Phenomenology 2016 Symposium

9-11 May 2016
University of Pittsburgh
US/Eastern timezone

HEP: Future Perspectives

Hitoshi Murayama (Berkeley, Kavli IPMU)

May 11, 2016

東京大学 THE UNIVERSITY OF TOKYO
BERKELEY CENTER FOR THEORETICAL PHYSICS
BERKELEY LAB
THE UNIVERSITY OF CALIFORNIA 1868
KAVLI IPMU

Phenomenology 2016 Symposium

9-11 May 2016
University of Pittsburgh
US/Eastern timezone

HEP: Future Perspectives

Hitoshi Murayama (Berkeley, Kavli IPMU)

May 11, 2016

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

Distance Visual Acuity Test (E Game)

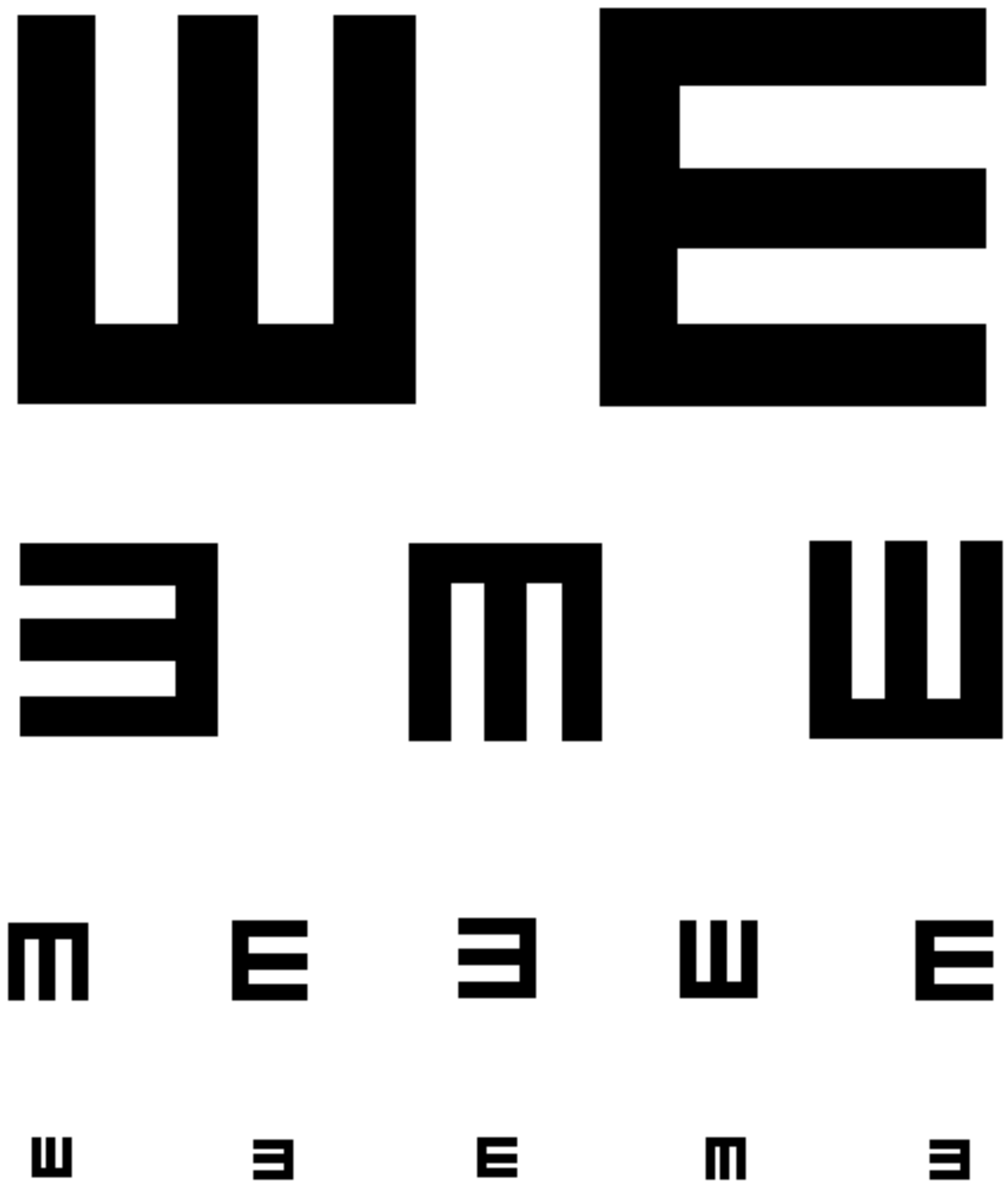
(Read in good light at 10 feet.)

Line 1
20/200

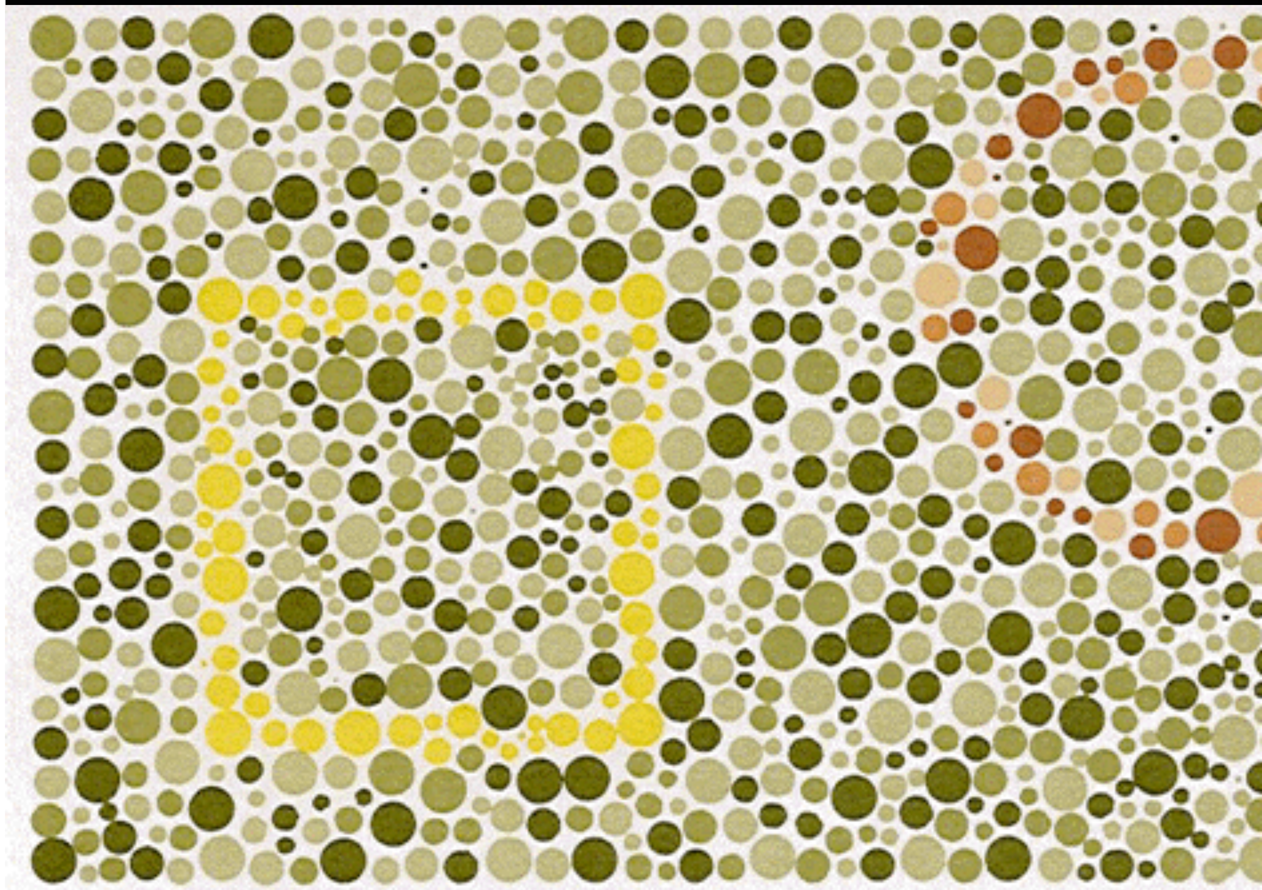
Line 2
20/100

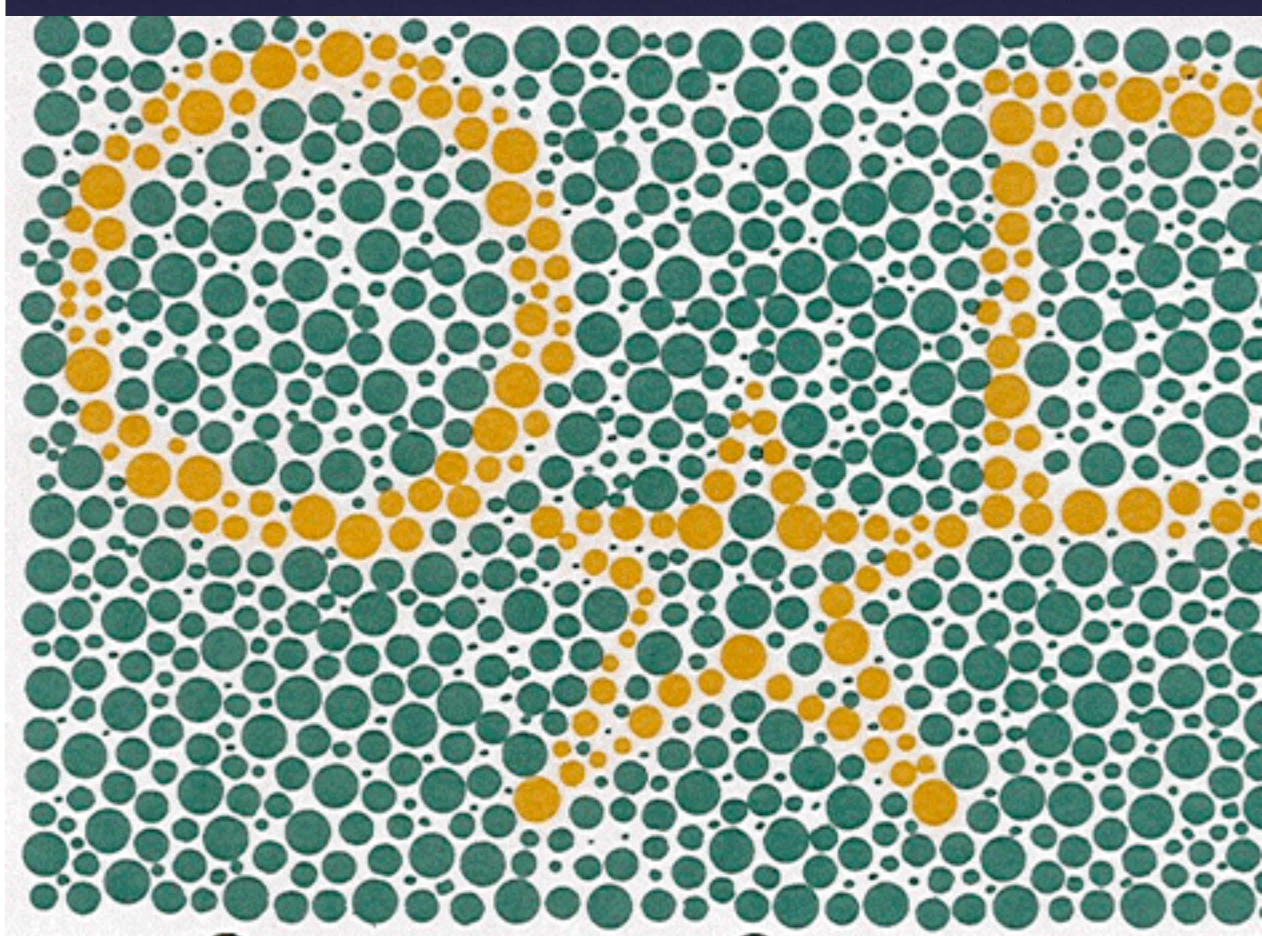
Line 3
20/40

Line 4
20/20



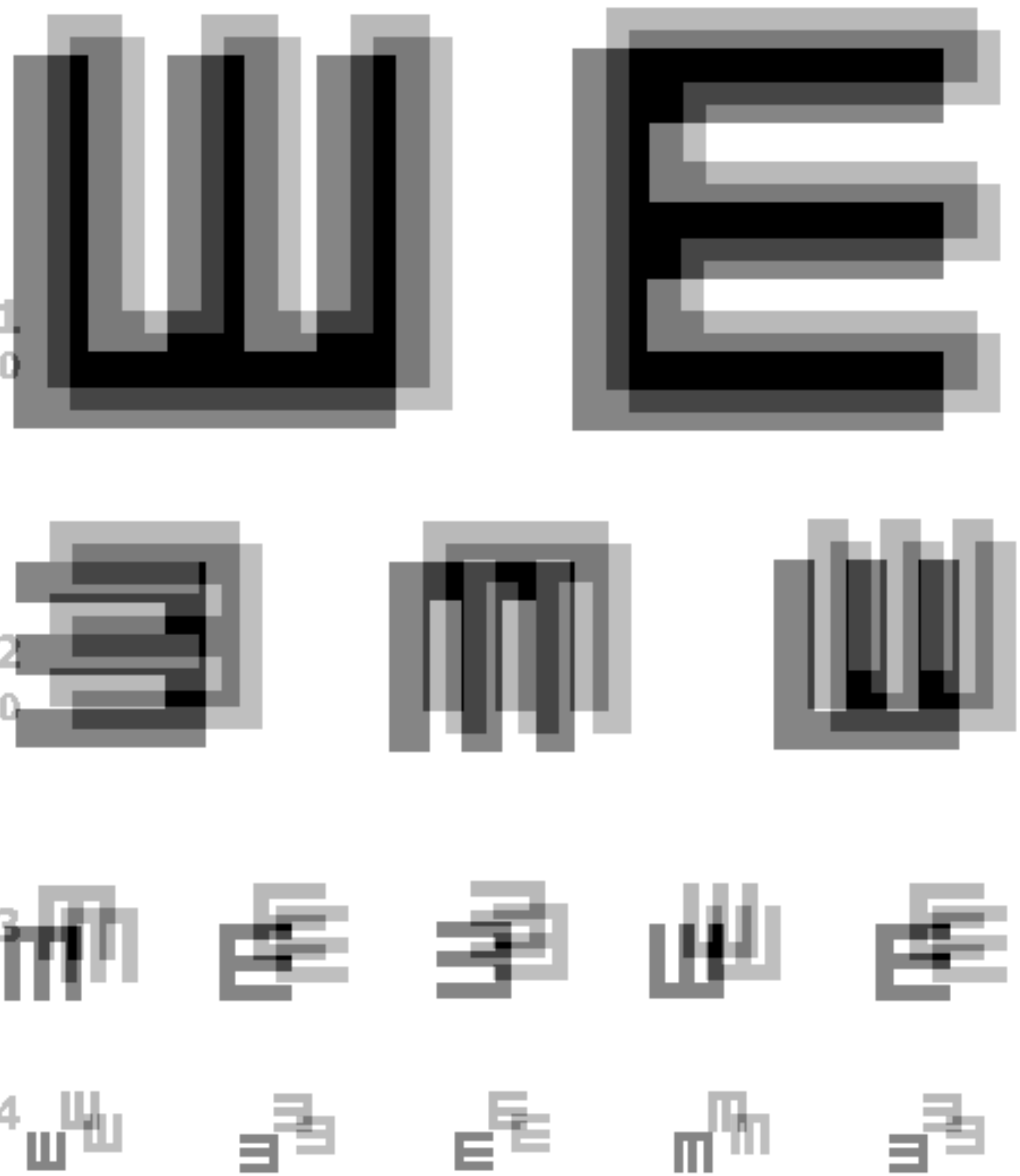
100 Millimeter Calibration Bar
(If not 100 mm, see text of visual acuity page.)





Distance Visual Acuity Test (E Game)

(Read in good light at 10 feet.)



