What is Dark Matter?

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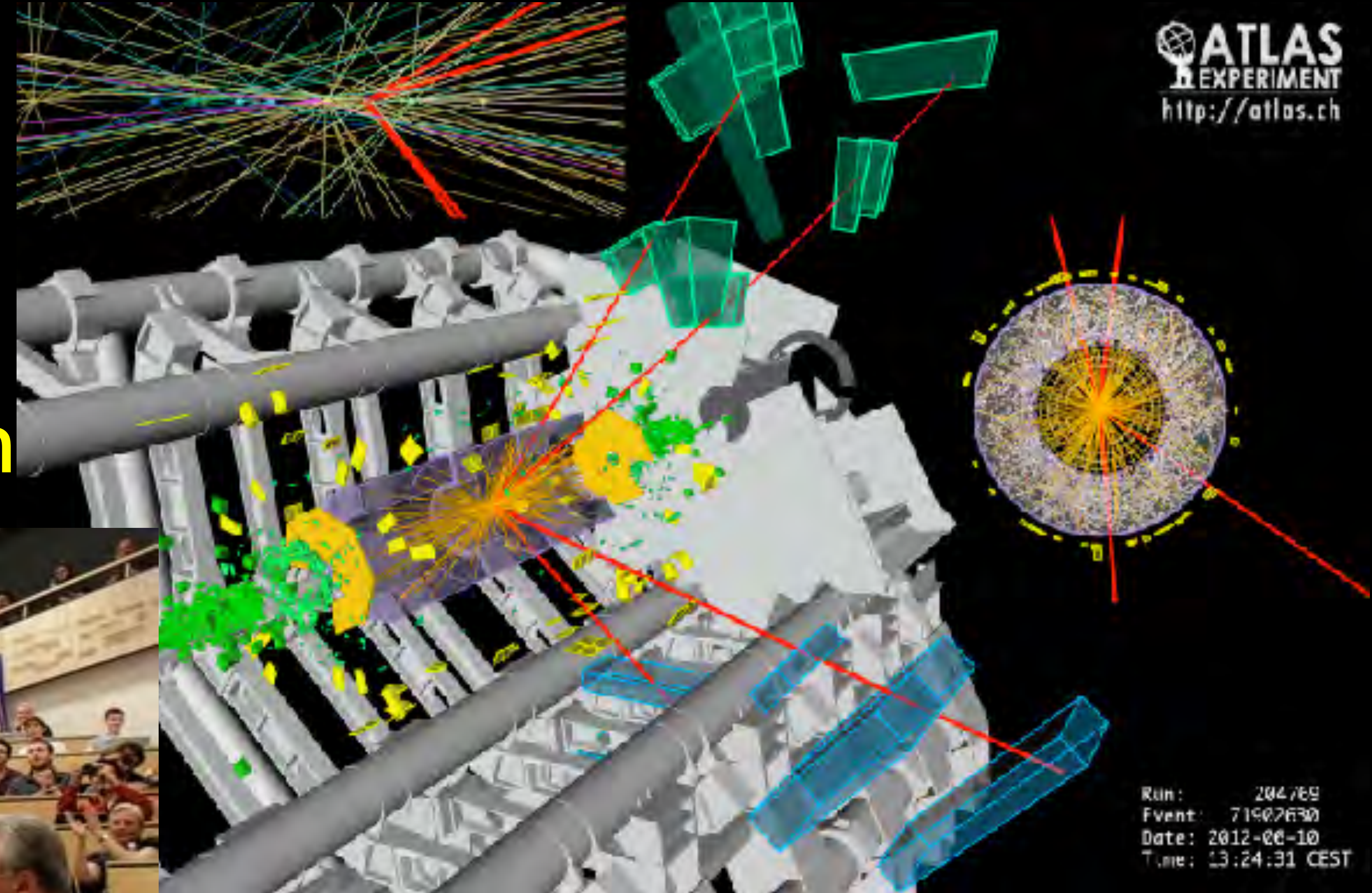
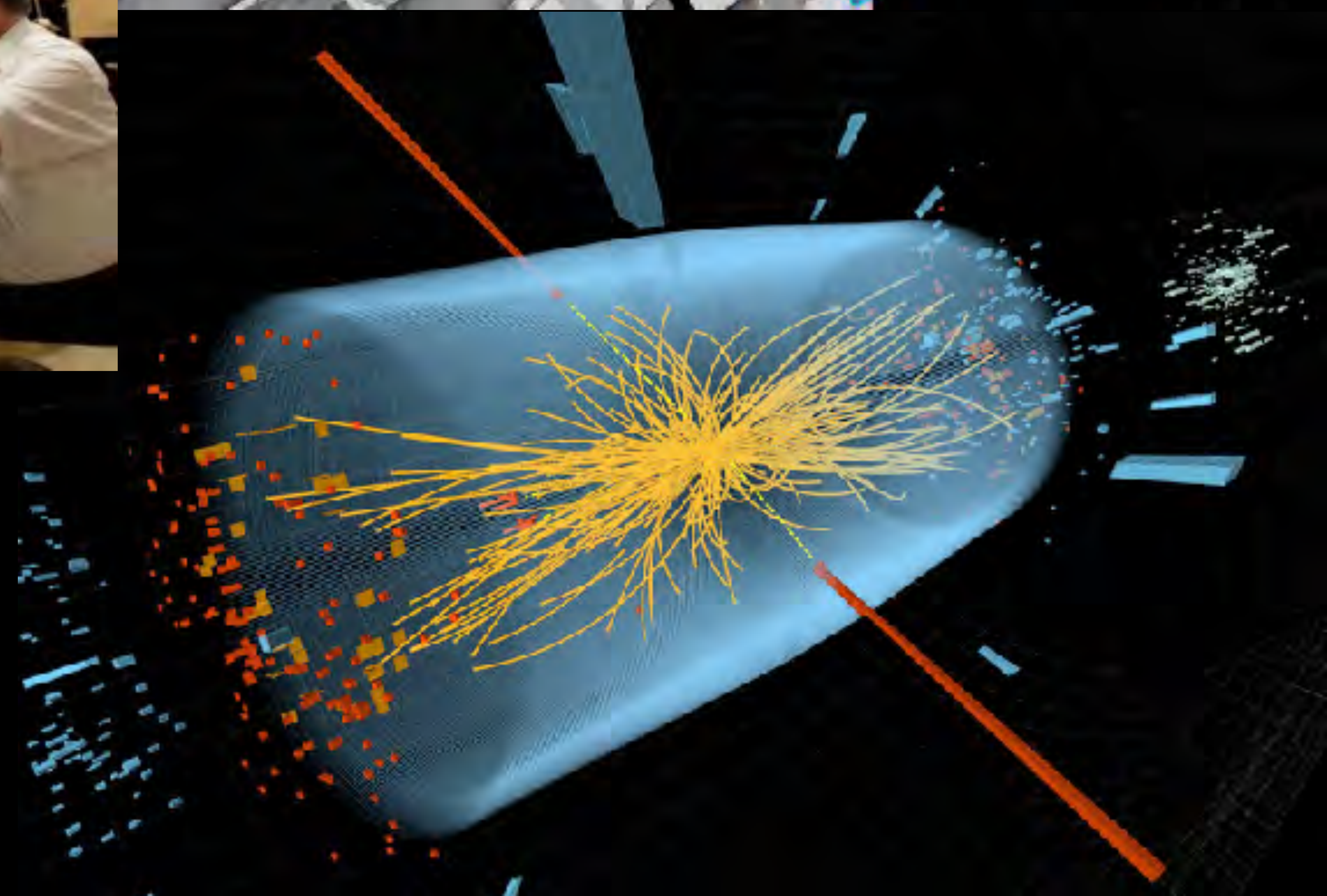
May 22, 2018, DESY Colloquium

東京大学
THE UNIVERSITY OF TOKYO
BERKELEY CENTER FOR THEORETICAL PHYSICS
BERKELEY LAB
KAVLI IPMU

2012.7.4

discovery of Higgs boson





theory：1964

design：1984

construction：1998


Higgsdependence Day
July 4, 2012

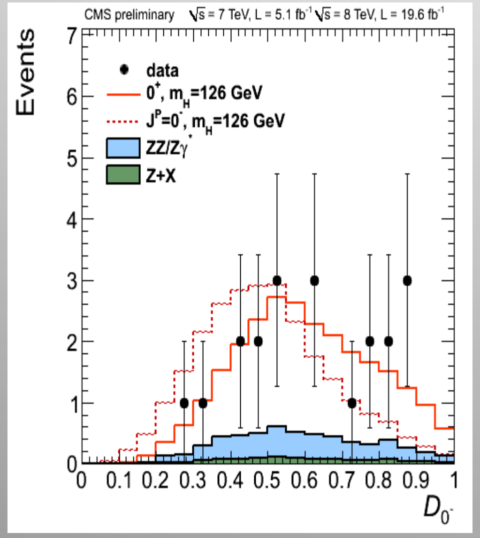
particle with a VEV

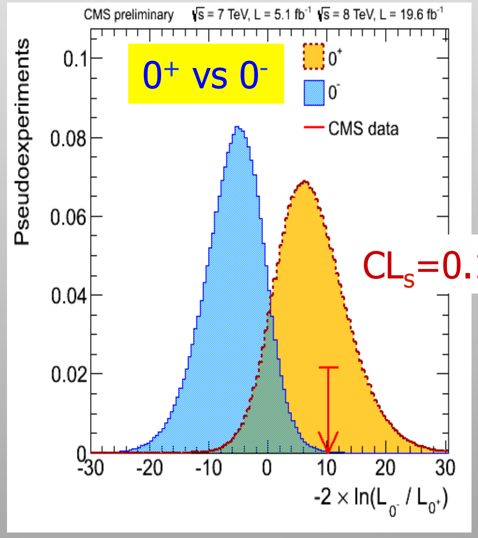
This observed particle
has a VEV!

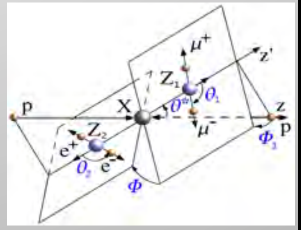
Spin/Parity Hypothesis Tests

Spin/parity hypothesis tests: H → ZZ → 4l channel

Kinematic discriminant built to describe the kinematics of production and decay of different J^P state of a "Higgs"







More J^P hypotheses have been tested in a similar way →

J^P	CL_s
0^-	0.16%
0_h^+	8.1%
2^+_{mgg}	1.5%
$2^+_{mq\bar{q}}$	<0.1%
1^-	<0.1%
1^+	<0.1%

$\cancel{h Z_{\mu\nu} Z^{\mu\nu}}$

$\cancel{h Z_{\mu\nu} \tilde{Z}^{\mu\nu}}$

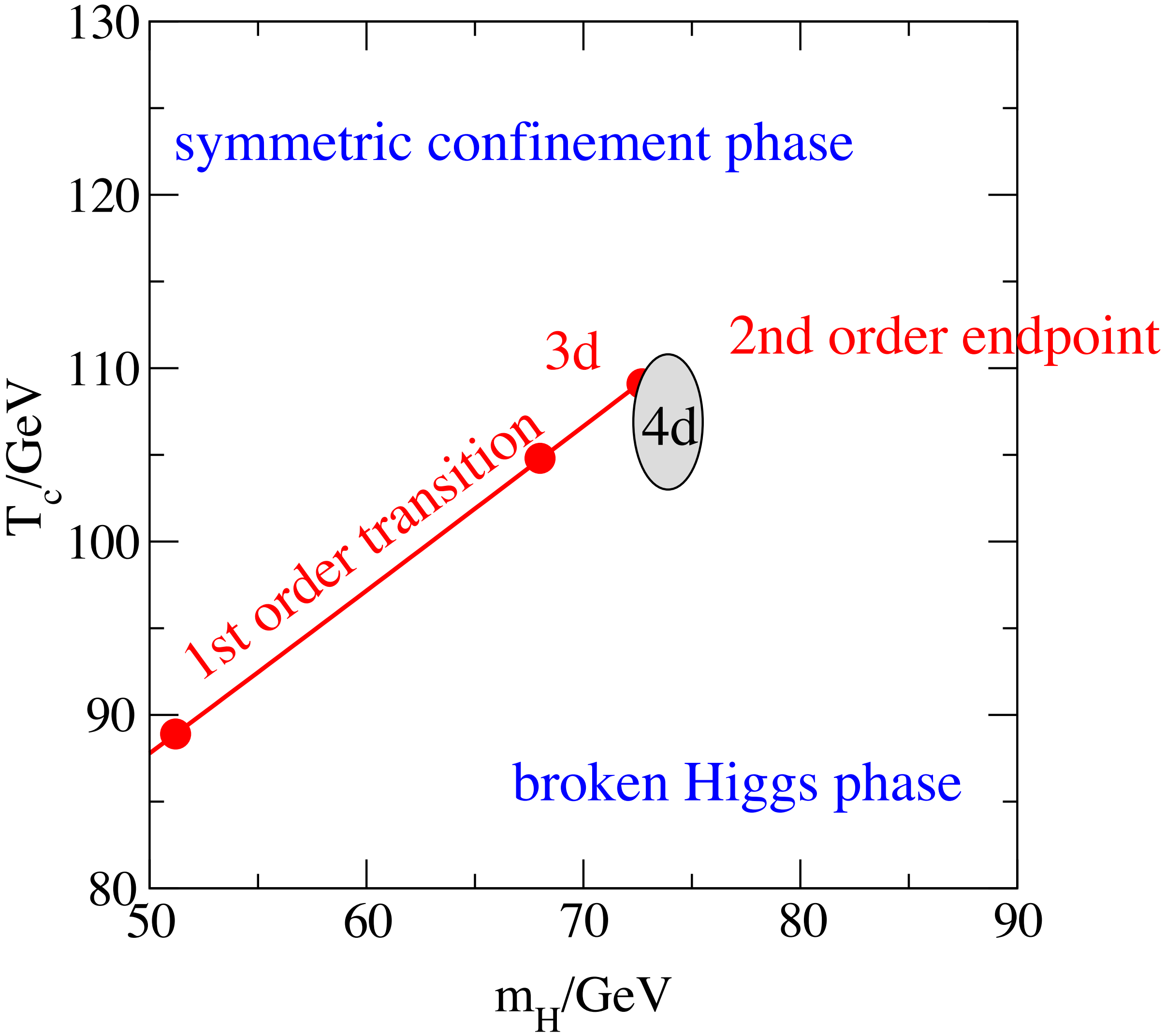
have seen $h Z_\mu Z^\mu$ $\cancel{h_{\mu\nu} Z^{\mu\rho} Z^\nu_\rho}$

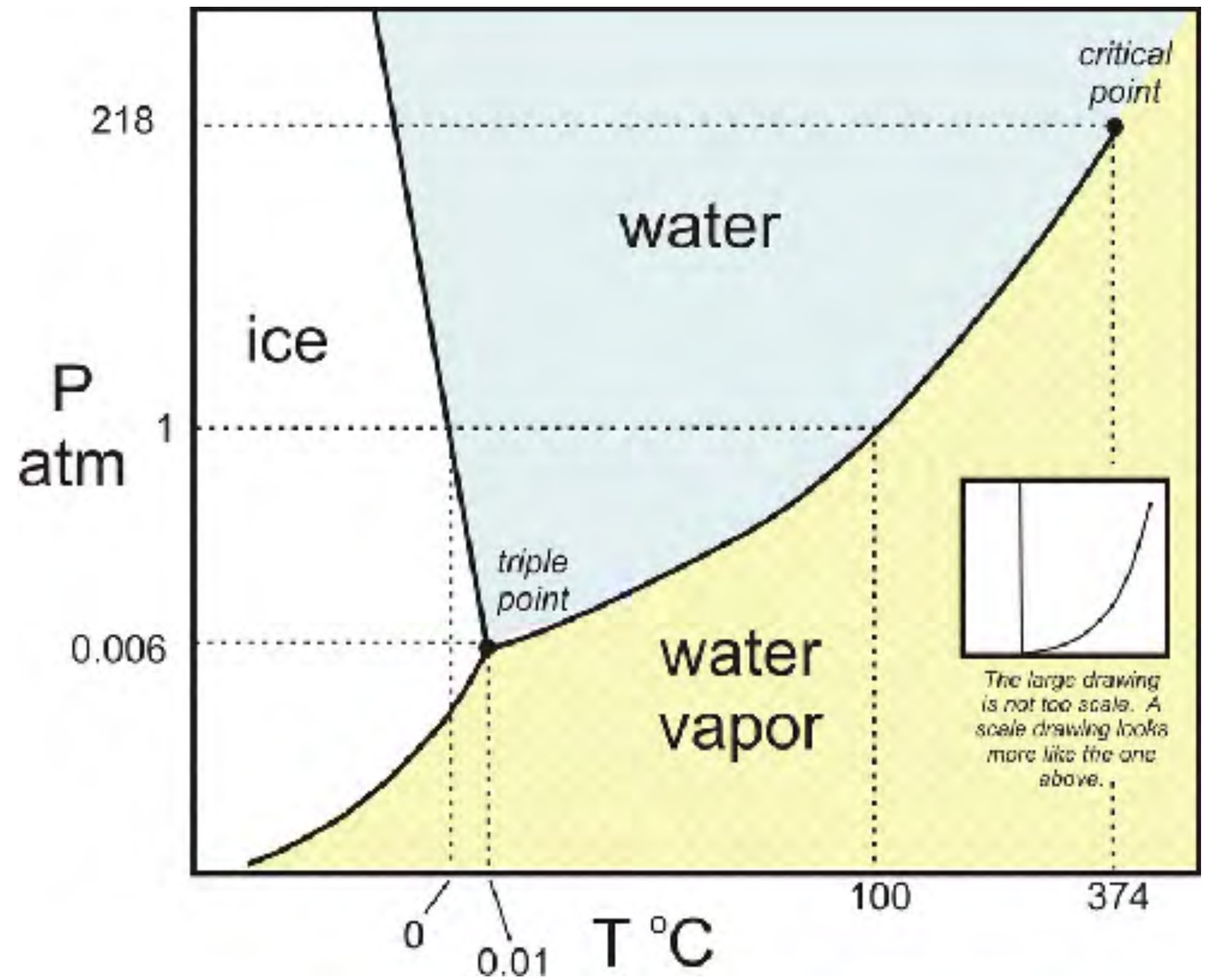
but a gauge boson $\phi^\dagger \phi Z_\mu Z^\mu$

only way $h \langle h \rangle Z_\mu Z^\mu$

we have discovered a particle
that has a value in vacuum

Mikko Laine (Bern)





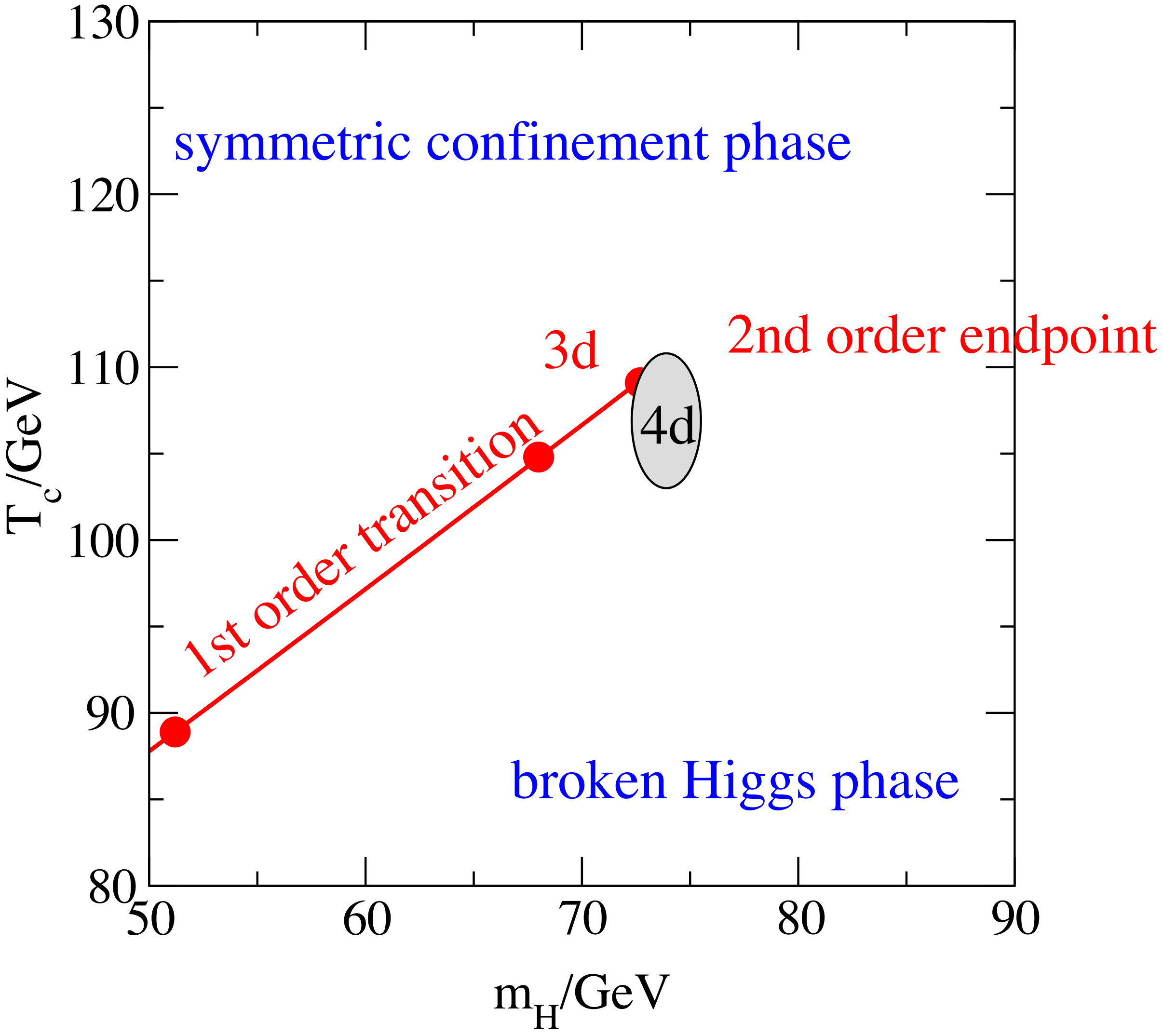
$\langle H \rangle$=0 from gauge invariance (Elitzur)

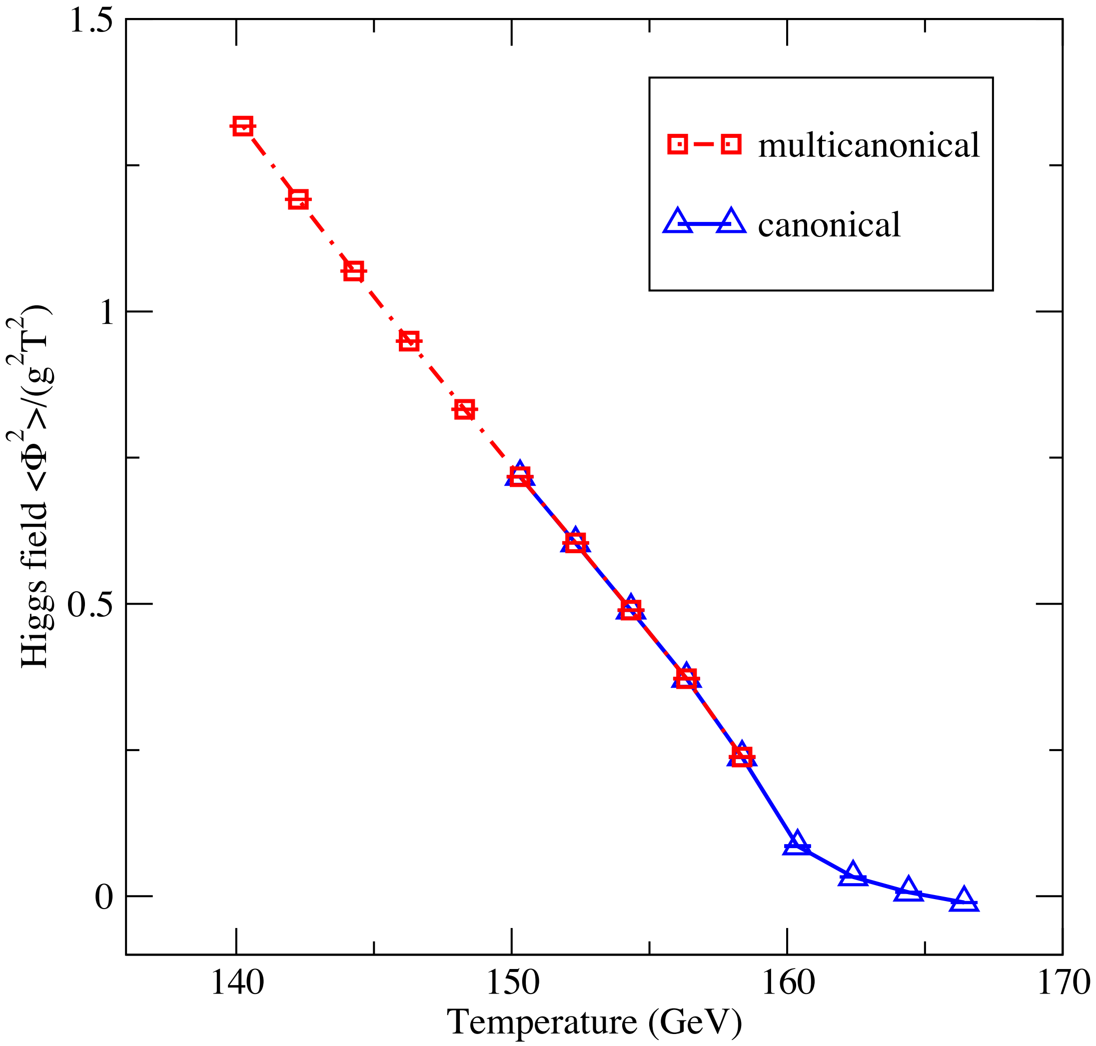
$\langle H^\dagger H \rangle$ is not an order parameter

for m_h=125GeV, it is crossover

No phase transition in the Minimal Standard Model

Mikko Laine (Bern)





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

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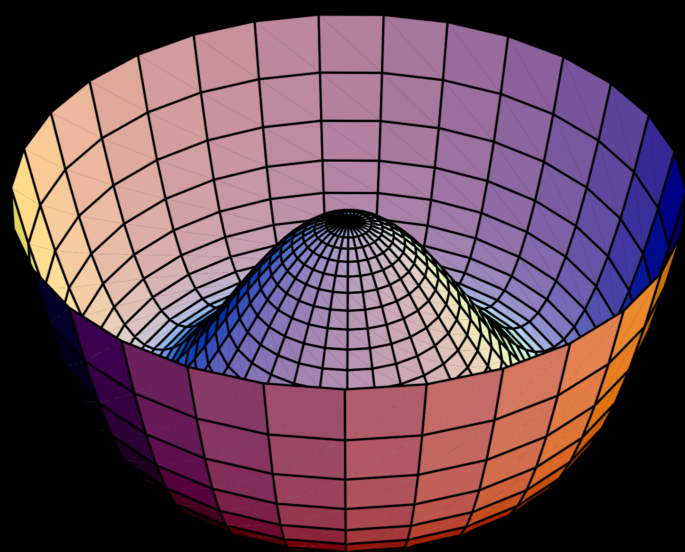
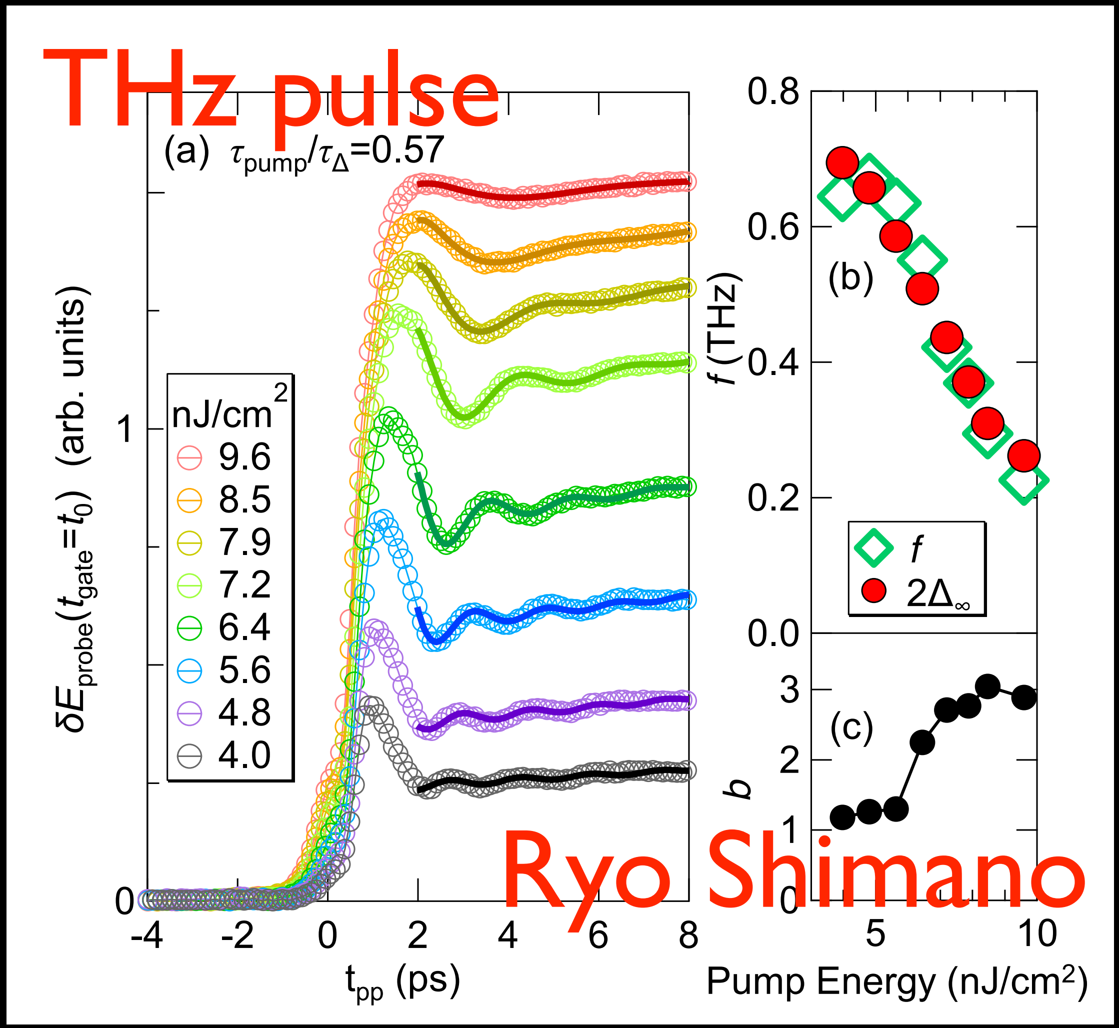
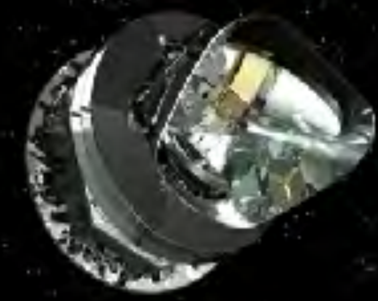
No phase transition in the Minimal Standard Model

superconductors

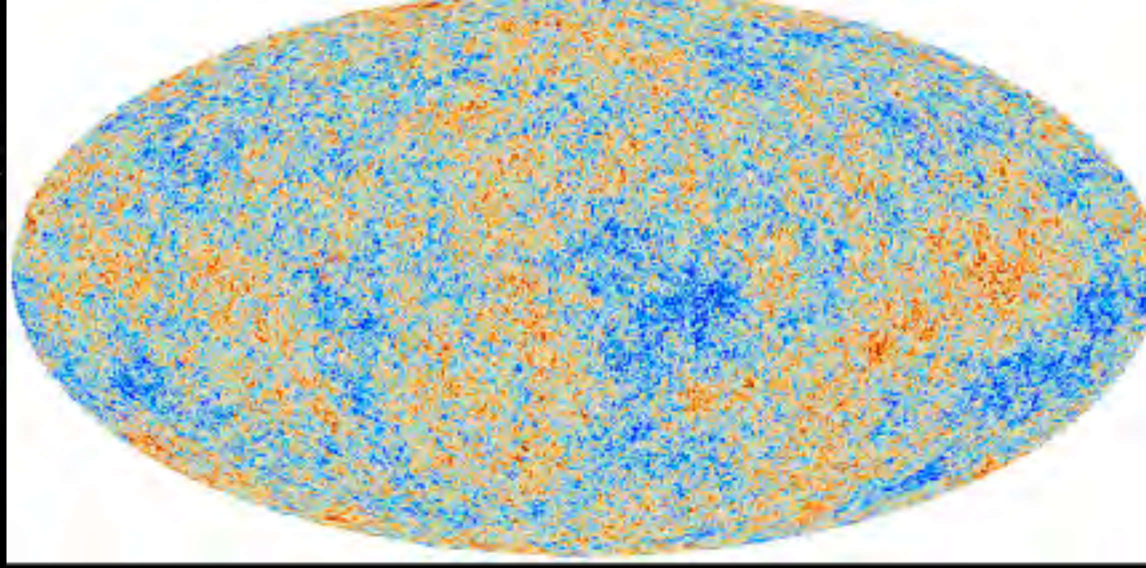




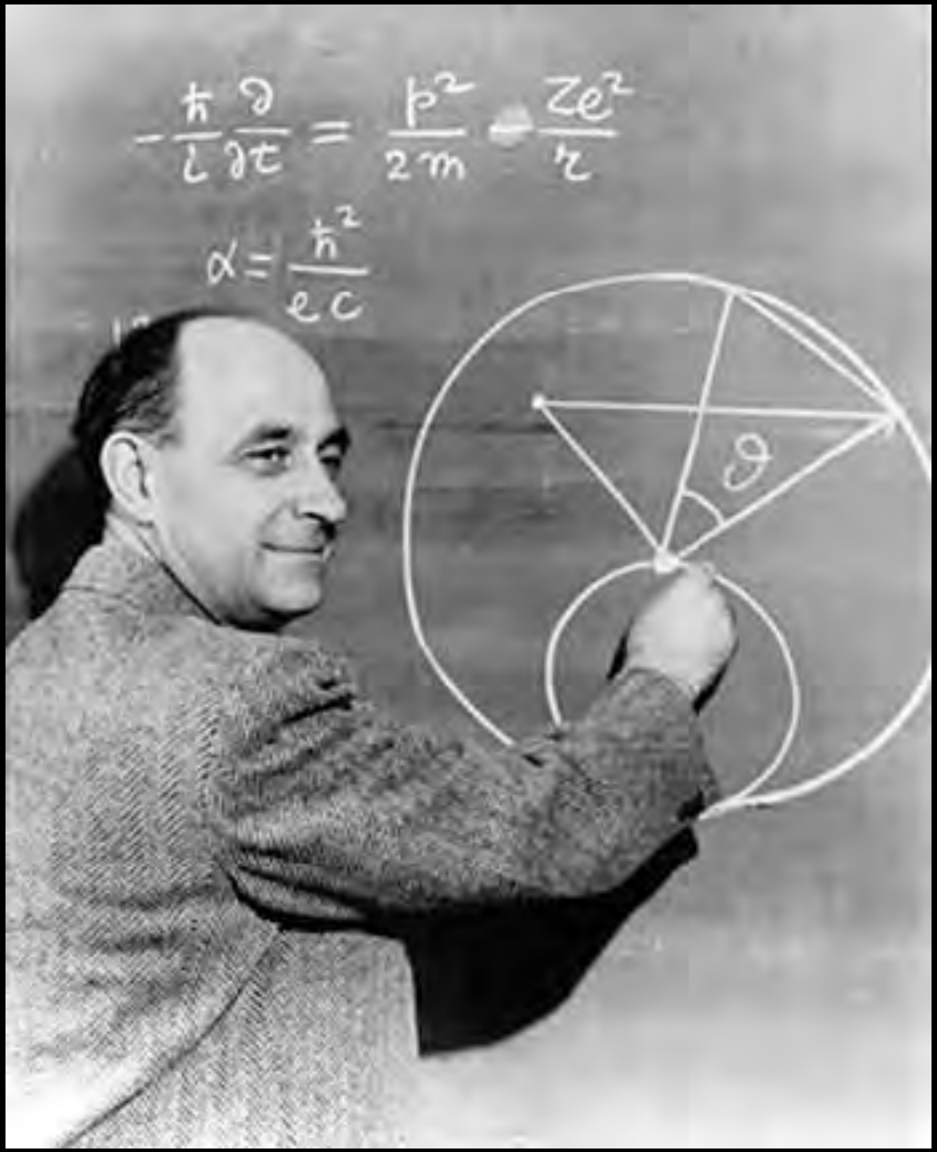
Minimal



Planck



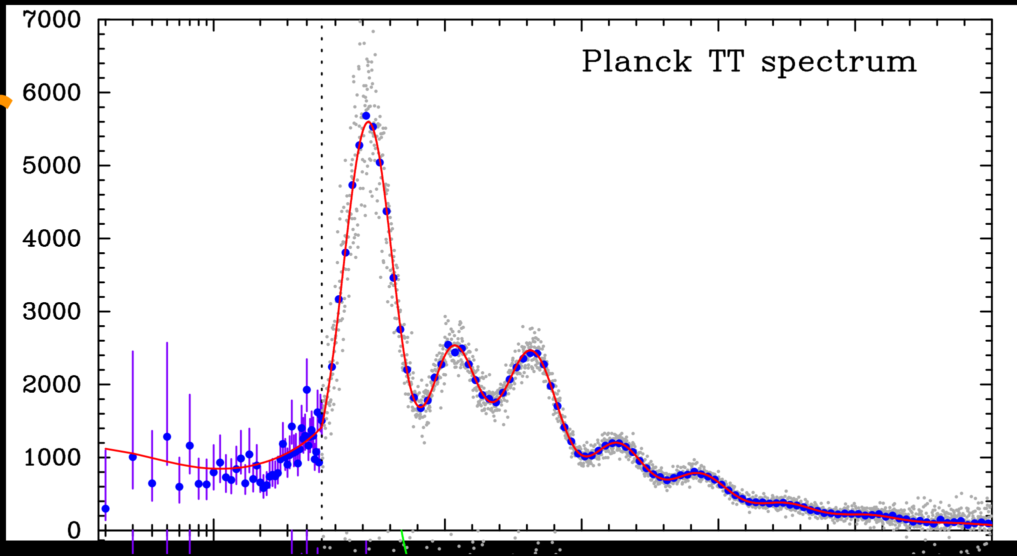
- It looks very much like *the* Standard Model Higgs boson
- We've known the energy scale to probe since 1933
- now a UV complete theory of strong, weak, EM forces possibly valid up to even M_{Pl}
- cosmology also looks minimal single-field inflation (Planck)



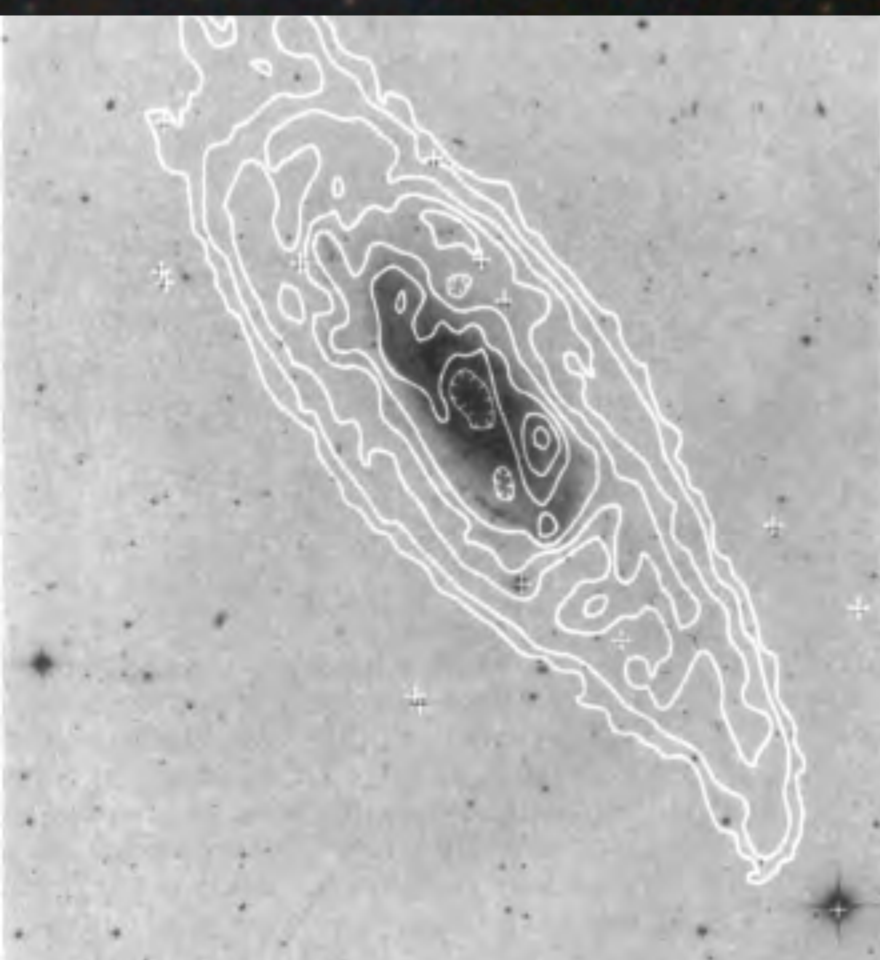
Where do we go next?

