Dark Colors

Hitoshi Murayama (Berkeley, Kavli IPMU)

RECONNECT 2020 May 26, 2020

hierarchy problem

There must be new particles discoverable at the LHC!

The New York Times

July 23, 2011

The Other Half of the Universe Discovered

Geneva, Switzerland

Squarks

J=0?

The following data are averaged over all light flavors, presumably u, d, s, c with both chiralities. For flavor-tagged data, see listings for Stop and Sbottom. Most results assume minimal supergravity, an untested hypothesis with only five parameters. Alternative interpretation as extra dimensional particles is possible. See KK particle listing.

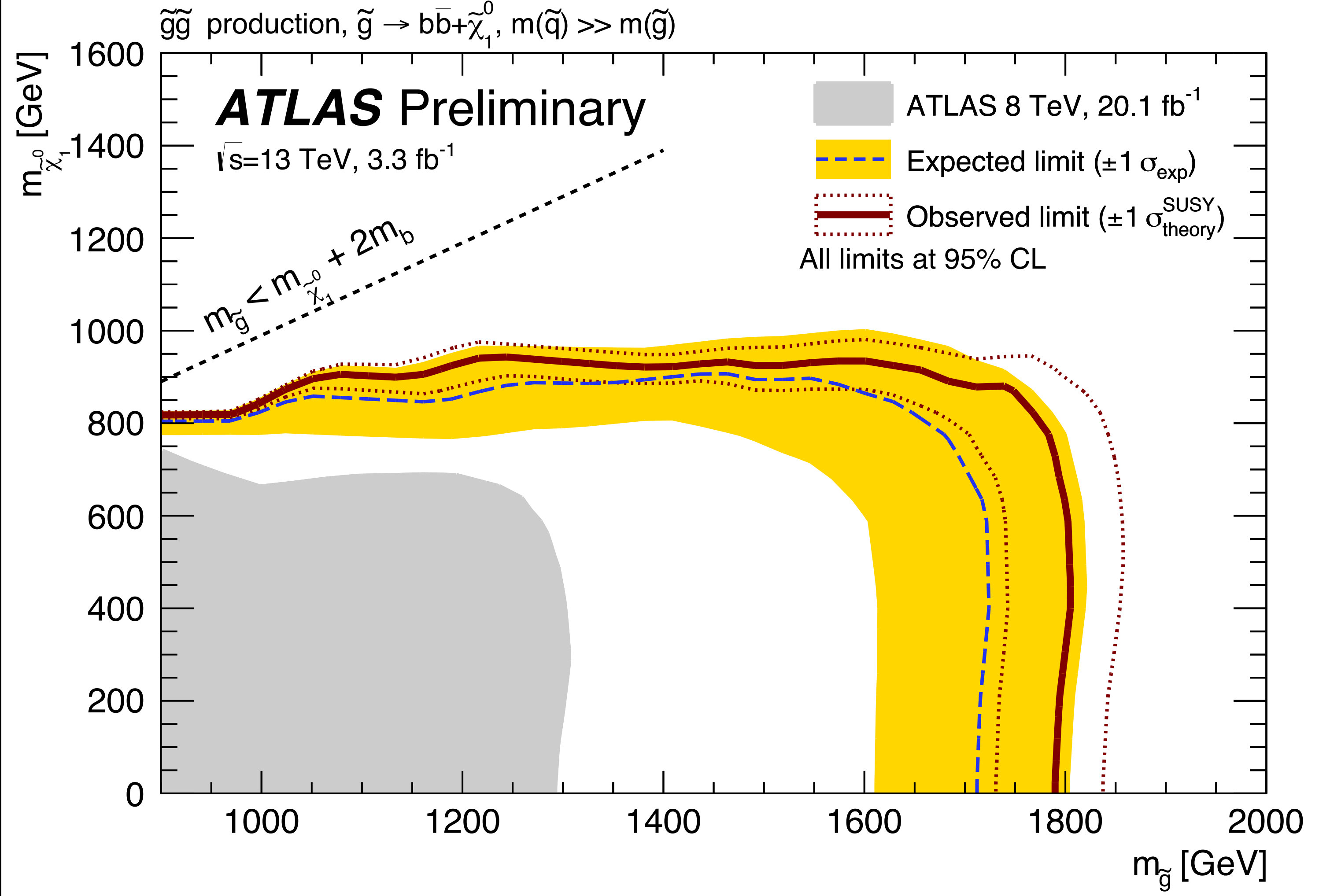
SQUARK MASS

VALUE (GeV)	DOCUMENT ID	TECN	COMMENT
538±10	**OUR FIT**		**mSUGRA assumptions**
532±11	[1]ABBIENDI 11D	CMS	Missing ET with mSUGRA assumptions
541±14	[2]ADLER 11O	ATLAS	Missing ET with mSUGRA assumptions
• • • We do not use the following data for averages, fits, limits, etc • • •			
652±105	[3]ABBIENDI 11K	CMS	extended mSUGRA with 5 more parameters

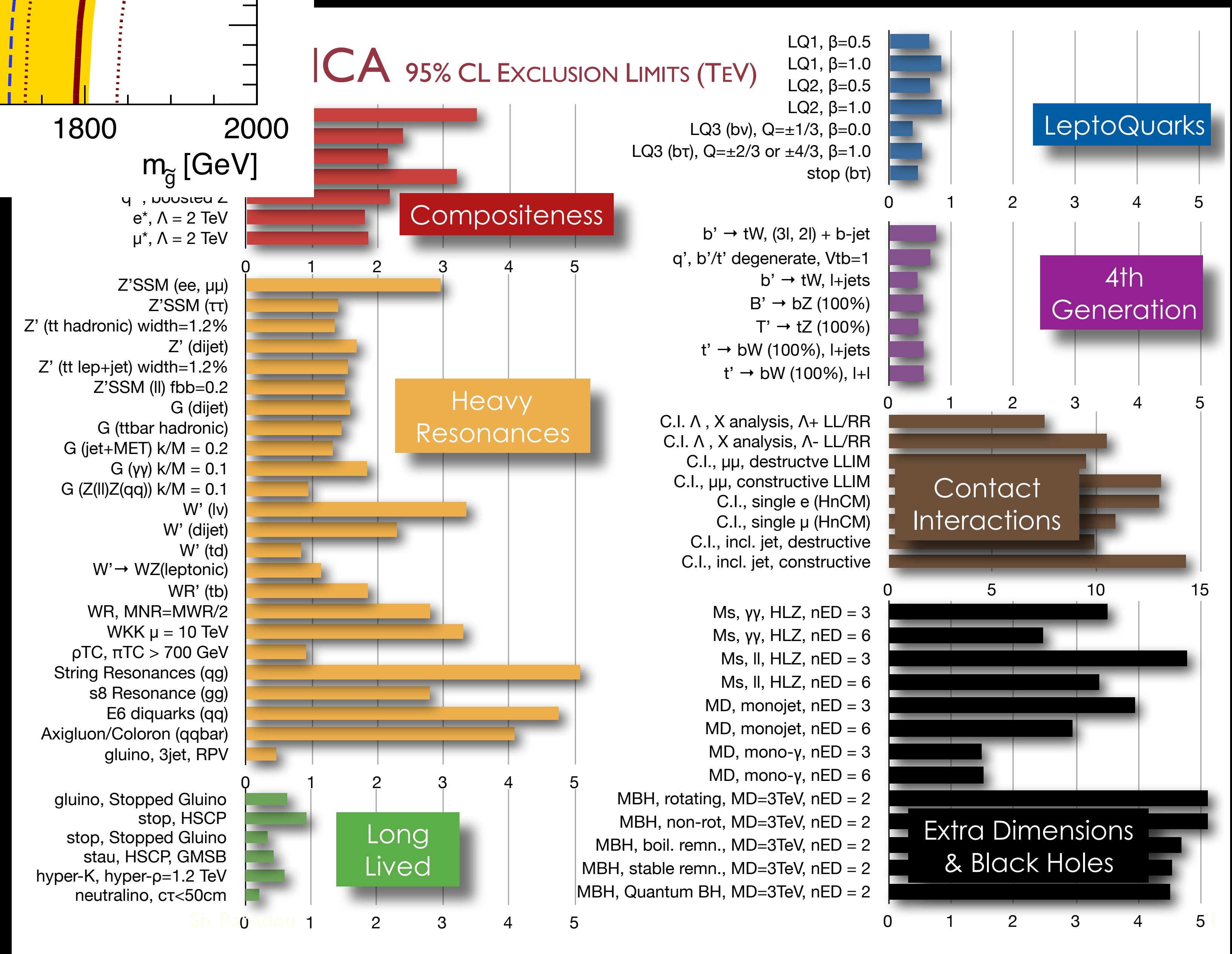
[1]ABBIENDI 11D assumes minimal supergravity in the fits to the data of jets and missing energies and set A_0=0 and tan$\beta = 3$. See Fig. 5 of the paper for other choices of A_0 and tanβ. The result is correlated with the gluino mass M_3. See listing for gluino.
[2]ADLER 11O uses the same set of assumptions as ABBIENDI 11D, but with tan$\beta = 5$.
[3]ABBIENDI 11K extends minimal supergravity by allowing for different scalar masses-squared for Hu, Hd, 5* and 10 scalars at the GUT scale.

SQUARK DECAY MODES

MODE	BR(%)	DOCUMENT ID	TECN	COMMENT
j+miss	32±5	ABE 10U	ATLAS	
j l+miss	73±10	ABE 10U	ATLAS	lepton universality
j e+miss	22±8	ABE 10U	ATLAS	
j μ +miss	25±7	ABE 10U	ATLAS	
q χ^+	seen	ABE 10U	ATLAS	



no sign of
new physics that
makes Higgs natural!



Five empirical evidences for physics beyond SM

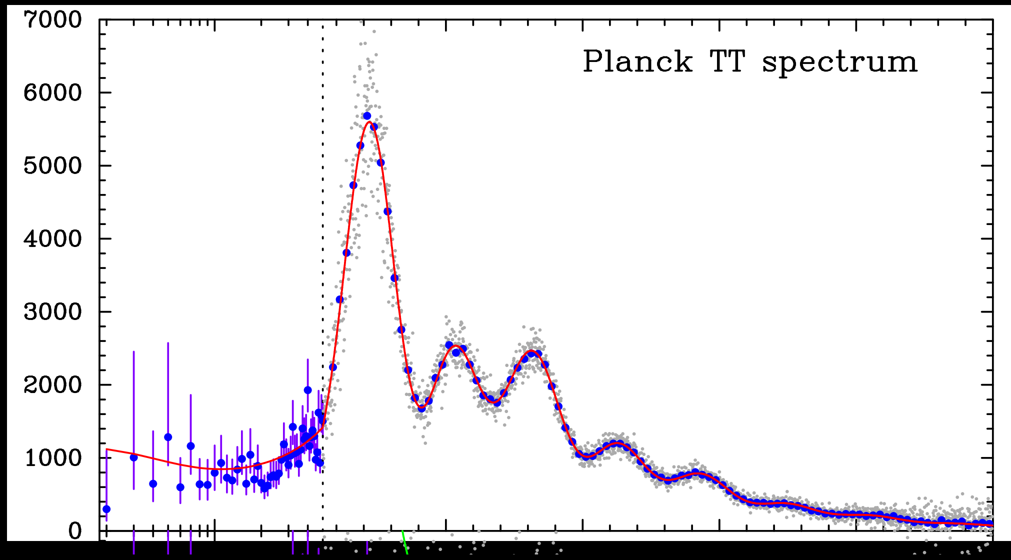
- at least five missing pieces in the SM:
  - dark matter
  - neutrino mass
  - dark energy
  - apparently acausal density fluctuations
  - baryon asymmetry

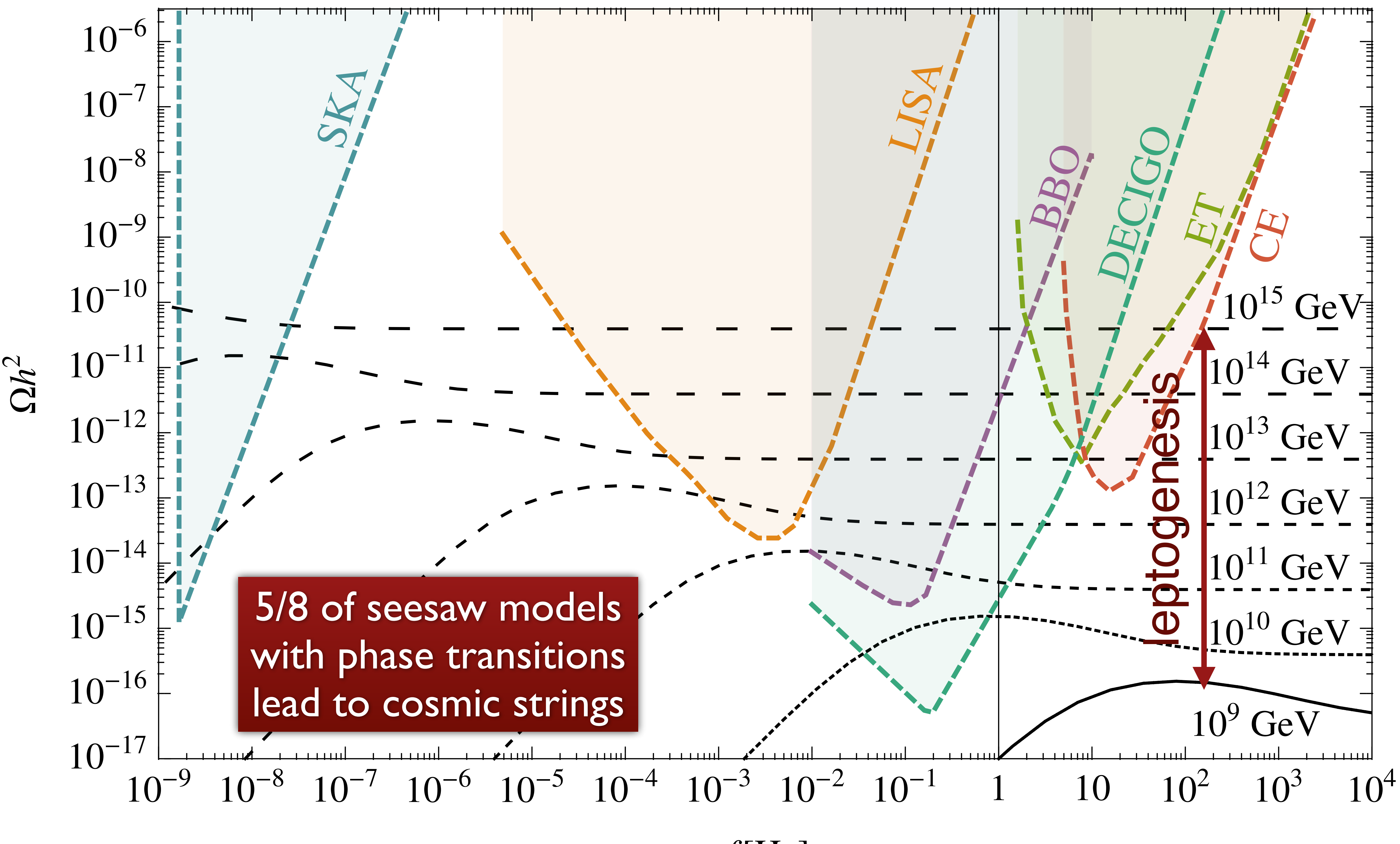
$0\nu\beta\beta$
gravitational wave

DES, HSC, DESI,
PFS, Euclid,
LSST, WFIRST

Simons Array
CMB S4
LiteBIRD

DUNE, HyperK,
LHCb, Belle II,
kaon, EDM



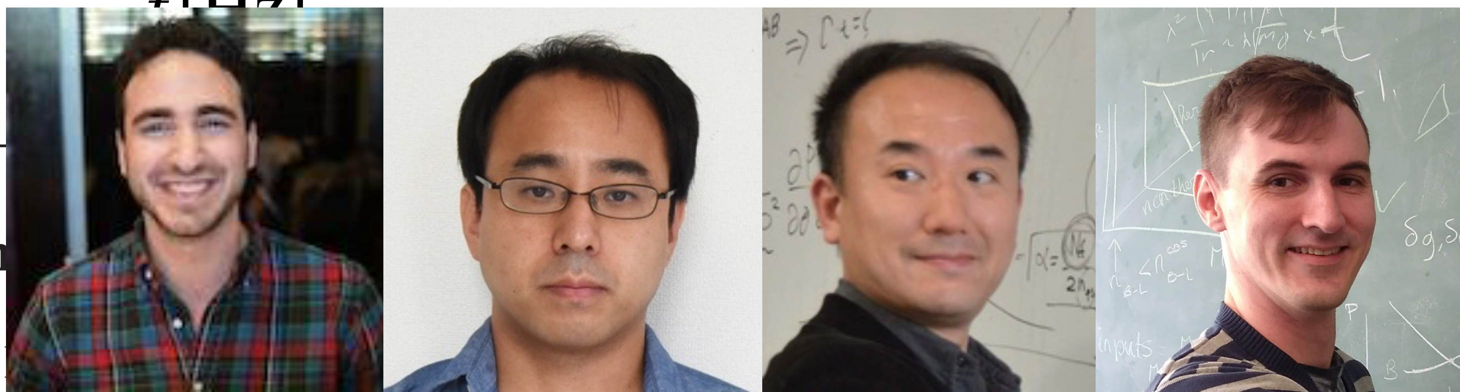


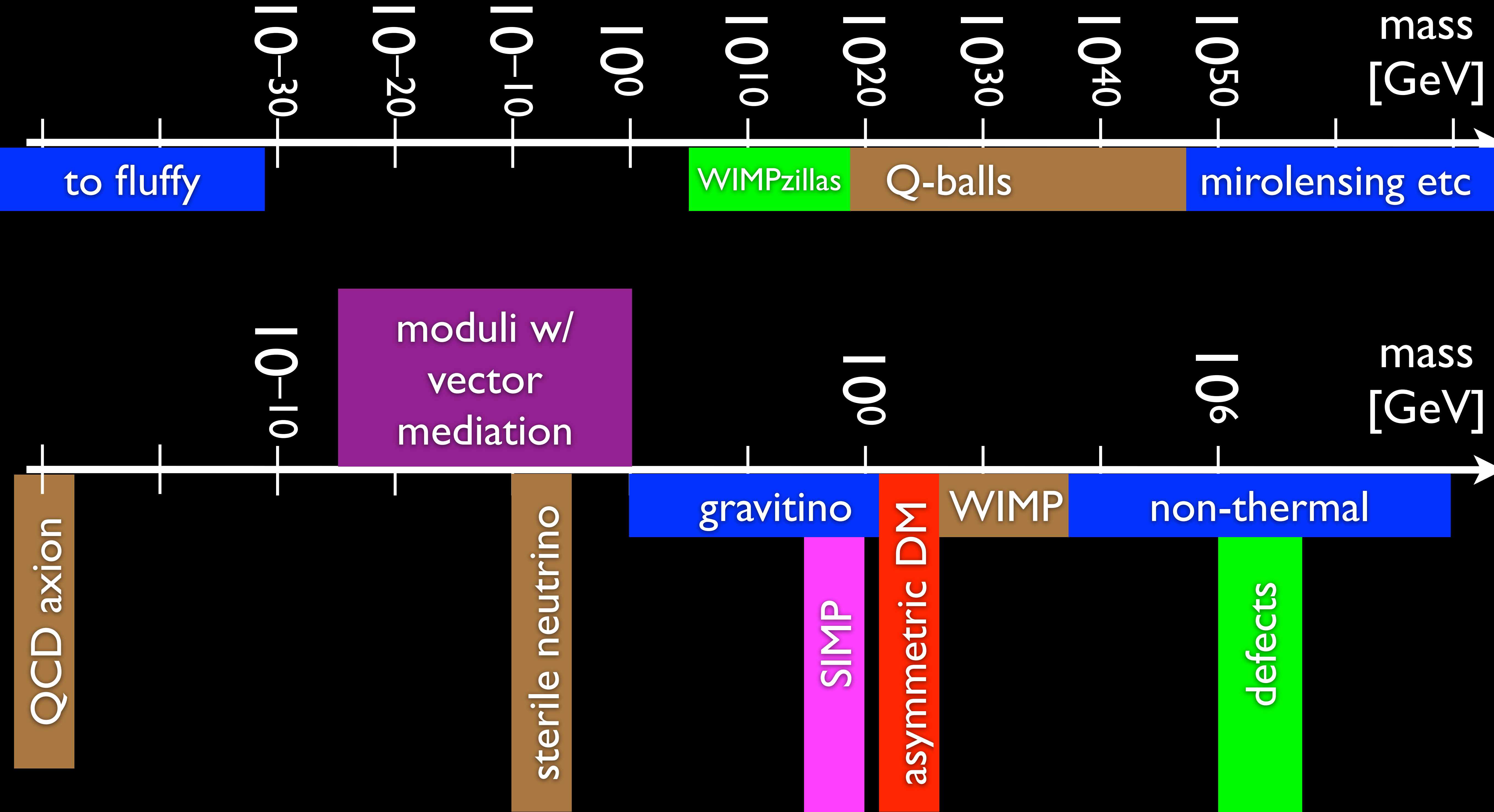
PHYSICAL REVIEW

Editors' Suggestion Featured in Physics

Testing the Seesaw Mechanism an

Jeff A. Dror,[1,2,*] Takashi Hiramatsu,[3,†] Kazunori





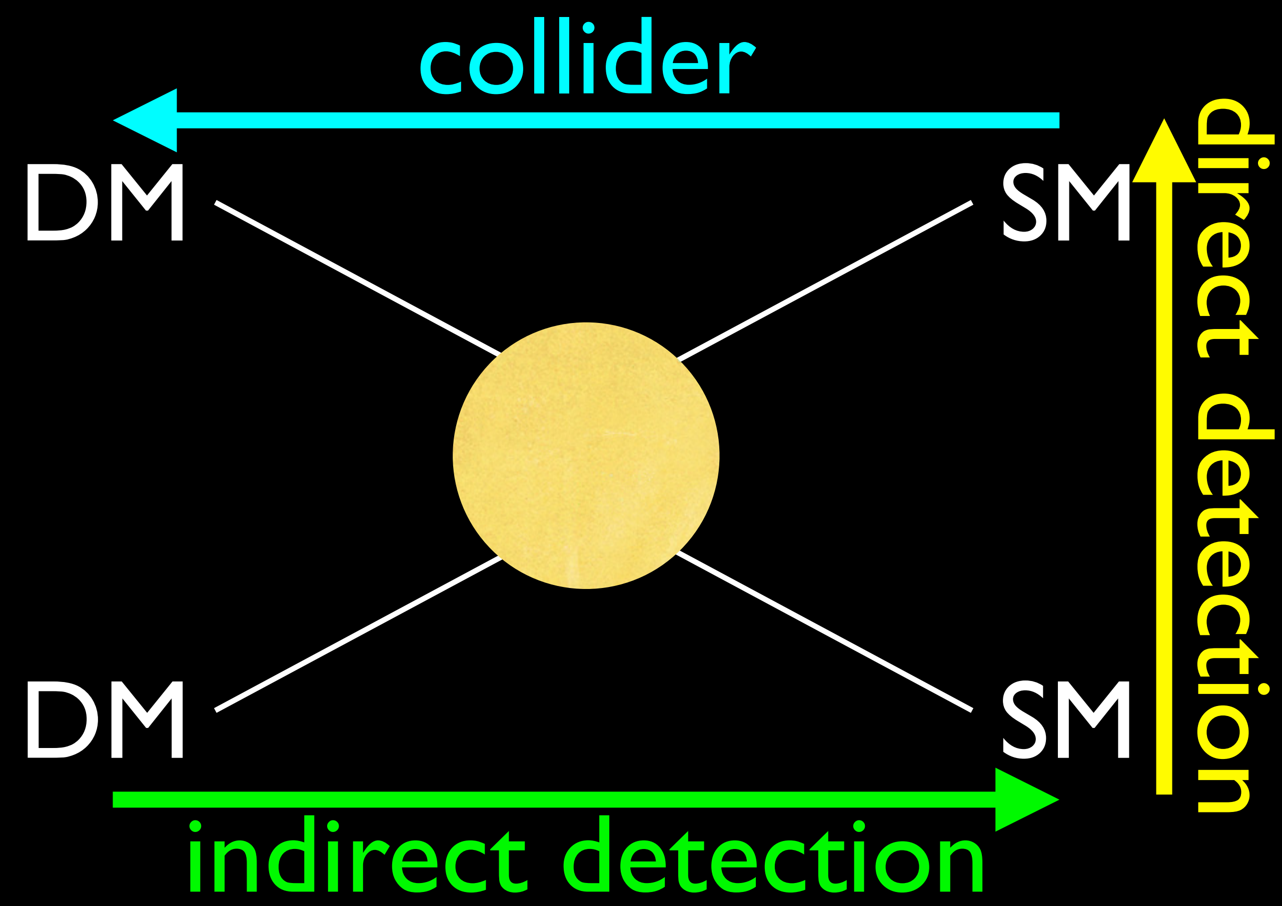
Can’t do justice to many many ideas in the literature!

old sociology

- We (community) used to think
  - must solve naturalness problems in 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 well established in 80's

