invisibles 15 Workshop 22nd-26th June, 2015

Place: IFT and Thyssen-Bornemisza Museum, Madrid

Beyond the Standard Model

Neutrinos
Dark Matter
Dark Energy
New Physics

Invisibles meets Visibles

Higgs and Colliders
CP Violation
Flavour Physics
Art
Astrophysics
Cosmology

Hitoshi Murayama (Berkeley, Kavli IPMU Tokyo)

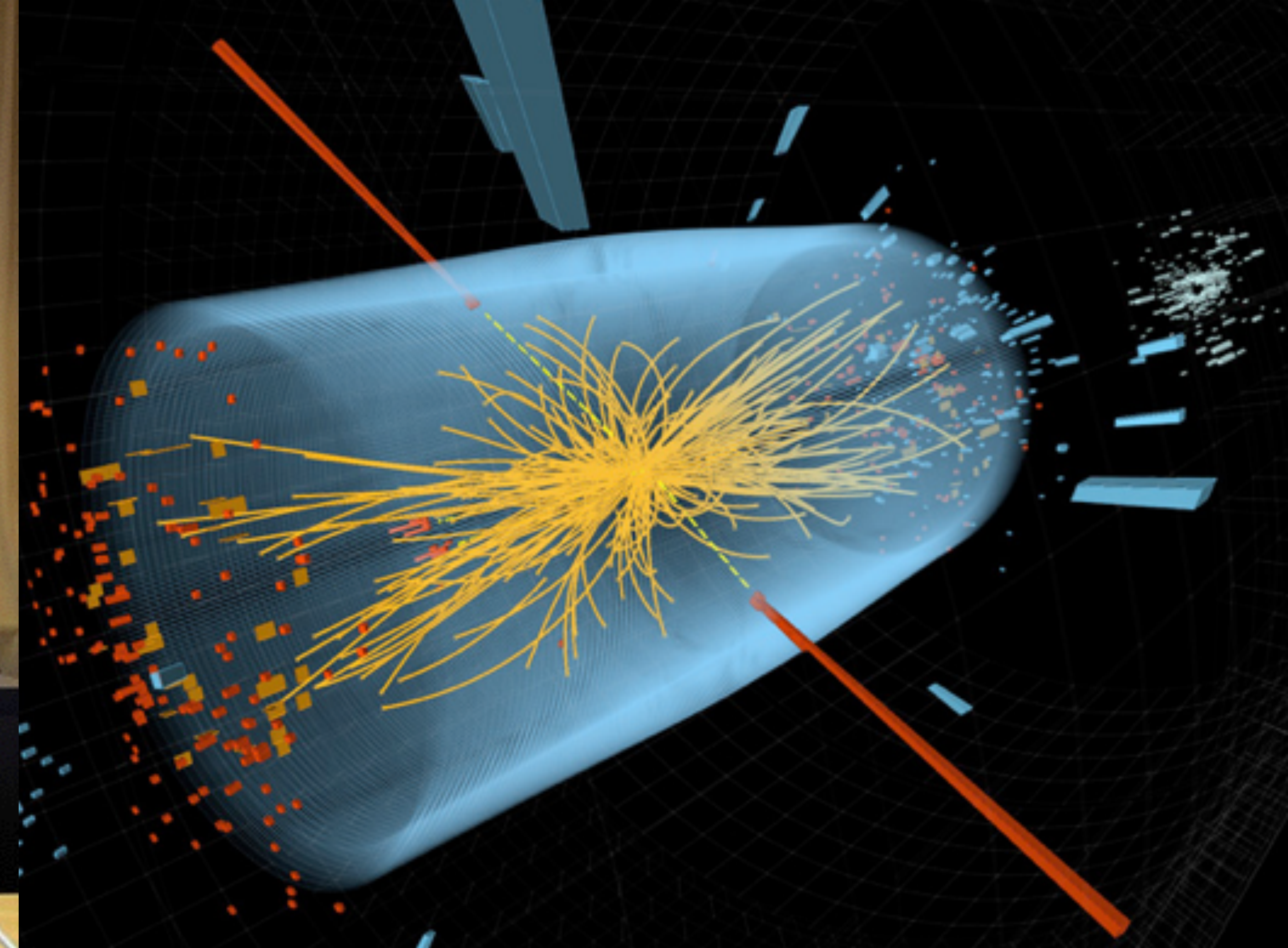
www.invisibles.eu

Workshop: http://www.invisibles.eu/news/invisibles15

André Derain. El puente de Waterloo, 1906

This project has received funding from the European Union's Seventh Framework Programme for research, technological development and demonstration under grant agreement no 289442.


CERN
iggs search
odate 04.07.2012

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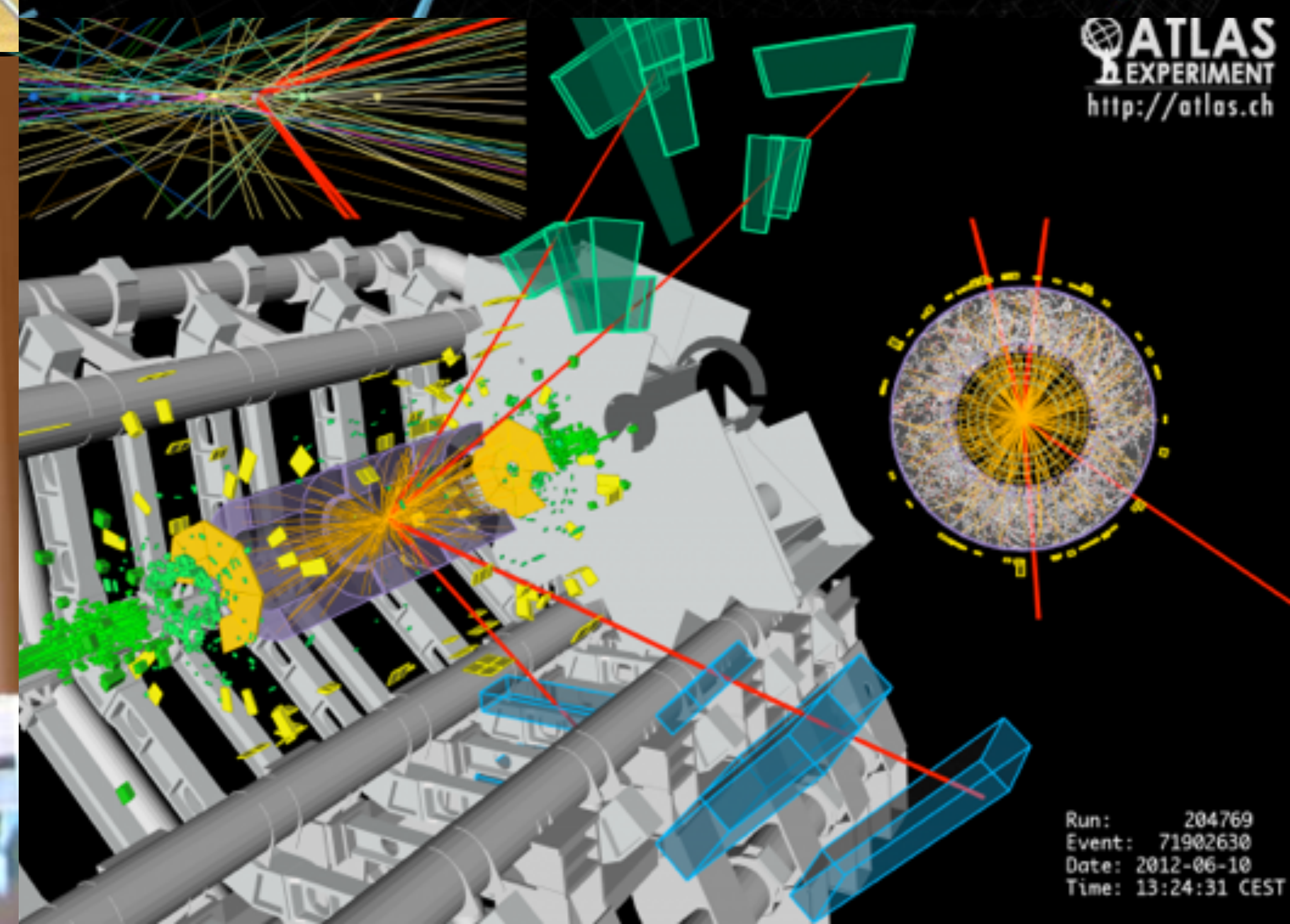
ATLAS
EXPERIMENT
http://atlas.ch
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Time: 13:24:31 CEST

So,
what’s the problem?

Five empirical evidences for physics beyond SM

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- Since 1998, it became clear that there are at least five missing pieces in the SM

