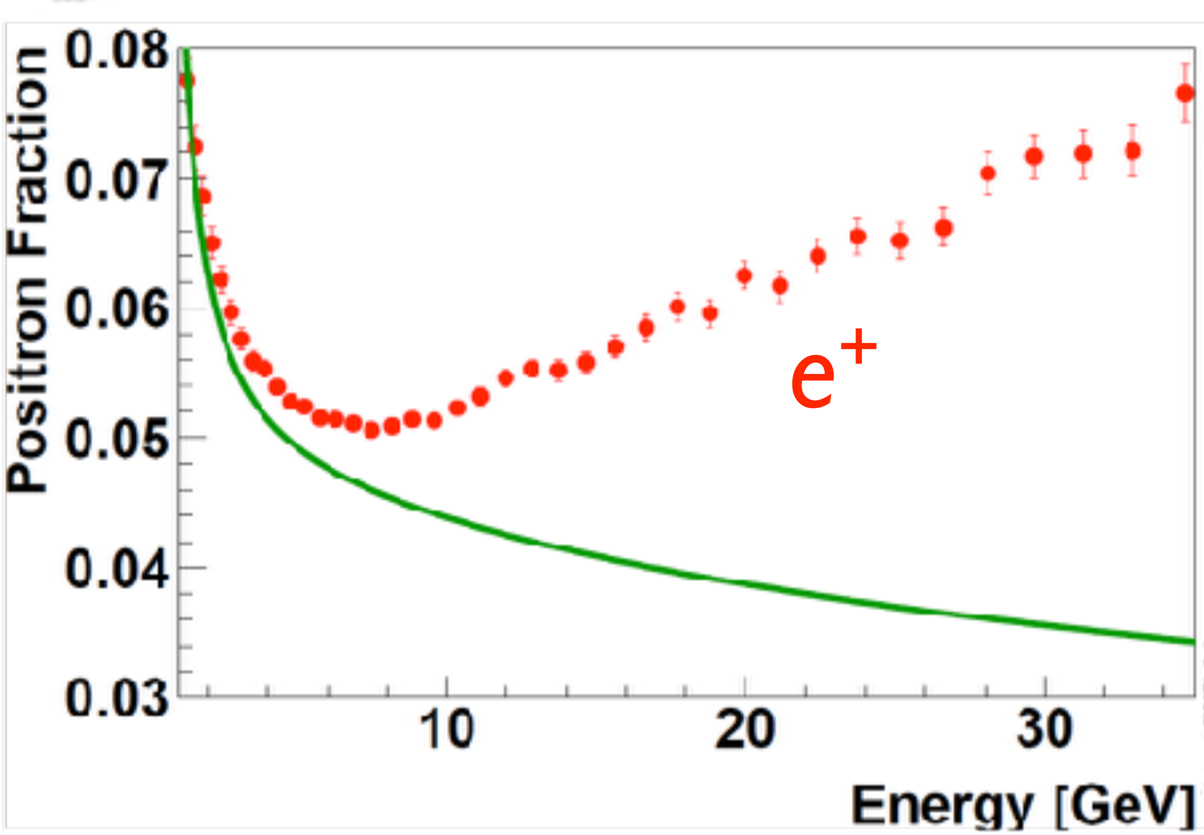
"weak" coupling
"weak" mass scale

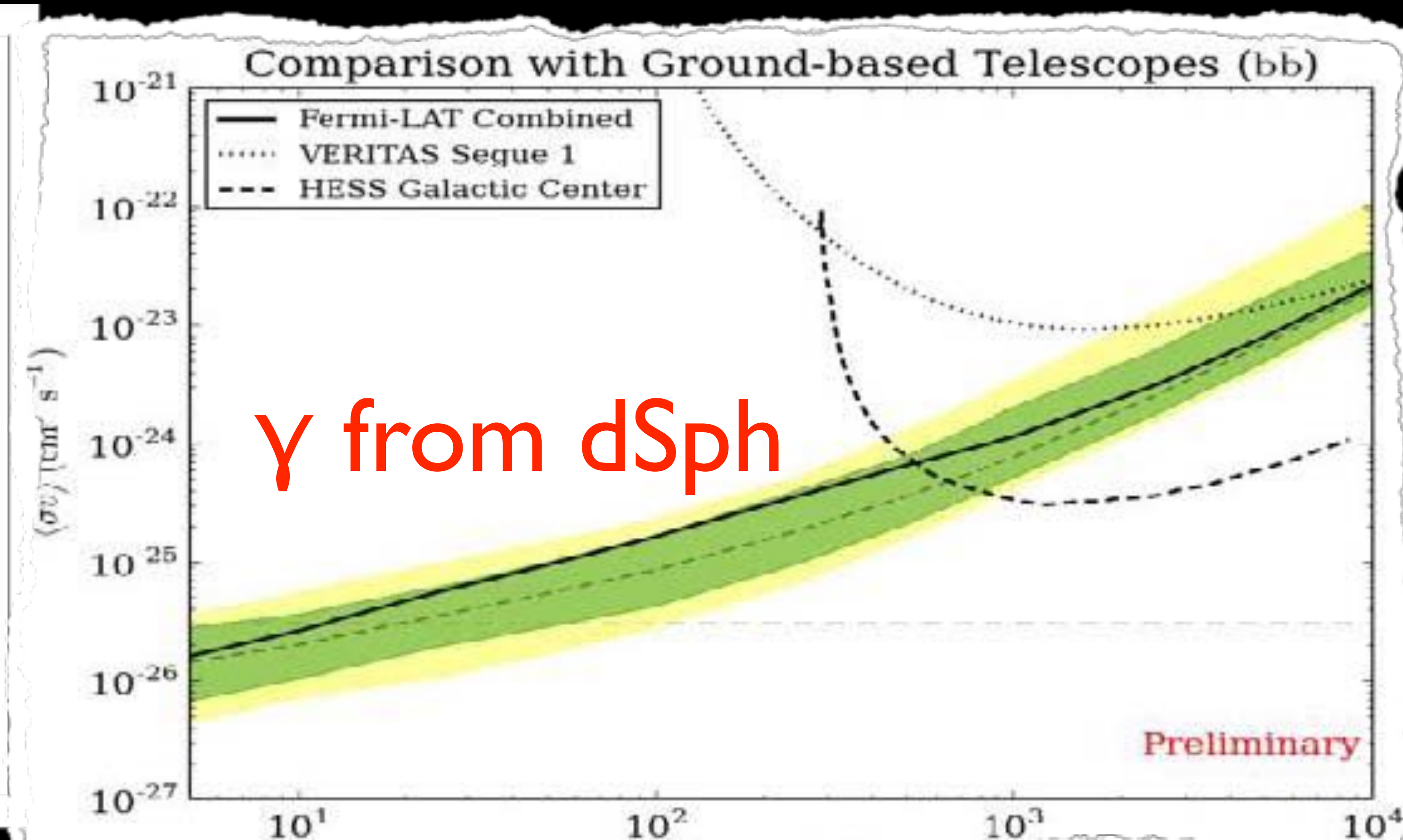
→ correct abundance

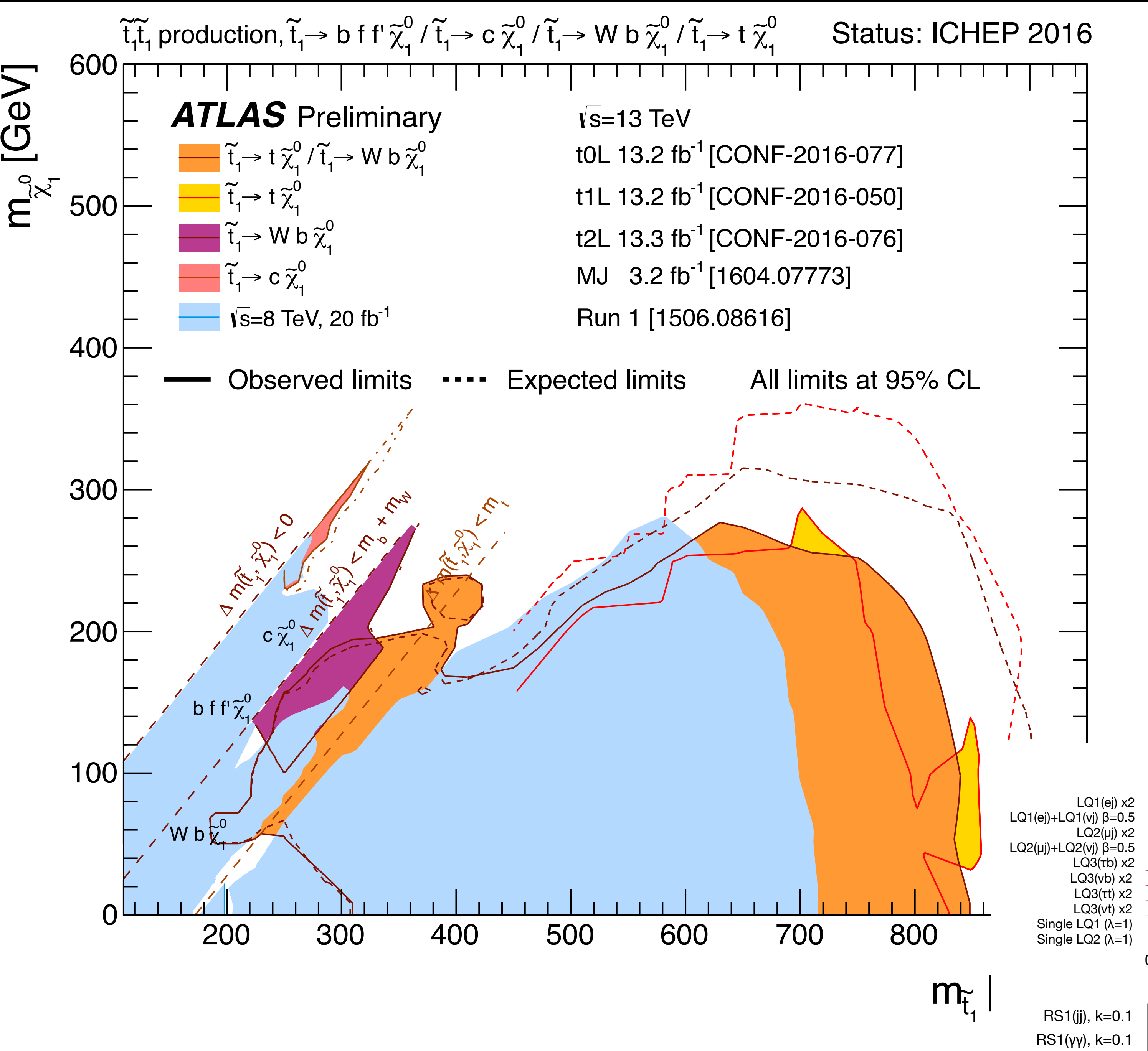
Miracle^2

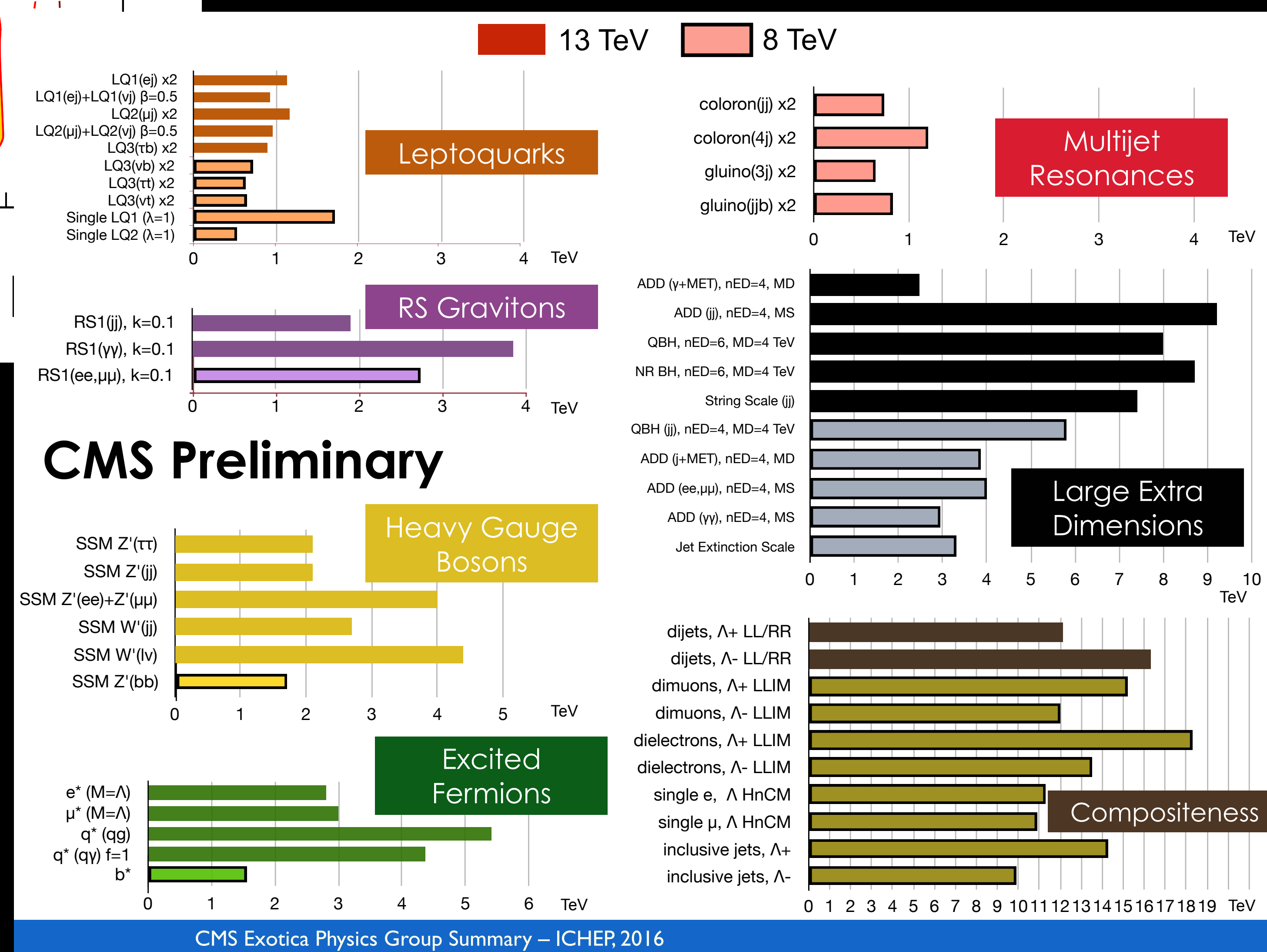

direct detection
XENON1t
WIMP–nucleon cross section [cm²]
WIMP Mass [GeV/c²]
CoGeNT (2012)
CDMS Si (2013)
SIMPLE (2012)
COUPP (2012)
ZEPLIN-III (2012)
CDMS II Ge (2009)
EDELWEISS (2011)
Xenon100 (2012)
LUX (2013)
DarkSide 50
SuperCDMS Soudan
LUX 300-day
PICO250-CF3I
SuperCDMS SNOLAB
XenonIT
DarkSide G2
LZ
DEAP3600
SuperCDMS SNOLAB
CRESST
PICO250-C3F8
CDMSlite (2013)
XENON 10 S2 (2013)
CDMS-II Ge Low Threshold (2011)
NEUTRINO COHERENT SCATTERING
⁷Be Neutrinos
⁸B Neutrinos
NEUTRINO COHERENT SCATTERING
Atmospheric and DSNB Neutrinos


CMS
LHC
χ-Nucleon Cross Section [cm²]
M [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
Scalar
LUX 2013
Spin Independent


Positron Fraction
Energy [GeV]
e⁺


Comparison with Ground-based Telescopes (bb)
Fermi-LAT Combined
VERITAS Segue 1
HESS Galactic Center
γ from dSph
Preliminary





no sign of
new physics
that explains
naturalness!

Beginning of Universe

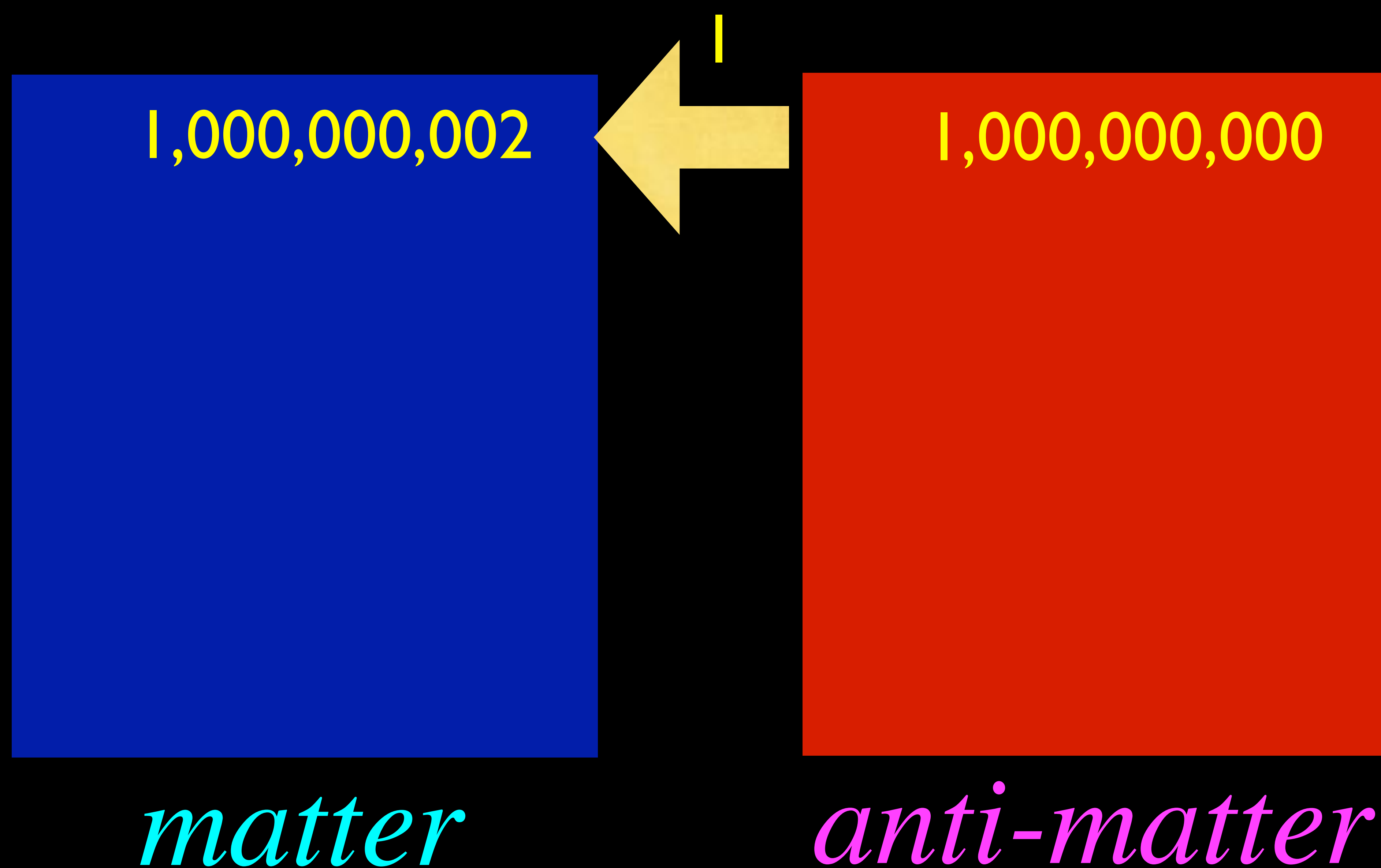
1,000,000,001

matter

1,000,000,001

anti-matter

fraction of second later



turned a billionth of anti-matter to matter

Universe Now

2

us

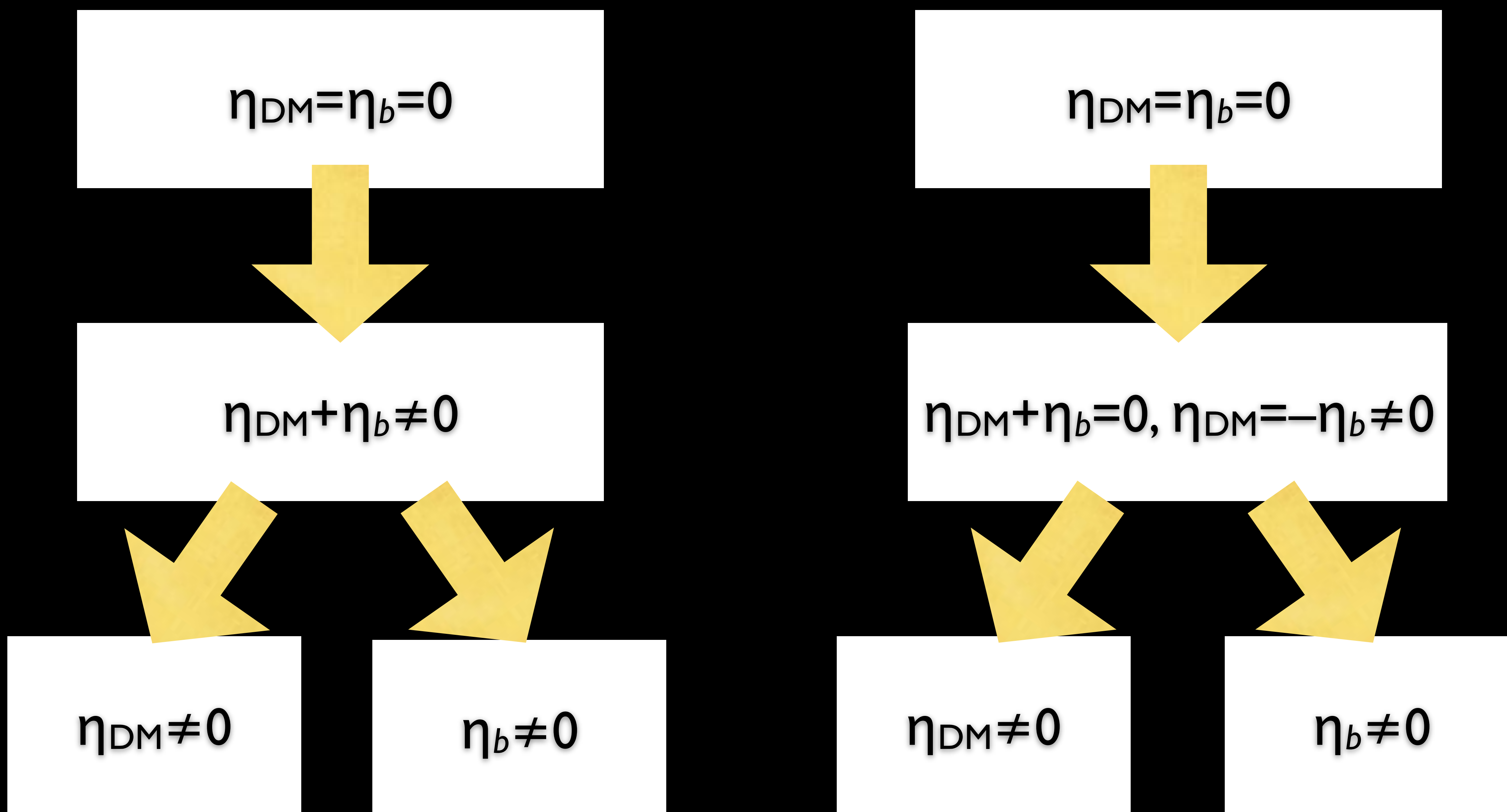
Gelmini, Hall, Lin (1987)
Kaplan, Luty, Zurek,
0901.4117

dark matter *dark anti-matter*

This must be how we survived the Big Bang!

they

Two ways



$\eta_{DM}=\eta_b=0$
$\eta_{DM}+\eta_b\neq0$
$\eta_{DM}\neq0$
$\eta_b\neq0$
$\eta_{DM}=\eta_b=0$
$\eta_{DM}+\eta_b=0,\ \eta_{DM}=-\eta_b\neq0$
$\eta_{DM}\neq0$
$\eta_b\neq0$