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

WIMP Miracle



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

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

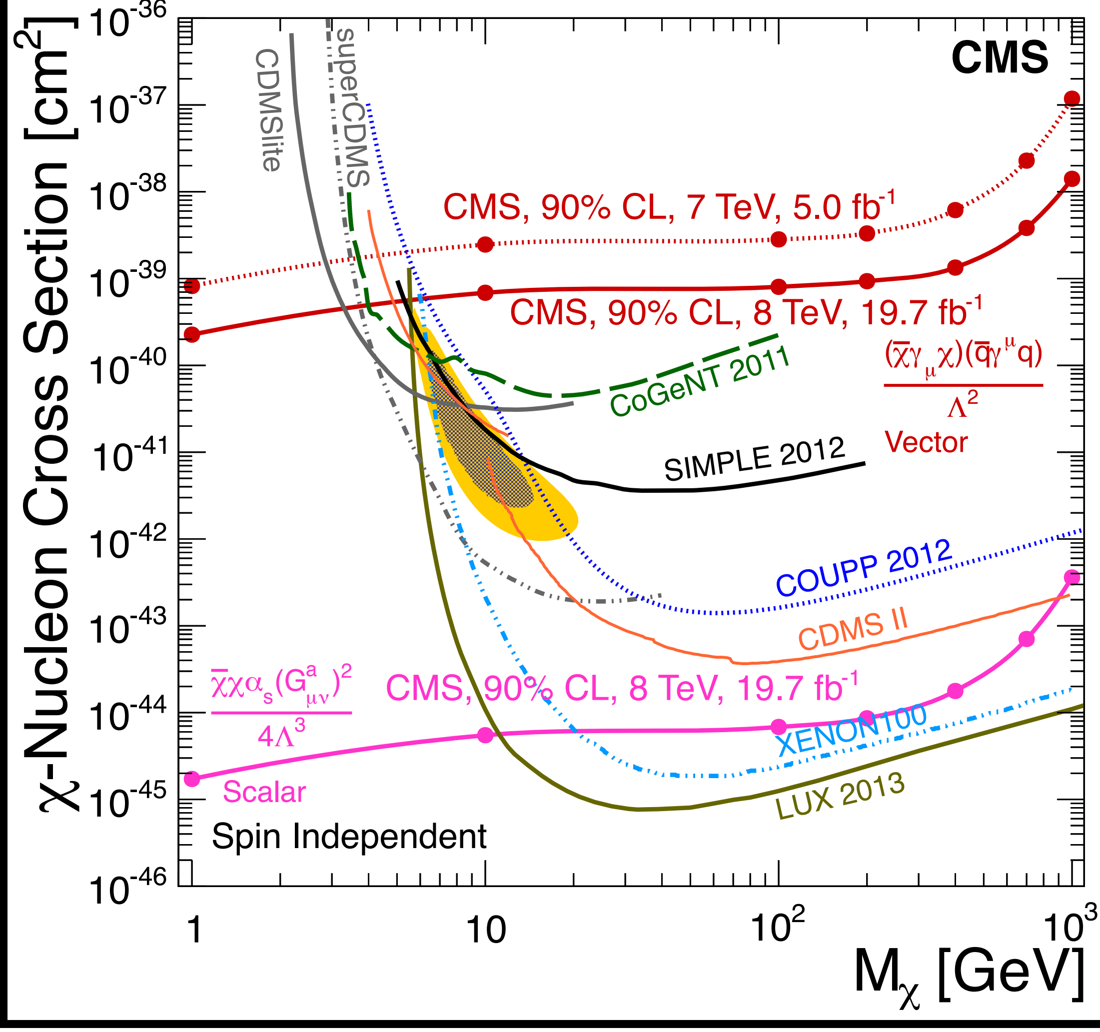
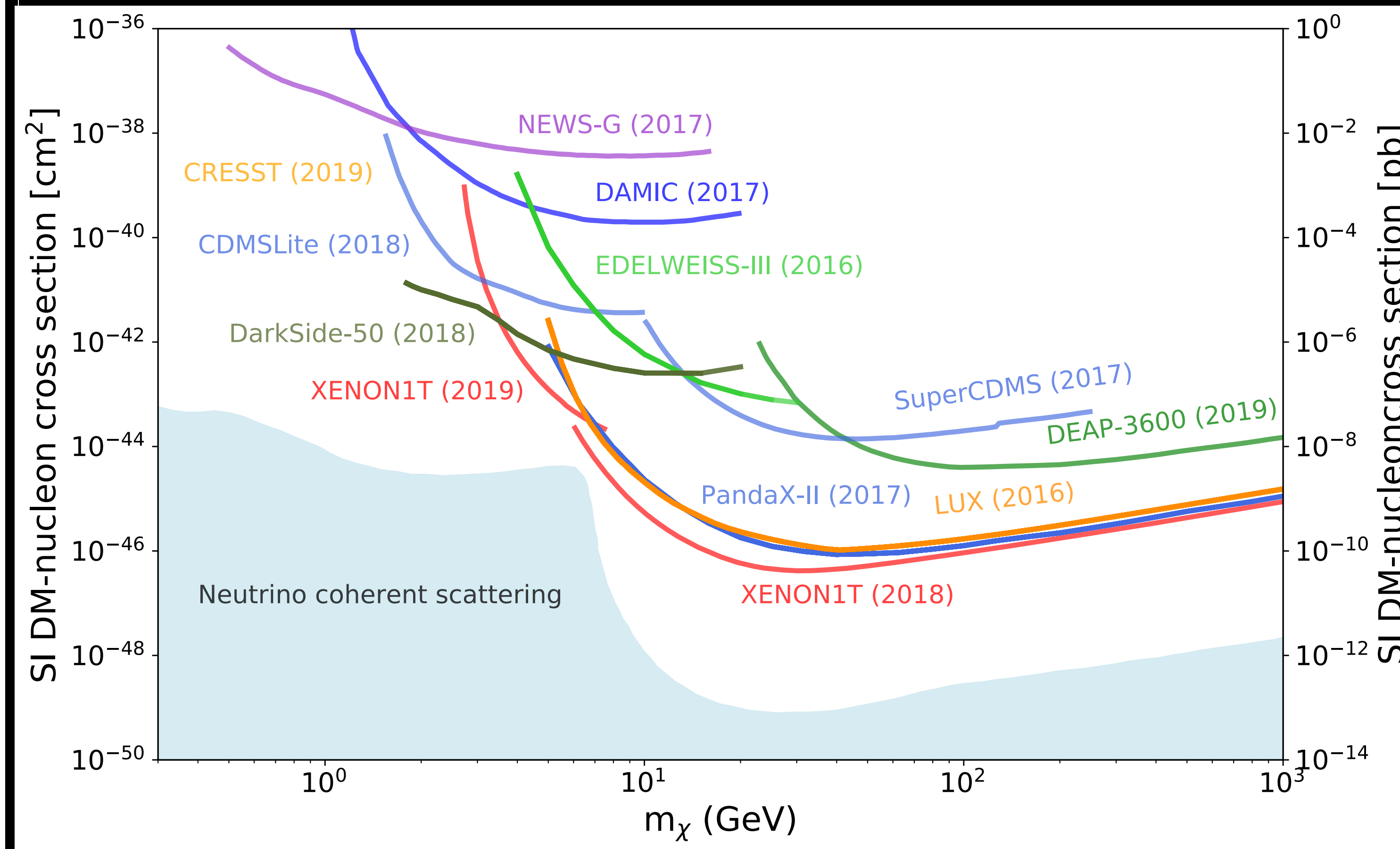
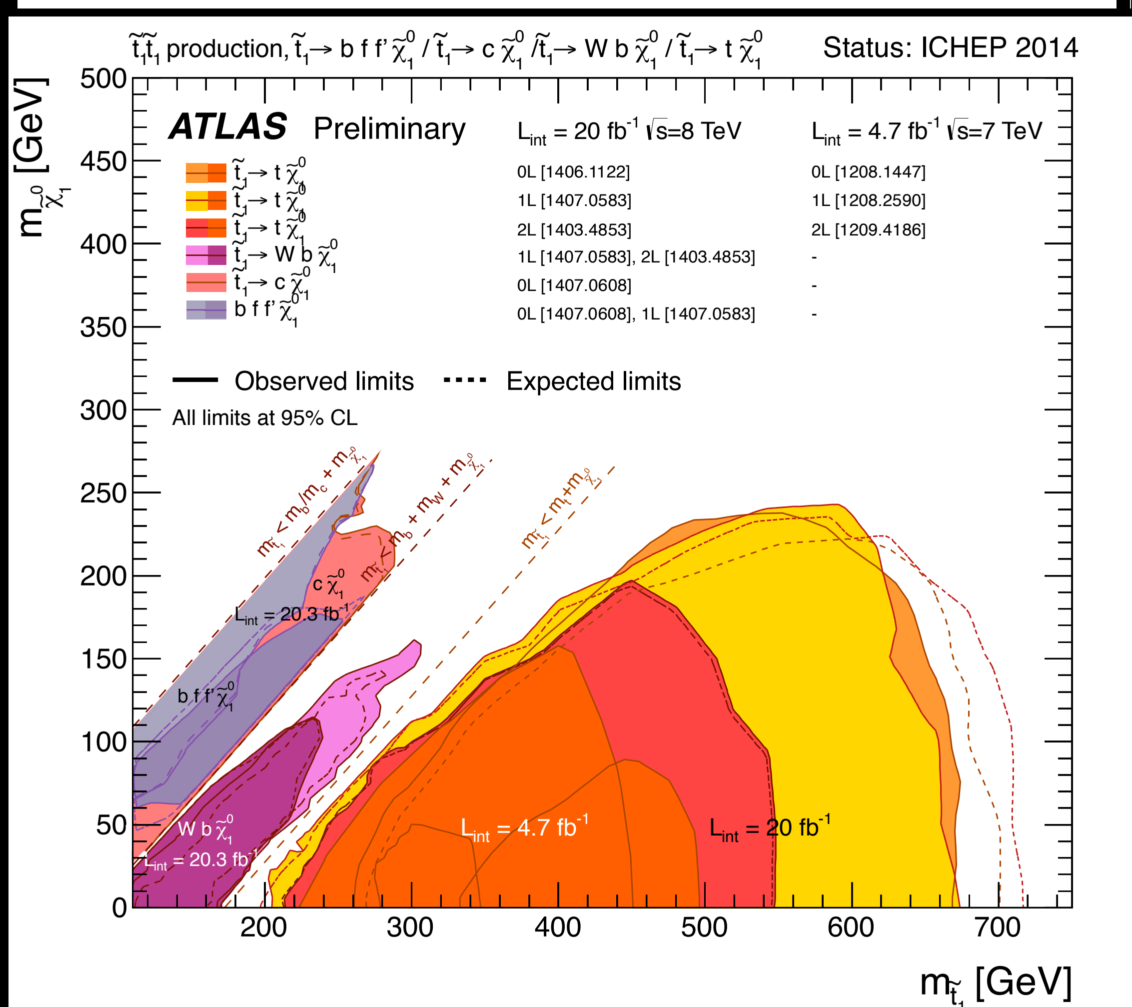
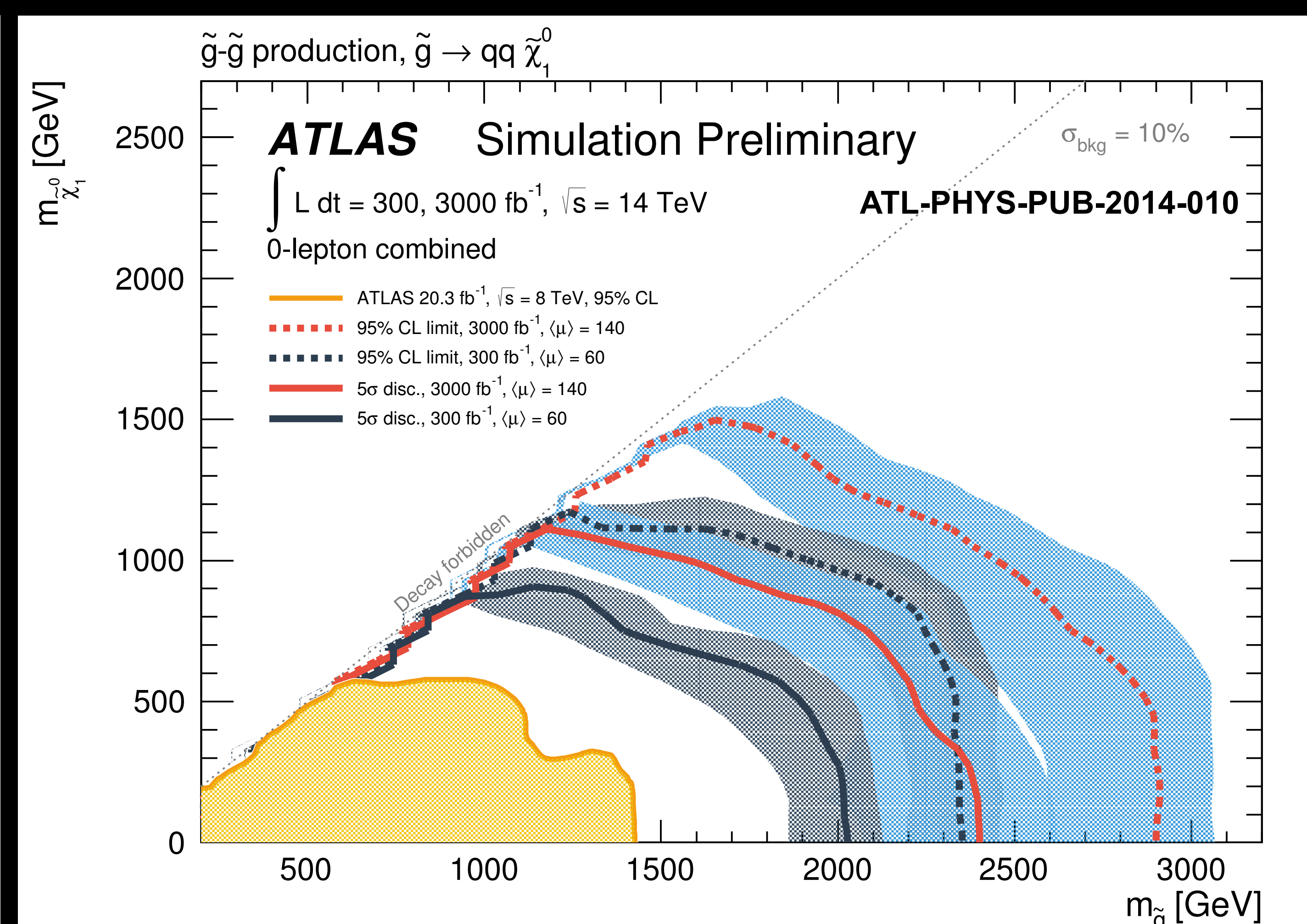
$$m \approx 300 \text{ GeV}$$

"weak" coupling
"weak" mass scale

$\Rightarrow$ correct abundance

We want new particles for naturalness anyway

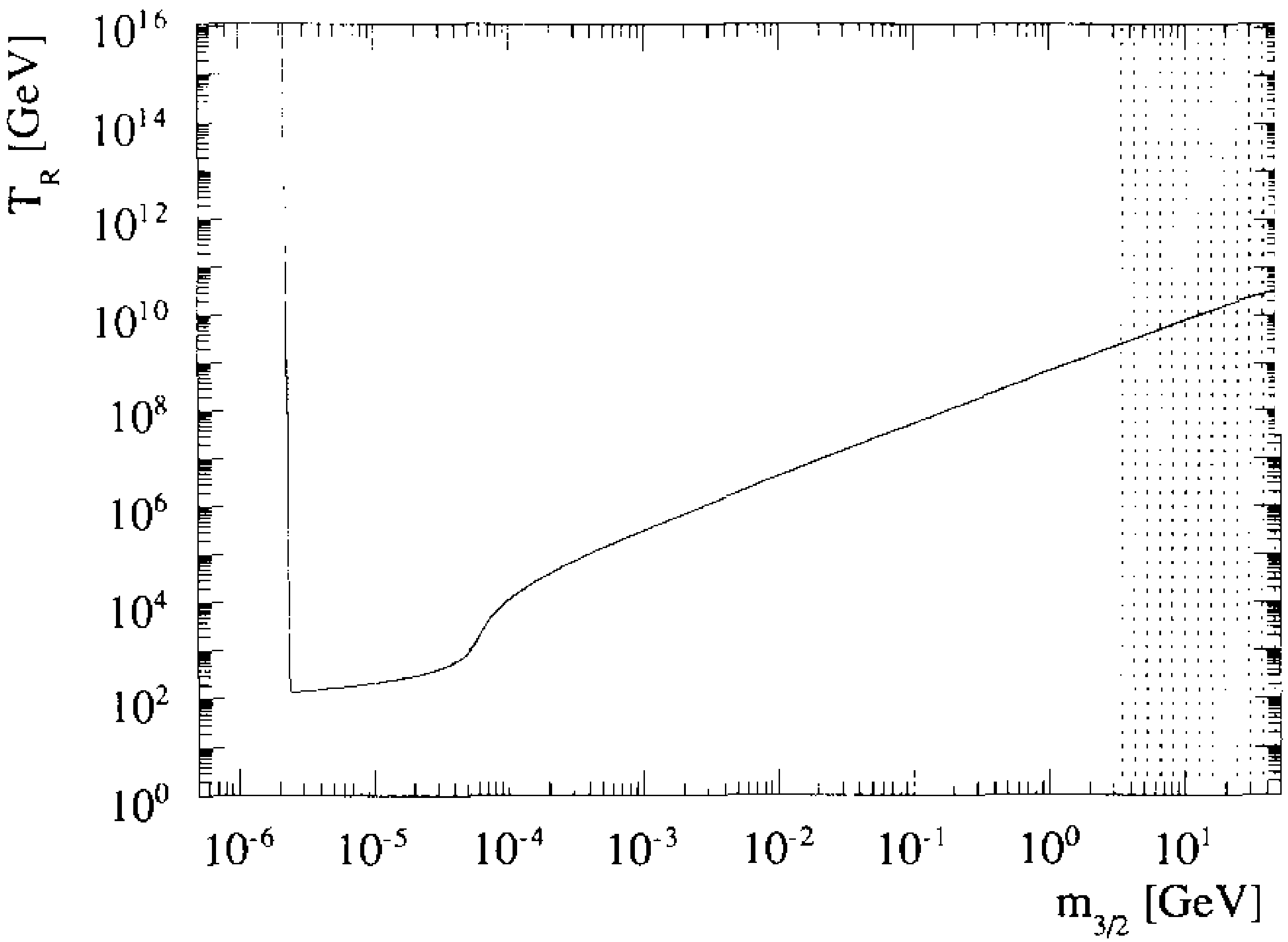
Miracle^2


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

SI DM-nucleon cross section [cm²]
SI DM-nucleoncross section [pb]
m_χ (GeV)
NEWS-G (2017)
CRESST (2019)
DAMIC (2017)
CDMSLite (2018)
EDELWEISS-III (2016)
DarkSide-50 (2018)
XENON1T (2019)
SuperCDMS (2017)
DEAP-3600 (2019)
PandaX-II (2017)
LUX (2016)
Neutrino coherent scattering
XENON1T (2018)

Status: ICHEP 2014
ATLAS Preliminary
Observed limits
Expected limits
All limits at 95% CL
0L [1406.1122]
1L [1407.0583]
2L [1403.4853]
1L [1407.0583], 2L [1403.4853]
0L [1407.0608]
0L [1407.0608], 1L [1407.0583]
0L [1208.1447]
1L [1208.2590]
2L [1209.4186]
m_t̃₁ [GeV]

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

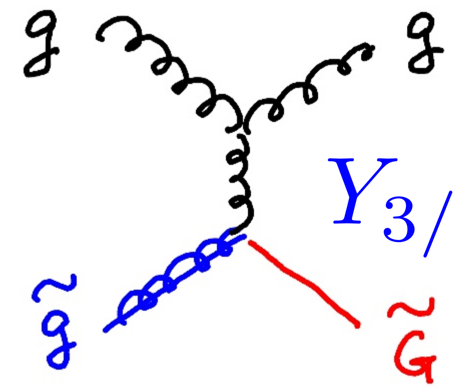
new sociology

- WIMP should be explored at least down to the neutrino floor
  - heavier? e.g., wino @ 3TeV $\Longrightarrow$CTA
- dark matter definitely exists
  - it is great if a theory also solves some particle physics problems as an *option*
- perhaps not heavier but rather lighter and weaker coupling?

freeze-in: light gravitino

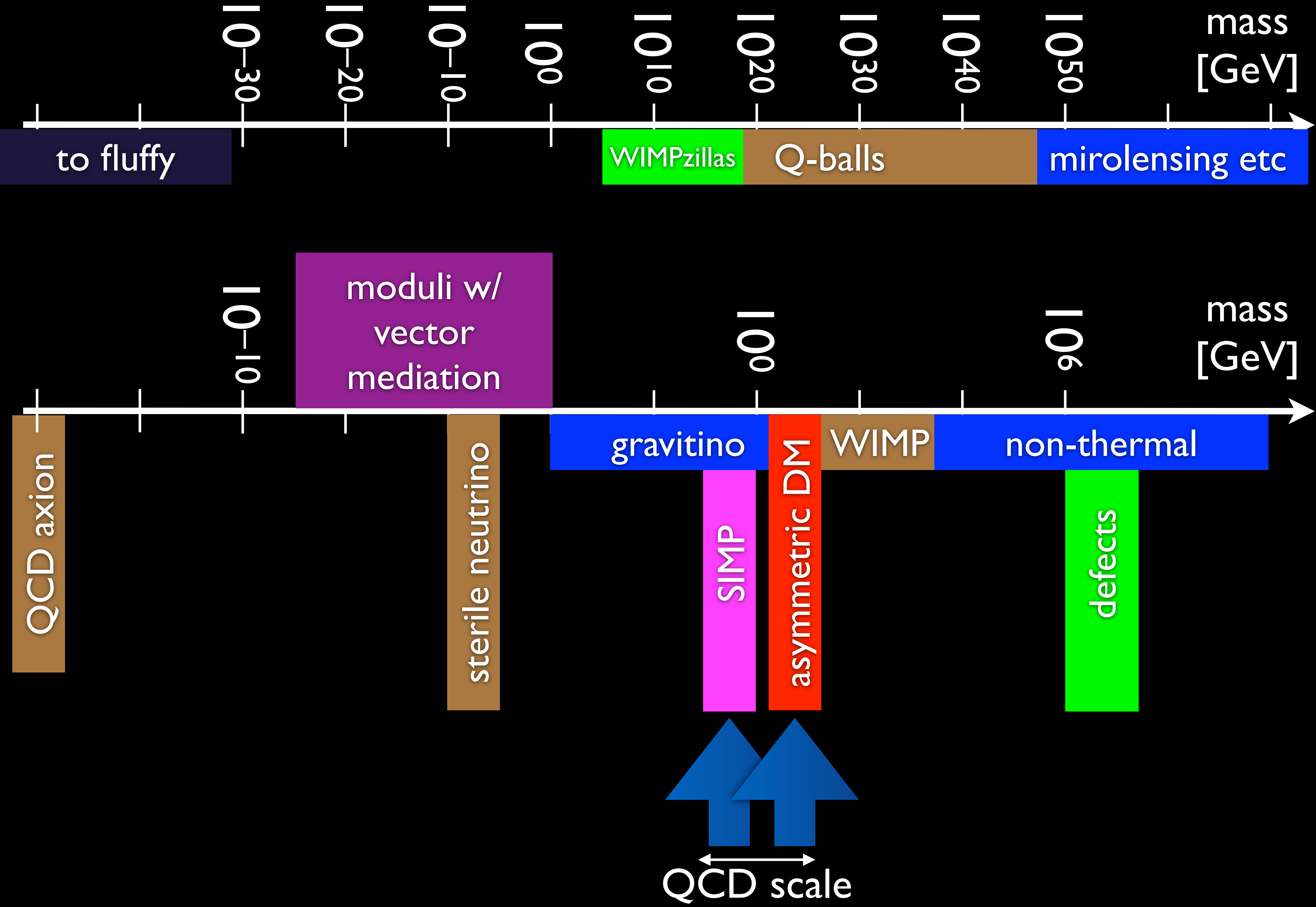


Moroi, HM, Yamaguchi, PLB 303 (1993) 389



$$Y_{3/2} = \frac{n_{3/2}}{s} \approx \frac{T_{RH}}{M_{Pl}}$$

- does not reach equilibrium
- SUSY breaking: non-perturbative dynamics
- *i.e.* SUSY QCD (ISS, IYIT, SO(10) etc)



10^{-30}
10^{-20}
10^{-10}
10^{0}
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10^{50}
mass [GeV]
to fluffy
WIMPzillas
Q-balls
mirolensing etc
moduli w/ vector mediation
10^{-10}
10^{0}
10^{6}
mass [GeV]
QCD axion
sterile neutrino
gravitino
asymmetric DM
WIMP
non-thermal
SIMP
defects
QCD scale

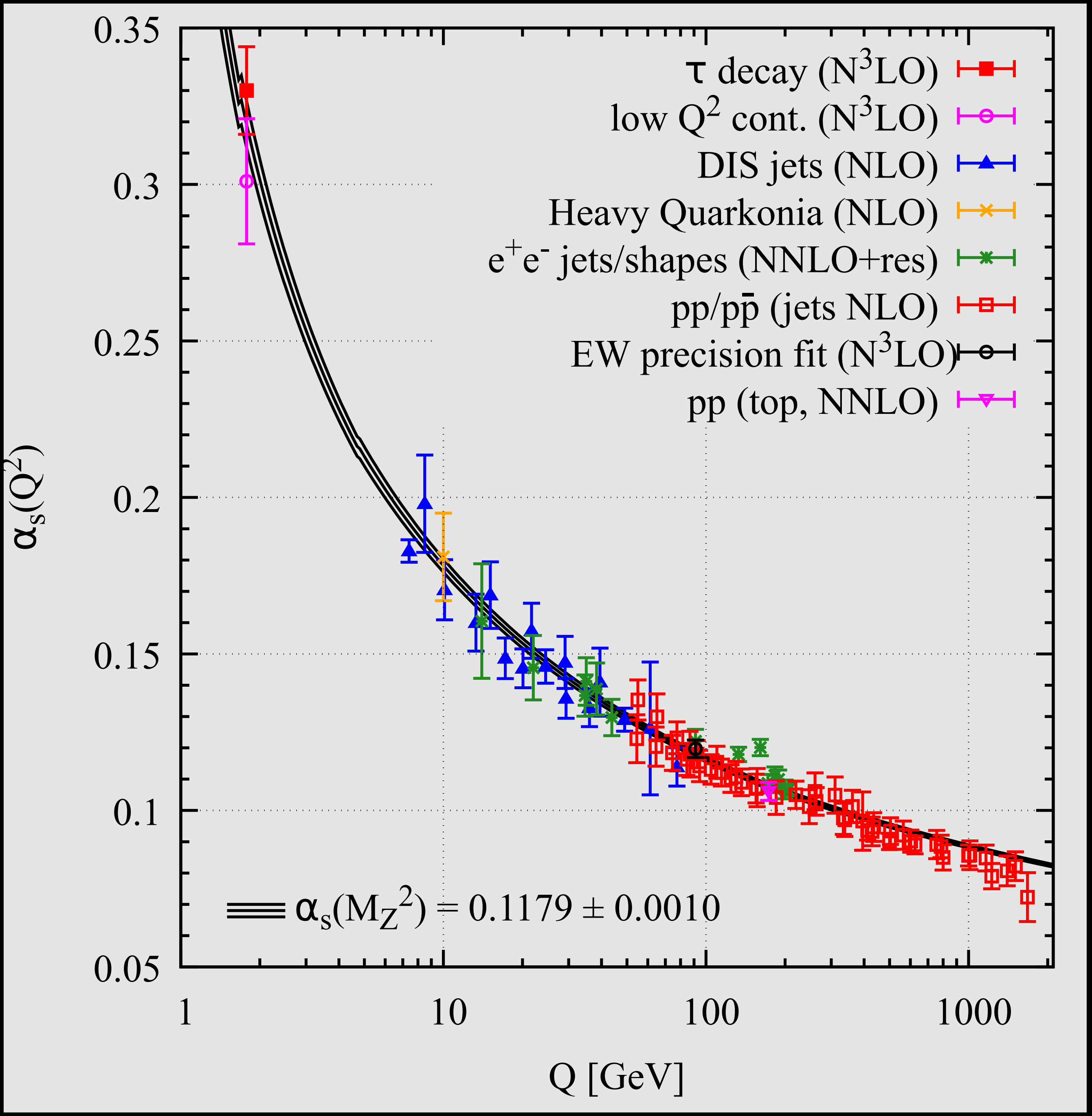
Why Dark Colors?

