TeV frontier in particle astrophysics

Hitoshi Murayama (Berkeley, Kavli IPMU)

TeVPA 2017, Columbus, Aug 11, 2017

sub-GeV frontier in particle astrophysics

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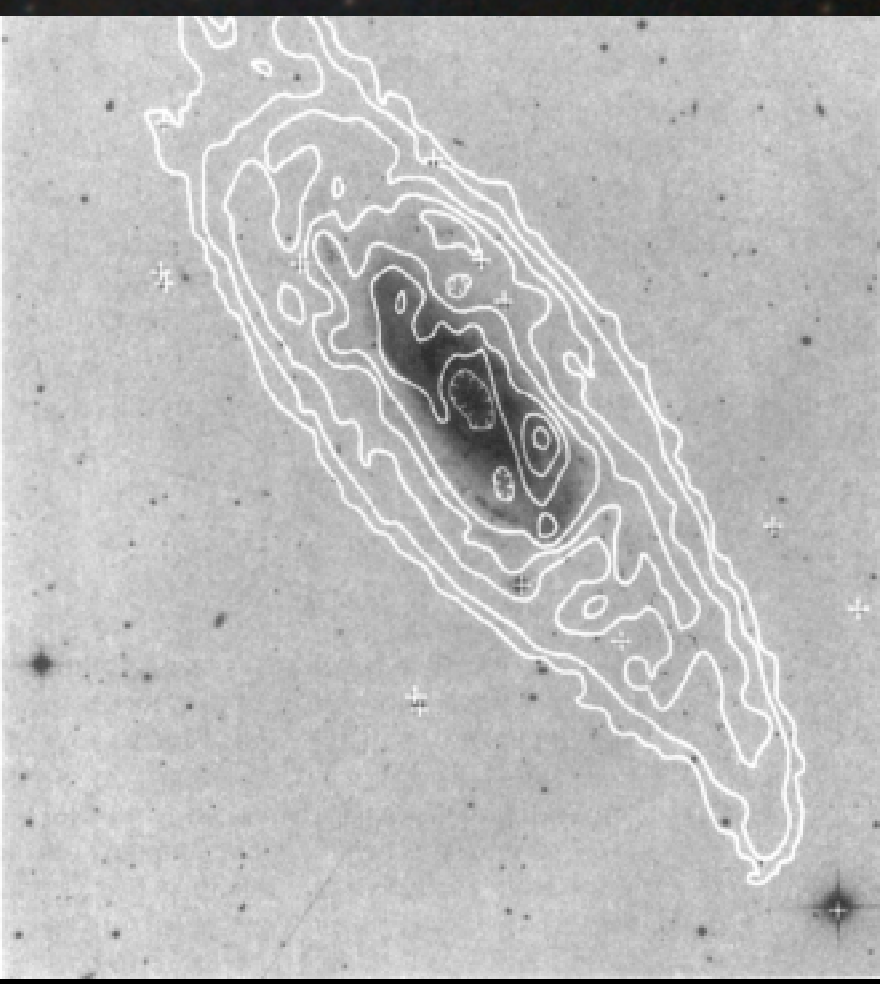
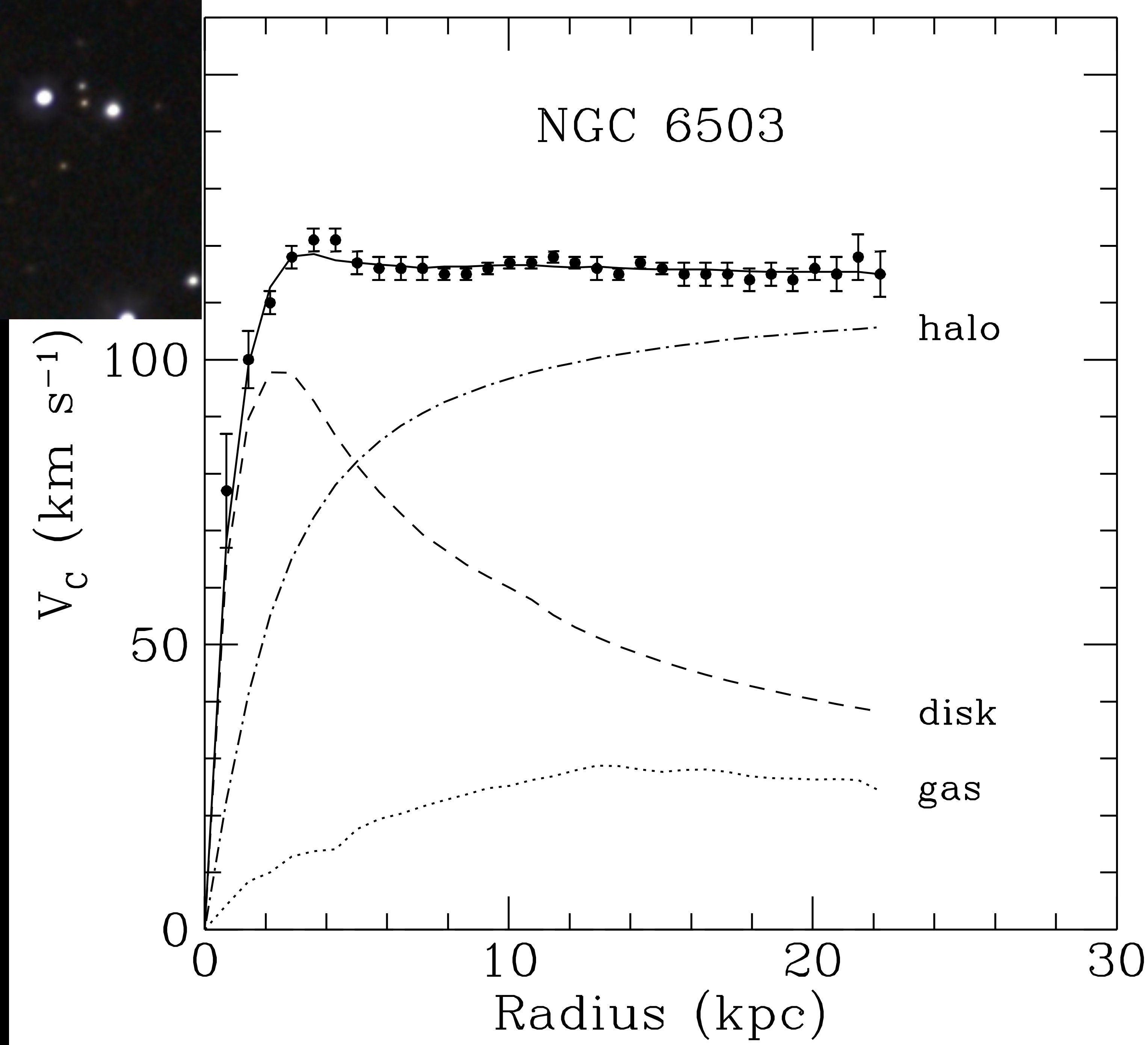
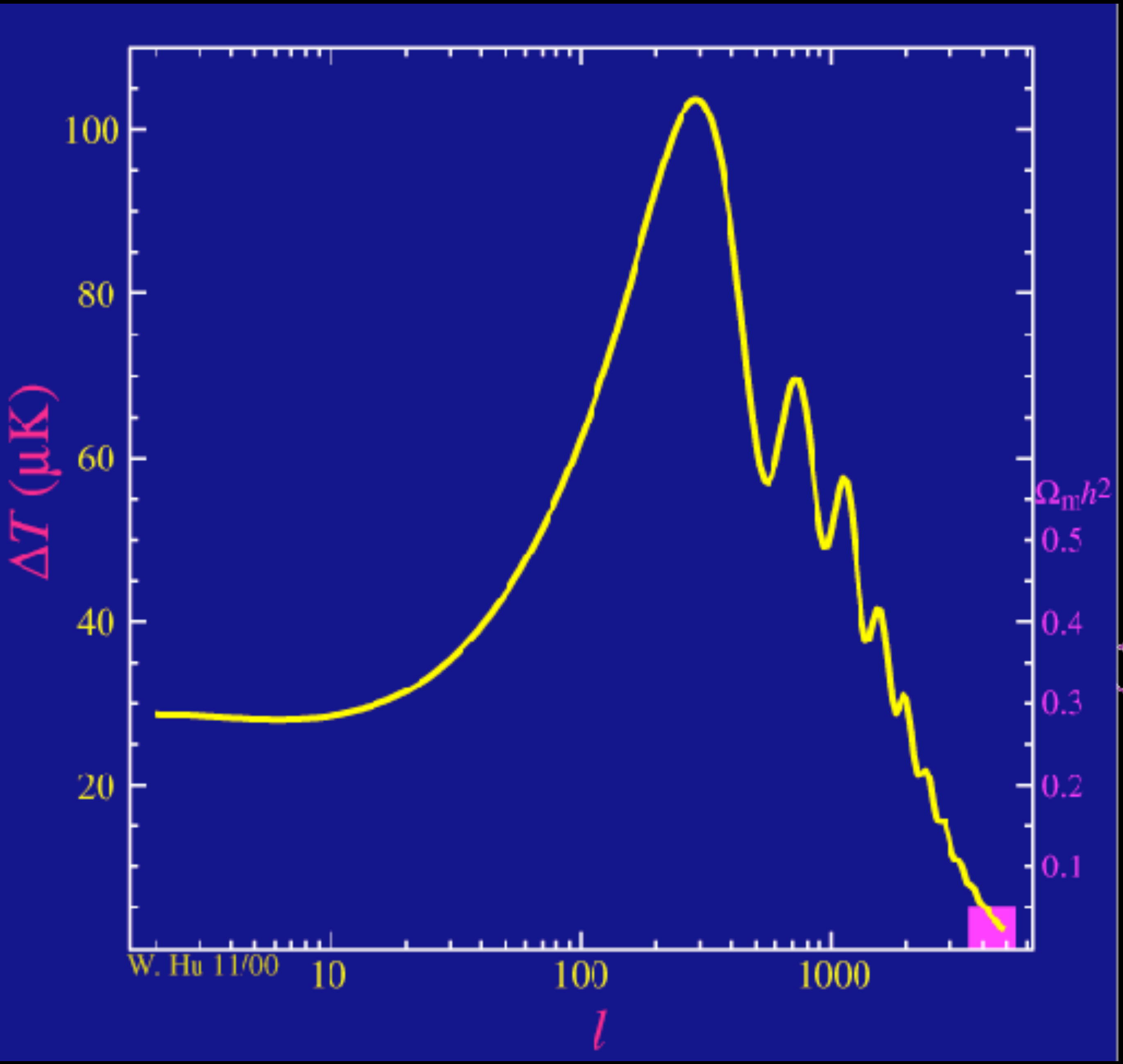
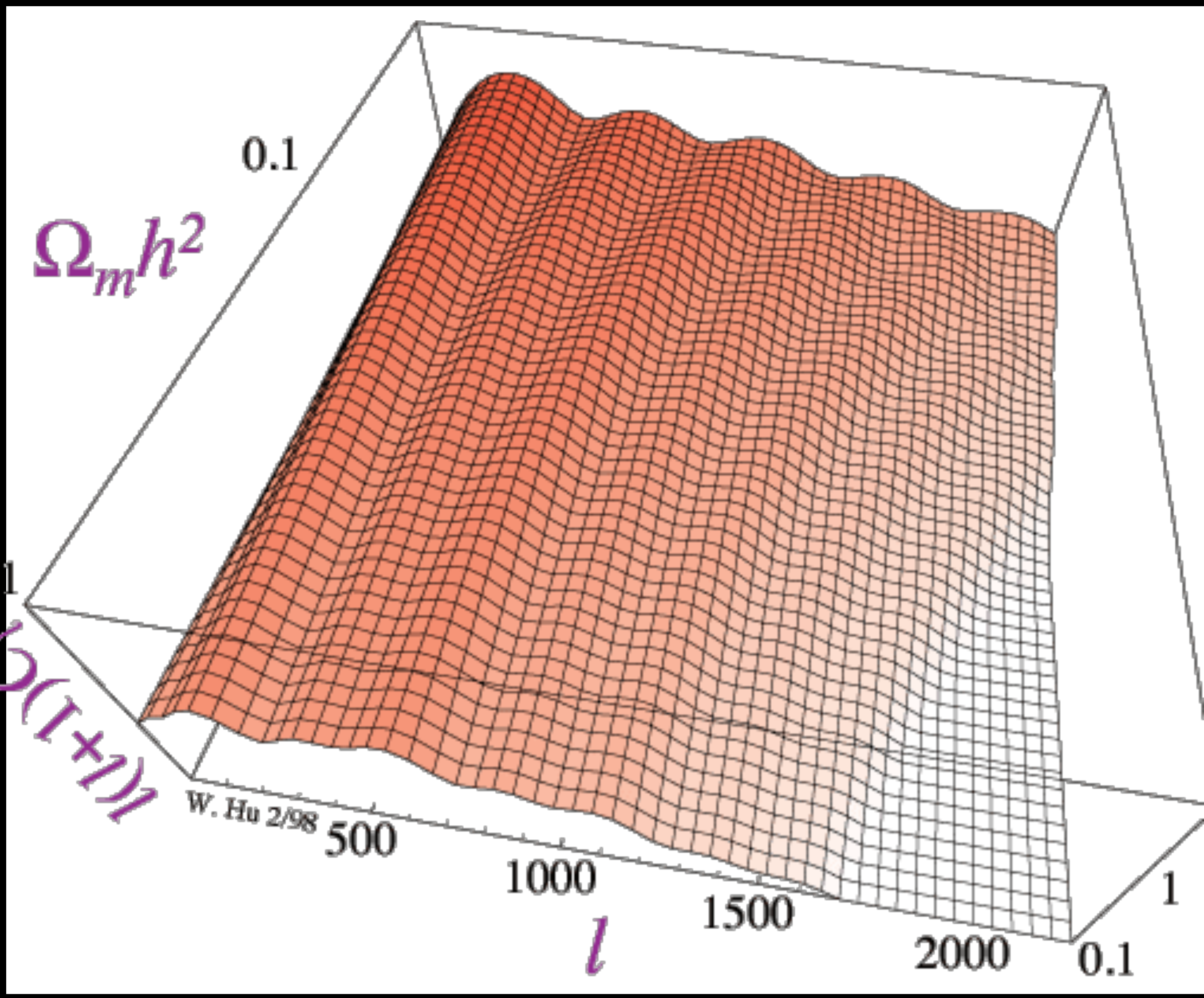
+Yonit Hochberg, Eric Kuflik




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

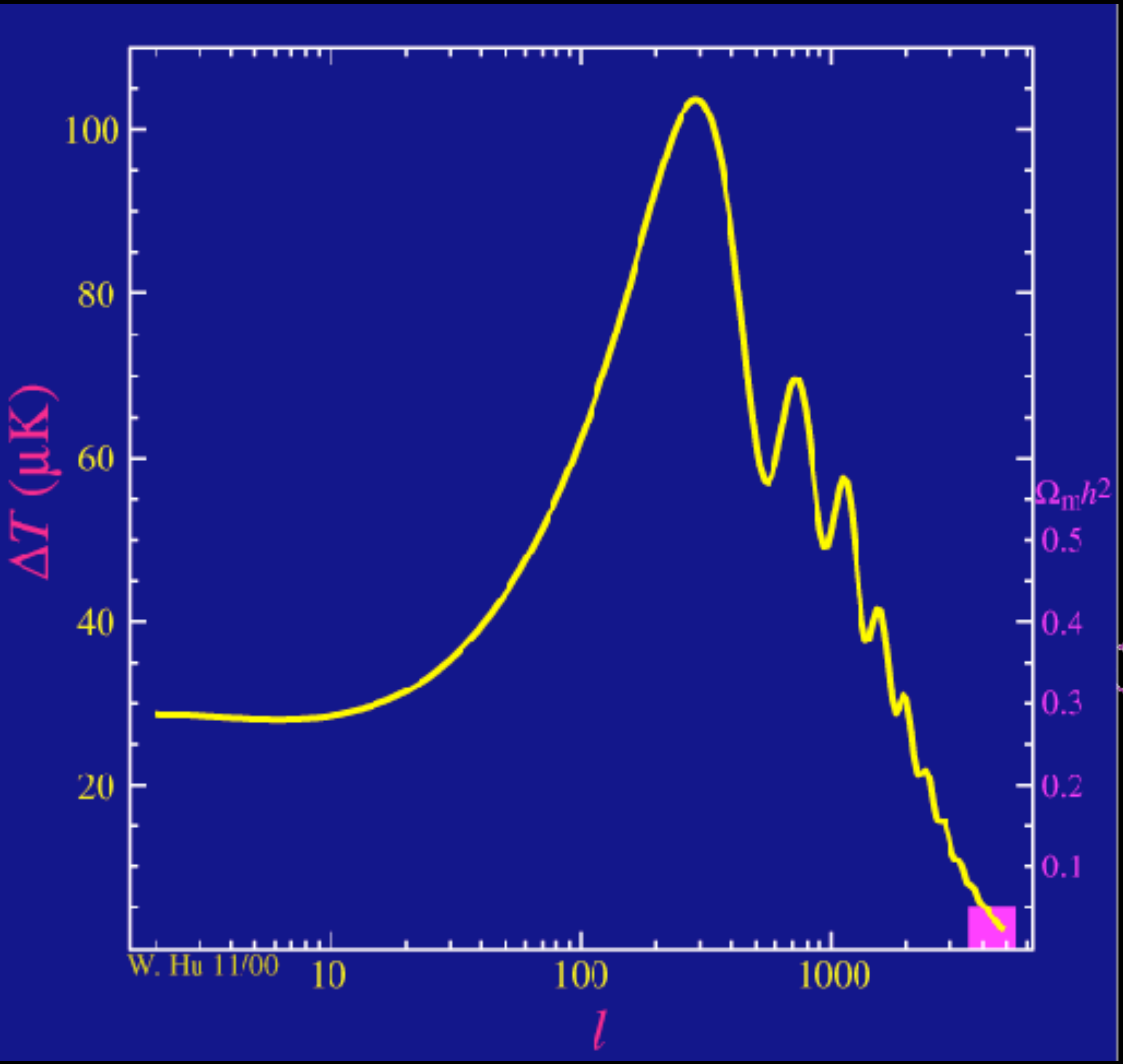
matter

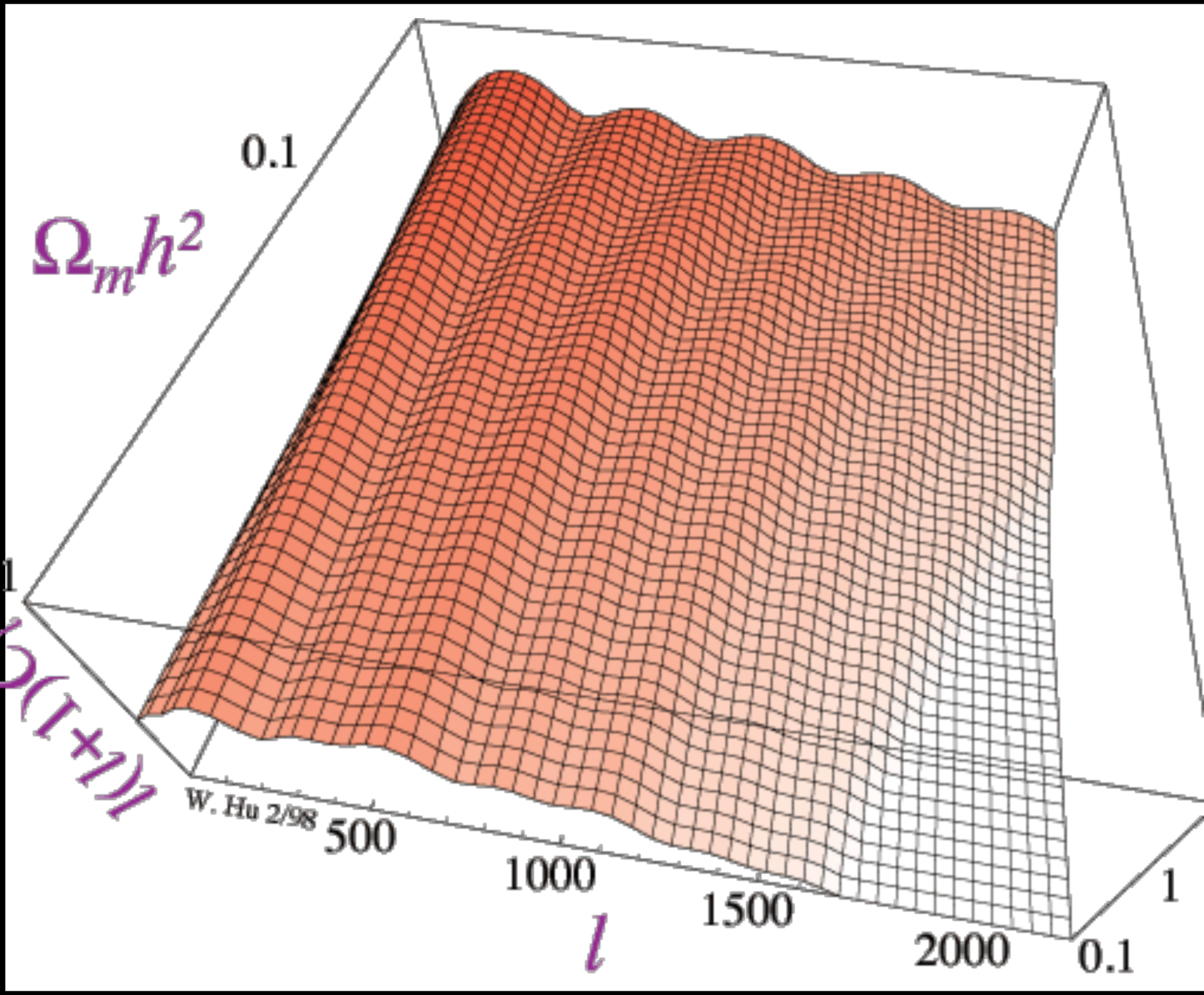




Ω_m changes the overall heights of the peaks

matter

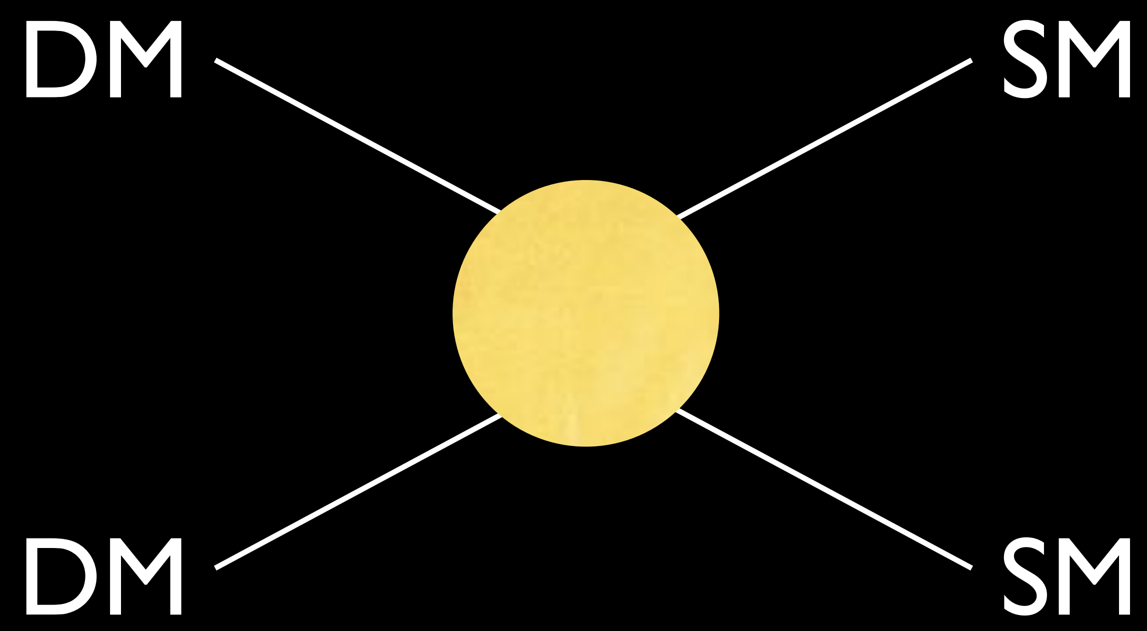




Ω_m changes the overall heights of the peaks

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

WIMP Miracle



“weak” coupling
“weak” mass scale → correct abundance

Miracle^2

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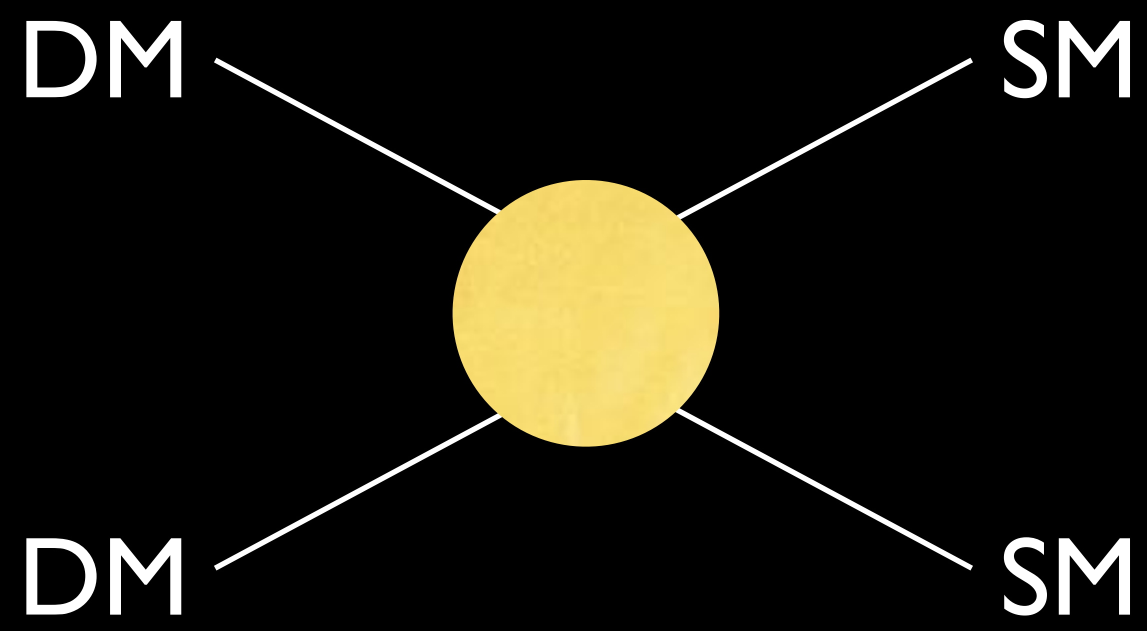

$$\langle \sigma_{2\to 2} v \rangle \approx \frac{\alpha^2}{m^2}$$

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

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

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"weak" mass scale → correct abundance

