SIMP, Hierarchy Problem, Quintessence

Hitoshi Murayama (Berkeley, Kavli IPMU)
Niels Bohr Institute, Aug 13, 2018

+Eric Kuflik, Yonit Hochberg
Katelin Schutz, Robert McGehee
Chien-I Chang

東京大学 THE UNIVERSITY OF TOKYO
BERKELEY LAB
KAVLI IPMU INSTITUTE FOR THE PHYSICS AND MATHEMATICS OF THE UNIVERSE

KAVLI IPMU 10th

Anniversary Symposium
with Ceremonial Session

Oct 16 (Mon) - 18 (Wed) , 2017

Kashiwanoha Conference Center

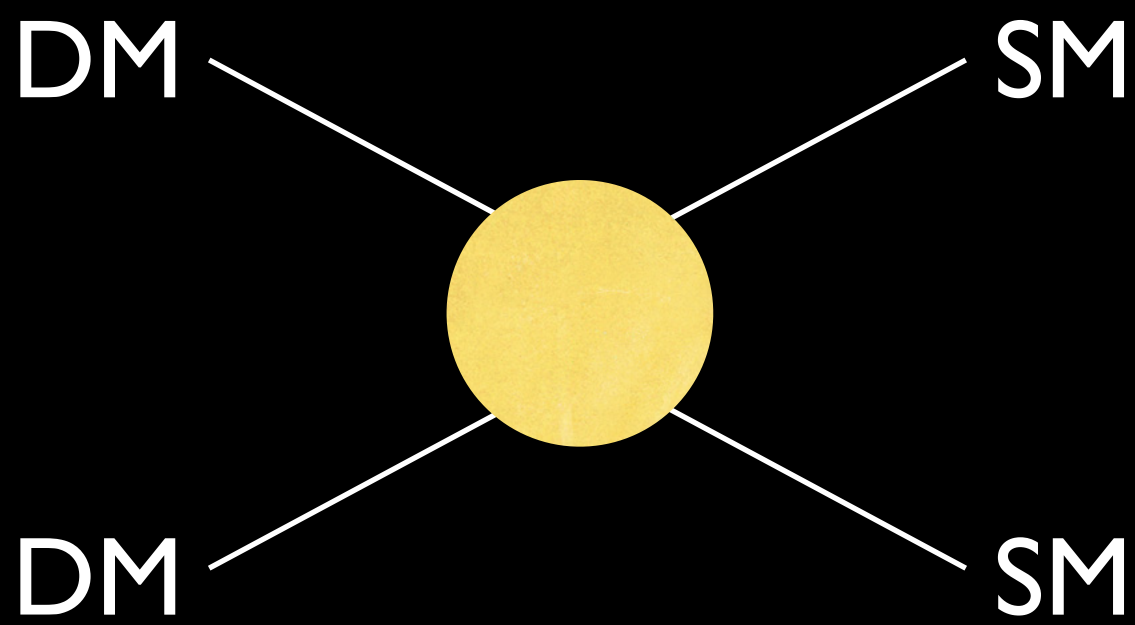
Kavli IPMU

Kavli IPMU is there to stay!

Wither WIMP?

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

WIMP Miracle



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

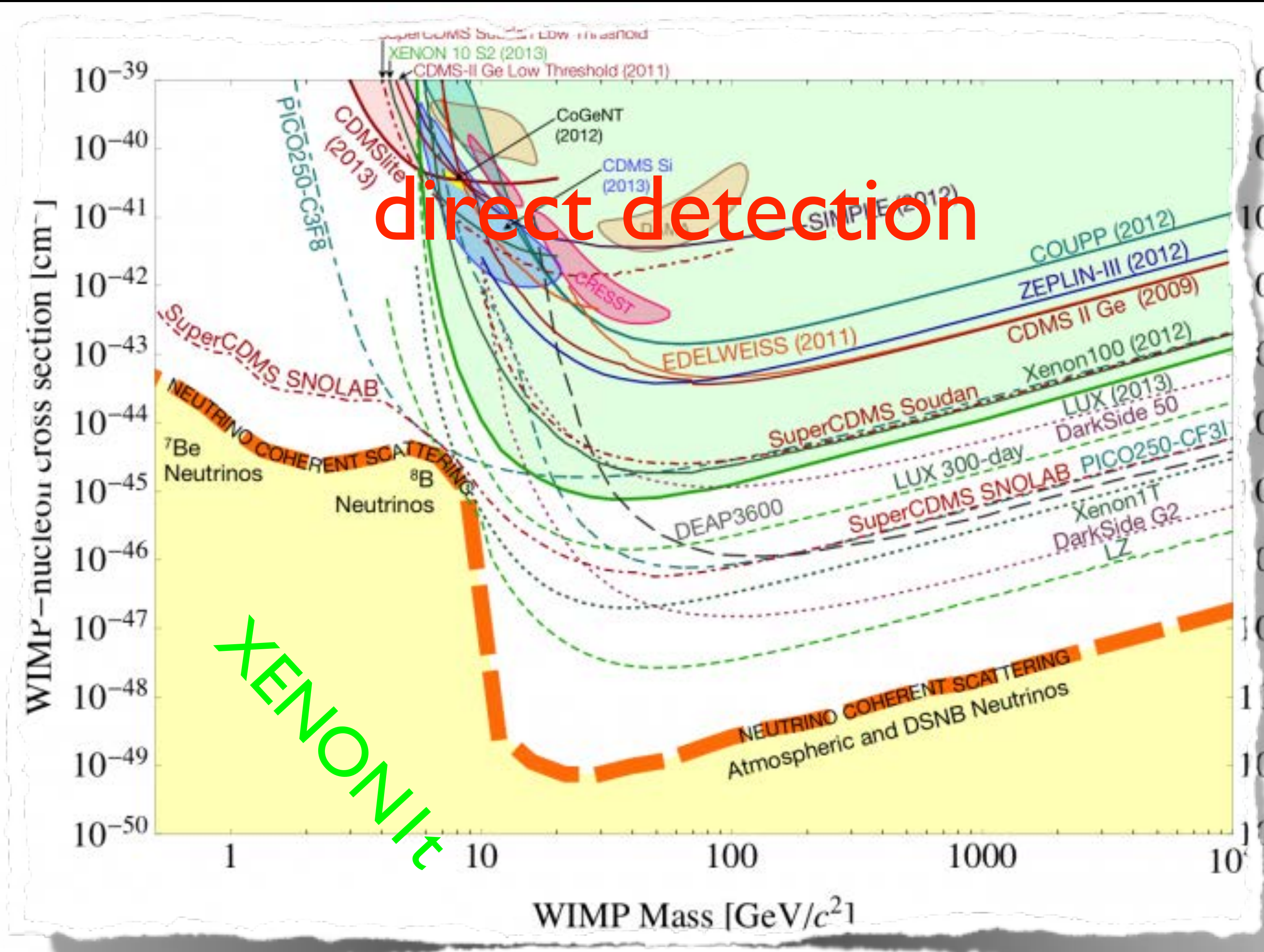
$$\alpha \approx 10^{-2}$$

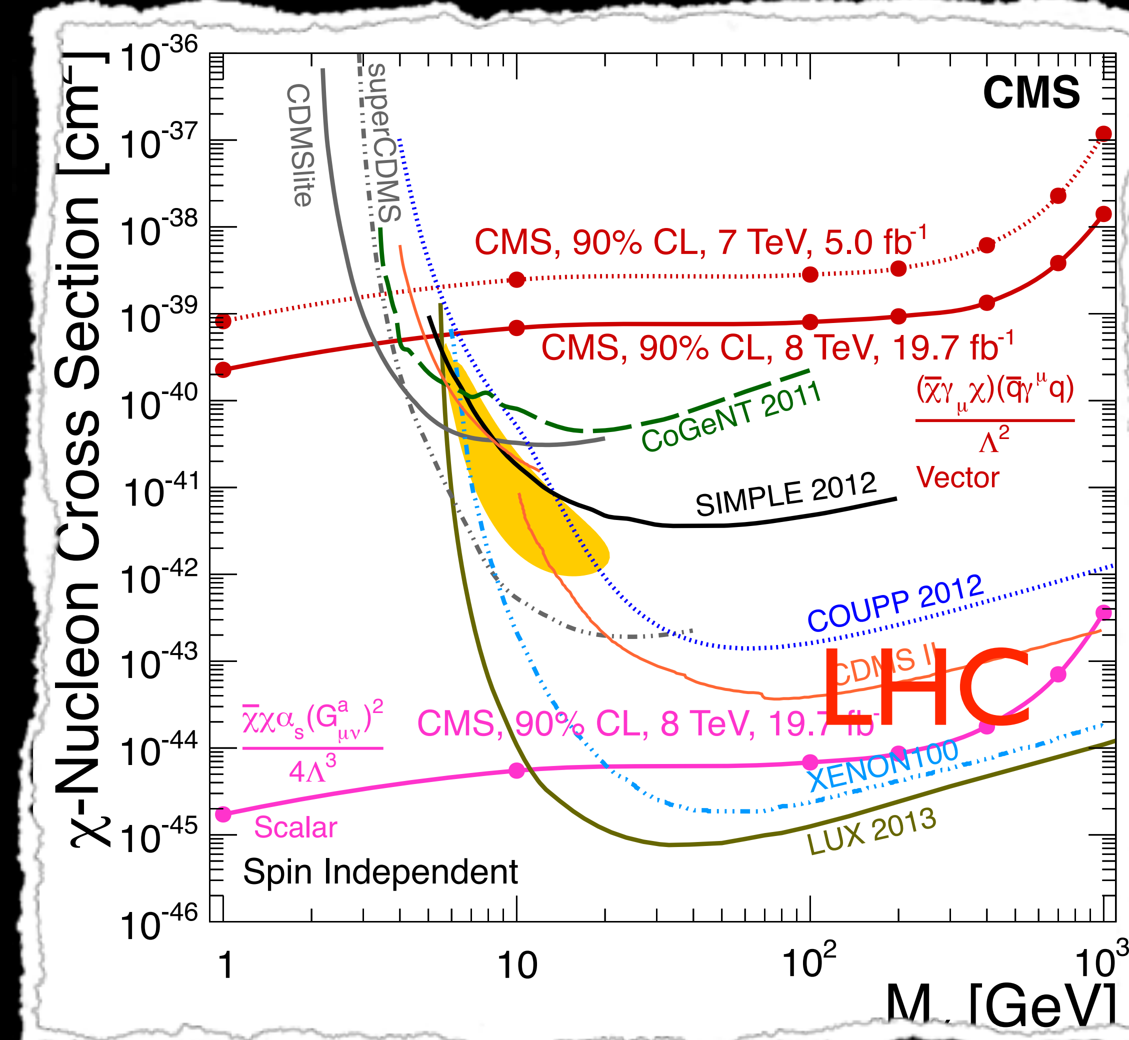
$$m \approx 300 \text{ GeV}$$

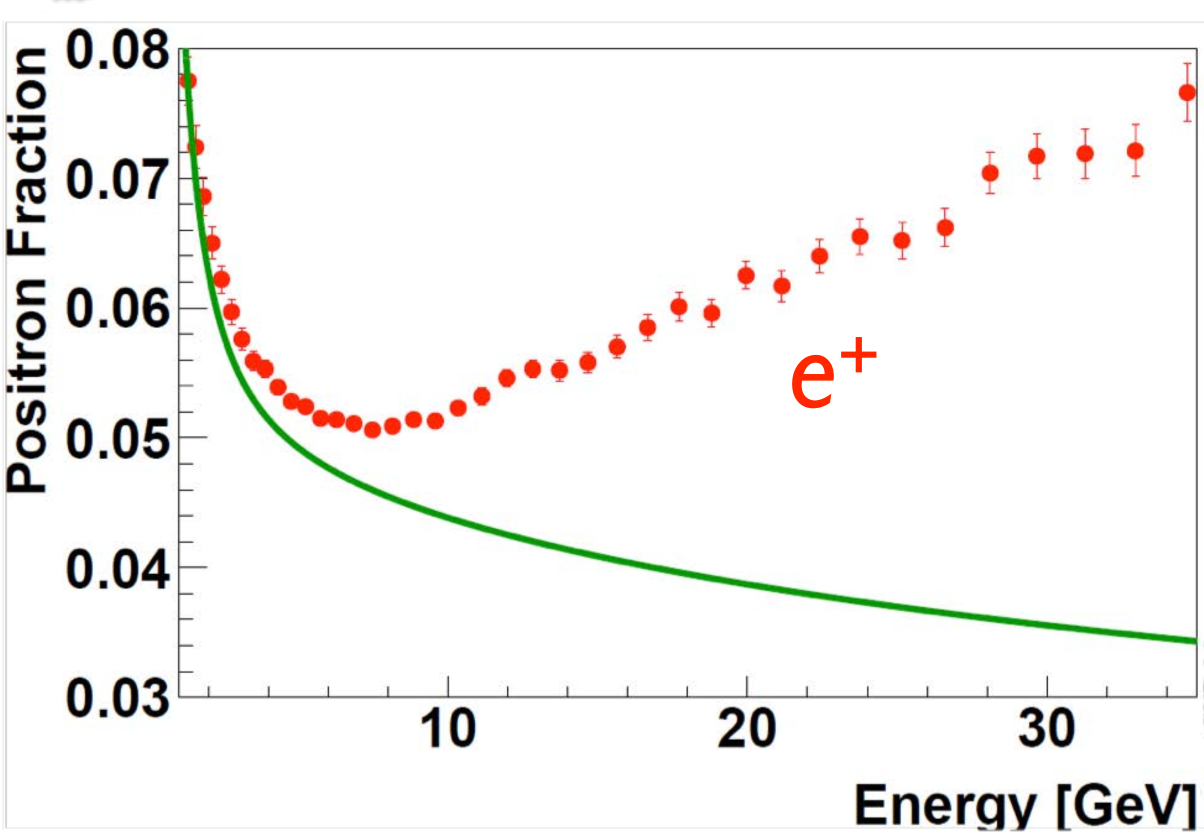
Relevant to hierarchy problem?

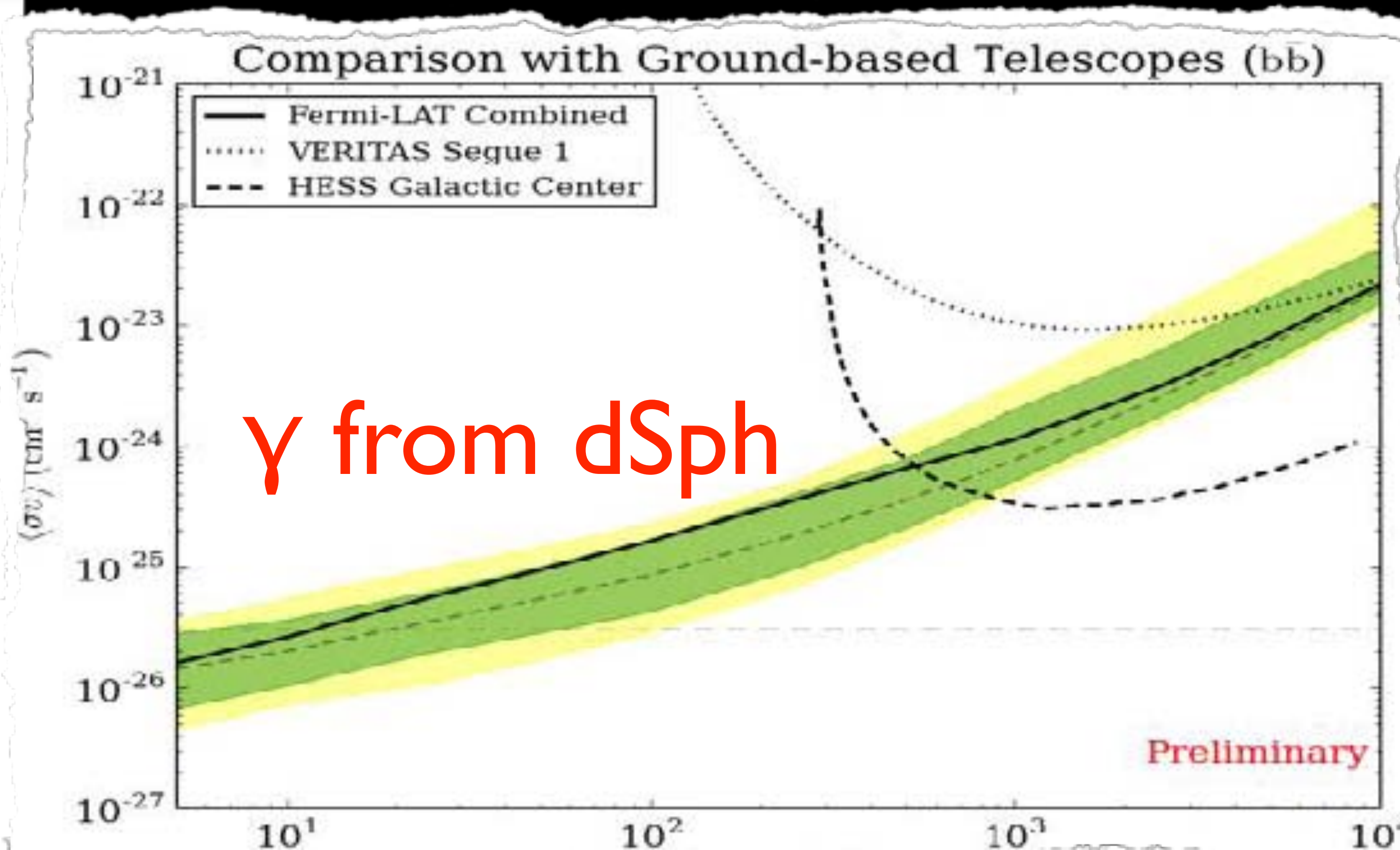
"weak" coupling
"weak" mass scale ⇒ correct abundance

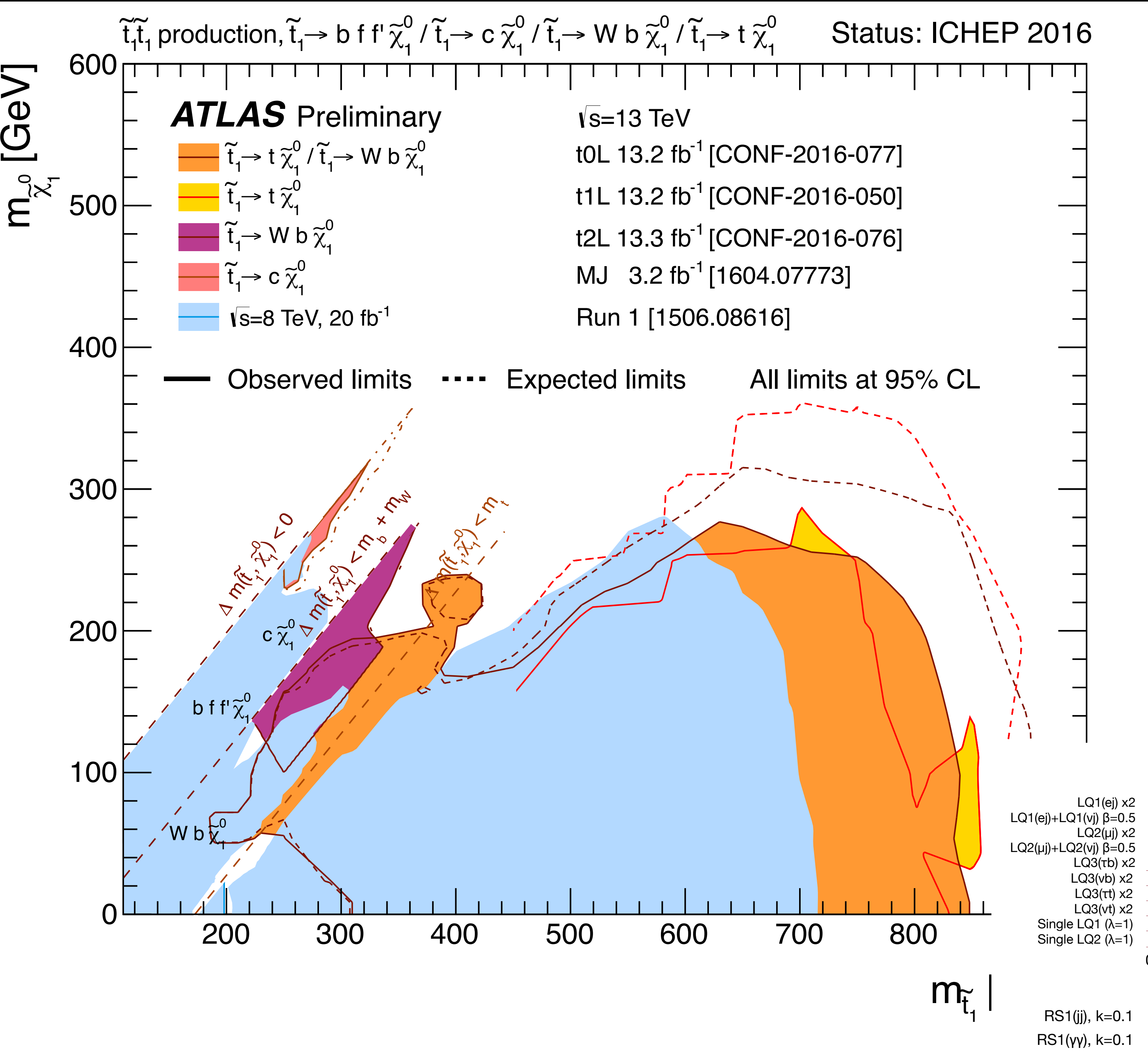
Miracle^2

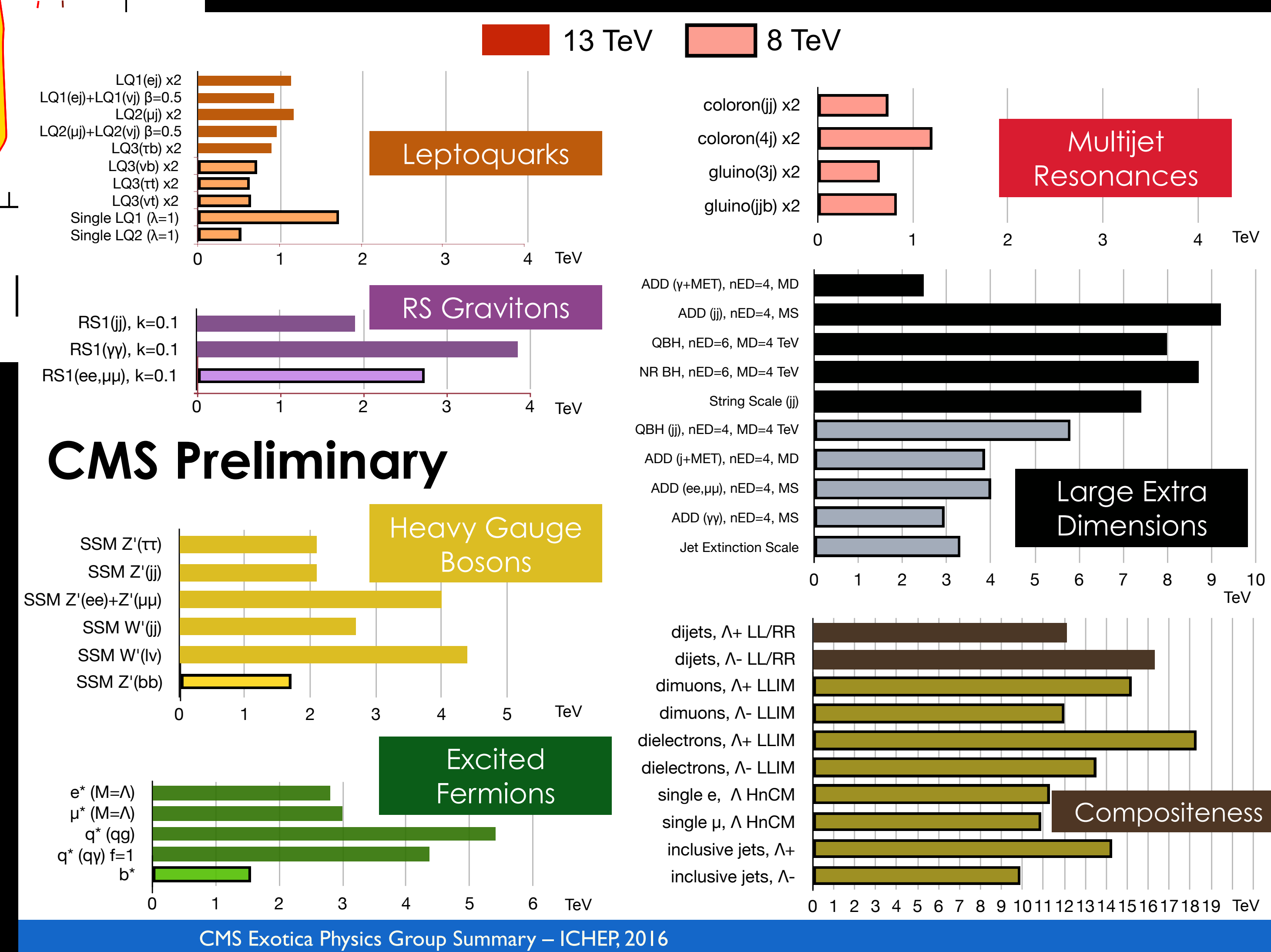

direct detection
XENON1t
WIMP-nucleon cross section [cm²]
WIMP Mass [GeV/c²]
CoGeNT (2012)
CDMS Si (2013)
COUPP (2012)
ZEPLIN-III (2012)
CDMS II Ge (2009)
EDELWEISS (2011)
Xenon100 (2012)
SuperCDMS Soudan
LUX (2013)
DarkSide 50
LUX 300-day
PICO250-CF3I
DEAP3600
SuperCDMS SNOLAB
Xenon1T
DarkSide G2
LZ
CRESST
PICO250-C3F8
CDMSlite (2013)
XENON 10 S2 (2013)
CDMS-II Ge Low Threshold (2011)
⁷Be Neutrinos
⁸B Neutrinos
NEUTRINO COHERENT SCATTERING
Atmospheric and DSNB Neutrinos