- QCD is *beautiful*. Nature may use it again.
- Self-interacting dark matter
  - large cross section and light dark matter. Dark QCD is perfect.
  - velocity dependence may need resonances. Dark QCD provides that.
- asymmetric dark matter
  - need to shed symmetric component. Easy for Dark QCD.
- Also hierarchy problem, baryon asymmetry

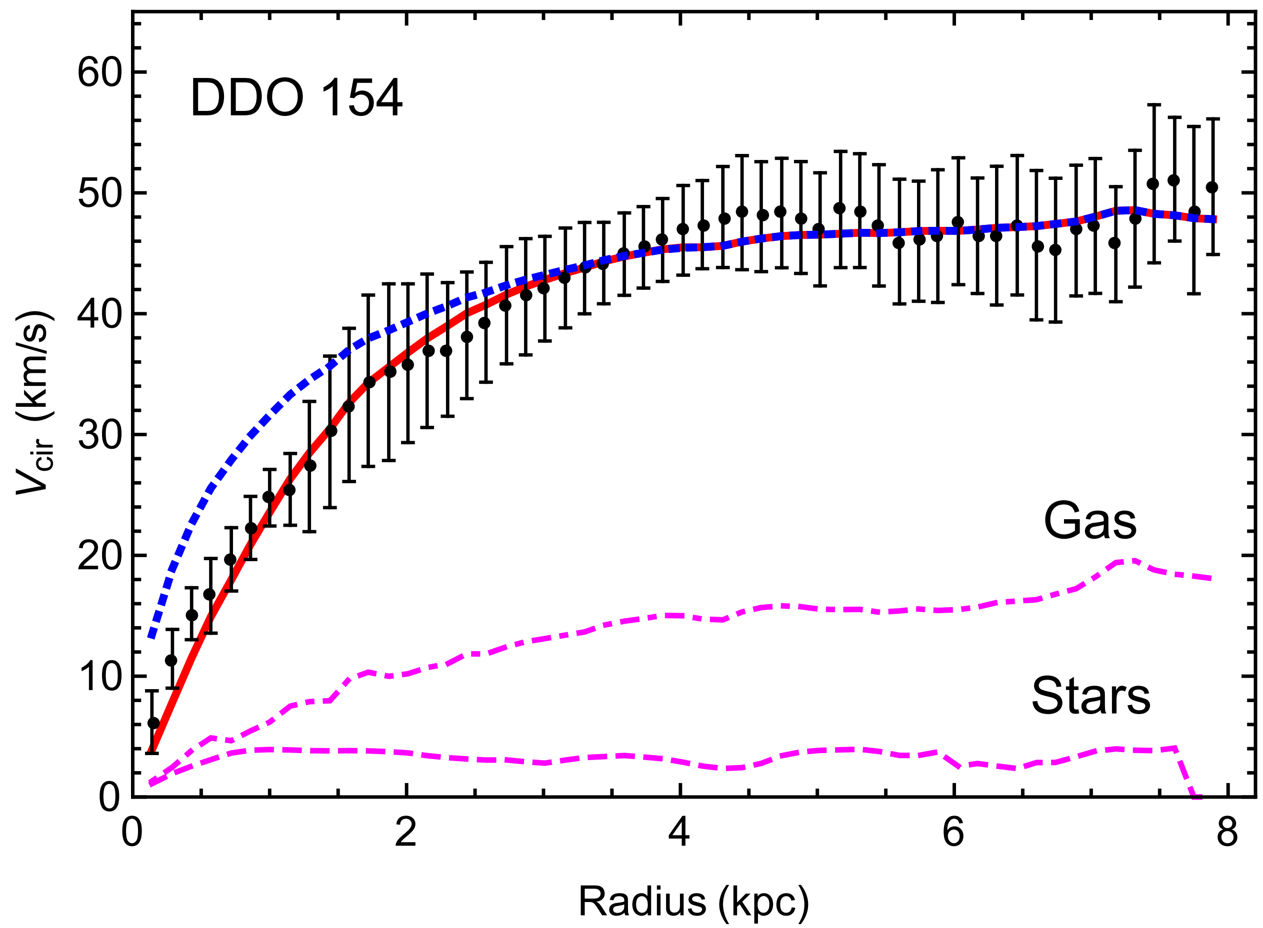
QCD

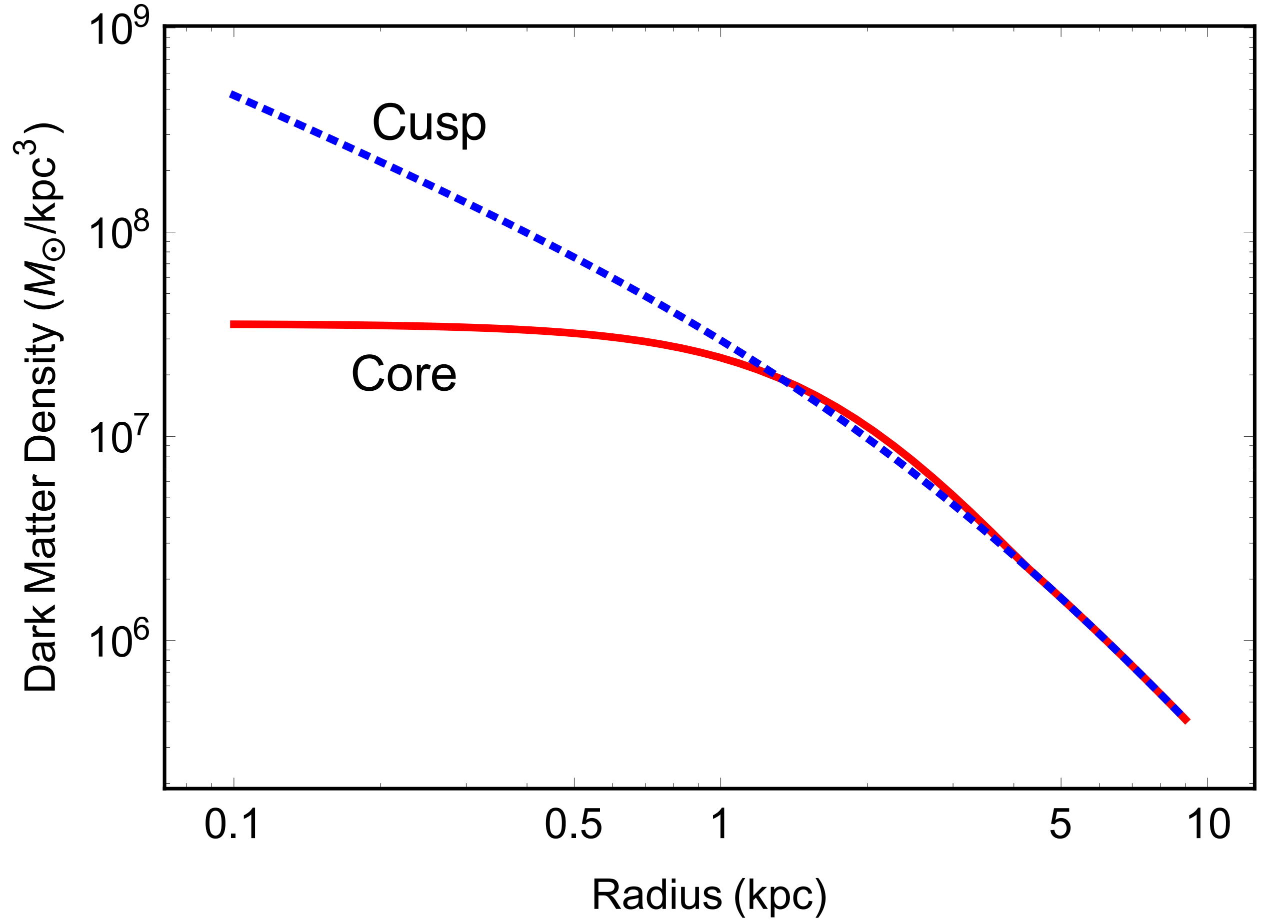
$$\mathcal{L} = \bar{\psi} i \gamma^\mu (\partial_\mu - ieA_\mu)\psi - m\bar{\psi}\psi - \frac{1}{2}\mathrm{Tr} F_{\mu\nu}F^{\mu\nu}$$

- non-abelian gauge theory
- no fine-tuning
- confinement
- chiral symmetry breaking
  - pions=NGBs
  - anomaly & instanton
- mesons, baryons, exotics
- jets
- deep non-pert. theory
- rich phenomenology



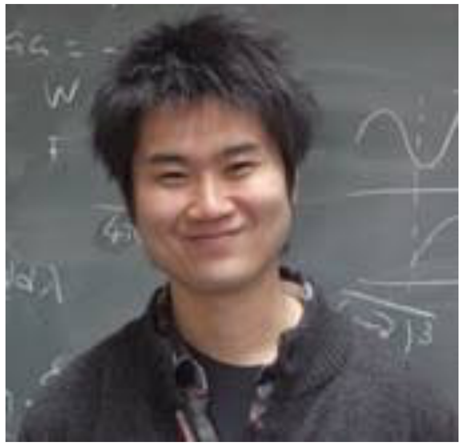
DDO 154 dwarf galaxy





can be explained if dark matter scatters against itself
Need Self-Interacting Dark Matter $\sigma/m \sim$ 1b / GeV
(Spergel, Steinhardt astro-ph/9909386)
if true, only astrophysical information beyond gravity

Diversity in stellar distribution

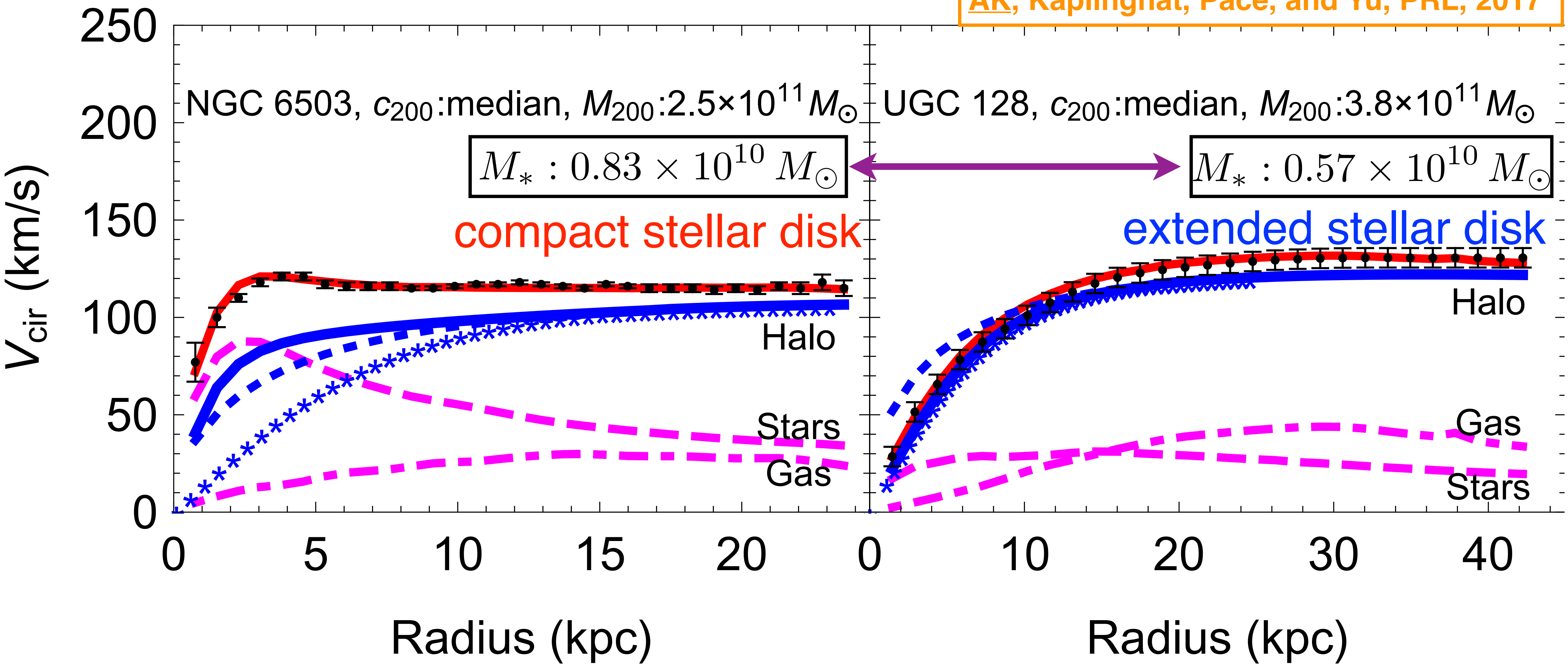


Ayuki Kamada

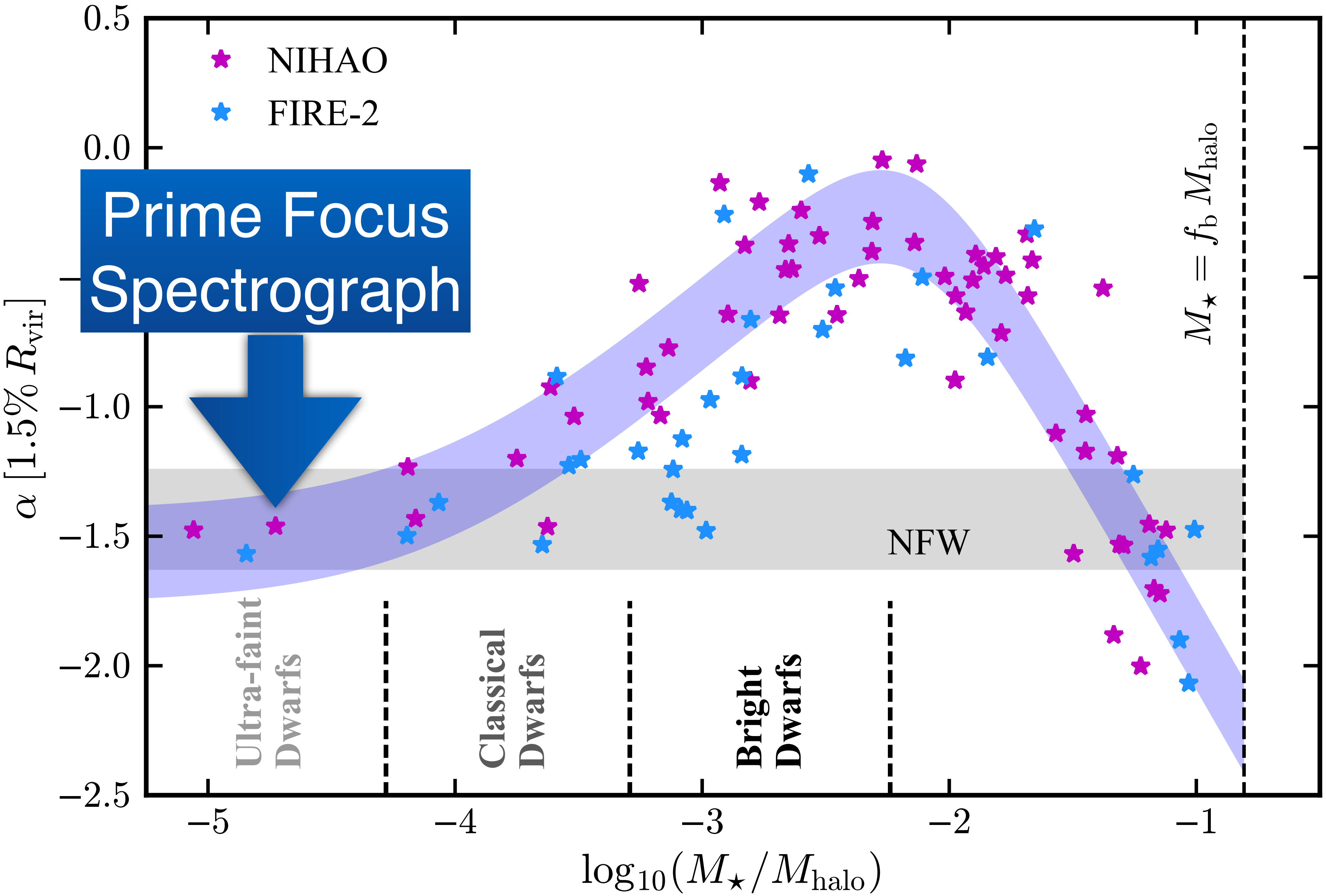
Similar outer circular velocity and stellar mass, but different stellar distribution

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

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



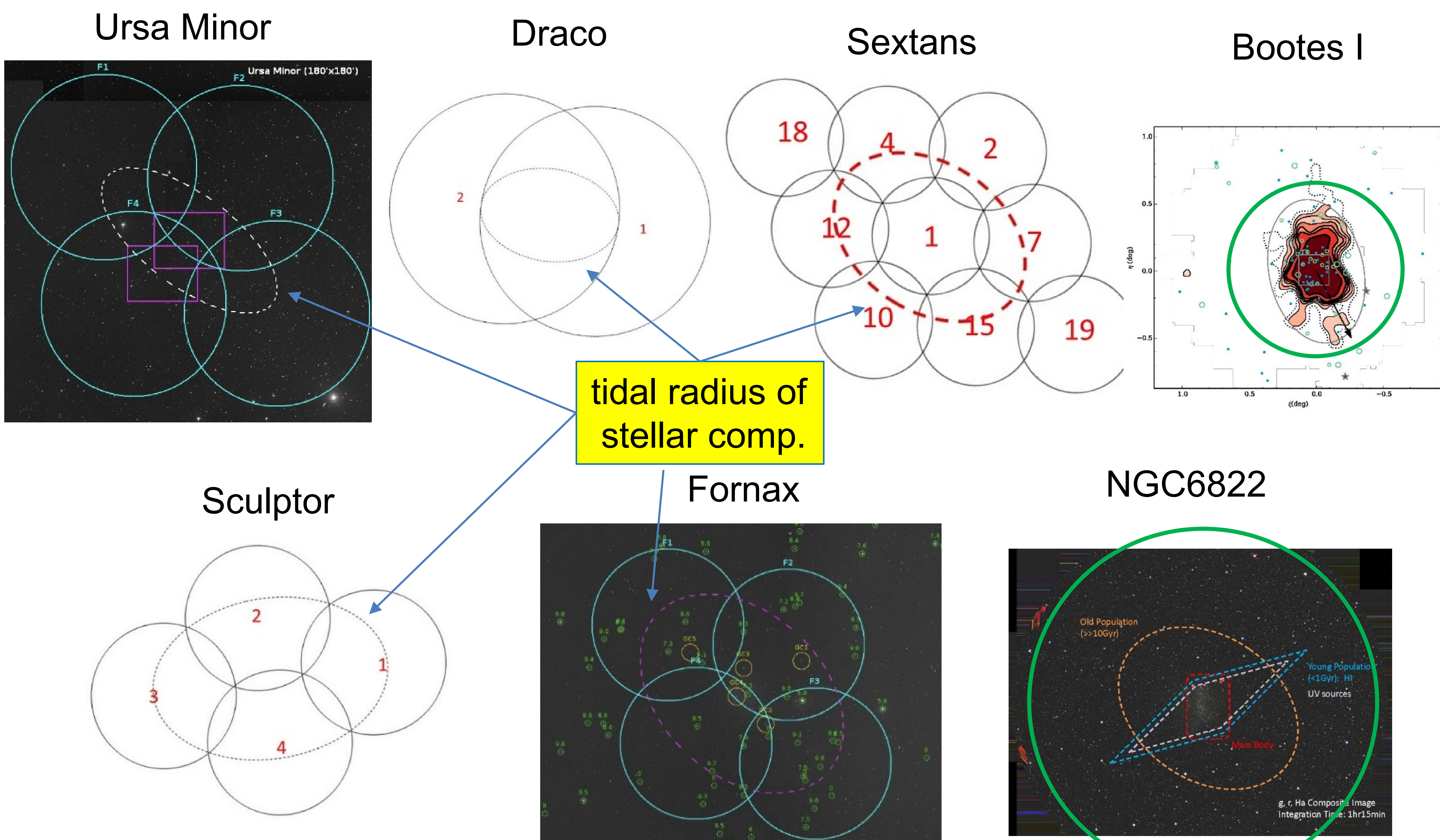
Baryonic Feedback?



James S. Bullock and Michael Boylan-Kolchin, arXiv:1707.04256

PFS pointings for MW satellites

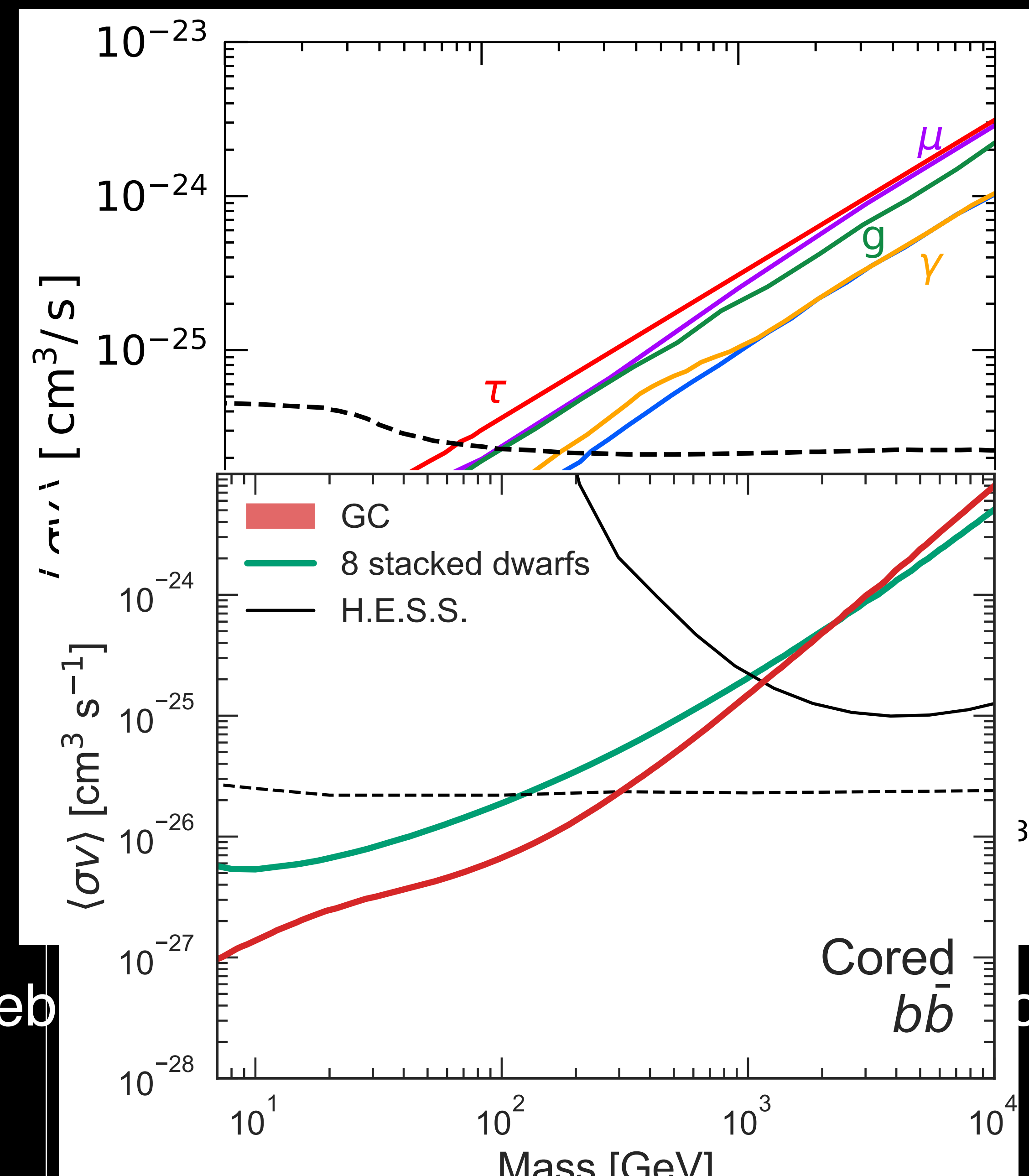
~ HSC imaging data are available for all samples ~



also cosmology, galaxy evolution

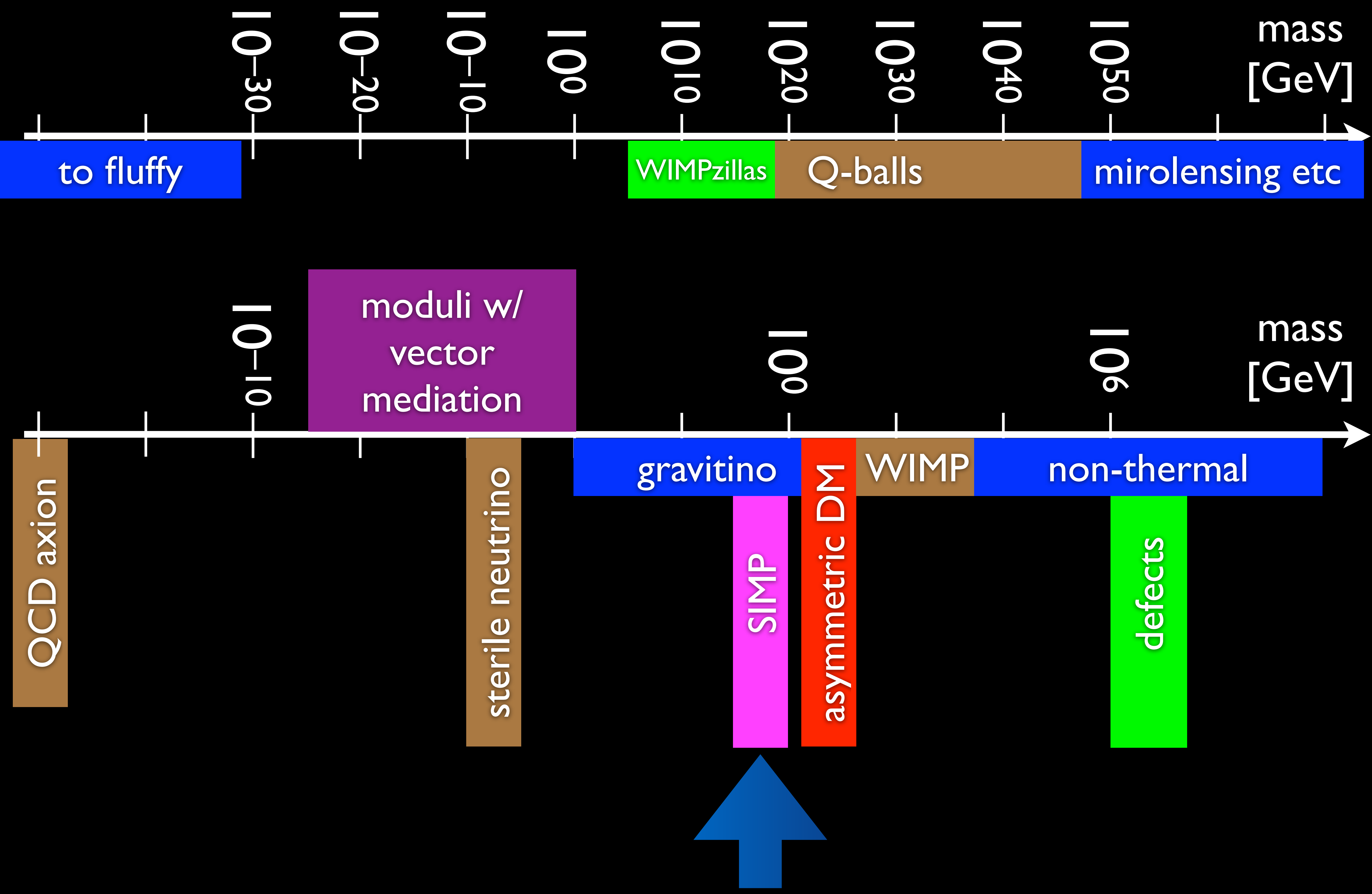
Standard Freeze-out doesn't work

- If self-interaction is in the S-wave, the unitarity limit says $\sigma_0 < 4\pi\hbar^2/(mv)^2$
- For $\sigma/m \sim \mathrm{cm}^2/\mathrm{g}$ for $v \sim 10^{-3}$, we need $m<14$ GeV
- CMB limit on dark matter annihilation $m>20$GeV
- GC γ ray: m>300GeV?
- options
  - SIMP: 3→2
  - asymmetric
  - freeze-in
  - secluded