Line 1
20/200

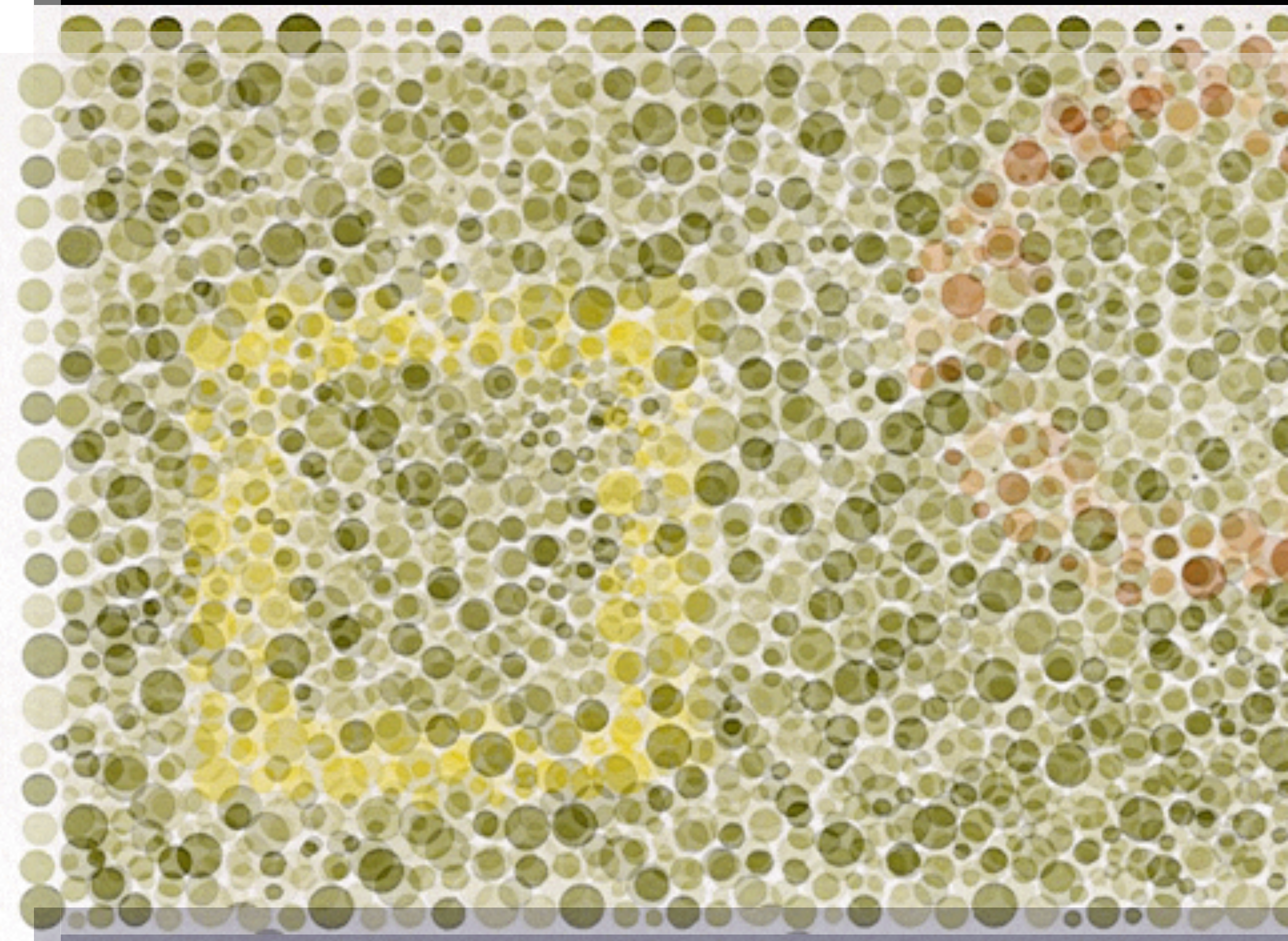
Line 2
20/100

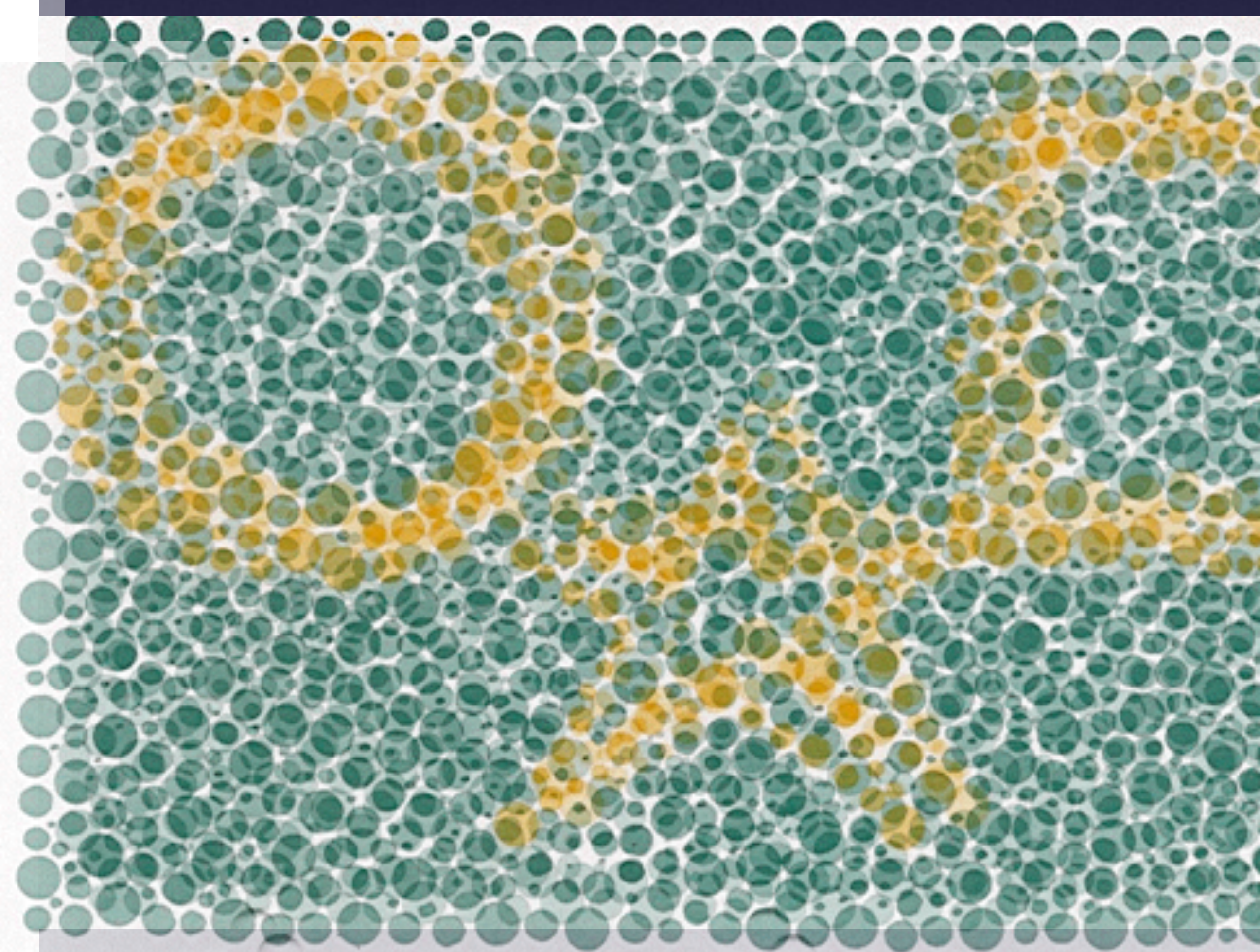
Line 3
20/40

Line 4
20/20

100 Millimeter Calibration Bar

(If not 100 mm, see text of visual acuity page.)





Disclaimer

- This type of talk can be dangerous
- Especially citing a paper but not its rival
- Solution:
  - no citations
  - except for mine

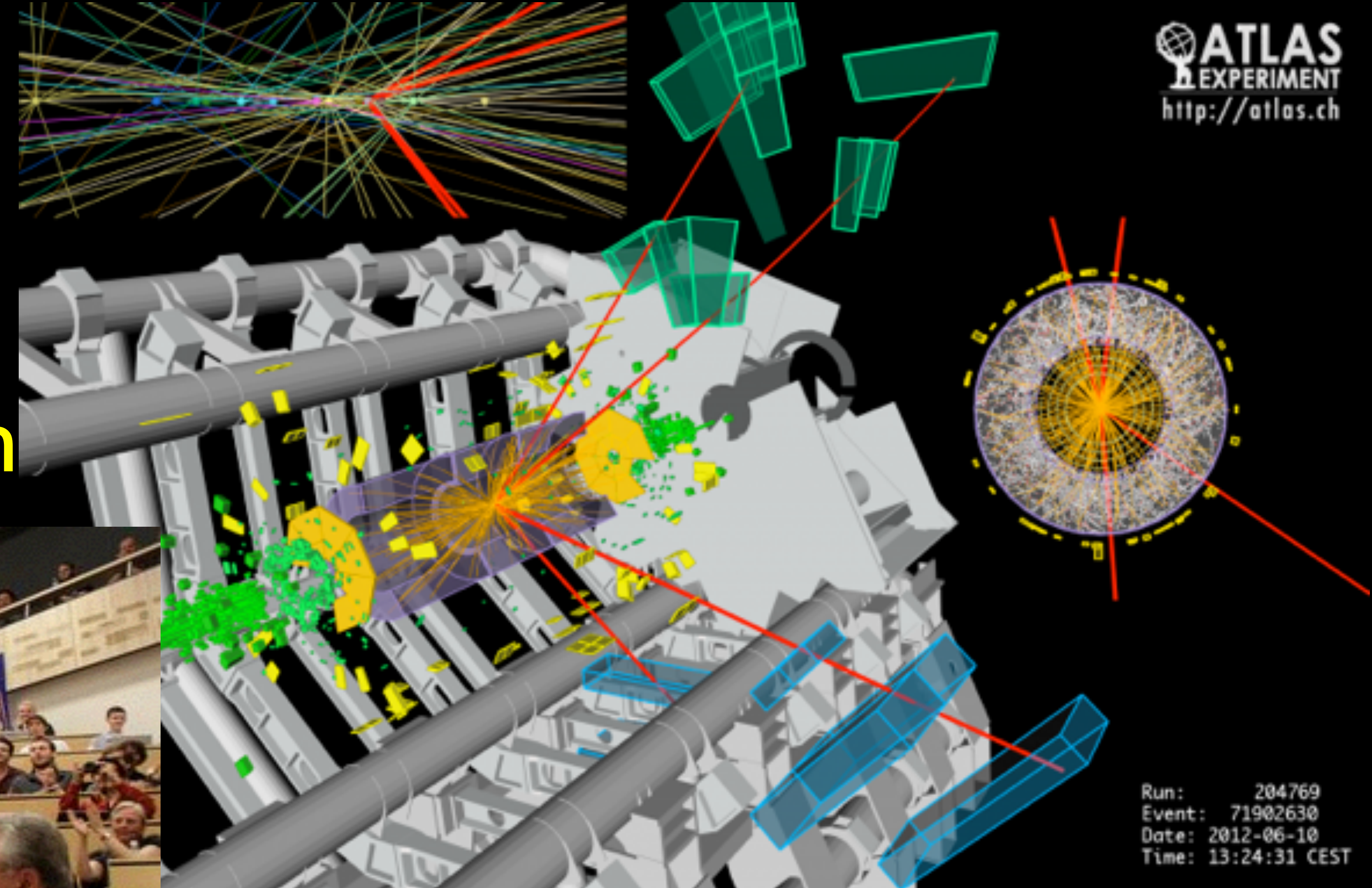
Agree

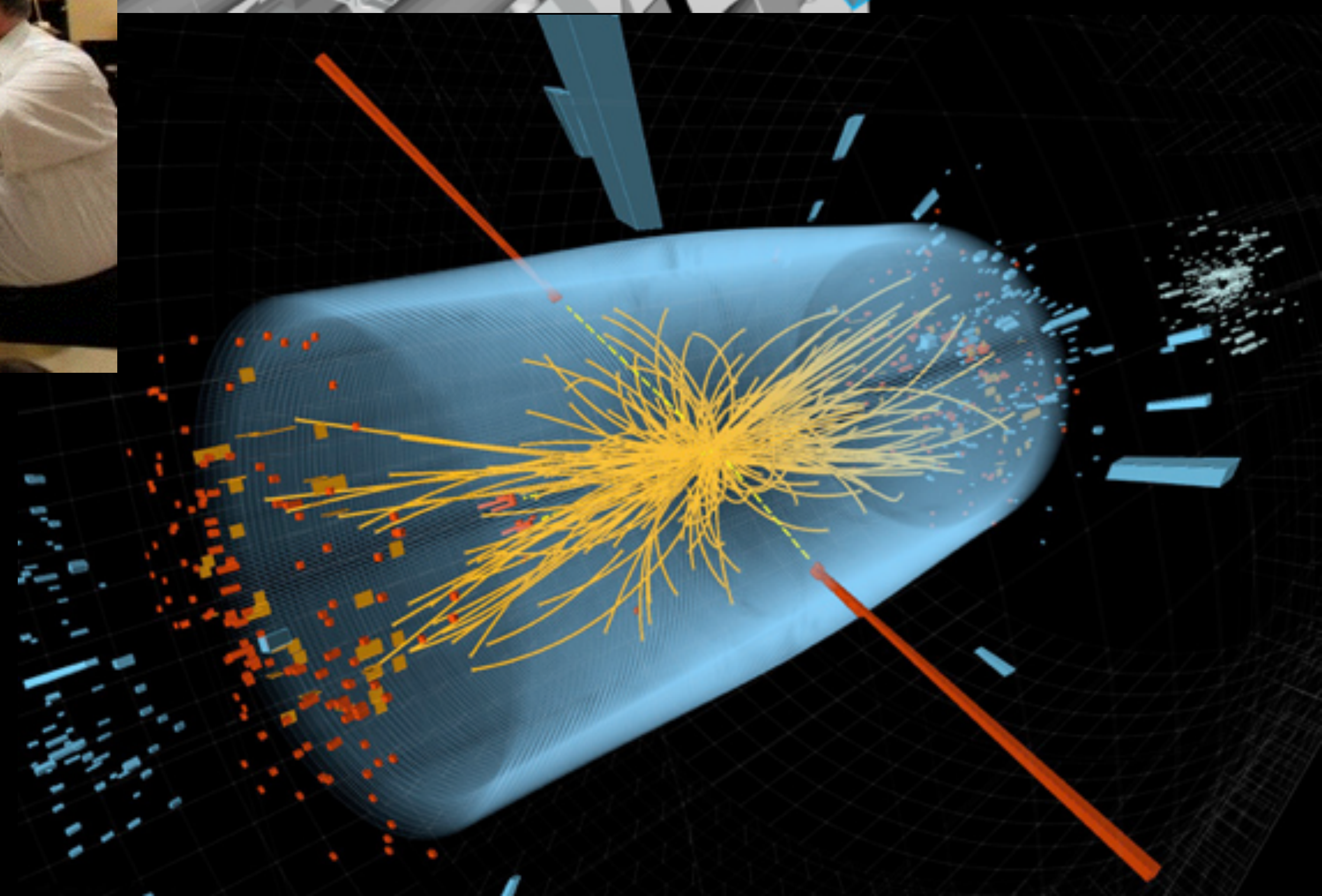
LHC score card

- origin of EWSB
  - Higgs discovery! But only a partial answer
- naturalness
  - None
- dark matter
  - None
- EW baryogenesis
  - No new CP violation
- unexpected
  - Perhaps??? 750 GeV diphoton???

July 4, 2012

discovery of Higgs boson





theory： 1964

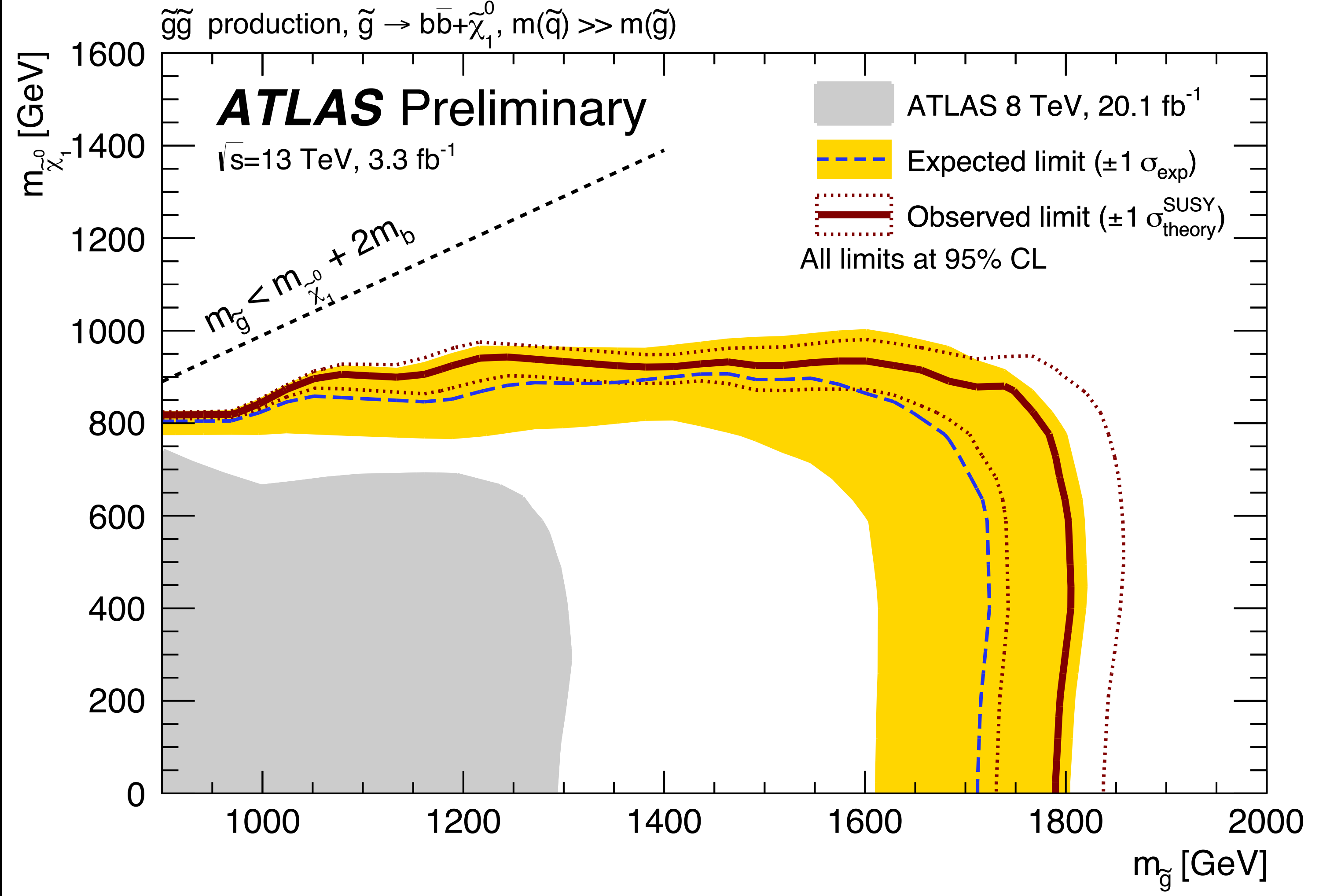
design： 1984

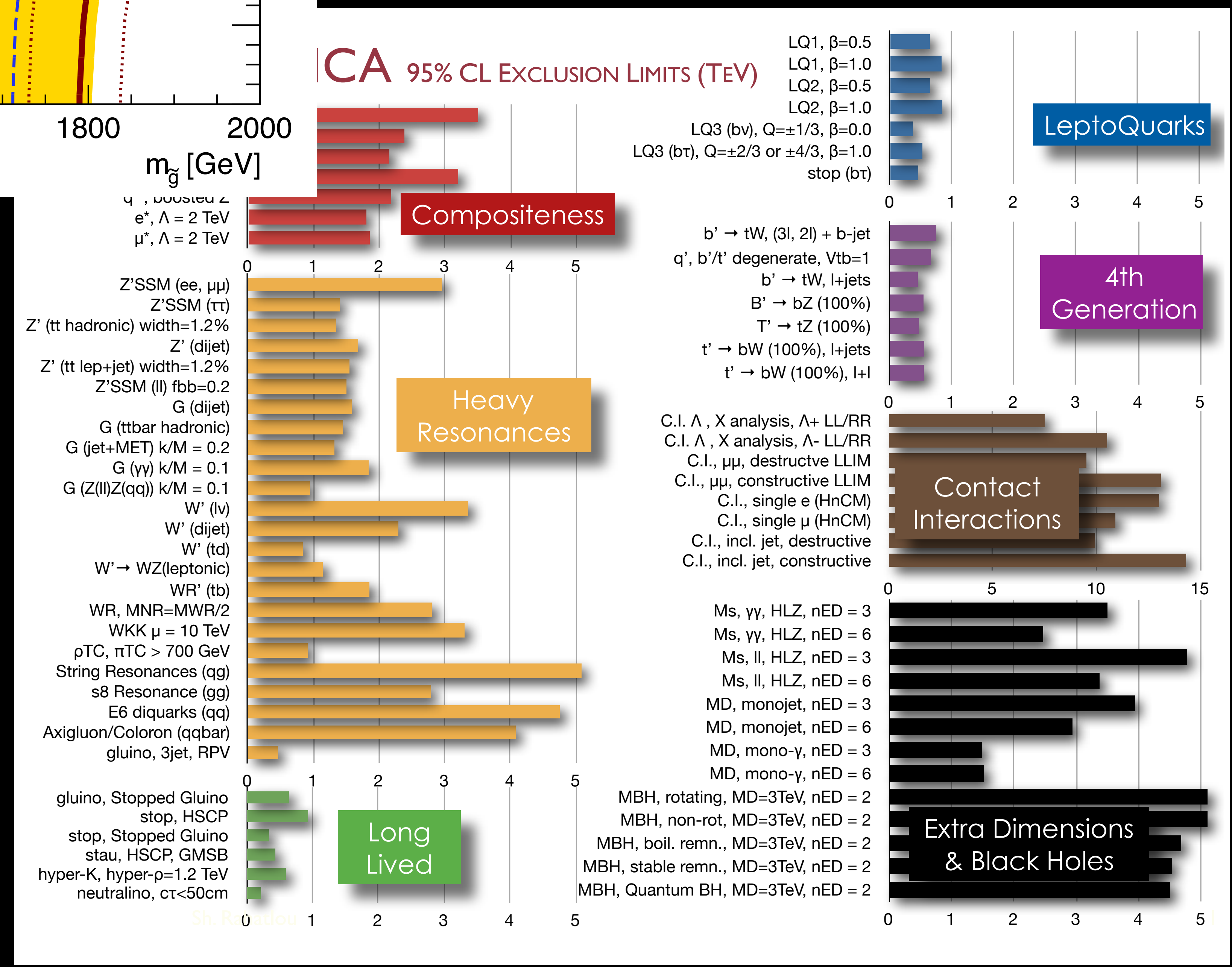
construction： 1998


Higgsdependence Day
July 4, 2012

Scalar

- every elementary particles have spin
- electrons, photons, quarks, ...
- only Higgs boson doesn't spin
- Faceless! A *spooky particle*
- I had proposed "Higgsless theories"
- *Is it the only one?*
- *does it have siblings? relatives?*
- *Maybe it's spinning in extra dimensions?*
- *maybe composite?*
- *why did it freeze in?*





no sign of
new physics
that explains Higgs!

LHC score card

- origin of EWSB
  - Higgs discovery: but only a partial answer
- naturalness
  - None
- dark matter
  - None
- EW baryogenesis
  - No new CP violation
- unexpected
  - Perhaps??? 750 GeV diphoton???

Supersymmetry

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

?

0 74470 38529 5

$5.99 U.S.

