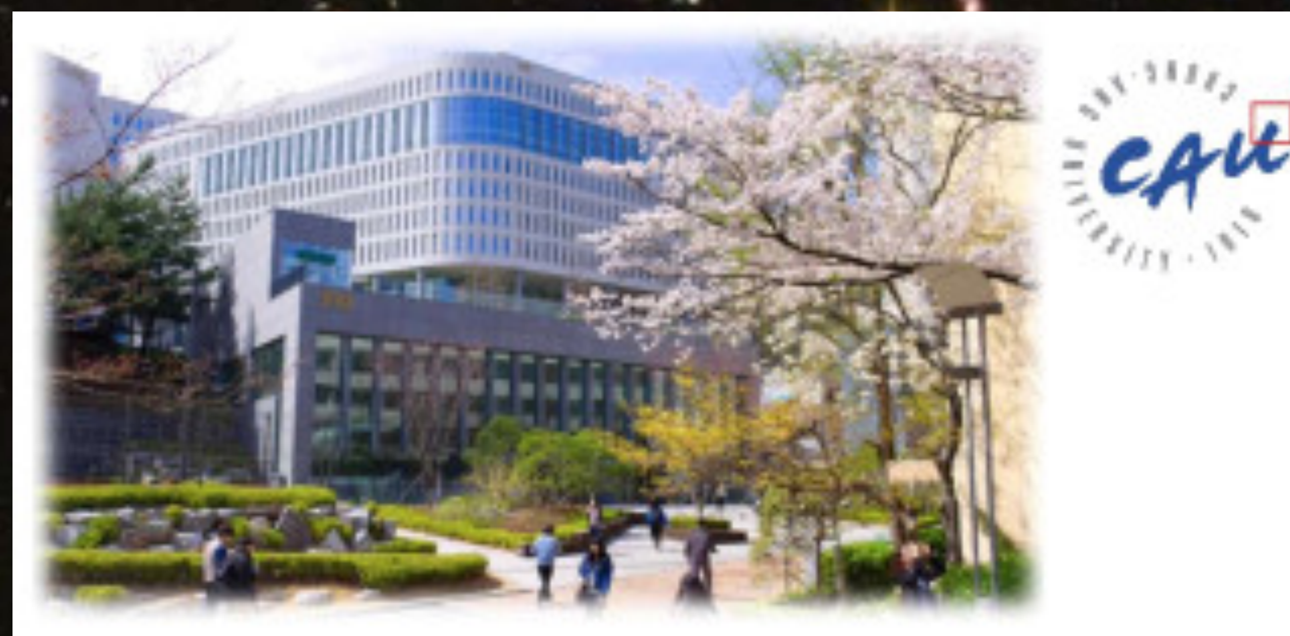
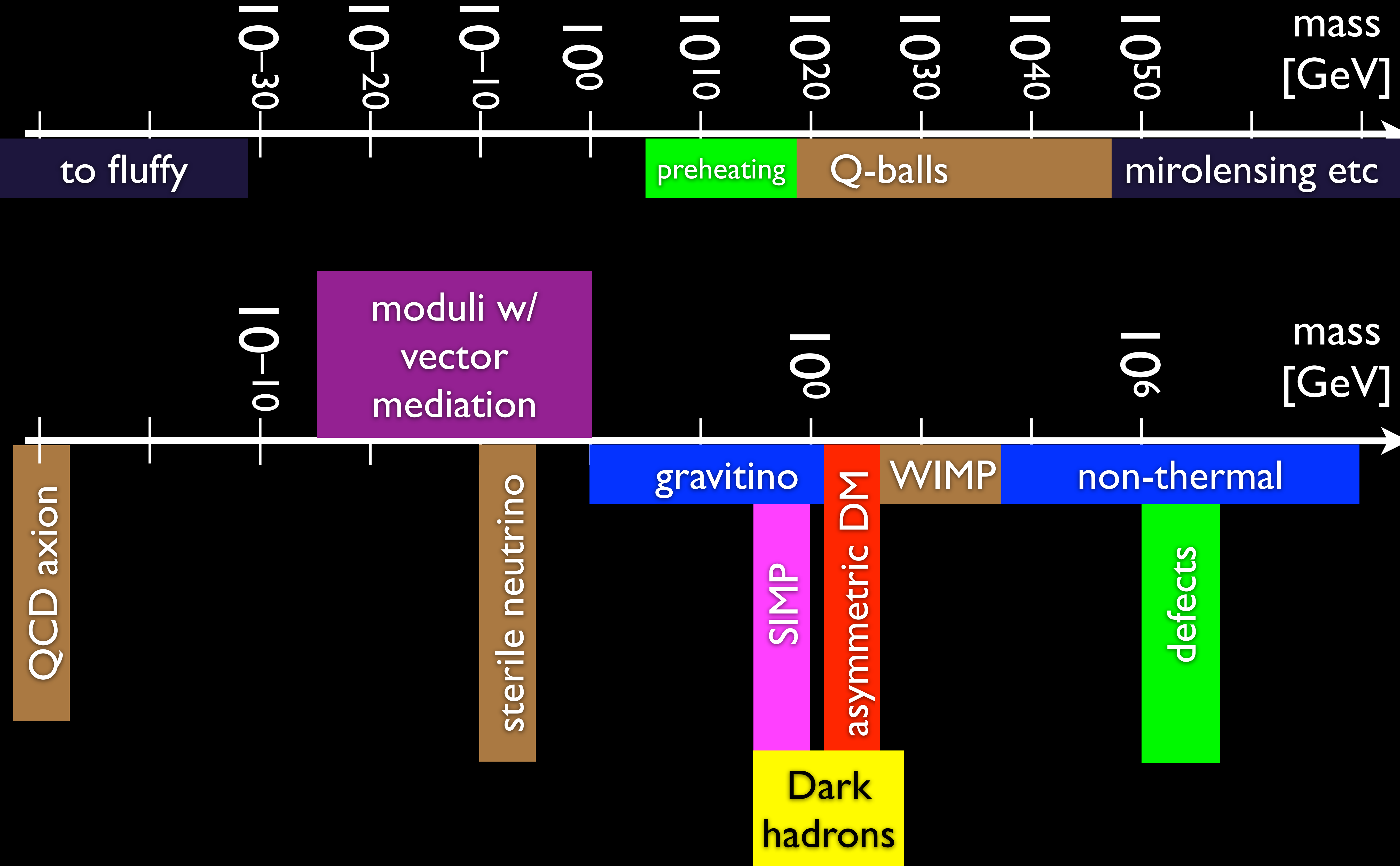
Fun with Composite Dark Matter



Hitoshi Murayama (Berkeley, Kavli IPMU)

2022 CAU BSM Workshop

Feb 8, 2022

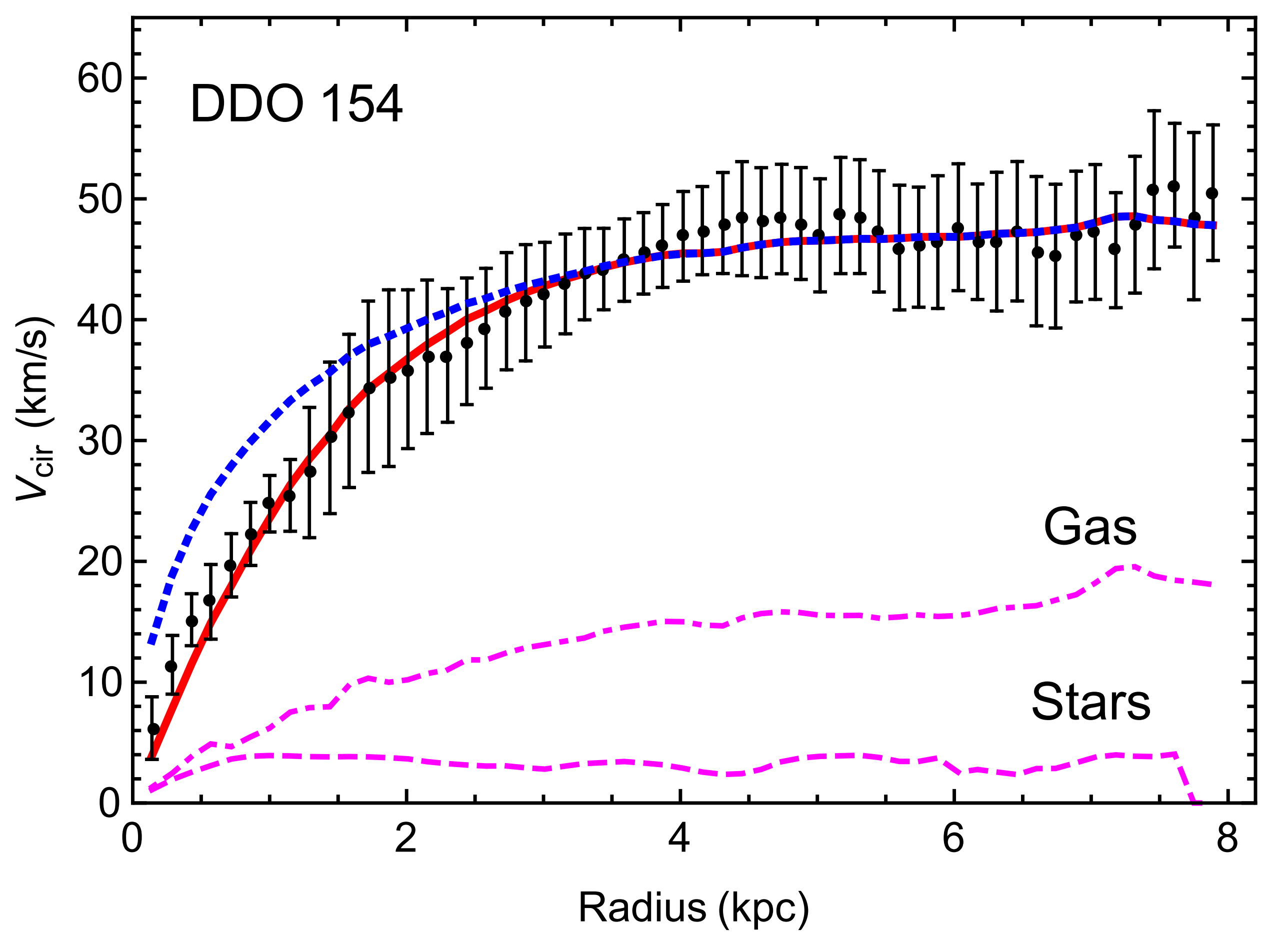


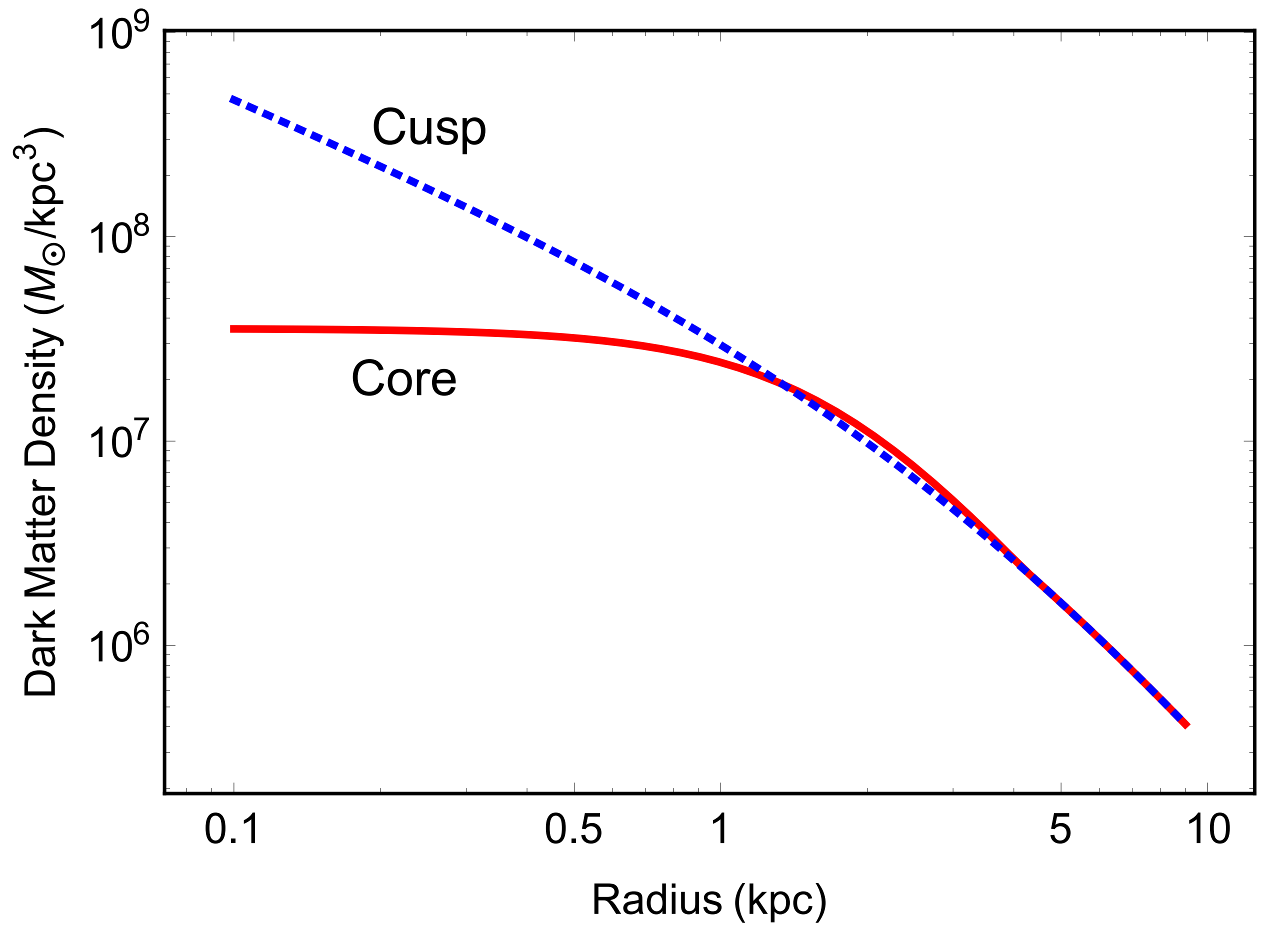
Can't do justice to many many ideas in the literature!

Why Composite?

- 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 resonance: Dark QCD can provide it
- asymmetric dark matter
  - need to shed symmetric component: Easy for Dark QCD
- Also hierarchy problem, baryon asymmetry

DDO 154 dwarf galaxy



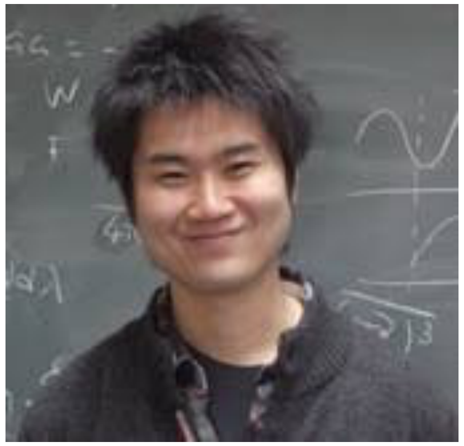


can be explained if dark matter scatters against itself
Need Self-Interacting Dark Matter $\sigma/m \sim$ 1b / GeV
(Spergel, Steinhardt astro-ph/9909386)
if true, only astrophysical information beyond gravity

Diversity in stellar distribution

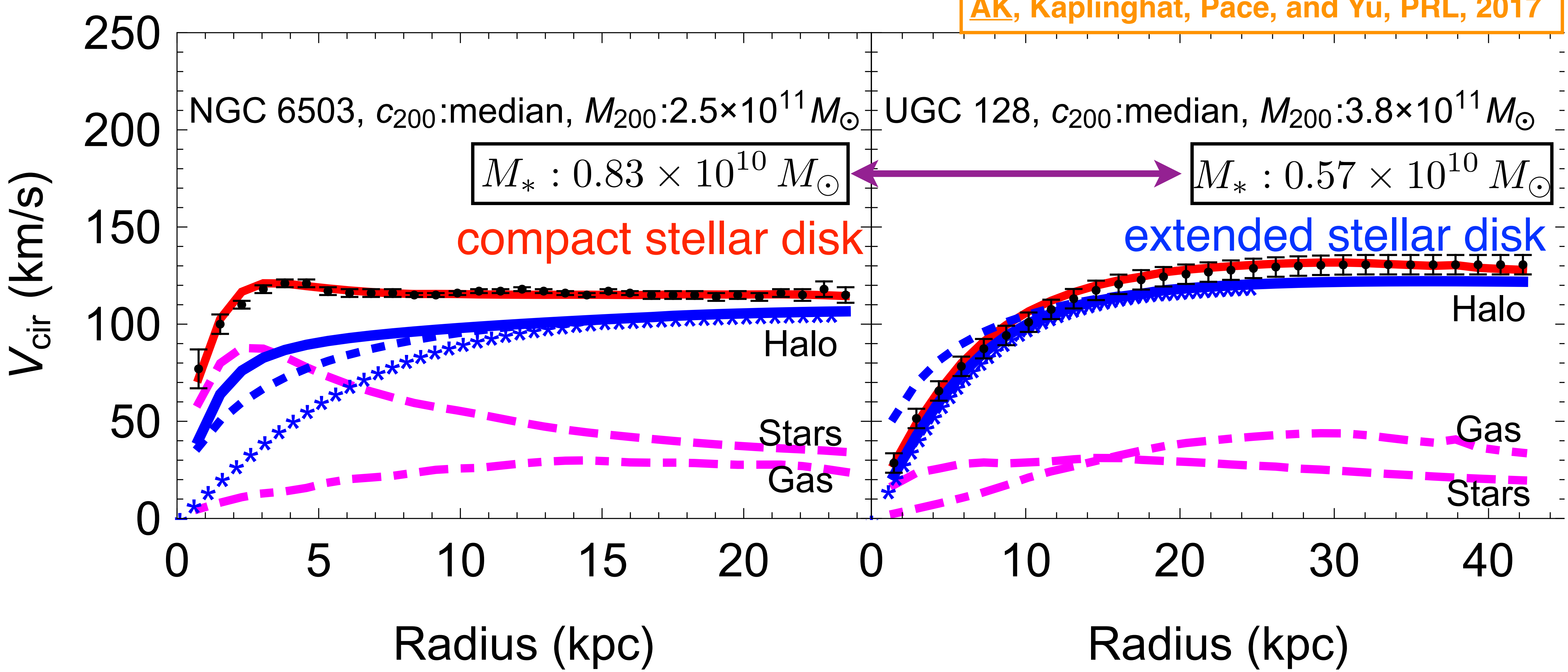
Similar outer circular velocity and stellar mass, but different stellar distribution