Reb ... com,

Abazajian, Horiuchi, Kaplinghat, Keeley, Macias, Ng, arXiv:2003.10416



10^{-30}
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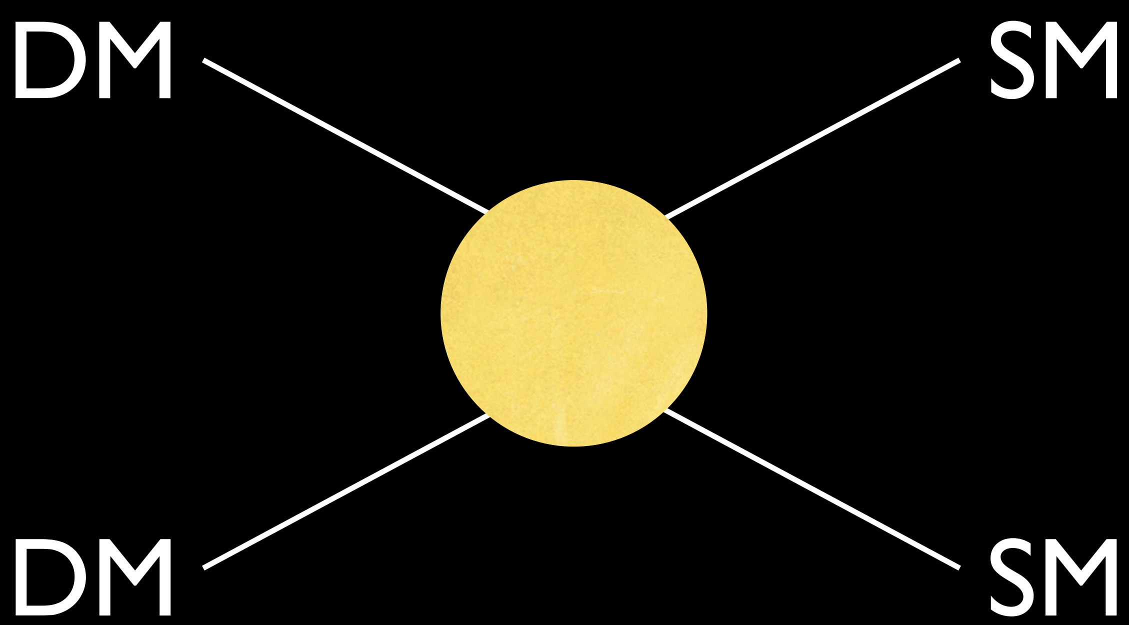
SIMP
defects

Strongly Interacting Massive Particles (SIMP)

Miracles



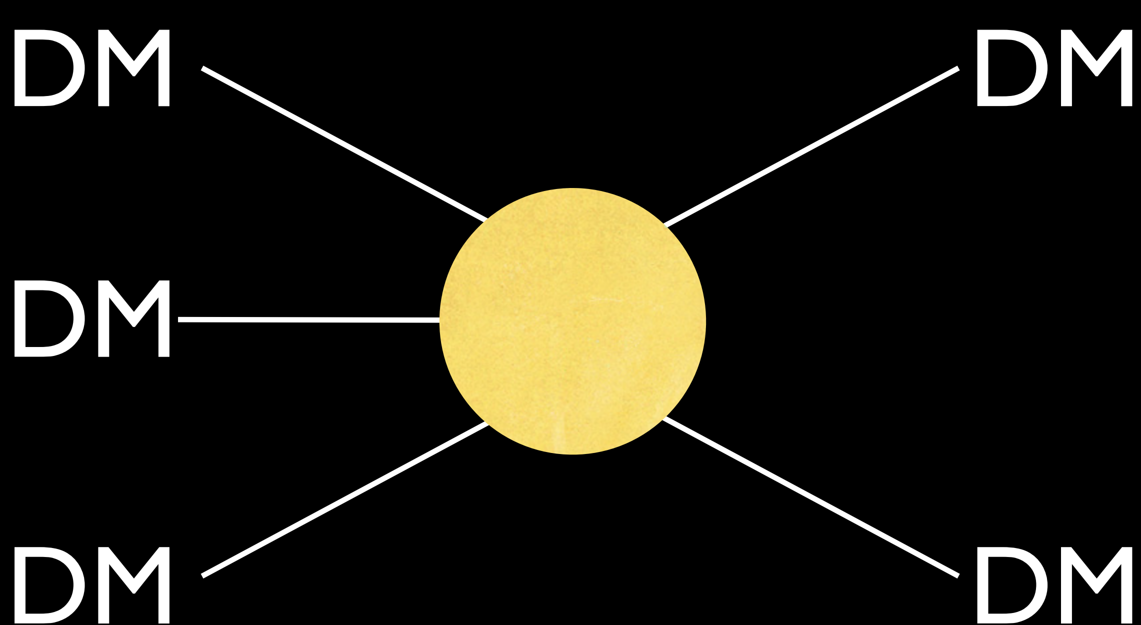
$$\langle \sigma_{2\to 2} v \rangle \approx \frac{\alpha^2}{m^2}$$

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

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

WIMP miracle!

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



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

$$\alpha \approx 4\pi$$

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

Hochberg, Kuflik, Volansky, Wacker arXiv:1402.5143

SIMP miracle!

~~LEE WEINBERG~~ 3→2 FREEZE-OUT

Back of the envelope calculation

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

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

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

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

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

$$n_b \sim \eta_b s$$

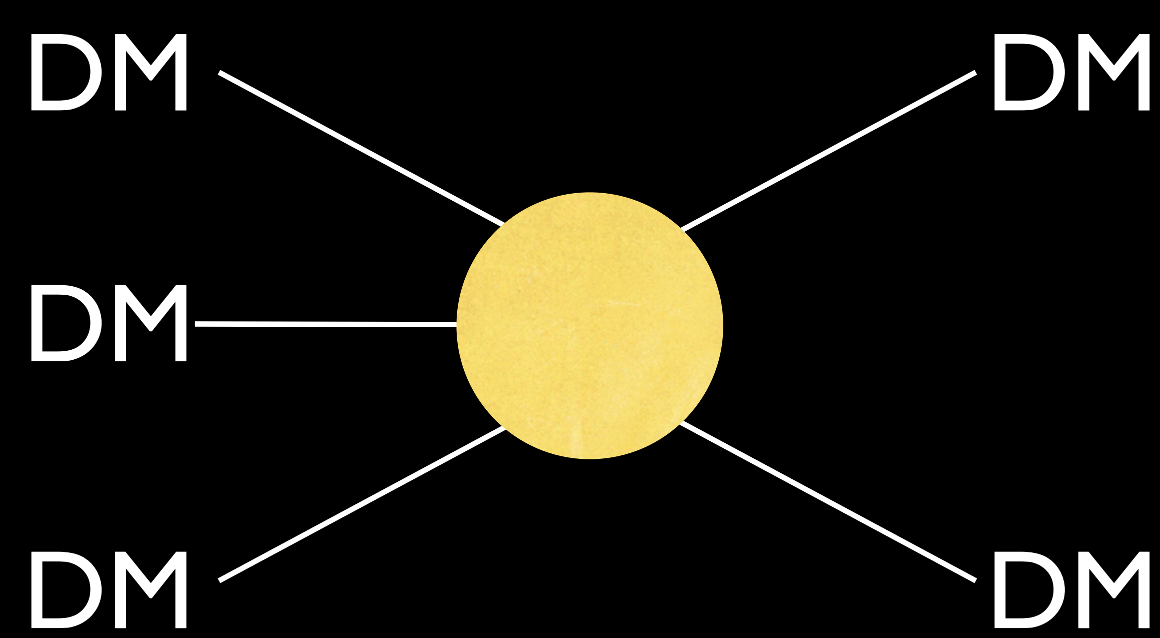
$$\eta_b \simeq T_{\rm eq}/m_p \qquad s \simeq T^3$$

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

Eric Kuflik

SIMPlest Miracle

- SU(2) with 4 doublets
- 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



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

Hochberg, Kuflik, HM, Volansky, Wacker
Phys.Rev.Lett. 115 (2015) 021301

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

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

Eric Kuflik

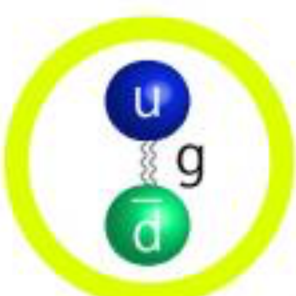
LAGRANGIANS

QCD

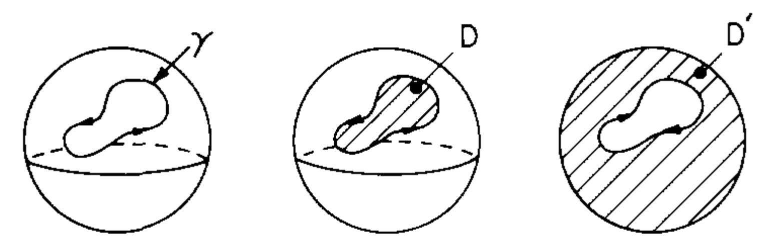
$$\mathcal{L}_{\text{quark}} = -\frac{1}{4}F^a_{\mu\nu}F^{\mu\nu a} + \bar{q}_i i\not{D} q_i \; -\frac{1}{2}m_Q \; J^{ij} q_i q_j + h.c.$$

Chiral Lagrangian

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



Pions

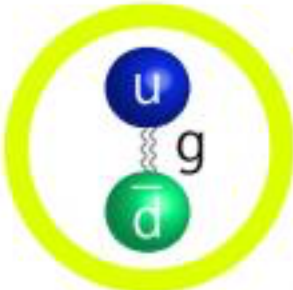


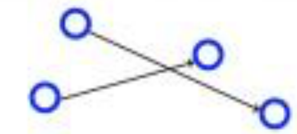
(a) (b) (c)

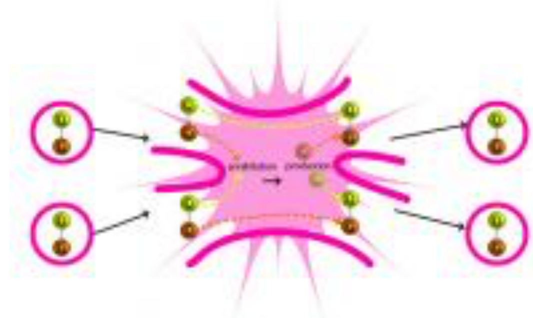
$$\mathcal{L}_{\text{pion}} = \frac{1}{4}\text{Tr}\partial_\mu \pi \partial^\mu \pi - \frac{m_\pi^2}{4}\text{Tr}\pi^2 + \frac{m_\pi^2}{12 f_\pi^2}\text{Tr}\pi^4 - \frac{1}{6 f_\pi^2}\text{Tr}\left(\pi^2 \partial^\mu \pi \partial_\mu \pi - \pi \partial^\mu \pi \pi \partial_\mu \pi\right)$$

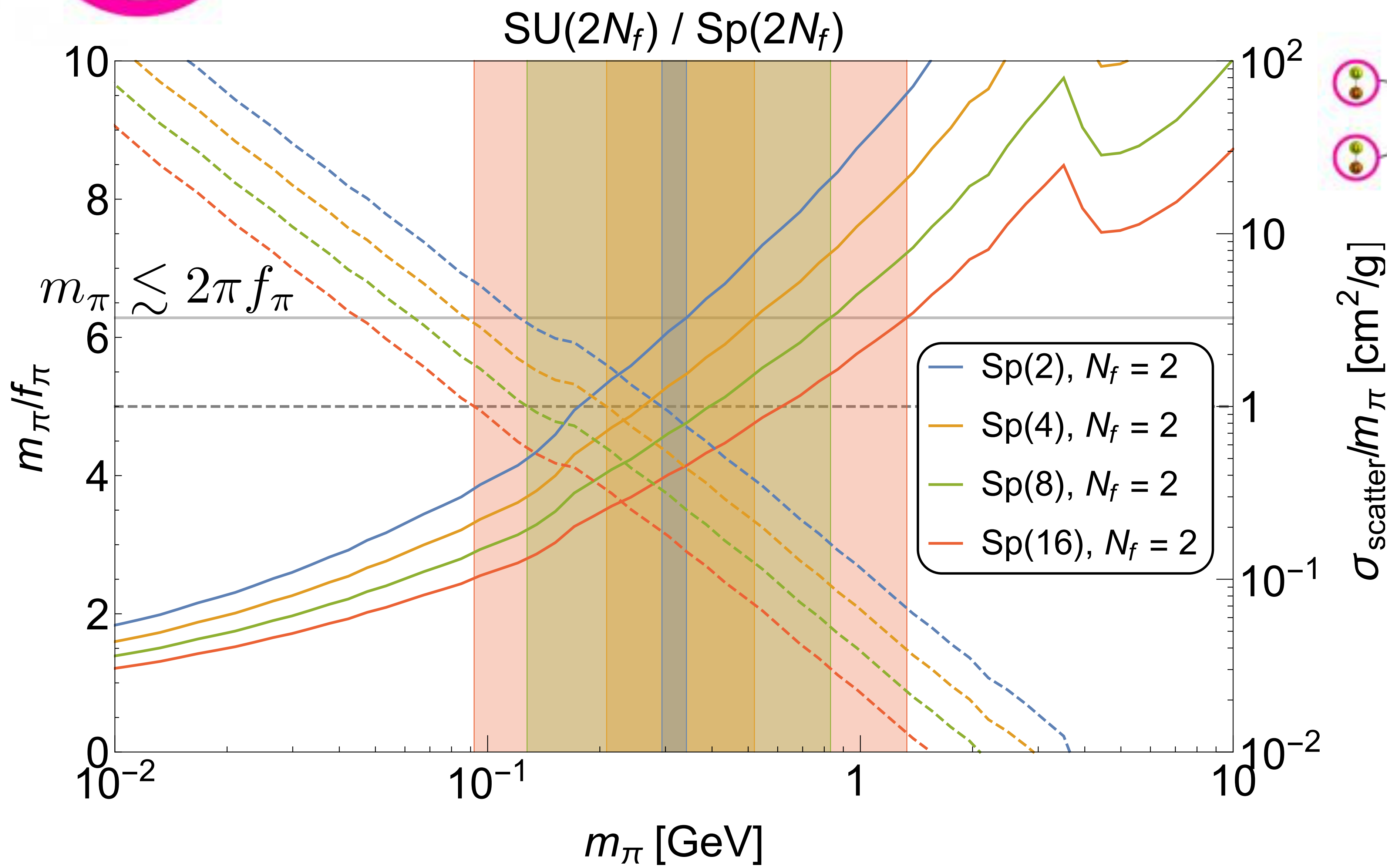
$$+ \frac{2N_c}{15\pi^2 f_\pi^5}\epsilon^{\mu\nu\rho\sigma}\text{Tr}\left[\pi \partial_\mu \pi \partial_\nu \pi \partial_\rho \pi \partial_\sigma \pi\right] + \mathcal{O}(\pi^6)$$

The Results









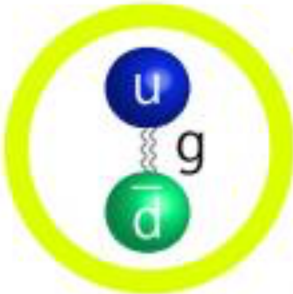
Solid curves: solution to Boltzmann eq.

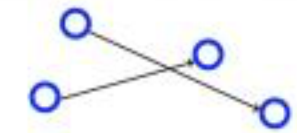
Dashed curves: along that solution

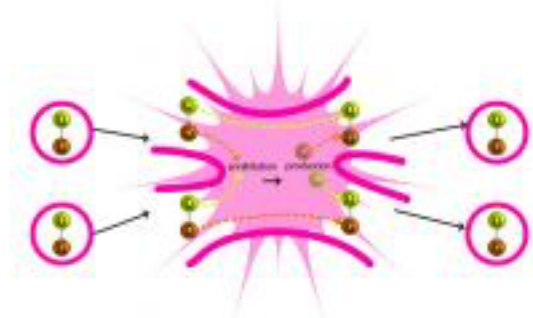
$$\frac{m_\pi}{f_\pi} \propto m_\pi^{3/10}$$

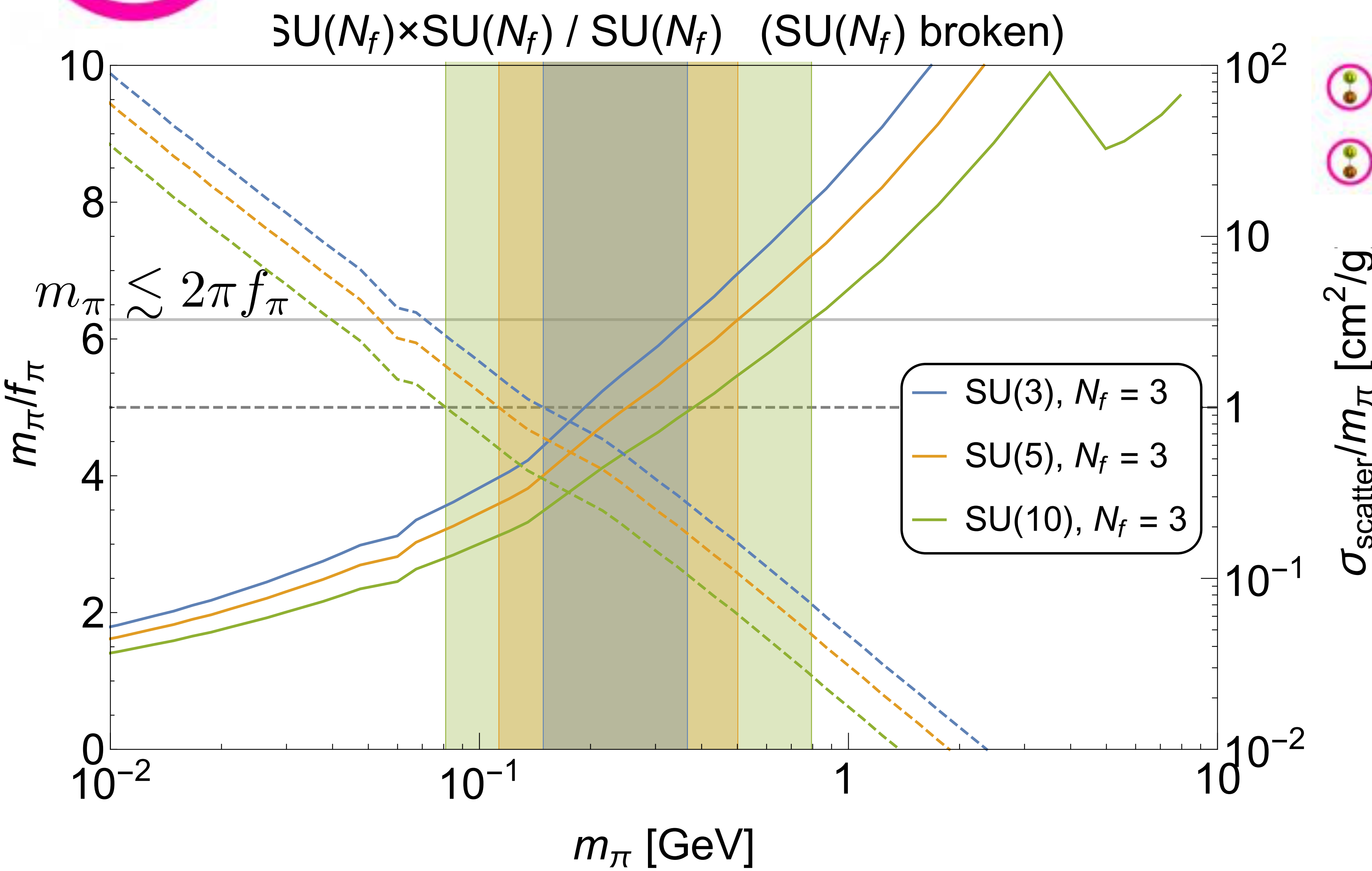
$$\frac{\sigma_{\rm scatter}}{m_\pi} \propto m_\pi^{-9/5}$$

The Results









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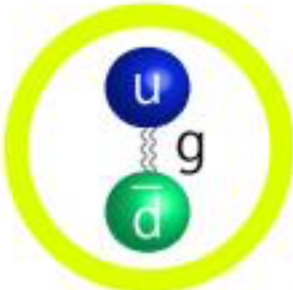
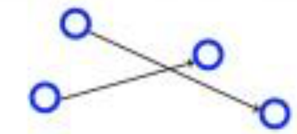
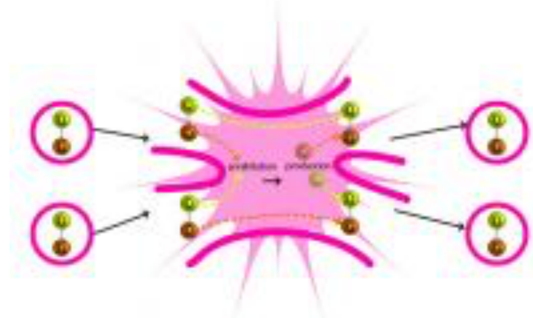
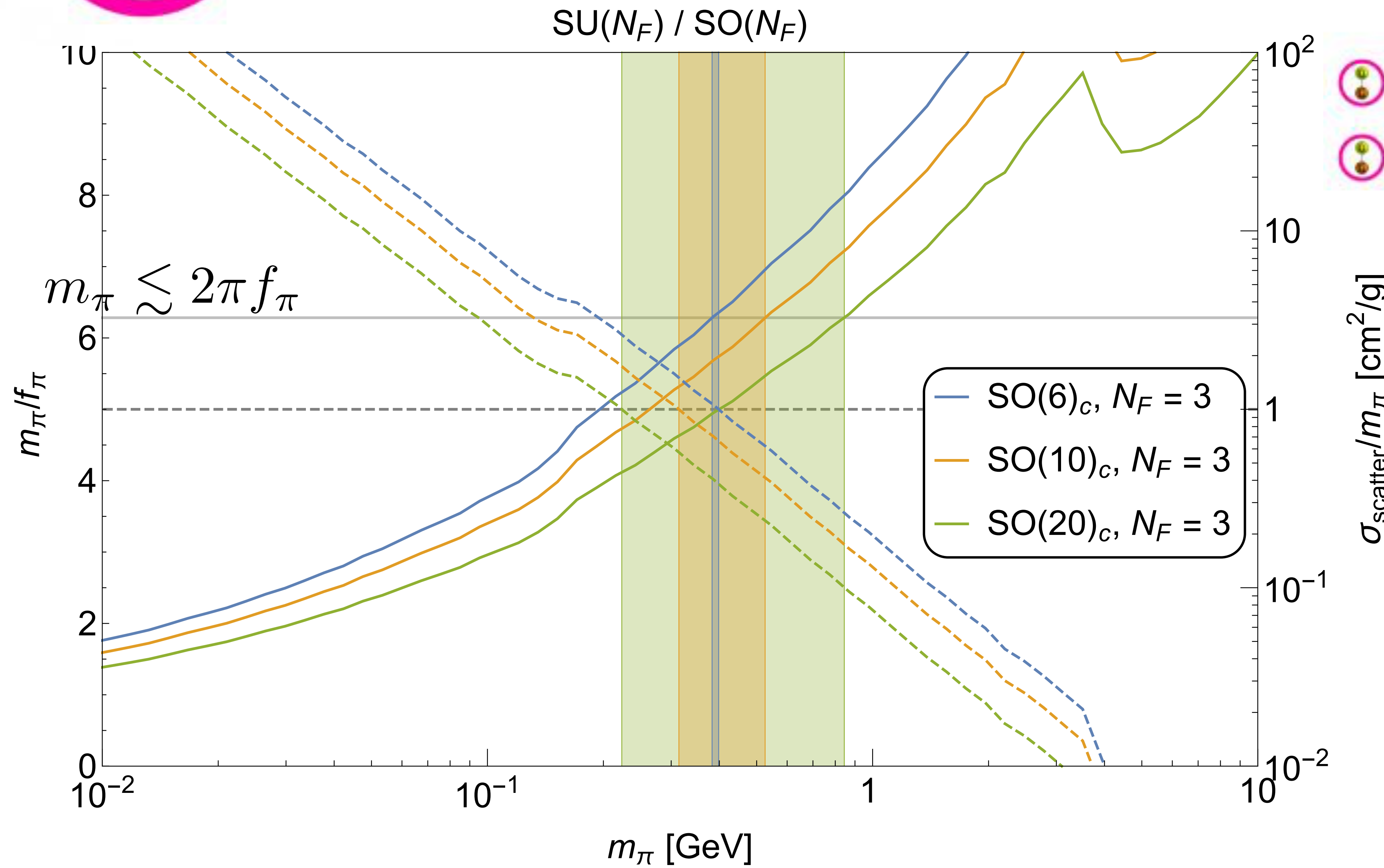
The Results









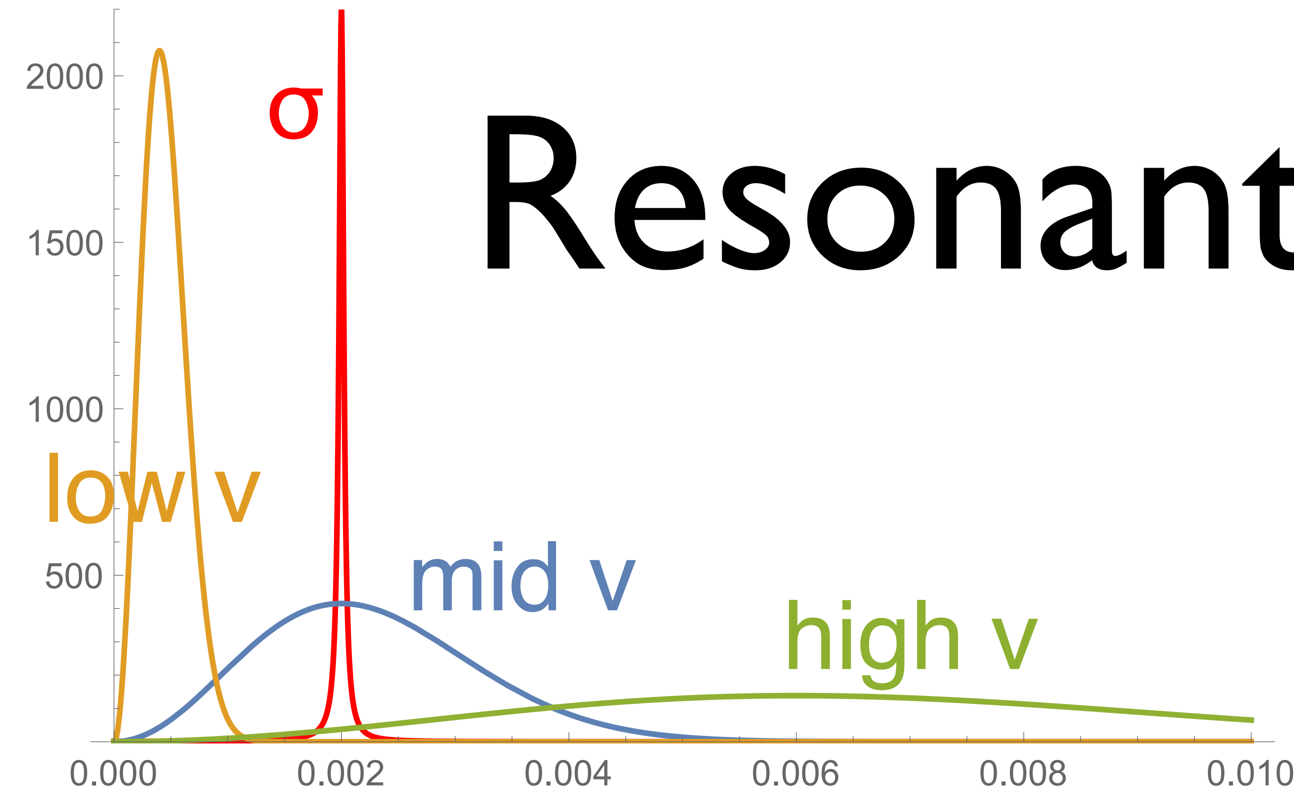
Solid curves: solution to Boltzmann eq.