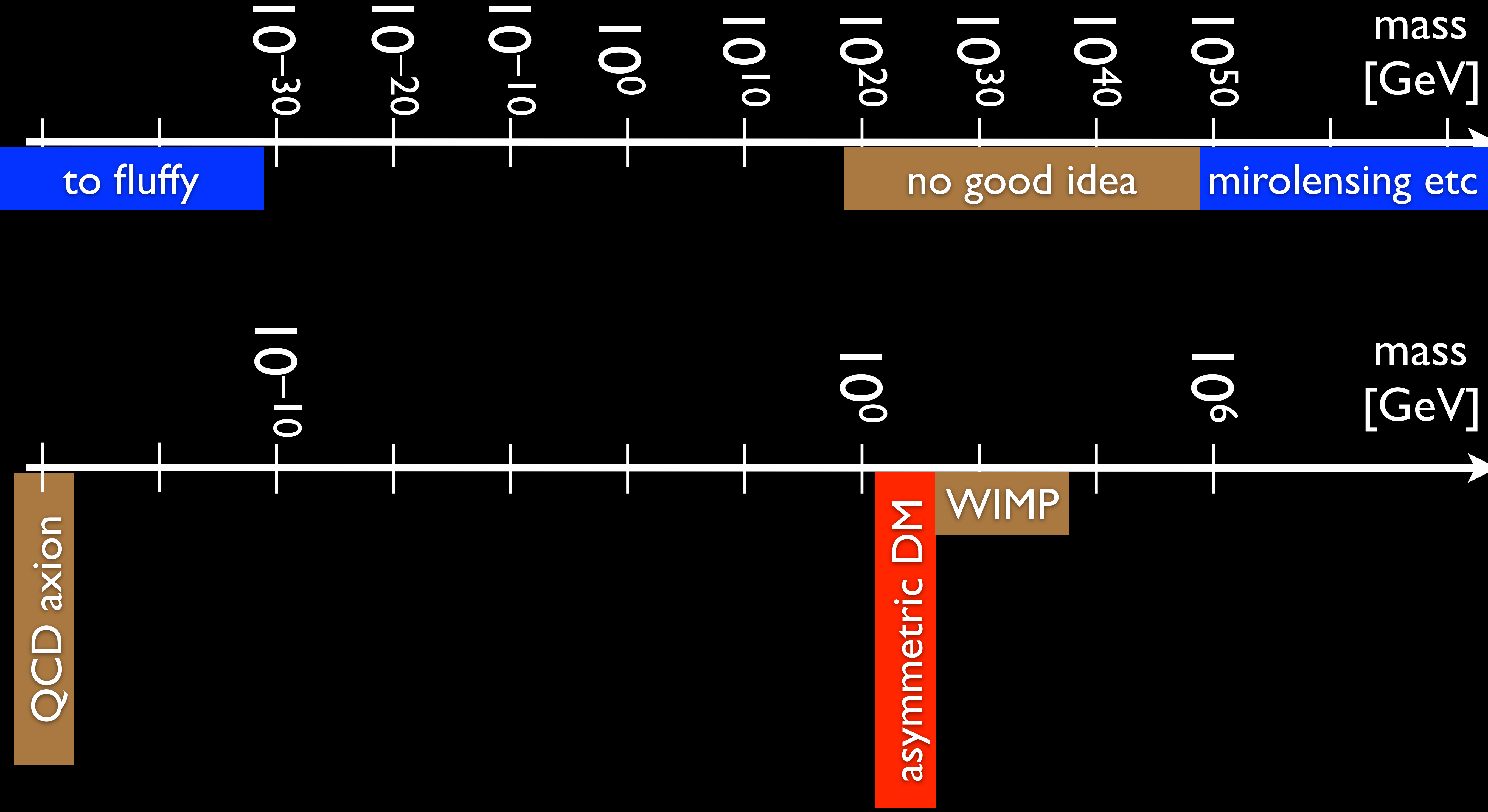
Asymmetric Dark Matter

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

- Does this explain the "similarity" of dark matter and baryons?

$$m_p \approx \Lambda e^{-8\pi^2/g_s^2(\Lambda) b_0}$$

- Need to come up with a dynamical origin of the dark matter mass linked to the QCD coupling



mass [GeV]
10^{-30}
10^{-20}
10^{-10}
10^{0}
10^{10}
10^{20}
10^{30}
10^{40}
10^{50}
to fluffy
no good idea
mirolensing etc
mass [GeV]
10^{-10}
10^{0}
10^{6}
QCD axion
asymmetric DM
WIMP

Topological defects

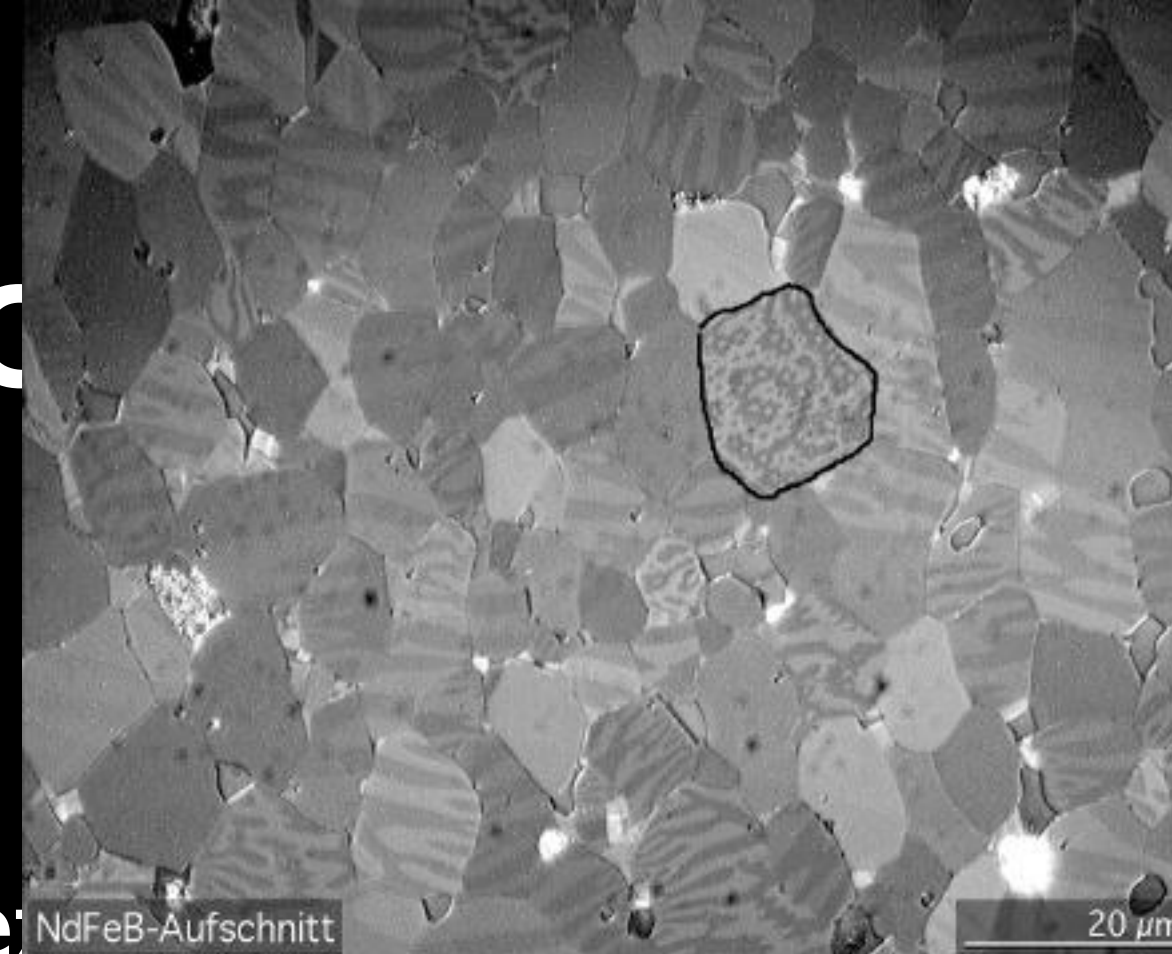
- common interest among AMO, condensed matter, particle physics, algebraic geometry
- symmetry breaking $G \to H$
- coset space G/H describes vacua
- can the space be mapped non-trivially into the coset space?
- $\pi_0(G/H) \neq 0$: domain walls
- $\pi_1(G/H) \neq 0$: string (vortex)
- $\pi_2(G/H) \neq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

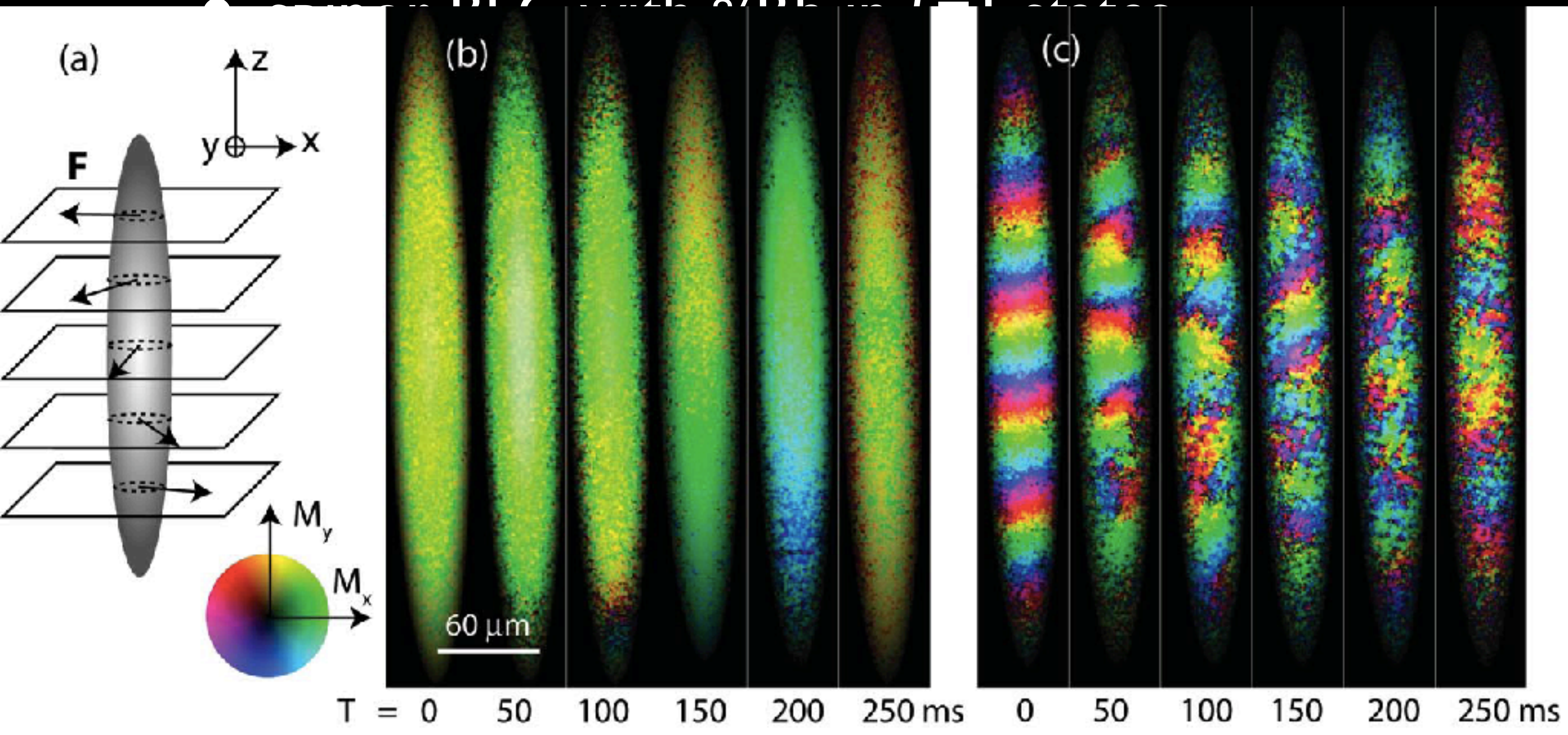
"Cosmological Experiments in Superfluid Helium?"

Phase transition revisited

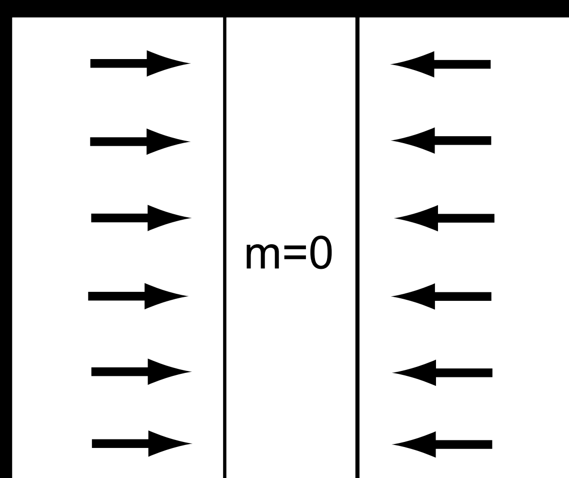
- correlation length: $\xi \propto |T - T_c|^{-\nu}$
- relaxation time: $\tau \propto |T - T_c|^{-\mu}$
- It takes an infinite amount of time for the system to "line up" at T_c
- If the system cools too quickly, it won't line up even within a causally connected region

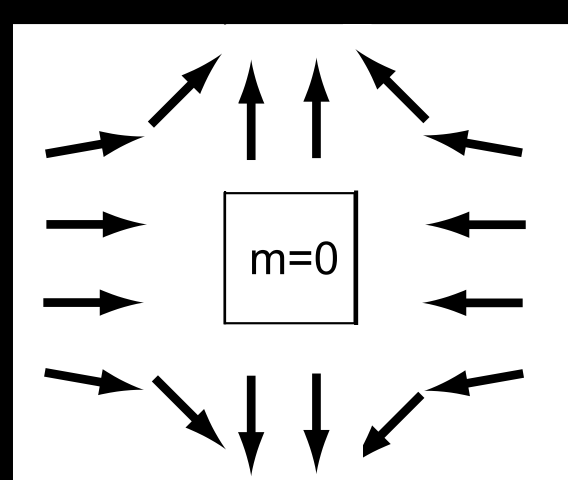
Experimental tests

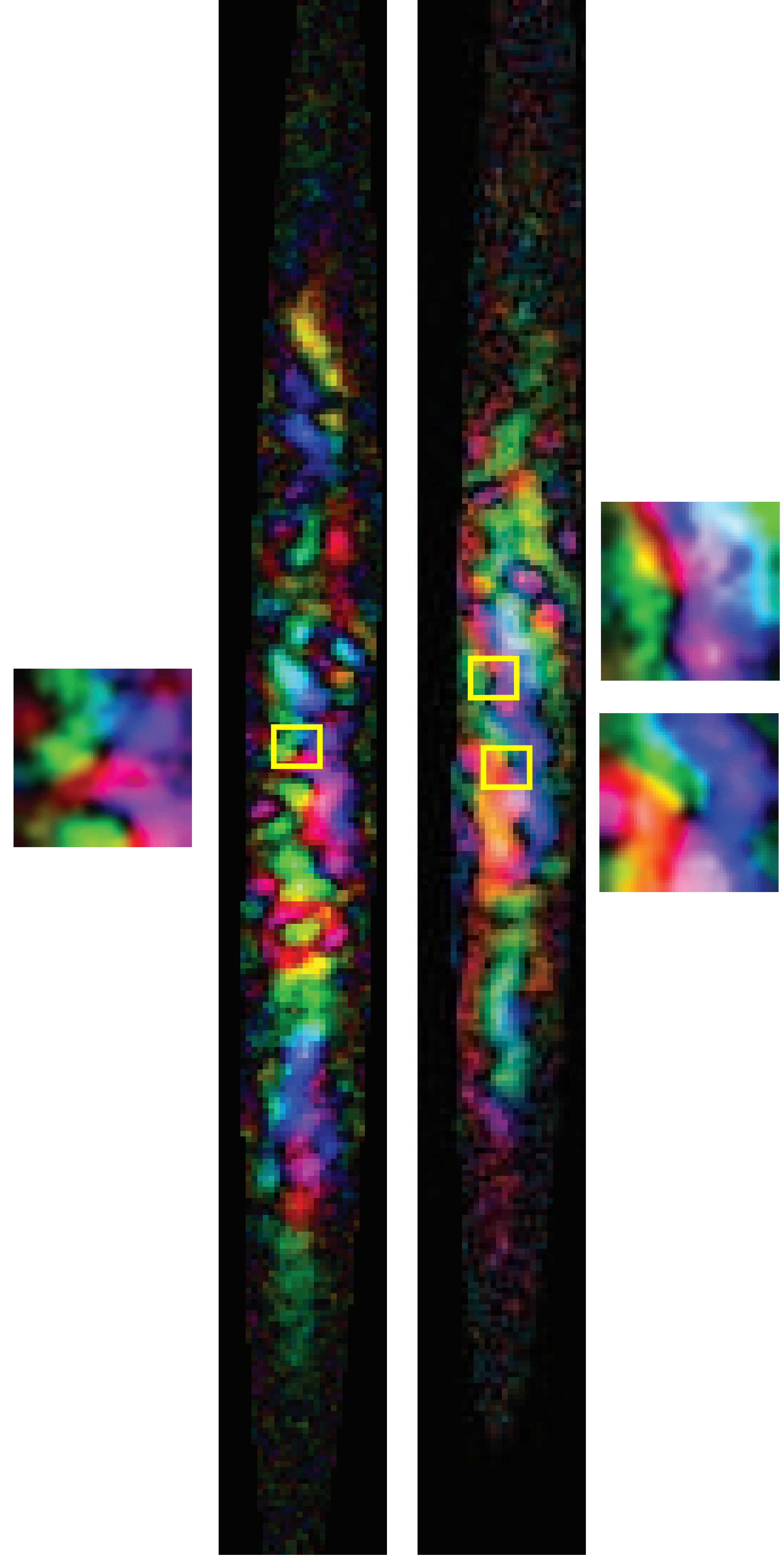
- D. Stamper-Kurn group (Berkeley)
- spinor BEC with ^{87}Rb in F=1 states



