ILC Overview

Hitoshi Murayama (Berkeley, Kavli IPMU)

HPNP 2021, March 25, 2021

You got an upgrade!

Higgs and Dark Sector

Hitoshi Murayama (Berkeley, Kavli IPMU)

HPNP 2021, March 26, 2021

what I want to know

- light dark sector is in vogue
  - Higgs is touted as a portal
- can we really address dark matter and/or baryon asymmetry?
- what do we learn from colliders?

Sakharov Conditions

- Standard Model may have all three ingredients
- Baryon number violation
  - Electroweak anomaly (sphaleron effect)
- CP violation
  - Kobayashi–Maskawa phase

$$J \propto \det[M_u^\dagger M_u, M_d^\dagger M_d]/T_{EW}^{12} \sim 10^{-20} \ll 10^{-10}$$

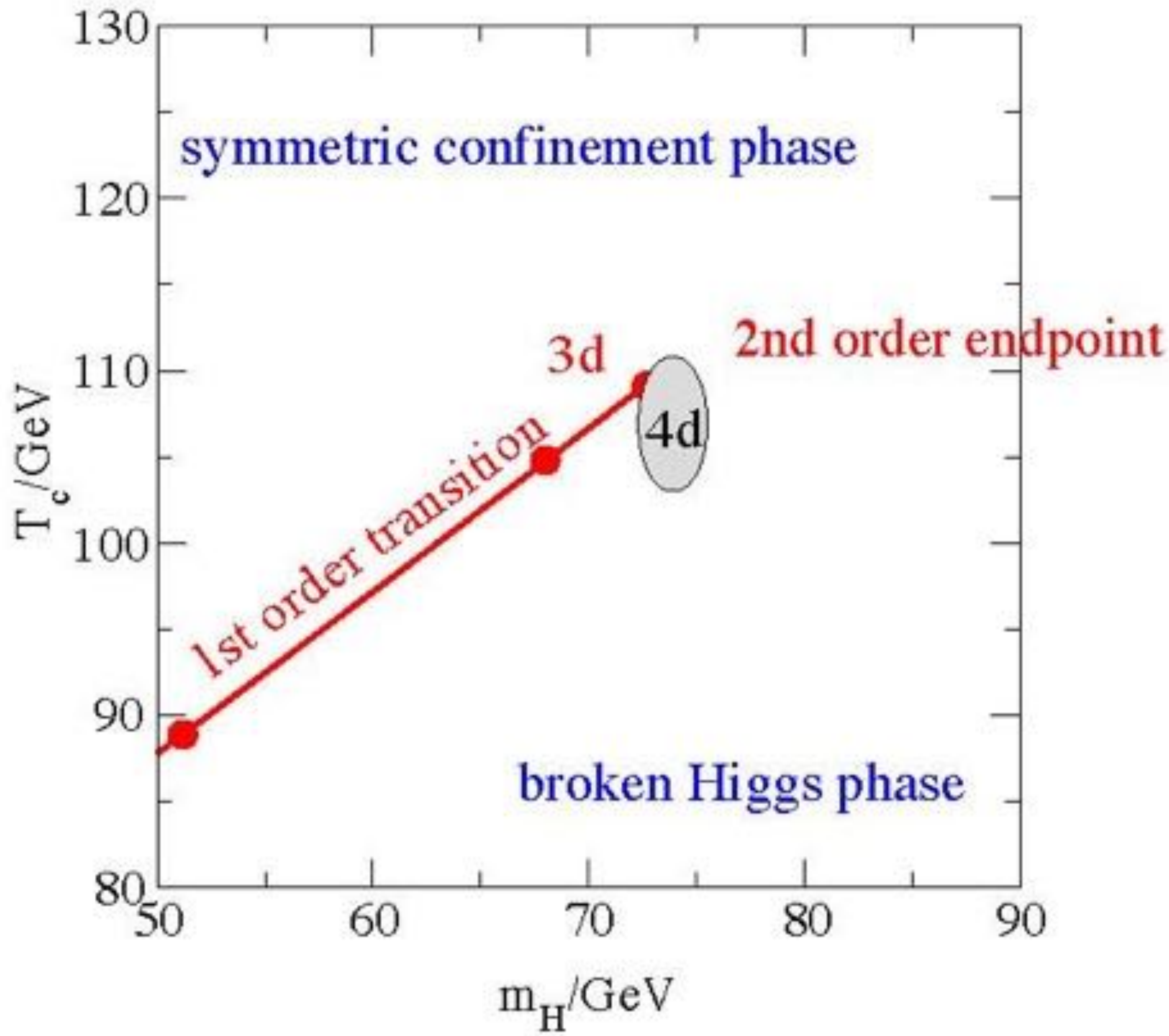
- Departure from equilibrium
  - First-order phase transition of Higgs

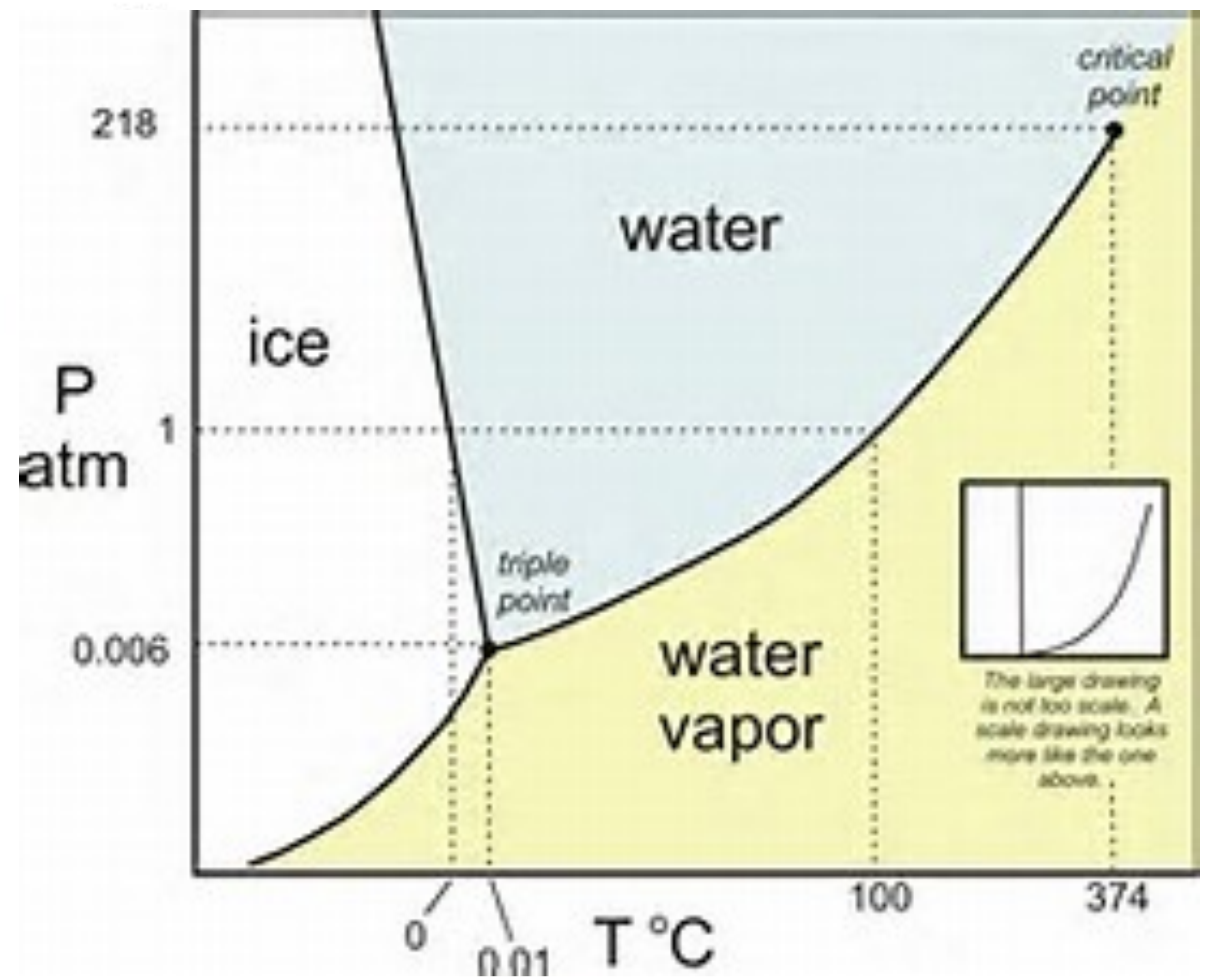
requires m_h < 75 GeV

- Experimentally testable?

Mikko Laine (Bern)

Phase diagram for the Standard Model:





$\langle H \rangle$=0 from gauge invariance (Elitzur)

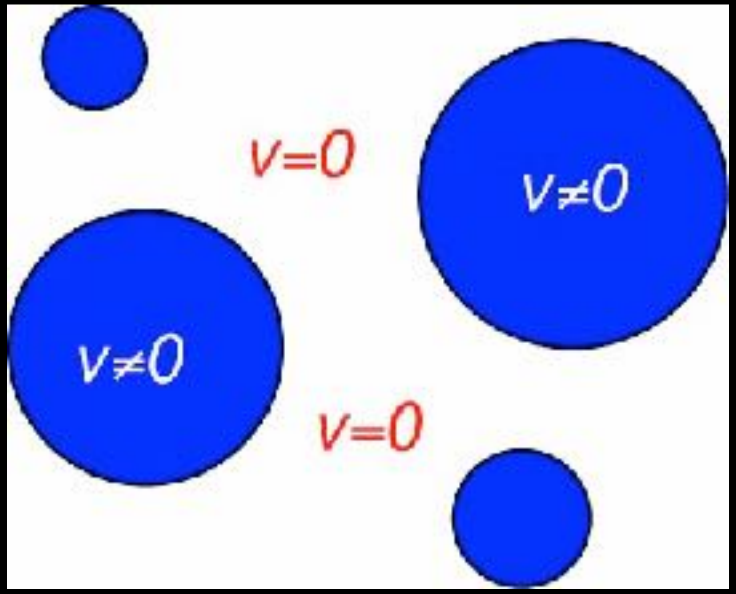
$\langle H^\dagger H \rangle$ is not an order parameter

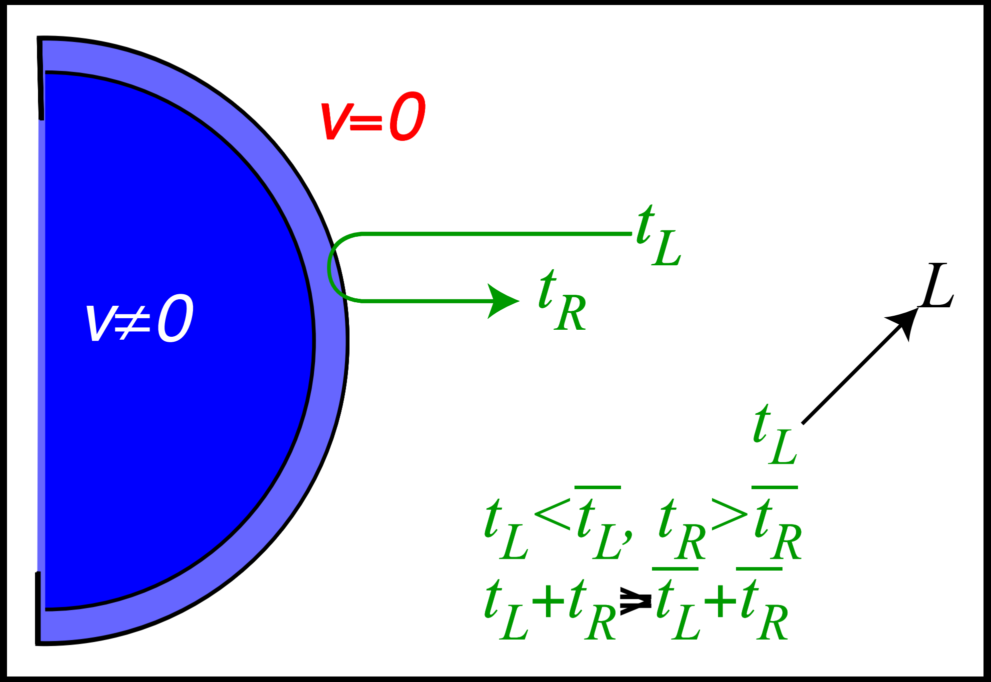
for m_h=125GeV, it is crossover

No phase transition in the Minimal Standard Model

Scenario
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





Electric Dipole Moment

- baryon asymmetry limited by the sphaleron rate $\Gamma \sim 20\, \alpha_W^5\, T \sim 10^{-6}\, T$

- Can't lose much more to obtain 10^{-9}

- need
  - new physics for 1st order PT at the Higgs scale v=250 GeV
  - CP violation×efficiency $\geq 10^{-3}$