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


e⁺
Positron Fraction
Energy [GeV]


γ from dSph
Comparison with Ground-based Telescopes (bb̄)
Fermi-LAT Combined
VERITAS Segue 1
HESS Galactic Center
Preliminary





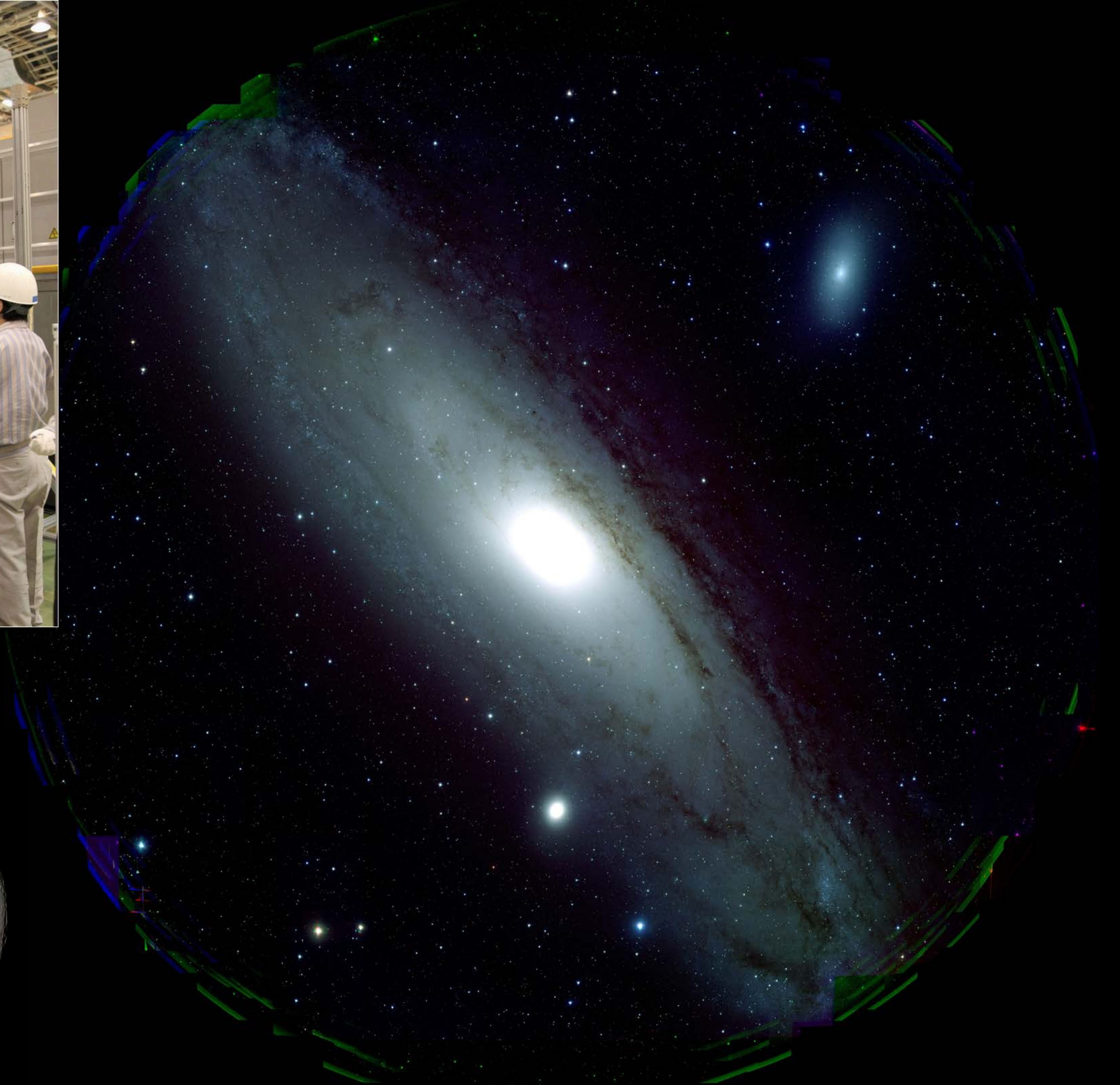
no sign of
new physics
at TeV scale

recent thinking

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

What do we know about Dark Matter?

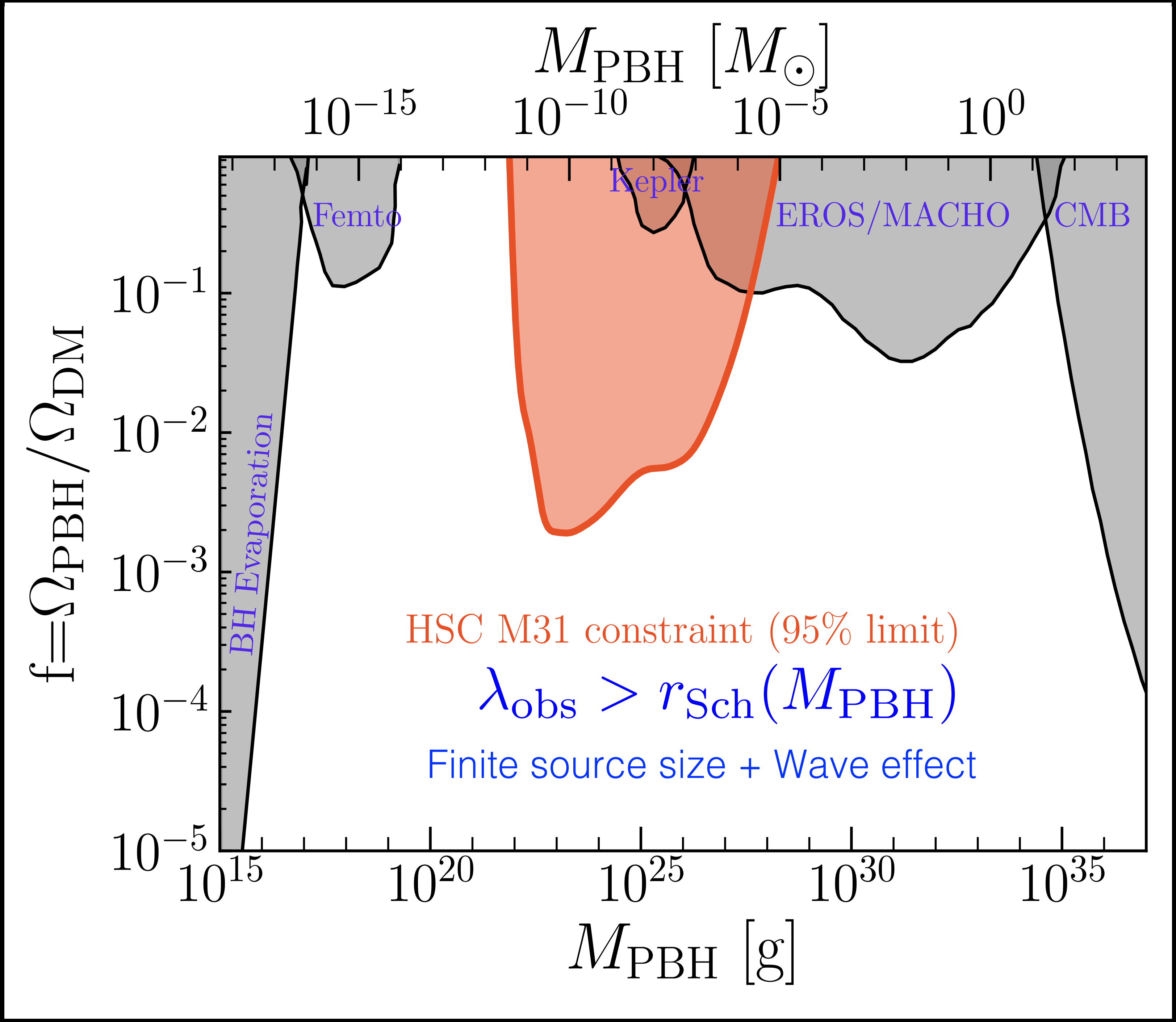
1.8 sq. deg.
870M pixels

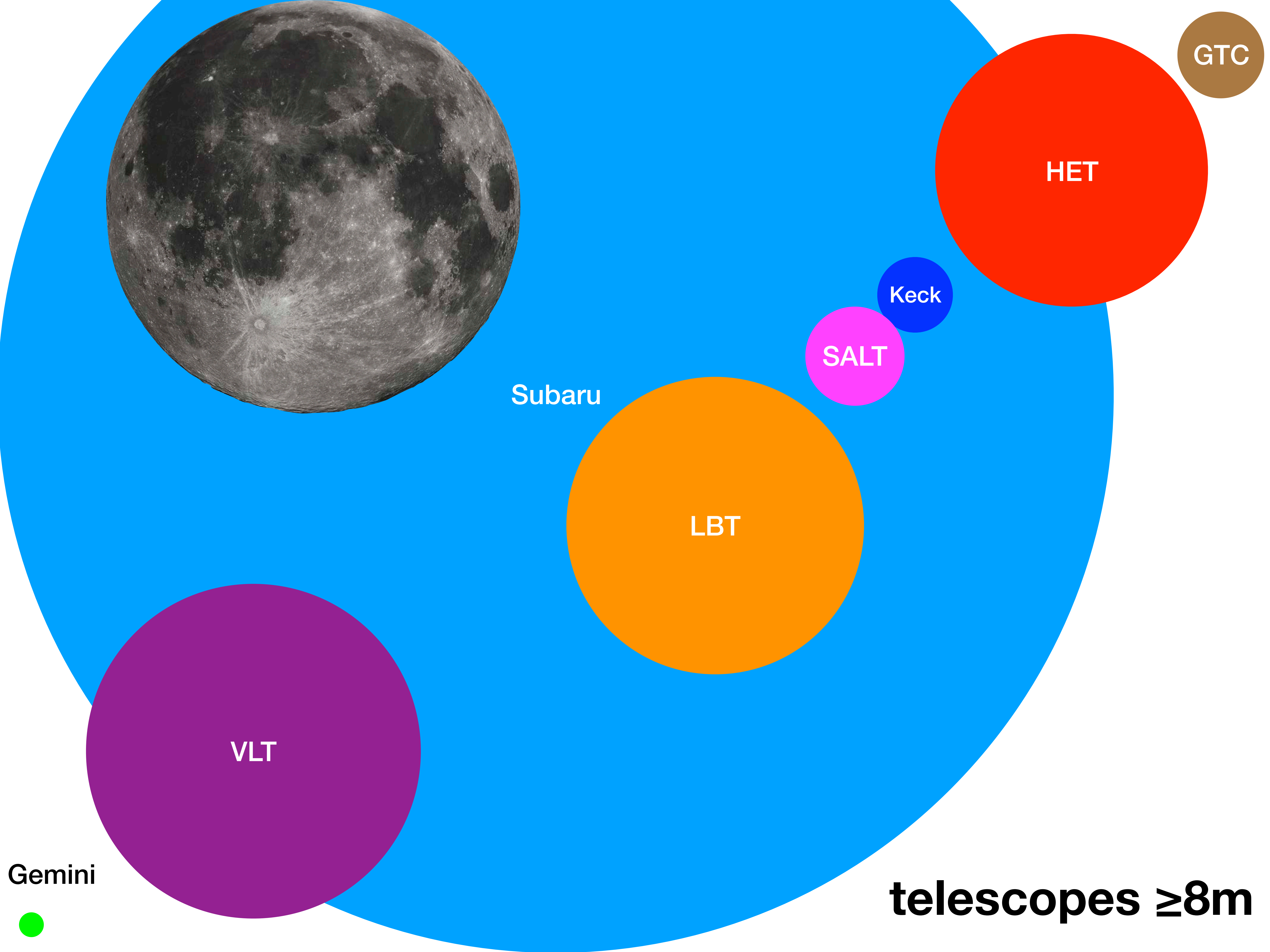


Best limit on Black Hole dark matter

Niikura, Takada et al. arXiv:1701.02151

Reading out every 2 minutes of HSC obs. of M31 to look for microlensing (just *one* night in Nov, 2015)

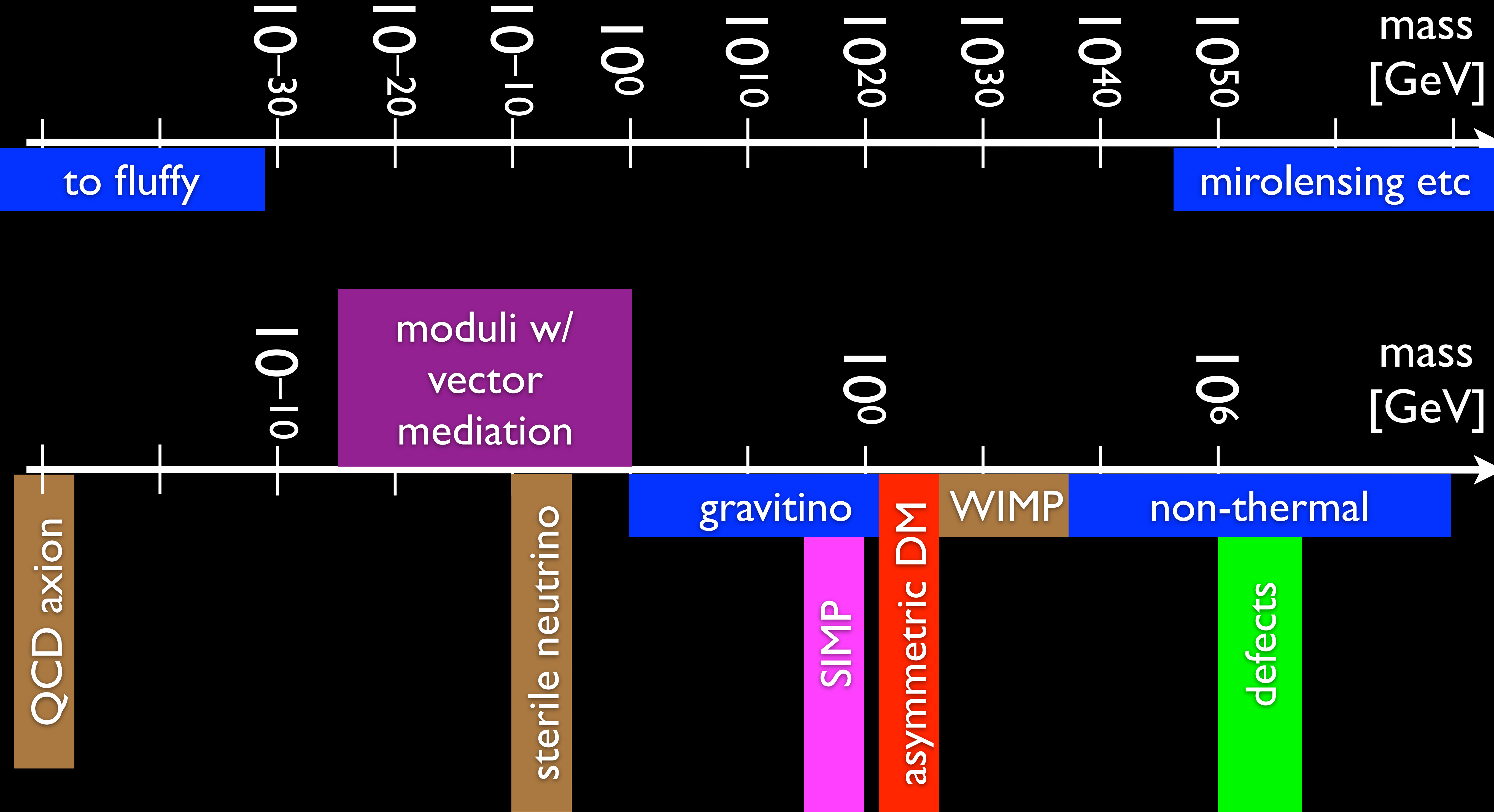




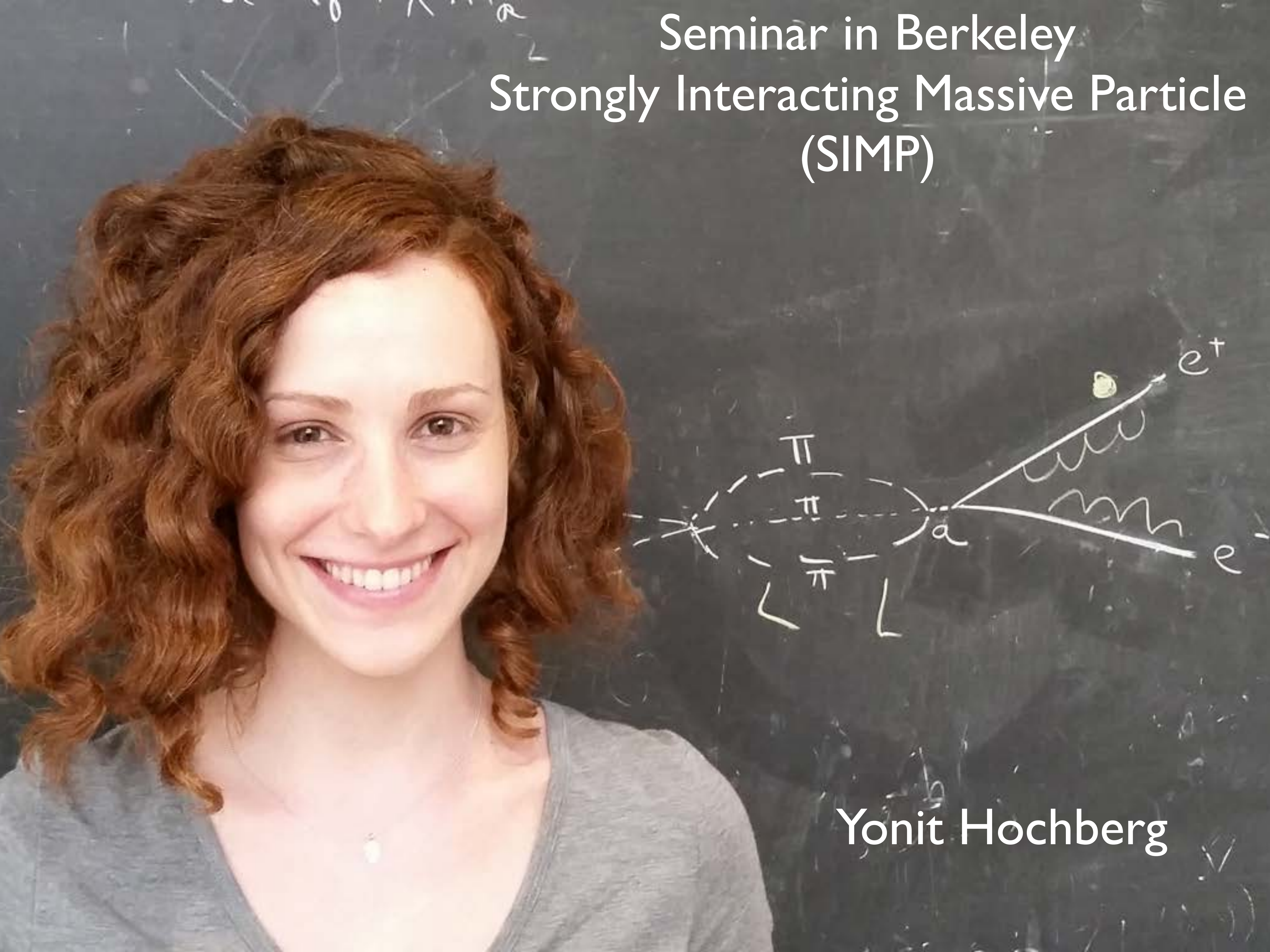
GTC
HET
Keck
SALT
Subaru
LBT
VLT
Gemini
telescopes ≥8m

Mass Limits
"Uncertainty Principle"

- Clumps to form structure
- imagine $V = G_N \frac{Mm}{r}$
- "Bohr radius": $r_B = \frac{\hbar^2}{G_N M m^2}$
- too small m ⇒ won't "fit" in a galaxy!
- $m > 10^{-22}$ eV "uncertainty principle" bound
  (modified from Hu, Barkana, Gruzinov, astro-ph/0003365)


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

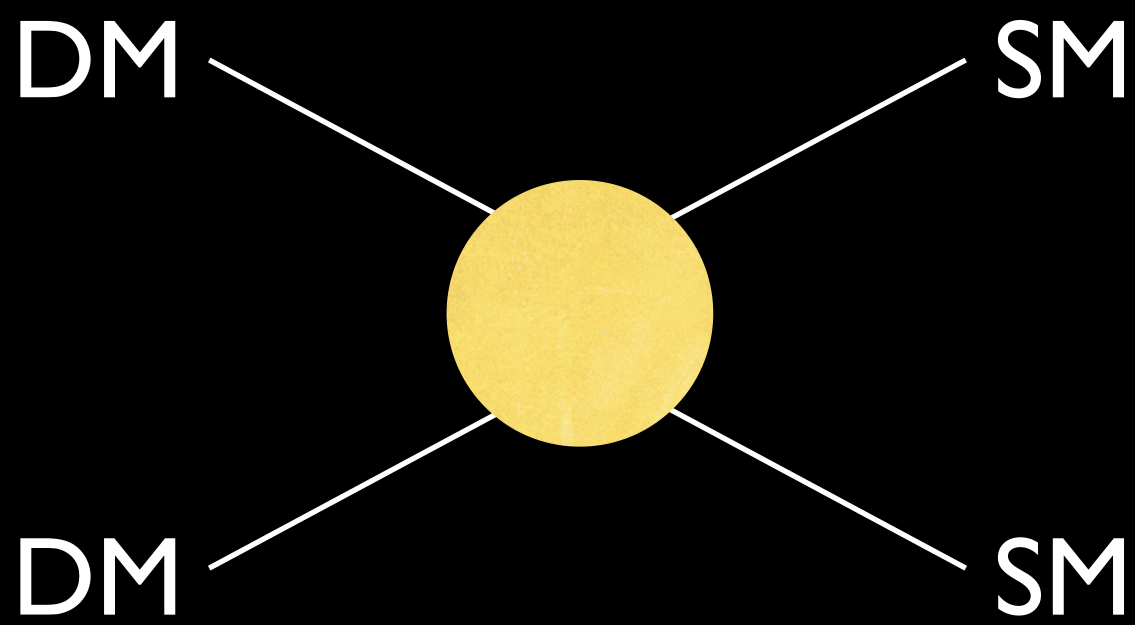
Seminar in Berkeley
Strongly Interacting Massive Particle
(SIMP)



Yonit Hochberg

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

Miracles

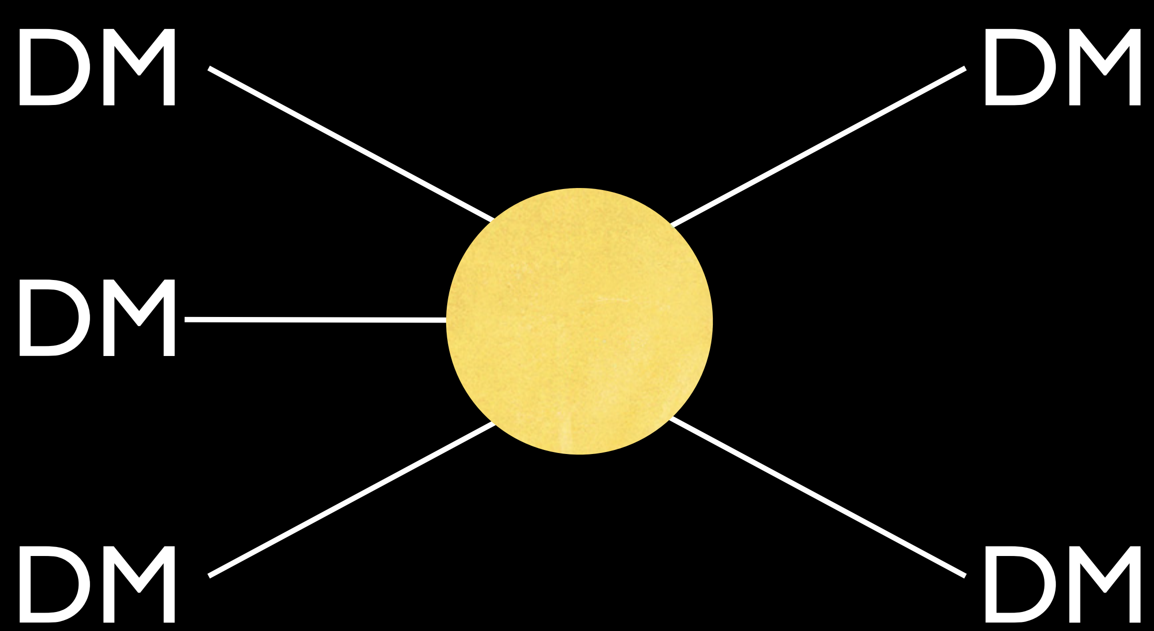


$$\langle \sigma_{2\to 2} v \rangle \approx \frac{\alpha^2}{m^2}$$

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

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

WIMP miracle!