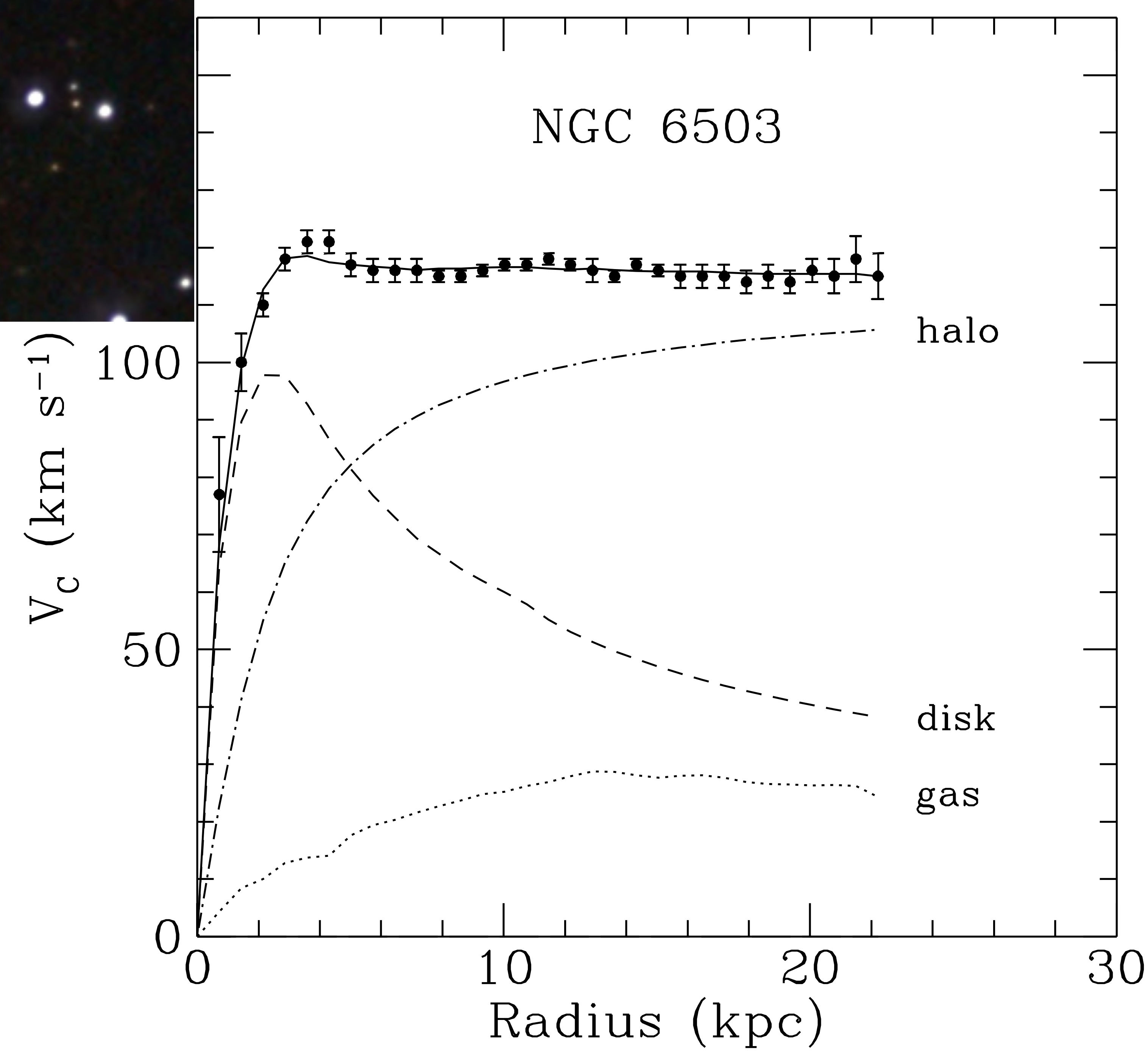
Five evidences for physics beyond SM

- Since 1998, it became clear that there are at least five missing pieces in the SM
  - non-baryonic dark matter
  - neutrino mass
  - dark energy
  - apparently acausal density fluctuations
  - baryon asymmetry

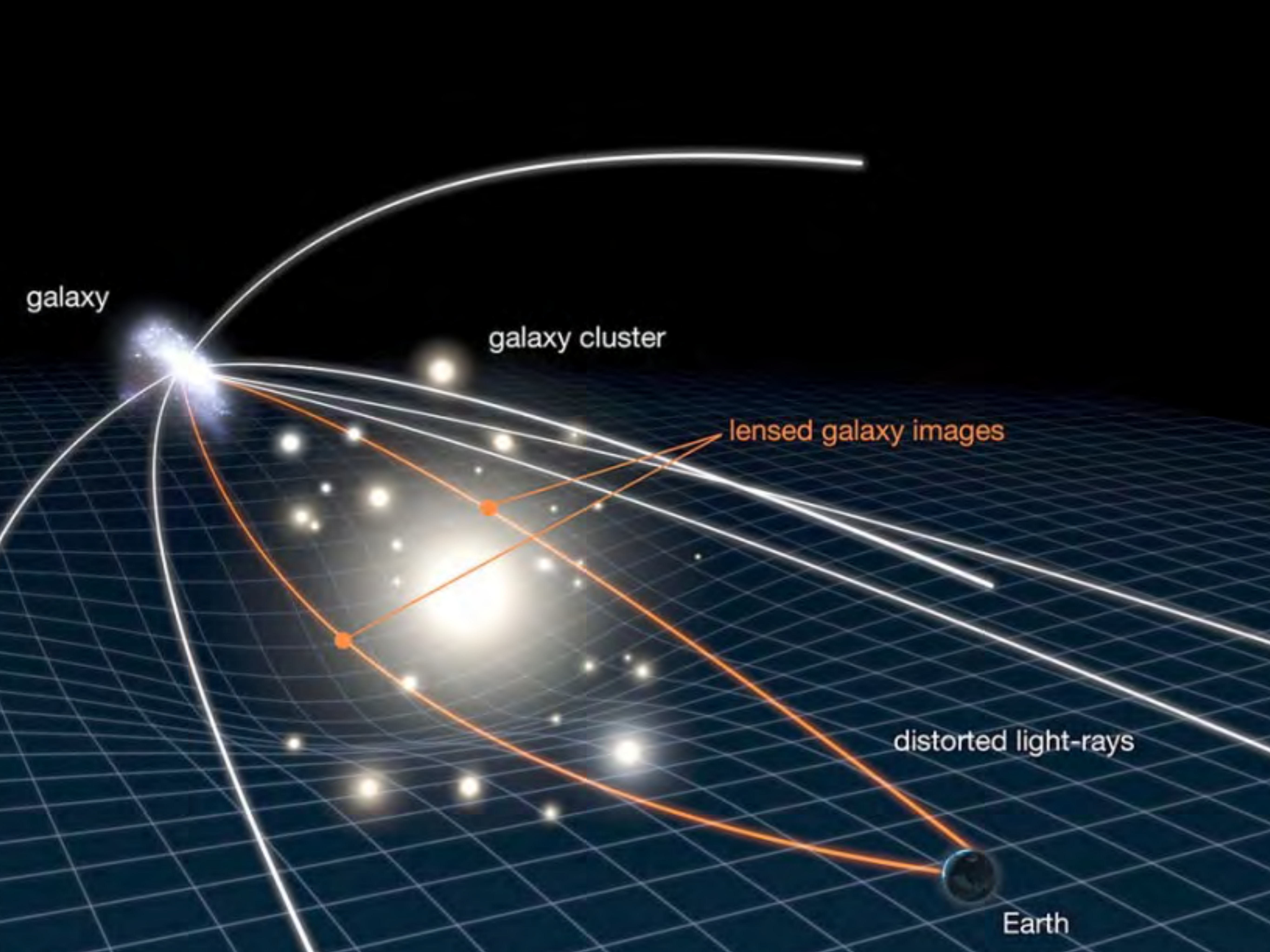


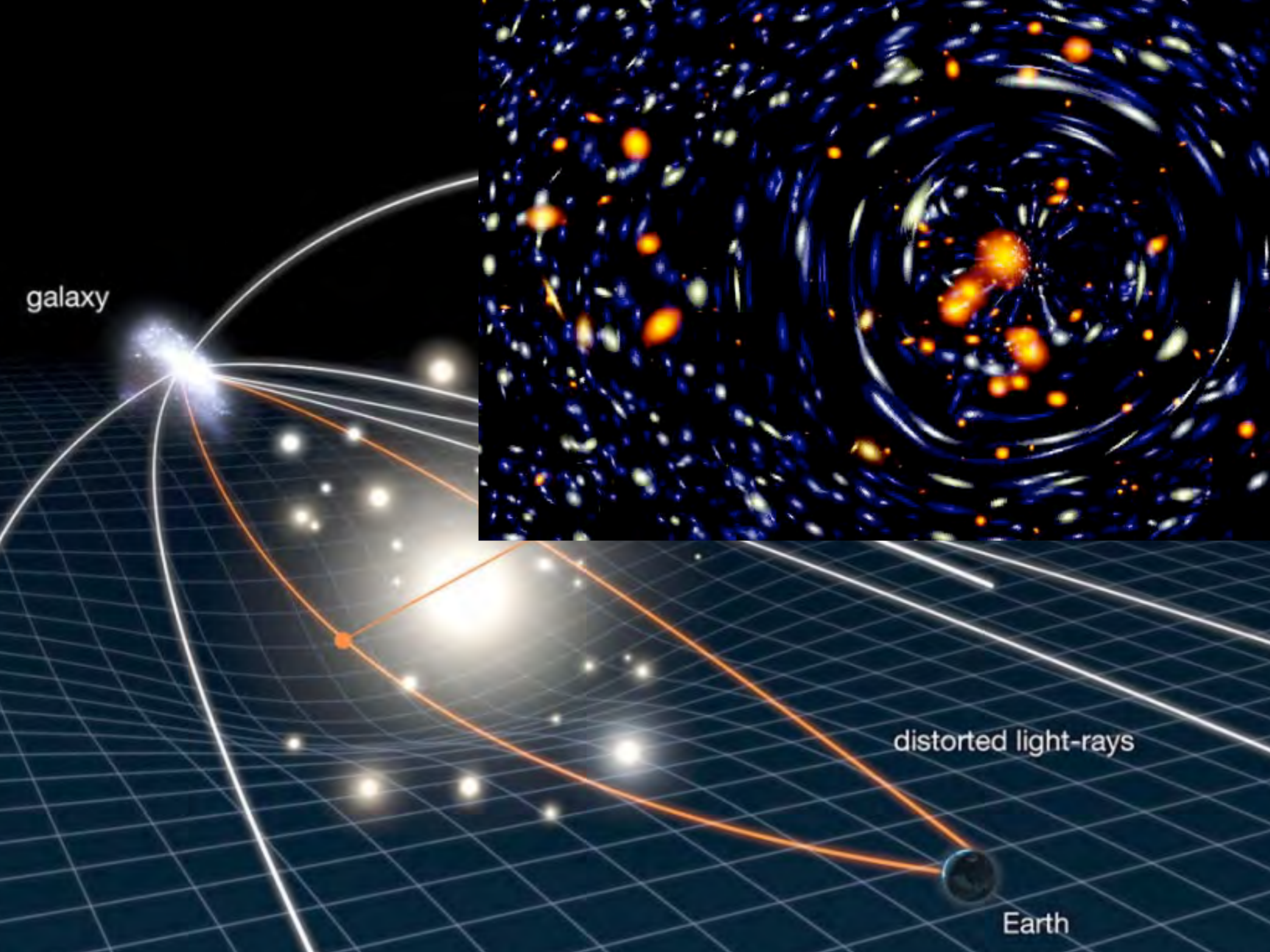
We don't really know their energy scales...




NGC 6503
halo
disk
gas
V_c (km s^{-1})
0
50
100
0
10
20
30
Radius (kpc)


cluster of galaxies
Abell 2218
2.1B lyrs


galaxy
galaxy cluster
lensed galaxy images
distorted light-rays
Earth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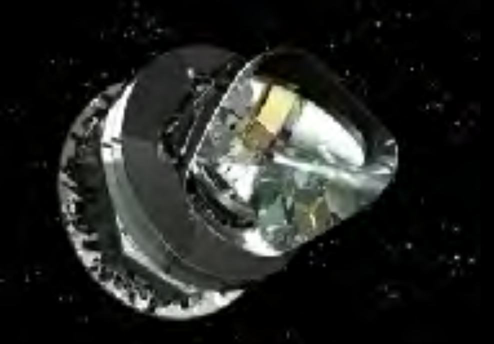
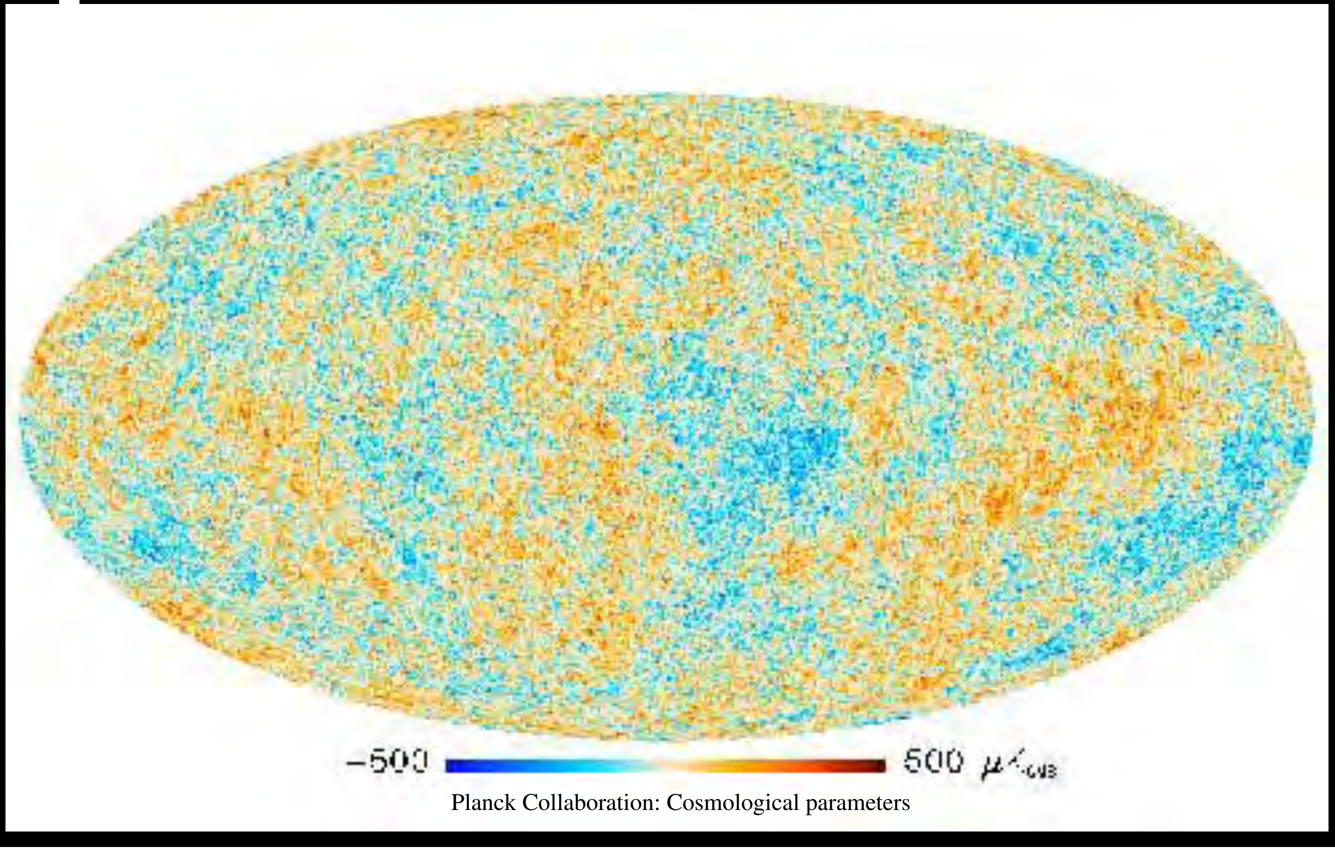


assumption

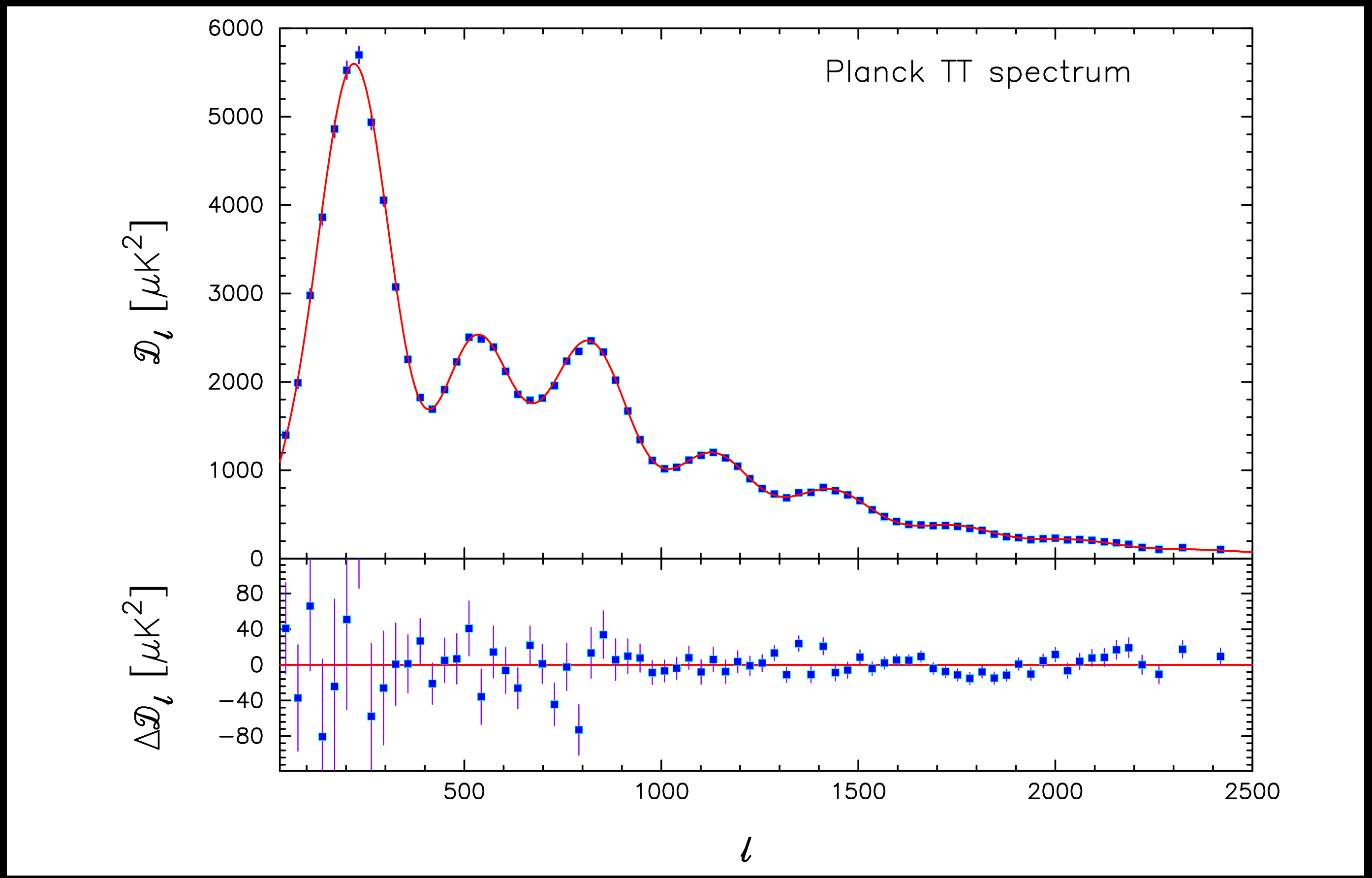


Planck Collaboration: Cosmological parameters

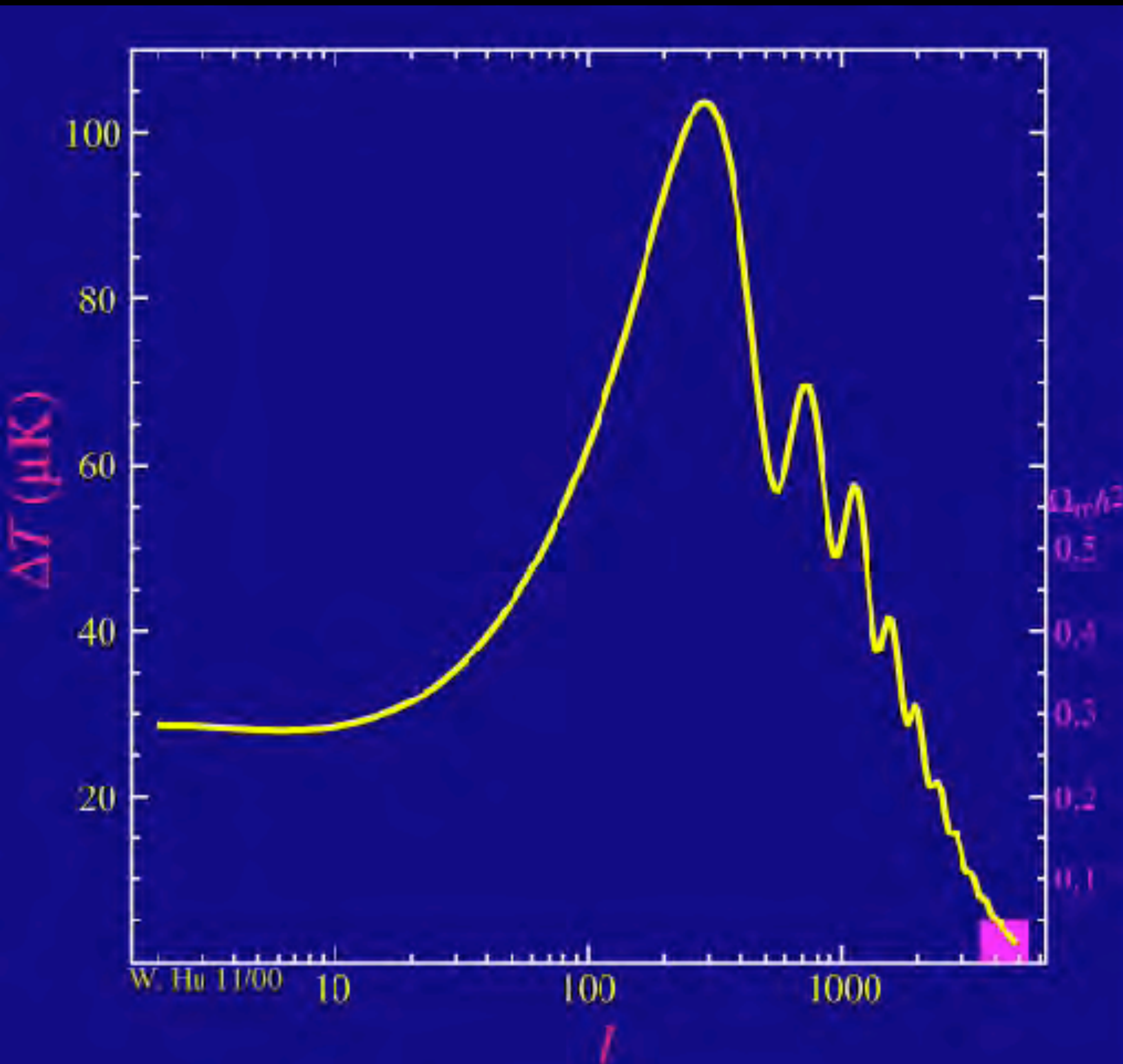
- a random density fluctuations ~O(10^{-5}) more-or-less scale invariant $P(\mathrm{k}) \propto \mathrm{k}^{n_s-1}$
- starts acoustic oscillation, amplified by gravitational attraction
- “knows” about everything between $0<z<1300$

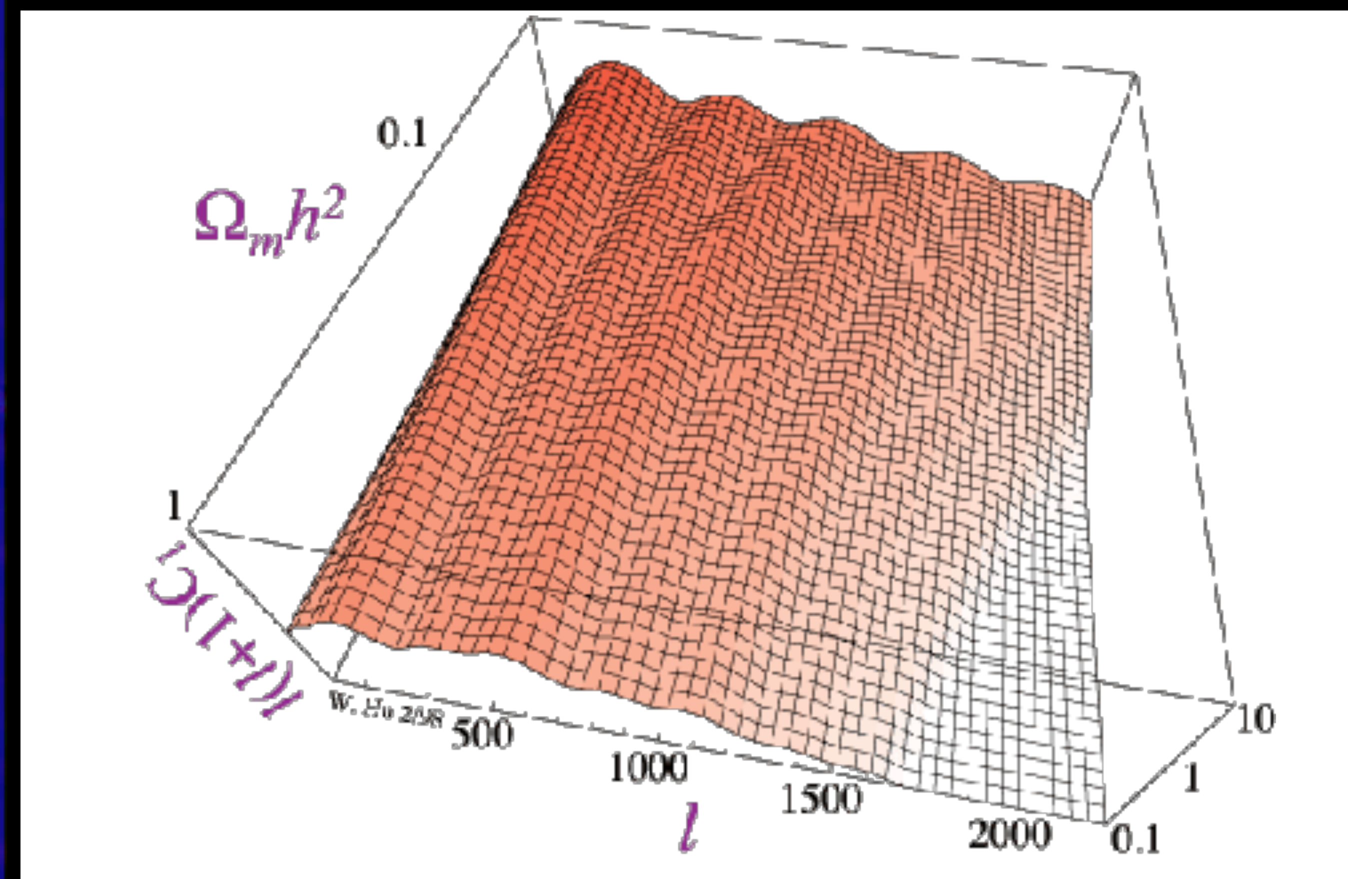
$$\delta T/T = a_{lm}\, Y_l^m$$

$$(2l+1)c_{lm} = \Sigma_m\, a_{lm}^* a_{lm}$$



dark matter





Ω_m changes overall power

HSC performance

HSC: riz in 2.5 hours

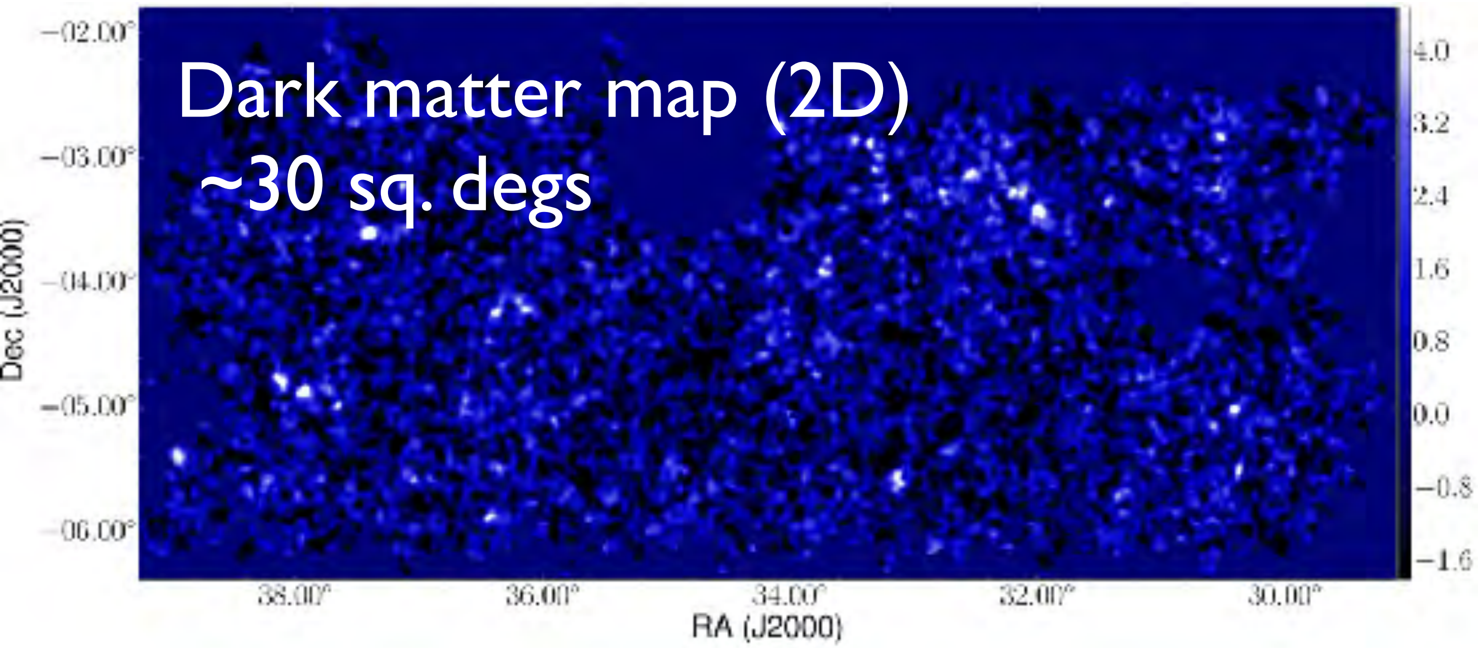
COSMOS HST (640 orbits: ~500hrs)

Conducting a major survey for 300 nights! First data release Feb 2017

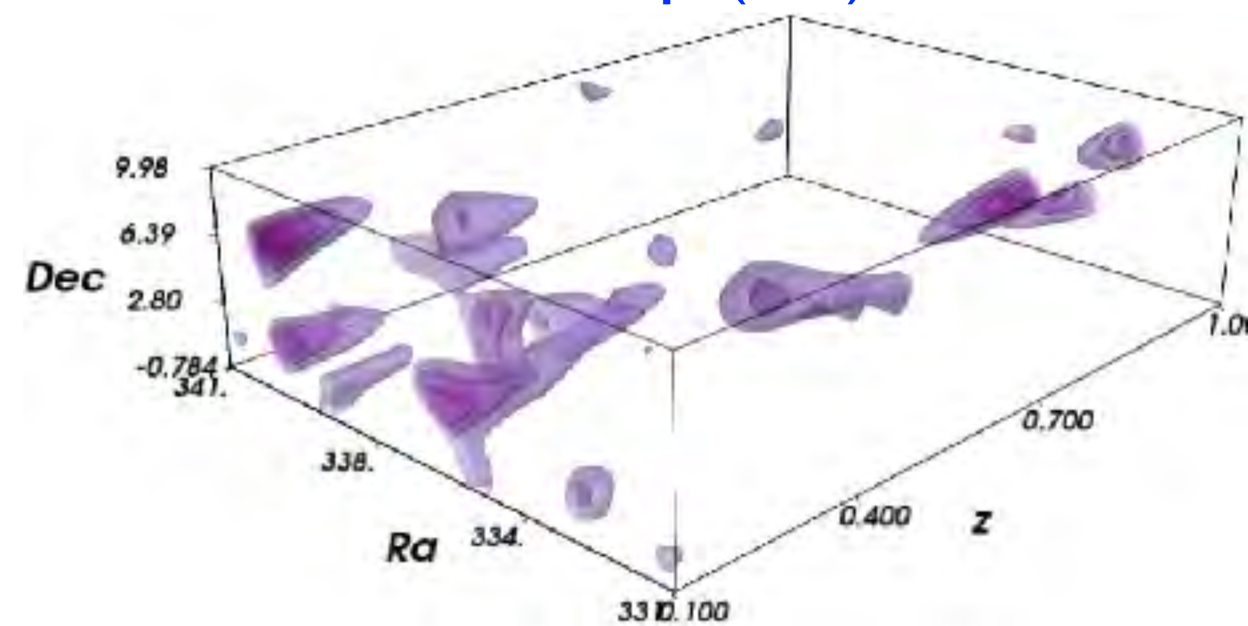
2D & 3D Dark Matter Map

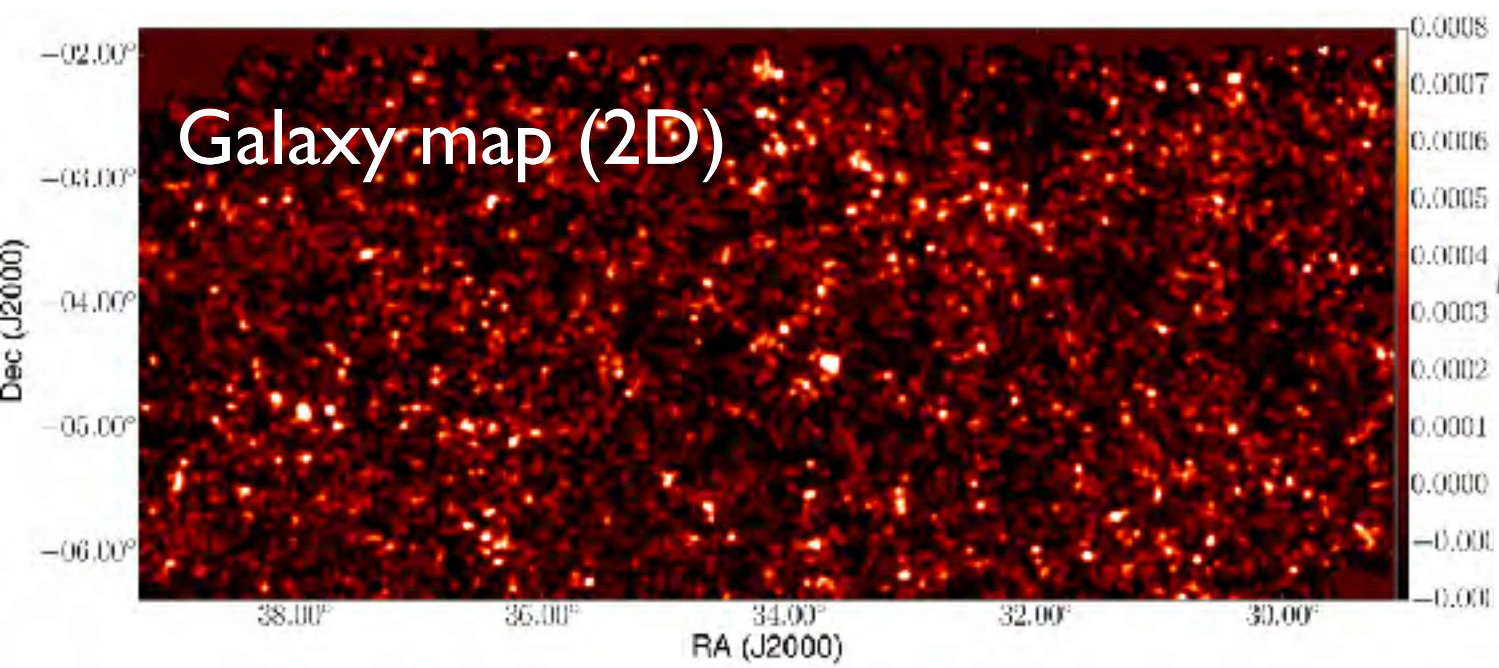
- Galaxy shape catalog now fixed (Mandelbaum, Miyatake + 17)
- Galaxy shapes + Photoz of gals → 3D mass & galaxy maps
- Strong correlations between DM and galaxy distributions