Oct 2018

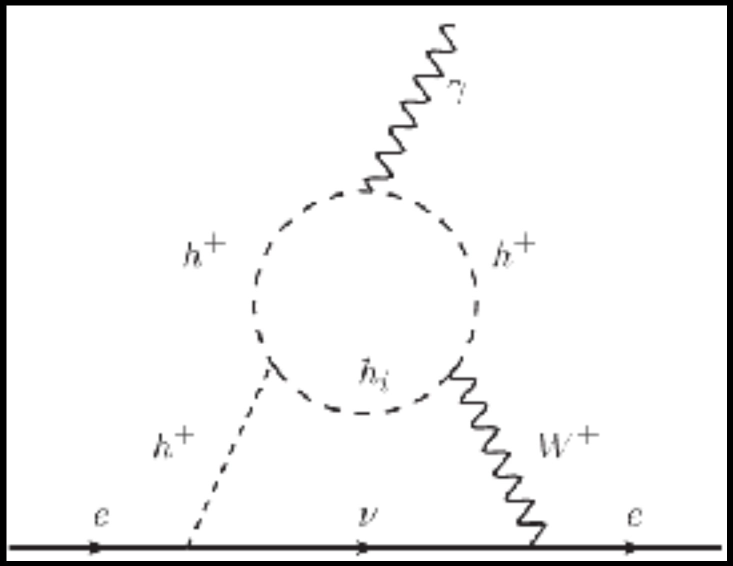
ARTICLE

https://doi.org/10.1038/s41586-018-0599-8

Improved limit on the electric dipole moment of the electron

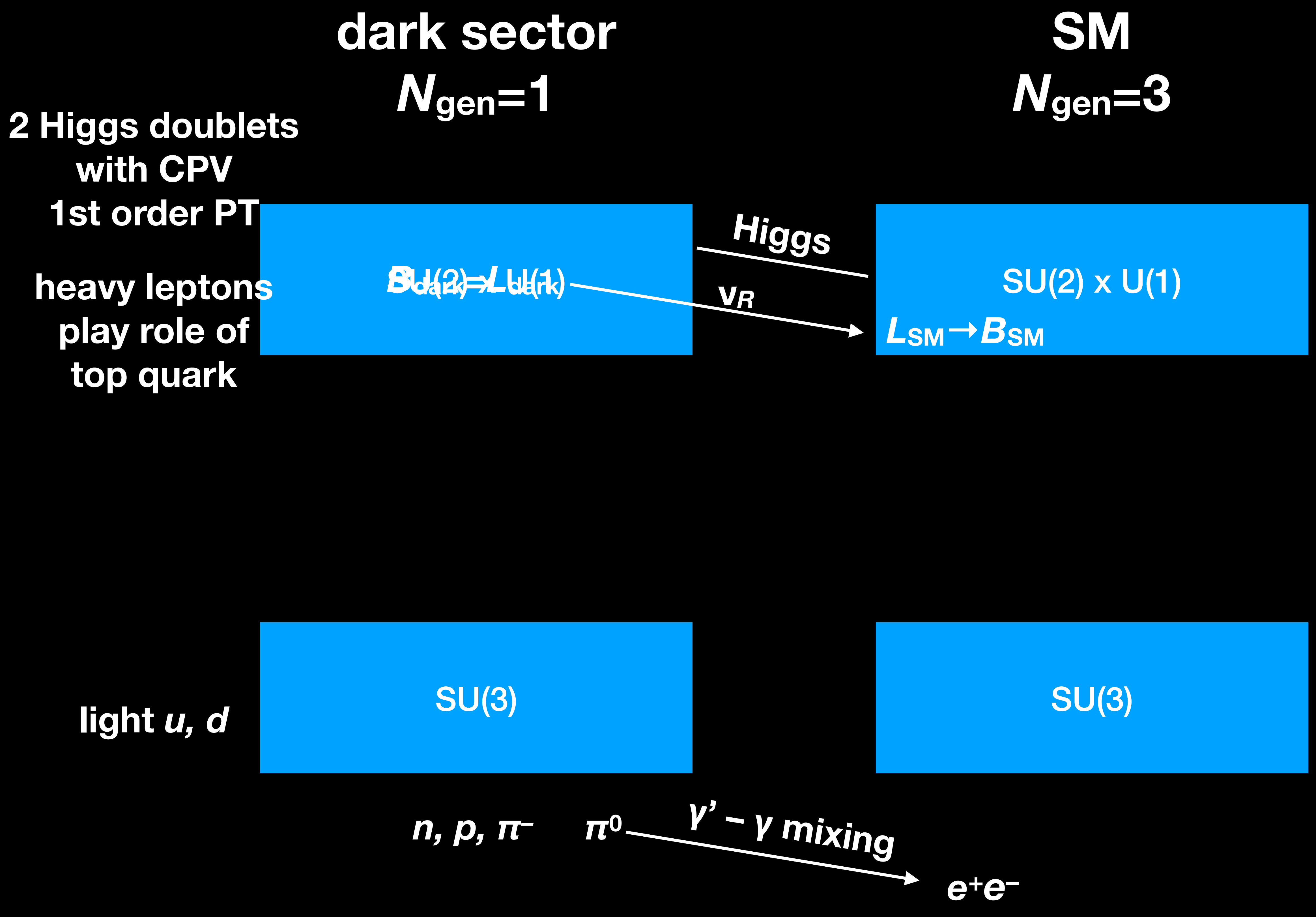
ACME Collaboration*

$d_e \leq 1.1 \times 10^{-29}\ e\ \mathrm{cm}$

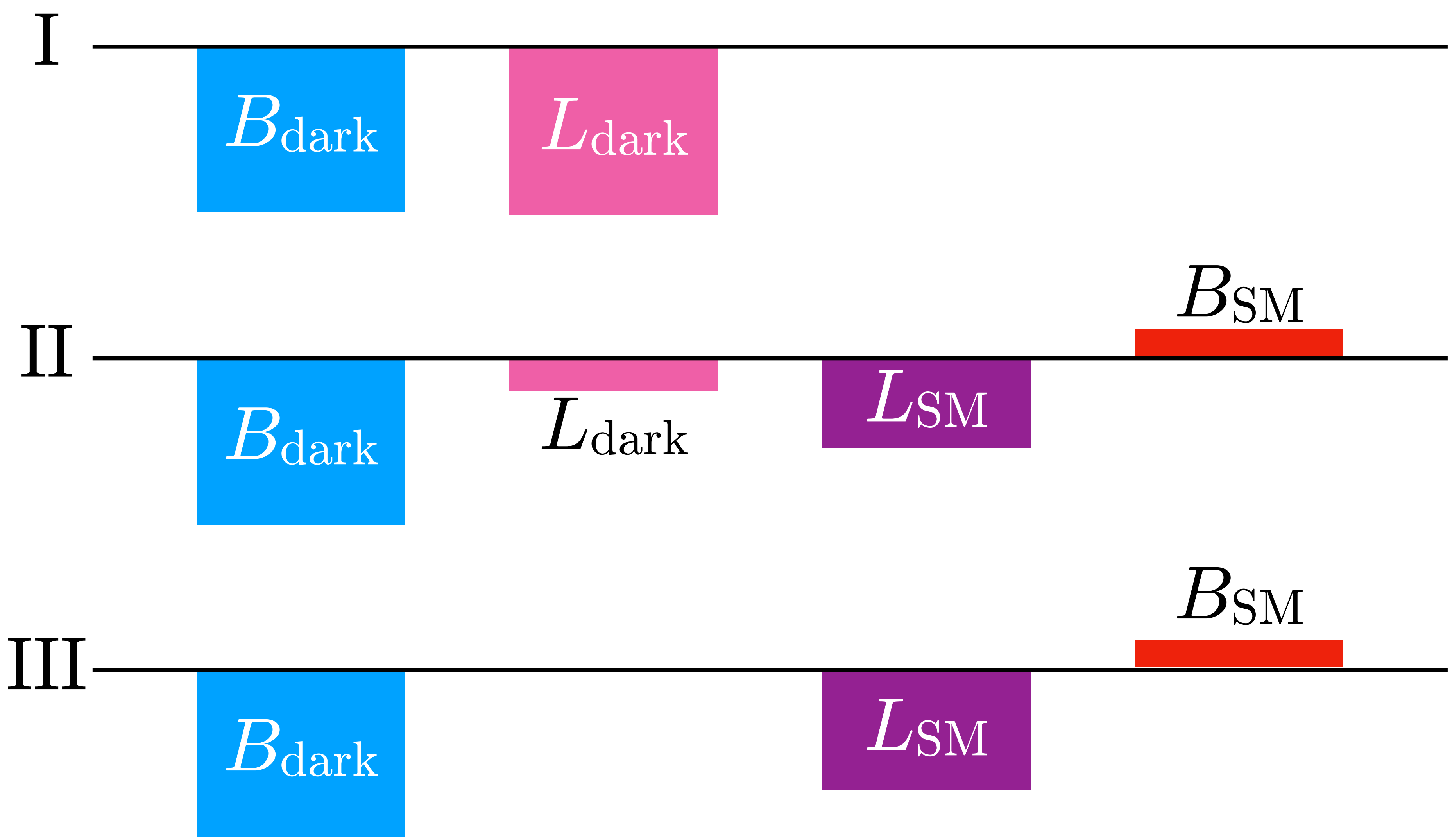


Barr-Zee diagrams

$$d_e \approx \frac{e m_e}{(16\pi^2)^2} \frac{1}{v^2} \sin\delta = 1.6 \times 10^{-22} e\mathrm{cm} \sin\delta$$



Nell Hall, Thomas Konstandin, HM, Robert McGehee, arXiv:1911.12342



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**

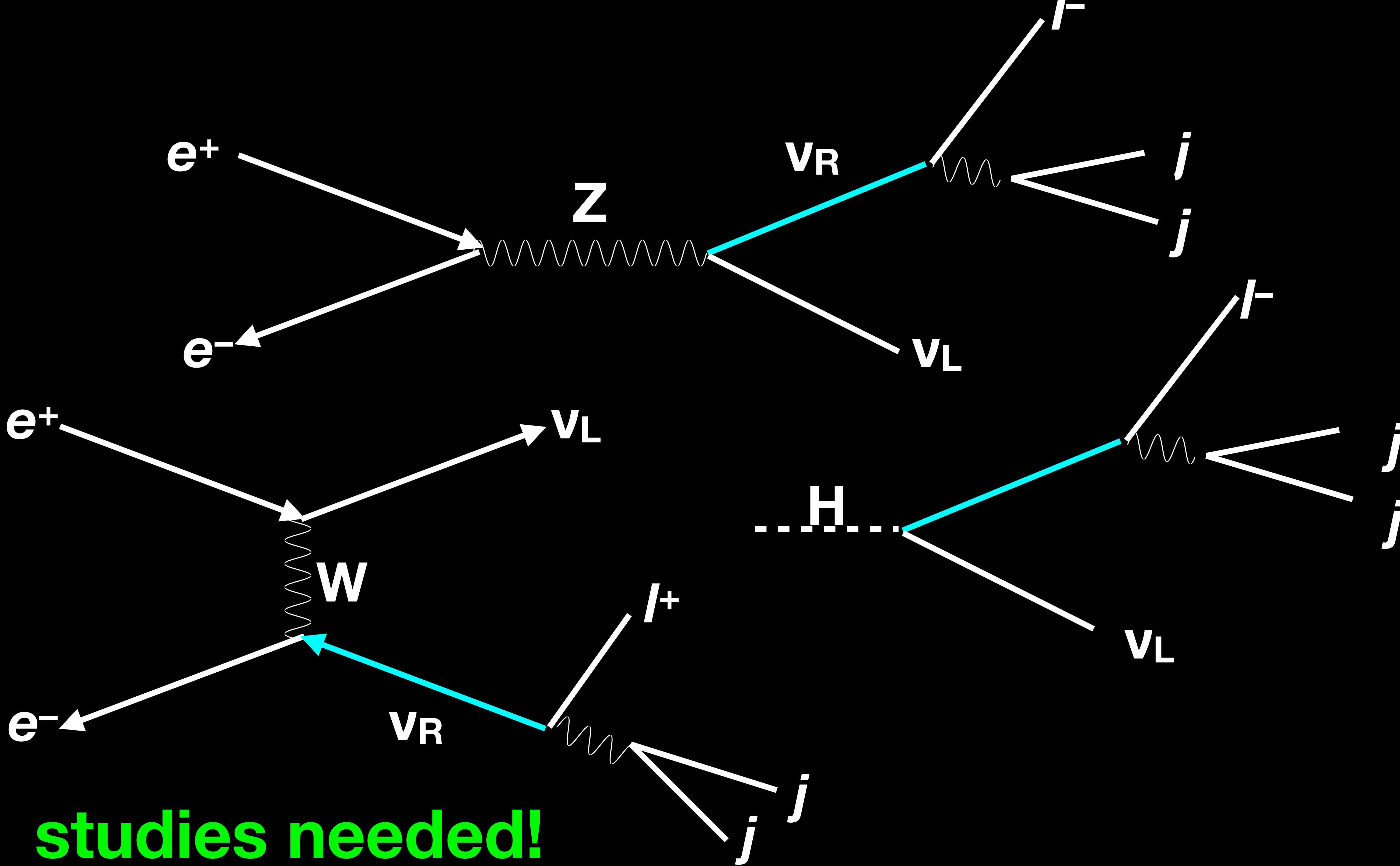
neutrino portal

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

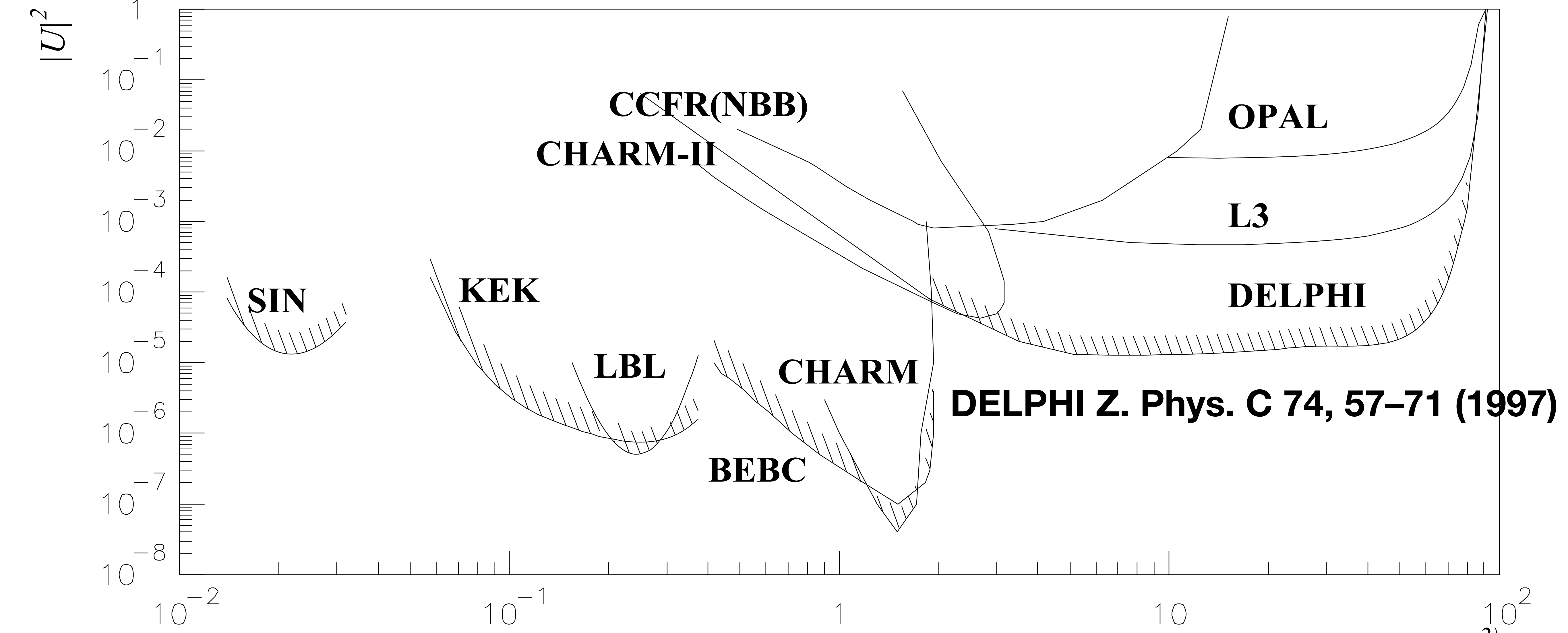
$$\epsilon_i = \frac{y_i}{\sqrt{(y')^2 + (y_i)^2}} \qquad M_\nu = \sqrt{(y')^2 + (y_i)^2} v$$

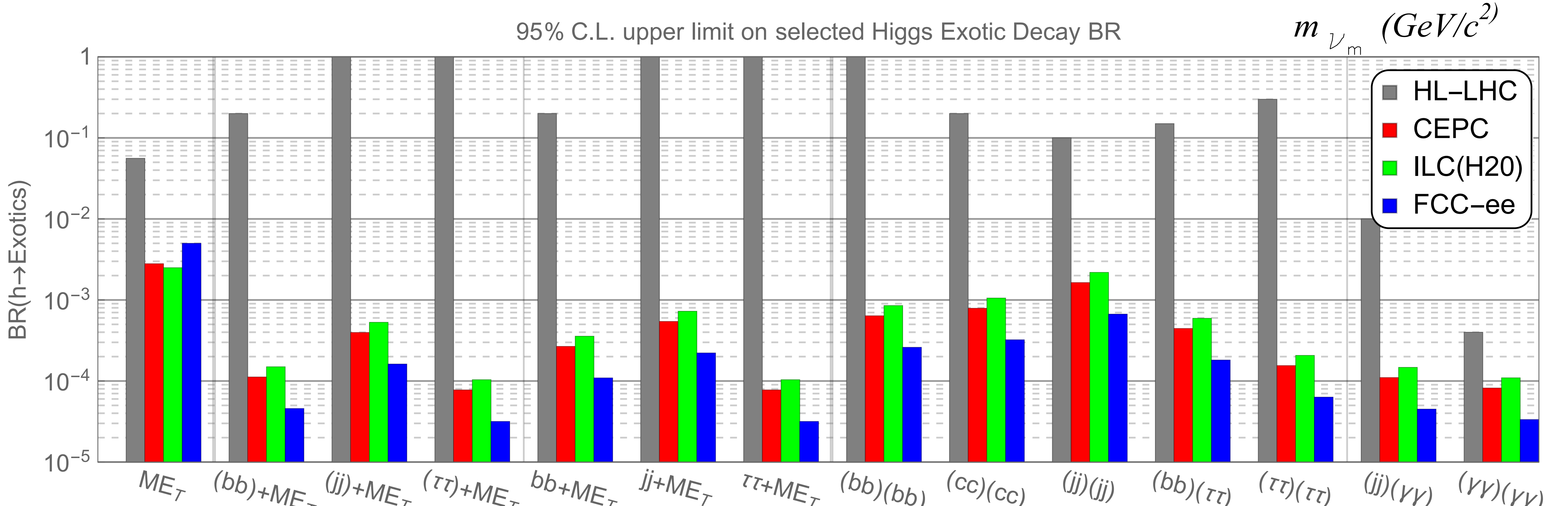
- charged current universality: $\varepsilon_i^2 < 10^{-3}$
- $\mu \to e\, \gamma$ constraint: $\varepsilon_e\, \varepsilon_\mu < 4\times10^{-5}\ (G_F M_\nu)$
- $\tau \to \mu\, \gamma$ constraint: $\varepsilon_e\, \varepsilon_\mu < 0.03\ (G_F M_\nu)$
- If $M_\nu < 70$ GeV, $\varepsilon_i^2 < 10^{-5}$ (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)