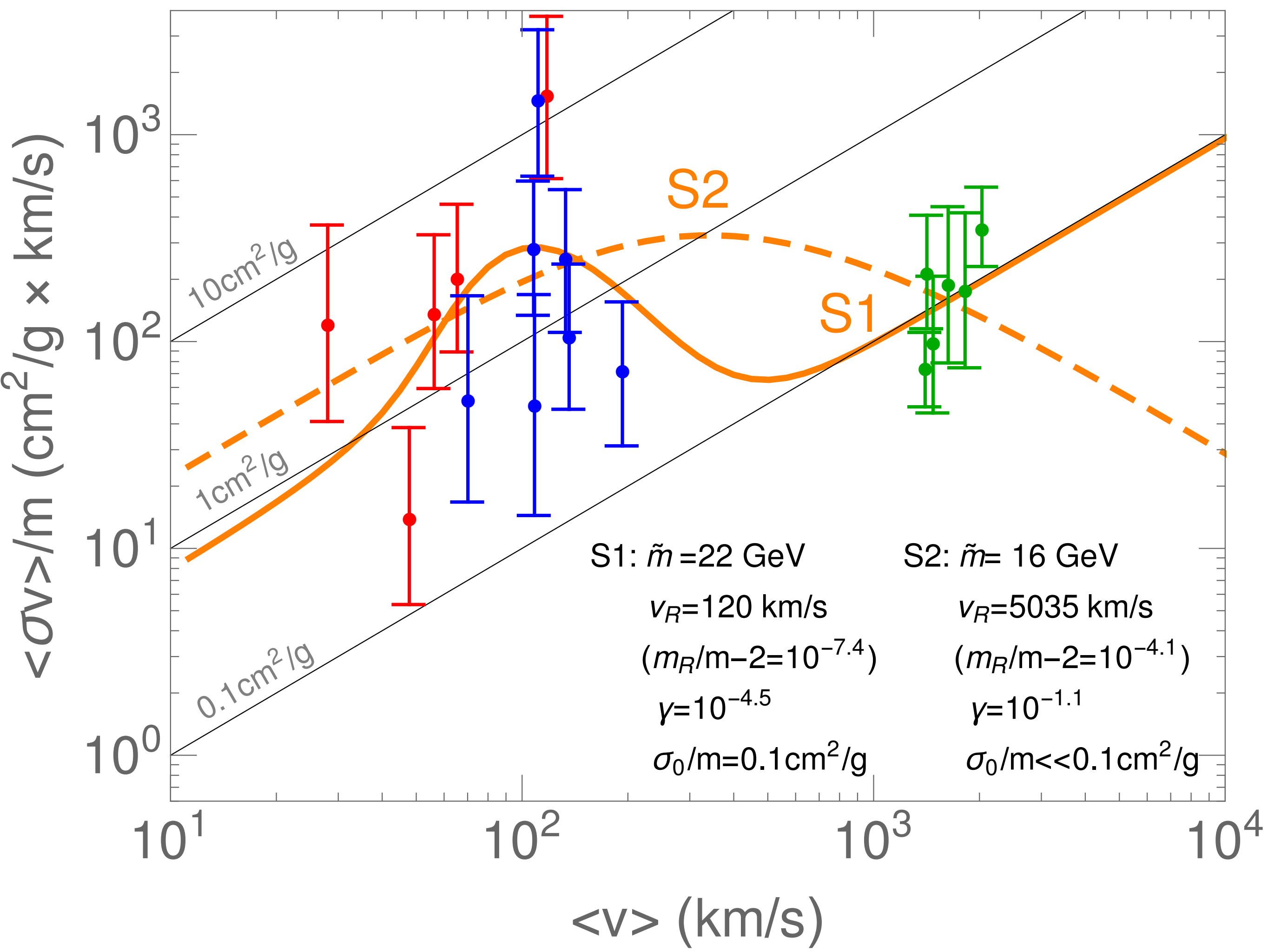
Dashed curves: along that solution

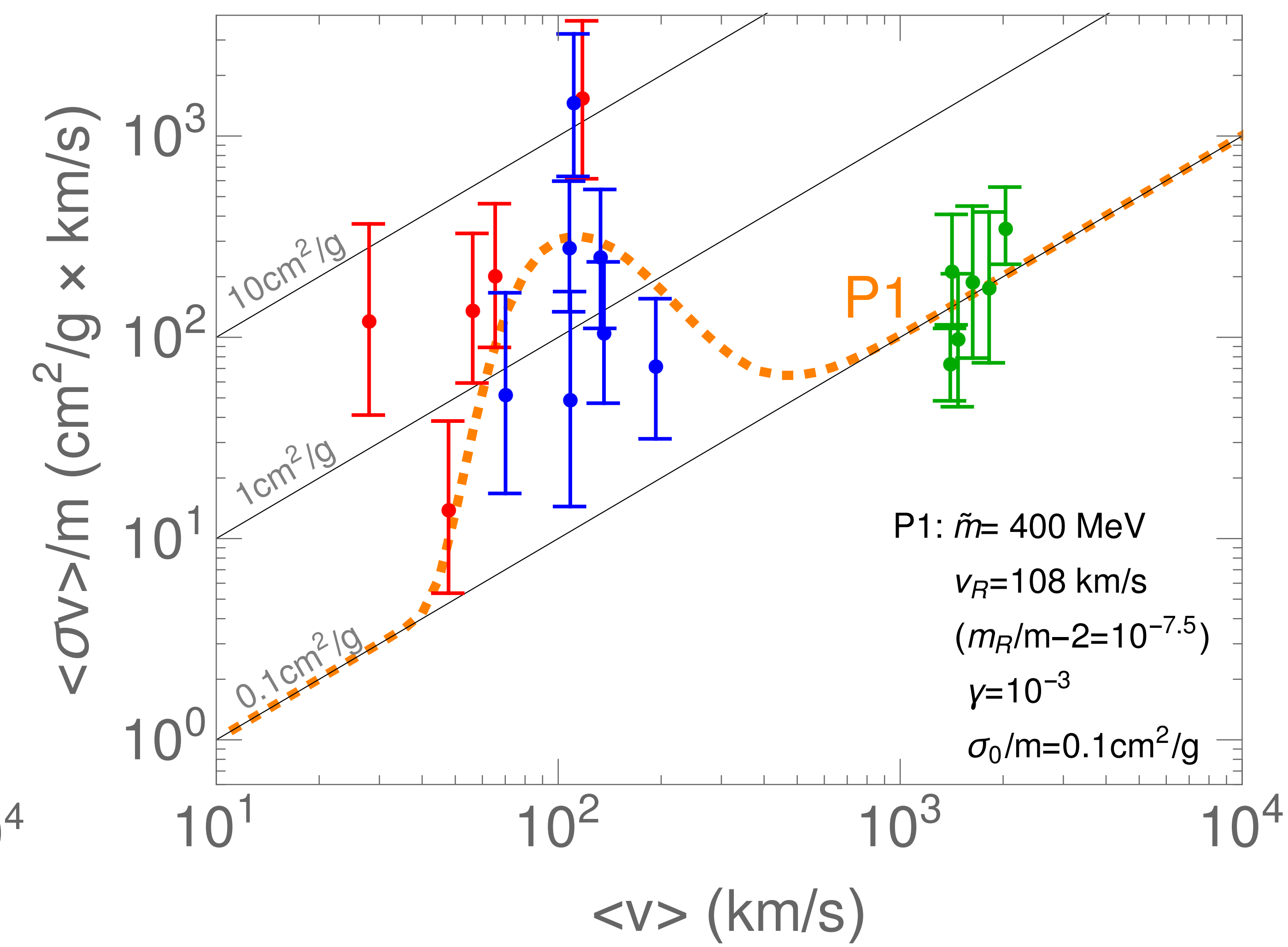
$$\frac{m_\pi}{f_\pi} \propto m_\pi^{3/10}$$

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

Resonant scattering

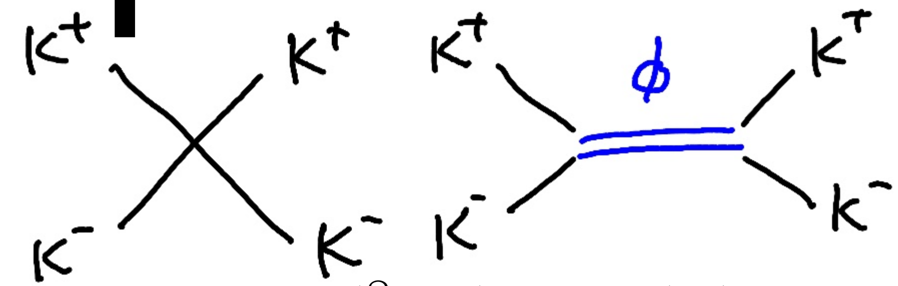






Xiaoyong Chu, Camilo Garcia-Cely, HM,
Phys.Rev.Lett. 122 (2019) no.7, 071103

Resonance is plausible



- e.g., $K^+K^- \to \phi \to K^+K^-$
  - requires $m_\phi = 2m_K$
  - $m_\phi \approx \Lambda + m_d + m_s$
  - $2m_K \approx 2((m_d+m_s)\,\Lambda)^{1/2}$
  - guaranteed to cross when $m_s < \Lambda/4$
- also for $\psi(3S)$, $\Upsilon(4S)$

$$\frac{m(^8\mathrm{Be}) - m(\alpha)}{m(^8\mathrm{Be})} = 0.000012,$$

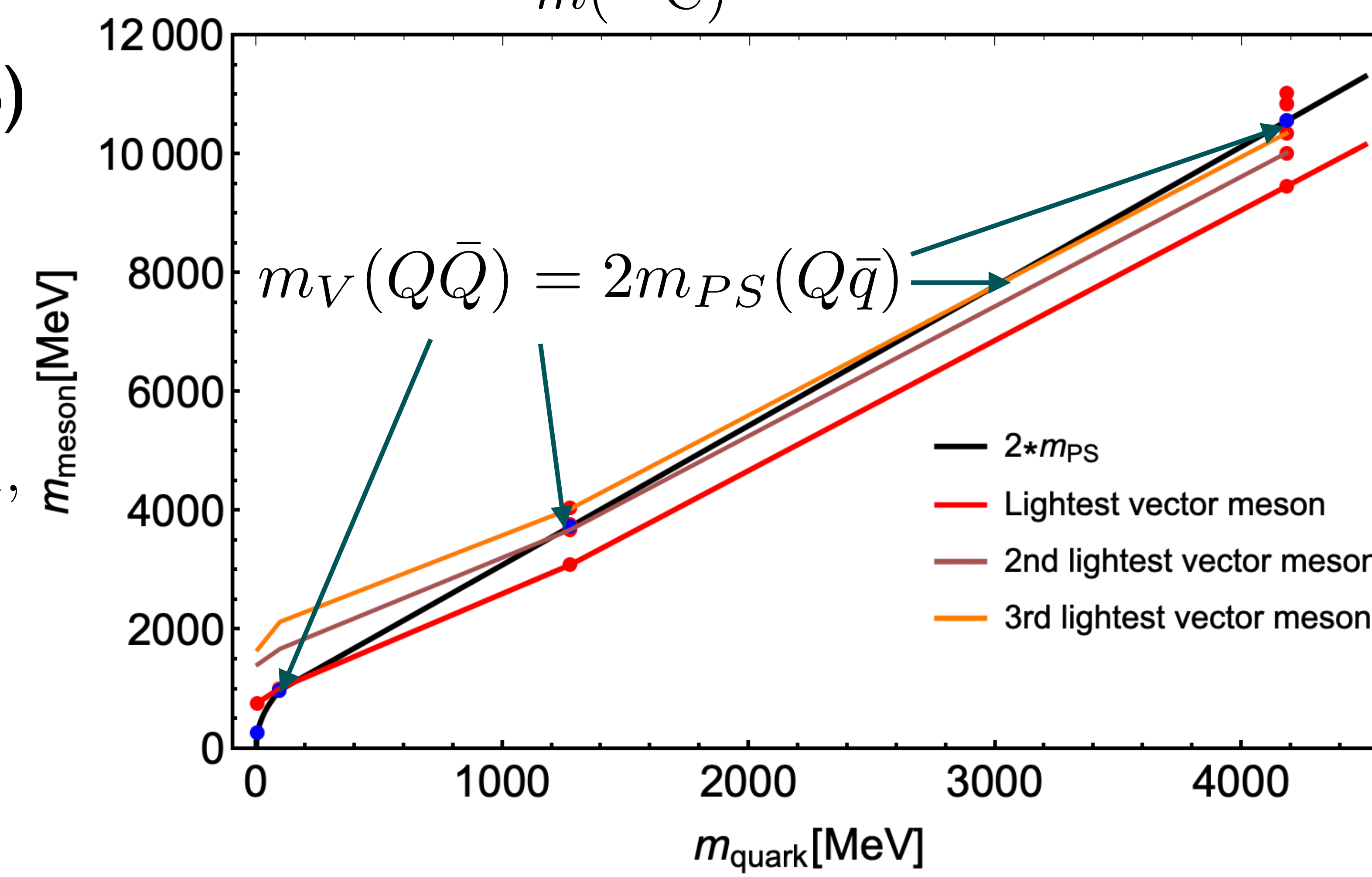
$$\frac{m(^{12}\mathrm{C}) - m(^8\mathrm{Be}) - m(\alpha)}{m(^{12}\mathrm{C})} = 0.000026,$$

$$\frac{m(\phi) - 2m(K^0)}{m(\phi)} = 0.024,$$

$$\frac{m(D^{+*}) - m(D^0) - m(\pi^+)}{m(D^{+*})} = 0.00051,$$

$$\frac{m(B_{s1}) - m(B^*) - m(K^0)}{m(B_{s1})} = 0.0011,$$

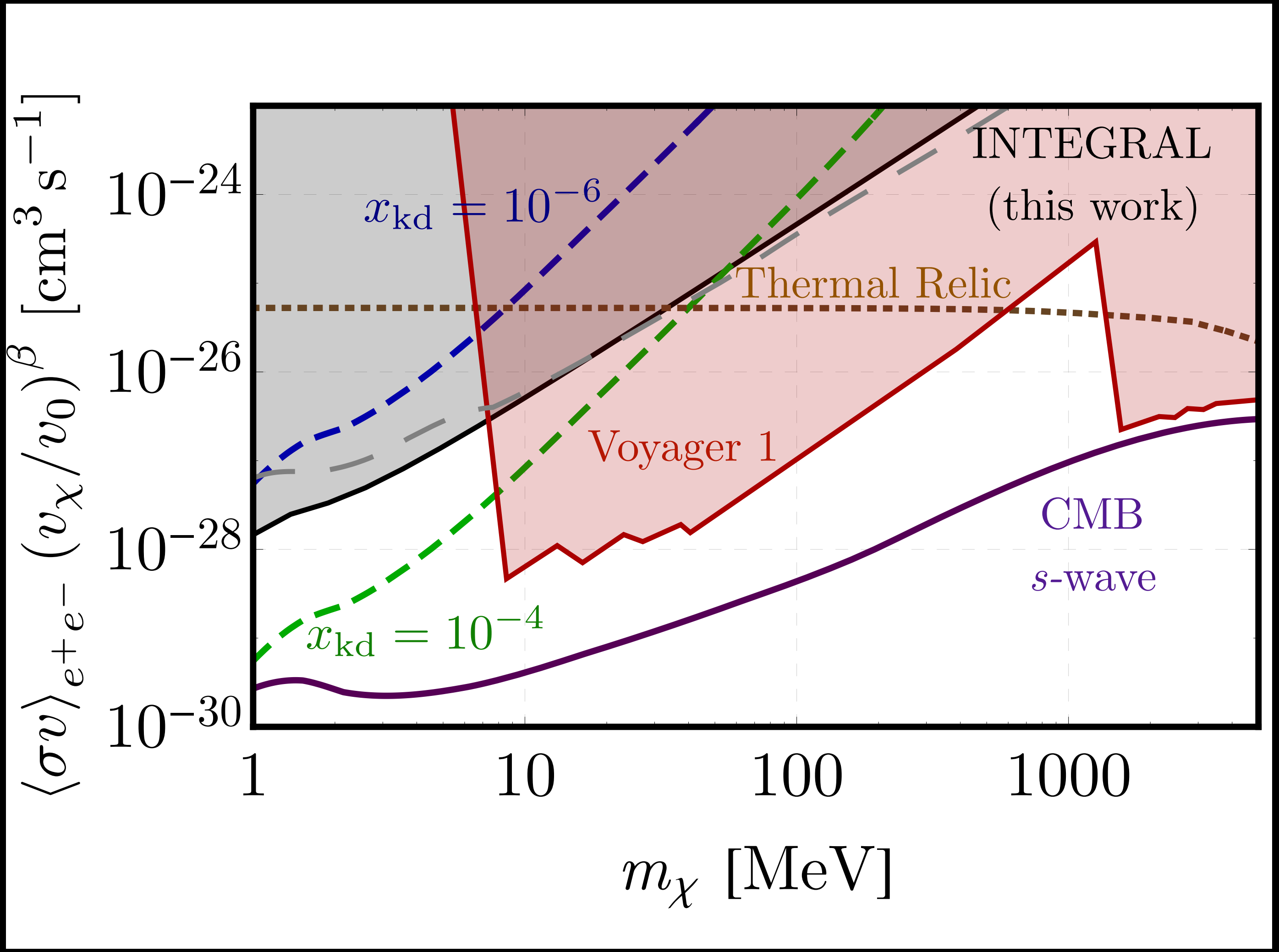
$$\frac{m(\Upsilon(4S)) - 2m(B^0)}{m(\Upsilon(4S))} = 0.0019.$$



Robert McGehee, HM, Yu-Dai Tsai, to appear

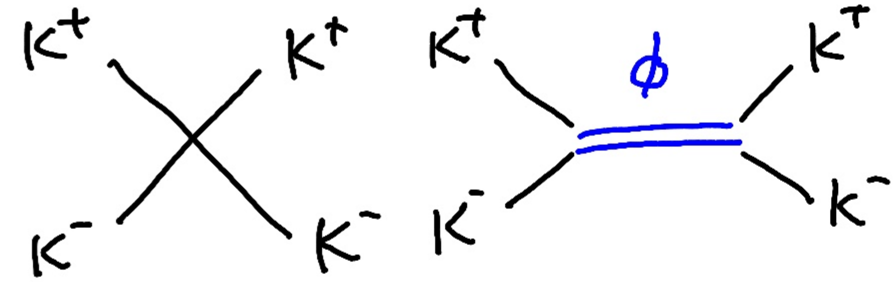
It’s P-wave!

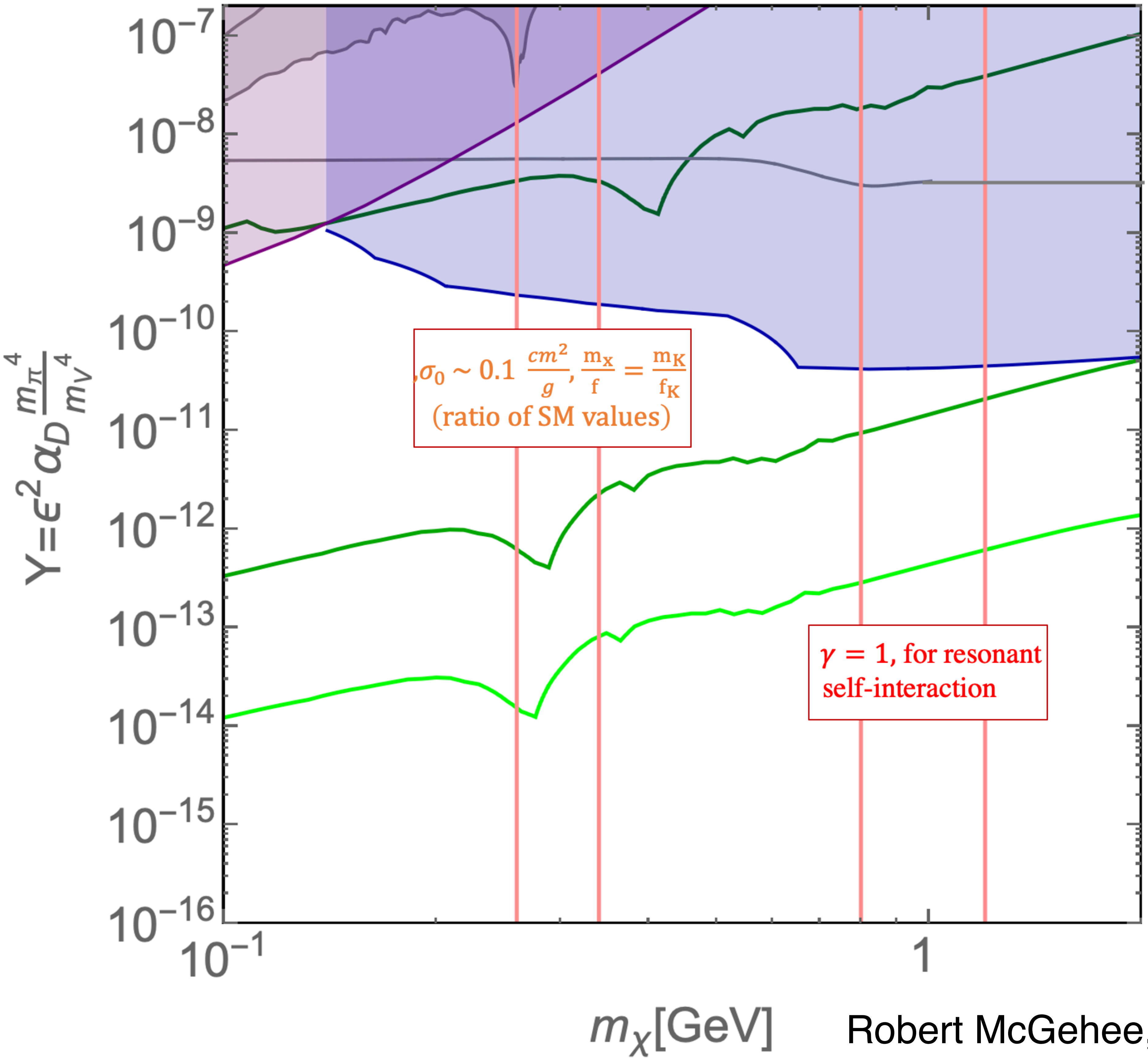
- typically light dark matter with thermal freeze out is excluded by CMB
- Exception: *P*-wave annihilation

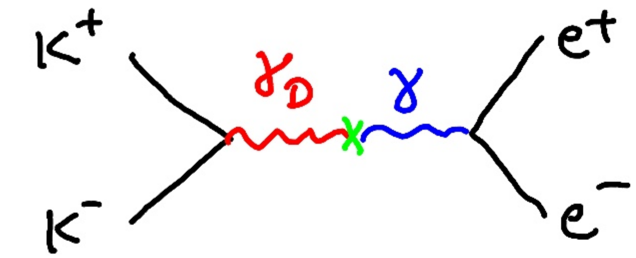


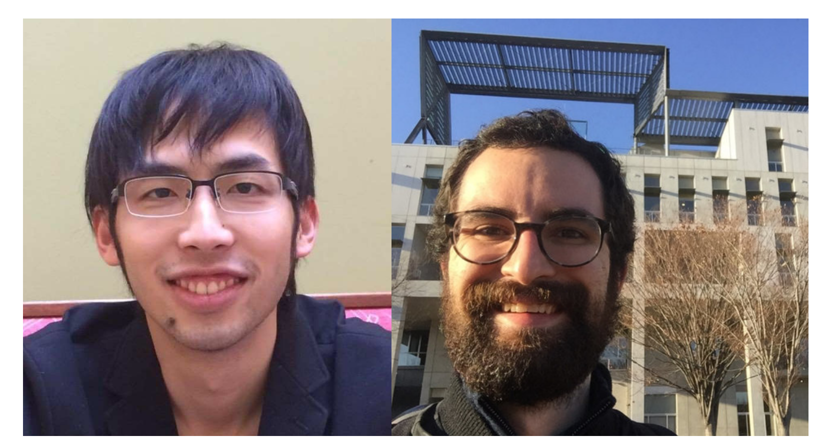
Ranjan Laha, Julian B. Muñoz, and Tracy R. Slatyer
arXiv:2004.00627

simple example









Robert McGehee, HM, Yu-Dai Tsai, to appear

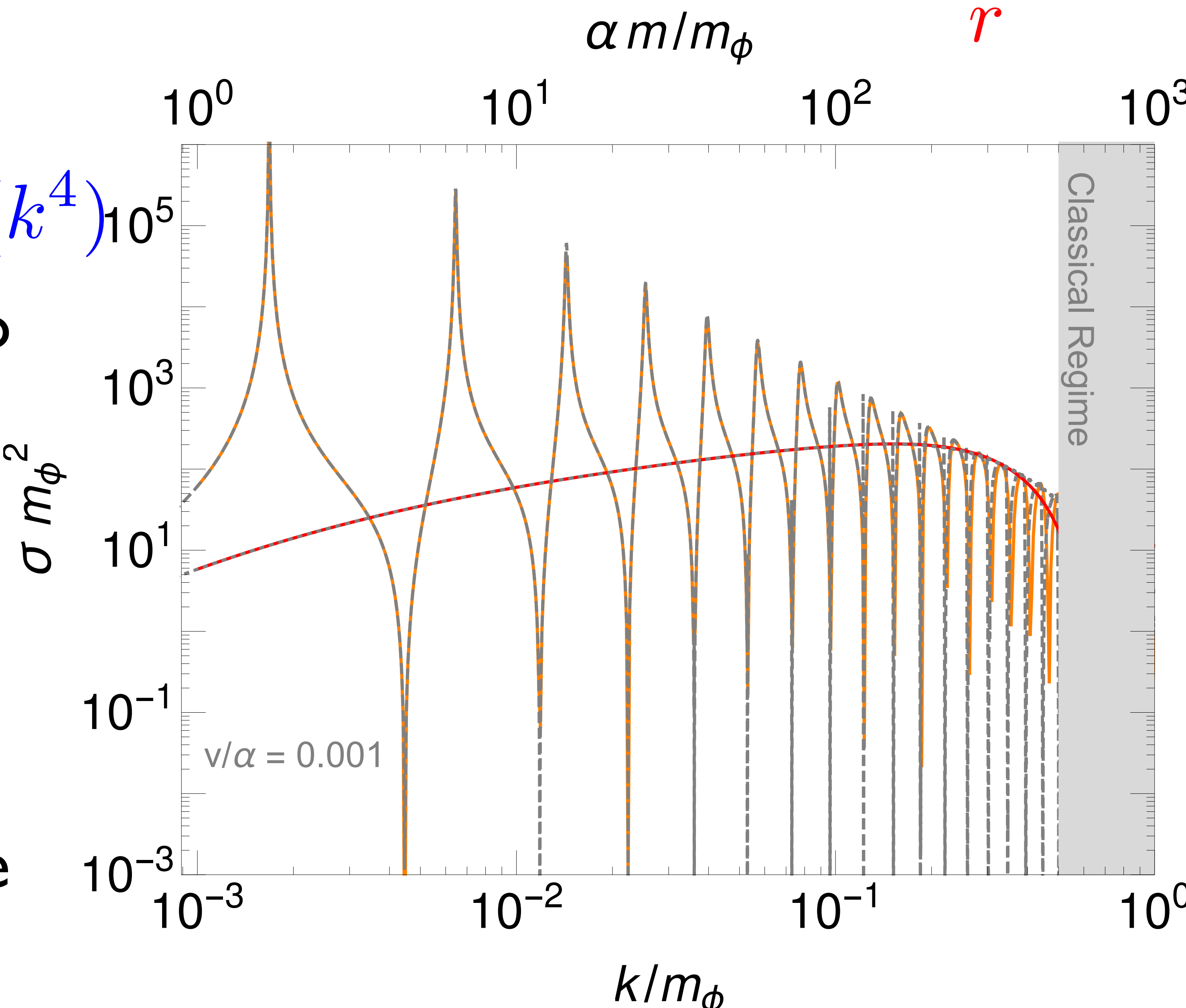
Unified description of SIDM

- Hans Bethe (1949): *effective range theory*

$$k \cot\delta = -\frac{1}{a} + \frac{1}{2} r_e k^2 + O(k^4)$$

- only two parameters to describe scattering at low velocities
- fully unitary and non-perturbative
- ideal for simulations!
- can include continuum + resonance