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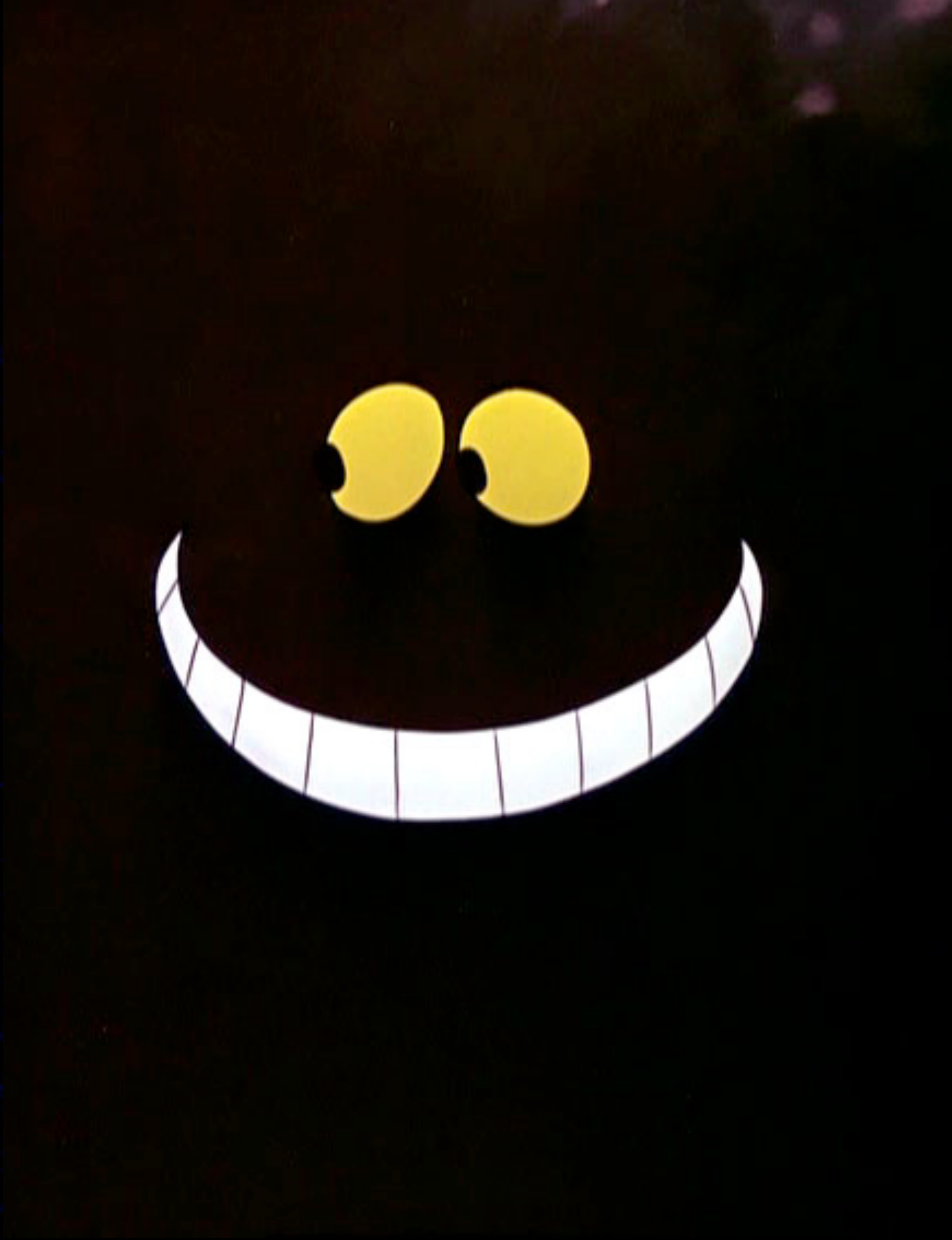
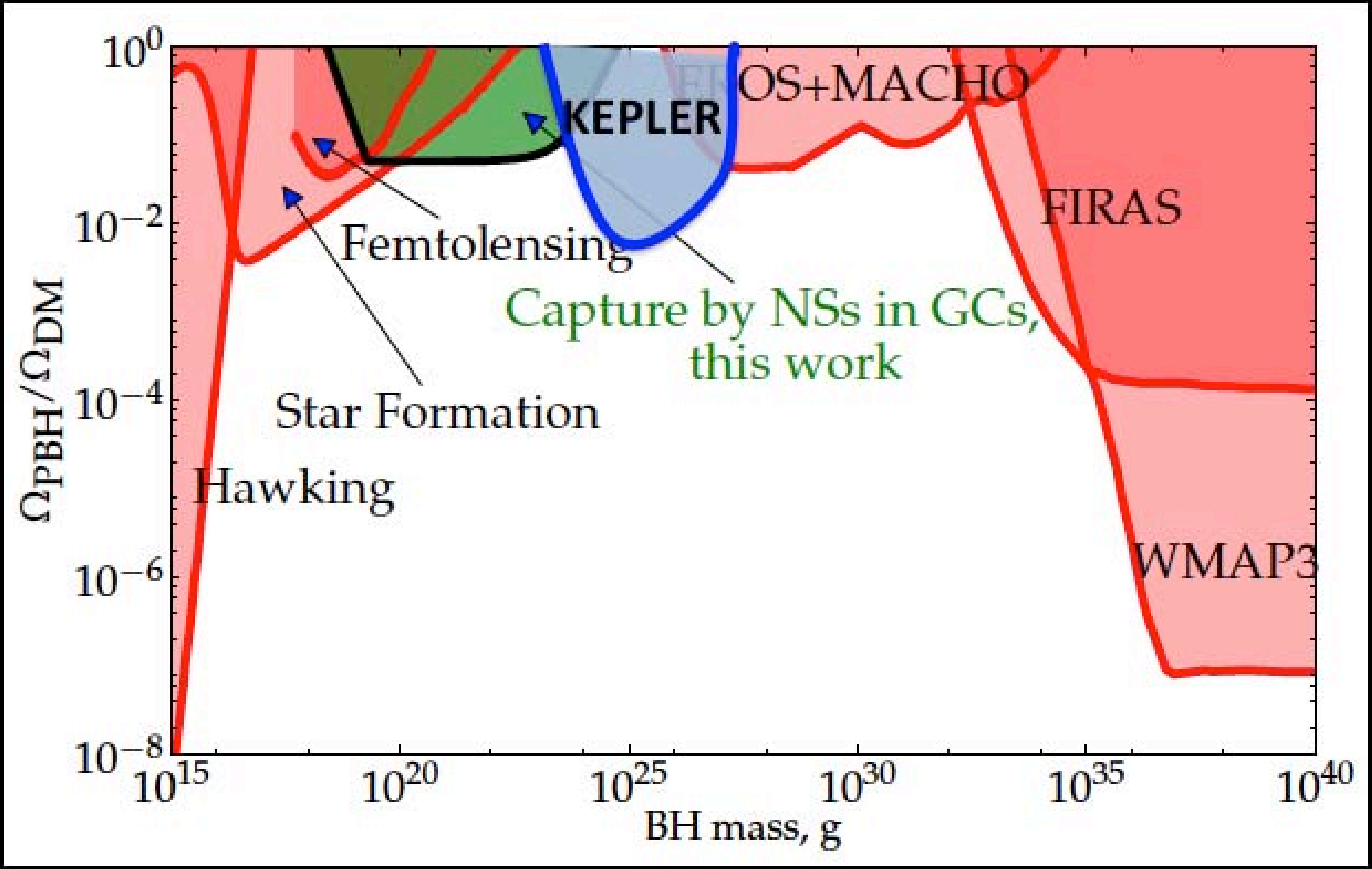
We don't really know their energy scales...

Dark Matter
our Mom

Cheshire cat

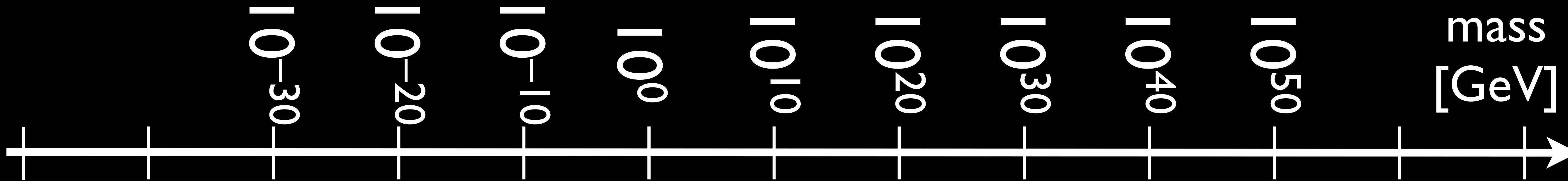
Closing the PBH as DM window

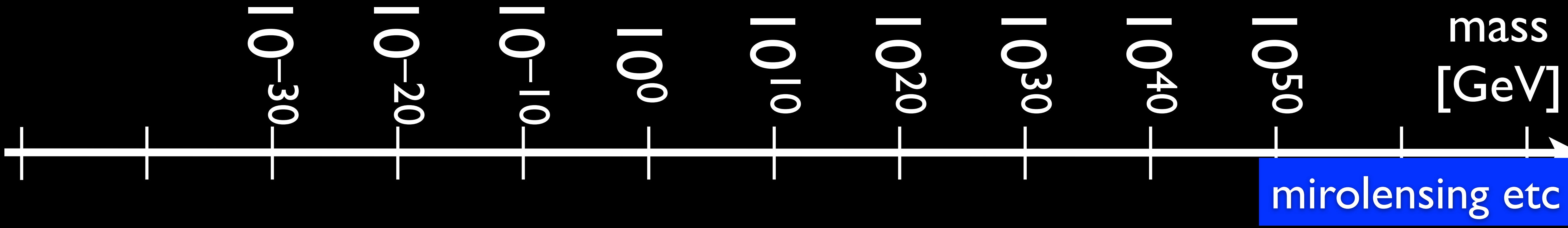


Capela, Pshirkov, & Tinyakov: arXiv:1301.4984

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
10^0
10^10
10^20
10^30
10^40
10^50
mass [GeV]



10−30
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10^20
10^30
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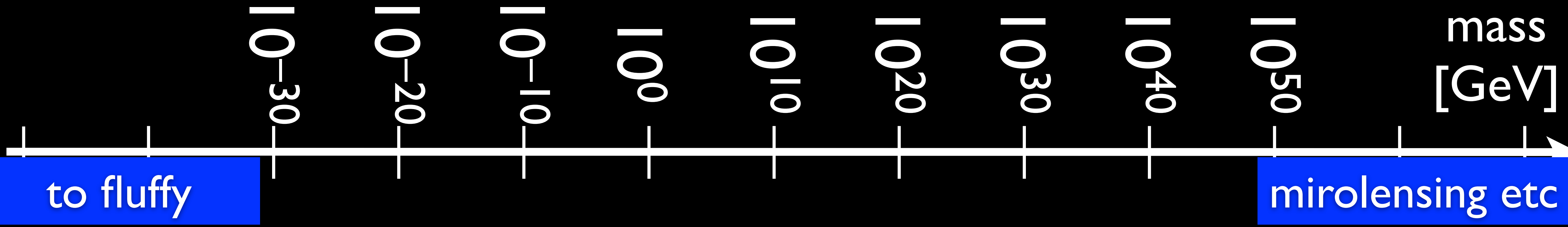
mass
[GeV]
mirolensing etc



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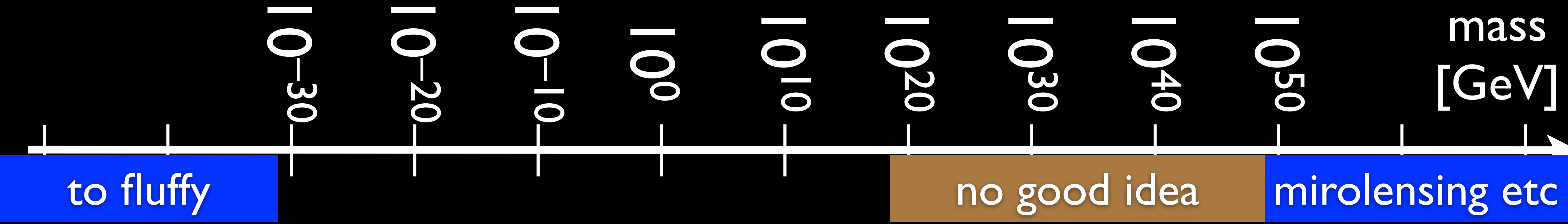
10^{50}
mass [GeV]
to fluffy
mirolensing etc



10^{-30}
10^{-20}
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10^{20}
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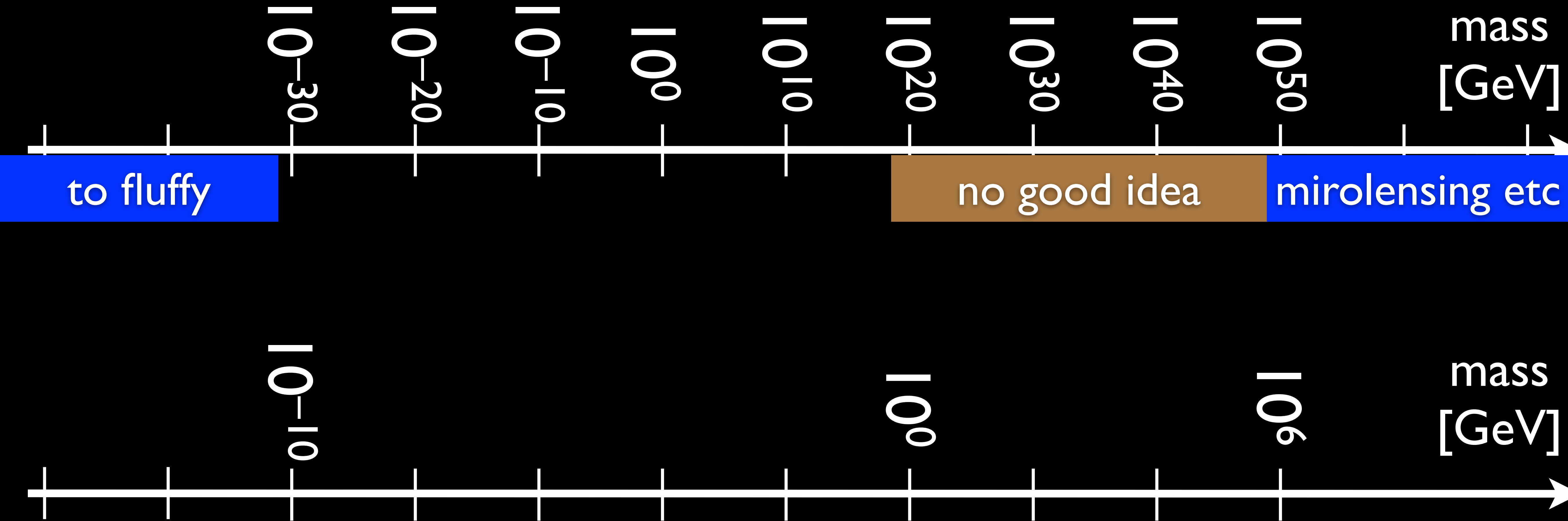
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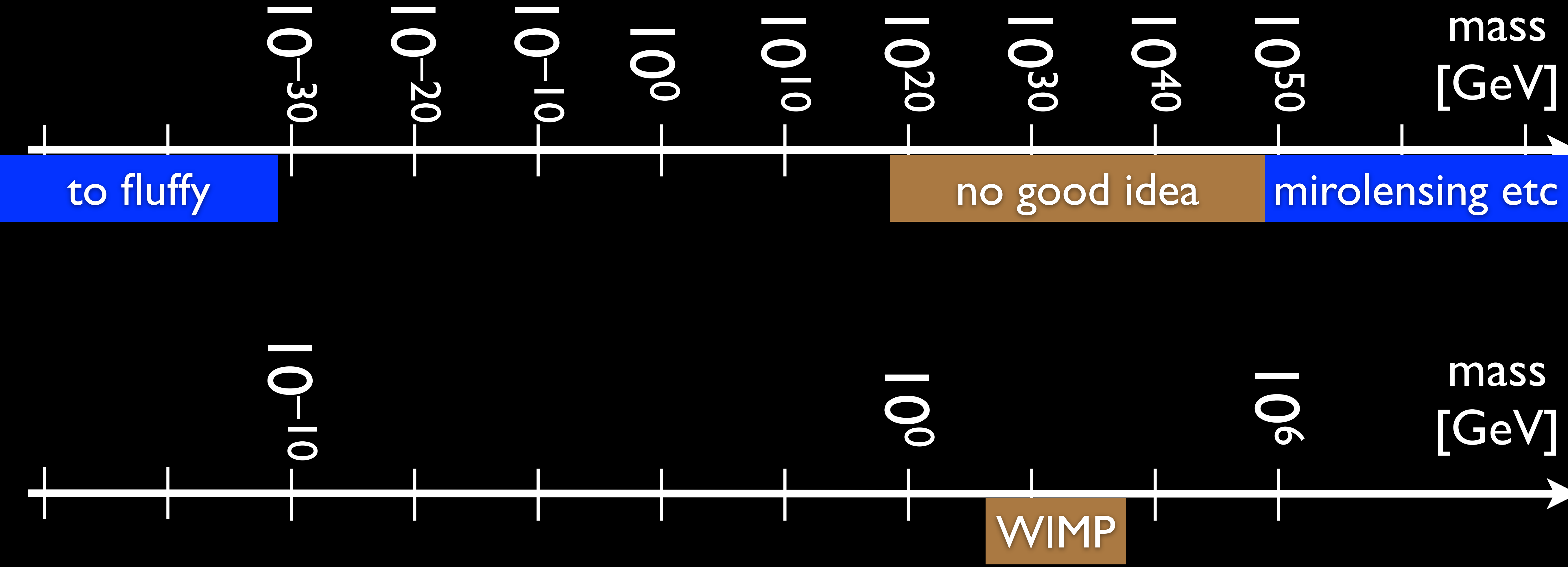