Miracle^2

sociology

- Particle physicists used to think

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  - need to solve problems with the SM

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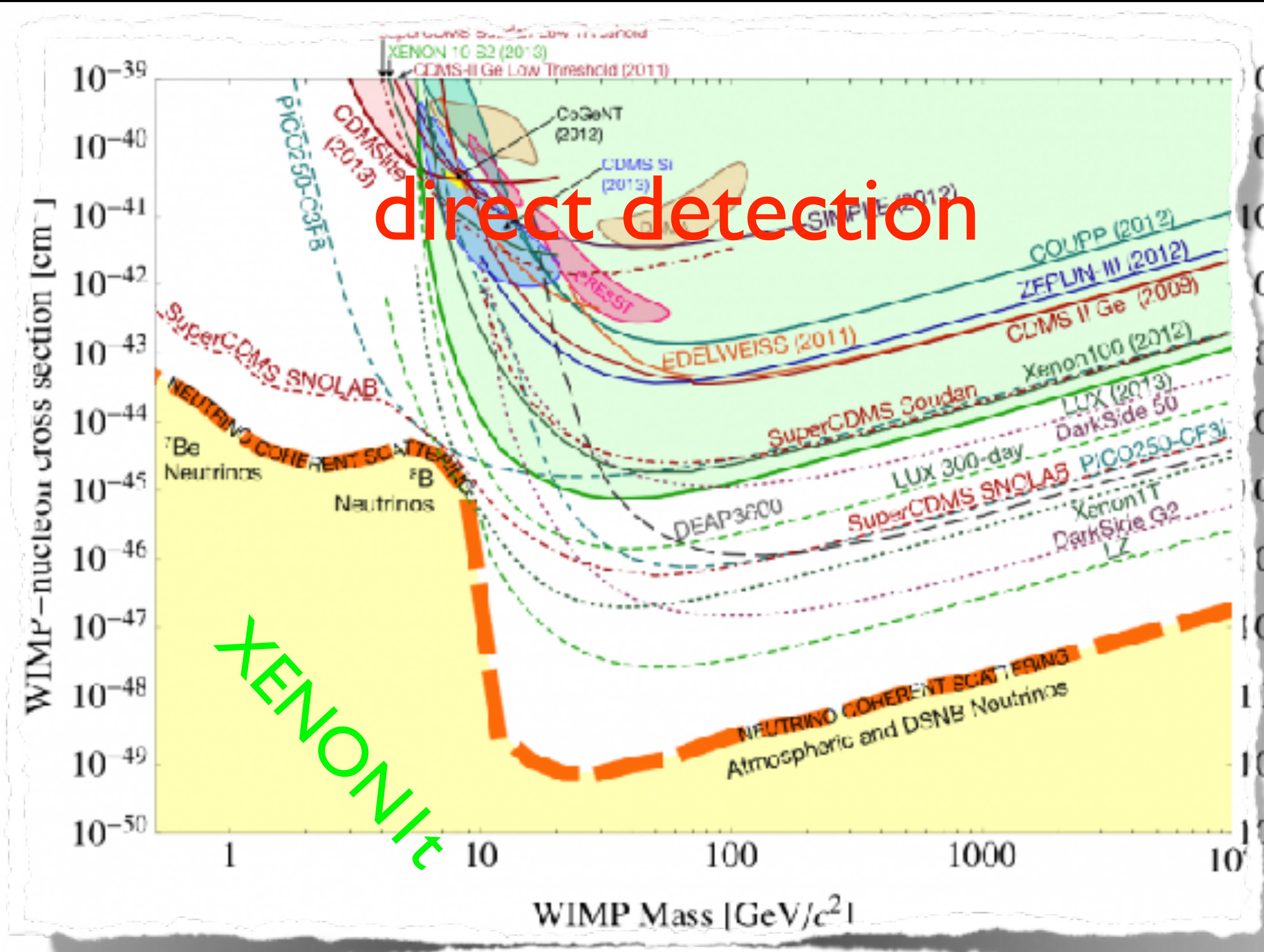
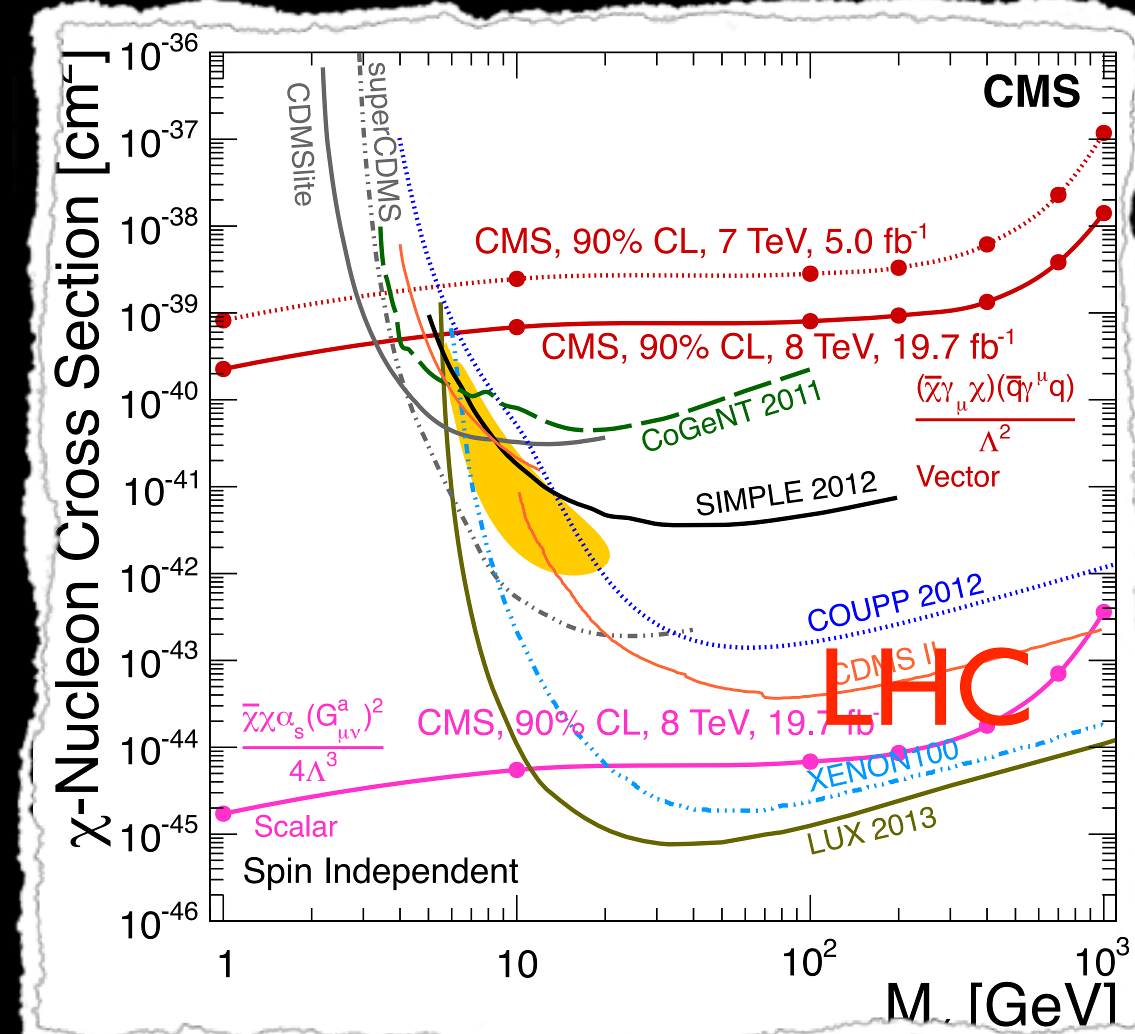
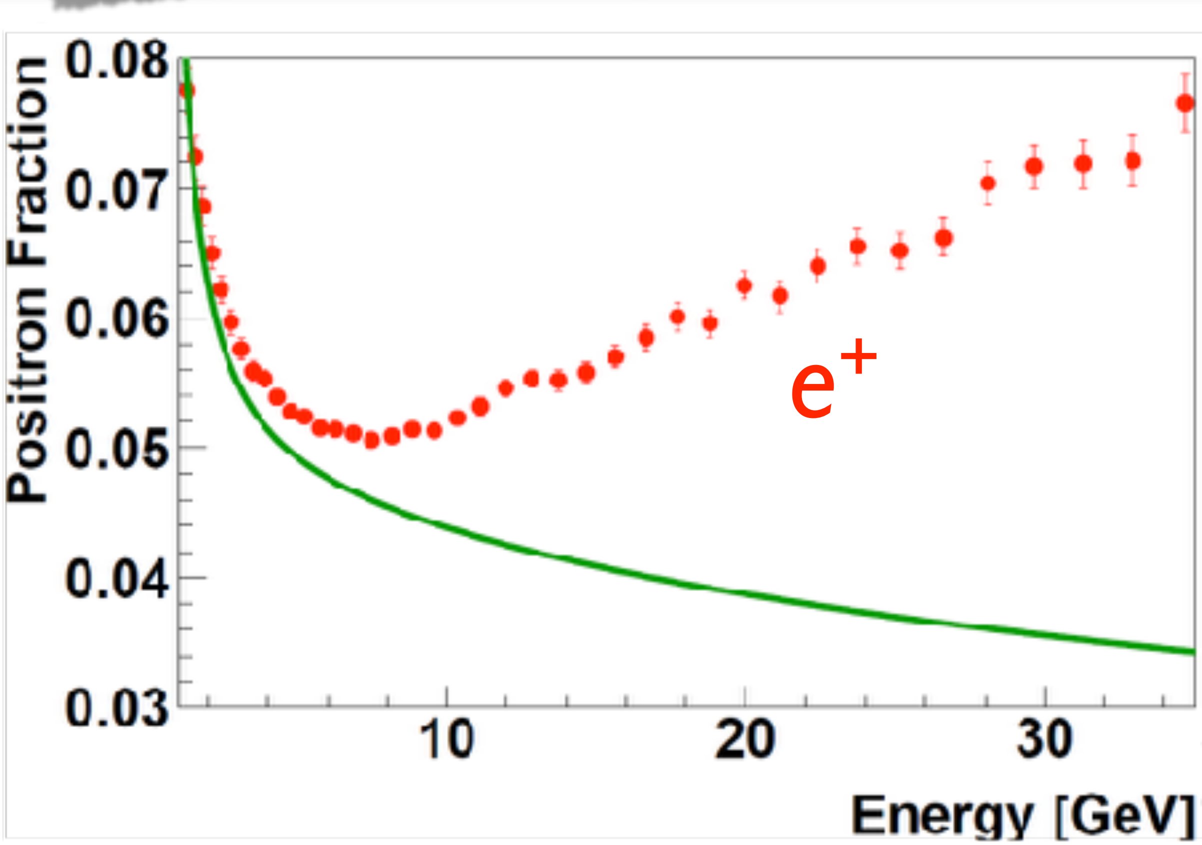
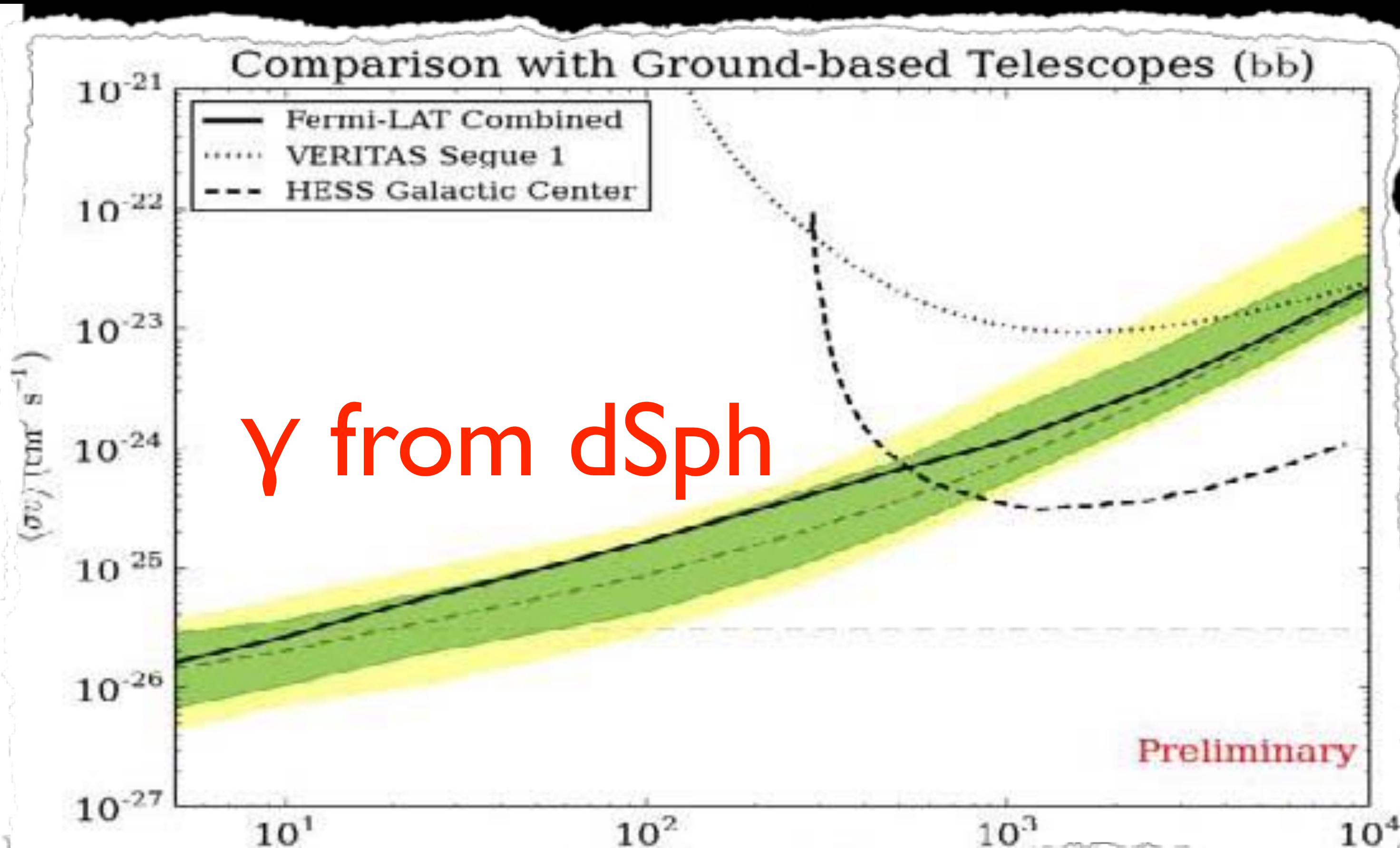
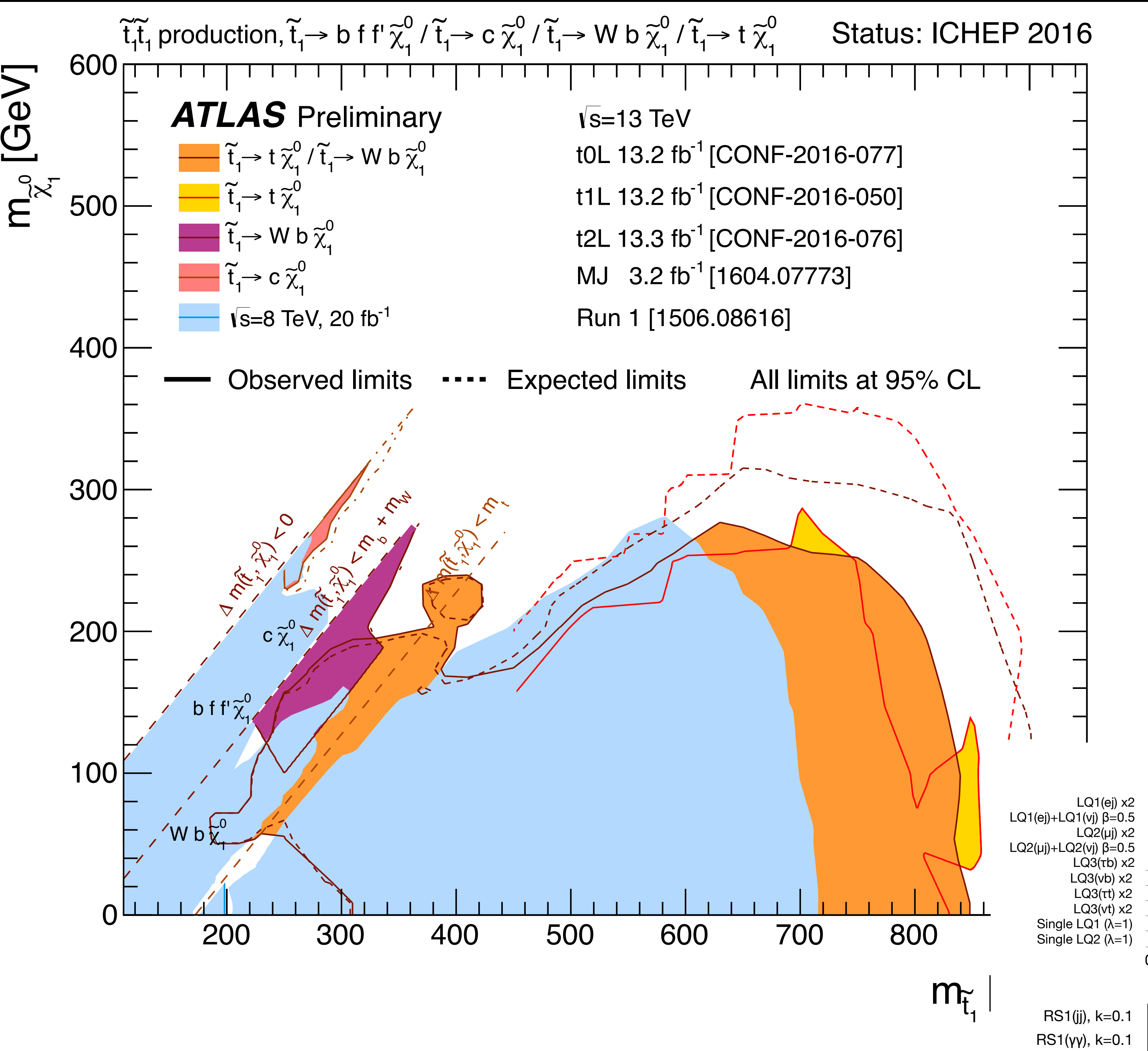
- Particle physicists used to think
  - need to solve problems with the SM
  - hierarchy problem, strong CP, etc
  - it is great if a solution also gives dark matter candidate as an *option*
  - big ideas: supersymmetry, extra dim
  - probably because dark matter problem was not so established in 80's

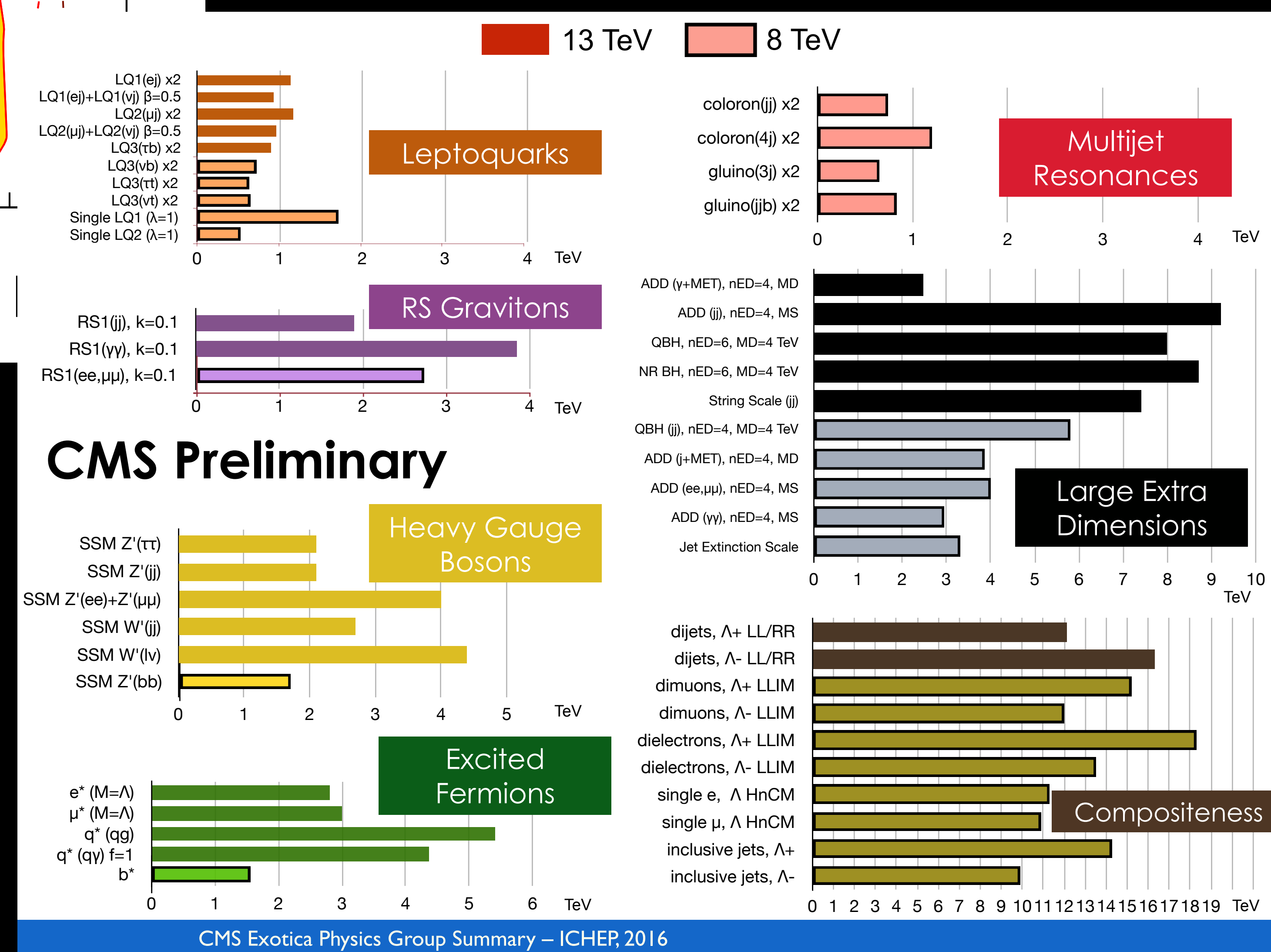

direct detection
XENONIt
WIMP Mass [GeV/c²]
CoGeNT (2012)
CDMS Si (2013)
SIMPLE (2012)
COUPP (2012)
ZEPLIN-III (2012)
CDMS II Ge (2009)
EDELWEISS (2011)
Xenon100 (2012)
LUX (2013)
DarkSide 50
SuperCDMS Soudan
LUX 300-day
PICO250-CF3I
SuperCDMS SNOLAB
DEAP3600
XenonIT
DarkSide G2
LZ
CRESST
PICO250-C3F8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


LHC
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
Scalar
XENON100
LUX 2013
Spin Independent


Positron Fraction
Energy [GeV]
e⁺


Comparison with Ground-based Telescopes (bb̄)
Fermi-LAT Combined
VERITAS Segue 1
HESS Galactic Center
⟨σv⟩ [cm³ s⁻¹]
γ from dSph
Preliminary





no sign of new physics that explains hierarchy problem!

recent thinking

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  - hierarchy problem may be optional?

