東京大学 THE UNIVERSITY OF TOKYO

UTIAS 東京大学国際高等研究所 THE UNIVERSITY OF TOKYO INSTITUTES FOR ADVANCED STUDY

KAVLI IPMU INSTITUTE FOR THE PHYSICS AND MATHEMATICS OF THE UNIVERSE

INTERNATIONAL WORKSHOP ON FUTURE LINEAR COLLIDERS

LCWS STRASBOURG 2017

Dark Spectroscopy

–a proposal for an ILC study–

Hitoshi Murayama (Berkeley, Kavli IPMU)
LCWS 2017, Strasbourg, Oct 26, 2017

+Yonit Hochberg, Eric Kuflik

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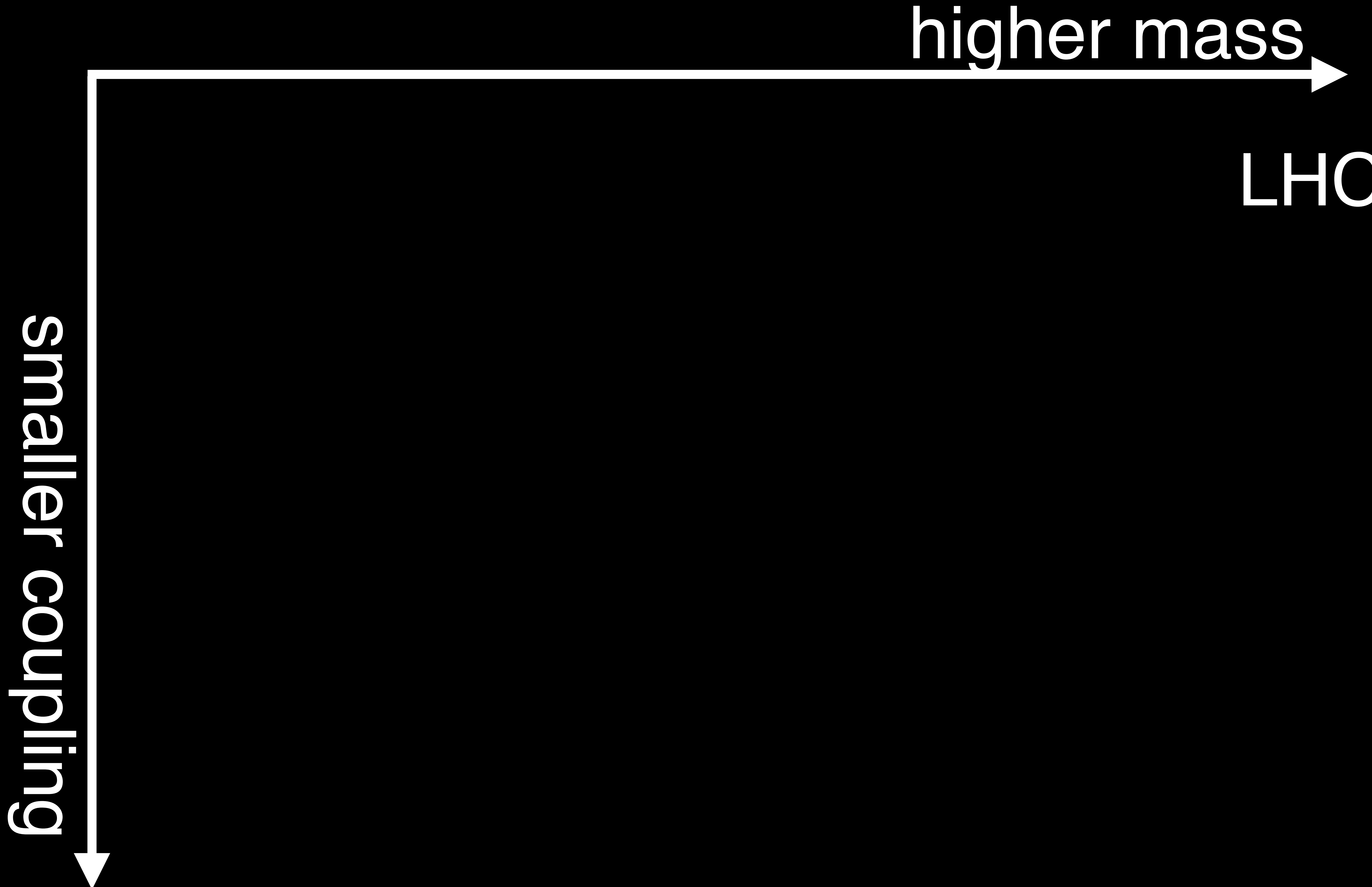
Where is new physics?

Where is new physics?

higher mass

LHC

Where is new physics?



Where is new physics?

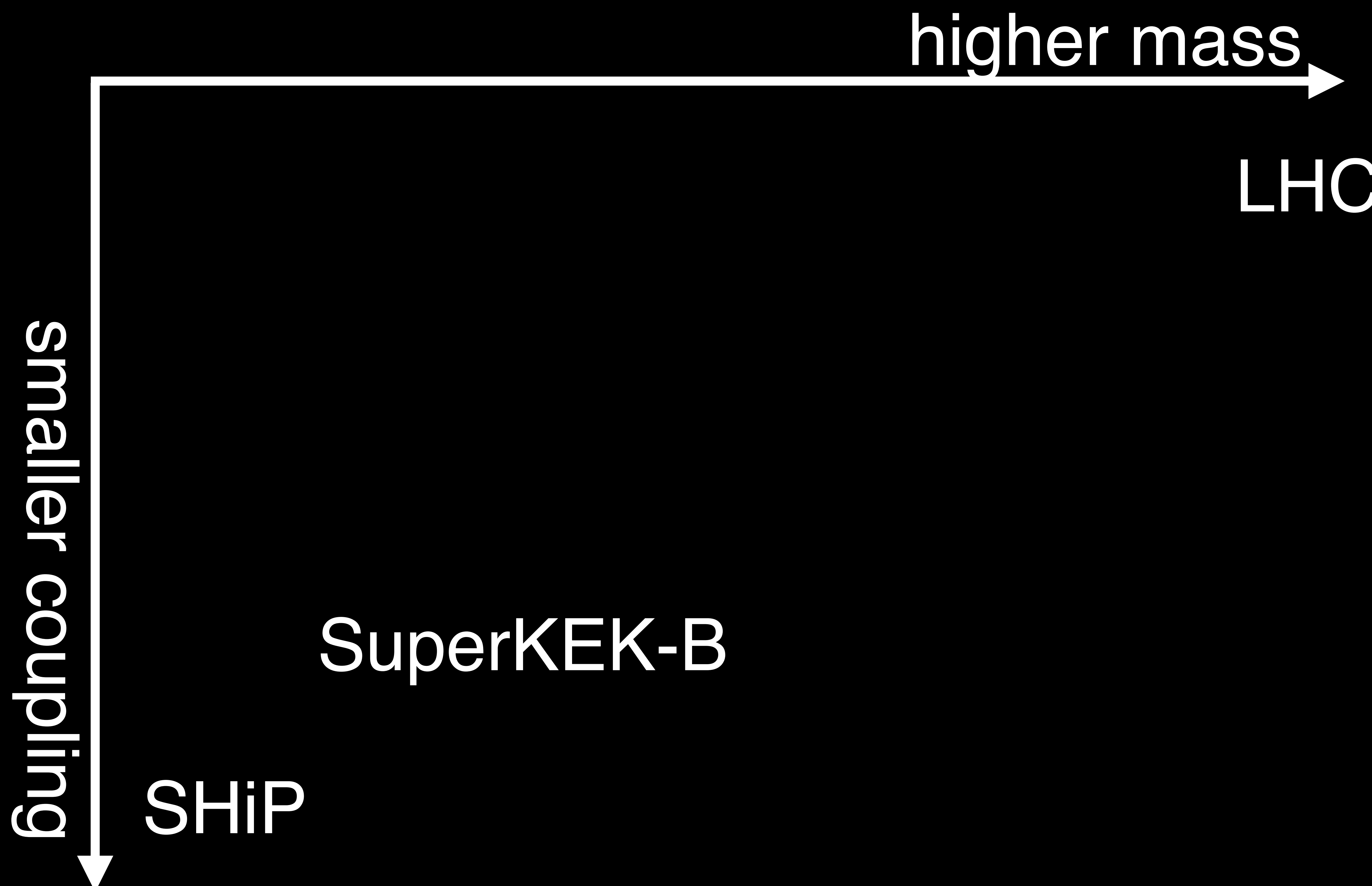
higher mass

LHC

smaller coupling

SHiP

Where is new physics?



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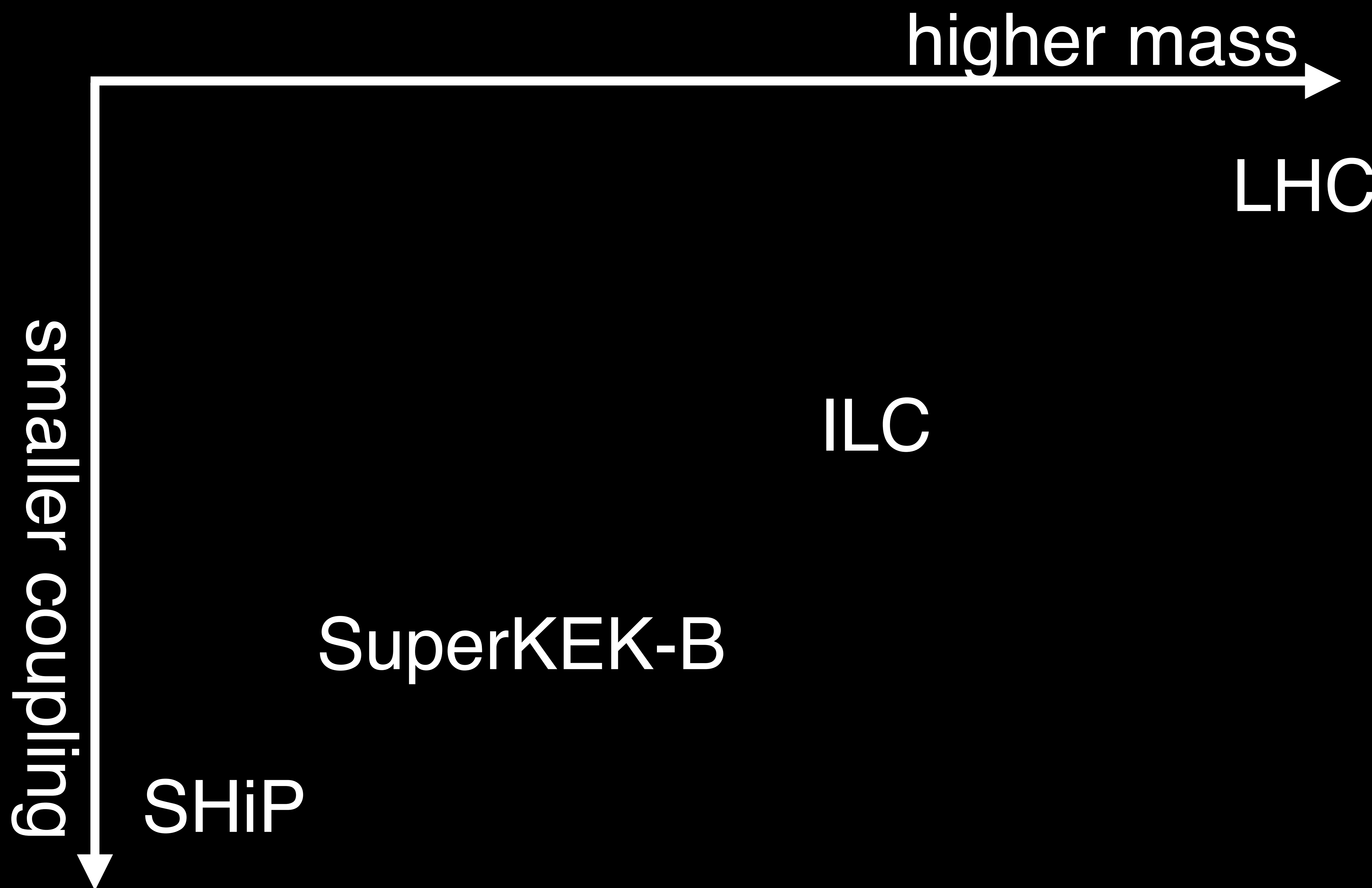
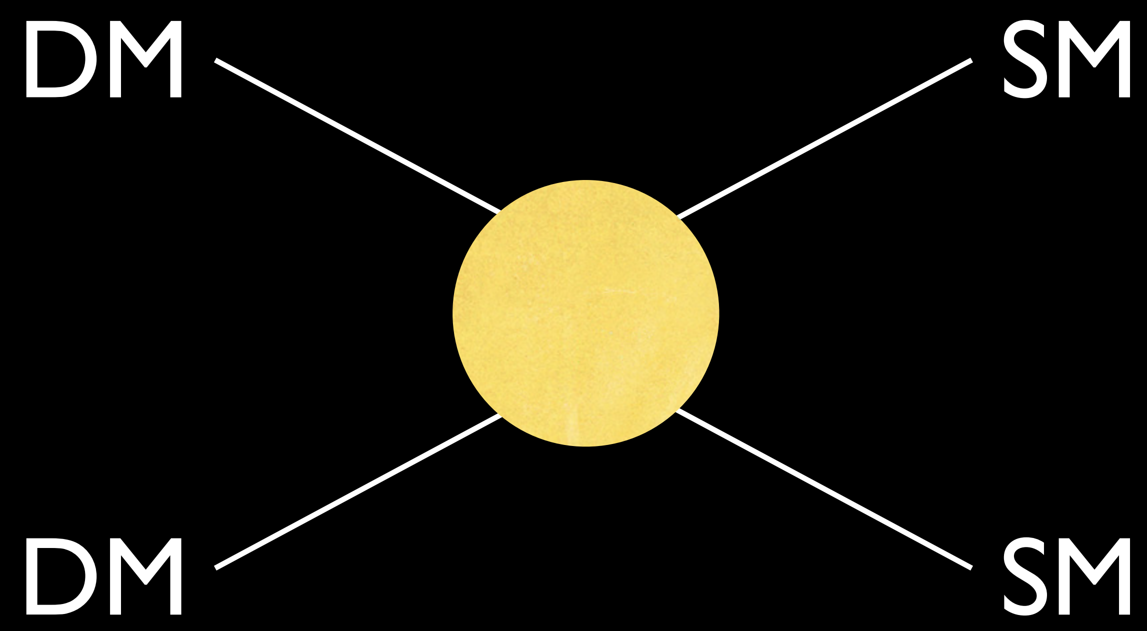


$$\frac{n_{\rm DM}}{s} = 4.4 \times 10^{-10} \frac{\rm GeV}{m_{\rm DM}}$$

Dark Matter 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!