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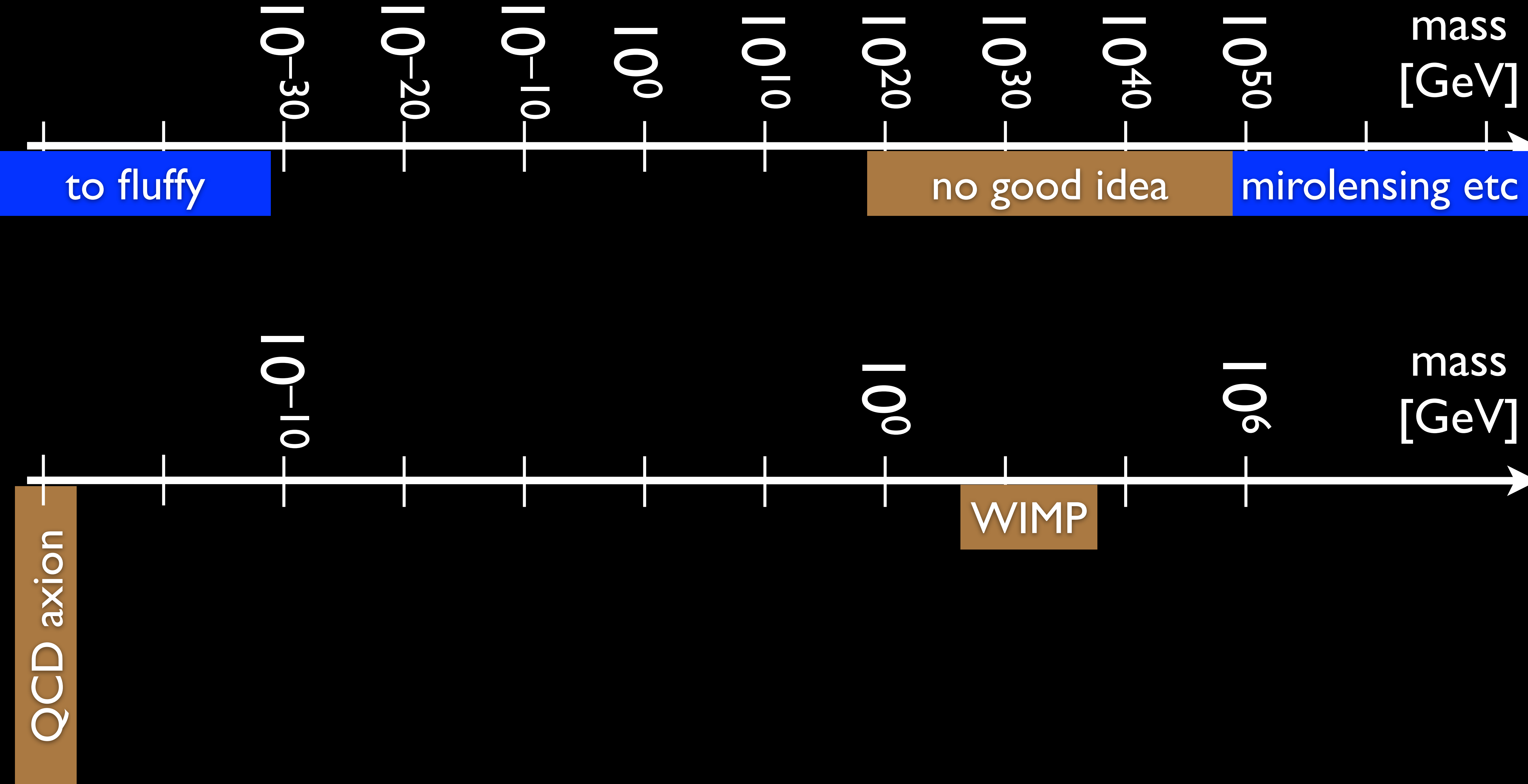
mass [GeV]
WIMP