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

$$\alpha \approx 4\pi$$

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

Hochberg, Kuflik, Volansky, Wacker arXiv:1402.5143

SIMP miracle!

3→2 ~~LEE WEINBERG~~ FREEZE-OUT

Back of the envelope calculation

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

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

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

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

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

$$n_b \sim \eta_b s$$

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

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

Eric Kuflik

THE SIMP MIRACLE

A coincidence of scales

$$m_{\rm dm} \simeq \alpha \left(T_{\rm eq}^2 M_{\rm pl}/x_F^4\right)^{\frac{1}{3}}$$

$$m_{\rm dm} \simeq \alpha \times 100 \text{ MeV}$$

- If $\alpha \sim 1$, the strong scale emerges $(x_F \sim 20)$
- Like the WIMP, no input of scales or particle physics

Eric Kuflik

Strongly interacting sub-GeV dark matter

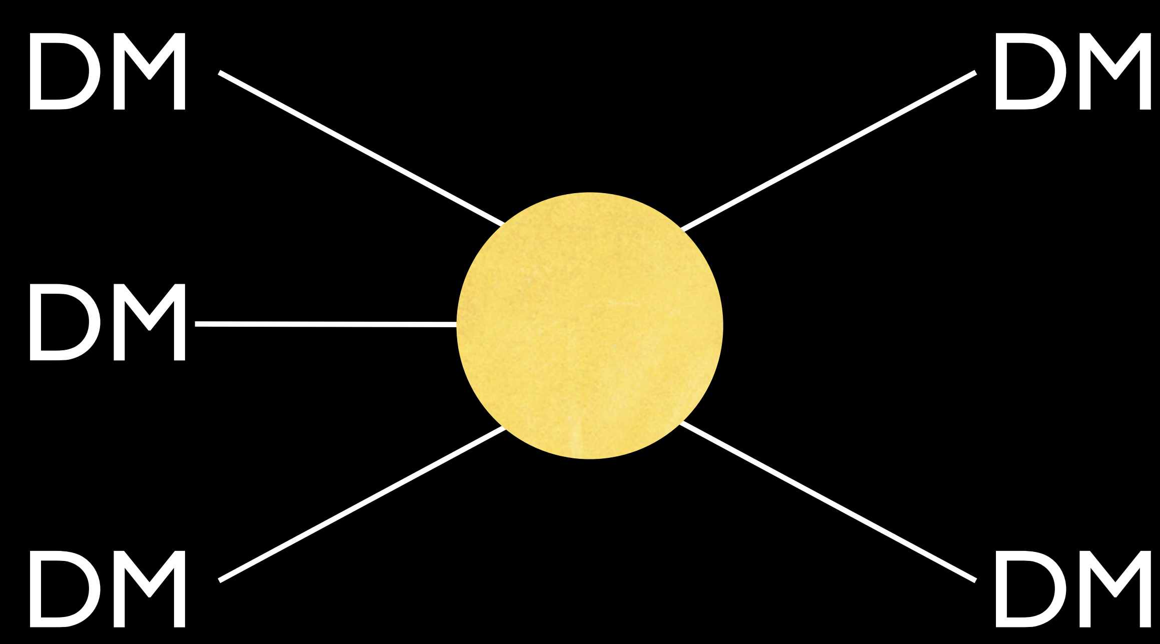
But not UV complete; coupling blows up very quickly

Dark Pions

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

SIMPlest Miracle

- Not only the mass scale is similar to QCD
- dynamics itself can be QCD! Miracle[3]
- DM = pions = $q\bar{q}$
- e.g. SU(4)/Sp(4) = S[5]



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

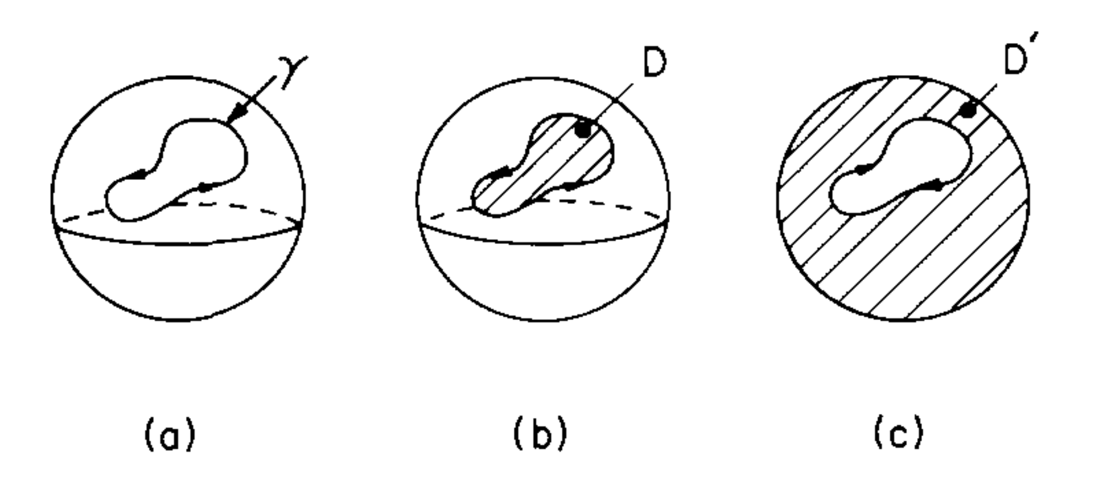
+HM
arXiv:1411.3727

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

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

Wess-Zumino term

- $\mathcal{L}_{WZ} \sim \varepsilon_{abcde}\, \varepsilon^{\mu\nu\rho\sigma}\, \pi^a \partial_\mu \pi^b \partial_\nu \pi^c \partial_\rho \pi^d \partial_\sigma \pi^e$
- SU(N_c) gauge theory
  - $\pi_5(SU(N_f))=\mathbb{Z}$ ($N_f \geq 3$)
- Sp(N_c) gauge theory
  - $\pi_5(SU(2N_f)/Sp(N_f))=\mathbb{Z}$ ($N_f \geq 2$)
- SO(N_c) gauge theory
  - $\pi_5(SU(N_f)/SO(N_f))=\mathbb{Z}$ ($N_f \geq 3$)



Witten

also, non-abelian vector bosons (vector SIMP)
+S-M Choi, HM Lee, Y. Mambrini, M. Pierre, arXiv:1707.01434

SIMPlest Miracle

$$\begin{pmatrix} u_1 \\ d_1 \end{pmatrix} \begin{pmatrix} u_2 \\ d_2 \end{pmatrix} \begin{pmatrix} u_3 \\ d_3 \end{pmatrix} \begin{pmatrix} u_4 \\ d_4 \end{pmatrix}$$

- SU(2) gauge theory with four doublets
- SU(4)=SO(6) flavor symmetry
- $\langle q^i q^j \rangle \neq 0$ breaks it to Sp(2)=SO(5)
- coset space SO(6)/SO(5)=S^5, 5 pions
- $\pi_5(S^5)=\mathbb{Z} \Rightarrow$ Wess-Zumino term
- $\mathcal{L}_{WZ}=\varepsilon_{abcde}\, \varepsilon^{\mu\nu\rho\sigma}\, \pi^a \partial_\mu \pi^b \partial_\nu \pi^c \partial_\rho \pi^d \partial_\sigma \pi^e$

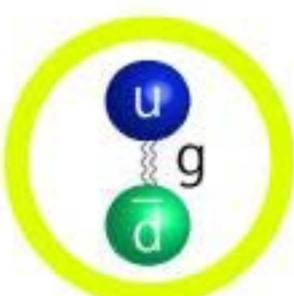
LAGRANGIANS

Quark theory

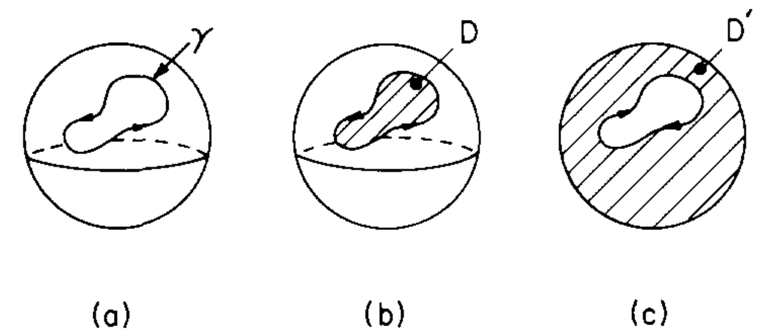
$$\mathcal{L}_{\text{quark}} = -\frac{1}{4}F^a_{\mu\nu}F^{\mu\nu a} + \bar{q}_i i\not{D} q_i \; -\frac{1}{2}m_Q \; J^{ij}q_i q_j + h.c.$$

Sigma theory

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

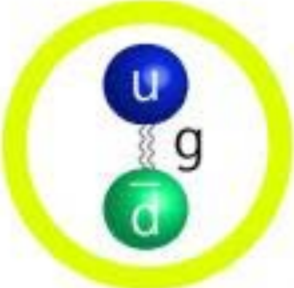


Pion theory

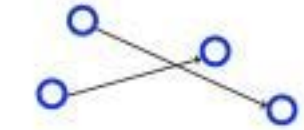


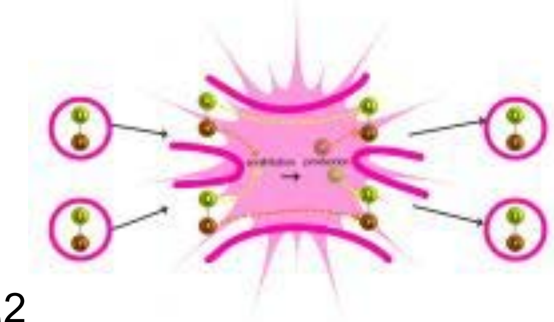
$$\mathcal{L}_{\text{pion}} = \frac{1}{4}\text{Tr}\partial_\mu\pi\partial^\mu\pi - \frac{m_\pi^2}{4}\text{Tr}\pi^2 + \frac{m_\pi^2}{12f_\pi^2}\text{Tr}\pi^4 - \frac{1}{6f_\pi^2}\text{Tr}\left(\pi^2\partial^\mu\pi\partial_\mu\pi - \pi\partial^\mu\pi\pi\partial_\mu\pi\right)$$

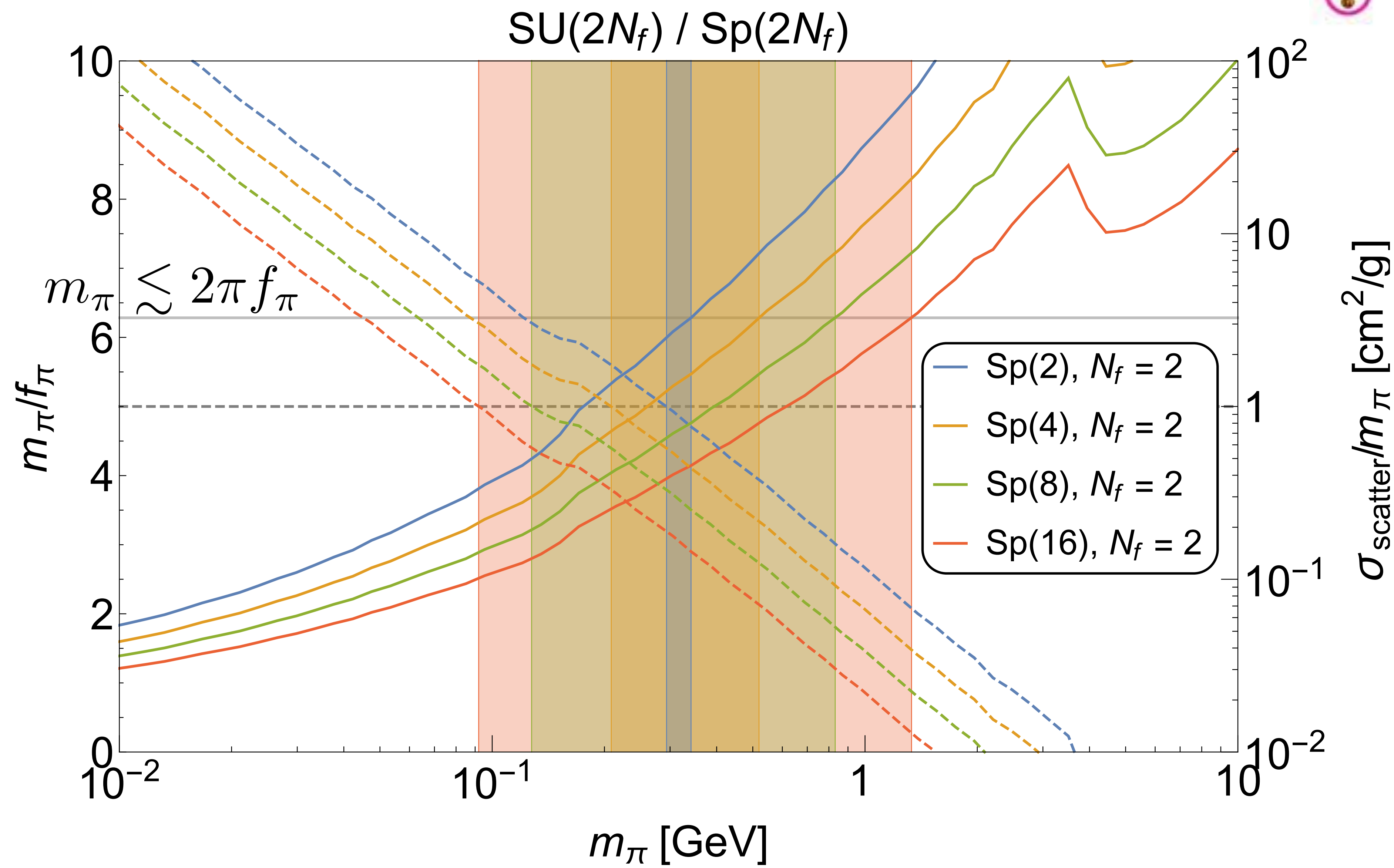
$$+ \frac{2N_c}{15\pi^2 f_\pi^5}\epsilon^{\mu\nu\rho\sigma}\text{Tr}\left[\pi\partial_\mu\pi\partial_\nu\pi\partial_\rho\pi\partial_\sigma\pi\right] + \mathcal{O}(\pi^6)$$



The Results







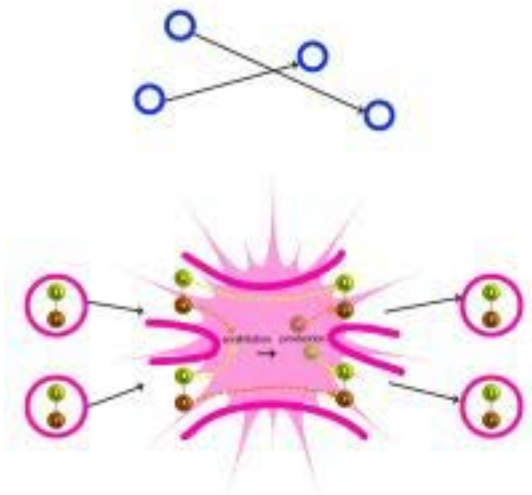
Solid curves: solution to Boltzmann eq.

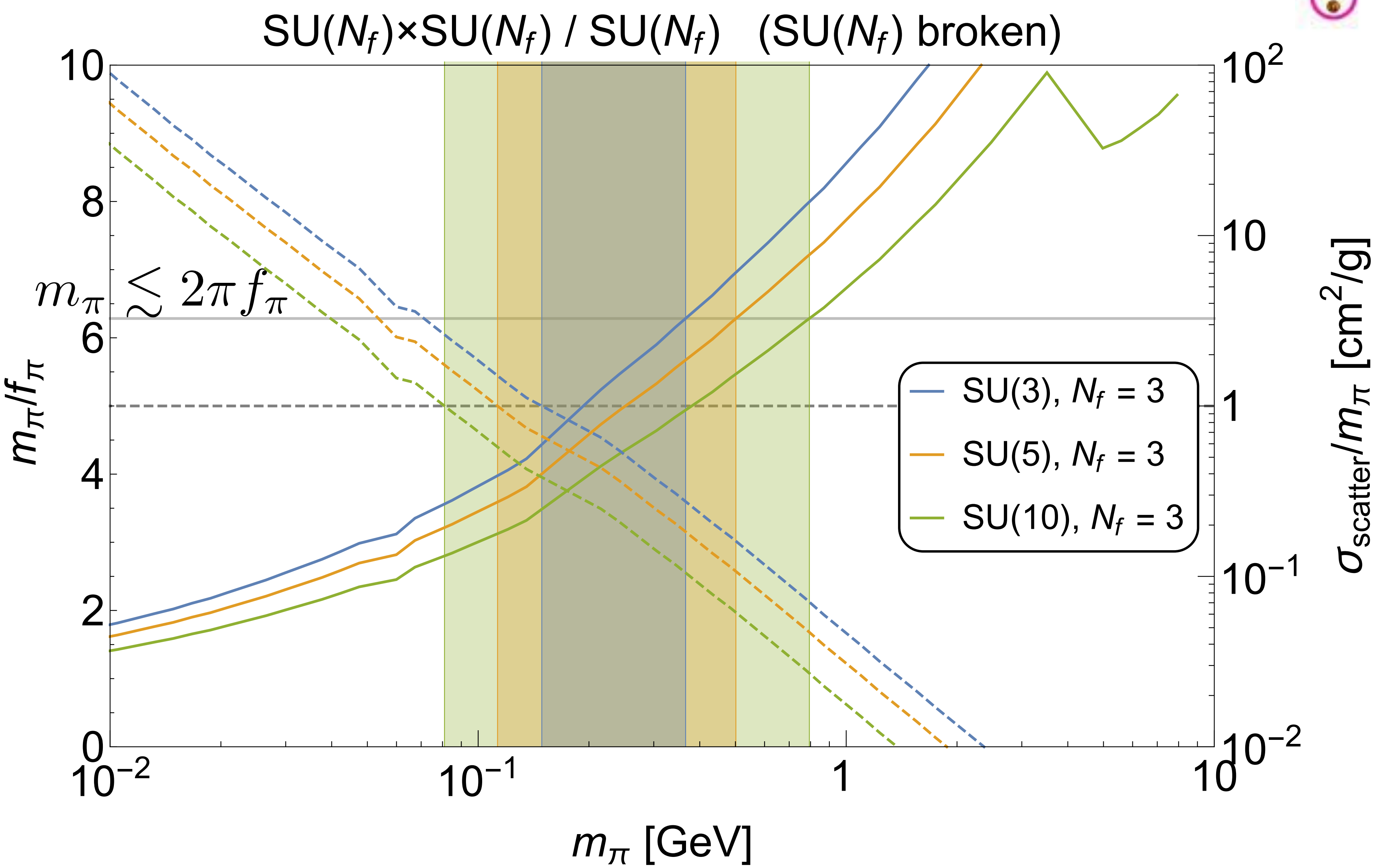
Dashed curves: along that solution

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

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

The Results





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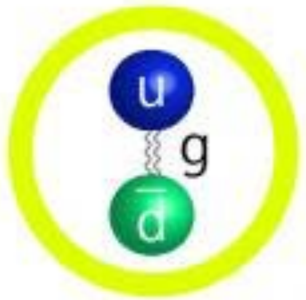

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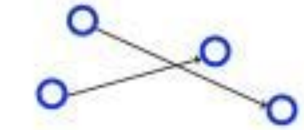