neutrino & Higgs portal

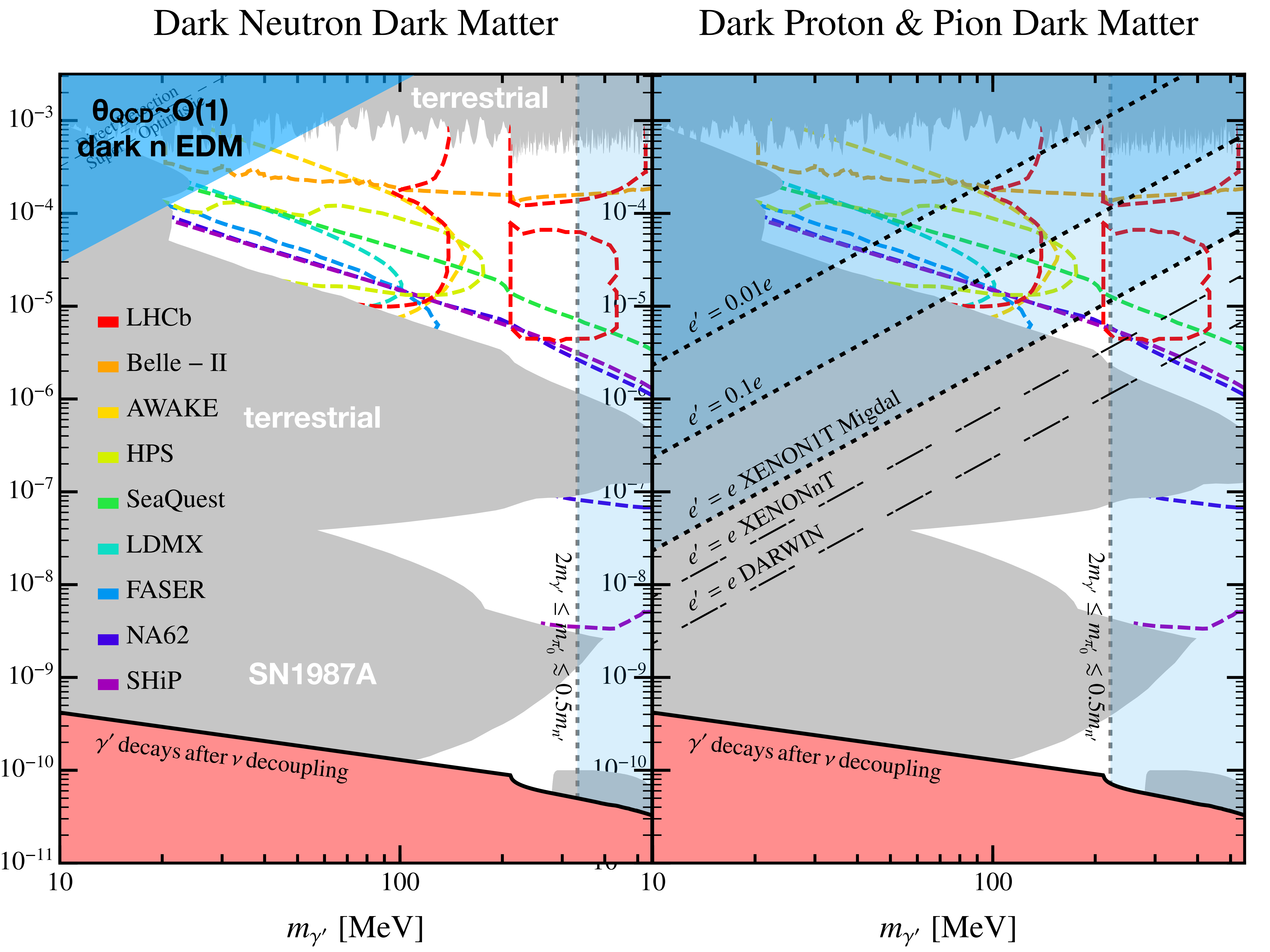


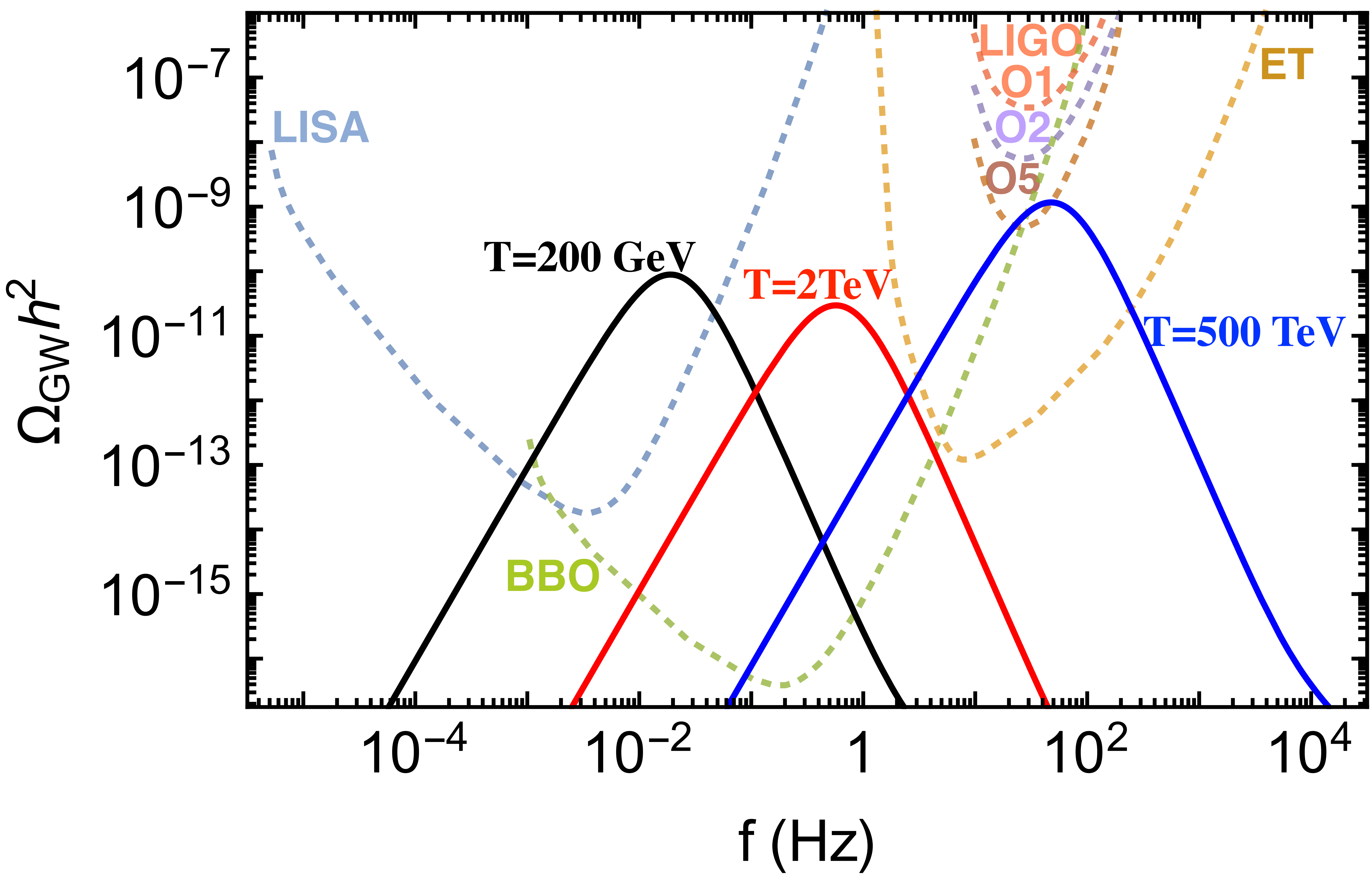
studies needed!





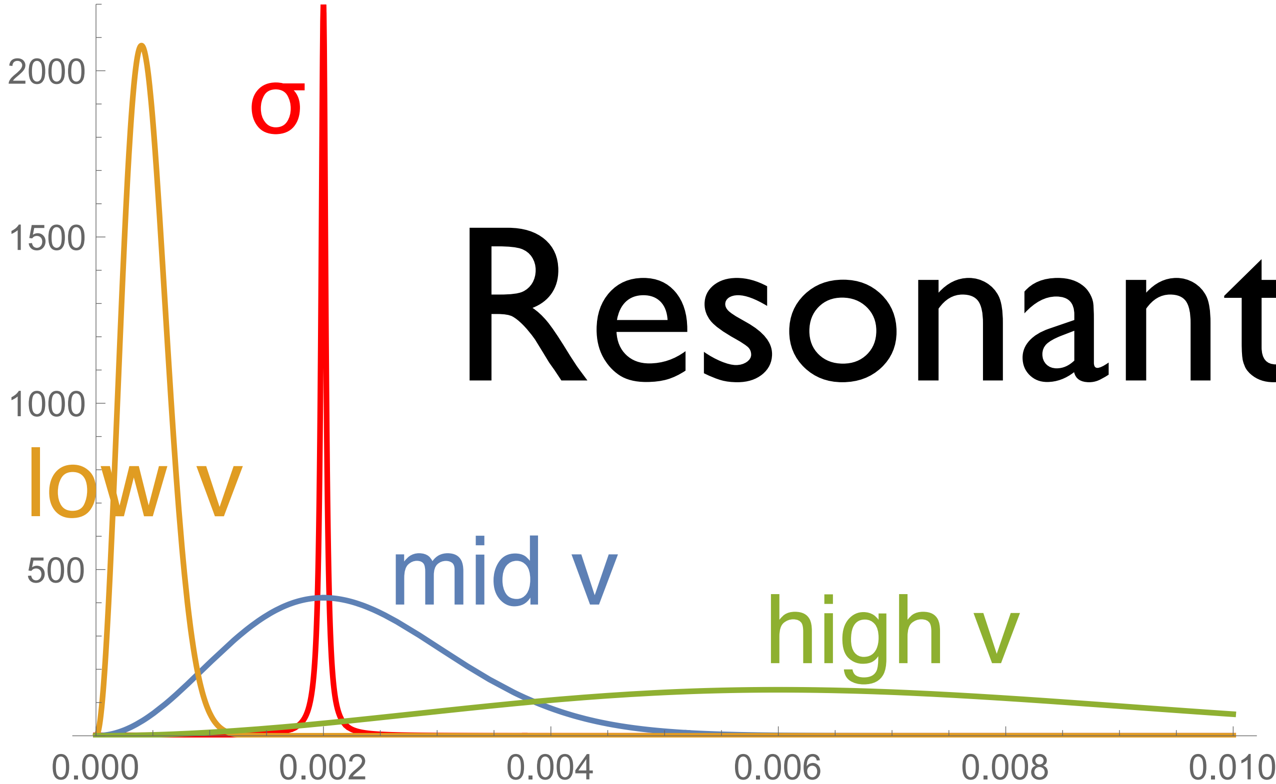
Zhen Liu, Lian-Tao Wang, Hao Zhang, arXiv:1612.09284

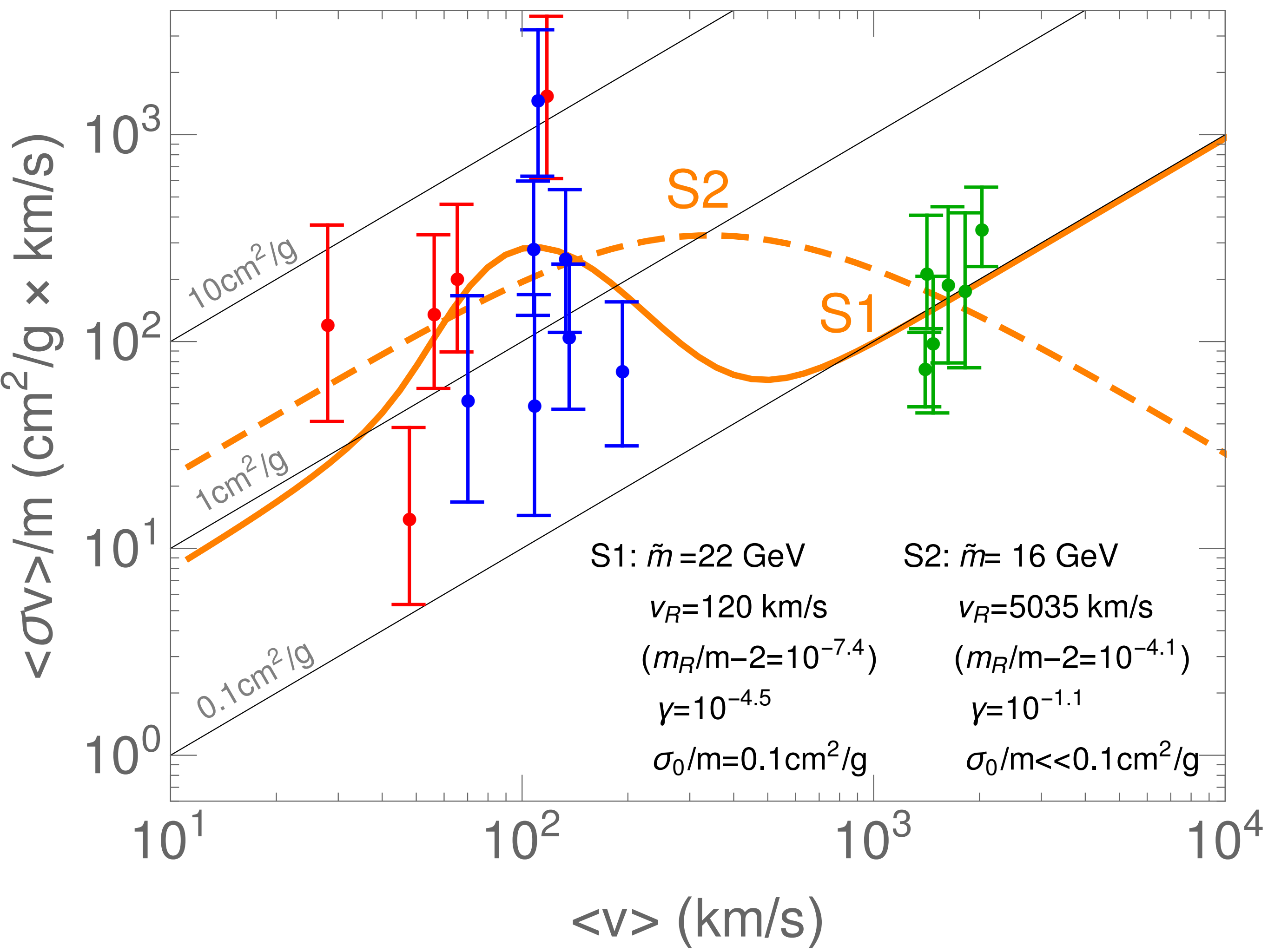

Dark Neutron Dark Matter
Dark Proton & Pion Dark Matter
terrestrial
θQCD~O(1)
dark n EDM
Direct Detection
Super Optimistic
LHCb
Belle – II
AWAKE
HPS
SeaQuest
LDMX
FASER
NA62
SHiP
terrestrial
SN1987A
γ′ decays after ν decoupling
2m_γ′ ≤ m_π′0 ≲ 0.5m_n′
e′ = 0.01e
e′ = 0.1e
e′ = e XENON1T Migdal
e′ = e XENONnT
e′ = e DARWIN
γ′ decays after ν decoupling
2m_γ′ ≤ m_π′0 ≲ 0.5m_n′
10^−3
10^−4
10^−5
10^−6
10^−7
10^−8
10^−9
10^−10
10^−11
10
100
m_γ′ [MeV]