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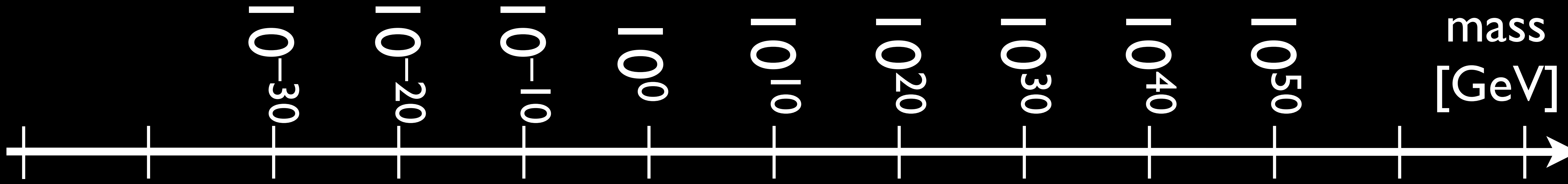
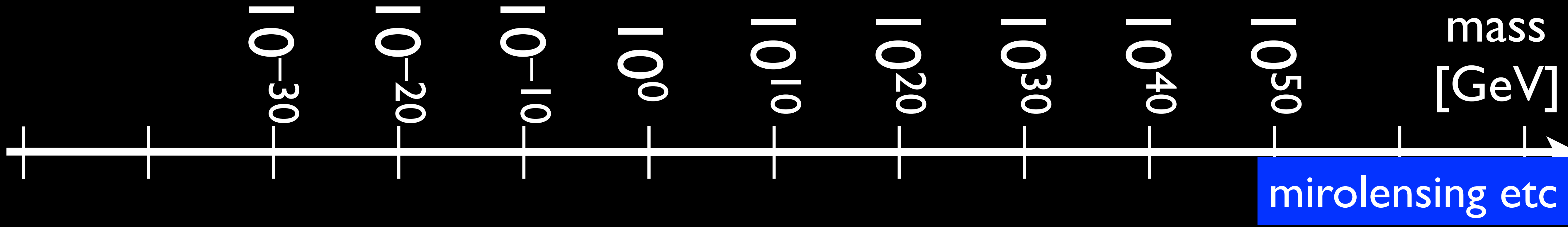
recent thinking

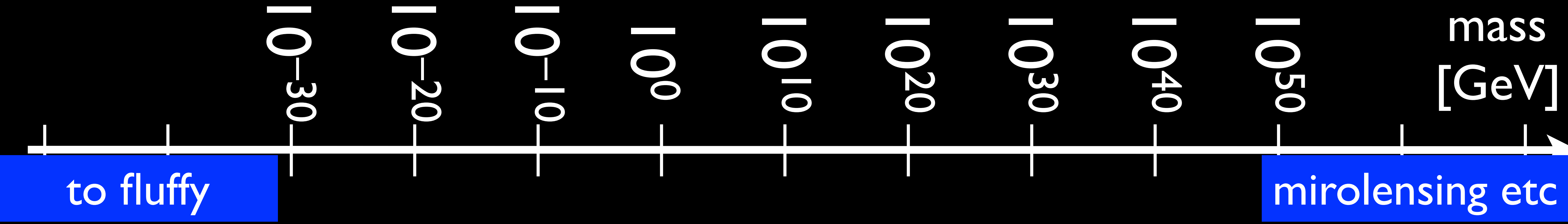
- dark matter definitely exists
  - hierarchy problem may be optional?
- need to explain dark matter on its own
- perhaps we should decouple these two
- do we really need big ideas like SUSY?
- perhaps we can solve it with ideas more familiar to us?



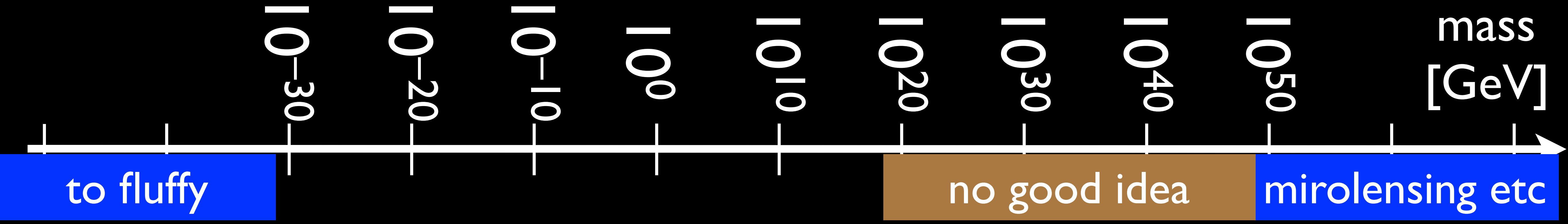
mass
[GeV]
10−30
10−20
10−10
100
1010
1020
1030
1040
1050

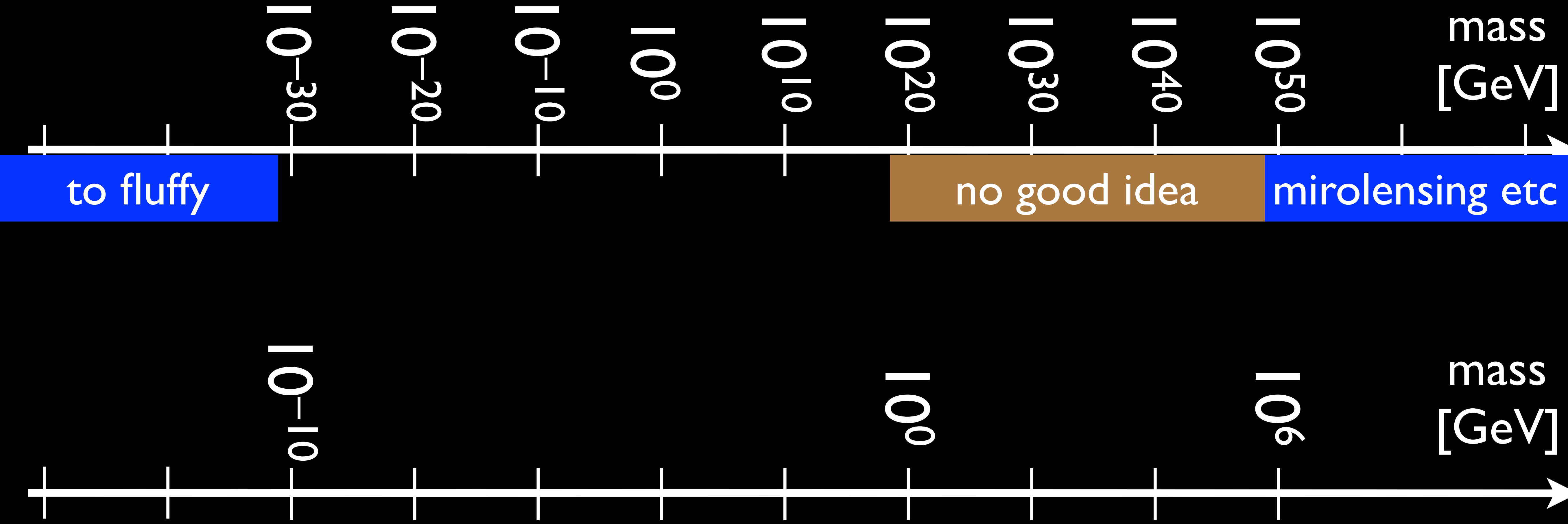


mass [GeV]
10^{-30}
10^{-20}
10^{-10}
10^{0}
10^{10}
10^{20}
10^{30}
10^{40}
10^{50}
mirolensing etc

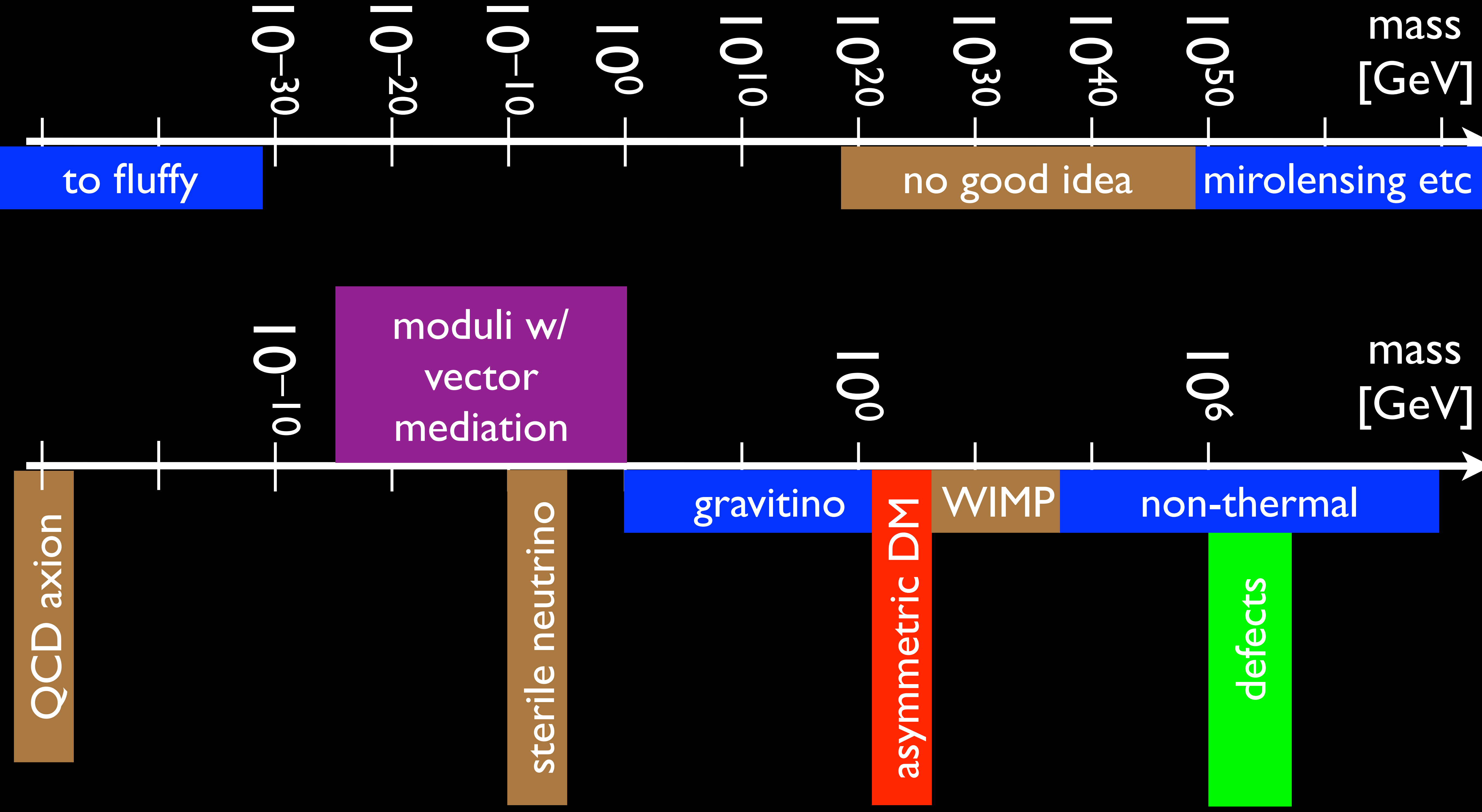


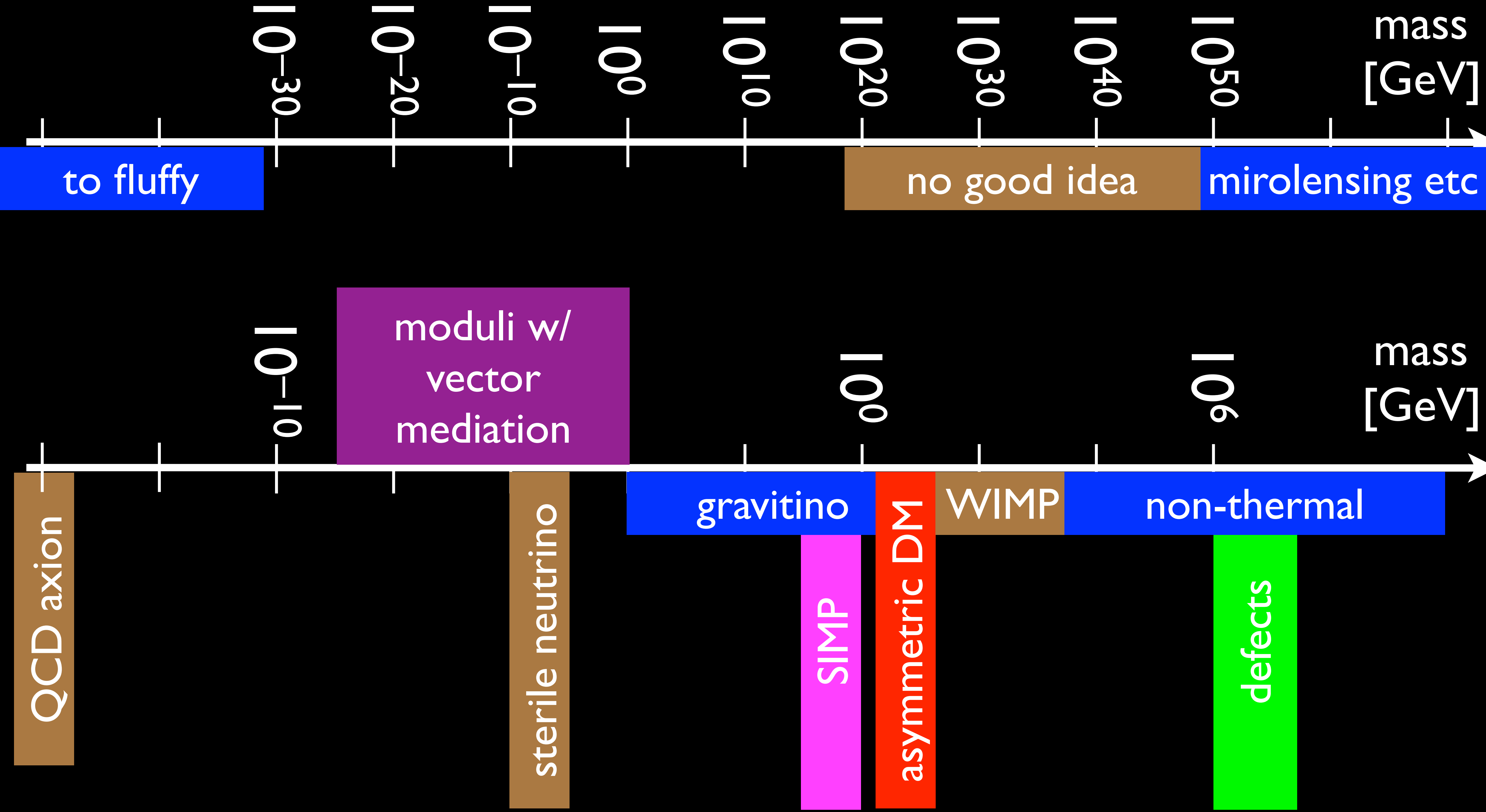
mass
[GeV]
10−30
10−20
10−10
100
1010
1020
1030
1040
1050
to fluffy
mirolensing etc


mass [GeV]
10−30
10−20
10−10
100
1010
1020
1030
1040
1050
to fluffy
no good idea
mirolensing etc



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


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
asymmetric DM
WIMP
non-thermal
defects


mass [GeV]
10^{-30}
10^{-20}
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10^{0}
10^{10}
10^{20}
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Seminar in Berkeley
Strongly Interacting Massive Particle (SIMP)

Yonit Hochberg

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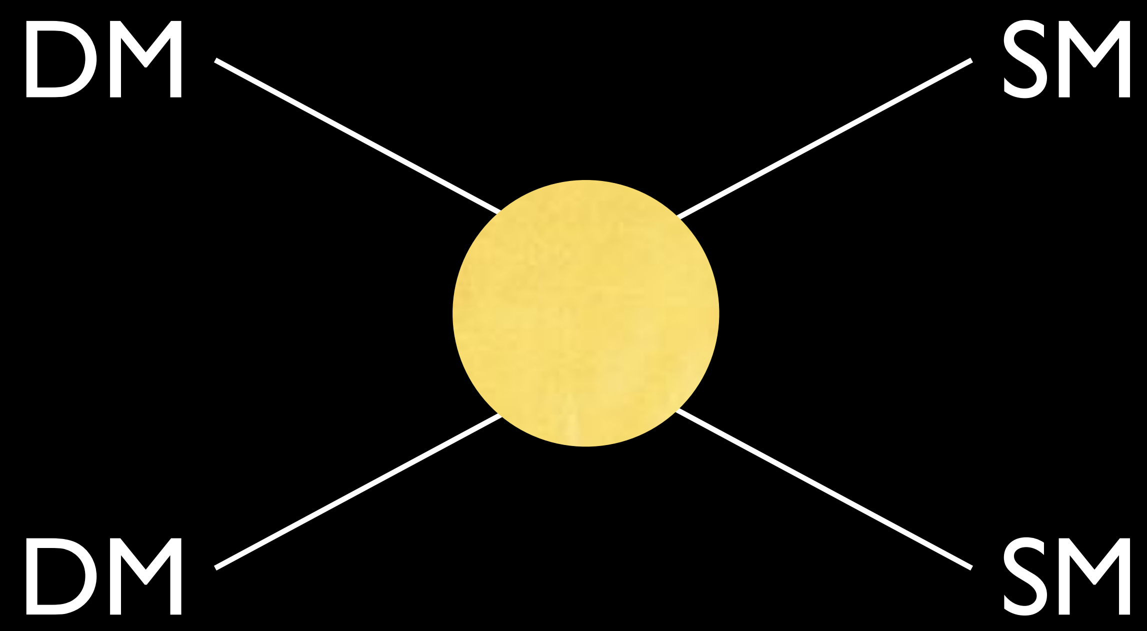
Miracles



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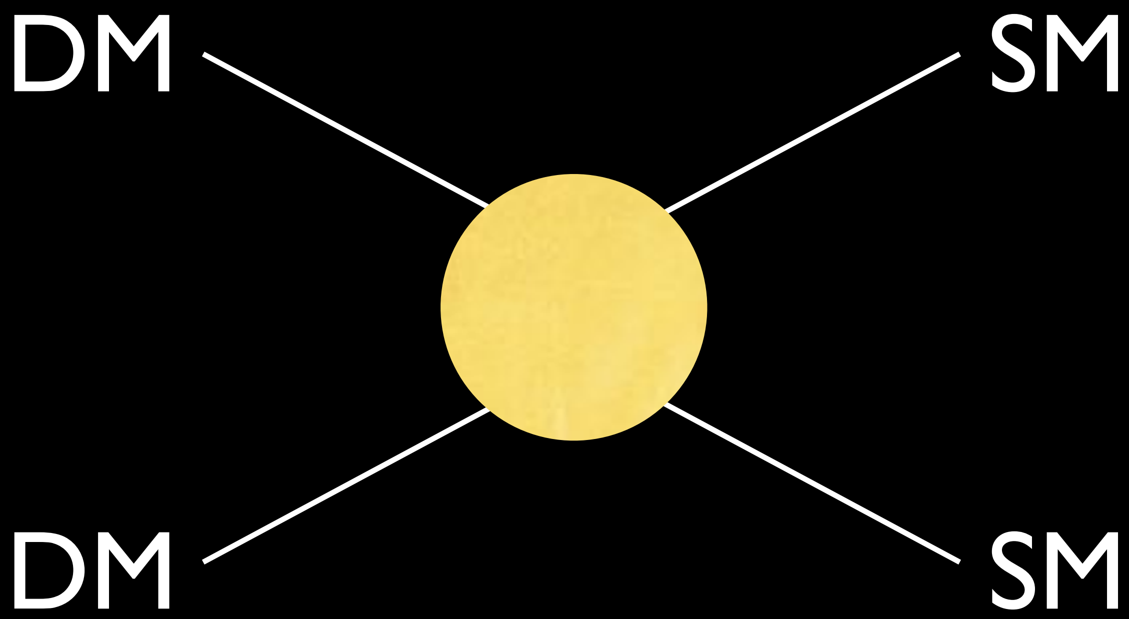

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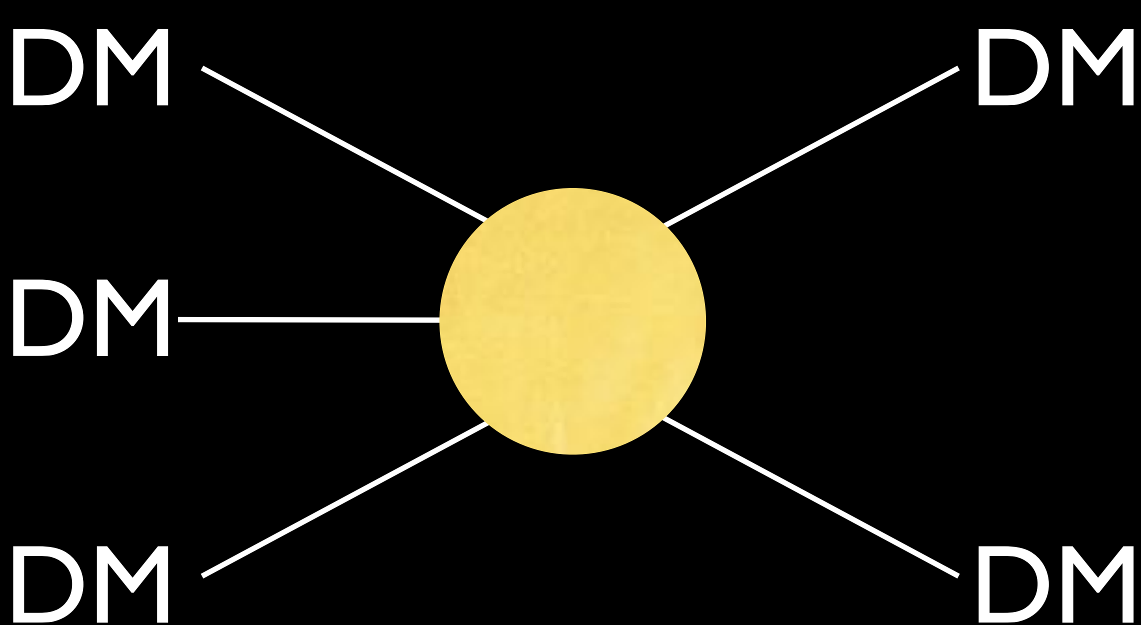

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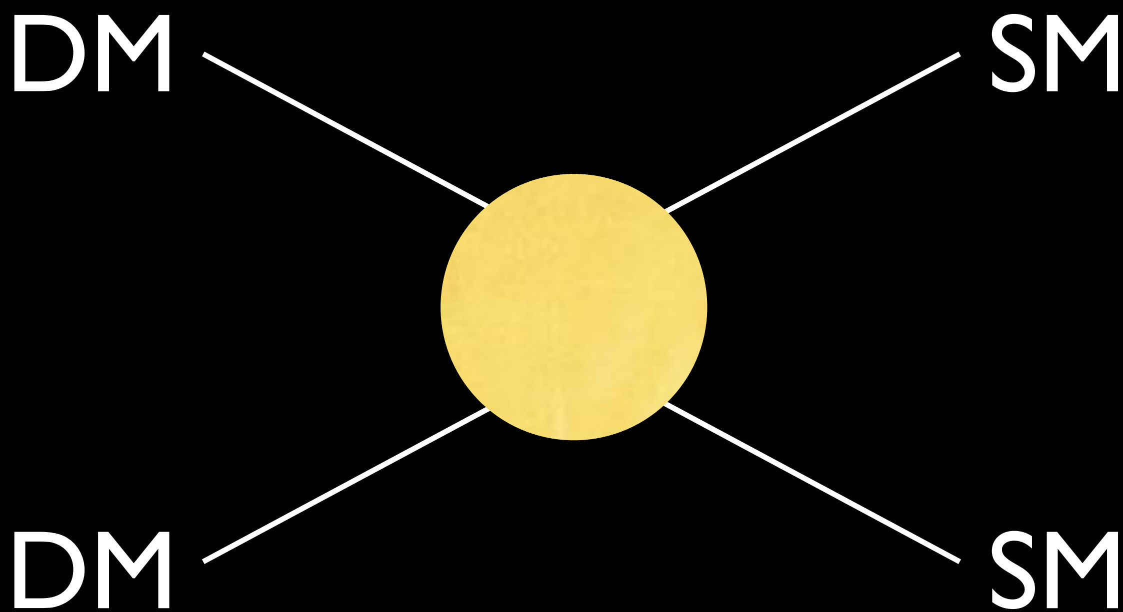