Vortex formation

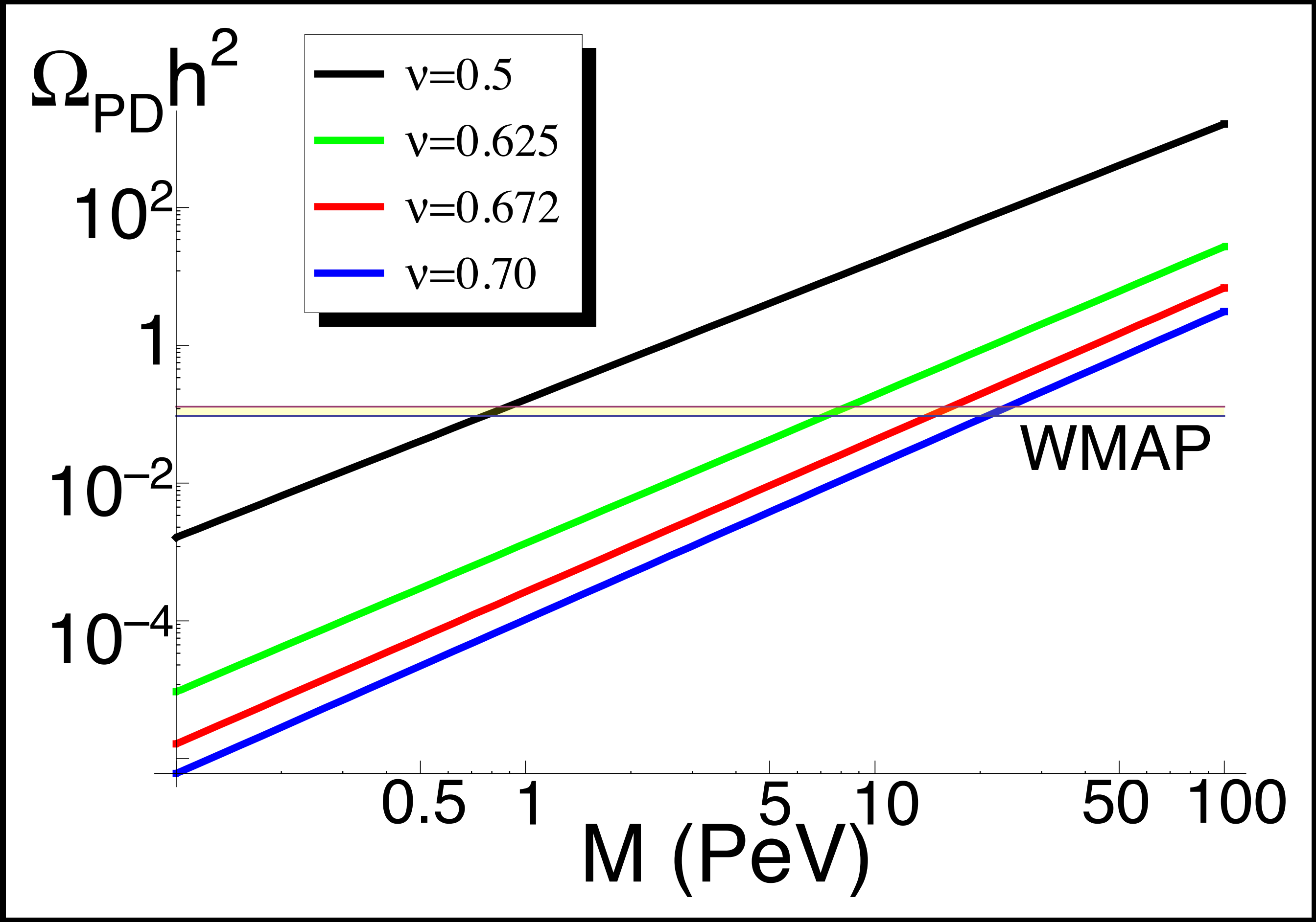




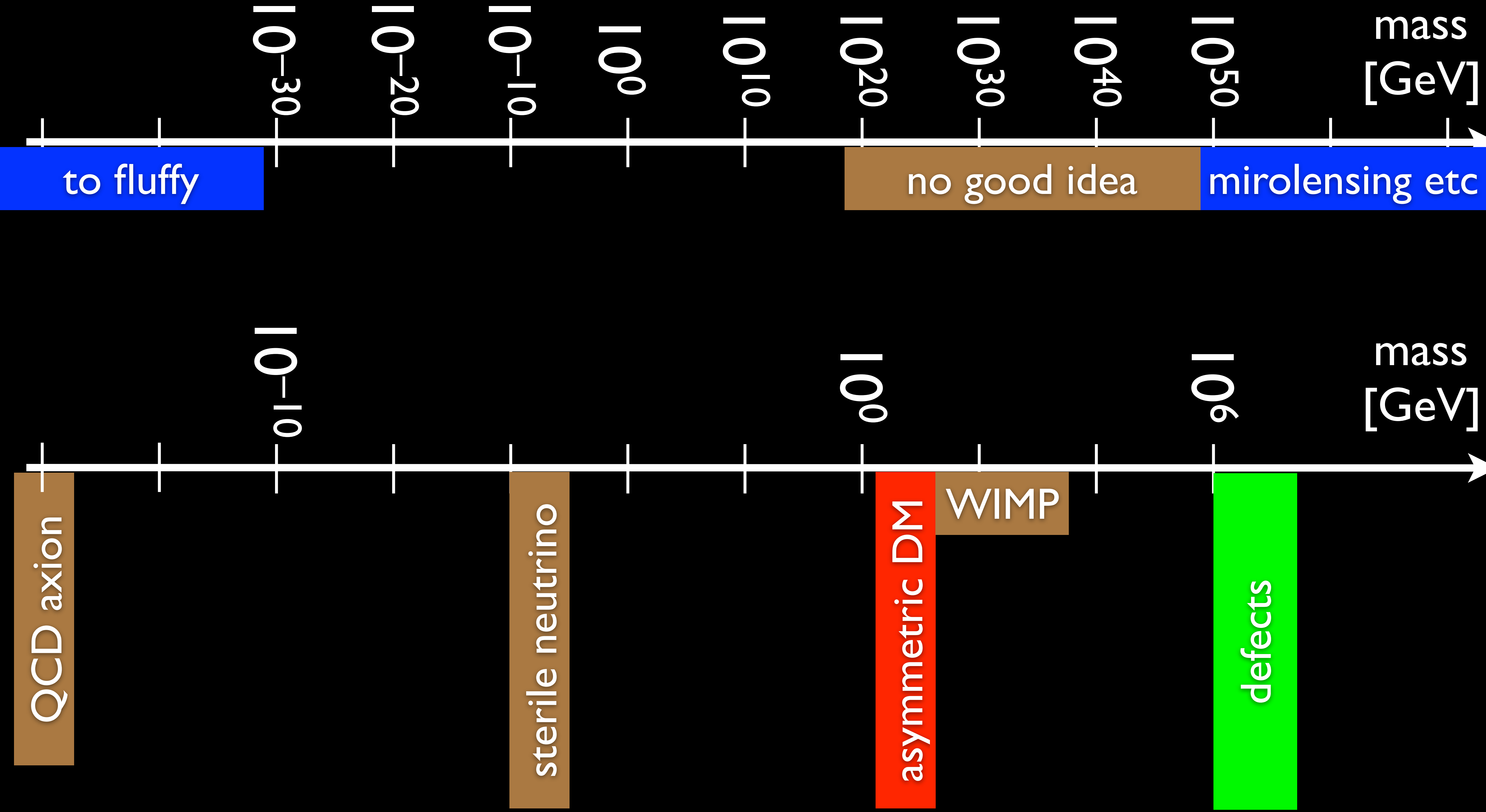


topological dark matter

- 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



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

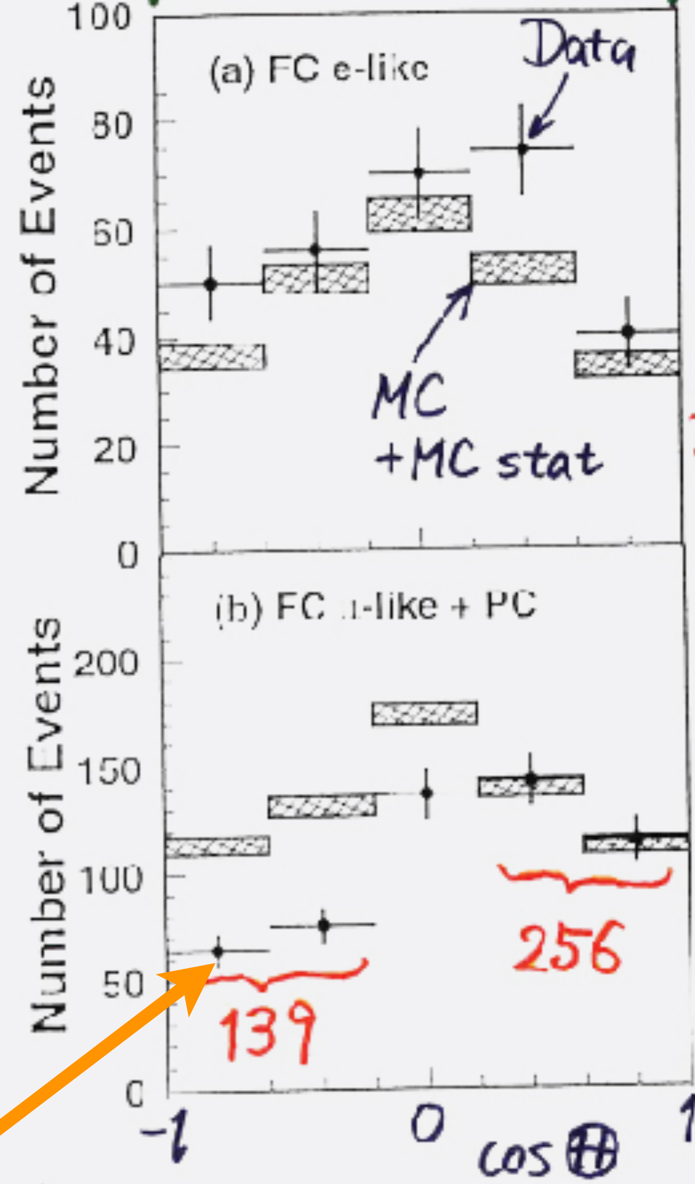
大気
ニュートリノ

1998

あるはずの
量の半分！

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 …… $\lesssim$ 1% ; 1km rock above SK …… 1.5%) 1.8%

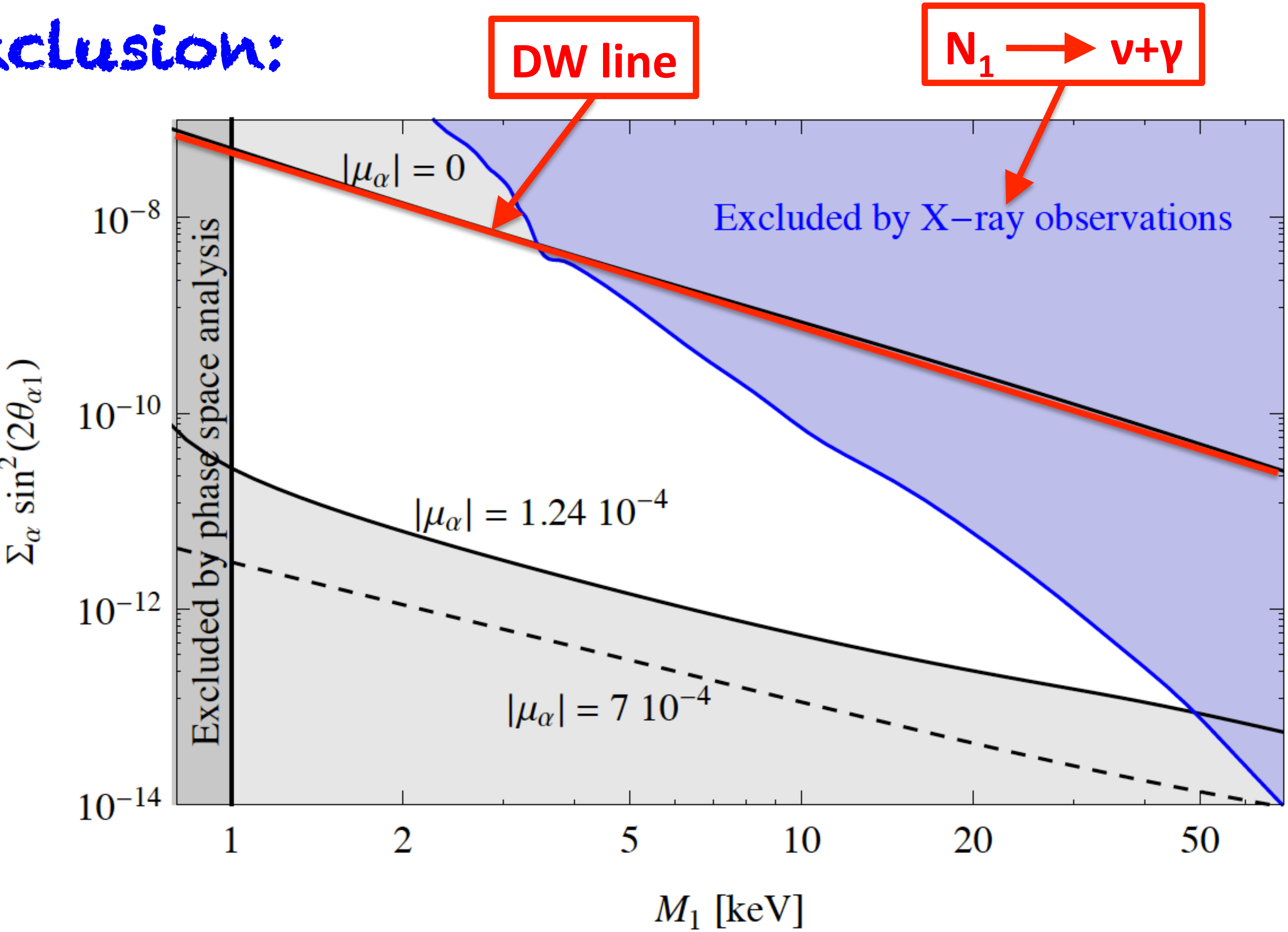
Data (Energy calib. for ↑↓ …… 0.7% ; Non ν Background …… < 2%) 2.1%

sterile neutrinos

- keV-scale sterile neutrinos could be dark matter
- >0.4keV because of the Pauli exclusion principle
- <50keV to avoid too rapid decay
- created by oscillation
- typically very small mixing angles
- requires non-zero asymmetry

2. Production Mechanisms

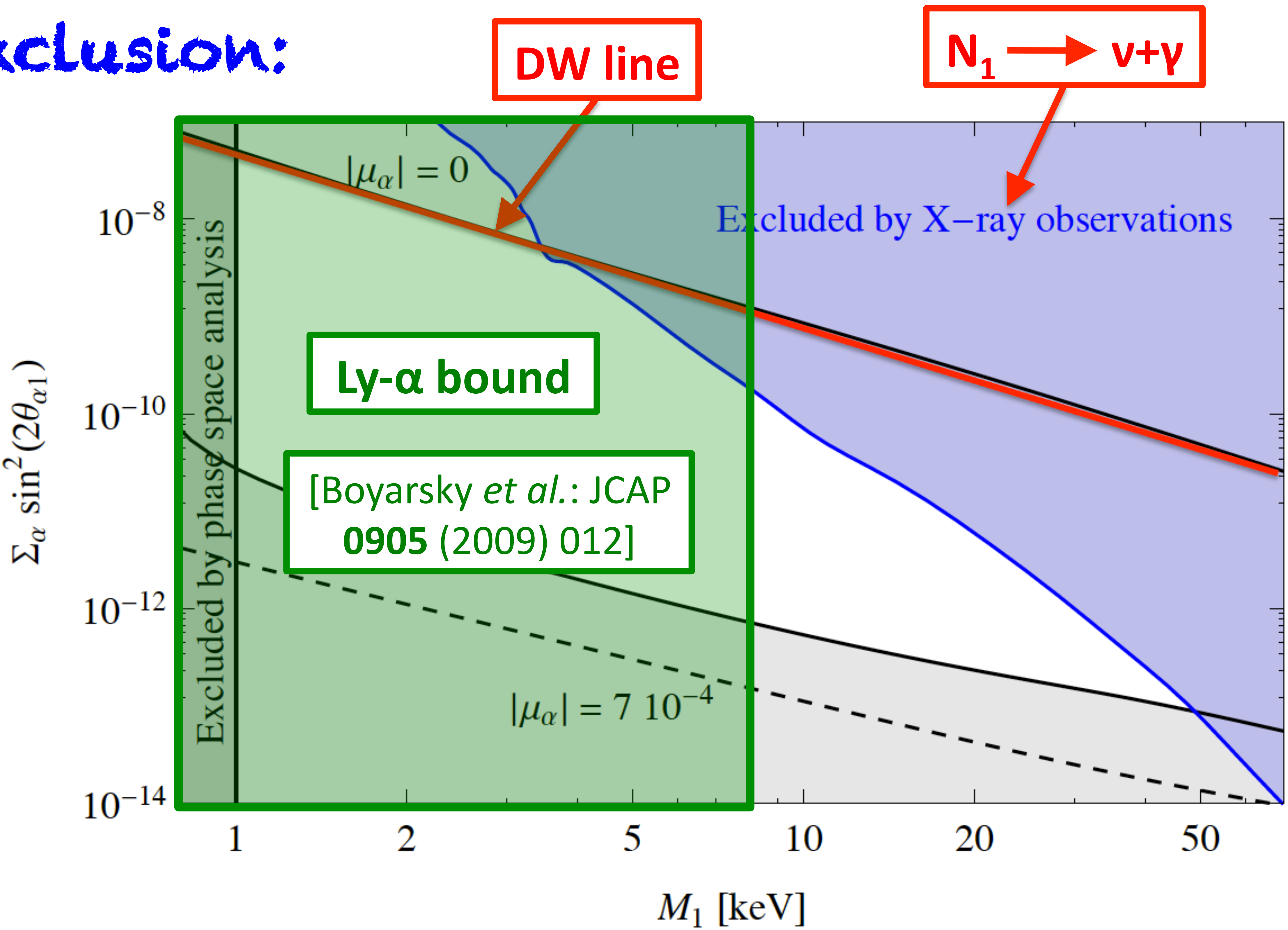
Exclusion:



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

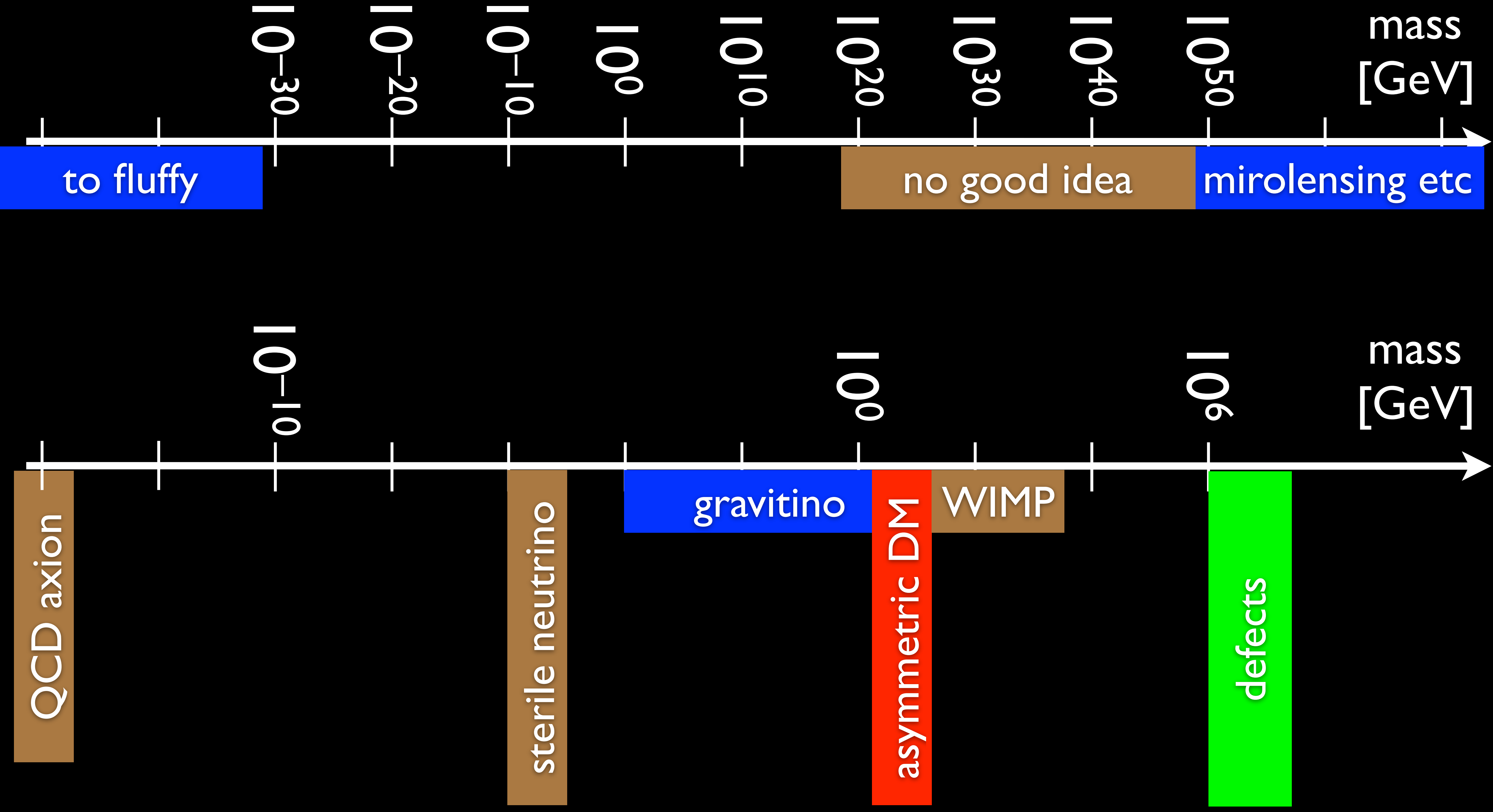
2. Production Mechanisms

Exclusion:



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

Alexander Merle



mass [GeV]
10^{-30} 10^{-20} 10^{-10} 10^{0} 10^{10} 10^{20} 10^{30} 10^{40} 10^{50}
to fluffy
no good idea
mirolensing etc
mass [GeV]
10^{-10} 10^{0} 10^{6}
QCD axion
sterile neutrino
gravitino
asymmetric DM
WIMP
defects

Gravitino problem

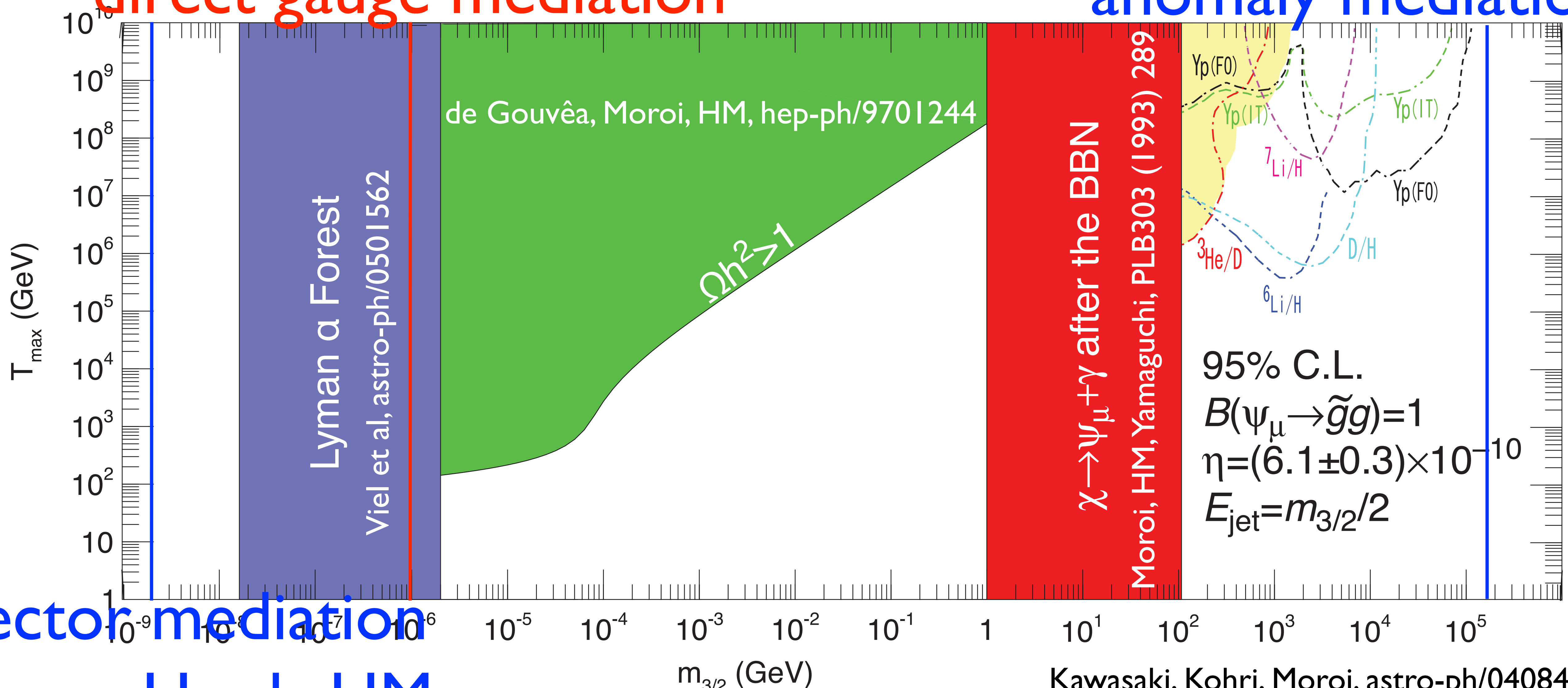
- Gravitinos produced thermally
- If decays after the BBN, dissociates synthesized light elements
- Hadronic decays particularly bad

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

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

direct gauge mediation

anomaly mediation



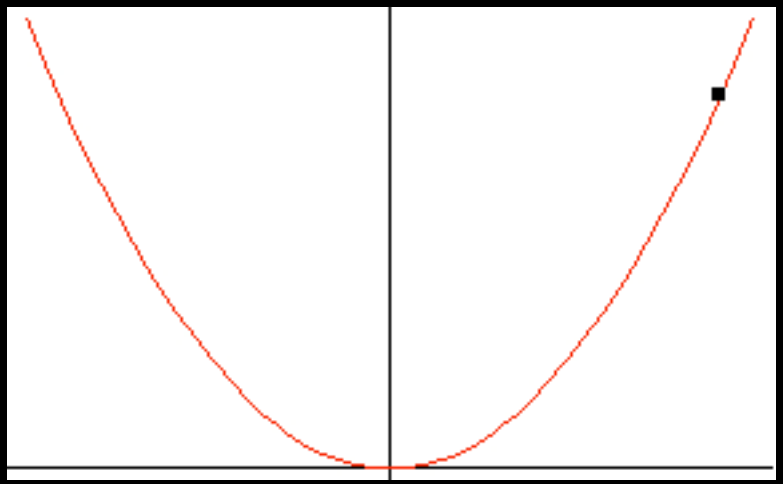
vector mediation

Anson Hook, HM

Kawasaki, Kohri, Moroi, astro-ph/0408426

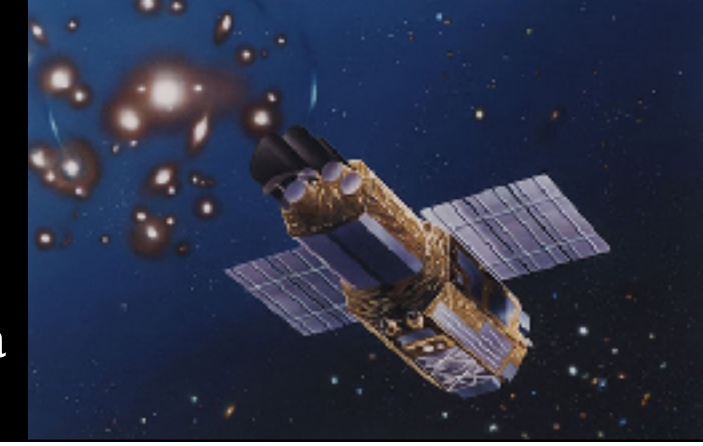
coherent oscillation

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



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

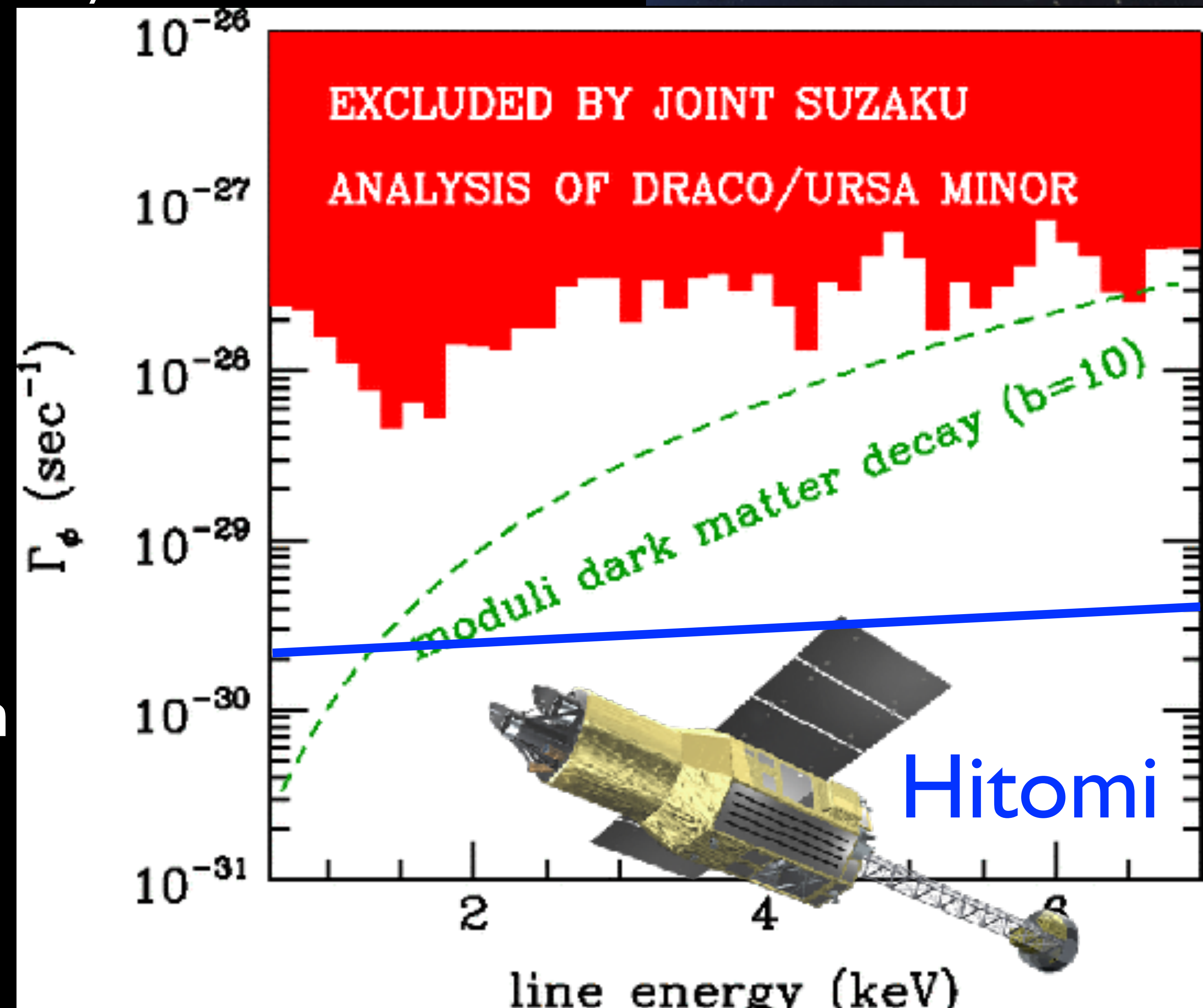
$$\tau(\phi \to \gamma\gamma) \sim 10^{28}\text{sec}\left(\frac{m_\phi}{10\text{keV}}\right)^{-3}$$