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

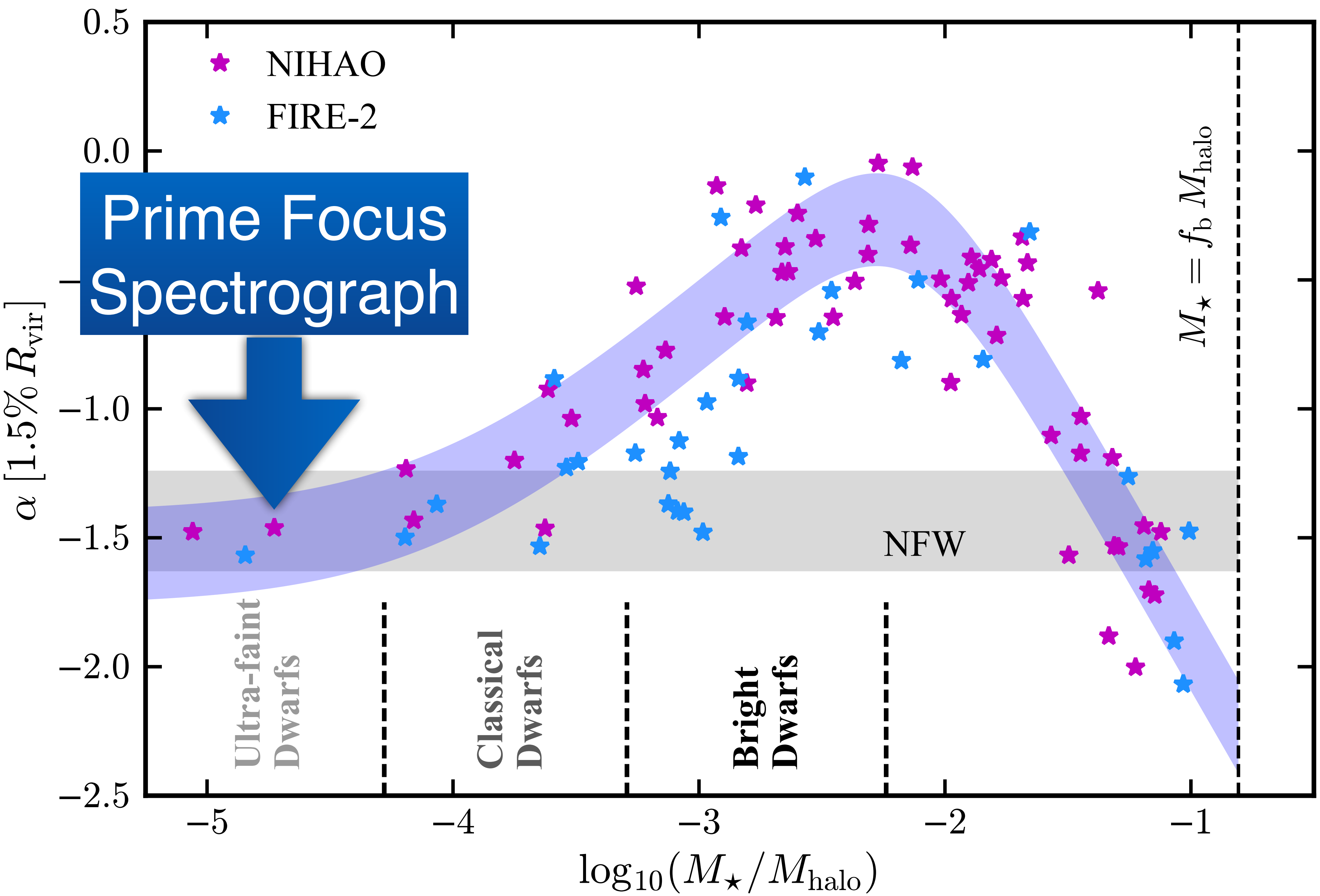


Ayuki Kamada

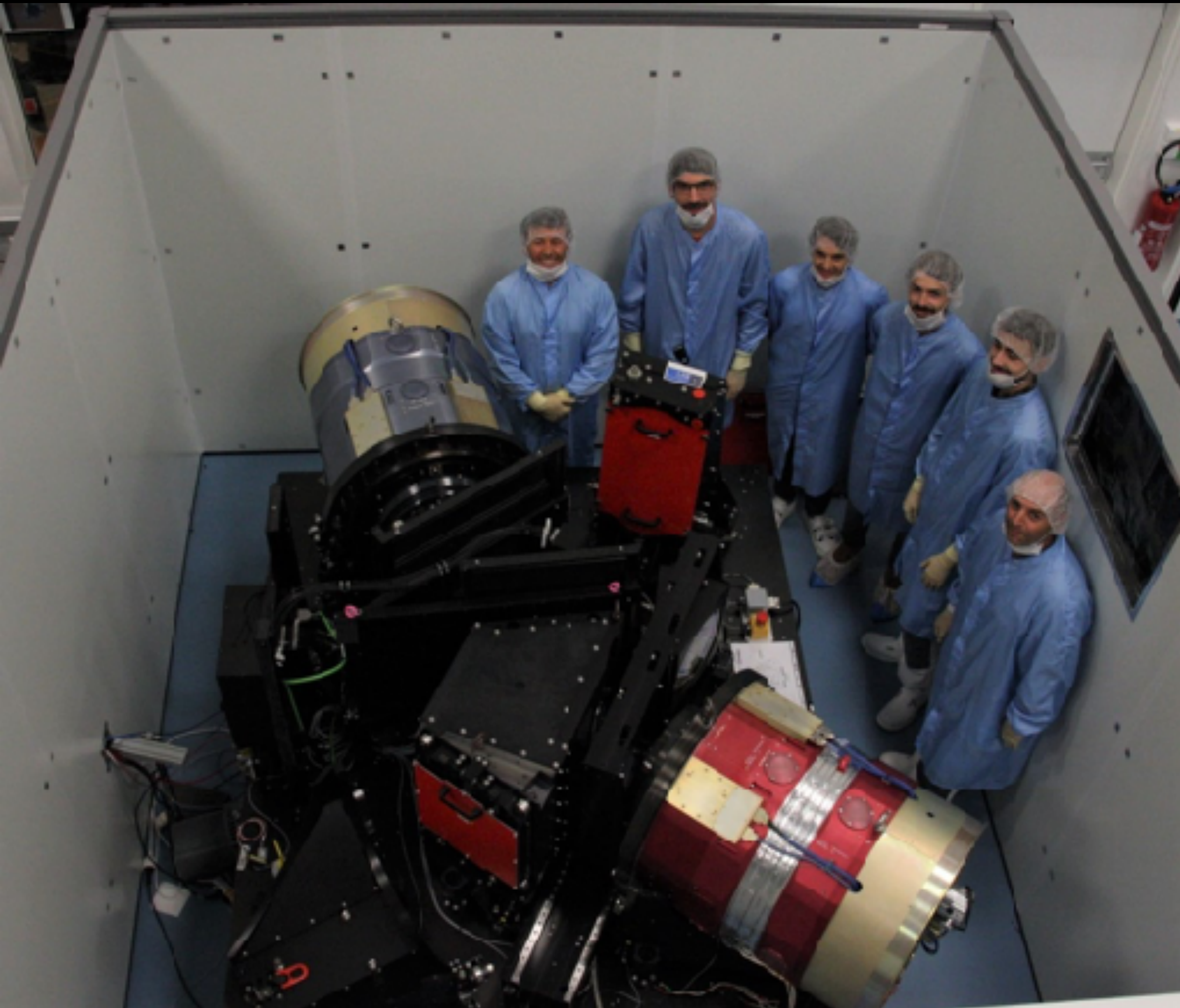
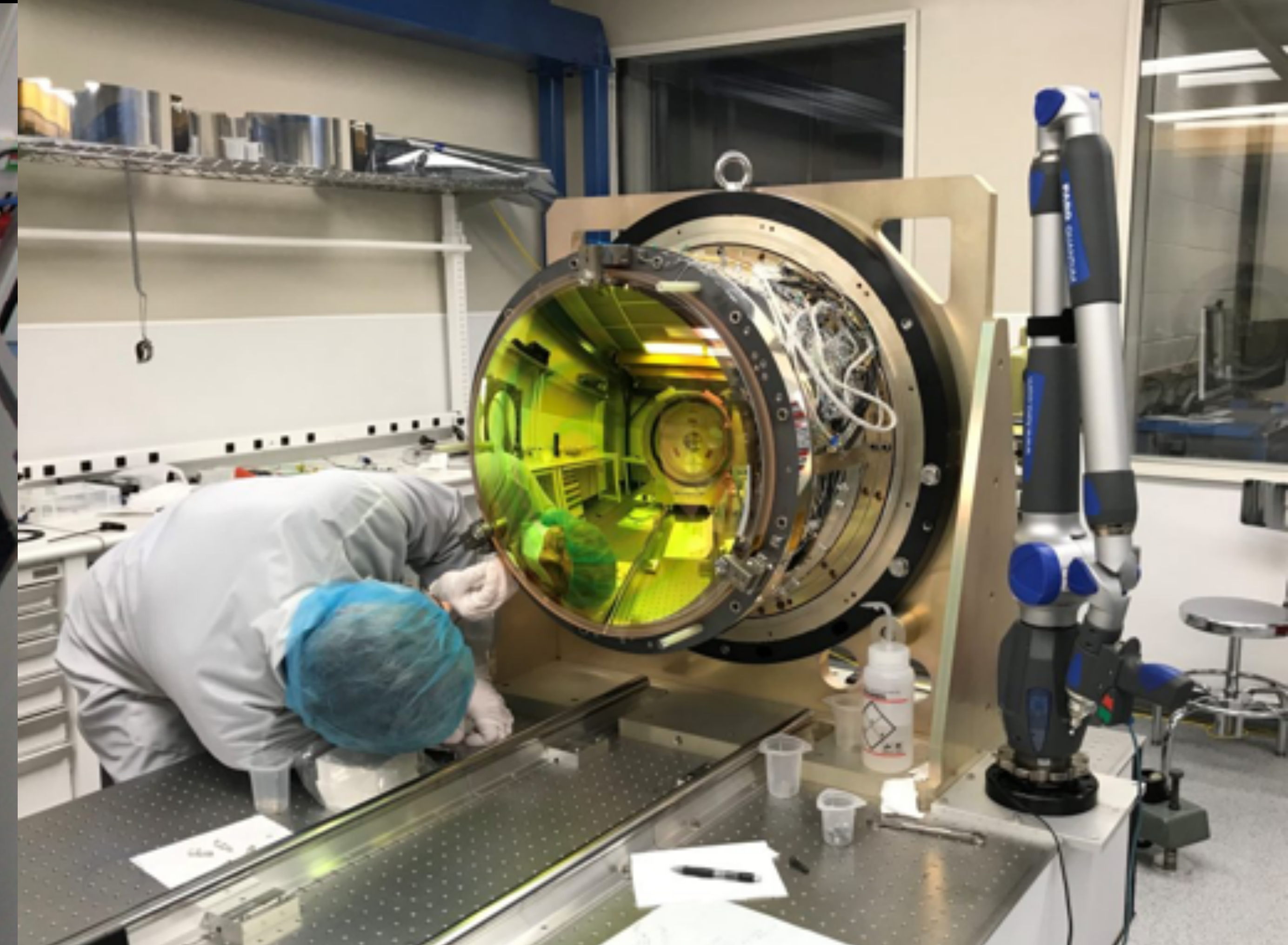
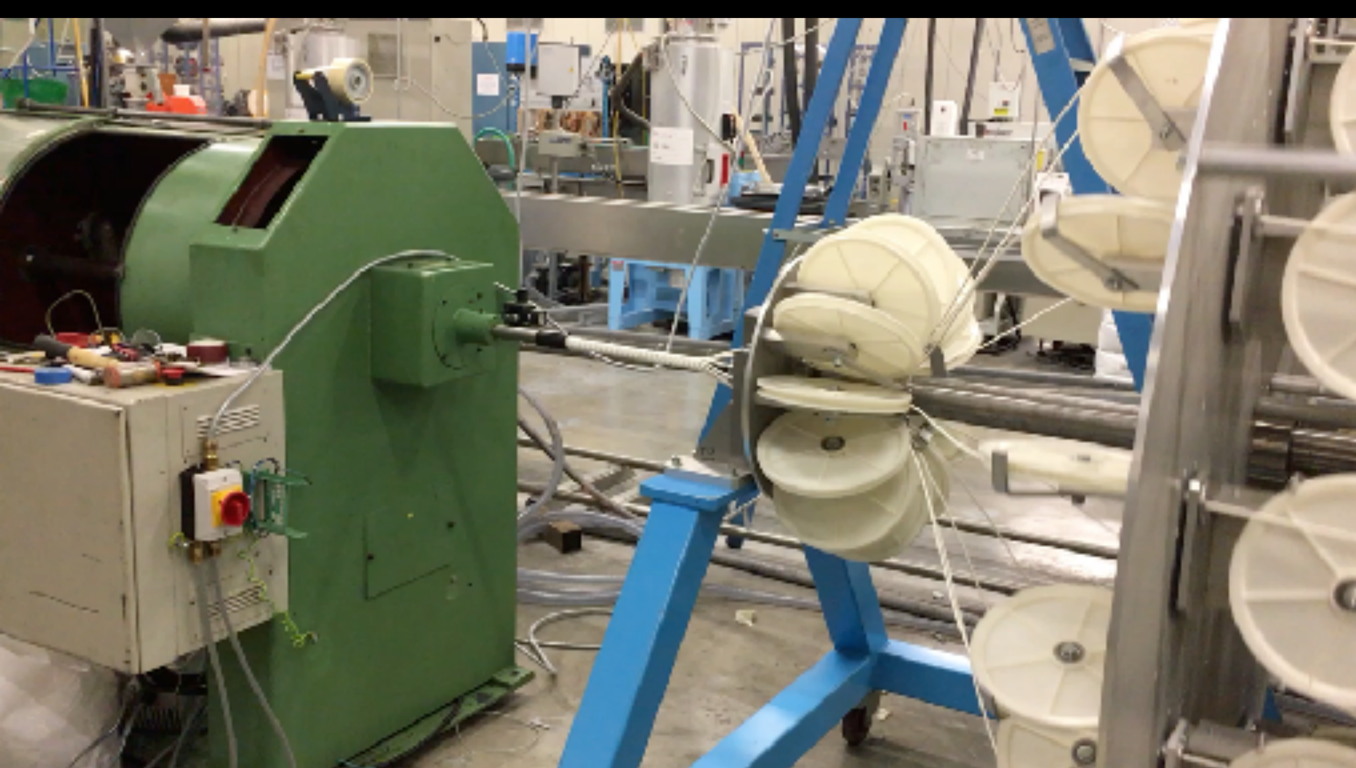
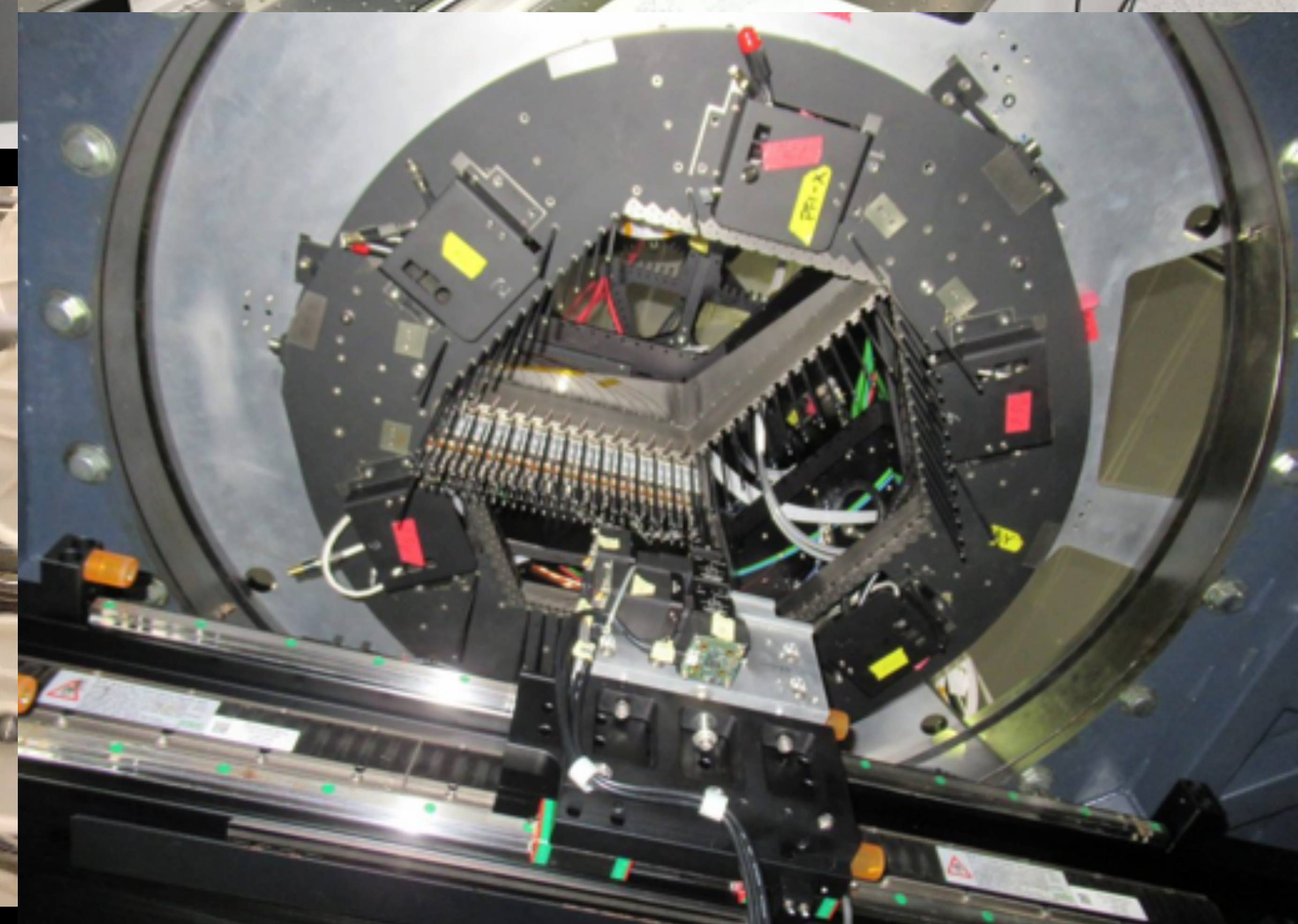
AK, Kaplinghat, Pace, and Yu, PRL, 2017



Baryonic Feedback?



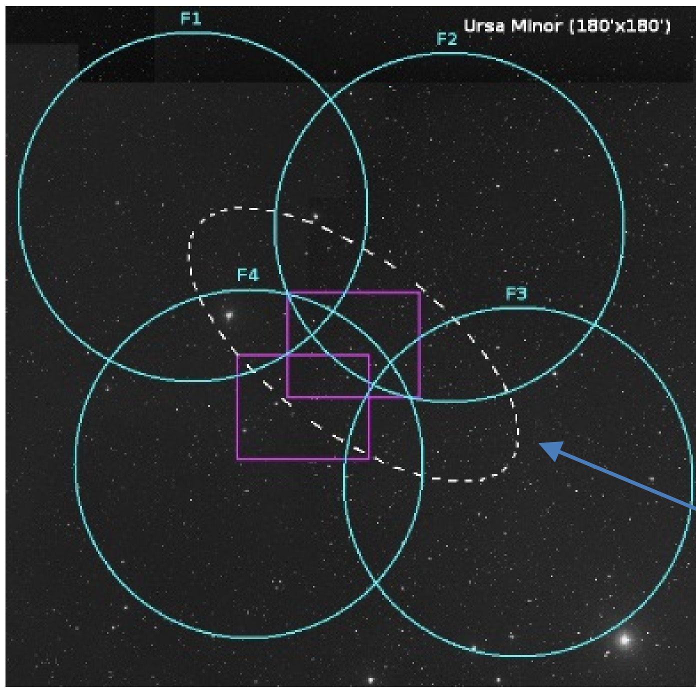
James S. Bullock and Michael Boylan-Kolchin, arXiv:1707.04256

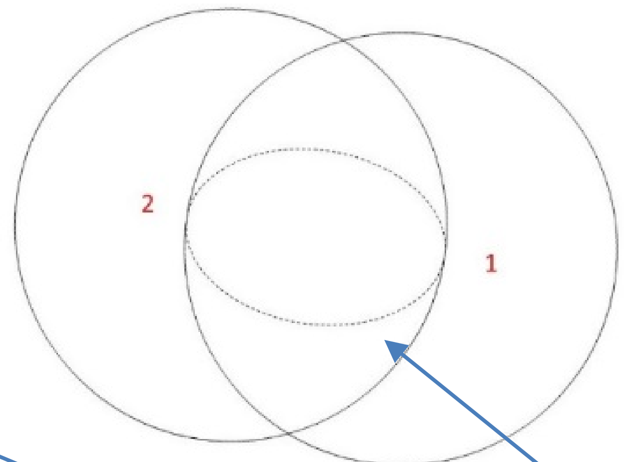
PFS pointings for MW satellites

~ HSC imaging data are available for all samples ~

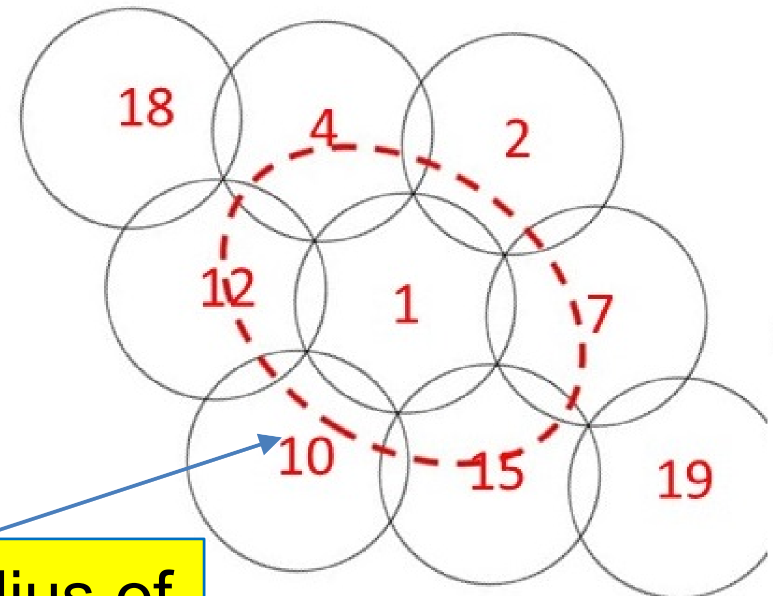
Ursa Minor



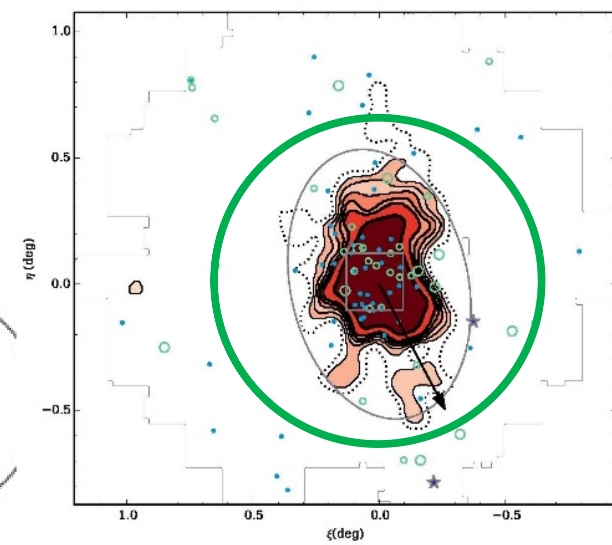
Draco



Sextans

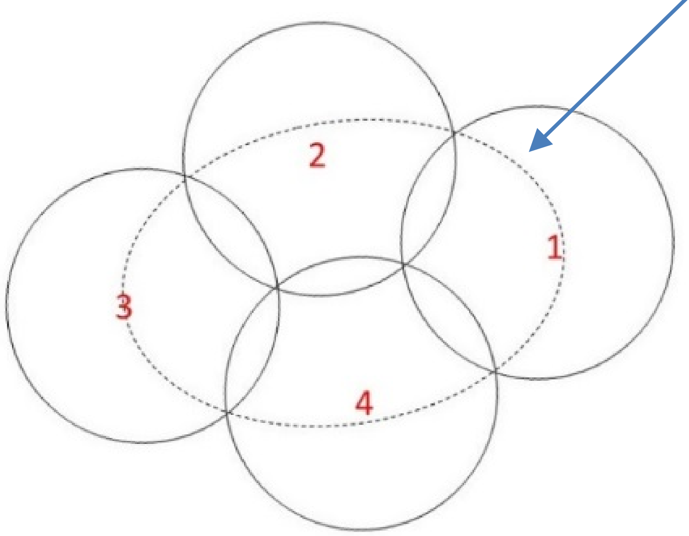


Bootes I

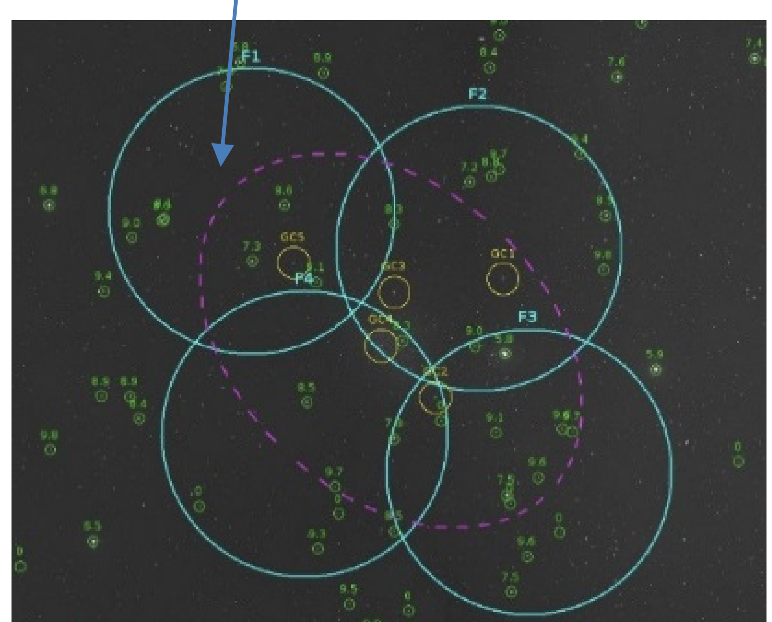


tidal radius of stellar comp.