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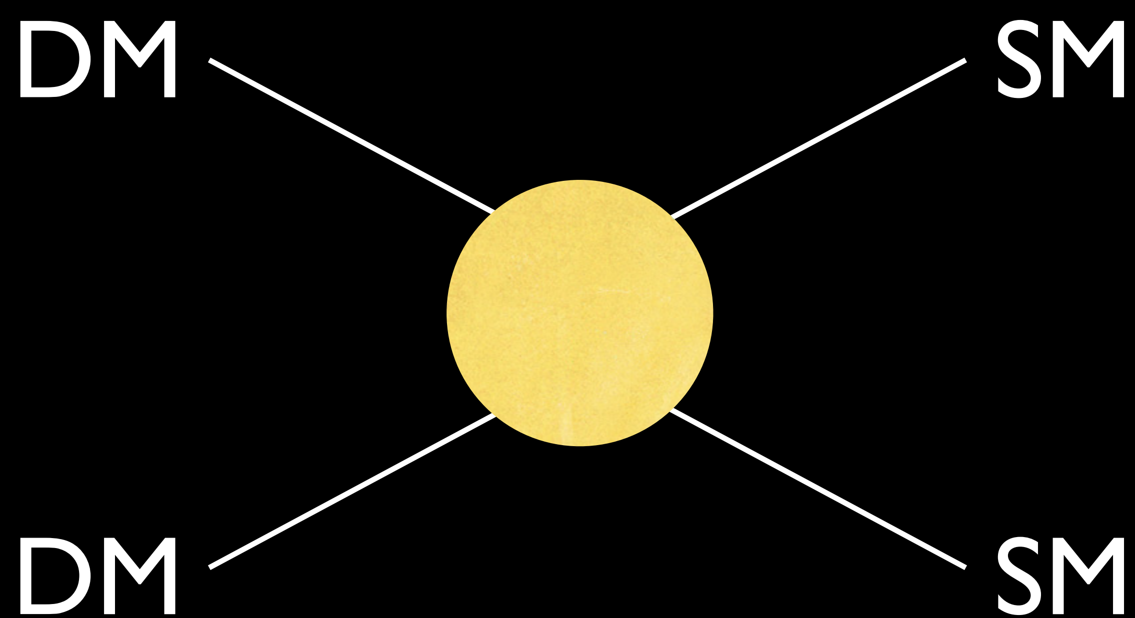
Dark Matter Miracles



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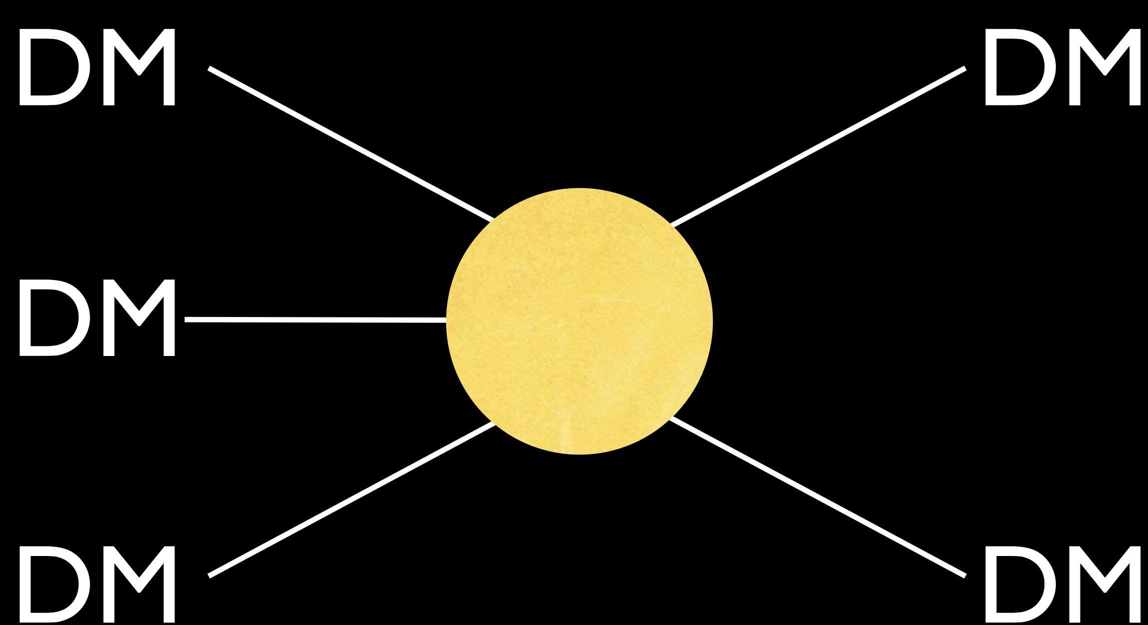

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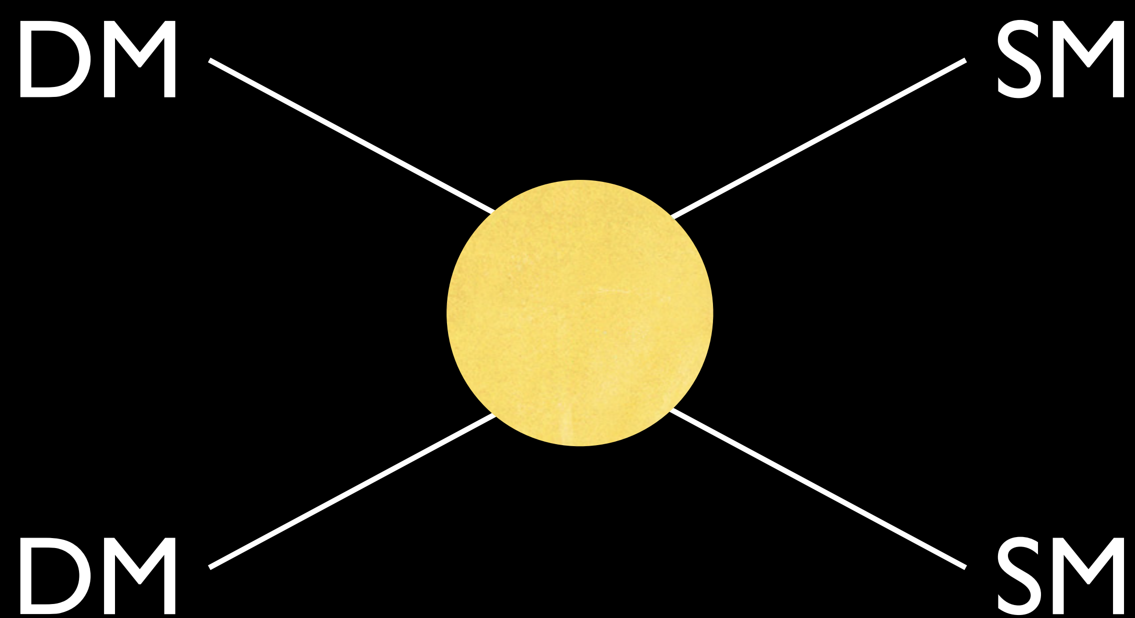

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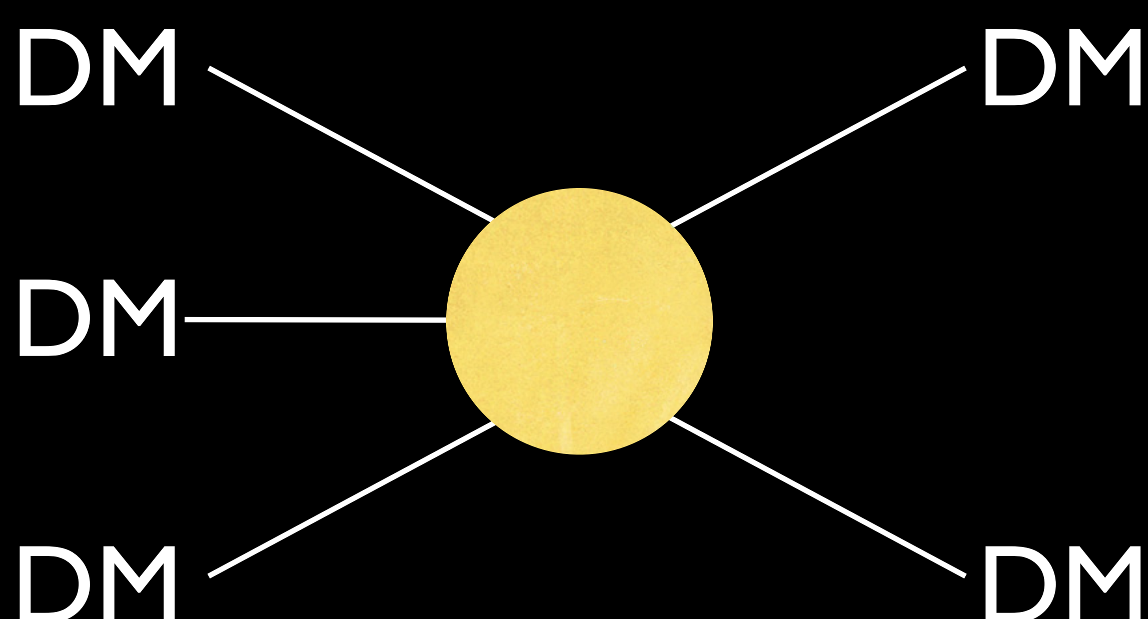

$$\langle \sigma_{3\to 2} v^2 \rangle \approx \frac{\alpha^3}{m^5}$$

$$\alpha \approx 4\pi$$

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

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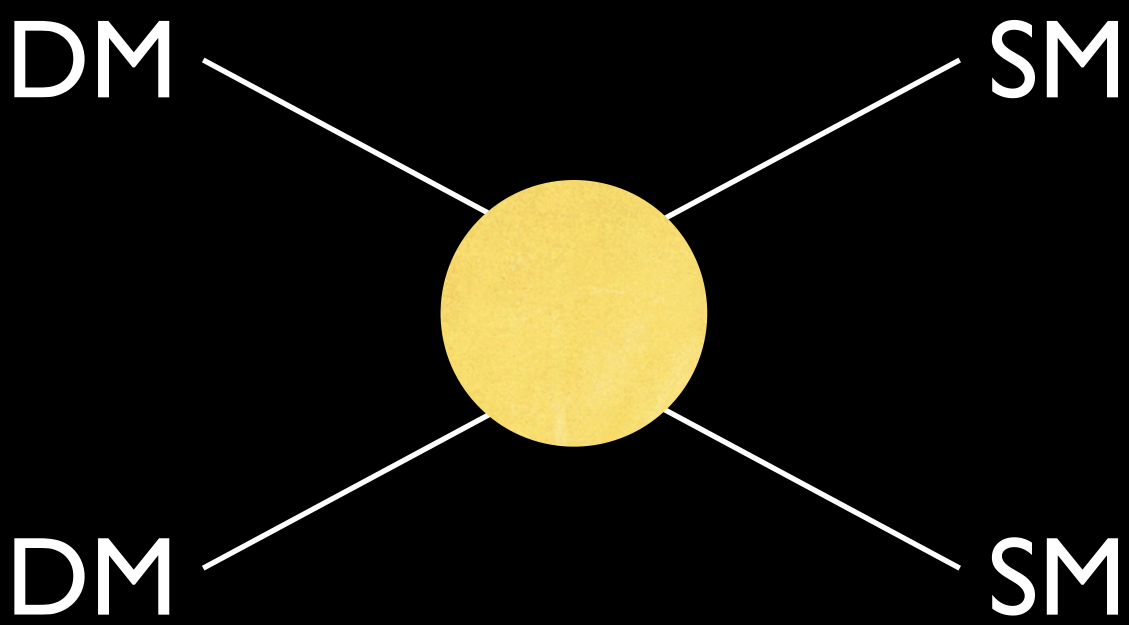
Dark Matter Miracles



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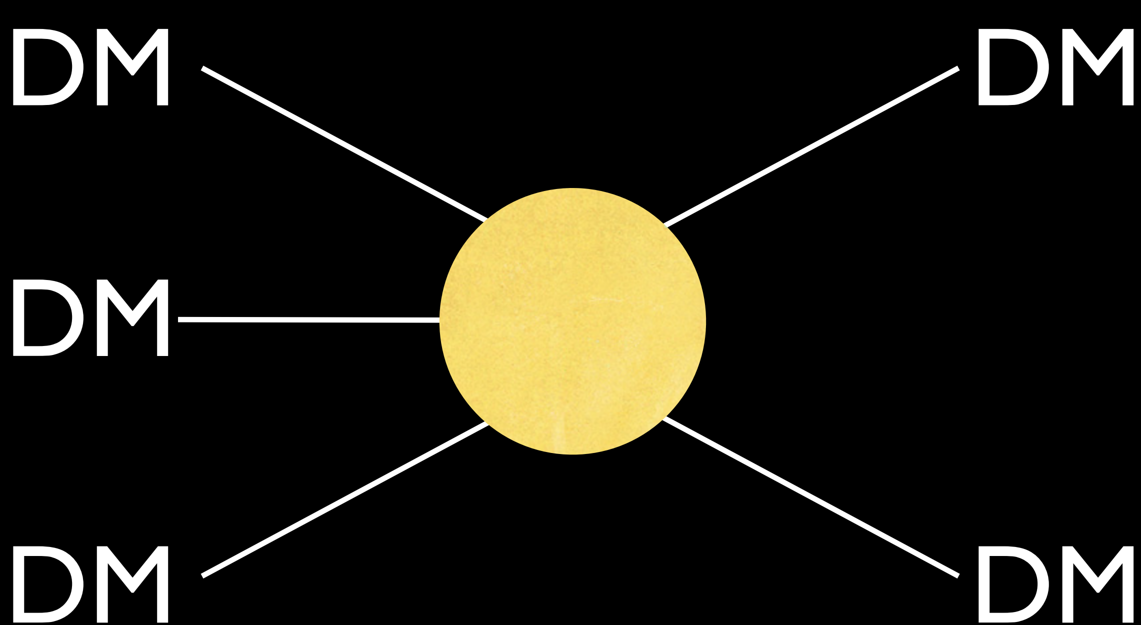

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SIMP miracle!