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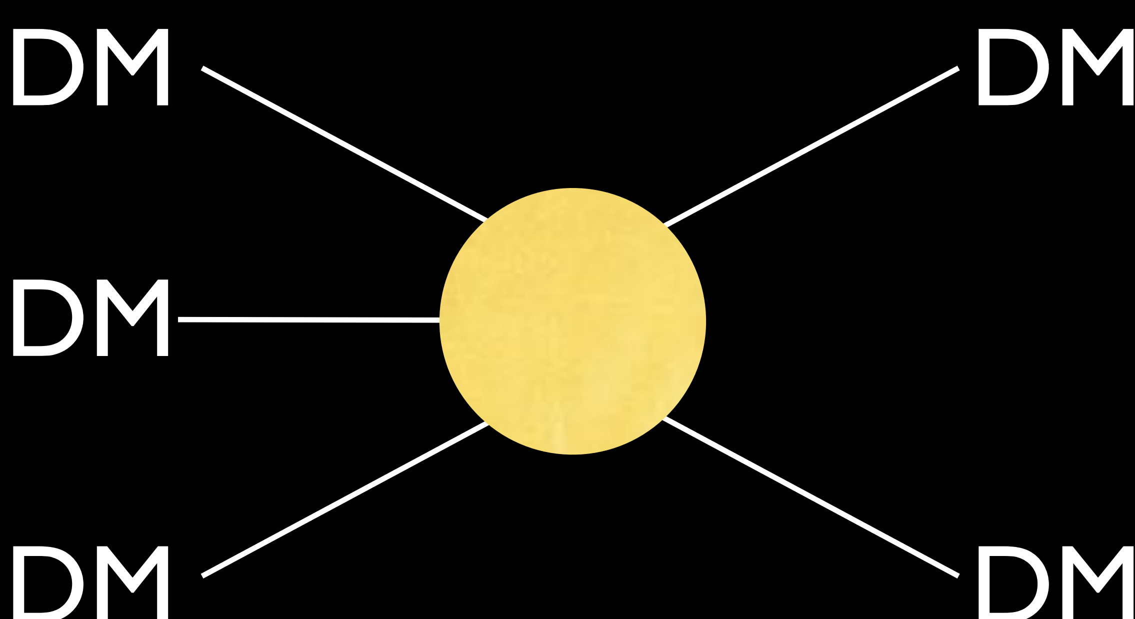

$$\langle \sigma_{3\to 2} v^2 \rangle \approx \frac{\alpha^3}{m^5}$$

$$\alpha \approx 4\pi$$

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

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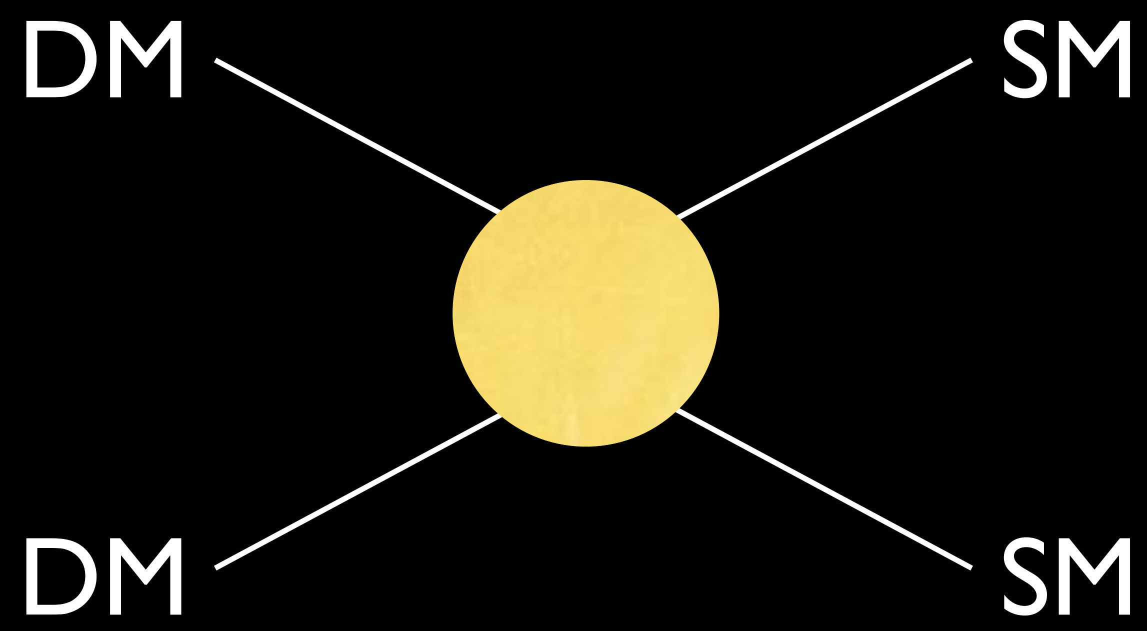
Miracles



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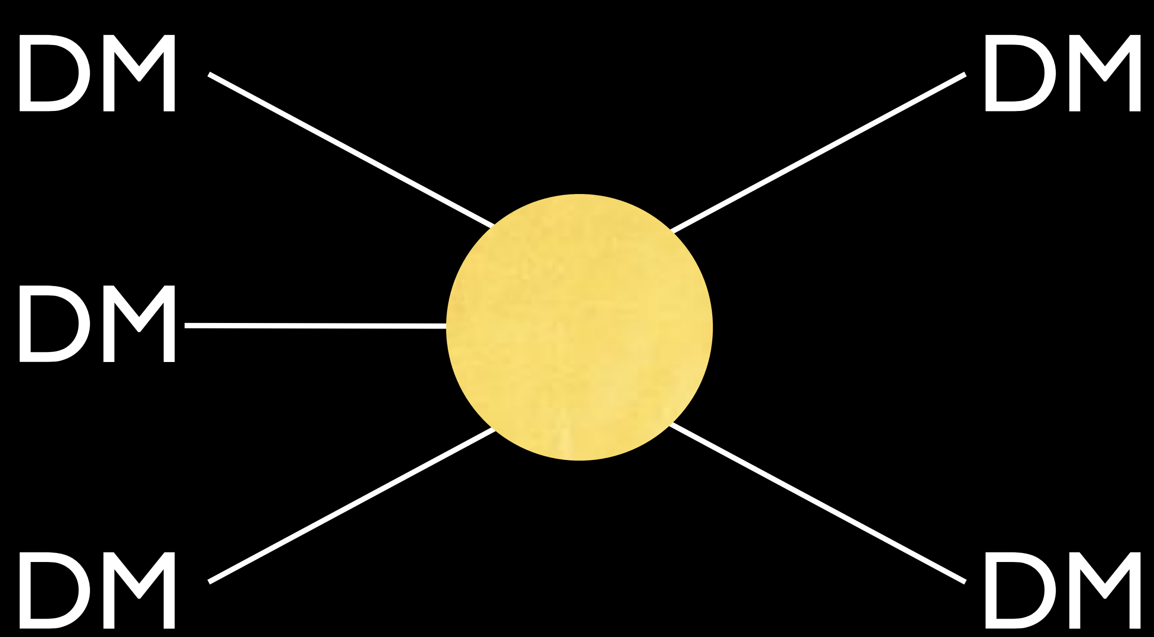

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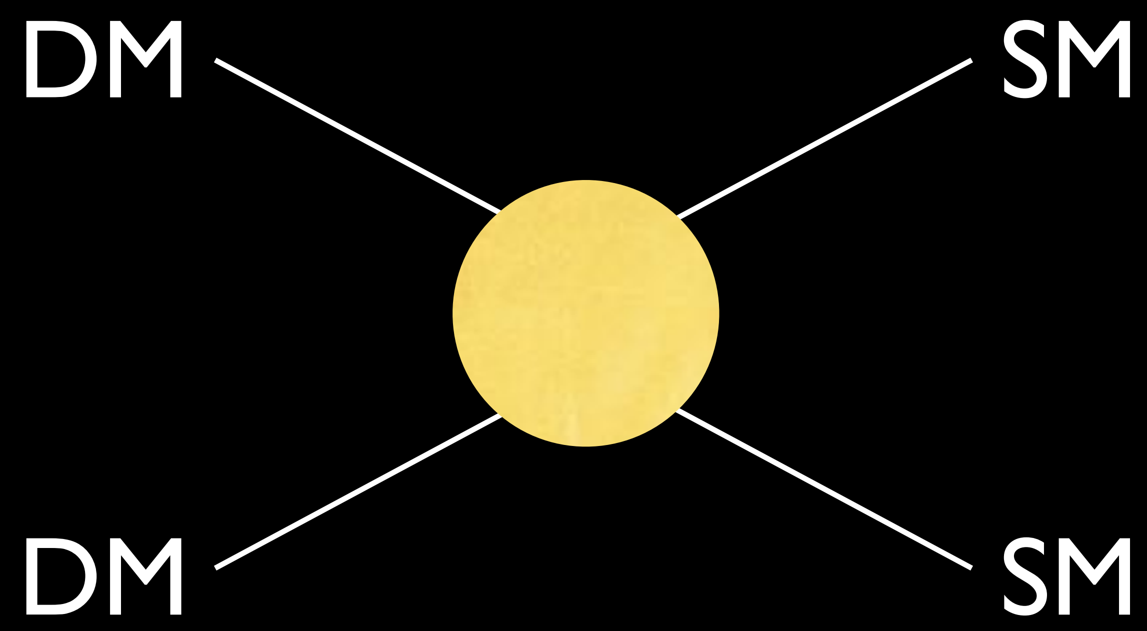

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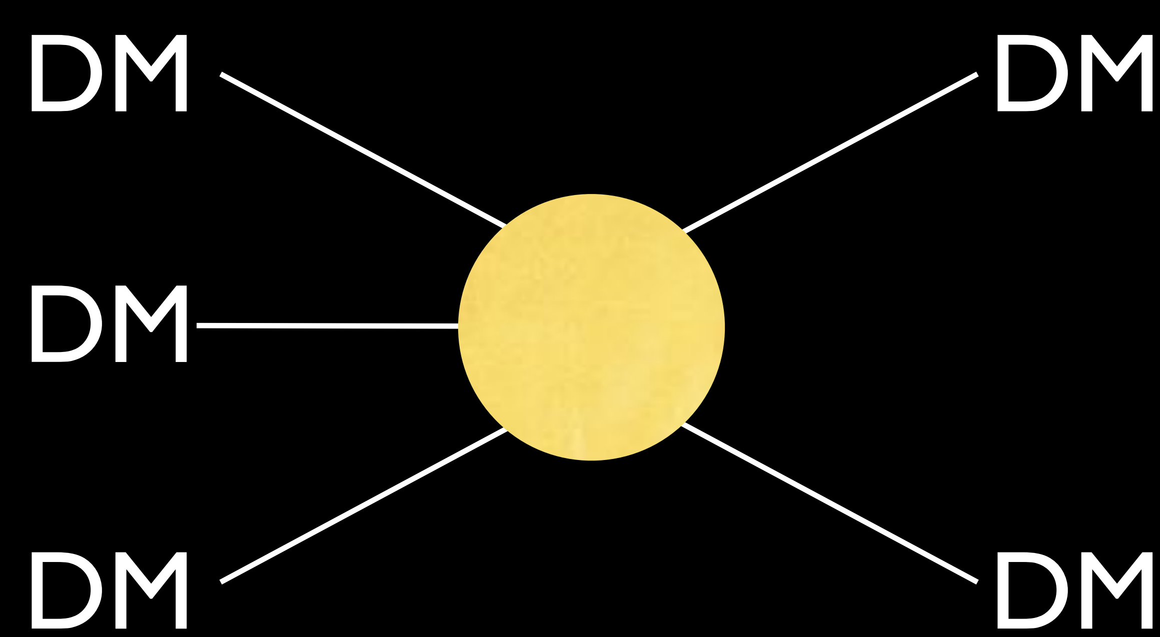

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Hochberg, Kuflik, Volansky, Wacker arXiv:1402.5143

SIMP miracle!

LEE-WEINBERG FREEZE-OUT

Back of the envelope calculation

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

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

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

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

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

$$n_b \sim \eta_b s$$

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

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

Eric Kuflik

3→2 ~~LEE WEINBERG~~ FREEZE-OUT

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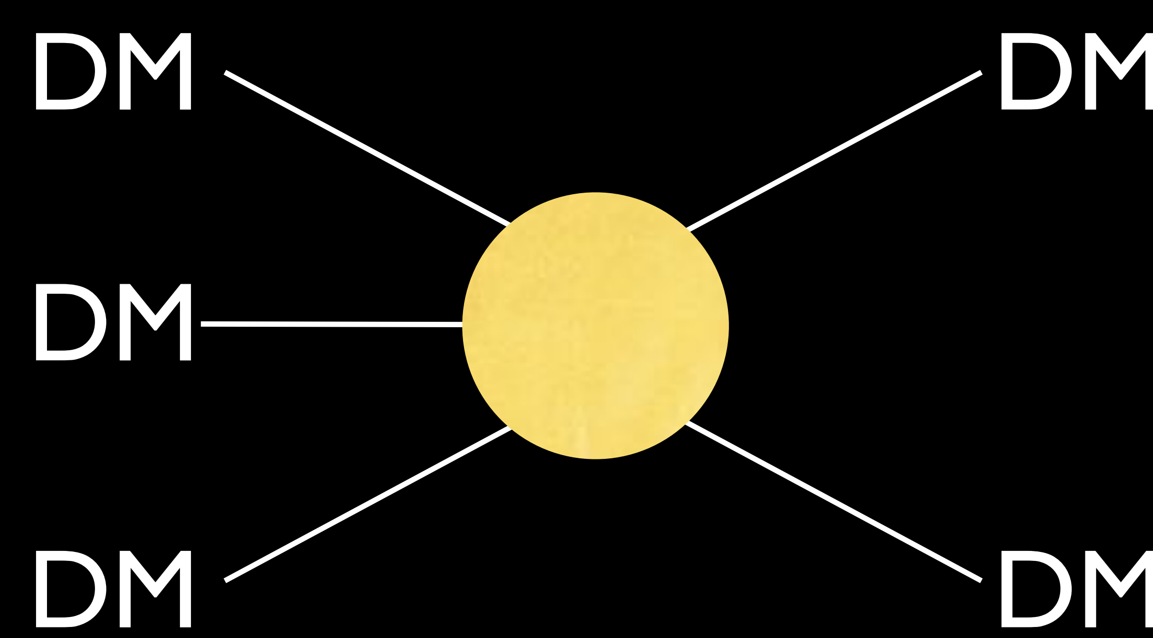
Eric Kuflik

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

SIMPlest Miracle

- Not only the mass scale is similar to QCD
- dynamics itself can be QCD! Miracle³
- DM = pions = $q\bar{q}$
- e.g. SU(4)/Sp(4) = S⁵



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

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

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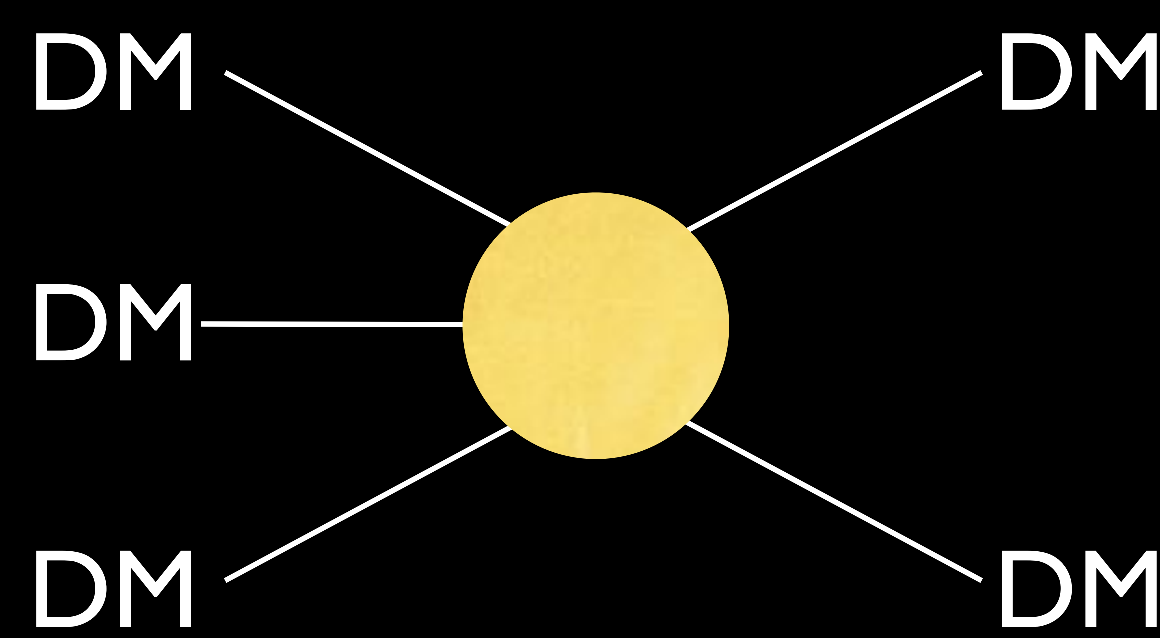

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+HM
arXiv:1411.3727

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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
- $\mathcal{L}_{WZ}=\varepsilon_{abcde}\,\varepsilon^{\mu\nu\rho\sigma}\,\pi^a\partial_\mu\pi^b\partial_\nu\pi^c\partial_\rho\pi^d\partial_\sigma\pi^e$

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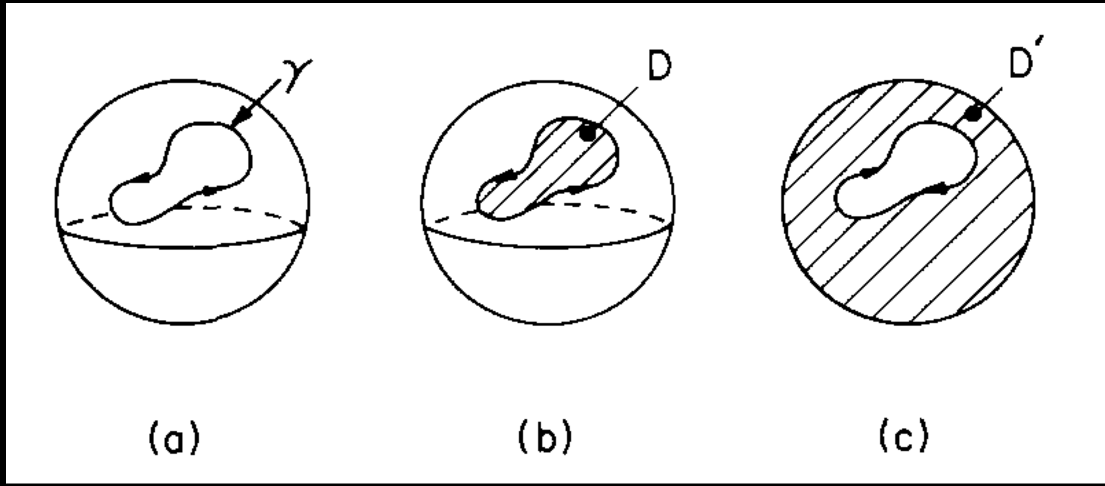
Wess-Zumino term

- 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

also, non-abelian vector bosons (vector SIMP)
+S-M Choi, HM Lee, Y. Mambrini, M. Pierre

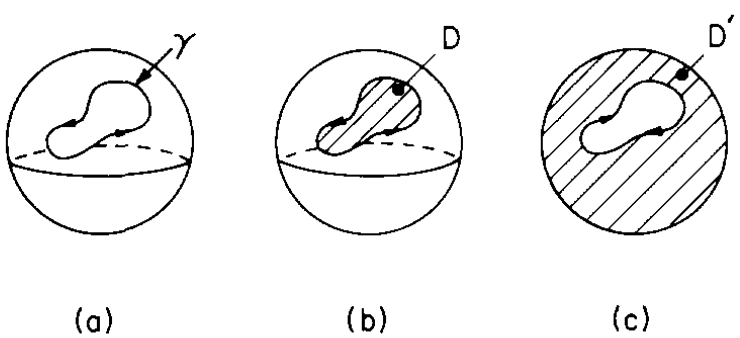
LAGRANGIANS

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

$$\mathcal{L}_{\text{pion}} = \frac{1}{4}\text{Tr}\partial_\mu\pi\partial^\mu\pi - \frac{m_\pi^2}{4}\text{Tr}\pi^2 + \frac{m_\pi^2}{12f_\pi^2}\text{Tr}\pi^4 - \frac{1}{6f_\pi^2}\text{Tr}\left(\pi^2\partial^\mu\pi\partial_\mu\pi - \pi\partial^\mu\pi\pi\partial_\mu\pi\right)$$
$$+ \frac{2N_c}{15\pi^2 f_\pi^5}\epsilon^{\mu\nu\rho\sigma}\text{Tr}\left[\pi\partial_\mu\pi\partial_\nu\pi\partial_\rho\pi\partial_\sigma\pi\right] + \mathcal{O}(\pi^6)$$

LAGRANGIANS

Quark theory

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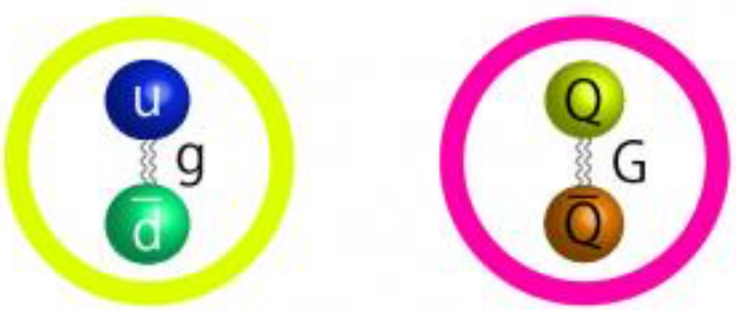
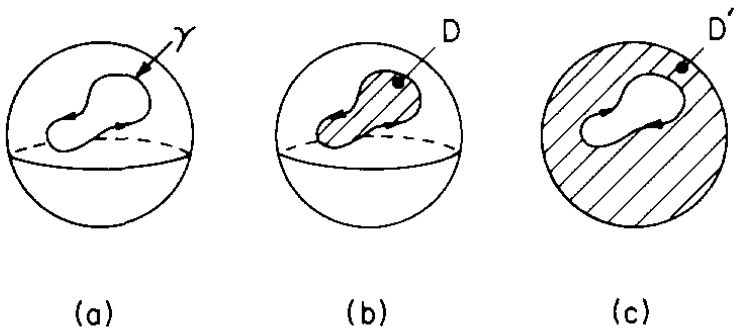


Pion theory



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

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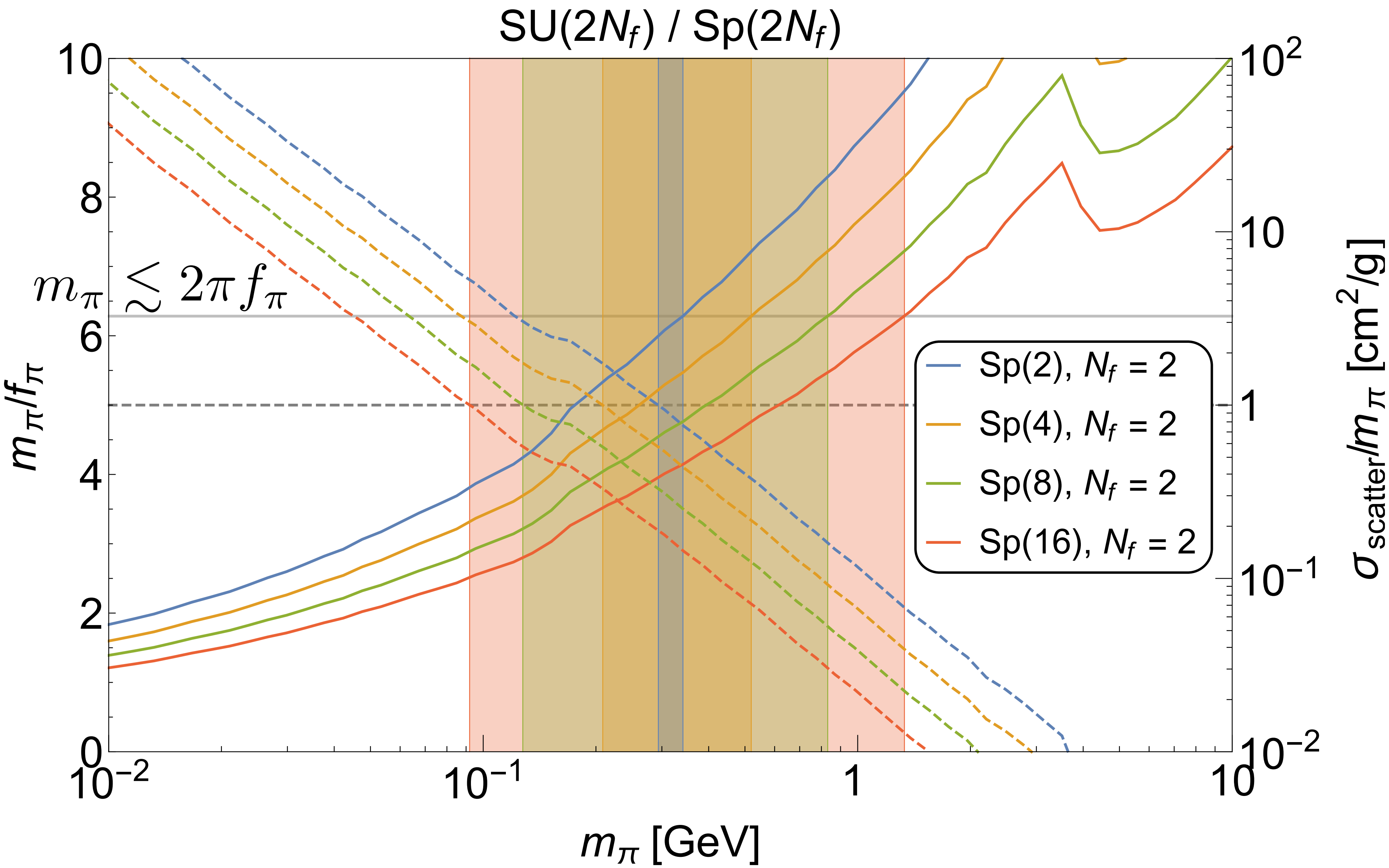
The Results

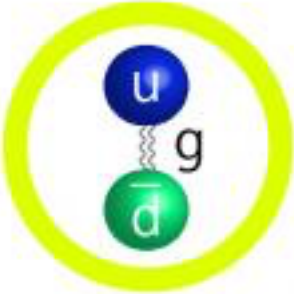


Solid curves: solution to Boltzmann eq.