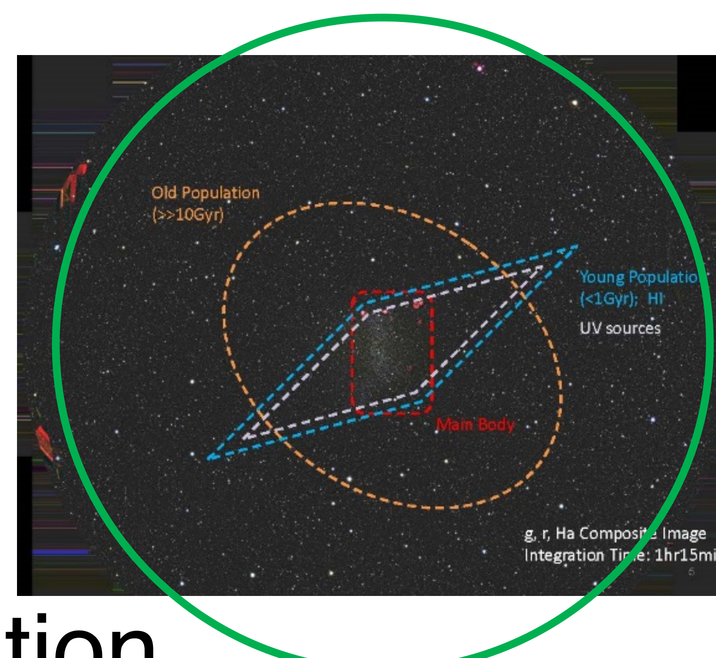
Sculptor



Fornax



NGC6822



also cosmology, galaxy evolution

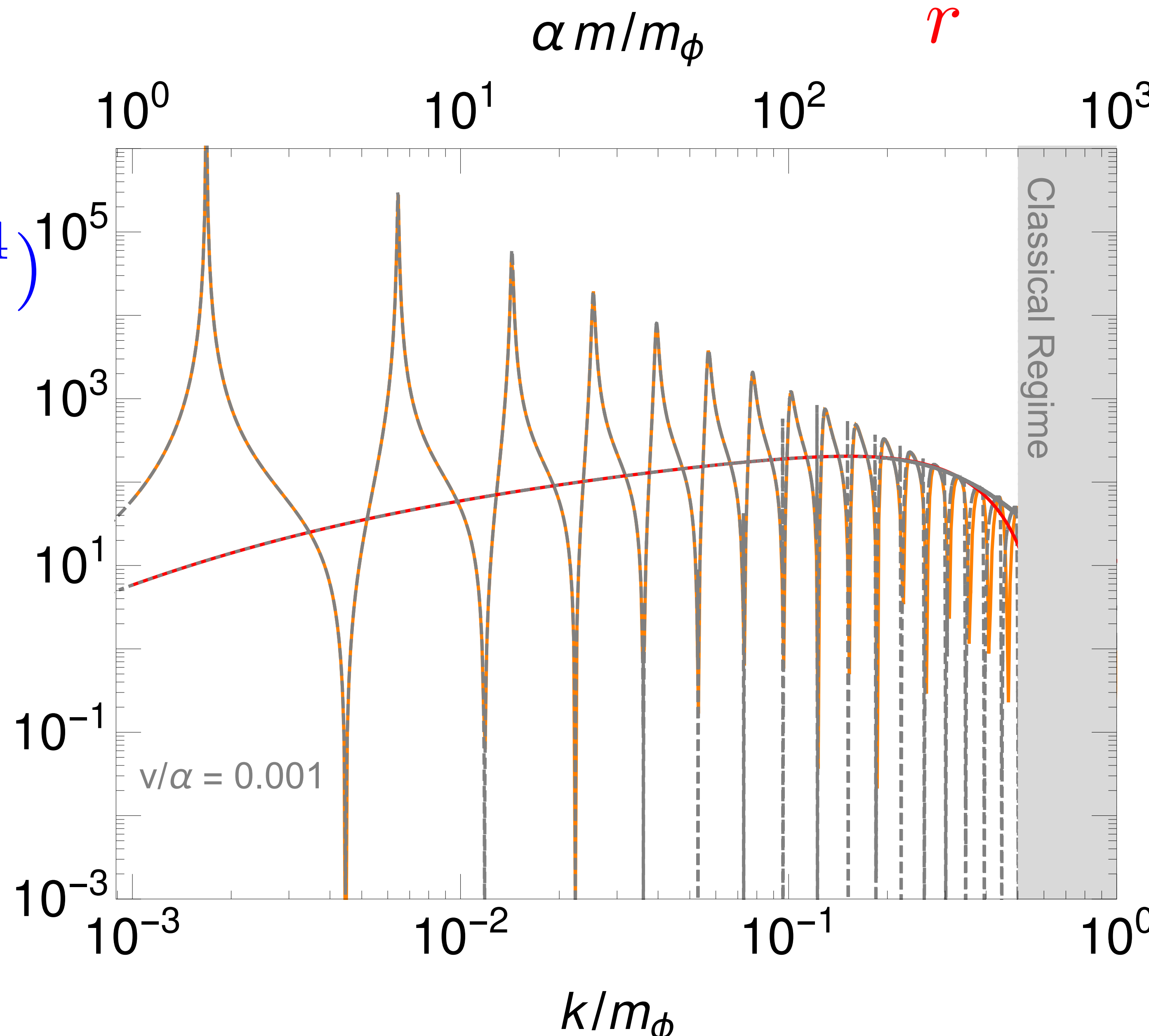
Unified description of SIDM

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

- Hans Bethe: effective range theory

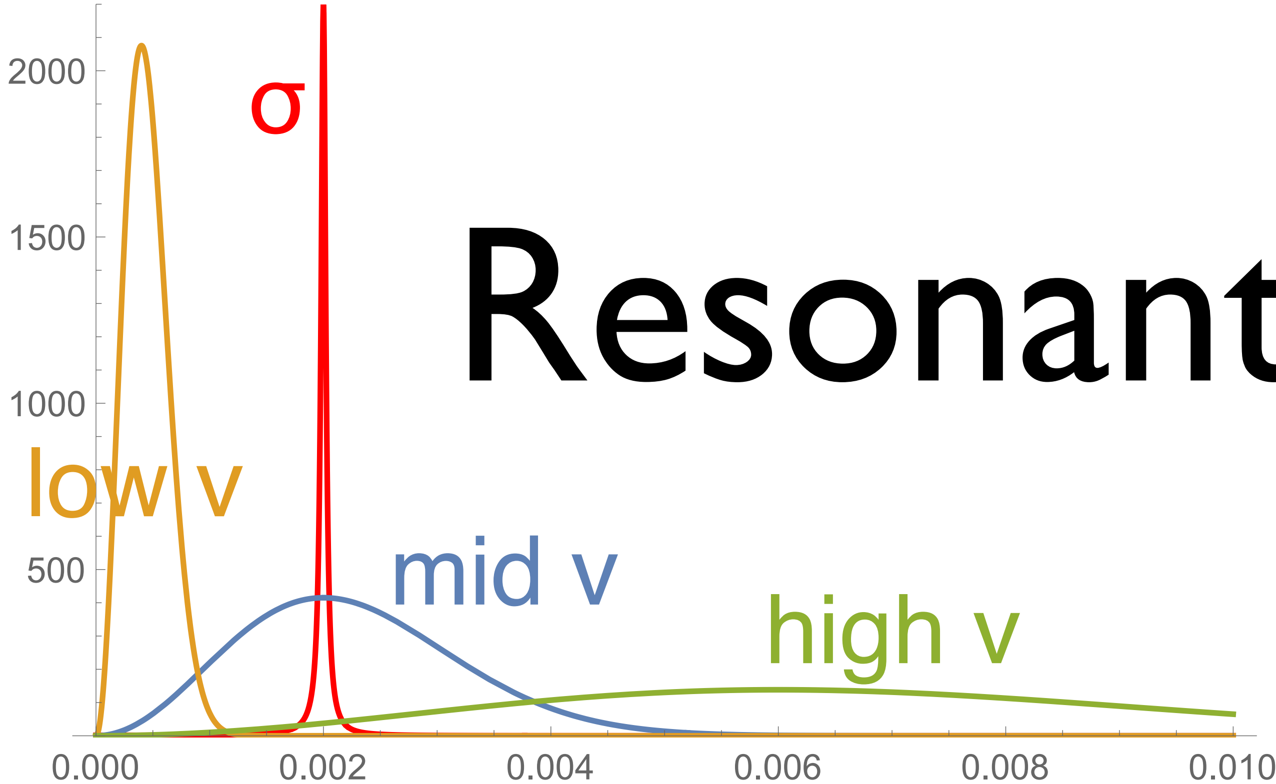
$$k \cot \delta = -\frac{1}{a} + \frac{1}{2} r_e k^2 + O(k^4)$$

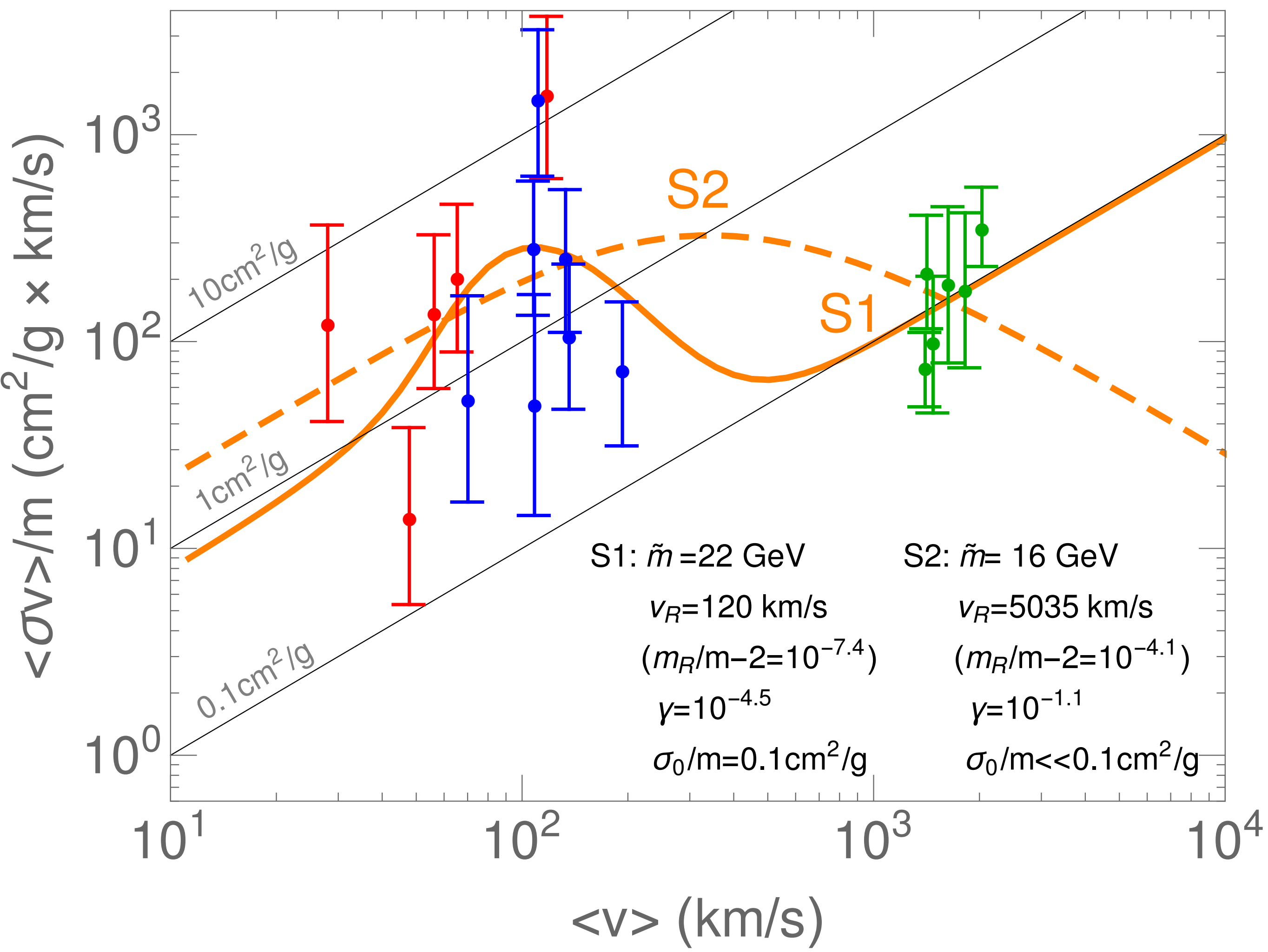
- only two parameters to describe scattering at low velocities
- fully unitary and non-perturbative
- ideal for simulations and phenomenology!

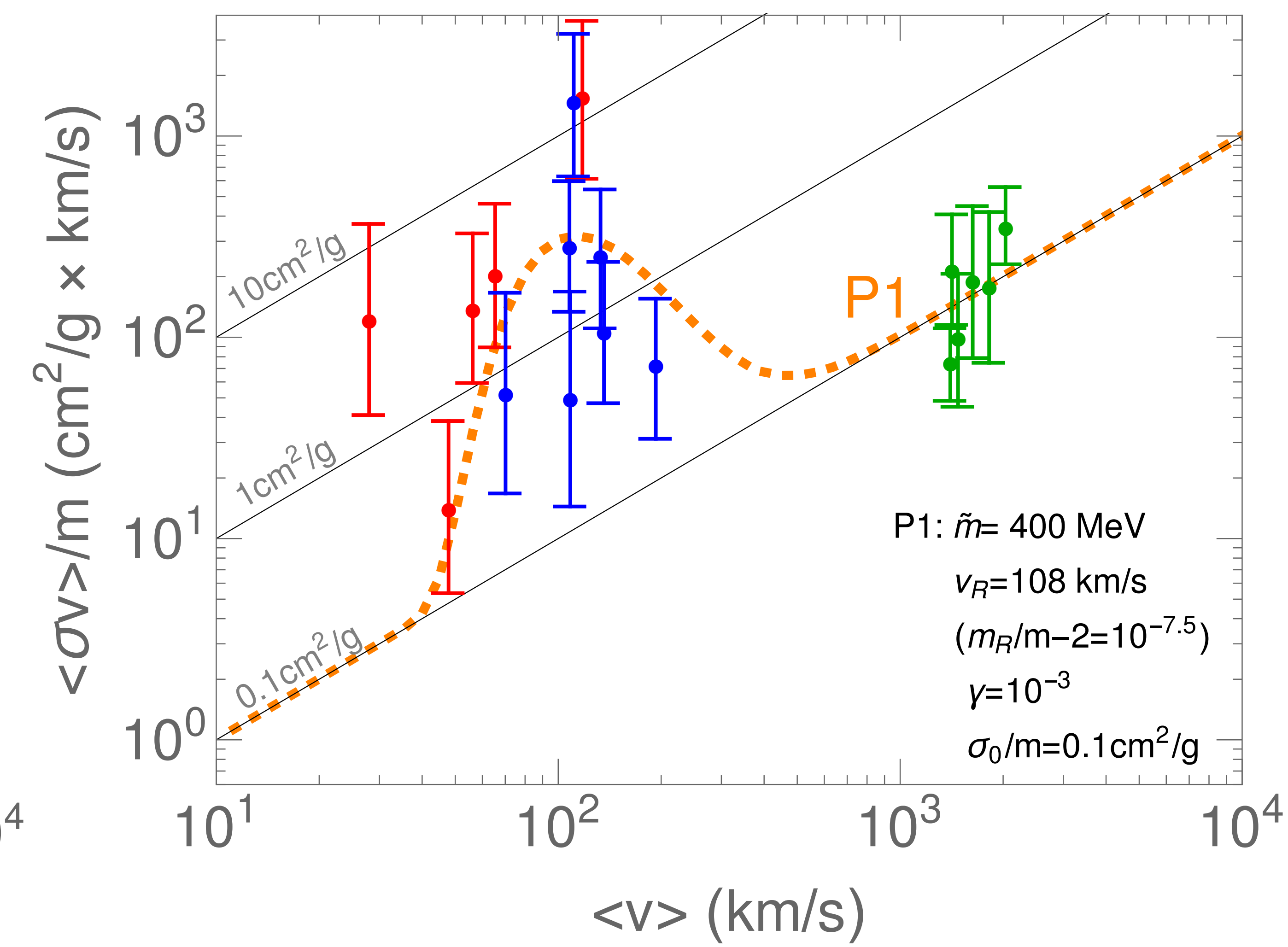


Xiaoyong Chu, Camilo Garcia-Cely, HM, arXiv:1908.06067, *JCAP* 06 (2020) 043

Resonant scattering

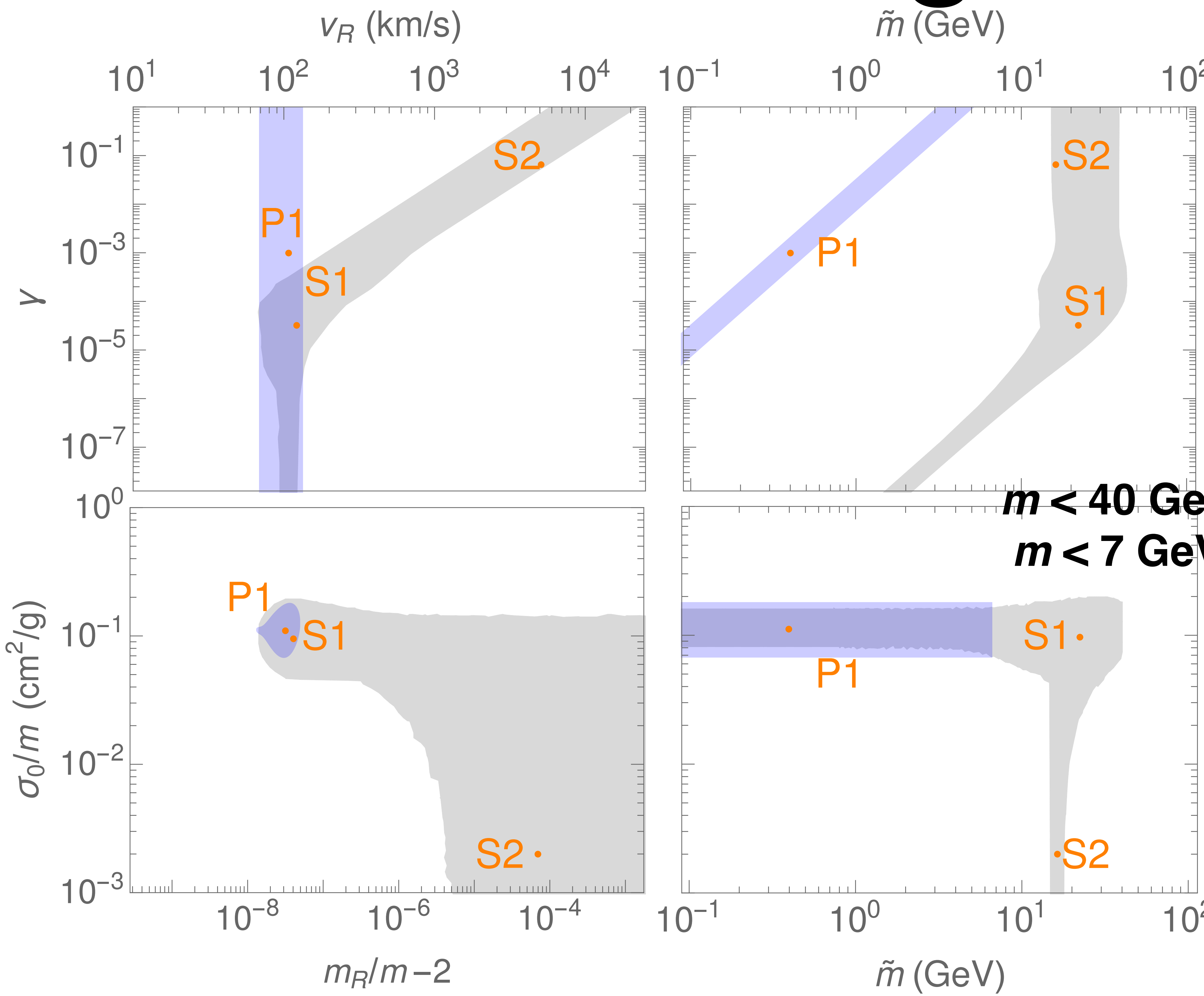






Xiaoyong Chu, Camilo Garcia-Cely, HM,
Phys.Rev.Lett. 122 (2019) no.7, 071103

needs to be light

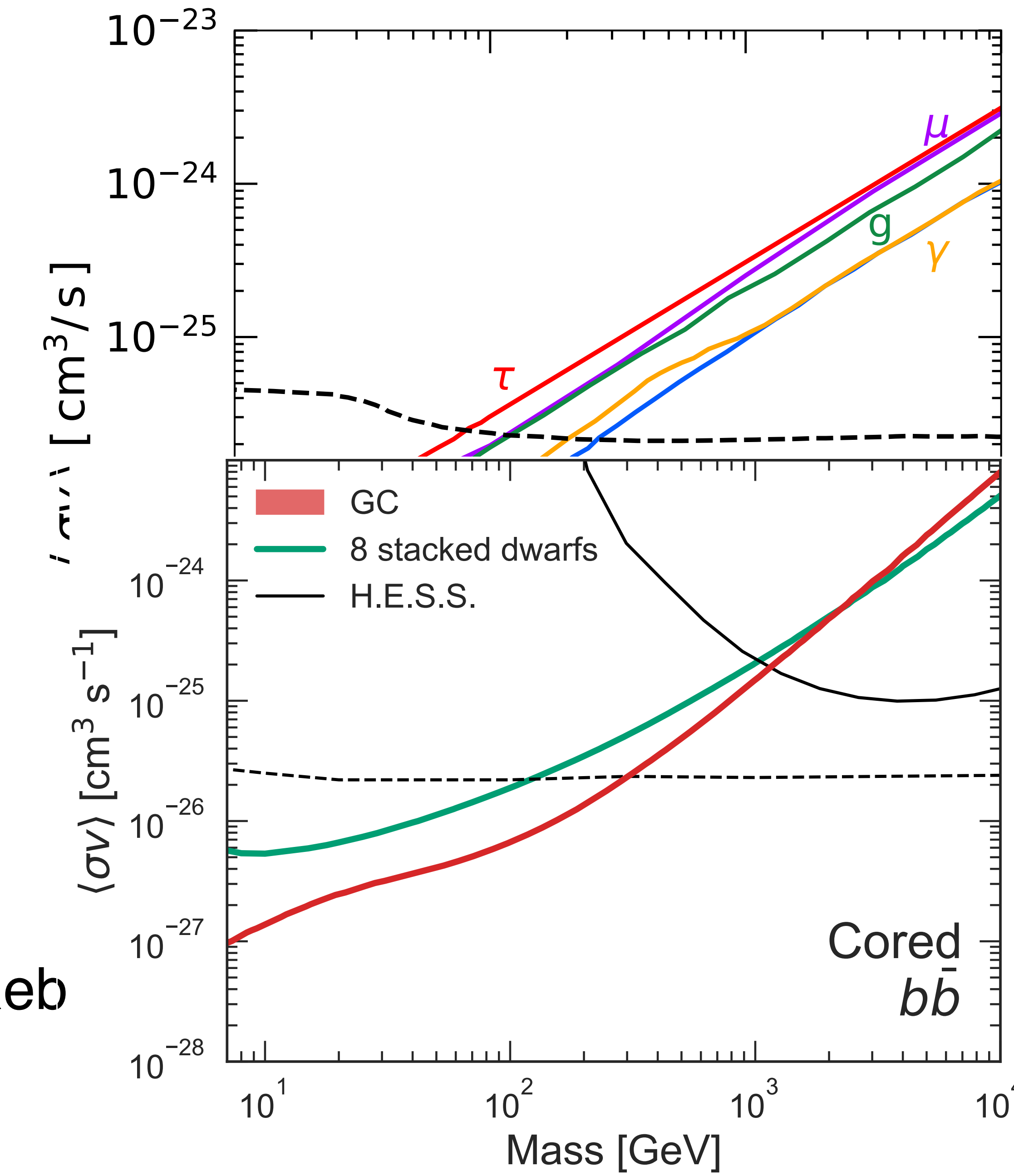


***m* < 40 GeV (S-wave)**
***m* < 7 GeV (P-wave)**

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

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 $\sigma/m \sim$ cm^2/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
  - down scattering

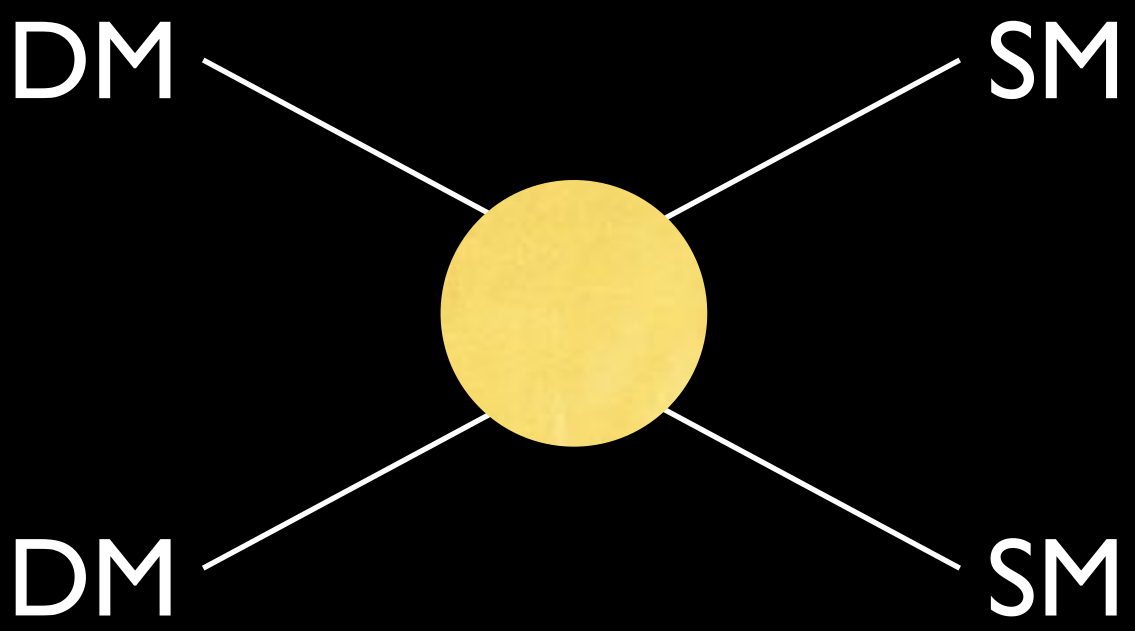


Reb :om,

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

Dark Pions

Miracles



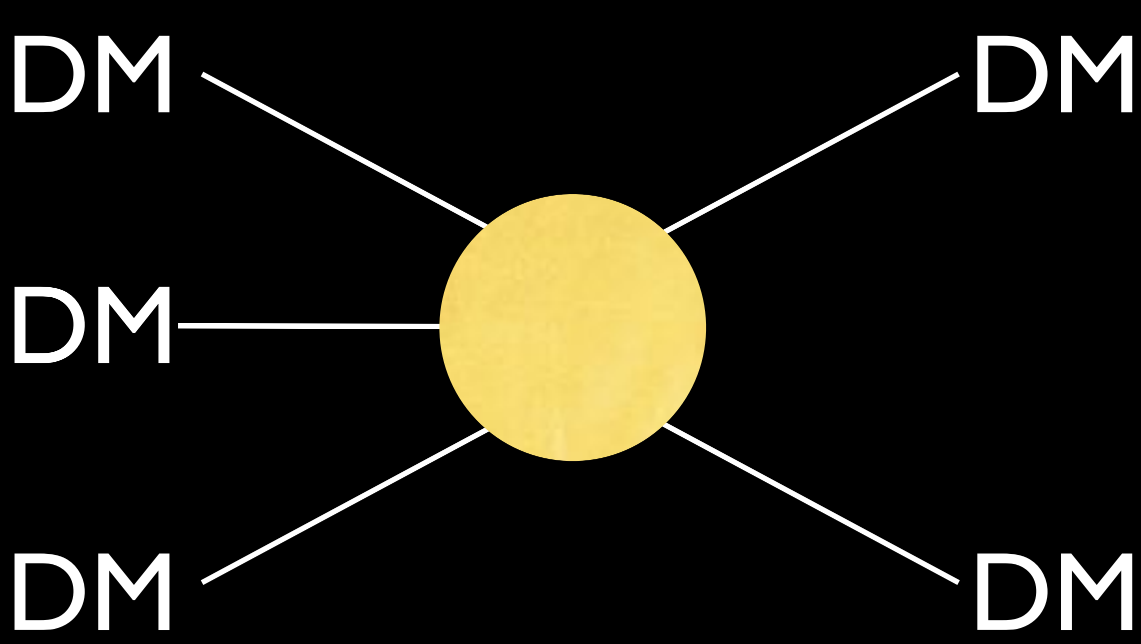
$$\langle \sigma_{2\to 2} v \rangle \approx \frac{\alpha^2}{m^2}$$

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

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

WIMP miracle!