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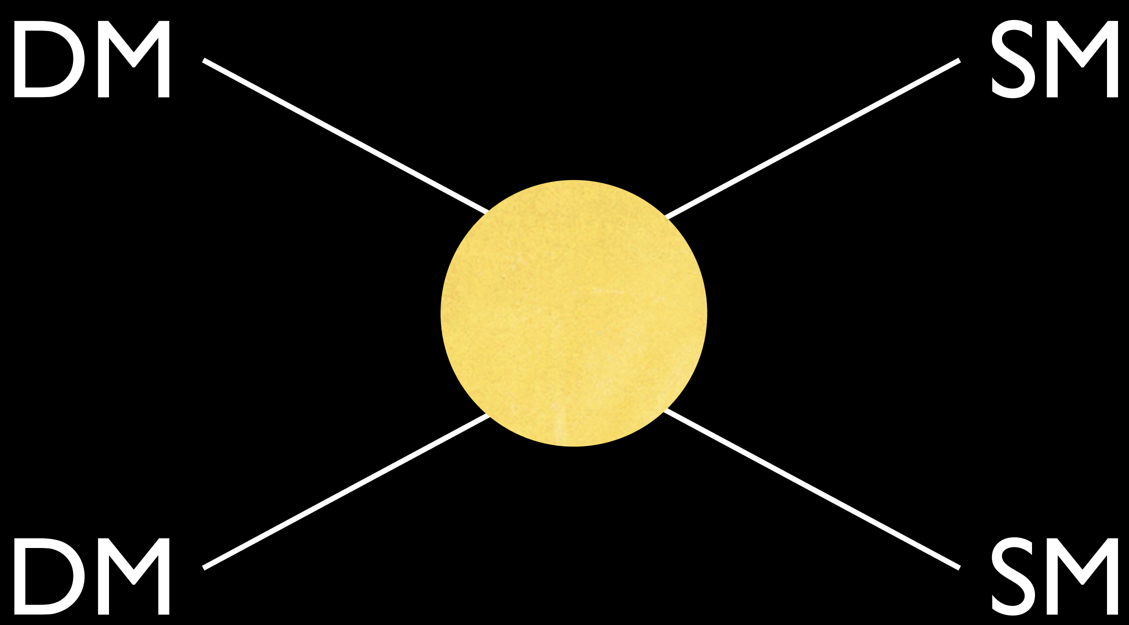
Dark Matter Miracles



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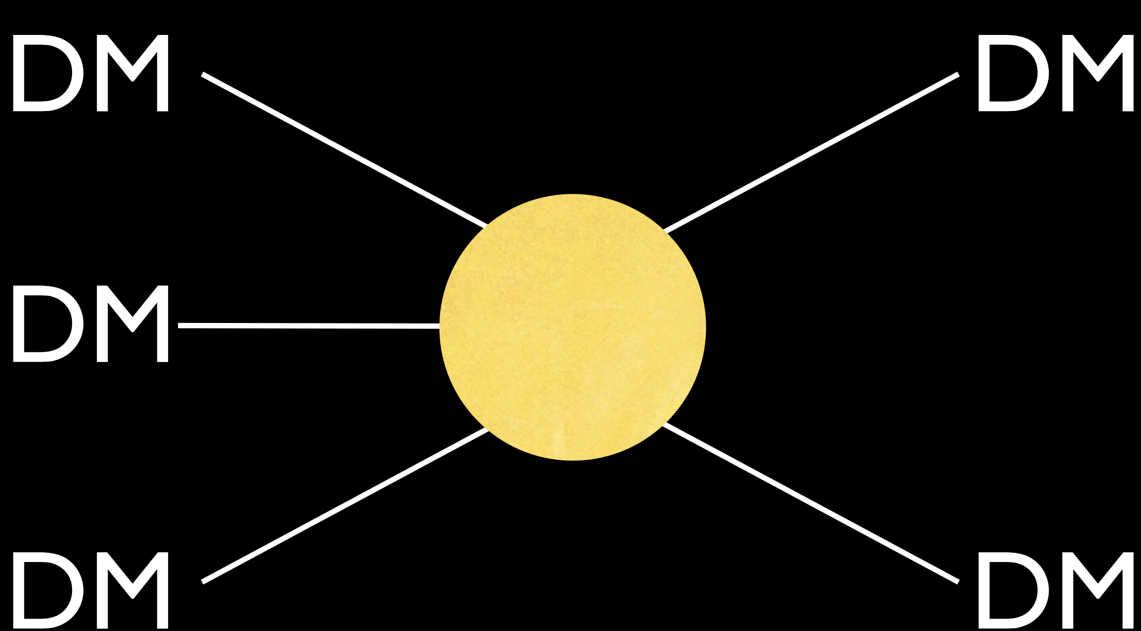


$$\langle \sigma_{3\to 2} v^2 \rangle \approx \frac{\alpha^3}{m^5}$$

$$\alpha \approx 4\pi$$

dark pion?

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

SIMP miracle!

LAGRANGIANS

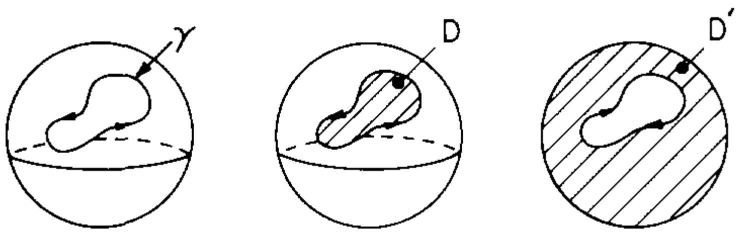
QCD with massive quarks

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

Chiral Lagrangian

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

Perturbation theory



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

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

LAGRANGIANS

QCD with massive quarks

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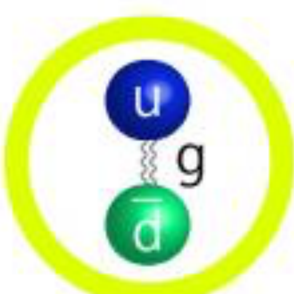
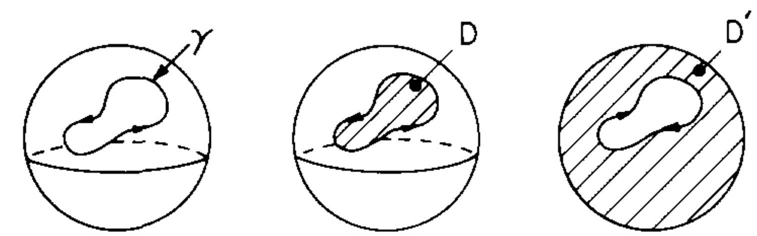
Chiral Lagrangian

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



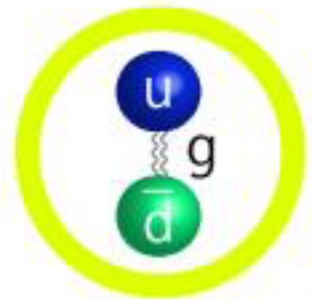
Perturbation theory



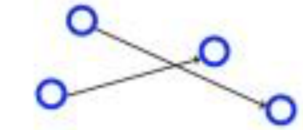
(a) (b) (c)

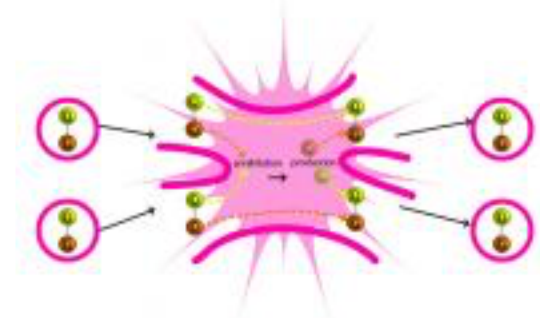
$$\mathcal{L}_{\rm pion} = \frac{1}{4}{\rm Tr}\partial_\mu\pi\partial^\mu\pi - \frac{m_\pi^2}{4}{\rm Tr}\pi^2 + \frac{m_\pi^2}{12f_\pi^2}{\rm Tr}\pi^4 - \frac{1}{6f_\pi^2}{\rm Tr}\left(\pi^2\partial^\mu\pi\partial_\mu\pi - \pi\partial^\mu\pi\pi\partial_\mu\pi\right)$$

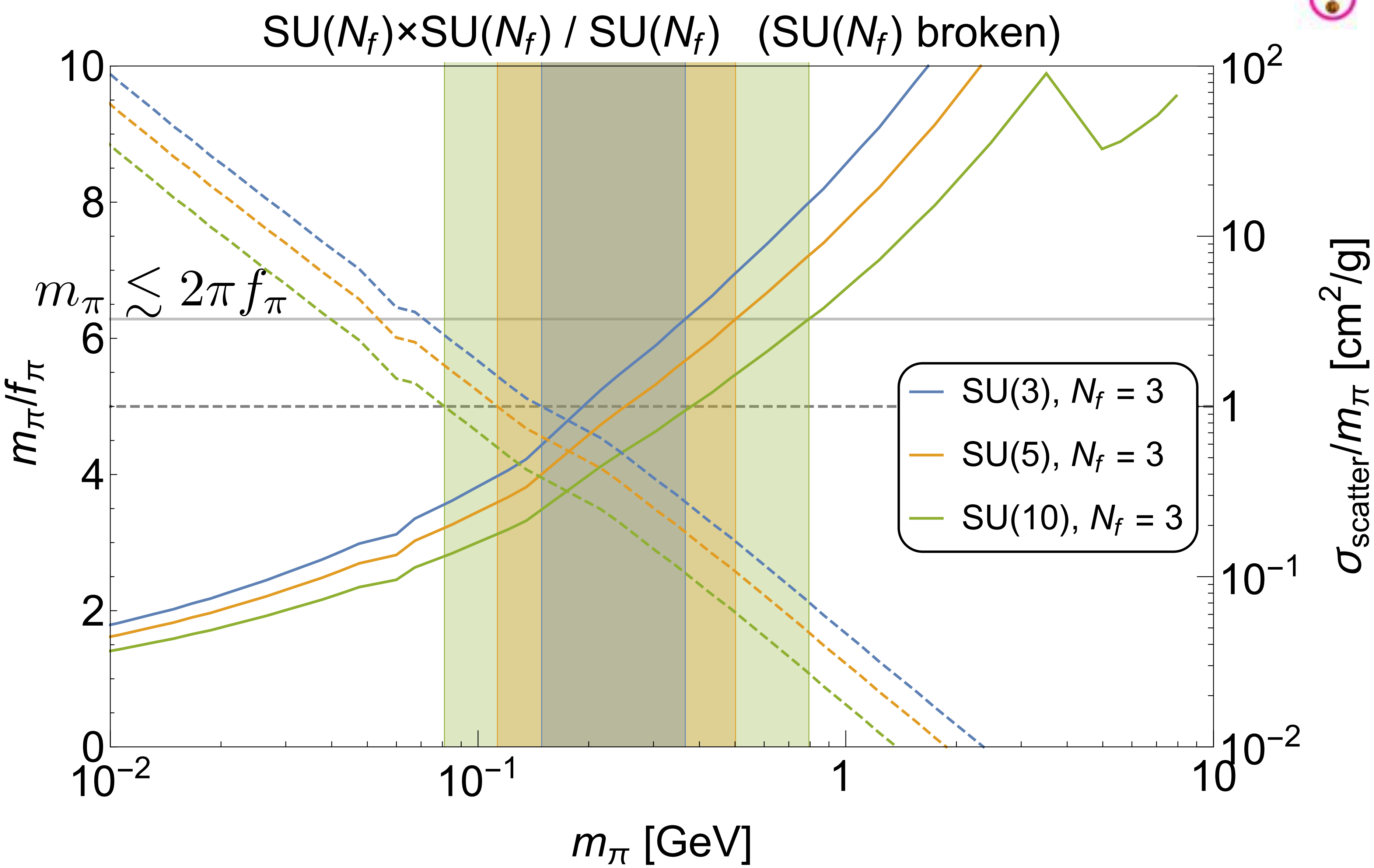
$$+\frac{2N_c}{15\pi^2 f_\pi^5}\epsilon^{\mu\nu\rho\sigma}{\rm Tr}\left[\pi\partial_\mu\pi\partial_\nu\pi\partial_\rho\pi\partial_\sigma\pi\right] + \mathcal{O}(\pi^6)$$



The Results





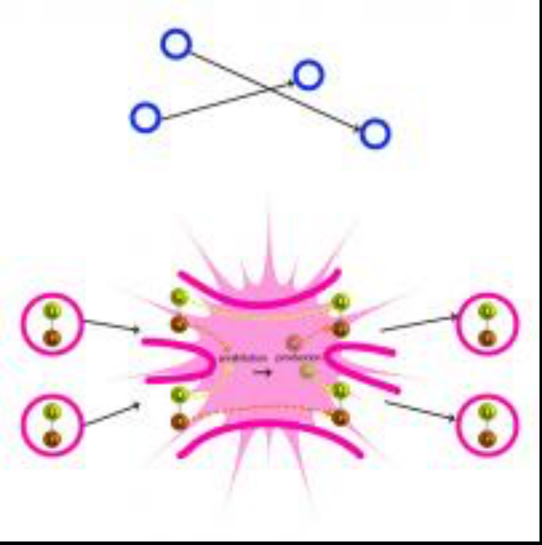


Solid curves: solution to Boltzmann eq.

Dashed curves: along that solution

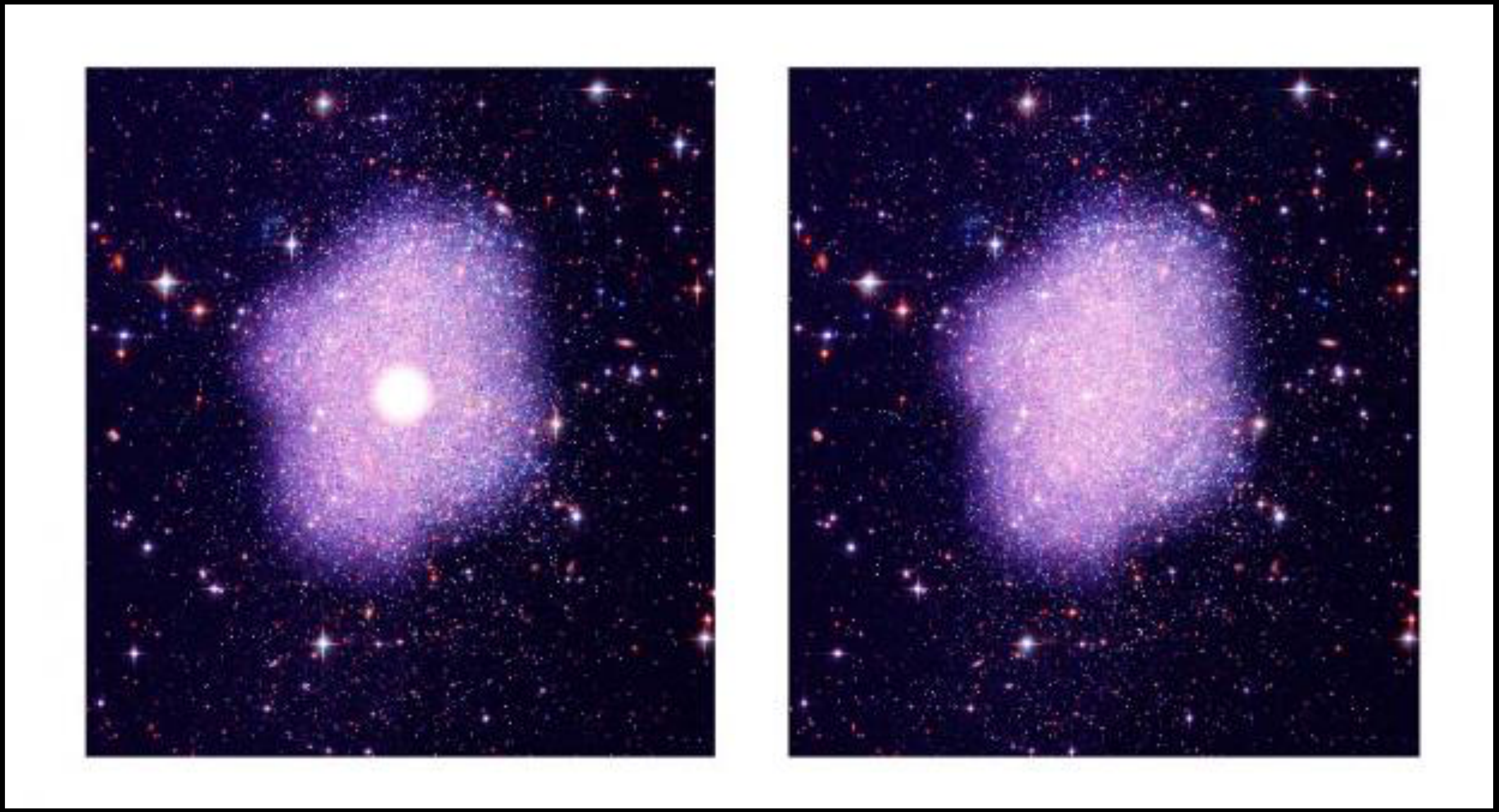
$$\frac{m_\pi}{f_\pi} \propto m_\pi^{3/10}$$