MAY 2014

been there before

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

been there before

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

1% tuning

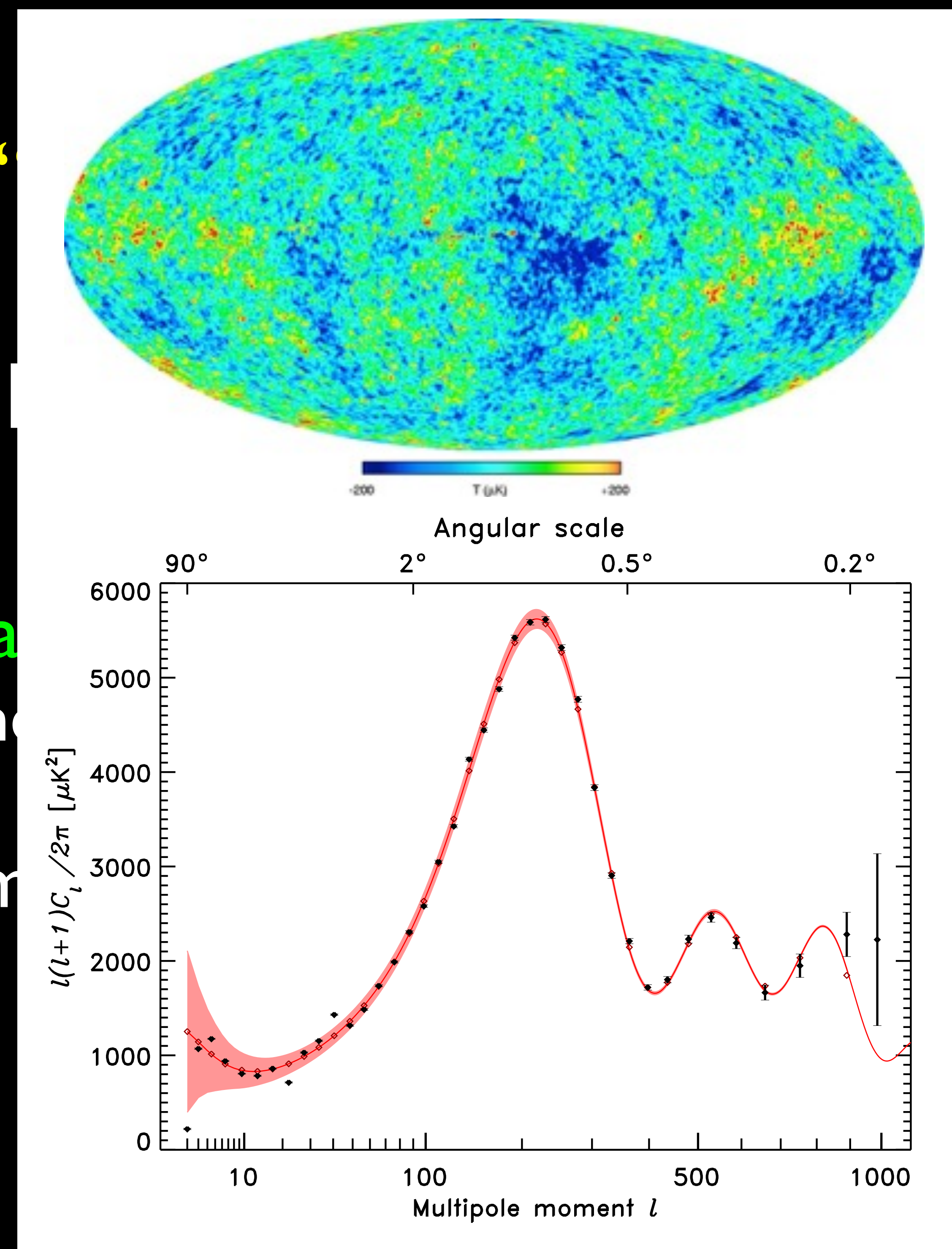
“

“Ba ”

A n e

the

Tim

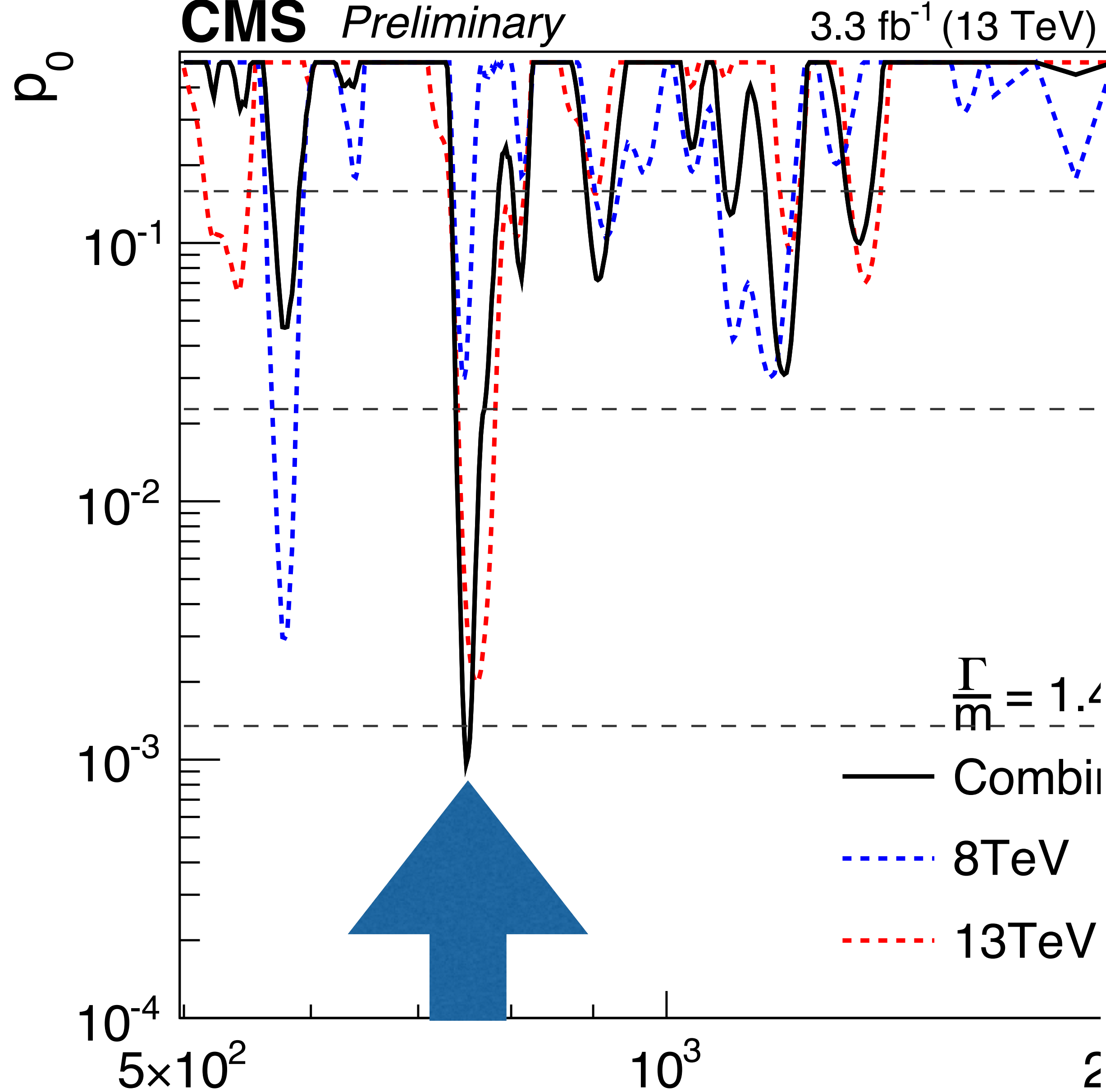


scalar top mass $\geq$ 10 TeV preferred

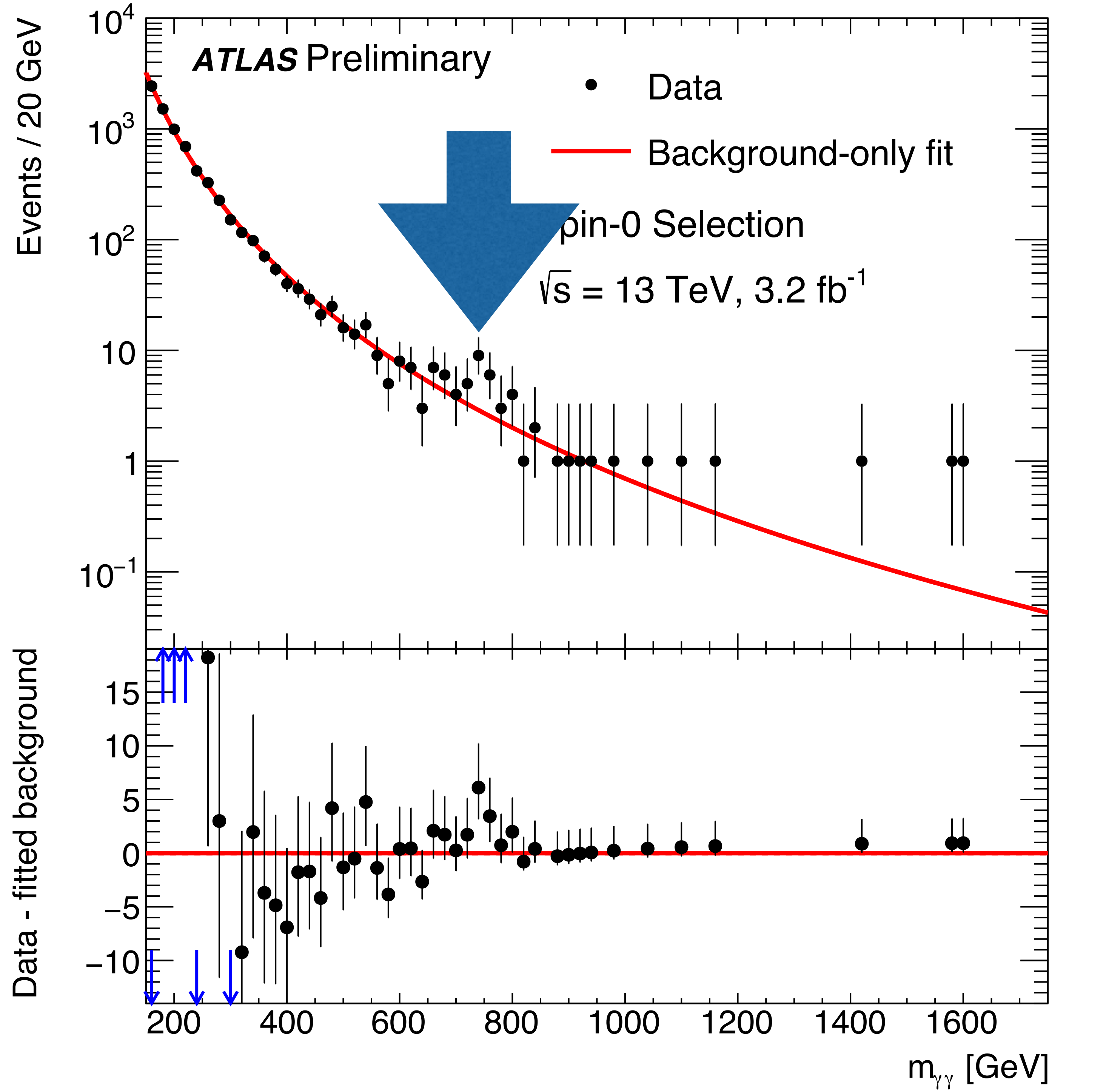
assumption: MSSM

Better Late Than Never

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



diphoton resonance @750 GeV

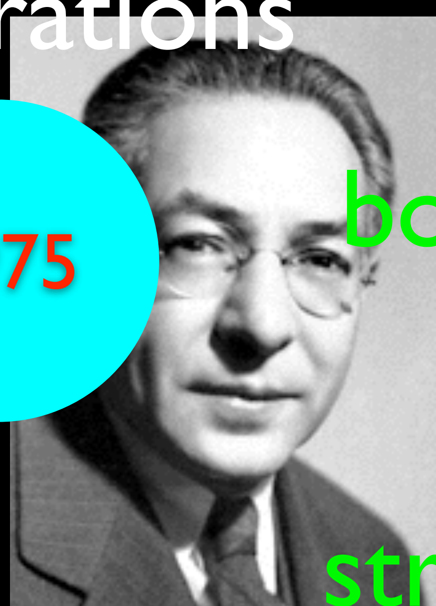


vector-like fermions? 100–1000 GeV

Nobody asked for it!

Matter pa

There must be three generations



top 1995

tau 1975

bottom 1978

muon

strange

charm 1974

Who ordered that??

I.I. Rabi

electron

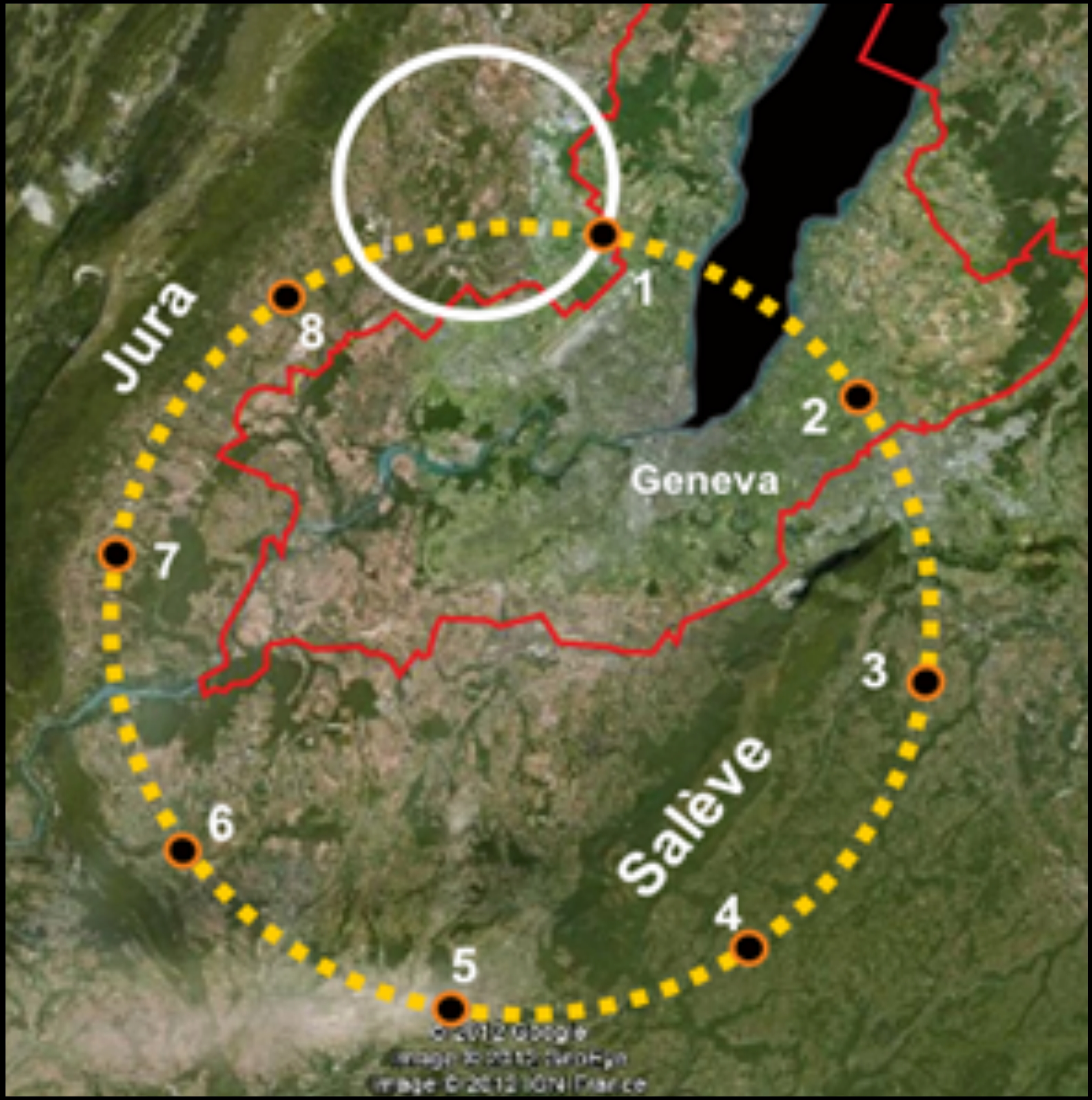
down

up

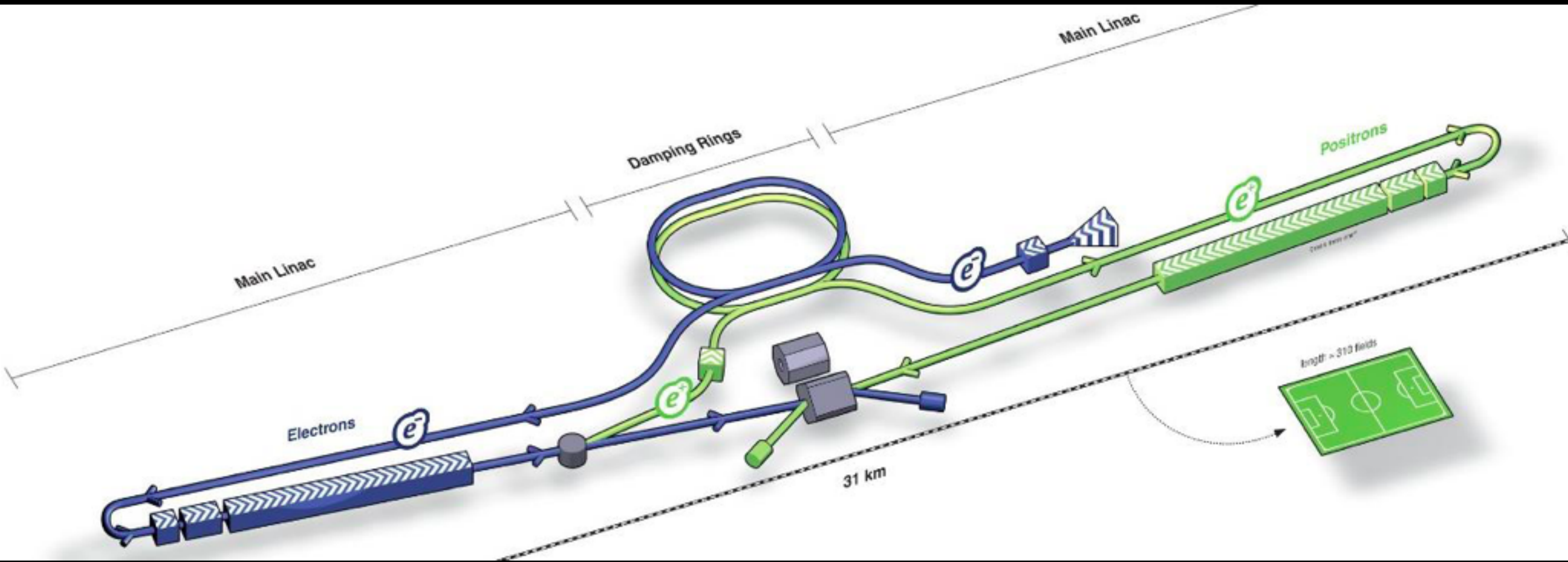
area ∝ mass

higher energies?

- Need to explore
- HL-LHC boosts reach
- We believe we should keep aiming at higher energies
- HE-LHC?
- *100 TeV pp would be great!*
- Need to continue magnet R&D
- Possible first stage: FCCee upto 350 GeV
- CDR by 2018?