mass
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mass
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10−10
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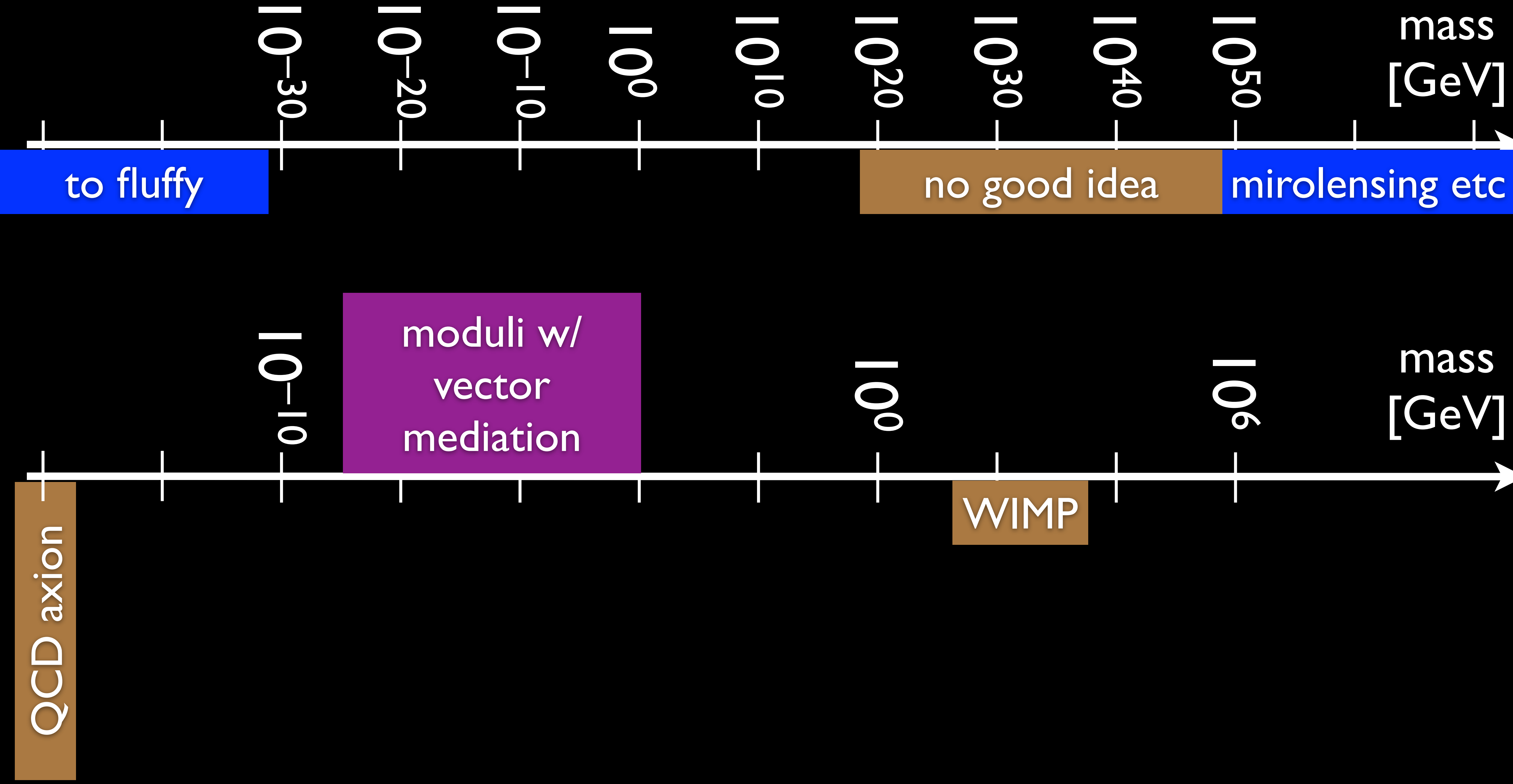
10^6
QCD axion
WIMP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moduli w/ vector mediation
10^−10
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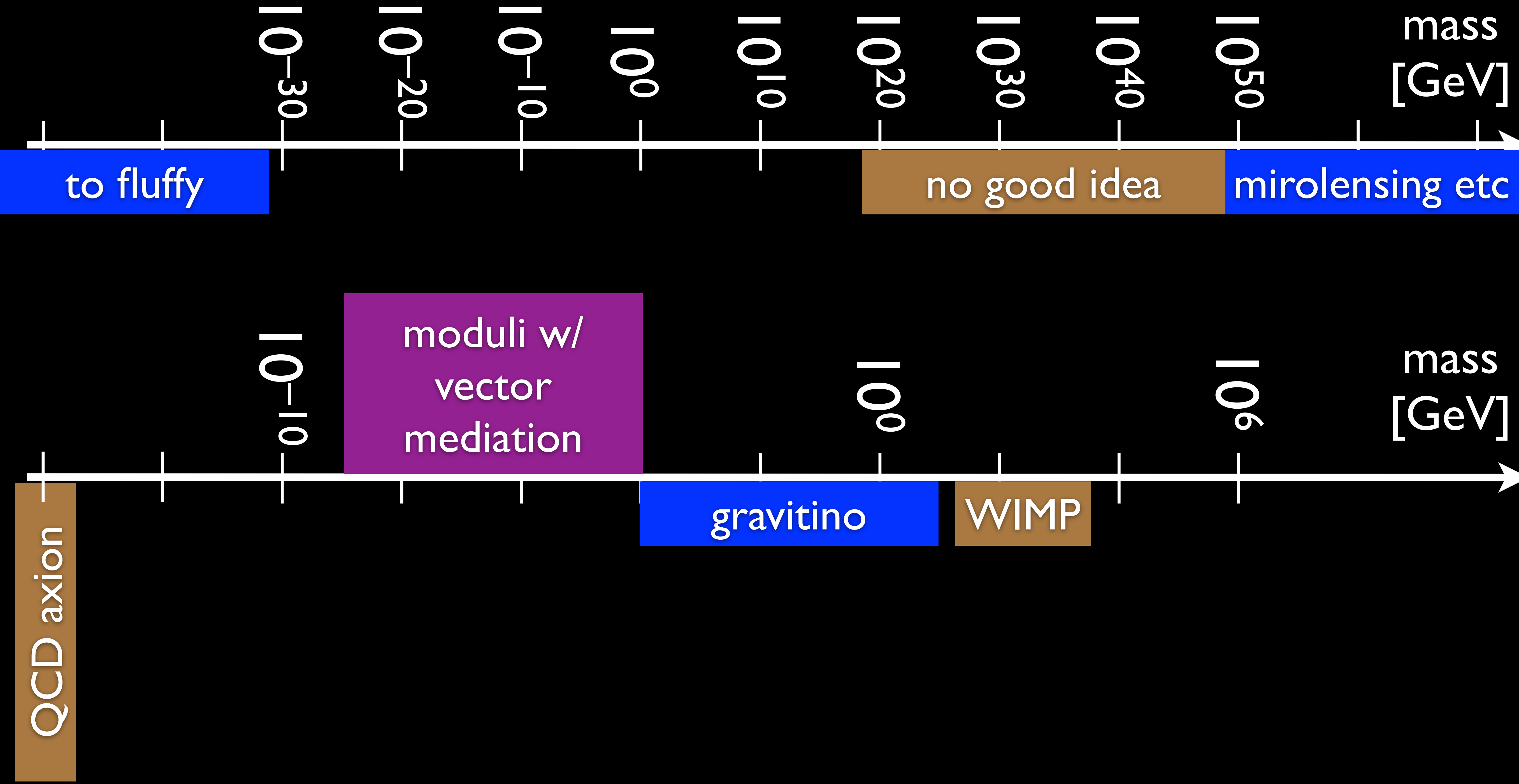
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gravitino