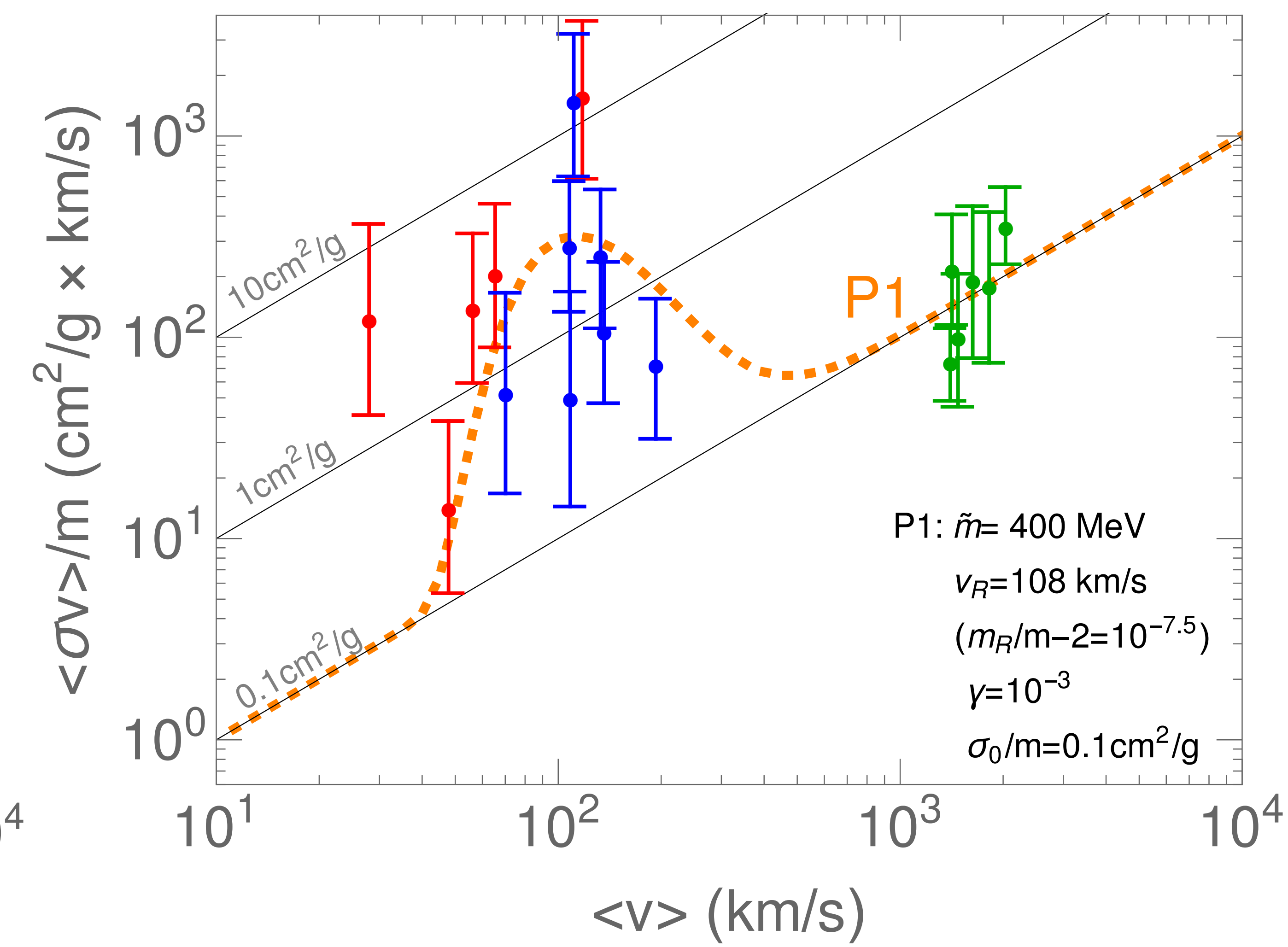


LIGO
O1
O2
O5
ET
LISA
BBO
T=200 GeV
T=2TeV
T=500 TeV
10^{-7}
10^{-9}
10^{-11}
10^{-13}
10^{-15}
$\Omega_{GW}h^2$
10^{-4}
10^{-2}
1
10^{2}
10^{4}
f (Hz)

Resonant scattering



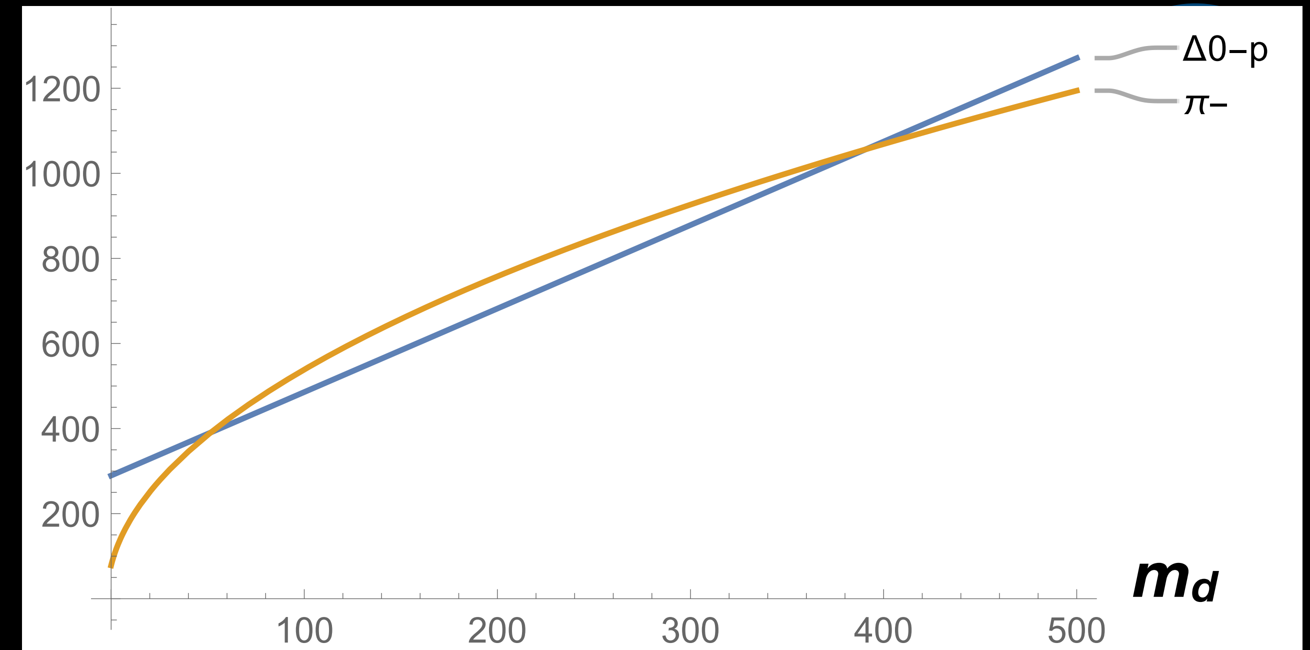




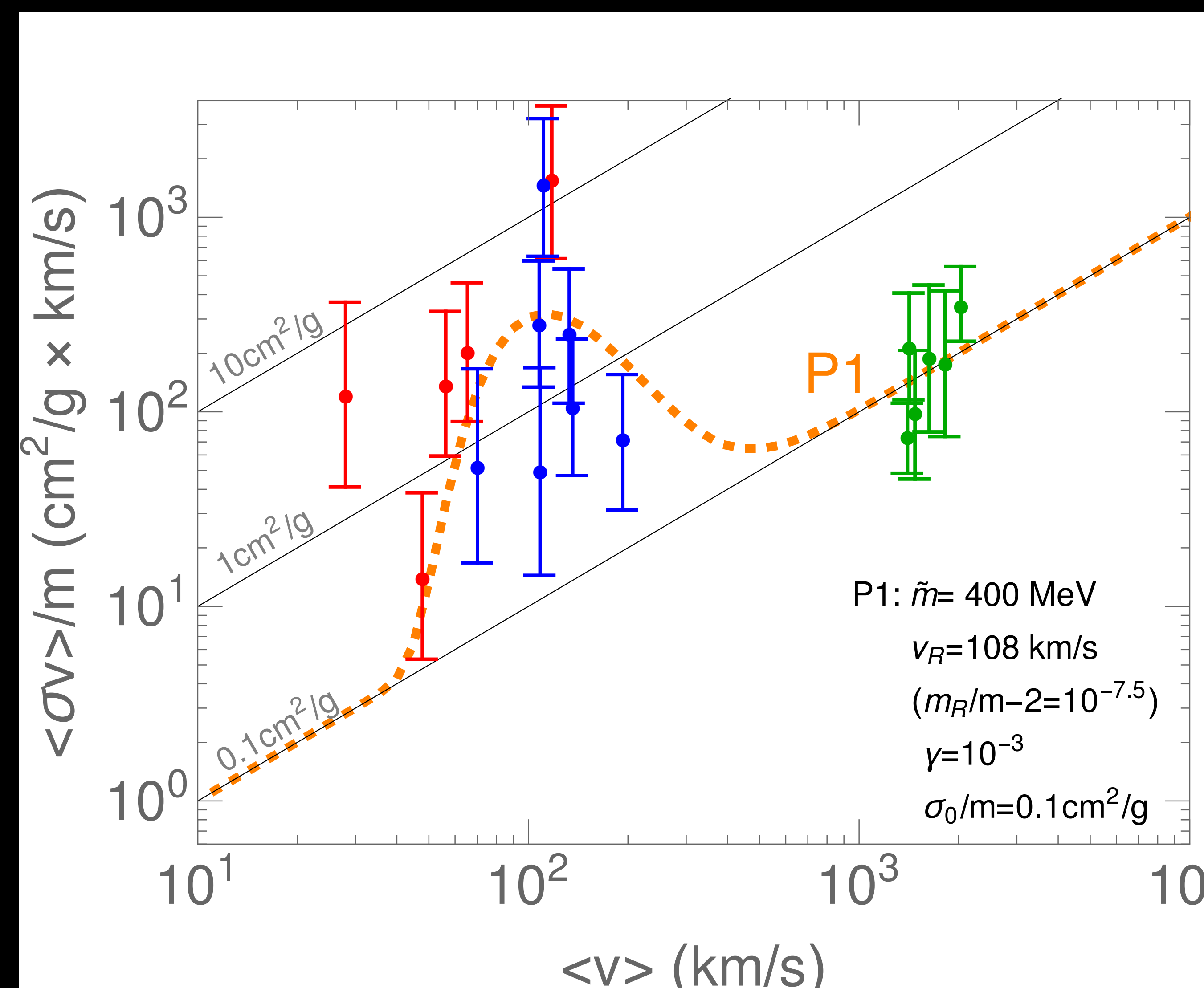
Xiaoyong Chu, Camilo Garcia-Cely, HM,
Phys.Rev.Lett. 122 (2019) no.7, 071103

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



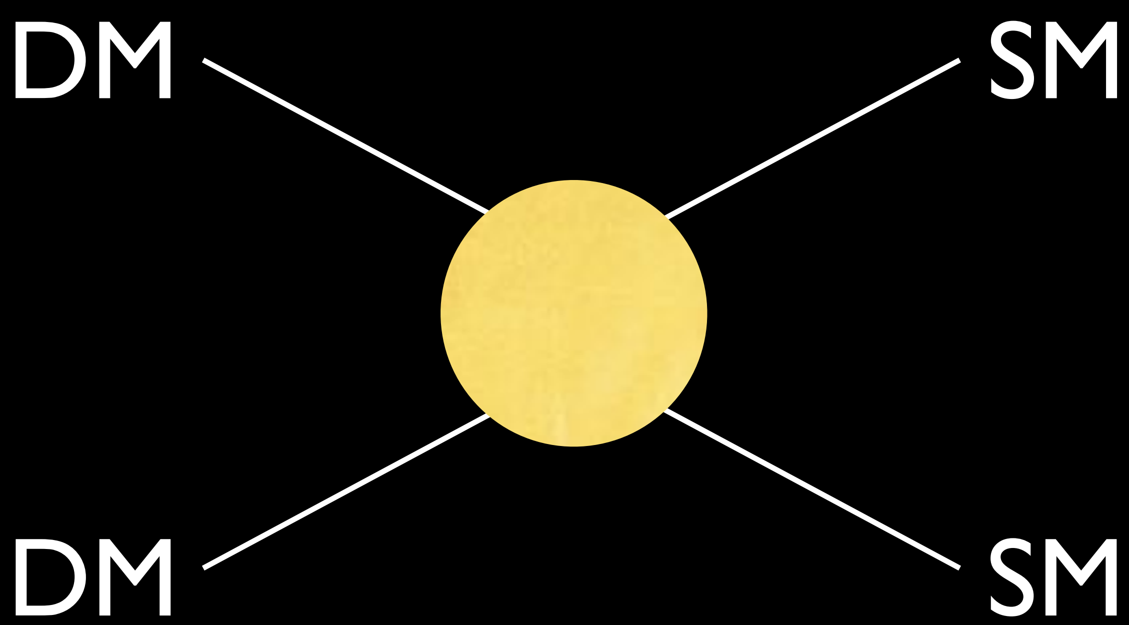
Robert McGehee, HM, Yu-Dai Tsai, 2008.08608



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

Strongly Interacting Massive Particles (SIMP)

Miracles



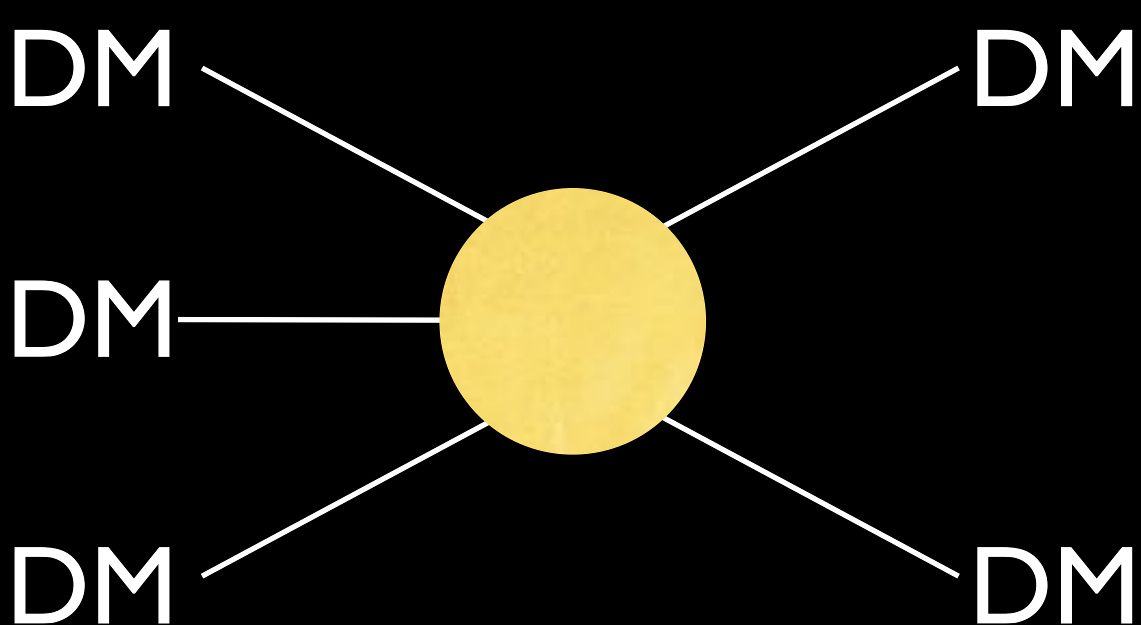
$$\langle \sigma_{2\to 2} v \rangle \approx \frac{\alpha^2}{m^2}$$

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

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

WIMP miracle!

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



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

$$\alpha \approx 4\pi$$

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

Hochberg, Kuflik, Volansky, Wacker arXiv:1402.5143

SIMP miracle!