Another staged path

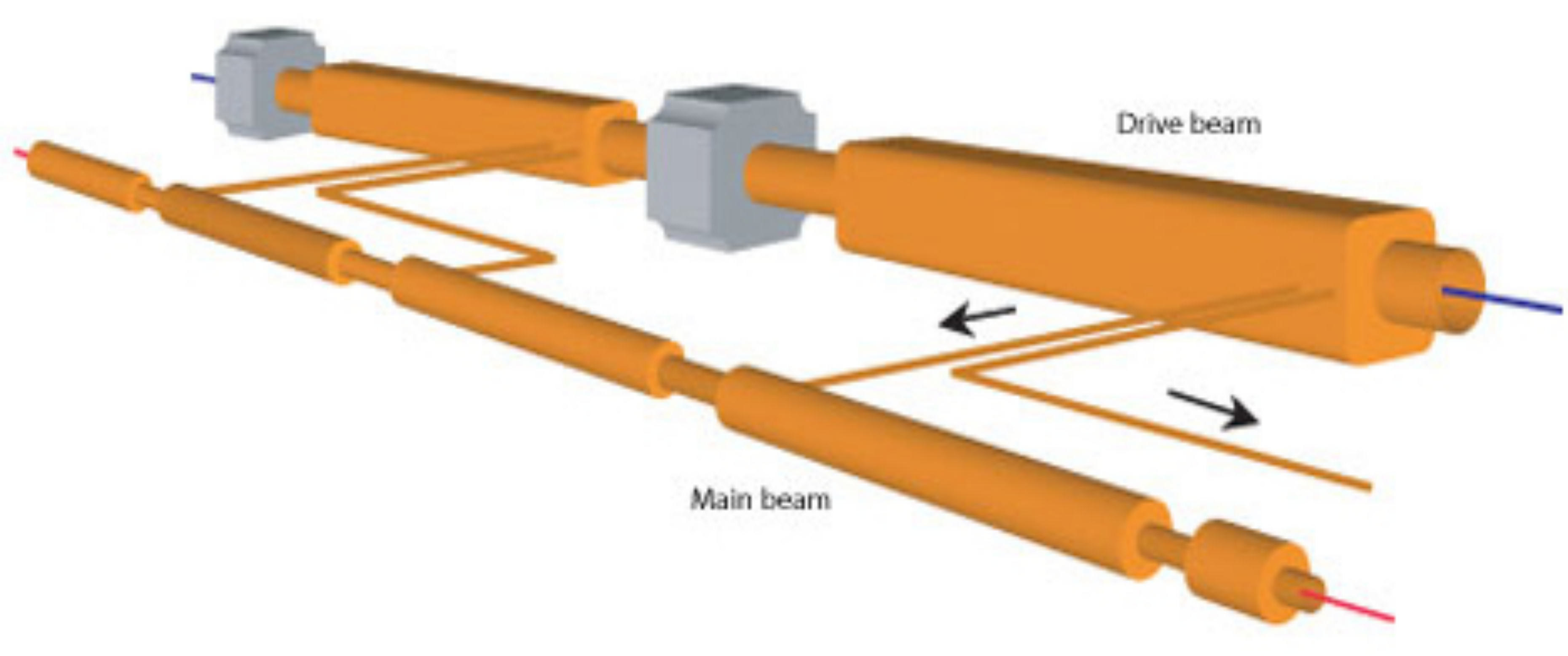


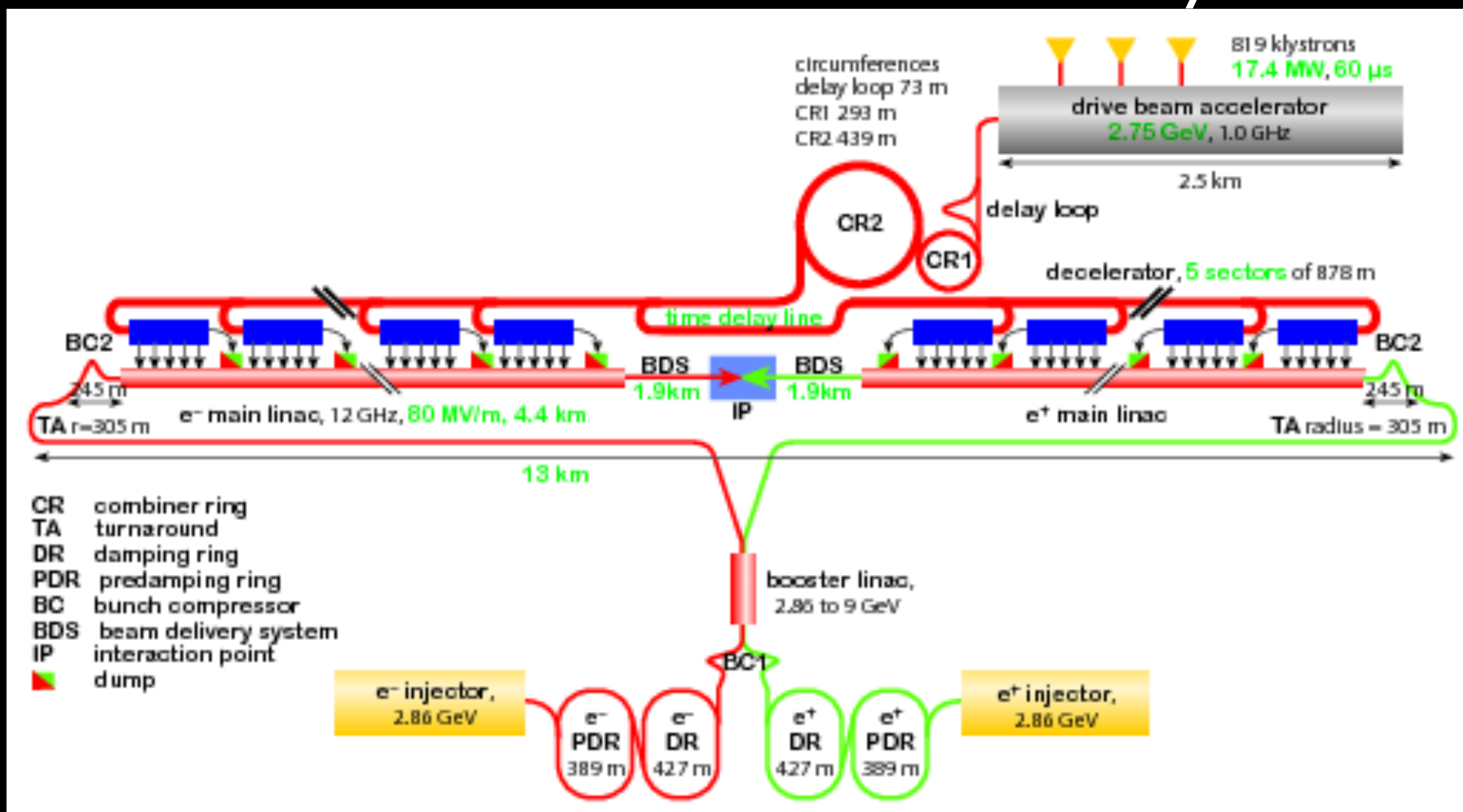
- guaranteed precision Higgs and top physics
- extendable 500 GeV to 1 TeV
- TDR exists

CLIC 3TeV

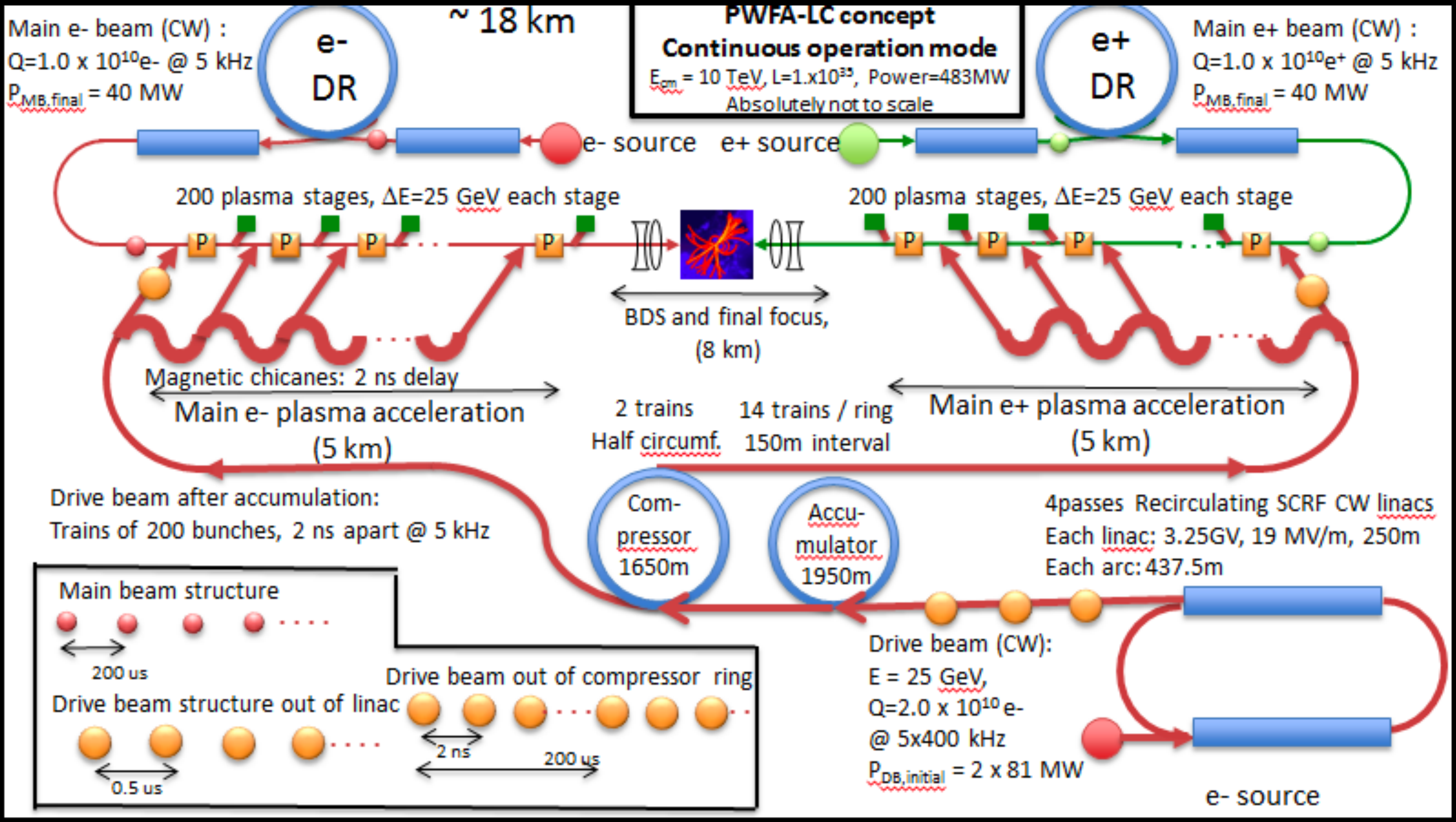
CDR exists

TDR by 2018?





Plasma Wakefield 10 TeV



Delahaye et al, IPAC 2014

Rare effects from high energies

- Effects of high-energy physics mostly disappear by power suppression

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \frac{1}{\Lambda}\mathcal{L}_5 + \frac{1}{\Lambda^2}\mathcal{L}_6 + \cdots$$

- can be classified systematically

$$\mathcal{L}_5 = (LH)(LH) \rightarrow \frac{1}{\Lambda}(L\langle H\rangle)(L\langle H\rangle) = m_\nu \nu\nu$$

$$\mathcal{L}_6 = QQQL, \bar{L}\sigma^{\mu\nu}W_{\mu\nu}Hl, \epsilon_{abc}W_\nu^{a\mu}W_\lambda^{b\nu}W_\mu^{c\lambda}, \\ (H^\dagger D_\mu H)(H^\dagger D^\mu H), B_{\mu\nu}H^\dagger W^{\mu\nu}H, \cdots$$

anarchy

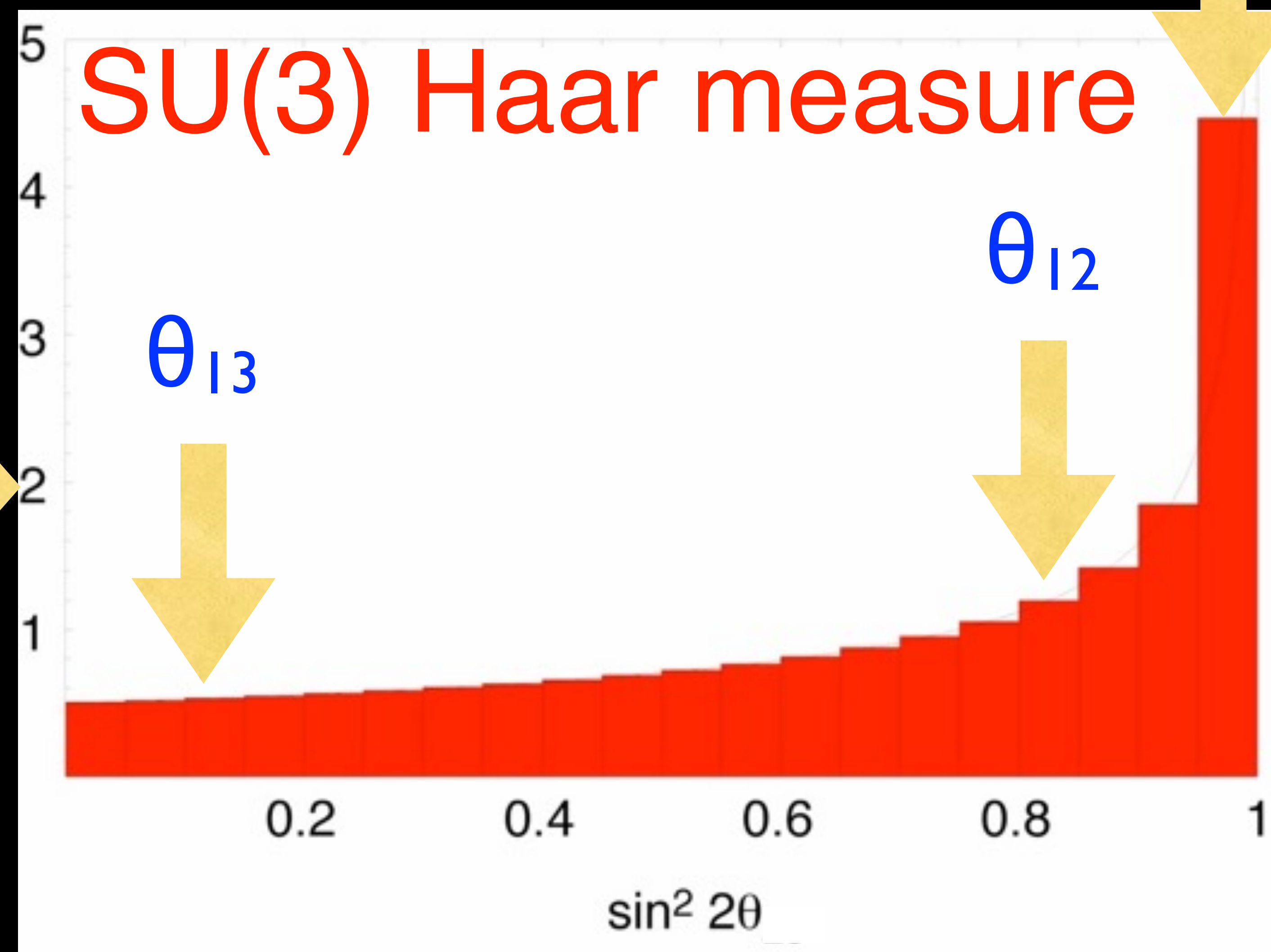
Miriam-Webster: "*A utopian society of individuals who enjoy complete freedom without government*"

neutrinos

large mixing

symmtery

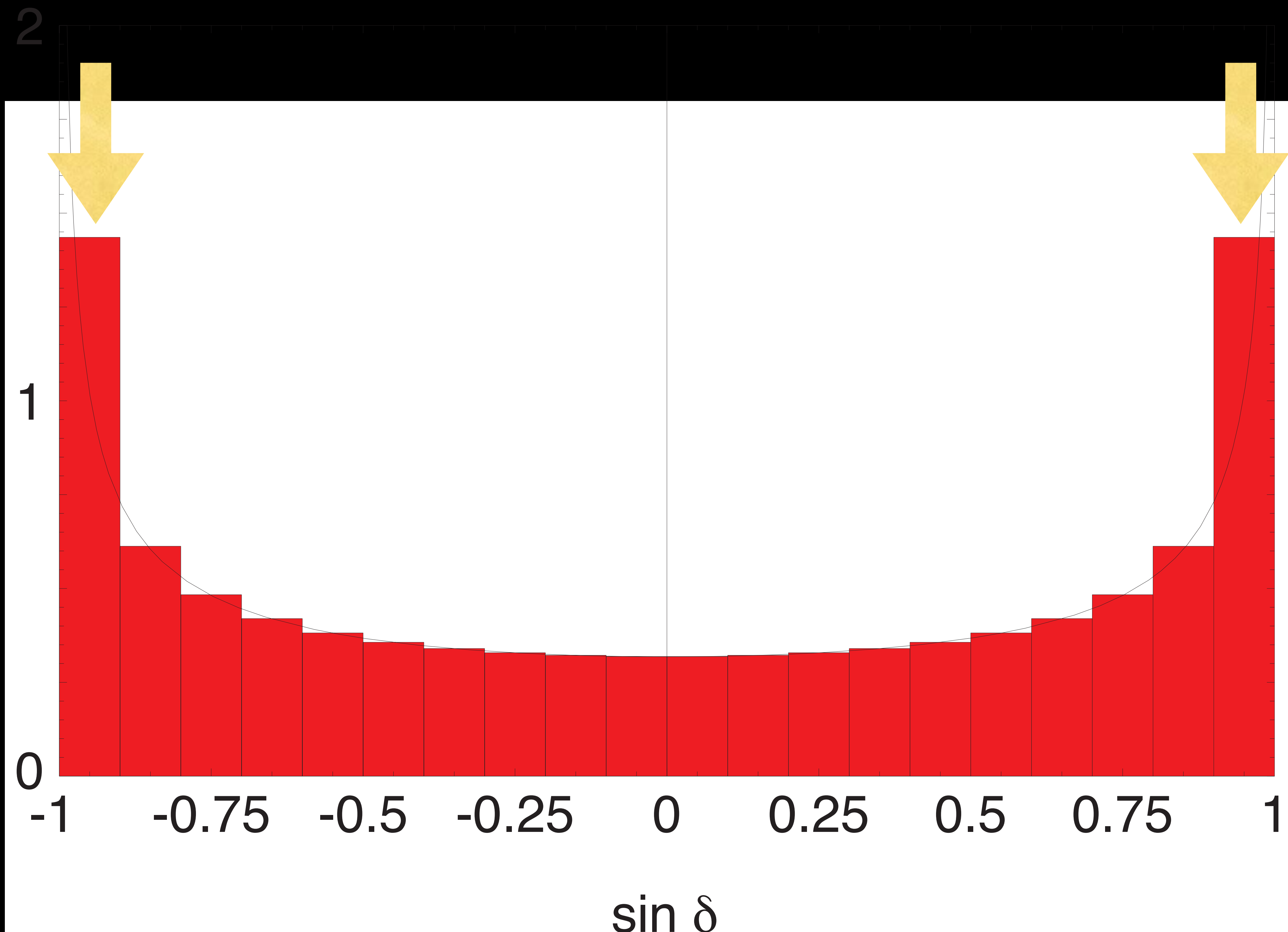
θ_{23}



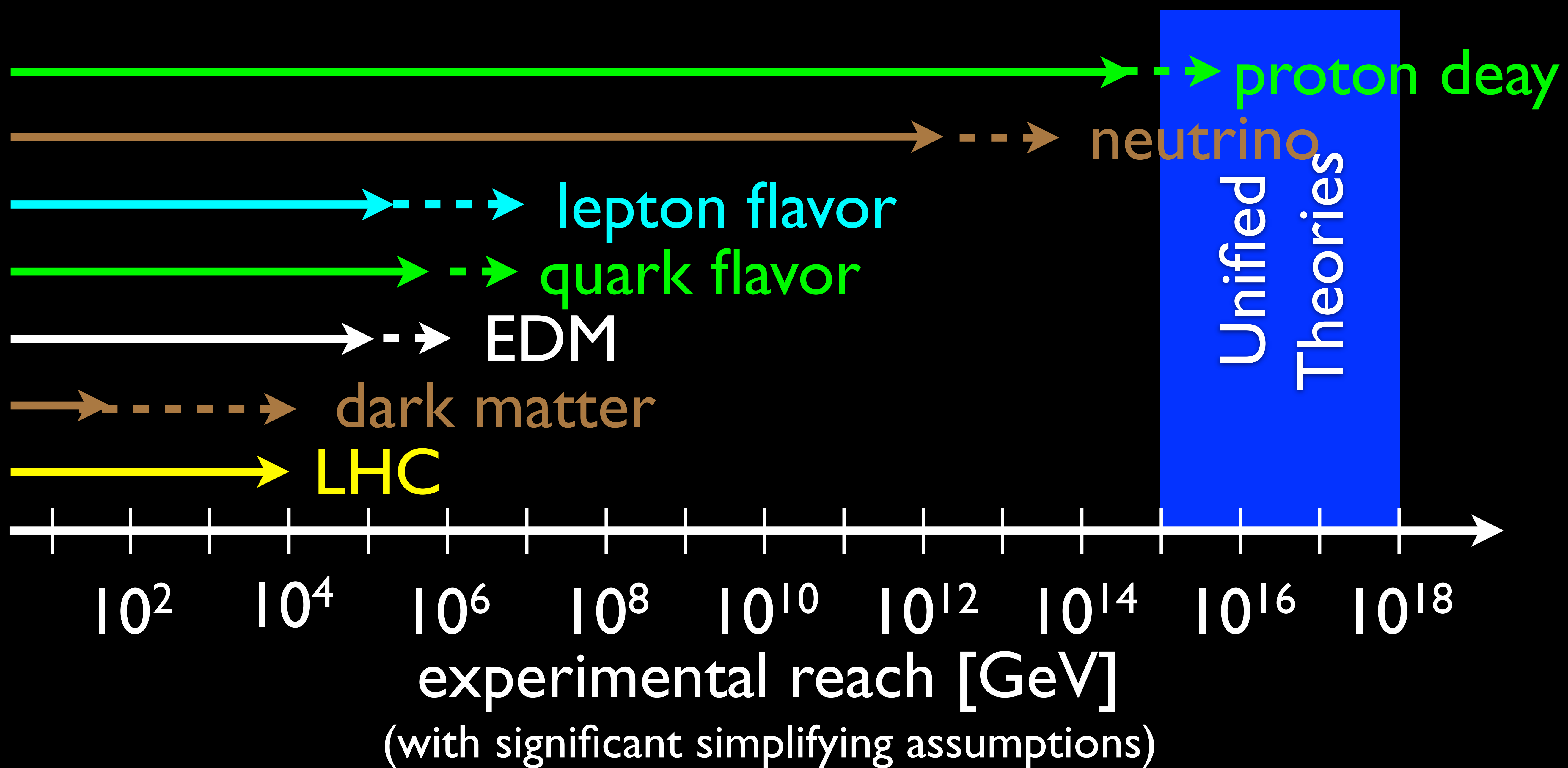
KS probability = 44%

(de Gouvêa, HM)

max $\not{C}\not{P}$ preferred



Power of Expedition



courtesy: Zoltan Ligeti

Effective Operators

- Surprisingly difficult question
- In the case of the Standard Model
  - Weinberg (1980) on D=6 $\not{B}$, D=5 $\not{L}$
  - Buchmüller-Wyler (1986) on D=6 ops
    - 80 operators for N_f=1, B, L conserving
  - Grzadkowski et al (2010) removed redundancies and discovered one missed
    - 59 operators for N_f=1, B, L conserving
    - redundancies due to EOM, IBP
  - Mahonar et al (2013) general N_f
  - Lehman-Martin (2014,15) D=7 for general N_f, D=8 for N_f=1 (incorrect)