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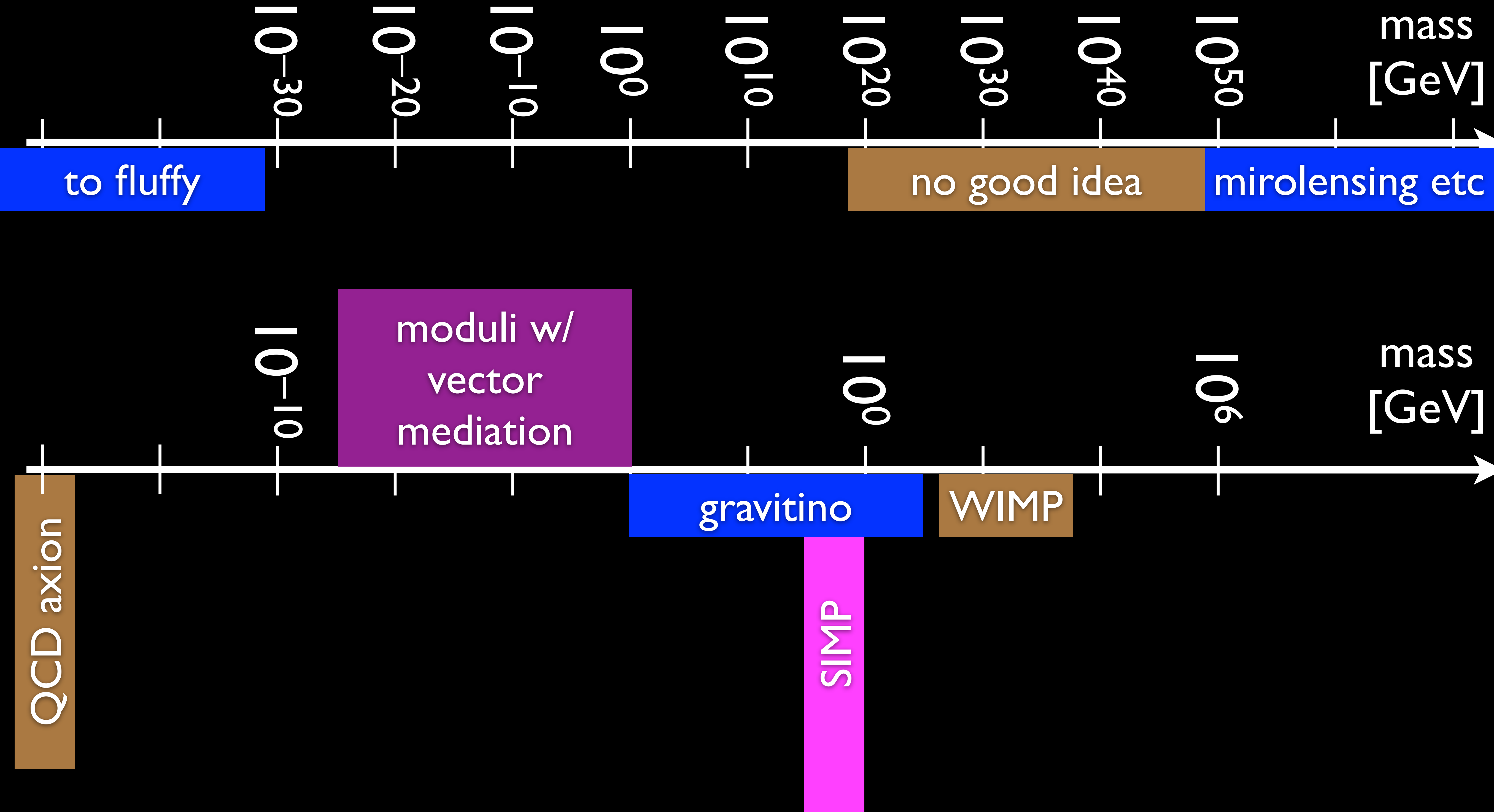

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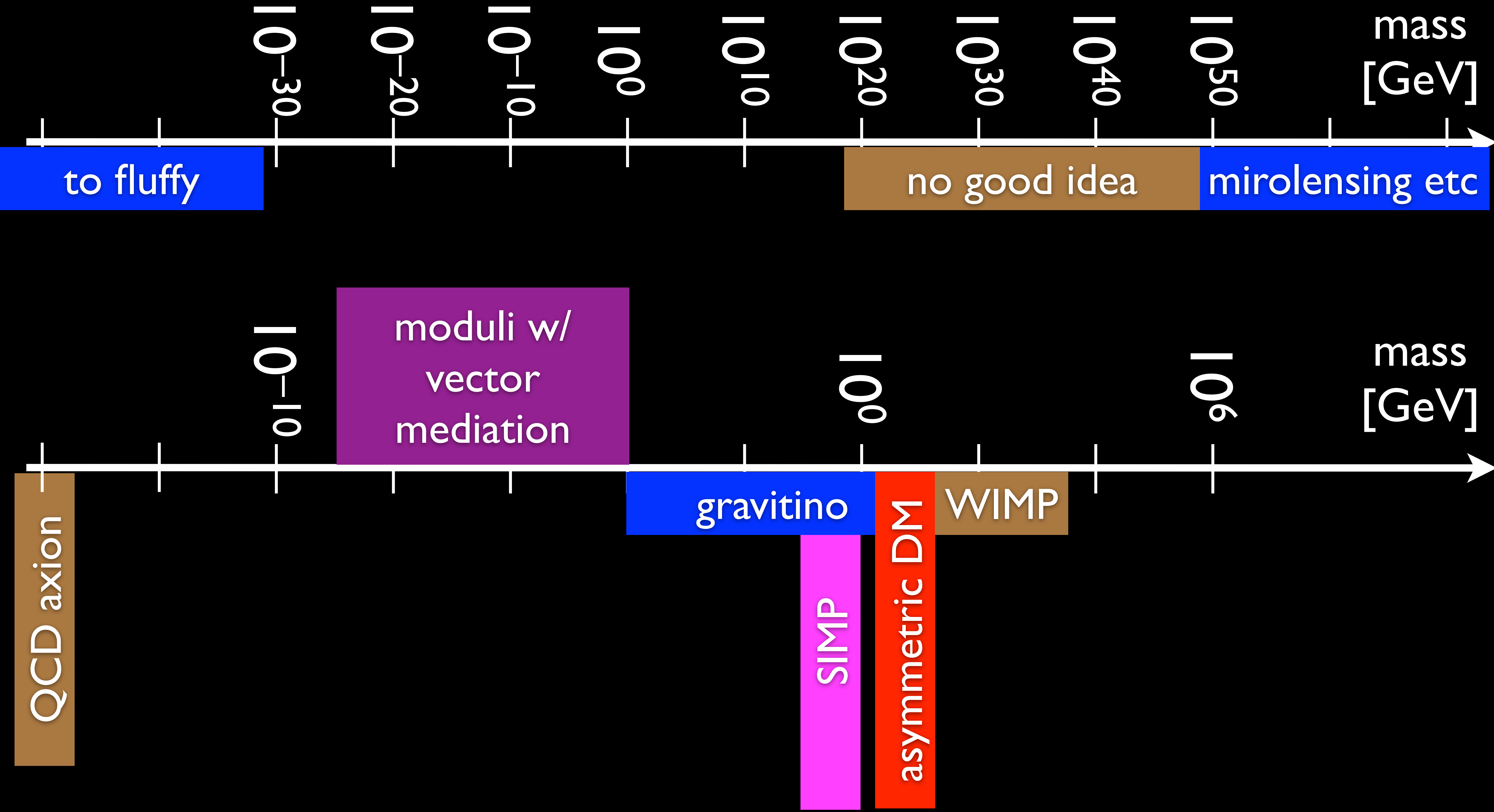
SIMP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10^{-10}
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mass [GeV]
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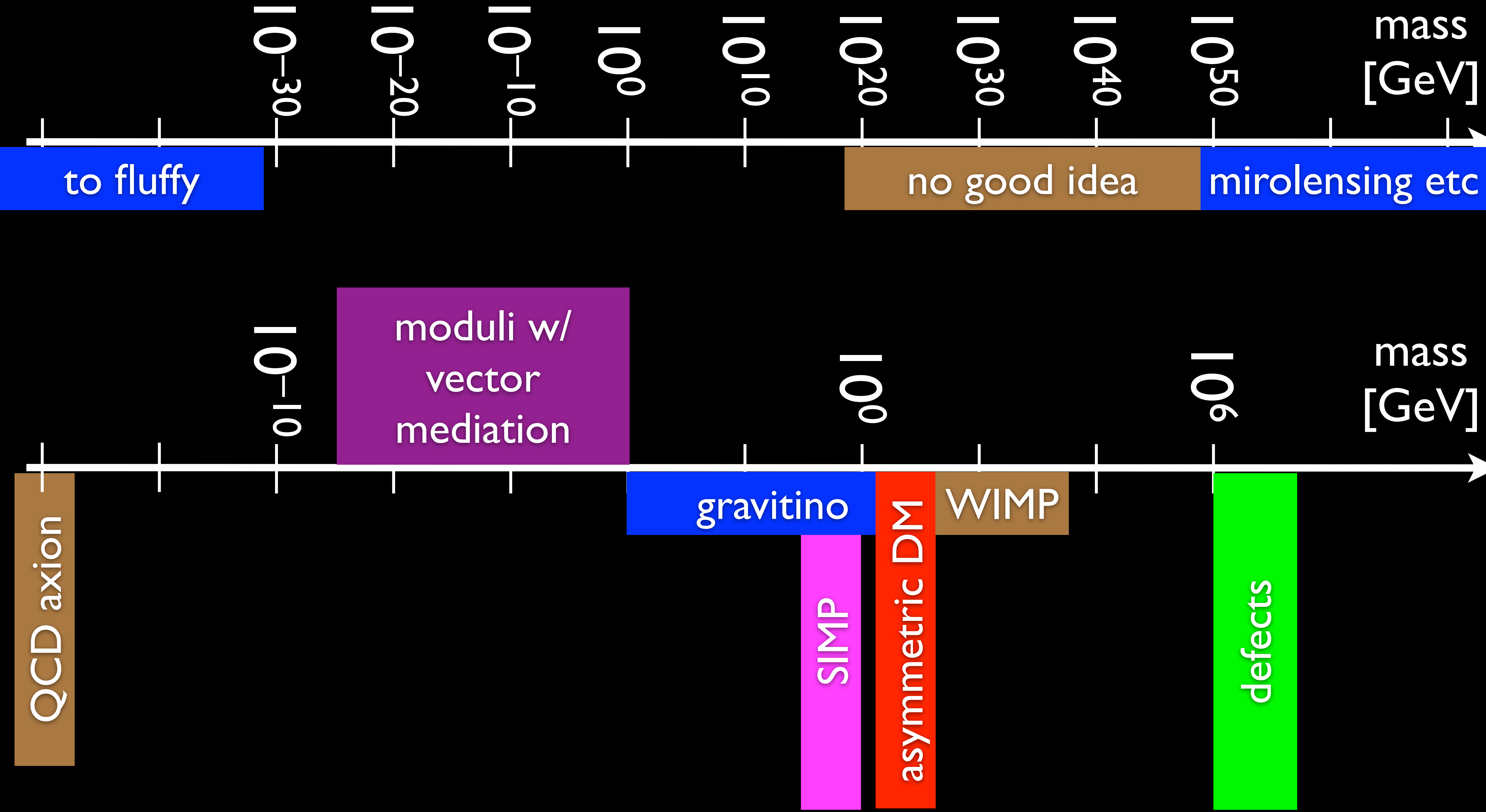
gravitino
WIMP
SIMP
asymmetric DM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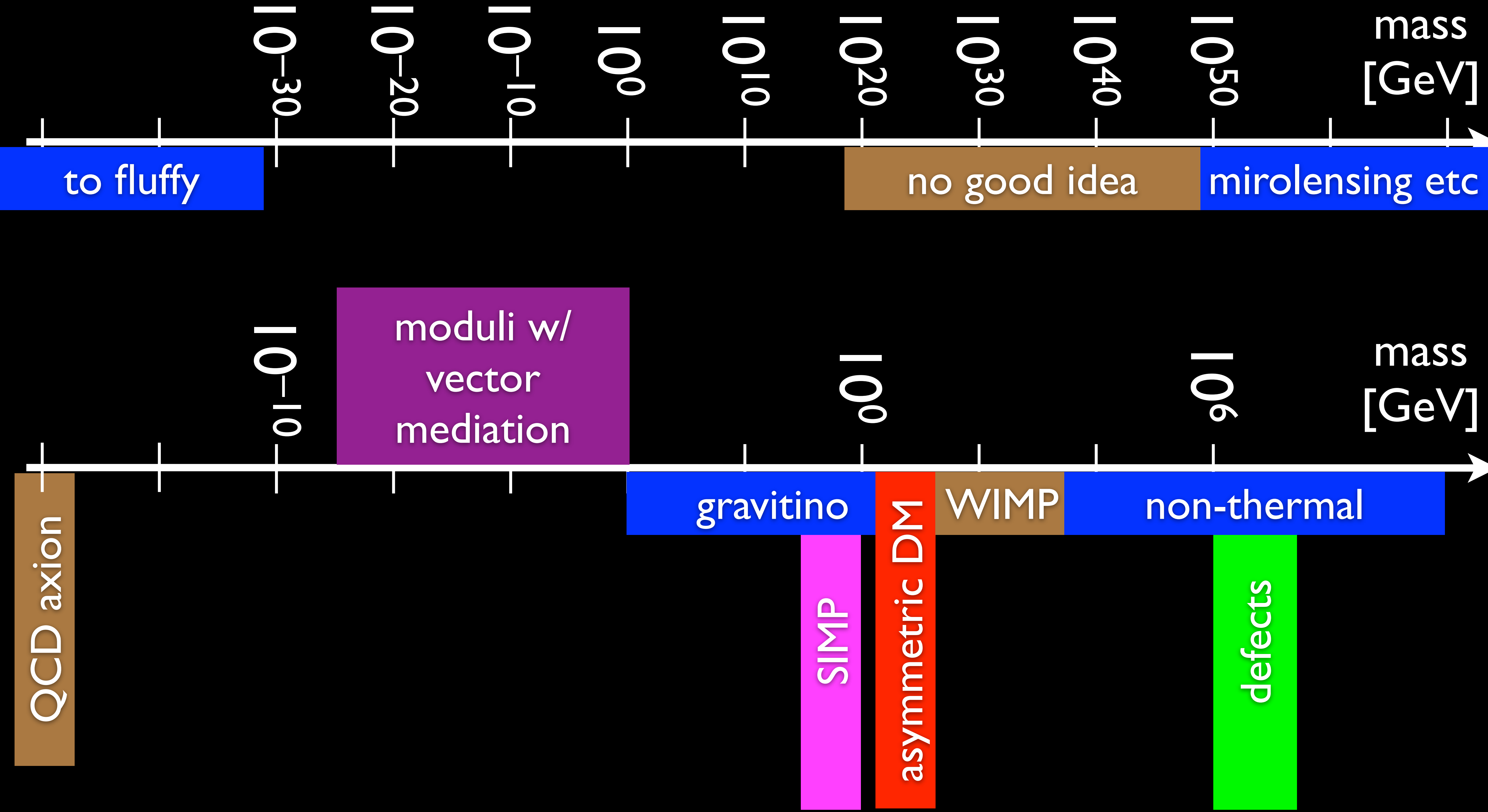
asymmetric DM
WIMP
defects