Oguri et al. arXiv:1705.06792

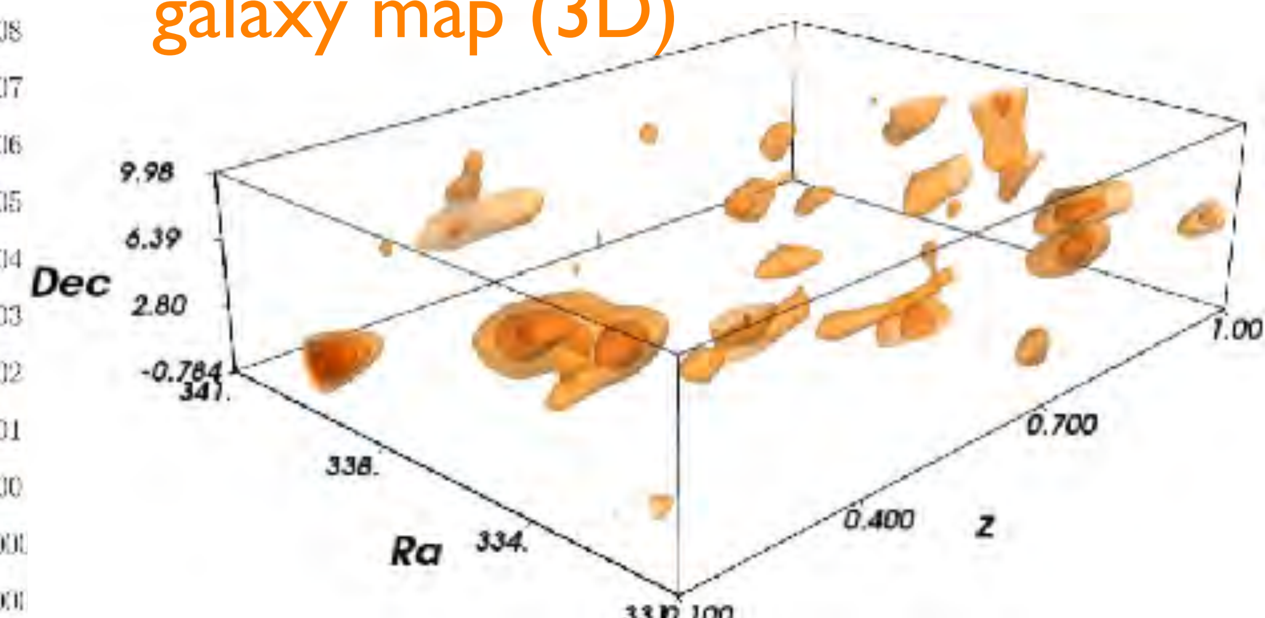


Dark matter map (3D)



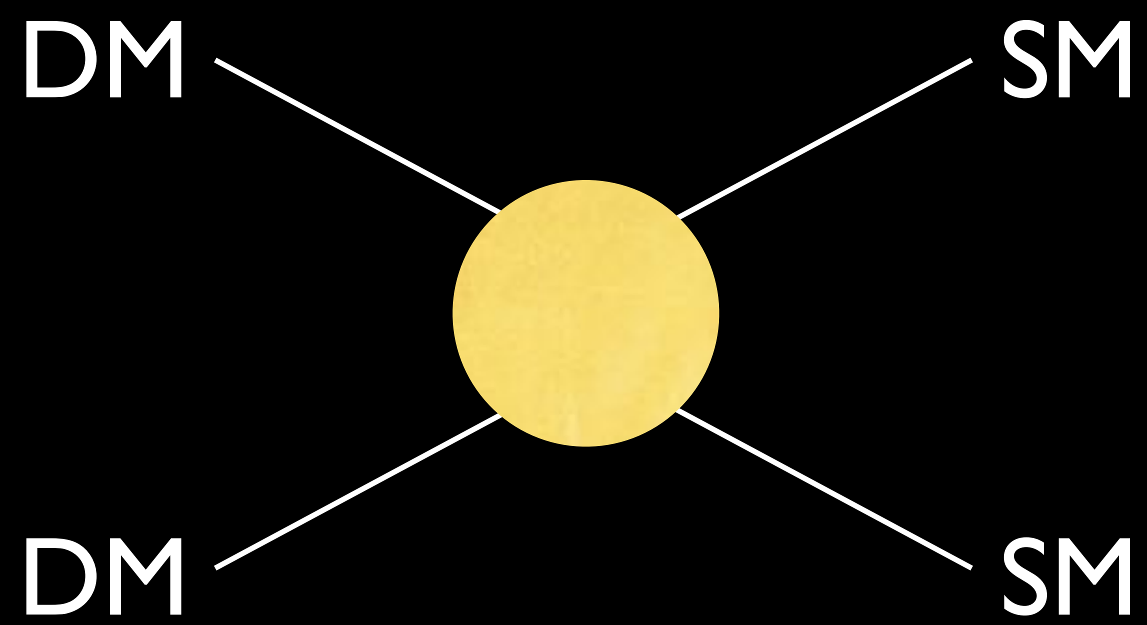


galaxy map (3D)



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

WIMP Miracle



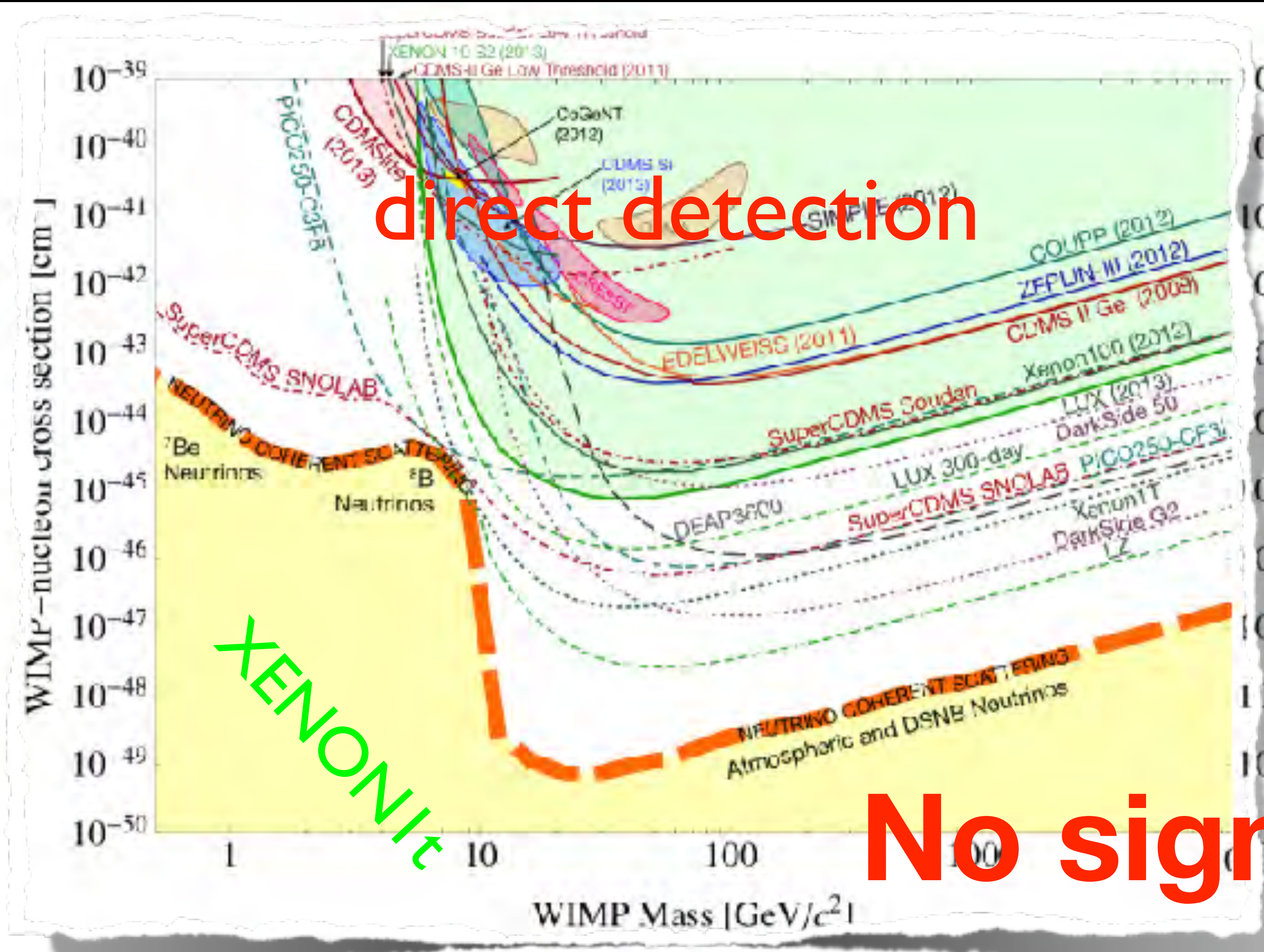
$$\langle \sigma_{2\to 2} v \rangle \approx \frac{\alpha^2}{m^2}$$

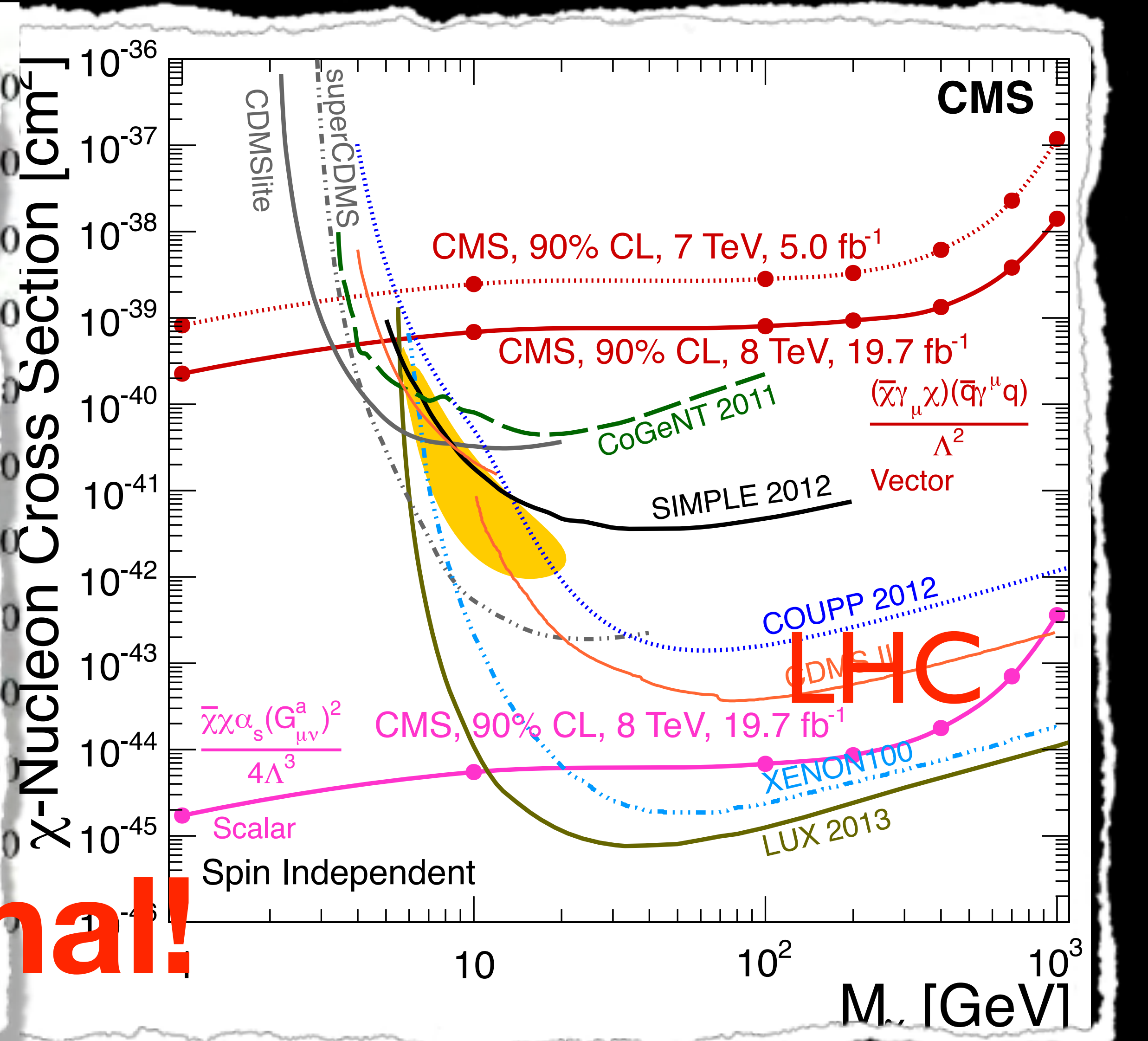
$$\alpha \approx 10^{-2}$$

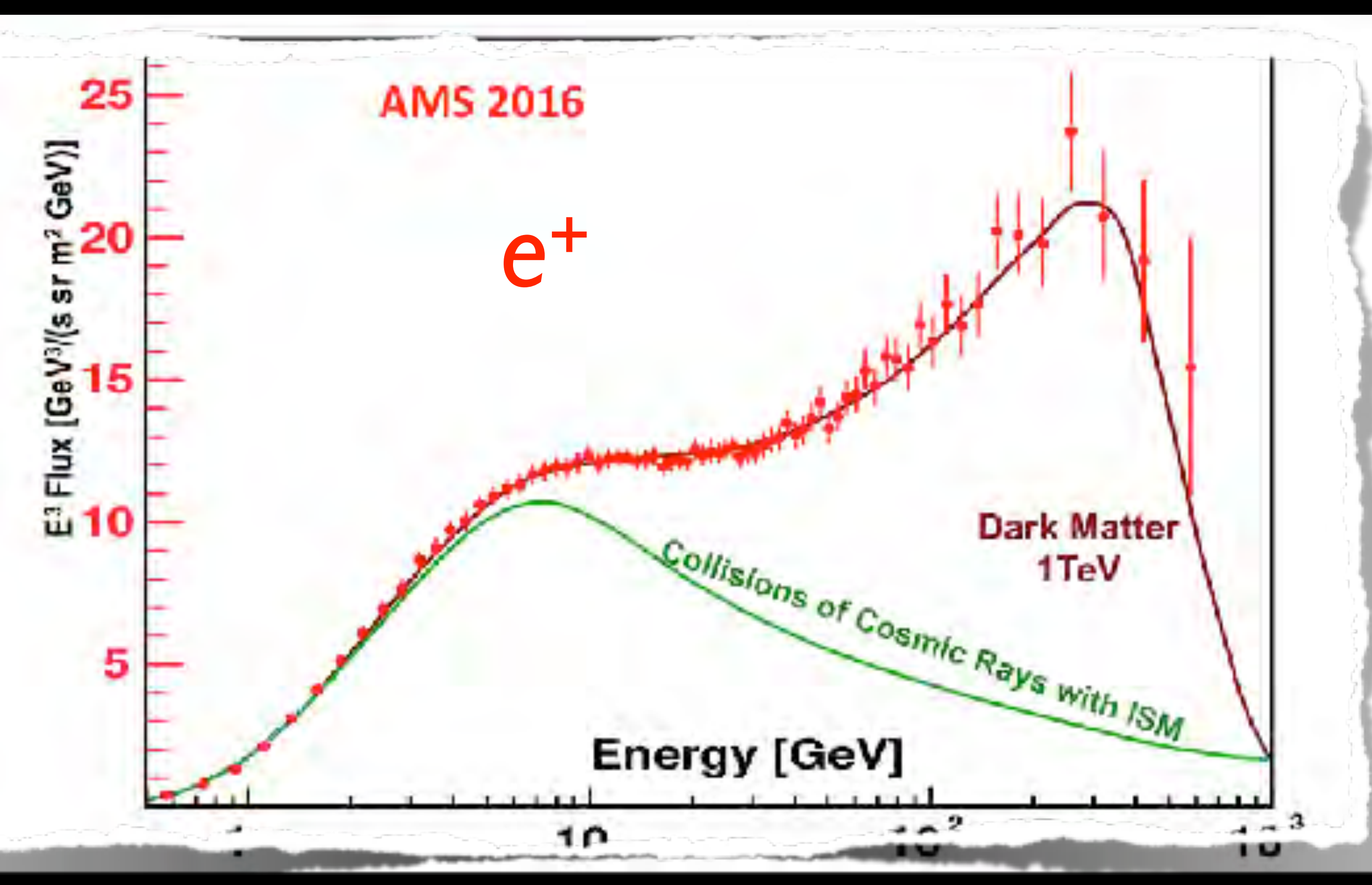
$$m \approx 300 \text{ GeV}$$

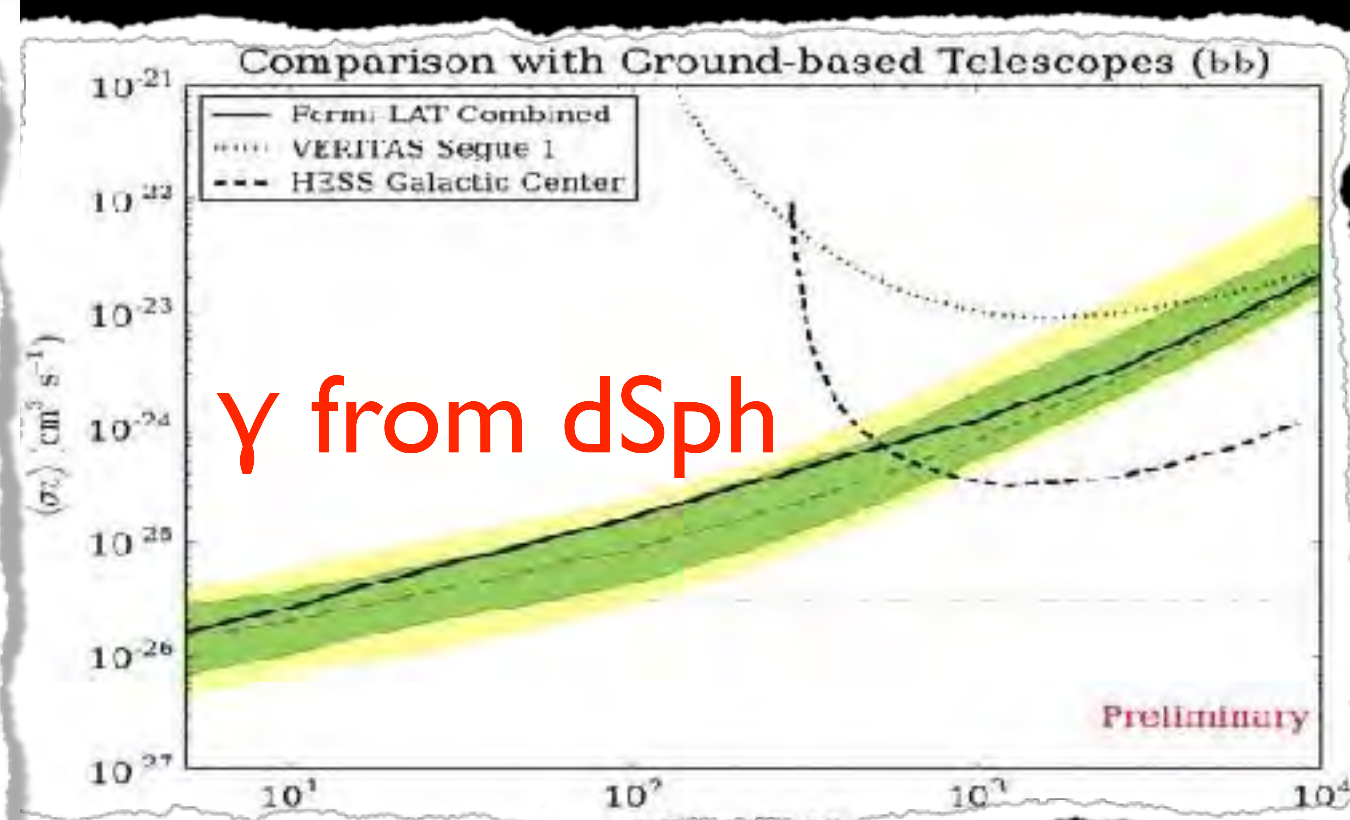
“weak” coupling
“weak” mass scale → correct abundance

Miracle^2


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


No signal!
LHC
CMS
χ-Nucleon Cross Section [cm²]
M_χ [GeV]
CMS, 90% CL, 7 TeV, 5.0 fb⁻¹
CMS, 90% CL, 8 TeV, 19.7 fb⁻¹
Vector
CoGeNT 2011
SIMPLE 2012
COUPP 2012
CDMS II
CMS, 90% CL, 8 TeV, 19.7 fb⁻¹
XENON100
LUX 2013
Scalar
Spin Independent
CDMSlite
superCDMS

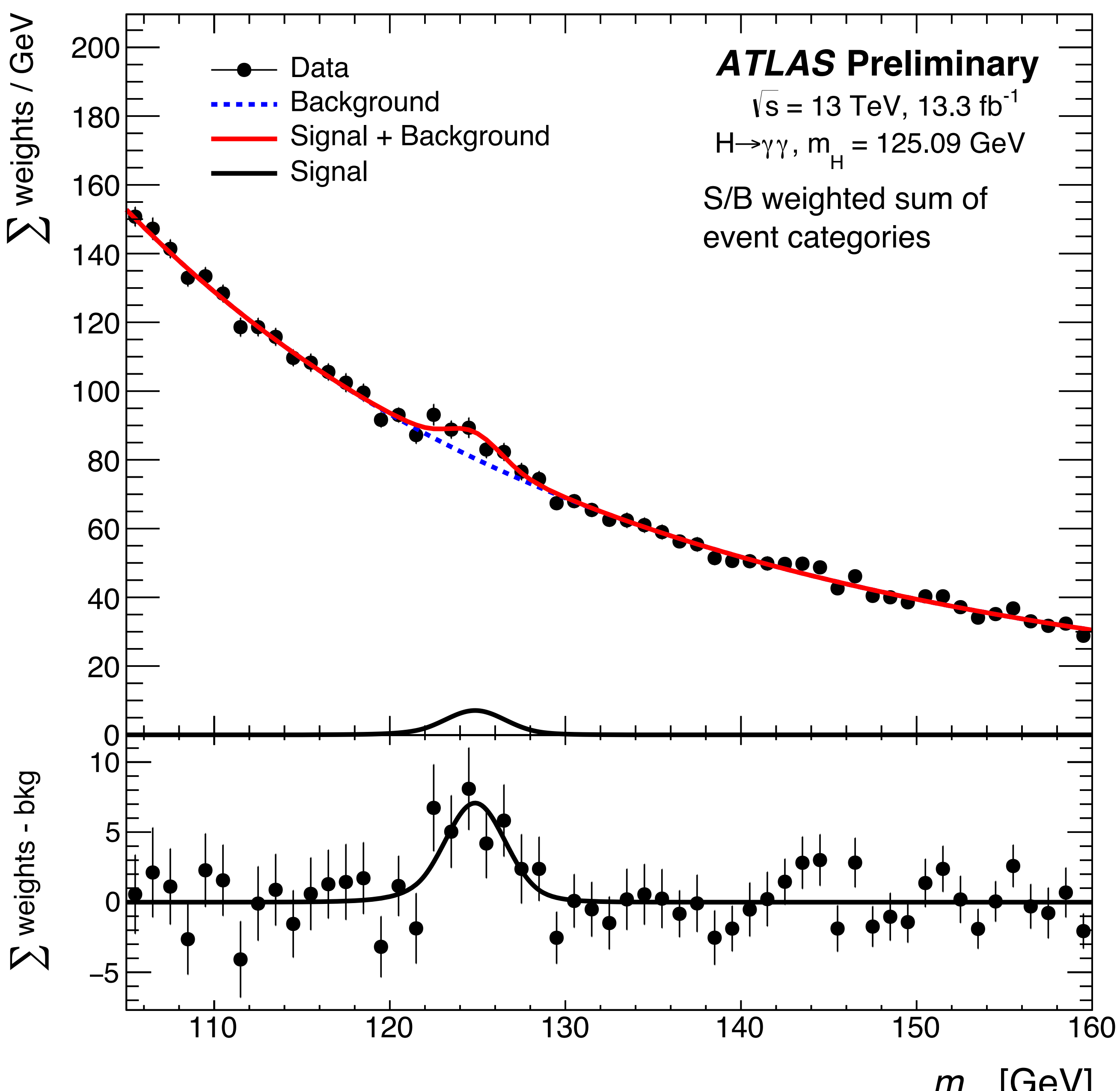

AMS 2016
e+
E³ Flux [GeV³/(s sr m² GeV)]
Dark Matter 1TeV
Collisions of Cosmic Rays with ISM
Energy [GeV]


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

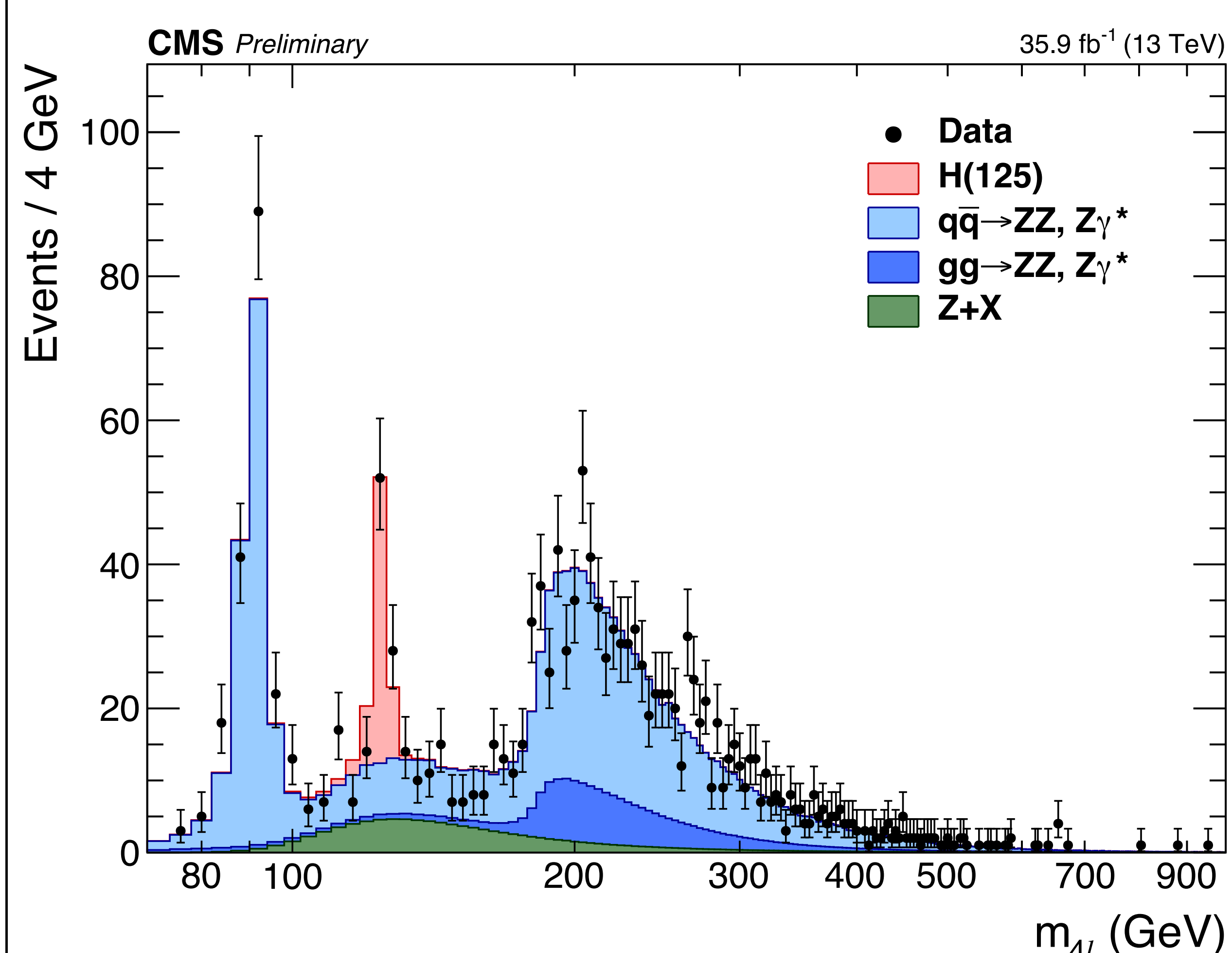
What have we learned about Higgs?

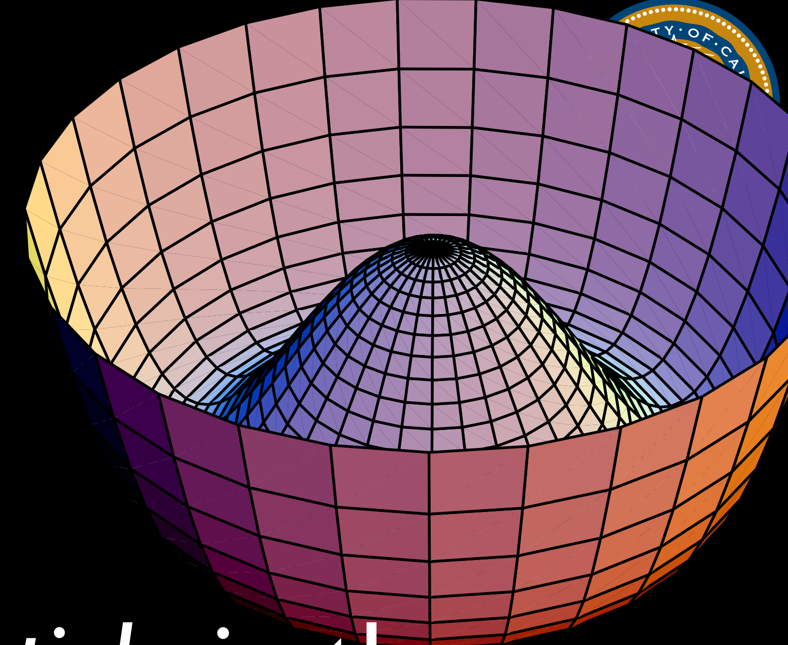
Beautiful data

ATLAS-CONF-2016-067



CMS-HIG-16-041





I hated it!

- Higgs boson is the *only spin 0 particle* in the standard model
  - we have never seen one before
  - one of its kind, no context
  - but does the most important job
- looks very artificial
- we still don't know *dynamics* behind the Higgs condensate
- *Higgsless theories*: now dead

Theoretical Foundation for Scalar Bosons?

Supersymmetry

- Higgs just one of *many* scalar bosons
- SUSY loops make m_h^2 negative
- superpartners

composite

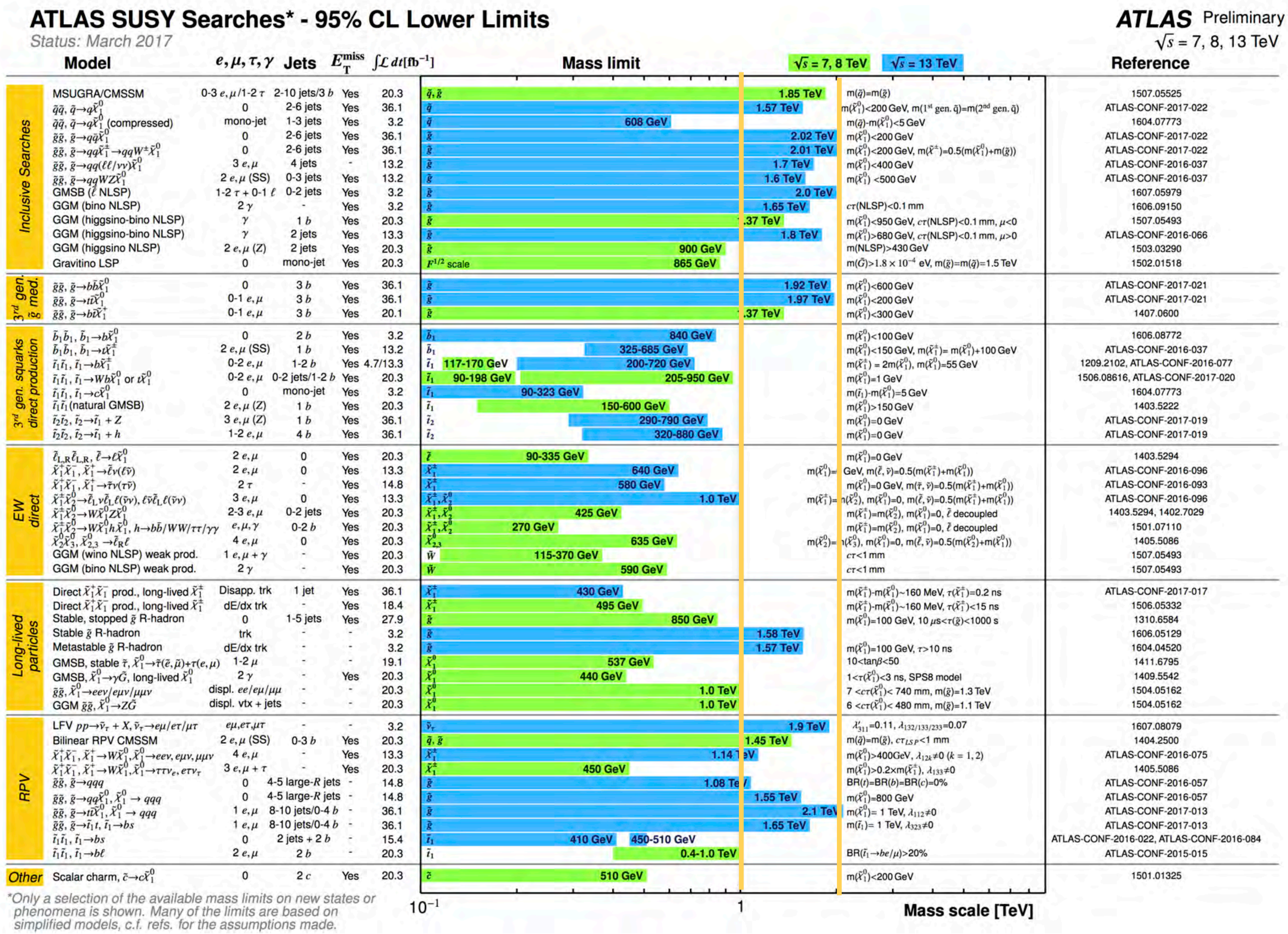
- spins cancel among constituents
- condensate by a strong attractive force, holography
- top partner, pNGBs, vector-like quarks

Extra dimension

- Higgs spinning in extra dimensions
- new forces from particles running in extra D
- KK particles

a different "naturalness" argument

no new physics



"The 2 TeV line has been reached for some scenarios"

Why SUSY?

- rationale for scalars
- helps stabilize inflaton potential
- gauge coupling unification
- dark matter candidate
- hierarchy (naturalness) problem
- *fun for colliders*
- baryogenesis?
- cosmological constant?
- mathematically interesting
- string theory needs it

Why SUSY?