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

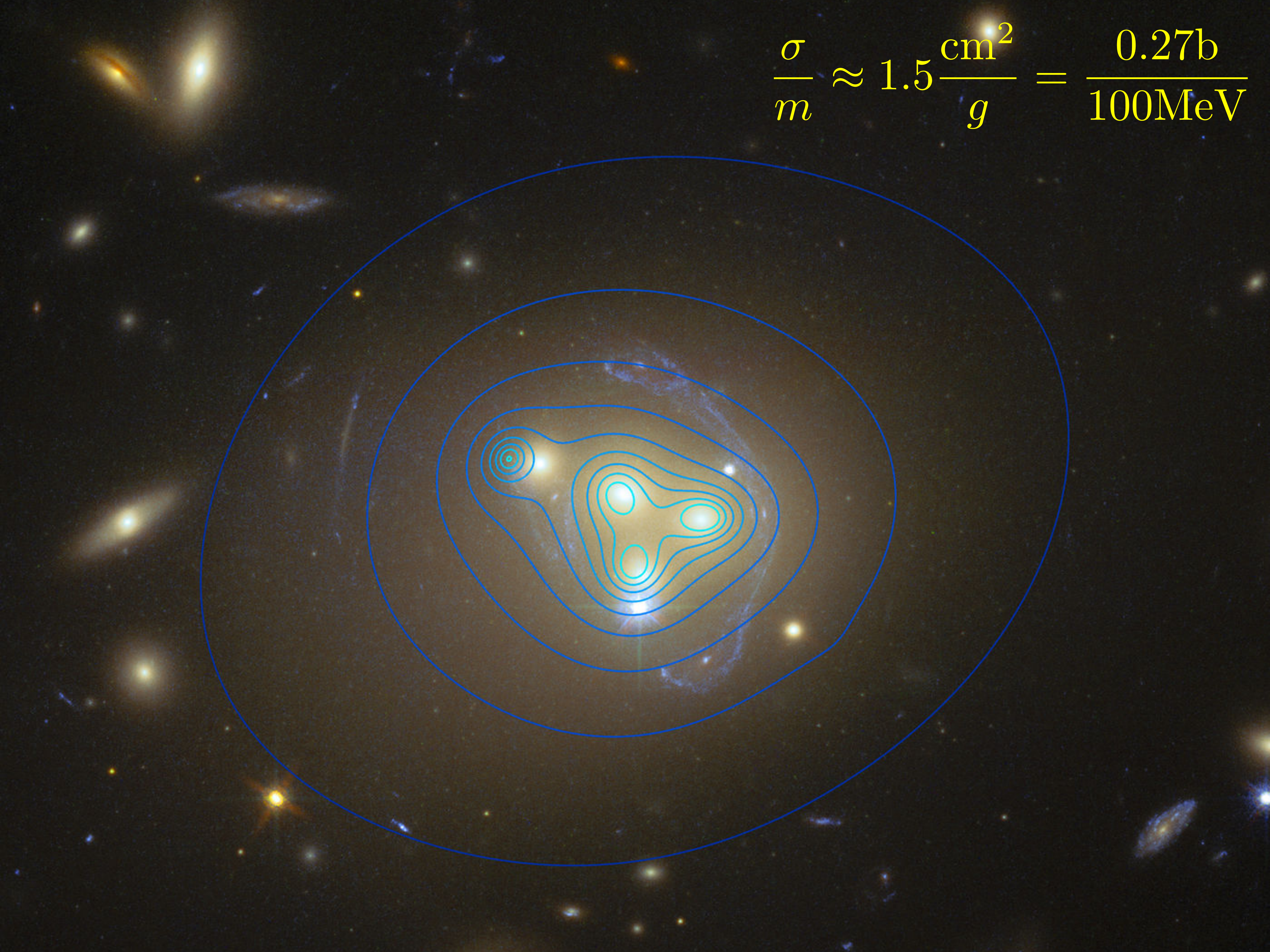


self interaction

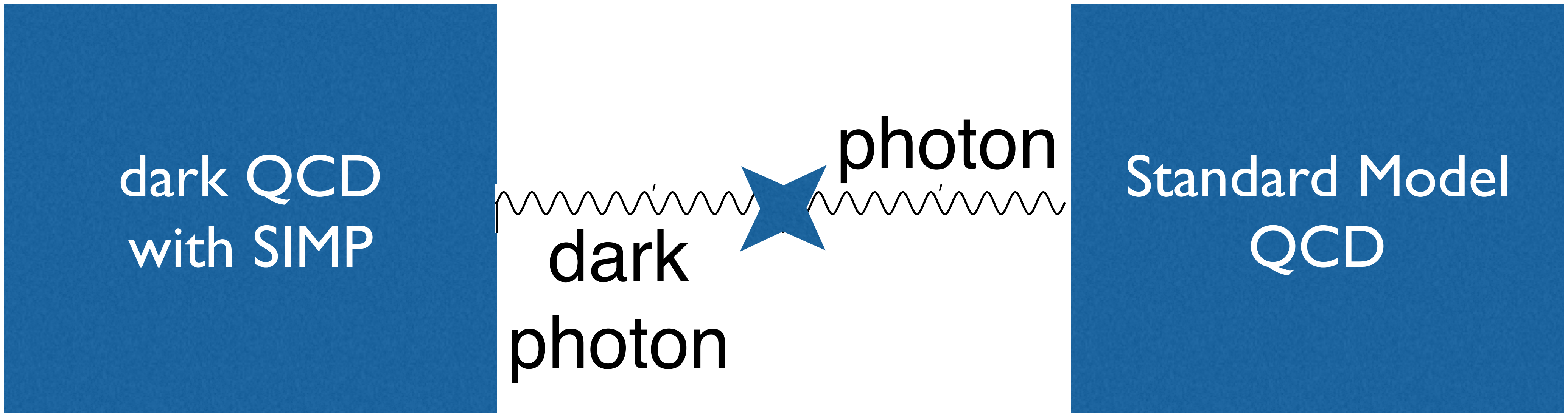
- $\sigma/m \sim \mathrm{cm}^2/g \sim 10^{-24}\mathrm{cm}^2$ / 300MeV
- flattens the cusps in NFW profile
- actually desirable for dwarf galaxies?



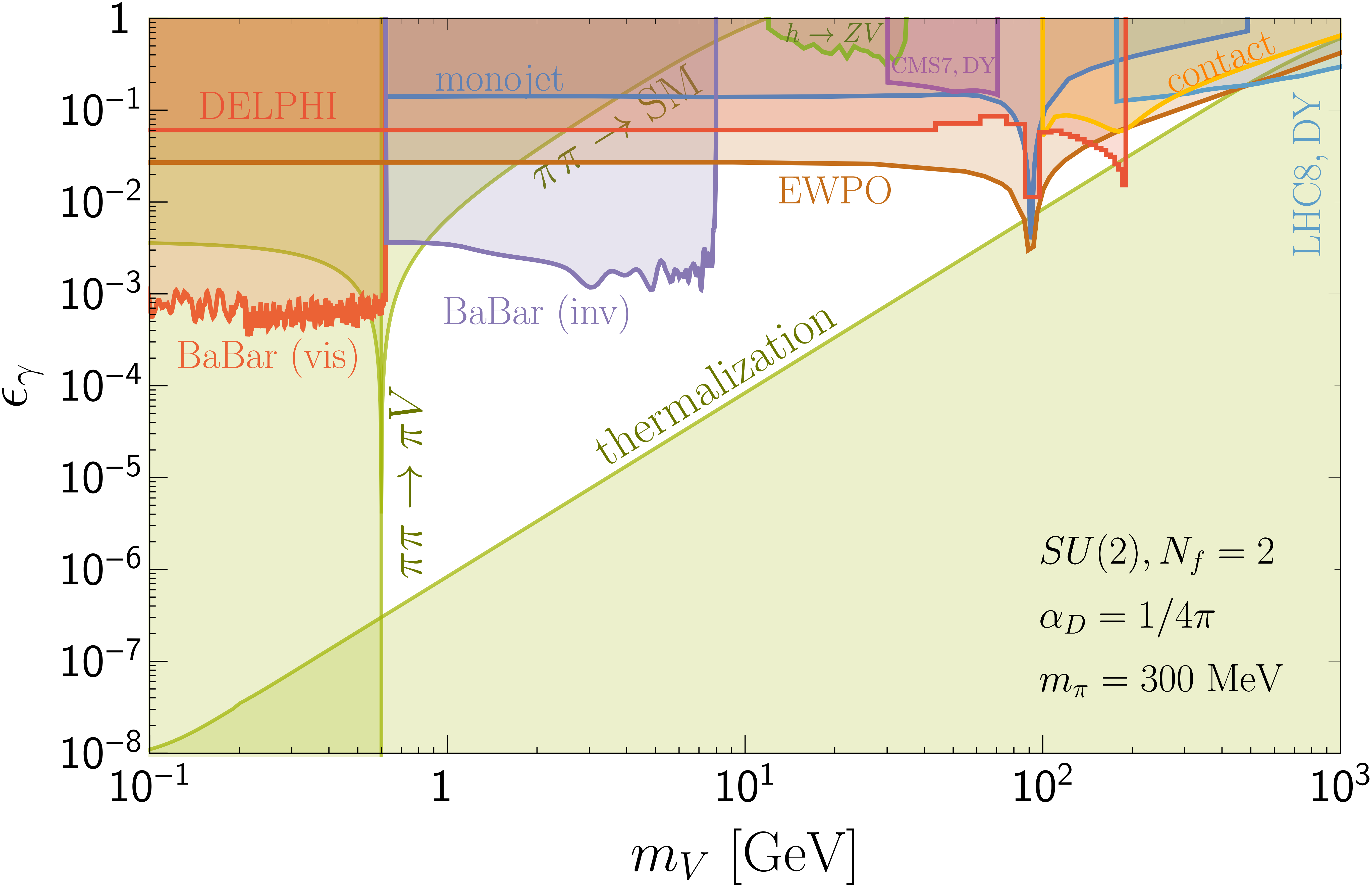
$$\frac{\sigma}{m} \approx 1.5\frac{\mathrm{cm}^2}{g} = \frac{0.27\mathrm{b}}{100\mathrm{MeV}}$$