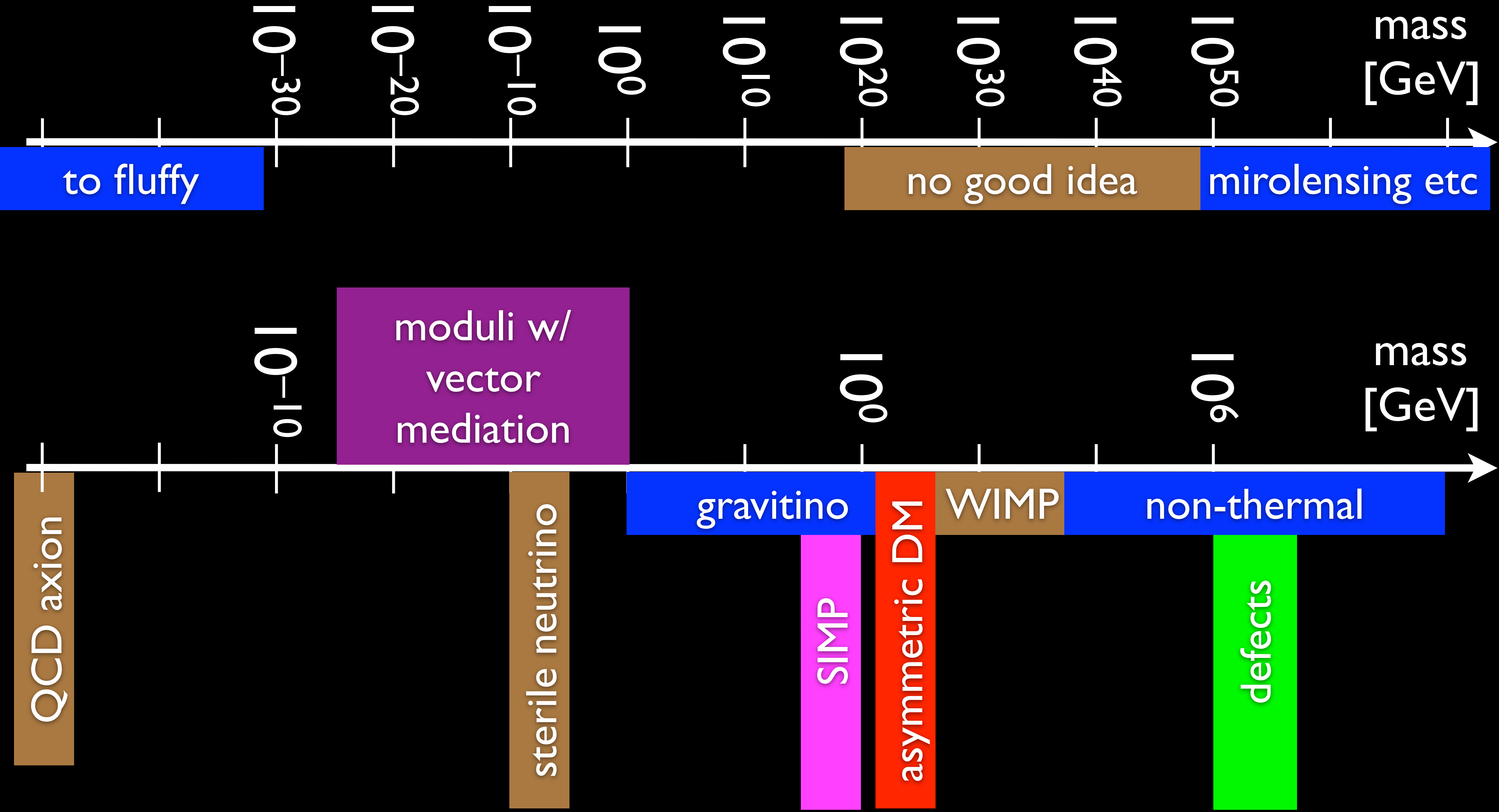
moduli

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}
10^{10}
10^{20}
10^{30}
10^{40}
10^{50}
to fluffy
no good idea
mirolensing etc
mass [GeV]
10^{-10}
10^{0}
10^{6}
moduli w/ vector mediation
QCD axion
sterile neutrino
gravitino
SIMP
asymmetric DM
WIMP
non-thermal
defects

recent thinking

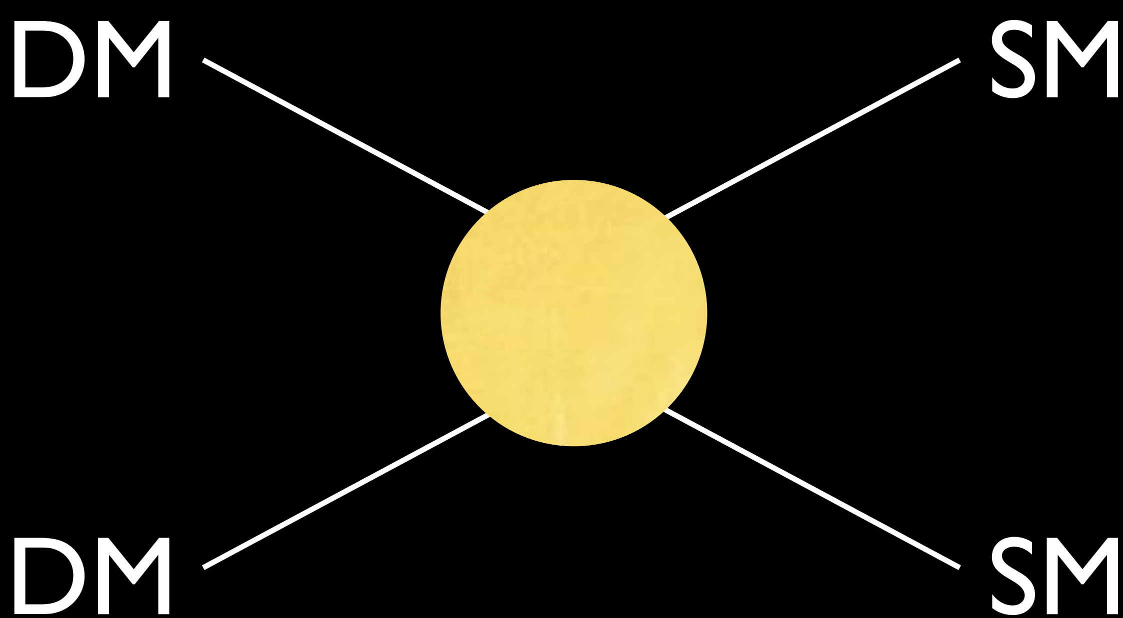
- dark matter definitely exists
  - naturalness problem may be optional?
- need to explain dark matter on its own
- perhaps we should decouple these two
- do we really need big ideas like SUSY?
- perhaps we can solve it with ideas more familiar to us?

Seminar in Berkeley
Strongly Interacting Massive Particle (SIMP)

Yonit Hochberg

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

Miracles

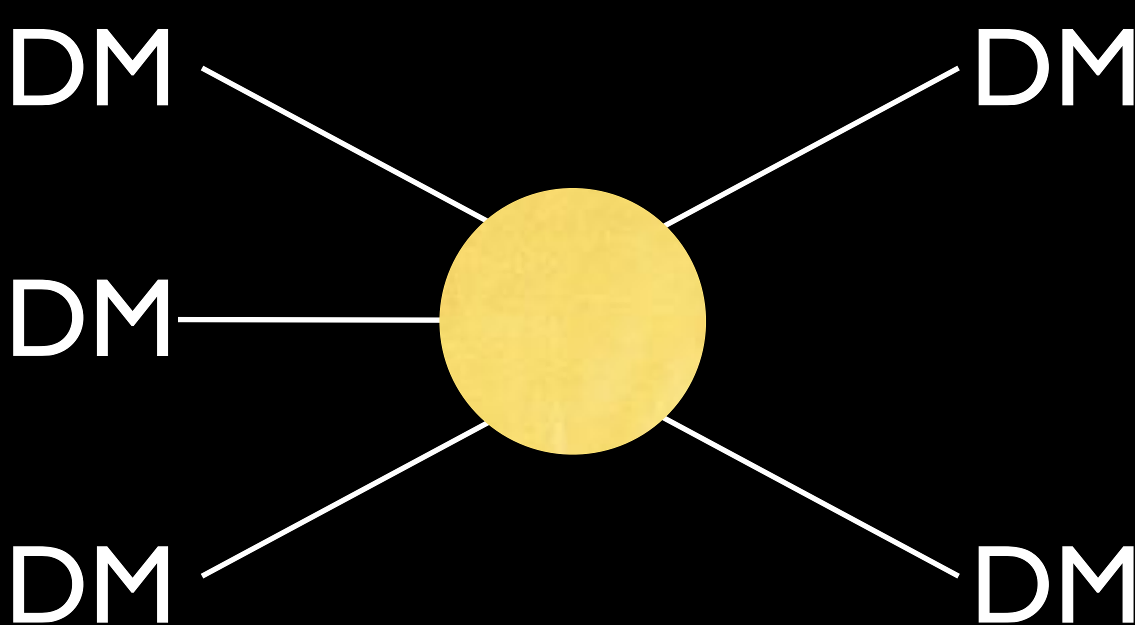


$$\langle \sigma_{2\to 2} v \rangle \approx \frac{\alpha^2}{m^2}$$

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

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

WIMP miracle!



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

$$\alpha \approx 4\pi$$

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

Hochberg, Kuflik, Volansky, Wacker arXiv:1402.5143

SIMP miracle!

~~LEE WEINBERG~~ 3→2 FREEZE-OUT

Back of the envelope calculation

$$\Gamma_{\rm ann} \simeq H|_{\rm freezeout}$$

$$\boldsymbol{\Gamma_{\rm ann} \simeq n_{\rm dm}^2 \langle \sigma v^2 \rangle_{3\to 2}}$$

$$H \simeq \frac{T^2}{M_{\rm pl}}$$

$$m_{\rm dm} n_{\rm dm} \sim m_p n_b$$

$$\langle \sigma v^2 \rangle_{3\to 2} \simeq \frac{\alpha^3}{m_{\rm dm}^5}$$

$$n_b \sim \eta_b s$$

$$\eta_b \simeq T_{\rm eq}/m_p \qquad s \simeq T^3$$

$$\boldsymbol{\Gamma_{\rm ann} \simeq \frac{T_{\rm eq}^2 \alpha^3}{x_F^4 \times m_{\rm dm}}} \quad = \quad H \simeq \frac{m_{\rm dm}^2}{M_{\rm pl} x_F^2}$$

Eric Kuflik

THE SIMP MIRACLE

A coincidence of scales

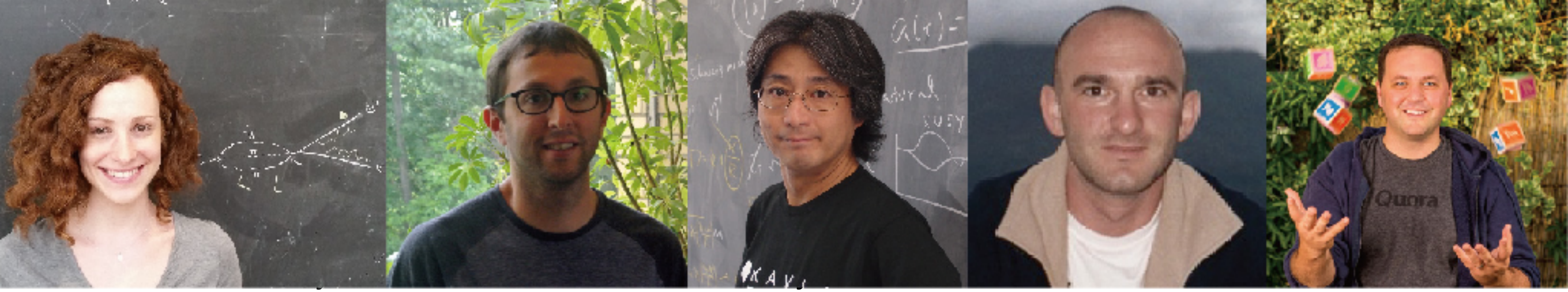
$$m_{\rm dm} \simeq \alpha \left(T_{\rm eq}^2 M_{\rm pl}/x_F^4\right)^{\frac{1}{3}}$$

$$m_{\rm dm} \simeq \alpha \times 100 \text{ MeV}$$

- If $\alpha \sim 1$, the strong scale emerges $(x_F \sim 20)$
- Like the WIMP, no input of scales or particle physics

Eric Kuflik

Strongly interacting sub-GeV dark matter



The absolutely SIMPlest is probably SU(2) gauge theory with six doublets = three flavors. In the massless limit, there is SU(6) global symmetry, which is anomalous if gauged. The quark bilinear breaks it down to Sp(3), with 14 NGBs in the rank-two anti-symmetric tensor representation 14 of Sp(3). Because of the homotopy exact sequence,

0 = pi_5 (Sp(3)) —> pi_5 (SU(6))=Z —> pi_5 (SU(6)/Sp(3)) —> pi_4 (Sp(3))=Z2 —> pi_4 (SU(6))=0,

we see that pi_5 (SU(6)/Sp(3)=Z and hence Wess-Zumino term is possible. This is of course expected because SU(6) is anomalous. Upon the common mass term, the entire 14-plet acquires the same mass. Because of the flavor quantum number, they are stable, and they have 2—>3 scattering because of the WZ term.

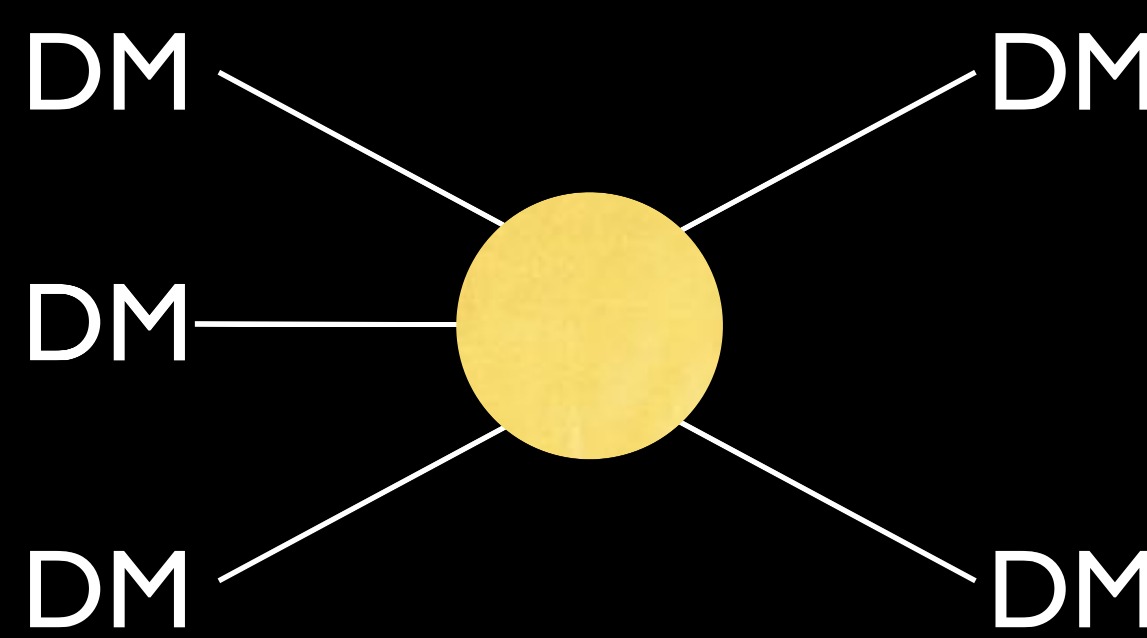
SU(3) or SU(2), the remaining question is how to couple them to the Standard Model. If we don't worry about naturalness, the simplest is to introduce a singlet that couples to quarks in the dark matter sector and Higgs in the Standard Model.

Hitoshi

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

SIMPlest Miracle

- Not only the mass scale is similar to QCD
- dynamics itself can be QCD! Miracle^3
- DM = pions
- e.g. SU(4)/Sp(4) = S^5



$$\mathcal{L}_{\rm chiral} = \frac{1}{16 f_\pi^2} {\rm Tr} \partial^\mu U^\dagger \partial_\mu U$$

+HM
arXiv:1411.3727

$$\mathcal{L}_{\rm WZW} = \frac{8 N_c}{15 \pi^2 f_\pi^5} \epsilon_{abcde} \epsilon^{\mu\nu\rho\sigma} \pi^a \partial_\mu \pi^b \partial_\nu \pi^c \partial_\rho \pi^d \partial_\sigma \pi^e + O(\pi^7)$$

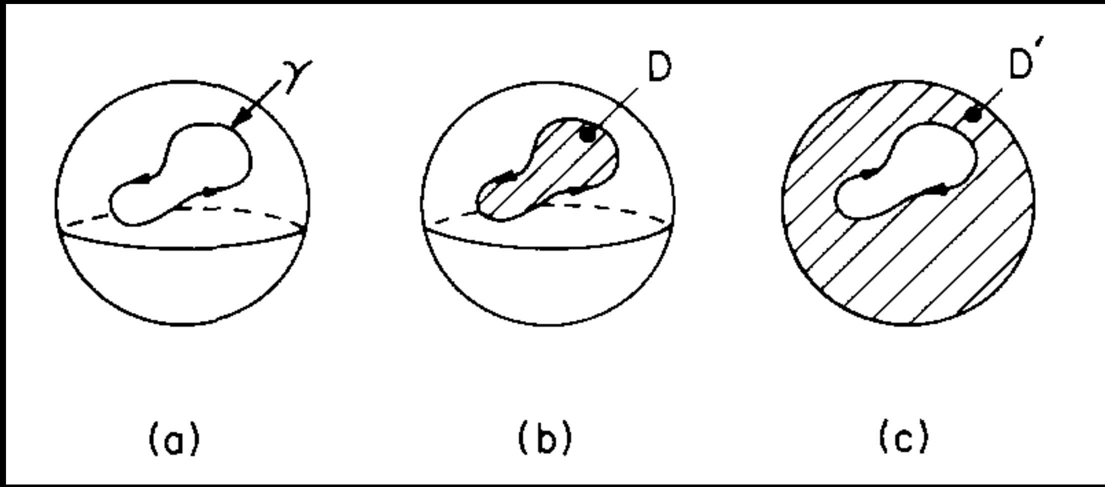
$$\pi_5(G/H) \neq 0$$

SIMPlest Miracle

- SU(2) gauge theory with four doublets
- SU(4)=SO(6) flavor symmetry
- $\langle q^i q^j \rangle \neq 0$ breaks it to Sp(2)=SO(5)
- coset space SO(6)/SO(5)=S^5
- $\pi_5(S^5)=\mathbb{Z} \Rightarrow$ Wess-Zumino term
- $\mathcal{L}_{WZ}=\varepsilon_{abcde}\, \varepsilon^{\mu\nu\rho\sigma}\, \pi^a \partial_\mu \pi^b \partial_\nu \pi^c \partial_\rho \pi^d \partial_\sigma \pi^e$

Wess-Zumino term

- $SU(N_c)$ gauge theory
  - $\pi_5(SU(N_f))=\mathbb{Z}$ ($N_f \geq 3$)
- $Sp(N_c)$ gauge theory
  - $\pi_5(SU(2N_f)/Sp(N_f))=\mathbb{Z}$ ($N_f \geq 2$)
- $SO(N_c)$ gauge theory
  - $\pi_5(SU(N_f)/SO(N_f))=\mathbb{Z}$ ($N_f \geq 3$)



Witten

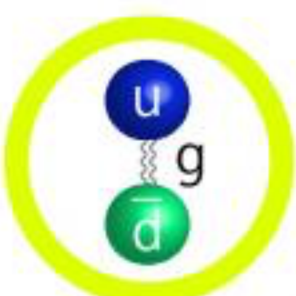
LAGRANGIANS

Quark theory

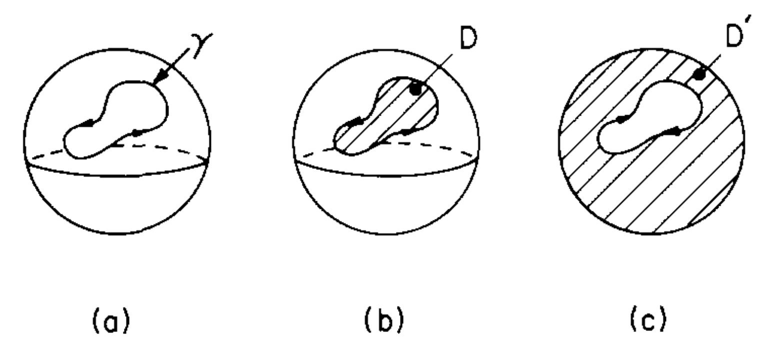
$$\mathcal{L}_{\text{quark}} = -\frac{1}{4}F^{a}_{\mu\nu}F^{\mu\nu a} + \bar{q}_i i\not{D} q_i \; -\frac{1}{2}m_Q \; J^{ij} q_i q_j + h.c.$$

Sigma theory

$$\mathcal{L}_{\text{Sigma}} = \frac{f_\pi^2}{16}\text{Tr}\partial_\mu\Sigma \, \partial^\mu\Sigma^\dagger - \frac{1}{2}m_Q\mu^3 \text{Tr} J\Sigma + h.c. - \frac{iN_c}{240\pi^2}\int \text{Tr}(\Sigma^\dagger d\Sigma)^5$$

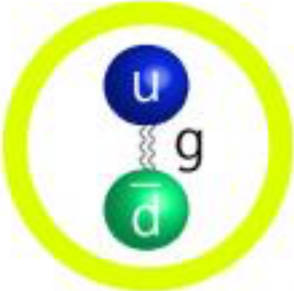


Pion theory

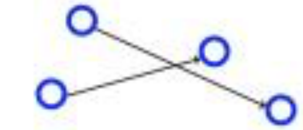


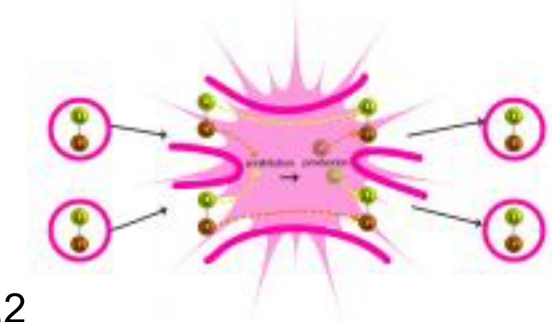
$$\mathcal{L}_{\text{pion}} = \frac{1}{4}\text{Tr}\partial_\mu\pi\partial^\mu\pi - \frac{m_\pi^2}{4}\text{Tr}\pi^2 + \frac{m_\pi^2}{12f_\pi^2}\text{Tr}\pi^4 - \frac{1}{6f_\pi^2}\text{Tr}\left(\pi^2\partial^\mu\pi\partial_\mu\pi - \pi\partial^\mu\pi\pi\partial_\mu\pi\right)$$