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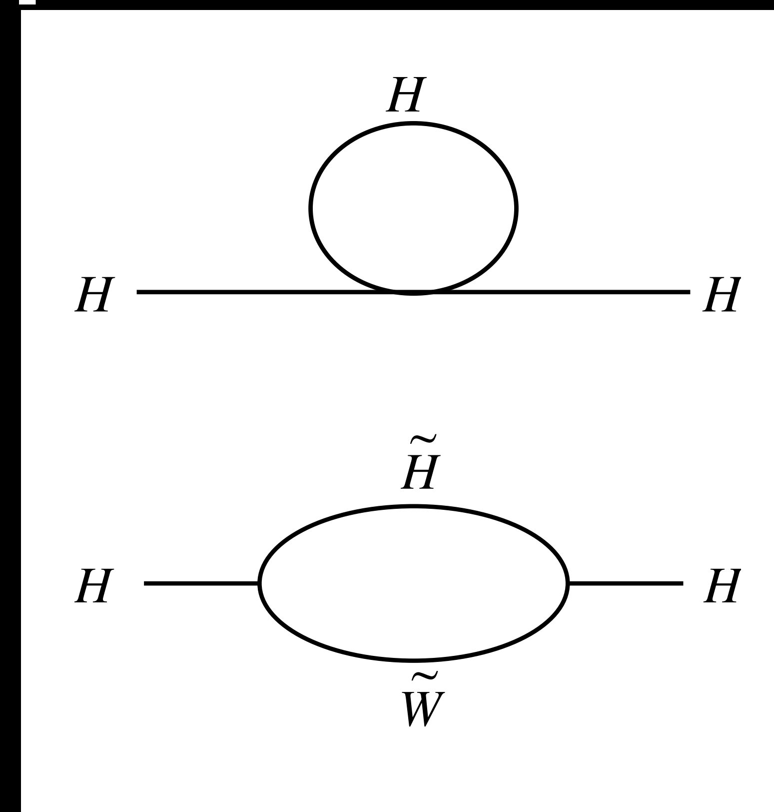
- helps stabilize inflaton potential
- gauge coupling unification
- dark matter candidate
- hierarchy (naturalness) problem
- *fun for colliders*
- baryogenesis?
- cosmological constant? 10^{-120} to 10^{-60}
- mathematically interesting
- string theory needs it

Higgs mass is natural by doubling #particles?

- Higgs also repels itself
- Double #particles again
  ⇒ superpartners
- only log sensitivity to UV
- Standard Model made consistent up to higher energies

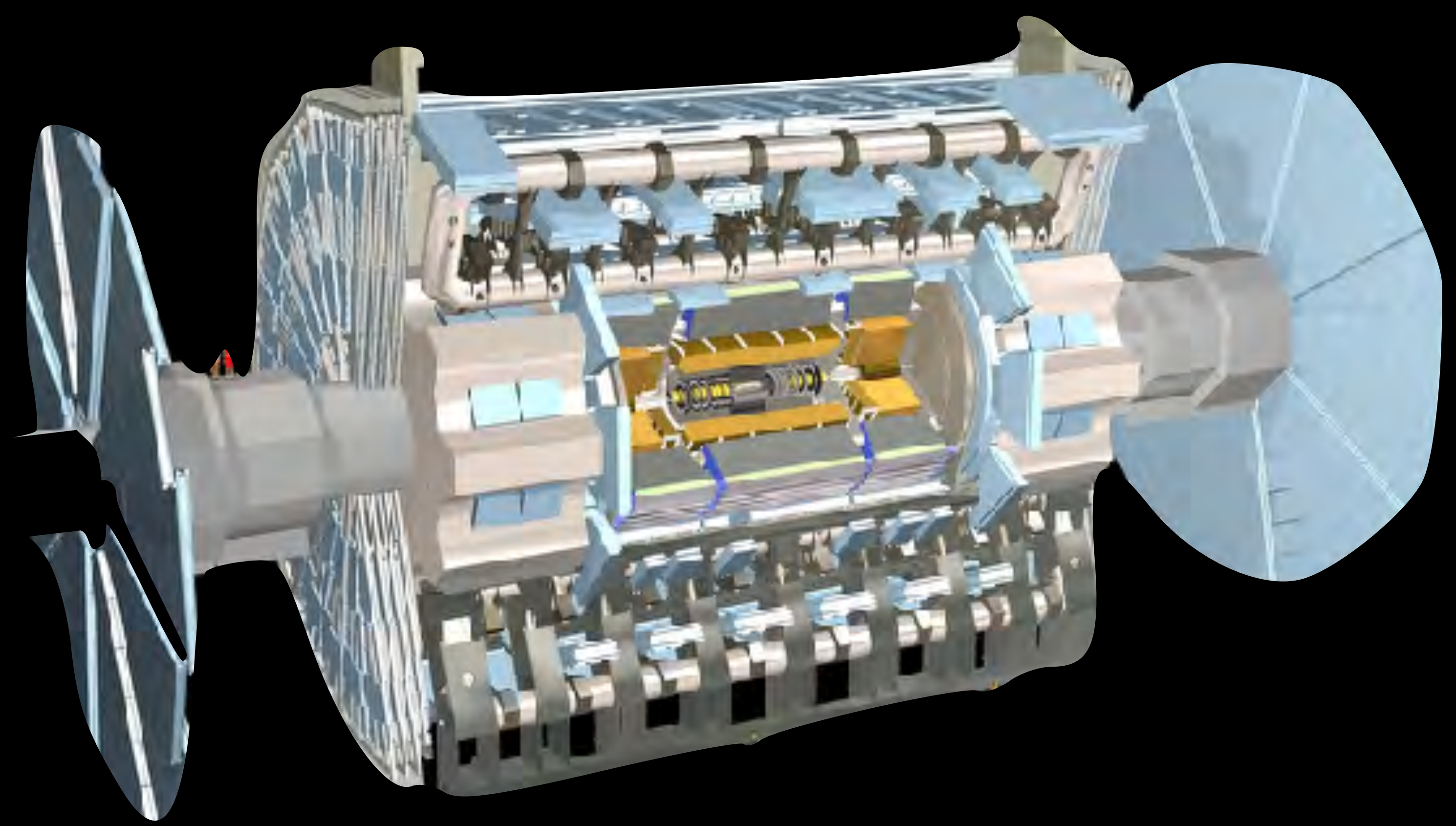


$$\Delta m_H^2 \sim \frac{\alpha}{4\pi} m_{SUSY}^2 \log(m_H r_H)$$

I still take it seriously

$$m_H^2 = (125)^2 = 15625\ \text{GeV}^2$$

$$
\begin{array}{rr}
 & 314\ 159\ 265\ 358\ 979\ 323\ 846\ 264\ 338\ 327\ 950\ 288 \\
- & 314\ 159\ 265\ 358\ 979\ 323\ 846\ 264\ 338\ 327\ 948\ 726 \\
= & 15\ 625
\end{array}
$$

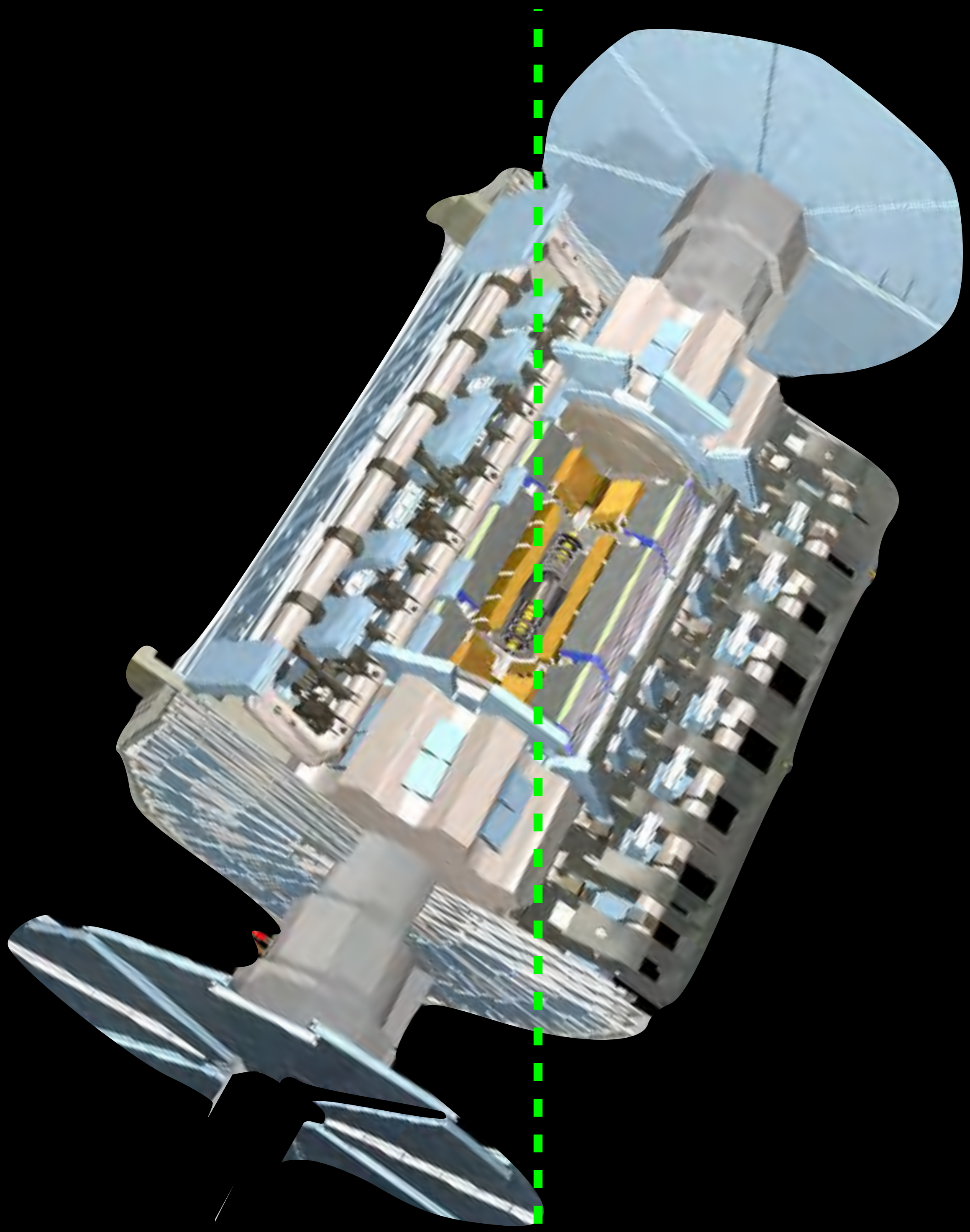


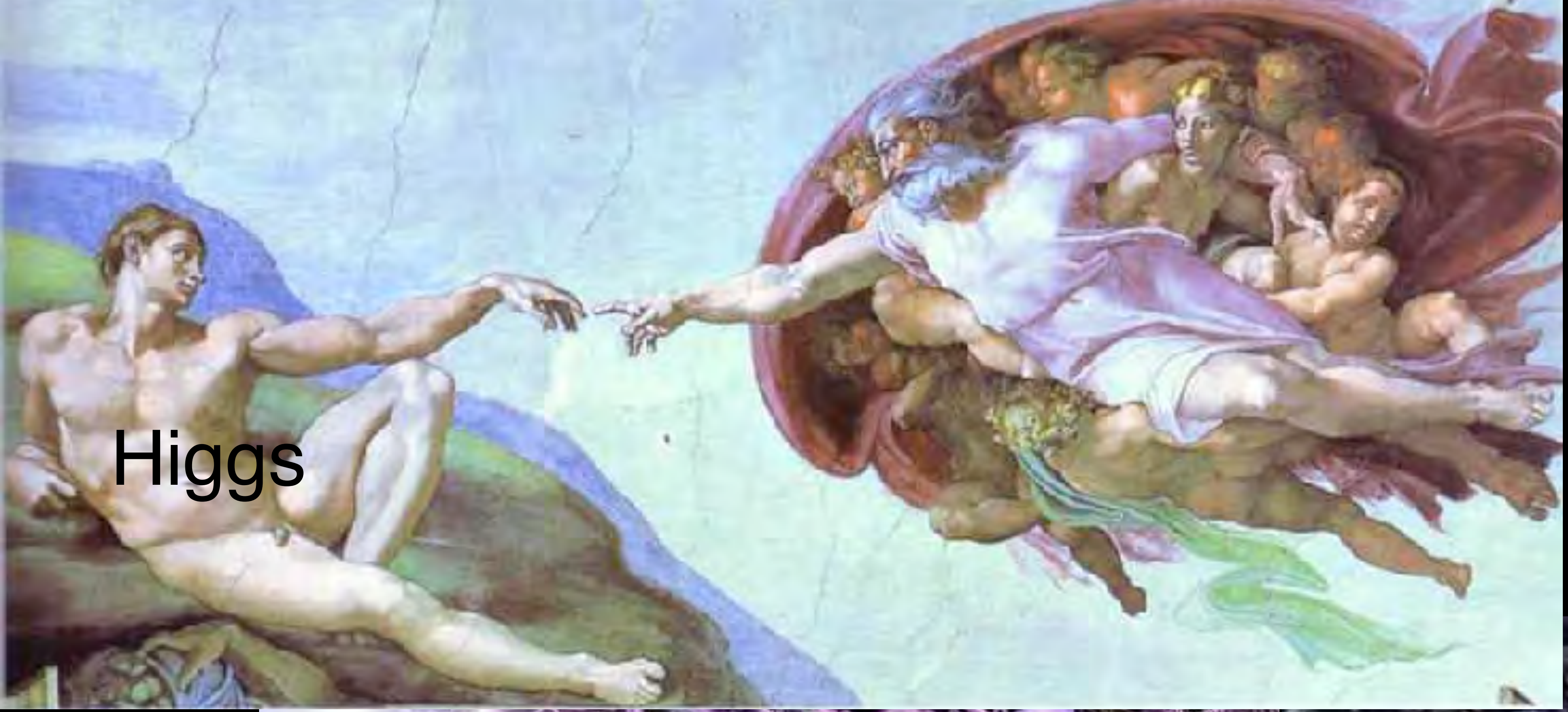
$m_H^2 = (125)^2 = 15625\ \text{GeV}^2$

314 159 265 358 979 323 846 264 338 327 950 288

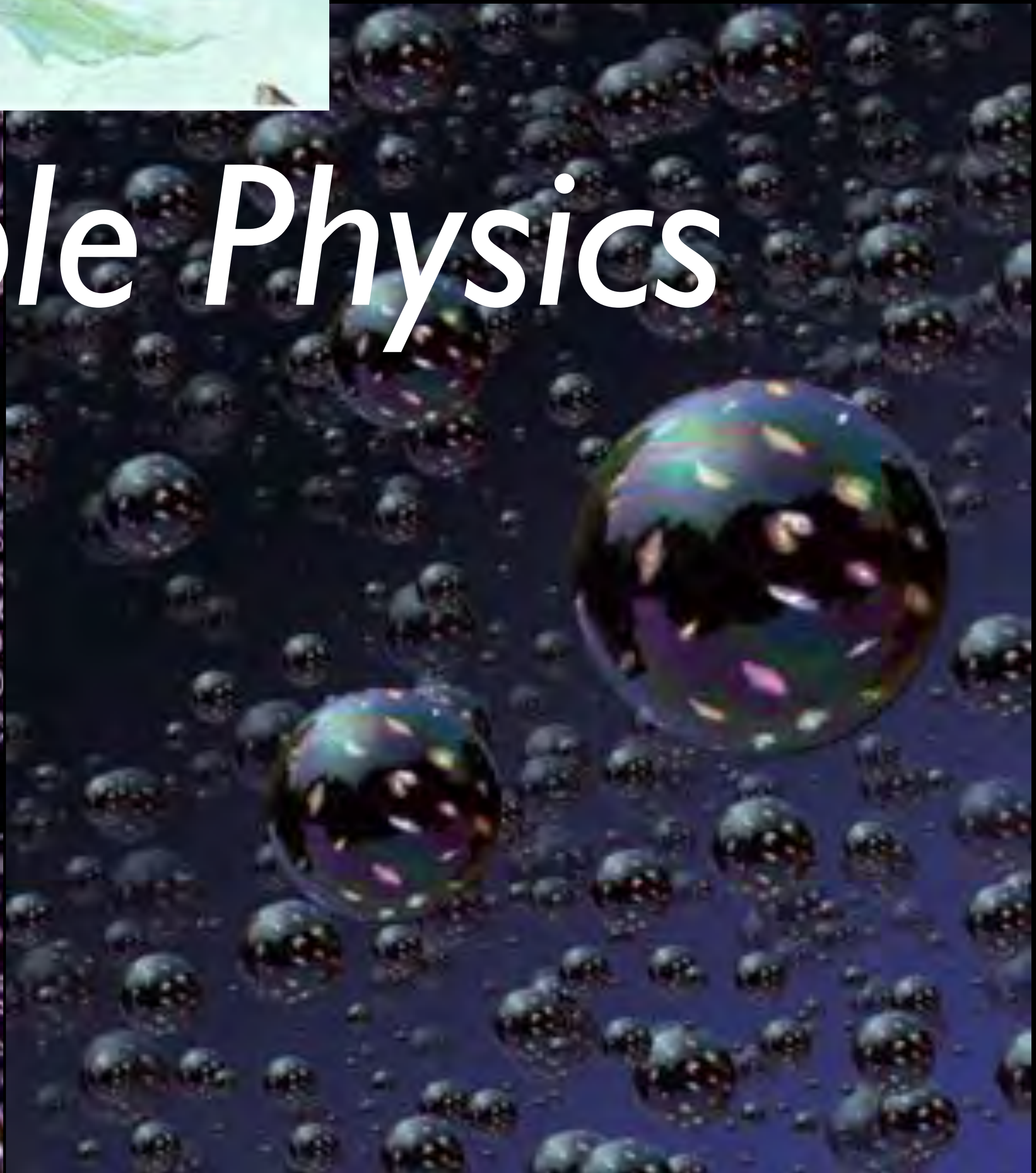
–314 159 265 358 979 323 846 264 338 327 948 726

= 15 625



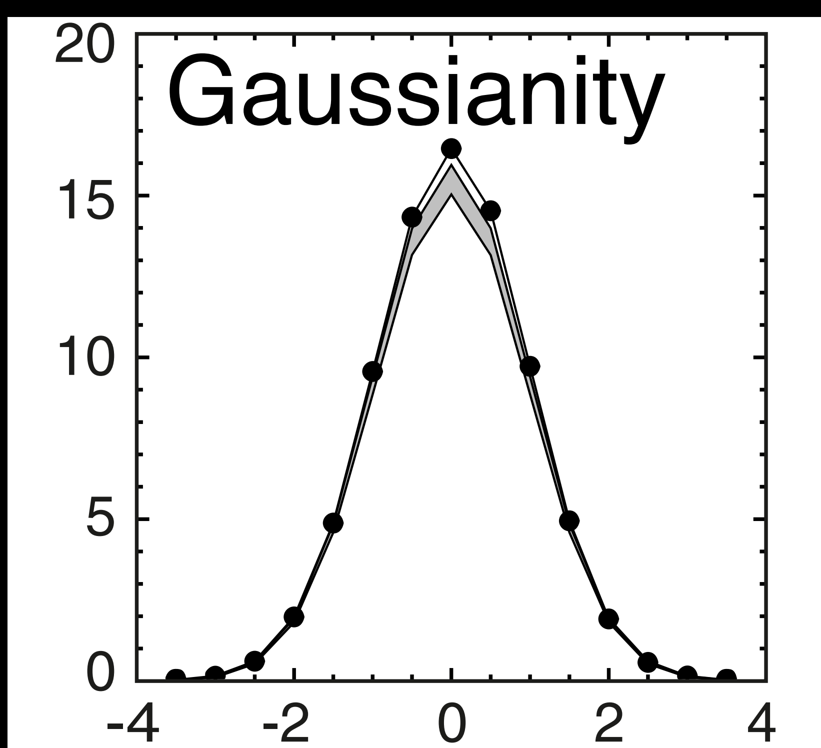


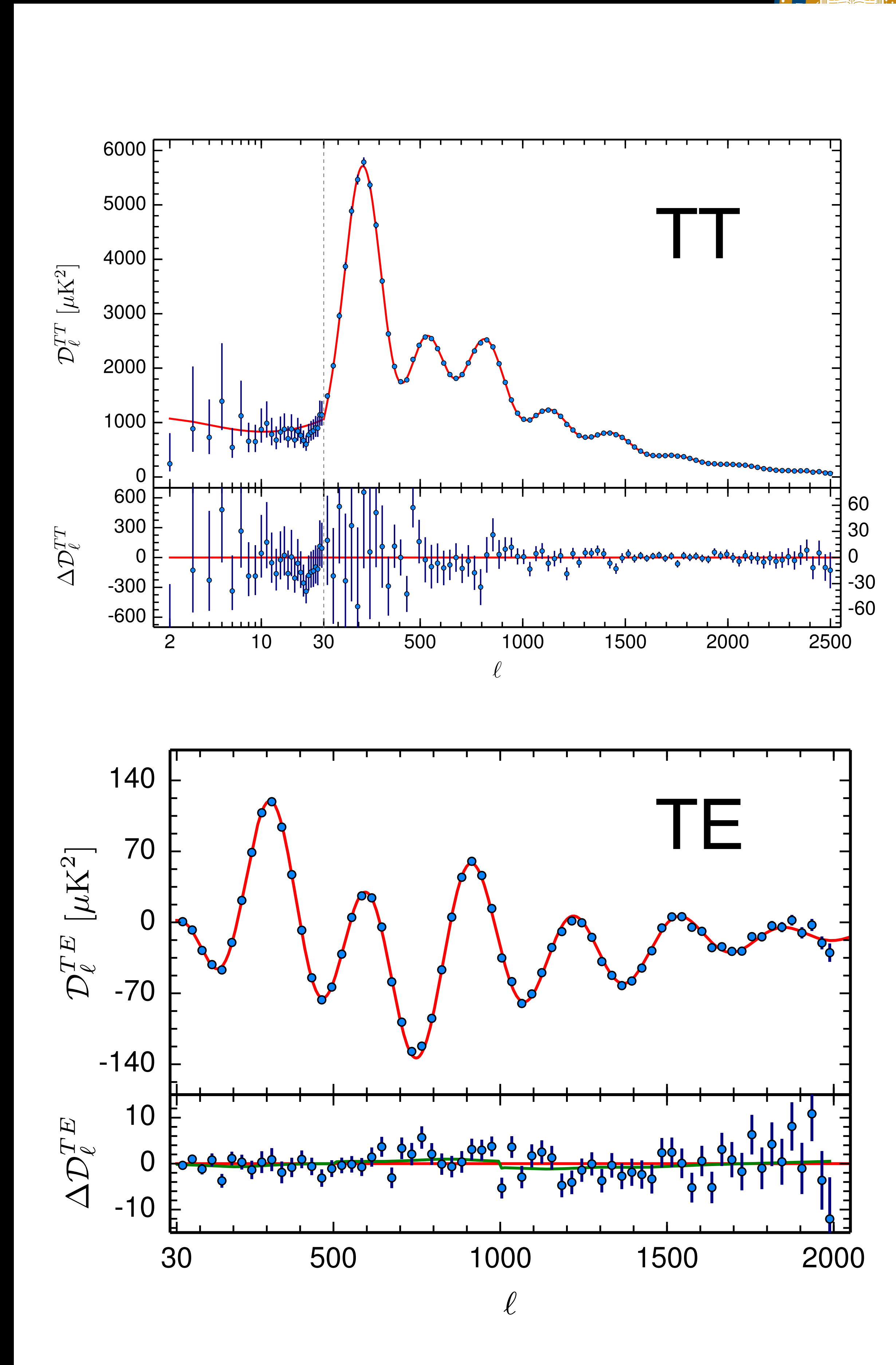
End of Falsifiable Physics



Naturalness works!

- Why is the Universe big?
- Inflation
  - horizon problem
  - flatness problem
  - large entropy





ENGINEERING
Machines That Change Shape

MEDICINE
An Off Switch for Cancer

NEUROSCIENCE
How to Reach "Vegetative" Patients

SCIENTIFIC AMERICAN

ScientificAmerican.com

A
IF SUPERSYMMETRY
CRISIS
DOESN'T PAN OUT,
IN
SCIENTISTS NEED A NEW WAY
PHYSICS
TO EXPLAIN THE UNIVERSE
?

$5.99 U.S.

MAY 2014

been there before

The New York Times **Science**

WORLD | U.S. | N.Y. / REGION | BUSINESS | TECHNOLOGY | SCIENCE | HEALTH

ENVIRONMENT

315 Physicists Report Failure In Search for Supersymmetry

By MALCOLM W. BROWNE
Published: January 5, 1993

Three hundred and fifteen physicists worked on the experiment.

Their apparatus included the Tevatron, the world's most powerful particle accelerator, as well as a $65 million detector weighing as

clever analysis
precision Higgs, flavor
HL-LHC, HE-LHC
ILC, CEPC, FCC…

Better Late Than Never

Even m_{SUSY}~10 TeV ameliorates fine-tuning from 10^{-36} to 10^{-4}

been there before

- CMB anisotropy
- universe younger than oldest stars?
- cosmologists got antsy
- it turned out a little "fine-tuned"
  - low quadrupole
  - dark energy

"Big Bang not yet dead but in decline"
Nature 377, 14 (1995)

"Bang! A Big Theory May Be Shot"
A new study of the stars could rewrite the history of the universe
Times, Jan 14 (1991)

been there before

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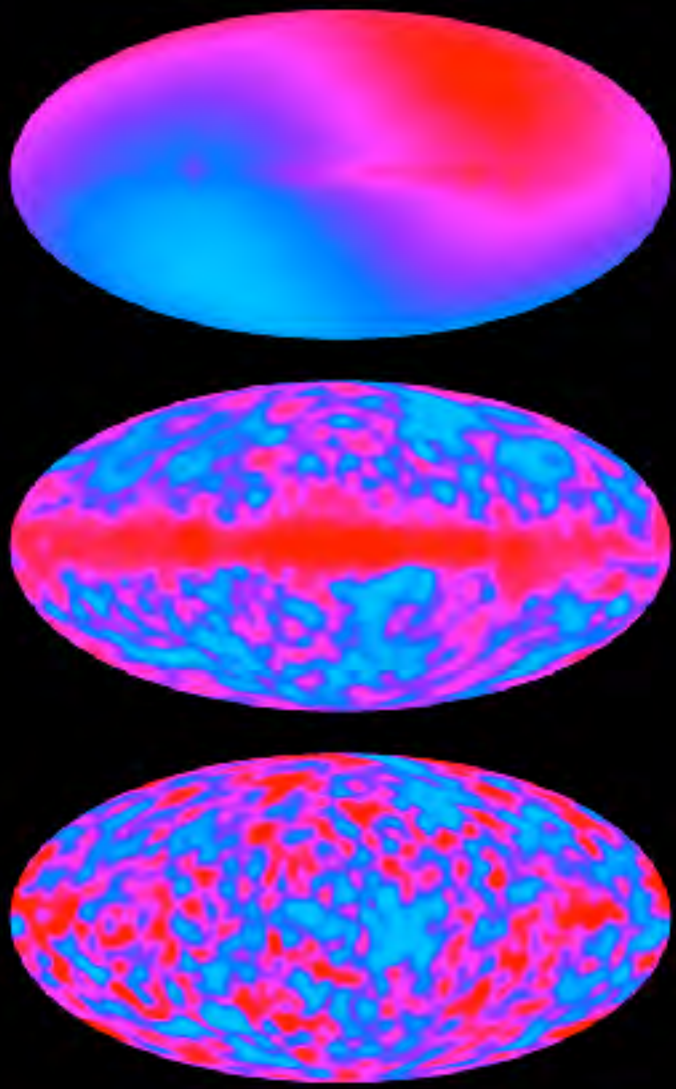
“Big B
bu
Natur



“Bang! A E hot”
A new stud write
the history
Times, Jan

been there before

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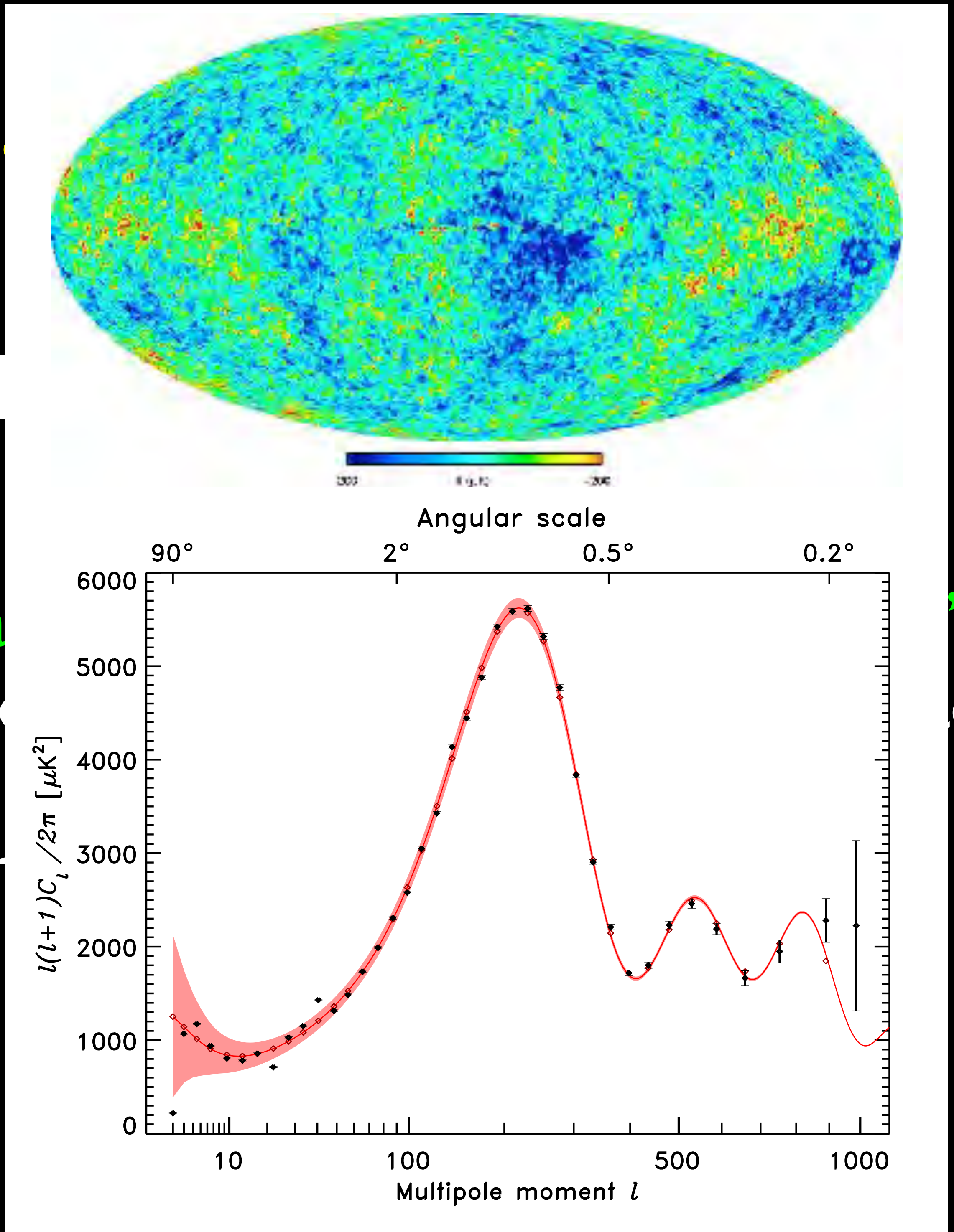
“

“Ba ”

A n e

the

Tim



bee

- CMB anisotropy
- universe younger
  oldest stars?
- cosmologists got
- it turned out a lit
  tuned"
  - low quadrupol
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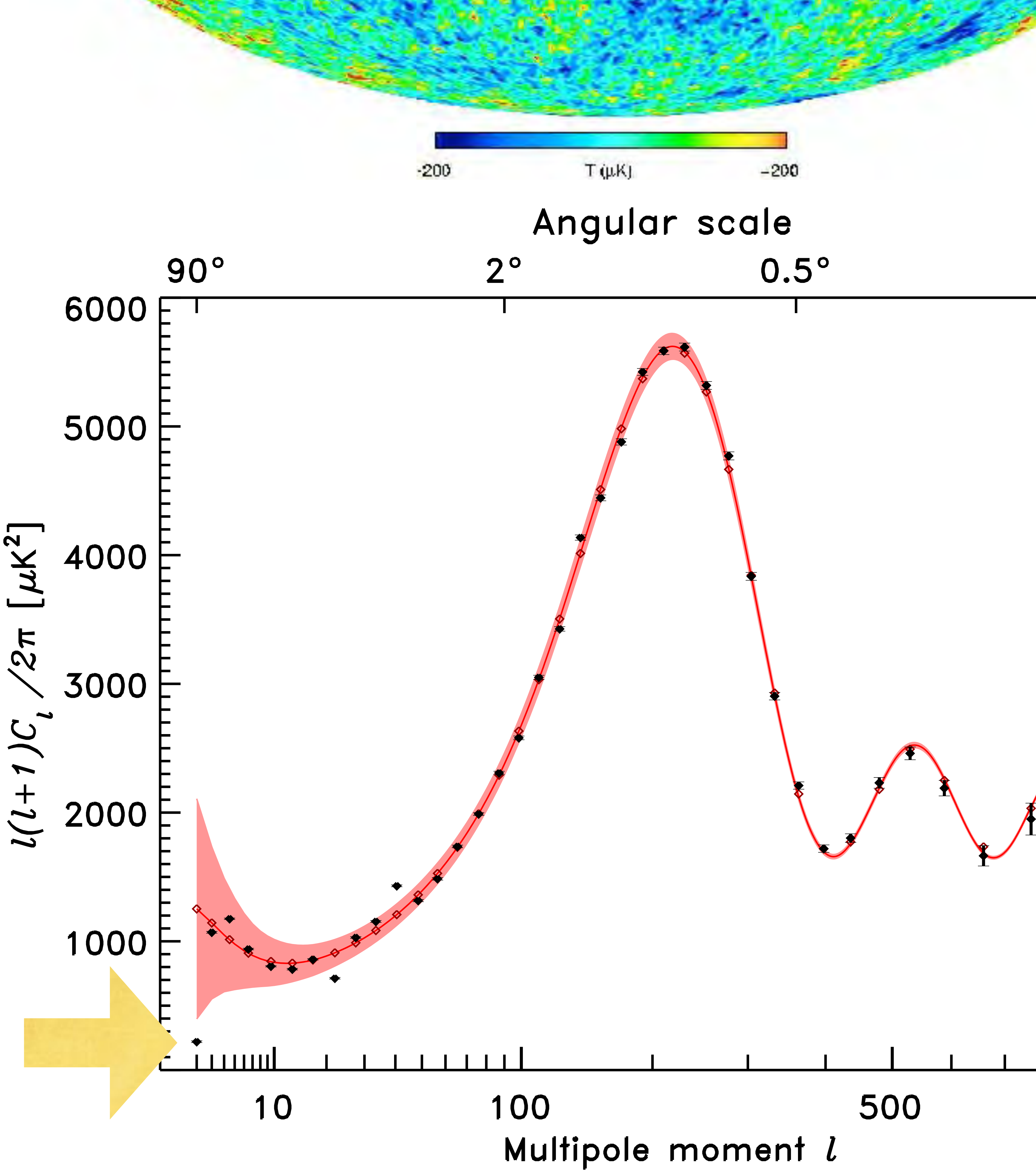
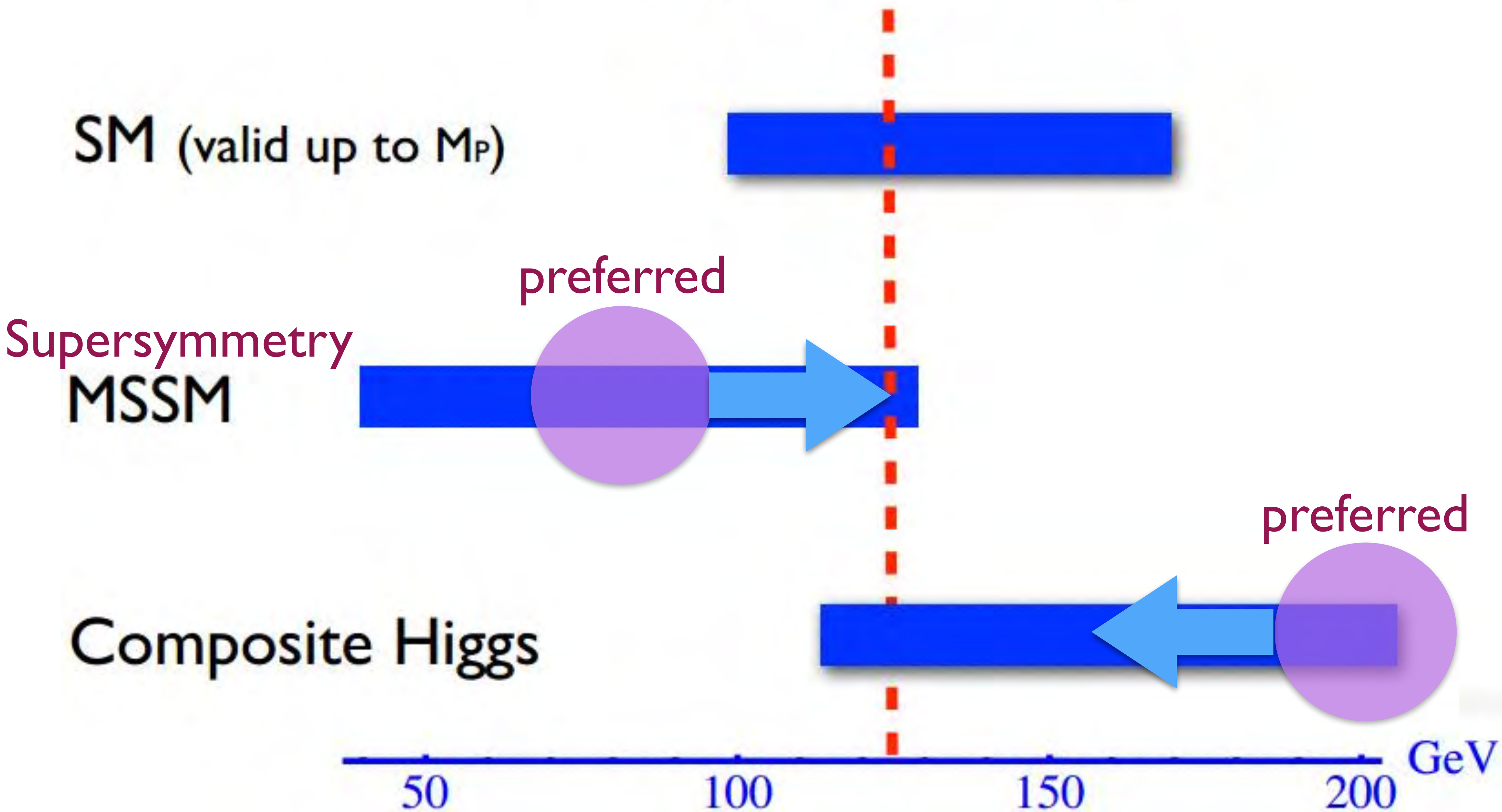


1% tuning

experiments

healthy field!