Repeating this at order ϵ^6 we obtain the Hilbert series for dimension-six operators of the SM EFT:

$$\begin{aligned}
\widehat{H}_6 \;=\;& H^3H^{\dagger\,3} + u^\dagger Q^\dagger H H^{\dagger\,2} + 2Q^2Q^{\dagger\,2} + Q^{\dagger\,3}L^\dagger + Q^3L + 2QQ^\dagger LL^\dagger + L^2L^{\dagger\,2} + uQH^2H^\dagger \\
&+ 2uu^\dagger QQ^\dagger + uu^\dagger LL^\dagger + u^2u^{\dagger\,2} + e^\dagger u^\dagger Q^2 + e^\dagger L^\dagger H^2H^\dagger + 2e^\dagger u^\dagger Q^\dagger L^\dagger + eLHH^{\dagger\,2} + euQ^{\dagger\,2} \\
&+ 2euQL + ee^\dagger QQ^\dagger + ee^\dagger LL^\dagger + ee^\dagger uu^\dagger + e^2e^{\dagger\,2} + d^\dagger Q^\dagger H^2H^\dagger + 2d^\dagger u^\dagger Q^{\dagger\,2} + d^\dagger u^\dagger QL \\
&+ d^\dagger e^\dagger u^{\dagger\,2} + d^\dagger eQ^\dagger L + dQHH^{\dagger\,2} + 2duQ^2 + duQ^\dagger L^\dagger + de^\dagger QL^\dagger + deu^2 + 2dd^\dagger QQ^\dagger + dd^\dagger LL^\dagger \\
&+ 2dd^\dagger uu^\dagger + dd^\dagger ee^\dagger + d^2d^{\dagger\,2} + u^\dagger Q^\dagger H^\dagger G_R + d^\dagger Q^\dagger HG_R + HH^\dagger G_R^2 + G_R^3 + uQHG_L \\
&+ dQH^\dagger G_L + HH^\dagger G_L^2 + G_L^3 + u^\dagger Q^\dagger H^\dagger W_R + e^\dagger L^\dagger HW_R + d^\dagger Q^\dagger HW_R + HH^\dagger W_R^2 + W_R^3 \\
&+ uQHW_L + eLH^\dagger W_L + dQH^\dagger W_L + HH^\dagger W_L^2 + W_L^3 + u^\dagger Q^\dagger H^\dagger B_R + e^\dagger L^\dagger HB_R \\
&+ d^\dagger Q^\dagger HB_R + HH^\dagger B_RW_R + HH^\dagger B_R^2 + uQHB_L + eLH^\dagger B_L + dQH^\dagger B_L + HH^\dagger B_LW_L \\
&+ HH^\dagger B_L^2 + 2QQ^\dagger HH^\dagger\mathcal{D} + 2LL^\dagger HH^\dagger\mathcal{D} + uu^\dagger HH^\dagger\mathcal{D} + ee^\dagger HH^\dagger\mathcal{D} + d^\dagger uH^2\mathcal{D} + du^\dagger H^{\dagger\,2}\mathcal{D} \\
&+ dd^\dagger HH^\dagger\mathcal{D} + 2H^2H^{\dagger\,2}\mathcal{D}^2\,. \qquad (3.16)
\end{aligned}$$

Setting all of the spurions equal to unity gives $\widehat{H}_6 = 84$, the total number of independent local operators at dimension 6, but more information is contained in eq.(3.16). For instance, the counting can easily be further decomposed by baryon number violation, $76 + 8$. The perhaps more familiar '$59 + 4$' counting is one in which hermitian conjugates of fermionic operators are not counted separately (such counting can of course also be obtained from eq. (3.16)).

Main idea

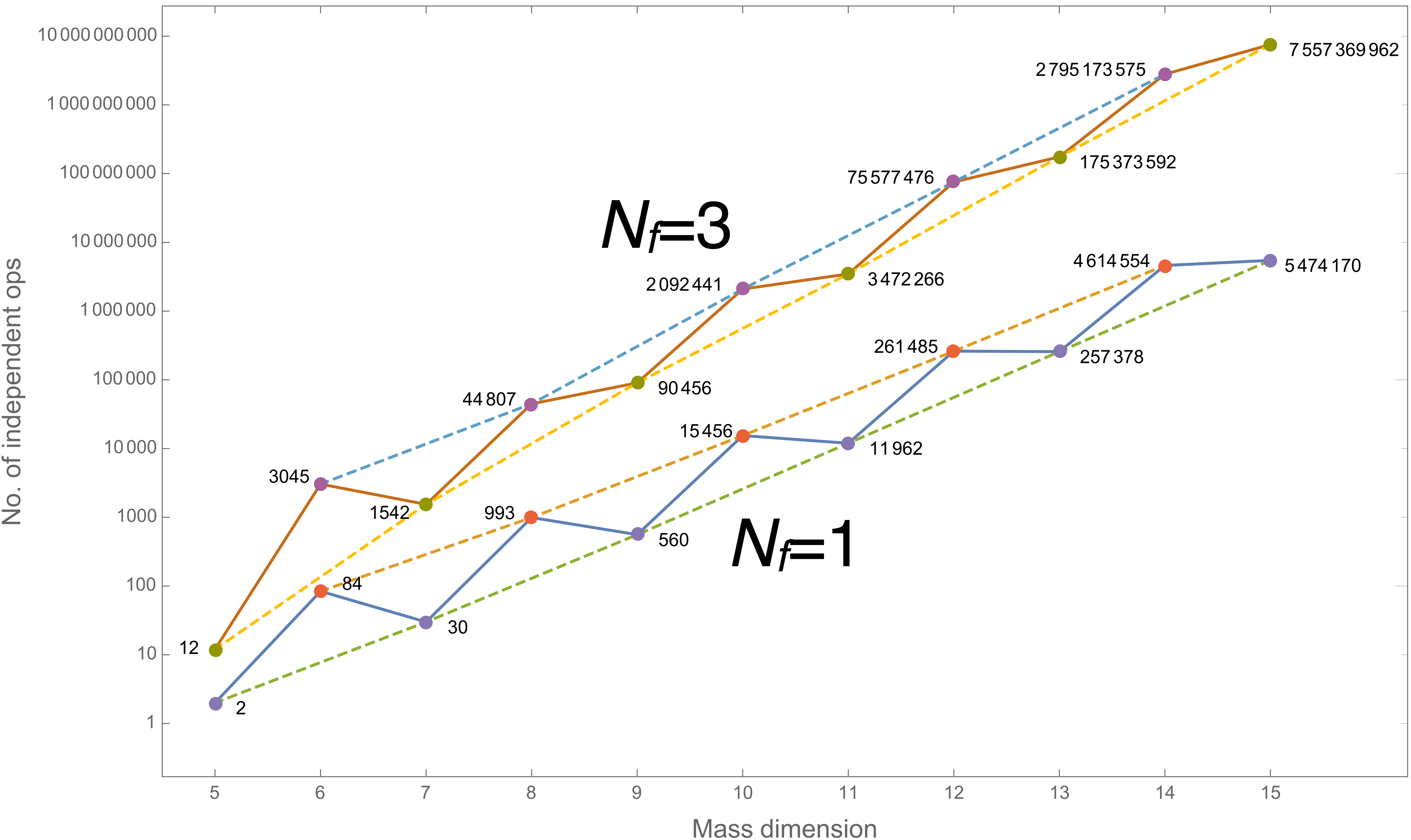
Brian Henning, Xiaochuan Lu, Tom Melia, HM

- Take kinetic terms as the zeroth order Lagrangian $(\partial\phi)^2,\ \bar{\psi} i \partial\!\!\!/ \psi,\ (F_{\mu\nu})^2$
- Classically, it is conformally invariant under SO(4,2)≃SO(6,C)
- Operator-State correspondence in CFT tells us that operators fall into representations of the conformal group
  - equation of motion: short multiplets
  - remove total derivatives: primary states

$$H(\mathcal{D}, \phi_1, \cdots, \phi_n) = \int d\mu_{\rm conf} d\mu_{\rm gauge} \sum_k \mathcal{D}^k \chi^*_{\Delta_0+k,0} PE\left[\frac{\phi_1}{\mathcal{D}^{d_1}}\chi_1\right] \cdots PE\left[\frac{\phi_n}{\mathcal{D}^{d_n}}\chi_n\right]$$

Terminal — tcsh — ttys001

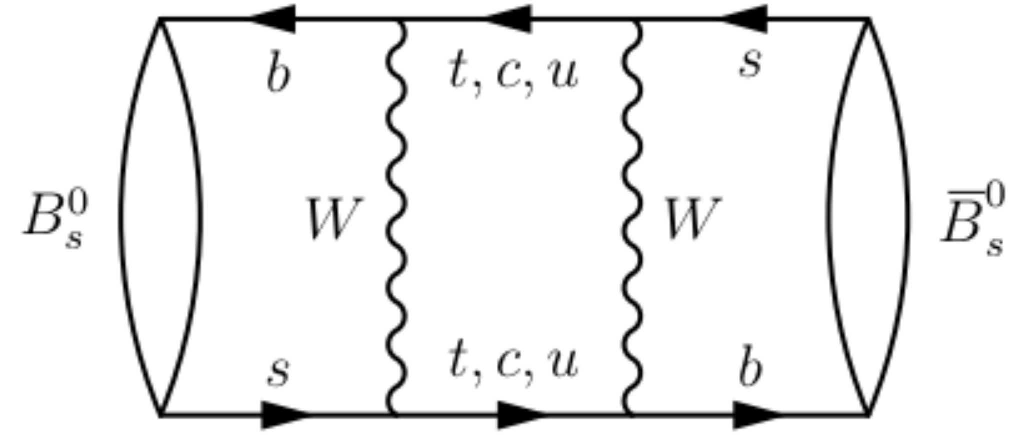
```
Hitoshi-no-MacBook-Pro.local 35: form hssm6.frm
```



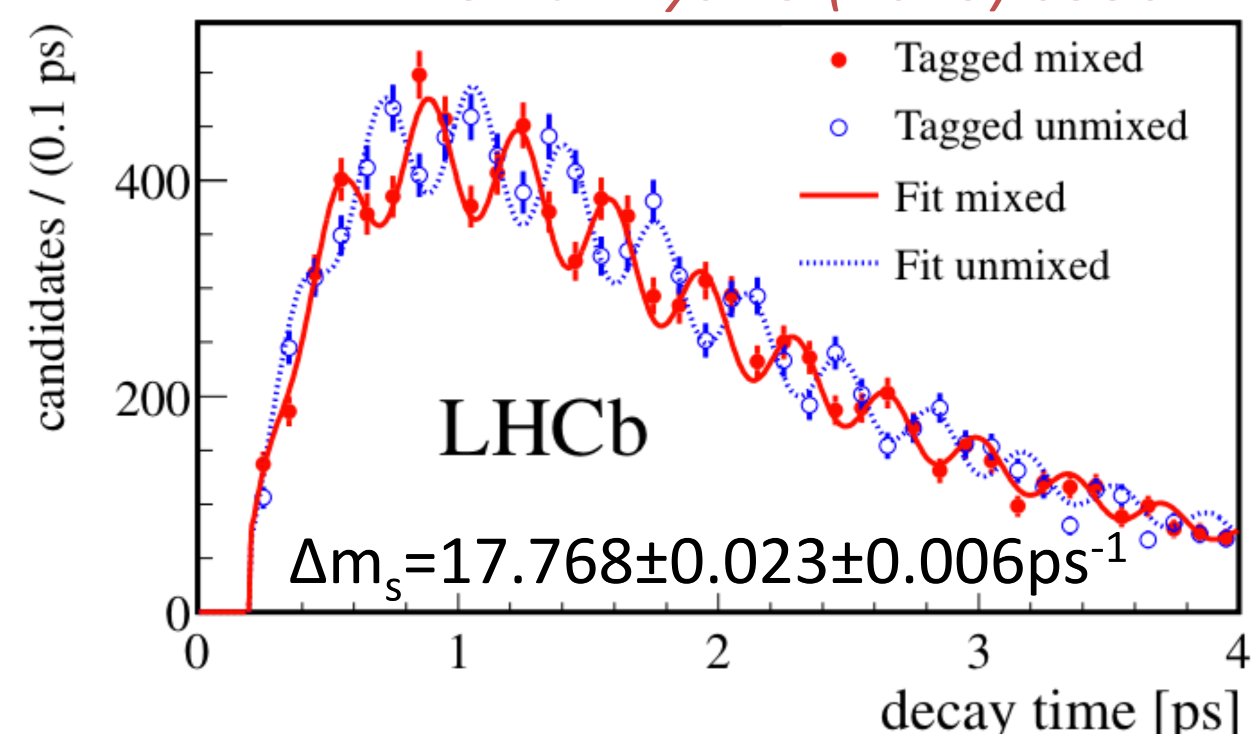
No. of independent ops
Mass dimension
N_f=3
N_f=1
10 000 000 000
1 000 000 000
100 000 000
10 000 000
1 000 000
100 000
10 000
1000
100
10
1
5
6
7
8
9
10
11
12
13
14
15
12
3045
1542
44 807
90 456
2 092 441
3 472 266
75 577 476
175 373 592
2 795 173 575
7 557 369 962
2
84
30
993
560
15 456
11 962
261 485
257 378
4 614 554
5 474 170

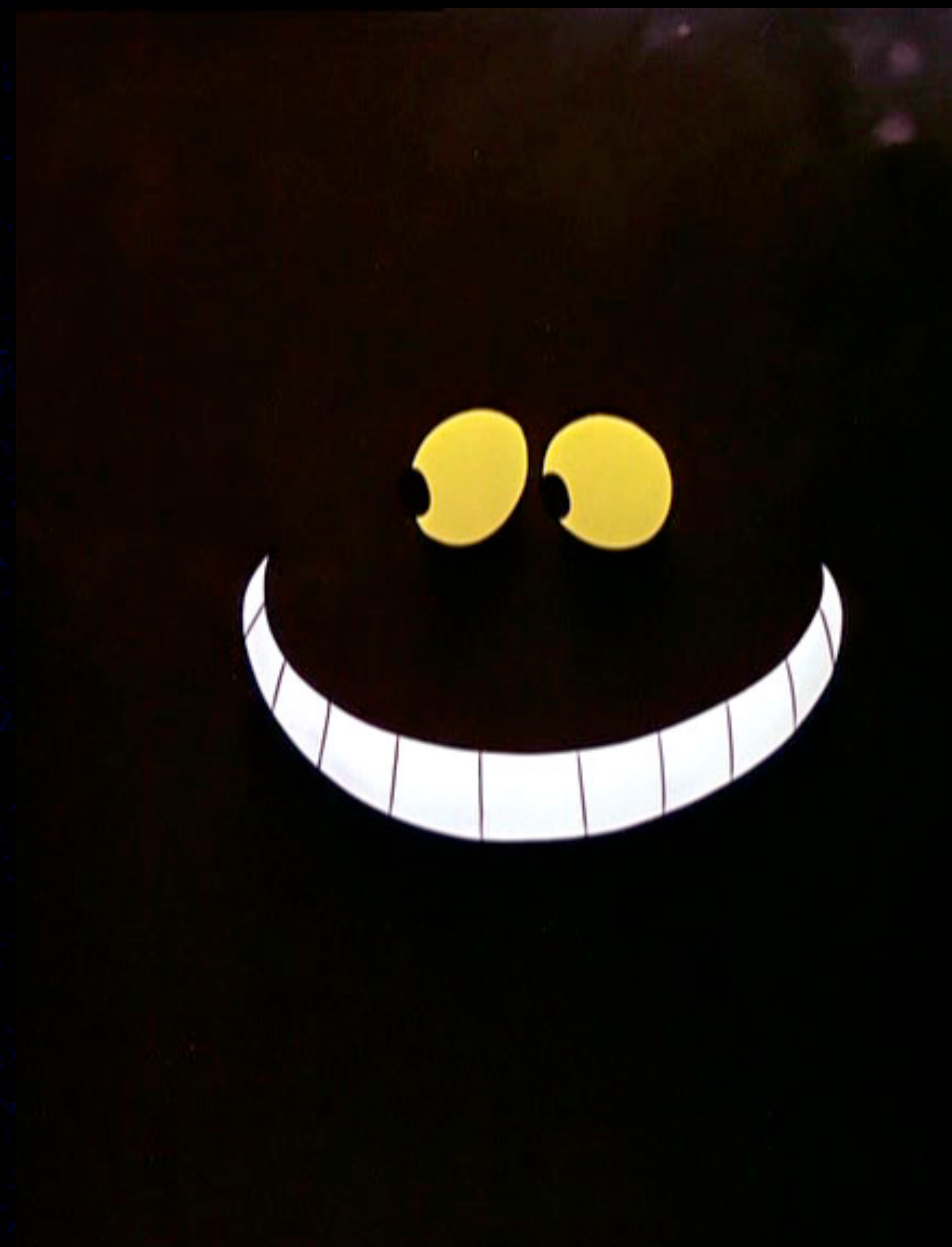
B_s: Strangely Beautiful

- ν_μ and ν_τ mix a lot
- (ν_μ, s_R), (ν_τ, b_R) under GUT
- Perhaps big mixing between s_R and b_R?
- I had predicted O(1) effects of new physics on B_s