Dashed curves: along that solution

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

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



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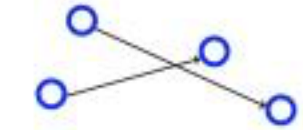

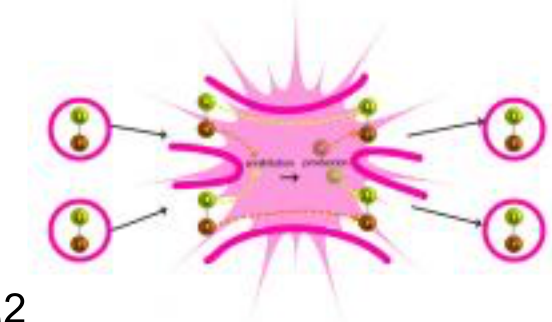

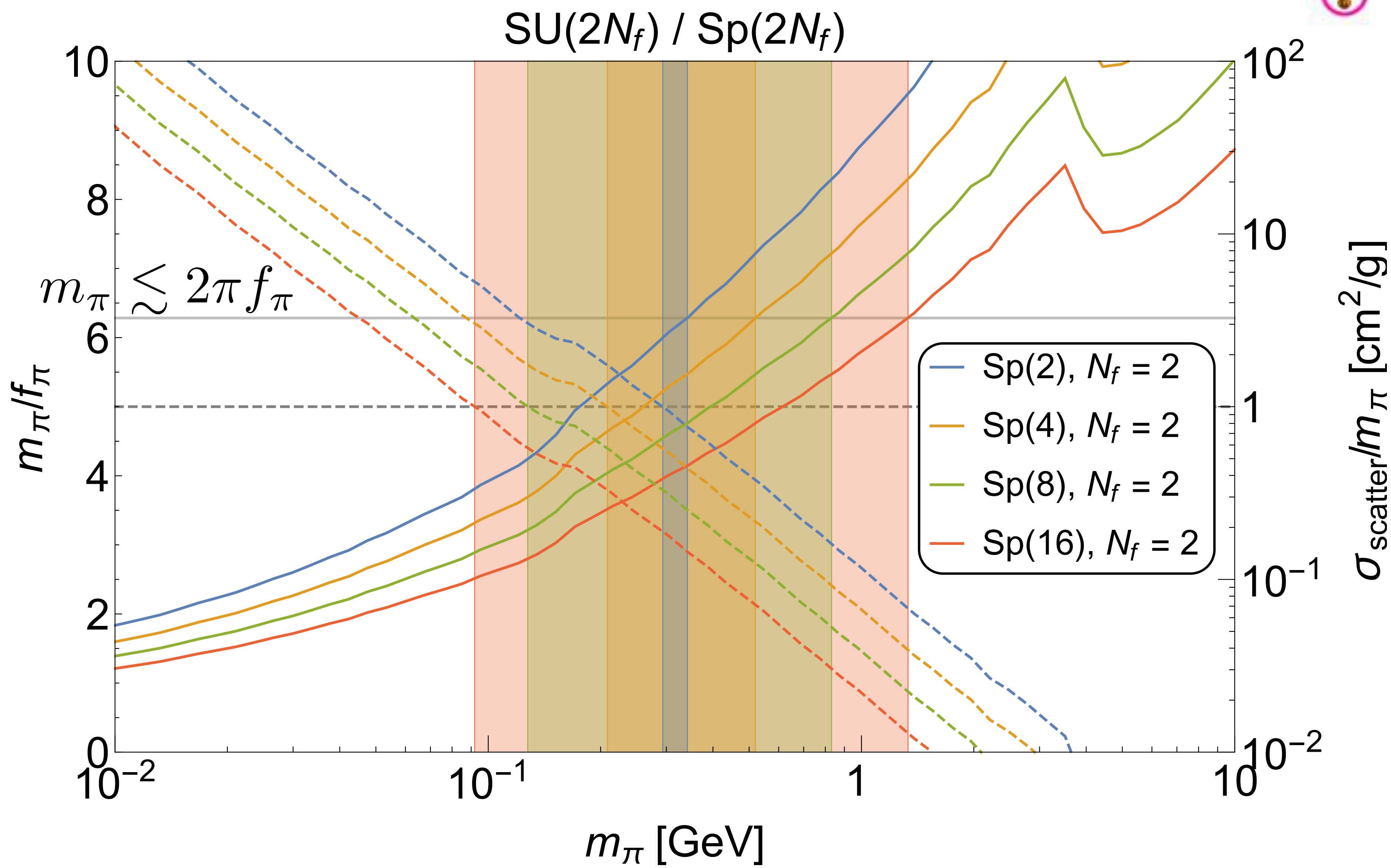

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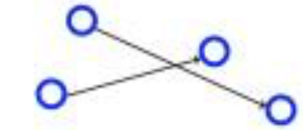

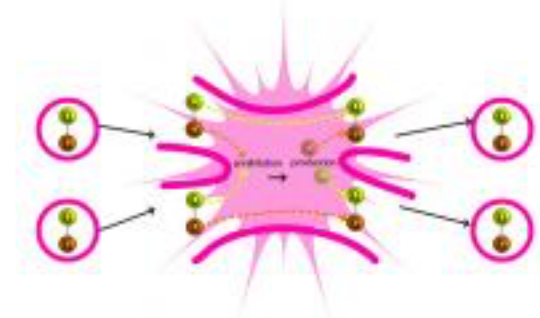

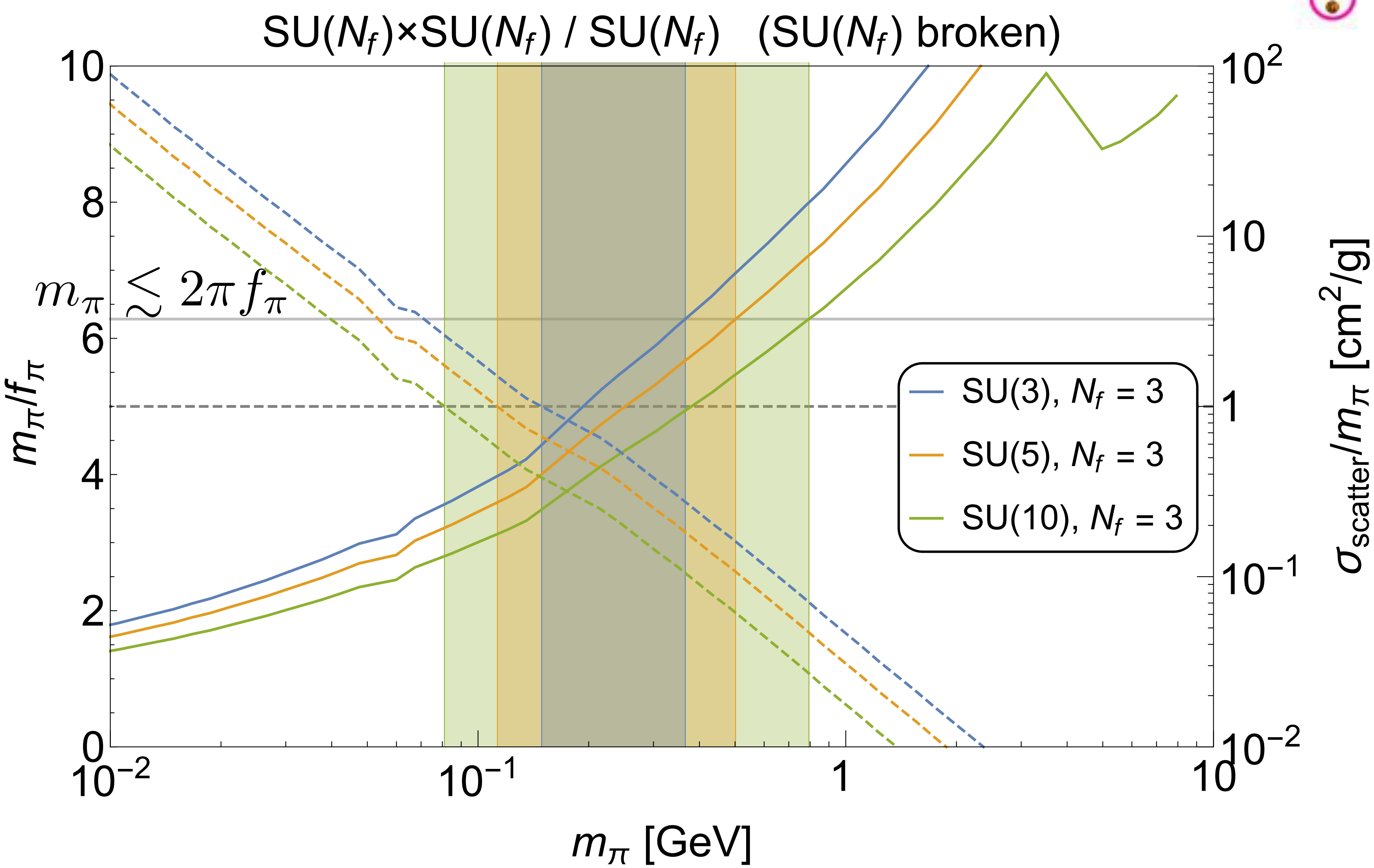

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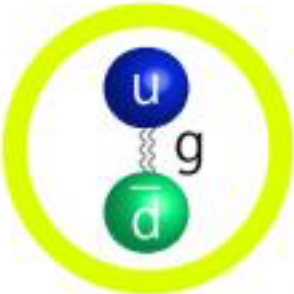

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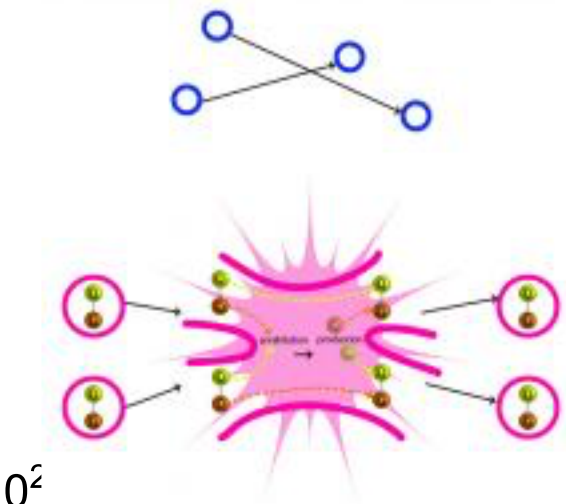

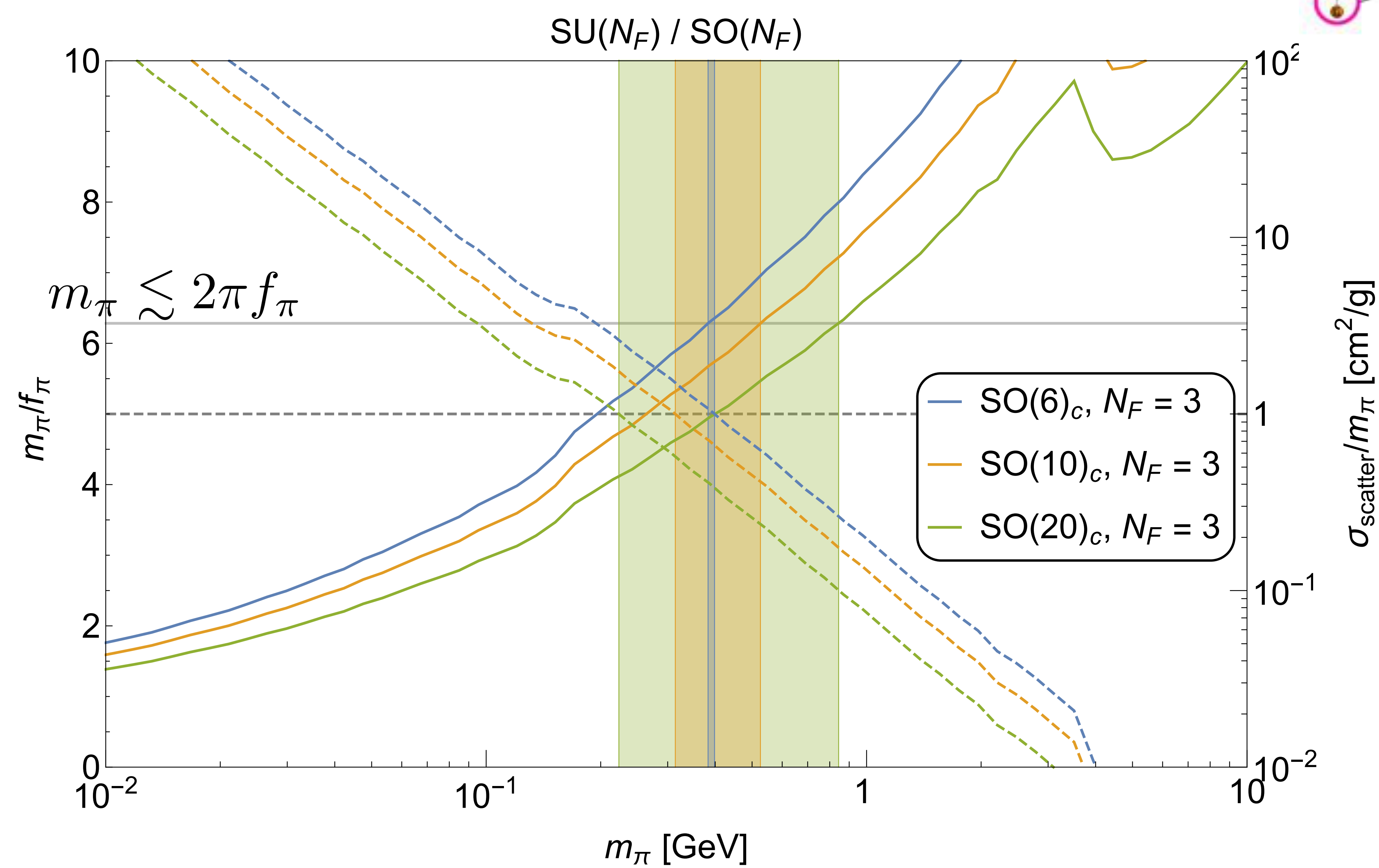

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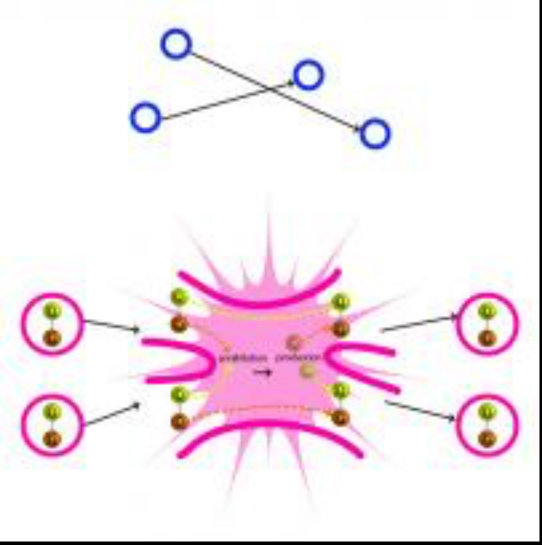
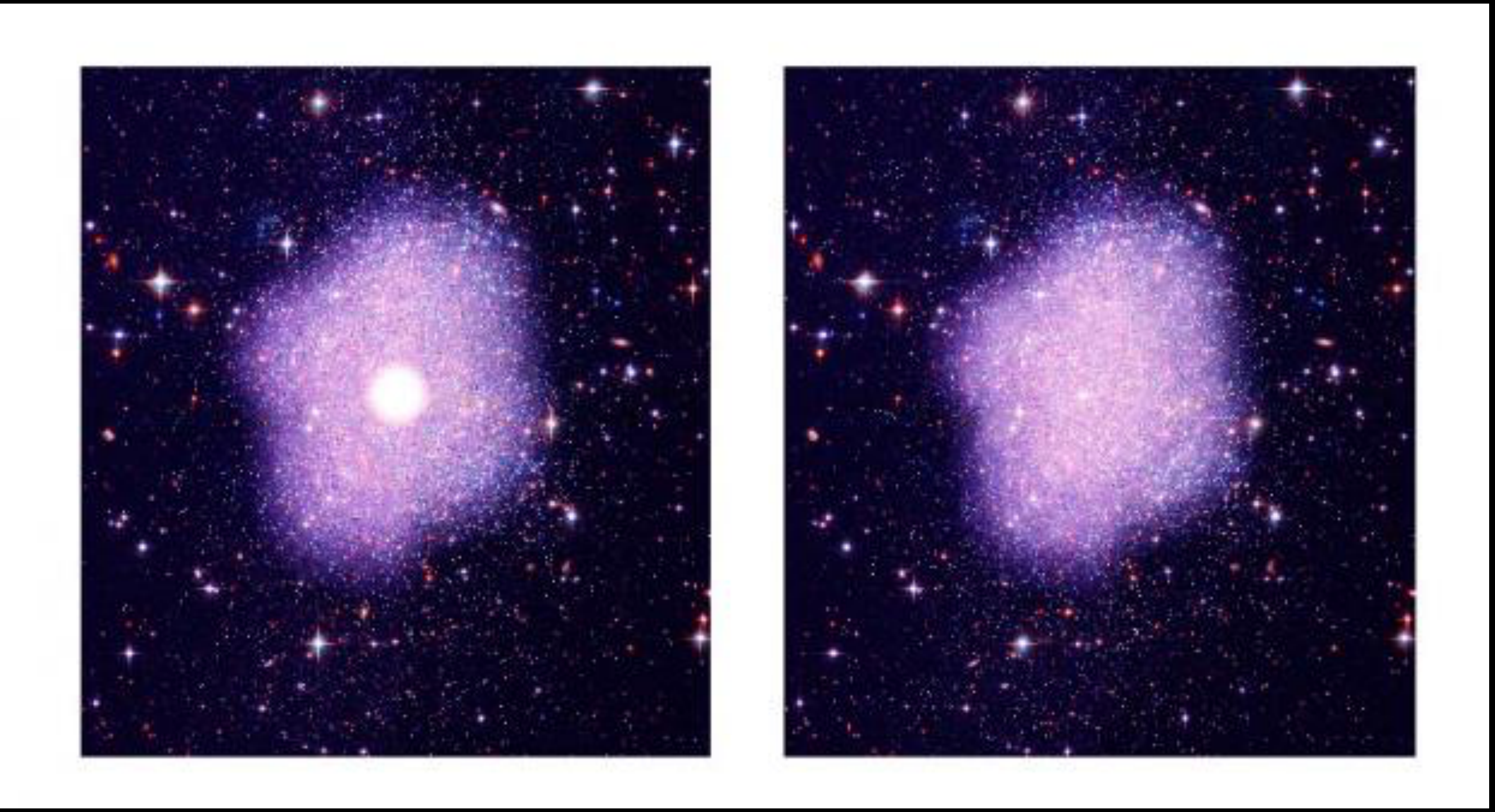
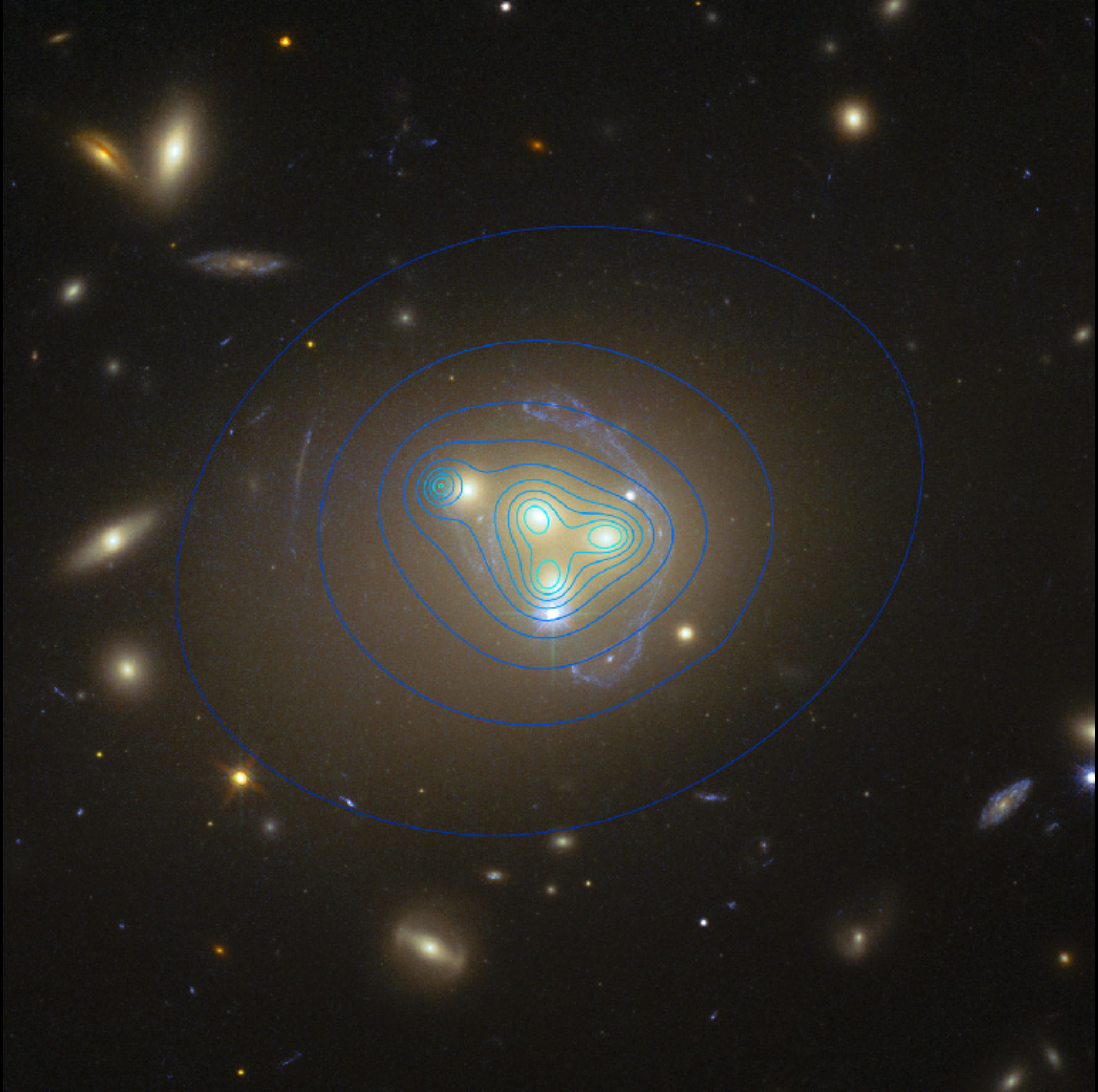


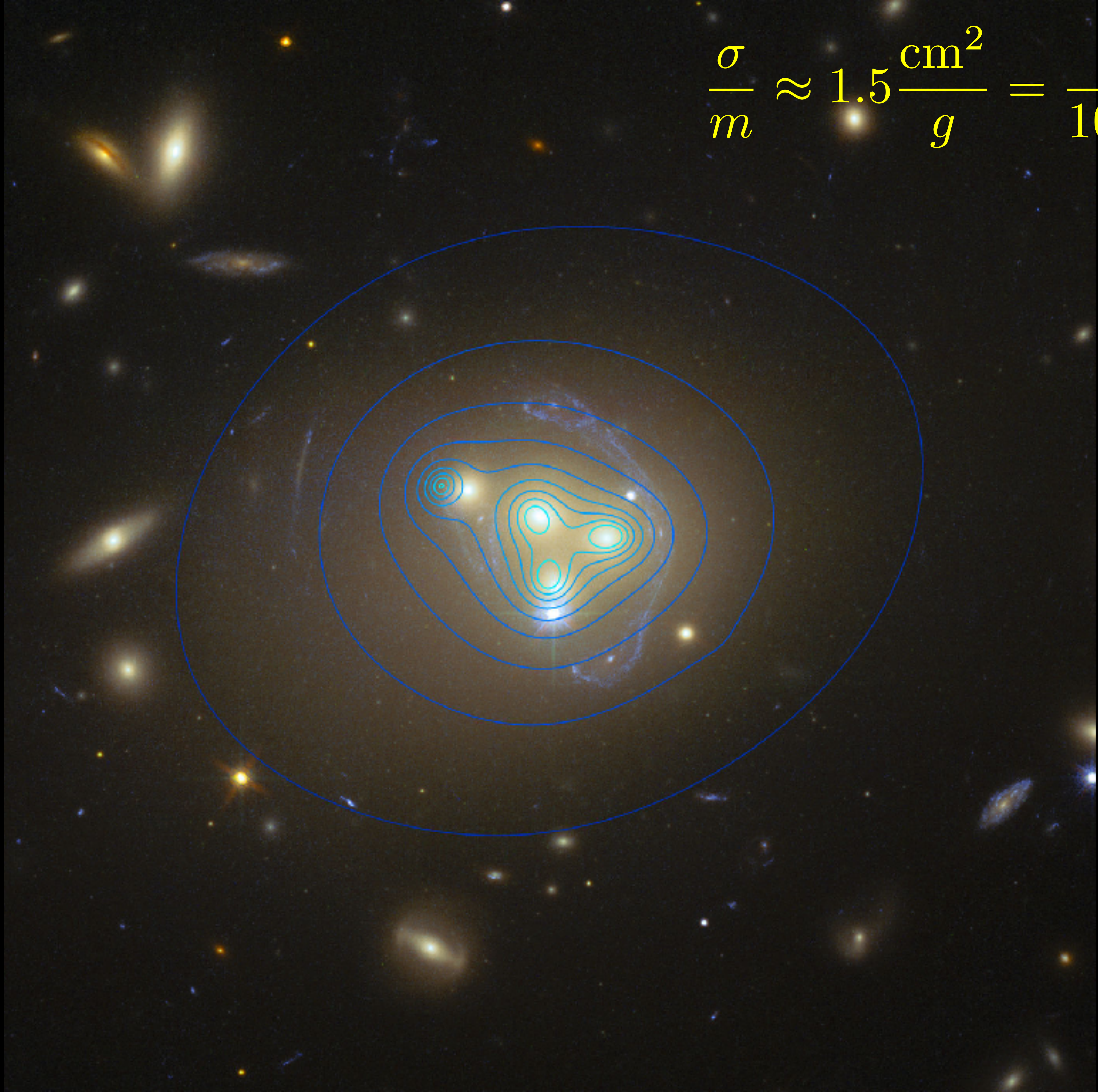
self interaction

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

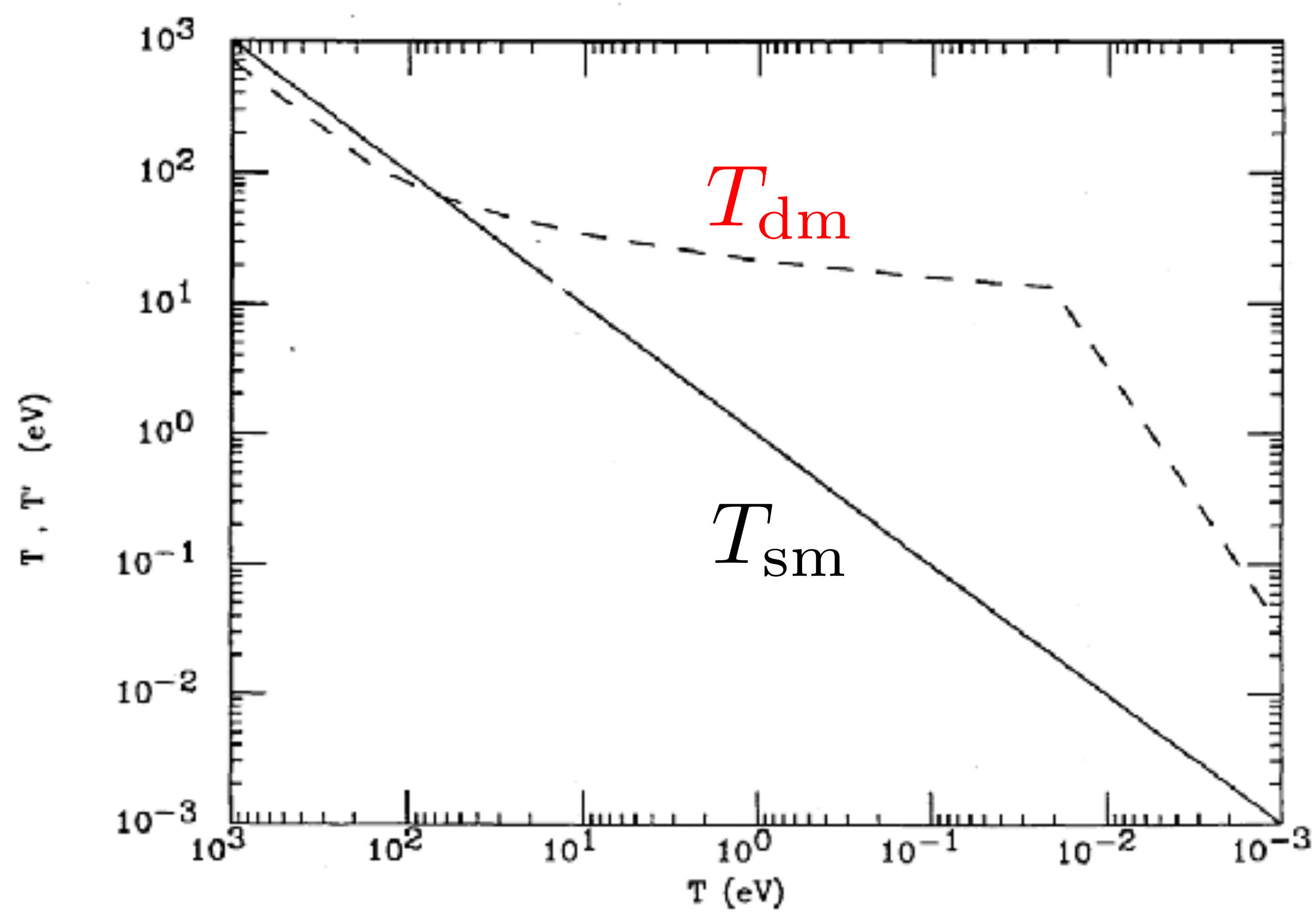




$$\frac{\sigma}{m} \approx 1.5 \frac{\mathrm{cm}^2}{g} = \frac{0.27\mathrm{b}}{100\mathrm{MeV}}$$