Higgs mass range

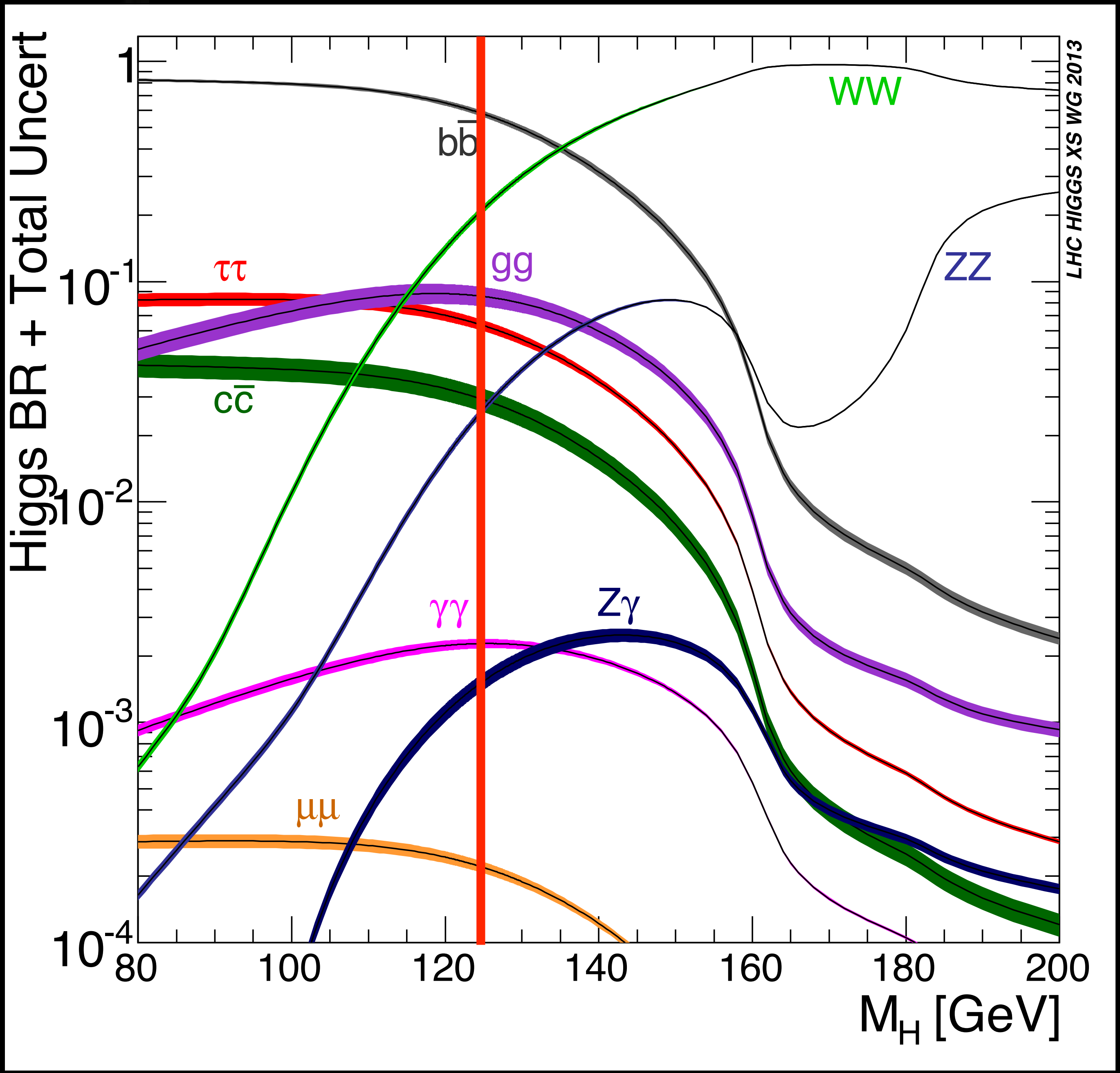


By A Pomarol

Nima's anguish

m_H=125 GeV seems almost maliciously designed to prolong the agony of BSM theorists….

dream case for experiments



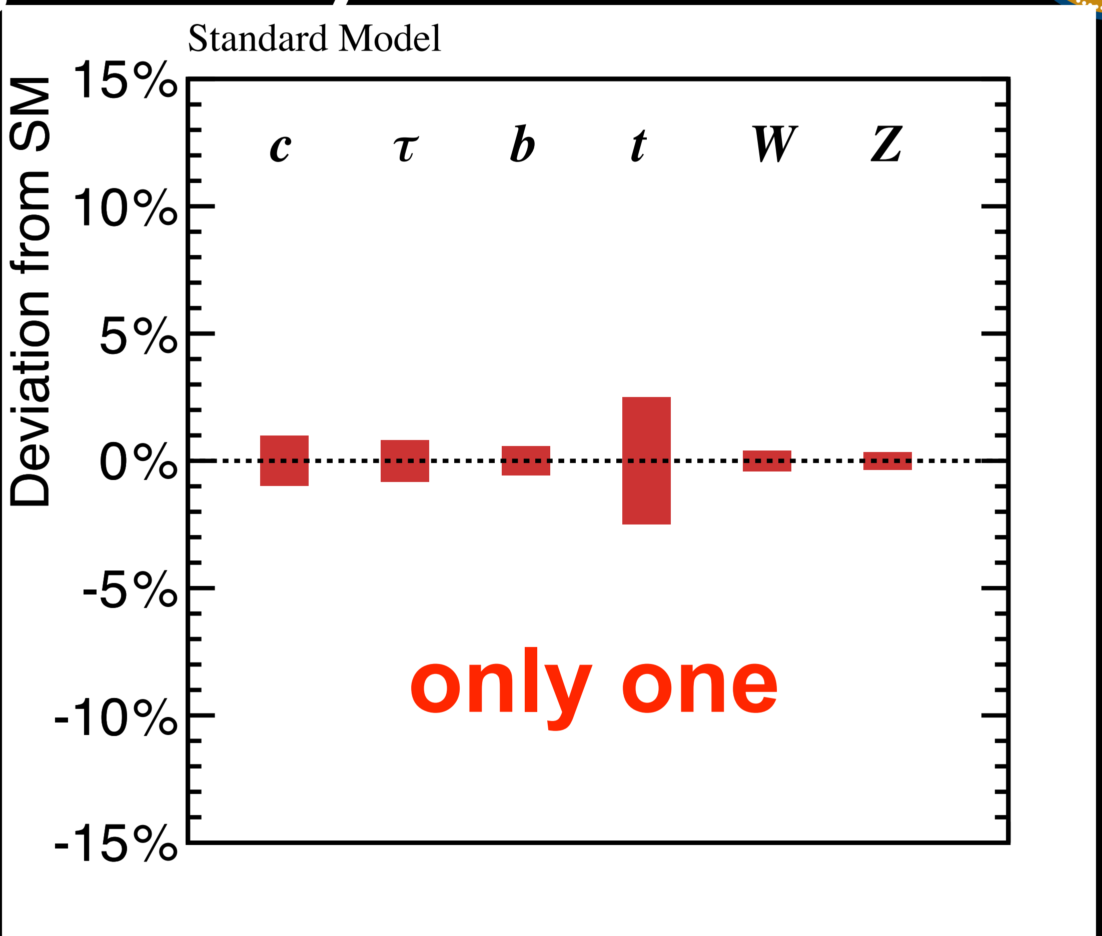
stupid not to do this!

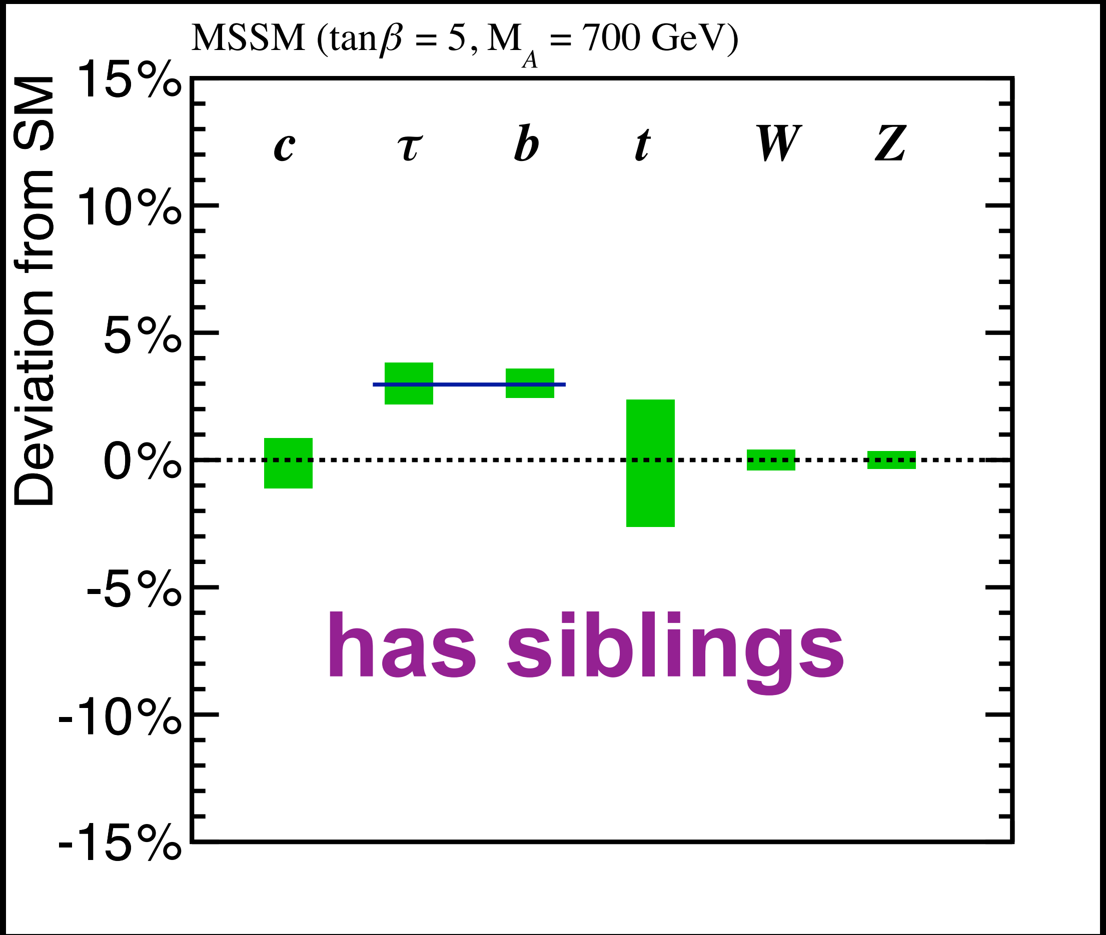
What is Higgs really?

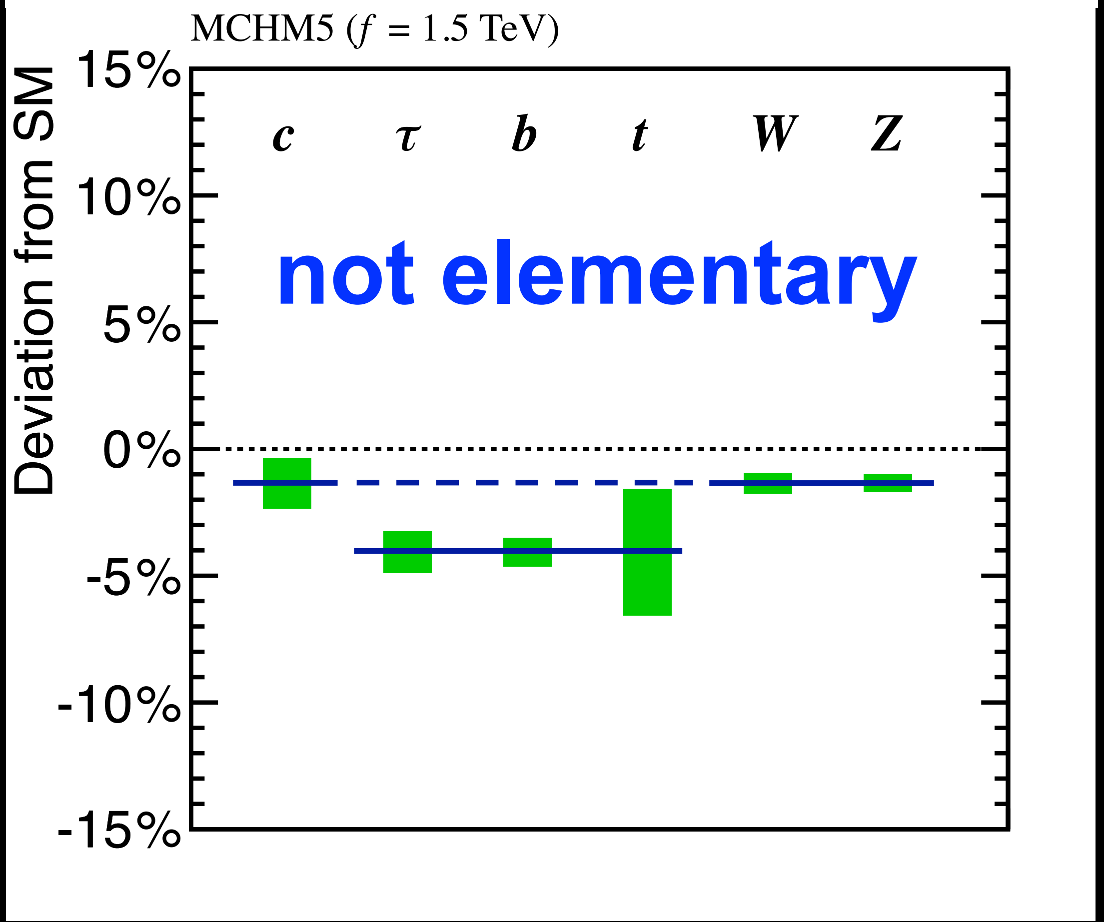
Only one? (SM)
has siblings? (2DHM)
not elementary?

ILC

Lumi 1920 fb-1, sqrt(s) = 250 GeV
Lumi 2670 fb-1, sqrt(s) = 500 GeV



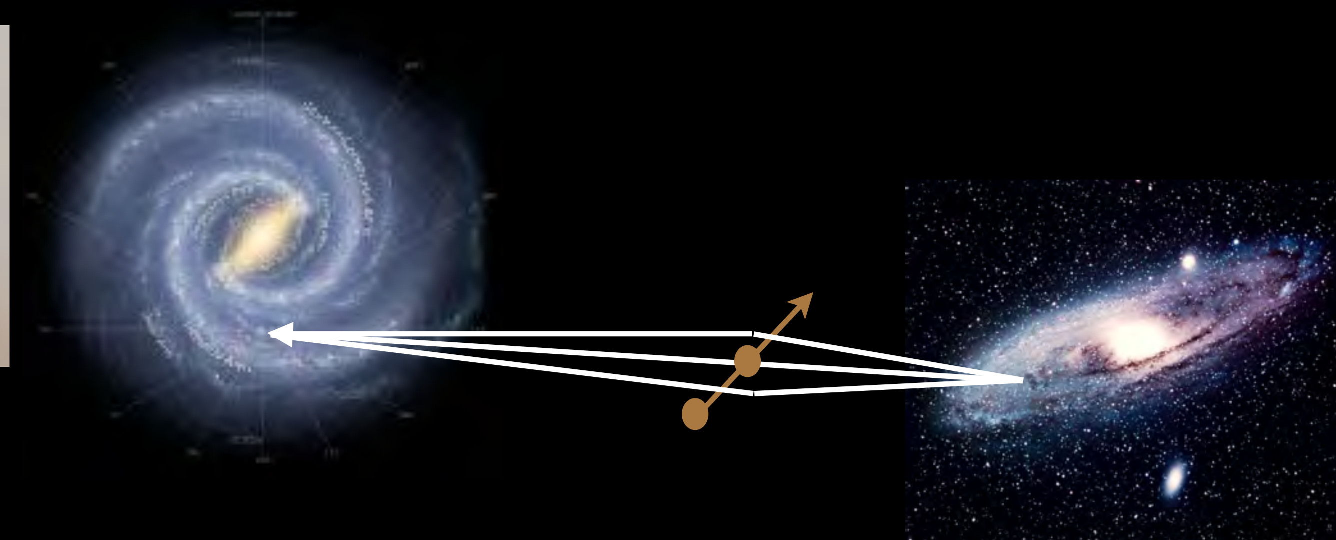


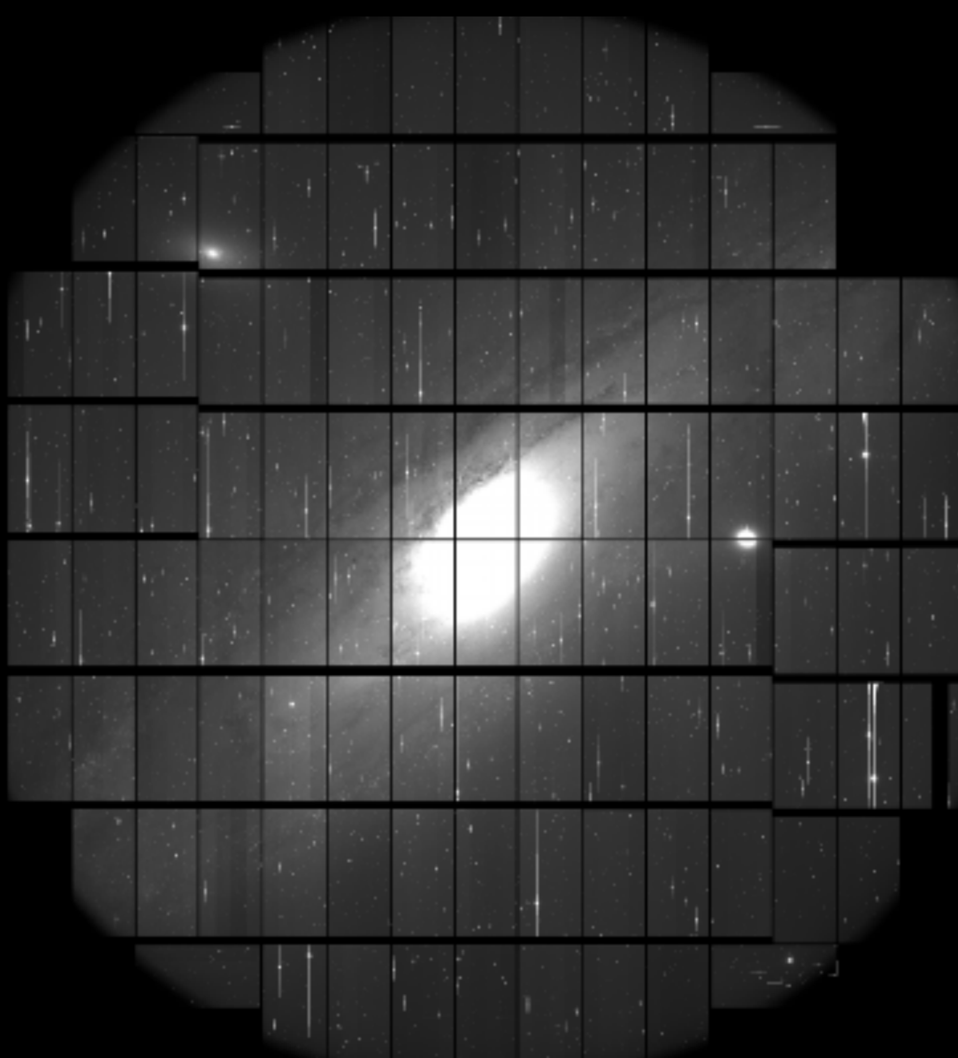


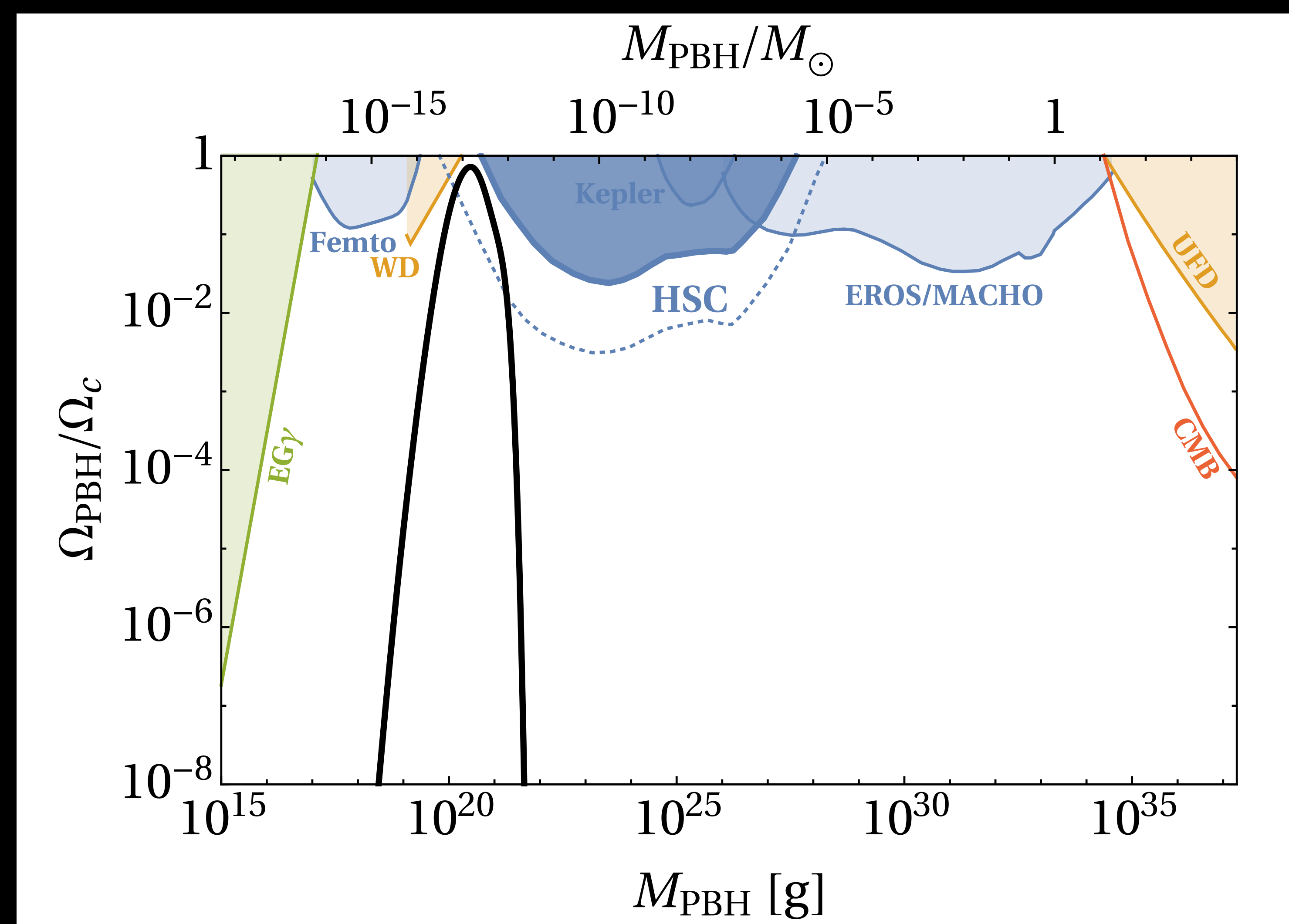
What do we know about dark matter?

Limits on PBH

Niikura, Takada, et al
one night on Subaru
observation on Andromeda
reading out every 2 min

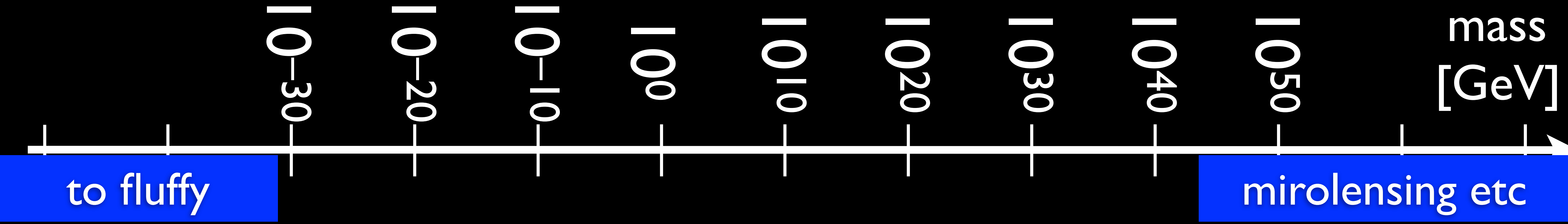




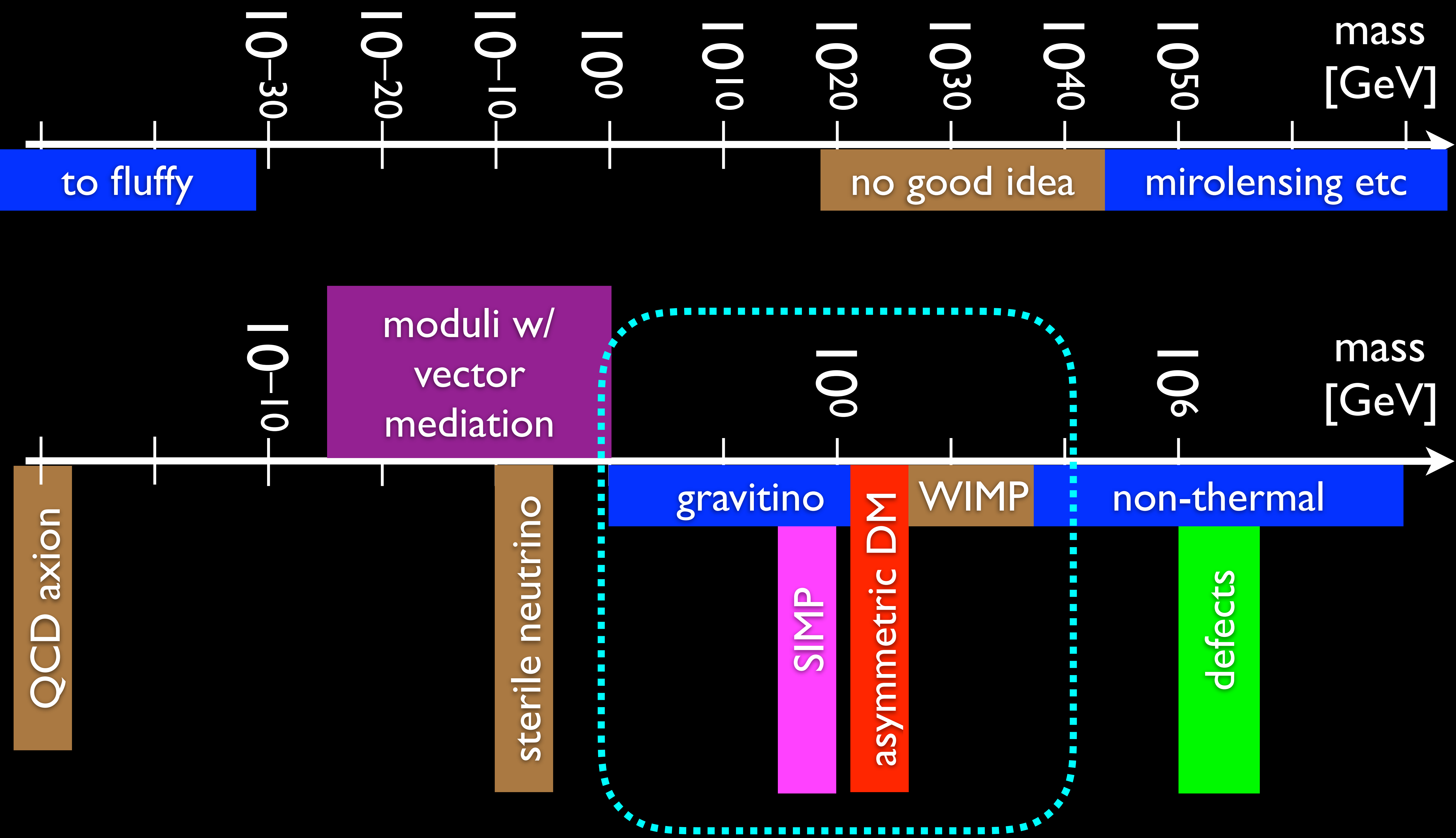


Mass Limits
"Uncertainty Principle"

- 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)
- m >10^{-21} eV from Lyman-α (Takeshi Kobayashi)

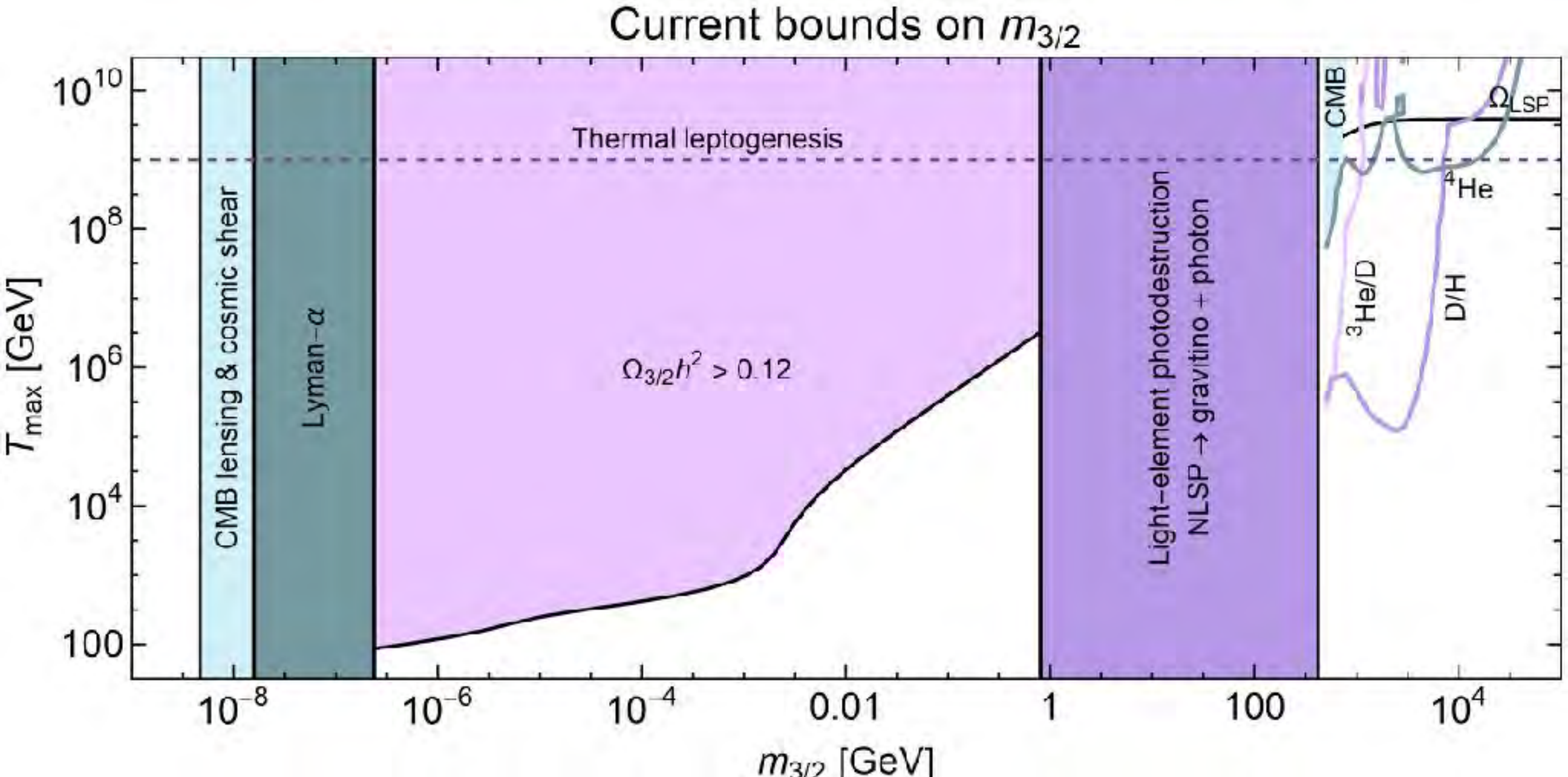


10^{-30}
10^{-20}
10^{-10}
10^{0}
10^{10}
10^{20}
10^{30}
10^{40}
10^{50}
mass [GeV]
to fluffy
mirolensing etc



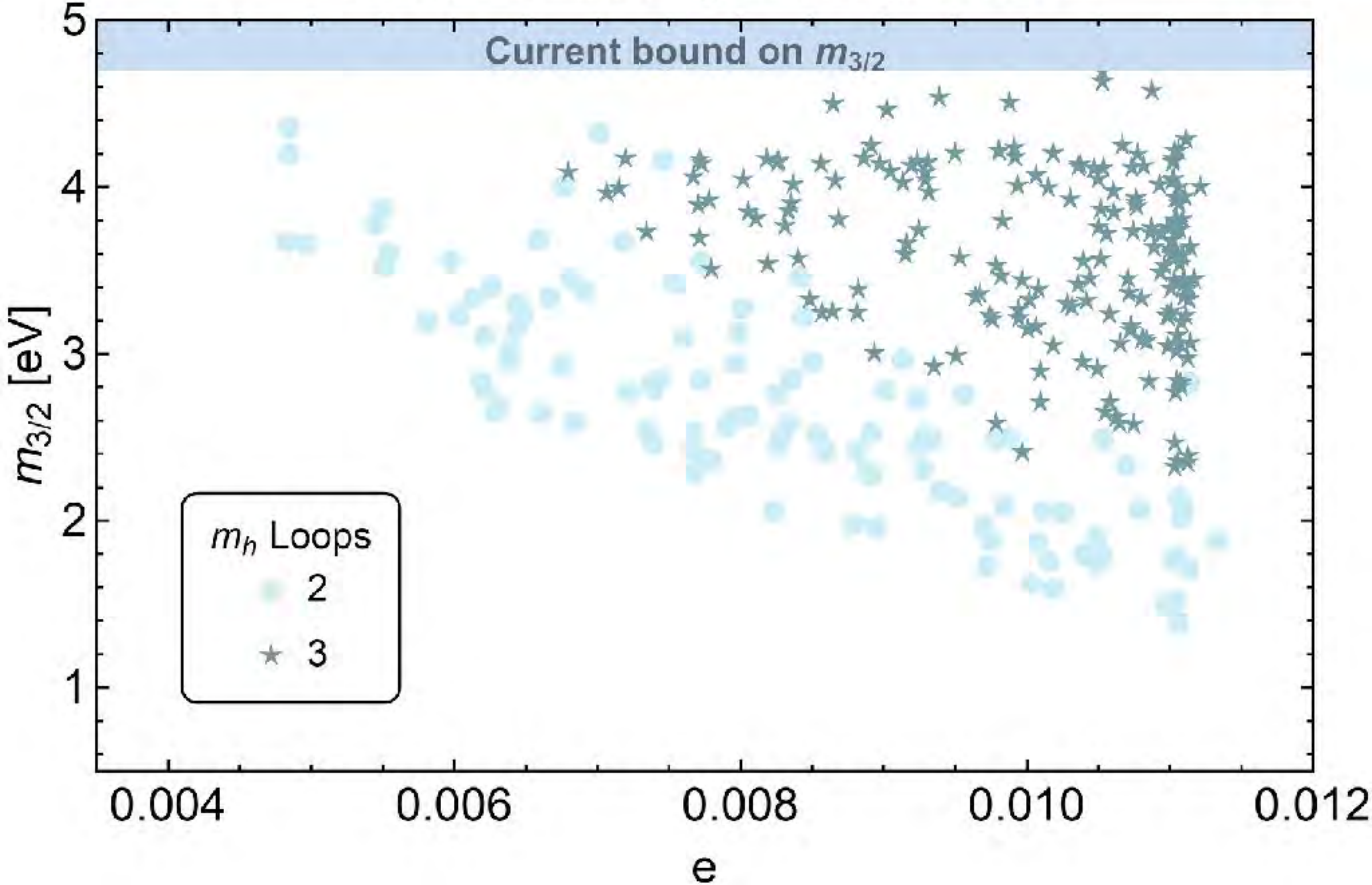
mass [GeV]
10^{-30}
10^{-20}
10^{-10}
10^{0}
10^{10}
10^{20}
10^{30}
10^{40}
10^{50}
to fluffy
no good idea
mirolensing etc
moduli w/ vector mediation
mass [GeV]
10^{-10}
10^{0}
10^{6}
QCD axion
sterile neutrino
gravitino
SIMP
asymmetric DM
WIMP
non-thermal
defects