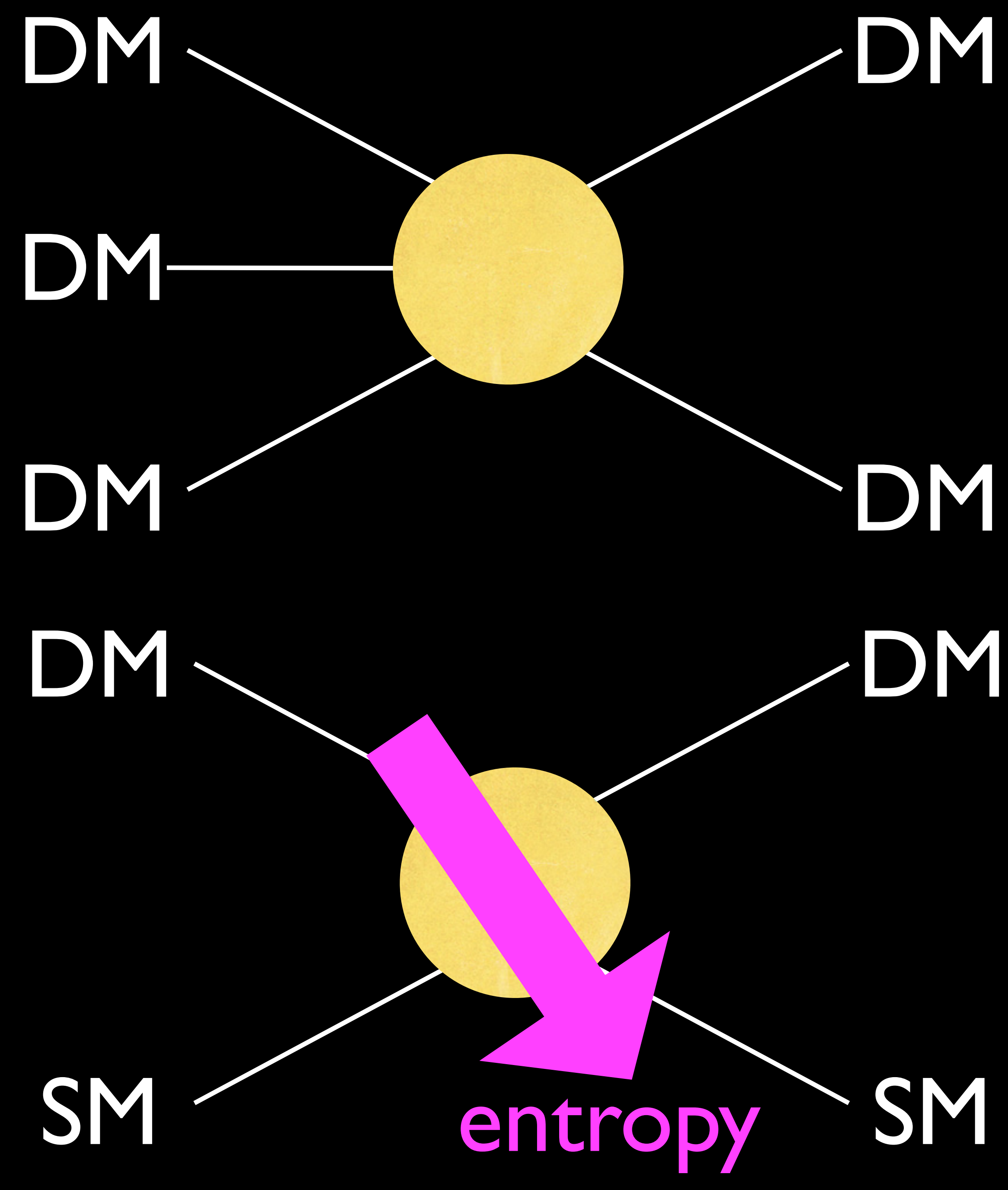
$$V = -\alpha \frac{e^{-m_\phi r}}{r}$$



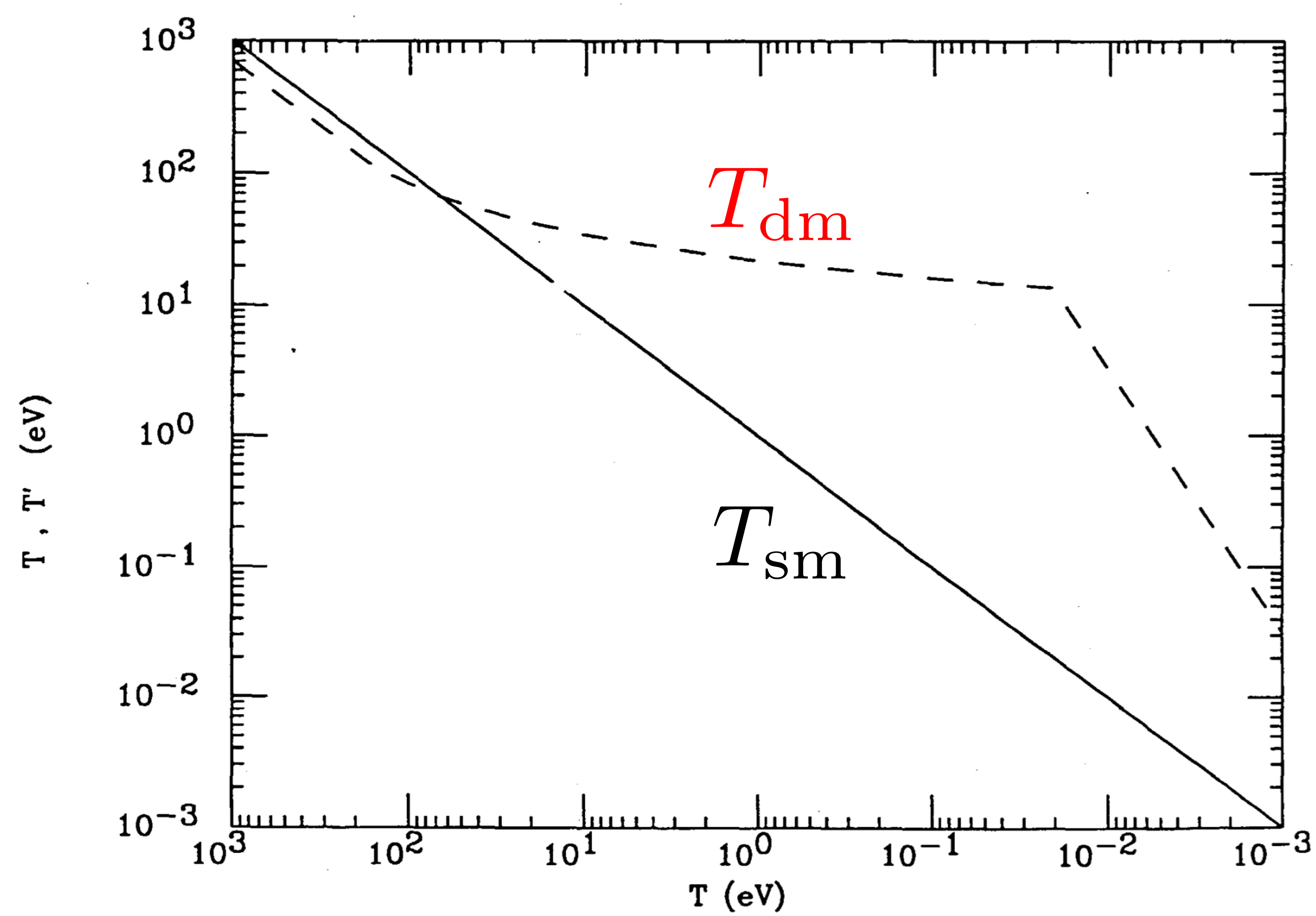
Xiaoyong Chu, Camilo Garcia-Cely, HM, arXiv:1908.06067

communication

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



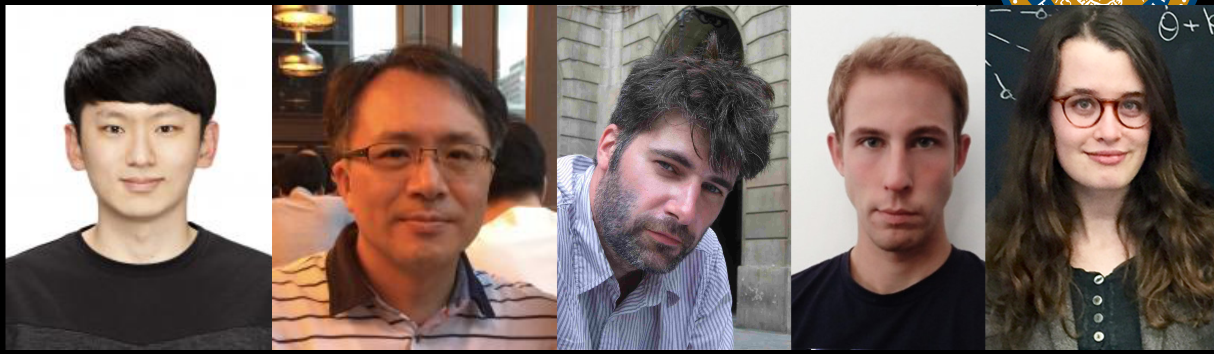
if totally decoupled

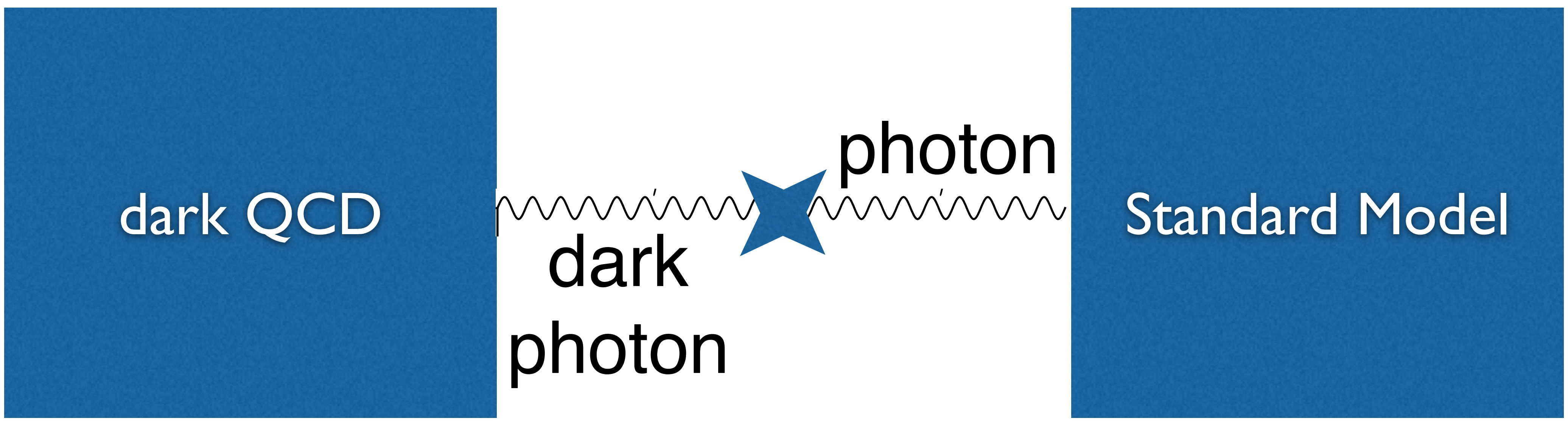


Carlson, Hall and Machacek, Astrophys. J. 398, 43 (1992)

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

vector portal





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

Yonit Hochberg, Eric Kuflik, HM arXiv:1512.07917, arXiv: 1706.05008
also axion portal: Hochberg, Kuflik, McGehee, HM, Schutz, arXiv:1806.10139
Higgs portal: Choi, Hochberg, Kuflik, Lee, Mambrini, HM, Pierre, arXiv:1707.01434

vector portal

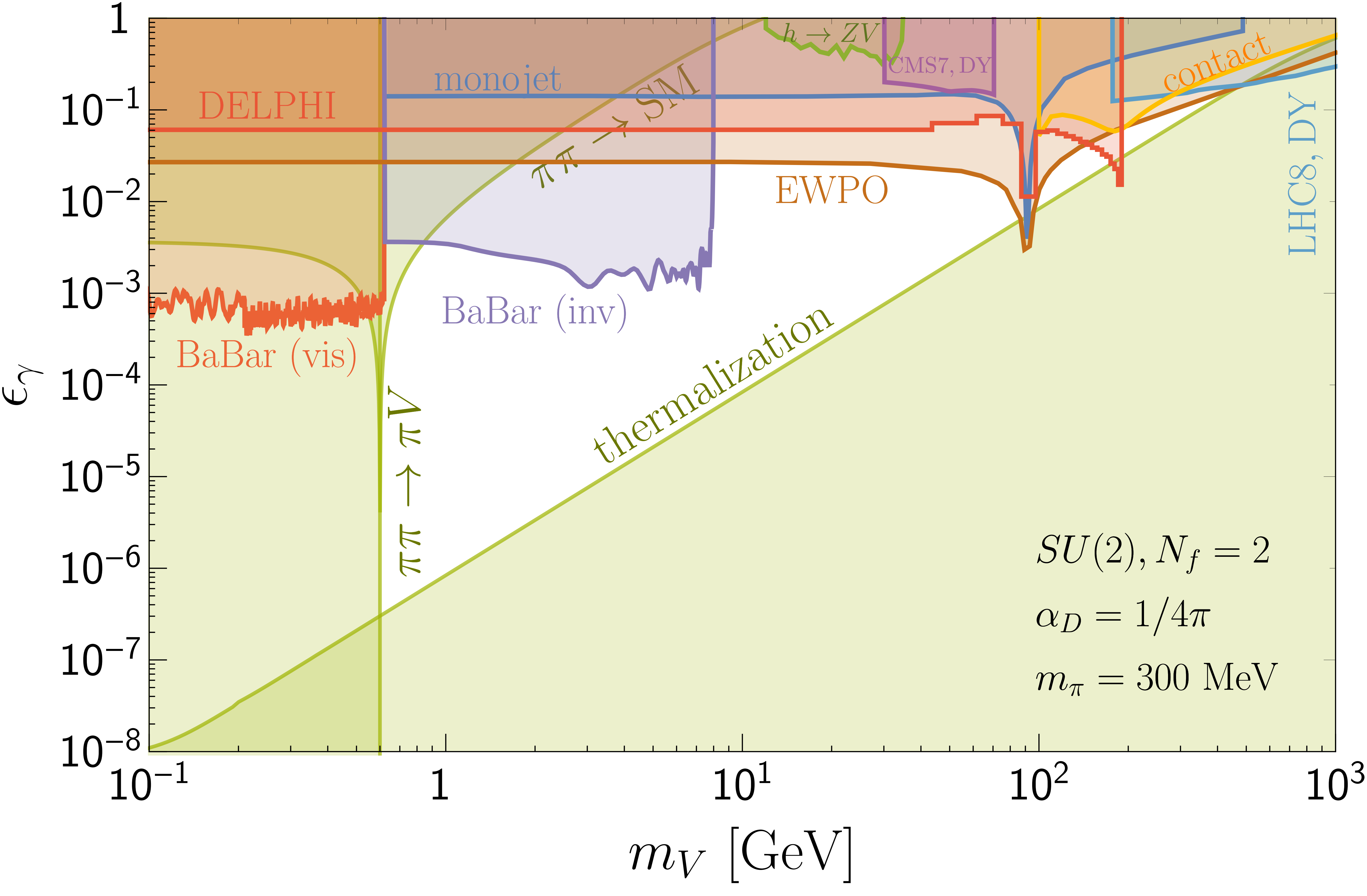
- e.g., the SIMPlest model SU(2) gauge group with N_f=2 (4 doublets)
- gauge U(1)=SO(2) ⊂ SO(2) ×SO(3) ⊂ SO(5)=Sp(4)
- maintains degeneracy of quarks
- near degeneracy of pions for co-annihilation

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

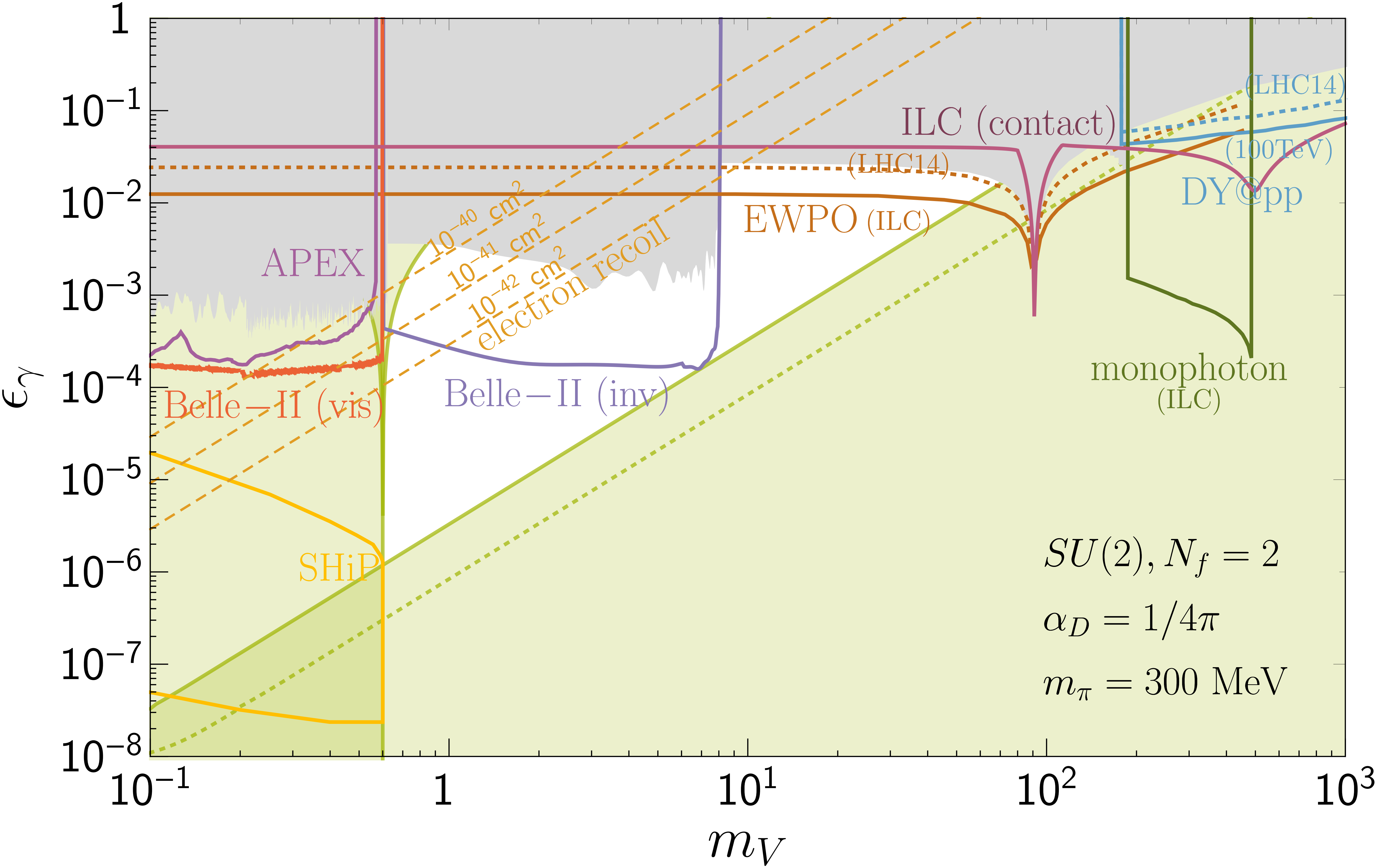
$$(q^+, q^+, q^-, q^-)$$

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

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

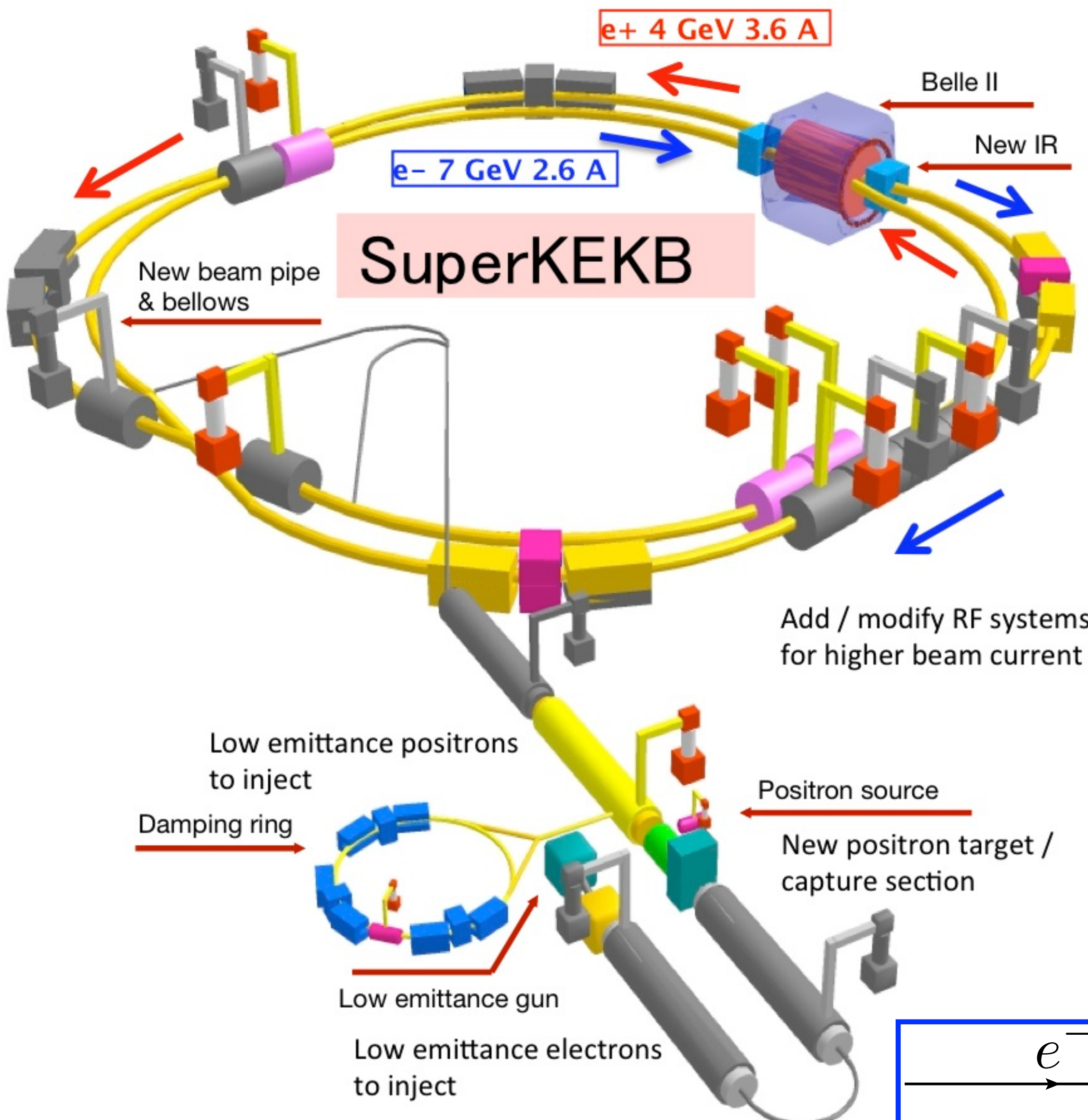


1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
ϵ_γ
10^{-1}
1
10^{1}
10^{2}
10^{3}
m_V [GeV]
DELPHI
monojet
$\pi\pi \to$ SM
$h \to ZV$
CMS7, DY
contact
LHC8, DY
EWPO
BaBar (inv)
BaBar (vis)
$\pi\pi \to \pi V$
thermalization
$SU(2), N_f = 2$
$\alpha_D = 1/4\pi$
$m_\pi = 300$ MeV