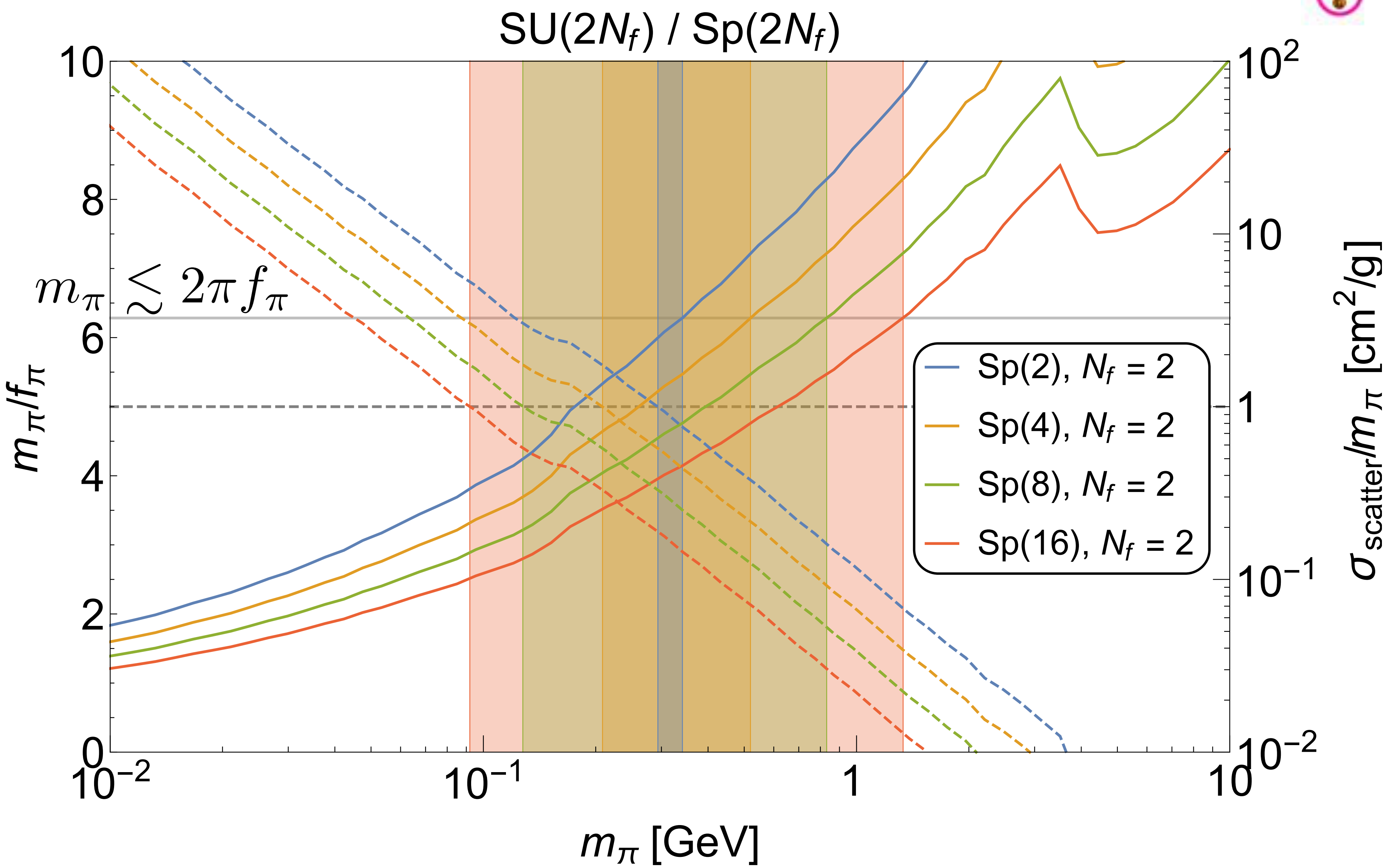
$$+ \frac{2N_c}{15\pi^2 f_\pi^5}\epsilon^{\mu\nu\rho\sigma}\text{Tr}\left[\pi\partial_\mu\pi\partial_\nu\pi\partial_\rho\pi\partial_\sigma\pi\right] + \mathcal{O}(\pi^6)$$



The Results





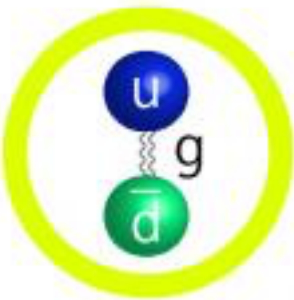


Solid curves: solution to Boltzmann eq.

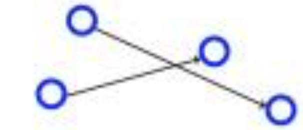
Dashed curves: along that solution

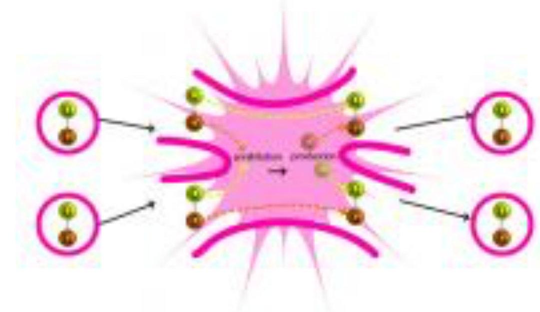
$$\frac{m_\pi}{f_\pi} \propto m_\pi^{3/10}$$

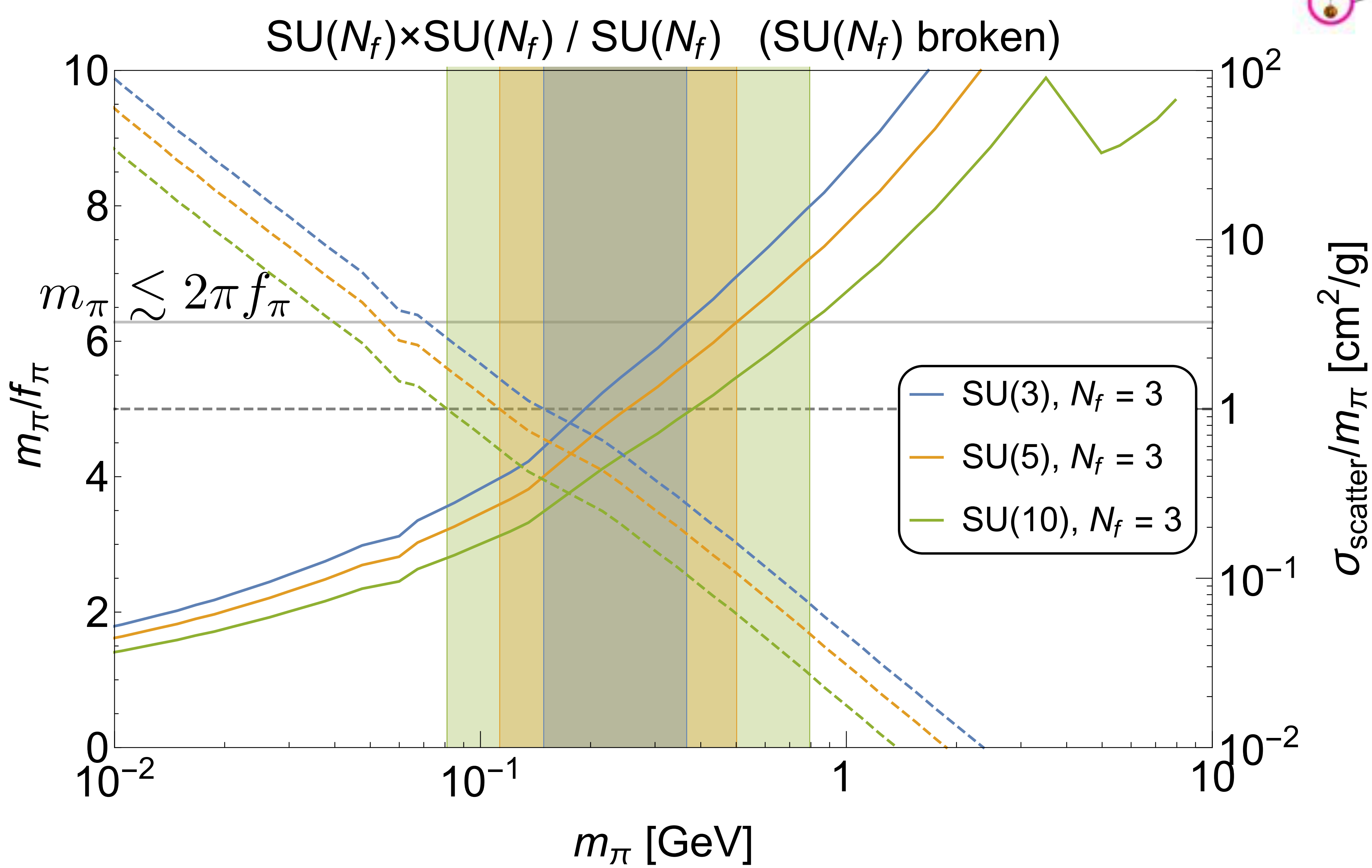
$$\frac{\sigma_{\rm scatter}}{m_\pi} \propto m_\pi^{-9/5}$$



The Results





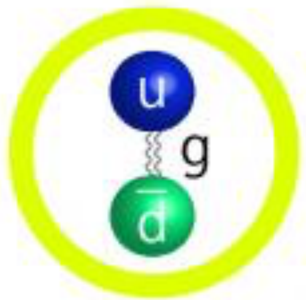


Solid curves: solution to Boltzmann eq.

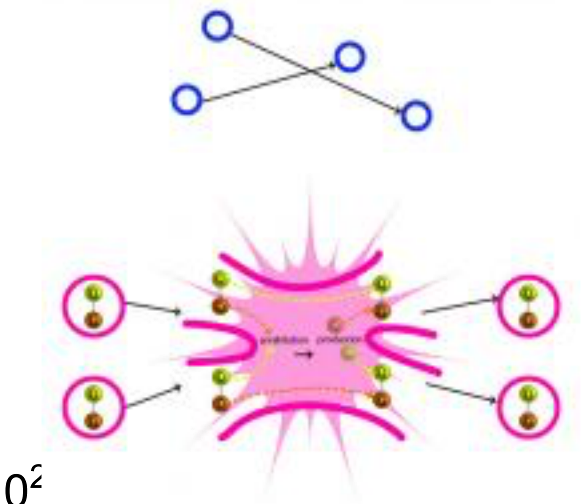
Dashed curves: along that solution

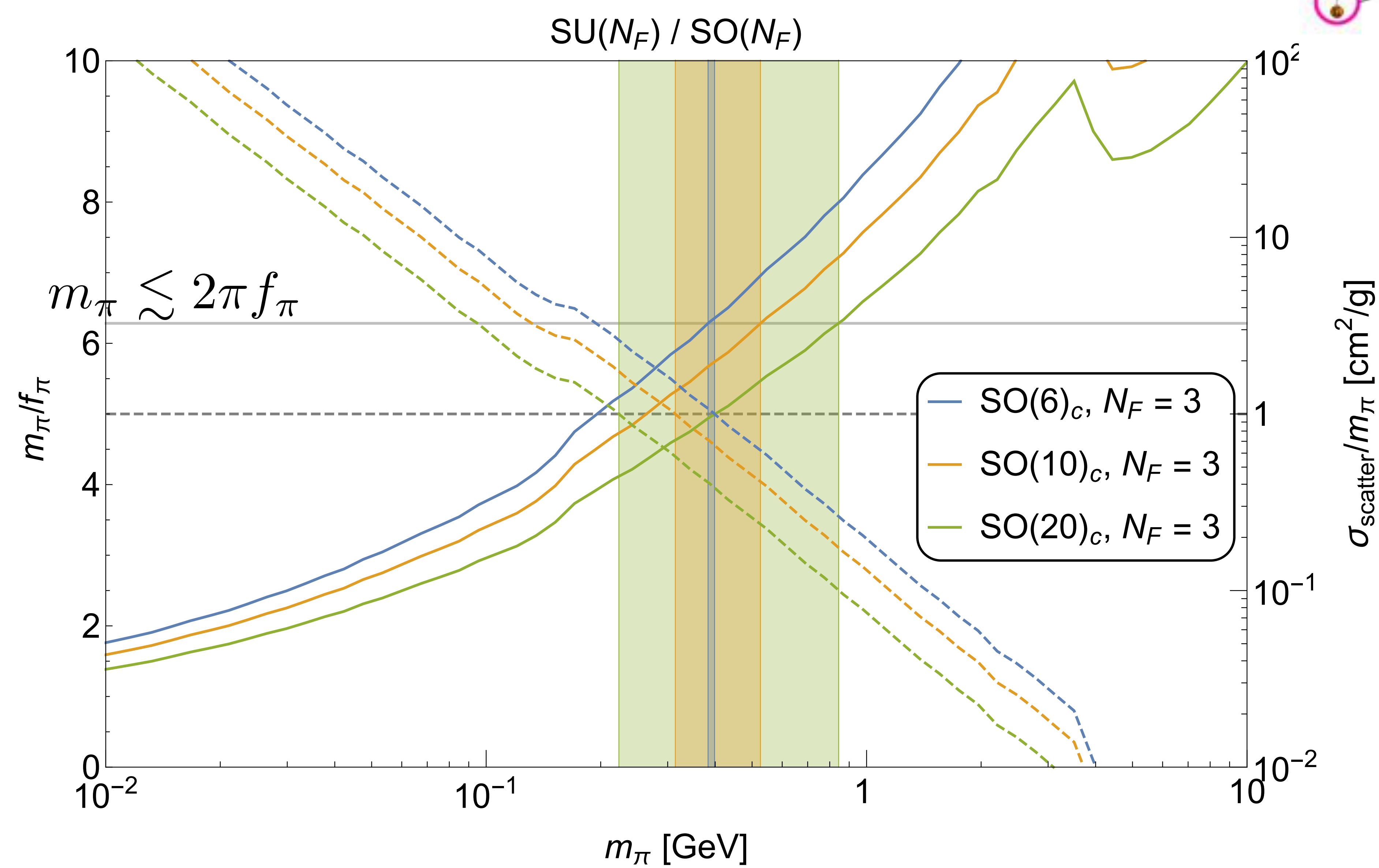
$$\frac{m_\pi}{f_\pi} \propto m_\pi^{3/10}$$

$$\frac{\sigma_{\rm scatter}}{m_\pi} \propto m_\pi^{-9/5}$$



The Results





Solid curves: solution to Boltzmann eq.

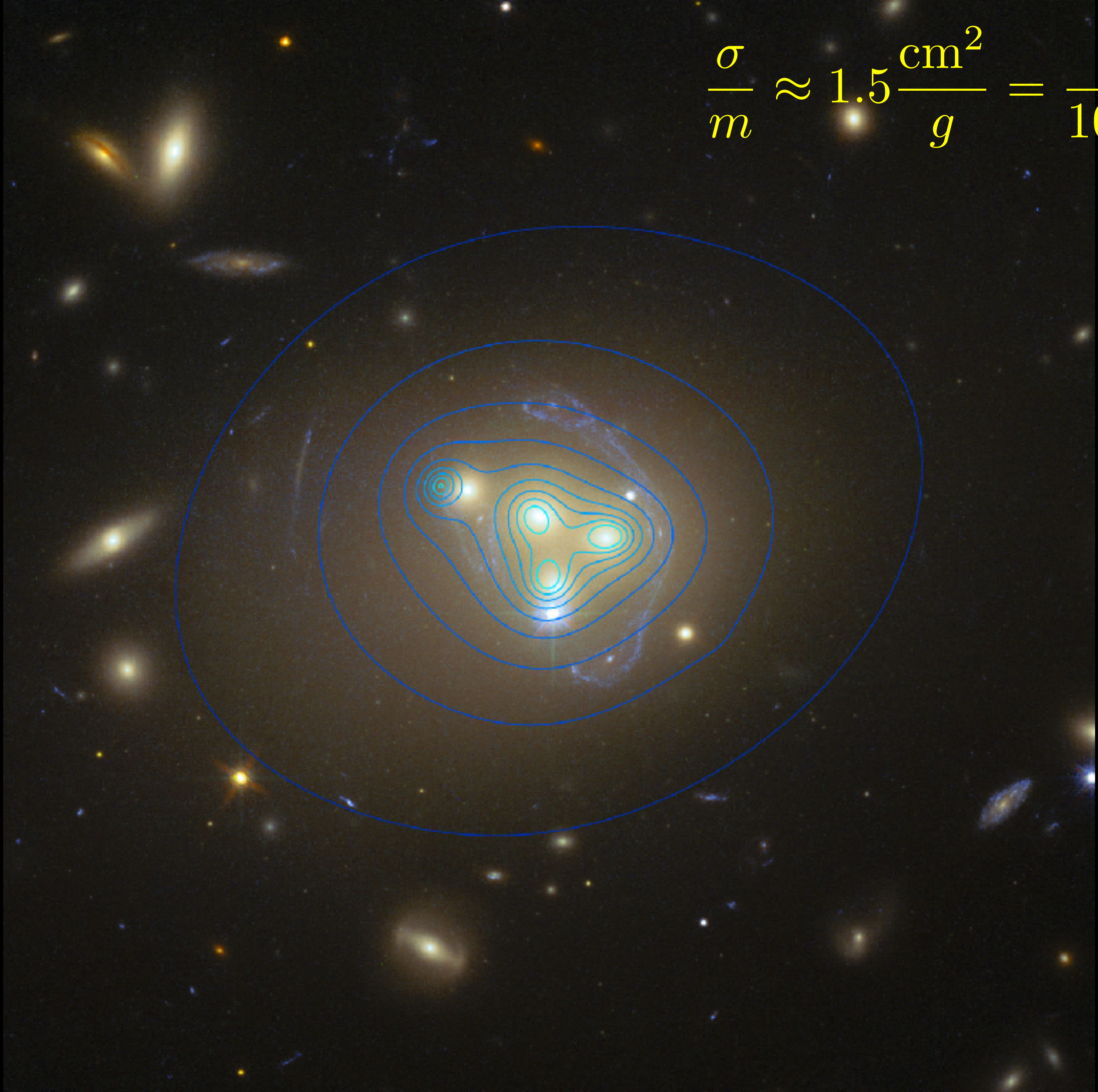
Dashed curves: along that solution

$$\frac{m_\pi}{f_\pi} \propto m_\pi^{3/10}$$

$$\frac{\sigma_{\text{scatter}}}{m_\pi} \propto m_\pi^{-9/5}$$


Abell 3827

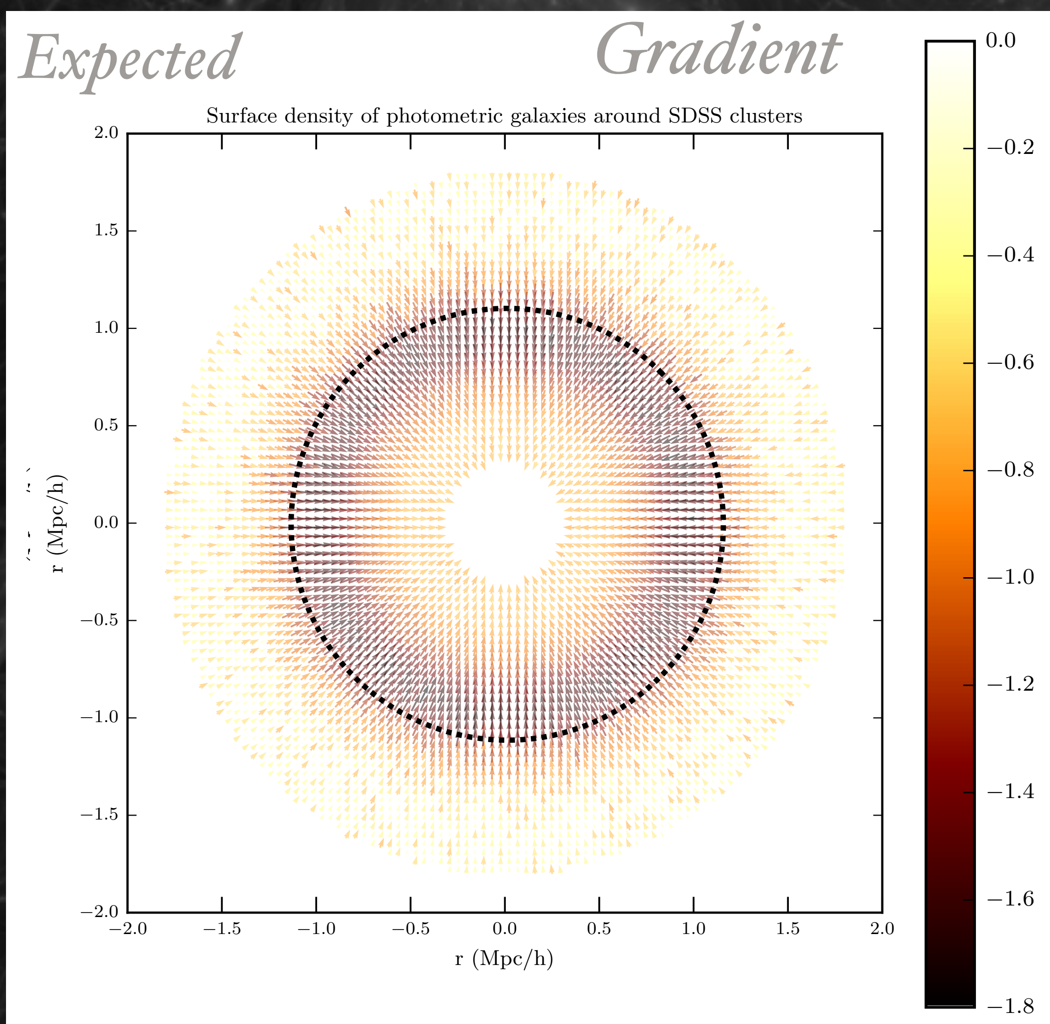
$$\frac{\sigma}{m} \approx 1.5 \frac{\mathrm{cm}^2}{g} = \frac{0.27\mathrm{b}}{100\mathrm{MeV}}$$



Astrophysics Particle physics

Galaxy distribution around SDSS galaxy clusters

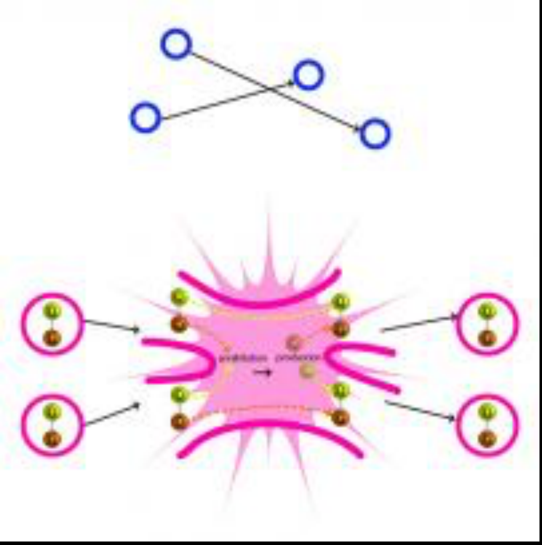
SM et al (2016), ApJ



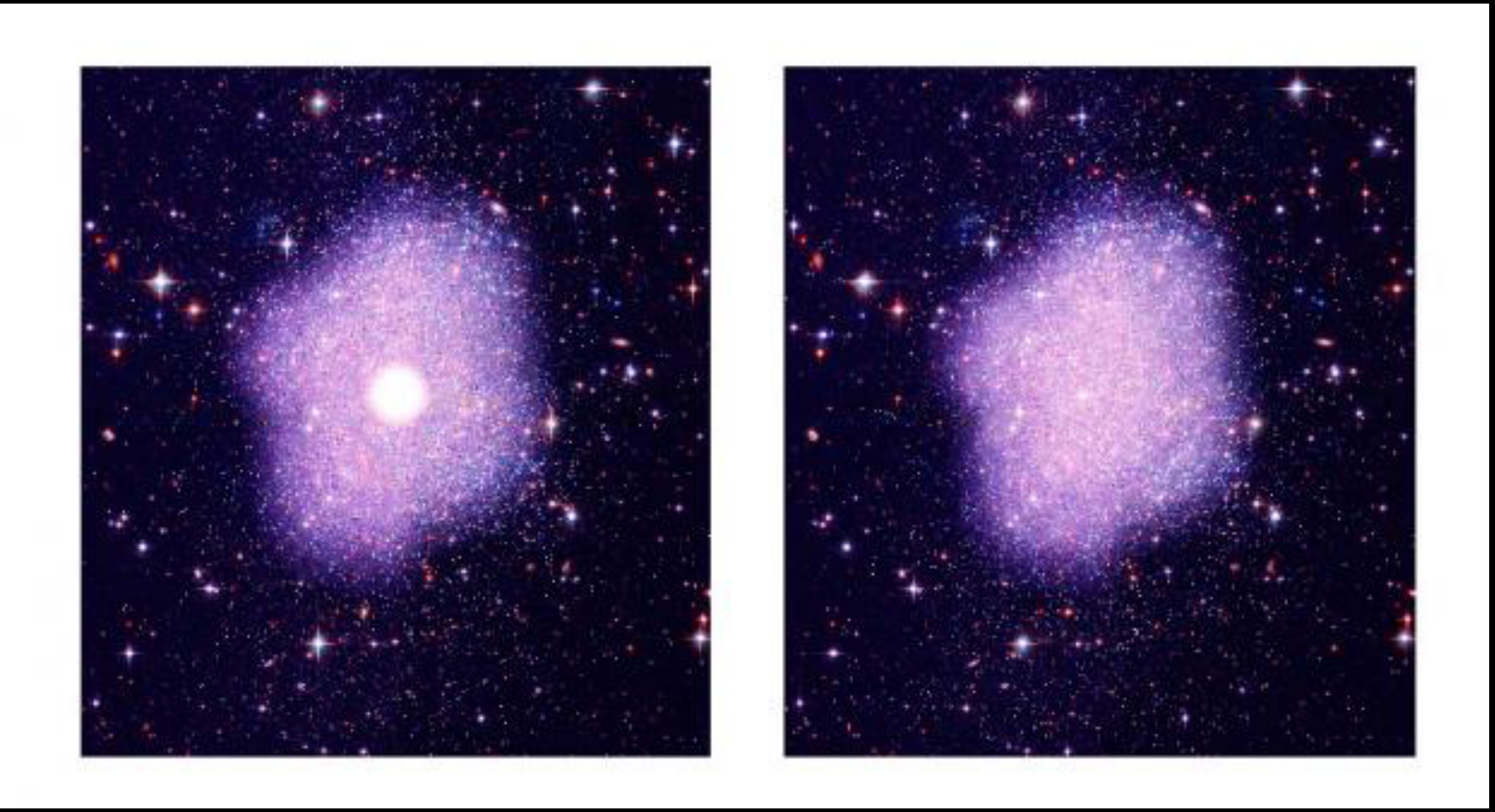
- *Extremely well measured cross-correlation of galaxy clusters and faint photometric galaxies*
- *First detection of the halo edge!*
- *The edge is smaller than expected by about 20 percent (nominally 4-sigma confidence)*
  - *Dark matter self-interactions(?!)*
    - *Discussions with Dalal, Murayama and Matsumoto*

Surhud More

self interaction



- self interaction of $\sigma/m \sim 10^{-24}\text{cm}^2$ / 300MeV
- flattens the cusps in NFW profile
- actually desirable for dwarf galaxies?