Light Gravitino

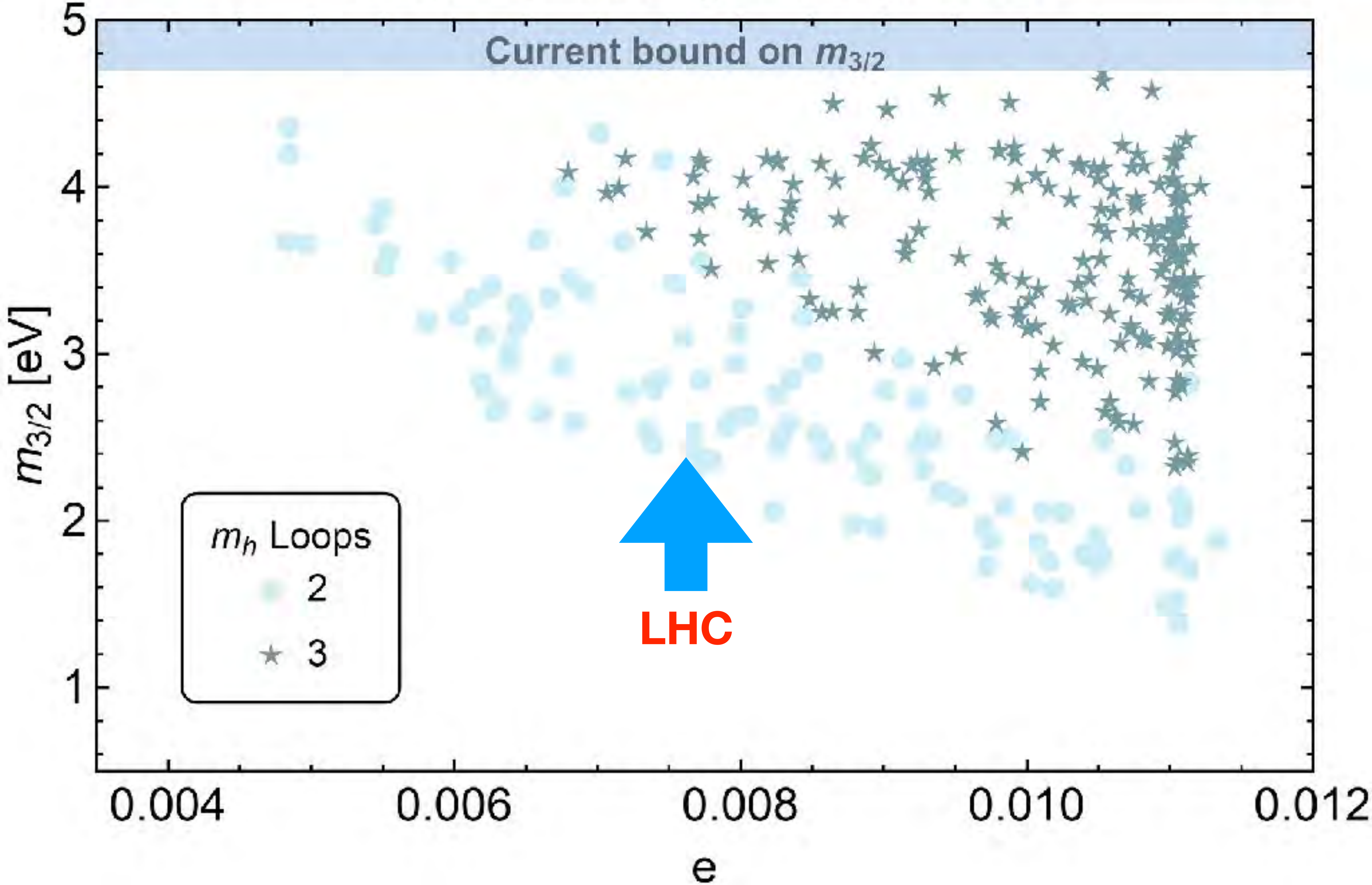


Anson Hook, Robert McGehee Jr, HM

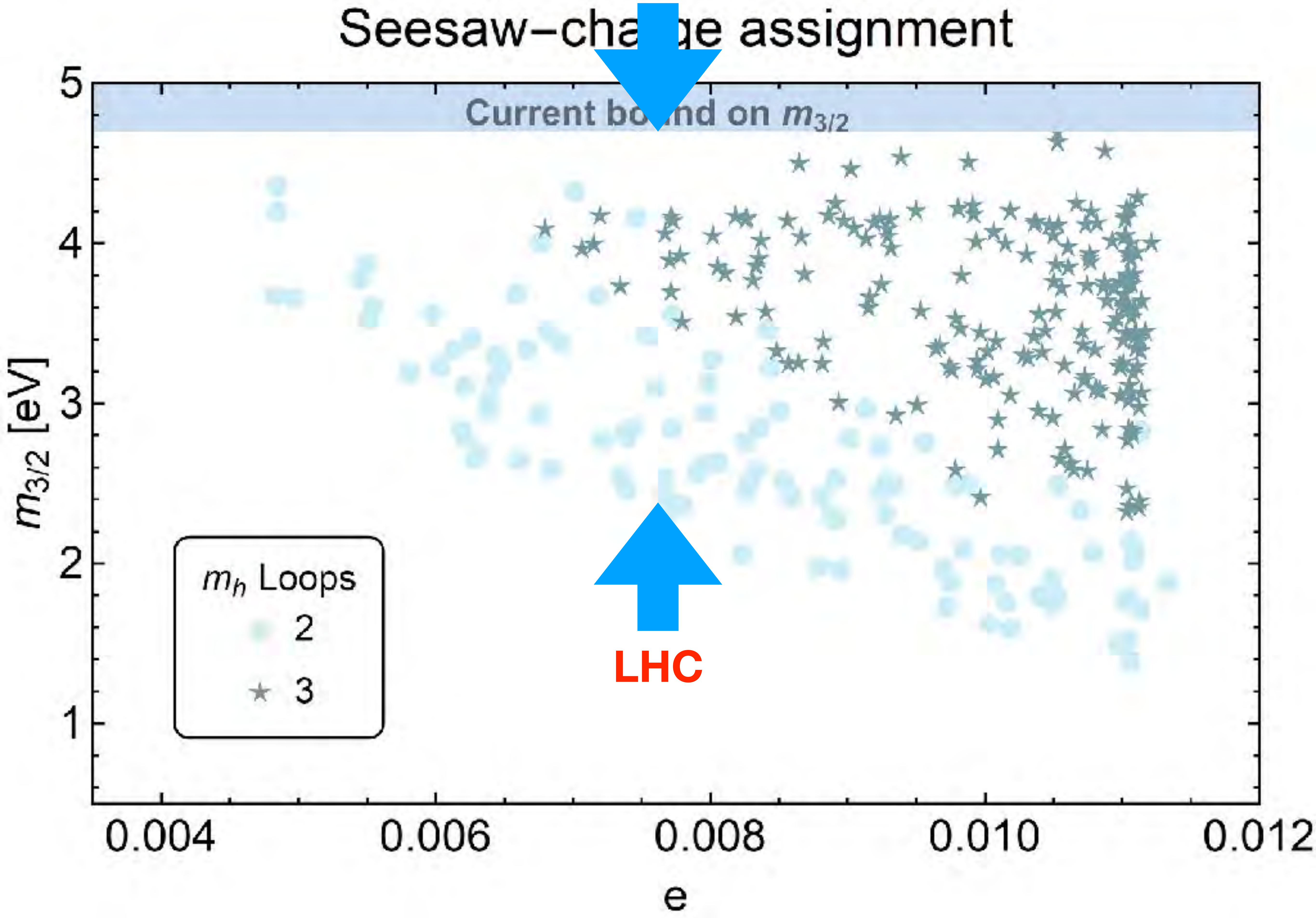
Seesaw−charge assignment



Seesaw–charge assignment



cosmology

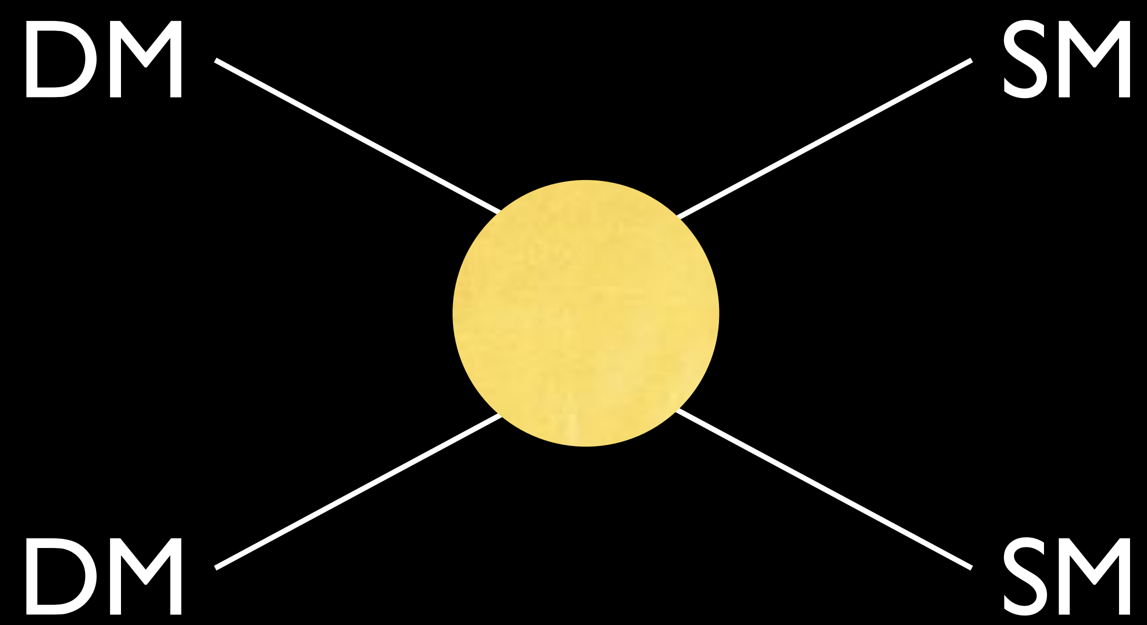


Seesaw−charge assignment
Current bound on $m_{3/2}$
m_h Loops
2
3
$m_{3/2}$ [eV]
e
1
2
3
4
5
0.004
0.006
0.008
0.010
0.012
LHC

New direction(s)

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

Miracles

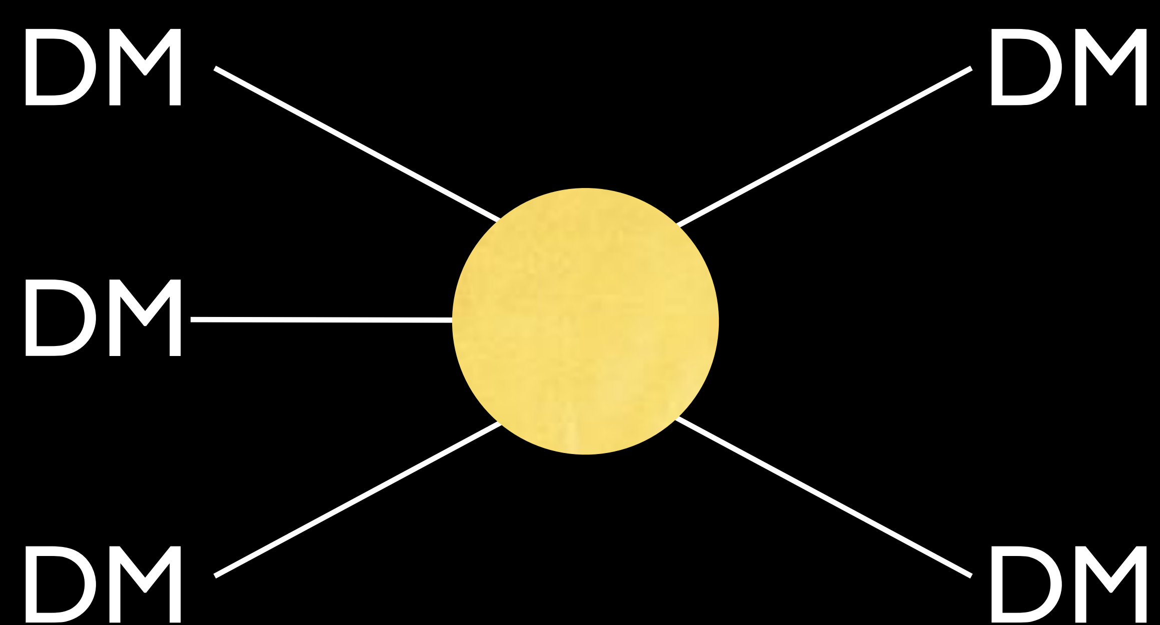


$$\langle \sigma_{2\to 2} v \rangle \approx \frac{\alpha^2}{m^2}$$

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

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

WIMP miracle!



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

$$\alpha \approx 4\pi$$

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

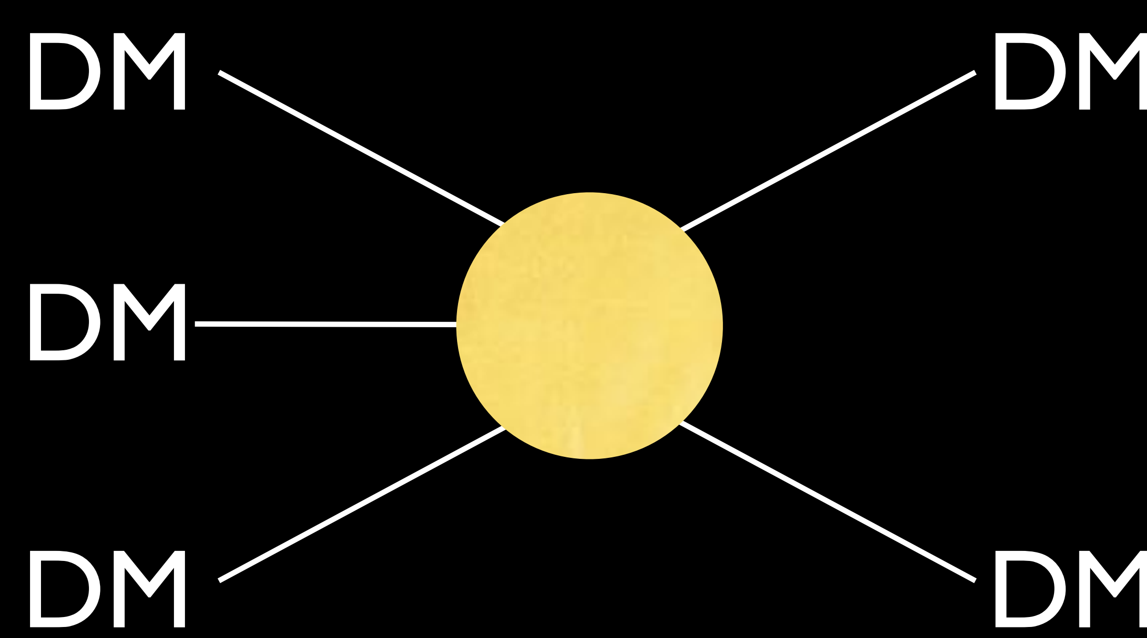
Hochberg, Kuflik, Volansky, Wacker arXiv:1402.5143

SIMP miracle!

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

SIMPI Miracle

- Not only the mass scale is similar to QCD
- dynamics itself can be QCD! Miracle^3
- DM = pions
- e.g. $SU(3)_f$



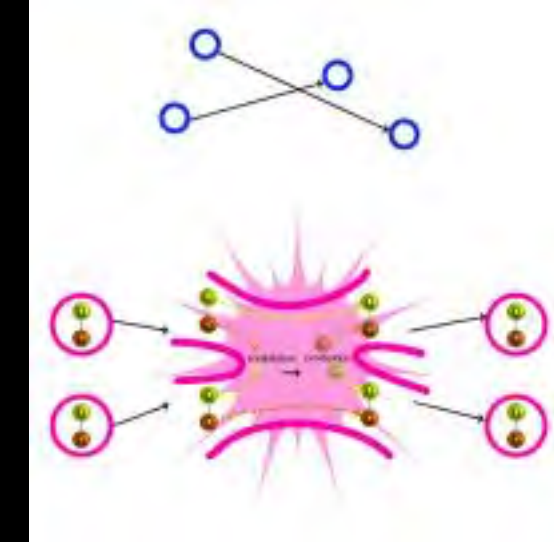
$$\mathcal{L}_{\mathrm{chiral}} = \frac{1}{16 f_\pi^2} \mathrm{Tr} \partial^\mu U^\dagger \partial_\mu U$$

$$\mathcal{L}_{\mathrm{WZW}} = \frac{2N_c}{15\pi^2 f_\pi^5} \epsilon^{\mu\nu\rho\sigma} \mathrm{Tr}(\pi \partial_\mu \pi \partial_\nu \pi \partial_\rho \pi \partial_\sigma \pi)$$

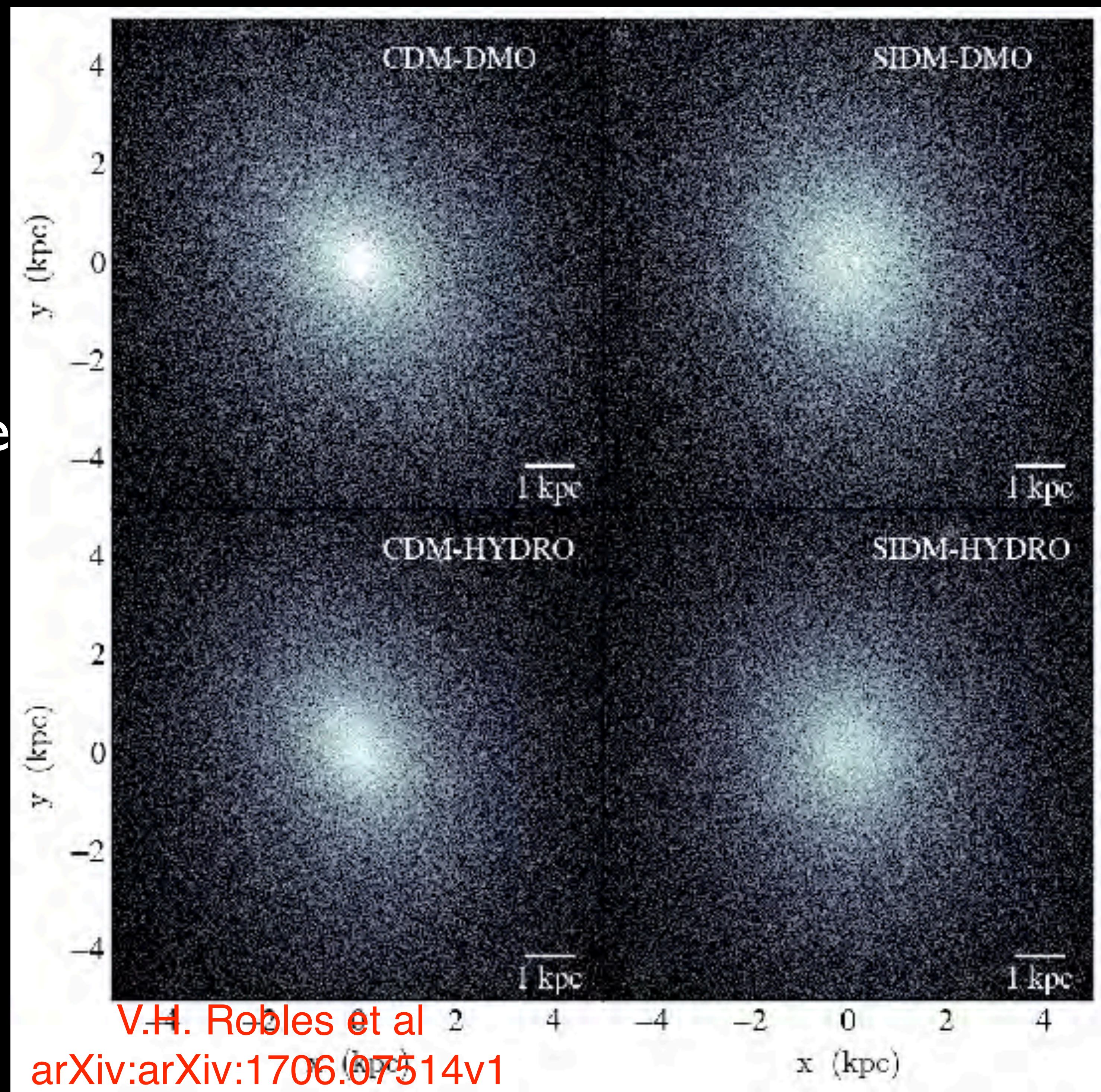
+HM
arXiv:1411.3727

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

self interaction



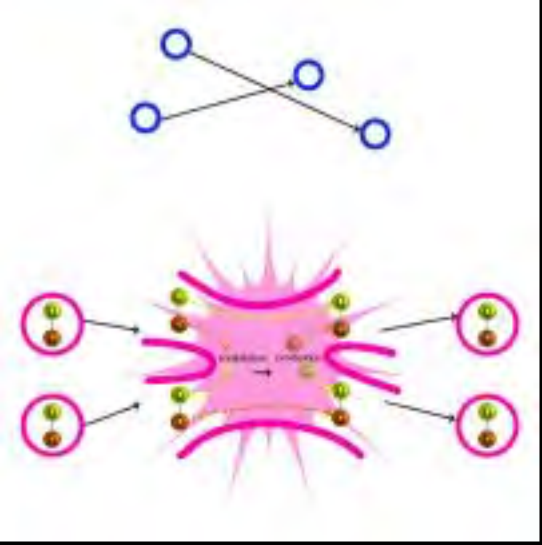
- $\sigma/m \sim \mathrm{cm}^2/\mathrm{g}$
  $\sim 10^{-24}\mathrm{cm}^2$ / 300MeV
- flattens the cusps in NFW profile
- suppresses substructure
- actually desirable for dwarf galaxies?



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

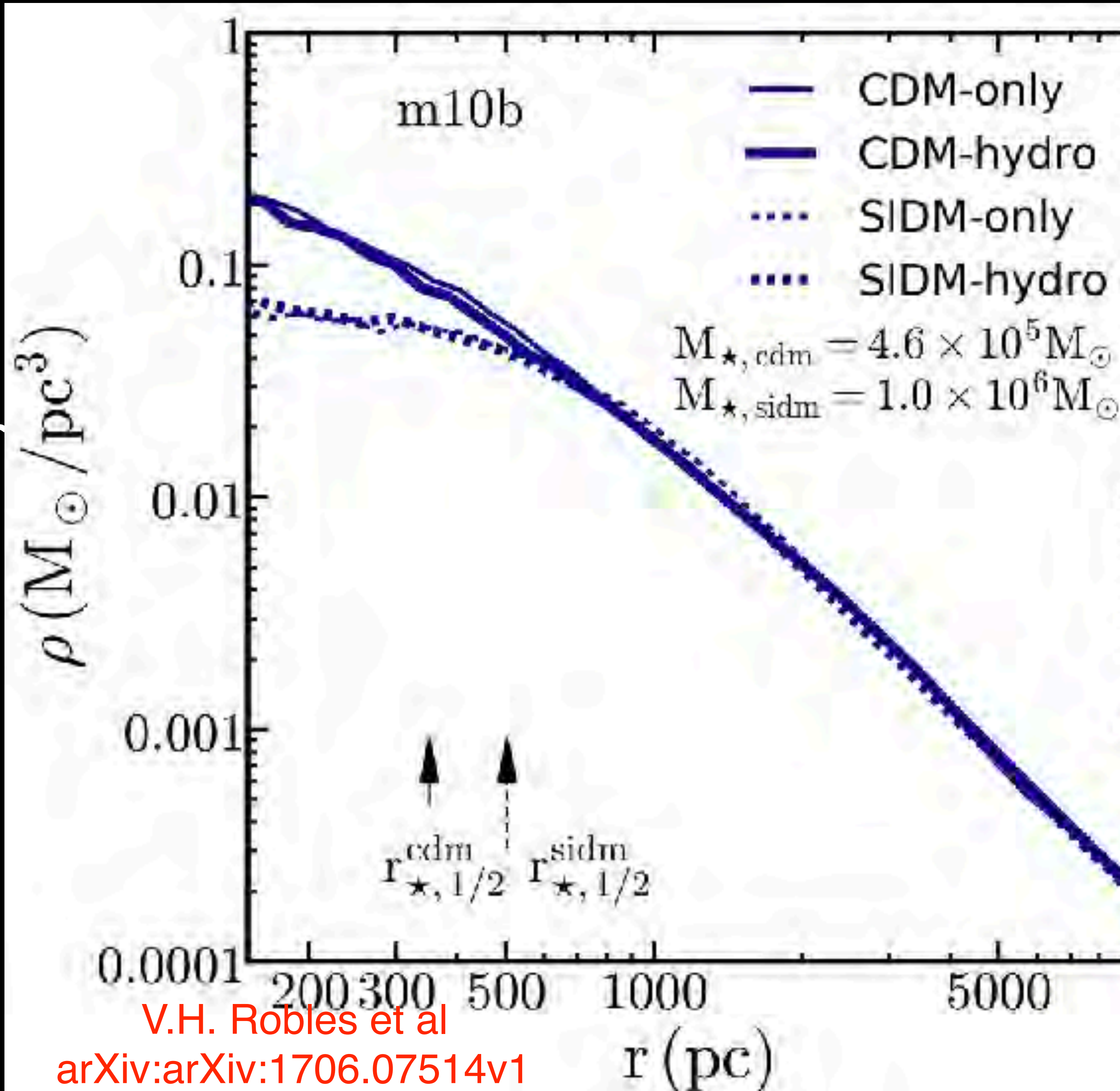
SIDM
Spergel & Steinhardt
(2000)
now complete theory

self interaction



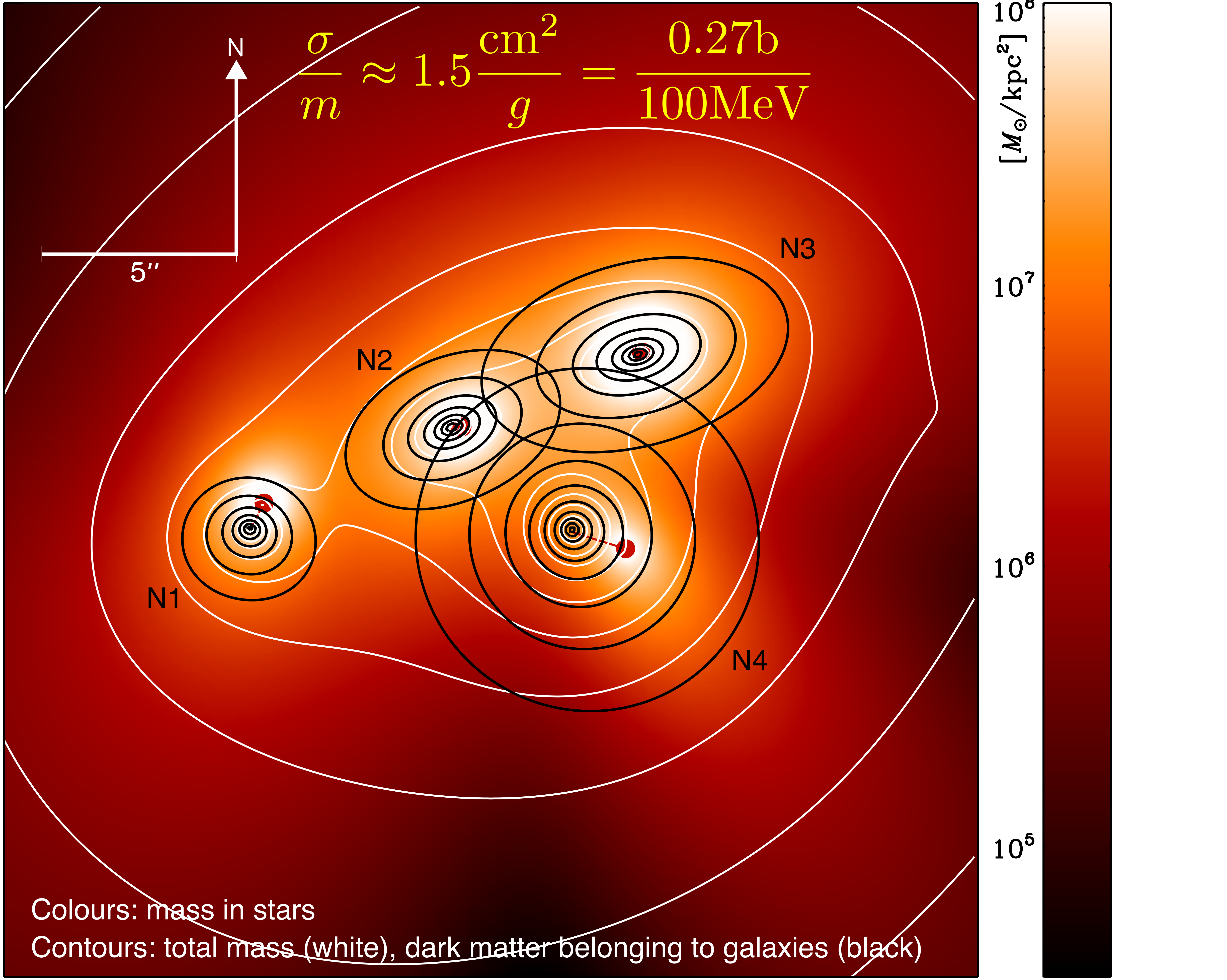
- σ/*m* ~ cm²/g
  ~10⁻²⁴cm² / 300MeV
- flattens the cusps in NFW profile
- suppresses substructure
- actually desirable for dwarf galaxies?

SIDM
Spergel & Steinhardt (2000)
now complete theory



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

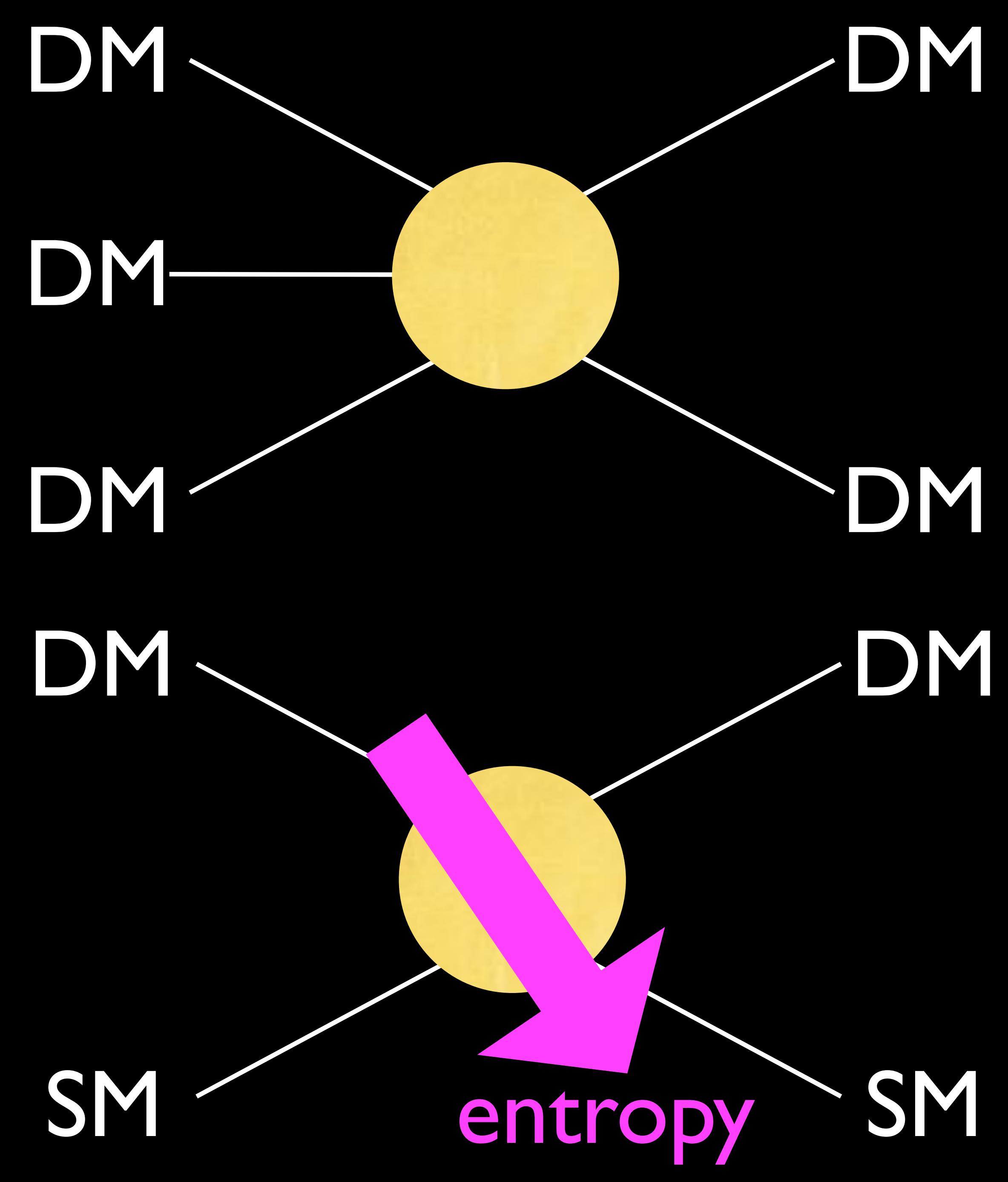

Abell 3827



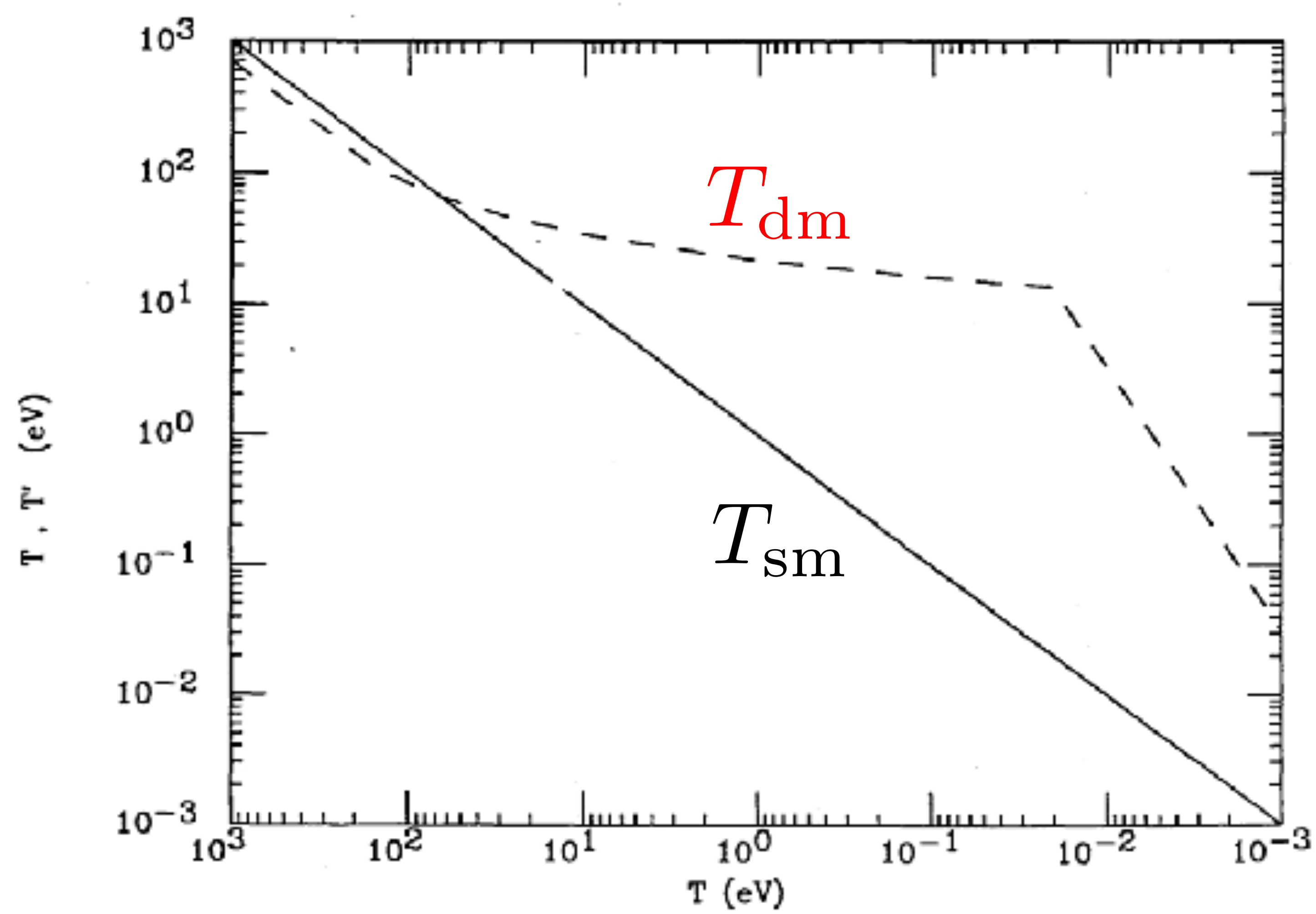
Peter Taylor et al, arXiv:1701.04412

communication

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



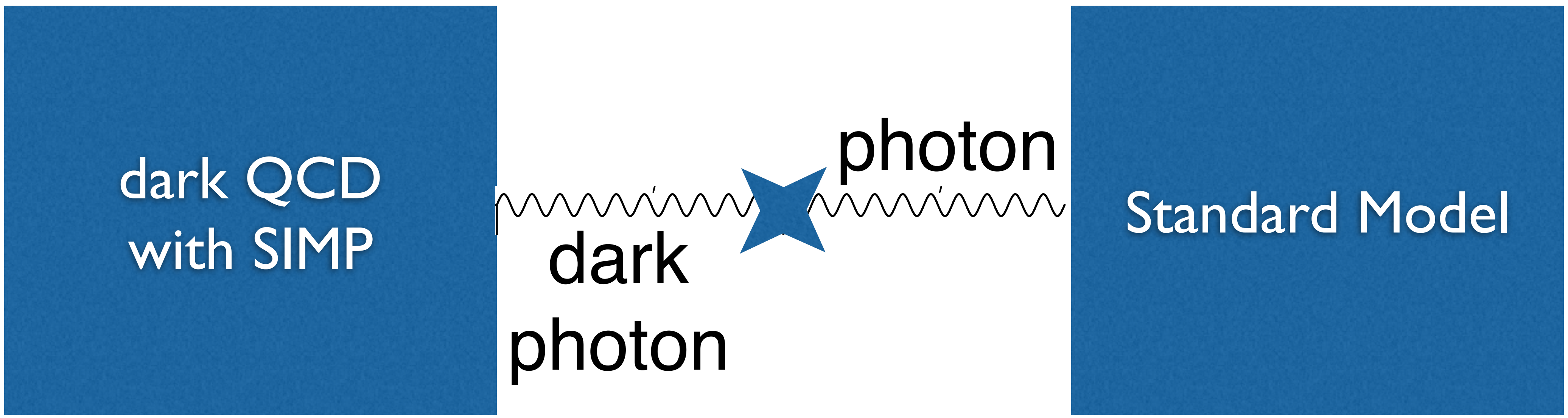
if totally decoupled



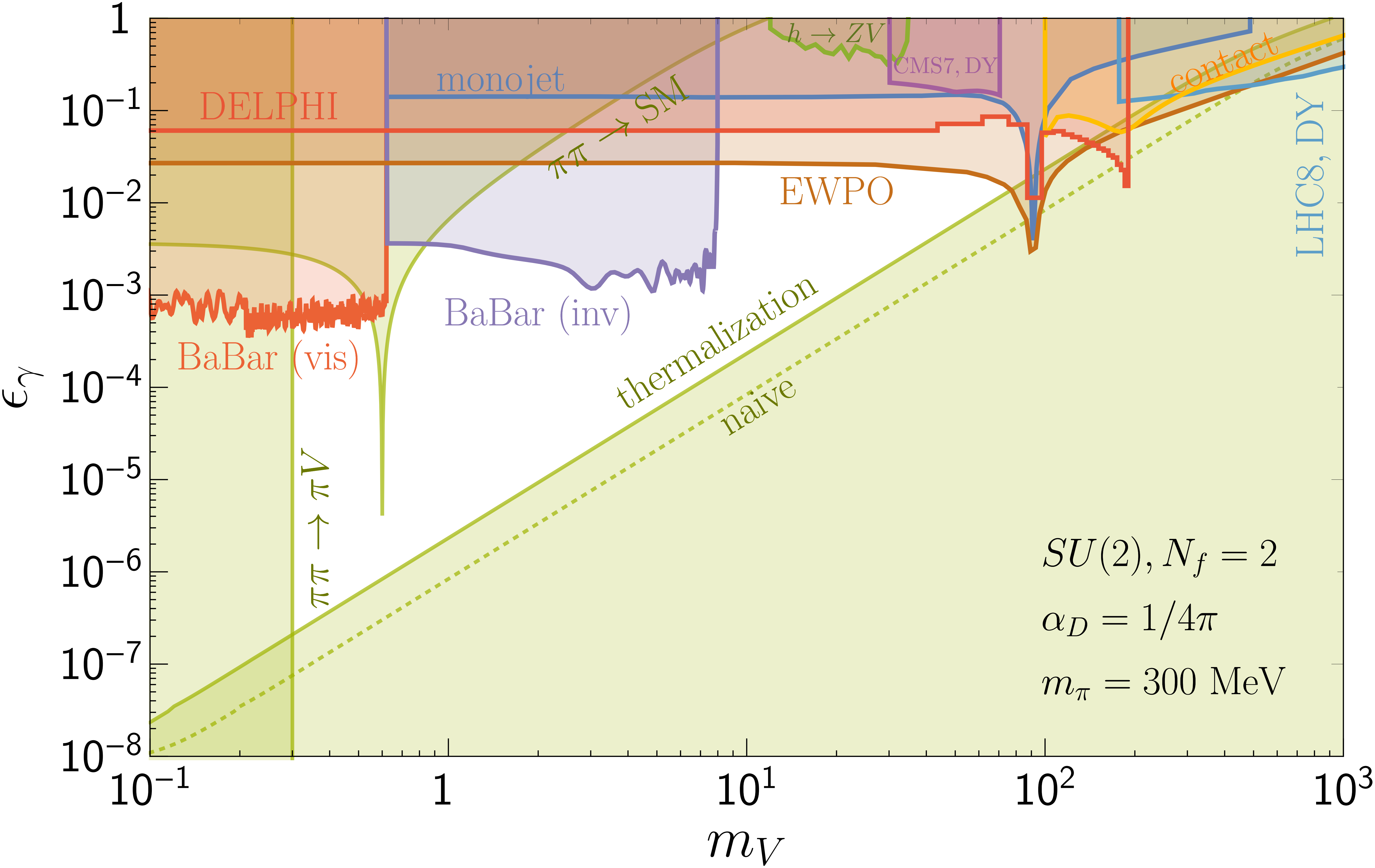
Carlson, Hall and Machacek, Astrophys. J. 398, 43 (1992)