~~LEE WEINBERG~~ 3→2 FREEZE-OUT

Back of the envelope calculation

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

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

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

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

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

$$n_b \sim \eta_b s$$

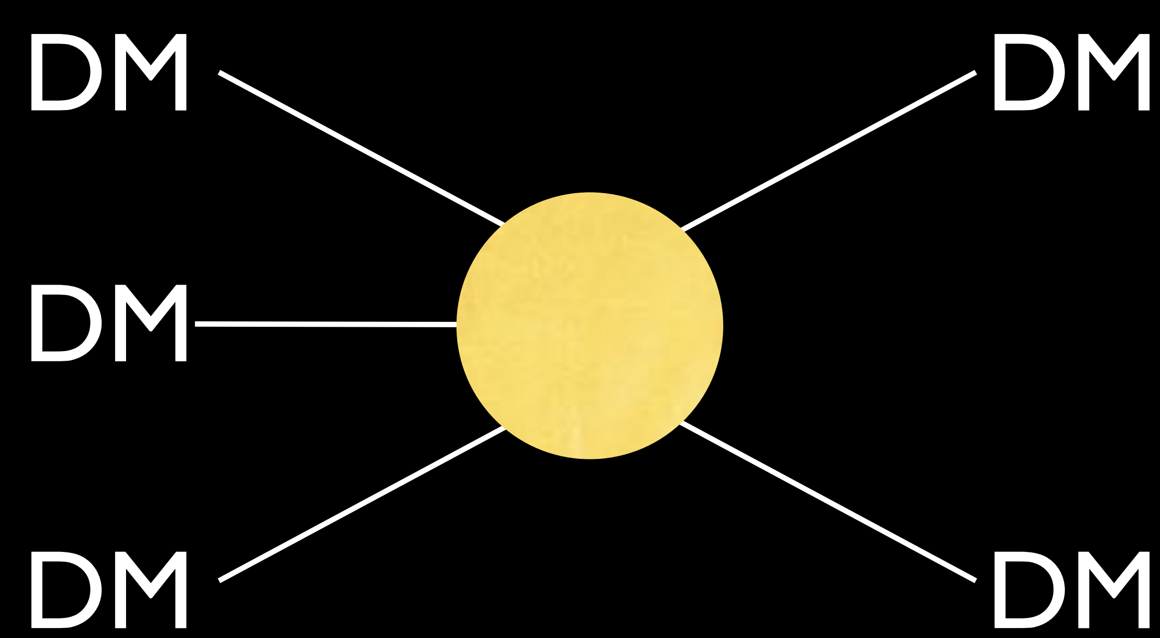
$$\eta_b \simeq T_{\text{eq}}/m_p \qquad s \simeq T^3$$

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

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



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

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

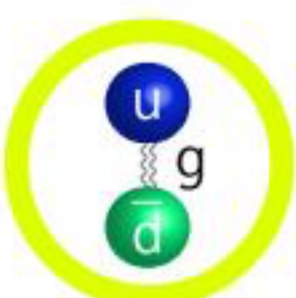
LAGRANGIANS

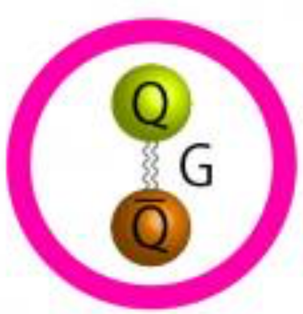
QCD

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

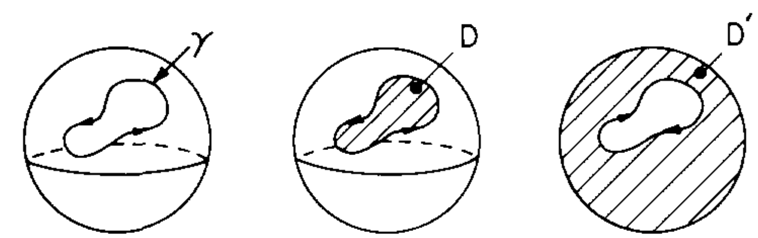
Chiral Lagrangian

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





Pions

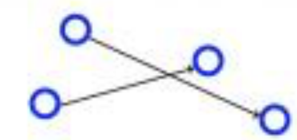


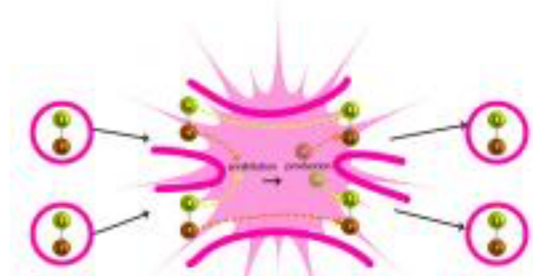
(a) (b) (c)

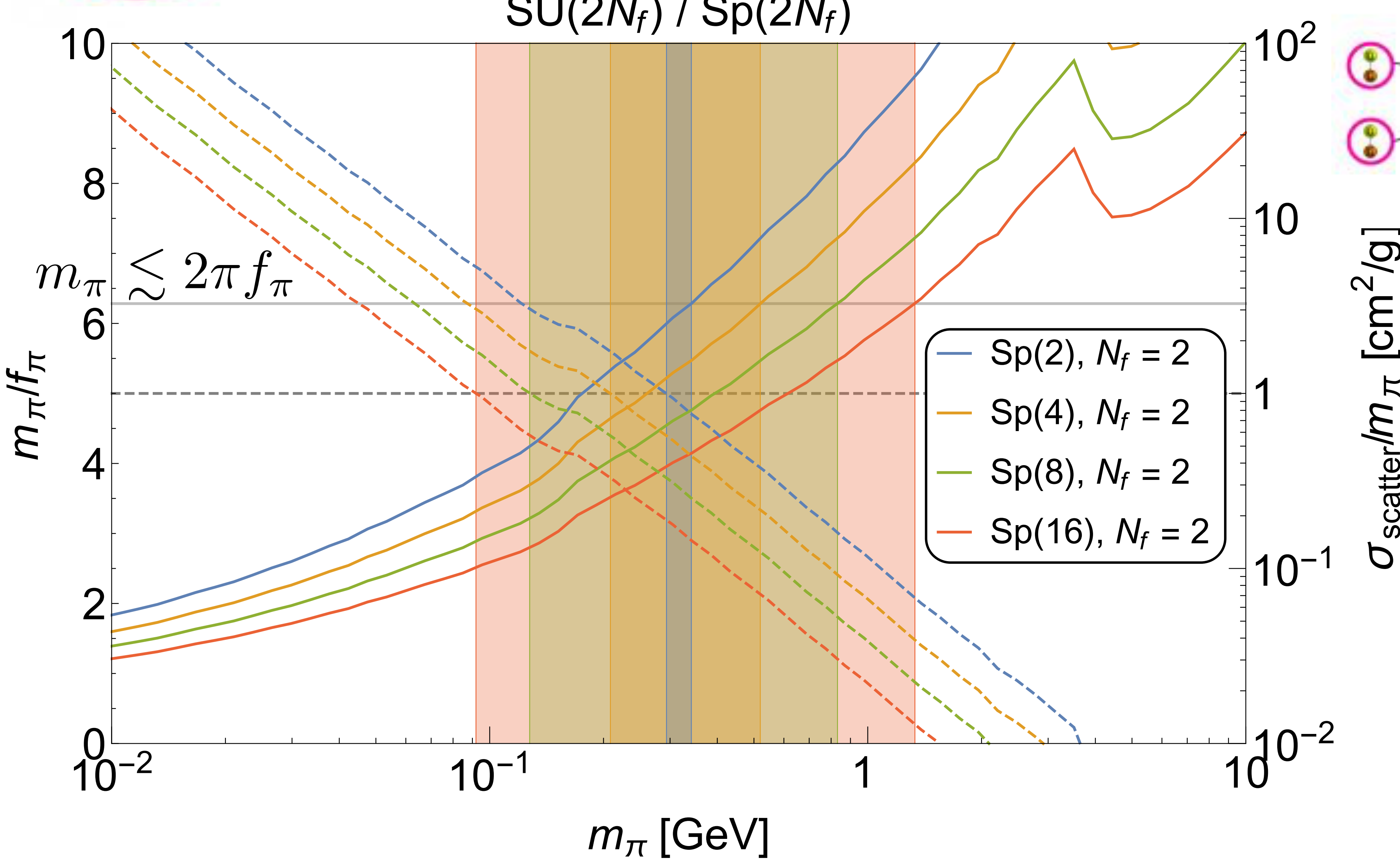
$$\mathcal{L}_{\text{pion}} = \frac{1}{4}\text{Tr}\partial_\mu\pi\partial^\mu\pi - \frac{m_\pi^2}{4}\text{Tr}\pi^2 + \frac{m_\pi^2}{12 f_\pi^2}\text{Tr}\pi^4 - \frac{1}{6 f_\pi^2}\text{Tr}\left(\pi^2\partial^\mu\pi\partial_\mu\pi - \pi\partial^\mu\pi\pi\partial_\mu\pi\right)$$

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

The Results







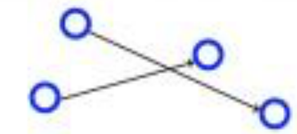
Solid curves: solution to Boltzmann eq.

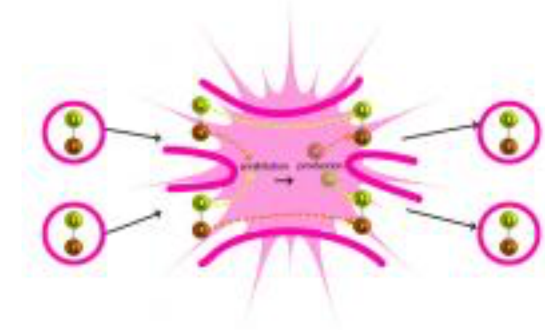
Dashed curves: along that solution

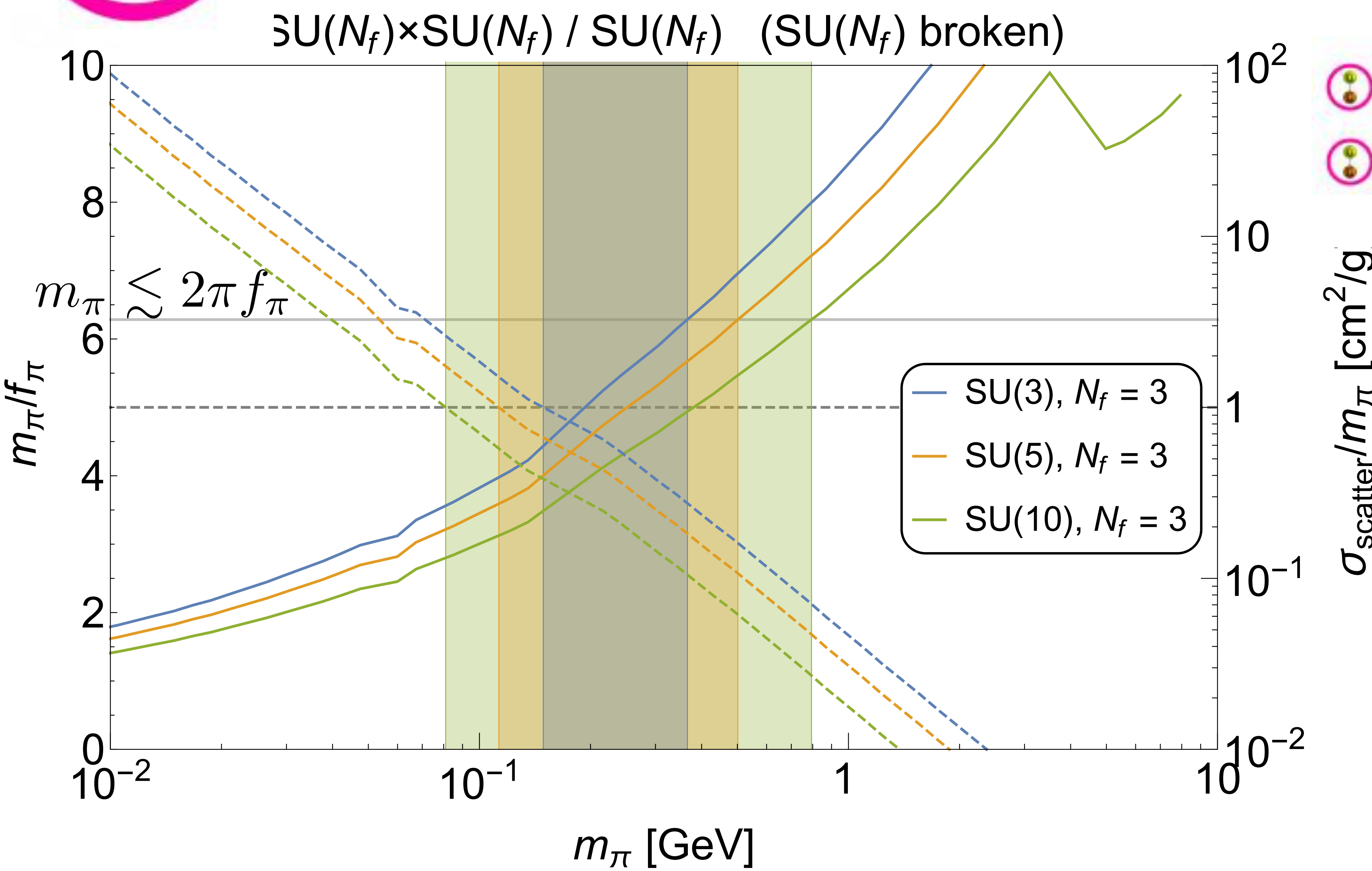
$$\frac{m_\pi}{f_\pi} \propto m_\pi^{3/10}$$

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

The Results







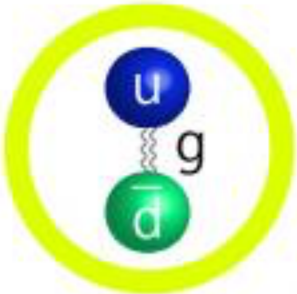
Solid curves: solution to Boltzmann eq.

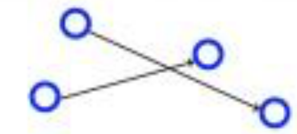
$$\frac{m_\pi}{f_\pi} \propto m_\pi^{3/10}$$

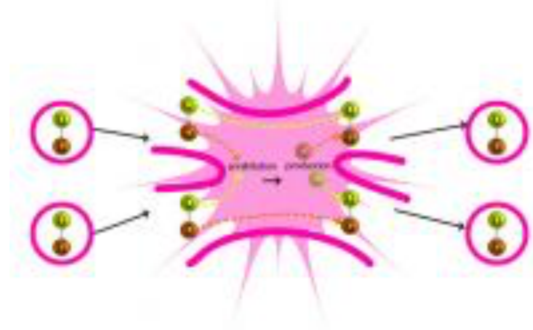
Dashed curves: along that solution

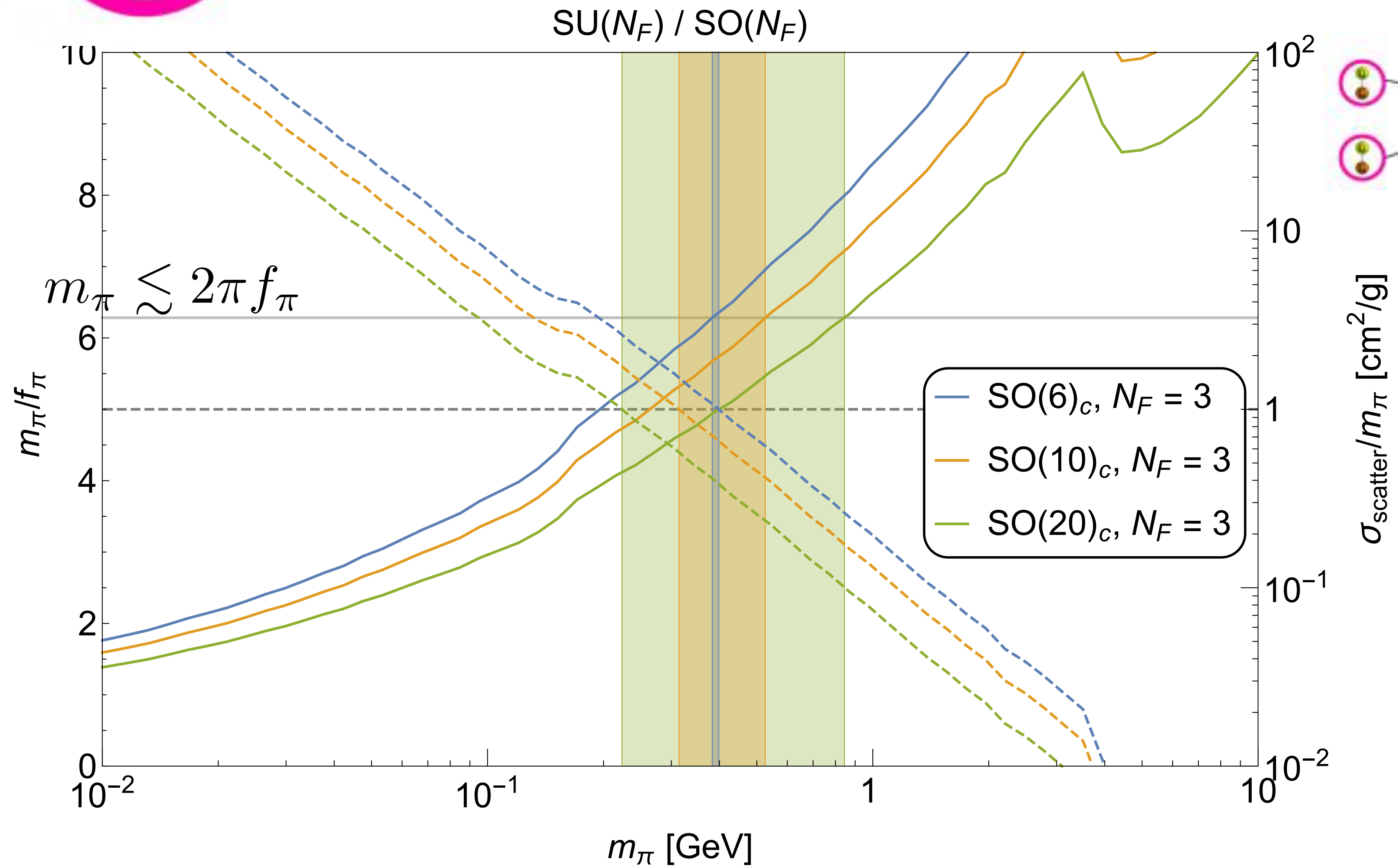
$$\frac{\sigma_{\rm scatter}}{m_\pi} \propto m_\pi^{-9/5}$$

The Results









Solid curves: solution to Boltzmann eq.