vector portal

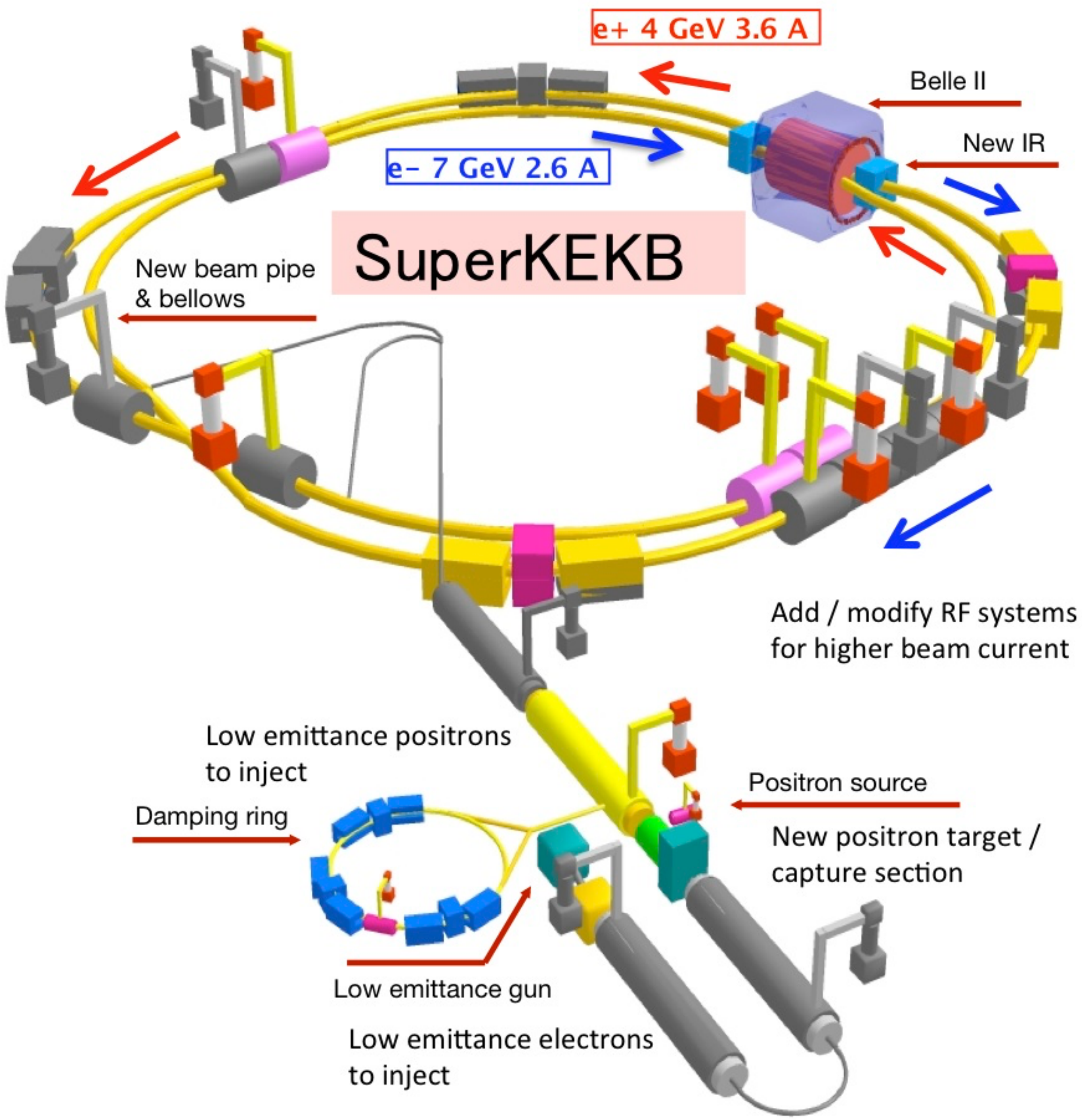


$$\frac{\epsilon_\gamma}{2c_W} B_{\mu\nu} F_D^{\mu\nu}$$

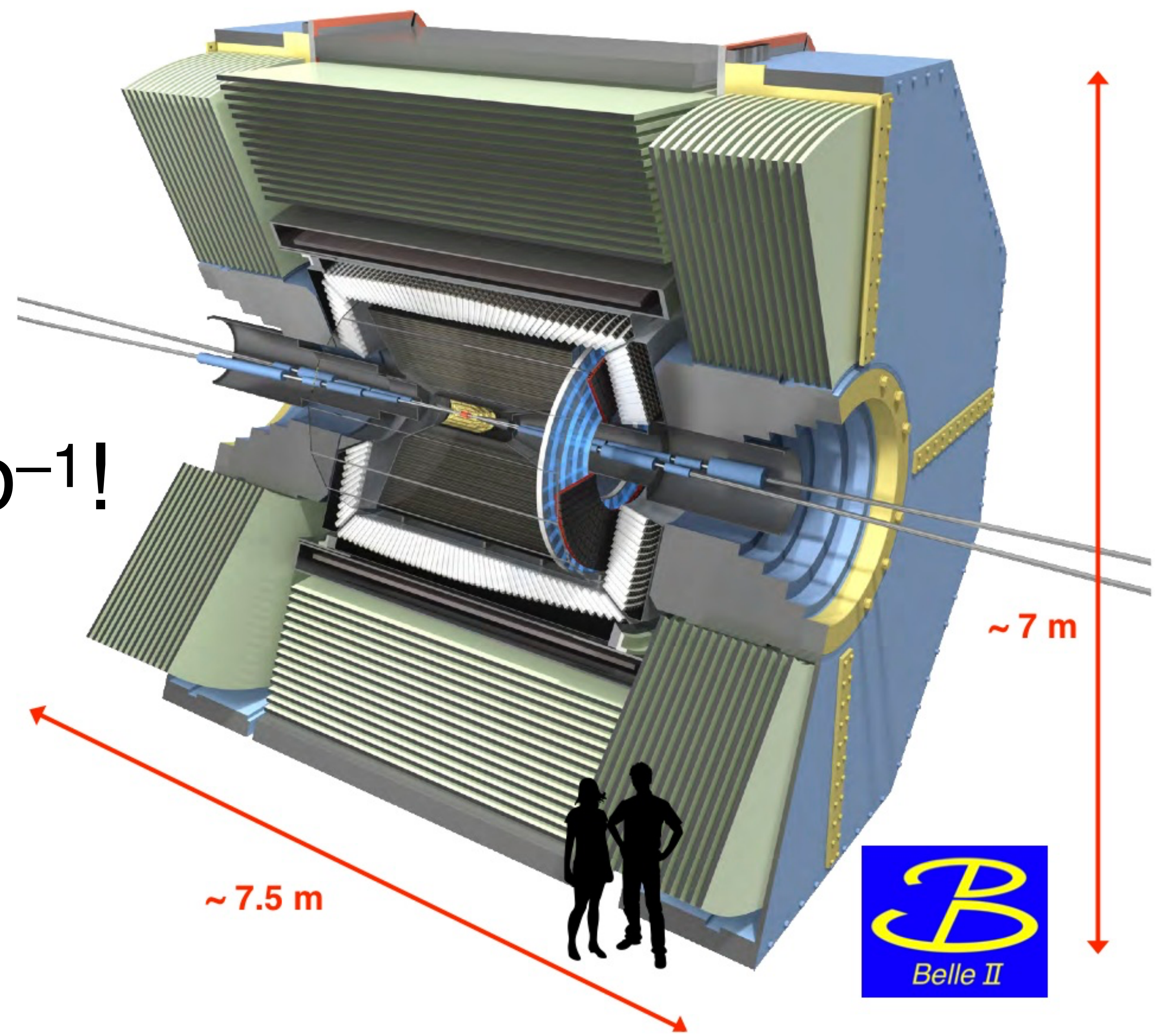


1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
ϵ_γ
10^{-1}
1
10^{1}
10^{2}
10^{3}
m_V [GeV]
DELPHI
monojet
$\pi\pi \to SM$
$h \to ZV$
CMS7, DY
contact
LHC8, DY
EWPO
BaBar (inv)
BaBar (vis)
$\pi\pi \to \pi V$
thermalization
$SU(2), N_f = 2$
$\alpha_D = 1/4\pi$
$m_\pi = 300$ MeV

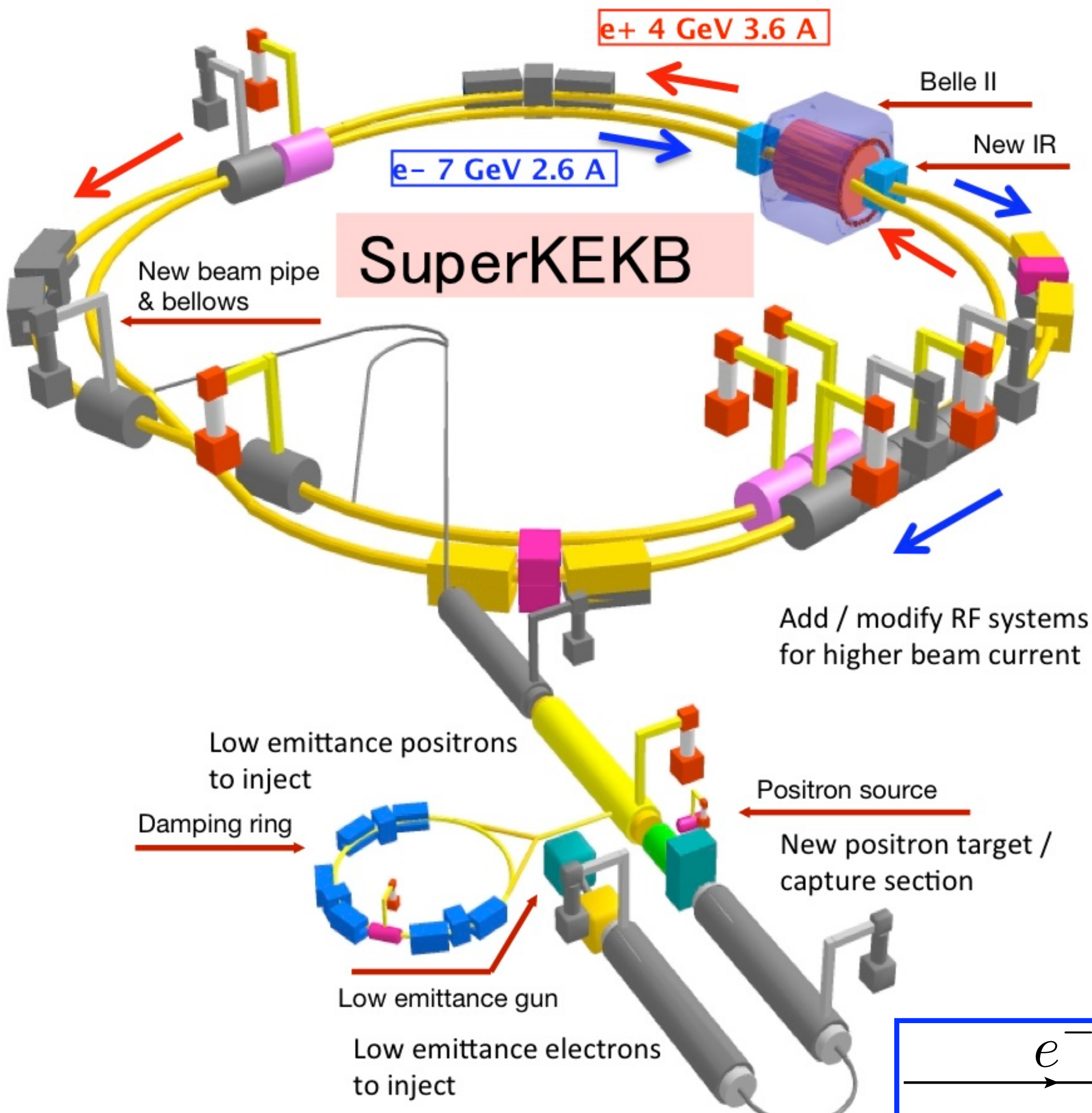
$e^+ e^-$ colliders



50 ab^{-1}!



$e^+ e^-$ colliders



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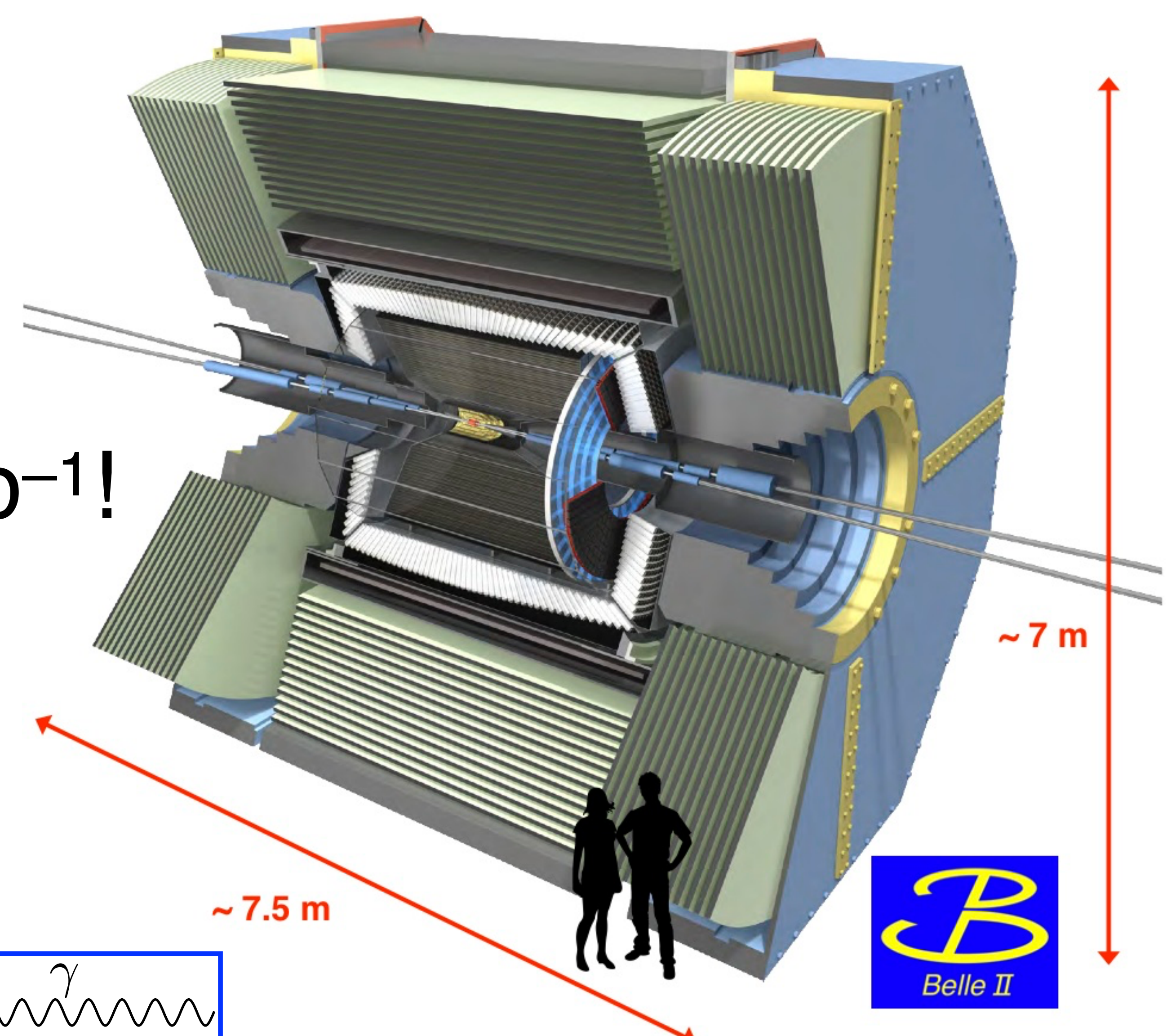
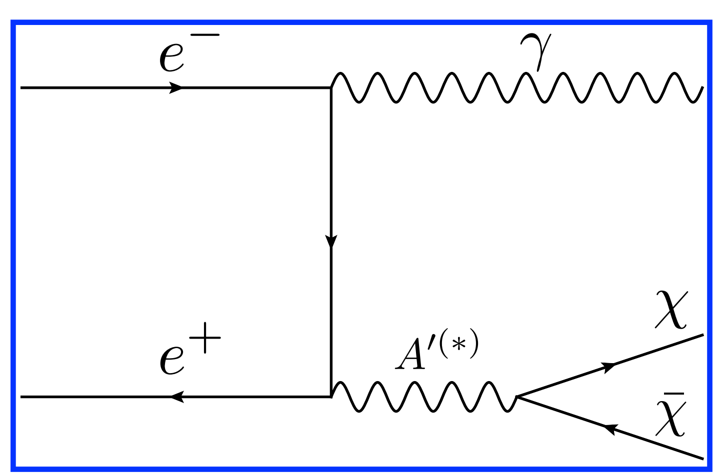
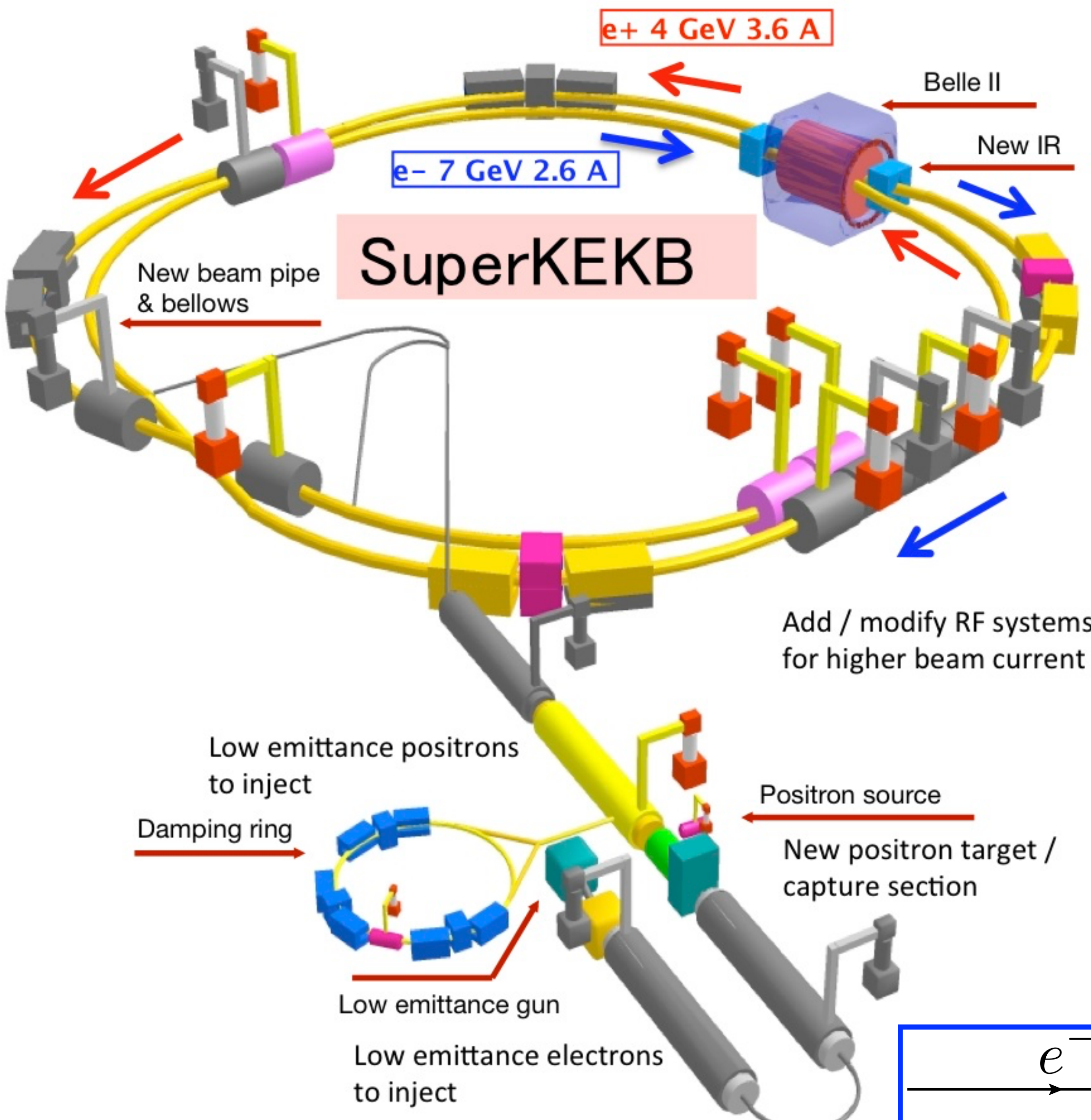
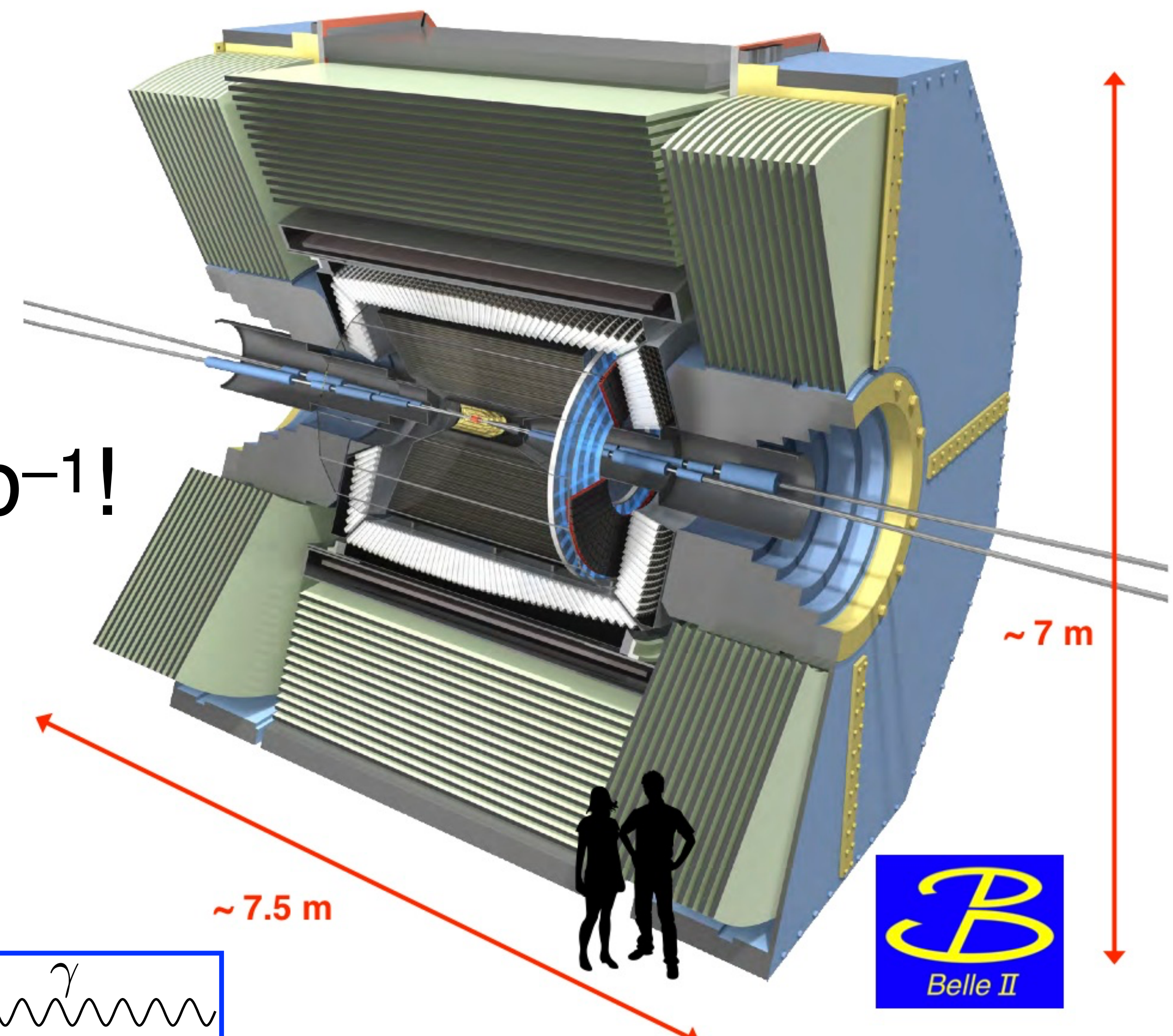