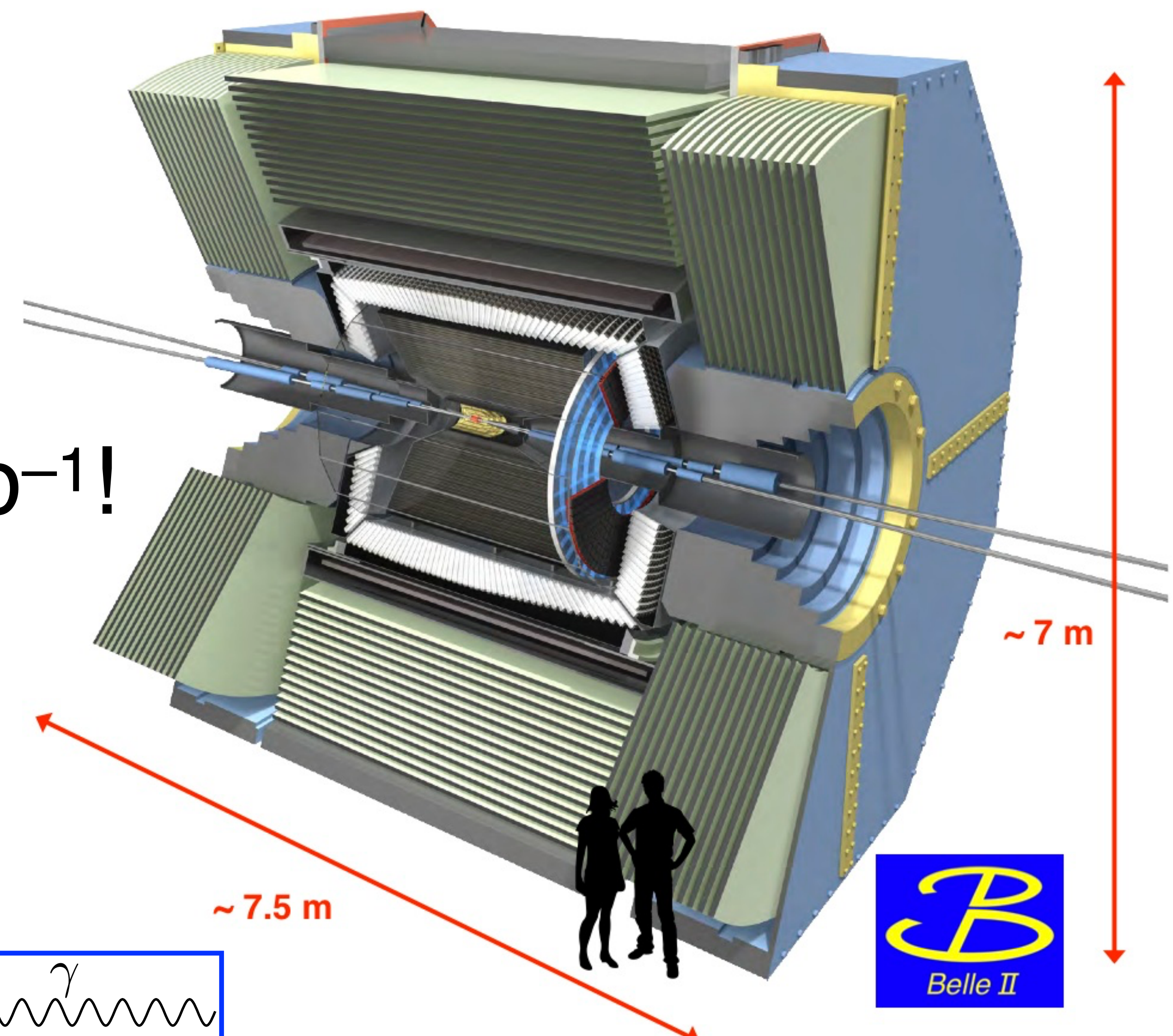


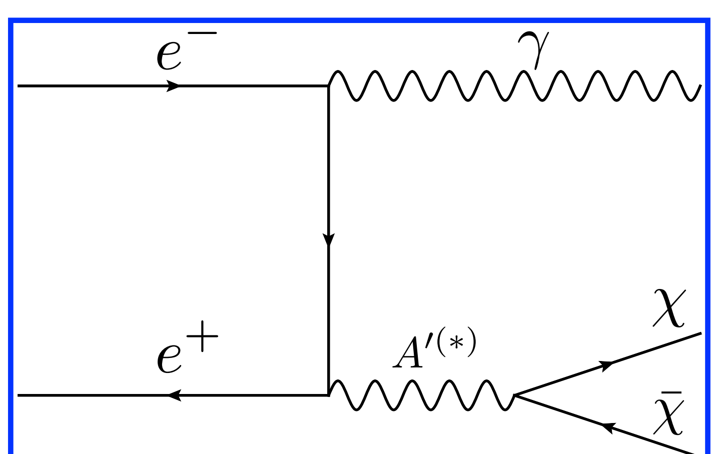
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
ϵ_γ
10^{-1}
1
10^{1}
10^{2}
10^{3}
m_V
ILC (contact)
(LHC14)
(LHC14)
(100TeV)
DY@pp
EWPO (ILC)
APEX
10^{-40} cm^2
10^{-41} cm^2
10^{-42} cm^2
electron recoil
Belle−II (vis)
Belle−II (inv)
monophoton
(ILC)
SHiP
$SU(2), N_f = 2$
$\alpha_D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

Super KEK B & Belle II



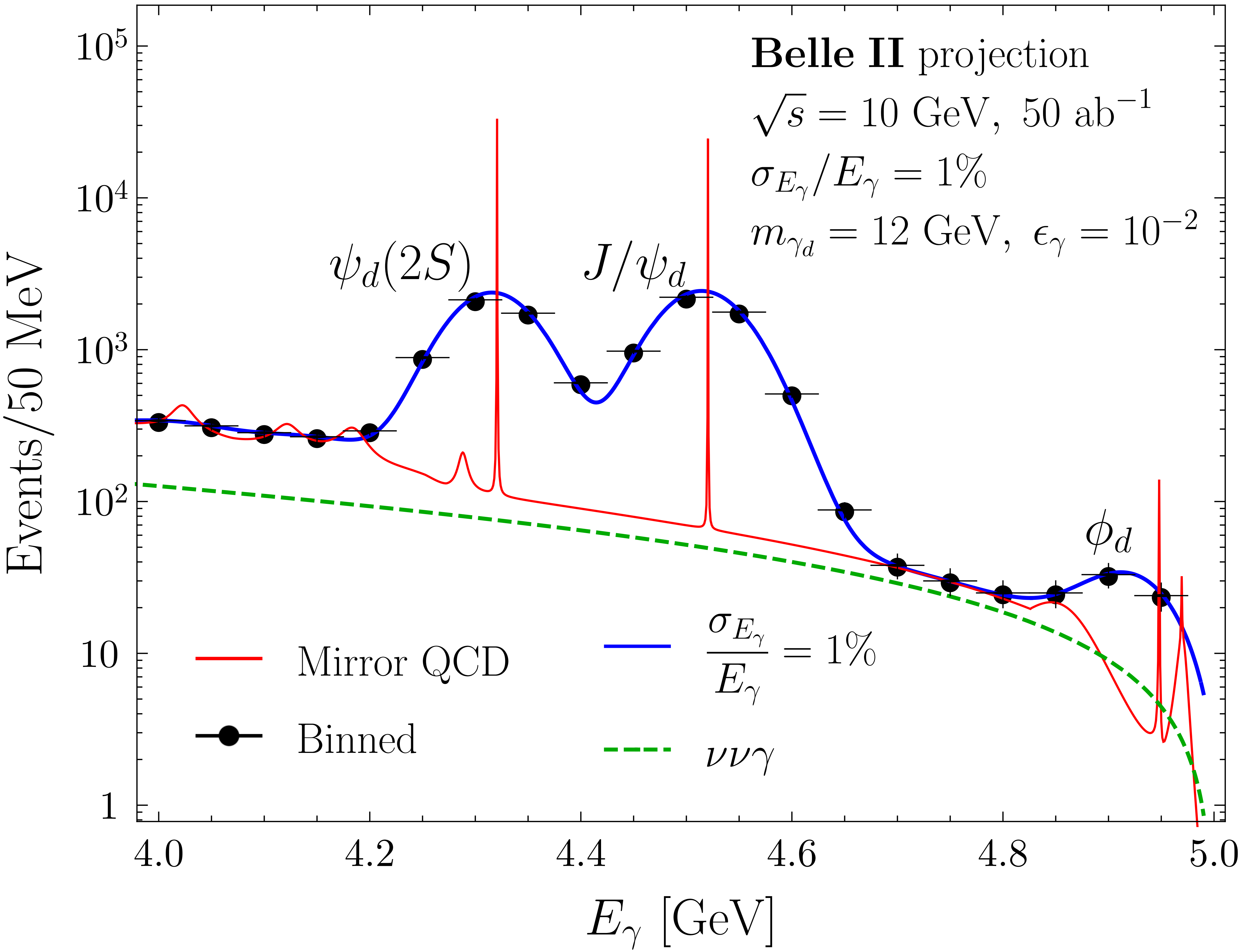
50 ab^{-1}!



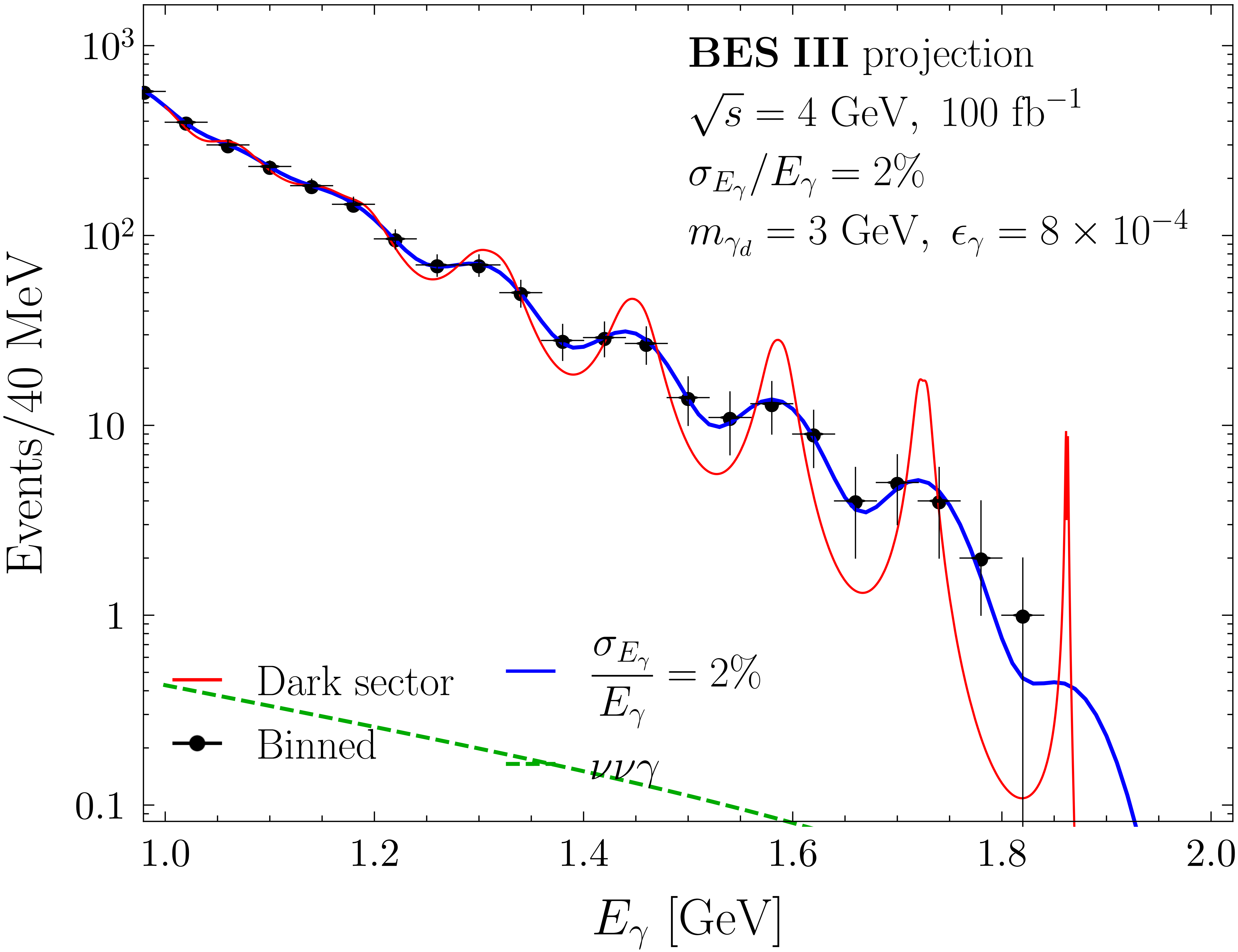


$$E_\gamma = \frac{\sqrt{s}}{2}\left(1 - \frac{M_{\rm inv}^2}{s}\right)$$

Dark Spectroscopy



Dark Spectroscopy



Twin Higgs

- Take two mirror copies of the SM:

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

$\mathbb{Z}_2$ An exchange symmetry. $A \leftrightarrow B$.

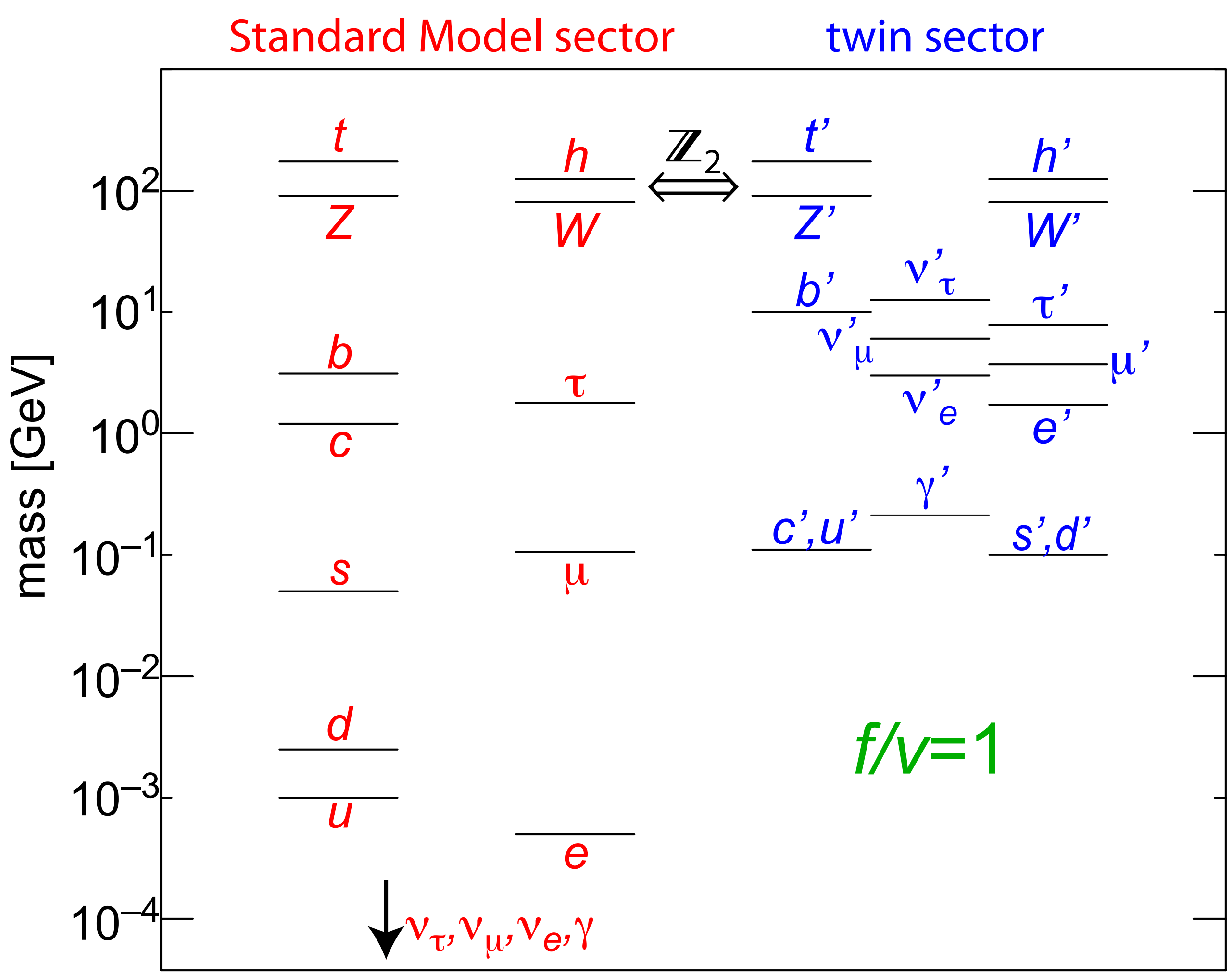
- Assume Higgs potential has an SU(4) or SO(8) global symmetry in the UV.

- Take a small hierarchy of Higgs vevs:

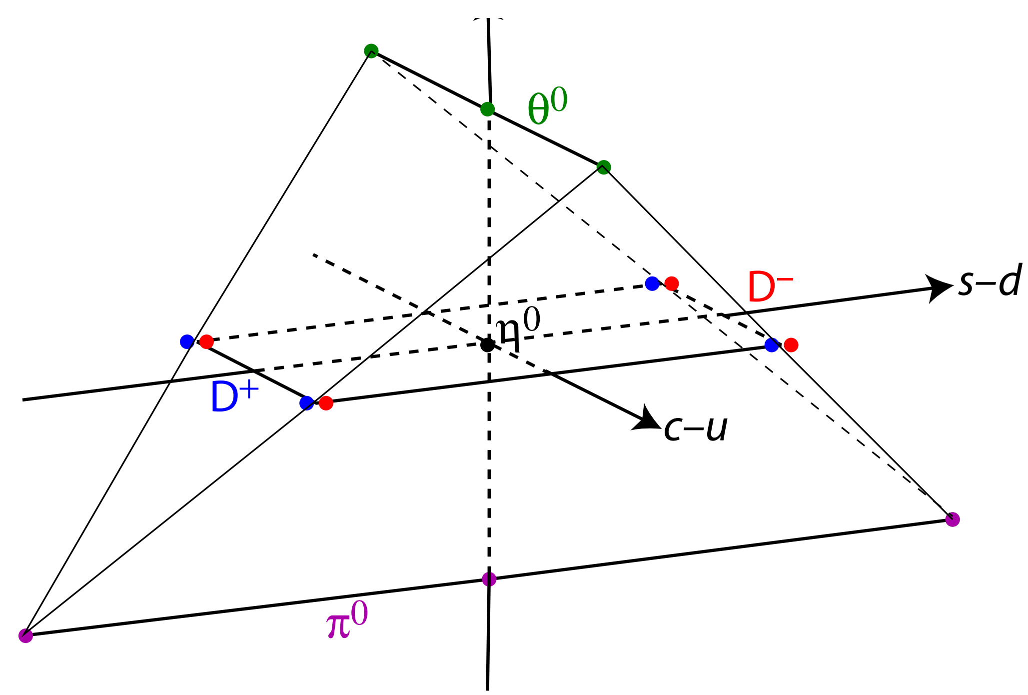
$$\langle H_A \rangle = v \qquad \langle H_B \rangle = f \qquad \text{with } v < f.$$

Chacko, Goh, RH (2005)

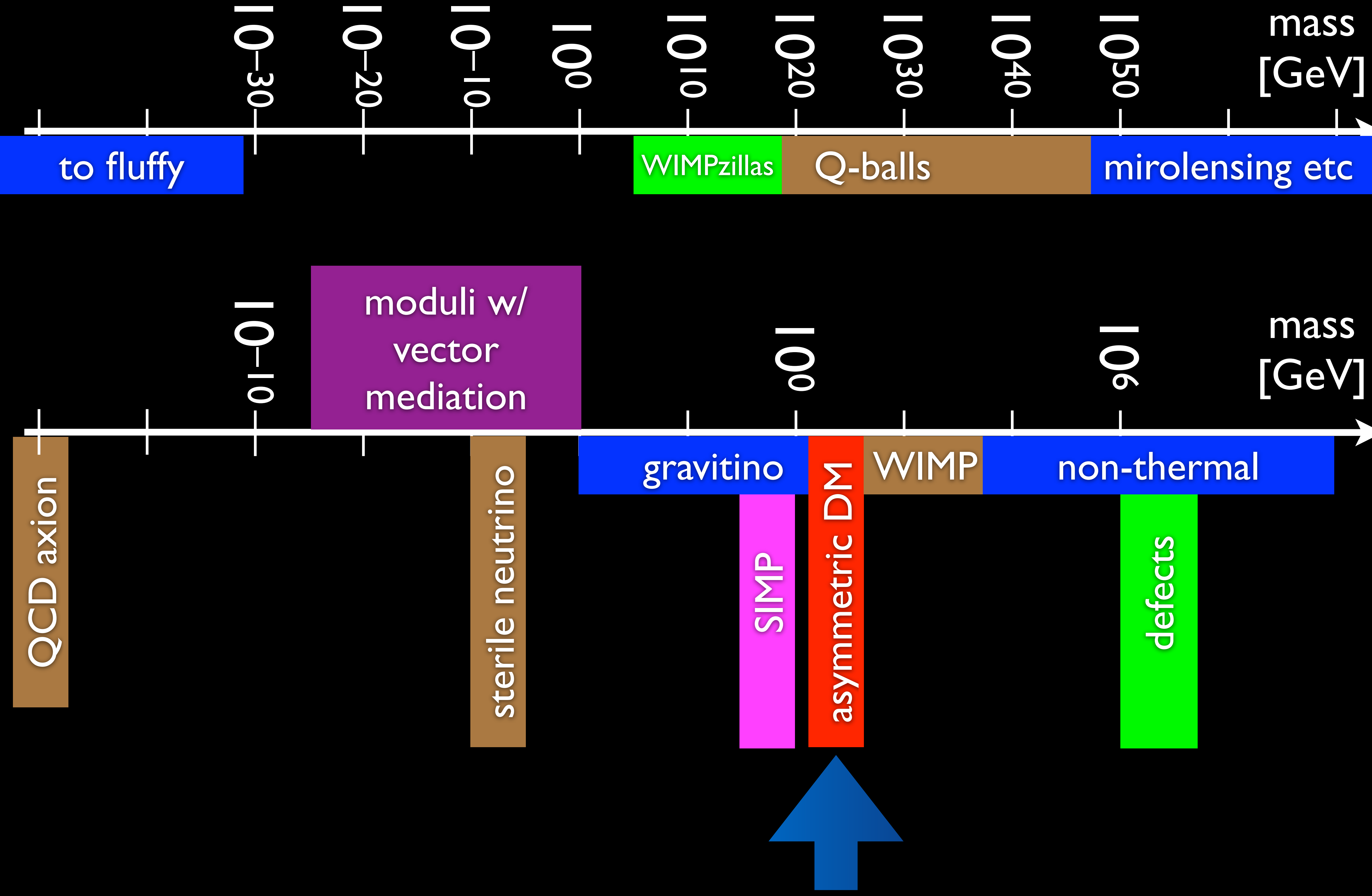
Twin Higgs



meson M	particle content	$m_M^2 \propto$	m_M
$\theta^0(\mathbf{3},\mathbf{1})$	$u'\bar{c}', c'\bar{u}', \frac{1}{\sqrt{2}}(u'\bar{u}' - c'\bar{c}')$	$2m_{u'}$	$m_\pi(1+\Delta)$
$D^+(\mathbf{2},\mathbf{2})$	$u'\bar{d}', c'\bar{d}', u'\bar{s}', c'\bar{s}'$	$m_{u'} + m_{d'}$	$m_\pi(1+\frac{\Delta}{2})$
$D^-(\mathbf{2},\mathbf{2})$	$d'\bar{u}', s'\bar{u}', d'\bar{c}', s'\bar{c}'$	$m_{u'} + m_{d'}$	$m_\pi(1+\frac{\Delta}{2})$
$\eta^0(\mathbf{1},\mathbf{1})$	$\frac{1}{2}(d'\bar{d}' + s'\bar{s}' - u'\bar{u}' - c'\bar{c}')$	$m_{u'} + m_{d'}$	$m_\pi(1+\frac{\Delta}{2})$
$\pi^0(\mathbf{1},\mathbf{3})$	$d'\bar{s}', s'\bar{d}', \frac{1}{\sqrt{2}}(d'\bar{d}' - s'\bar{s}')$	$2m_{d'}$	m_π

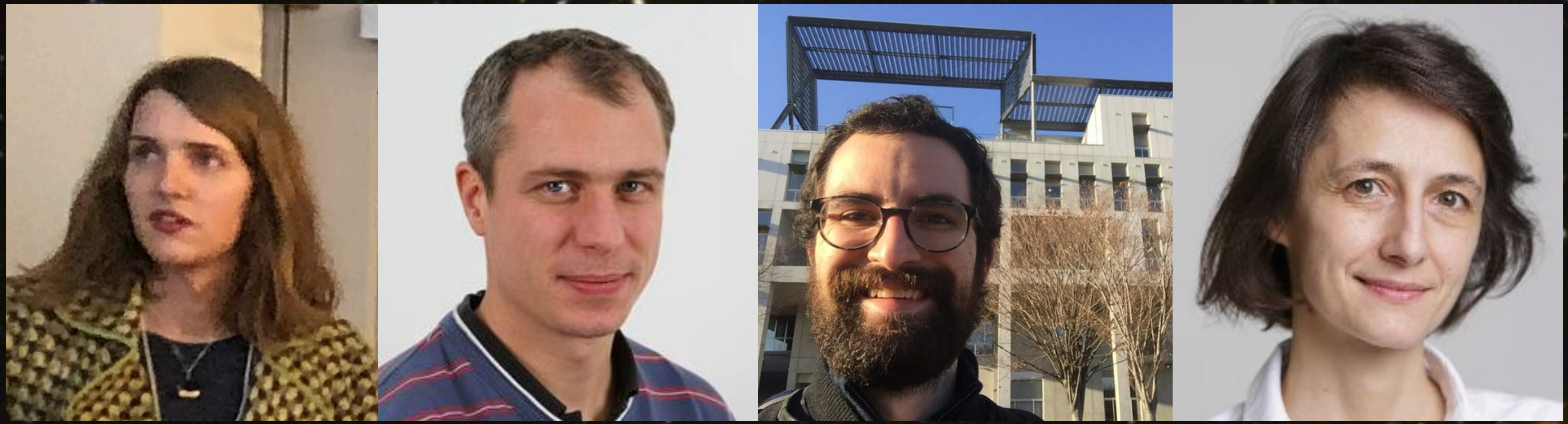


Yonit Hochberg, Eric Kuflik, HM arXiv:1805.09345


10−30
10−20
10−10
100
1010
1020
1030
1040
1050
mass [GeV]
to fluffy
WIMPzillas
Q-balls
mirolensing etc
10−10
moduli w/ vector mediation
100
106
mass [GeV]
QCD axion
sterile neutrino
gravitino
SIMP
asymmetric DM
WIMP
non-thermal
defects

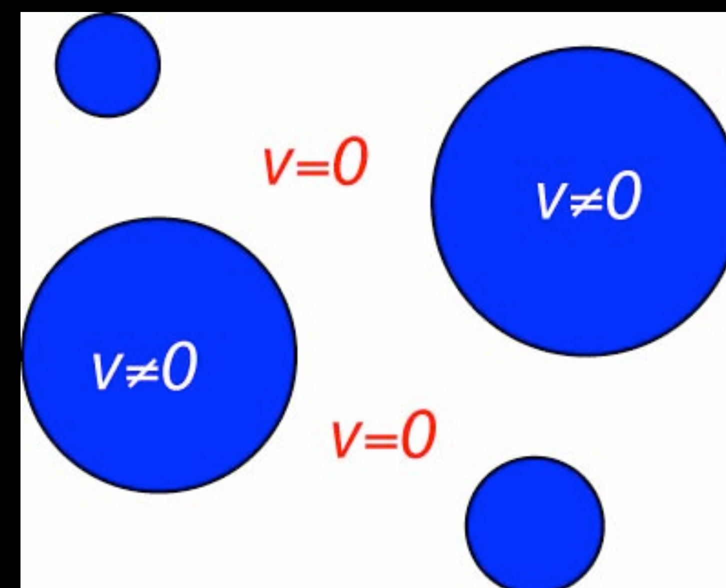
Matters Genesis

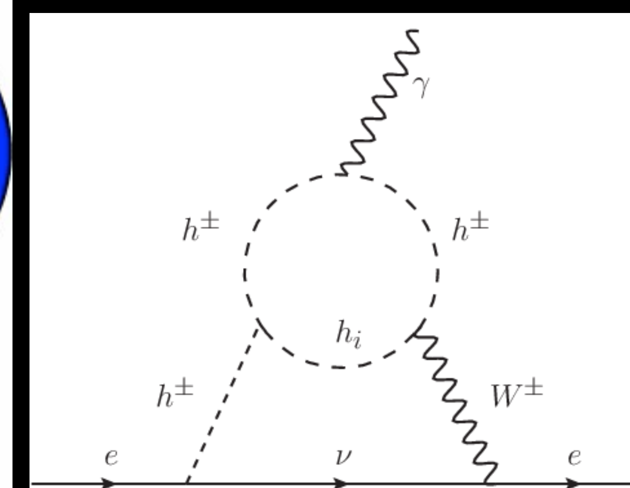
Eleanor Hall, Thomas Konstandin, Robert McGehee, HM,
Géraldine Servant, arXiv:1910.08068, 1911.12342