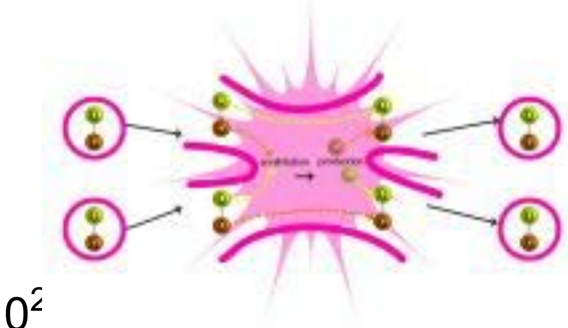

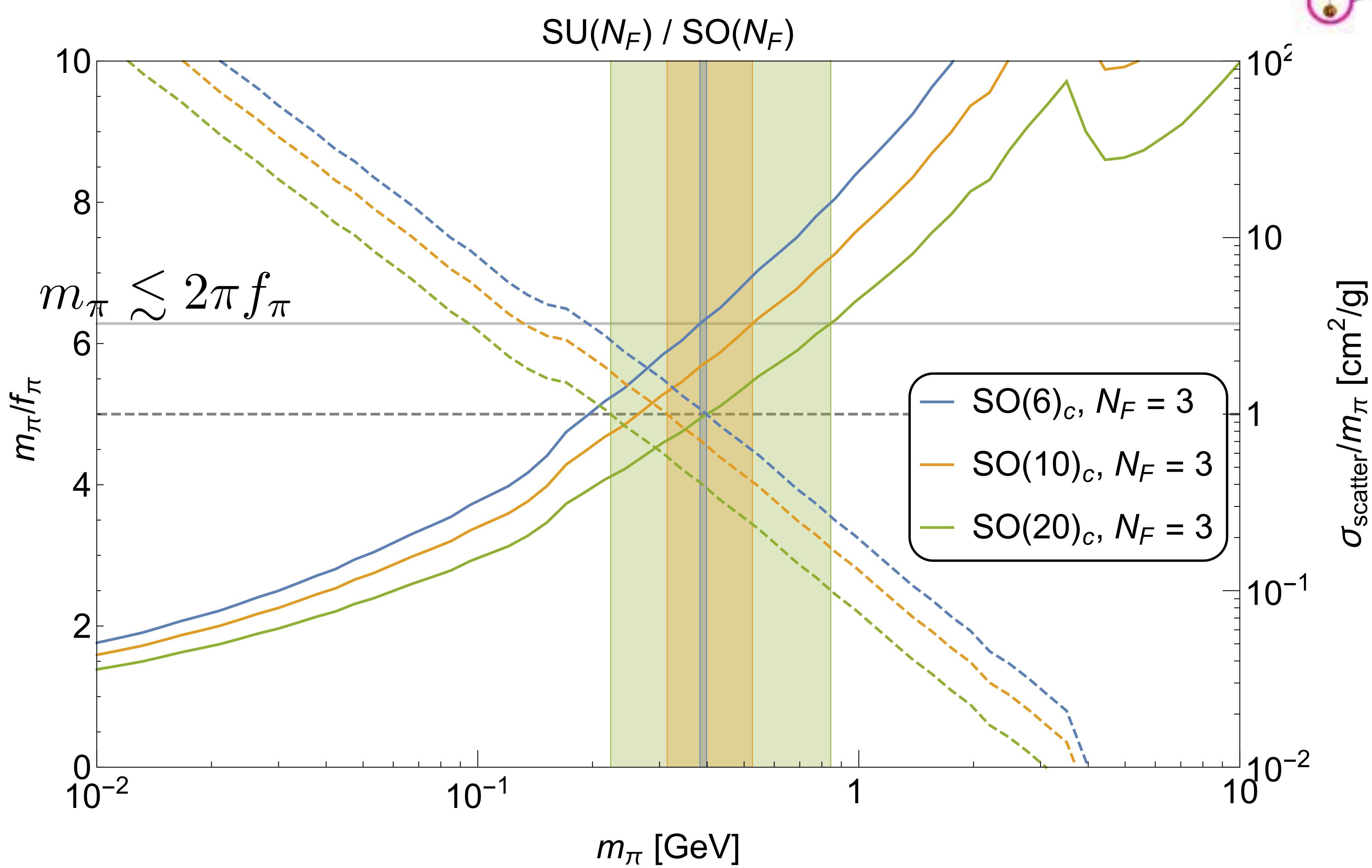

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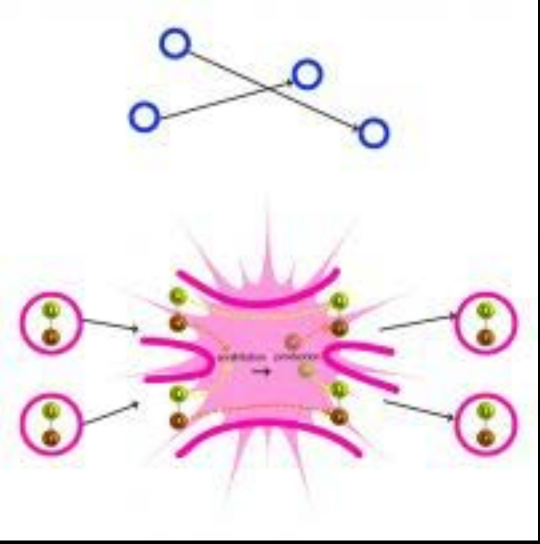
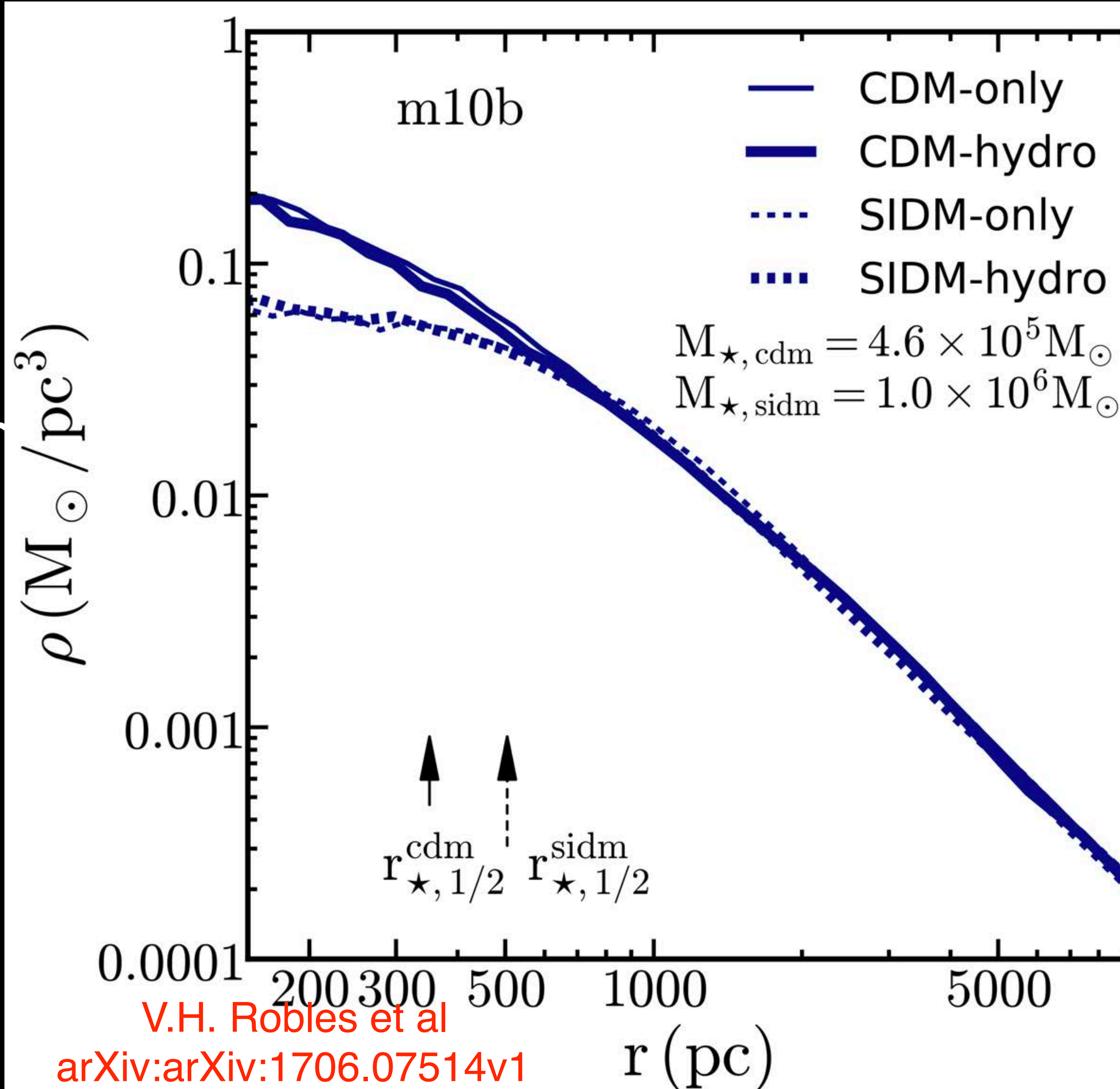
$$\frac{\sigma_{\rm scatter}}{m_\pi} \propto m_\pi^{-9/5}$$

self interaction

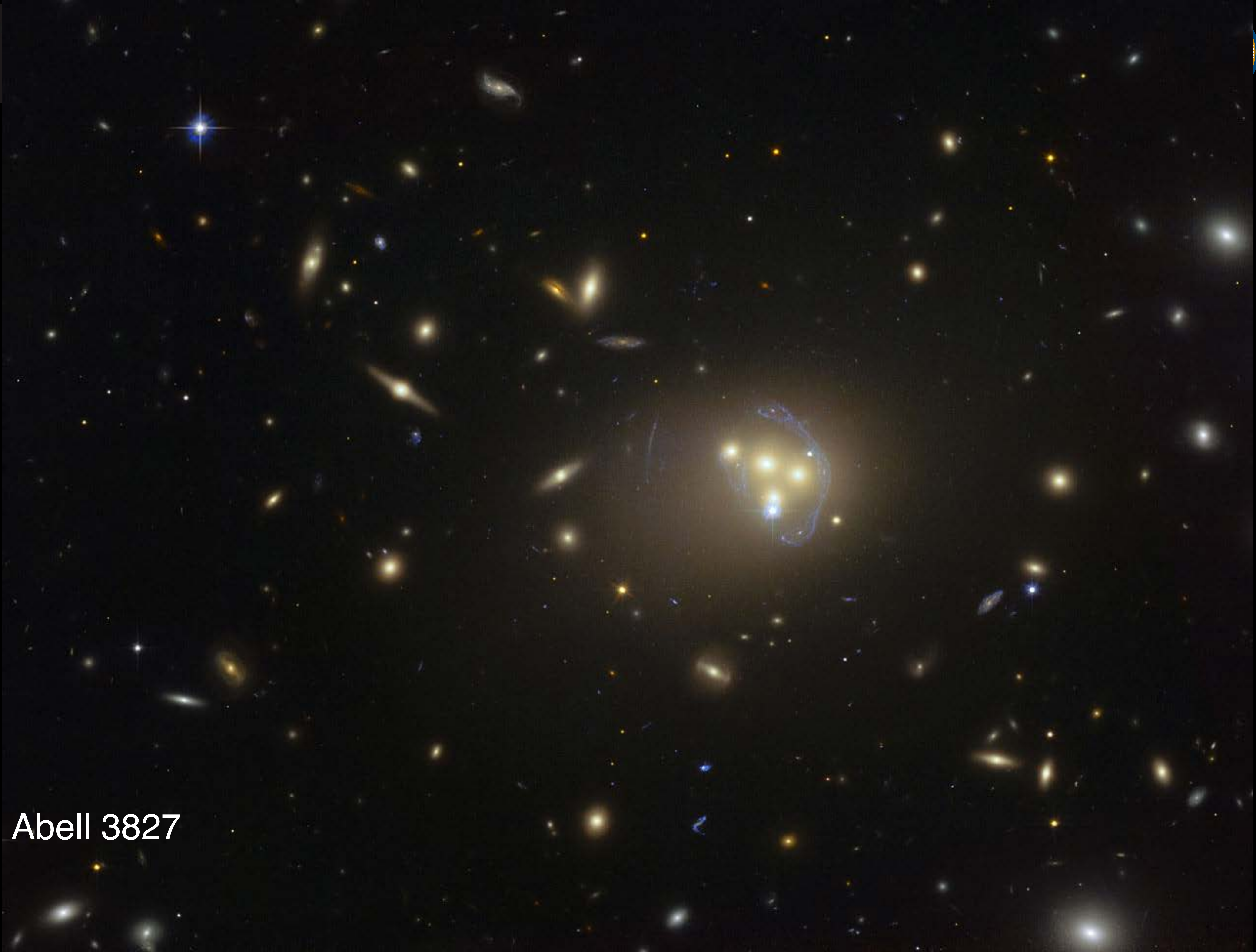


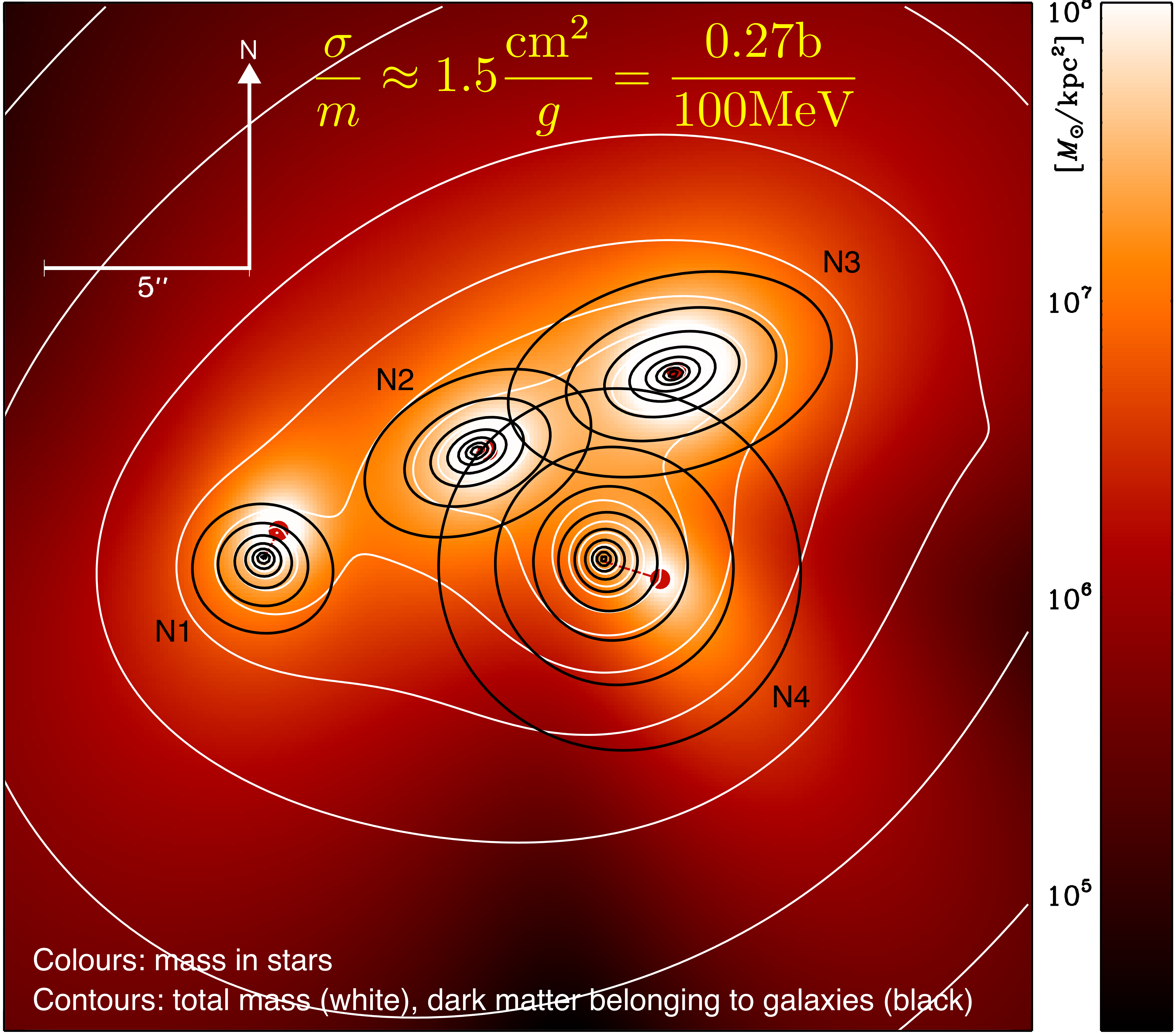
- $\sigma/m \sim \mathrm{cm}^2/g$
  $\sim 10^{-24}\mathrm{cm}^2$ / 300MeV
- flattens the cusps in NFW profile
- suppresses substructur
- actually desirable for dwarf galaxies?



V.H. Robles et al
arXiv:arXiv:1706.07514v1

SIDM
Spergel & Steinhardt (2000)
now complete theory


Abell 3827



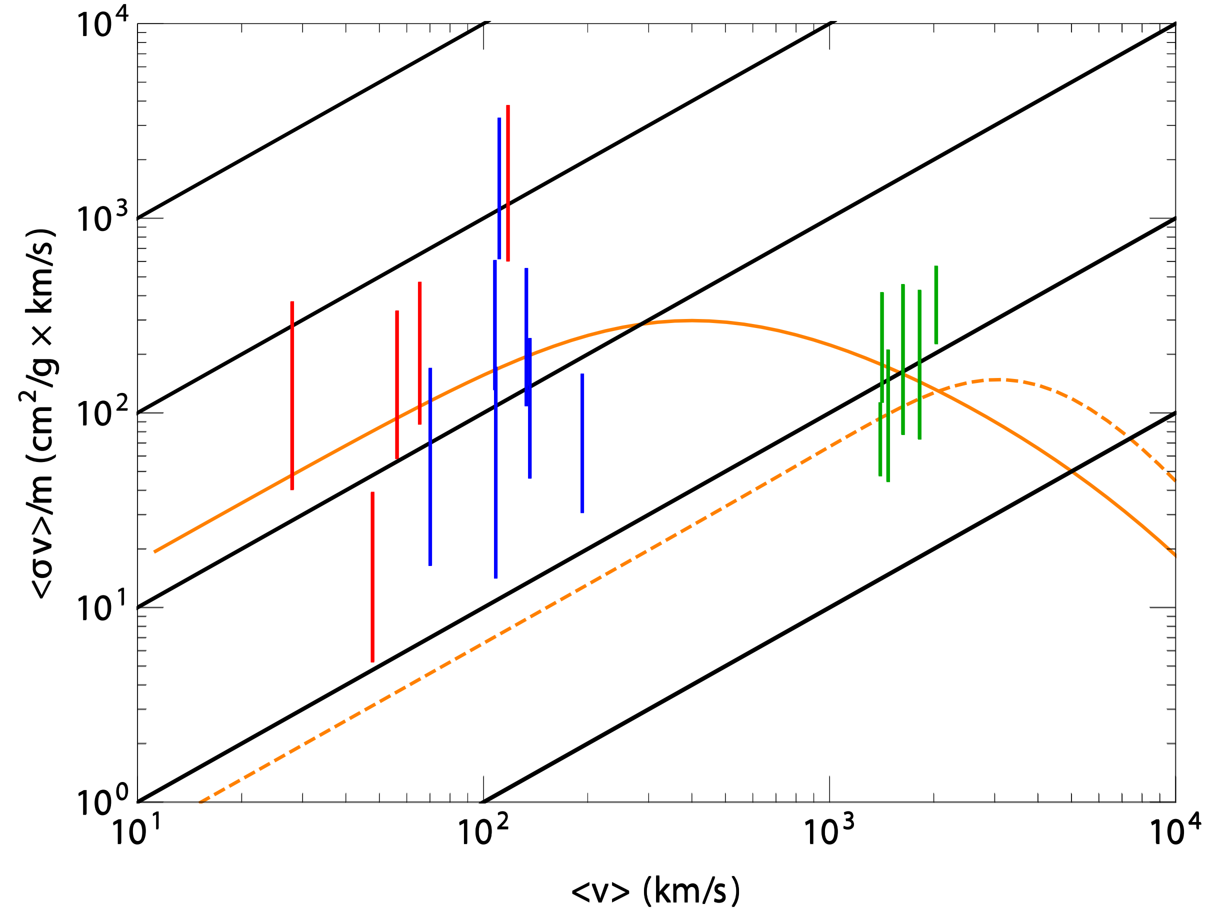
Peter Taylor et al, arXiv:1701.04412

velocity dependence?

- cluster data prefer smaller σ?
- near constant ⟨σ*v*⟩?
- Sommerfeld effect (S. Tulin, H.-B. Yu, and K.M. Zurek, arXiv:1302.3898)
  - requires light mediator
- near-threshold resonance can "fit" the data
- *i.e.*, ππ→σ→ππ
  - (Xiaoyong Chu, Camilo Garcia-Cely, Yonit Hochberg, Eric Kuik, HM)

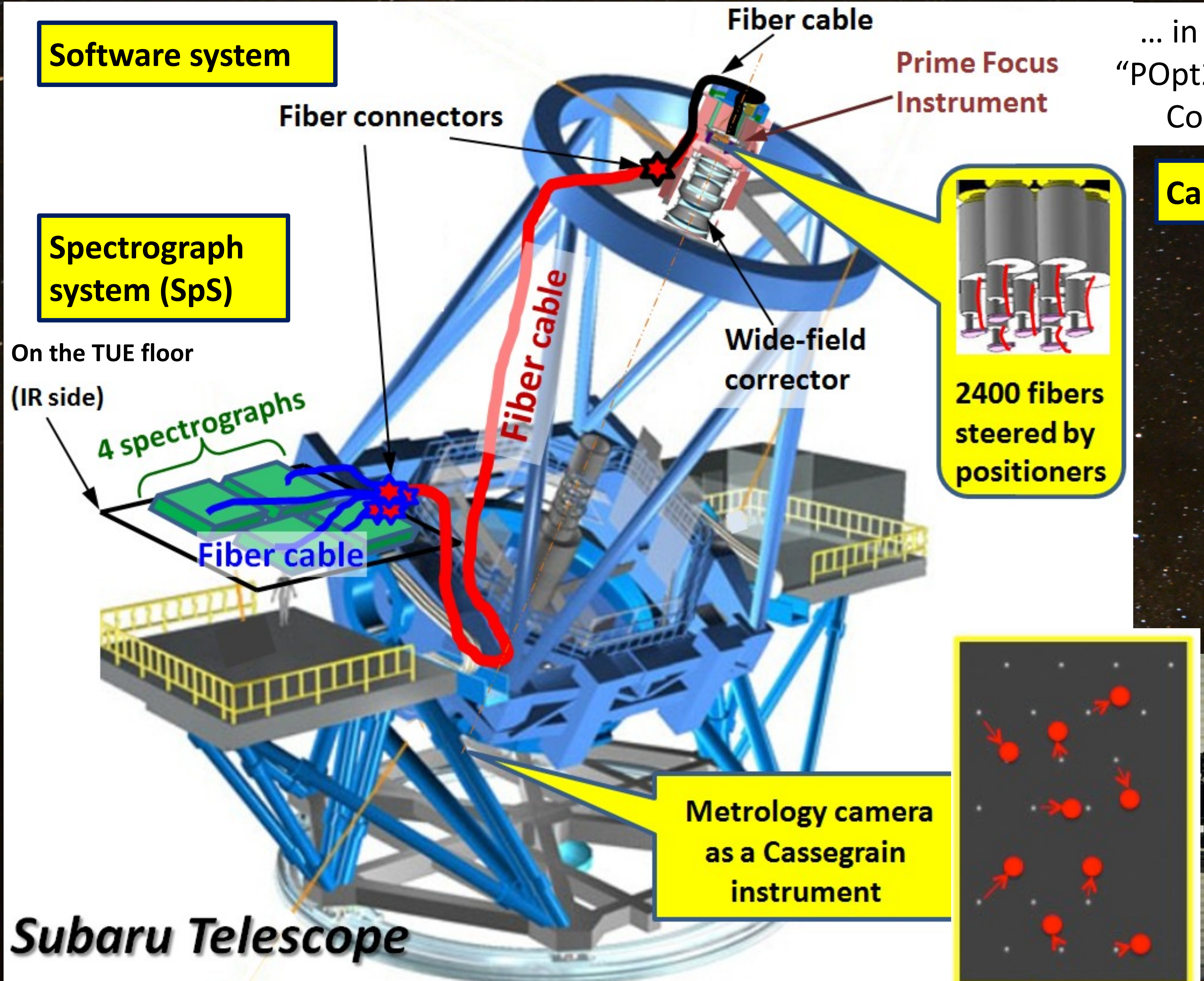
$$\mathcal{L} = m_R g \, \mathrm{RDM}^2 \, .$$

n	a	b	γ_0	v_R (km/s)	m_R (GeV)	χ^2/d.o.f.
0	24	32	$10^{-4.3}$	1829	26	2.1



M. Kaplinghat, S. Tulin, and H.-B. Yu, arXiv:1508.03339.

PFS subsystems distribution



… in Prime focus unit "POpt2" with Wide Field Corrector "WFC".