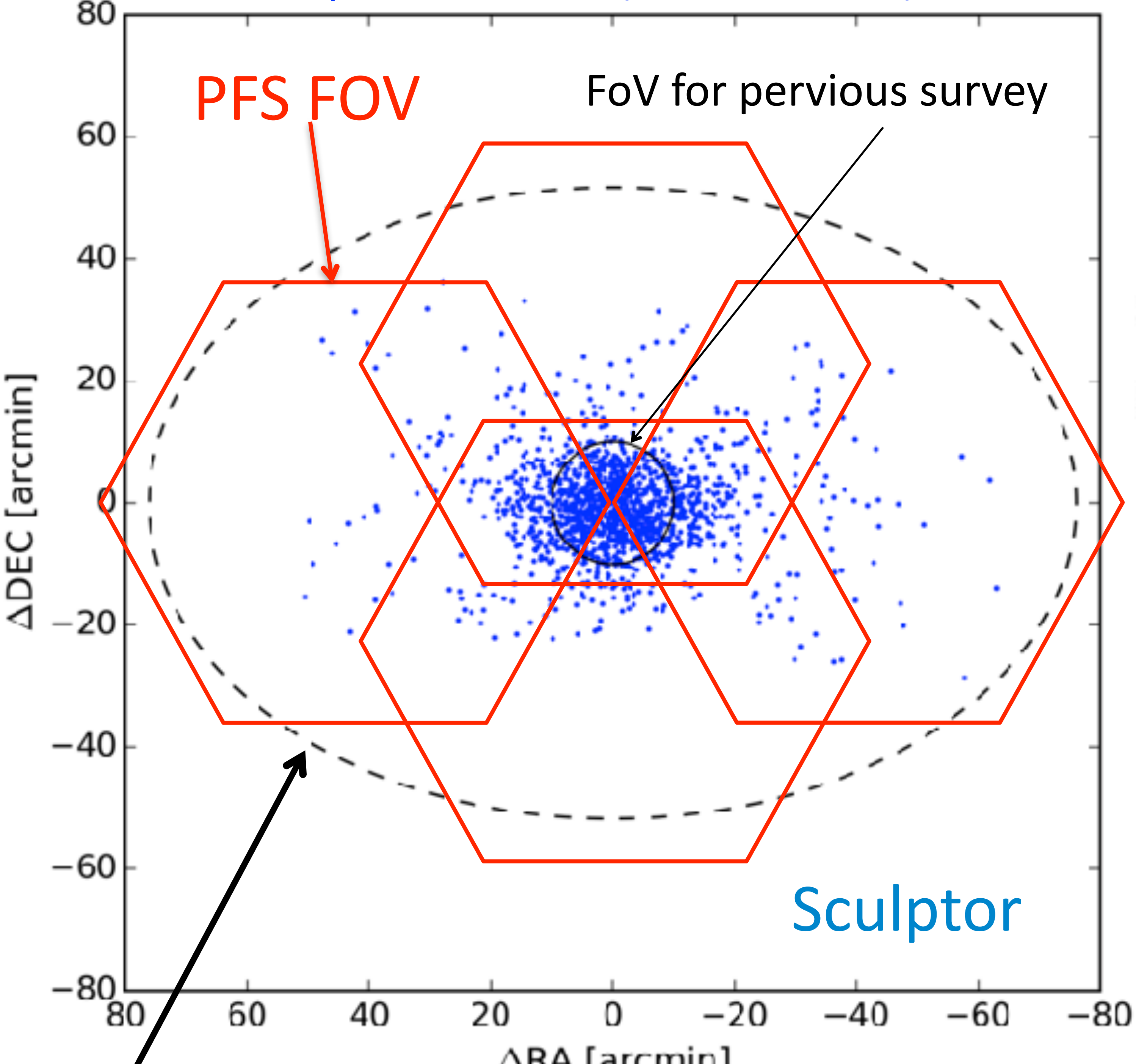


Too big to fail?

NASA/ESA/T. Brown and J. Tumlinson (STScI)]

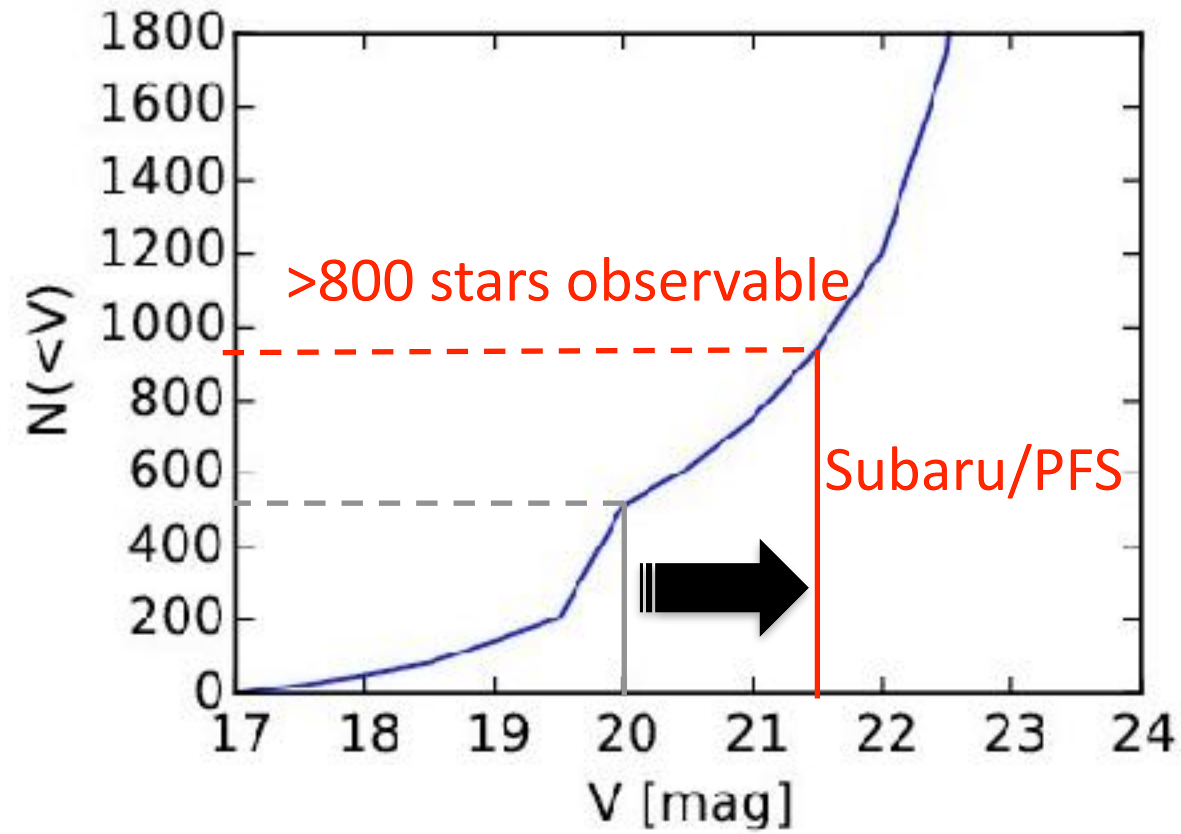
Wide & deep survey of MW dwarf galaxies w. Subaru/PFS

Blue dots: spectroscopic targets
in previous work (Walker+ 2009)



nominal boundary ($r_t \sim 76'$), but more member stars actually exist inside/beyond this limit.

Cumulative number of observable stars
w. Subaru/PFS



Subaru/PFS enables us to measure a large number of stellar spectra over unprecedentedly wide outer areas, <u>where DM largely dominates</u>!

⇒ Best for studying the nature of DM

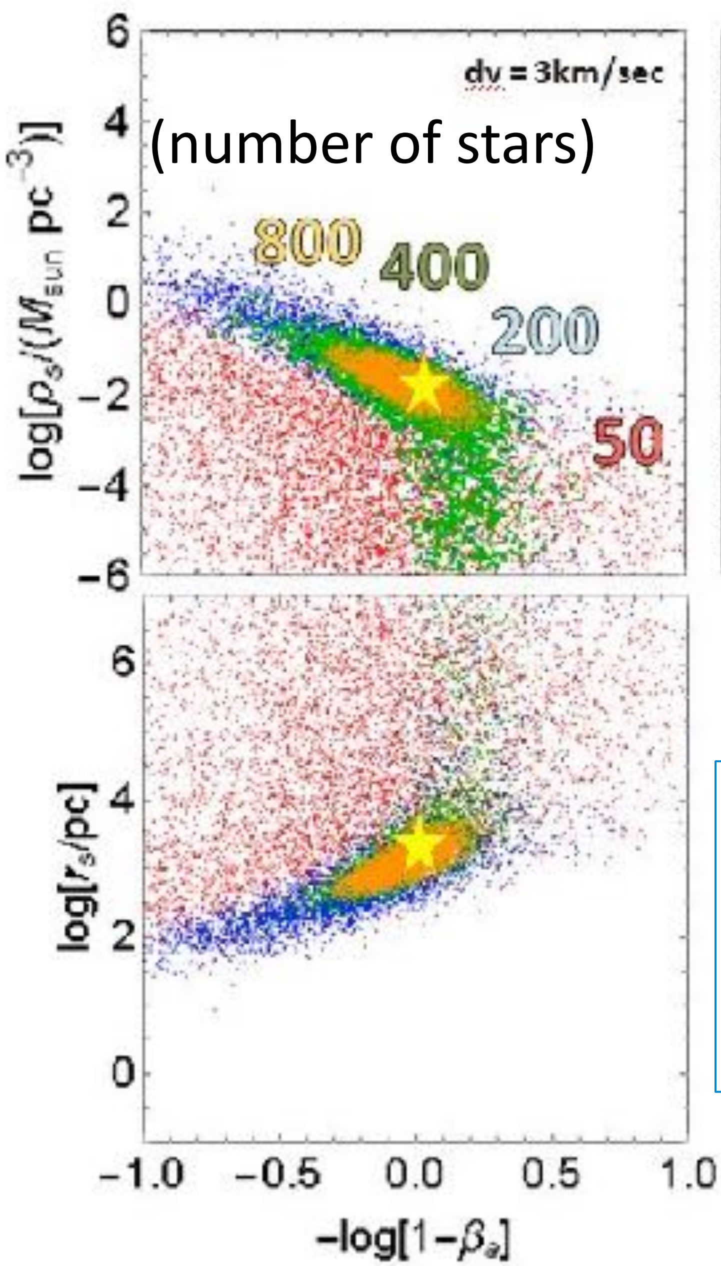
PFS Survey

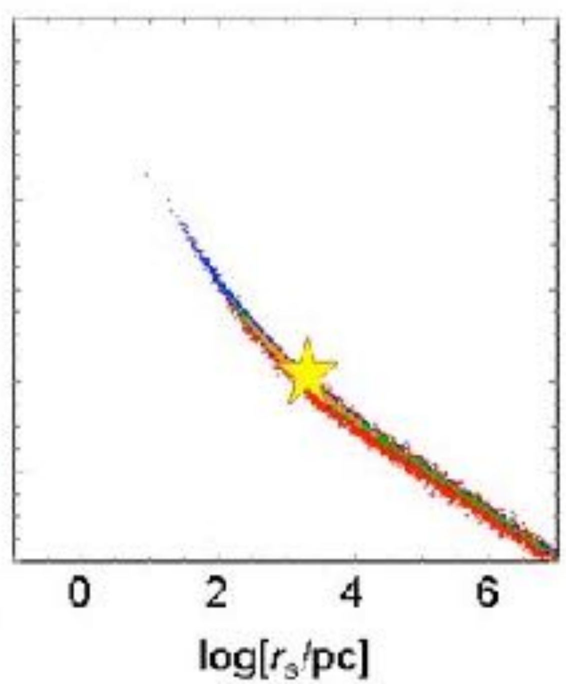
Precise measurement of DM Halo Profiles

Stellar Velocity Data ⟷ DM Gravitational Potential

Fit

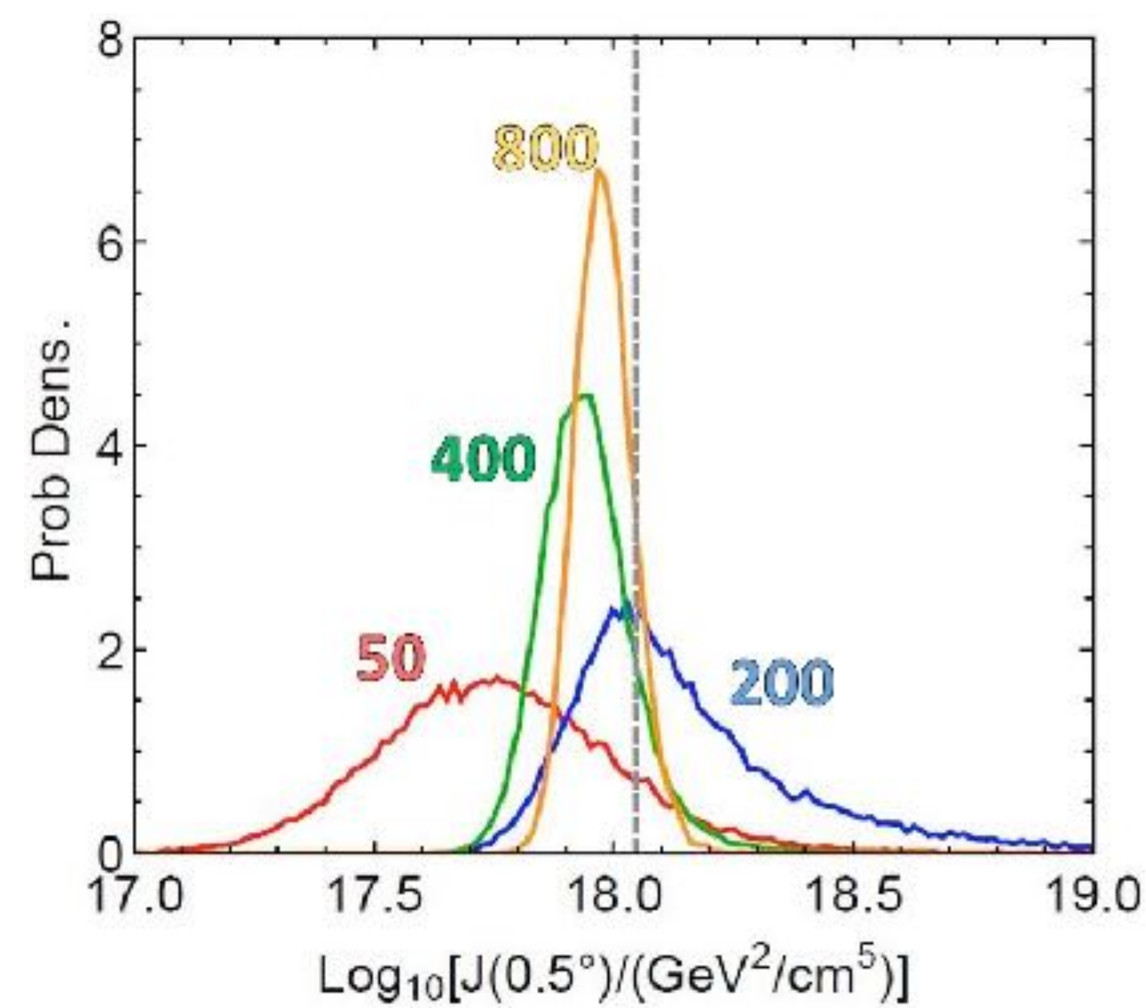
DM Halo: $\rho(r) = \rho_s (r/r_s)^{-1}(1 + r/r_s)^{-2}$



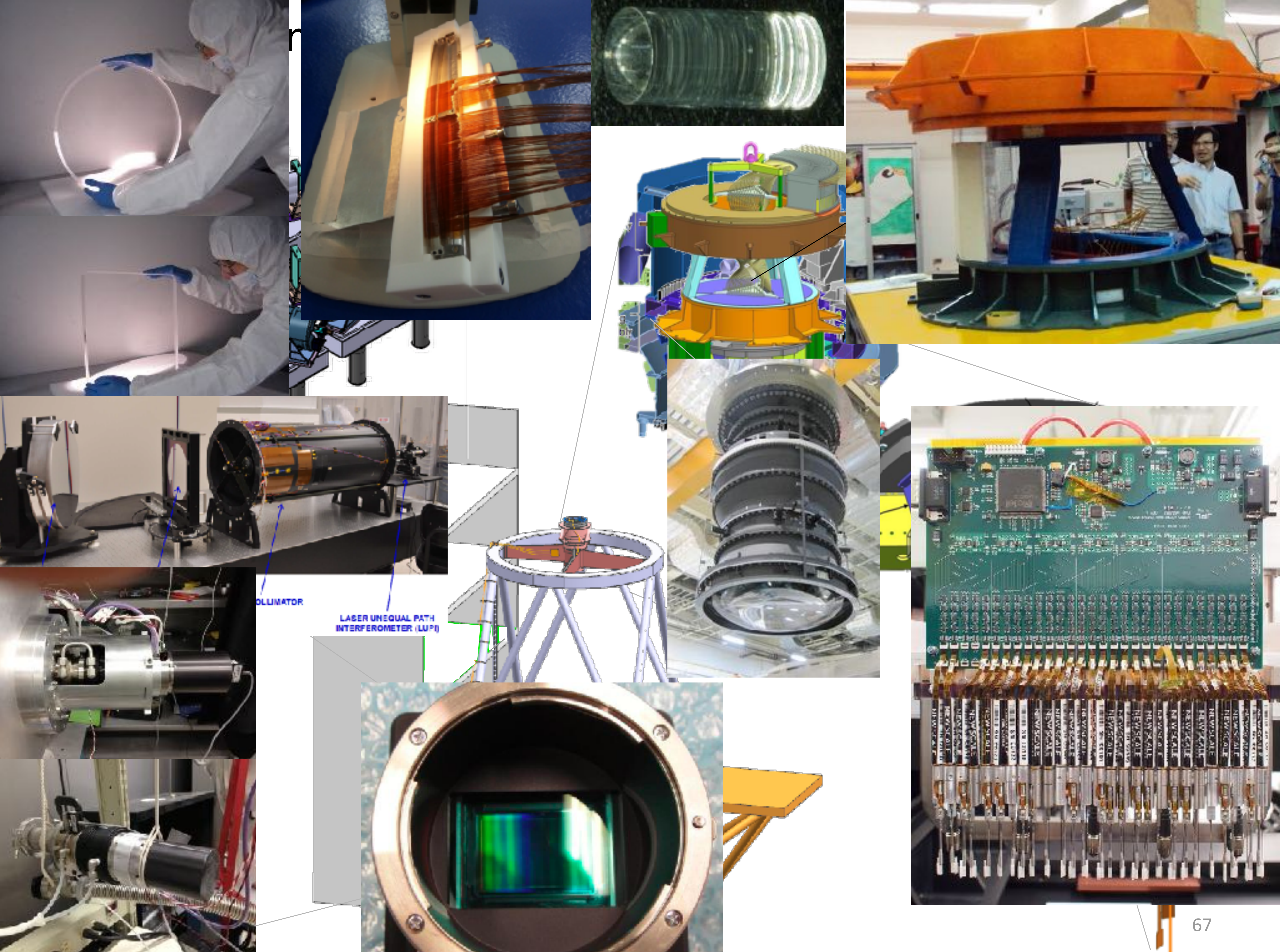


Velocity data of >~ 800 stars enable to determine DM halo profiles very precisely!