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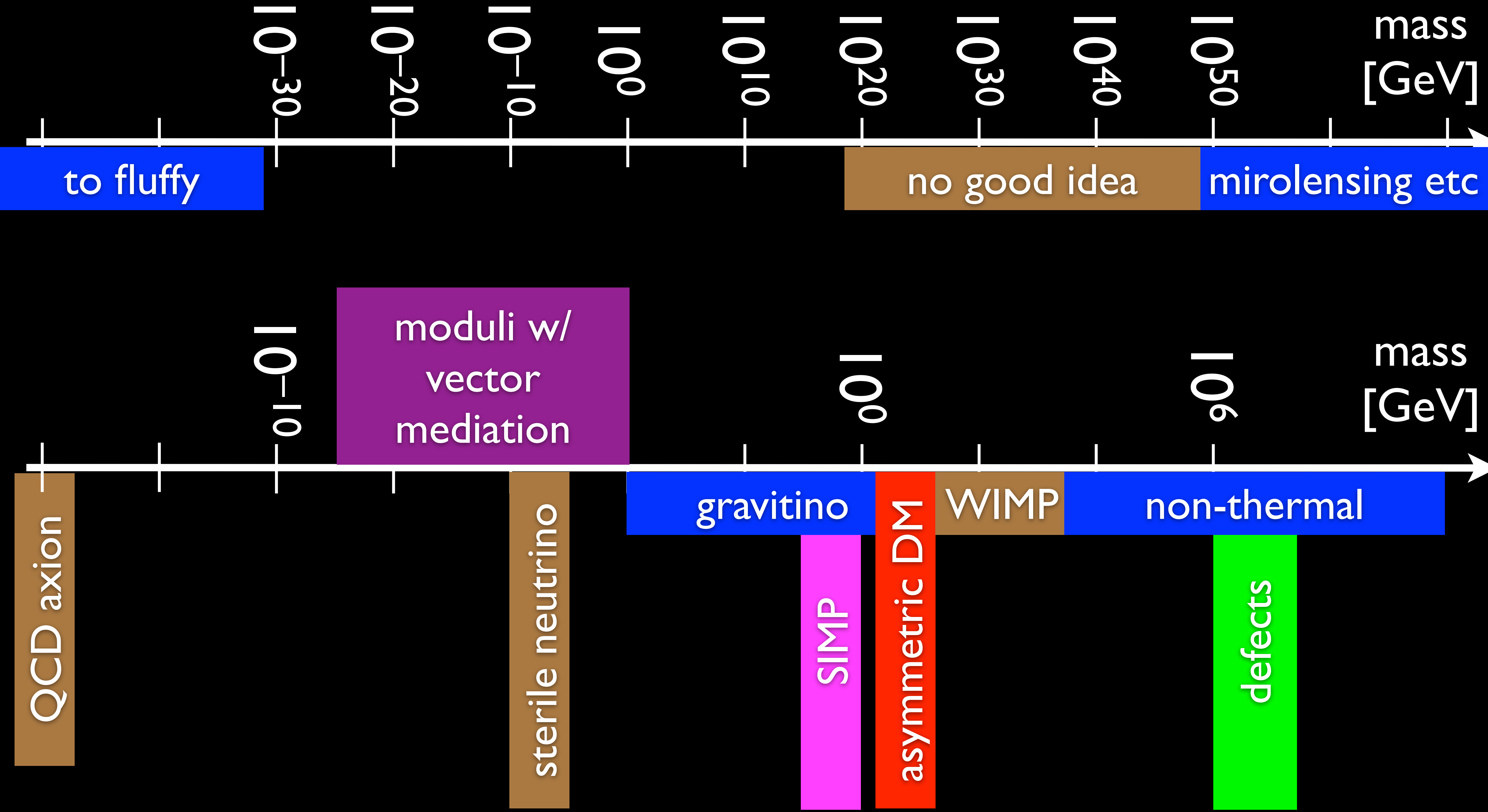
non-thermal
defects



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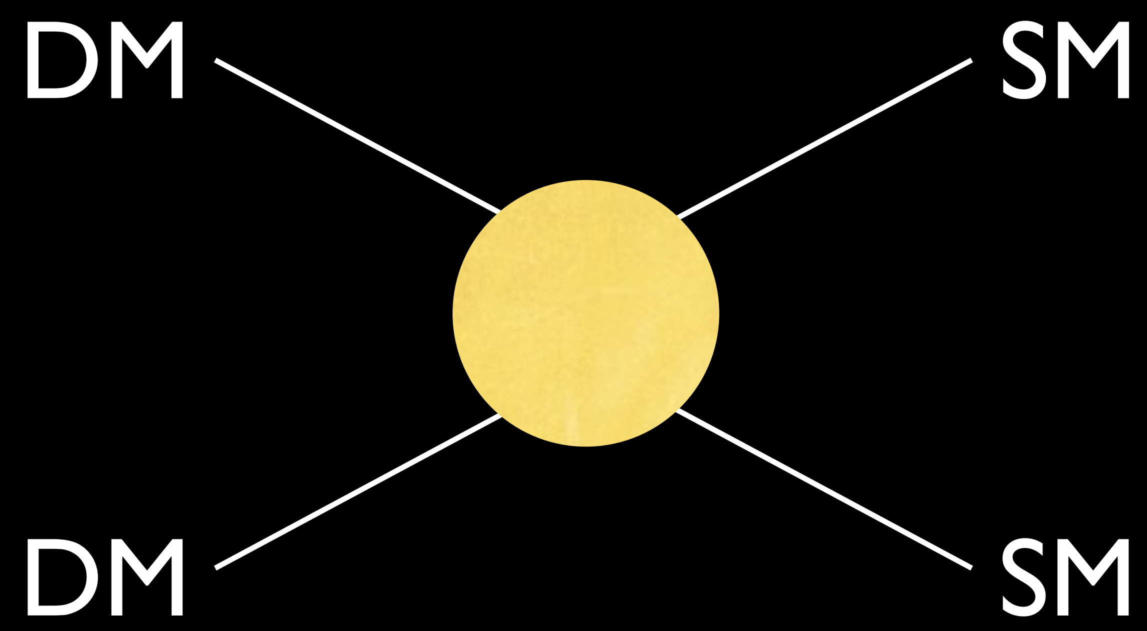
$$\frac{n_{\rm DM}}{s} = 4.4 \times 10^{-10} \frac{\rm GeV}{m_{\rm DM}}$$