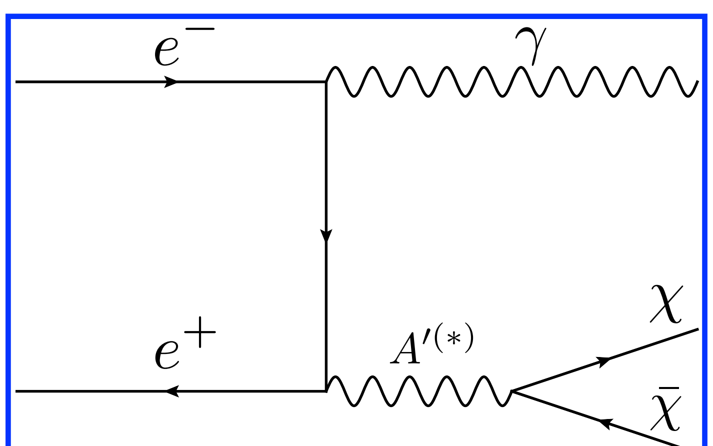


$e^+ e^-$ colliders

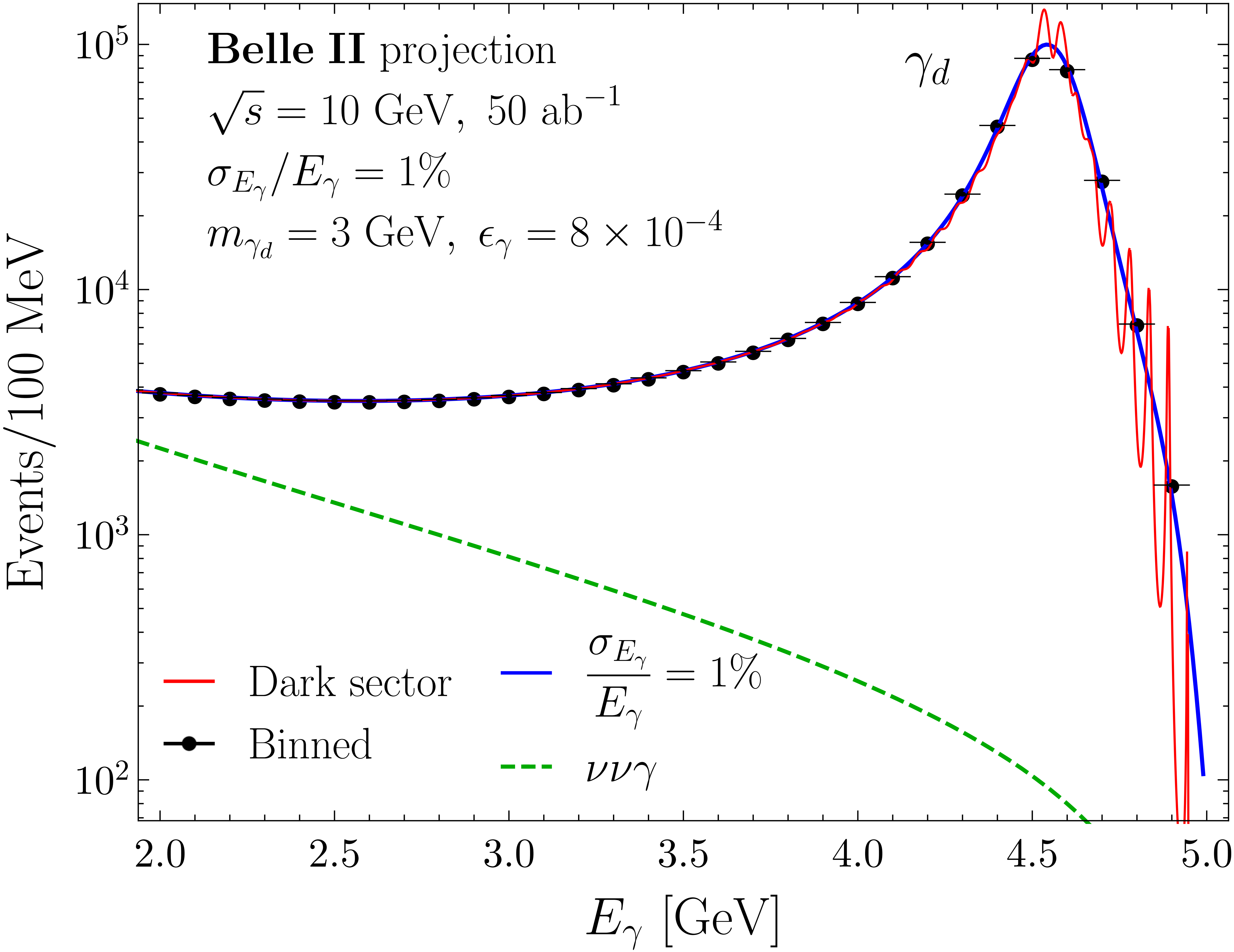


50 ab^{-1}!

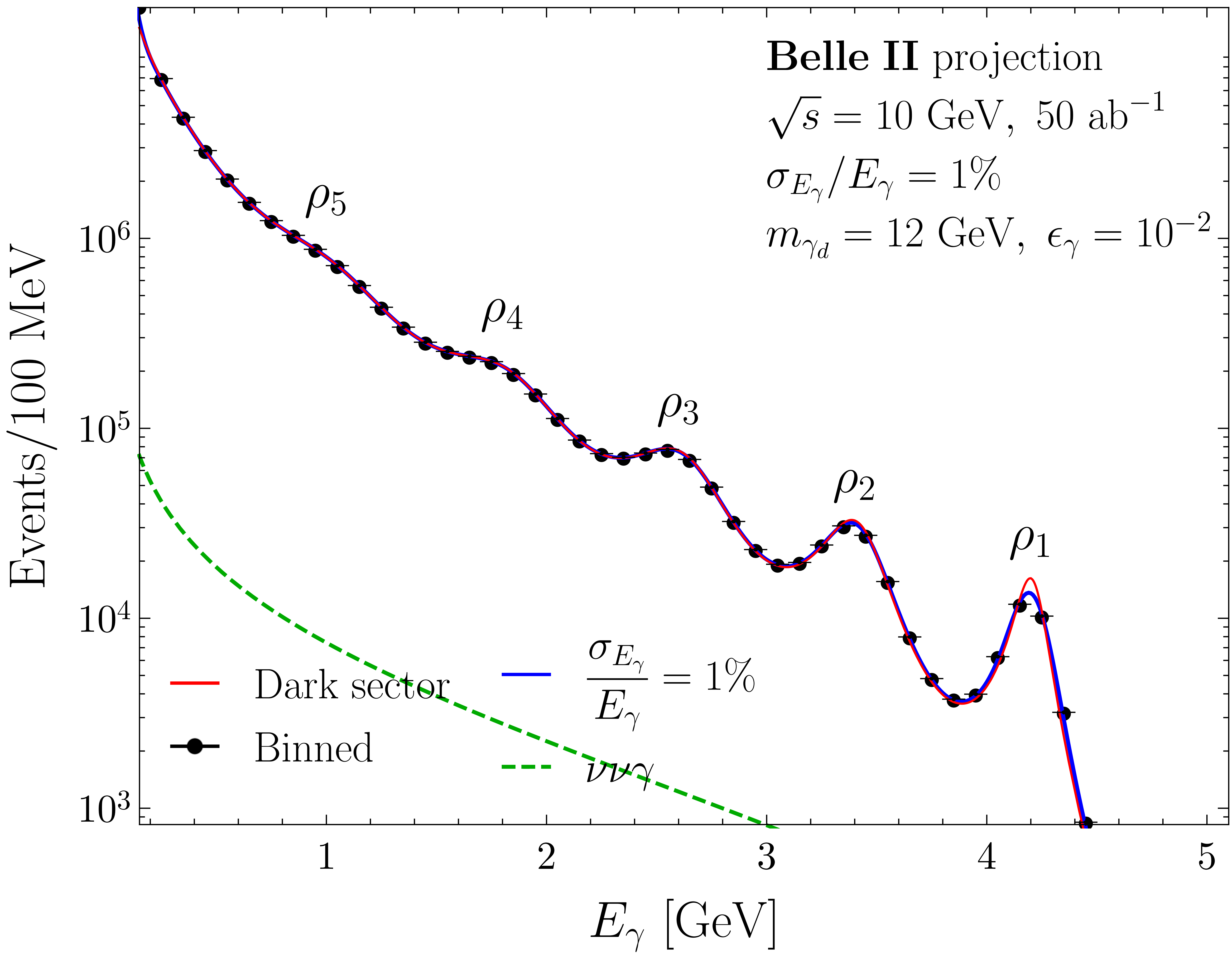




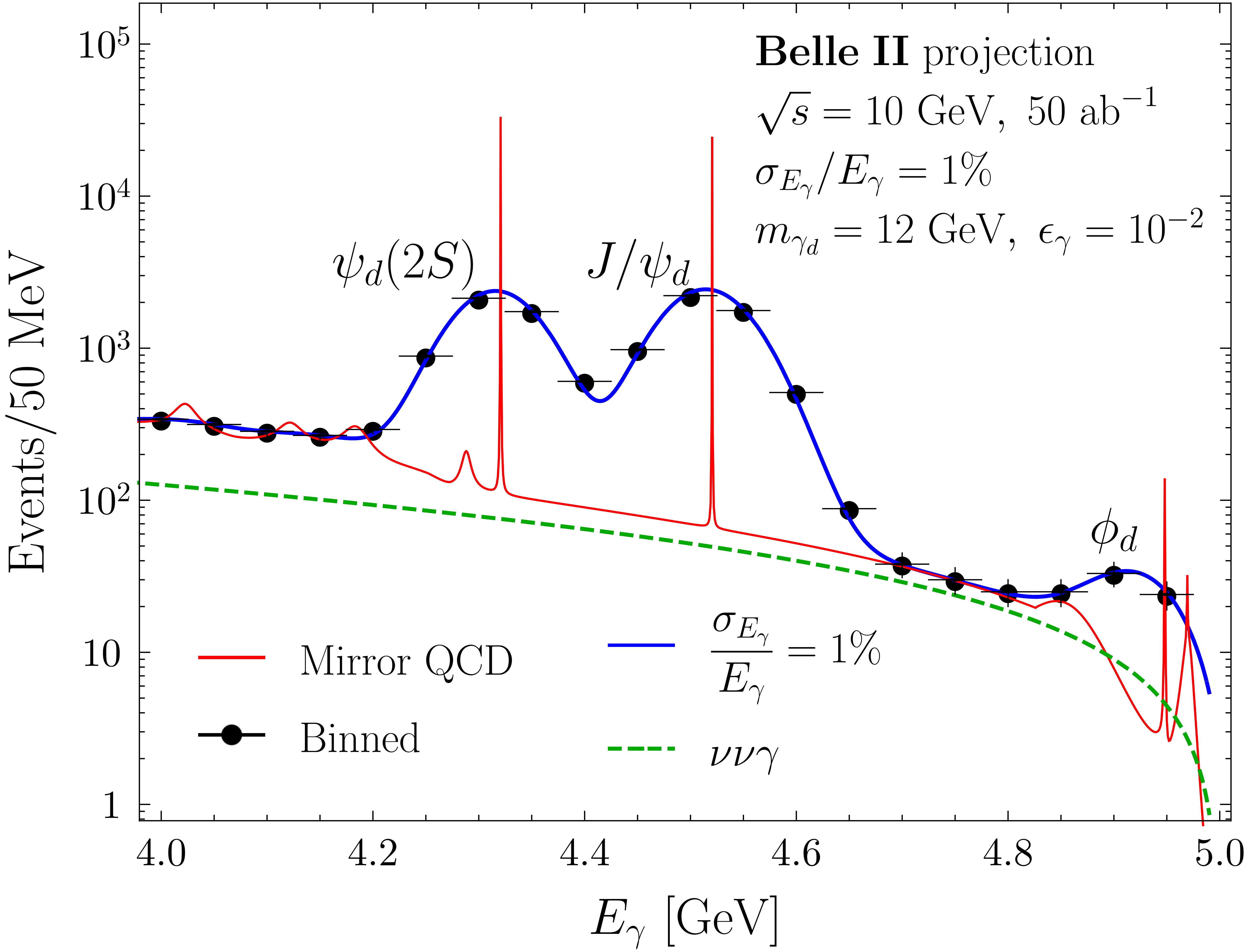
$$E_\gamma = \frac{\sqrt{s}}{2}\left(1 - \frac{M_{\text{inv}}^2}{s}\right)$$