Calibration system

PFS collaboration

Caltech

Jet Propulsion Laboratory
California Institute of Technology

国立天文台 NAOJ

中央研究院 ACADEMIA SINICA 1928

CPPC

PRINCETON UNIVERSITY

Max-Planck-Institut für Astrophysik

MPE Max-Planck-Institut für extraterrestrische Physik

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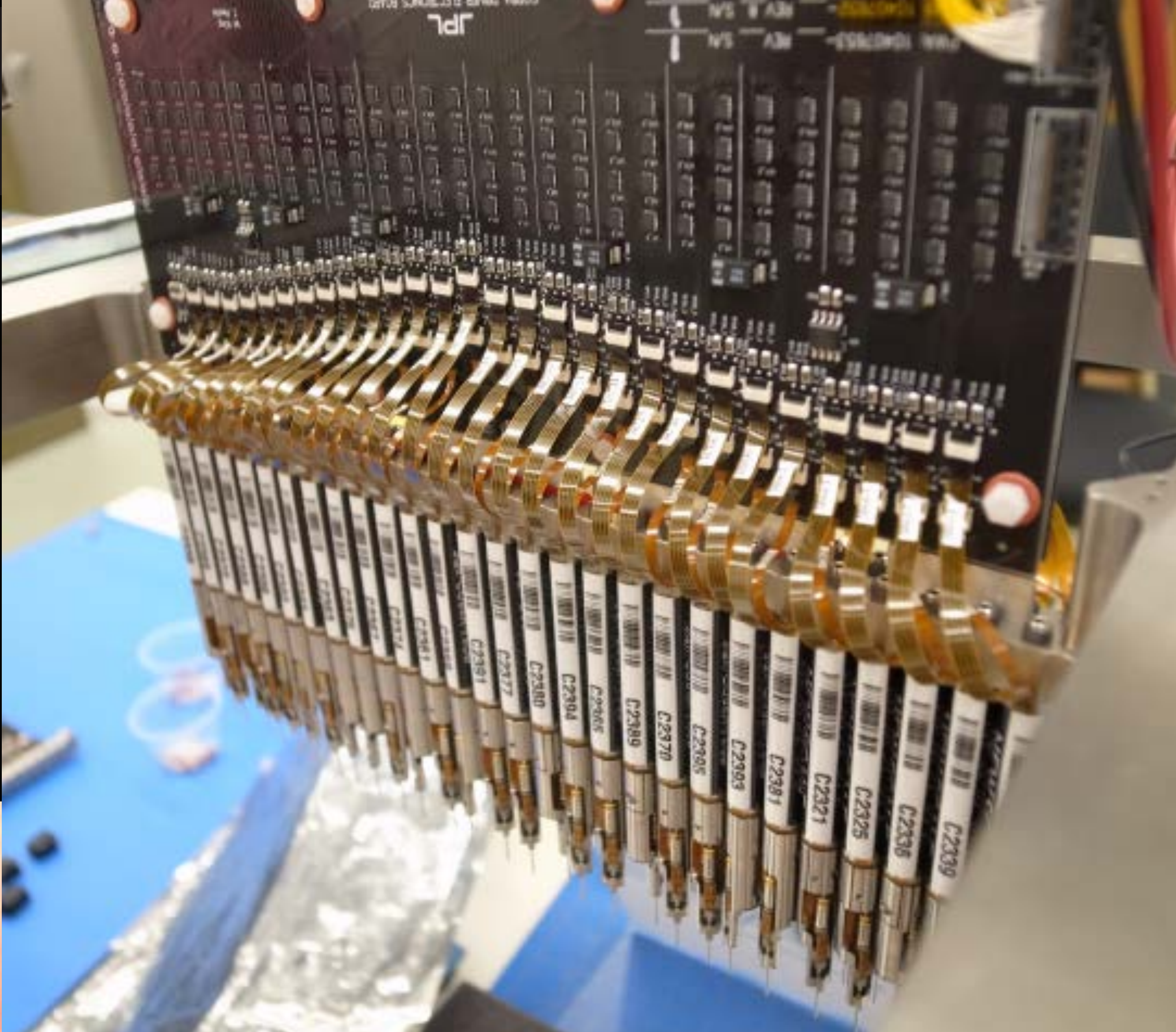
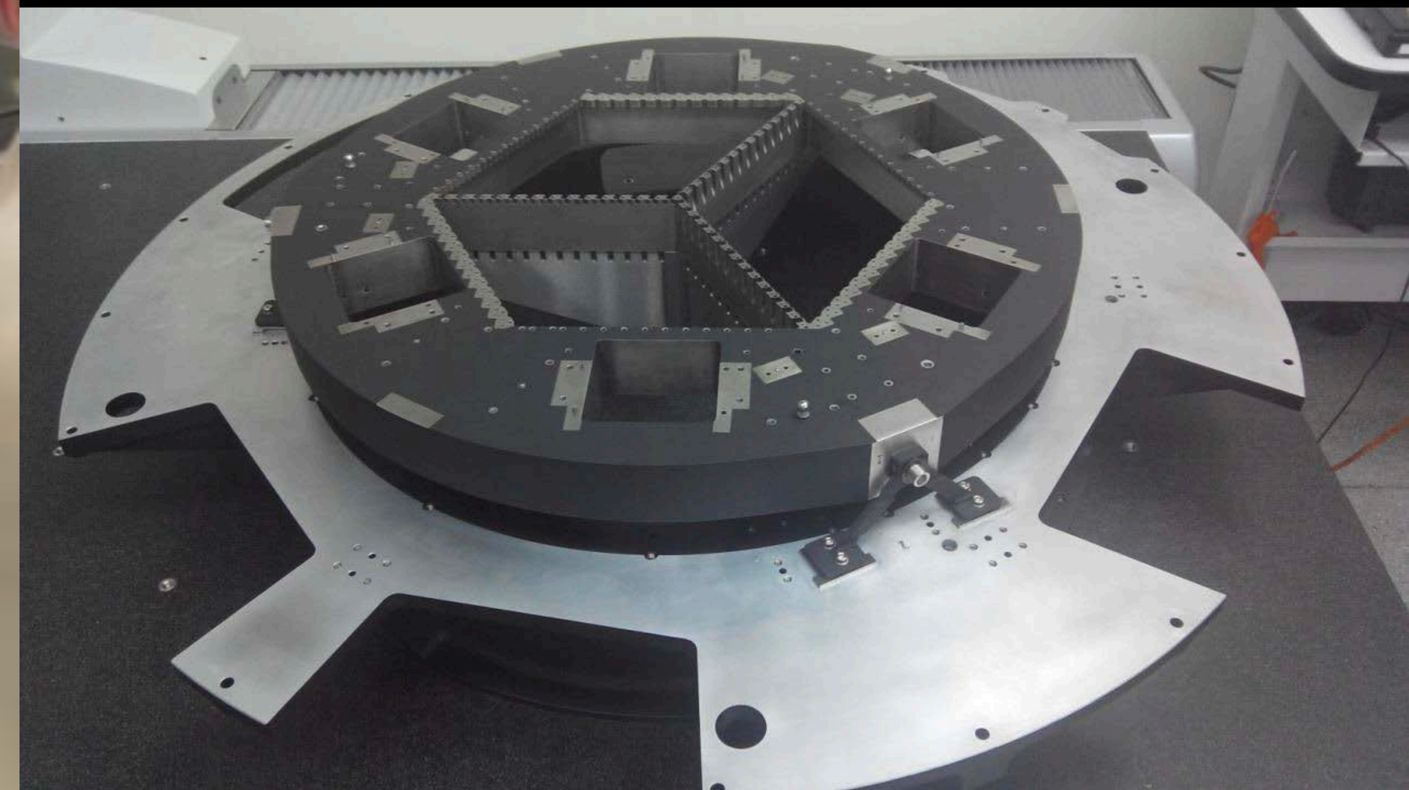
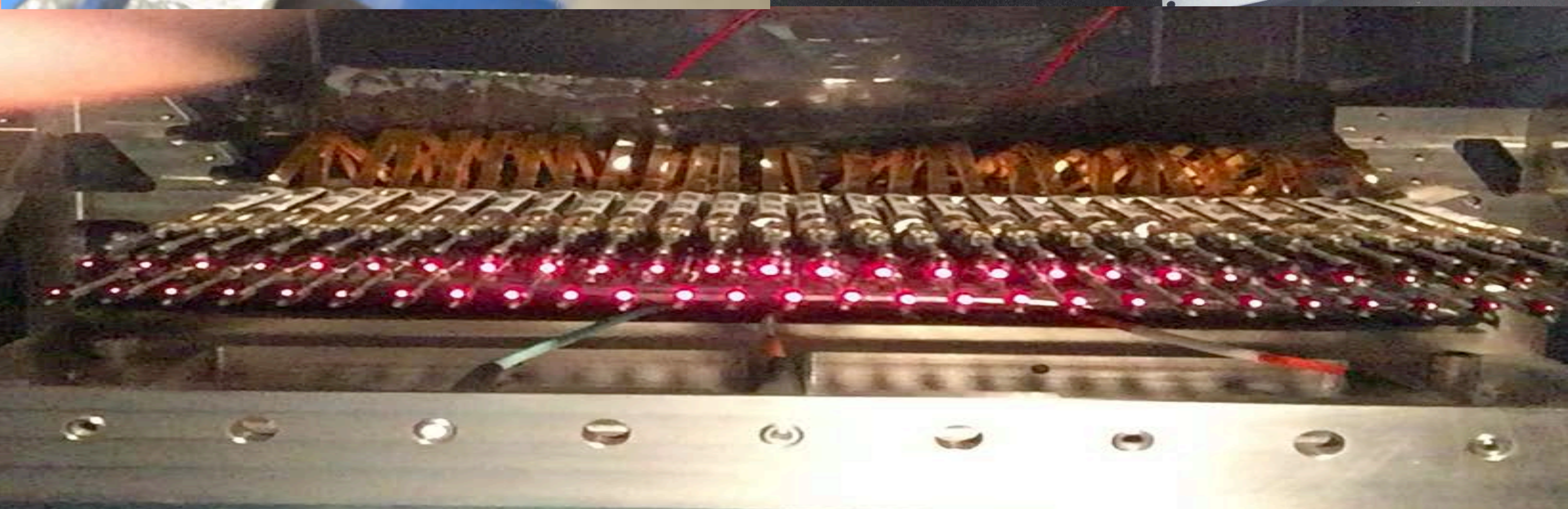


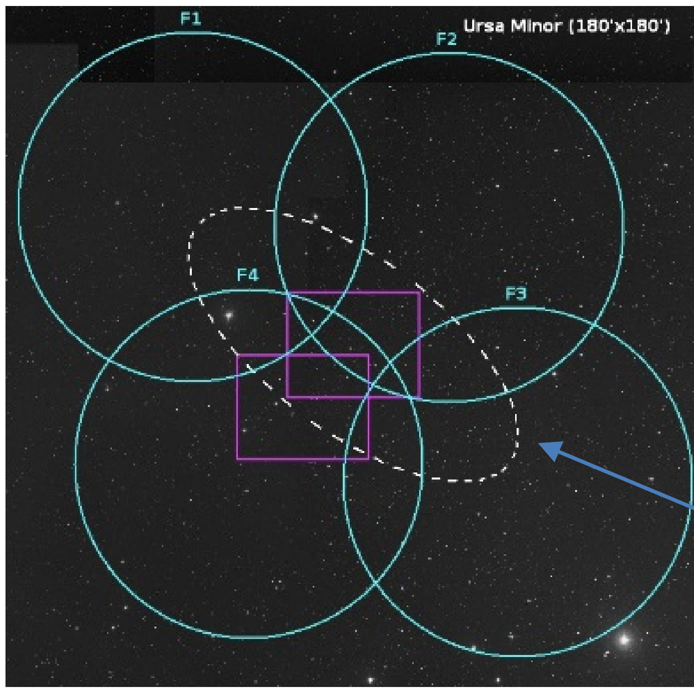




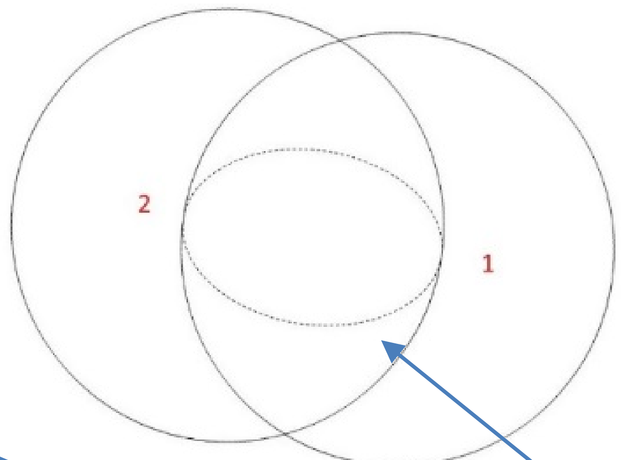
PFS pointings for MW satellites

~ HSC imaging data are available for all samples ~

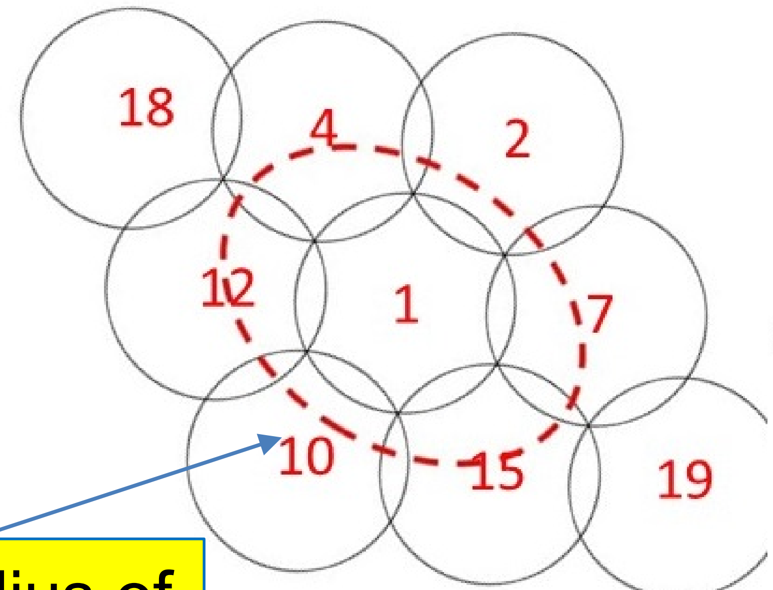
Ursa Minor



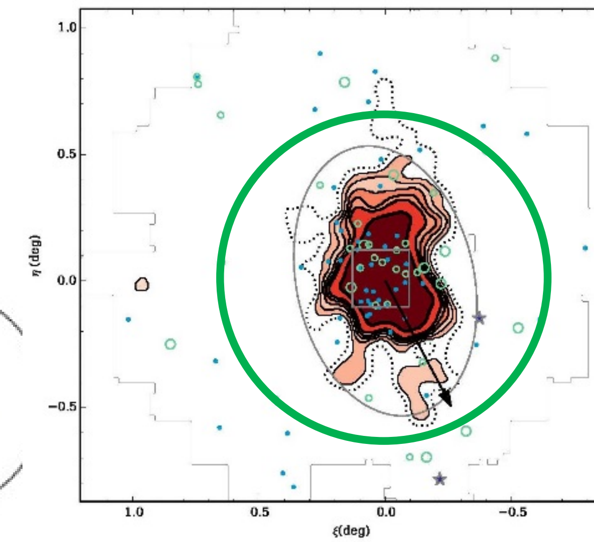
Draco



Sextans

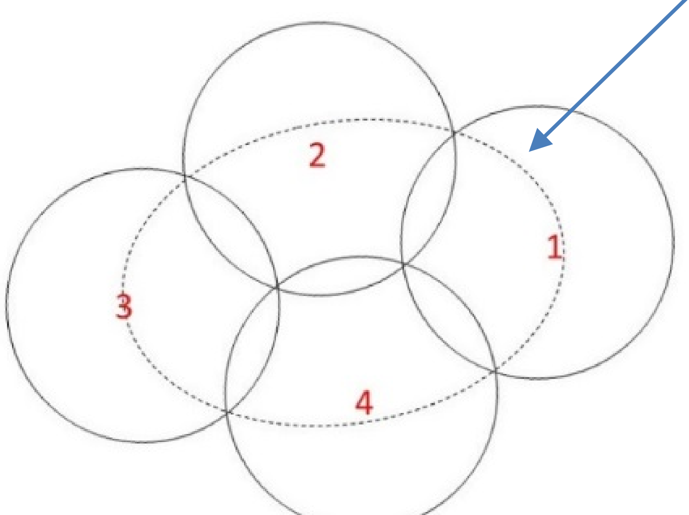


Bootes I

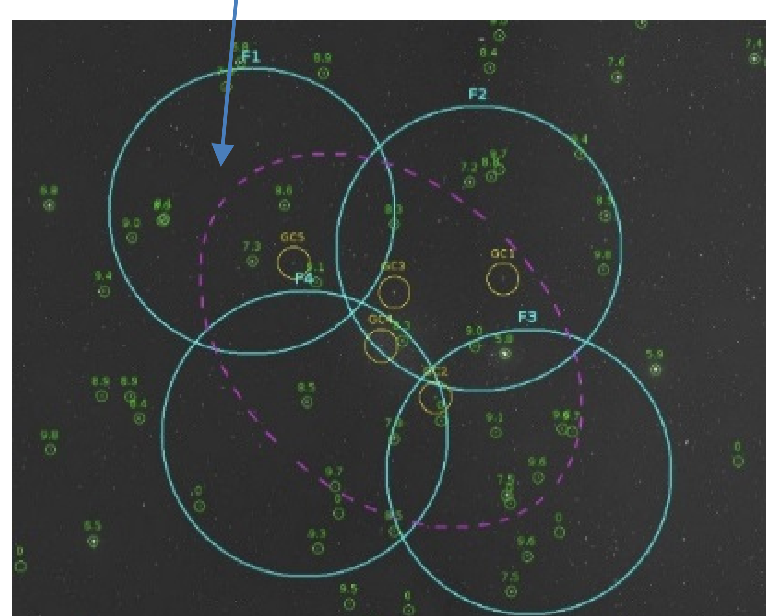


tidal radius of stellar comp.

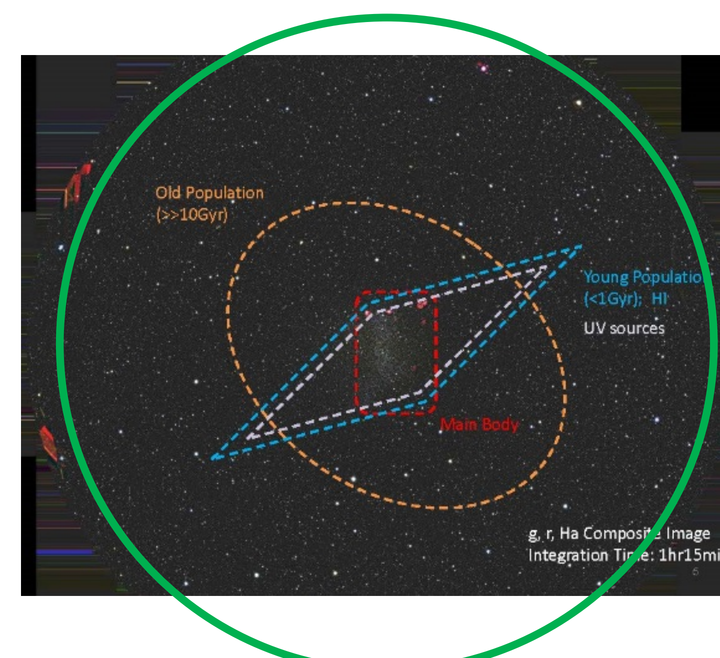
Sculptor



Fornax

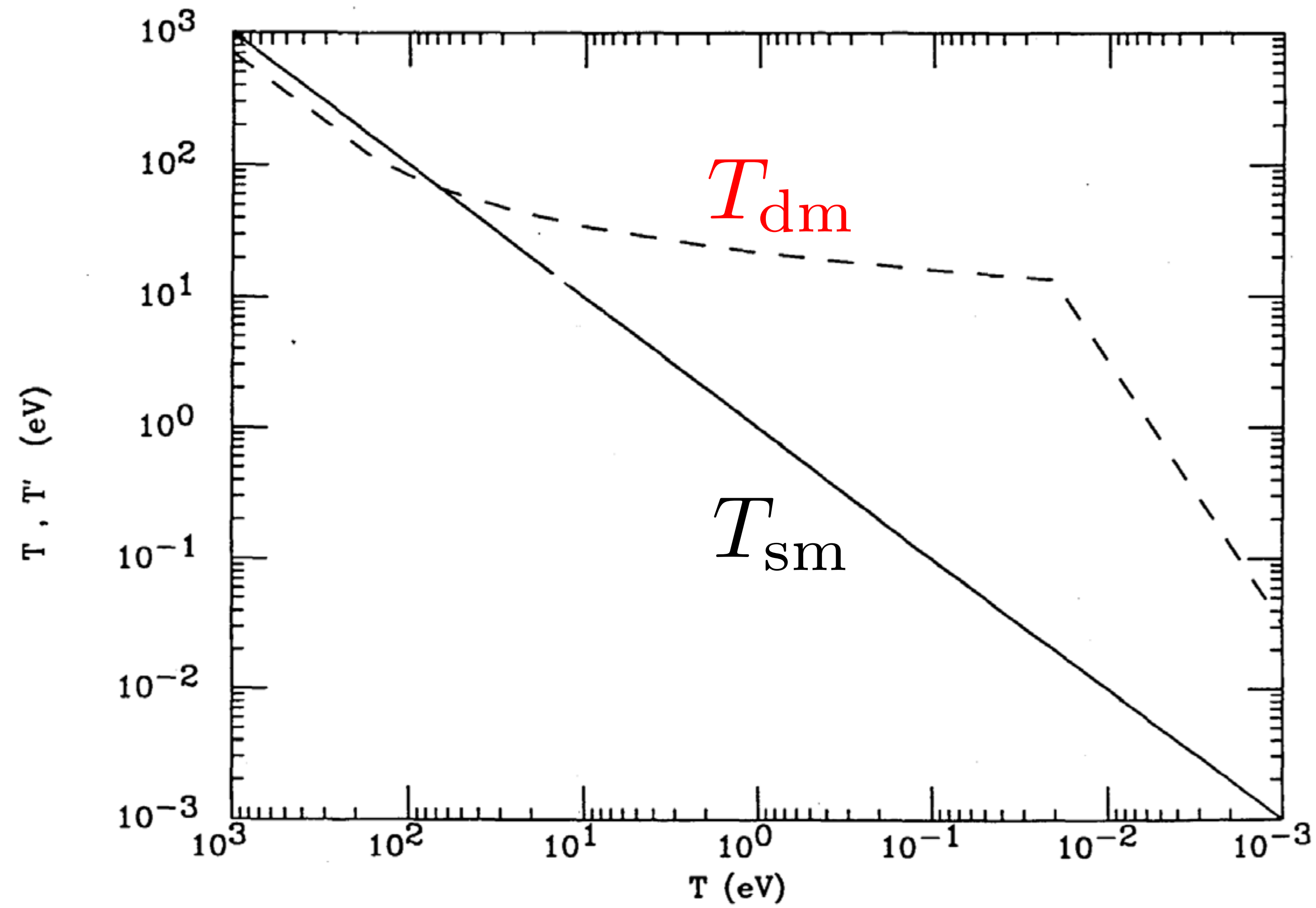


NGC6822



Interactions with SM

if totally decoupled

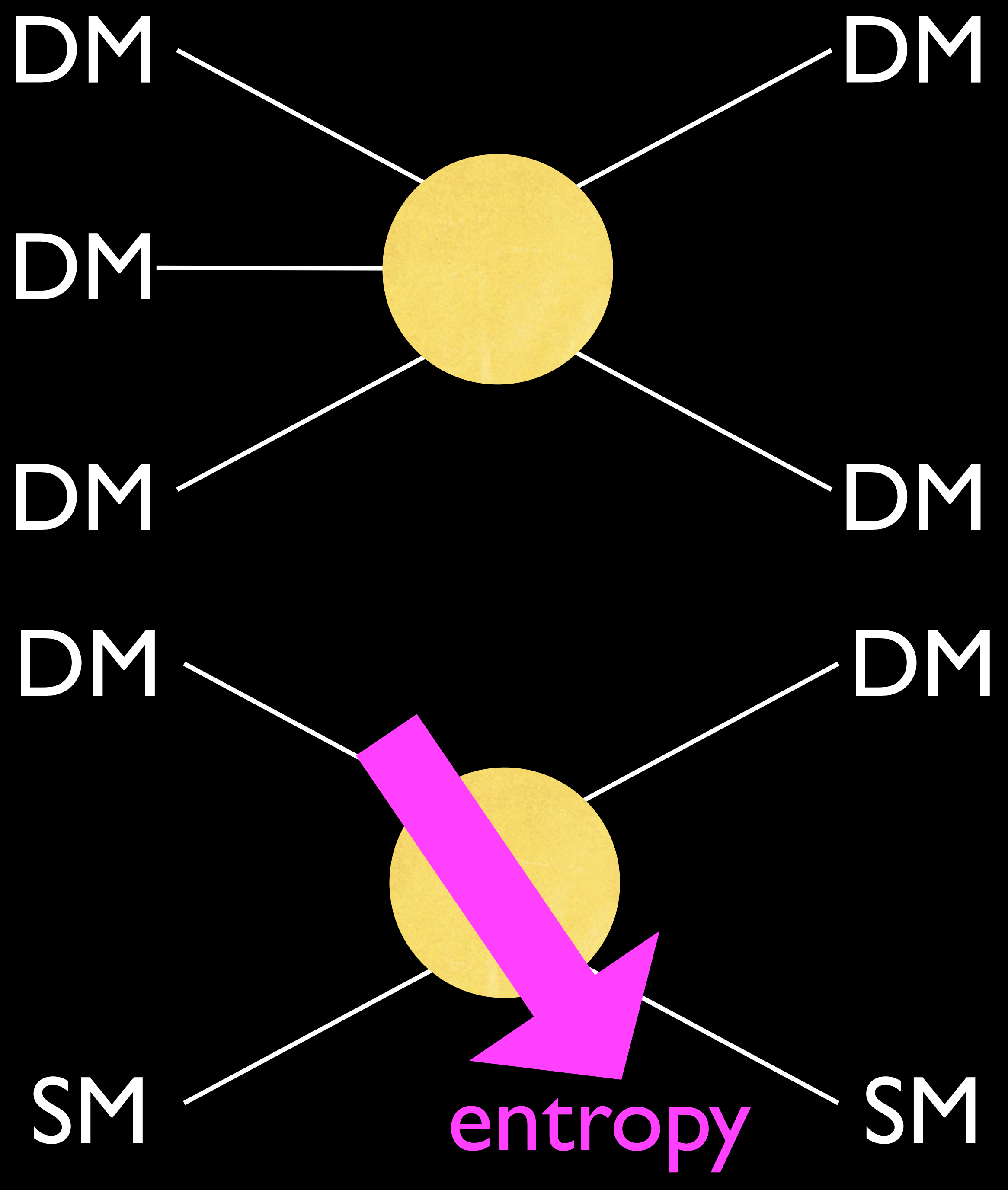


Carlson, Hall and Machacek, Astrophys. J. 398, 43 (1992)