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

vector portal

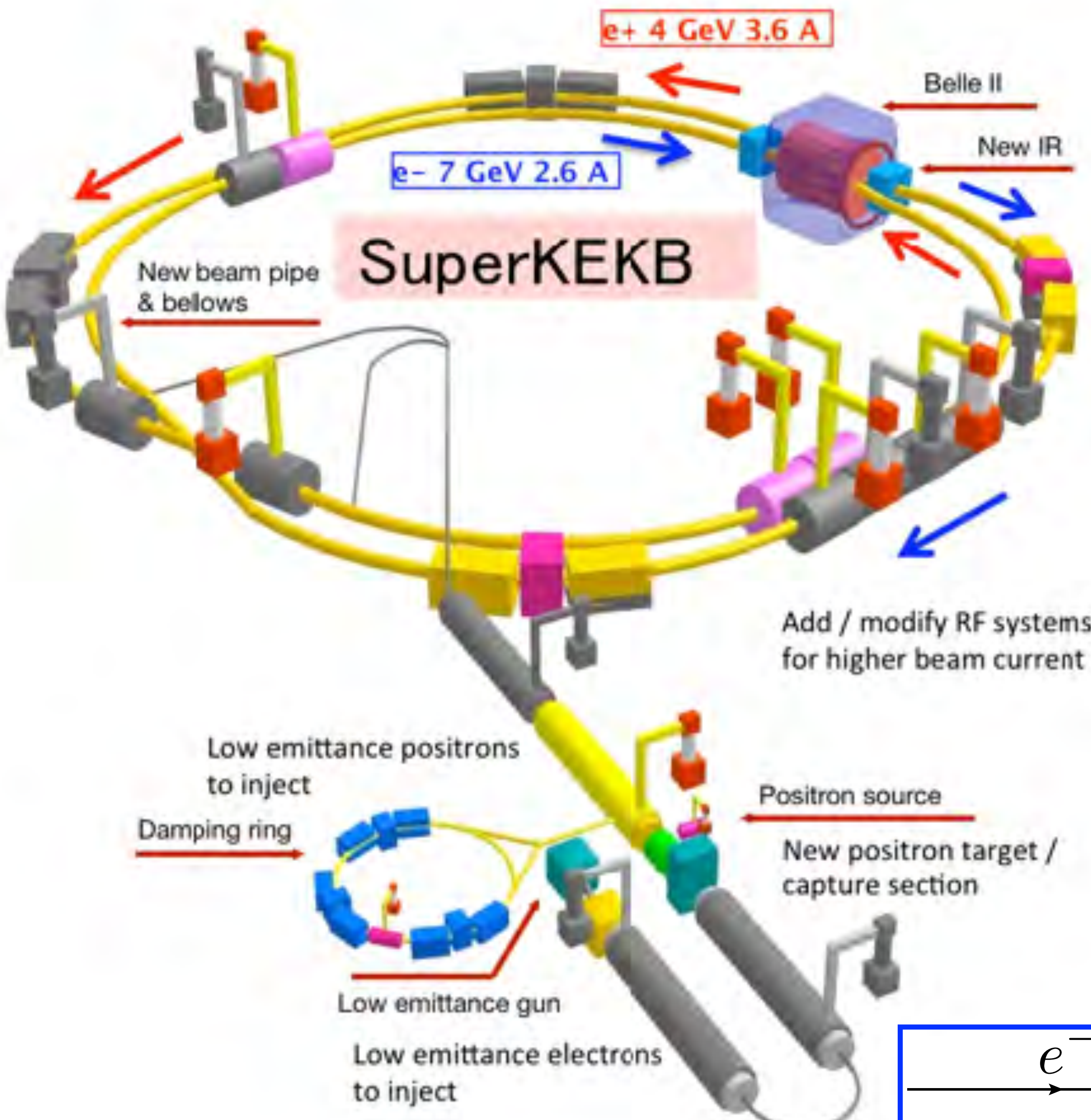


$$\frac{\epsilon_\gamma}{2c_W} B_{\mu\nu} F_D^{\mu\nu}$$

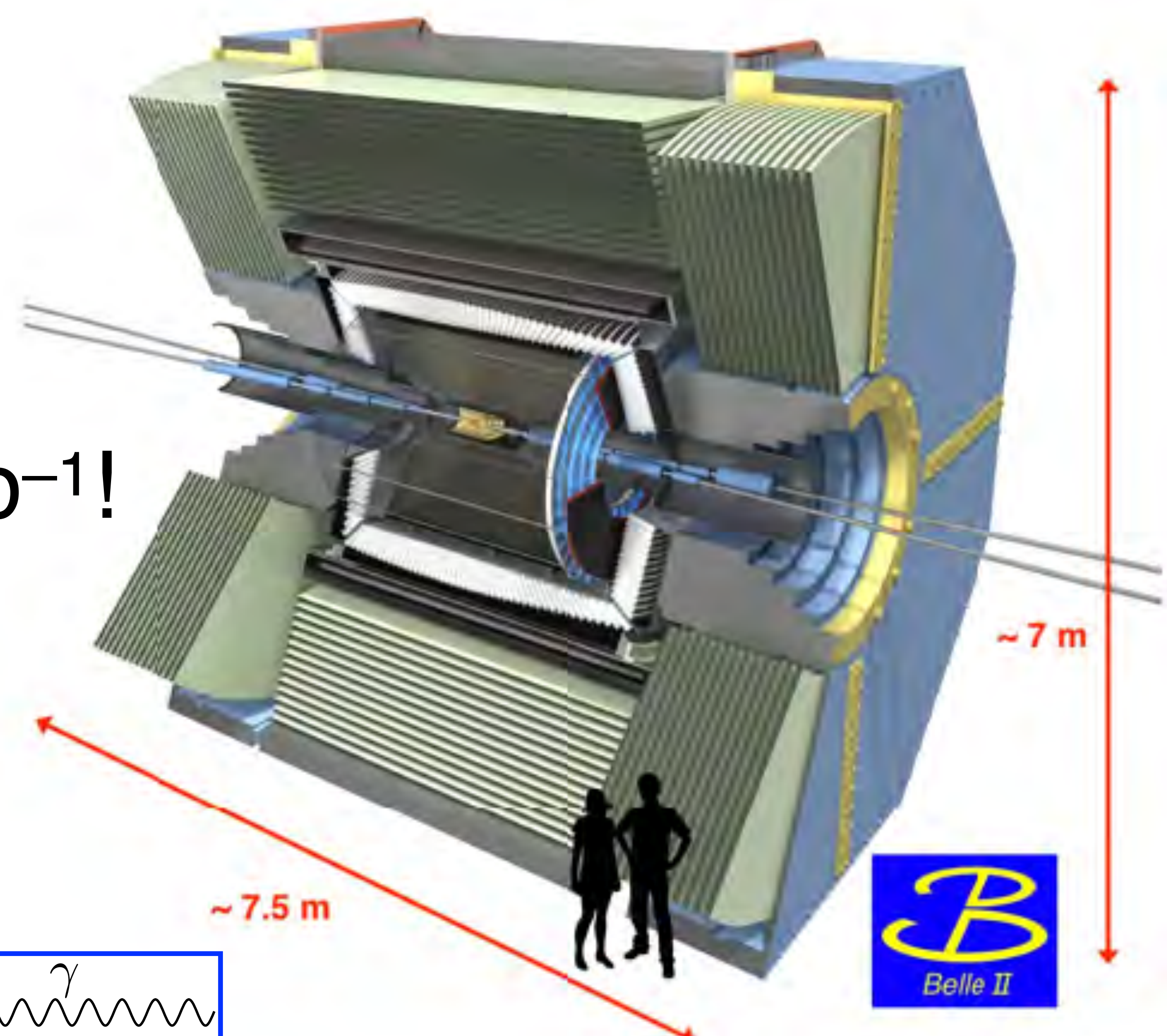


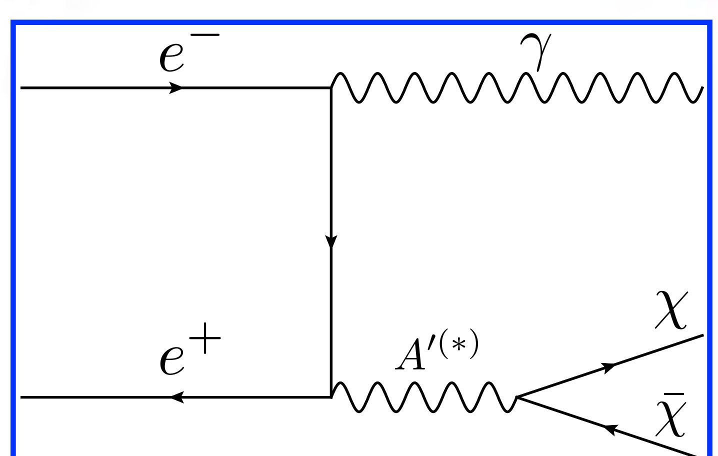
$h \to ZV$
CMS7, DY
monojet
DELPHI
$\pi\pi \to SM$
contact
EWPO
LHC8, DY
BaBar (inv)
BaBar (vis)
thermalization
naive
$\pi\pi \to \pi V$
$SU(2), N_f = 2$
$\alpha_D = 1/4\pi$
$m_\pi = 300$ MeV
ϵ_γ
m_V

Super KEK B & Belle II

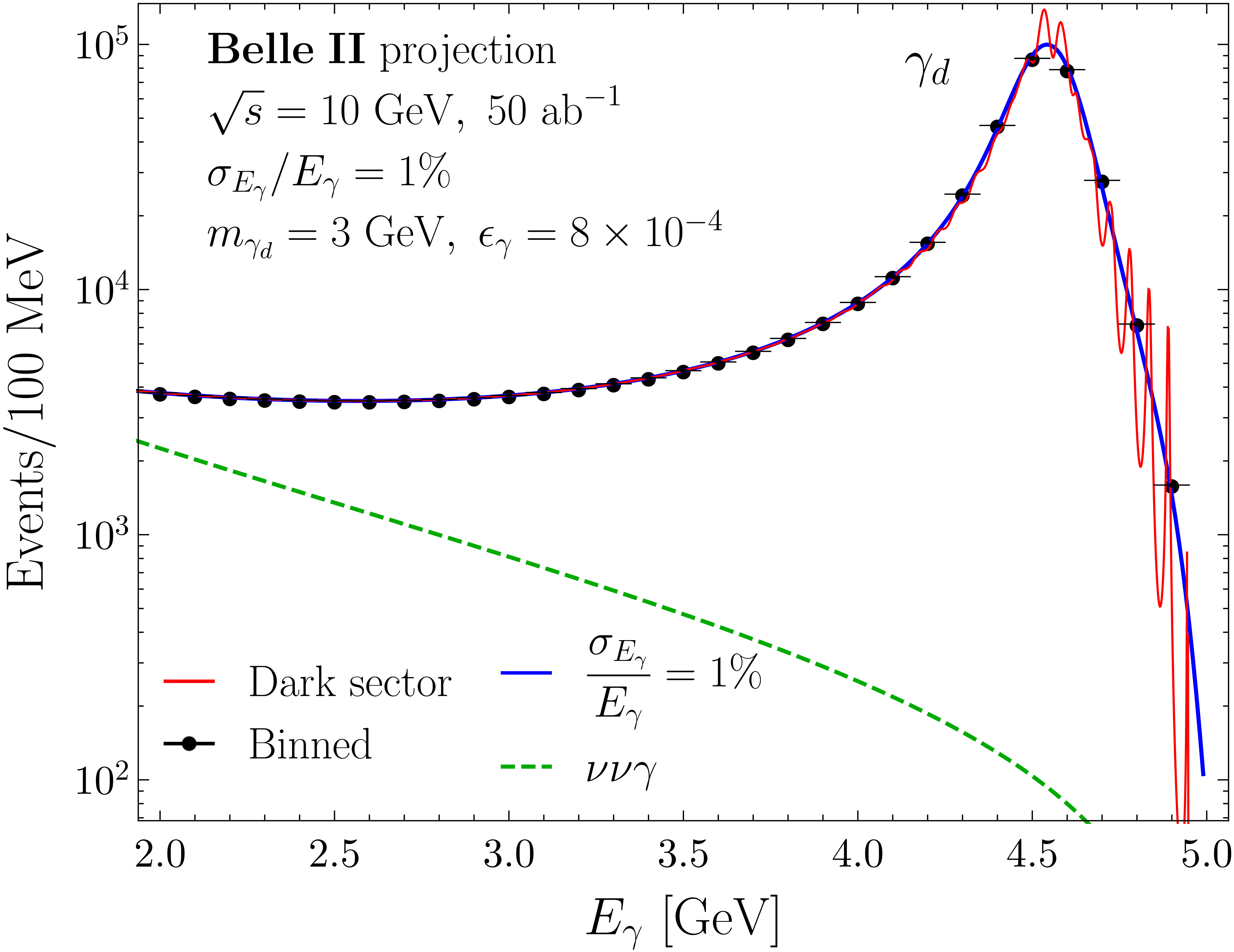


50 ab^{-1}!

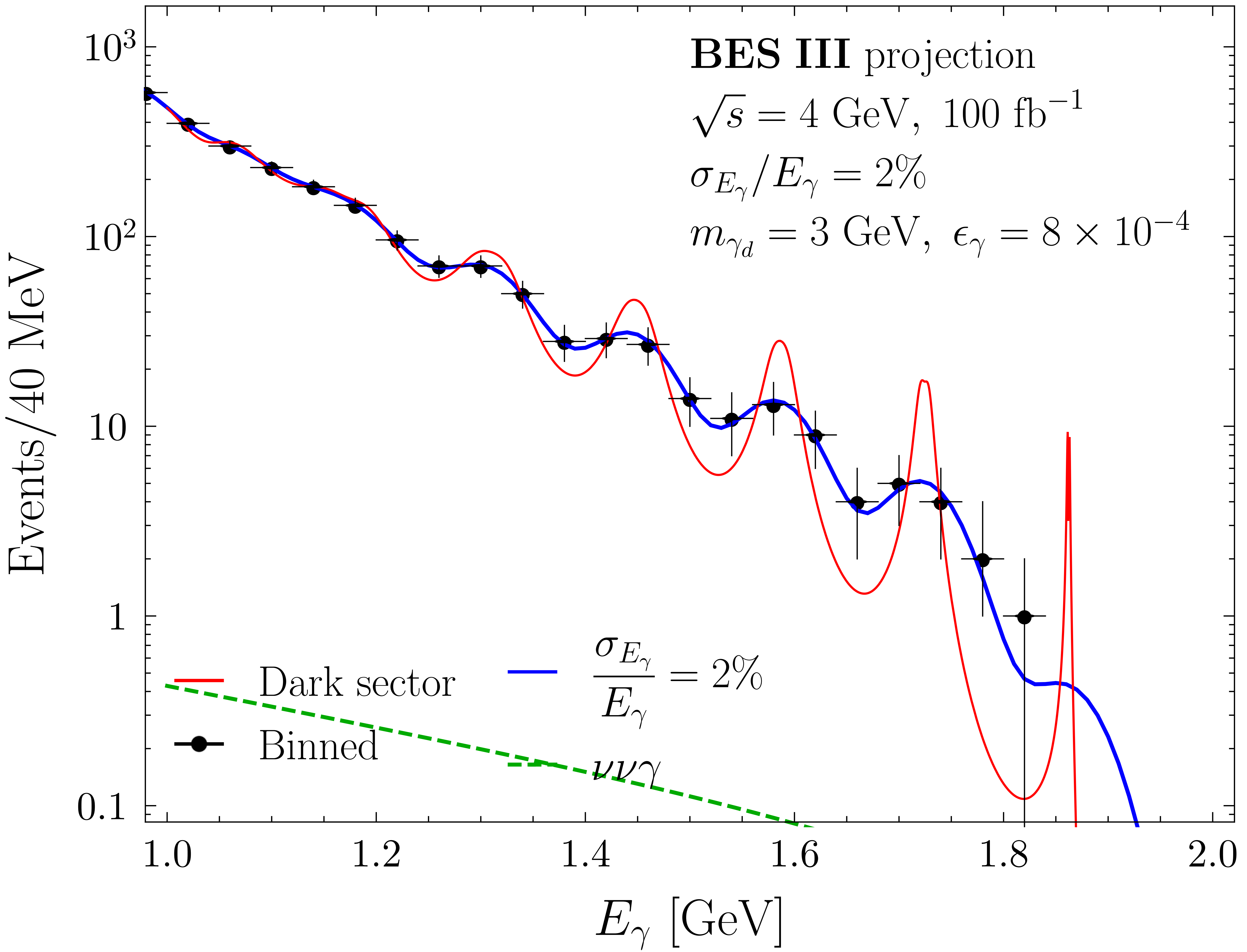




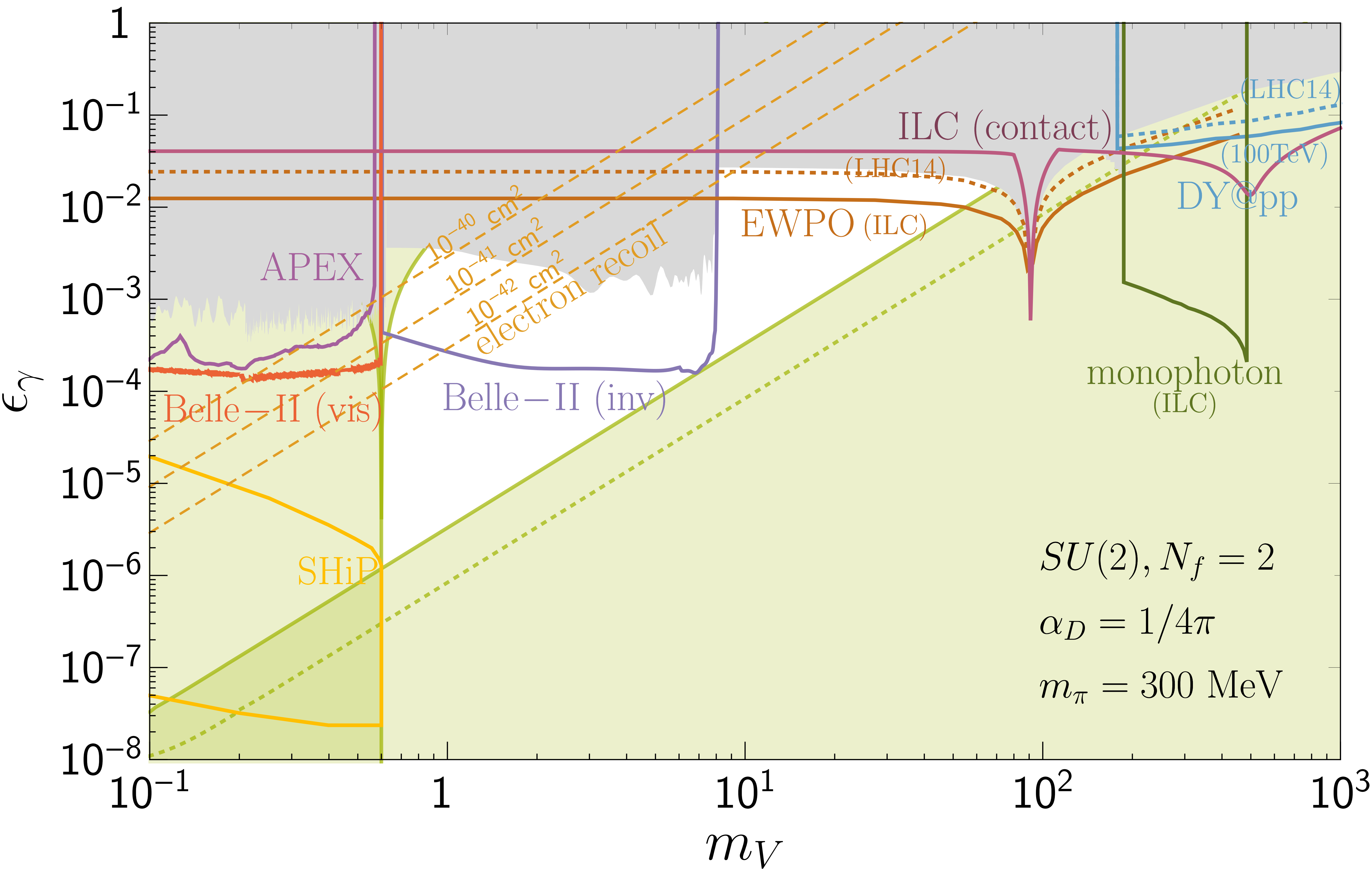
$$E_\gamma = \frac{\sqrt{s}}{2}\left(1 - \frac{M_{\rm inv}^2}{s}\right)$$



Belle II projection
$\sqrt{s} = 10$ GeV, 50 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



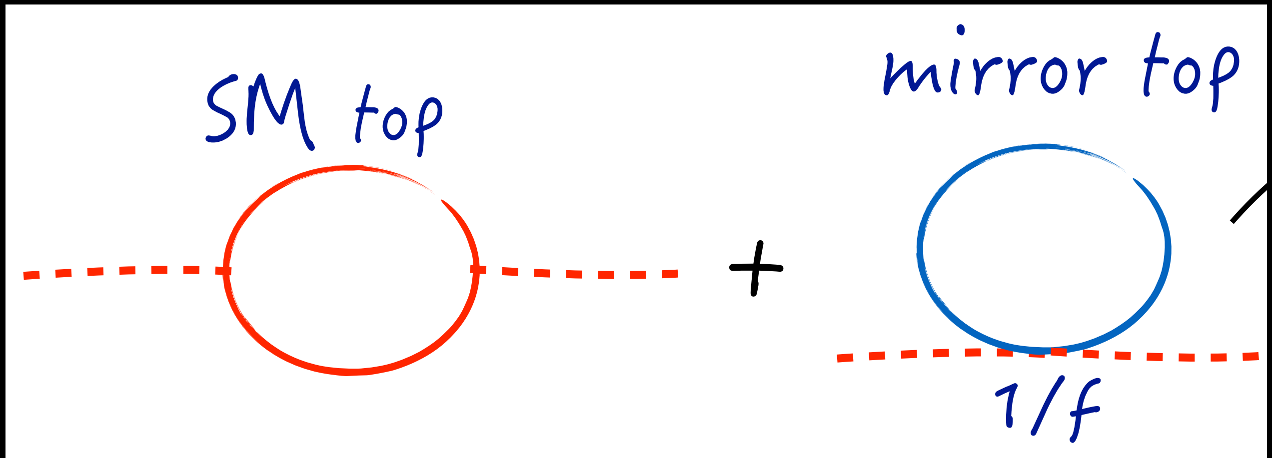
BES III projection
$\sqrt{s} = 4$ GeV, 100 fb^{-1}
$\sigma_{E_\gamma}/E_\gamma = 2\%$
$m_{\gamma_d} = 3$ GeV, $\epsilon_\gamma = 8 \times 10^{-4}$
Dark sector
Binned
$\frac{\sigma_{E_\gamma}}{E_\gamma} = 2\%$
$\nu\nu\gamma$
Events/40 MeV
E_γ [GeV]
10^3
10^2
10
1
0.1
1.0
1.2
1.4
1.6
1.8
2.0



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

Twin Higgs

- some new particles needed to cancel the top quark loop $\Rightarrow$ 3 of them
- if not charged under "our QCD", no LHC signal
- Z_2 copy of SM
  - SM + SM'
- accidentally, approx. SU(4) symmetry in Higgs potential
- Higgs = PNGB SU(4)/SU(3)



Z. Chacko, H.-S. Goh, R. Harnik

$$V = -\mu^2|H_1|^2 - \mu^2|H_2|^2$$
$$+ \lambda(|H_1|^2)^2 + \lambda(|H_2|^2)^2 + 2\kappa(|H_1|^2 + |H_2|^2)^2$$
$$= -m^2\mathcal{H}^\dagger\mathcal{H} + \lambda(\mathcal{H}^\dagger\mathcal{H})^2$$

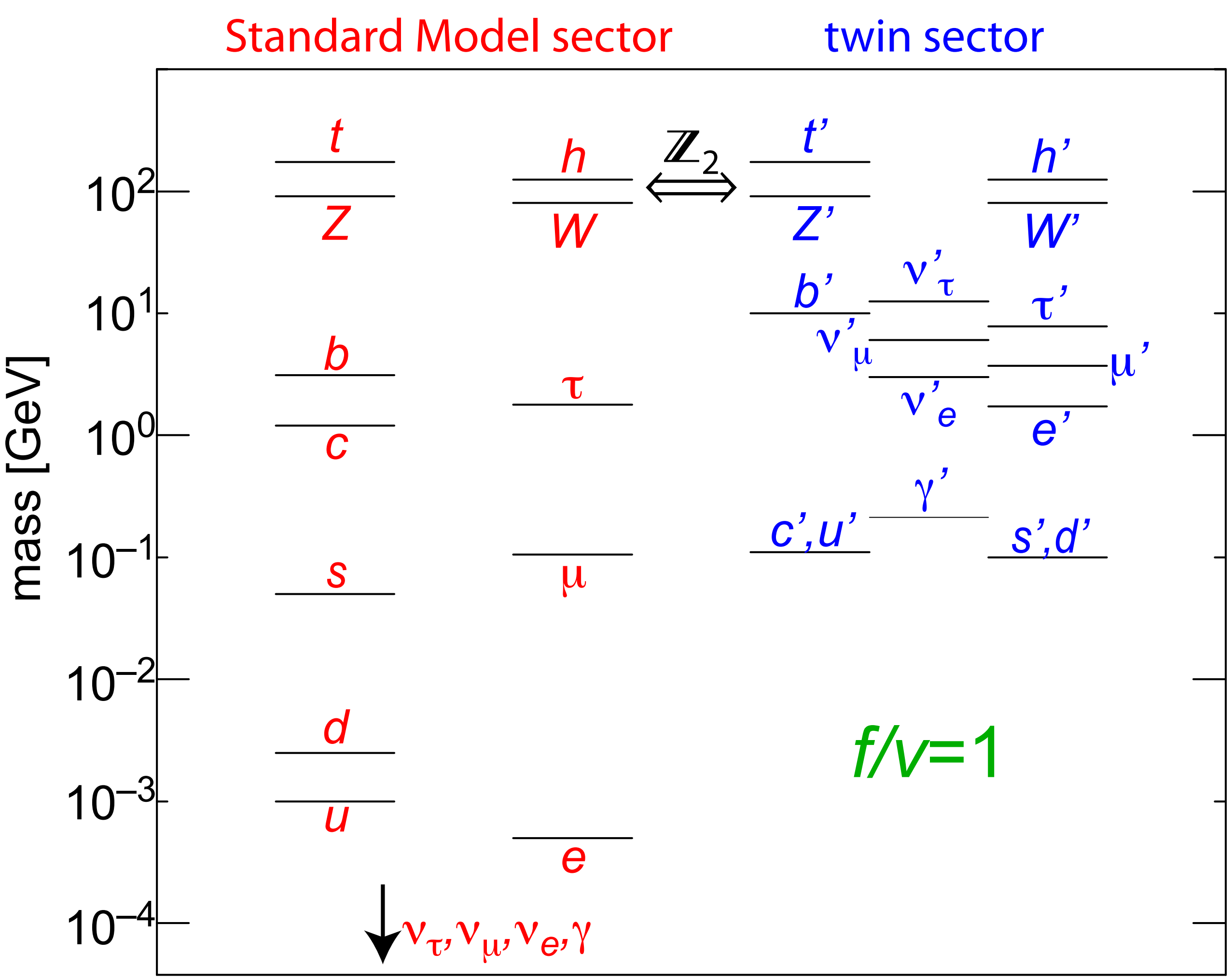


FIG. 1. A sample spectrum of twin particles. Here we use $f/v = 1$ to demonstrate the $\mathbb{Z}_2$ invariance between the visible and twin sectors for t, h, Z, W; lighter particles are subject to $\mathbb{Z}_2$-breaking effects without spoiling the solution to the hierarchy problem. In practice, twin sector masses are of course raised by a factor of $f/v \gtrsim 3$.

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 $SU(2)_U \times SU(2)_D \times U(1)_{\mathrm{EM}}$. 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 $m_{d'} = m_{s'} < m_{u'} = m_{c'} = m_{d',s'}(1+\Delta)$.

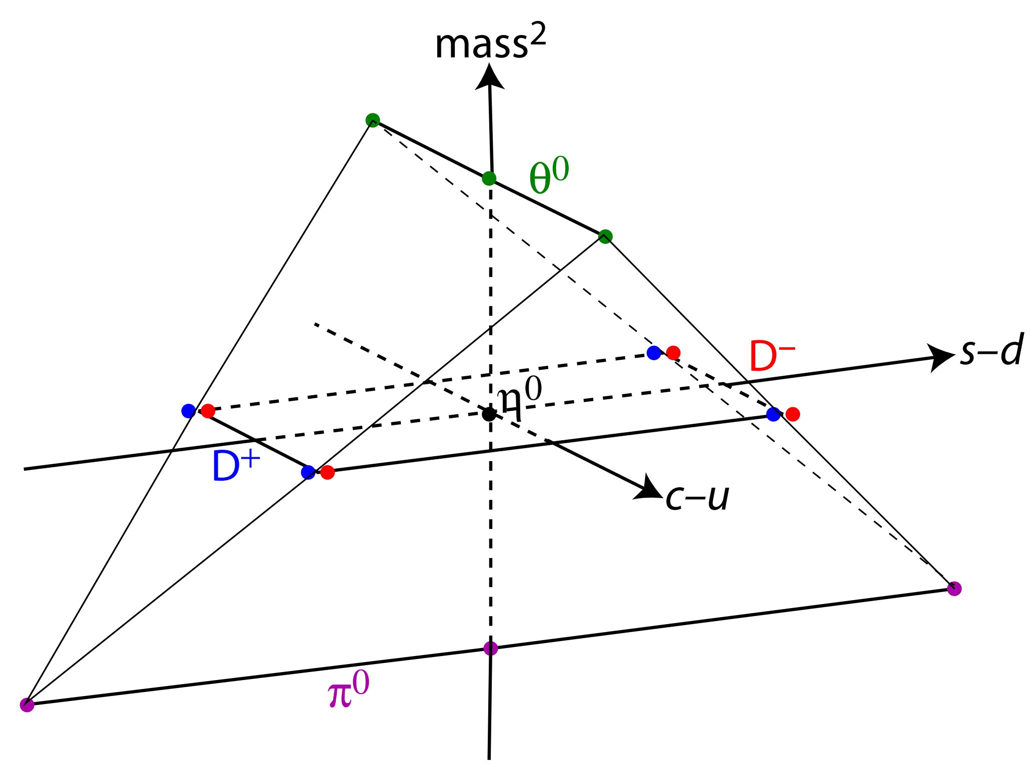


FIG. 2. A visual representation of the meson spectrum.

lifetimes

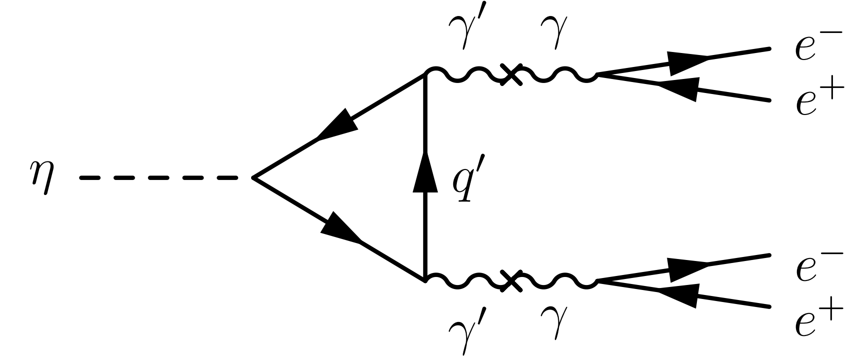


Figure 1: Sample Feynman diagram for $\eta \to 2(e^+e^-)$.

- $\tau_\eta \sim 10^2$–10^{11} sec
  - does not modify 3→2 freezeout
  - For $\tau_\eta < 10^6$ sec, consistent with CMB, BBN limits
- $\tau_\theta \gg$ age of the Universe

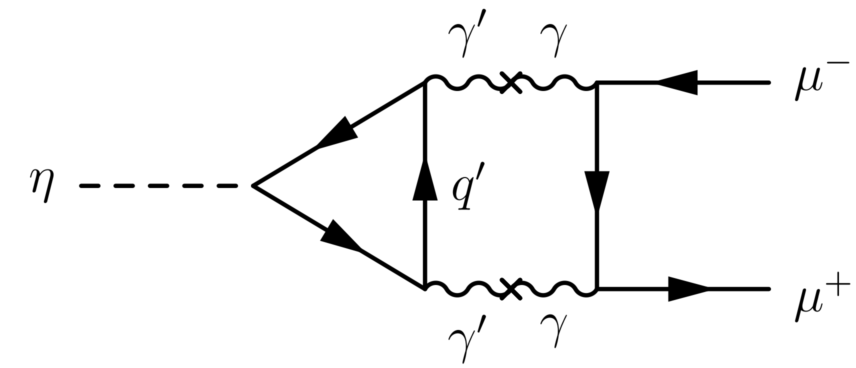


Figure 2: Sample Feynman diagram for $\eta \to \mu^+\mu^-$.