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



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

$$\alpha \approx 4\pi$$

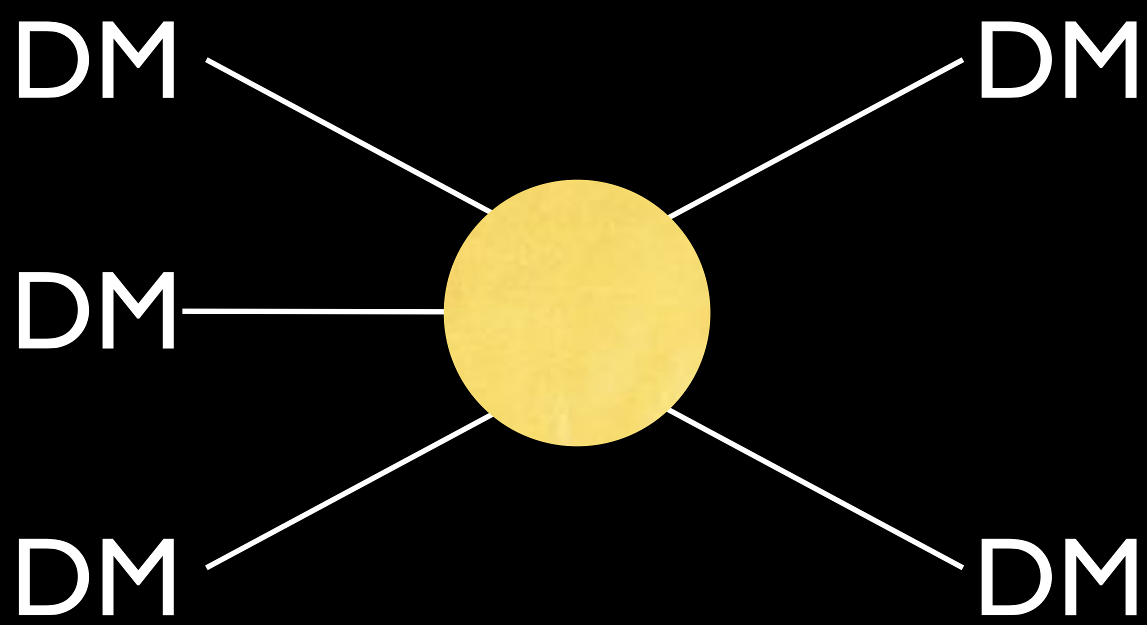
$$m \approx 300\mathrm{MeV}$$

Hochberg, Kuflik, Volansky, Wacker arXiv:1402.5143

SIMP miracle!

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



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

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

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

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

Eric Kuflik

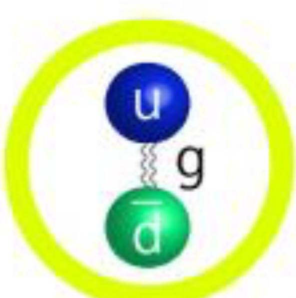
LAGRANGIANS

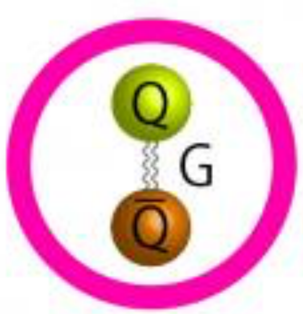
QCD

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

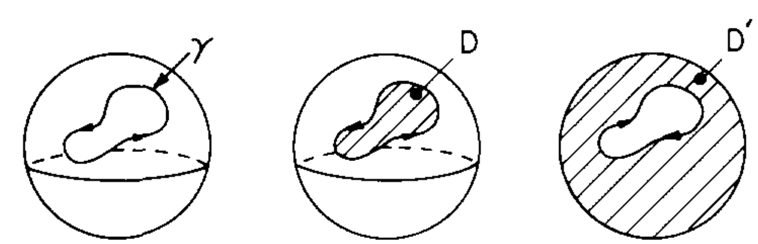
Chiral Lagrangian

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





Pions

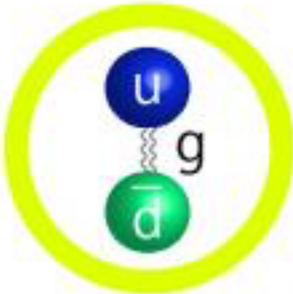


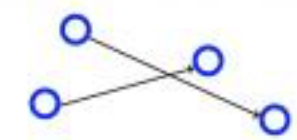
(a) (b) (c)

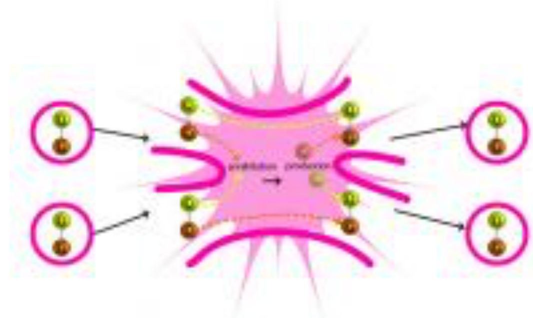
$$\mathcal{L}_{\rm pion} = \frac{1}{4}{\rm Tr}\partial_\mu\pi\partial^\mu\pi - \frac{m_\pi^2}{4}{\rm Tr}\pi^2 + \frac{m_\pi^2}{12f_\pi^2}{\rm Tr}\pi^4 - \frac{1}{6f_\pi^2}{\rm Tr}\left(\pi^2\partial^\mu\pi\partial_\mu\pi - \pi\partial^\mu\pi\pi\partial_\mu\pi\right)$$

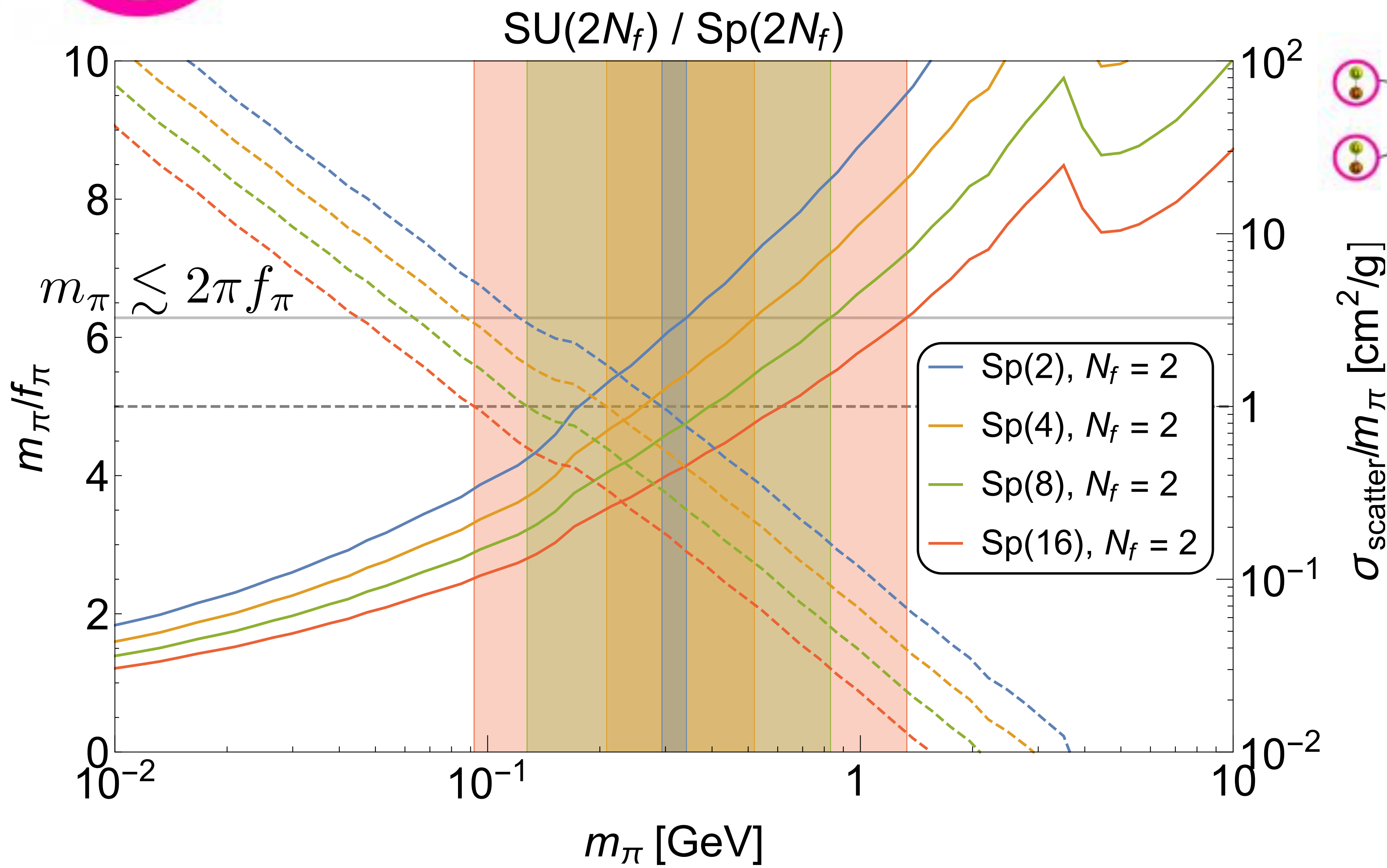
$$+ \frac{2N_c}{15\pi^2 f_\pi^5}\epsilon^{\mu\nu\rho\sigma}{\rm Tr}\left[\pi\partial_\mu\pi\partial_\nu\pi\partial_\rho\pi\partial_\sigma\pi\right] + \mathcal{O}(\pi^6)$$

The Results









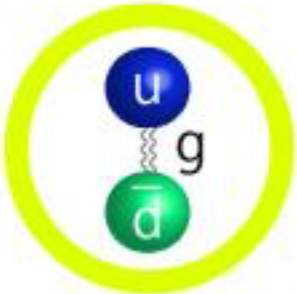
Solid curves: solution to Boltzmann eq.

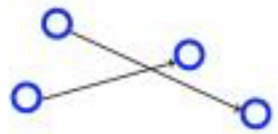
Dashed curves: along that solution

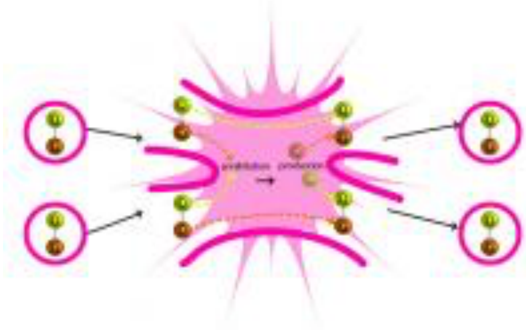
$$\frac{m_\pi}{f_\pi} \propto m_\pi^{3/10}$$

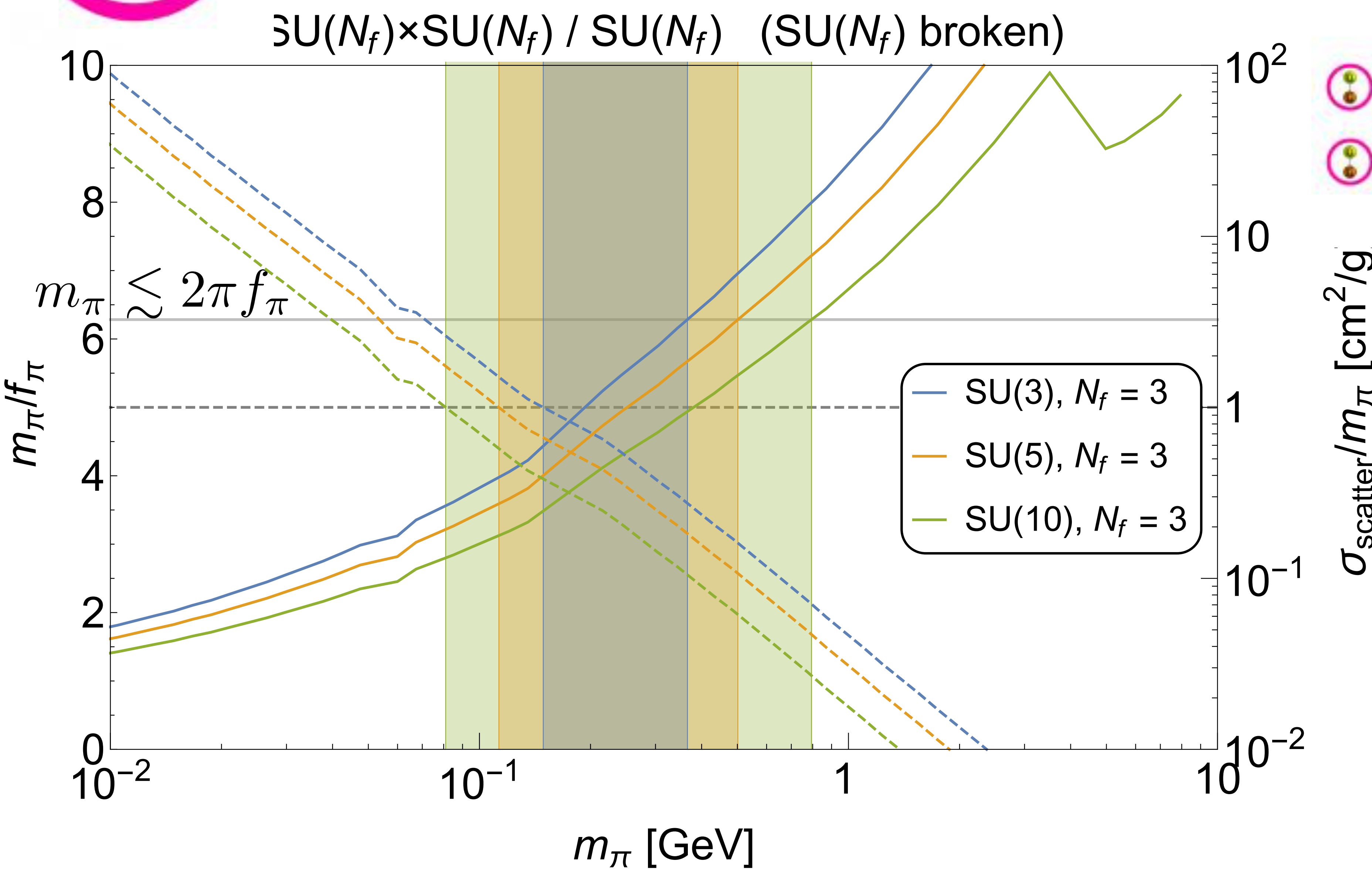
$$\frac{\sigma_{\rm scatter}}{m_\pi} \propto m_\pi^{-9/5}$$

The Results









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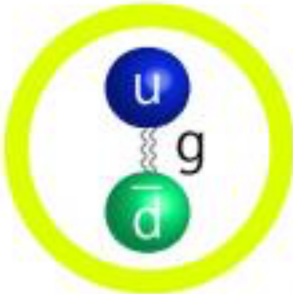

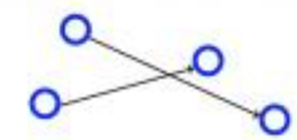

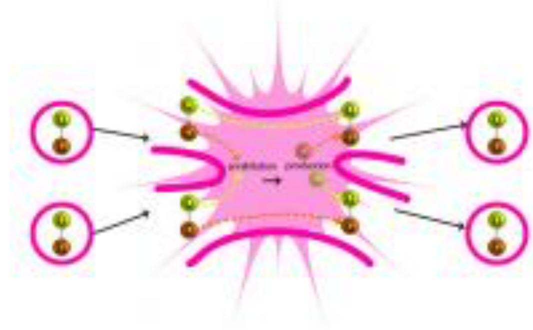

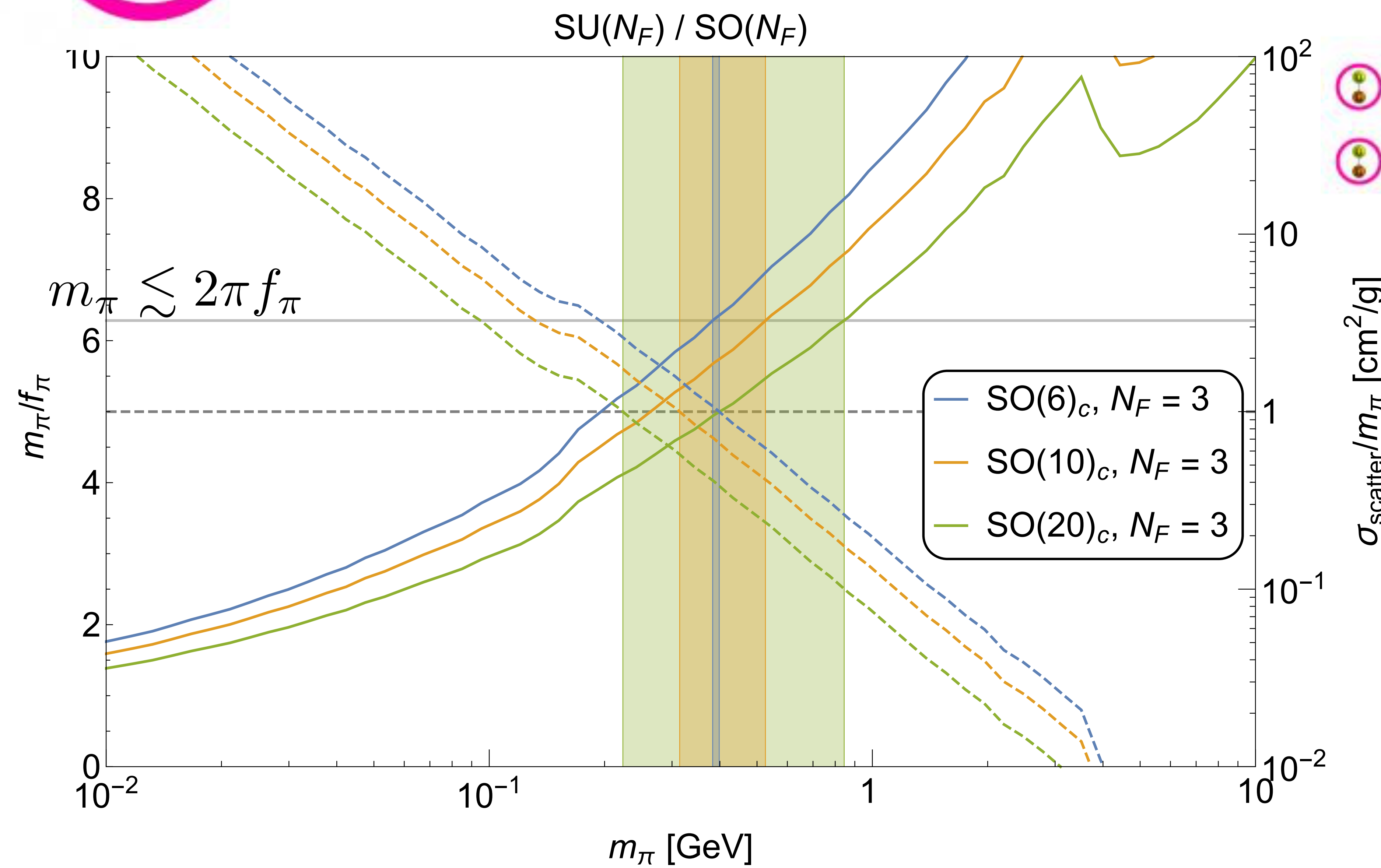

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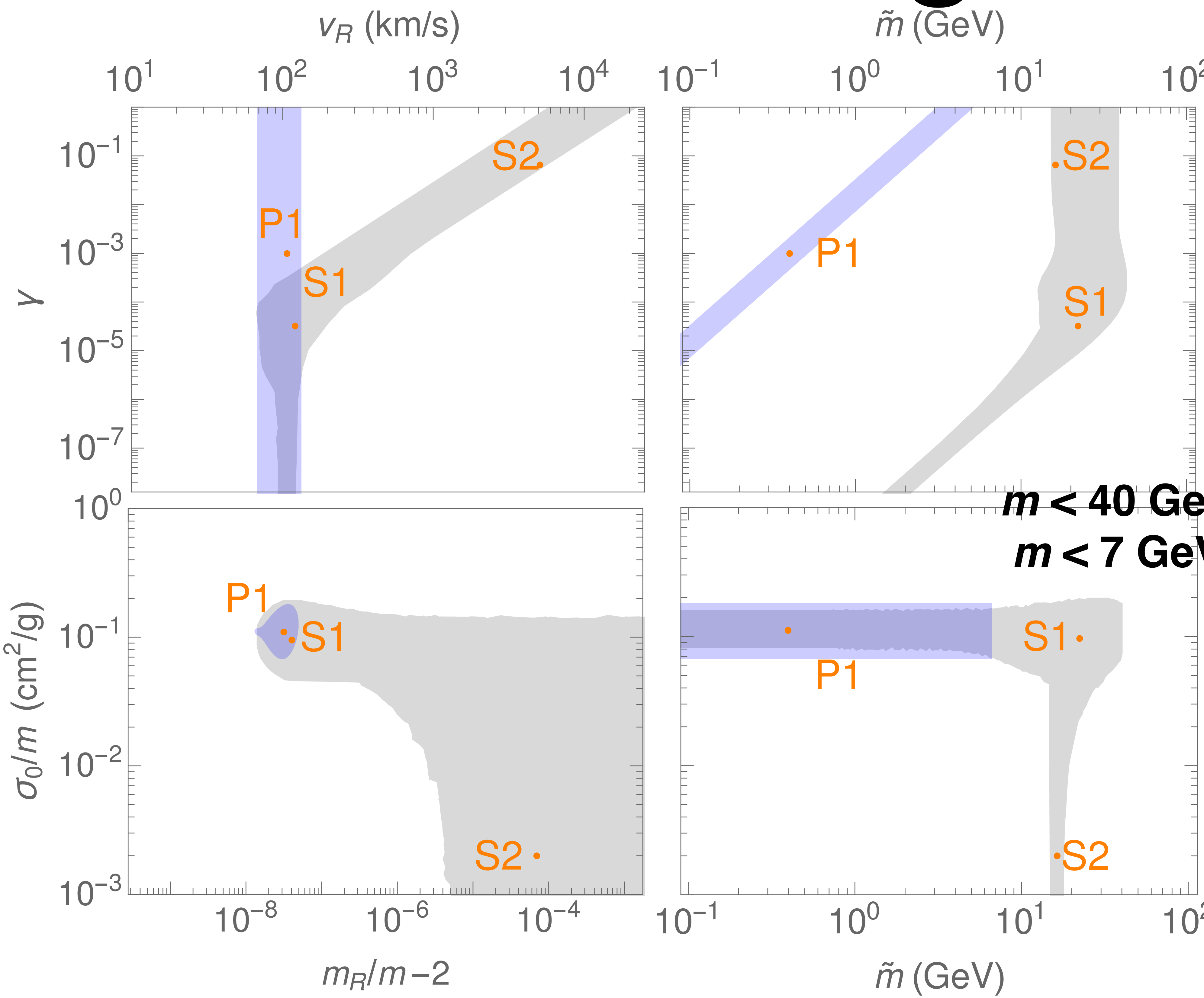
Dashed curves: along that solution