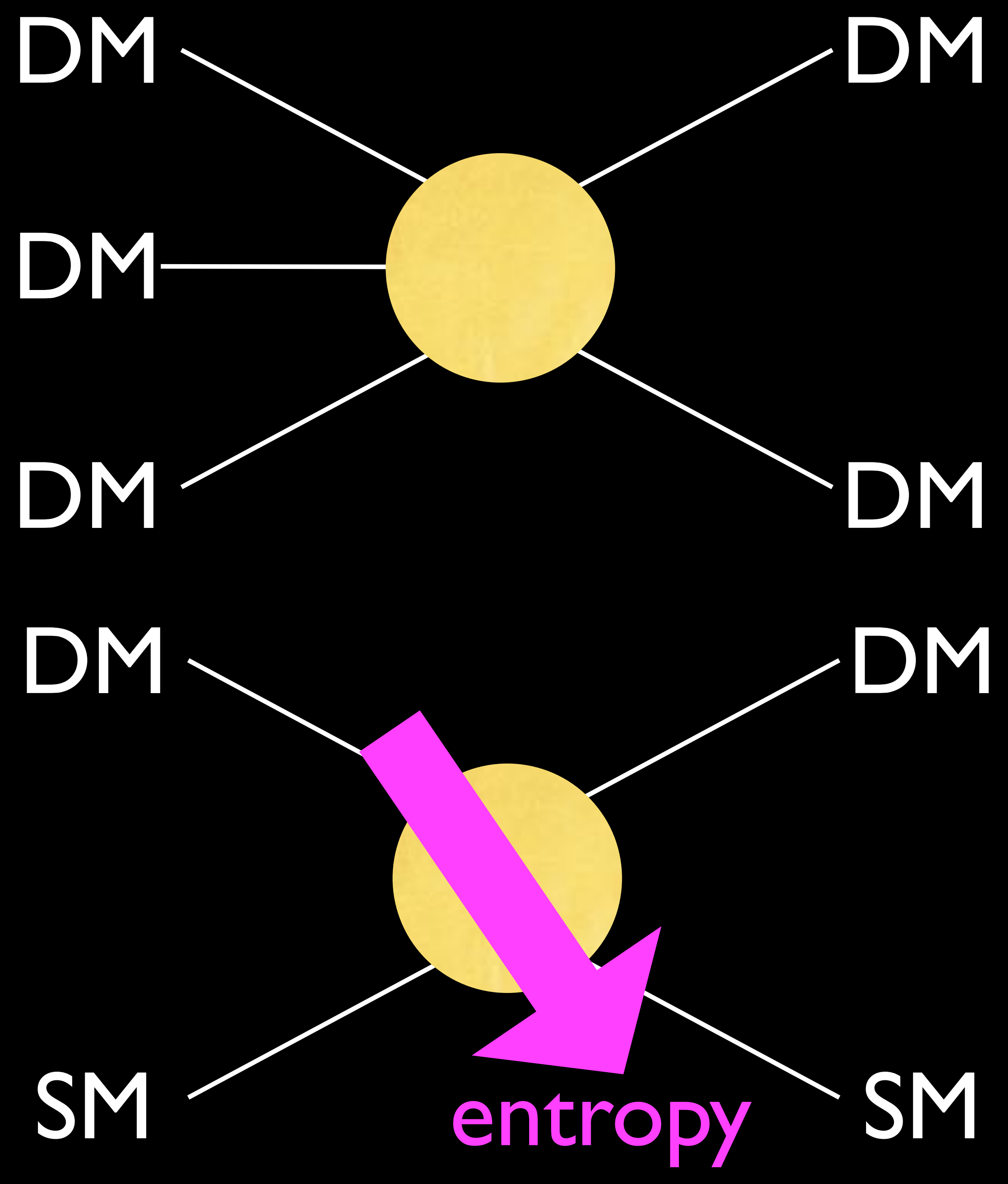
Dashed curves: along that solution

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

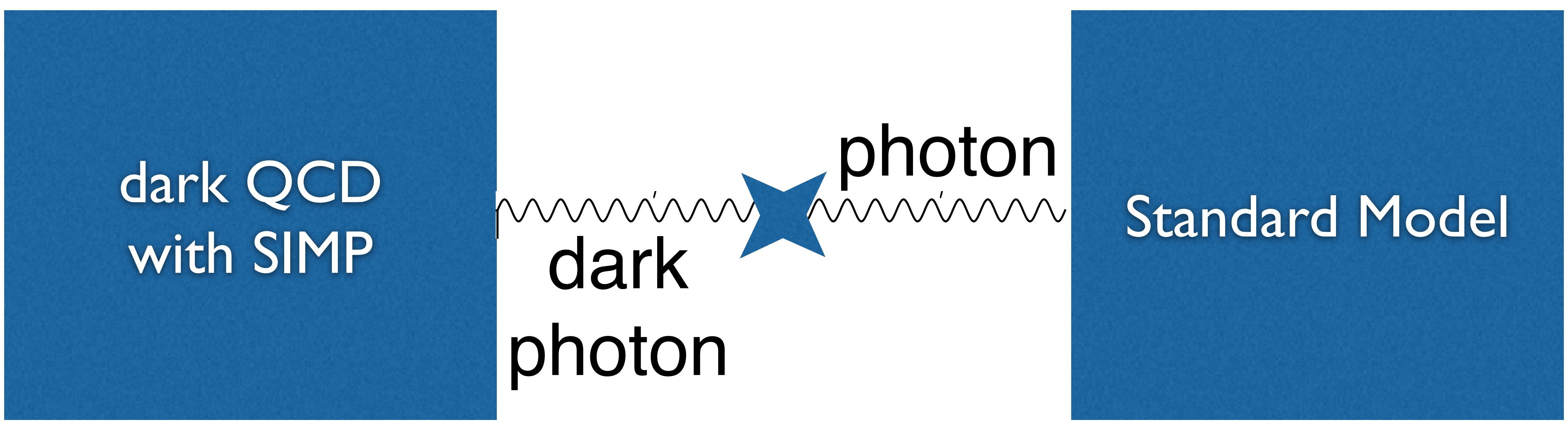
$$\frac{\sigma_{\rm scatter}}{m_\pi} \propto m_\pi^{-9/5}$$

communication

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



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)

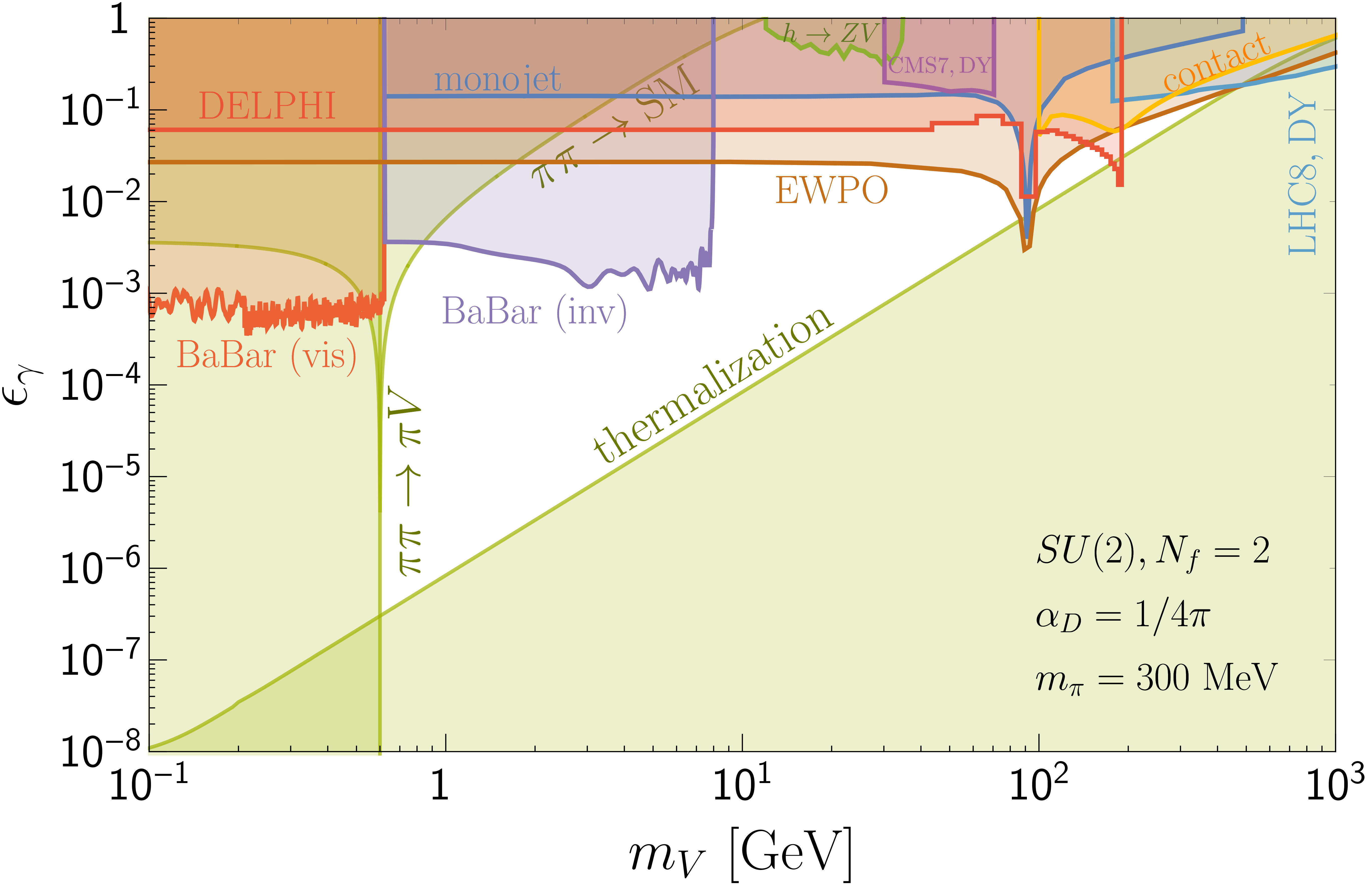
- e.g., the SIMPlest model SU(2) gauge group with N_f=2 (4 doublets)
- gauge U(1)=SO(2) ⊂ SO(2) ×SO(3) ⊂ SO(5)=Sp(4)
- maintains degeneracy of quarks
- near degeneracy of pions for co-annihilation