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

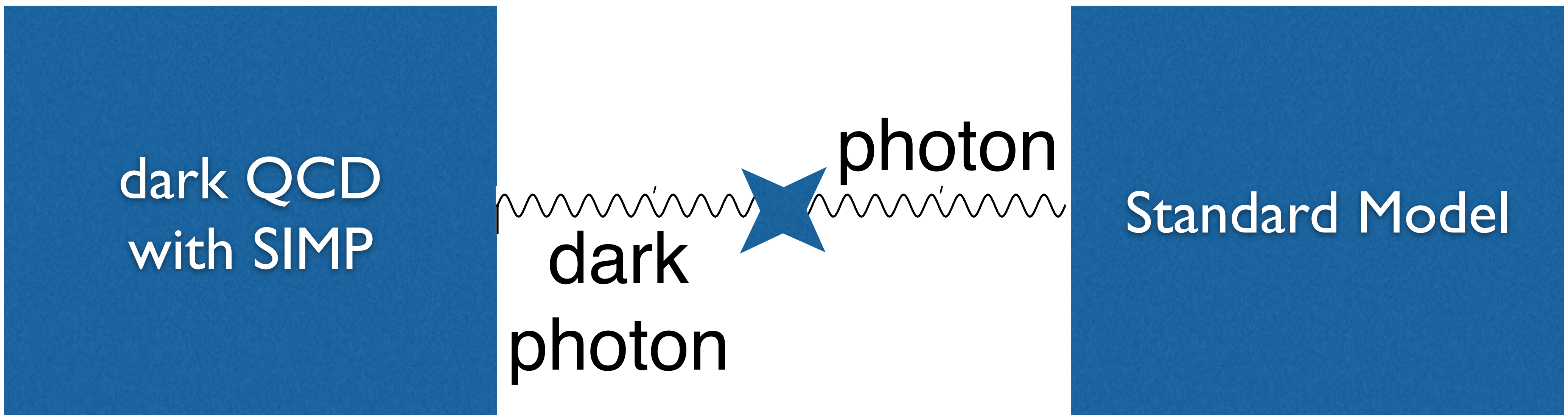
communication

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



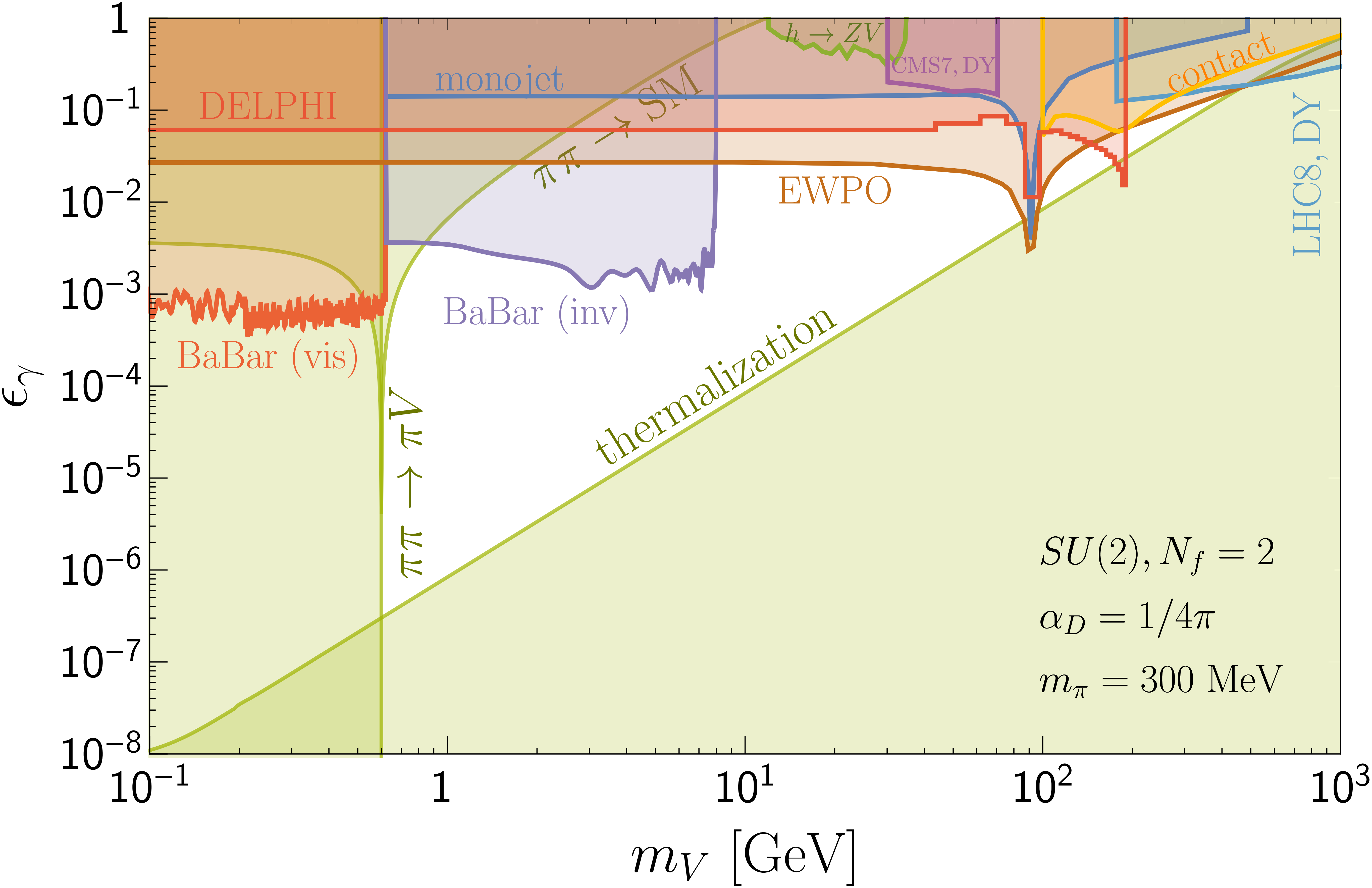
vector portal

arXiv:1512.07917



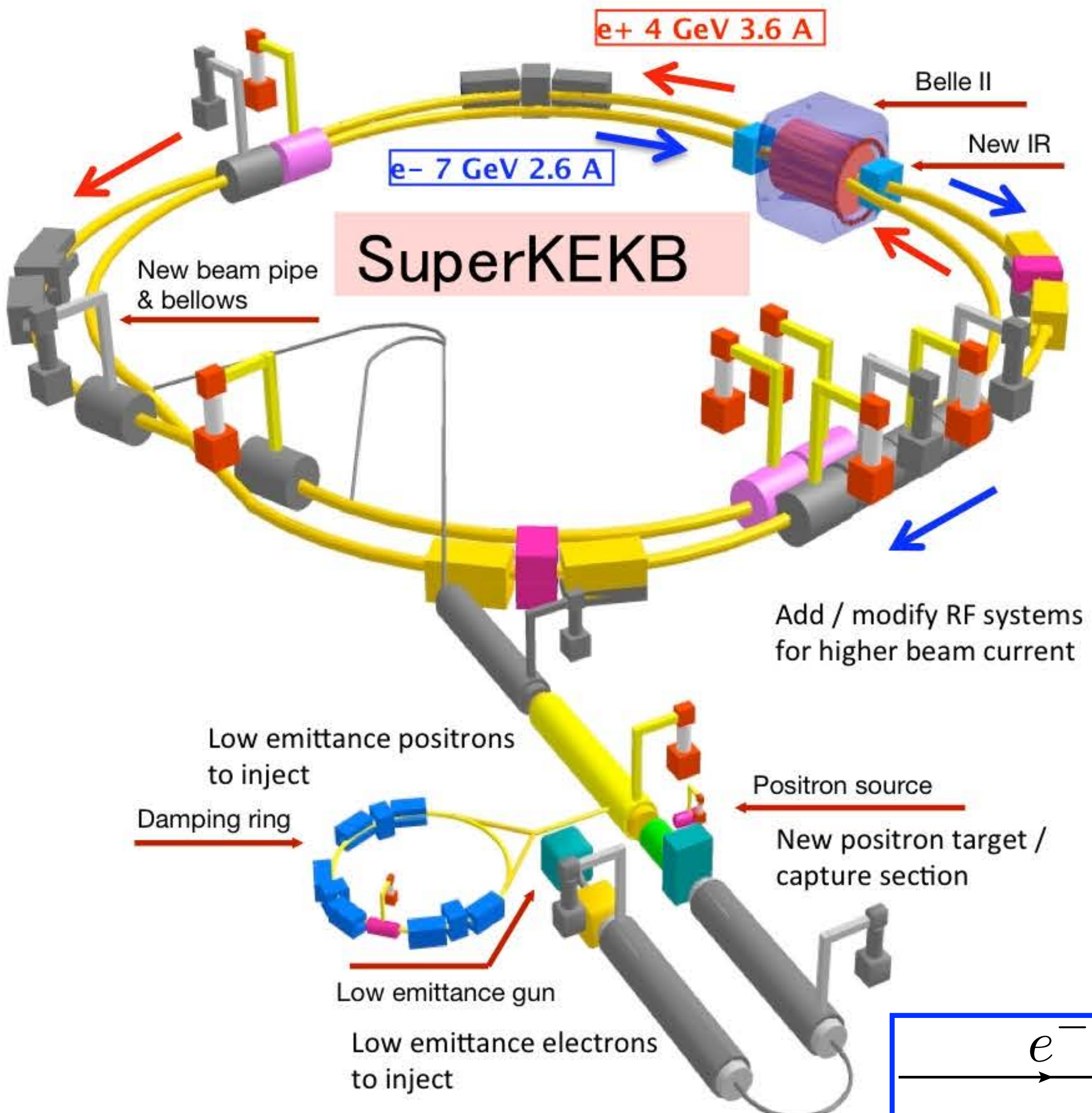
$$\frac{\epsilon_\gamma}{2} F_{\mu\nu} F_D^{\mu\nu}$$

also axion portal: +Katelin Schutz, Robert McGehee, arXiv:1806.10139

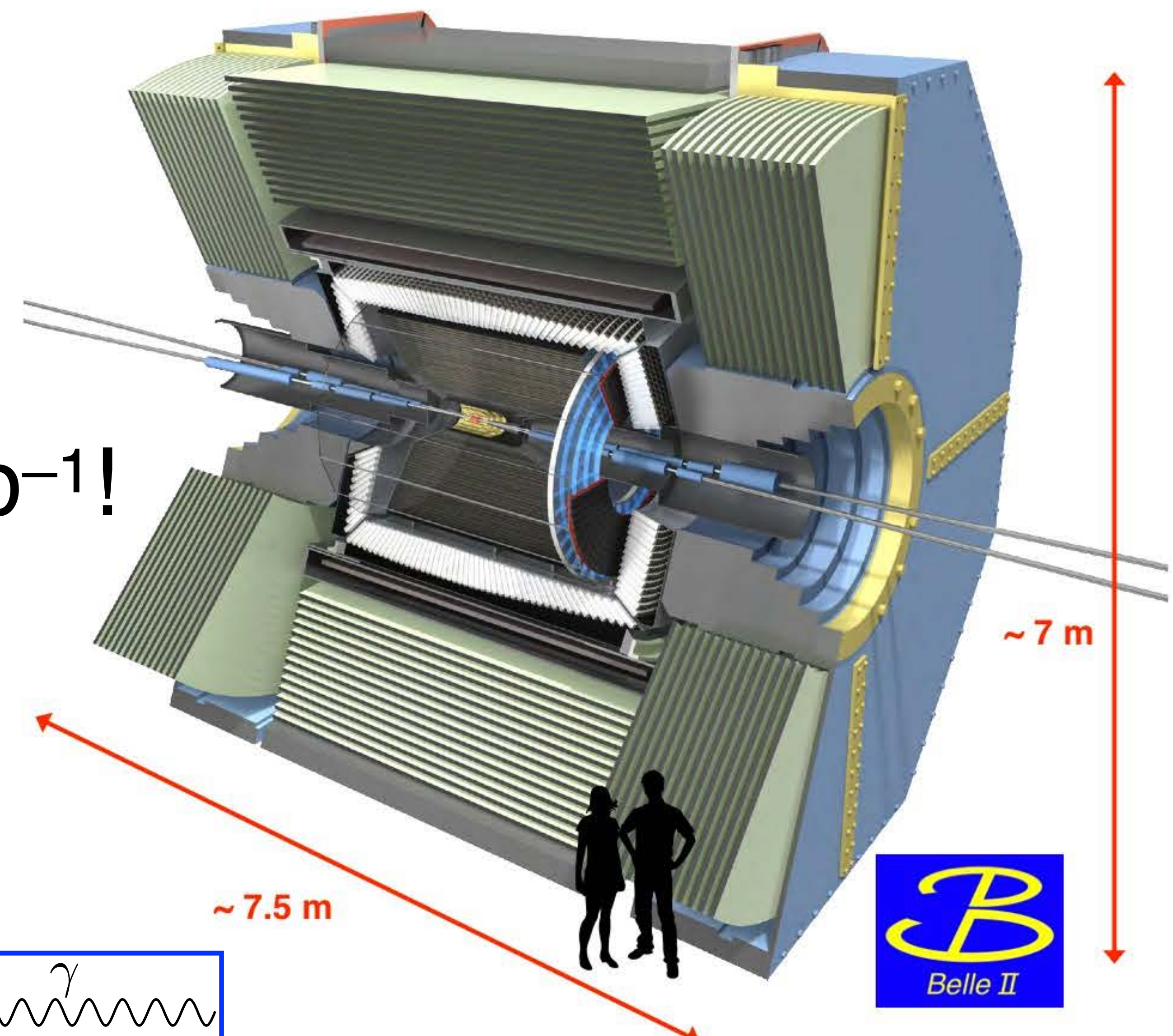


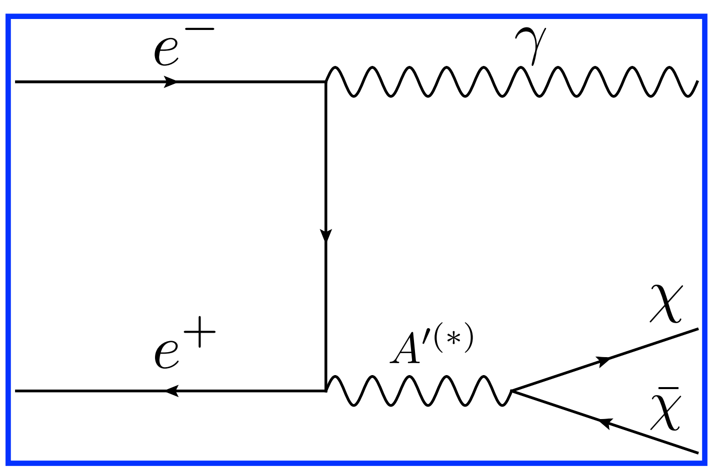
monojet
DELPHI
$h \to ZV$
CMS7, DY
$\pi\pi \to$ SM
contact
EWPO
LHC8, DY
BaBar (inv)
BaBar (vis)
$\pi\pi \to \pi V$
thermalization
$SU(2), N_f = 2$
$\alpha_D = 1/4\pi$
$m_\pi = 300$ MeV
ϵ_γ
m_V [GeV]

$e^+ e^-$ colliders

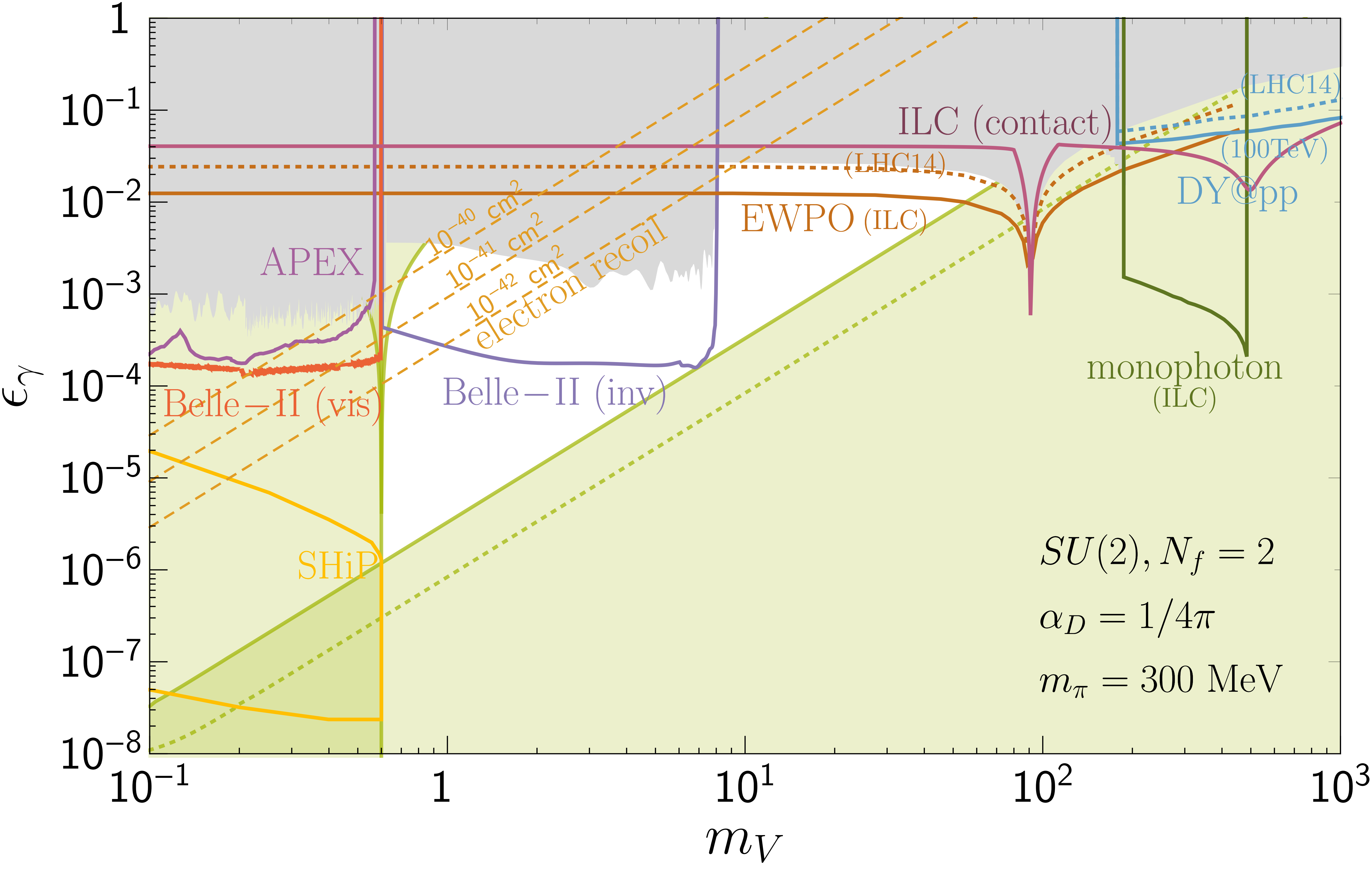


50 ab^{-1}!

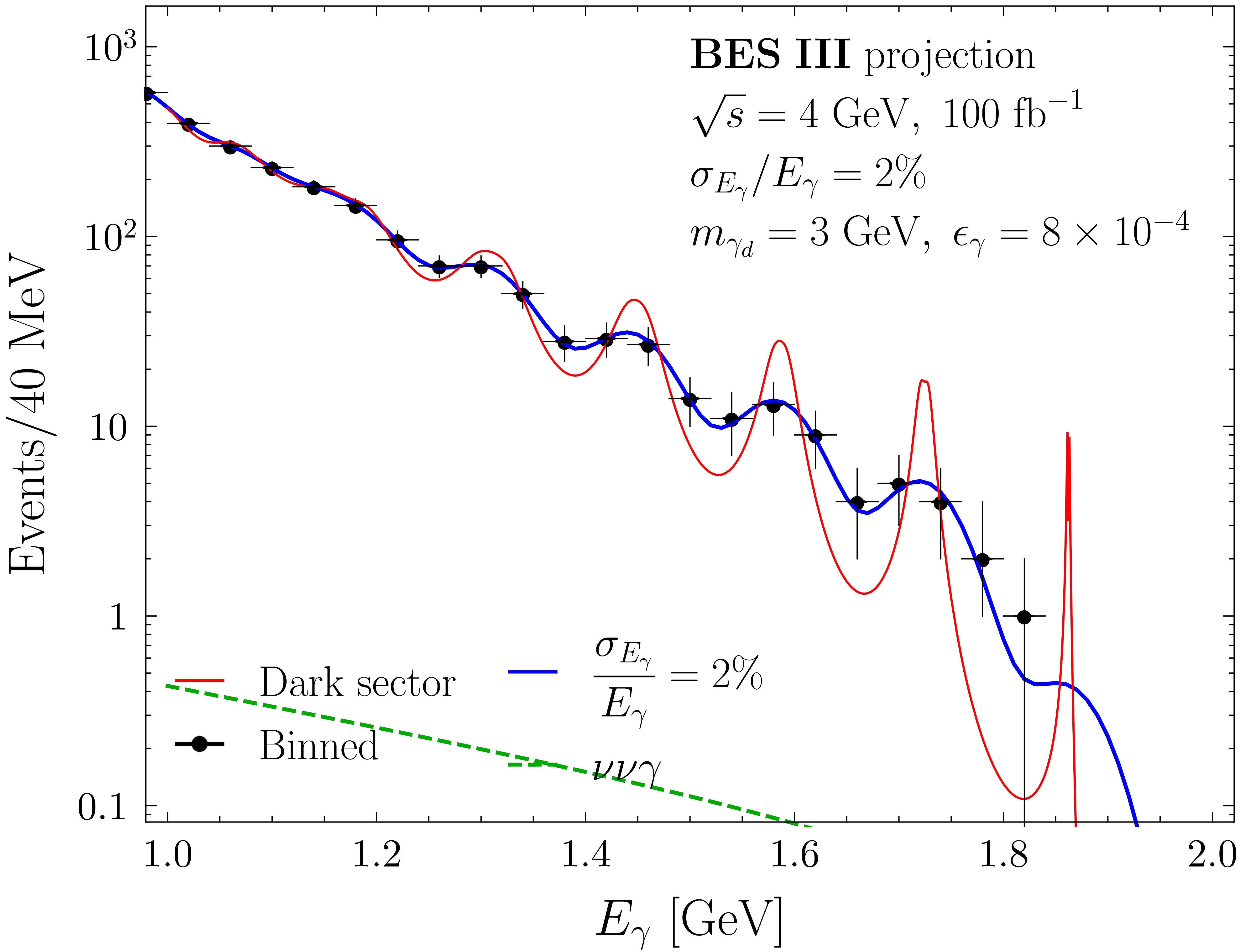




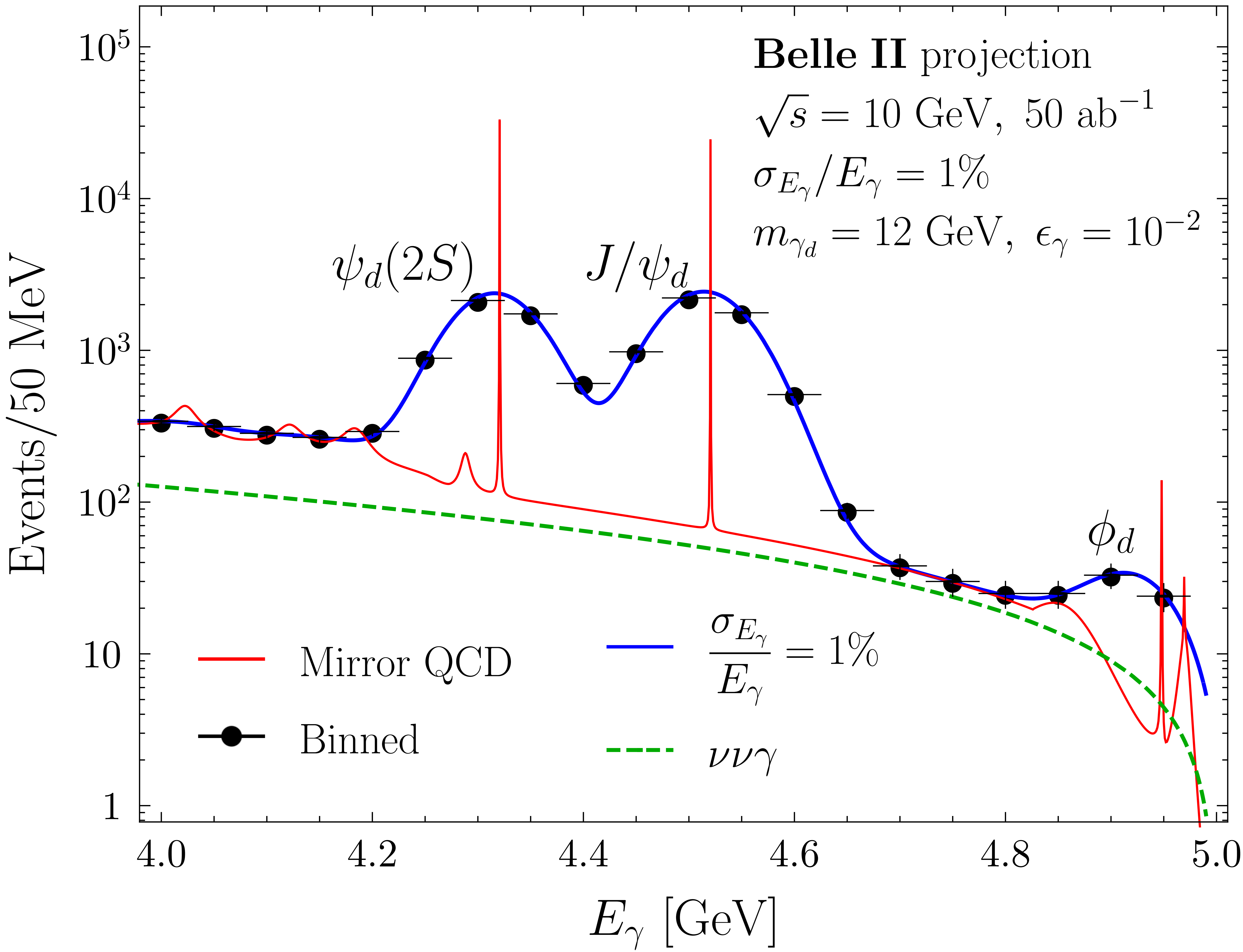
$$E_\gamma = \frac{\sqrt{s}}{2}\left(1 - \frac{M_{\rm inv}^2}{s}\right)$$