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

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

needs to be light



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***m* < 7 GeV (P-wave)**

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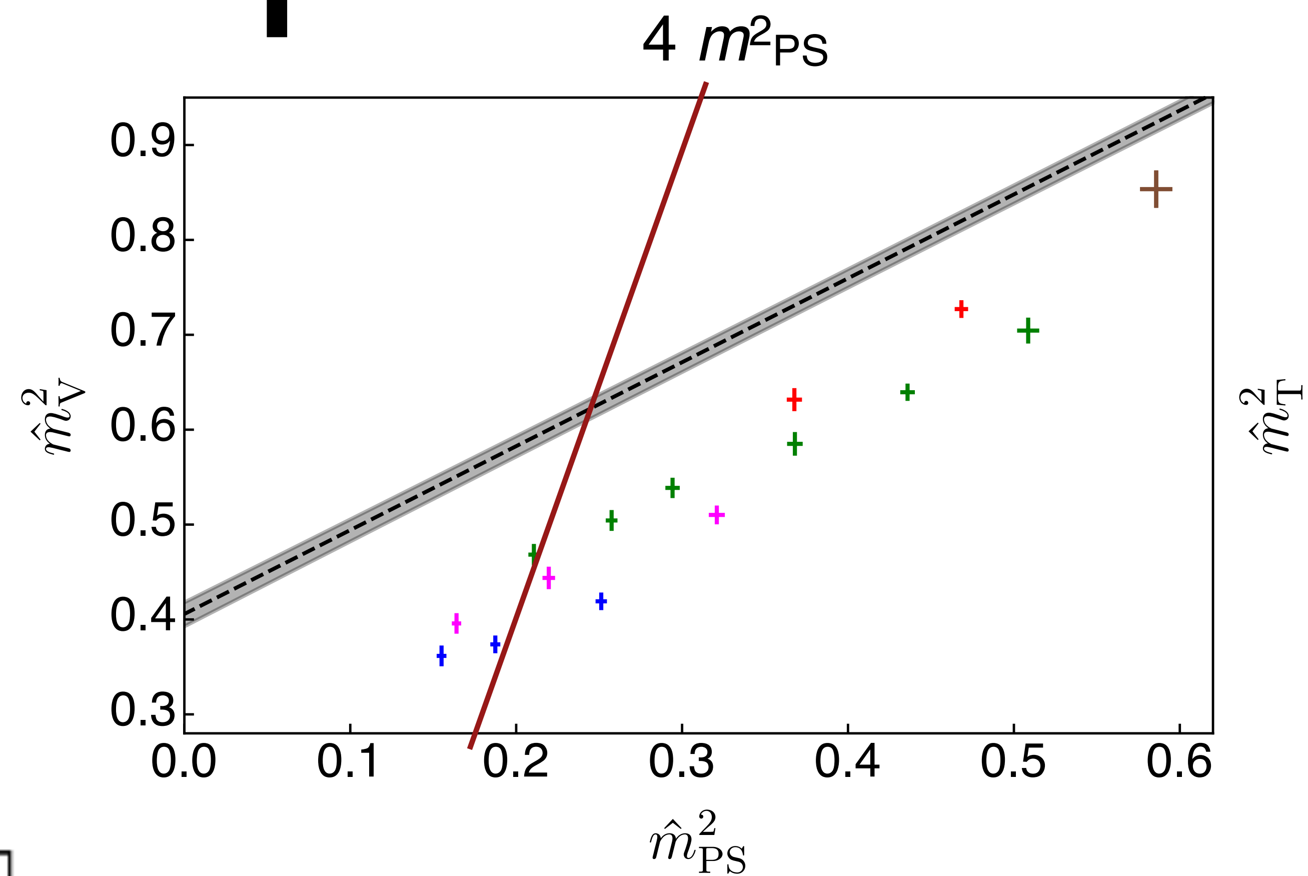
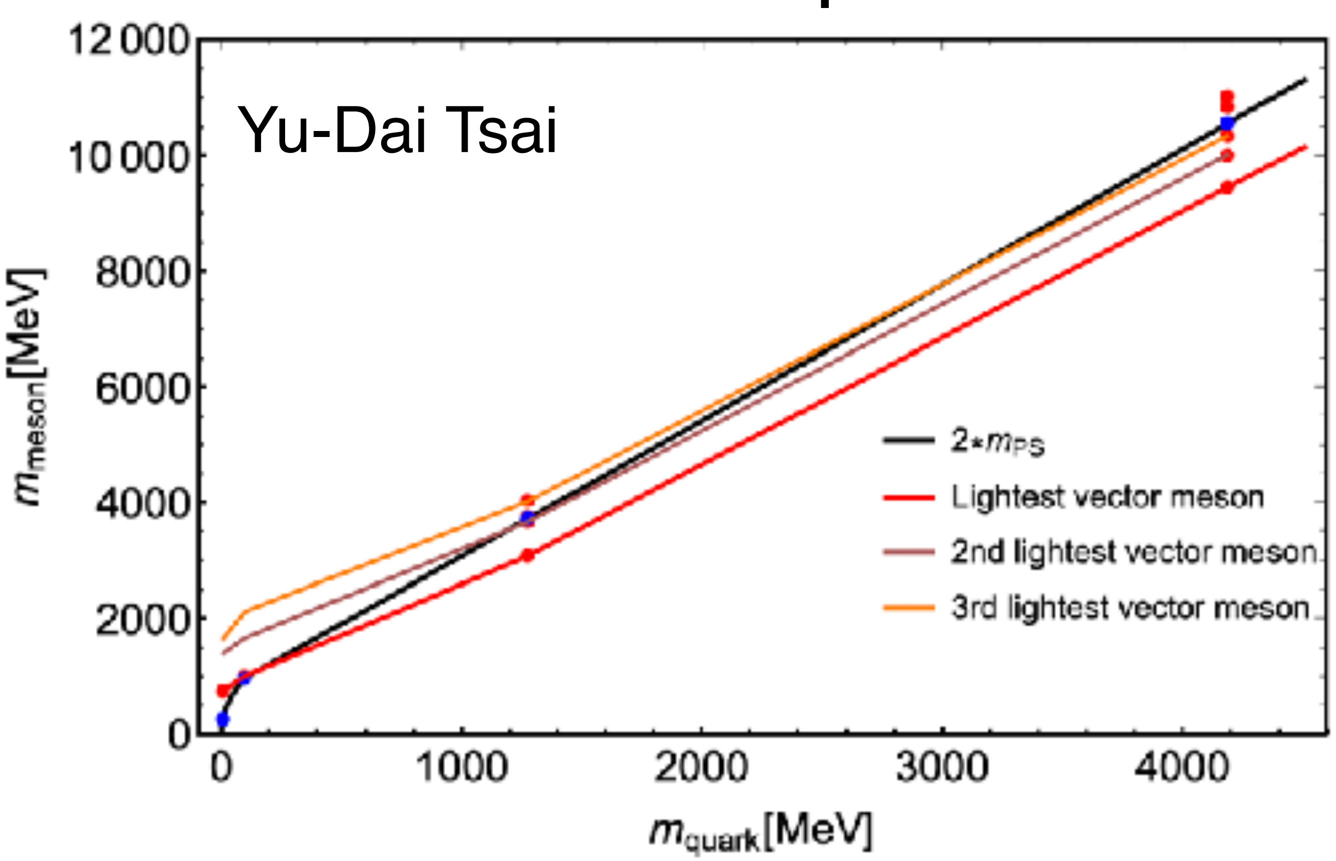
Phys.Rev.Lett. 122 (2019) no.7, 071103

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 ψ(3S), Υ(4S)
- but limited parameters



lattice calculation of Sp(4) with N_f=4
arXiv:1911.00437



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

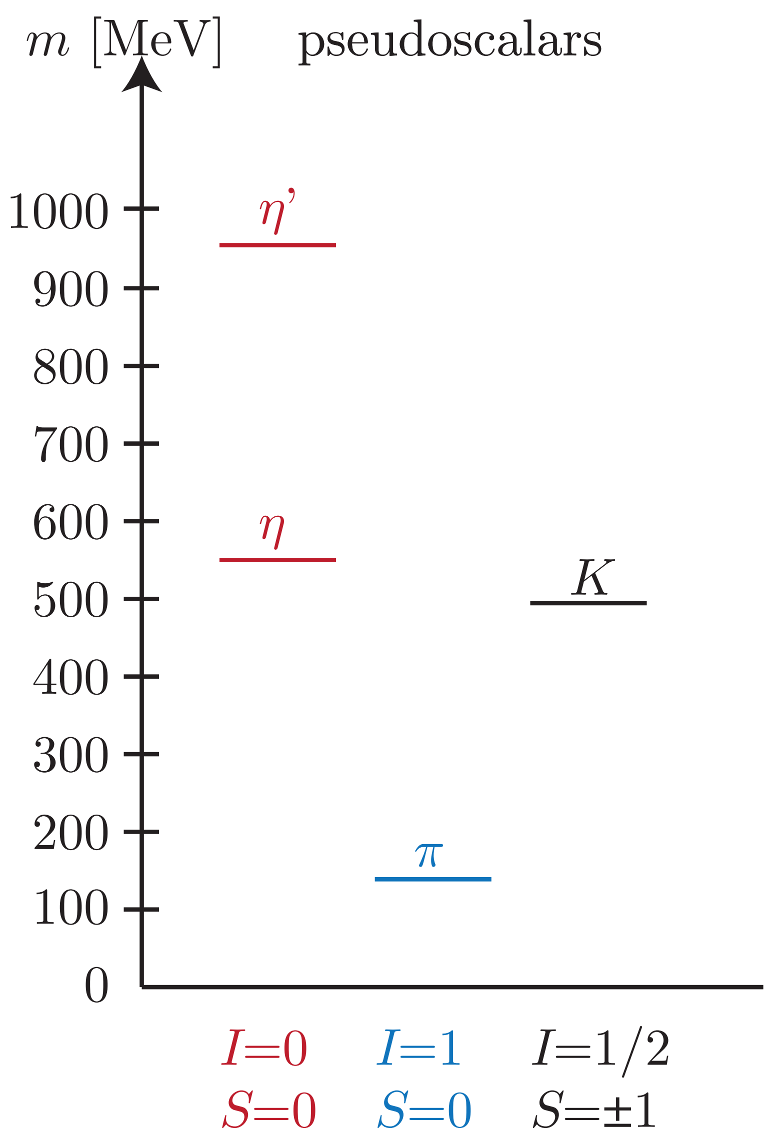
$$\frac{m(^{12}\mathrm{C}) - m(^8\mathrm{Be}) - m(\alpha)}{m(^{12}\mathrm{C})} = 0.000026,$$

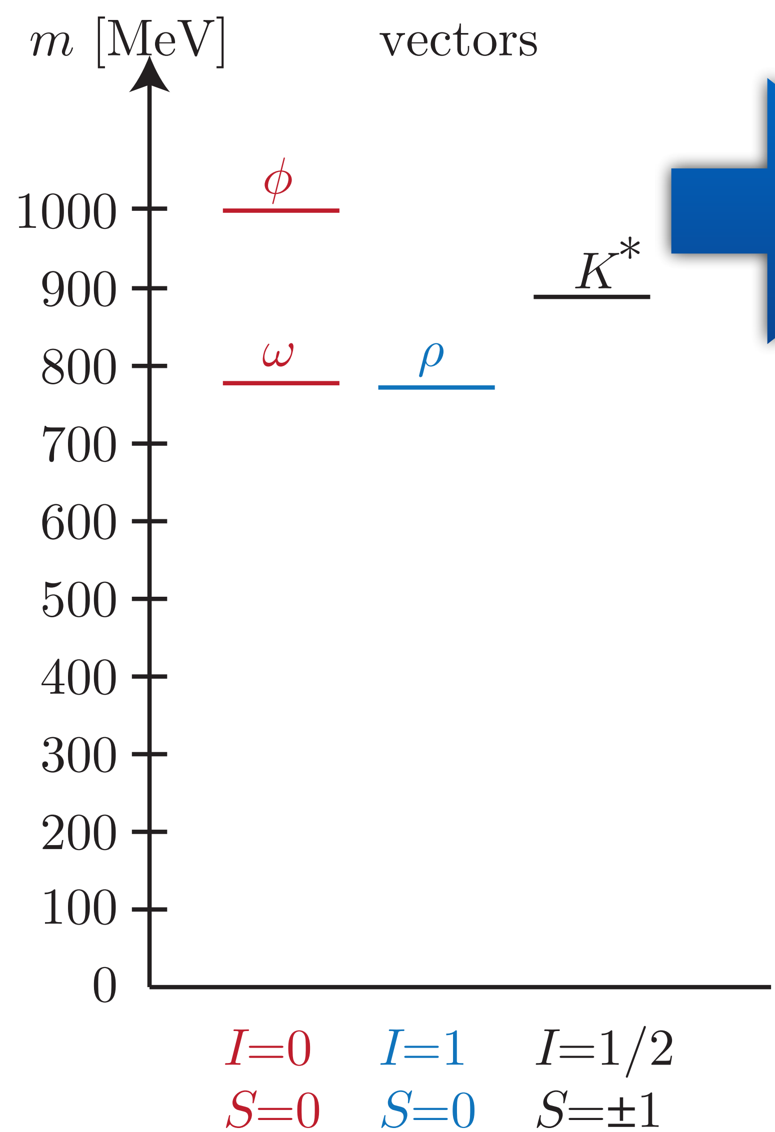
$$\frac{m(D^{+*}) - m(D^0) - m(\pi^+)}{m(D^{+*})} = 0.00051.$$

Robert McGehee, HM, Yu-Dai Tsai, arXiv:2008.08608

Robert McGehee, Dan Kondo, Tom Melia, HM, Kevin Zhang, to appear

revenge of sigmas





tetra quarks $(qq)(\overline{qq})$

meson molecule K^+K^-

Gell-Mann–Okubo relation

K: $4 \times 0.496^2 = 0.984$ GeV^2

π_0, η: $0.140^2 + 3 \times 0.550^2 = 0.927$ GeV^2

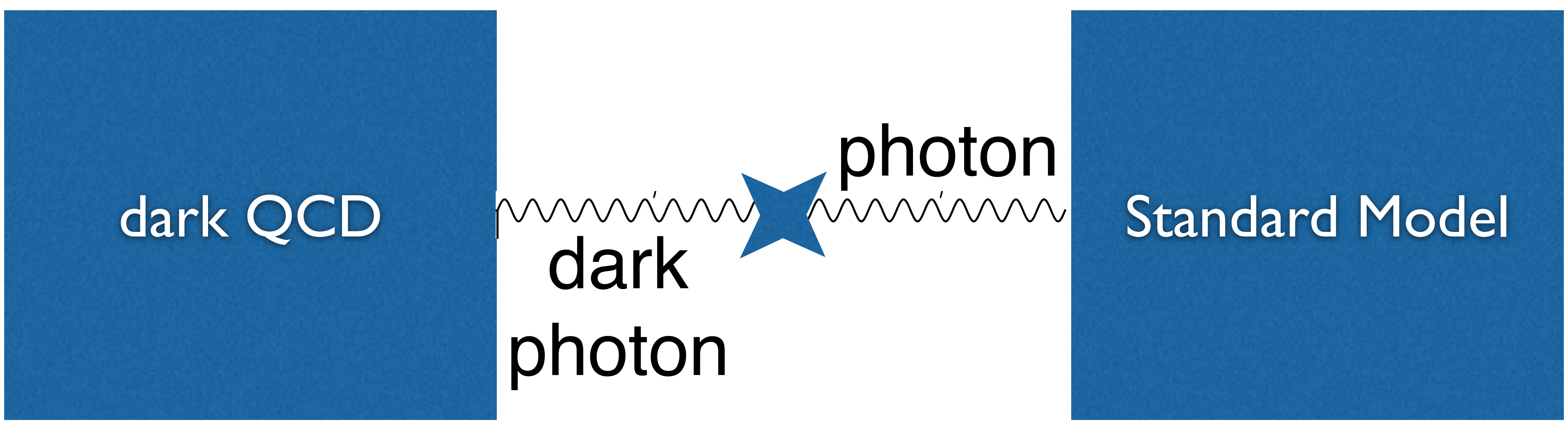
K_0^*: $4 \times 0.680^2 = 1.85$ GeV^2

f_0: $0.980^2 + 3 \times 0.500^2 = 1.71$ GeV^2

K^*: $4 \times 0.890^2 = 3.168$ GeV^2

ρ, ωϕ: $0.780^2 + (0.780^2 + 2 \times 1.00^2) = 3.217$ GeV^2

vector portal



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

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

Kinetically mixed U(1)

- e.g., the SIMPlest model SU(2) gauge group with N_f=2 (4 doublets)
- SU(4)=SO(6)
- gauge U(1)=SO(2) ⊂ SO(2) × SO(3) ⊂ SO(5)=Sp(4)
- maintains degeneracy of quarks
- near degeneracy of pions for co-annihilation
- SO(6)/SO(5) linear sigma model

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

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

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

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

revenge of WIMP

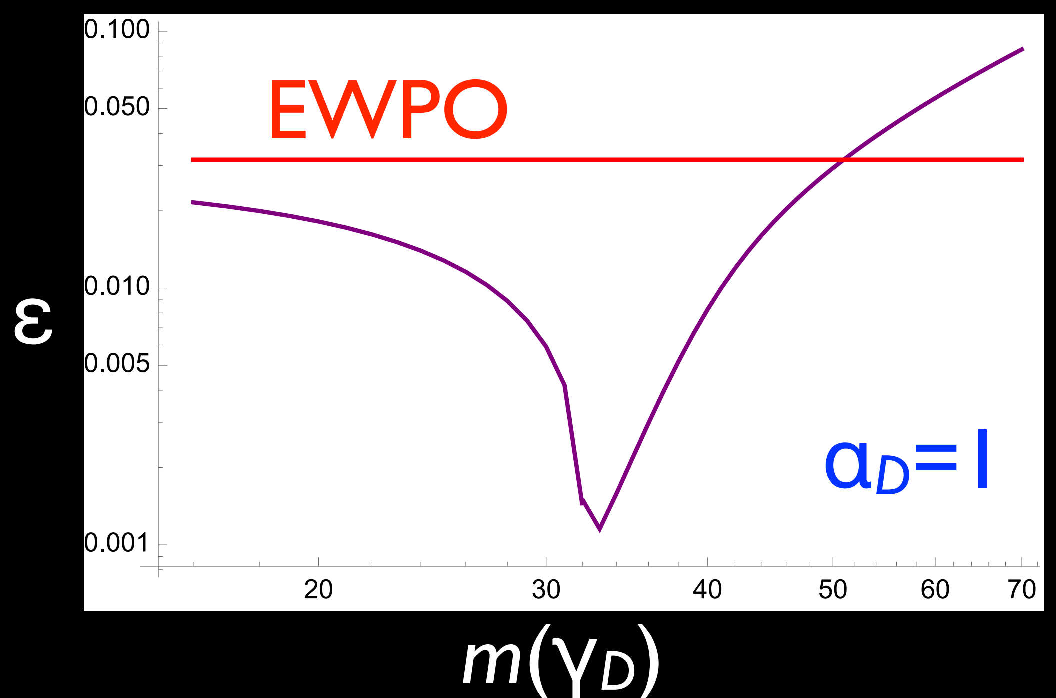
- annihilation

$$\pi^{++}\pi^{--} \to \gamma_D \to \gamma \to f\bar{f}$$

- after freeze out, charged pions down scatter to neutral ones

$$\pi^{++}\pi^{--} \to \pi_i^0\pi_i^0$$

- no direct/indirect limits



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

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

$$(\pi^{++}, \pi^{--}, \pi_x^0, \pi_y^0, \pi_z^0) + \sigma$$

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

or freeze-in

- if freeze-in, kinetic mixing can be very small
- both direct and indirect detection can be suppressed
- SO(N_c) gauge theory with N_f=2
- SU(N_f)/SO(N_f) = SU(2)/SO(2) = SO(3)/SO(2) linear sigma model

$$SU(2)/SO(2) = S^2$$

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

$$(\pi^{++}, \pi^{--}) + \sigma$$

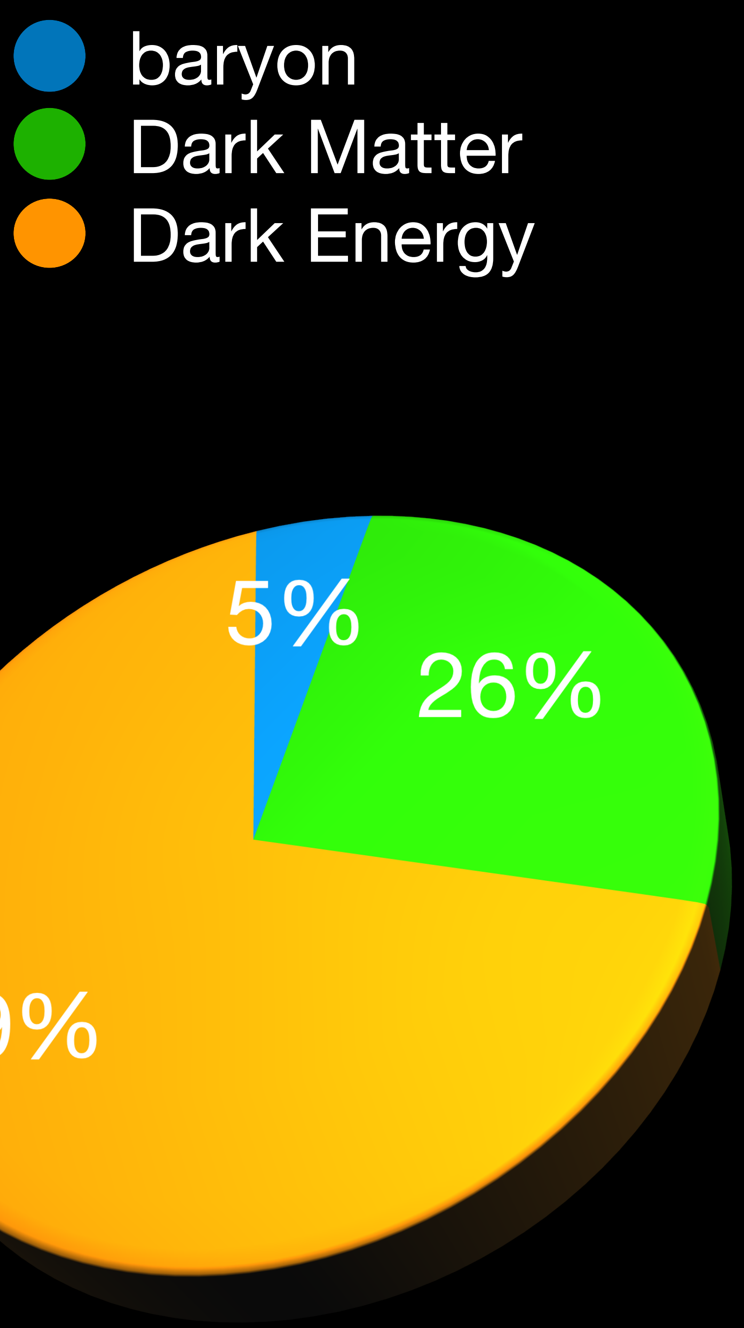
$$\frac{\epsilon_\gamma}{2c_W} B_{\mu\nu} F_D^{\mu\nu}$$

Dark Nucleons

Nell Hall (Berkeley), Thomas Konstandin (DESY), HM, Robert McGehee (Michigan)
arXiv:1911.12342
+Bethany Suter (Berkeley) arXiv:2107.03398