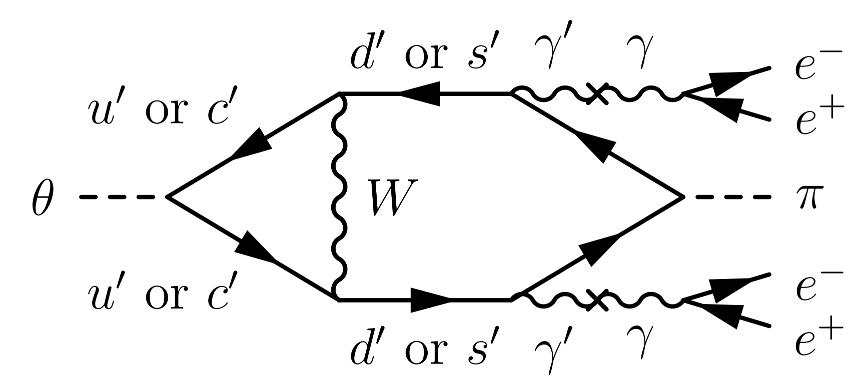
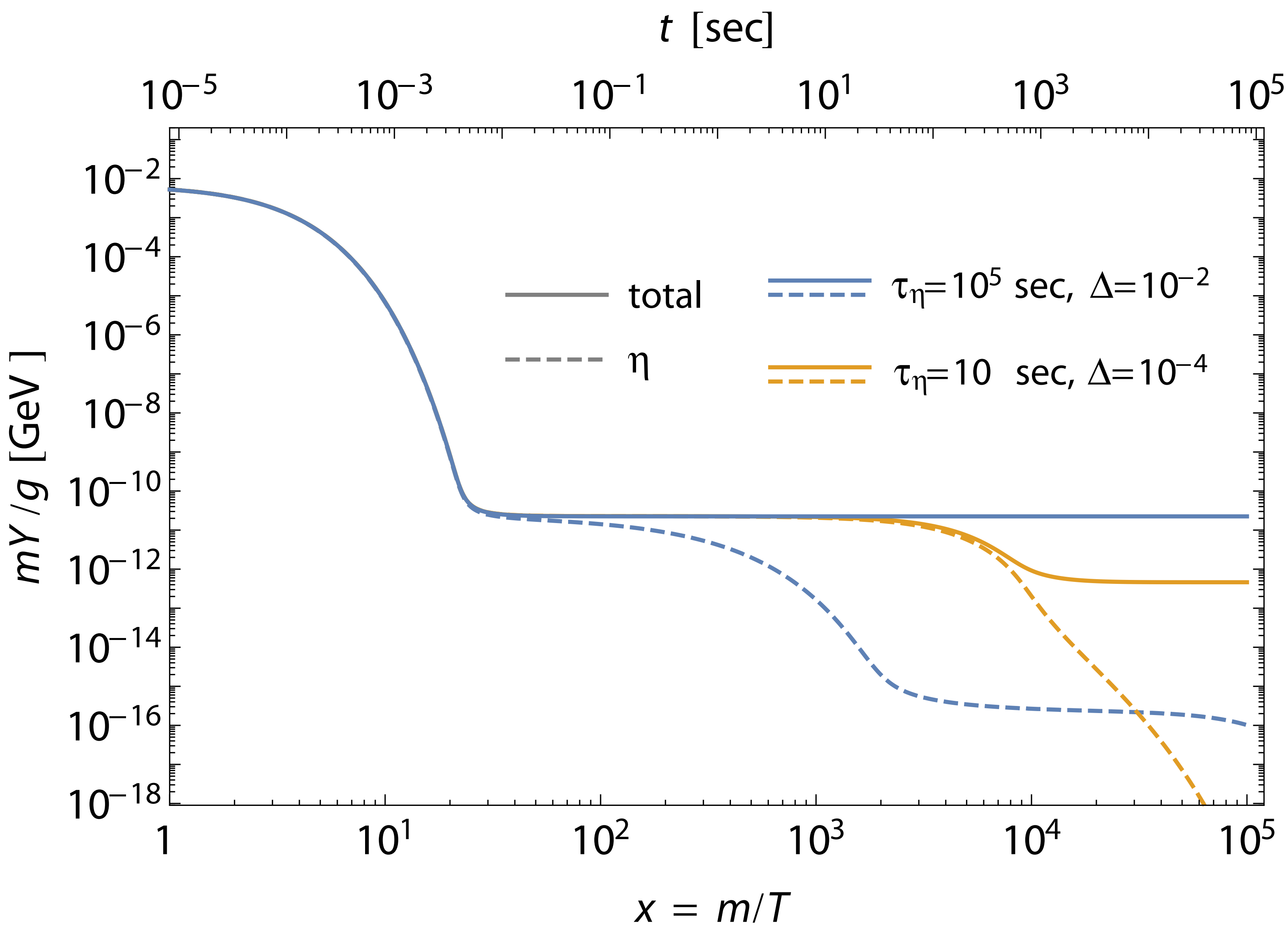


Figure 3: Sample Feynman diagram for $\theta \to \pi + 2(e^+e^-)$.

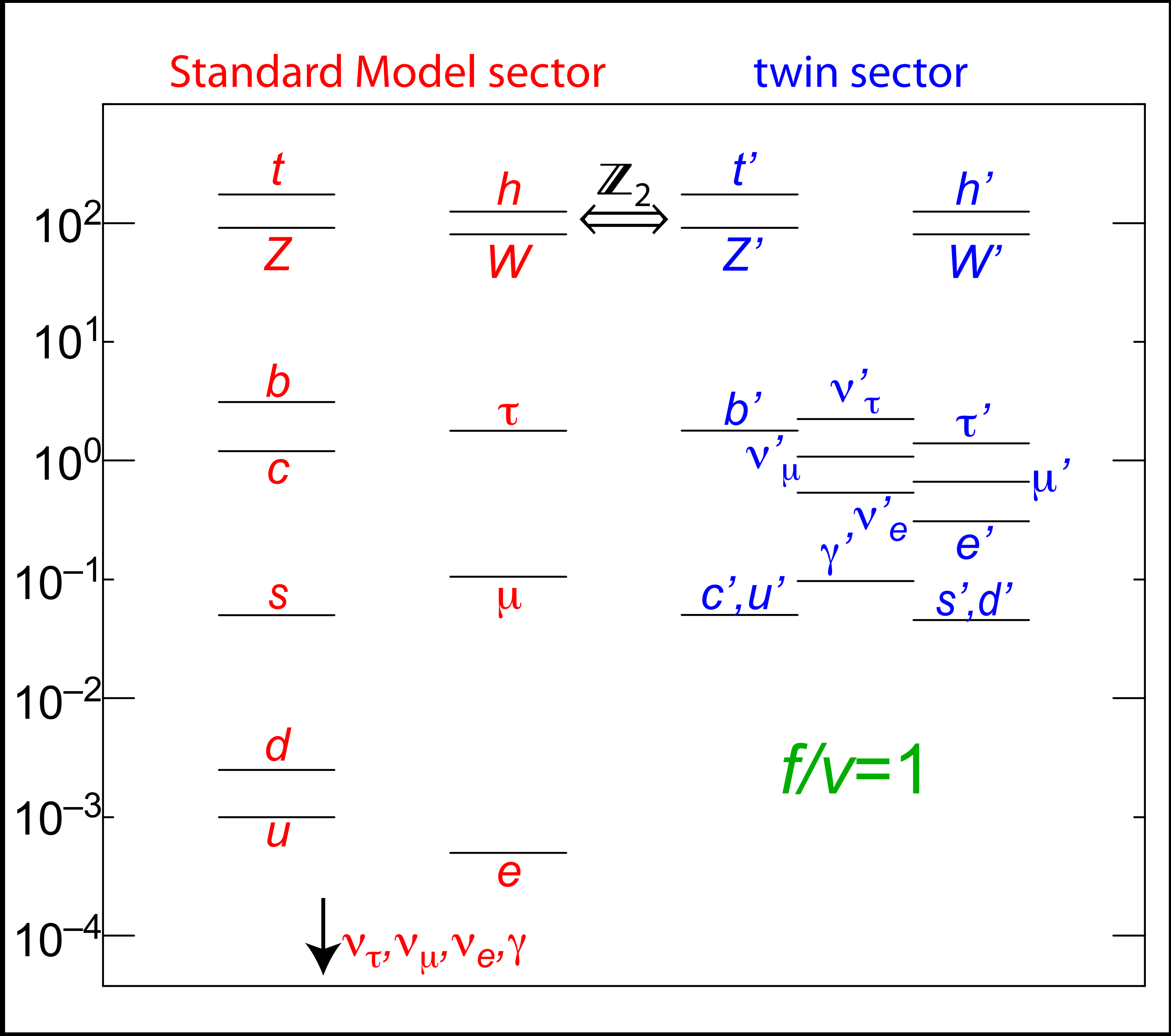
$\pi\pi \to \eta\eta \to$ SM

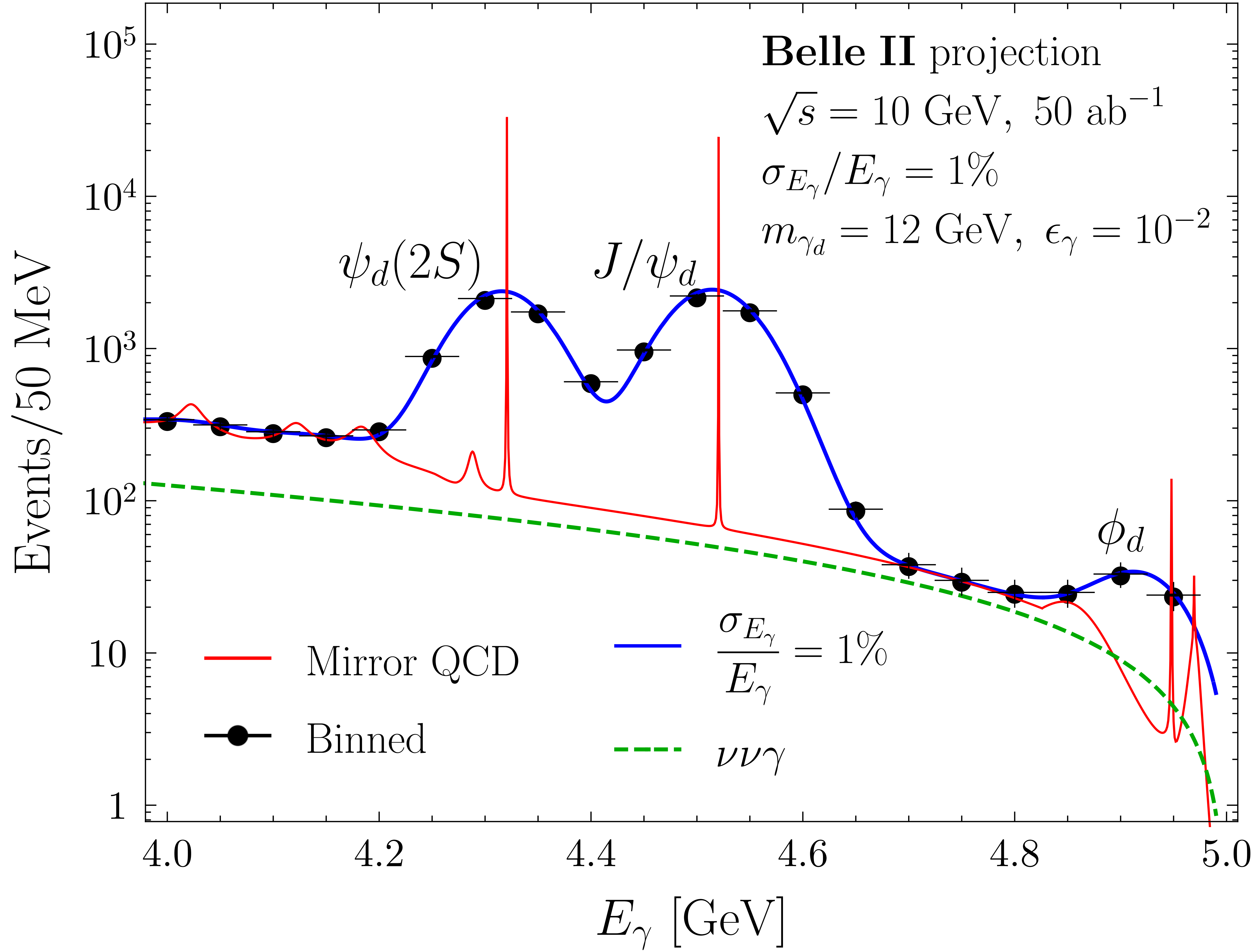
- If $\pi\pi \to \eta\eta$ is still in chemical equilibrium when η starts to decay, we will lose π
- need η lifetime to be longer than the decoupling of the chemical equilibrium
- This shouldn't happen in the halo today either
- can be avoided if $\Delta > v_{halo}^2 \sim 10^{-6}$



Twin Higgs

- invisible Higgs decay
  - 50% if $f/v=1$
  - now $f/v>3$
  - ILC down to 0.3% $\approx 10^{-3}$ fine-tuning
  - "invisible" Higgs may have many low-mass collimated e^+e^- pairs at LHC
- Belle II covers ~a half of the parameter space (single γ)

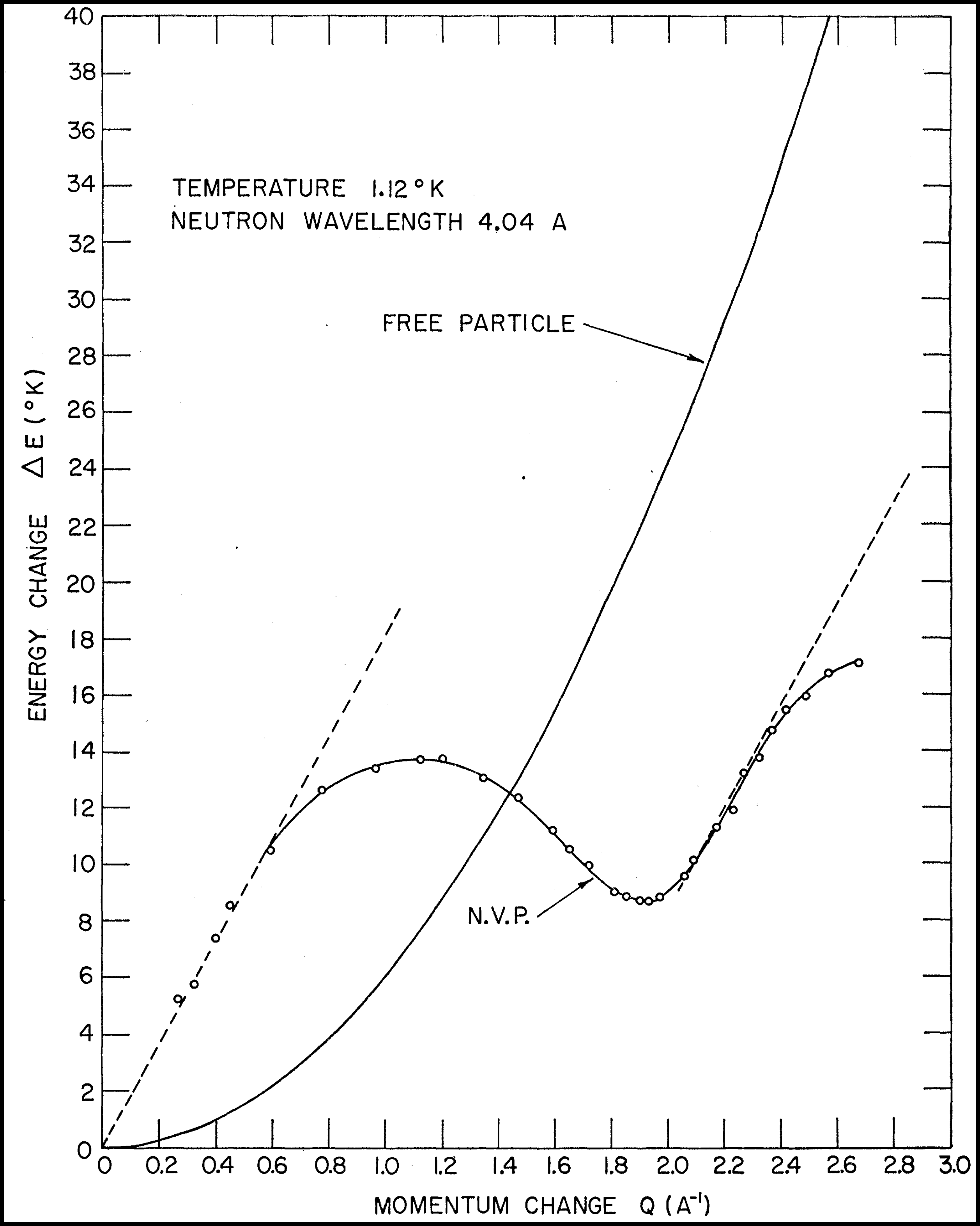




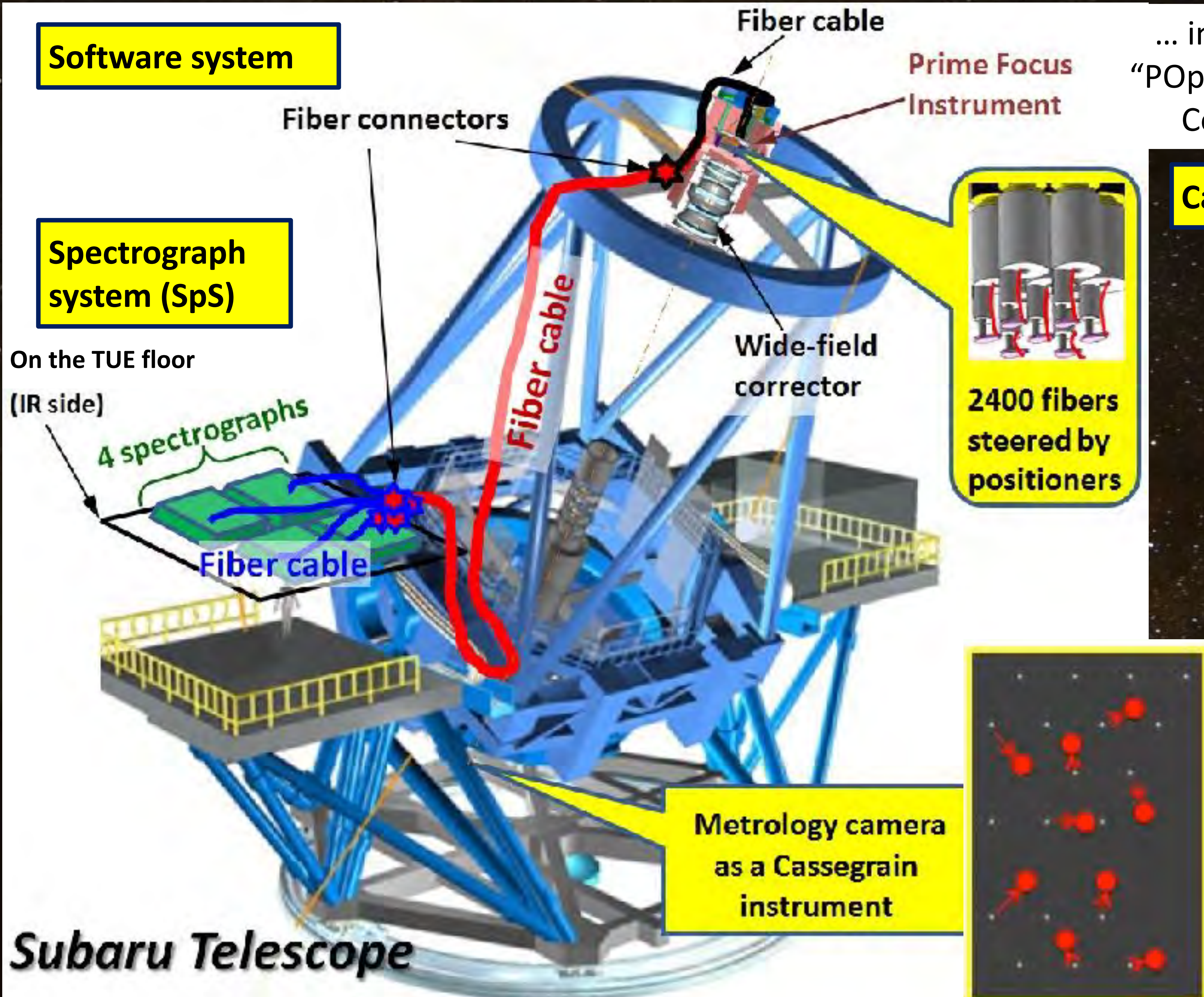
Belle II projection
$\sqrt{s} = 10$ GeV, 50 ab^{-1}
$\sigma_{E_\gamma}/E_\gamma = 1\%$
$m_{\gamma_d} = 12$ GeV, $\epsilon_\gamma = 10^{-2}$
$\psi_d(2S)$
J/ψ_d
ϕ_d
Mirror QCD
Binned
$\frac{\sigma_{E_\gamma}}{E_\gamma} = 1\%$
$\nu\nu\gamma$
Events/50 MeV
E_γ [GeV]
10^5
10^4
10^3
10^2
10
1
4.0
4.2
4.4
4.6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

Direct Detection

- Many new ideas on light dark matter detection
- m=MeV–GeV
- v~10^{-3} c
- E_{kin} ~ 10^{-6} m
- E_{kin} ~ eV–keV
- little radioactivity BG
- much higher number density n~0.3GeV/m
- use collective excitations
- e.g.,phonon/roton in ^{4}He
- $D^{\pm}$ mesons in twin SIMP



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

NAOJ

Academia Sinica

CPPC

Princeton University

Max-Planck-Institut für Astrophysik

Max-Planck-Institut für extraterrestrische Physik

Kavli IPMU
Institute for the Physics and Mathematics of the Universe

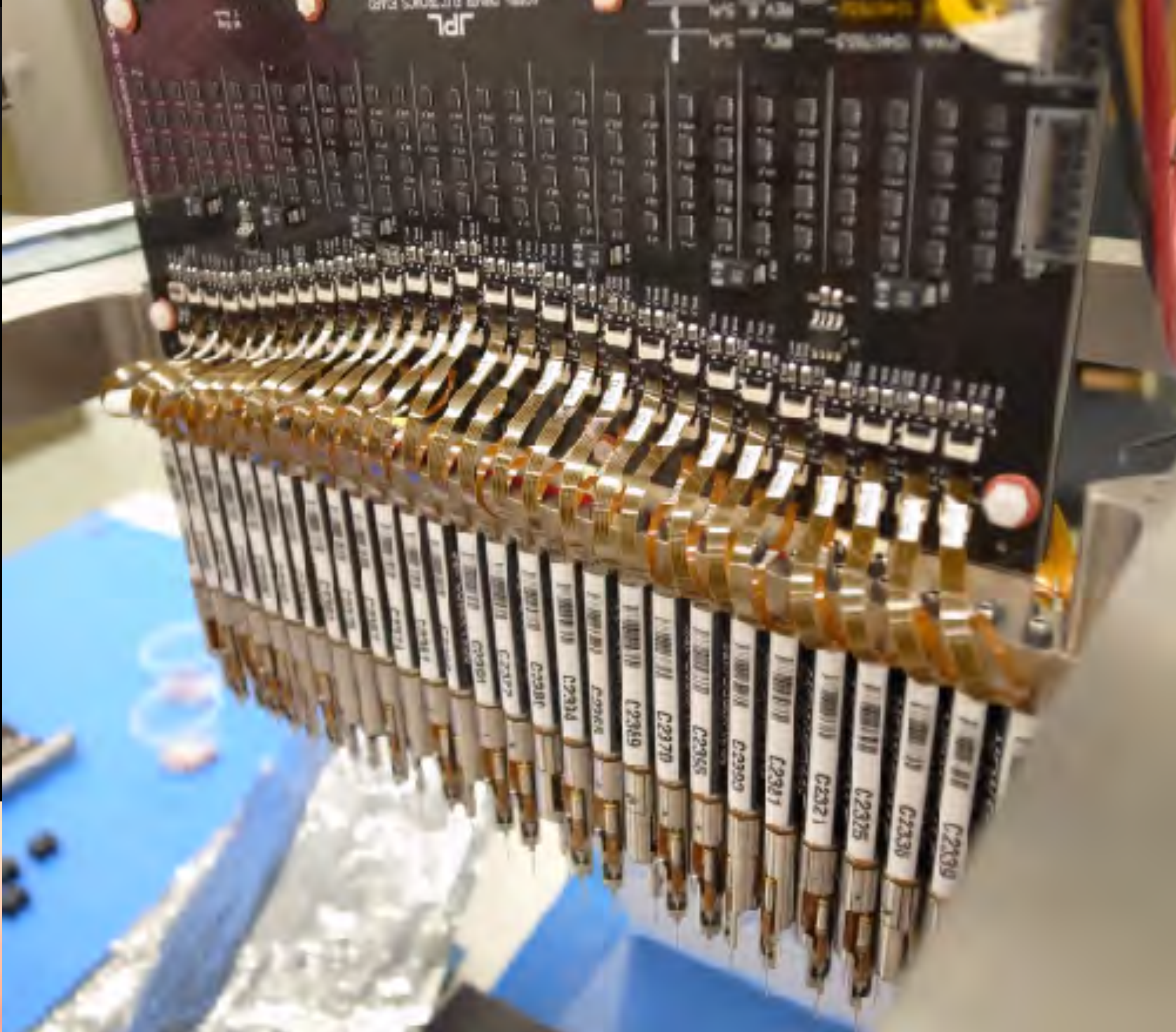
NEPG

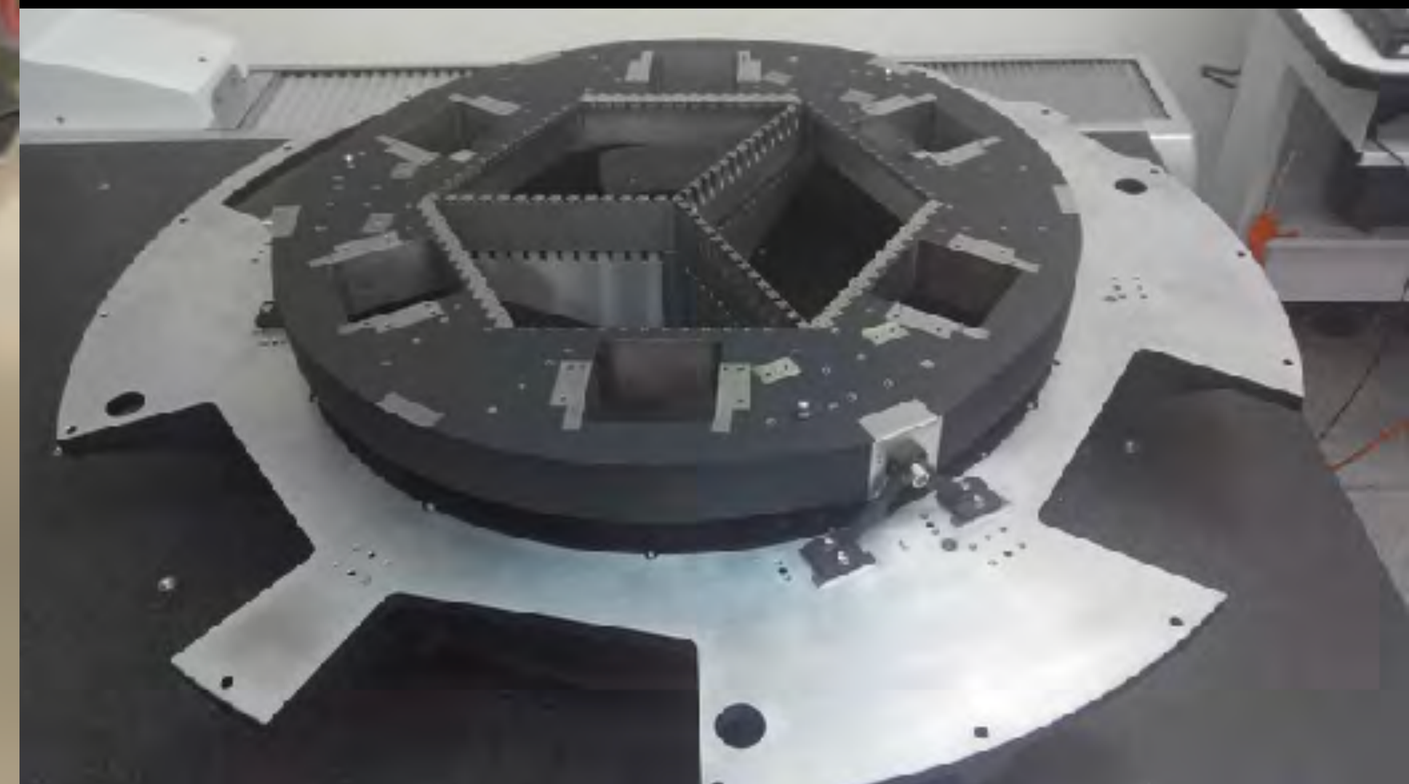
LNA Laboratório Nacional de Astrofísica

LAM
Laboratoire d'Astrophysique de Marseille

Johns Hopkins University

2394 Cobras

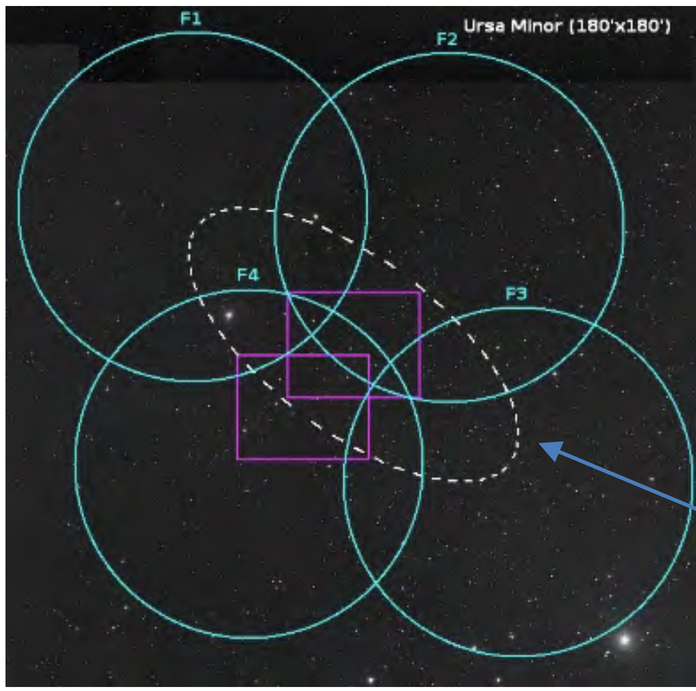




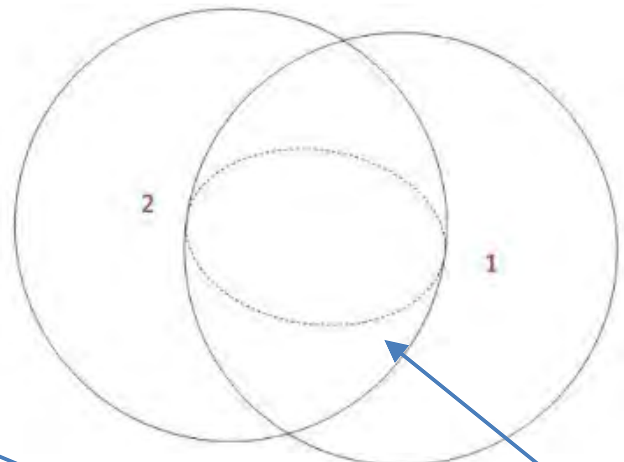
PFS pointings for MW satellites

~ HSC imaging data are available for all samples ~

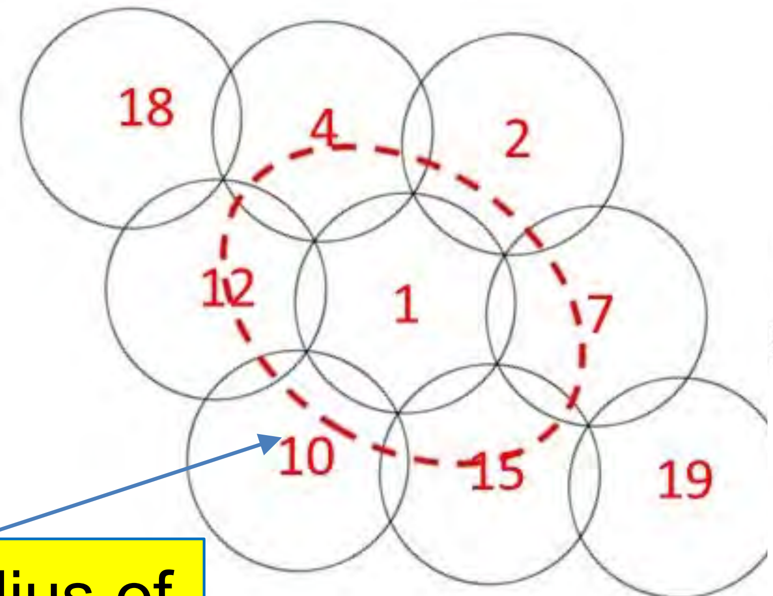
Ursa Minor



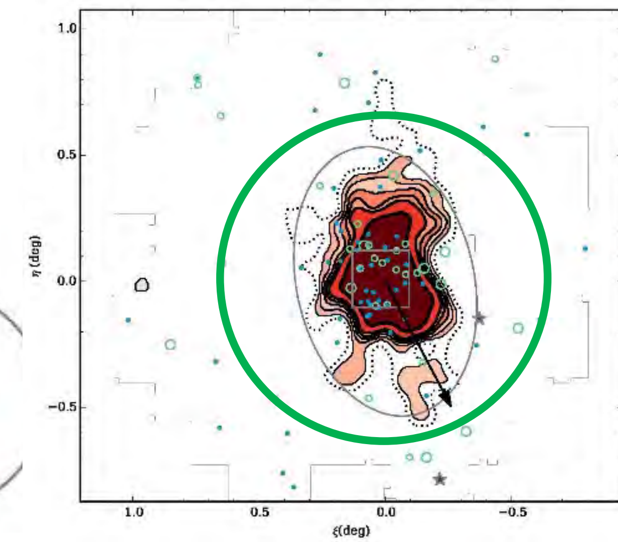
Draco



Sextans

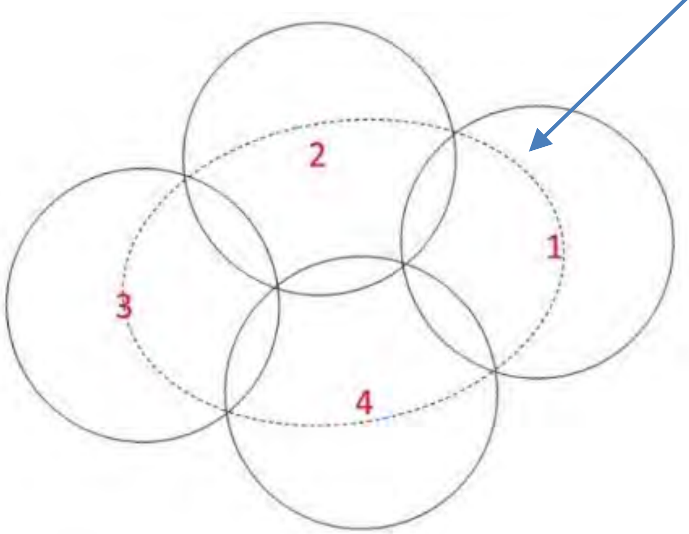


Bootes I

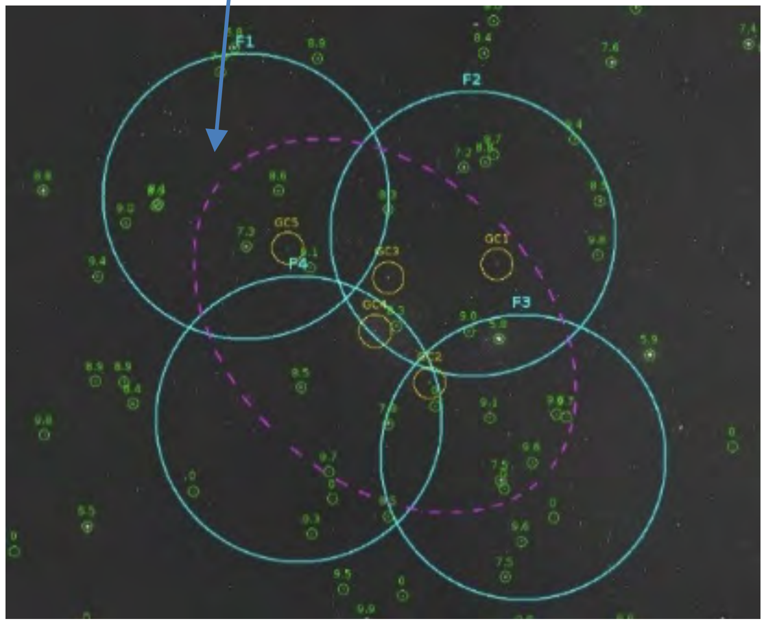


tidal radius of stellar comp.

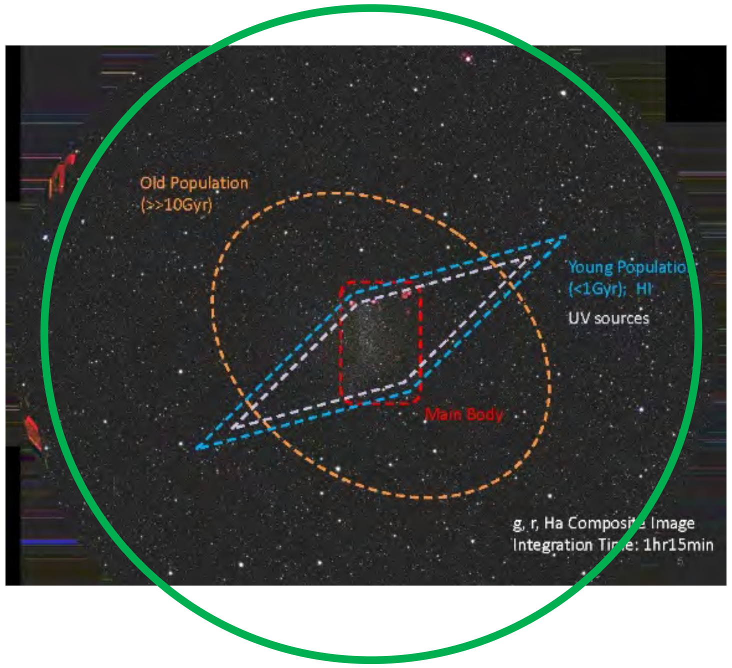
Sculptor



Fornax



NGC6822



Conclusion

- null signal at LHC and WIMPs forcing theorists to examine
  - new solutions to the hierarchy problem
  - new candidates for dark matter
  - can do both in some models
- New experimental signals
  - *tradition*: go to as high mass as possible
  - *new trend*: low mass but weaker coupling
  - ILC, Belle II, SHIP
  - new methods for MeV–GeV dark matter
- *Don't give up till we find something new!*