if totally decoupled

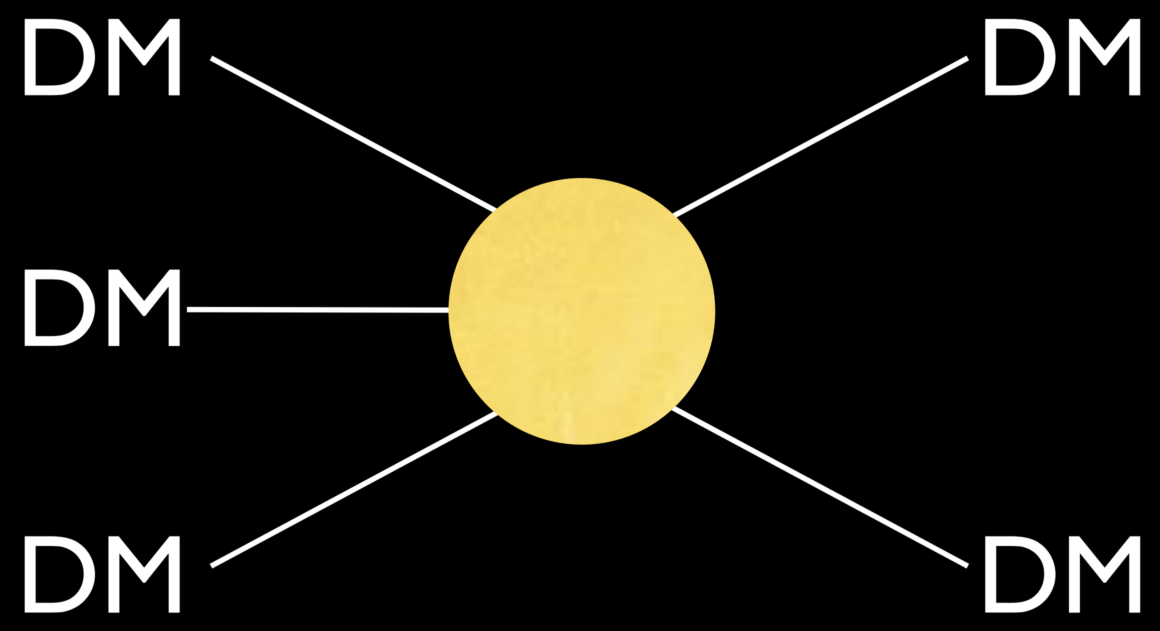


Carlson, Hall and Machacek, Astrophys. J. 398, 43 (1992)

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

communication

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



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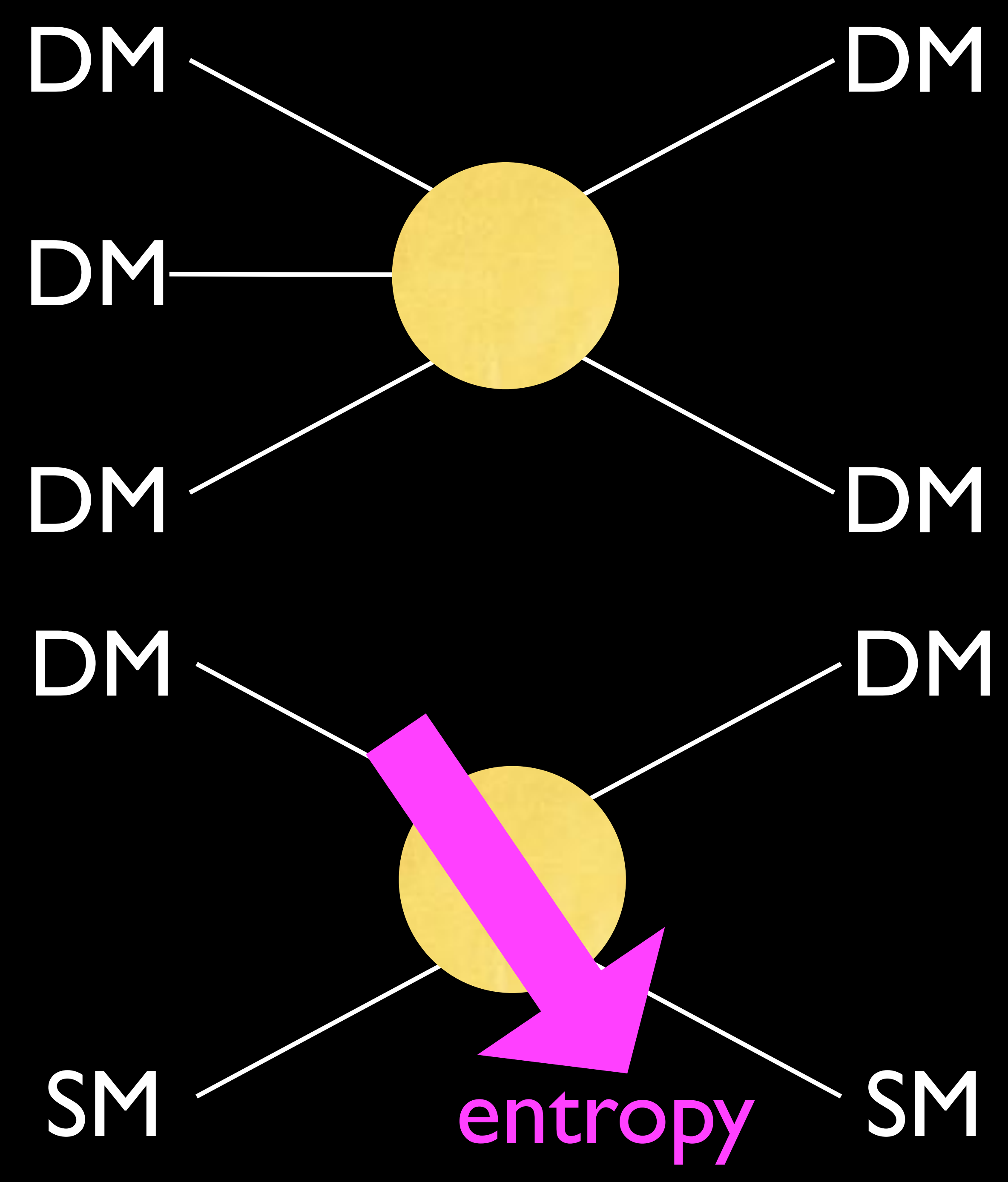
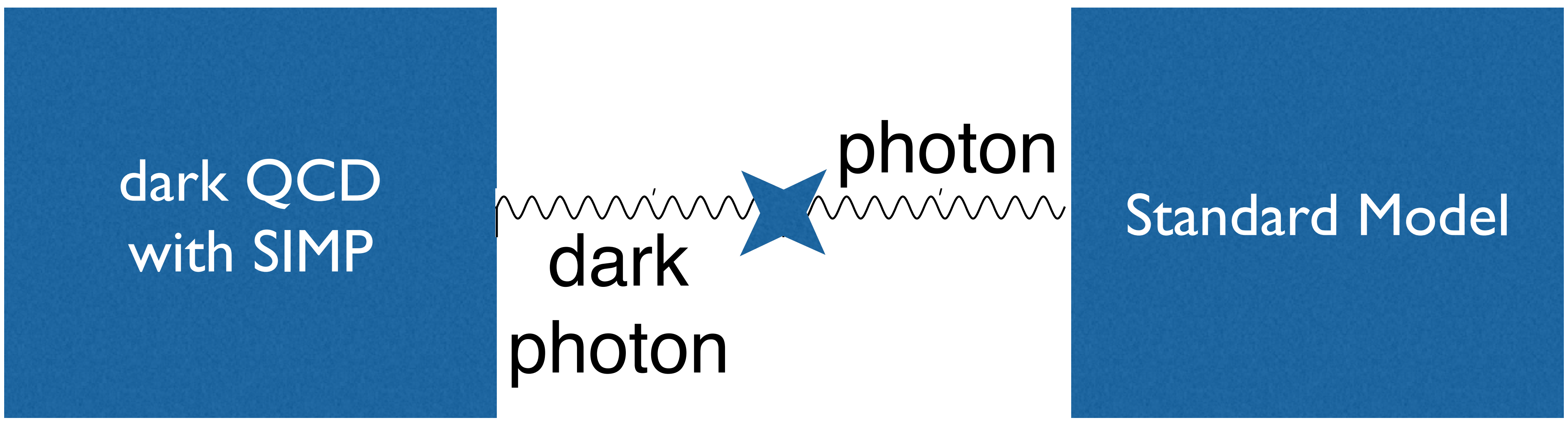


vector portal



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

also axion portal: +Katelin Schutz, Robert McGehee in preparation

Kinetically mixed U(1)

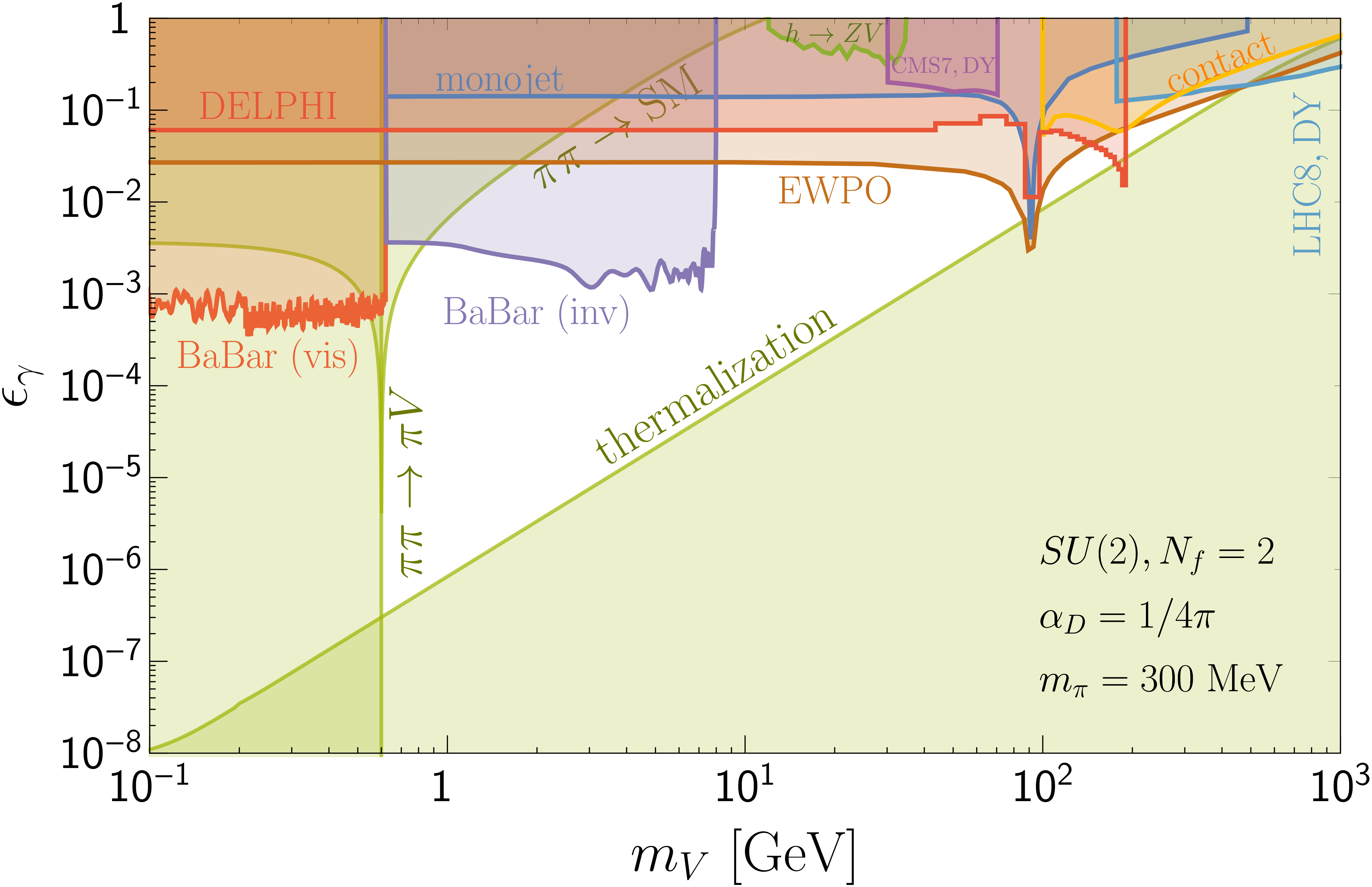
- e.g., the SIMPlest model SU(2) gauge group with N_f=2 (4 doublets)
- gauge U(1)=SO(2) ⊂ SO(2) ×SO(3) ⊂ SO(5)=Sp(4)
- maintains degeneracy of quarks
- near degeneracy of pions for co-annihilation

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

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

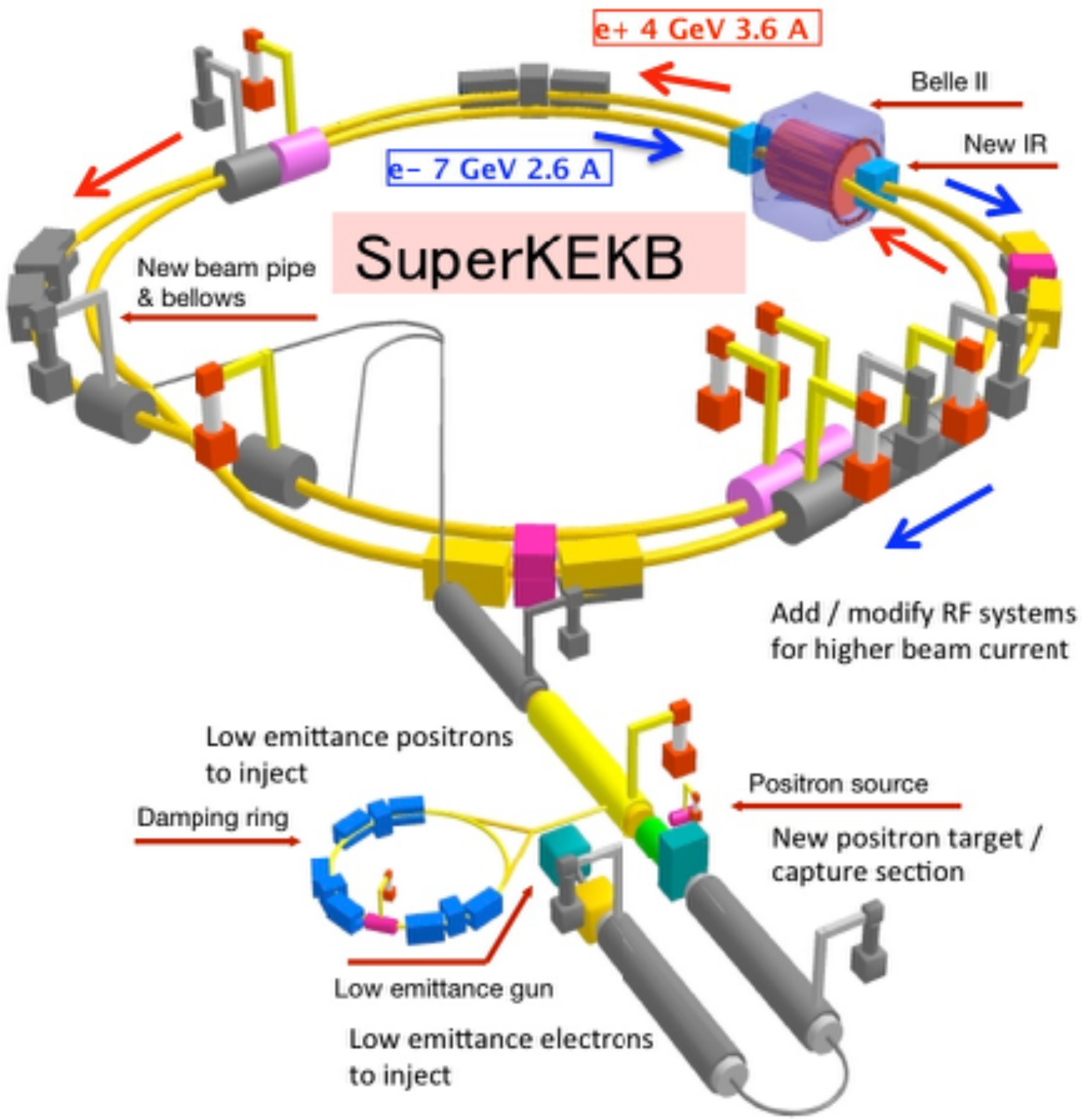
$$(\pi^{++}, \pi^{--}, \pi^0_x, \pi^0_y, \pi^0_z)$$

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

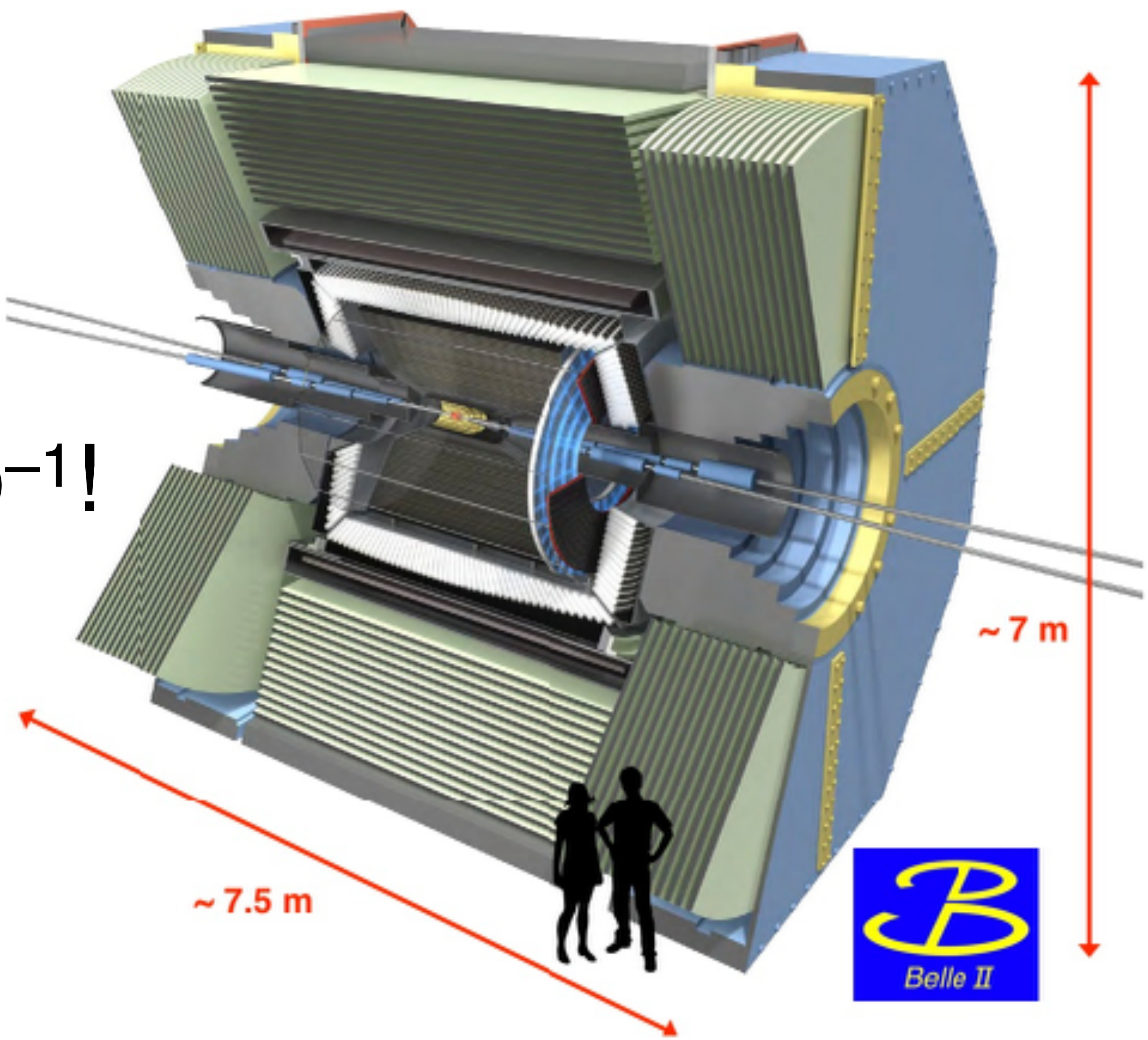


$h \to ZV$
CMS7, DY
monojet
DELPHI
$\pi\pi \to$ SM
EWPO
contact
LHC8, DY
BaBar (inv)
BaBar (vis)
$\pi\pi \to \pi V$
thermalization
$SU(2), N_f = 2$
$\alpha_D = 1/4\pi$
$m_\pi = 300$ MeV
ϵ_γ
m_V [GeV]
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{1}
10^{2}
10^{3}