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

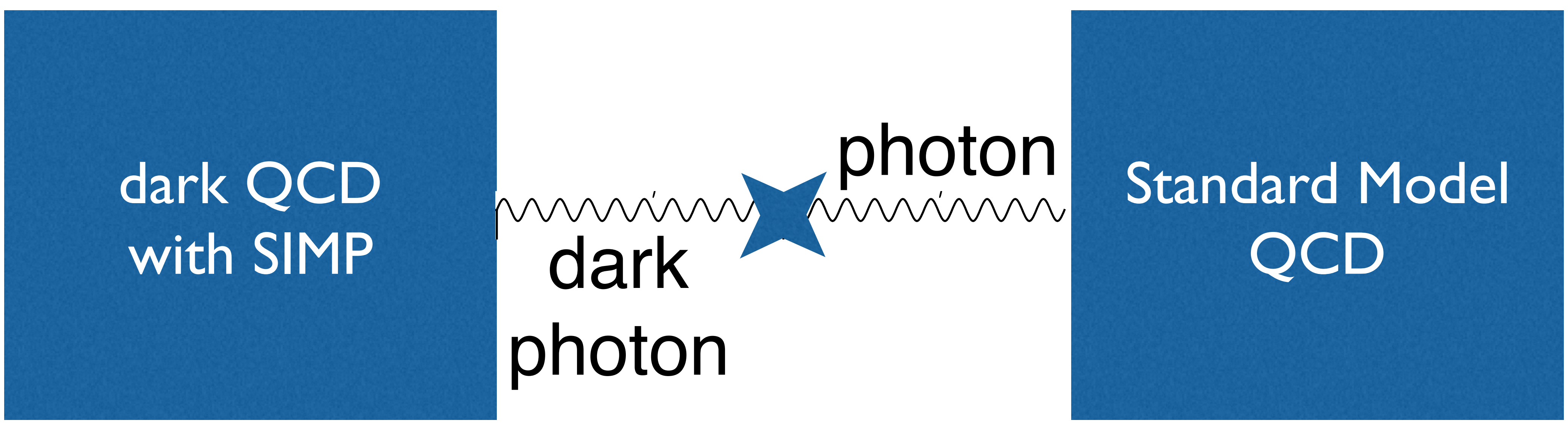


Belle II projection
$\sqrt{s} = 10$ GeV, 50 ab^{-1}
$\sigma_{E_\gamma}/E_\gamma = 1\%$
$m_{\gamma_d} = 12$ GeV, $\epsilon_\gamma = 10^{-2}$
ρ_5
ρ_4
ρ_3
ρ_2
ρ_1
Dark sector
Binned
$\frac{\sigma_{E_\gamma}}{E_\gamma} = 1\%$
$\nu\nu\gamma$
Events/100 MeV
E_γ [GeV]
10^3
10^4
10^5
10^6
1
2
3
4
5



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]

Hierarchy Problem?



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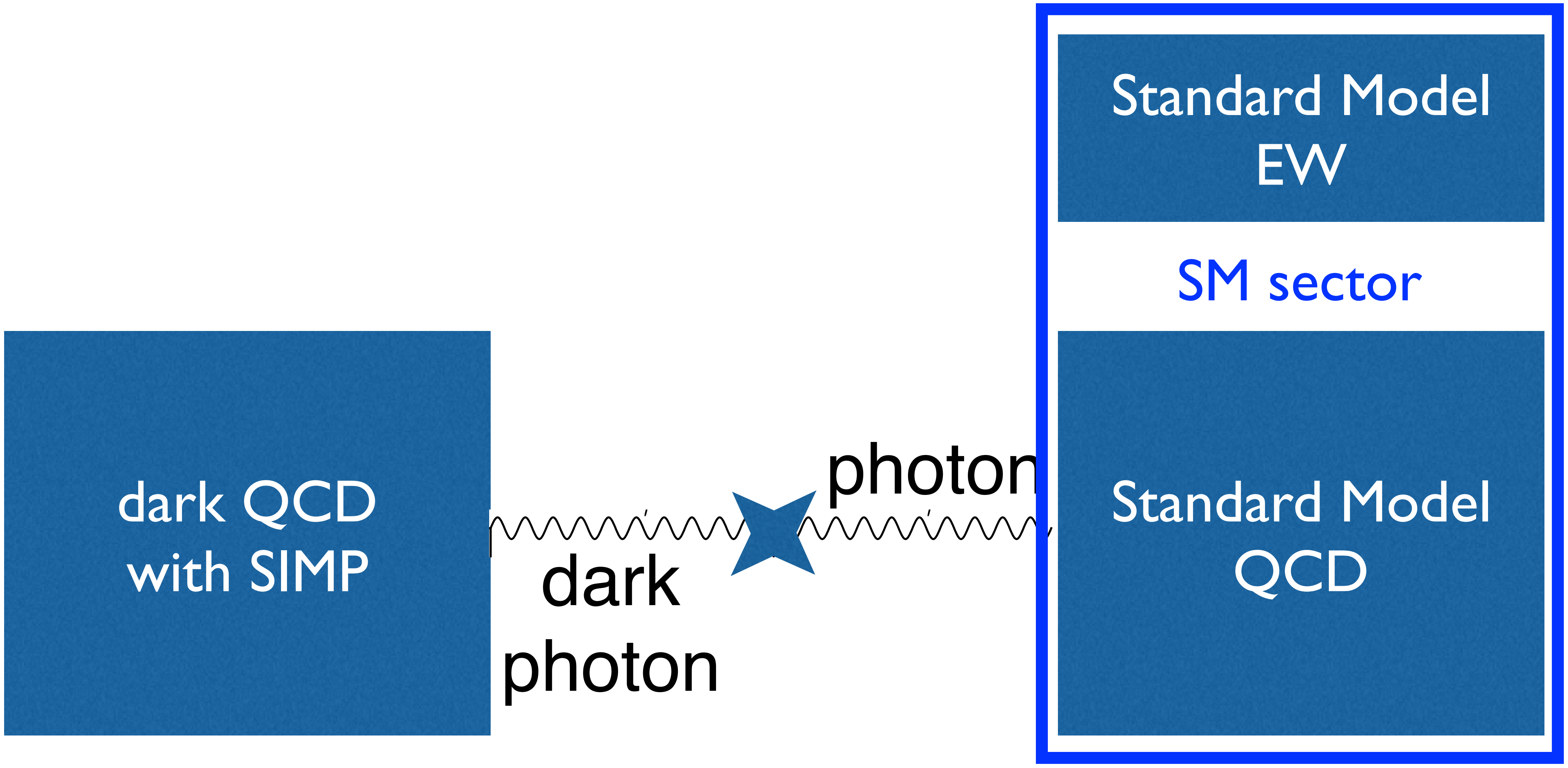

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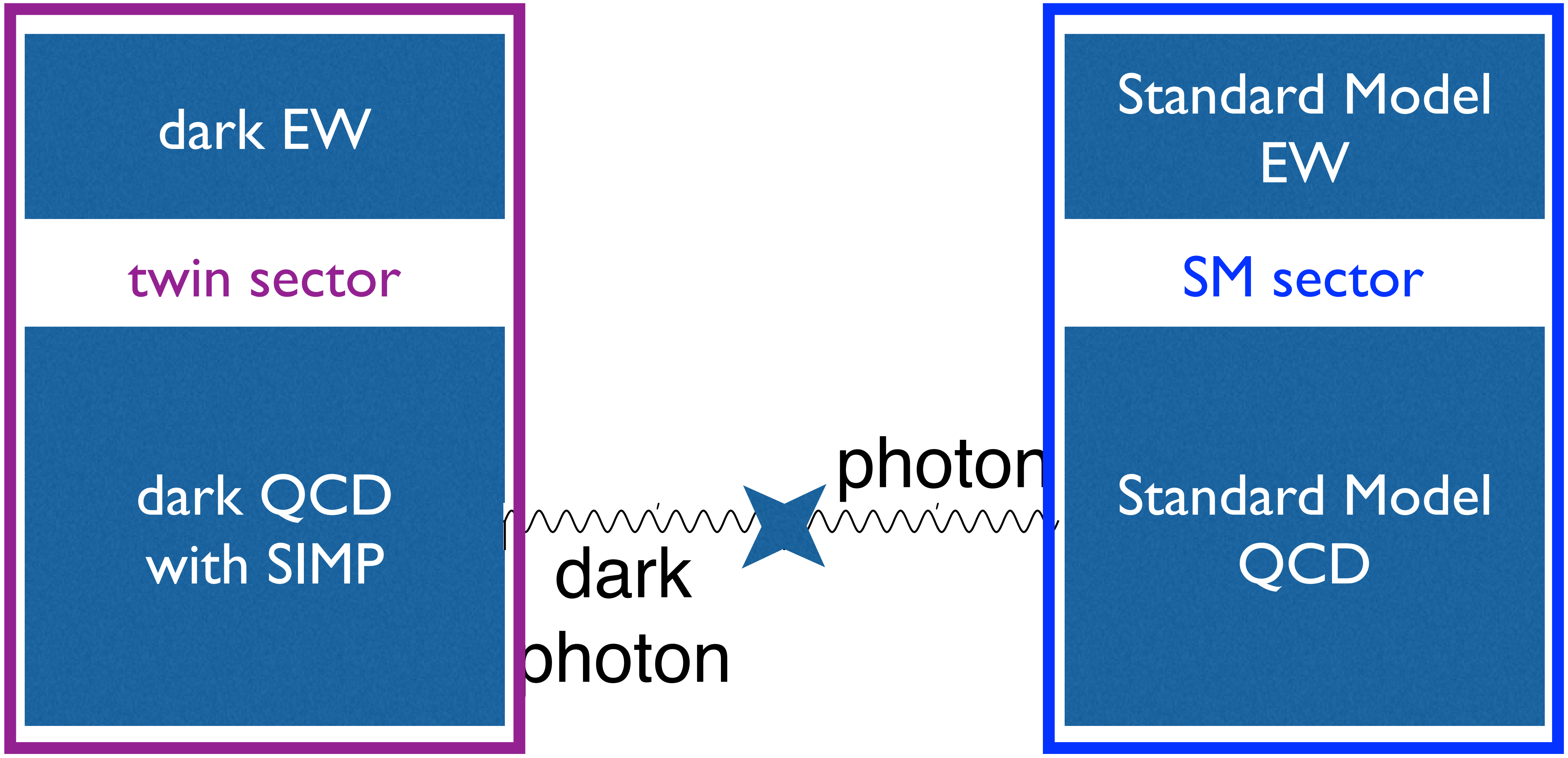
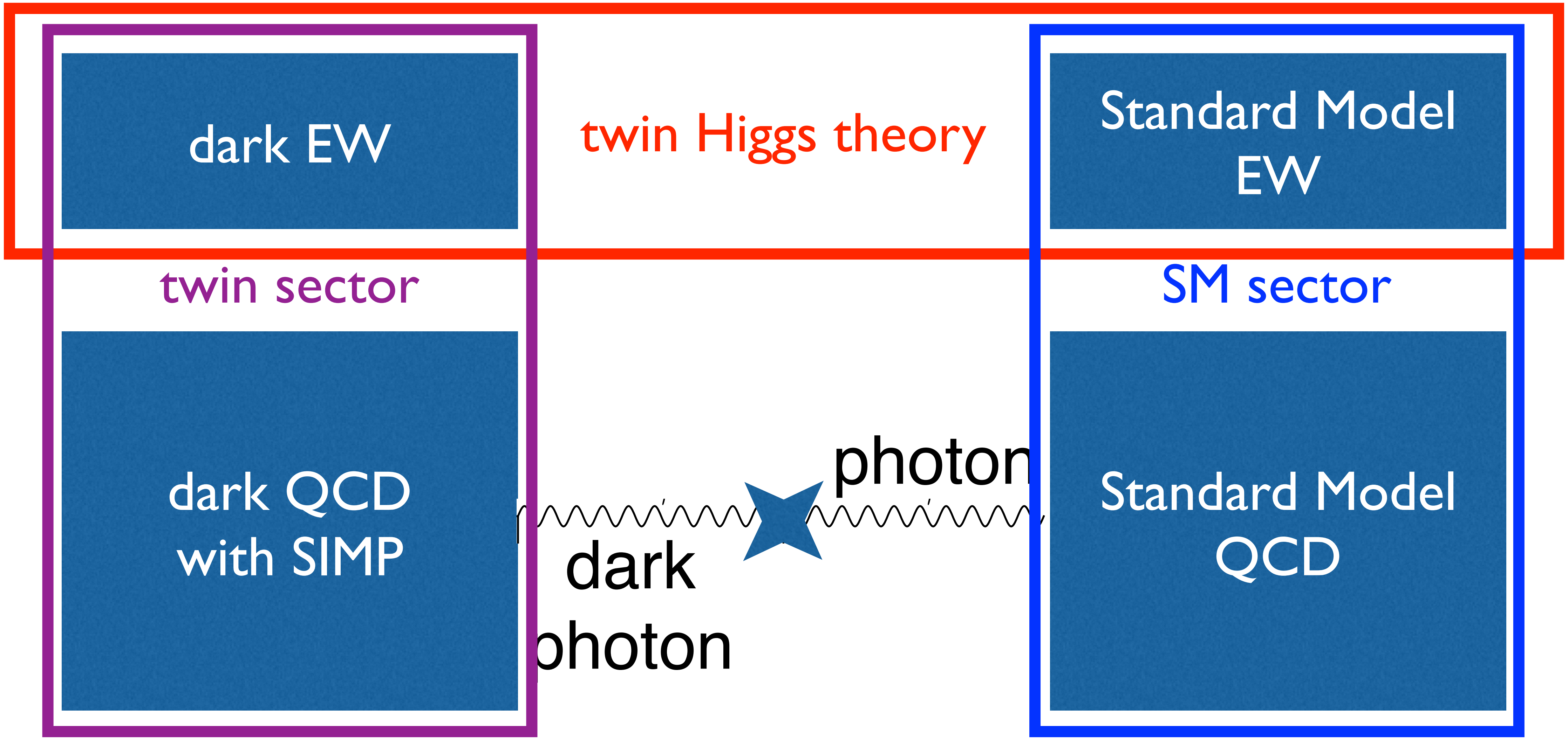
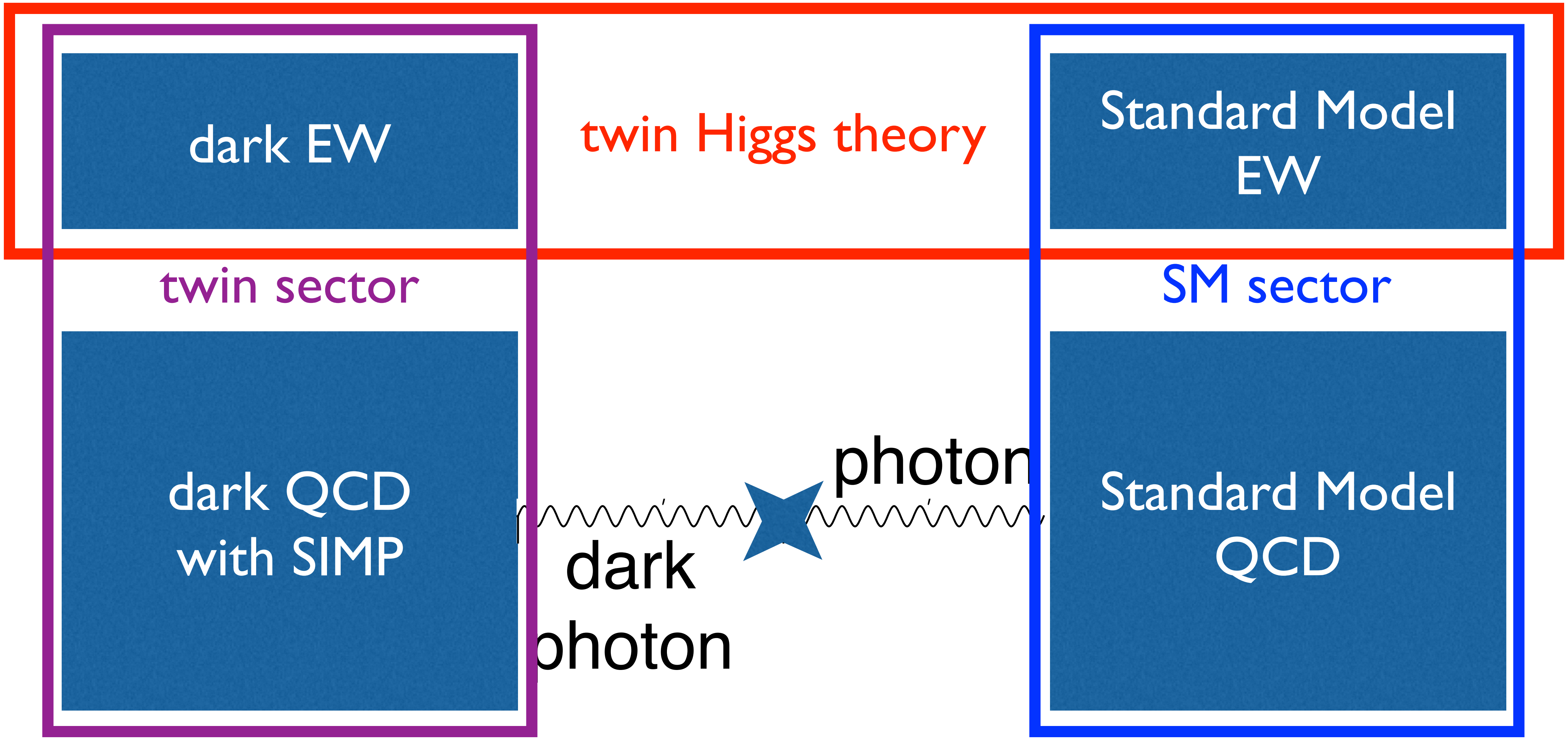