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

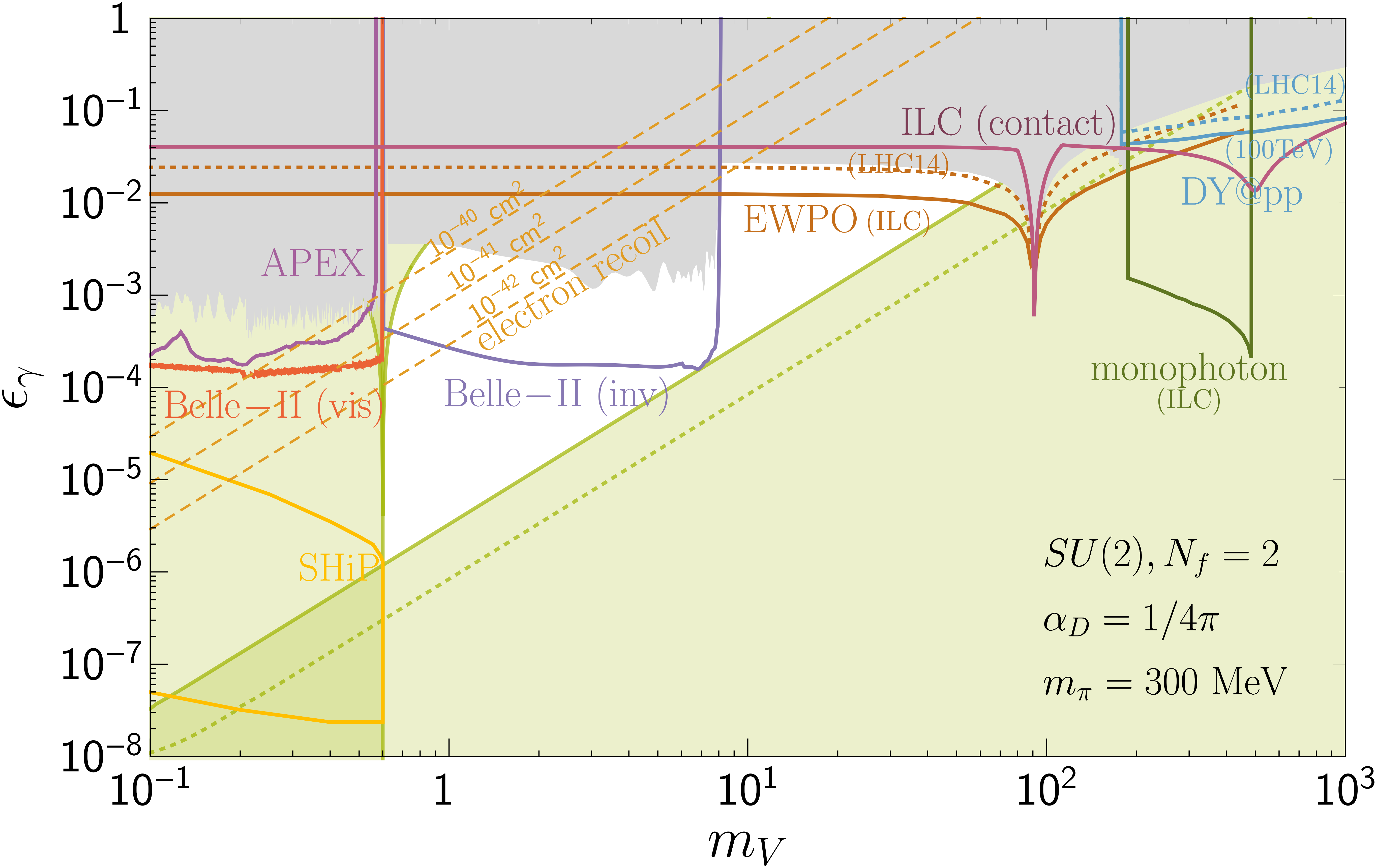
$$(q^+, q^+, q^-, q^-)$$

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

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

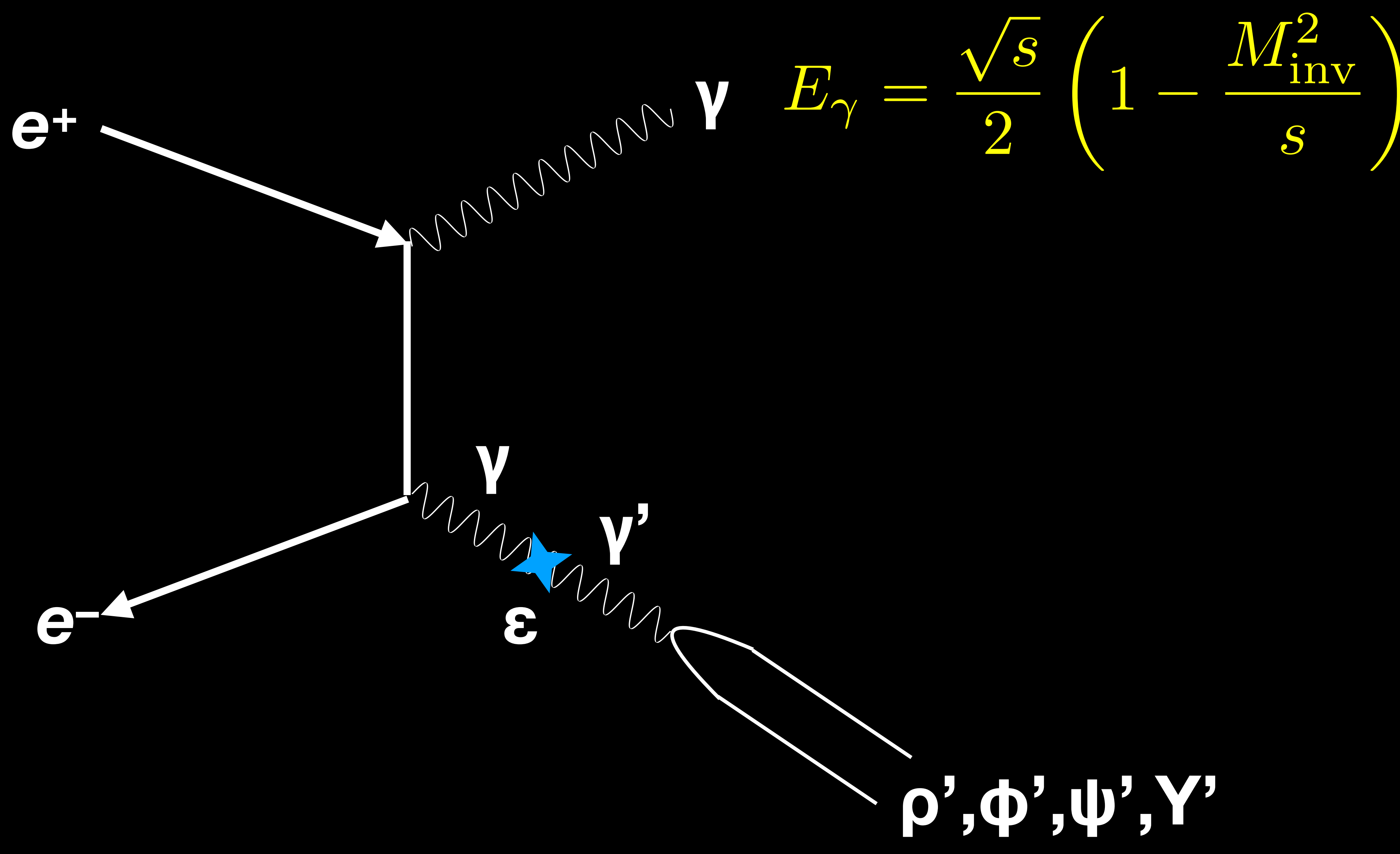


DELPHI
monojet
$\pi\pi \to SM$
$h \to ZV$
CMS7, DY
contact
LHC8, DY
EWPO
BaBar (inv)
BaBar (vis)
$\pi\pi \to \pi V$
thermalization
$SU(2), N_f = 2$
$\alpha_D = 1/4\pi$
$m_\pi = 300$ MeV
ϵ_γ
m_V [GeV]
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-1}
1
10^{1}
10^{2}
10^{3}



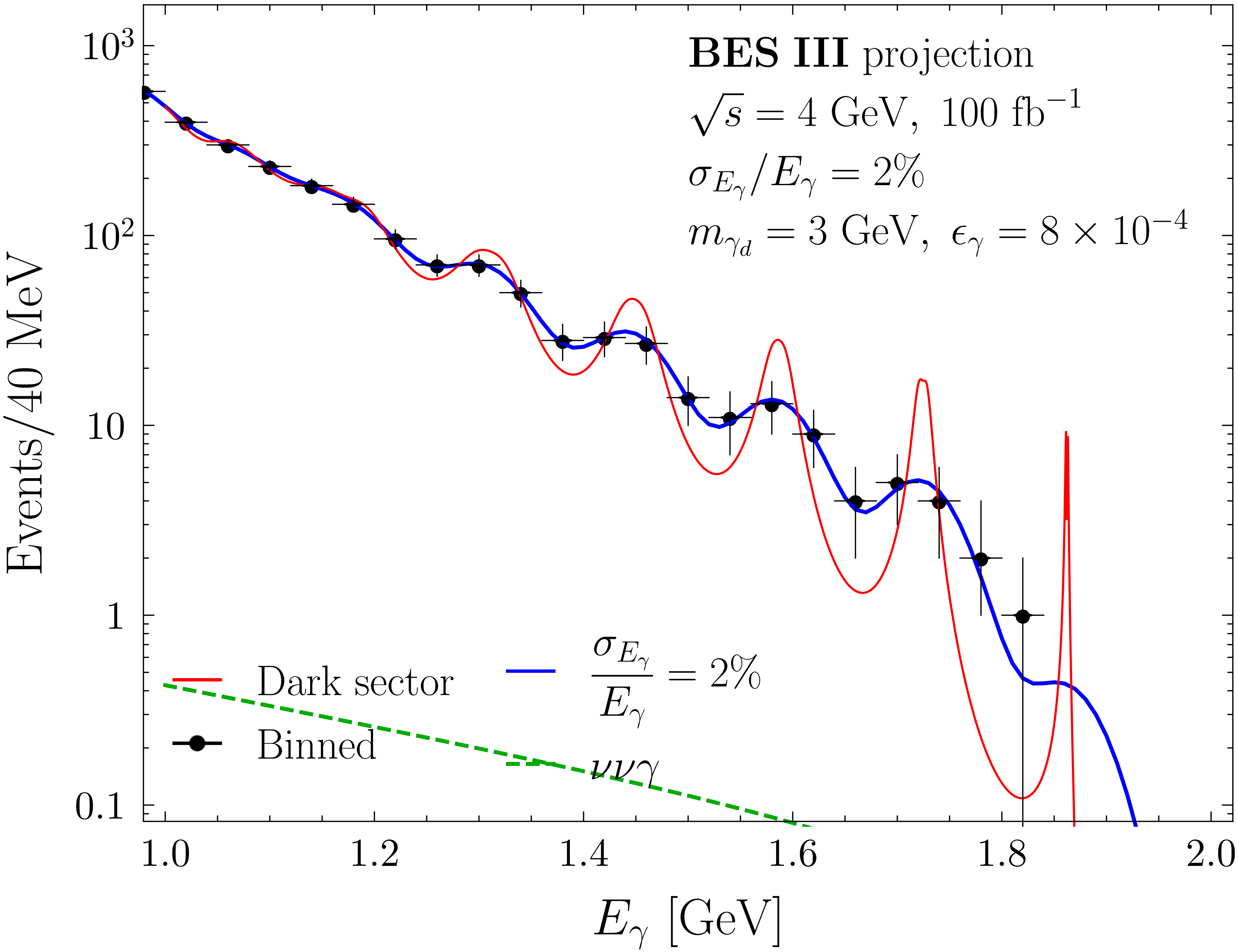
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
ϵ_γ
10^{-1}
1
10^{1}
10^{2}
10^{3}
m_V
APEX
Belle−II (vis)
Belle−II (inv)
SHiP
10^{-40} cm^2
10^{-41} cm^2
10^{-42} cm^2
electron recoil
ILC (contact)
(LHC14)
EWPO (ILC)
(LHC14)
(100TeV)
DY@pp
monophoton
(ILC)
$SU(2), N_f = 2$
$\alpha_D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