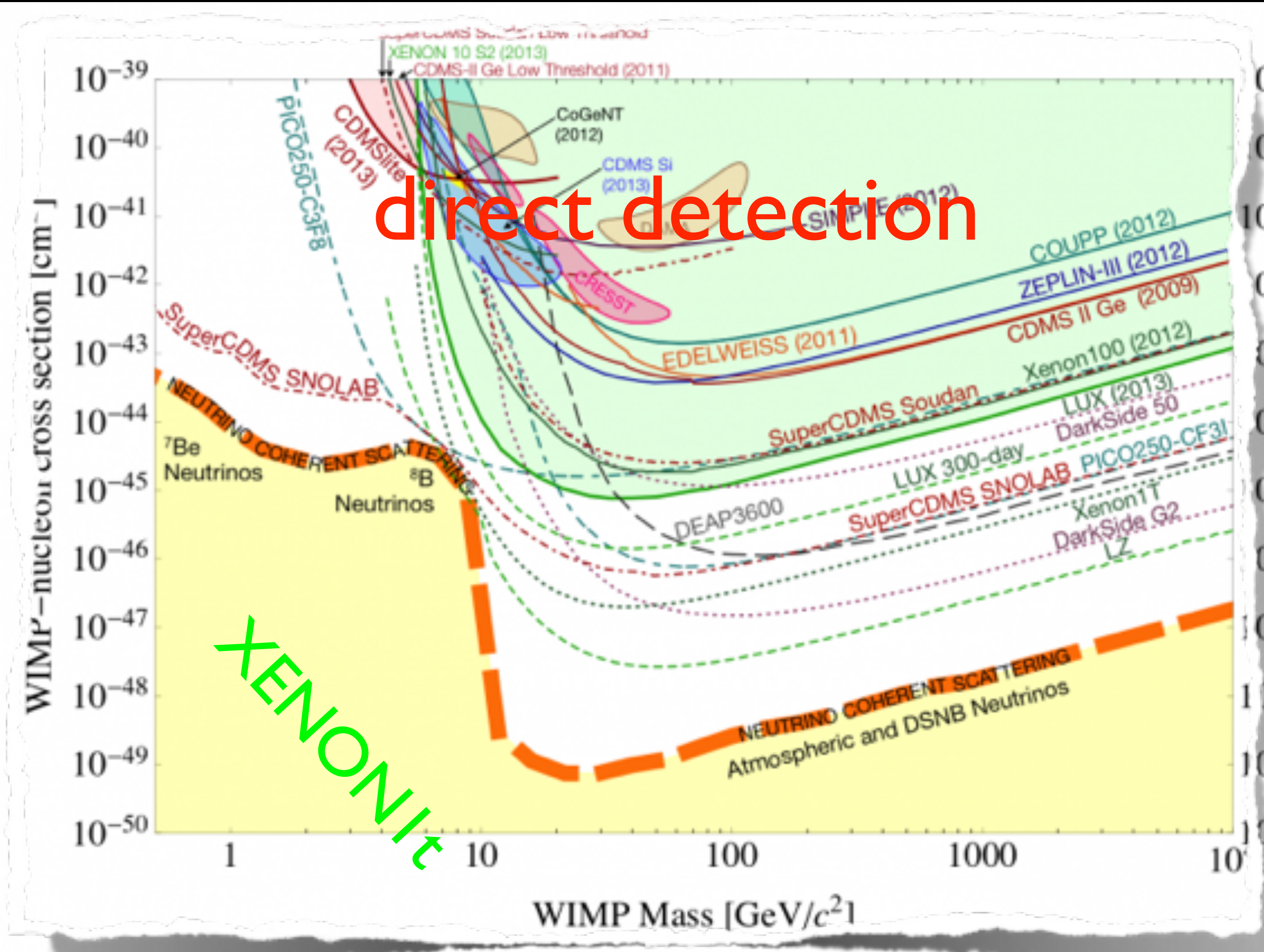


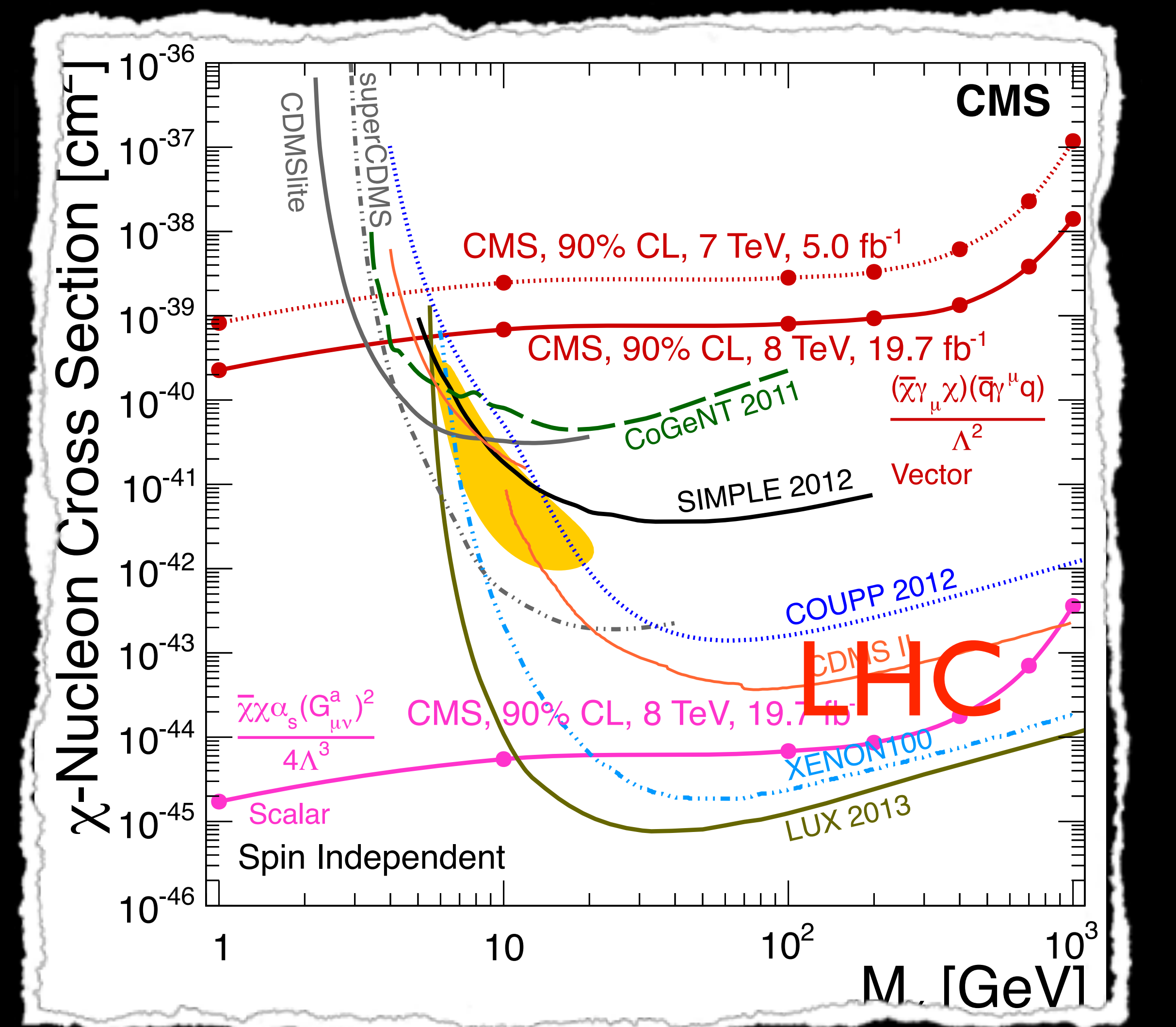
New J Phys 15 (2013) 053021

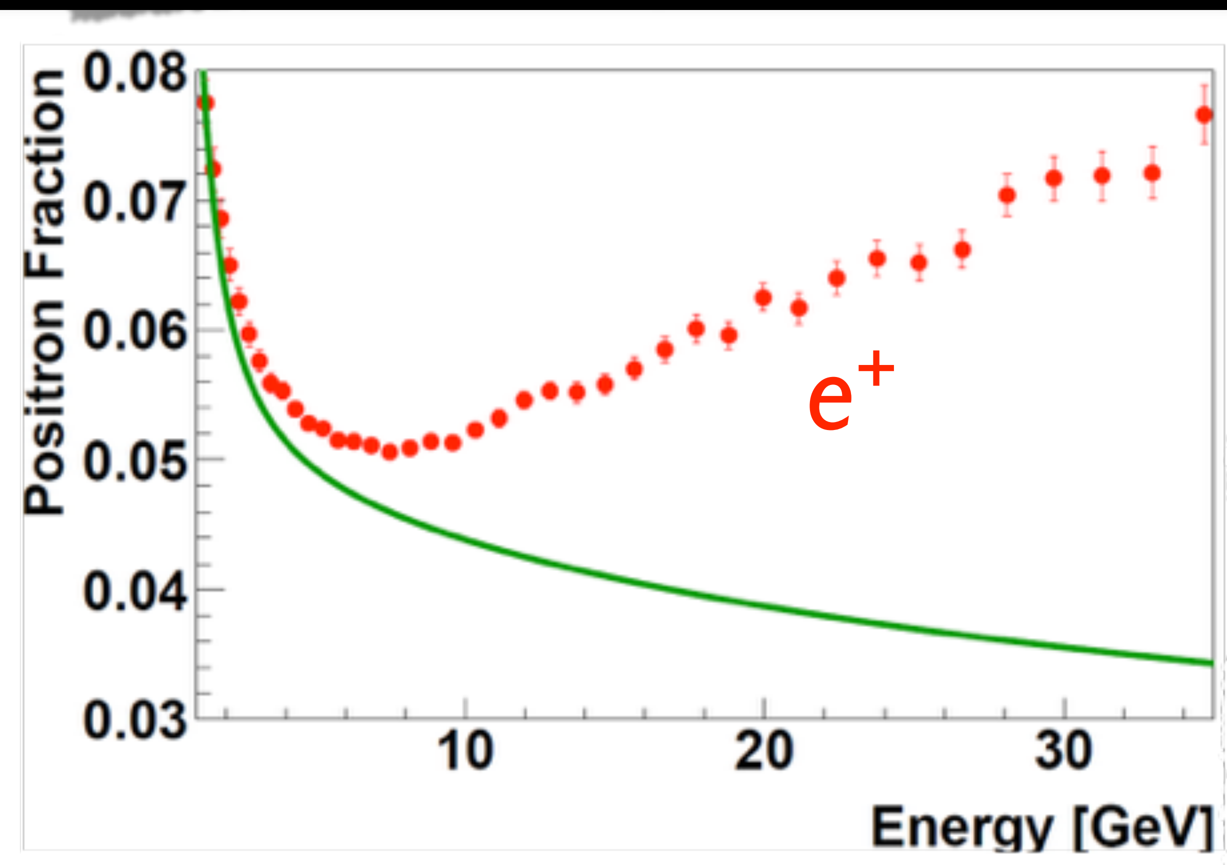


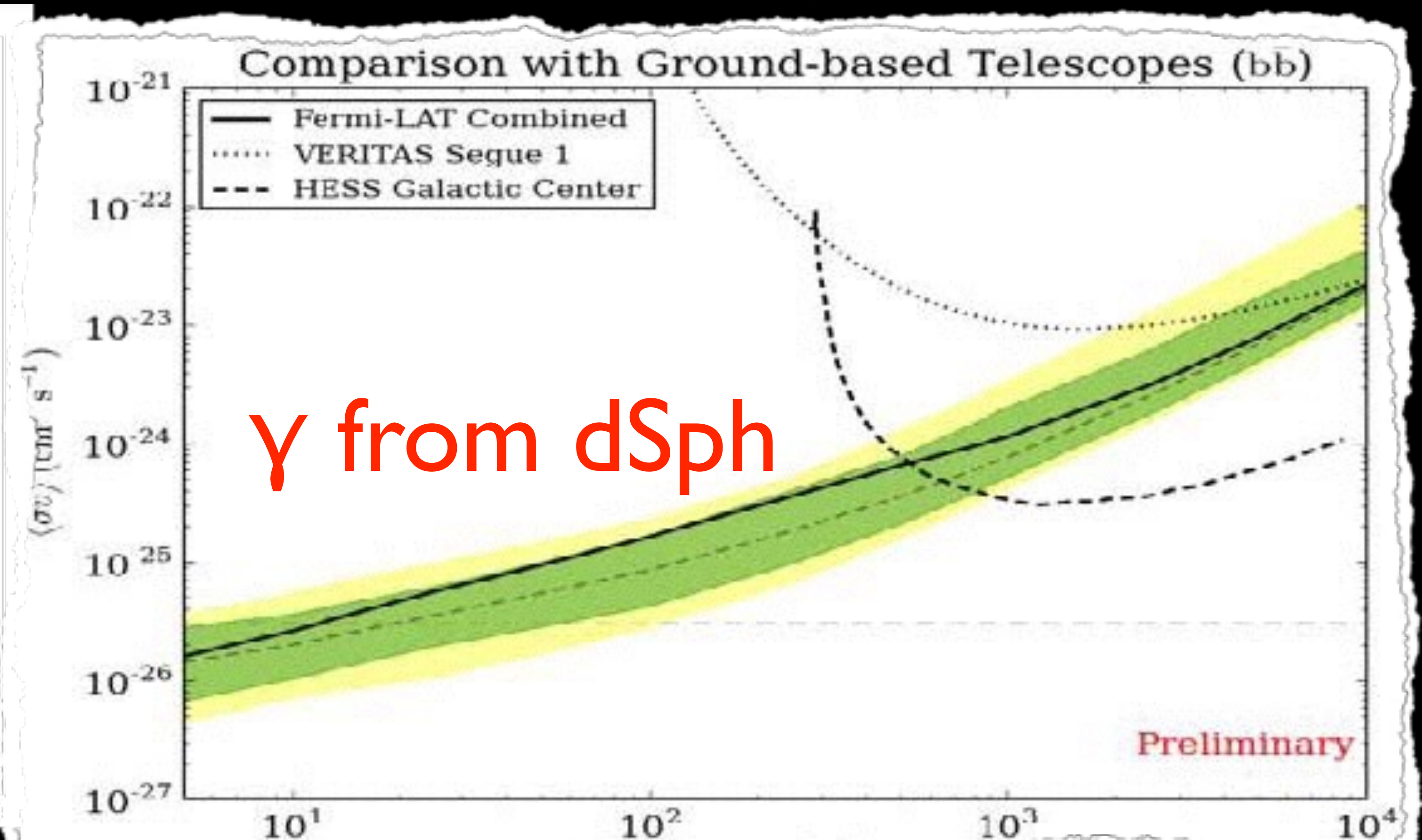


Ceshire cat


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


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


e⁺
Positron Fraction
Energy [GeV]

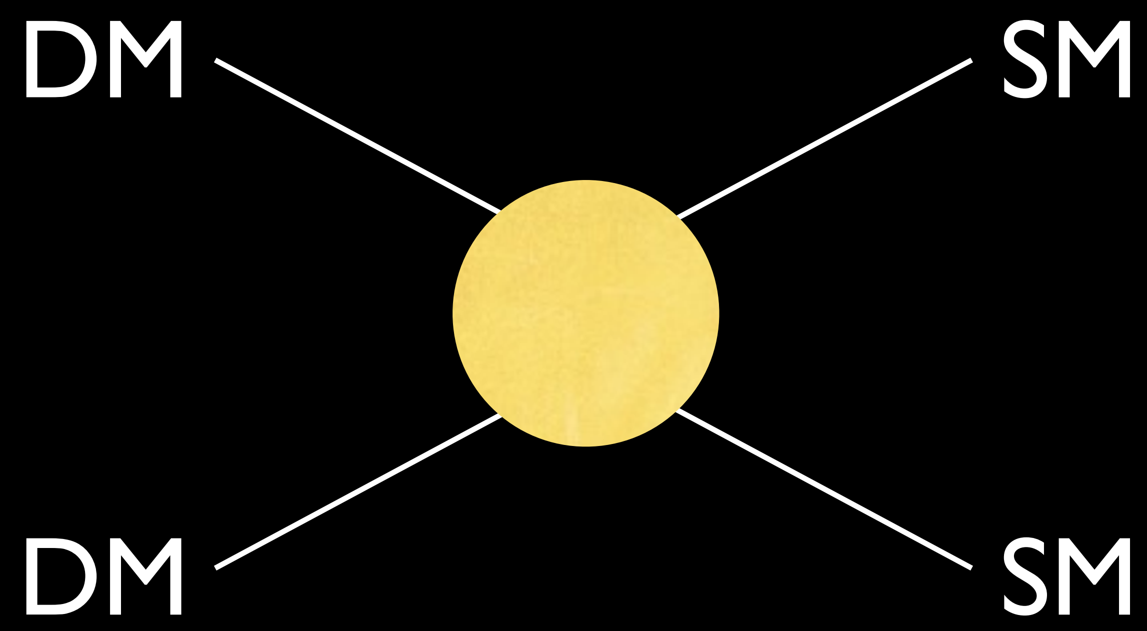

Comparison with Ground-based Telescopes (bb̄)
Fermi-LAT Combined
VERITAS Segue 1
HESS Galactic Center
γ from dSph
⟨σv⟩ [cm³ s⁻¹]
Preliminary

sociology

- in 1980s, dark matter was not as clear
- people tried to solve big problems in particle physics, i.e. naturalness, strong CP
- dark matter was optional, *i.e.* WIMP
- in 2010s, dark matter is a glaring problem
- but no sign of solution to naturalness
- perhaps naturalness is optional?
- rethinking: be more open-minded

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

Miracles

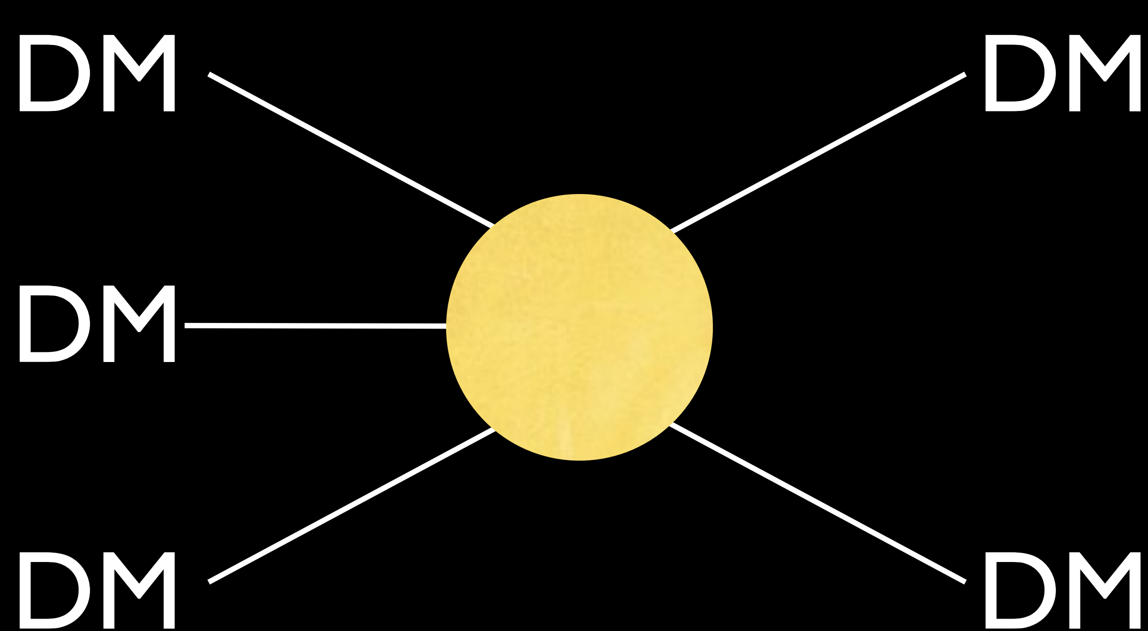


$$\langle \sigma_{2\to 2} v \rangle \approx \frac{\alpha^2}{m^2}$$

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

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

WIMP miracle[2]



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

$$\alpha \approx 4\pi$$

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

SIMP miracle[2]