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

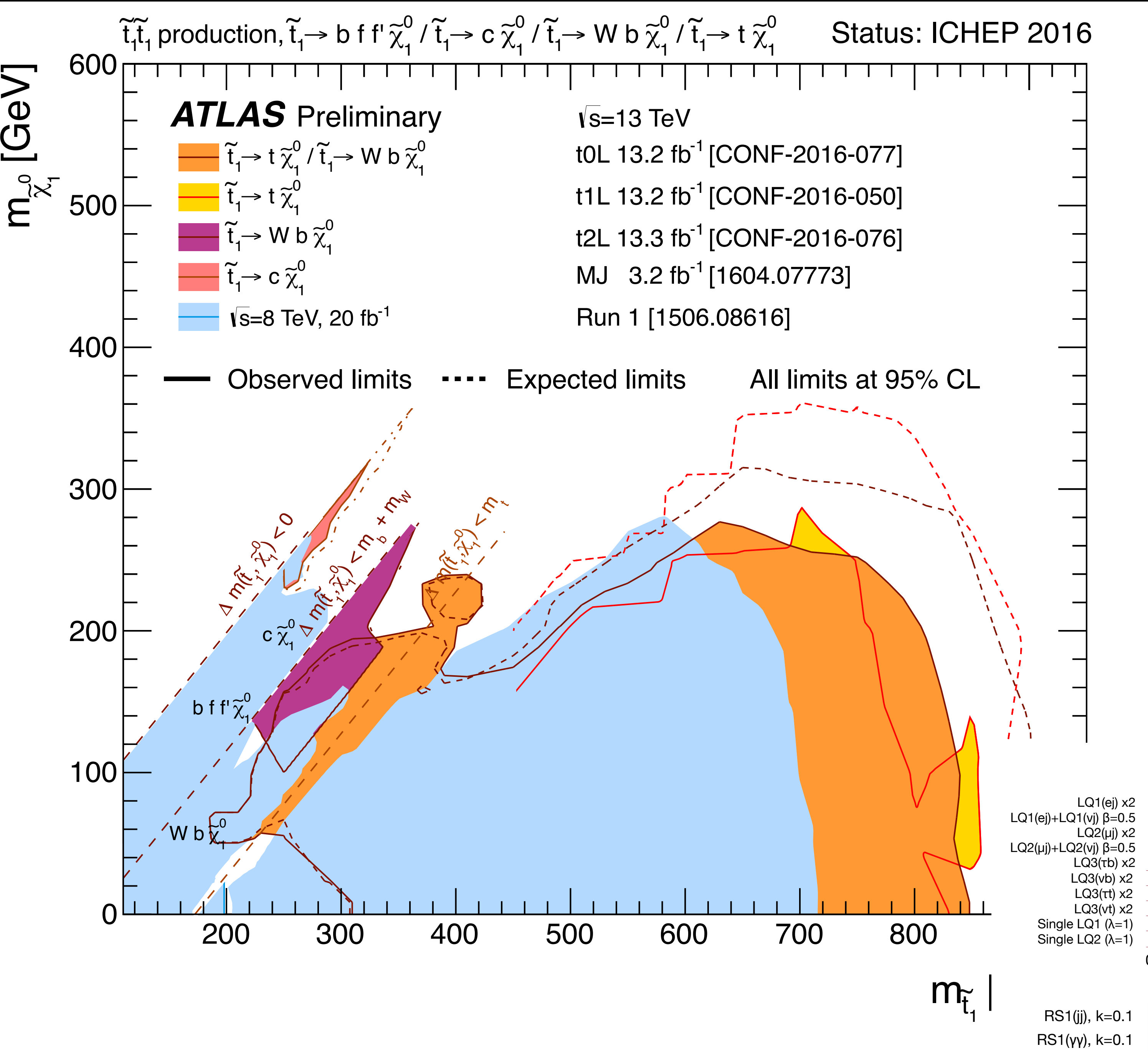


BES III projection
$\sqrt{s} = 4$ GeV, 100 fb^{-1}
$\sigma_{E_\gamma}/E_\gamma = 2\%$
$m_{\gamma_d} = 3$ GeV, $\epsilon_\gamma = 8 \times 10^{-4}$
Dark sector
Binned
$\frac{\sigma_{E_\gamma}}{E_\gamma} = 2\%$
$\nu\nu\gamma$
Events/40 MeV
E_γ [GeV]
10^3
10^2
10
1
0.1
1.0
1.2
1.4
1.6
1.8
2.0

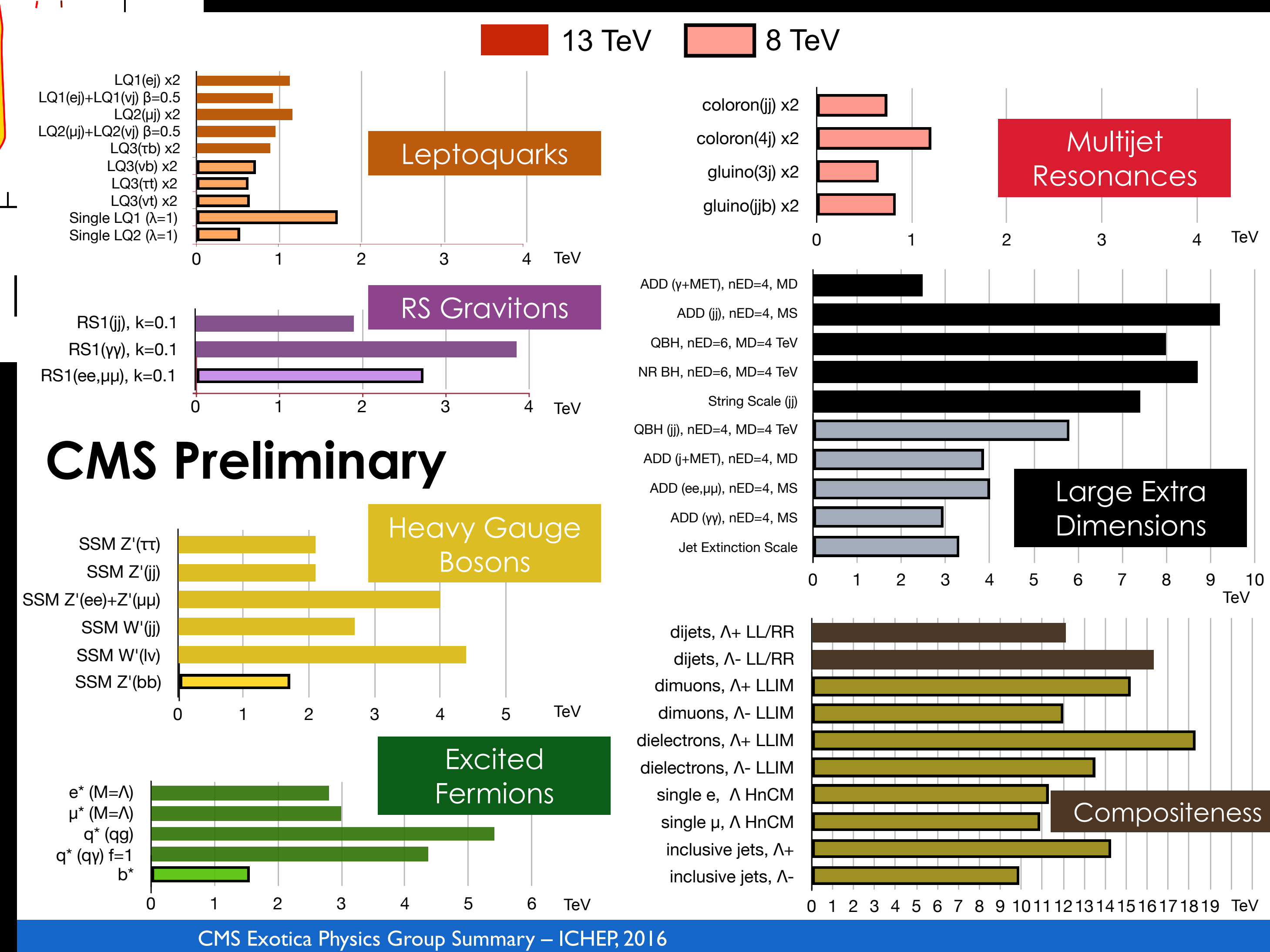


Belle II projection
$\sqrt{s} = 10$ GeV, 50 ab^{-1}
$\sigma_{E_\gamma}/E_\gamma = 1\%$
$m_{\gamma_d} = 12$ GeV, $\epsilon_\gamma = 10^{-2}$
$\psi_d(2S)$
J/ψ_d
ϕ_d
Mirror QCD
Binned
$\frac{\sigma_{E_\gamma}}{E_\gamma} = 1\%$
$\nu\nu\gamma$
Events/50 MeV
E_γ [GeV]
10^5
10^4
10^3
10^2
10
1
4.0
4.2
4.4
4.6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

Back to
Hierarchy Problem



LHC excludes mostly colored particles



no sign of
new physics
that explains
hierarchy problem!

Twin Higgs

- Take two mirror copies of the SM:

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

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

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

$$V = -\mu^2(|H_{SM}|^2 + |H_{twin}|^2) + \lambda(|H_{SM}|^2 + |H_{twin}|^2)^2 + \kappa|H_{SM}|^2|H_{twin}|^2$$

- Take a small hierarchy of Higgs vevs:

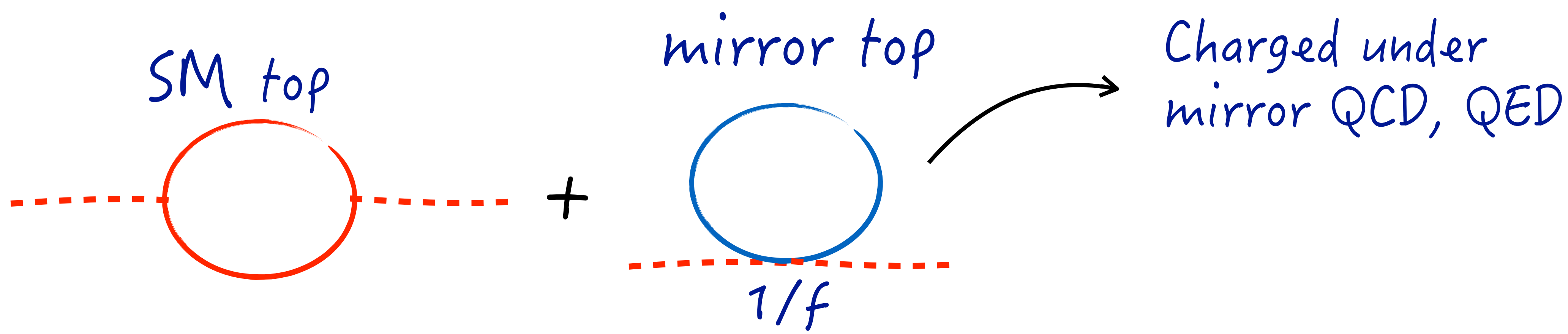
$$\langle H_A \rangle = v \qquad \langle H_B \rangle = f \qquad \text{with } v < f.$$

SO(8)/SO(7): 7 NGBs
3: eaten by $SU(2)_{twin}$
4: Standard Model Higgs

Chacko, Goh, RH (2005)

Twin Higgs

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

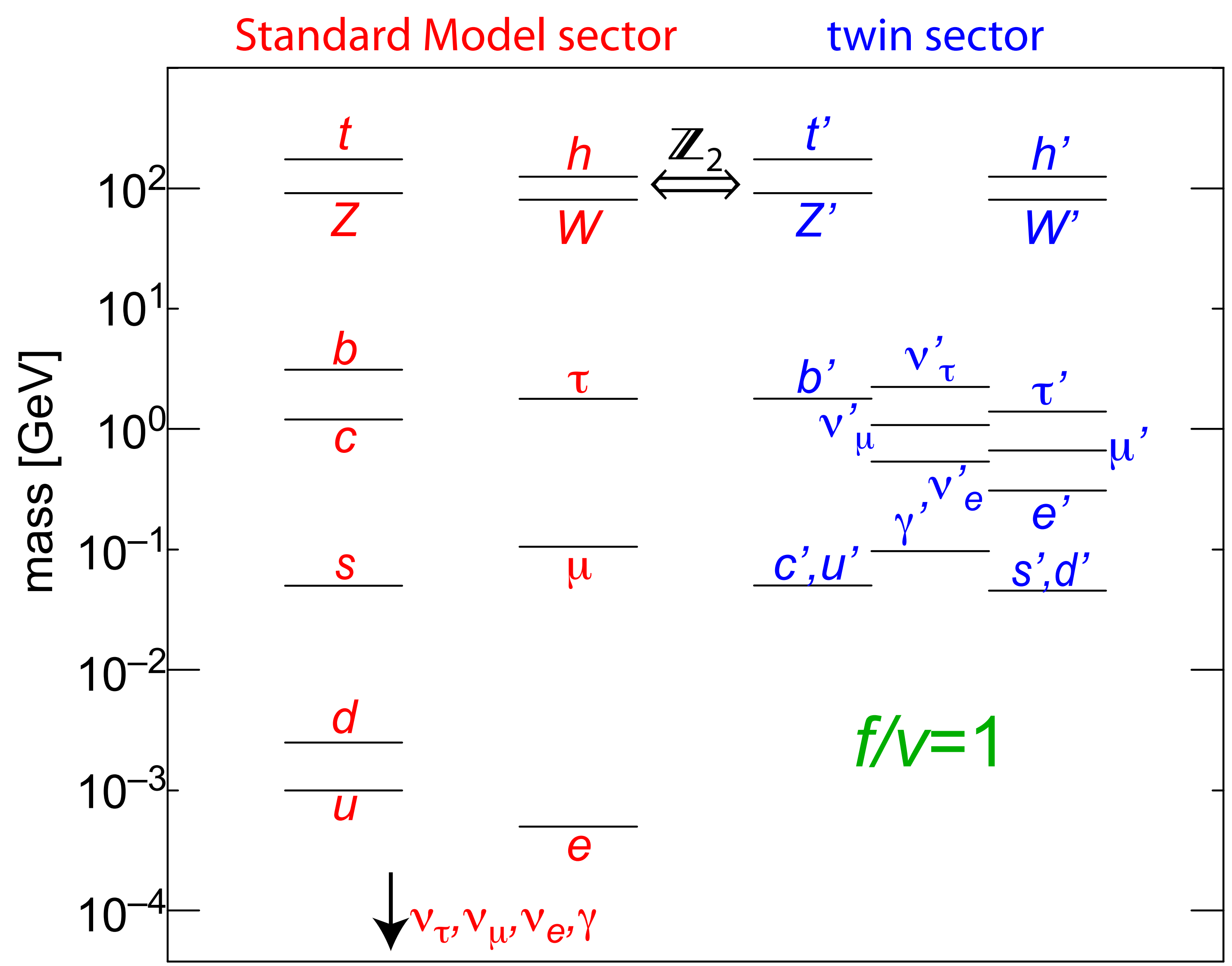


Roni Harnik and Zackaria Chacko, JHU workshop 2017 in Budapest

Twin spectrum

arXiv:1805.09345

- light fermion spectrum not important to hierarchy because of small Yukawas
- Planck: ΔN_{eff}<0.29
  - assume leptons heavy
  - no N_{eff} problem
- assume exact SU(2)
  - (u,d) vs (c,s)
- lightest pions are triplet in $SU(2)_{d,s}$
  - stable



mesons

- assume exact SU(2)
  - (u,d) vs (c,s)
  - approximate SU(4)
  - $m_{u,c}=m_{d,s}(1+\Delta)$
  - 15 mesons
- lightest pions are triplet in $SU(2)_{d,s}$
  - stable
- triplet in $SU(2)_{u,c}$ also practically stable
- 8 charged ones stable
- only one unstable η

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

TABLE I. Decomposition of the meson $SU(4)_f$ 15-plet under $SU(2)_U \times SU(2)_D \times U(1)_{\rm EM}$. The third column shows the linear combination of quark masses that determines the meson masses-squared. From top to bottom, the meson masses go from heaviest to lightest, assuming $m_{d'} = m_{s'} < m_{u'} = m_{c'} = m_{d',s'}(1+\Delta)$.

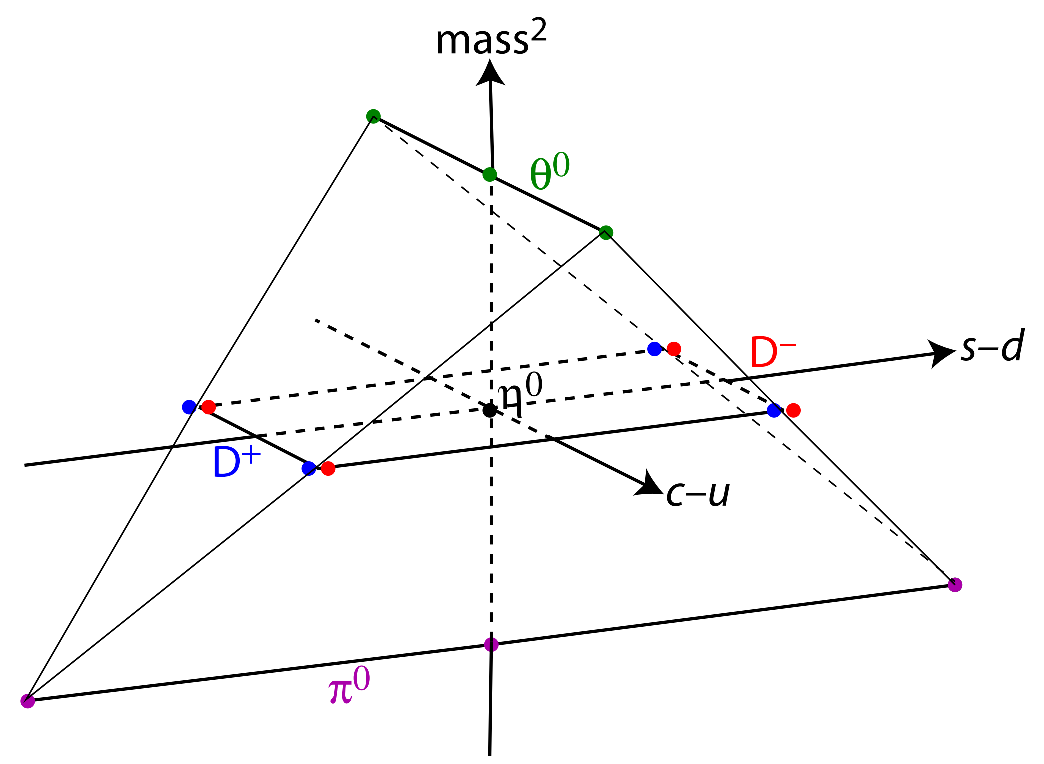


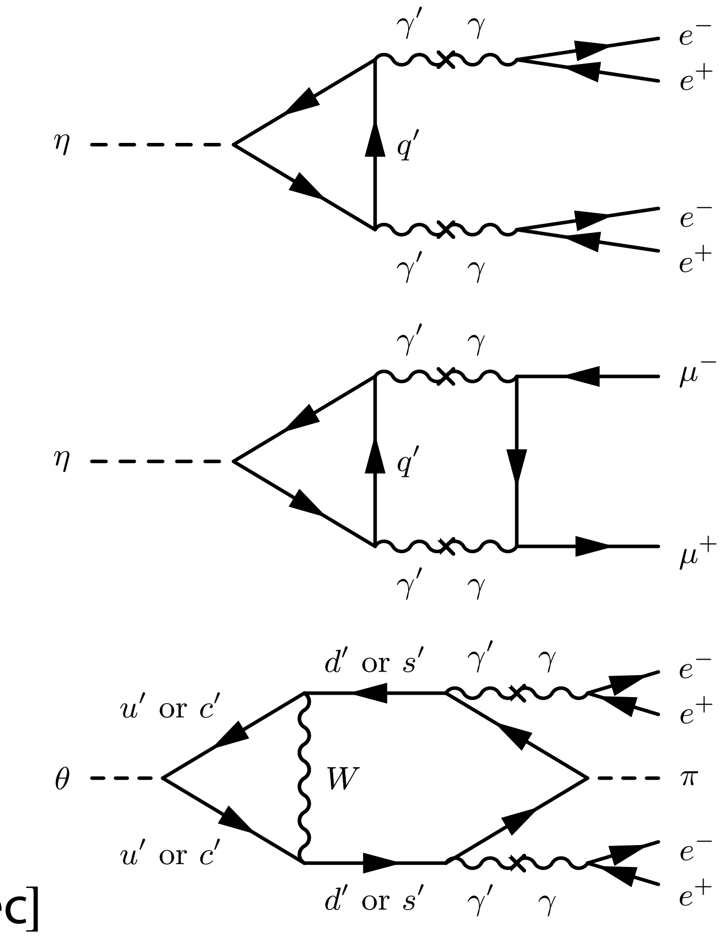
FIG. 2. A visual representation of the meson spectrum.

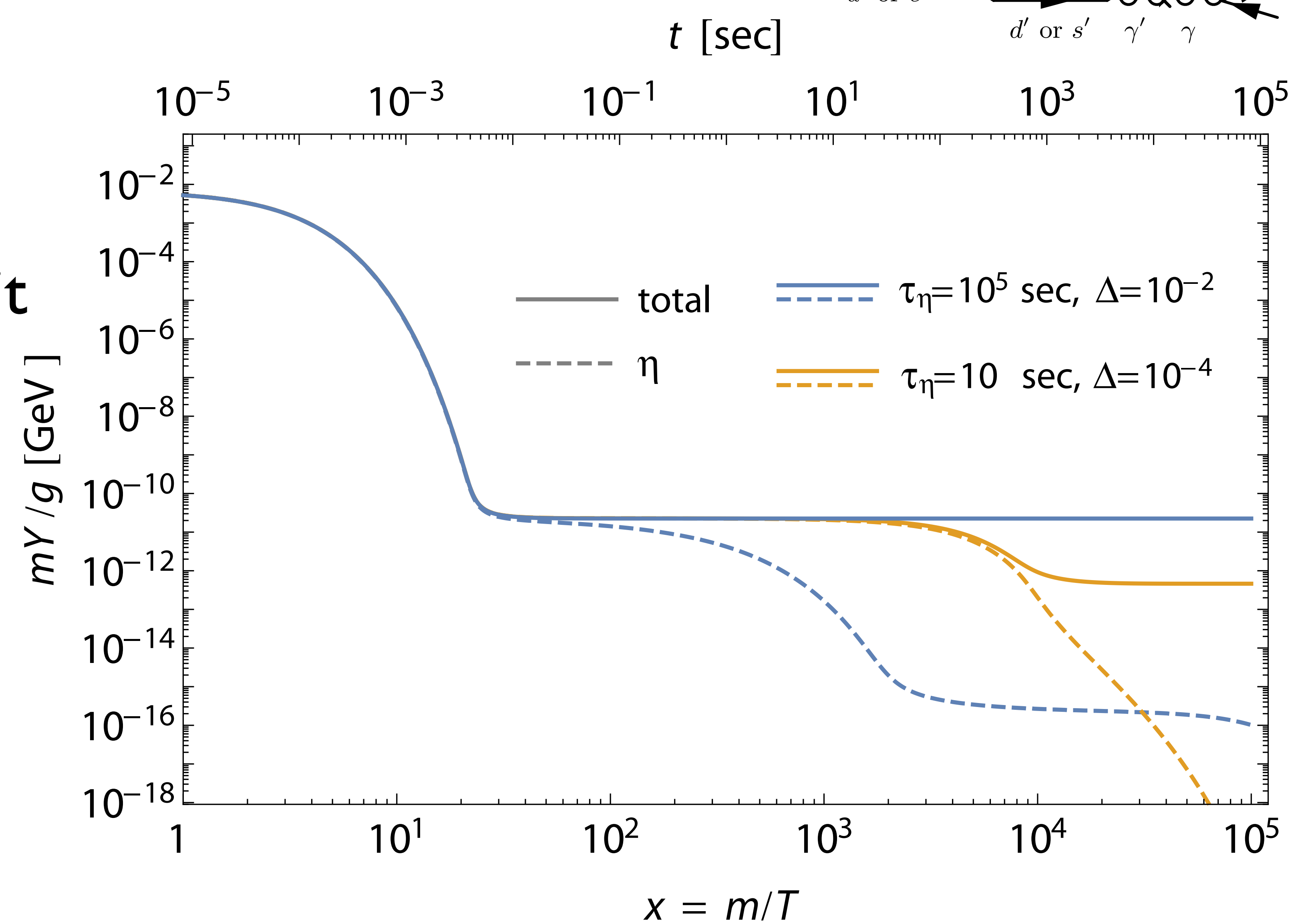
$\eta\eta \to \pi\pi$

- $\eta \to \mu^+\mu^-$ or $2(e^+e^-)$
- $\tau_\eta \sim 10^5$ sec

1. $\pi\pi \to \eta\eta$ kinematically not possible
2. lose η by $\eta\eta \to \pi\pi$
3. η decays before BBN limit