Hierarchy Problem?



Hierarchy Problem?

SU(4)⇒SU(3), SM Higgs doublet as pNGBs



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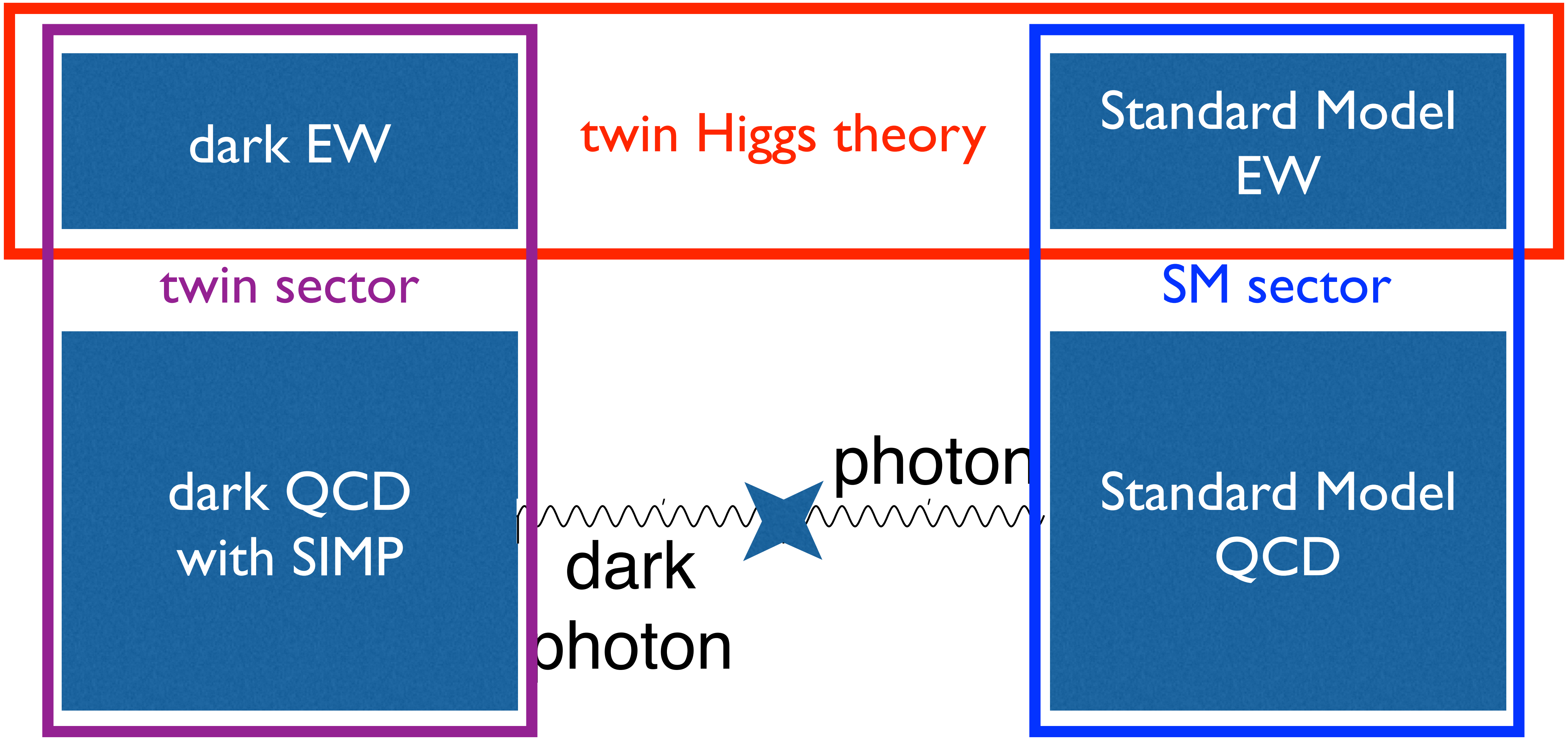

dark QCD is natural in twin Higgs theory with Z_2 symmetry
dark QCD scale presumably higher ~(f/v) GeV

Twin SIMP

- Make all leptons > GeV
  - quarks: lightest particles in the twin sector
- degenerate *u*, *d*, *s*, no CKM mixing
  - approximate SU(3) flavor symmetry
  - exact $U(1)_f$, $U(1)_{EM}$
  - π^+, K^+, K^0 absolutely stable
  - π^0, η decay to $\gamma_D^* \gamma_D^* \to (e^+e^-)(e^+e^-)$ before BBN limit

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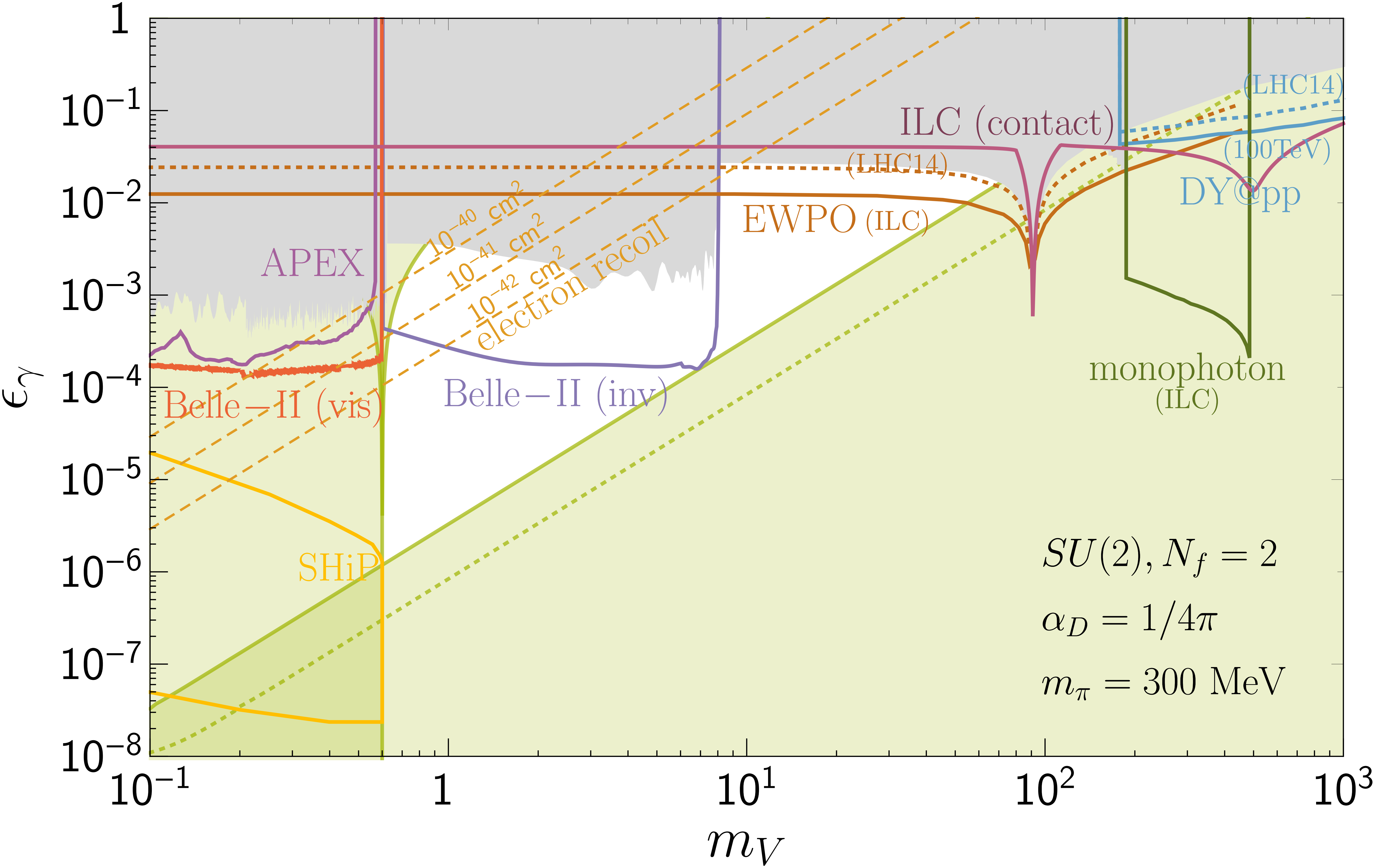
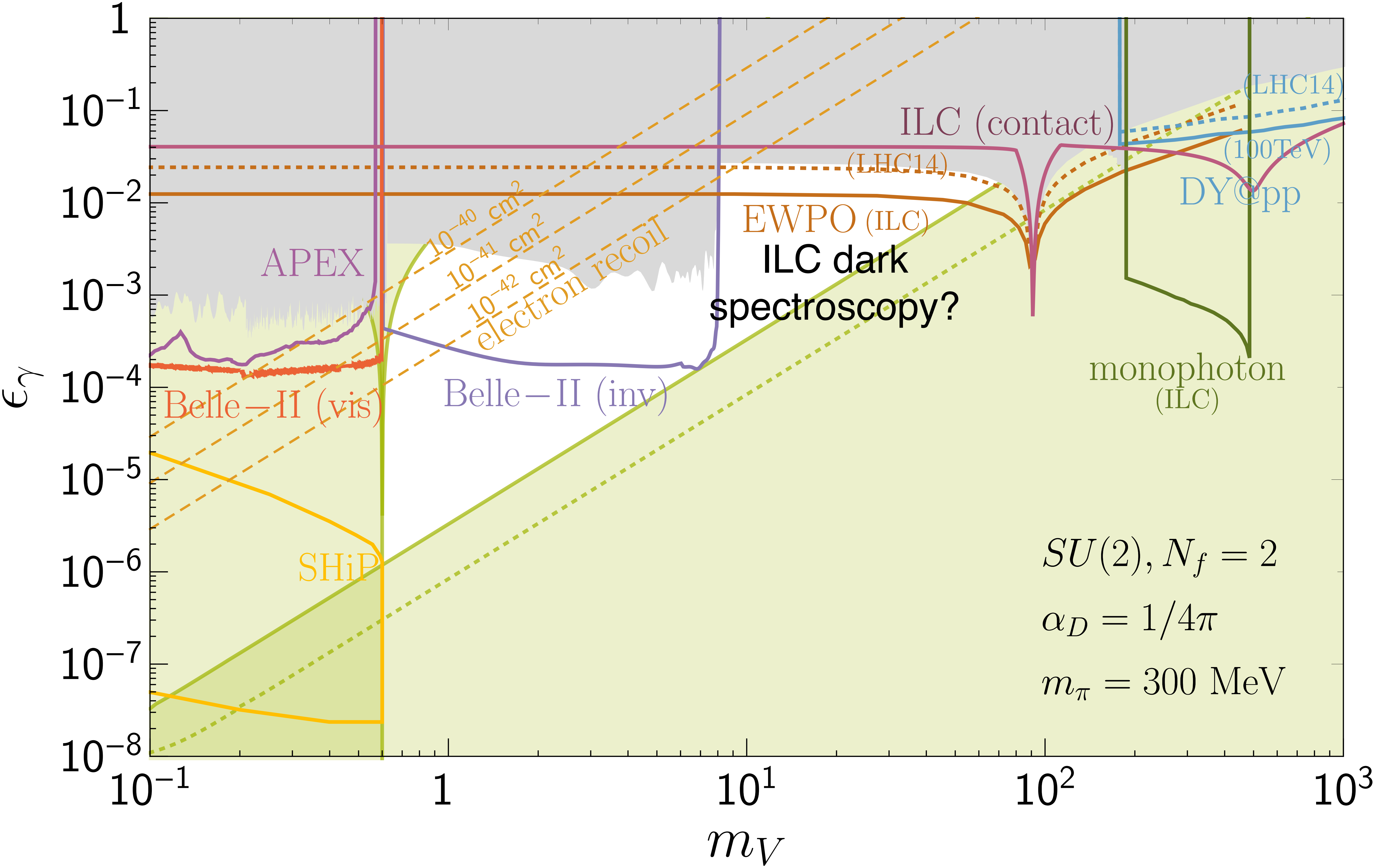
Can solve the hierarchy problem, too!



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
ϵ_γ
m_V



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

Conclusion

- surprisingly an *old* theory for dark matter
- SIMP Miracle^3
  - mass ~ QCD
  - coupling ~ QCD
  - theory ~ QCD
- can solve problem with DM profile
- may also solve the hierarchy problem
- more generally, dark resonances fascinating
- *Can ILC do dark spectroscopy?*
- *absolutely unique to e^+e^-*
- Fun beyond EFT