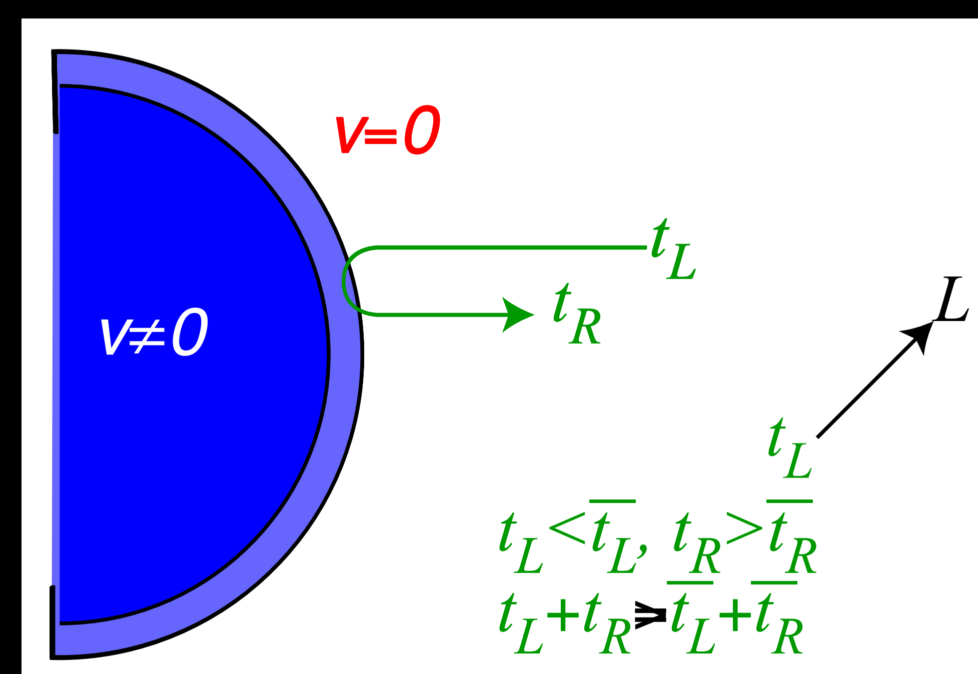


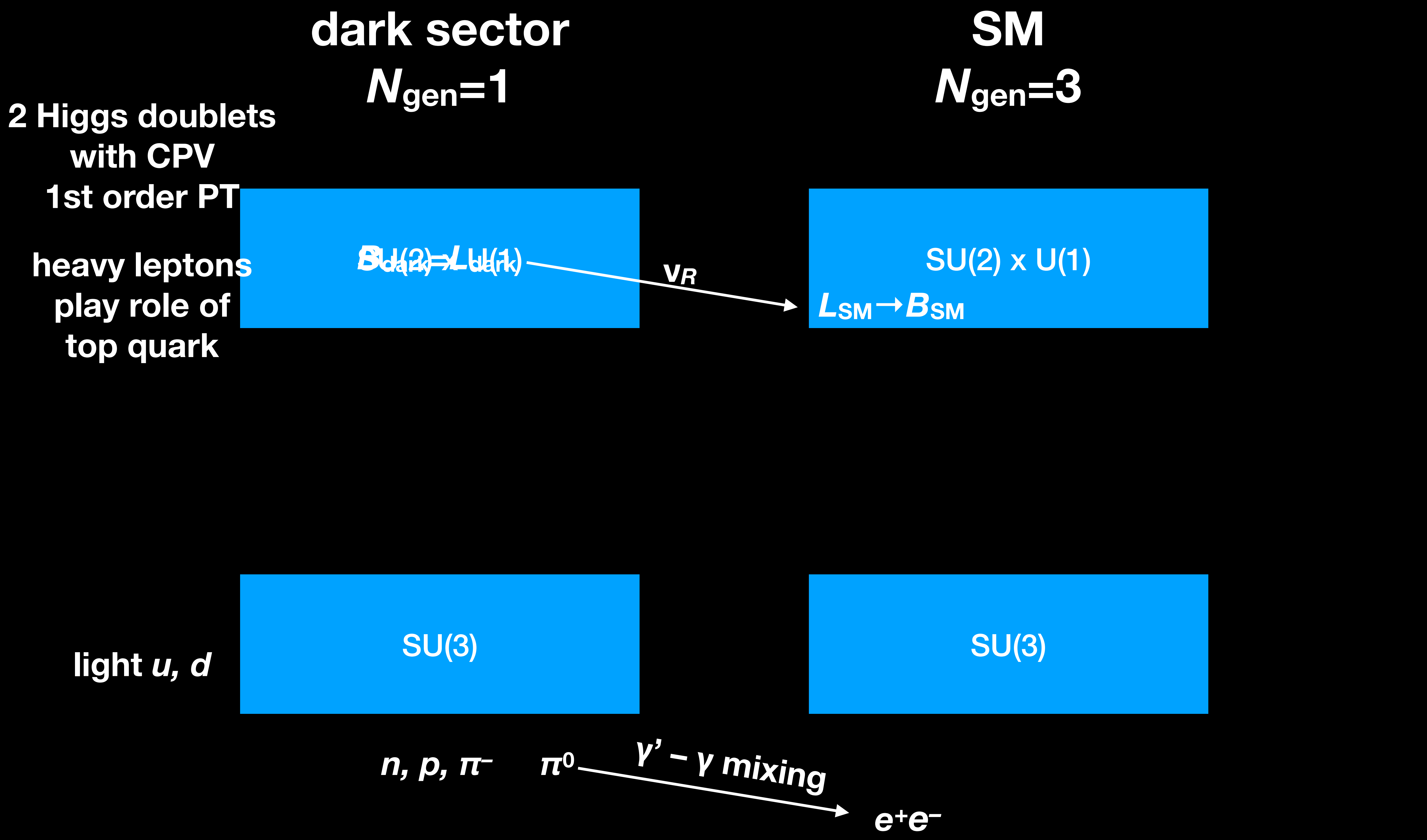
Electroweak Baryogenesis Cohen, Kaplan, Nelson

- First-order phase transition
- Different reflection probabilities for t_L, t_R
- asymmetry in top quark
- Left-handed top quark asymmetry partially converted to lepton asymmetry via anomaly
- Remaining top quark asymmetry becomes baryon asymmetry
- need *varying CP phase* inside the bubble wall (G. Servant)
- fixed KM phase doesn't help
- need CPV in Higgs sector
- but ACME limit on EDM

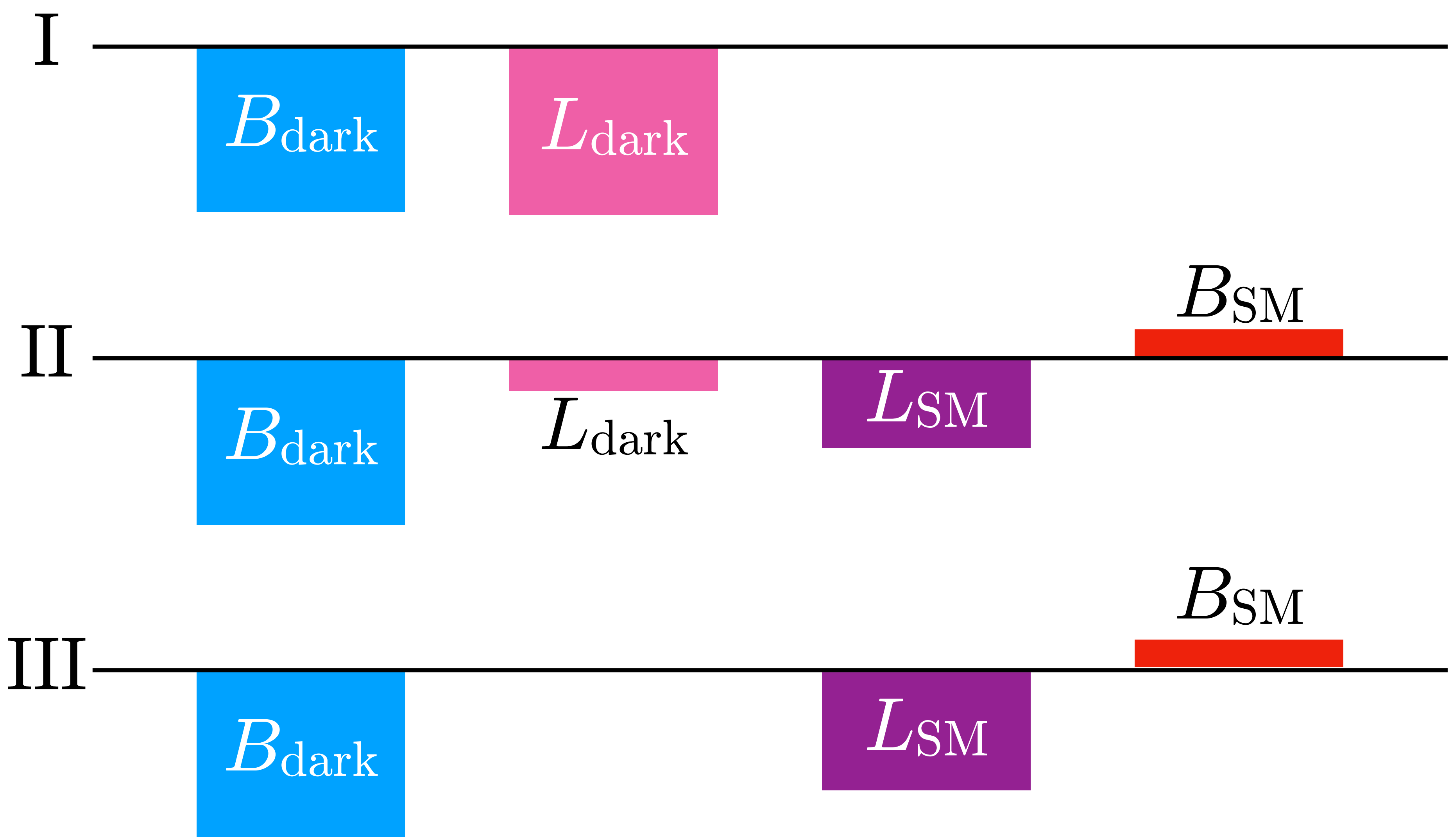








Eleanor Hall, Thomas Konstandin, Robert McGehee, HM + Géraldine Servant
arXiv:1911.12342



If $M_N > T_{\rm sphaleron}$ $B_{\rm SM} = \frac{36}{133} B_{\rm dark}$, $L_{\rm SM} = -\frac{97}{133} B_{\rm dark}$ **$m_{n'}$=1.58 GeV**

If $M_N < T_{\rm sphaleron}$ $B_{\rm SM} = \frac{12}{37} B_{\rm dark}$, $L_{\rm SM} = -\frac{25}{37} B_{\rm dark}$ **$m_{n'}$=1.33 GeV**

some history

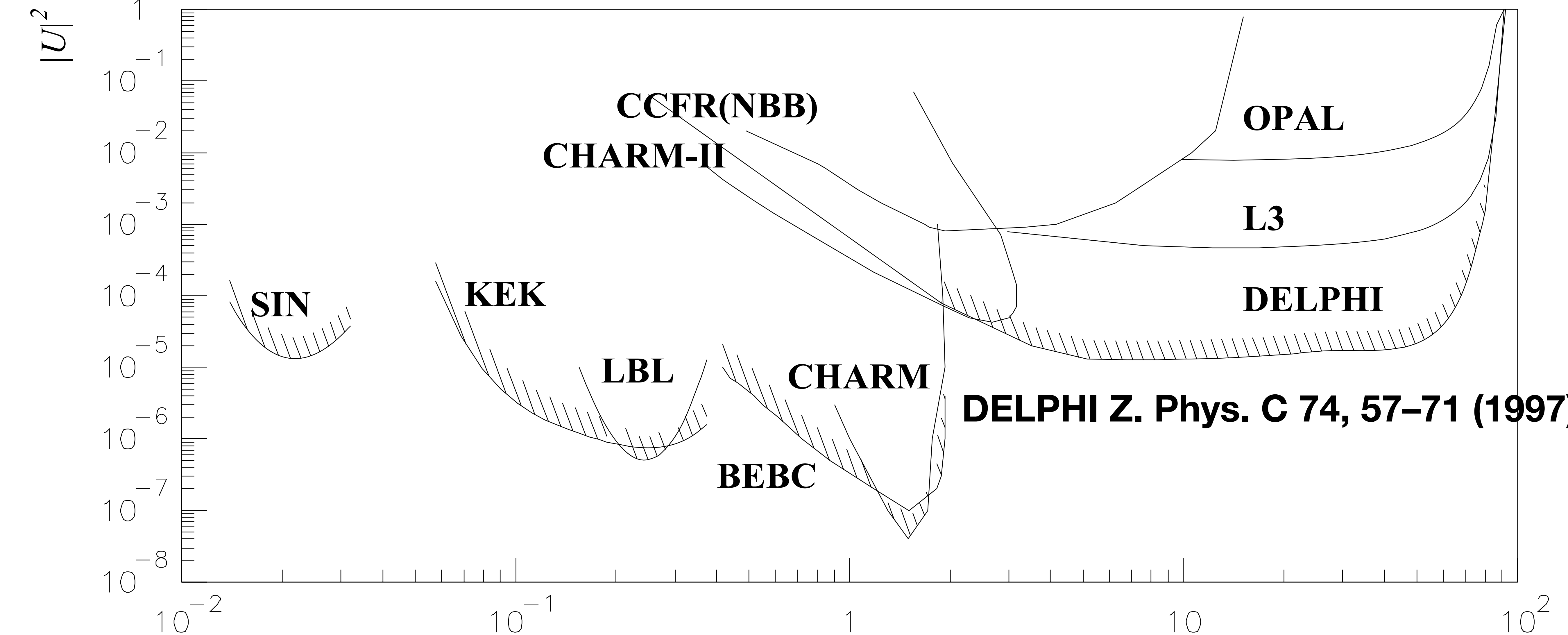
- asymmetric dark matter (why $\Omega_b/\Omega_{DM} \approx O(1)$?)
  - S. Nussinov, PLB 165, 55 (1985) “technocosmology”
  - R. Kitano, HM, M. Ratz, arXiv:0807.4313, moduli decay
  - D.E. Kaplan, M. Luty, K. Zurek, arXiv:0901.4117
- darkogenesis (= “EW baryogenesis” in the dark sector)
  - J. Shelton, K. Zurek, arXiv:1008.1997

neutrino portal

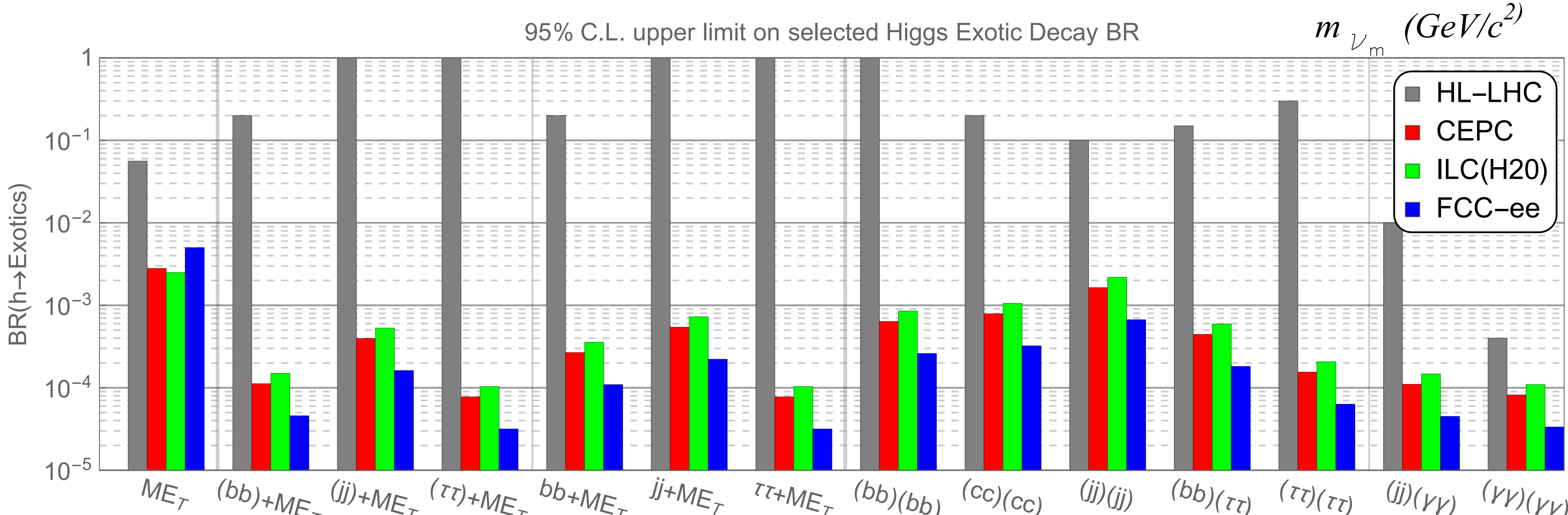
$$\mathcal{L} = y' \bar{L}' H \nu_R + y_i \bar{L}_i H \nu_R$$

$$\epsilon_i = \frac{y_i}{\sqrt{(y')^2 + (y_i)^2}} \qquad M_\nu = \sqrt{(y')^2 + (y_i)^2} v$$

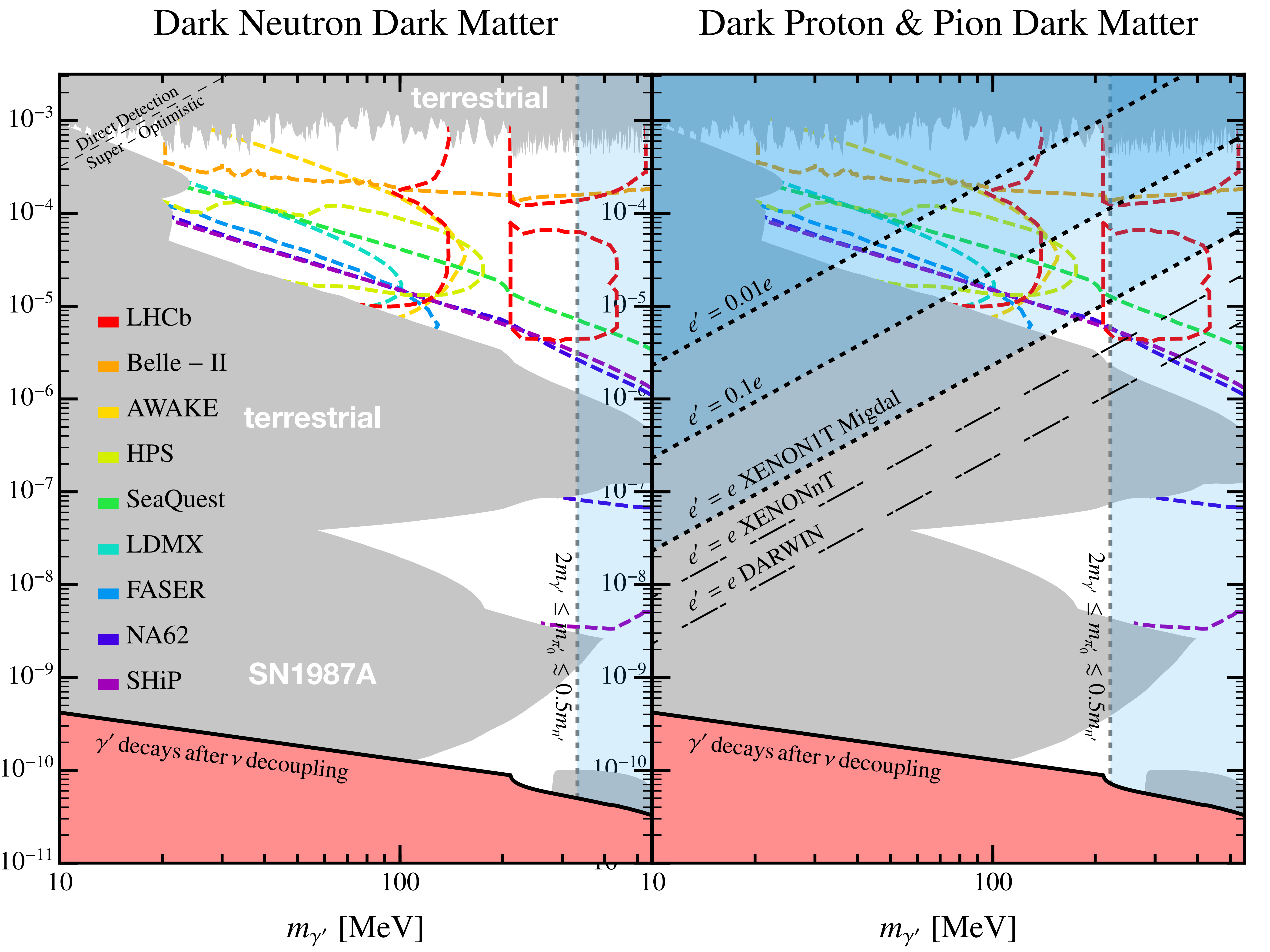
- charged current universality: $\varepsilon_i^2 < 10^{-3}$
- $\mu \rightarrow e\, \gamma$ constraint: $\varepsilon_e\, \varepsilon_\mu < 4\times10^{-5}$ $(G_F M_\nu)$
- $\tau \rightarrow \mu\, \gamma$ constraint: $\varepsilon_e\, \varepsilon_\mu < 0.03$ $(G_F M_\nu)$
- If M_ν <70 GeV, $\varepsilon_i^2 < 10^{-5}$
  (DELPHI: $Z \rightarrow \nu\, \nu_R$, $\nu_R \rightarrow l f f$)
- equilibration of asymmetries requires only $\varepsilon_i > 10^{-16}$ or so



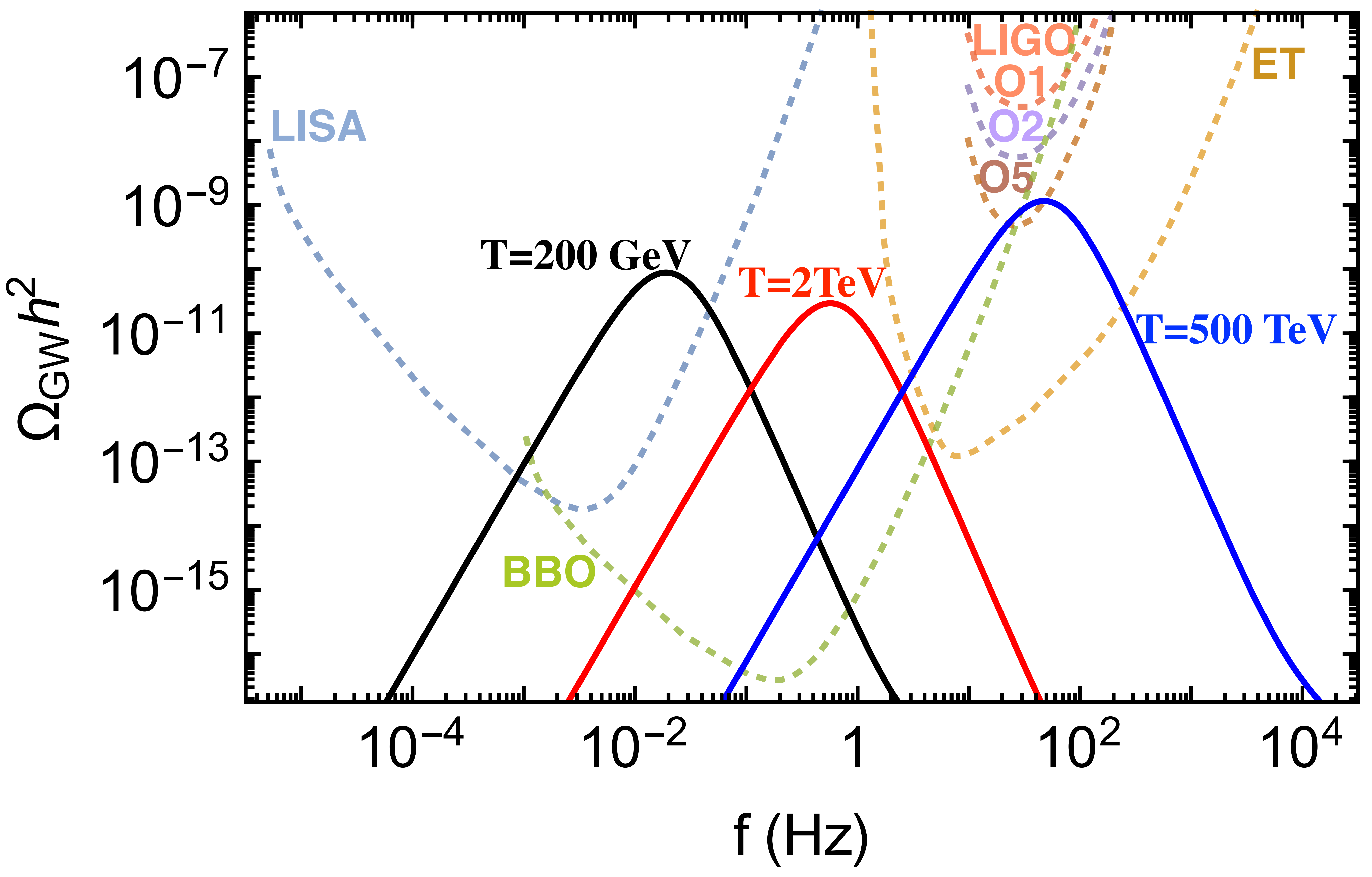
DELPHI Z. Phys. C 74, 57–71 (1997)



Zhen Liu, Lian-Tao Wang, Hao Zhang, arXiv:1612.09284



Dark Neutron Dark Matter
Dark Proton & Pion Dark Matter
terrestrial
Direct Detection
Super − Optimistic
LHCb
Belle − II
AWAKE
HPS
SeaQuest
LDMX
FASER
NA62
SHiP
terrestrial
SN1987A
γ' decays after ν decoupling
$2m_{\gamma'} \leq m_{\pi'_0} \lesssim 0.5 m_{n'}$
$e' = 0.01e$
$e' = 0.1e$
$e' = e$ XENON1T Migdal
$e' = e$ XENONnT
$e' = e$ DARWIN
$m_{\gamma'}$ [MeV]
10
100
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}



LISA
LIGO
O1
O2
O5
ET
BBO
T=200 GeV
T=2TeV
T=500 TeV
10^{-7}
10^{-9}
10^{-11}
10^{-13}
10^{-15}
$\Omega_{GW}h^2$
10^{-4}
10^{-2}
1
10^{2}
10^{4}
f (Hz)

New Methods for Dark Matter Discovery

- QCD is *beautiful*. Nature may use it again.
- dark matter, baryon asymmetry, hierarchy problem
- direct detection, beam dump, Mu2e, etc
- Dark spectroscopy
- resonant self-interaction in dwarf galaxies
- rare Z and Higgs decays
- gravitational wave

dark
sector

QCD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OF PHYSICS

Thank you!