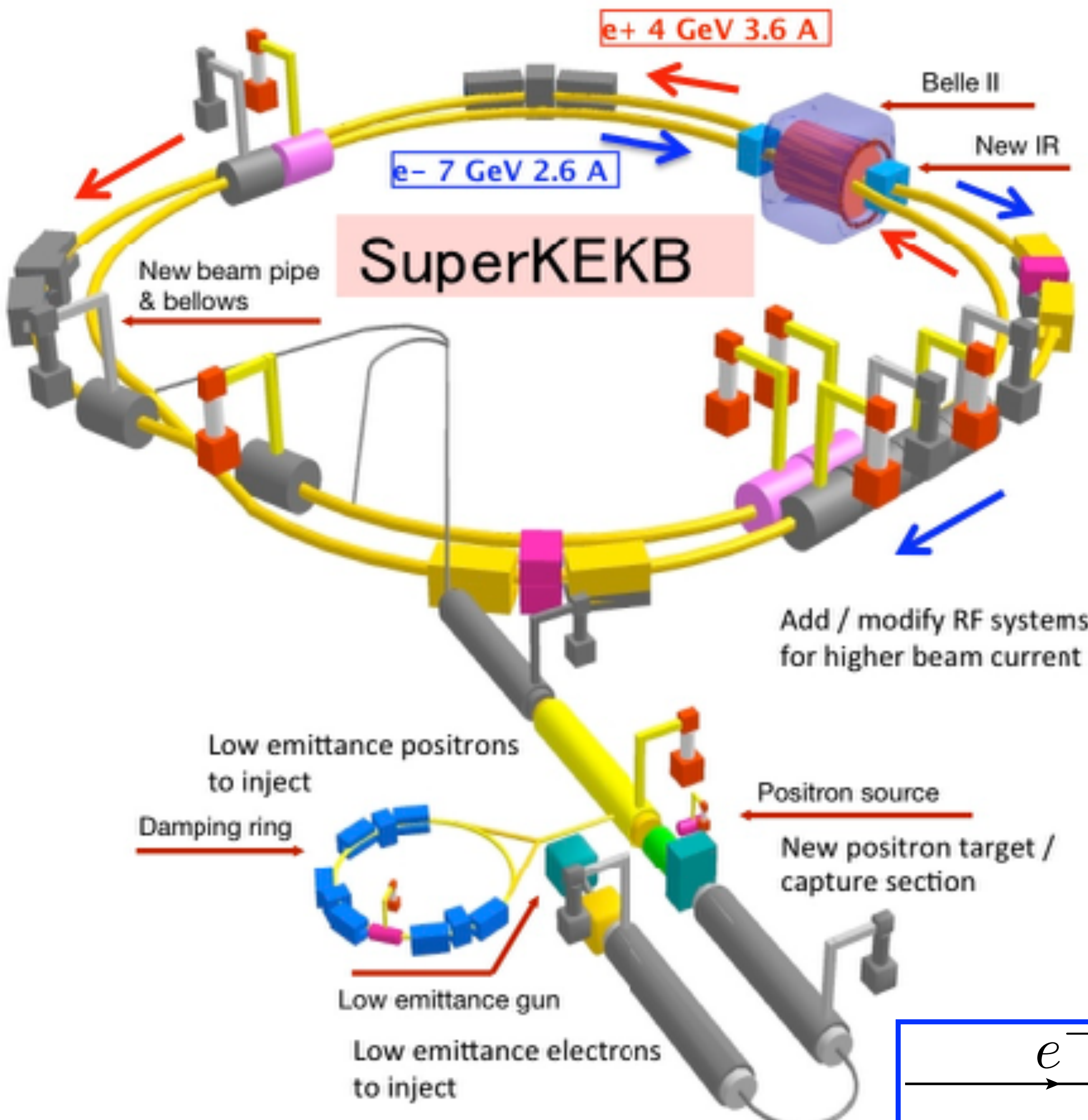
$e^+ e^-$ colliders



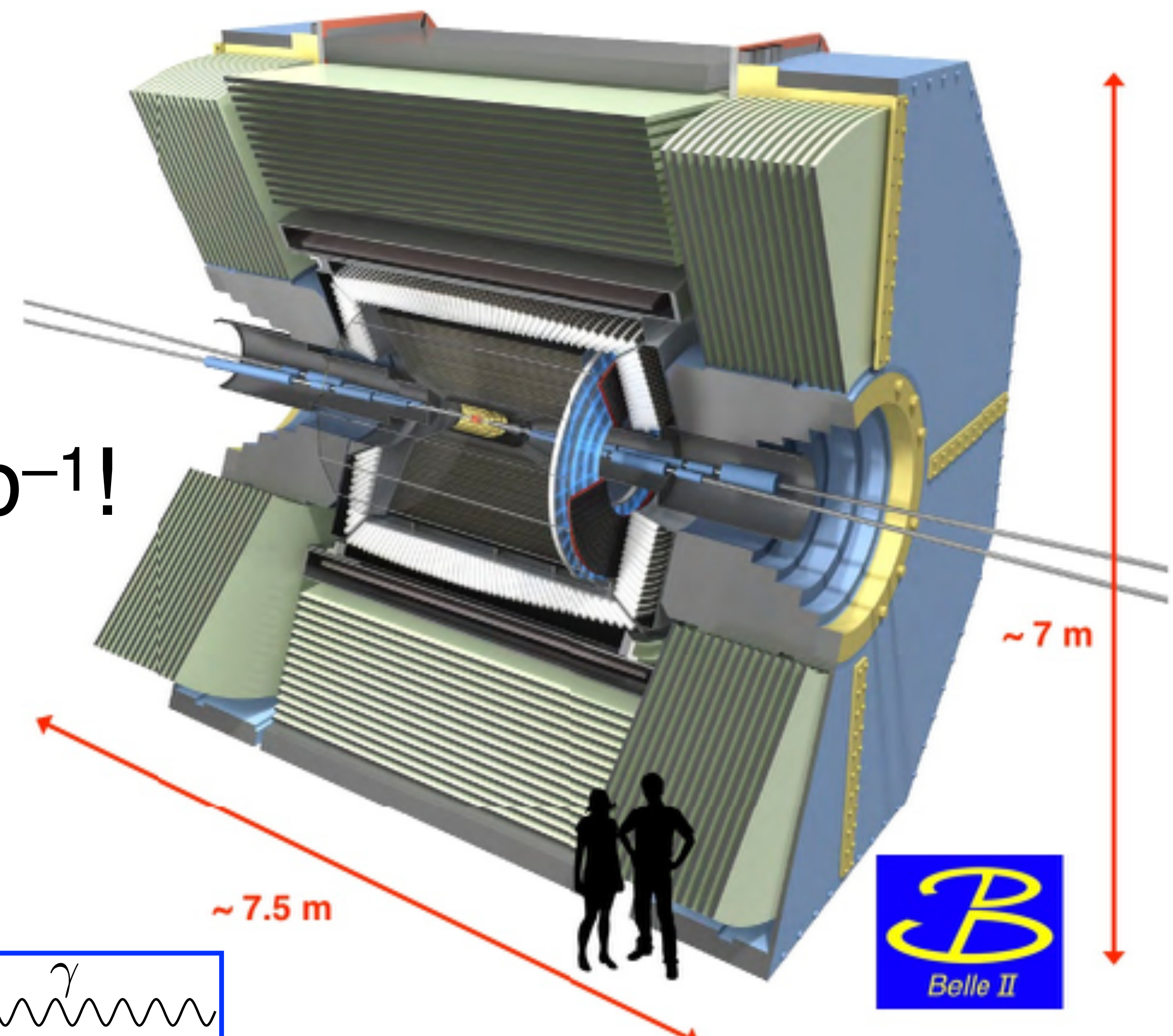
$50\ ab^{-1}$!

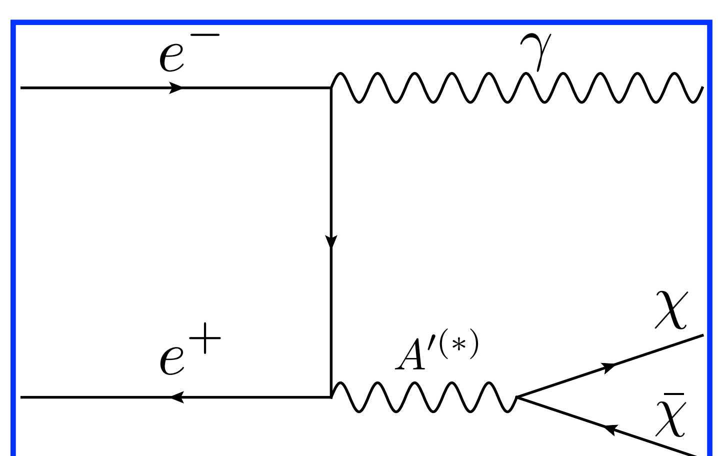


$e^+ e^-$ colliders

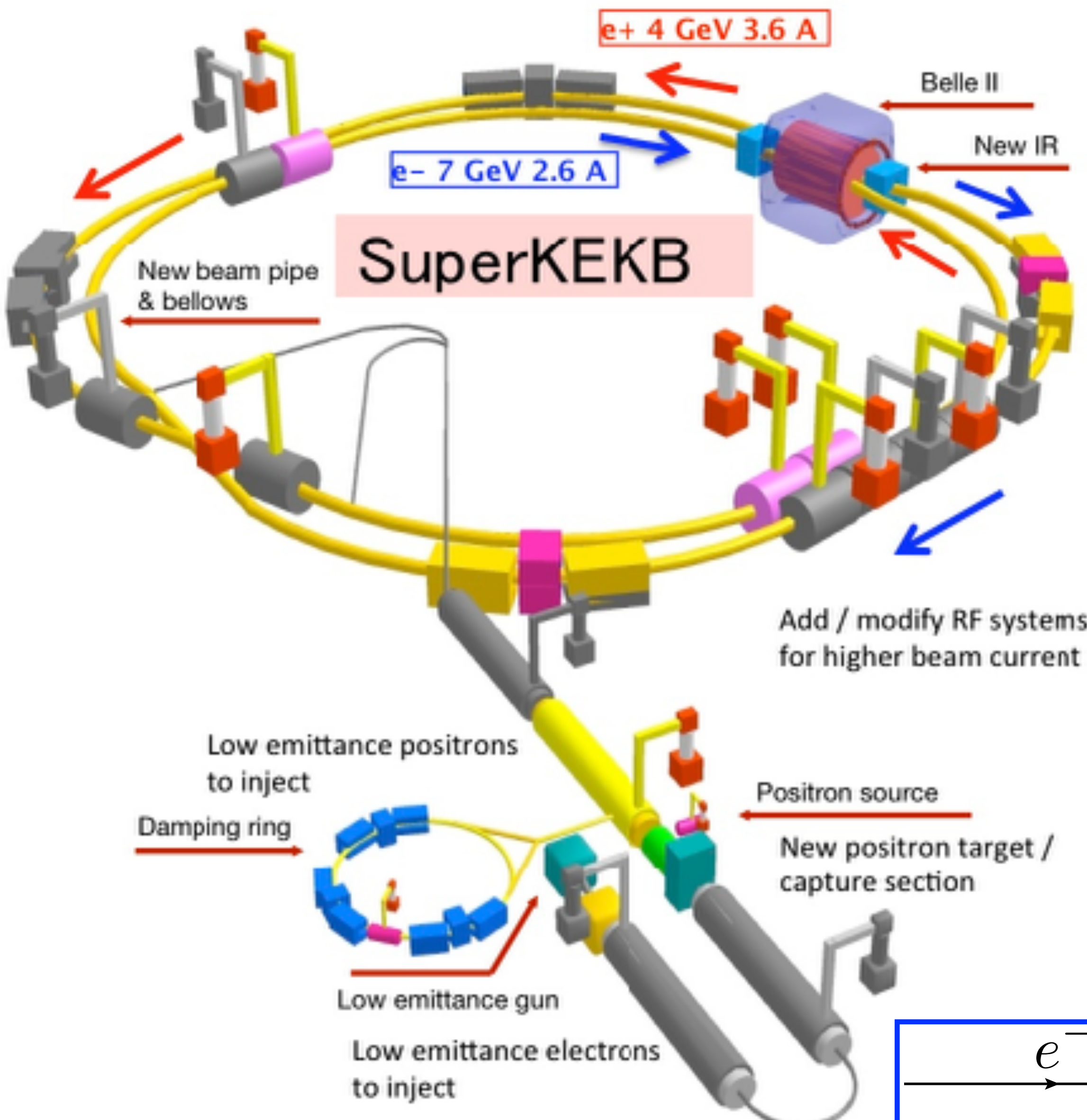


50 ab^{-1}!

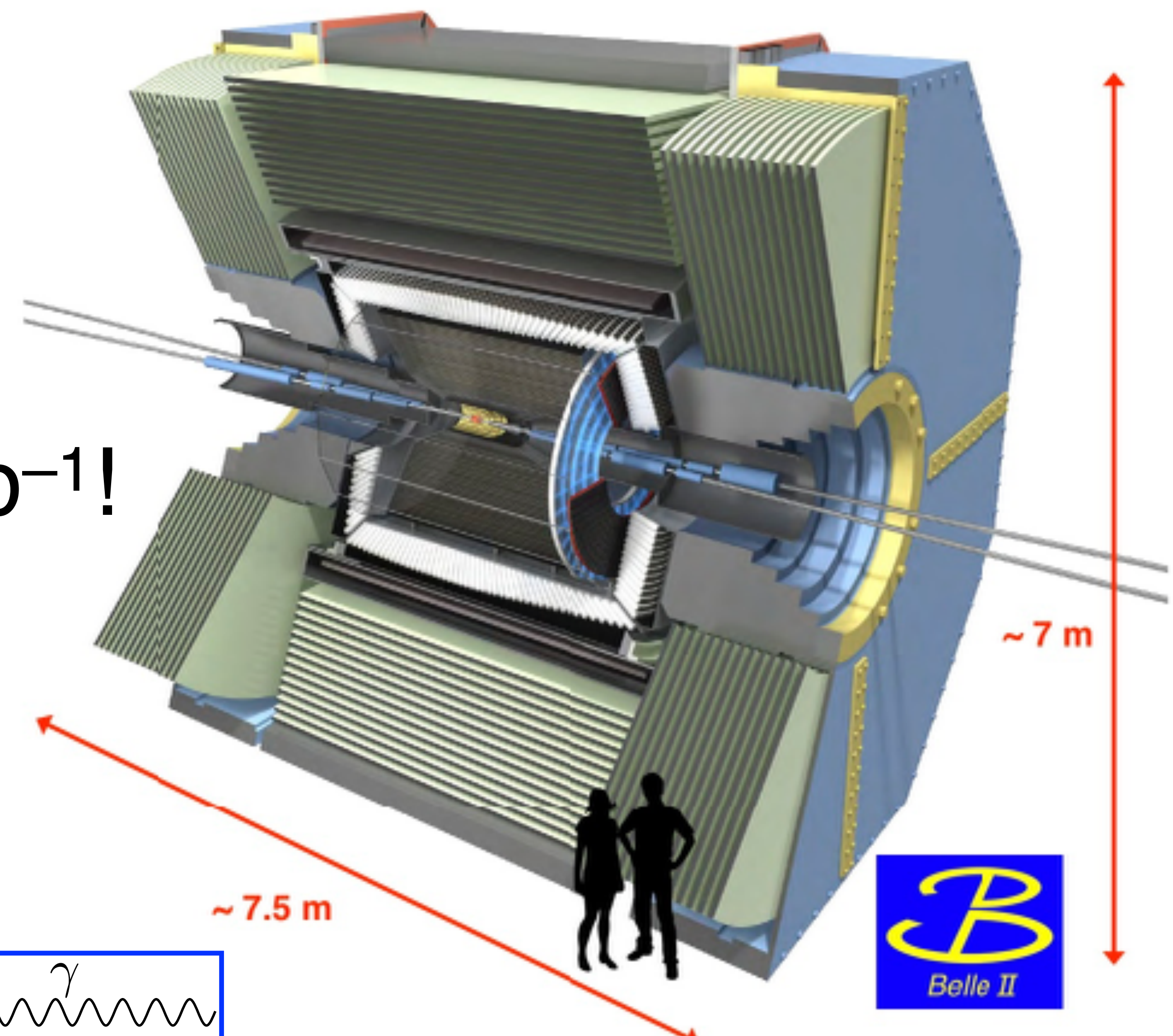


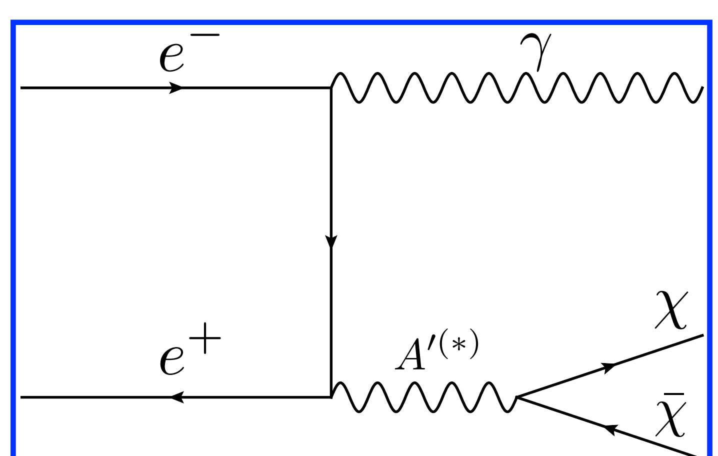


$e^+ e^-$ colliders

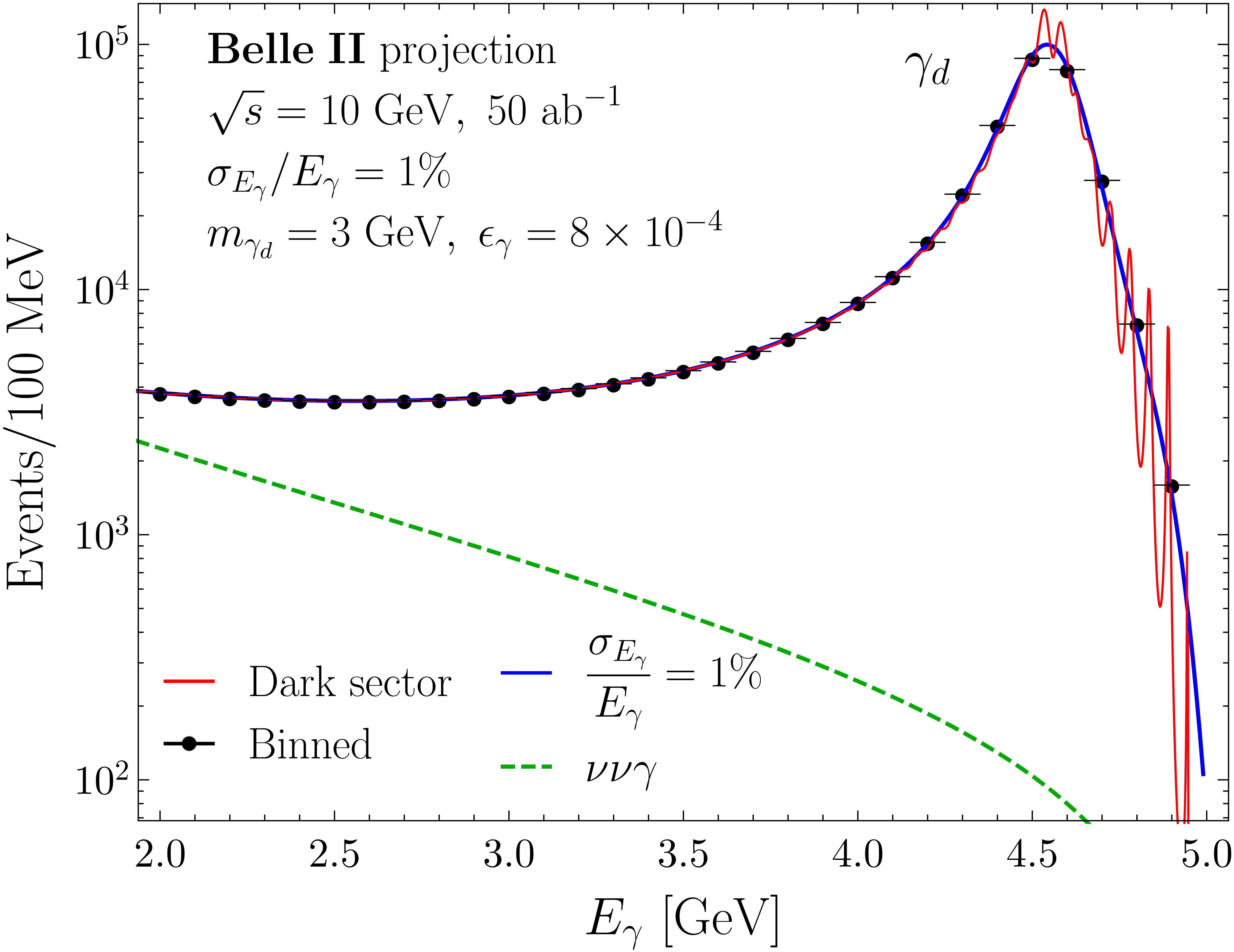


50 ab^{-1}!

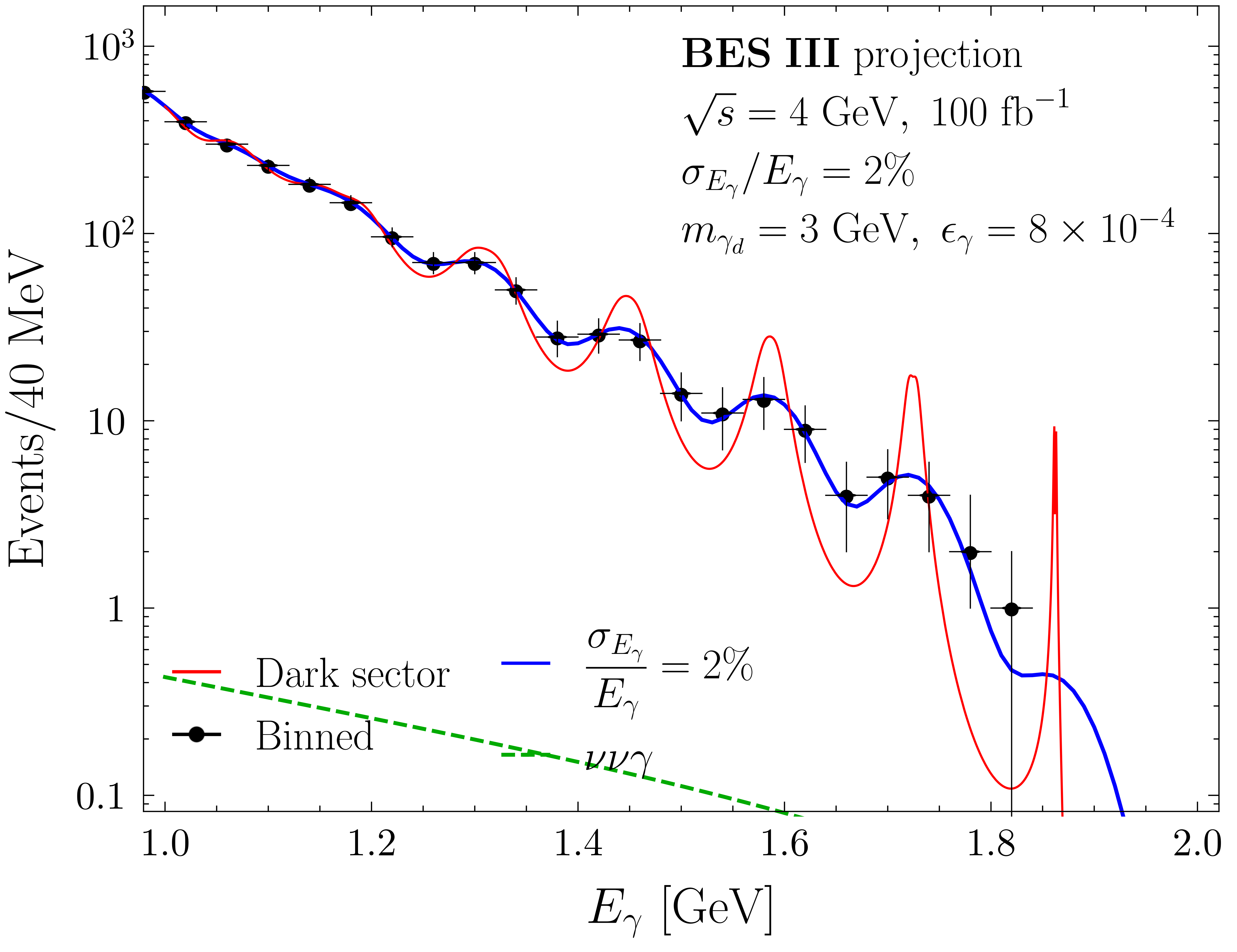




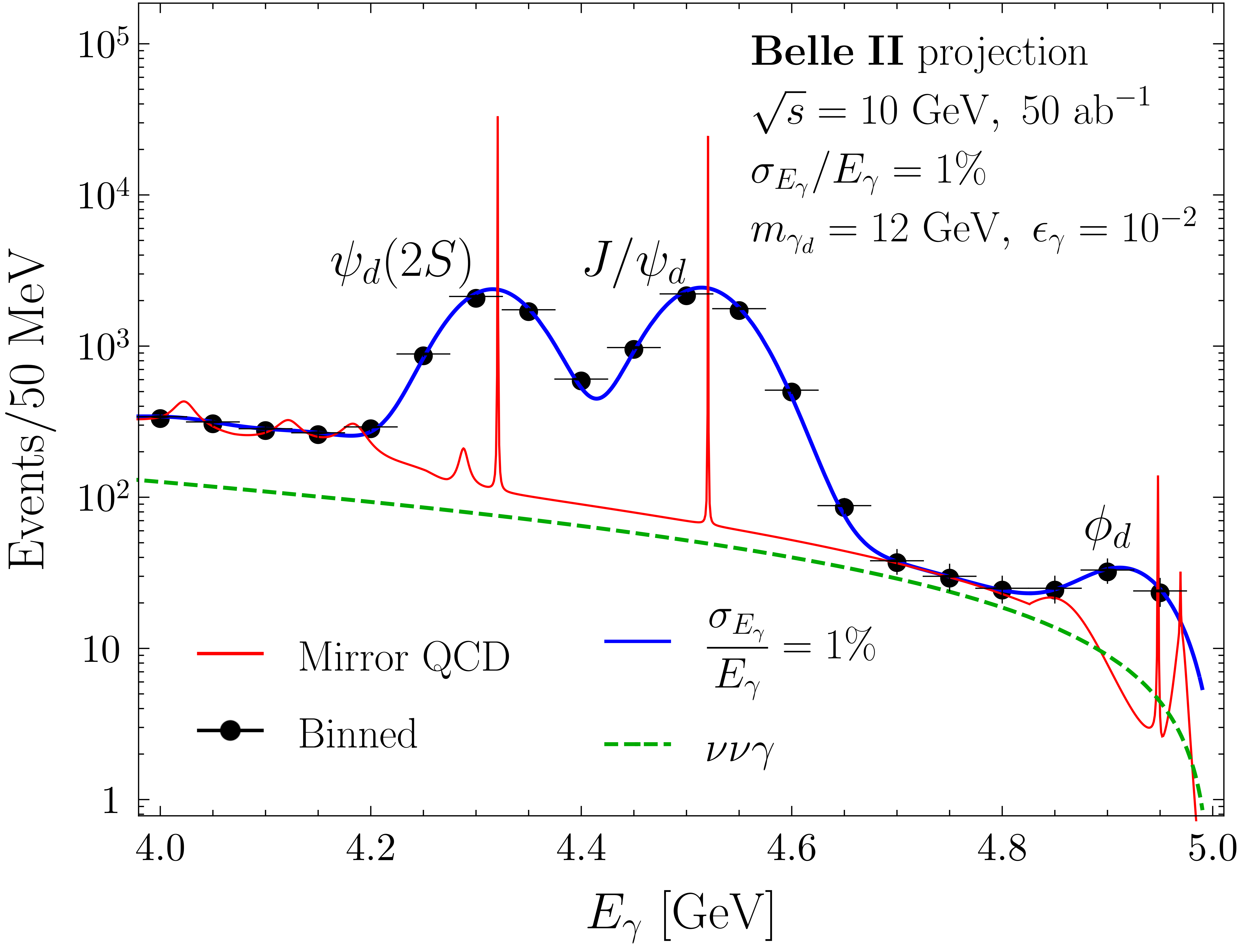
$$E_\gamma = \frac{\sqrt{s}}{2}\left(1 - \frac{M_{\rm inv}^2}{s}\right)$$