Dark Spectroscopy

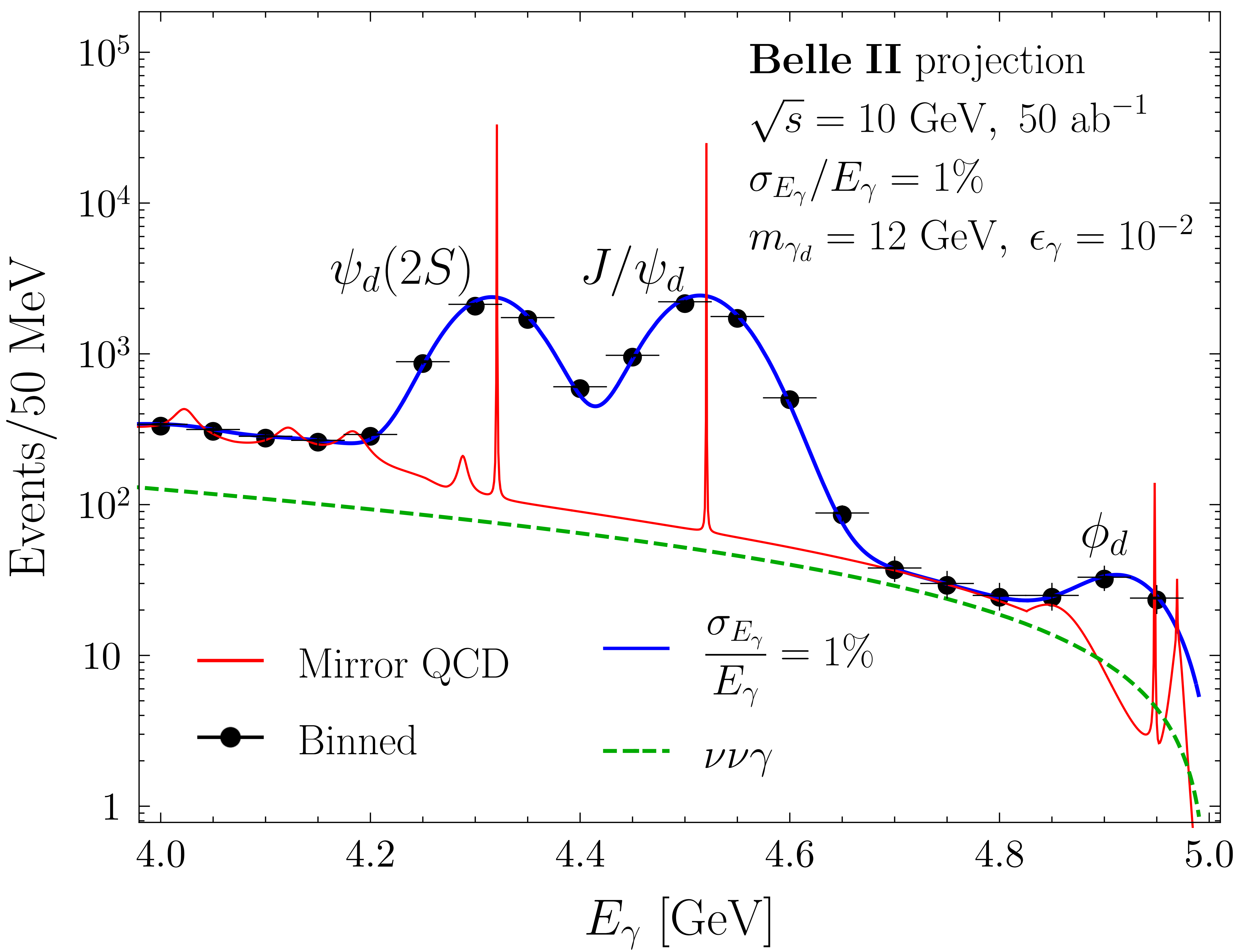


Yonit Hochberg, Eric Kuflik, HM, arXiv:1512.07917, 1706.05008

Dark Spectroscopy

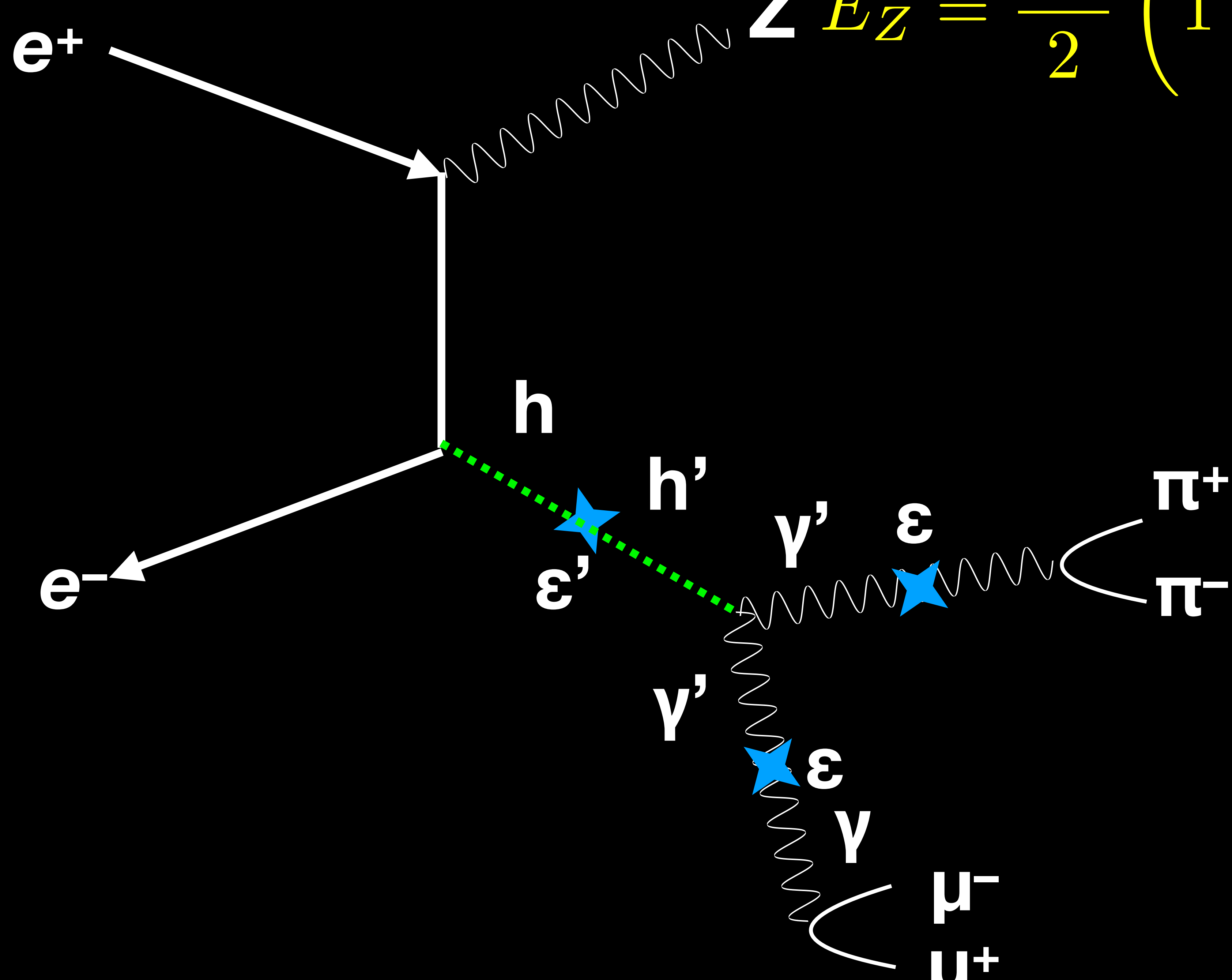


Dark Spectroscopy

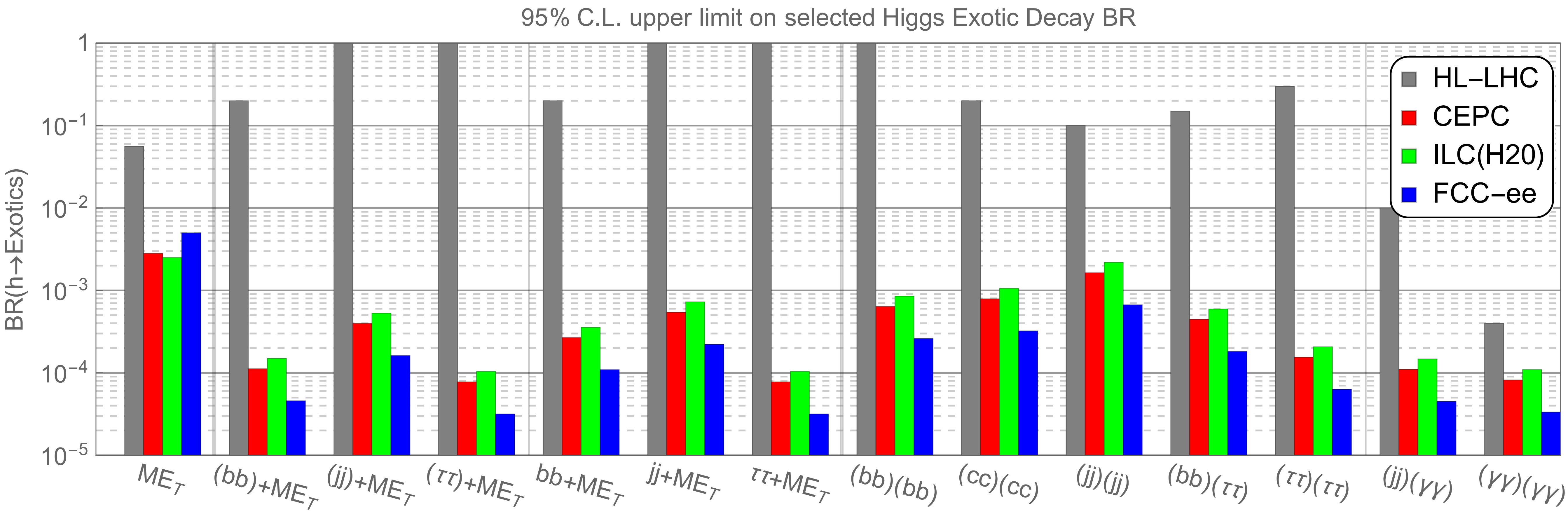


Higgs portal

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



Exotic Higgs Decays

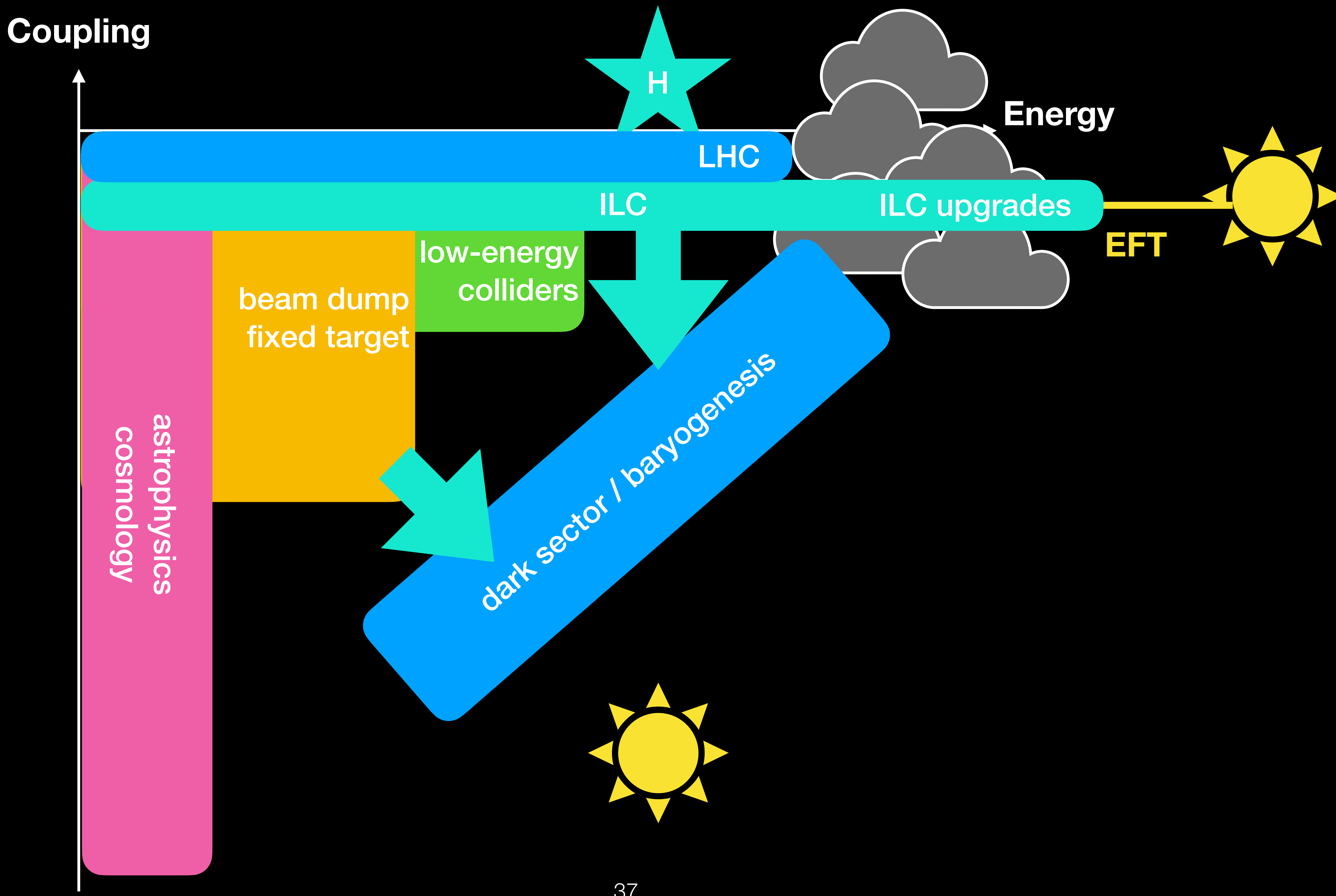


Zhen Liu, Lian-Tao Wang, Hao Zhang, arXiv:1612.09284

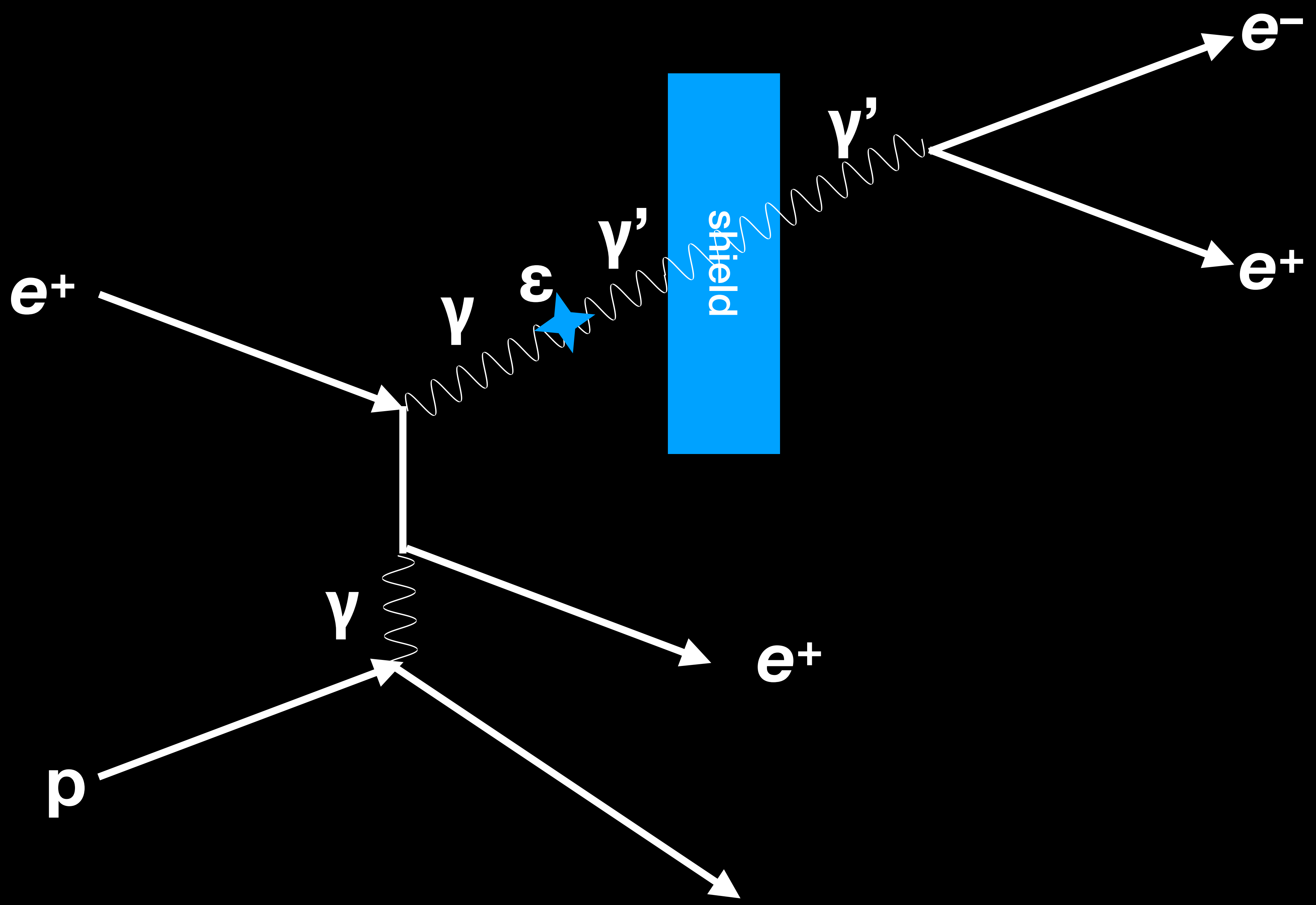
Conclusions

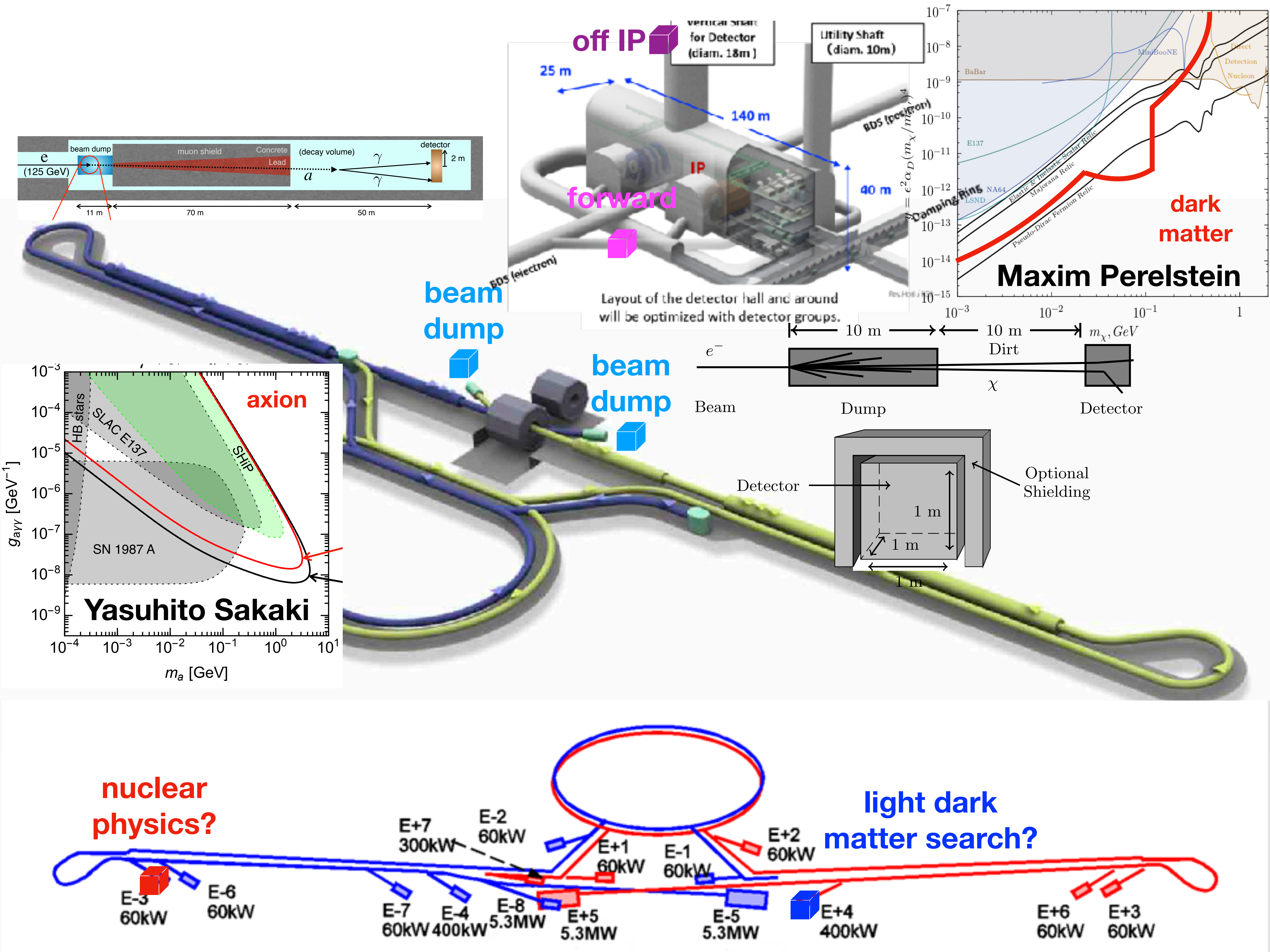
- light dark sector well-motivated
  - dark matter, baryon asymmetry
- asymmetric dark matter
- Strongly Interactive Massive Particles (SIMP)
- amazingly wide array of experimental signatures
  - dark proton good target for direct detection
  - exotic *Z*-decay, *h*-decay (HL-LHC, ILC, CEPC, FCC-ee)
  - dark photon search at Belle II, LHC-b, beam dump
  - If baryon asymmetry originates from the SM, desired dark matter mass ~ 40 GeV $\Longrightarrow$ spectroscopy@ILC!
  - gravitational wave at LIGO, LISA, Einstein Telescope, etc
- explain coincidence $\Omega_{DM} \sim \Omega_b$ if $N_{gen}=3$ and unification

ILC++


Coupling
Energy
H
LHC
ILC
ILC upgrades
EFT
low-energy colliders
beam dump fixed target
astrophysics cosmology
dark sector / baryogenesis

dark photon, axion, neutrino portal, etc





beam dump
muon shield
Concrete
Lead
(decay volume)
detector
e
(125 GeV)
2 m
11 m
70 m
50 m
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.
dark matter
Maxim Perelstein
BaBar
MiniBooNE
E137
NA64
LSND
Direct Detection
Nucleon
Elastic & Inelastic Scalar Relic
Majorana Relic
Pseudo-Dirac Fermion Relic
m_χ, GeV
beam dump
beam dump
10 m
10 m
Dirt
Beam
Dump
Detector
Optional Shielding
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

WG3 Organisation and mandates

Chair: Hitoshi Murayama (Berkeley/Tokyo)

Deputies: Jenny List (DESY) and Claude Vallée (Marseille)

Coordinator and Deputy coordinator(s)

Secretariat?

Steering Group
Subgroup conveners, Coordinator and Deputy Coordinator(s)

Andy White (UT Arlington), Ties Behnke (DESY), Yuanning Gao (Peking), Frank Simon (MPP), Jim Brau (Oregon), Keisuke Fujii (KEK), Phil Burrows (Oxford), Francesco Forti (INFN), Filip Zarnecki (Warsaw), Patty McBride (Fermilab), Mihoko Nojiri (KEK), CERN member, Timothy Nelson (SLAC), Kajari Mazumdar (Mumbai), Phillip Urquijo (Melbourne), Dmitri Denisov (Brookhaven)

Speaker's bureau

Kiyotomo Kawagoe (Kyushu), Alain Bellerive (Carleton), Ivanka Božović Jelisavčić (Belgrade)

Interface with machine

Coordinate the interactions between the accelerator and facility infrastructure planning and the needs of the experiments

Karsten Buesser (DESY), Yasuhiro Sugimoto (KEK), Roman Poeschl (Orsay), US

Detector and technology R&D

Provide a forum for discussion and coordination of the detector and technology R&D for the future experimental programme

Marcel Vos (Valencia), Katja Krueger (DESY)
Petra Merkel (Fermilab), David Miller (Chicago)

Software and computing

Promote and provide coordination of the software development and computing planning

Frank Gaede (DESY), Jan Strube (PNNL)
Daniel Jeans (KEK)

Physics potential and opportunity

Encourage and develop ideas for exploiting the physics potential of the ILC collider and by use of the beams available for more specialised experiments

Michael Peskin (SLAC), Junping Tian (Tokyo)
Aidan Robson (Glasgow)

Open to anybody interested!

https://linearcollider.org/team/

approved by IDT EB Feb 4, 2021

Physics potential and Opportunities

Michael Peskin
Aidan Robson
Junping Tian

Topical Groups

–> broad scope

- Higgs properties
- Top / heavy flavour / QCD
- EW
- BSM particle production
- Global Interpret.
- Modelling and precision theory

Task Forces

–> specific advice

Definition / discussion ongoing; may reach across WG3 groups; may include WG2;

- Energy upgrade
- Positron polarization
- Fixed-target programme
- Alternative collider modes
- Z pole and WW threshold
- Systematic uncertainties
- Global fitting
- Physics benchmarks
- Theory perspective
- …

Topical Groups being set up now

Task Forces will be added later *

* Study Group on fixed-target / dark sector has started to meet


I WANT YOU
FOR IDT WG3
NEAREST RECRUITING STATION