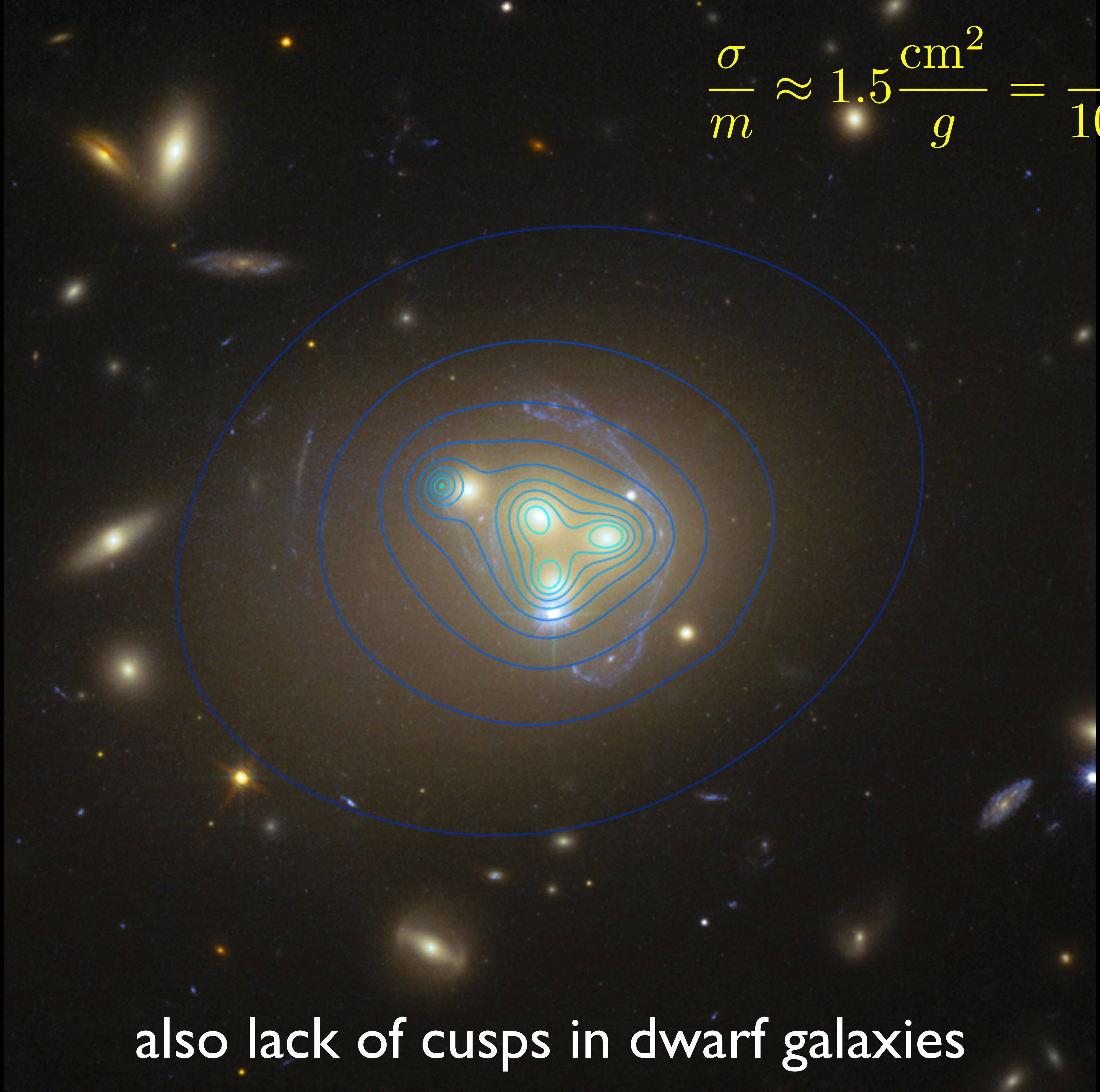
Hochberg, Kuflik, Volansky, Wacker
arXiv:1402.5143

SIMPlest Miracle

Yonit Hochberg, Eric Kuflik, HM, Tomer Volansky, Jay Wacker

- 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 stable pions
- $\pi_5(S^5)=Z \Rightarrow$ Wess-Zumino term
  - $L_{WZ}=\epsilon_{abcde}\, \epsilon^{\mu\nu\rho\sigma}\, \pi^a \partial_\mu \pi^b \partial_\nu \pi^c \partial_\rho \pi^d \partial_\sigma \pi^e$

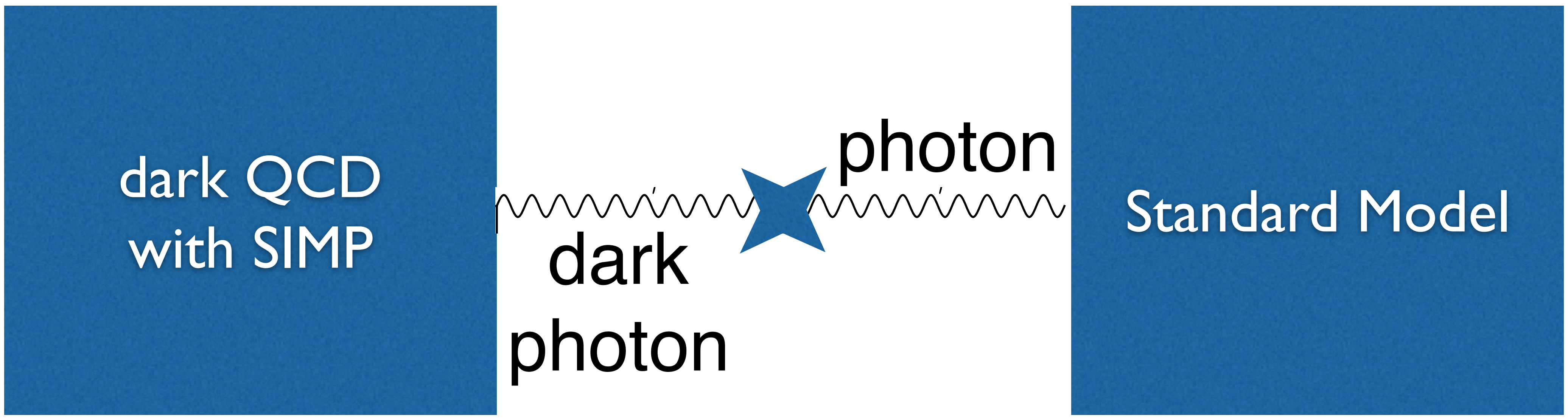
SIMP miracle^3

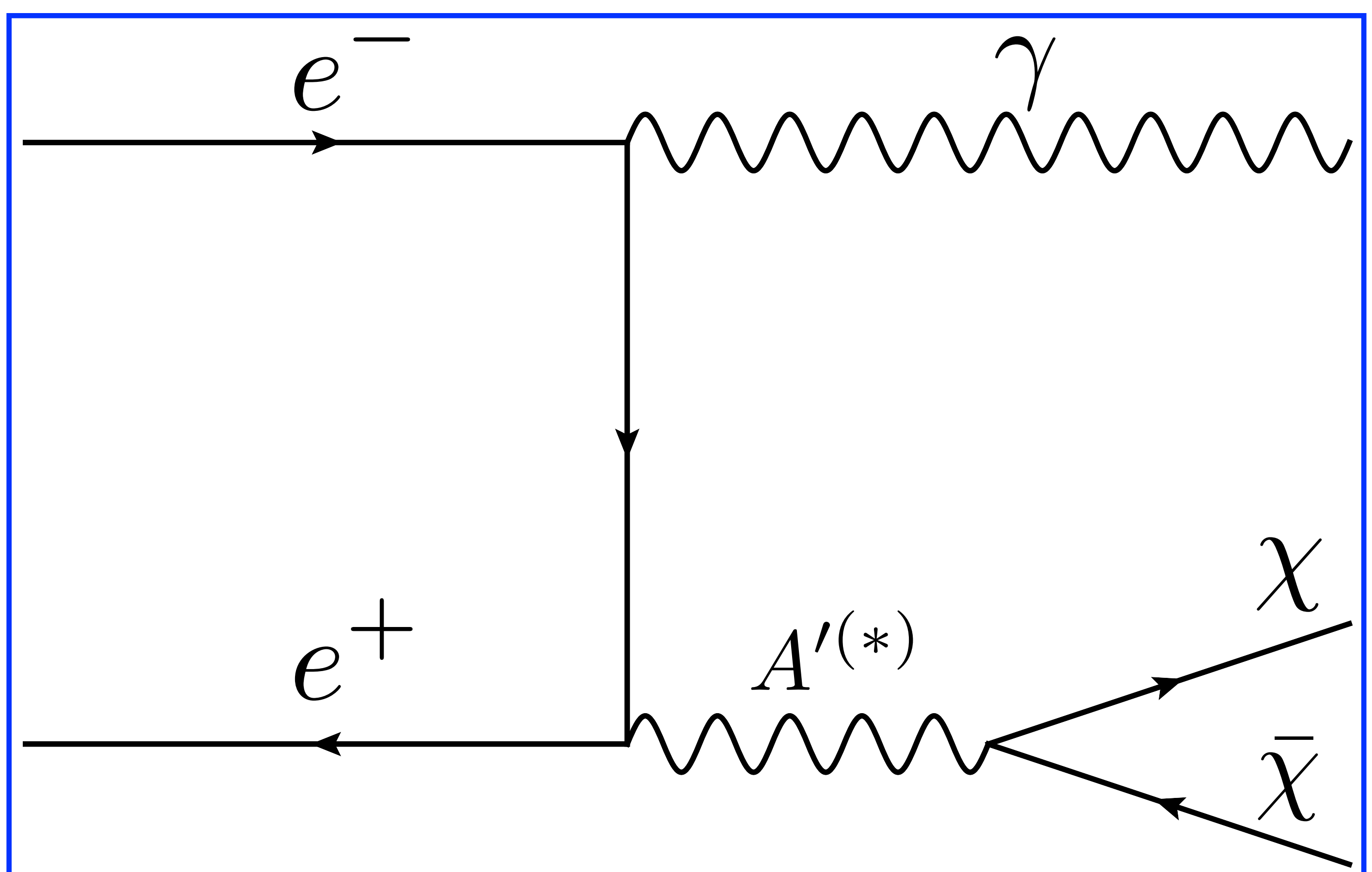


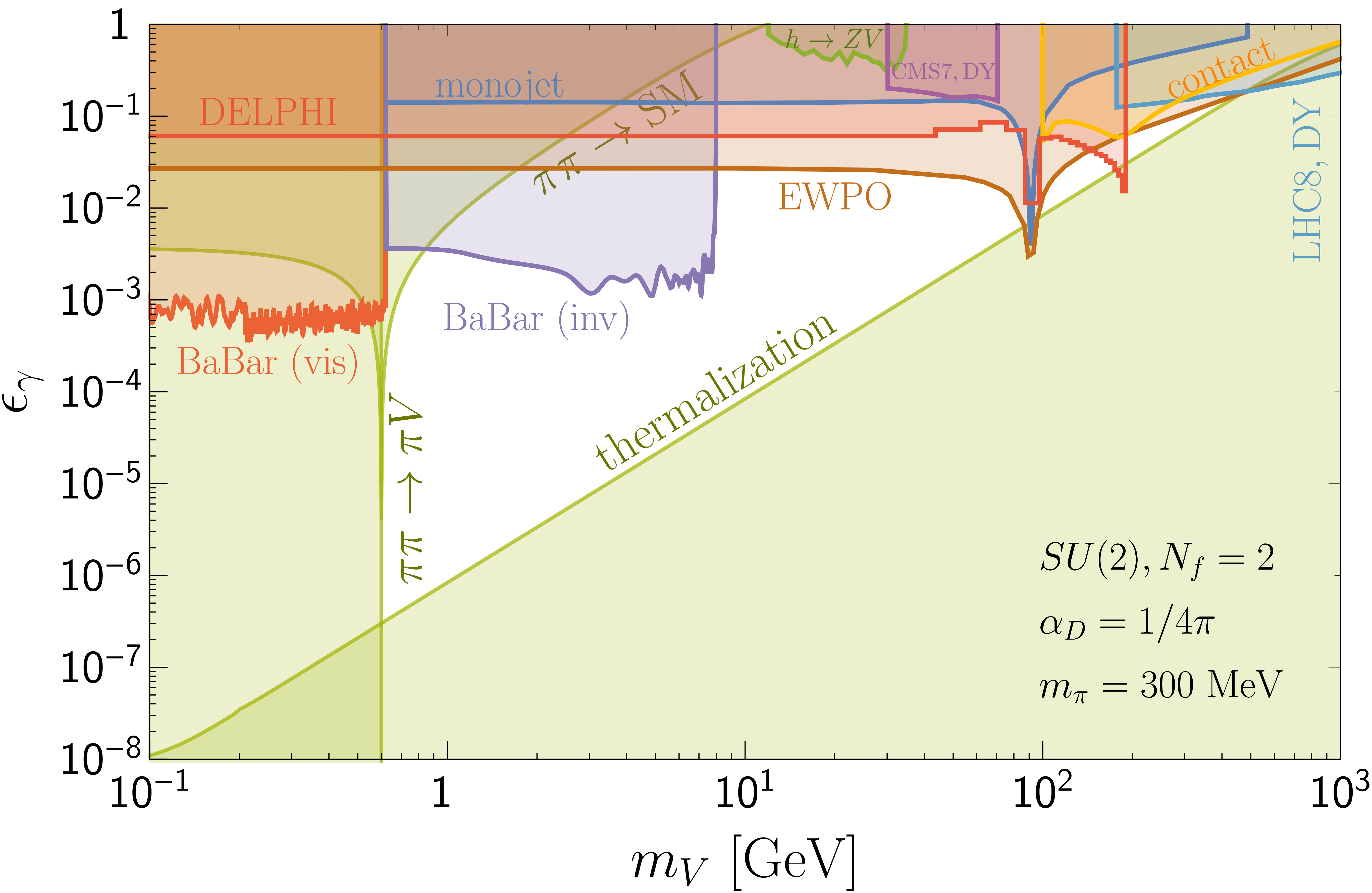
$$\frac{\sigma}{m} \approx 1.5 \frac{\text{cm}^2}{g} = \frac{0.27\text{b}}{100\text{MeV}}$$

also lack of cusps in dwarf galaxies

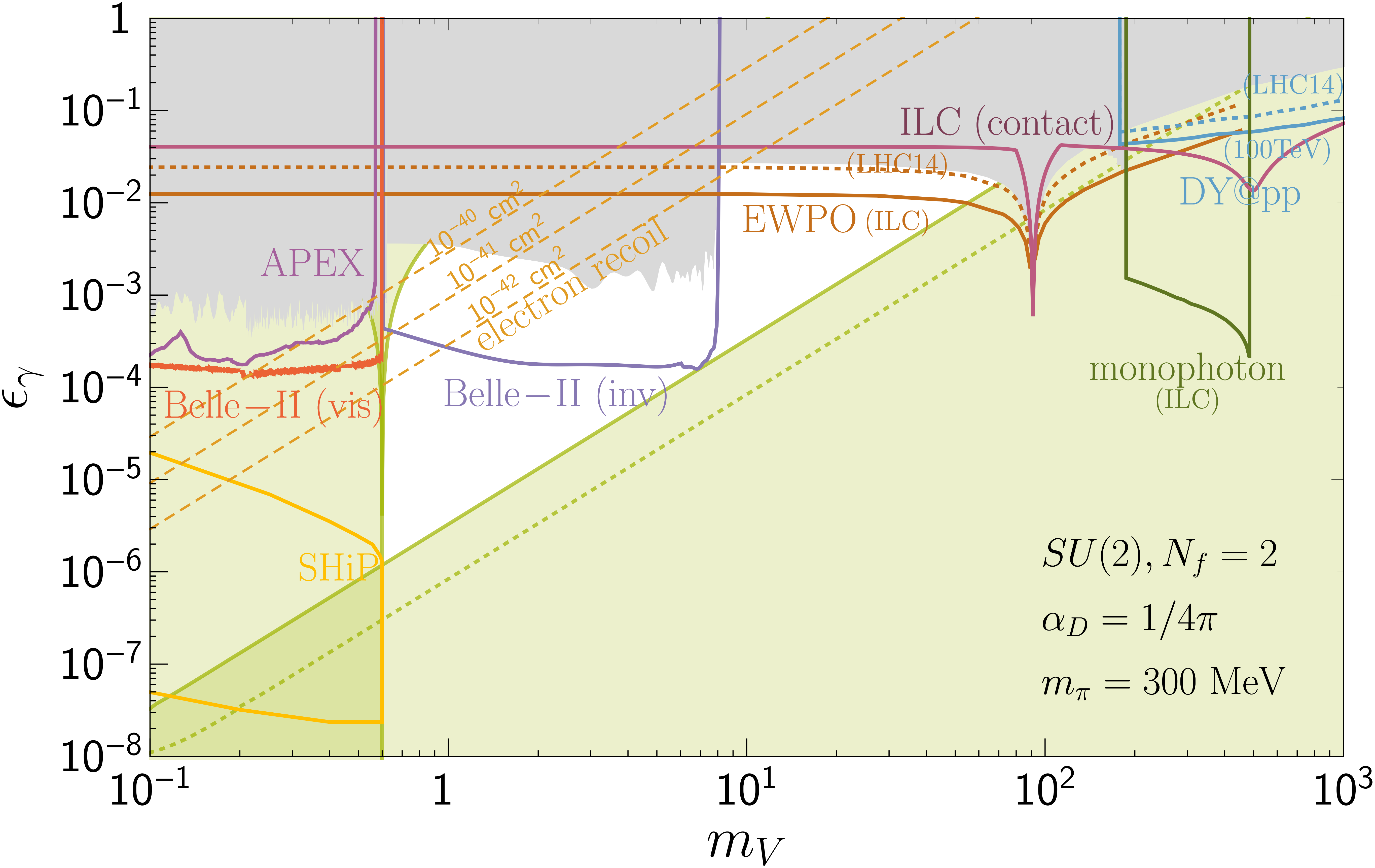
explore dark sector





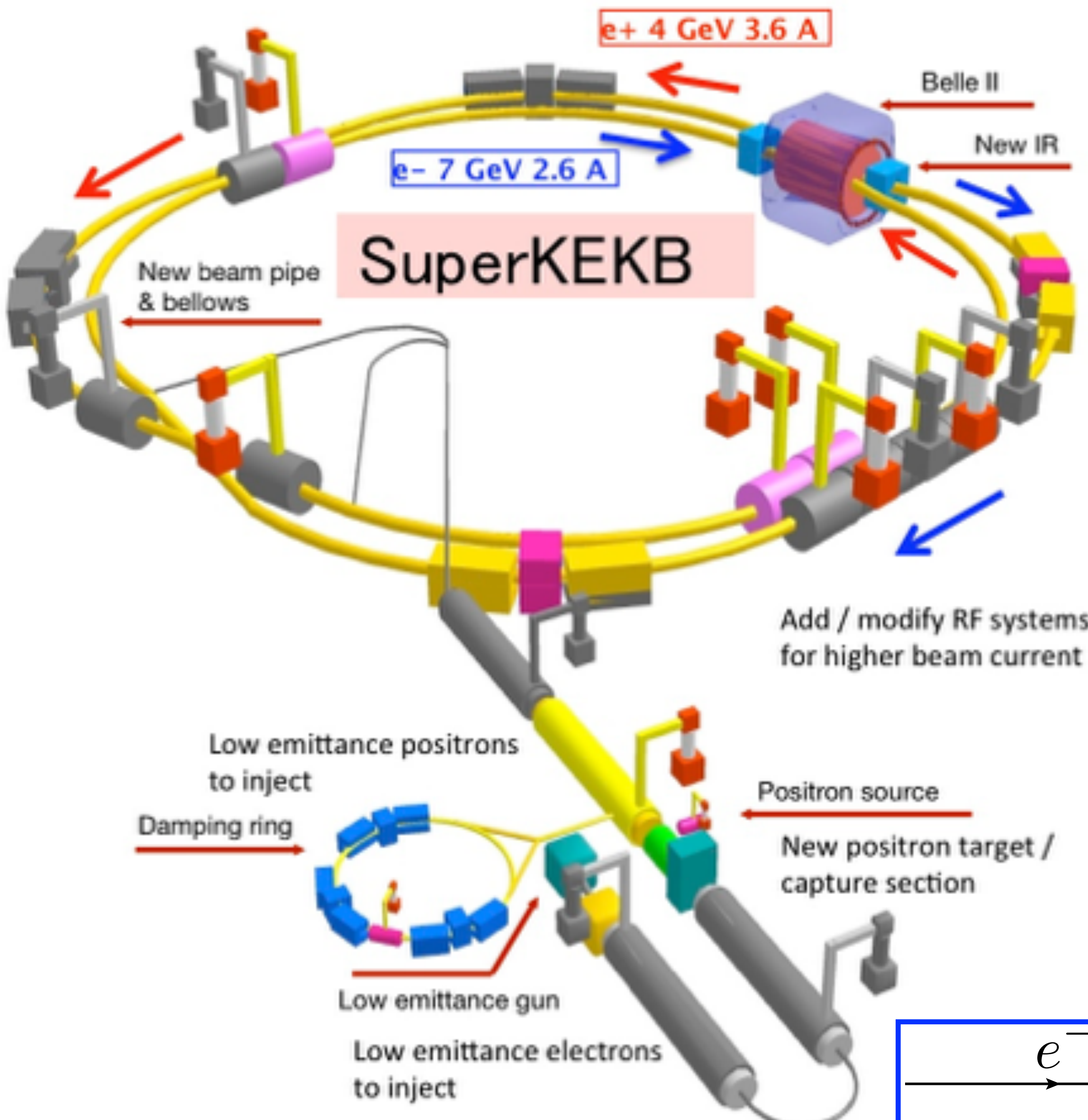


DELPHI
monojet
$\pi\pi \to SM$
$h \to ZV$
CMS7, DY
contact
LHC8, DY
EWPO
BaBar (inv)
BaBar (vis)
$\pi\pi \to \pi V$
thermalization
$SU(2), N_f = 2$
$\alpha_D = 1/4\pi$
$m_\pi = 300$ MeV
ϵ_γ
m_V [GeV]
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-1}
1
10^{1}
10^{2}
10^{3}