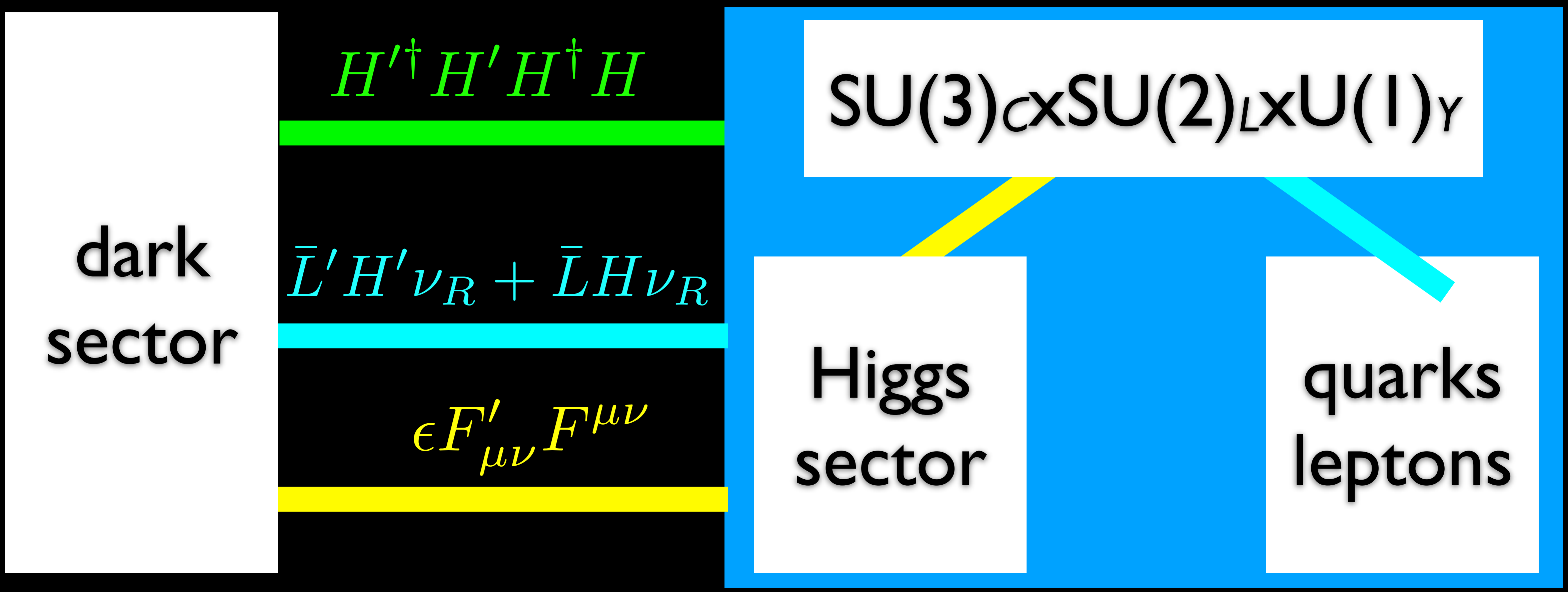
asymmetric dark matter

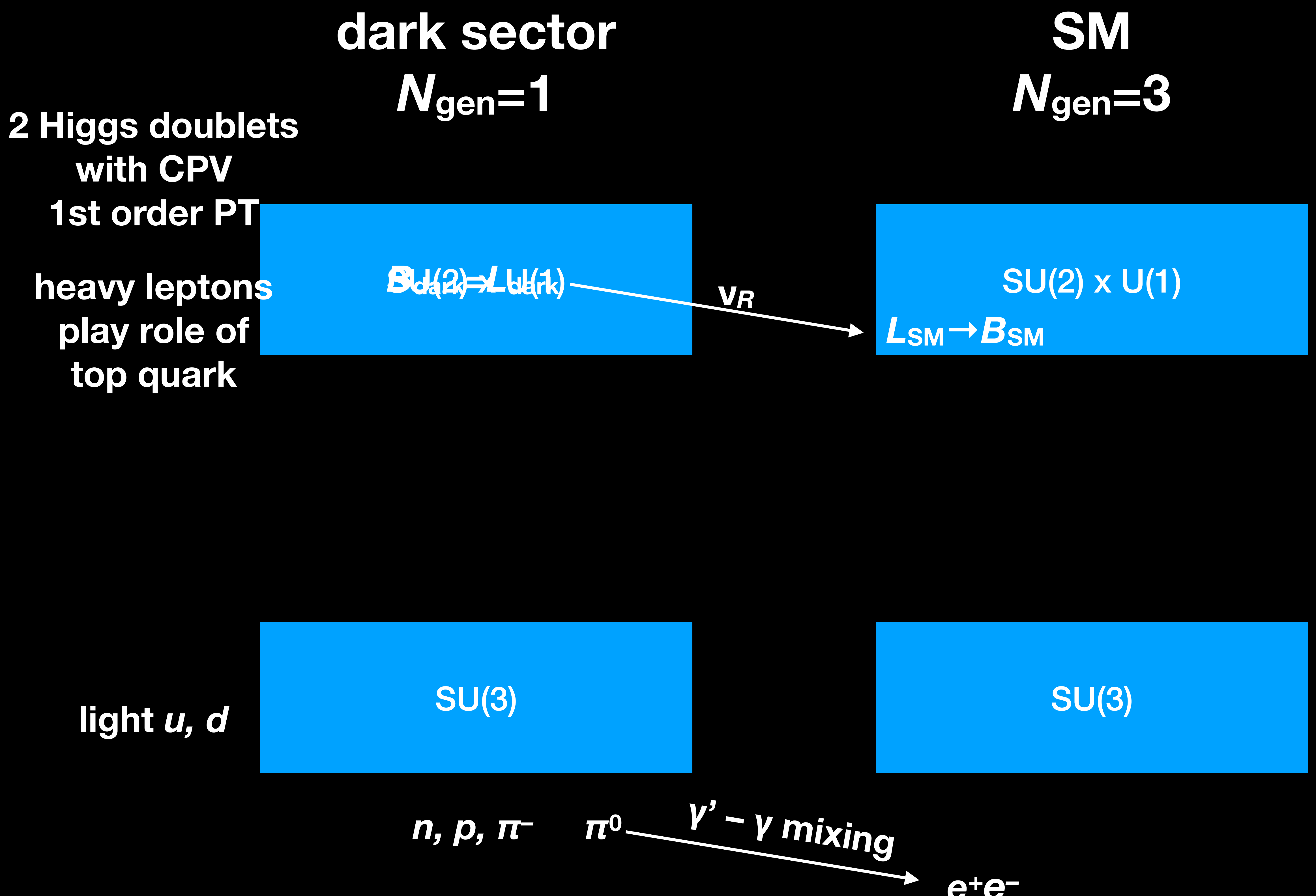
- may explain the coincidence between baryon and dark matter densities today
- need to efficiently get rid of symmetric component
  → strongly coupled?
- proton mass is dynamical. also "dark proton?"
- If the same asymmetries, m_{ADM}~6GeV, "light" dark matter
- need anomalies and non-anomalous gauge
  - simplest structure: copy of SM
- need equilibration mechanism between two asymmetries
  → neutrino portal



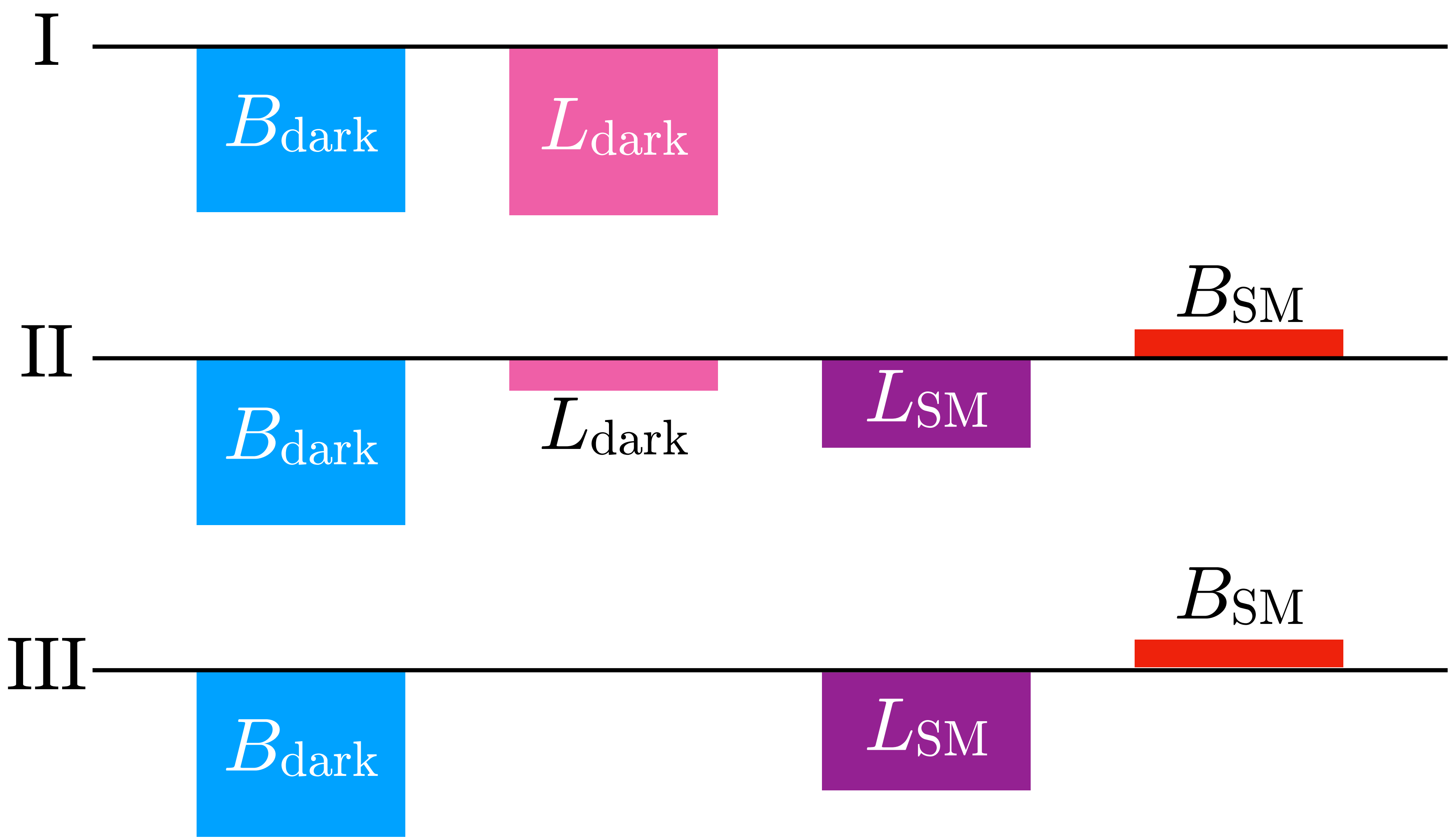
portals

three possible portals in renormalizable theories





dark sector
N_{gen}=1
SM
N_{gen}=3
2 Higgs doublets
with CPV
1st order PT
heavy leptons
play role of
top quark
SU(2) x U(1)
$B_{dark} \to L_{dark}$
ν_R
SU(2) x U(1)
$L_{SM} \to B_{SM}$
light u, d
SU(3)
SU(3)
n, p, π^-
π^0
$\gamma' - \gamma$ mixing
e^+e^-

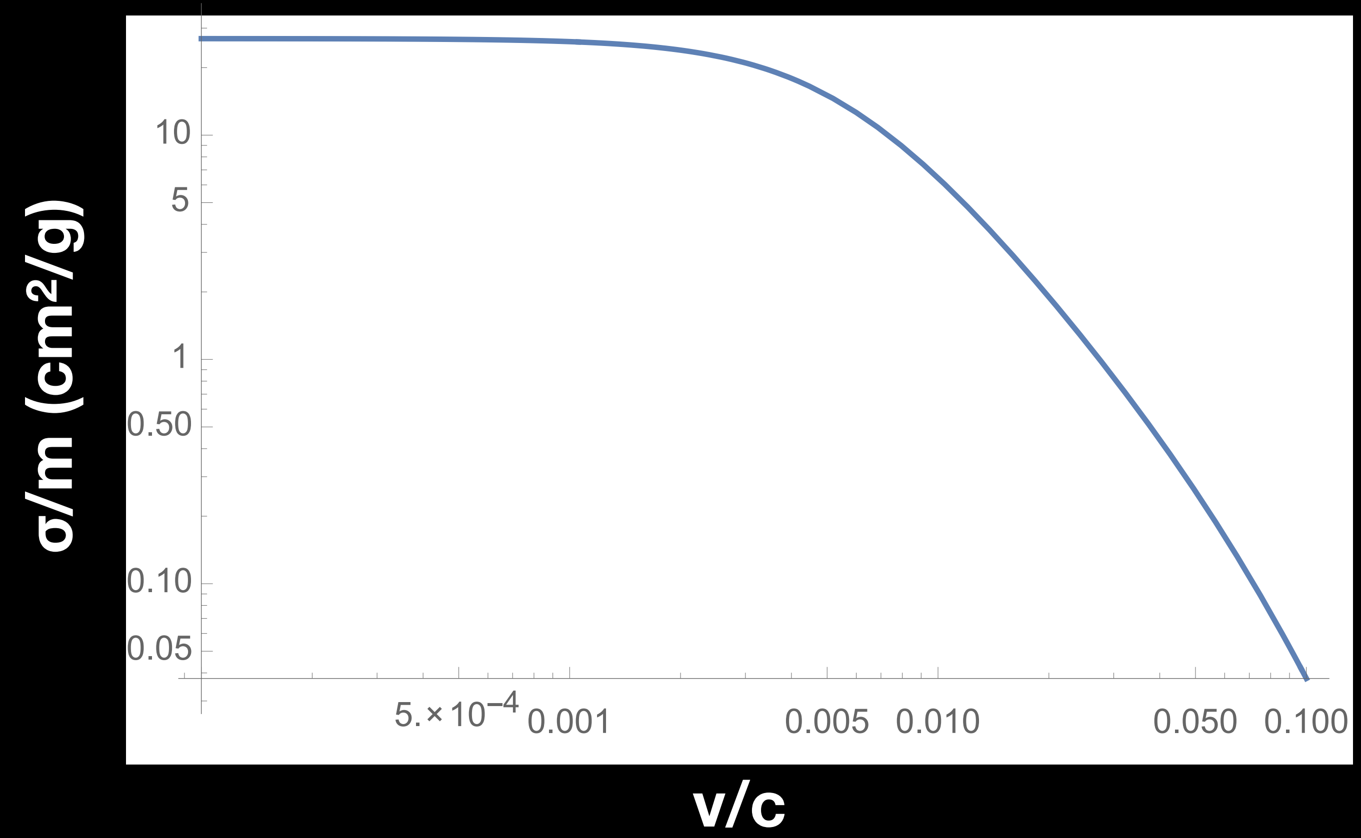


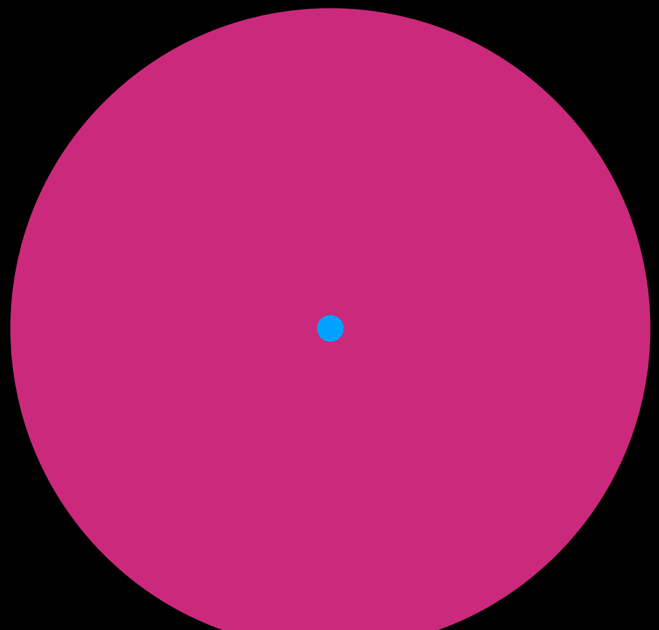
If $M_N > T_{\rm sphaleron}$ $B_{\rm SM} = \frac{36}{133} B_{\rm dark}, \quad L_{\rm SM} = -\frac{97}{133} B_{\rm dark}$ **$m_{n'}$=1.63 GeV**

If $M_N < T_{\rm sphaleron}$ $B_{\rm SM} = \frac{12}{37} B_{\rm dark}, \quad L_{\rm SM} = -\frac{25}{37} B_{\rm dark}$ **$m_{n'}$=1.36 GeV**

n-*n* scattering

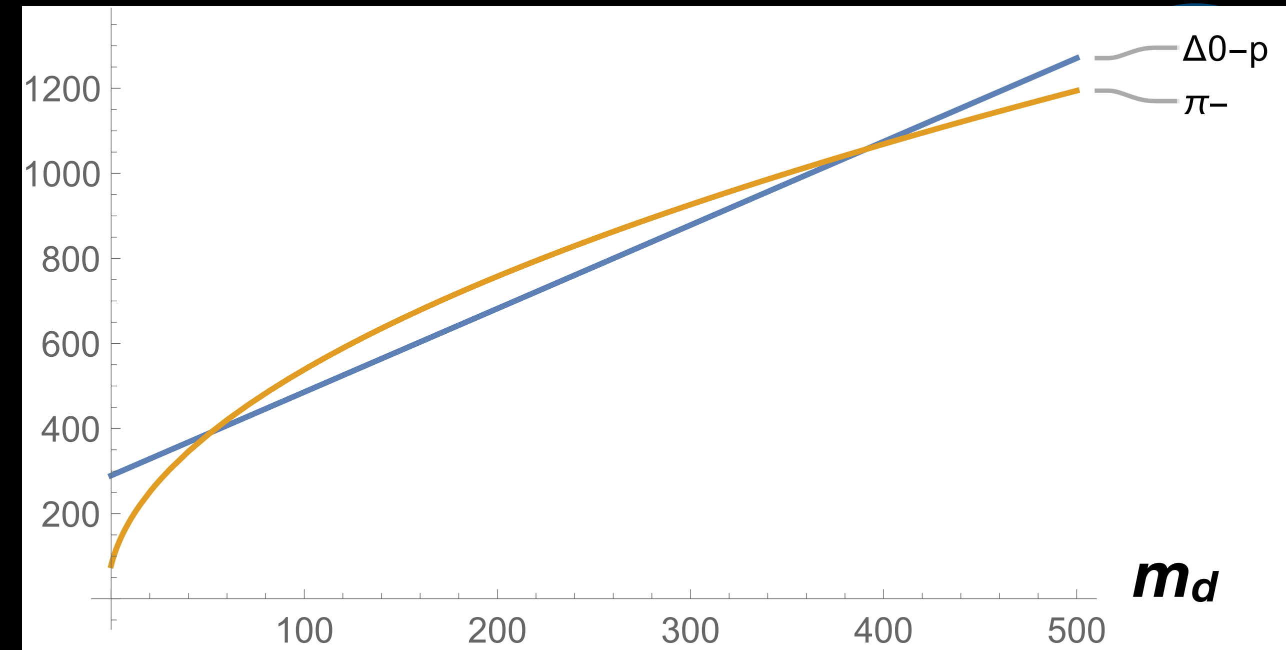
- *n*-*n* scattering has an anomalously large cross section a=18.9fm
- also steep velocity dependence
- depending on the details of the QCD-like dynamics, it could provide SIDM



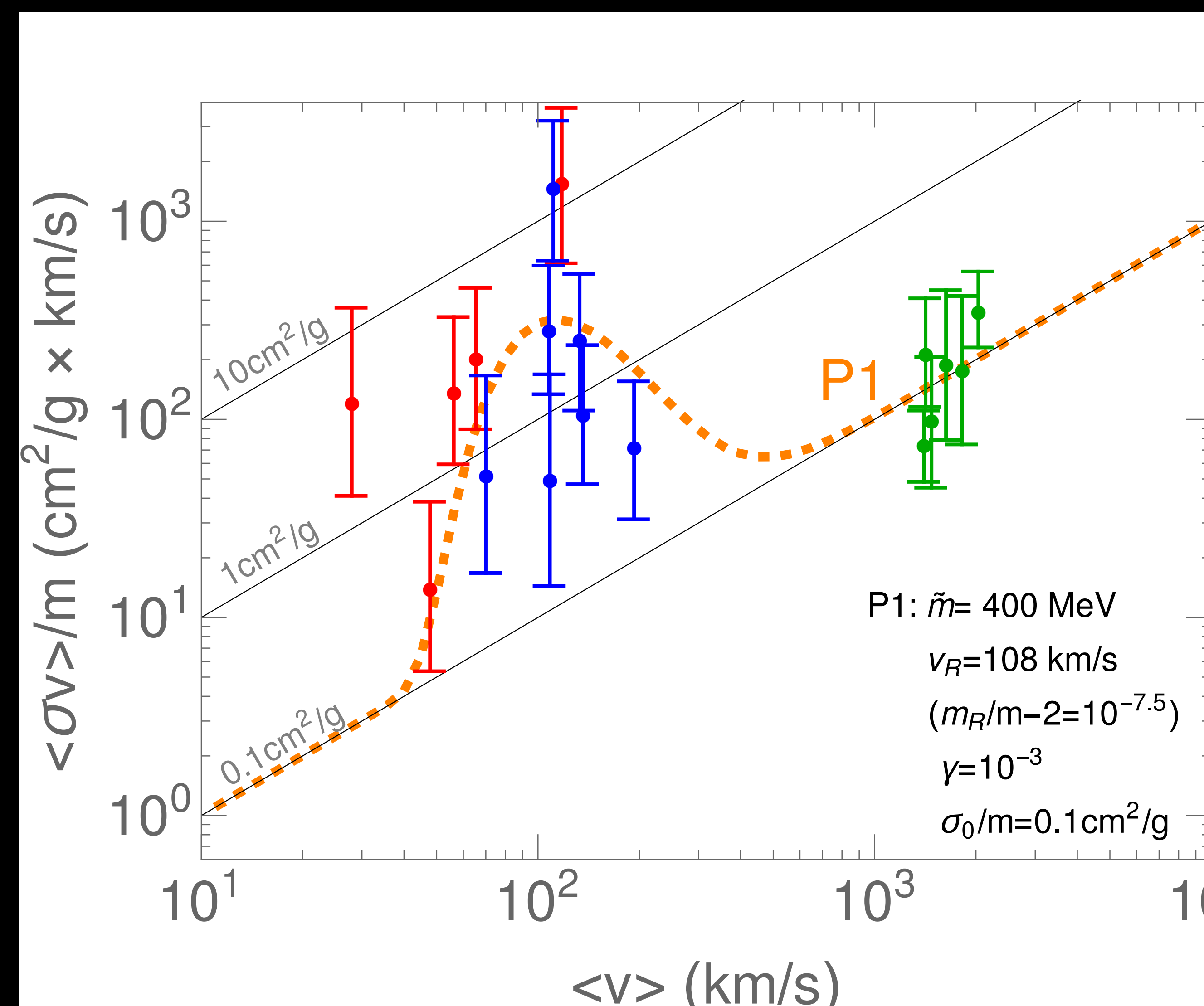


baryon spectrum

- m_u and m_d free parameters
- If $m_d \ll m_u \ll \Lambda_{QCD}$, n' dominates
- If $m_u \ll m_d \ll \Lambda_{QCD}$, p' dominates, together with π'^- for charge neutrality
  - possibly a resonant interaction $\pi'^- p' \to \Delta^0 \to \pi'^- p'$
  - may solve core/cusp problem



Robert McGehee, HM, Yu-Dai Tsai, in prep



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

neutrino portal

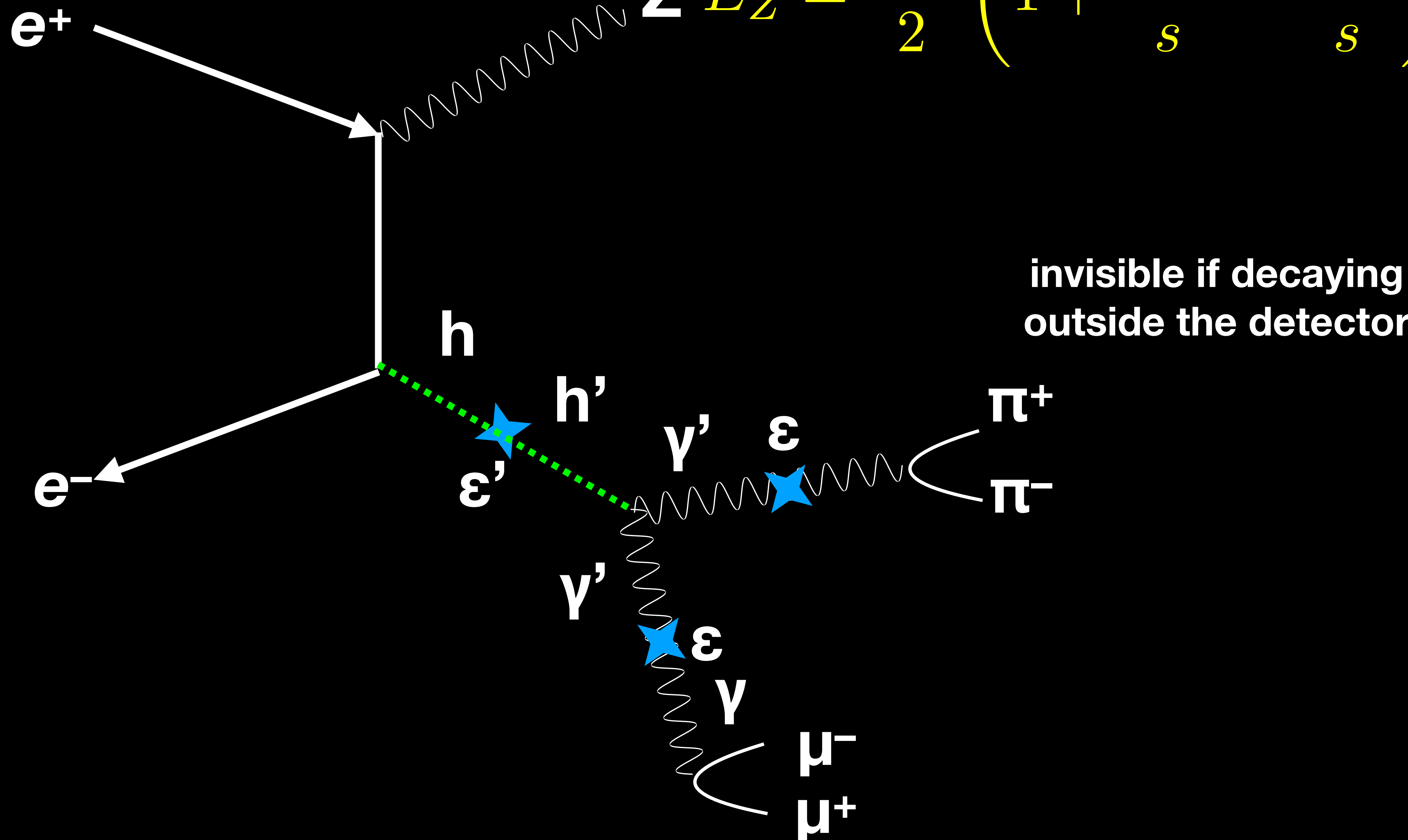
$$\mathcal{L} = y' \bar{L}' H \nu_R + y_i \bar{L}_i H \nu_R$$