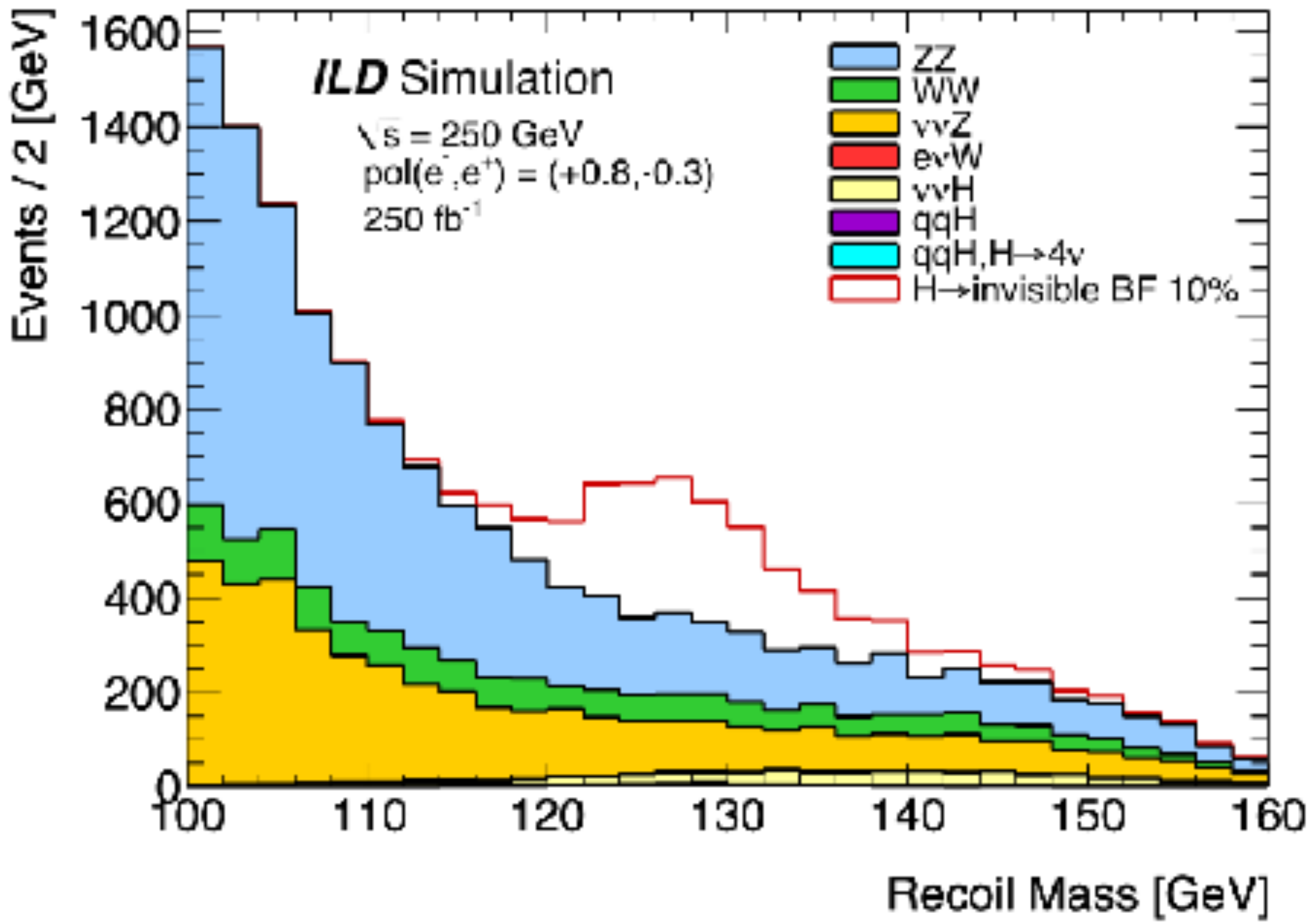
- $\pi\pi \to \eta\eta \to$ SM shouldn't happen in halo today
- can easily be avoided $\Delta > v_{halo}^2 \sim 10^{-6}$





invisible Higgs @ ILC

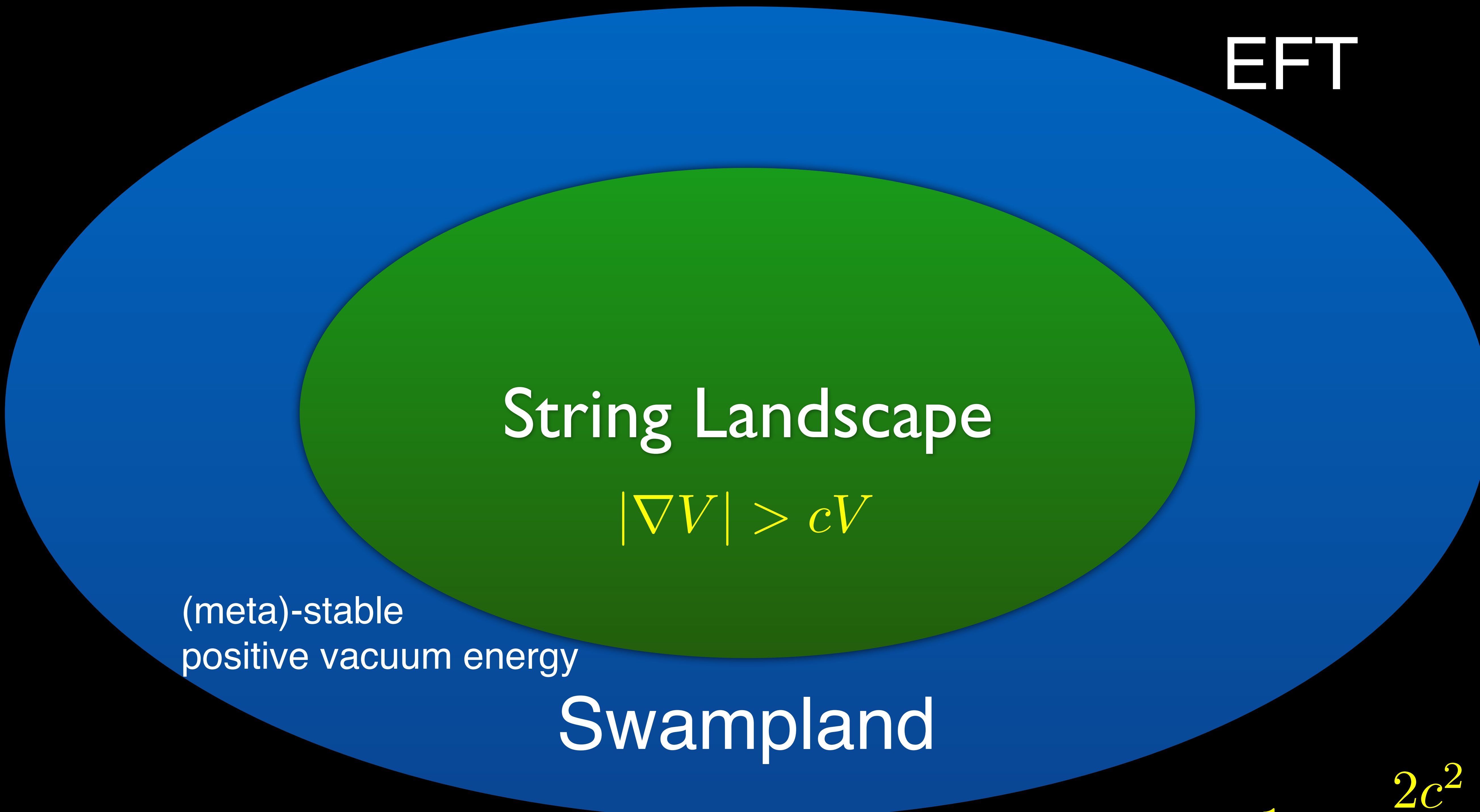
Keisuke Fujii



BR($H\rightarrow$invisible) ~ $(v/f)^2$ down to 0.3%

Quintessence

Swampland



Obied, Ooguri, Spodyneiko, Vafa

$$w = -1 + \frac{2c^2}{3 + c^2}$$

“Quintessence”

- Accelerated Expansion happened before
  - Inflation
- Is current acceleration also by scalar field?
  - very difficult to keep flat potential for Q
  - SUSY broken > TeV
  - at the least, $m_{3/2} > (\text{TeV}^2/M_{Pl}) \sim \text{eV}$
    - *i.e.*, vector mediation (Hook, HM)
  - more typically $m_{3/2} > \text{TeV}$
  - but we need $m_Q \sim H_0 \sim 10^{-33}$ eV

shift symmetry

- incorporate into supergravity
- shift symmetry (monodromy) in Kähler
  - $Q \to Q + i\,\alpha$
  - $K(Q,Q^*) = K(Q+Q^*) \sim (Q+Q^*)^2/2$

$$V = e^K\left((K_i W + W_i)^* K_{\bar{i}}^{-1j}(K_j W + W_j) - 3|W|^2\right)$$

$$= \cancel{|W_Q|^2} - 3m_{3/2}(W(Q) + W^*(Q))$$

- need $m_{3/2}W(Q) \sim m_{3/2}\Lambda^3 \sim H_0^2$
- *any* potential can be lifted to supergravity
- also radiatively stable $\delta K \sim m_{3/2}^2\Lambda^6$
- no fifth force

Chien-I Chiang, HM, arXiv:1808.02279

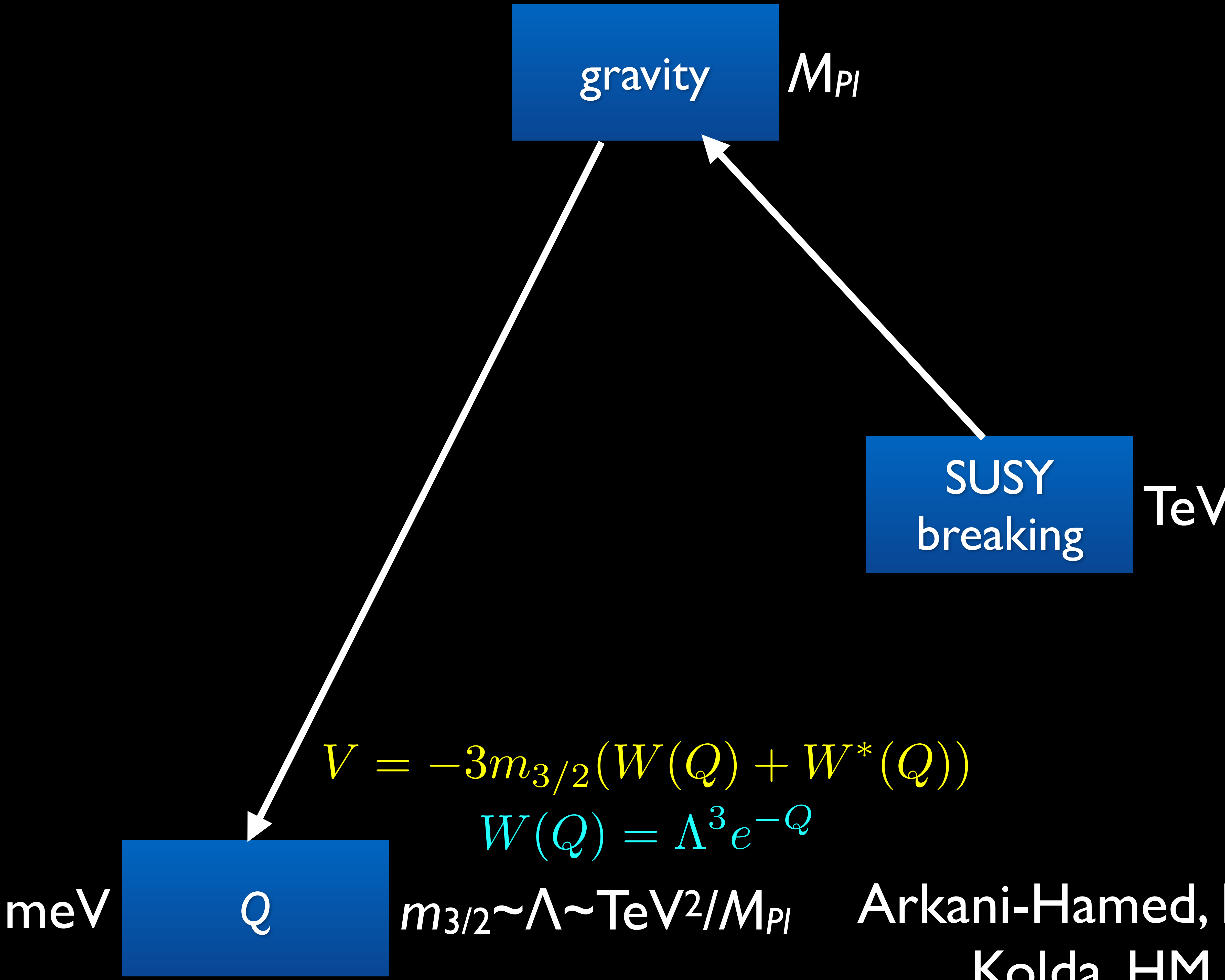
axion-like example

- incorporate into supergravity
- shift symmetry (monodromy) in Kähler, *W*
  - $Q \to Q + i\,\alpha$
  - $K(Q,Q^*) = K(Q+Q^*) \sim (Q+Q^*)^2/2$

$$V = e^K((K_i W + W_i)^* K^{-1j}_{\bar{i}}(K_j W + W_j) - 3|W|^2)$$

$$= |\cancel{W_Q}|^2 - 3m_{3/2}(W(Q) + W^*(Q))$$

- shift symmetry = $U(1)_R$ symmetry
- $W(Q) = \Lambda^3 e^{-Q}$, $V = 3m_{3/2}\Lambda^3 \cos(\mathrm{Im}\ Q)$
- symmetry spontaneously broken by $m_{3/2}$



$$V = -3m_{3/2}(W(Q) + W^*(Q))$$

$$W(Q) = \Lambda^3 e^{-Q}$$

Arkani-Hamed, Hall, Kolda, HM

shift symmetry

- incorporate into supergravity
- shift symmetry (monodromy) in Kähler
  - $Q \rightarrow Q + i\,\alpha$
  - $K(Q,Q^*) = K(Q+Q^*) \sim (Q+Q^*)^2/2$

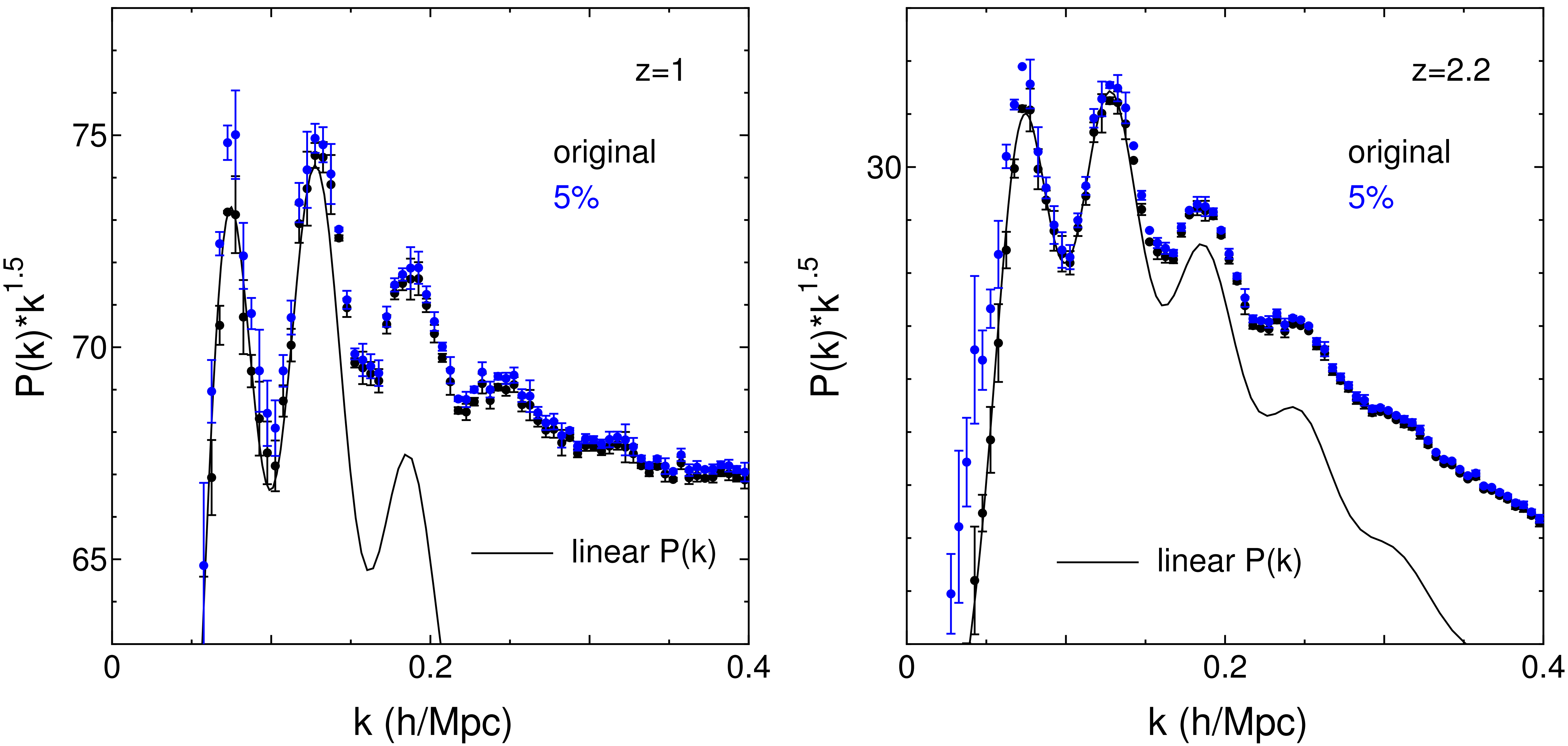
$$V = e^K \left((K_i W + W_i)^* K^{-1j}_{\bar{i}} (K_j W + W_j) - 3|W|^2 \right)$$

$$= |\cancel{W_Q}|^2 - 3 m_{3/2} (W(Q) + W^*(Q))$$

- need $m_{3/2} W(Q) \sim m_{3/2} \Lambda^3 \sim H_0^2$
- *any* potential can be lifted to supergravity
- also radiatively stable $\delta m_Q^2 \sim m_{3/2}^4 \Lambda^6$
- no fifth force

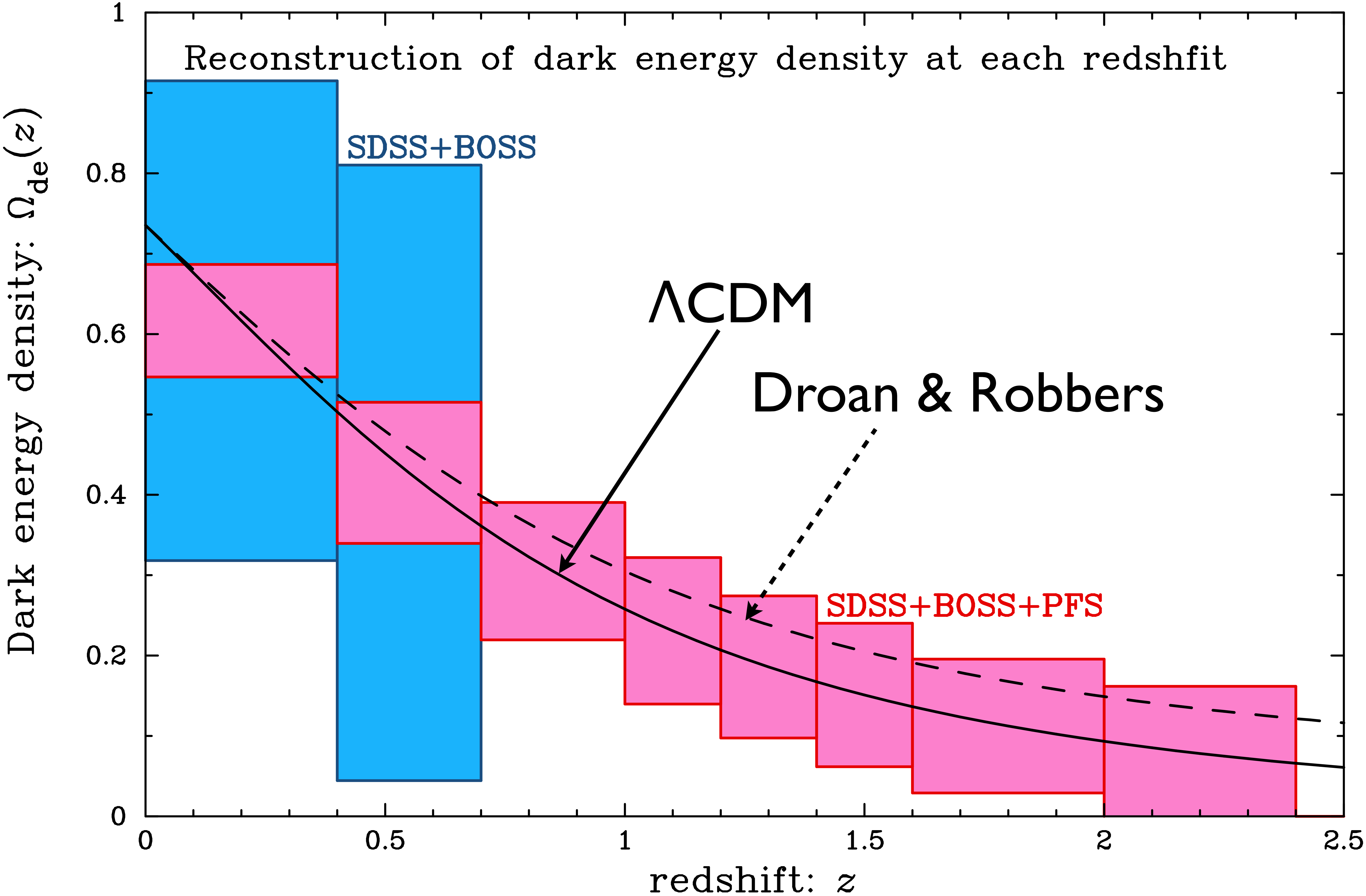
Chien-I Chiang, HM

Baryon Acoustic Oscillations

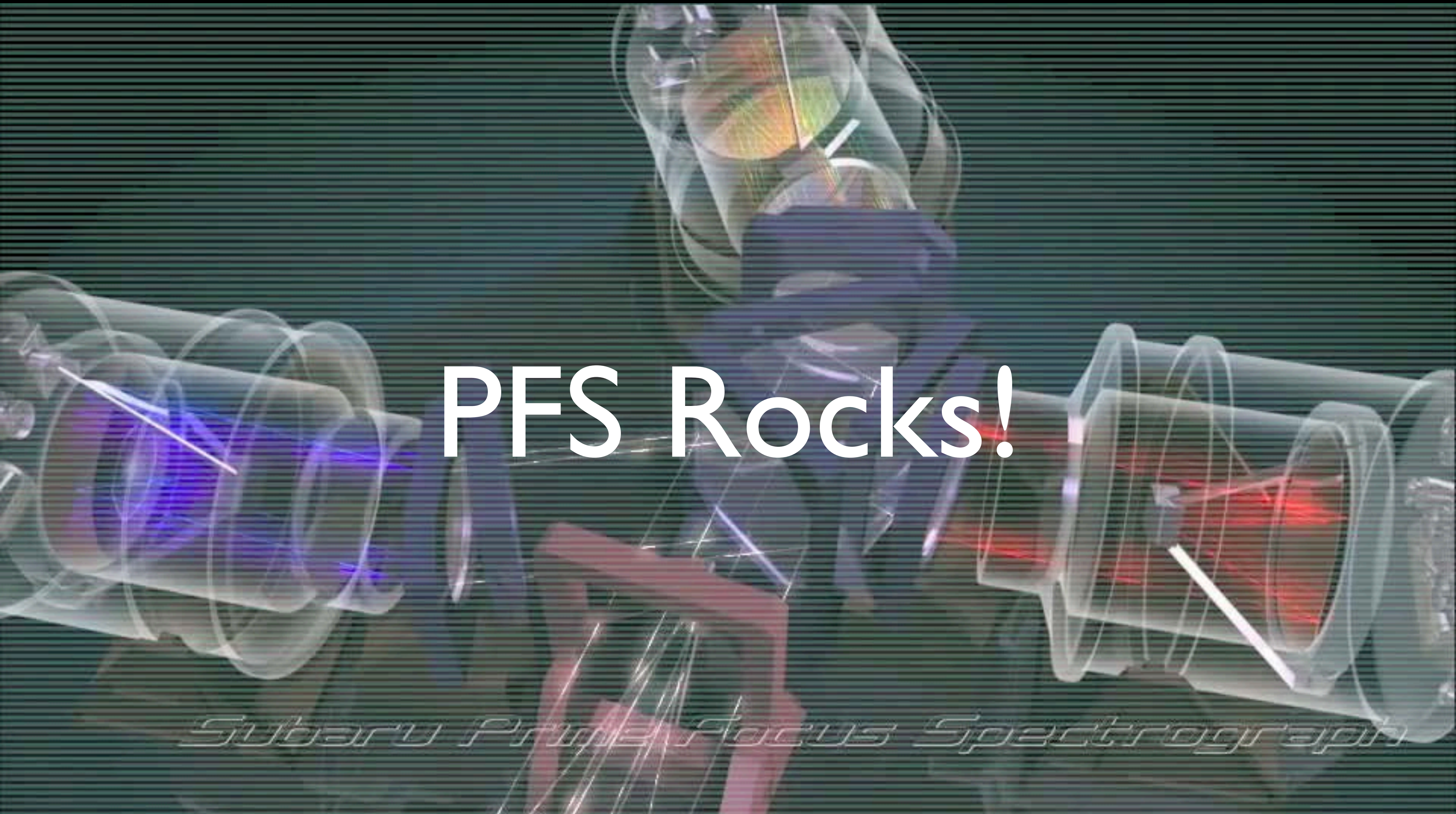


ELGs [OII] > 8.5σ, 15 min exposure

cosmology $H(z)$ with BAO



PFS Rocks!



http://pfs.ipmu.jp/intro.html

Conclusion

- We still have *no idea* what dark matter is
- WIMP still the main paradigm
  - but no sign of it
- SIMP can solve problems with DM profile
  - core/cusp, missing satellites
  - very rich phenomenology
  - Exciting dark spectroscopy
  - Can also address the hierarchy problem
- cosmological constant in swampland?
  - Can lift any quintessence potential to supergravity
  - renewed interest in observation