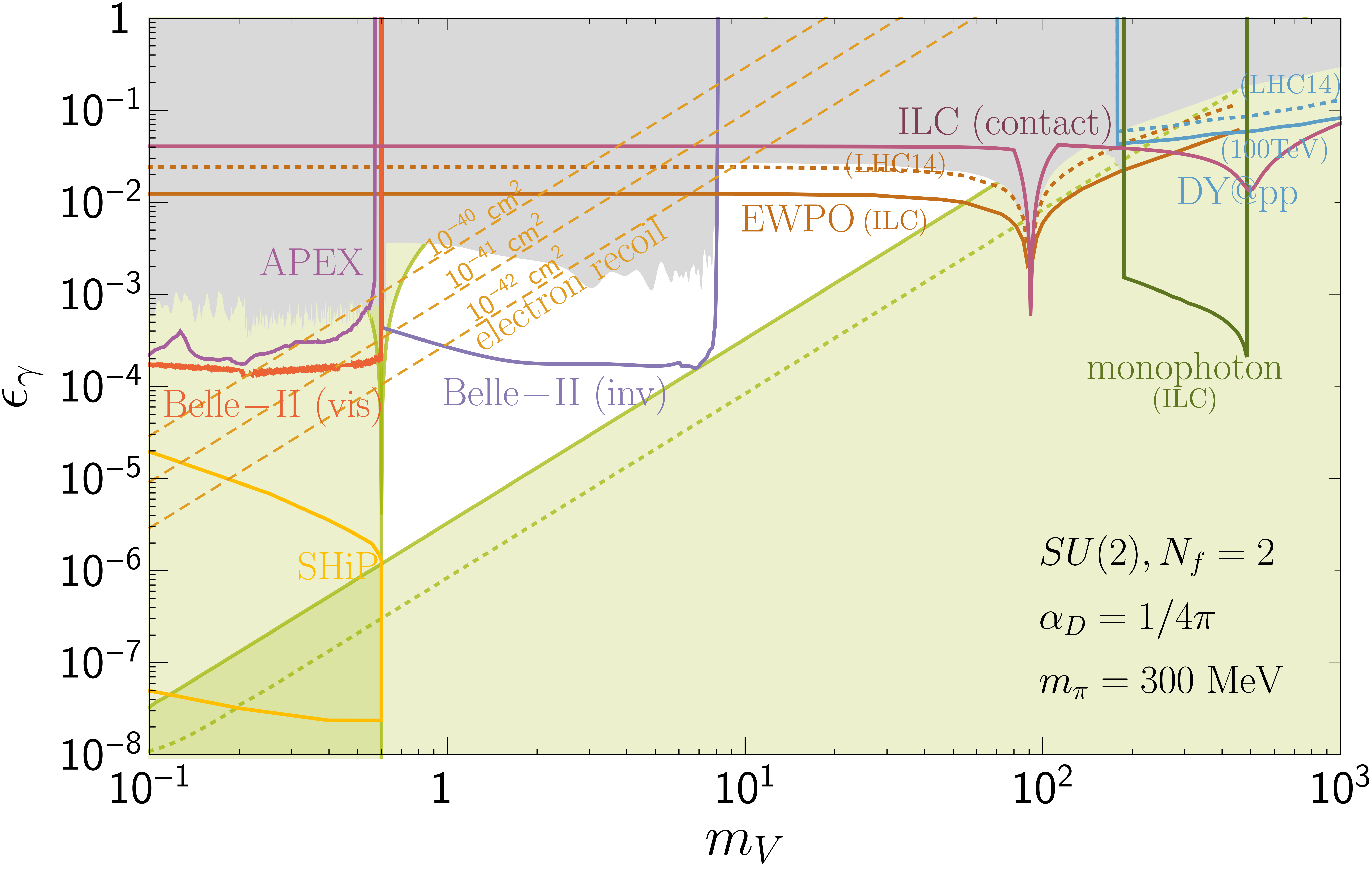
Belle II projection
$\sqrt{s} = 10$ GeV, 50 ab^{-1}
$\sigma_{E_\gamma}/E_\gamma = 1\%$
$m_{\gamma_d} = 3$ GeV, $\epsilon_\gamma = 8 \times 10^{-4}$
γ_d
Events/100 MeV
E_γ [GeV]
Dark sector
Binned
$\frac{\sigma_{E_\gamma}}{E_\gamma} = 1\%$
$\nu\nu\gamma$
10^5
10^4
10^3
10^2
2.0
2.5
3.0
3.5
4.0
4.5
5.0



BES III projection
$\sqrt{s} = 4$ GeV, 100 fb^{-1}
$\sigma_{E_\gamma}/E_\gamma = 2\%$
$m_{\gamma_d} = 3$ GeV, $\epsilon_\gamma = 8 \times 10^{-4}$
Dark sector
Binned
$\frac{\sigma_{E_\gamma}}{E_\gamma} = 2\%$
$\nu\nu\gamma$
Events/40 MeV
E_γ [GeV]
10^3
10^2
10
1
0.1
1.0
1.2
1.4
1.6
1.8
2.0

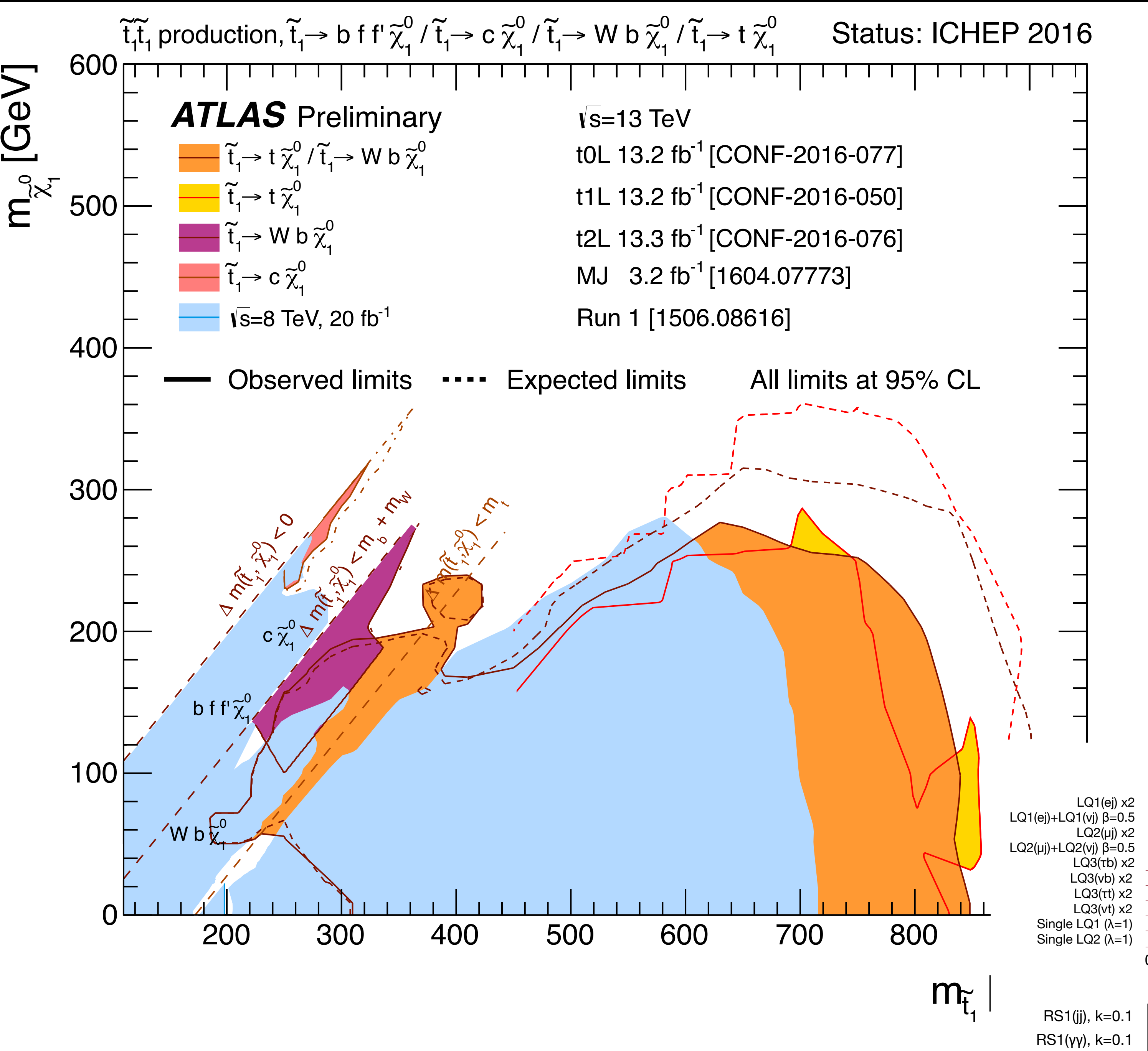


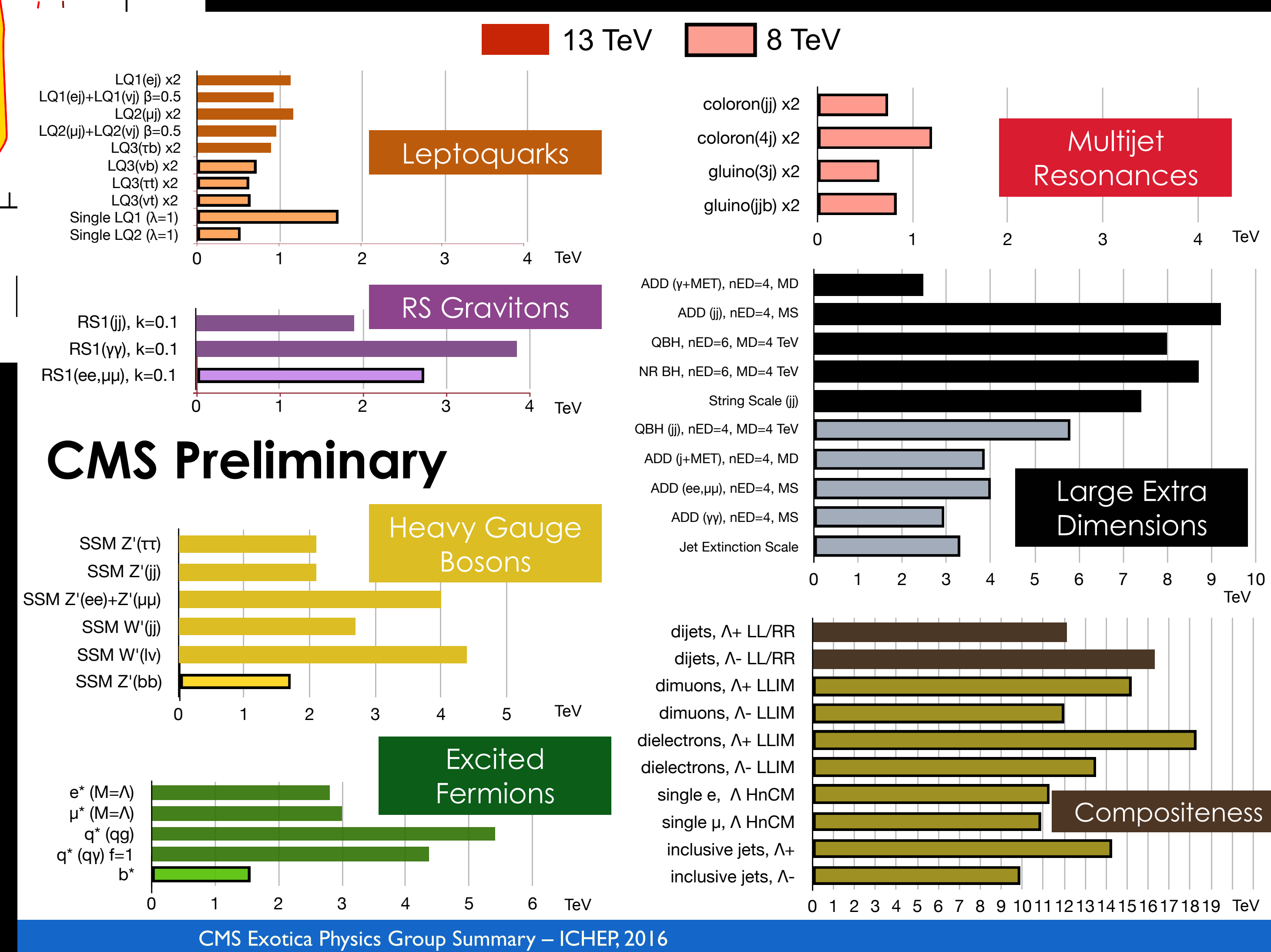
Belle II projection
$\sqrt{s} = 10$ GeV, 50 ab^{-1}
$\sigma_{E_\gamma}/E_\gamma = 1\%$
$m_{\gamma_d} = 12$ GeV, $\epsilon_\gamma = 10^{-2}$
$\psi_d(2S)$
J/ψ_d
ϕ_d
Mirror QCD
Binned
$\frac{\sigma_{E_\gamma}}{E_\gamma} = 1\%$
$\nu\nu\gamma$
Events/50 MeV
E_γ [GeV]
10^5
10^4
10^3
10^2
10
1
4.0
4.2
4.4
4.6
4.8
5.0



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

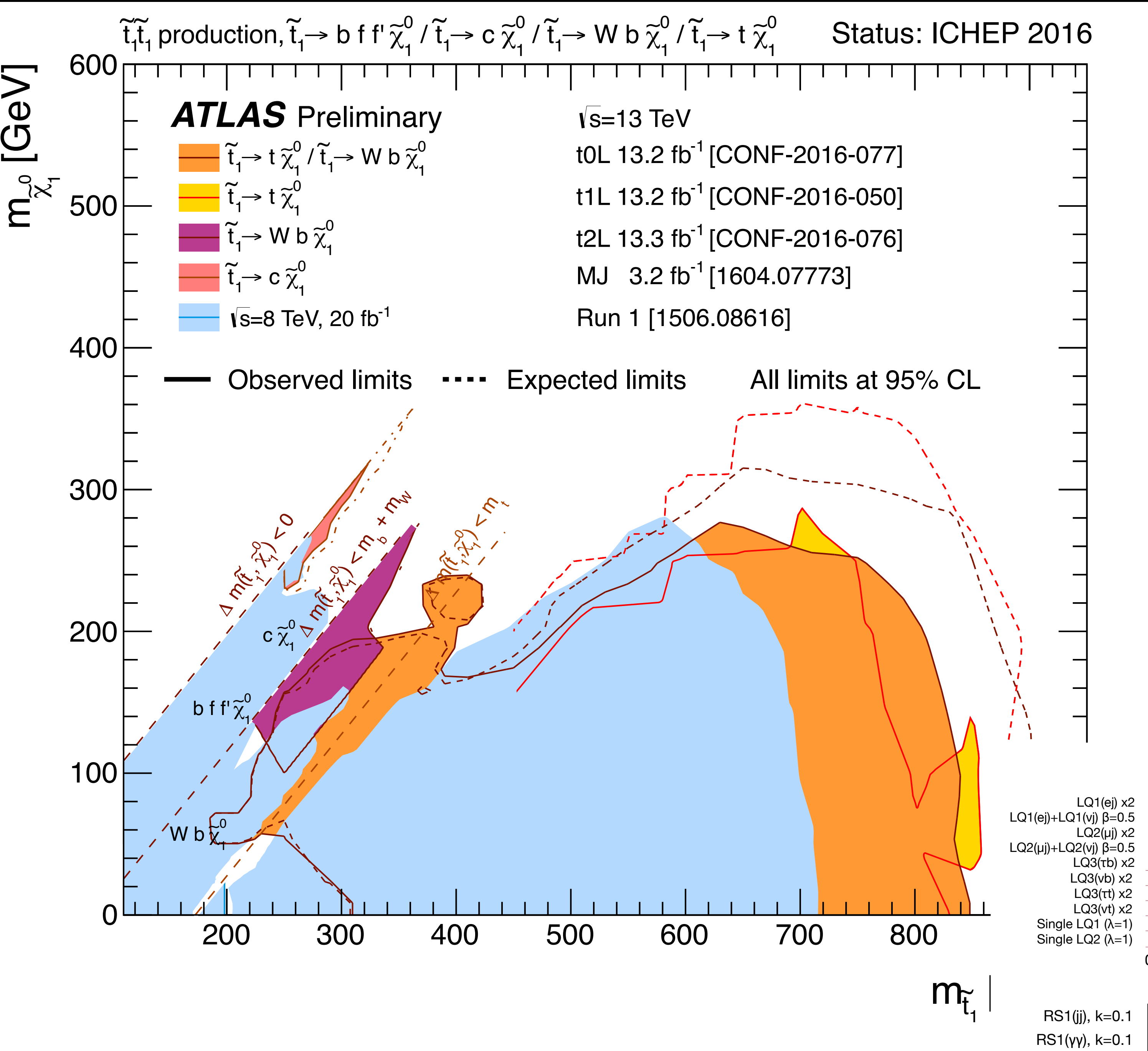
Back to TeV

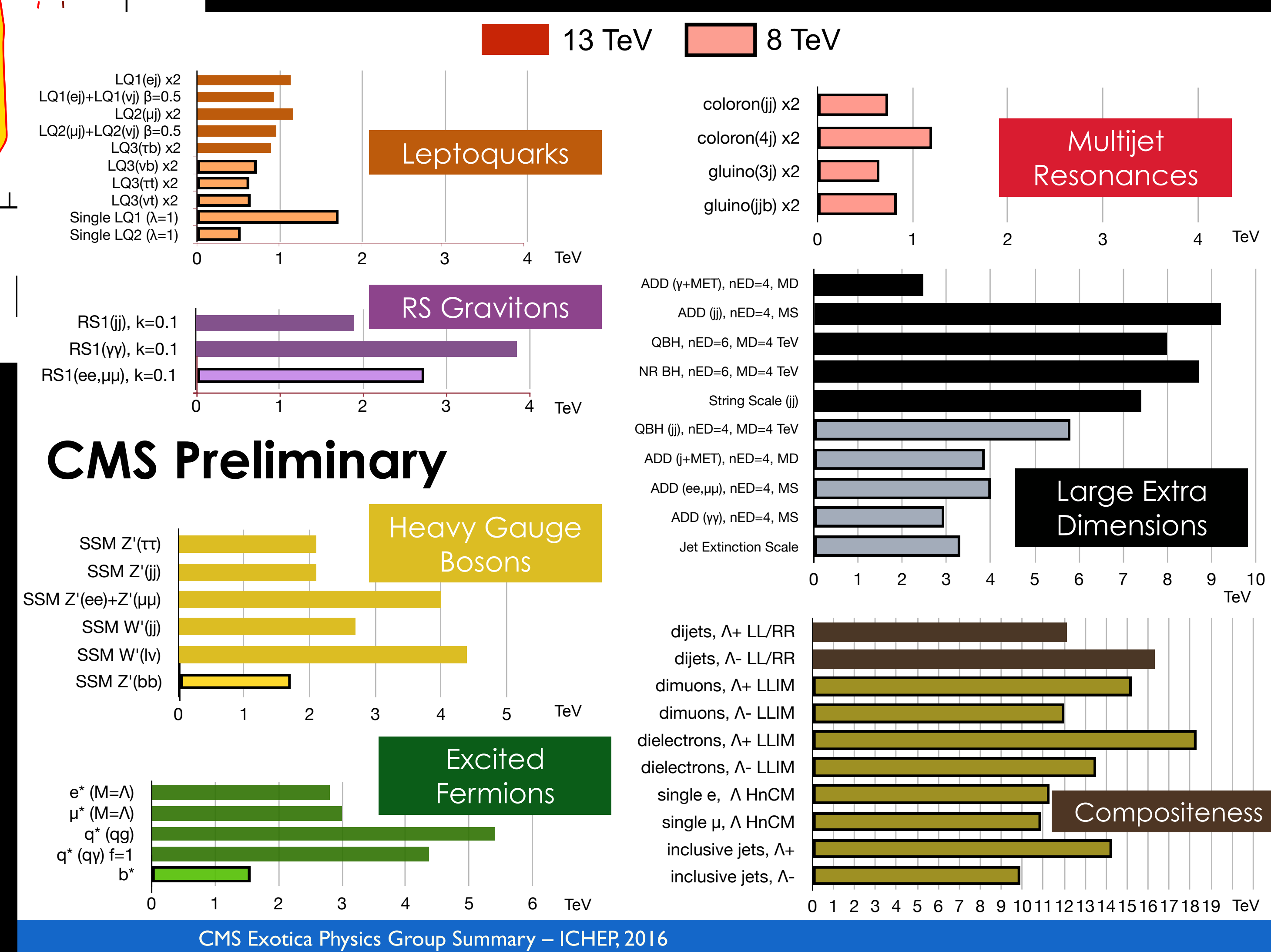




no sign of new physics that explains hierarchy problem!

LHC excludes mostly colored particles





no sign of
new physics
that explains
hierarchy problem!

Twin Higgs

- Take two mirror copies of the SM:

$$(SM_A) \times (SM_B)$$

Z_2 An exchange symmetry. $A \leftrightarrow B$.

- Assume Higgs potential has an SU(4) or SO(8) global symmetry in the UV.

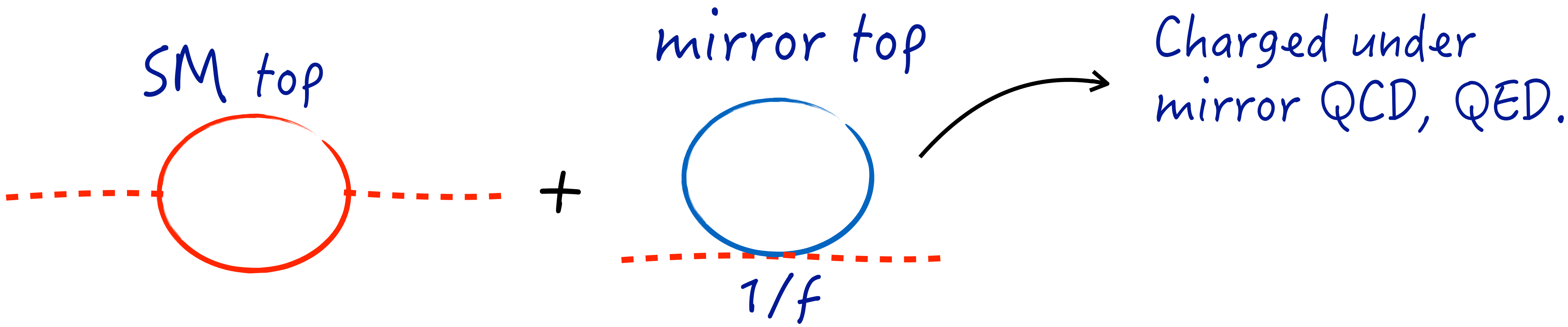
- Take a small hierarchy of Higgs vevs:

$$\langle H_A \rangle = v \qquad \langle H_B \rangle = f \qquad \text{with } v < f.$$

Chacko, Goh, RH (2005)

Twin Higgs

- All NP within LHC reach is SM neutral.
- PNGB Higgs, cancelation ...



Roni Harnik and Zackaria Chacko, JHU workshop 2017 in Budapest

Twin Higgs

- degenerate *u*, *d*, *s*, *c*, *b*, no CKM mixing
  - SU(5) flavor symmetry
- Make all leptons > GeV
  - charged pions don't decay by *W*-boson
- hyper charge assignment: $Y-(B-L)/2$
  - anomaly-free
  - all quarks and leptons have charge ±1/2
  - neutral pions don't decay into $\gamma\gamma$

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- hyper charge assignment: $Y-(B-L)/2$
  - anomaly-free
  - all quarks and leptons have charge ±1/2
  - neutral pions don't decay into γ γ

Can solve hierarchy problem, too!

Conclusion

- surprisingly 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
- May also solve the hierarchy problem