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

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

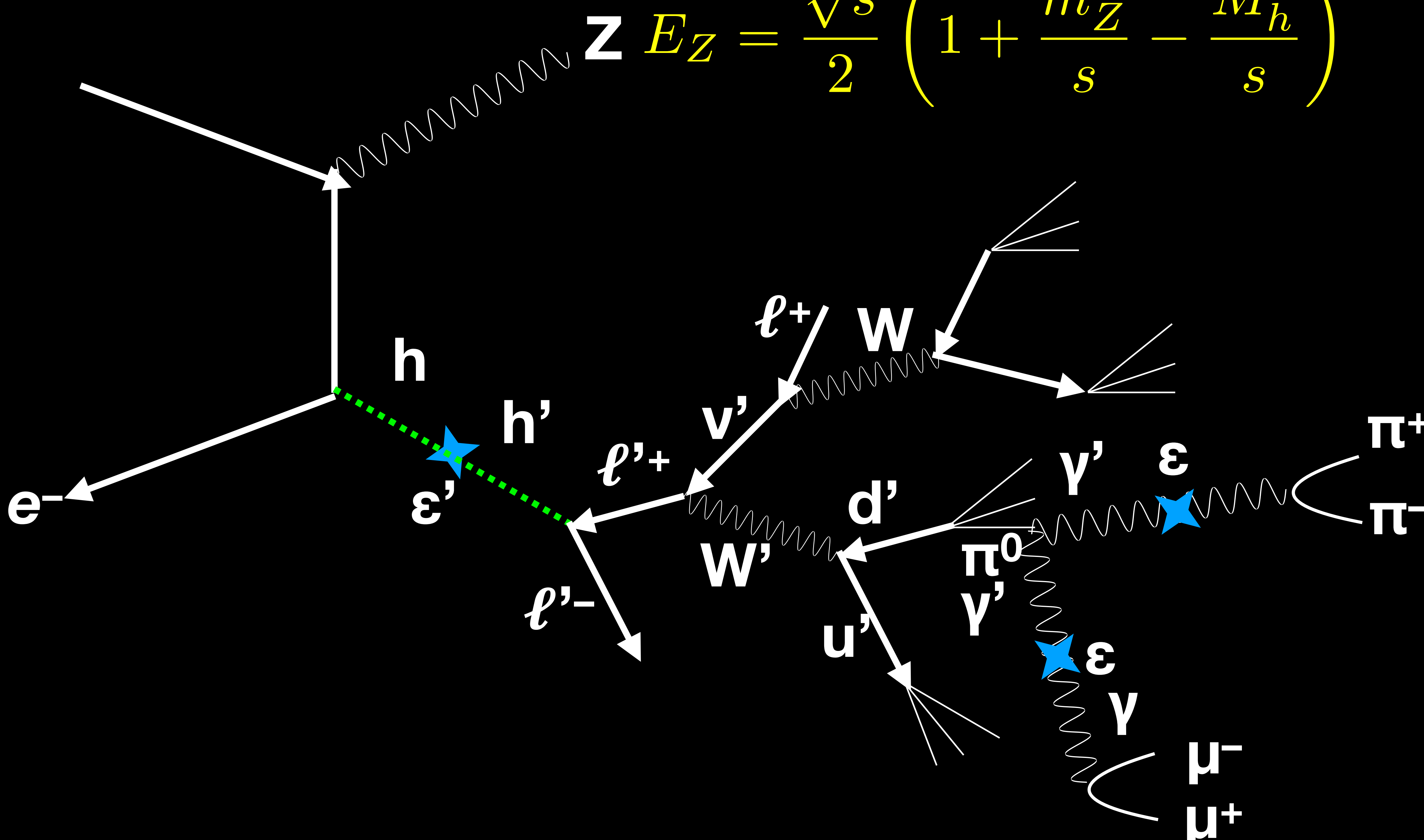
Higgs portal

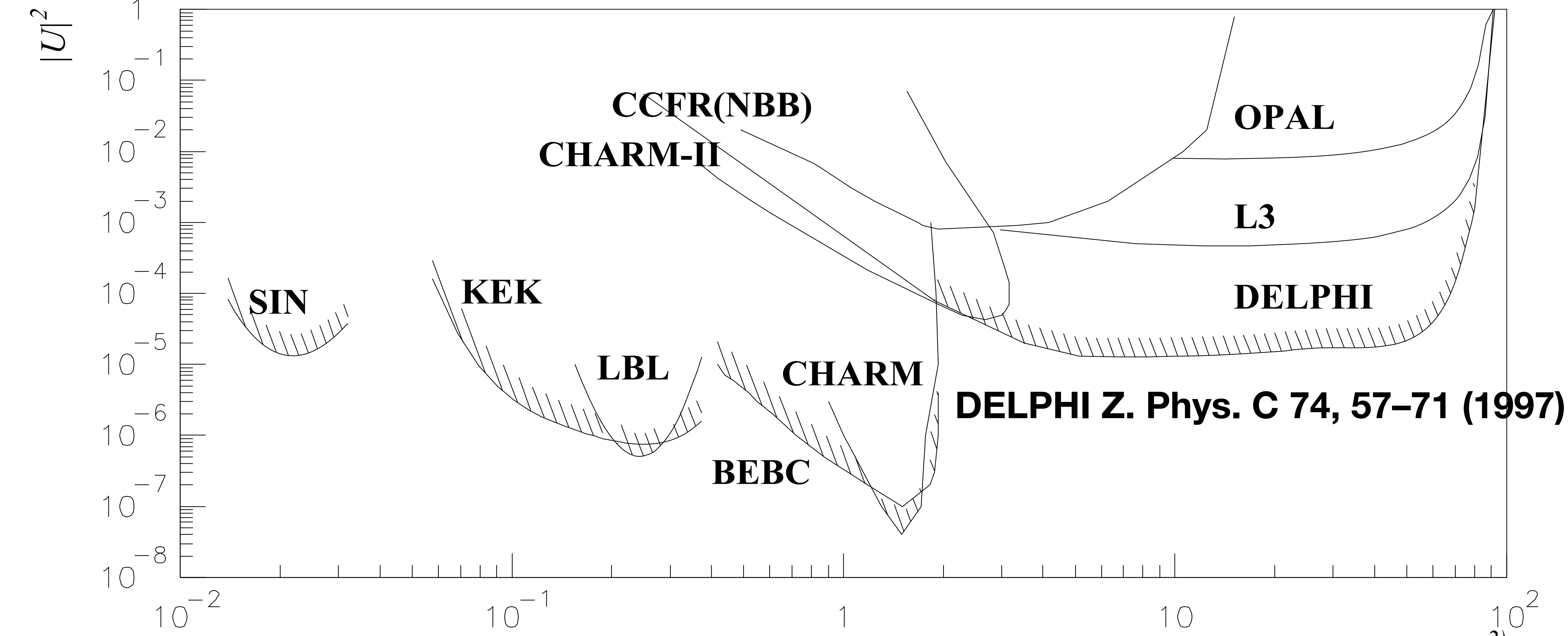
$$E_Z = \frac{\sqrt{s}}{2}\left(1 + \frac{m_Z^2}{s} - \frac{M_h^2}{s}\right)$$

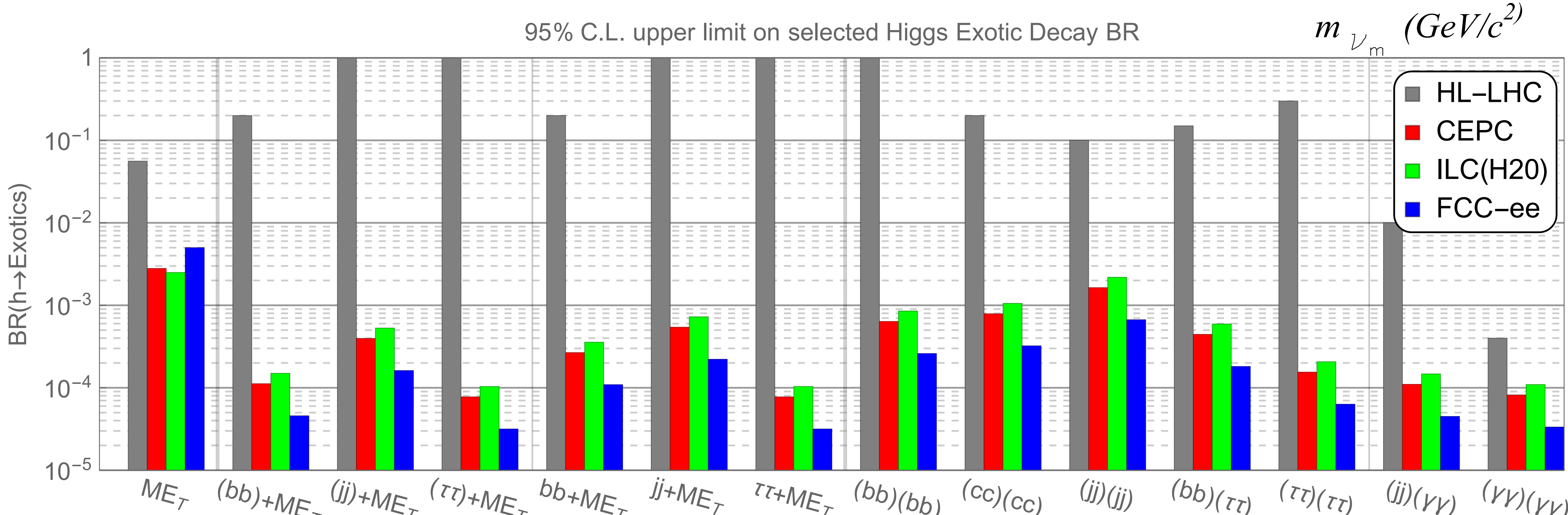


Higgs portal

$$E_Z = \frac{\sqrt{s}}{2}\left(1 + \frac{m_Z^2}{s} - \frac{M_h^2}{s}\right)$$

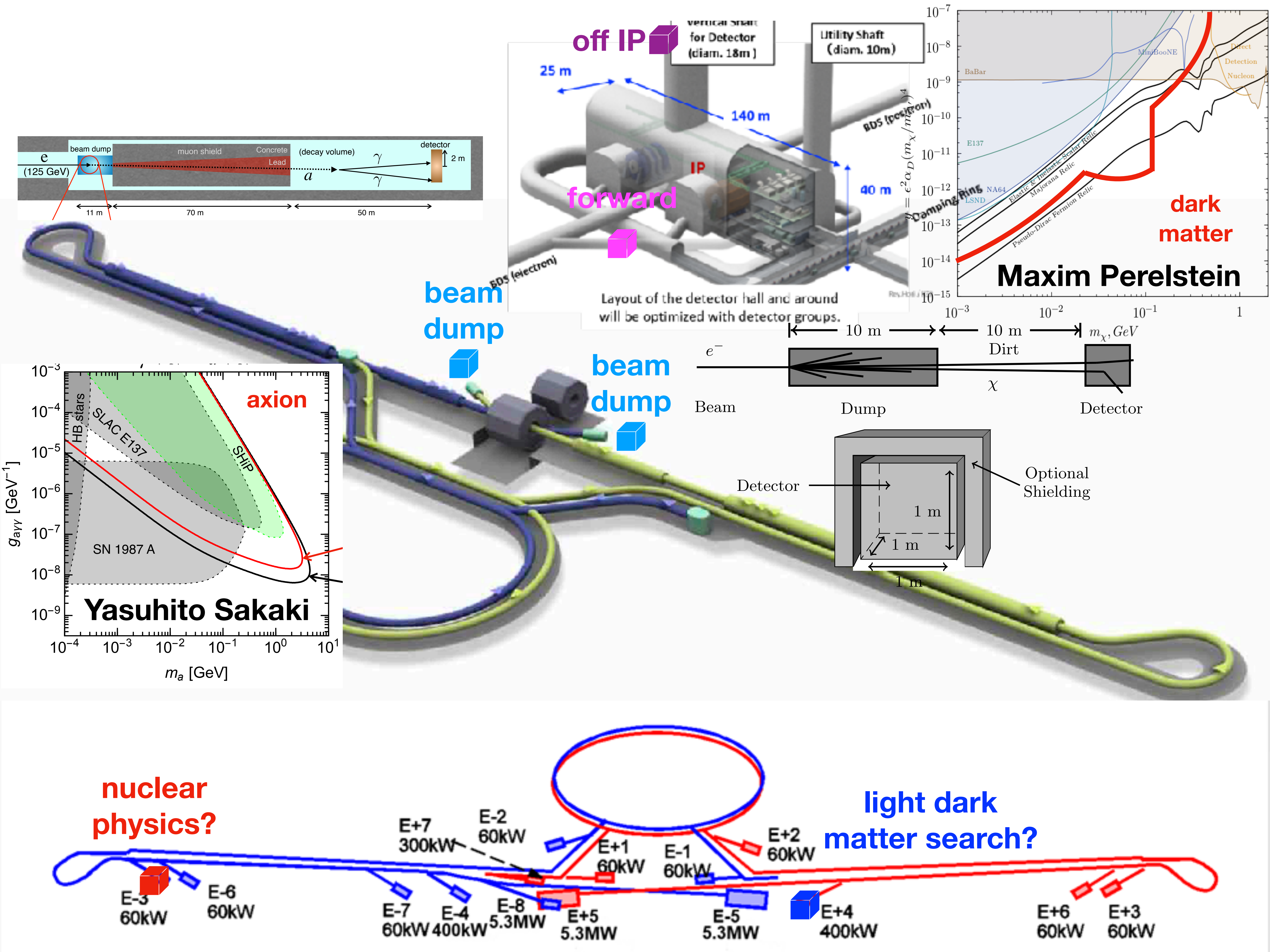






Zhen Liu, Lian-Tao Wang, Hao Zhang, arXiv:1612.09284


ILCX2021
ILC Workshop
on Potential Experiments
Super
symmetry
Dark photon
Laser
Vacuum
decay
e^+
e^-
Nuclear
science
Beam dump
Beam dump
Higgs
Axion
Dark matter
Material
Science
Nano
etching
26–29 October 2021,
Tsukuba, Japan



off IP
Vertical Shaft for Detector (diam. 18m)
Utility Shaft (diam. 10m)
25 m
140 m
40 m
IP
forward
BDS (positron)
BDS (electron)
Damping Ring
Layout of the detector hall and around will be optimized with detector groups.
beam dump
beam dump
e
(125 GeV)
beam dump
muon shield
Concrete
Lead
(decay volume)
detector
2 m
11 m
70 m
50 m
BaBar
MiniBooNE
Direct Detection Nucleon
E137
NA64
LSND
Elastic & Inelastic Scalar Relic
Majorana Relic
Pseudo-Dirac Fermion Relic
dark matter
Maxim Perelstein
m_χ, GeV
10 m
10 m
Dirt
Beam
Dump
Detector
Optional Shielding
1 m
1 m
1 m
axion
HB stars
SLAC E137
SHiP
SN 1987 A
Yasuhito Sakaki
$g_{a\gamma\gamma}$ [GeV^{-1}]
m_a [GeV]
nuclear physics?
light dark matter search?
E+7 300kW
E-2 60kW
E+1 60kW
E-1 60kW
E+2 60kW
E-3 60kW
E-6 60kW
E-7 60kW
E-4 400kW
E-8 5.3MW
E+5 5.3MW
E-5 5.3MW
E+4 400kW
E+6 60kW
E+3 60kW

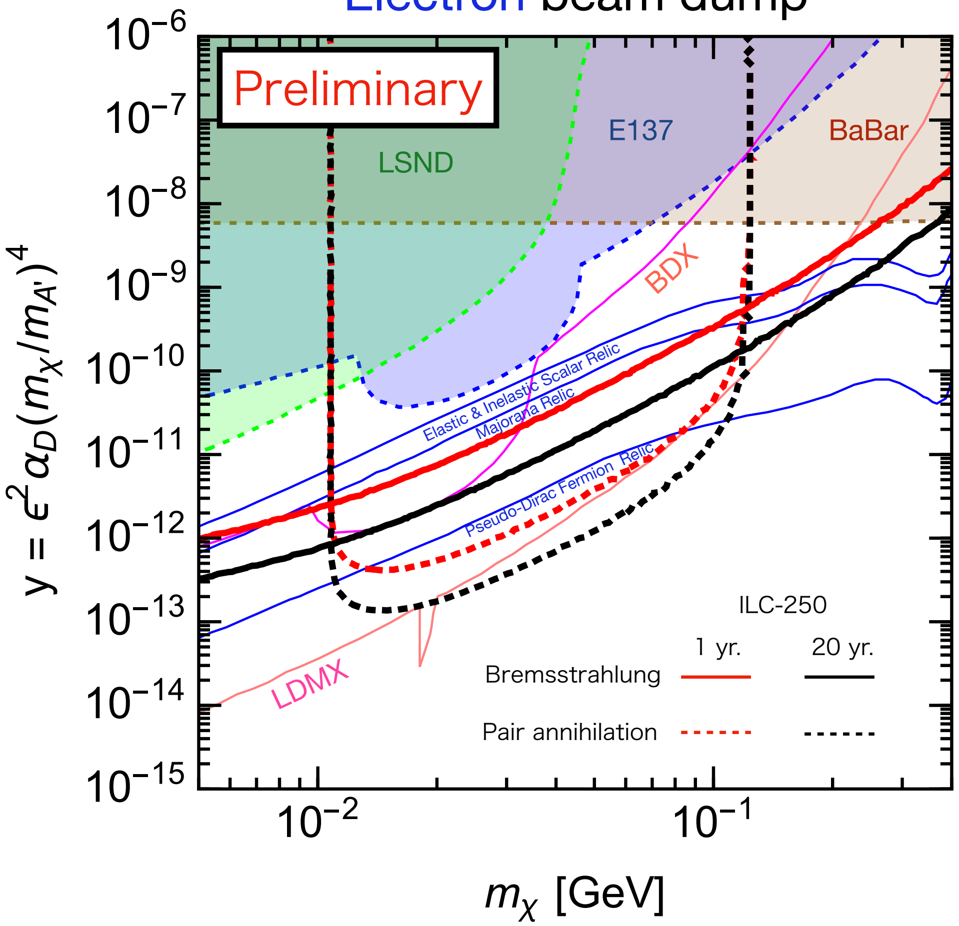
[Talk by D. Ueda, O-1]

Results of invisible decay search

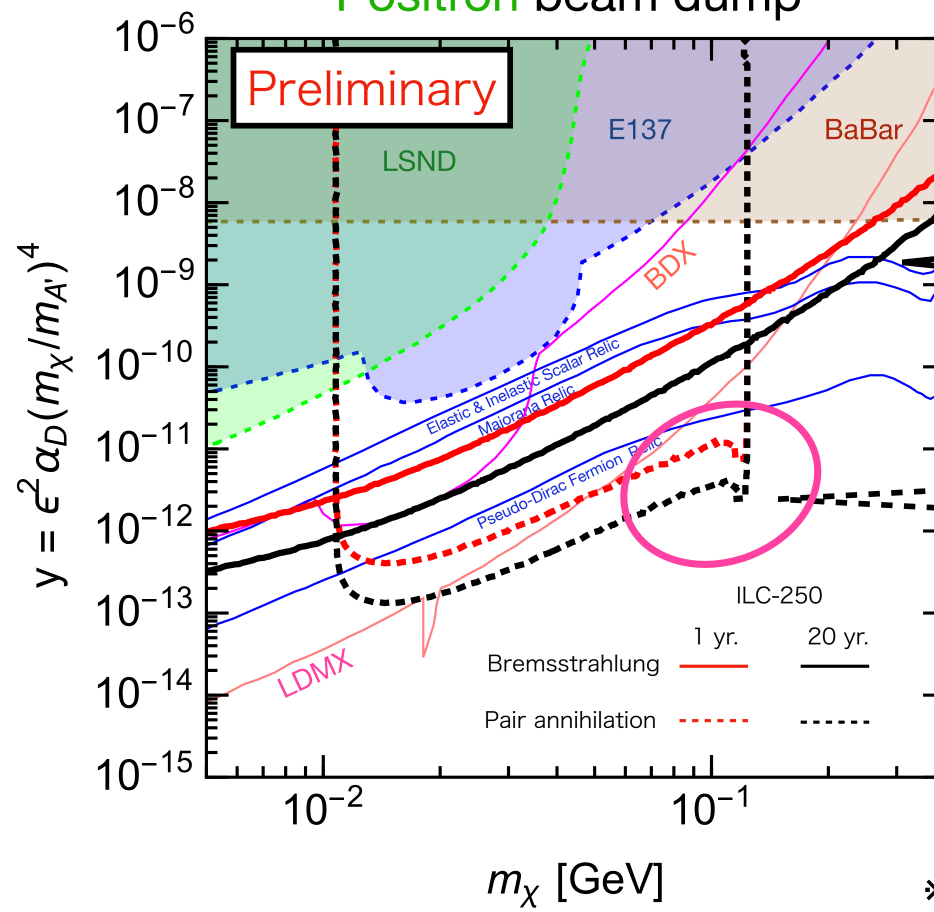
Sensitivity comparison of positron and electron beam dump experiment

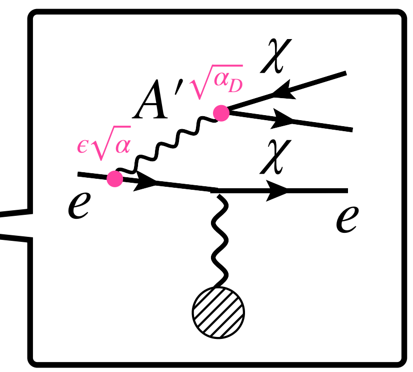
[K. Asai, S. Iwamoto, M. Perelstein, Y. Sakaki, DU.]