J-factor = $\left[\int_{\Delta\Omega} d\Omega \int_{\rm l.o.s} dl \rho^2(l,\Omega)\right]$

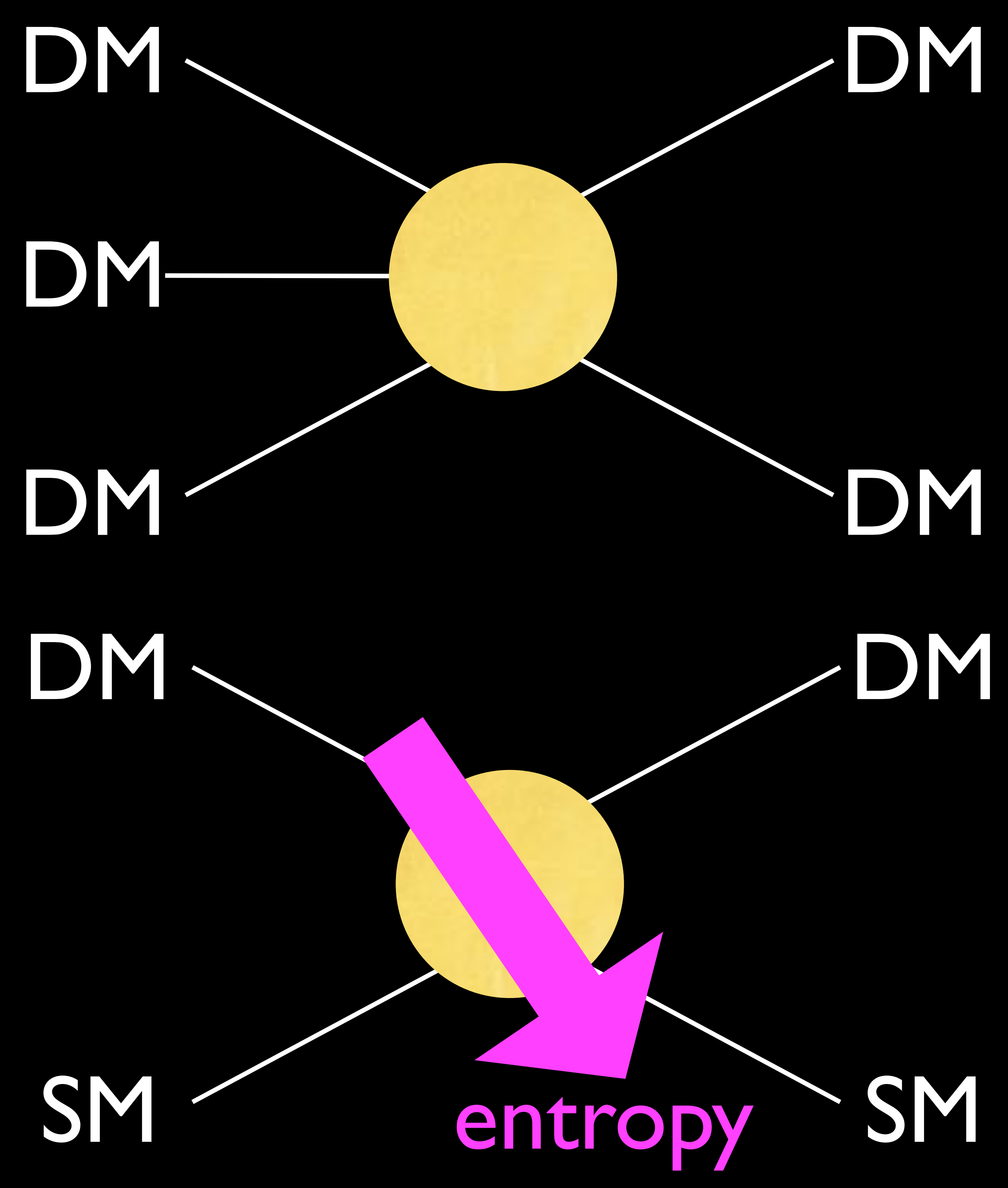


J-factor is determined very precisely!
⇒ nature of DM

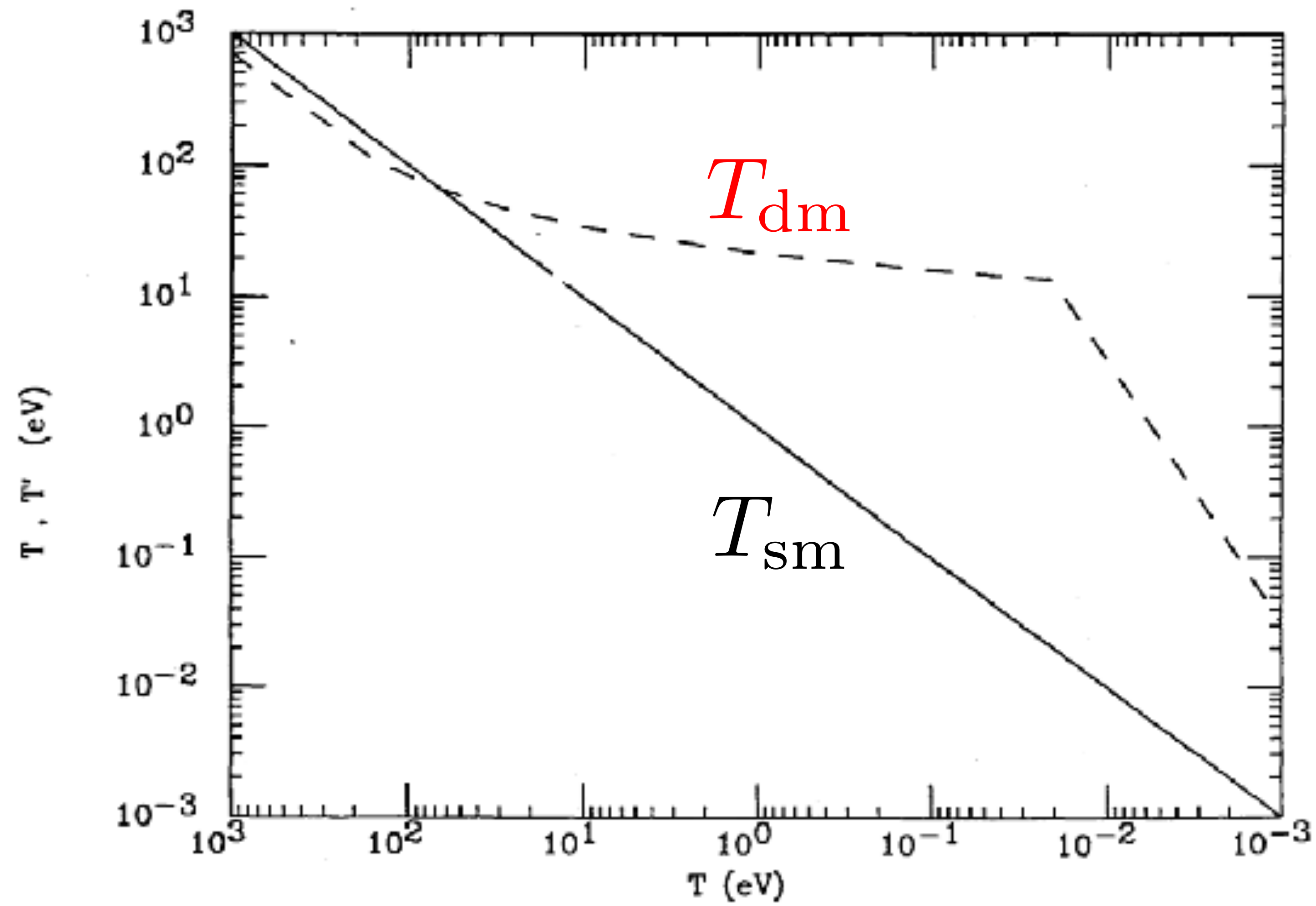

OLLIMATOR
LASER UNEQUAL PATH
INTERFEROMETER (LUPI)

communication

- 3 to 2 annihilation
- excess entropy *must* be transferred to $e^{\pm}$, γ
- need communication at some level
- leads to experimental signal



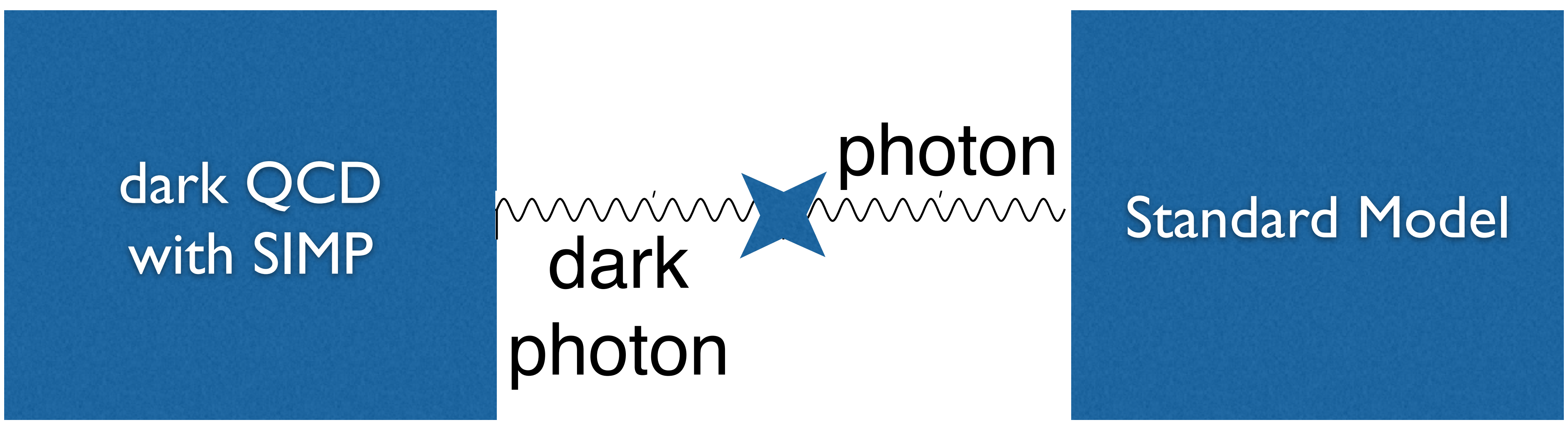
if totally decoupled



Carlson, Hall and Machacek, Astrophys. J. 398, 43 (1992)

- 3→2 annihilations without heat exchange is excluded by structure formation, [de Laix, Scherrer and Schaefer, Astrophys. J. 452, 495 (1995)]

vector portal



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

Kinetically mixed U(1)

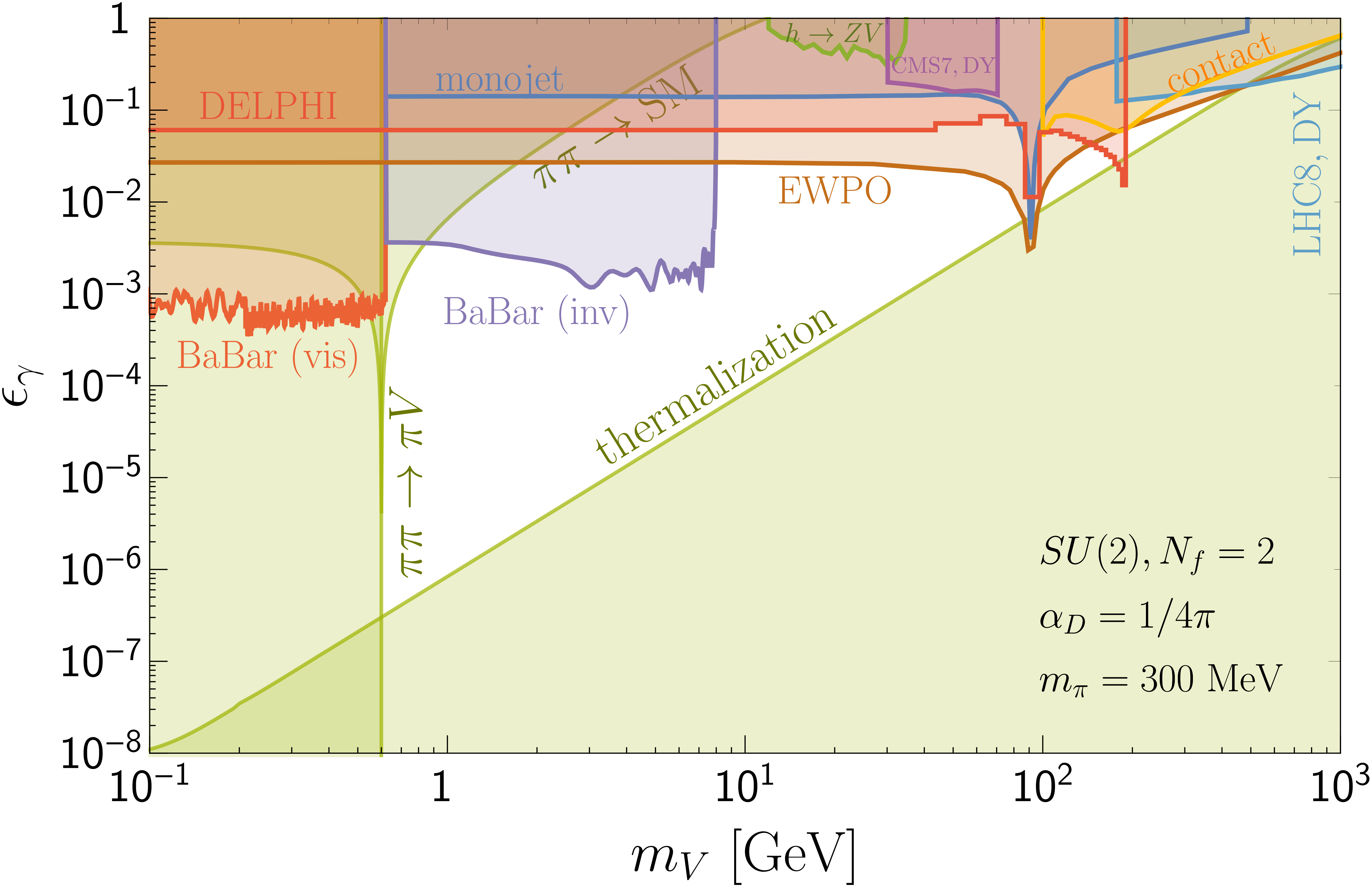
- e.g., the SIMPlest model SU(2) gauge group with N_f=2 (4 doublets)
- gauge U(1)=SO(2) ⊂ SO(2) ×SO(3) ⊂ SO(5)=Sp(4)
- maintains degeneracy of quarks
- near degeneracy of pions for co-annihilation

$$SU(4)/Sp(4) = S^5$$

$$(q^+, q^+, q^-, q^-)$$

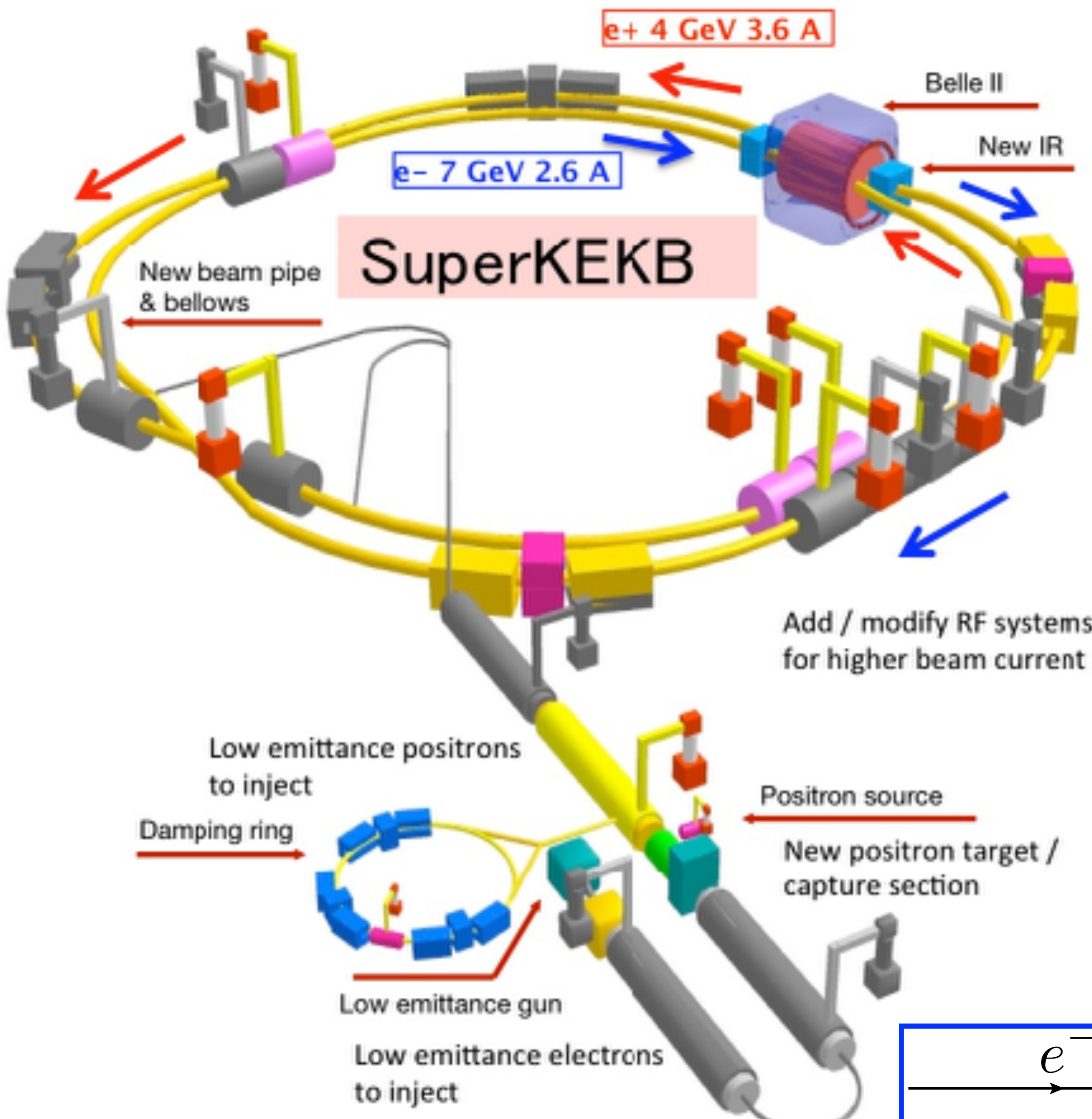
$$(\pi^{++}, \pi^{--}, \pi^0_x, \pi^0_y, \pi^0_z)$$

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

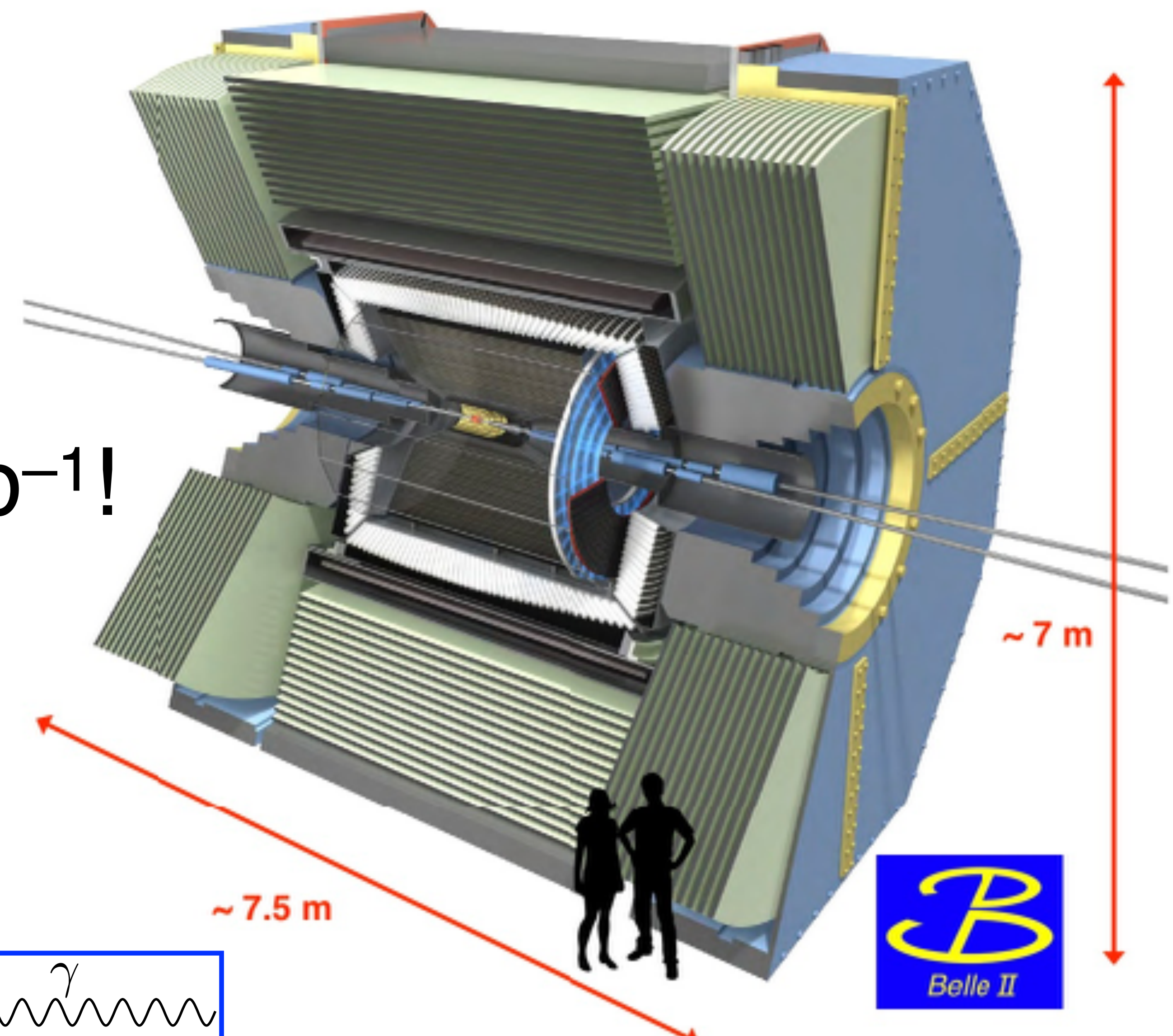


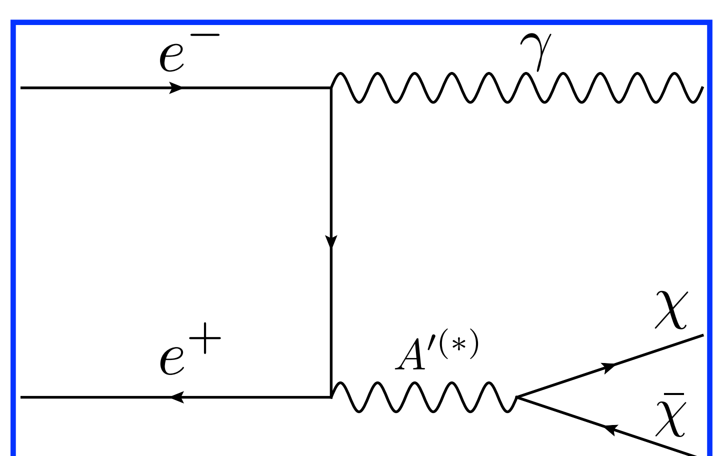
$h \to ZV$
CMS7, DY
monojet
DELPHI
$\pi\pi \to$ SM
contact
EWPO
LHC8, DY
BaBar (inv)
BaBar (vis)
$\pi\pi \to \pi V$
thermalization
$SU(2), N_f = 2$
$\alpha_D = 1/4\pi$
$m_\pi = 300$ MeV
ϵ_γ
m_V [GeV]
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{1}
10^{2}
10^{3}

Super KEK B & Belle II

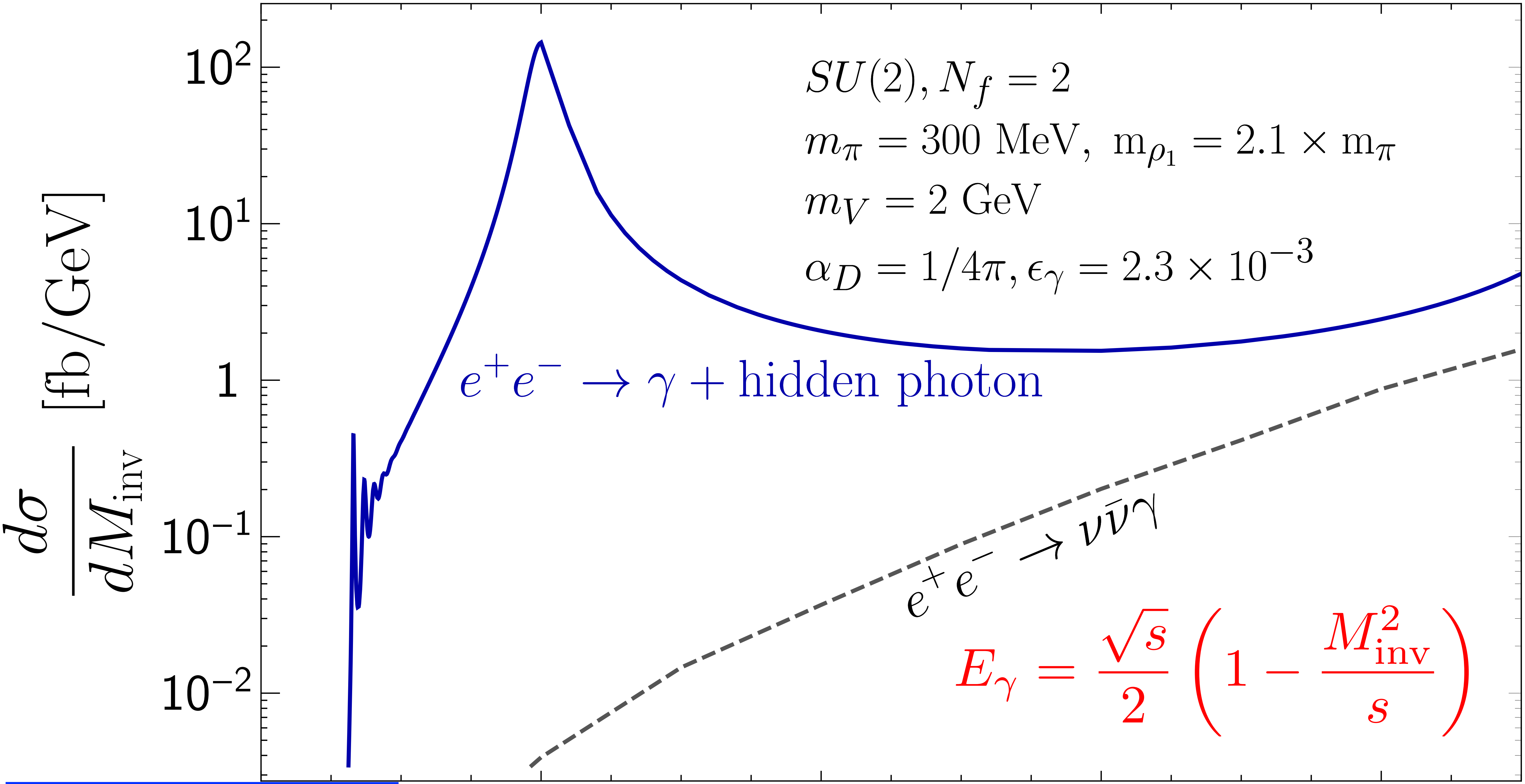


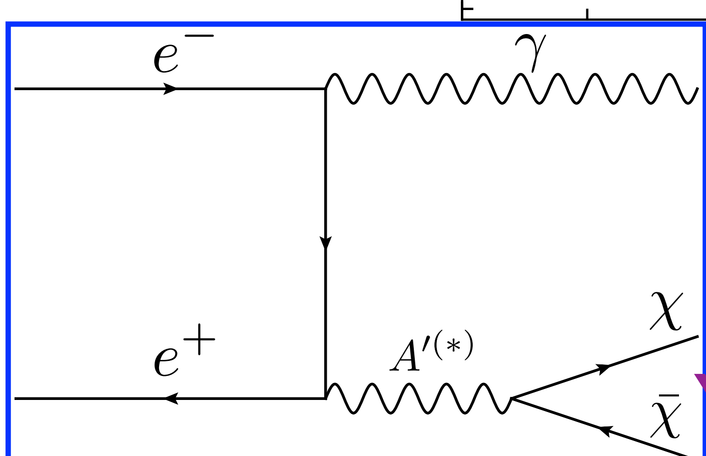
50 ab^{-1}!