WIMP Miracle



"weak" coupling
"weak" mass scale

→ correct abundance

Miracle^2

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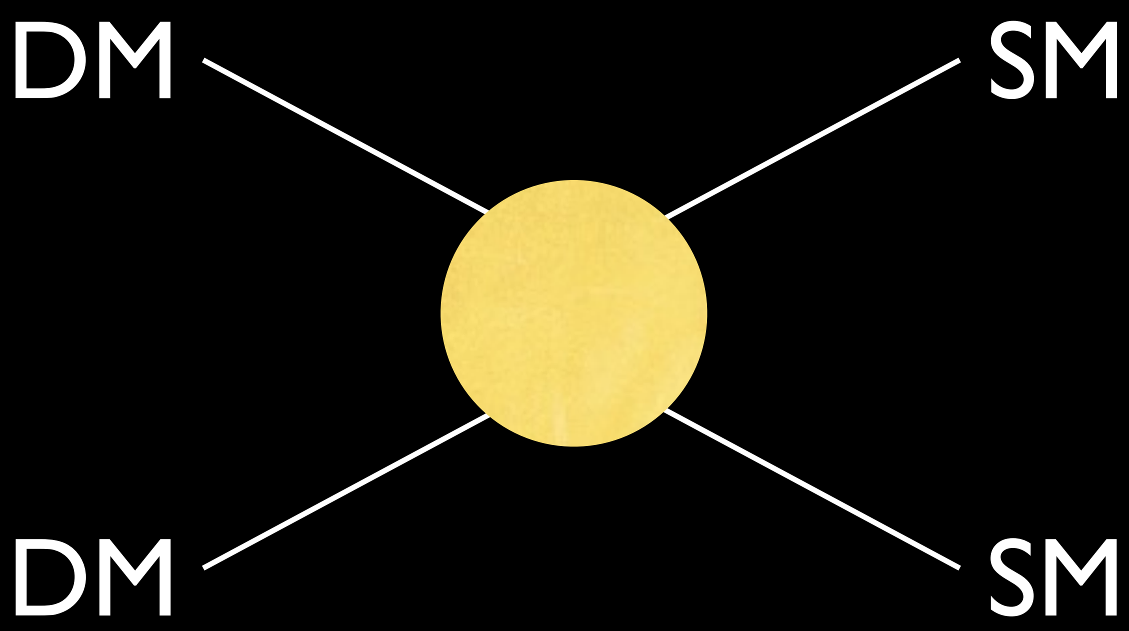
WIMP Miracle



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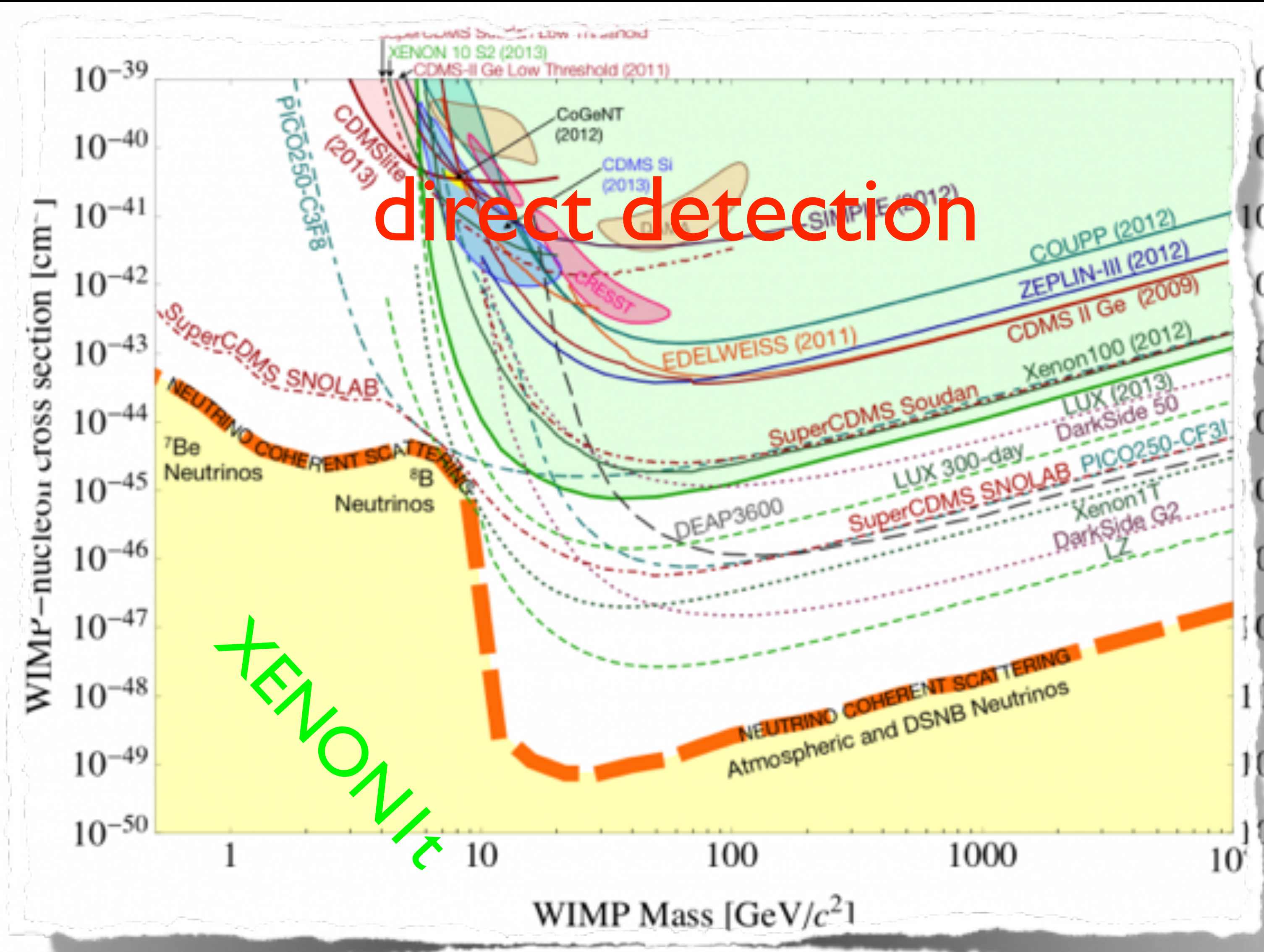
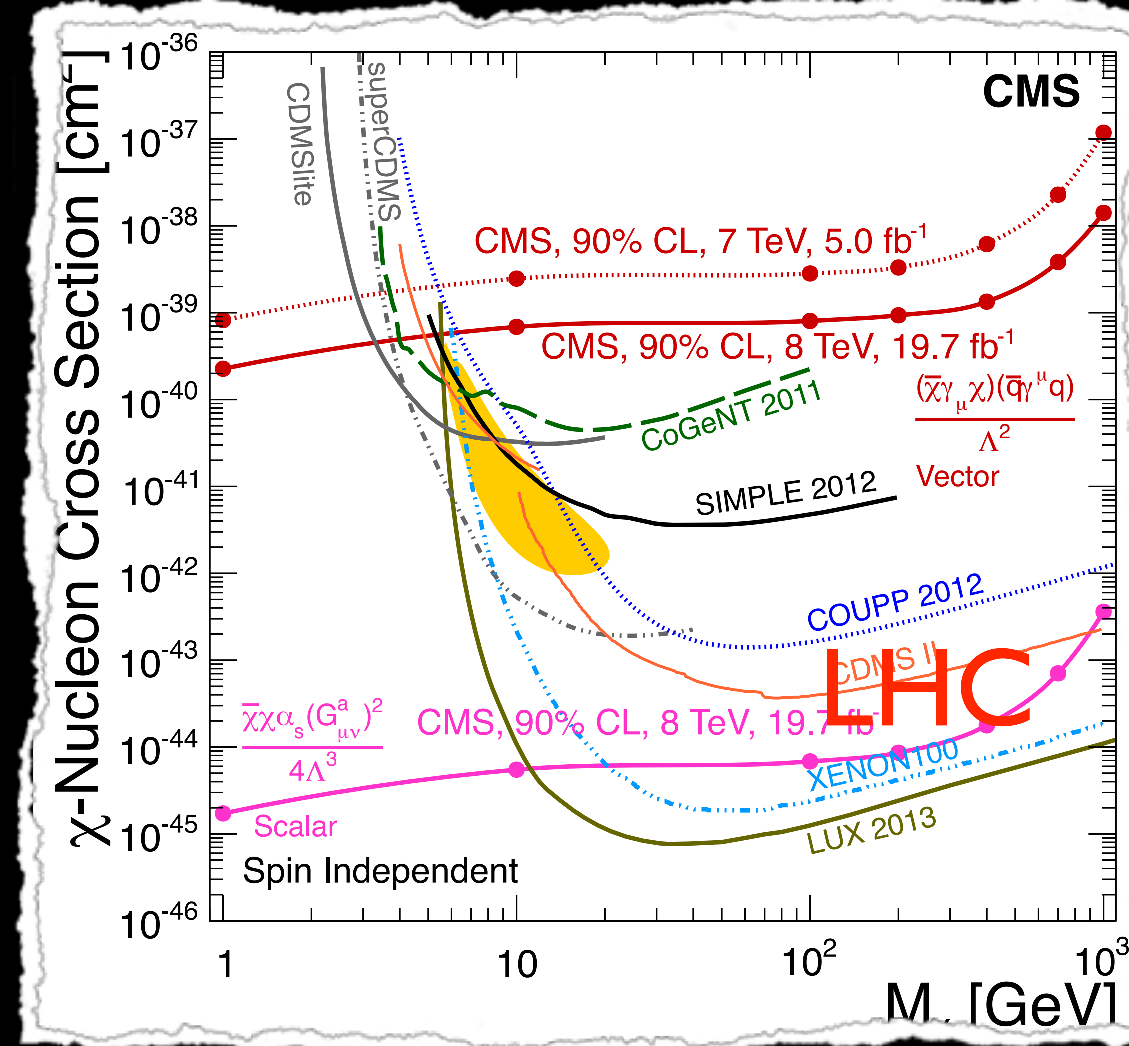
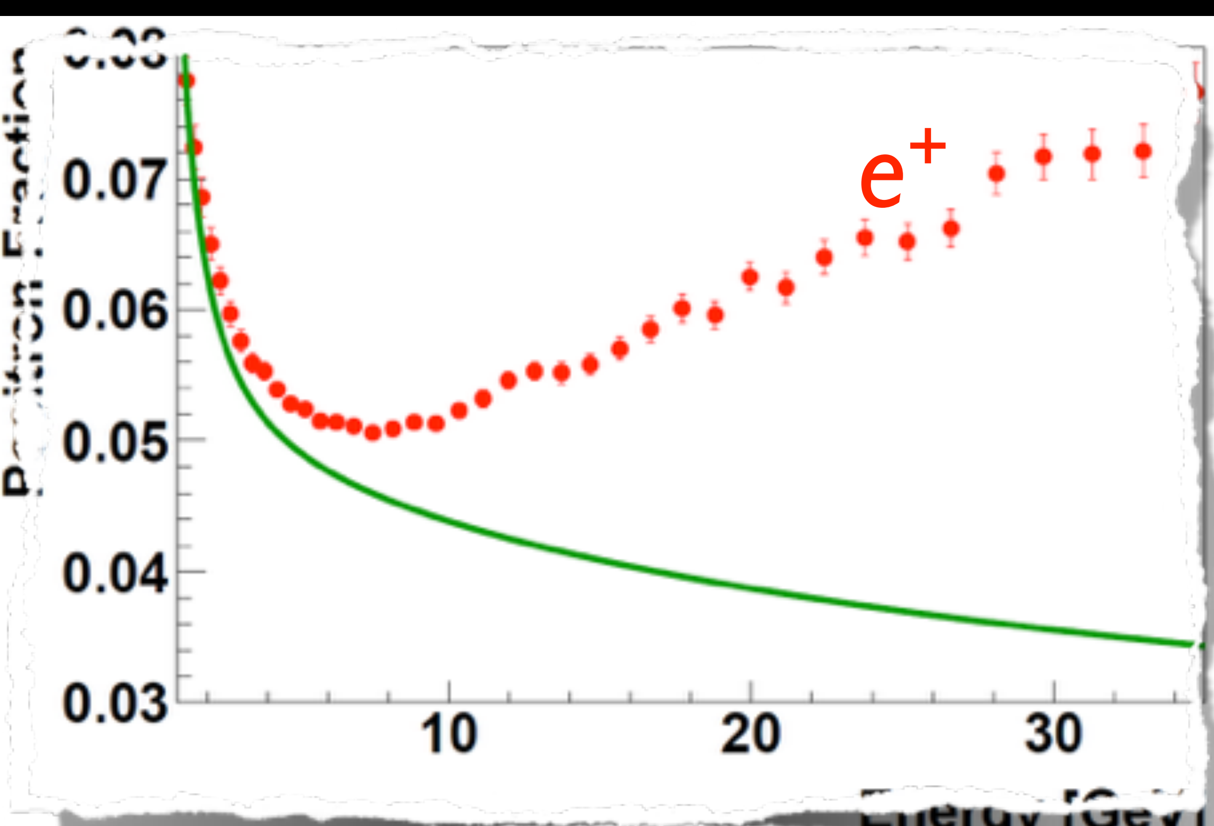
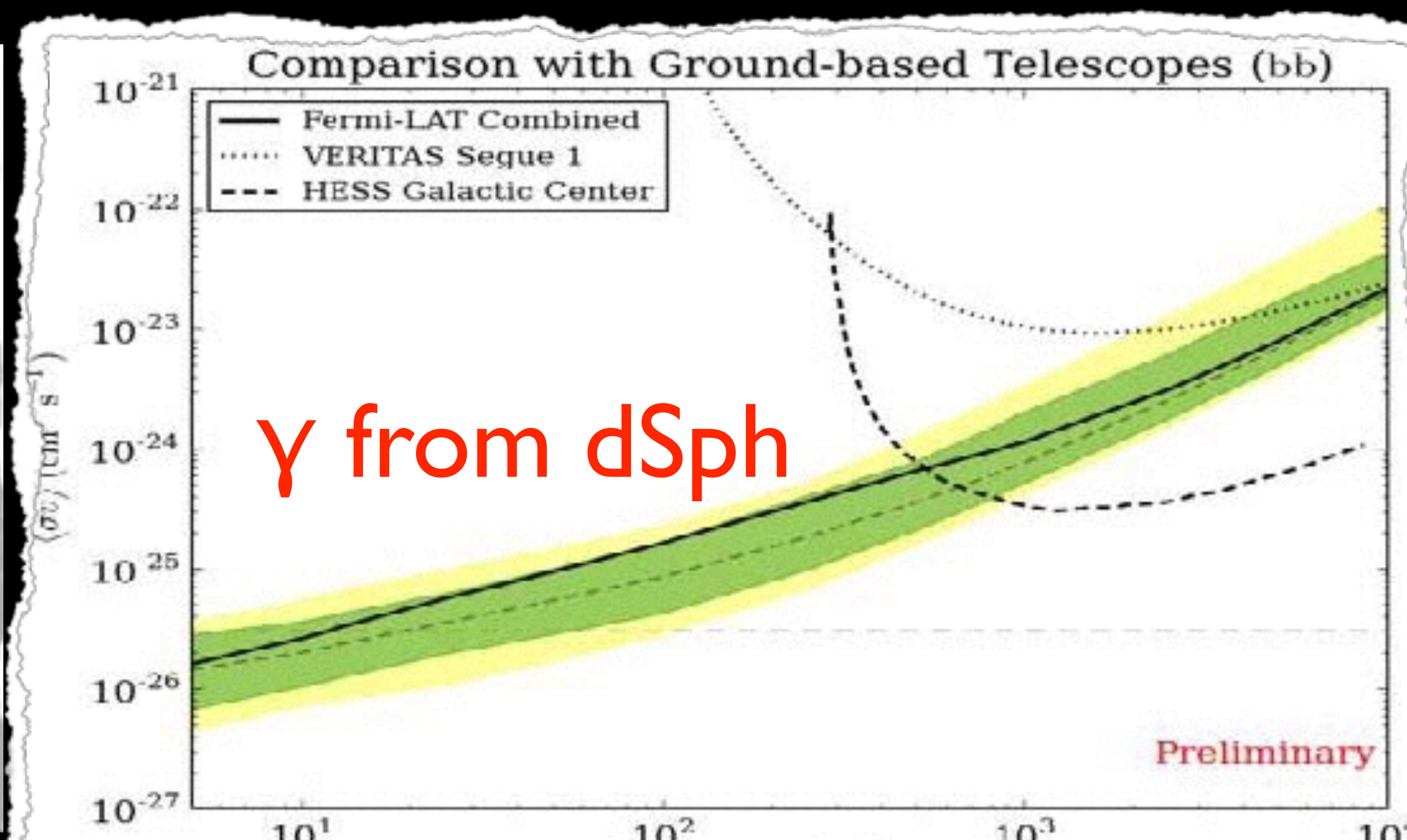
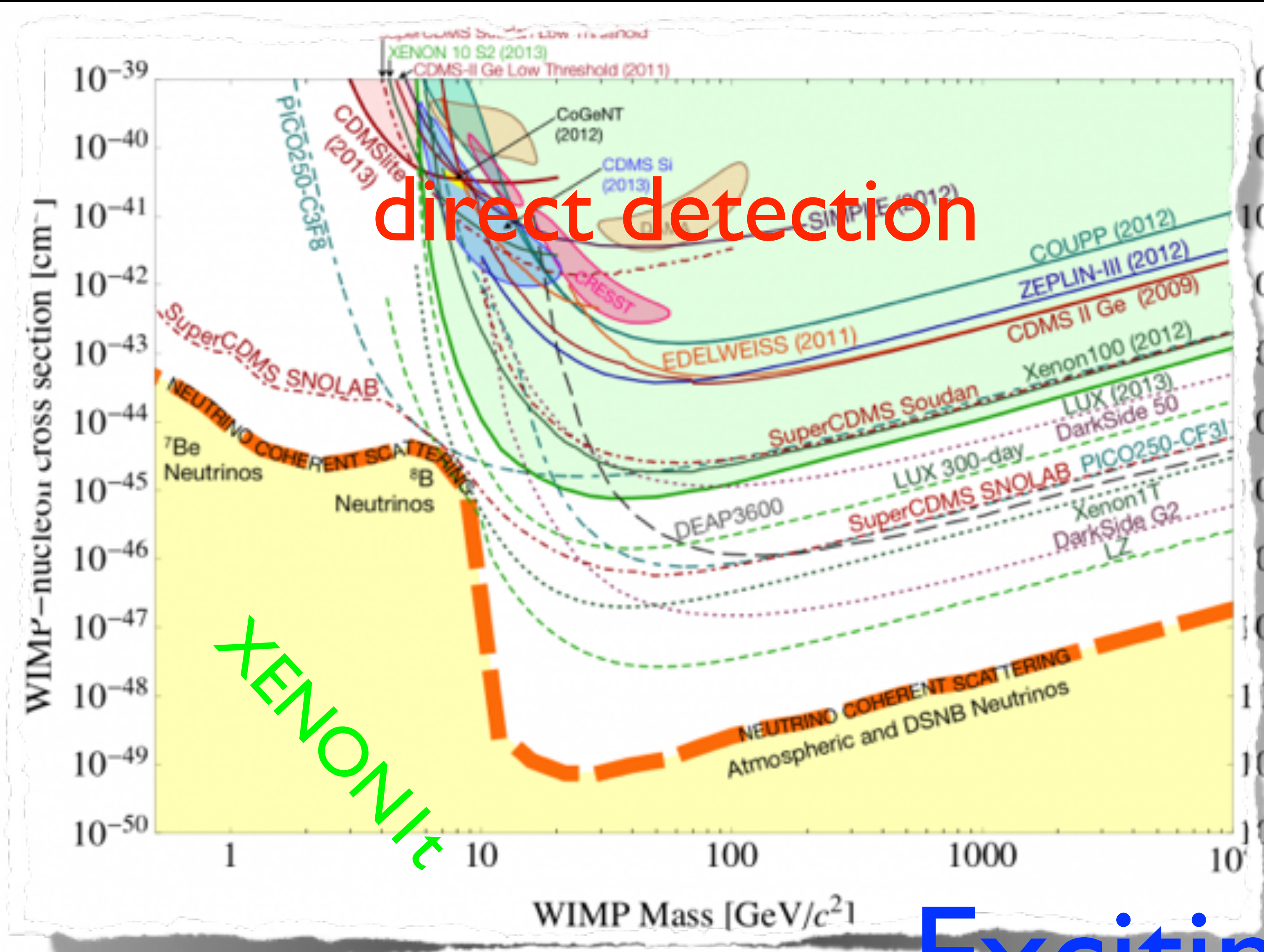