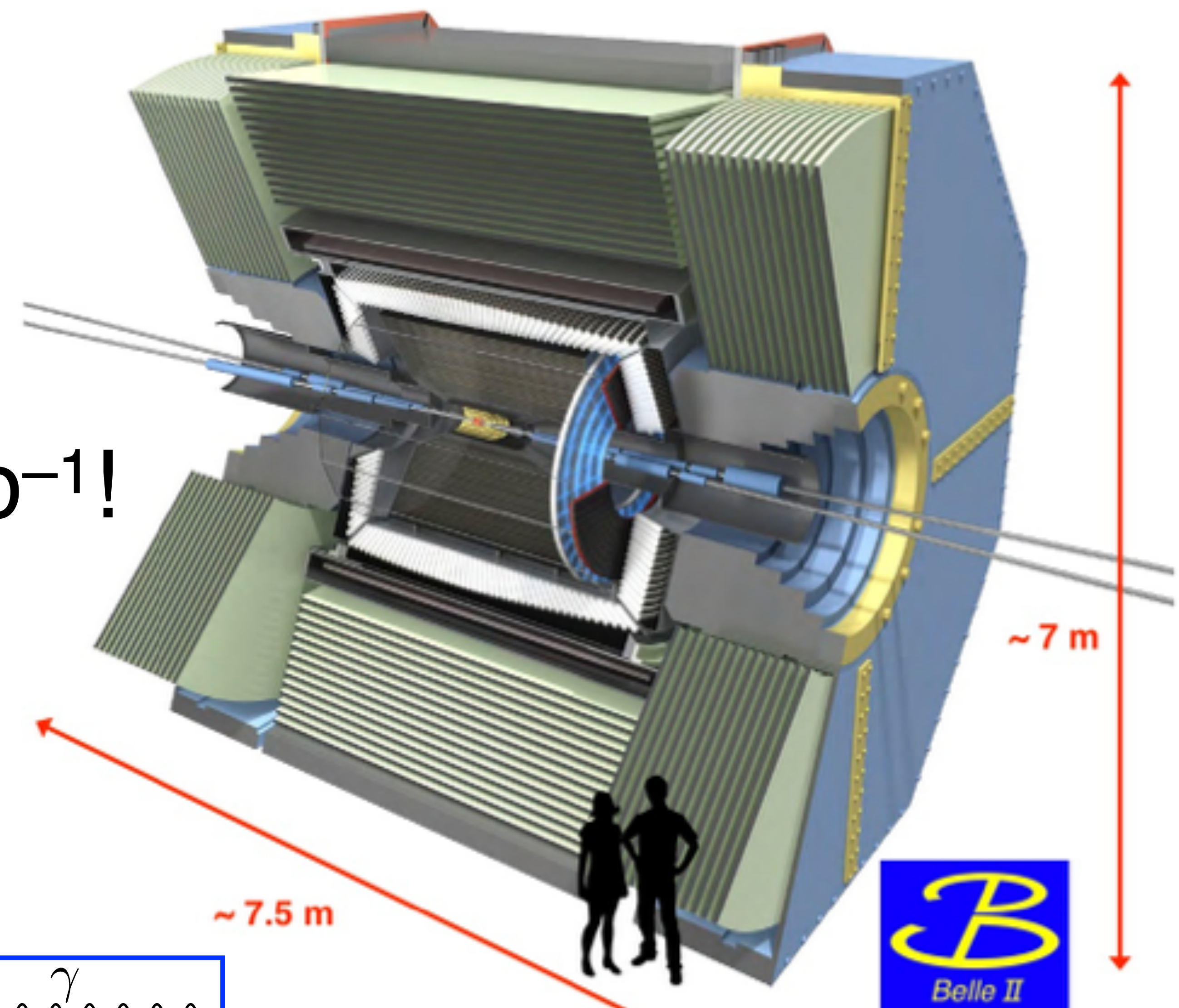


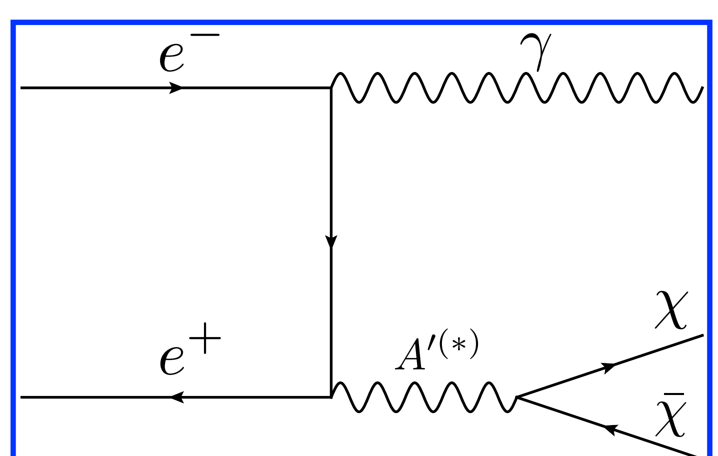
APEX
Belle−II (vis)
Belle−II (inv)
SHiP
ILC (contact)
(LHC14)
EWPO (ILC)
10^{-40} cm^2
10^{-41} cm^2
10^{-42} cm^2
electron recoil
(LHC14)
(100TeV)
DY@pp
monophoton
(ILC)
$SU(2), N_f = 2$
$\alpha_D = 1/4\pi$
$m_\pi = 300$ MeV
ϵ_γ
m_V

Super KEK B & Belle II

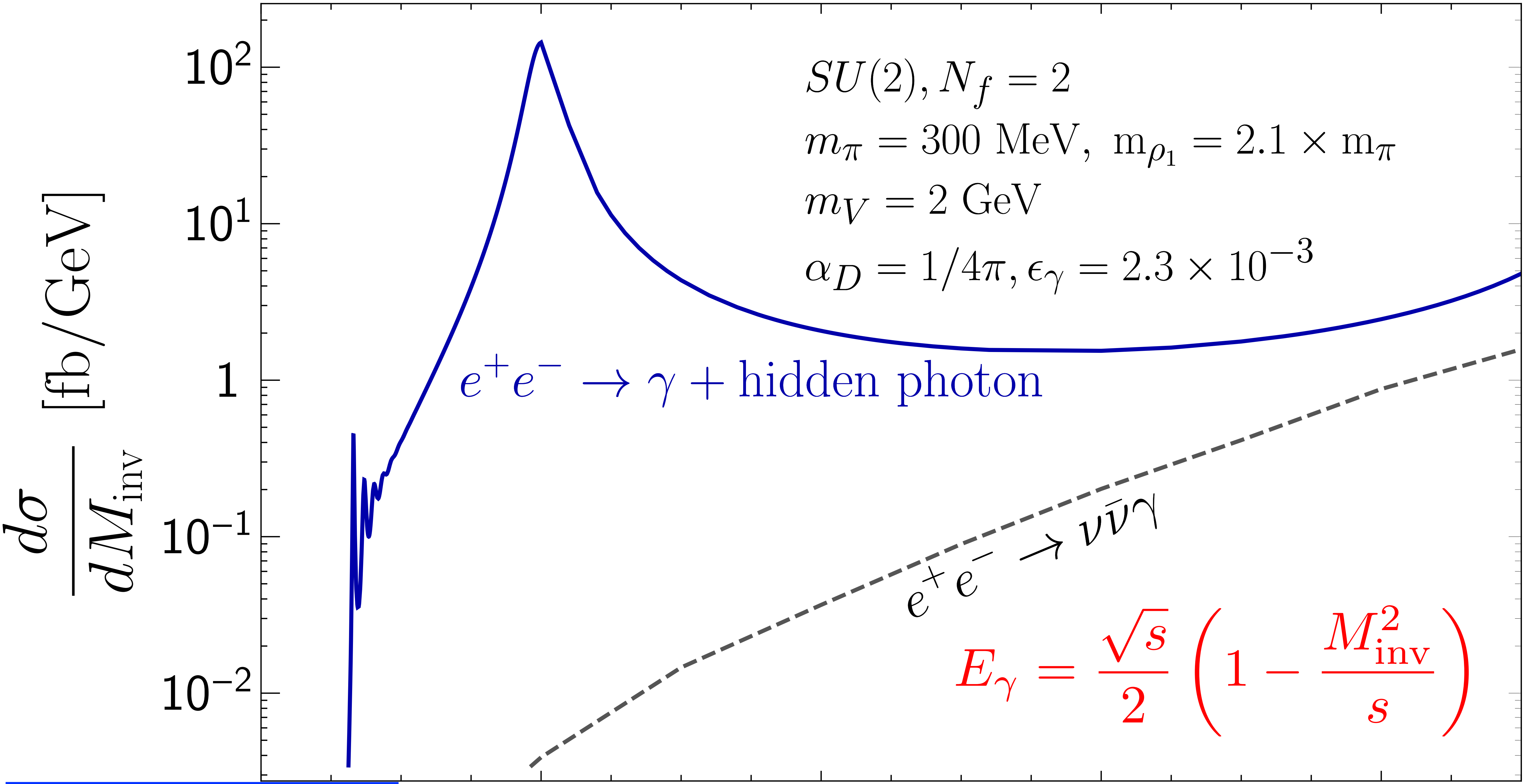


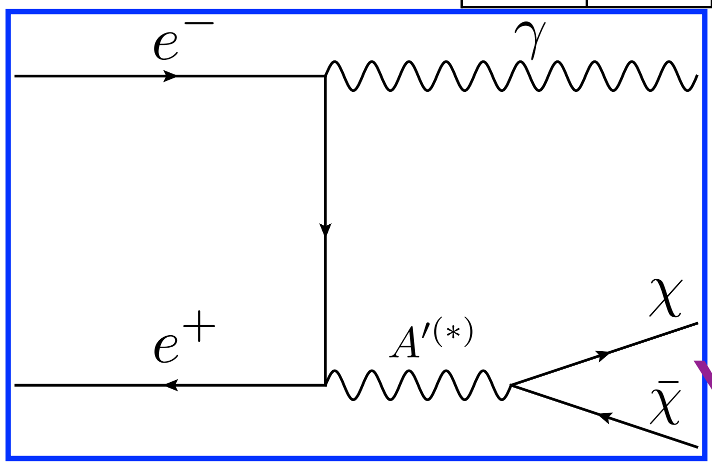
50 ab^{-1}!



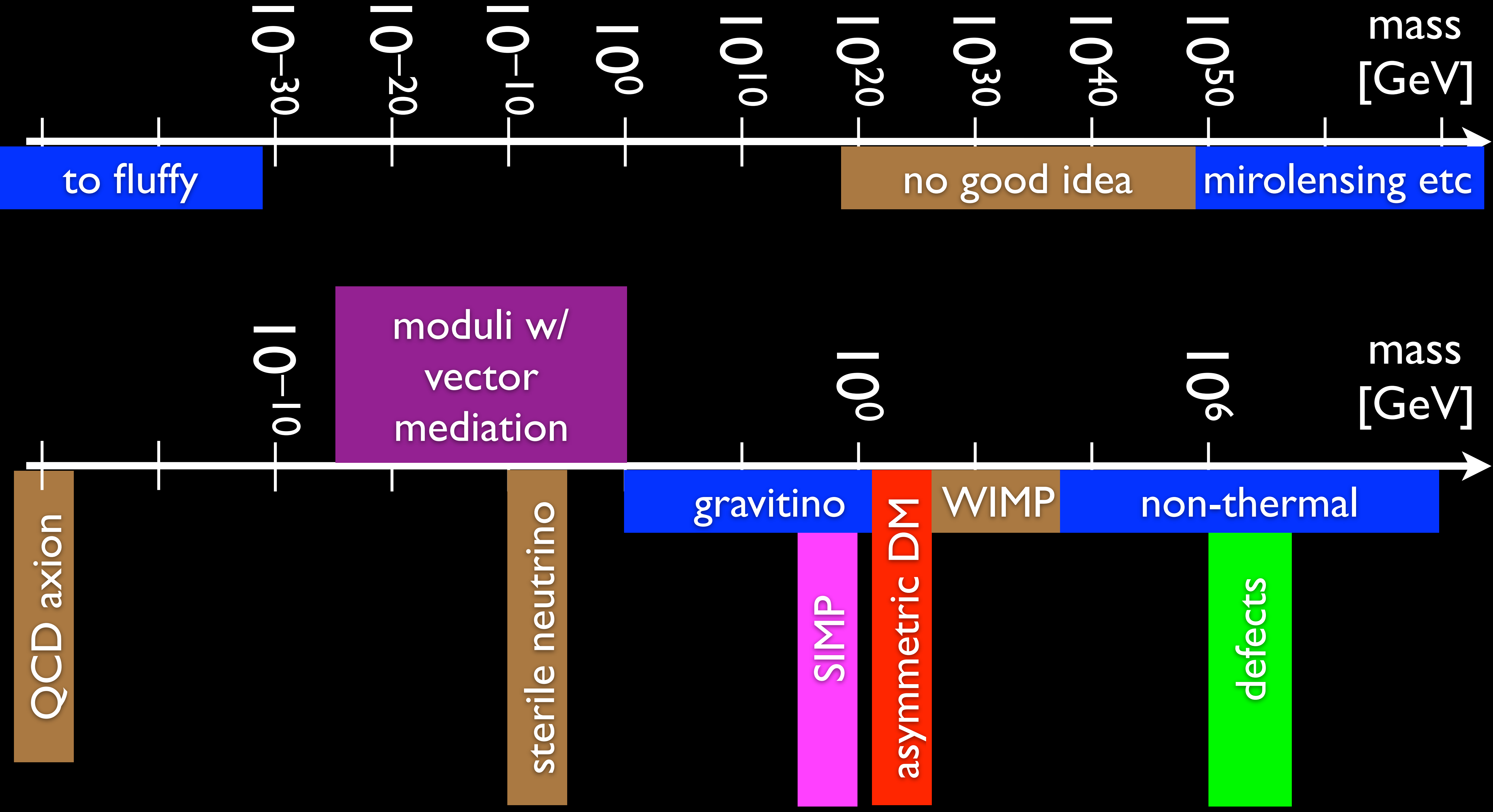


$$E_\gamma = \frac{\sqrt{s}}{2}\left(1 - \frac{M_{\rm inv}^2}{s}\right)$$





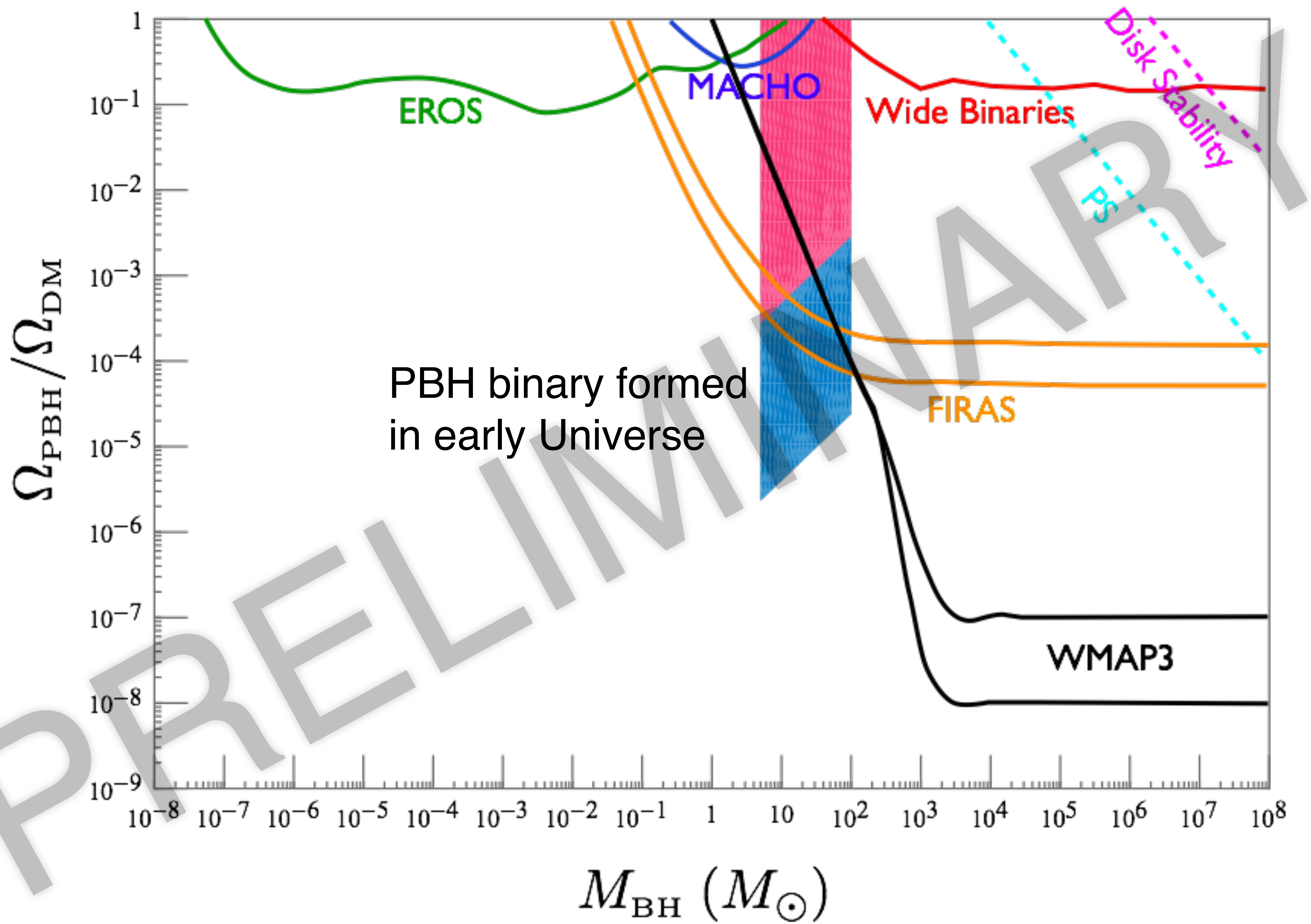
Yonit Hochberg, Eric Kuflik, HM



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

LIGO

Chien-I Chang
Keisuke Harigaya
HM



Conclusions

- HEP: very exciting
- Higgs: need to understand it better
  - HL-LHC, ILC, FCCee
- naturalness: higher energies, precision
  - HE-LHC, FCCpp, CLIC, PWFA
  - flavor physics, EDM, $0\nu\beta\beta$, p-decay
- baryogenesis:
  - *B*, *K*, LFV, neutrino oscillation
- dark matter: open mind, broad search
  - cosmology, direct, indirect, collider

experiments

healthy field!