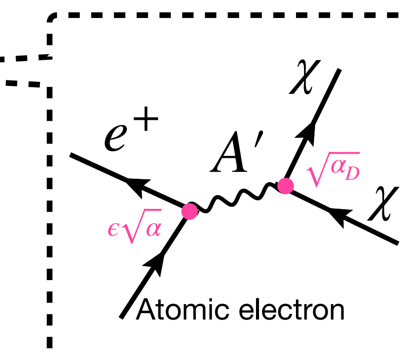
Electron beam dump



Positron beam dump

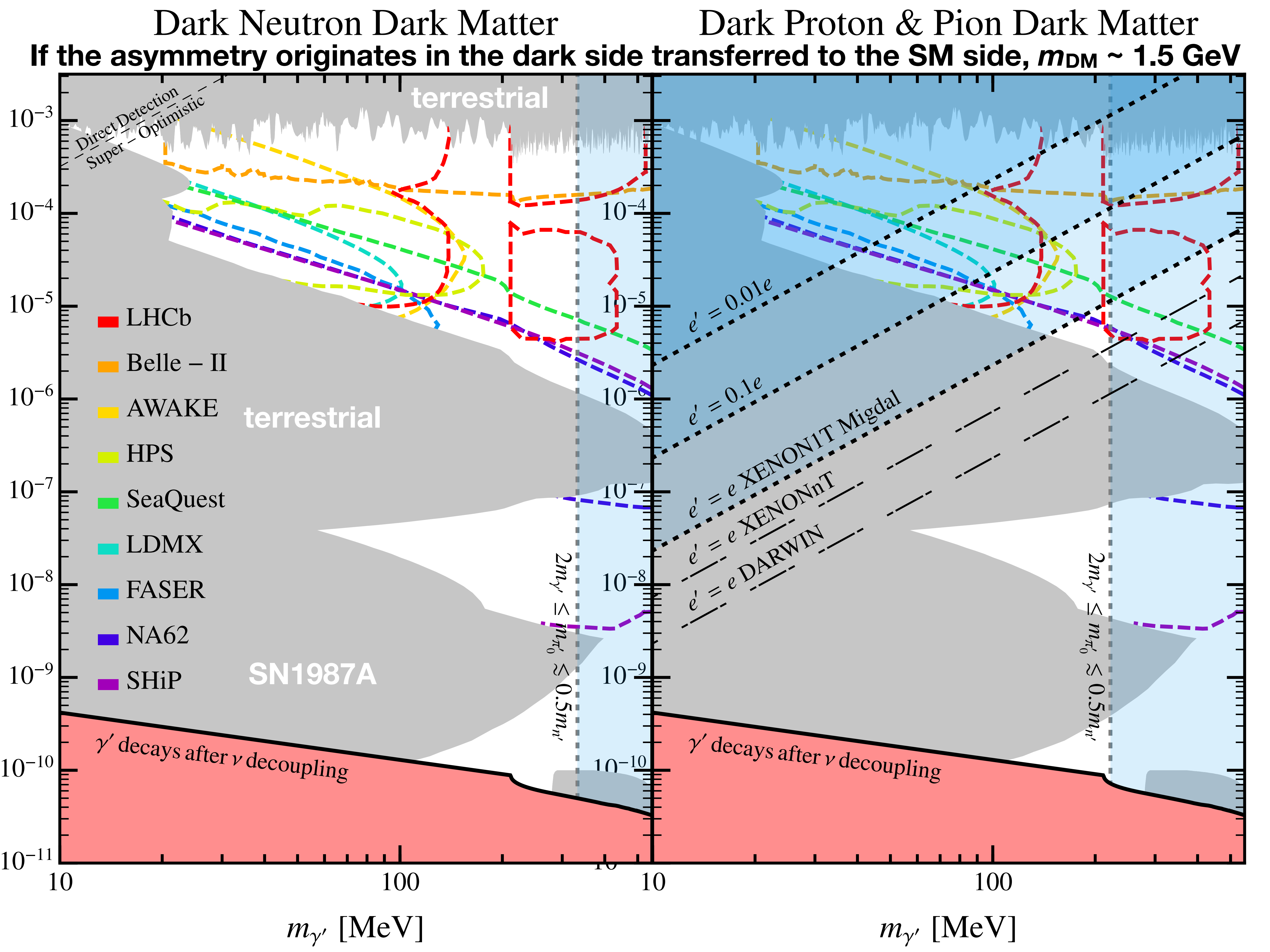






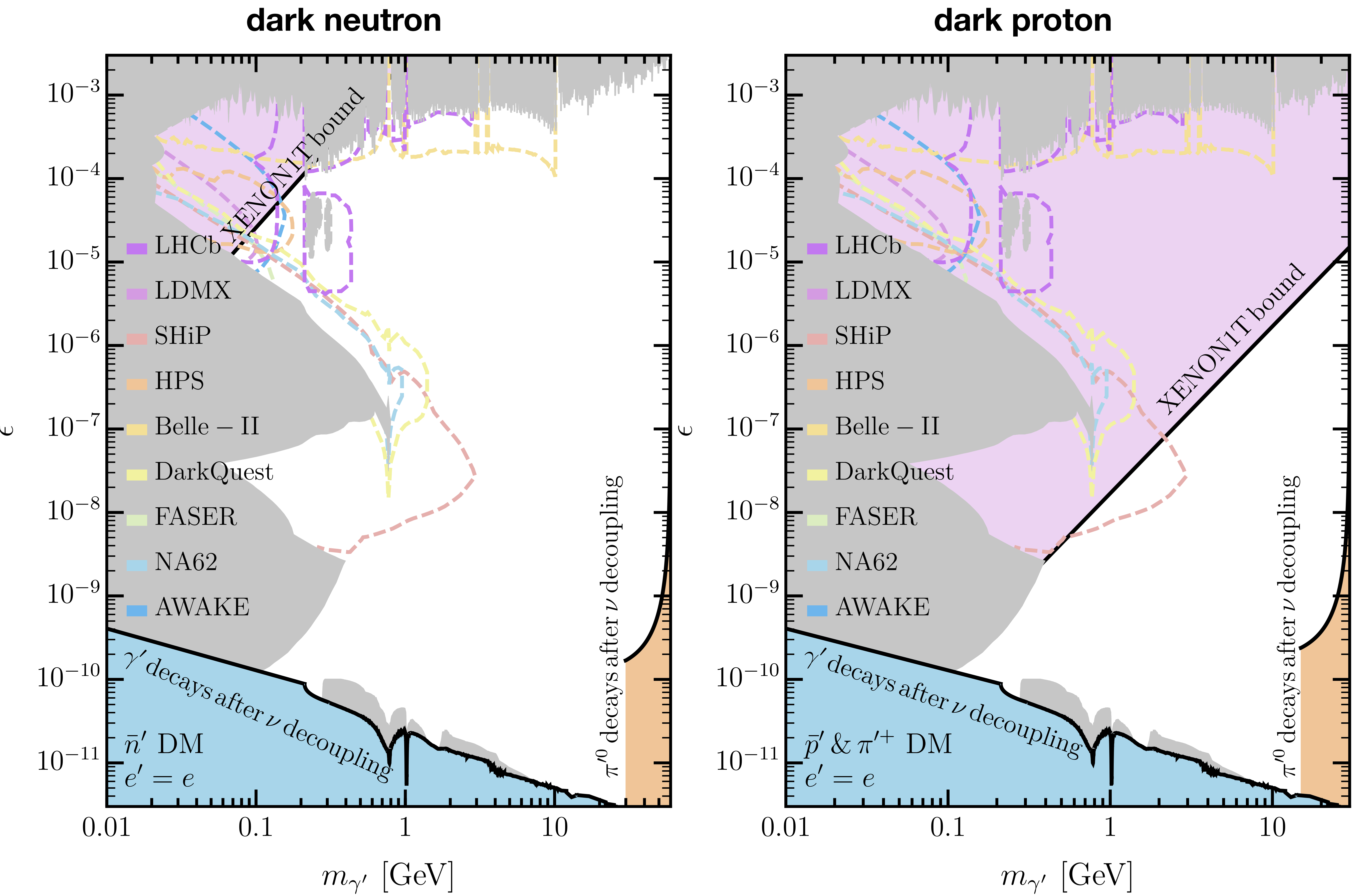
※ $\alpha_D \equiv g_D^2/4\pi = 0.5, \quad m_{A'} = 3m_\chi$

A benchmark Model: $-\frac{1}{4}F^{A'}_{\mu\nu}F^{A'}_{\mu\nu} - \frac{\epsilon}{2}F_{\mu\nu}F^{A'}_{\mu\nu} + \frac{m^2_{A'}}{2}A'_\mu A'_\mu + \bar{\chi}(iD_\mu\gamma^\mu - m_\chi)\chi, \quad D_\mu = \partial_\mu + ig_D A'_\mu$

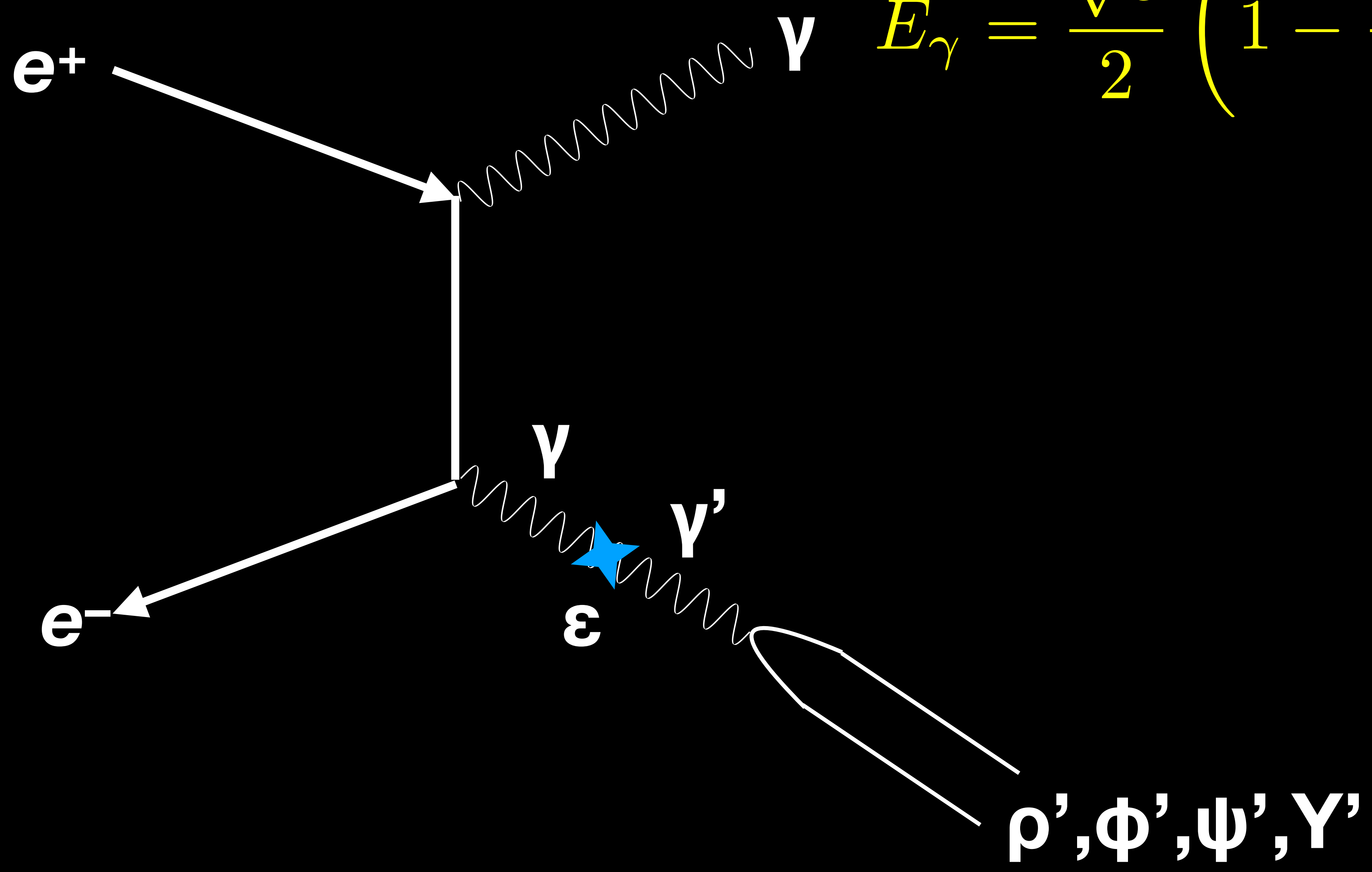


Dark Neutron Dark Matter
Dark Proton & Pion Dark Matter
If the asymmetry originates in the dark side transferred to the SM side, $m_{\rm DM}$ ~ 1.5 GeV
terrestrial
Direct Detection
Super − Optimistic
LHCb
Belle − II
AWAKE
HPS
SeaQuest
LDMX
FASER
NA62
SHiP
terrestrial
SN1987A
γ' decays after ν decoupling
$2m_{\gamma'} \leq m_{\pi_0'} \lesssim 0.5 m_{n'}$
$e' = 0.01e$
$e' = 0.1e$
$e' = e$ XENON1T Migdal
$e' = e$ XENONnT
$e' = e$ DARWIN
$m_{\gamma'}$ [MeV]

If the asymmetry originates in the SM side transferred to the dark side
$m_{\rm DM}$ ~ 60 GeV! Not light even though asymmetric



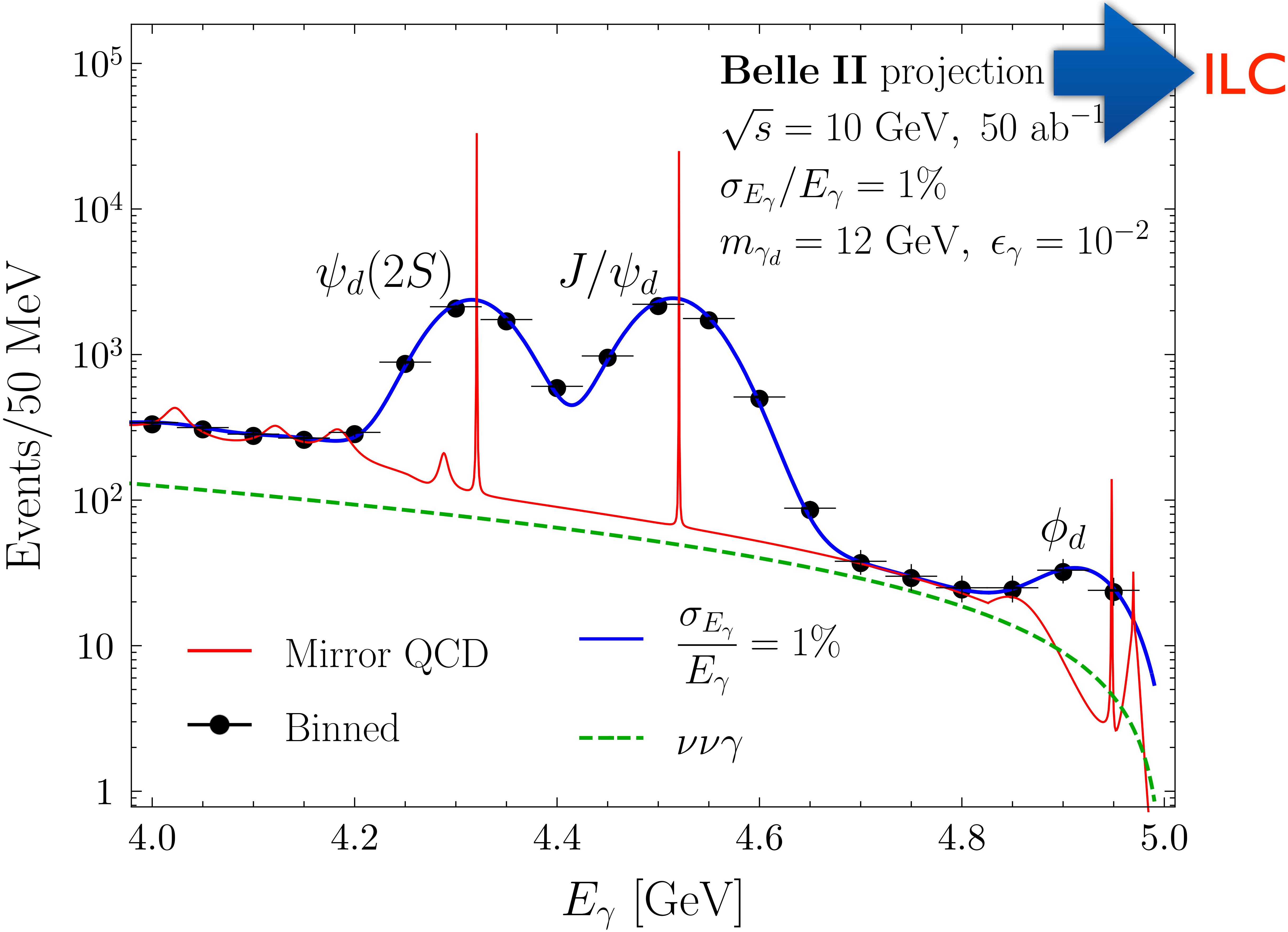
Dark Spectroscopy

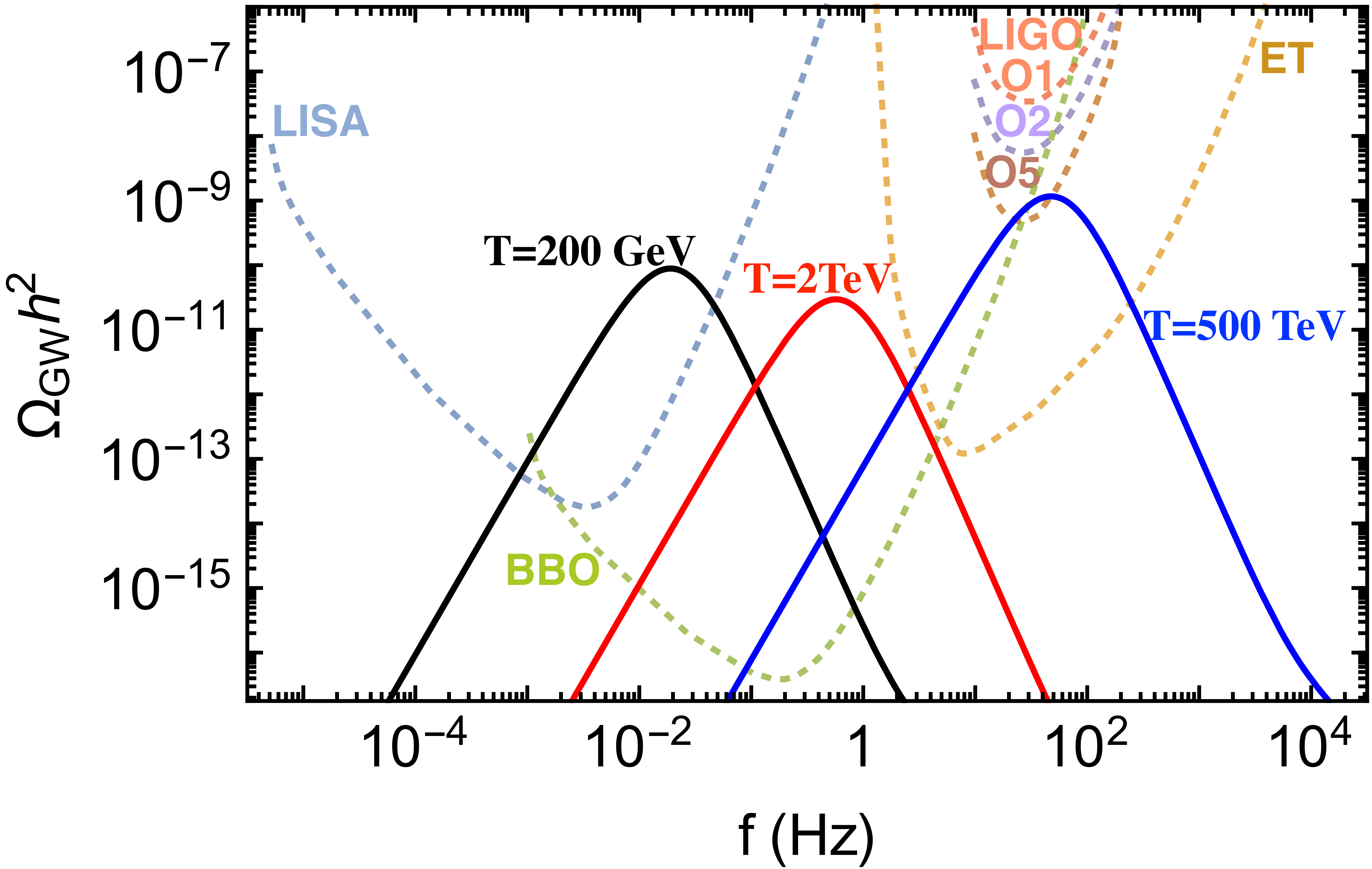


$$E_\gamma = \frac{\sqrt{s}}{2}\left(1 - \frac{M_{\rm inv}^2}{s}\right)$$

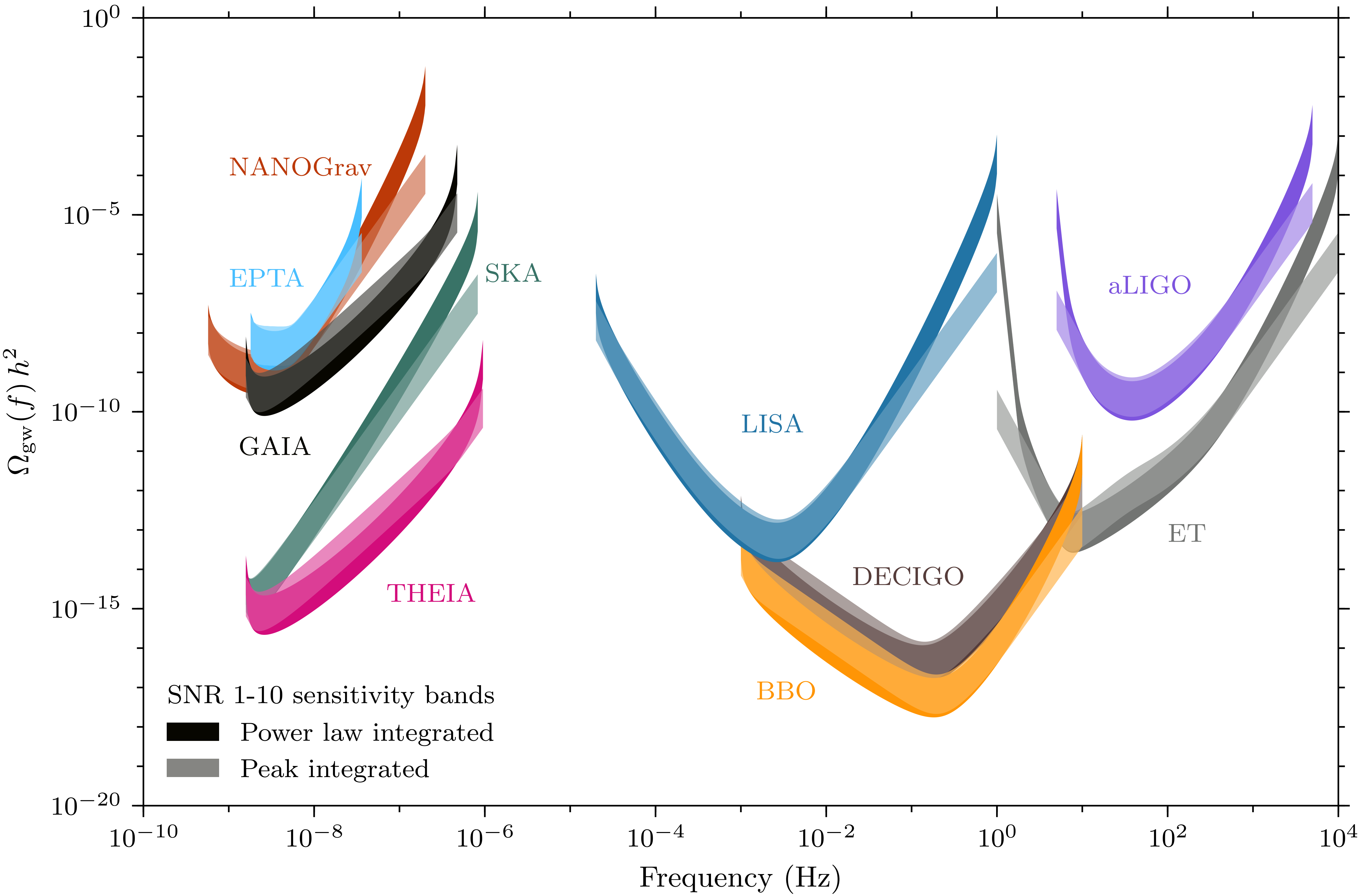
Yonit Hochberg, Eric Kuflik, HM, arXiv:1512.07917, 1706.05008

Dark Spectroscopy





+Géraldine Servant

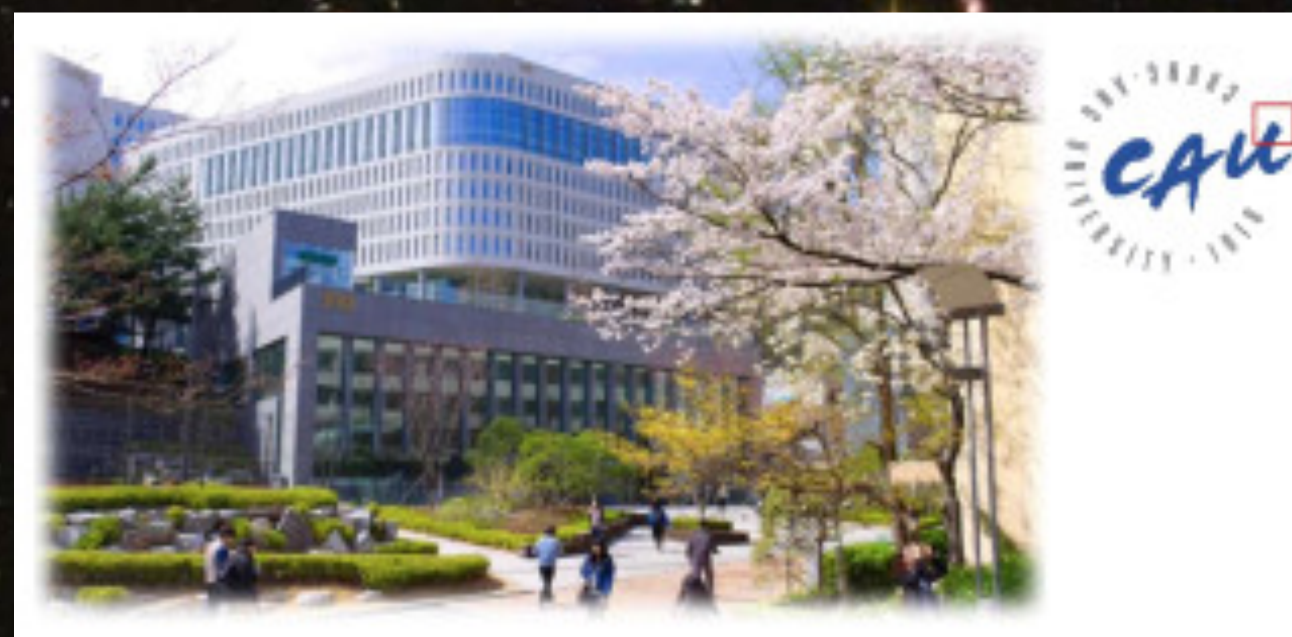


Juan Garcia-Bellido, Hitoshi Murayama, Graham White, arXiv:2104.04778

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, ILC
- Dark spectroscopy!
- resonant self-interaction in dwarf galaxies
- rare Z and Higgs decays
- gravitational wave

Fun with
Composite Dark Matter



Hitoshi Murayama (Berkeley, Kavli IPMU)

2022 CAU BSM Workshop

Feb 8, 2022