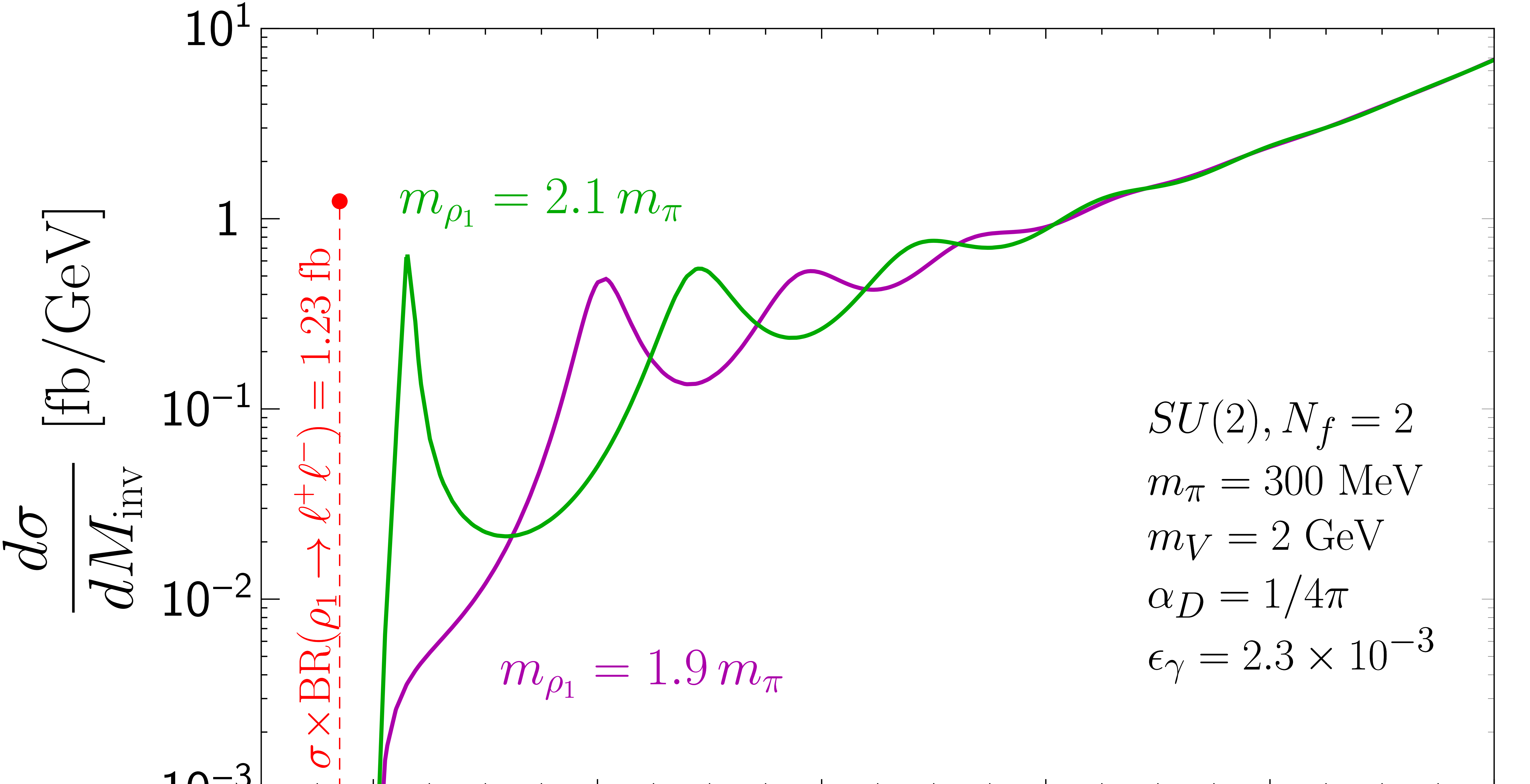


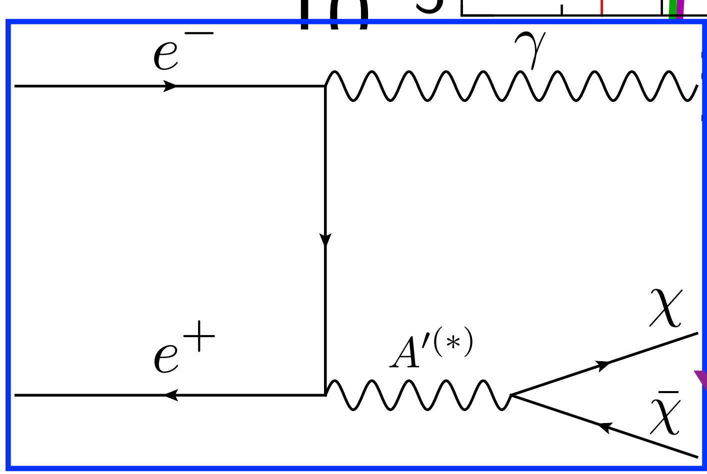
$$E_\gamma = \frac{\sqrt{s}}{2}\left(1 - \frac{M_{\mathrm{inv}}^2}{s}\right)$$



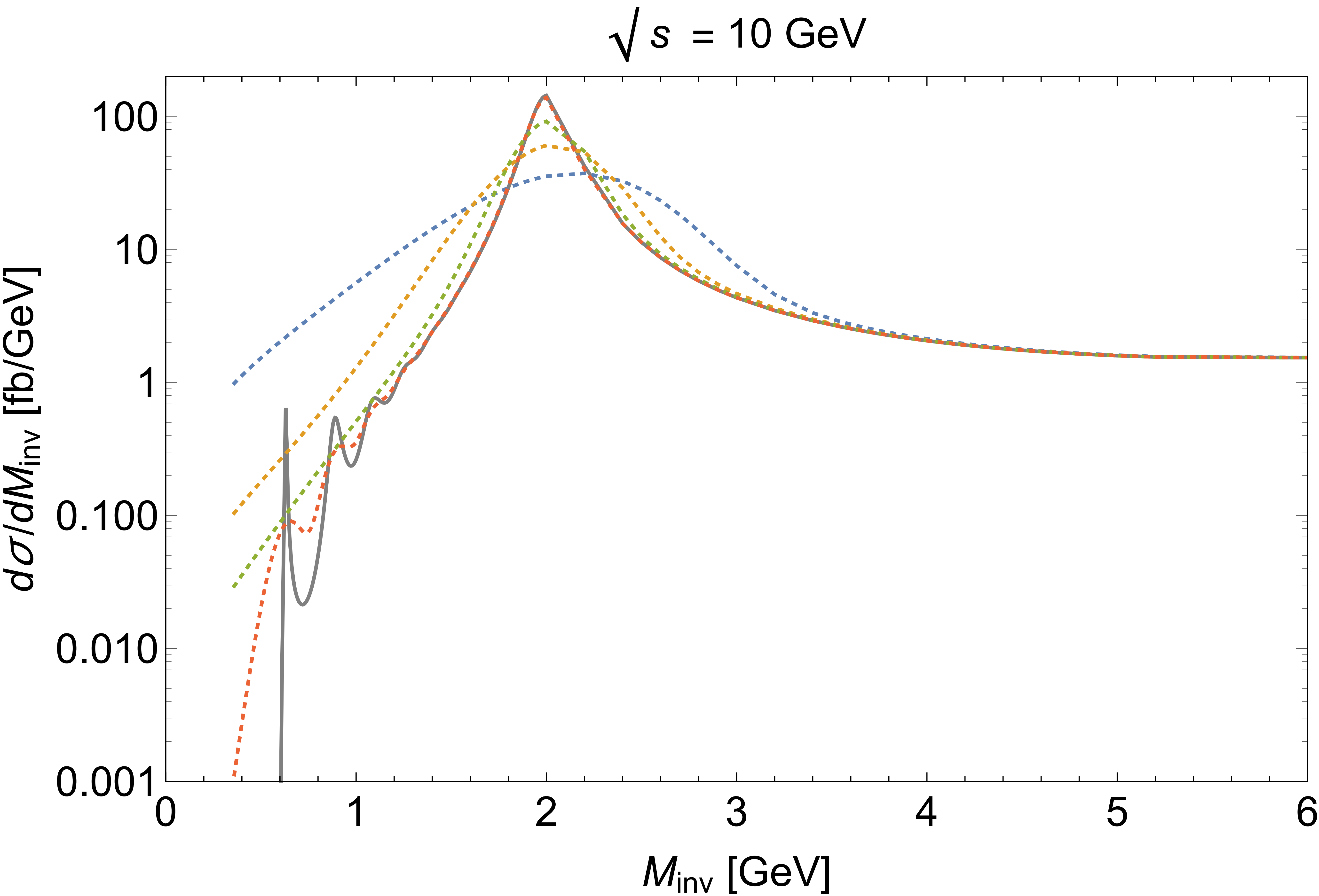


Yonit Hochberg, Eric Kuflik, HM





Yonit Hochberg, Eric Kuflik, HM



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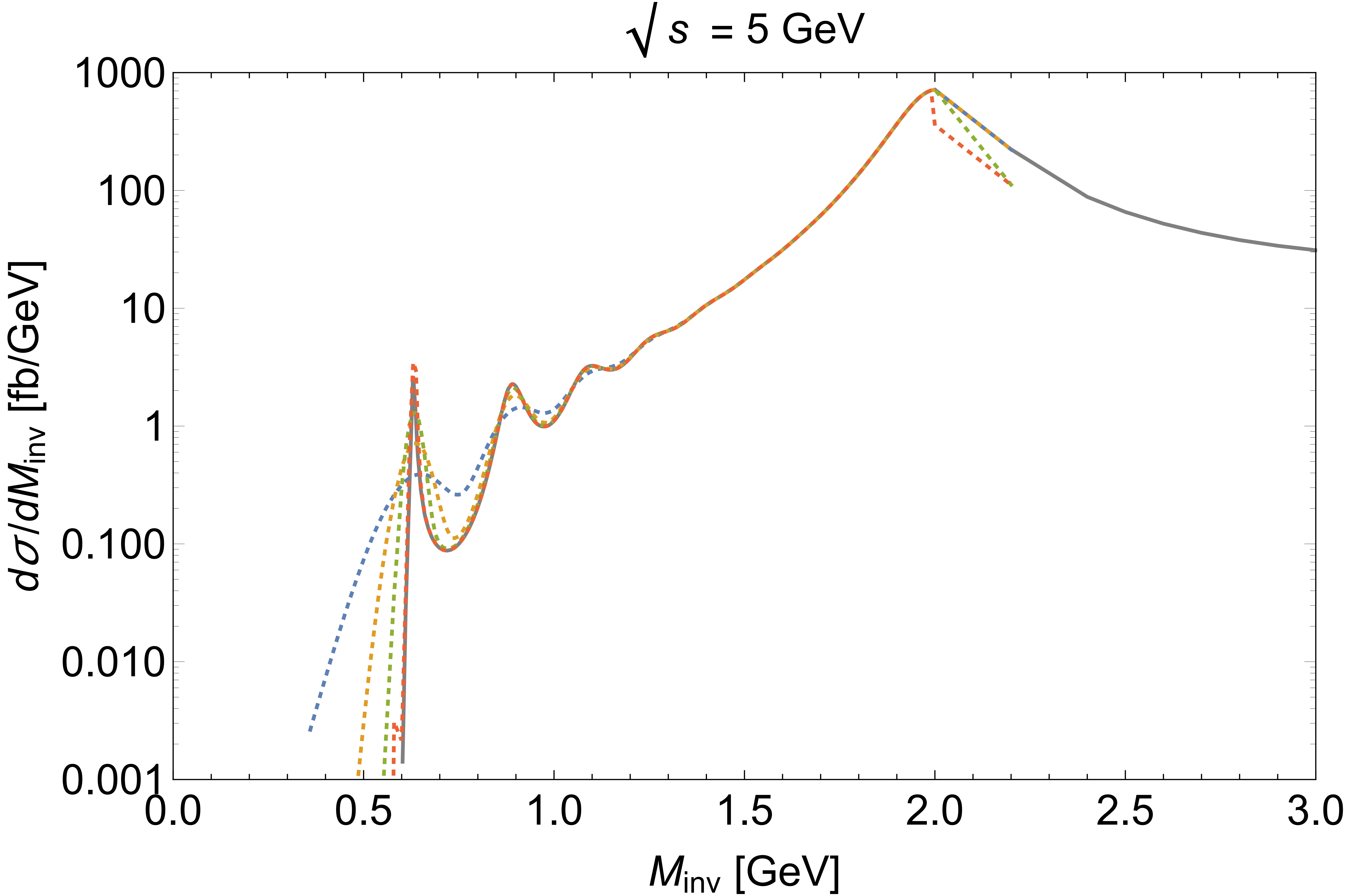

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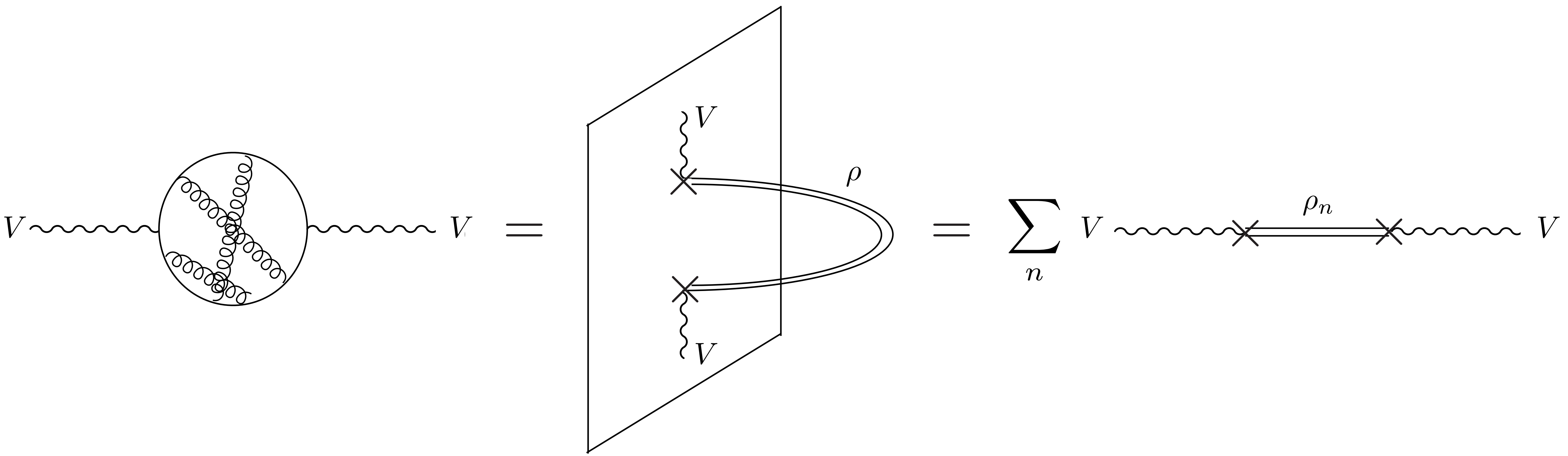
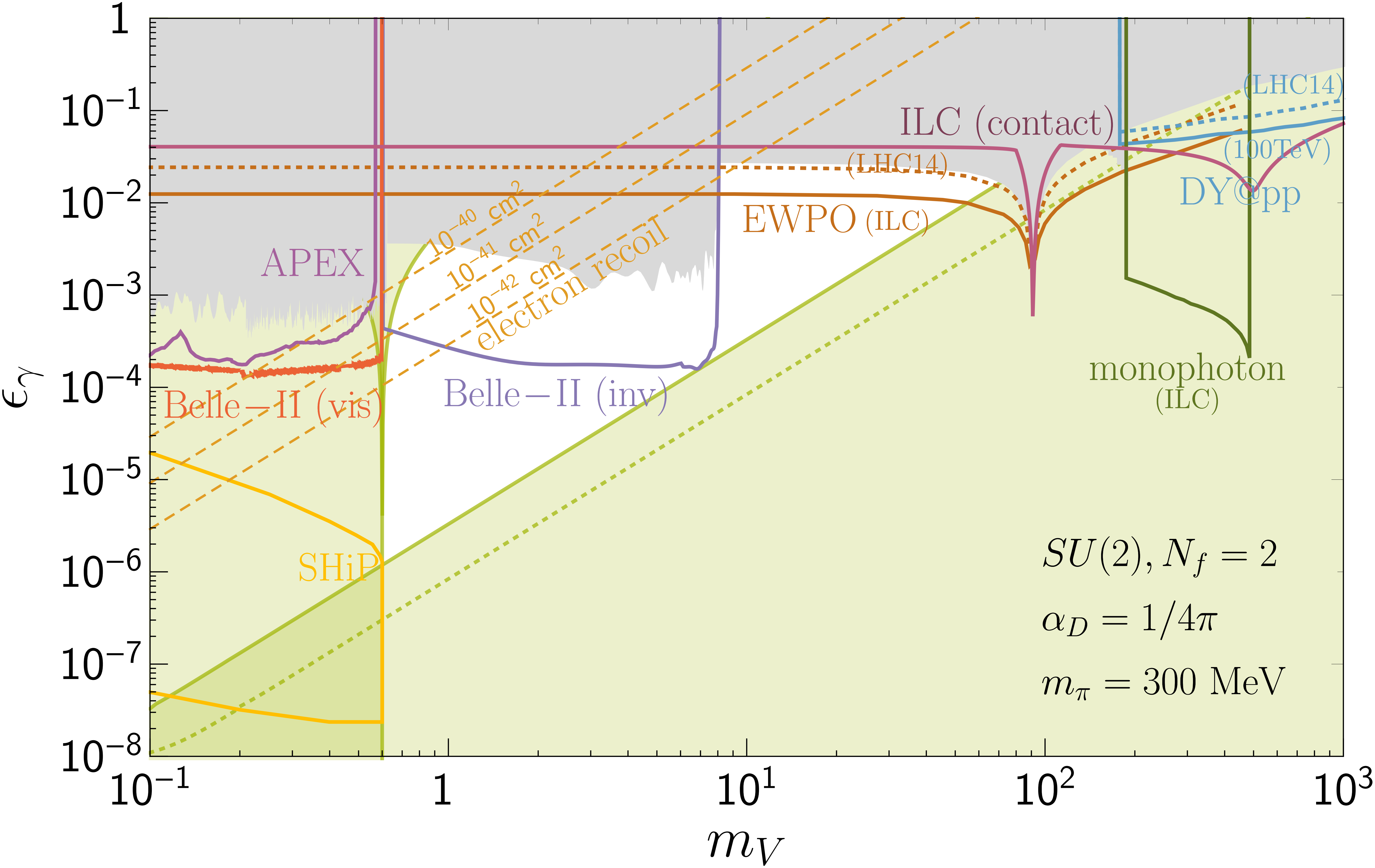
Holographic QCD



inspired by AdS/CFT from string theory



1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
ϵ_γ
10^{-1}
1
10^{1}
10^{2}
10^{3}
m_V
ILC (contact)
(LHC14)
(LHC14)
(100TeV)
DY@pp
EWPO (ILC)
10^{-40} cm^2
10^{-41} cm^2
10^{-42} cm^2
electron recoil
APEX
Belle−II (vis)
Belle−II (inv)
monophoton
(ILC)
SHiP
$SU(2), N_f = 2$
$\alpha_D = 1/4\pi$
$m_\pi = 300$ MeV

Conclusion

- surprising an *old* theory for dark matter
- SIMP Miracle^3
  - mass ~ QCD
  - coupling ~ QCD
  - theory ~ QCD
- can solve problem with DM profile
- very rich phenomenology

- Exciting *dark spectroscopy*!

主催：東京大学国際高等研究所カブリ数物連携宇宙研究機構 (Kavli IPMU)、東京大学物性研究所 (ISSP)、東京大学宇宙線研究所 (ICRR)
11/19
Sat
INVITATION
対象：女子学部学生・院生
やっぱり
物理が好き！
－物理に進んだ女性のキャリア
永村直佳（物質・材料研究機構）
「ヴィジュアル系物理学のすすめ～叡智の光と魔法の杖で切り開く表面・界面物理学の世界～」
森絵美（講談社）
「文系の会社で働いてます～3.11 の前と後で見えたもの」
神戸美花（旭硝子）
「やっぱり、、、ガラスが好き ??」
丹治はるか（電気通信大学）
「殻から出てみて見えたもの～米国大学院への留学とその後～」
谷茉莉（お茶の水女子大学院理）
「ソフトなポスドク生活＠パリ、やっています」
村山斉（東京大学 Kavli IPMU）
「物理に進んで見えてきたこと－宇宙研究最前線と女性研究者の活躍」
これから物理を学ぼうという学部生や物理学科に進学した学部生及び大学院生のみなさんに向けて、様々な講師の方をお招きしキャリアパスをご紹介します。施設見学や交流会もあり、参加者同士のネットワークをつくり、広く物理学分野(素粒子・原子核、宇宙・天文、物性、物理工学) の魅力を感じていただく稀有な機会となります、奮ってご参加下さい。
日　時：2016 年 11 月 19 日 (土) 11:00-17:00 (開場 : 10:30)
会　場：カブリ数物連携宇宙研究機構棟 1F レクチャーホール ほか (東京大学柏キャンパス)
対　象：首都圏を中心とする物理学科及び物理専攻の女子大生及び大学院生
参加費：無料
定　員：50 名程度
後　援：東京大学理学部物理学科 , 東京大学男女共同参画室 , 日本物理学会 , 応用物理学会 , 高エネルギー加速器研究機構 , お茶の水女子大学理学部物理学科 , 東京農工大学工学部物理システム工学科 , 法政大学理工学部創生科学科 , 総合研究大学院大学
申　込：応募フォーム (11 月 2 日申込締切)
http://www.ipmu.jp/ja/20161119-WomenStudents
通　知：応募多数の場合は抽選となります。決定の通知は詳細とともに 11 月 7 日ごろにご連絡いたします。
問合せ：☎ 04-7136-5977
Email: koukai-kouza@ipmu.jp (Kavli IPMU 広報)
東京大学 THE UNIVERSITY OF TOKYO
KAVLI IPMU
ICRR Institute for Cosmic Ray Research University of Tokyo
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