direct detection
XENON1t
WIMP Mass [GeV/c²]
WIMP–nucleon cross section [cm²]
CoGENT (2012)
CDMS Si (2013)
COUPP (2012)
ZEPLIN-III (2012)
CDMS II Ge (2009)
EDELWEISS (2011)
Xenon100 (2012)
LUX (2013)
DarkSide 50
SuperCDMS Soudan
LUX 300-day
PICO250-CF3I
SuperCDMS SNOLAB
DEAP3600
Xenon1T
DarkSide G2
LZ
SuperCDMS SNOLAB
CDMSlite (2013)
PICO250-C3F8
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⁺

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


direct detection
XENON1t
WIMP–nucleon cross section [cm²]
WIMP Mass [GeV/c²]
XENON 10 S2 (2013)
CDMS-II Ge Low Threshold (2011)
CoGeNT (2012)
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⁷Be Neutrinos
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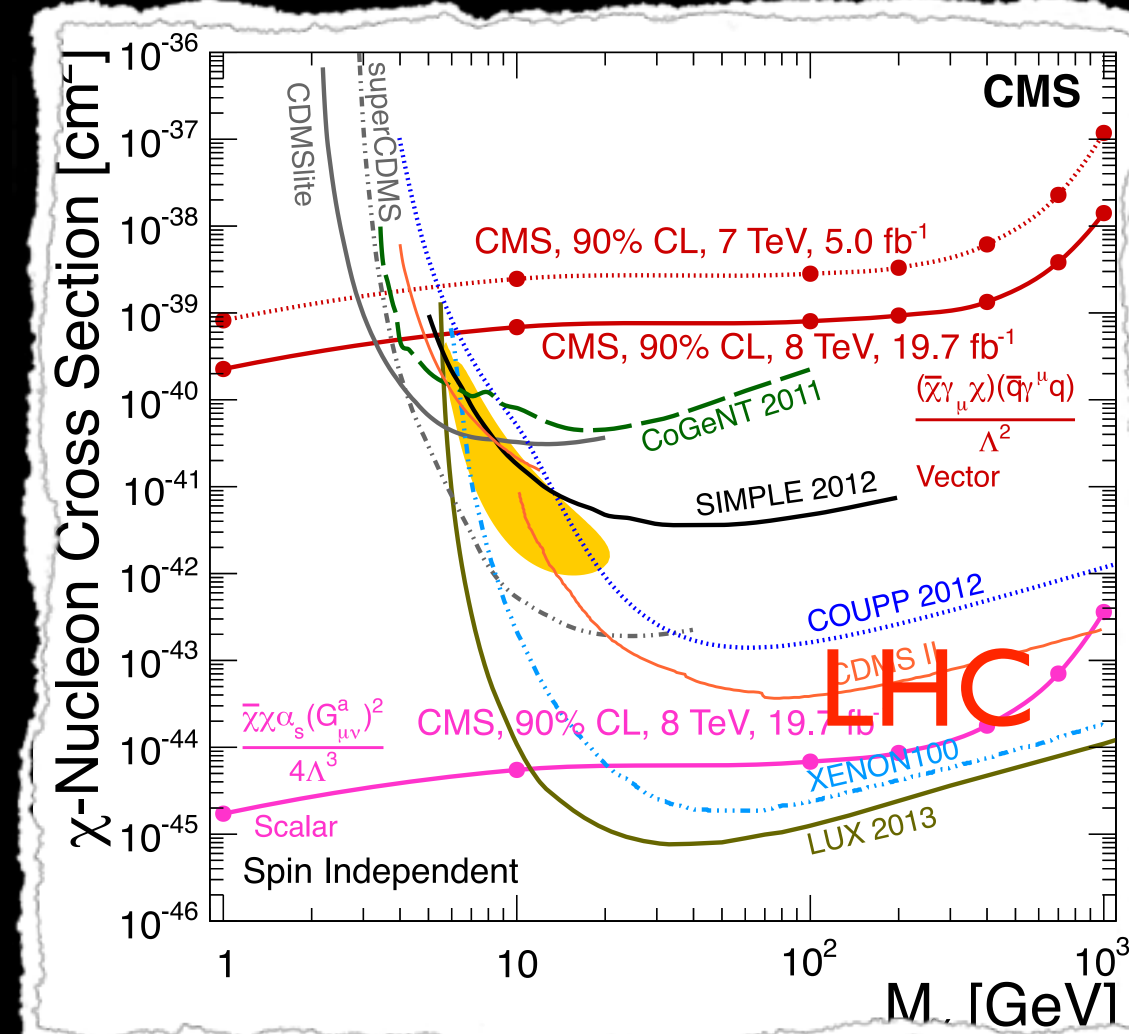
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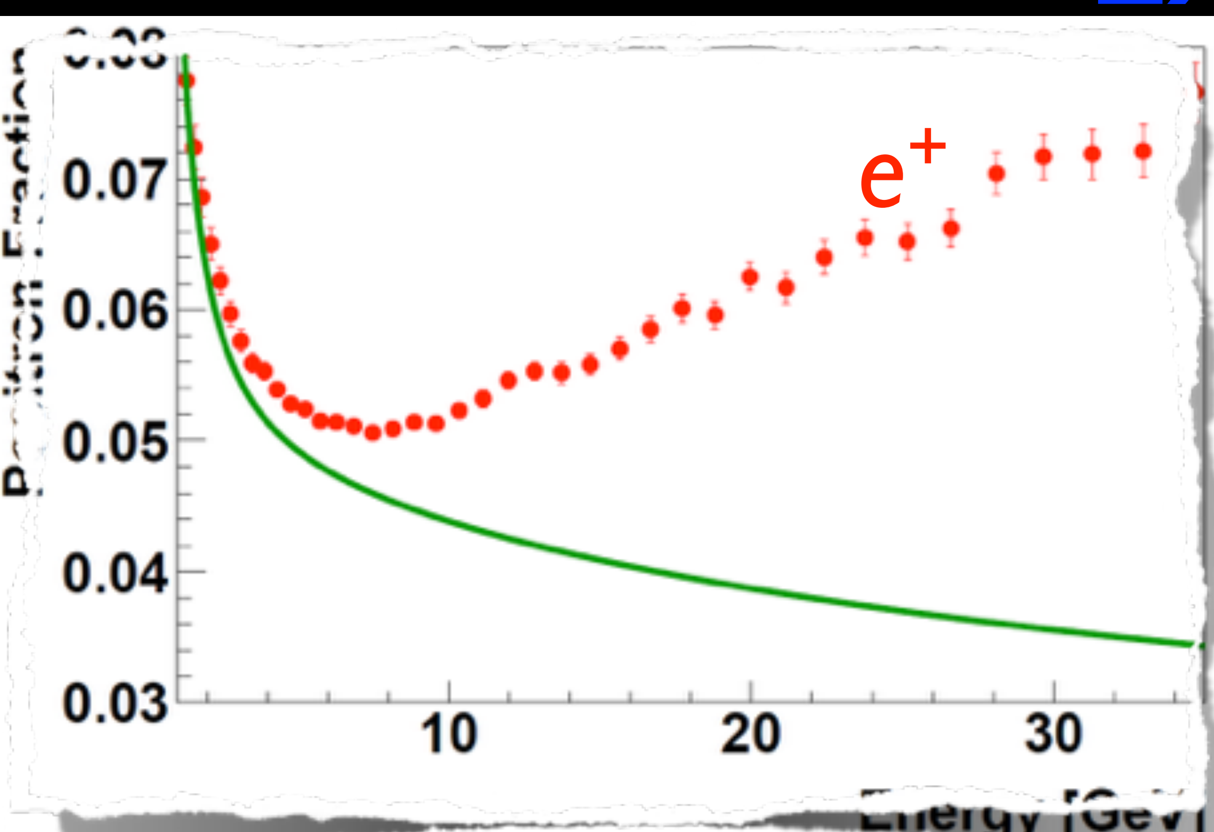
Exciting!


e⁺
0.07
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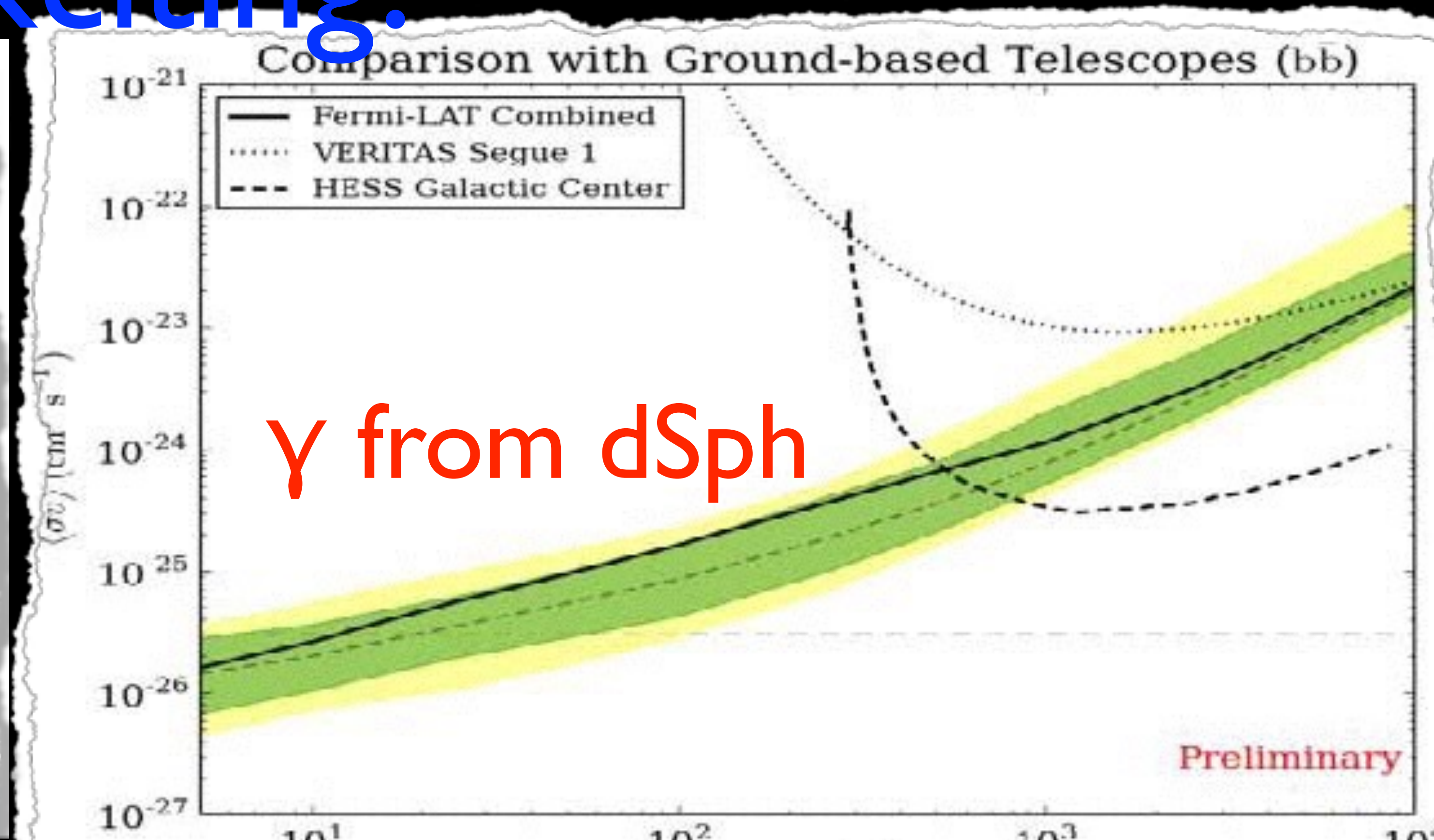
0.05
0.04
0.03
10
20
30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Comparison with Ground-based Telescopes (bb)
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VERITAS Segue 1
HESS Galactic Center
Preliminary

Galactic center

Daylan et al, arXiv:1402.6703

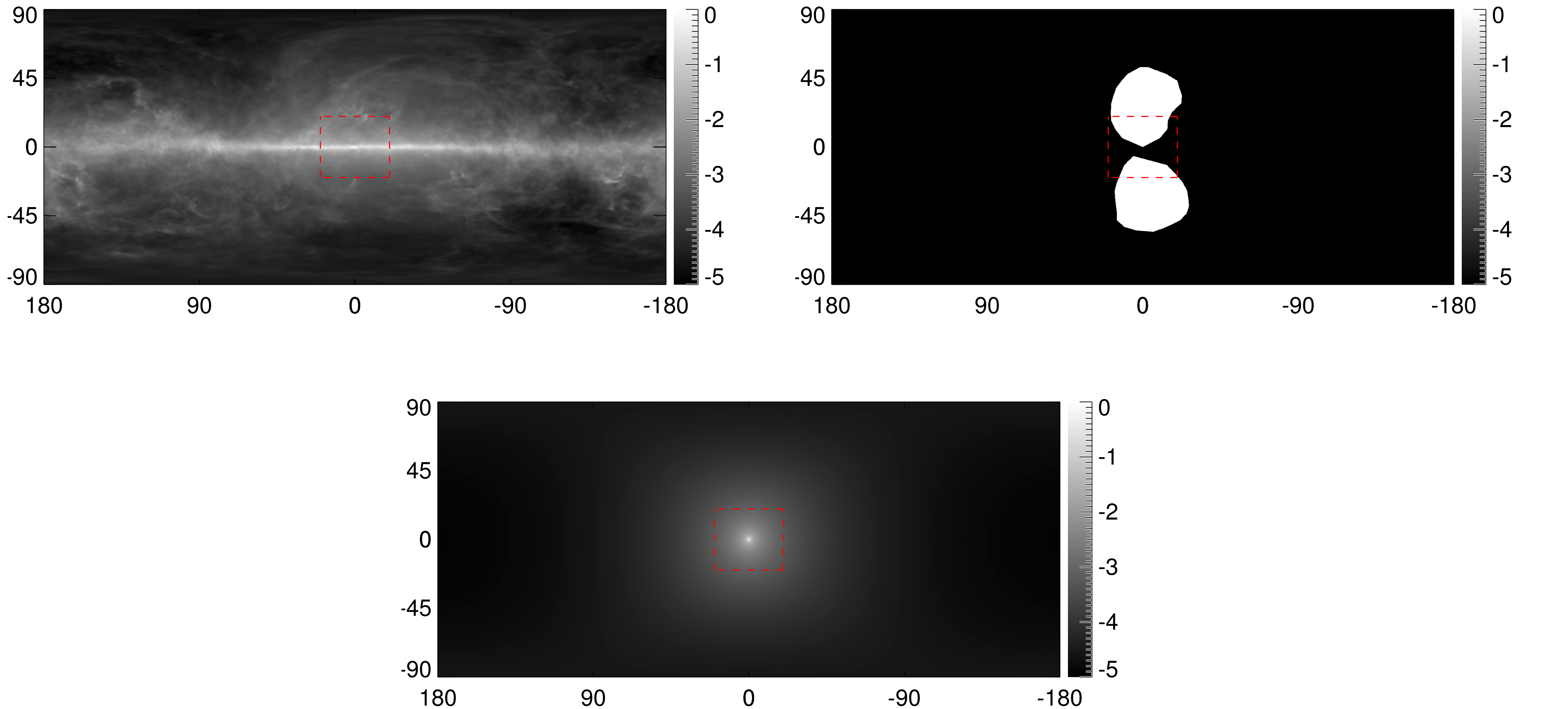


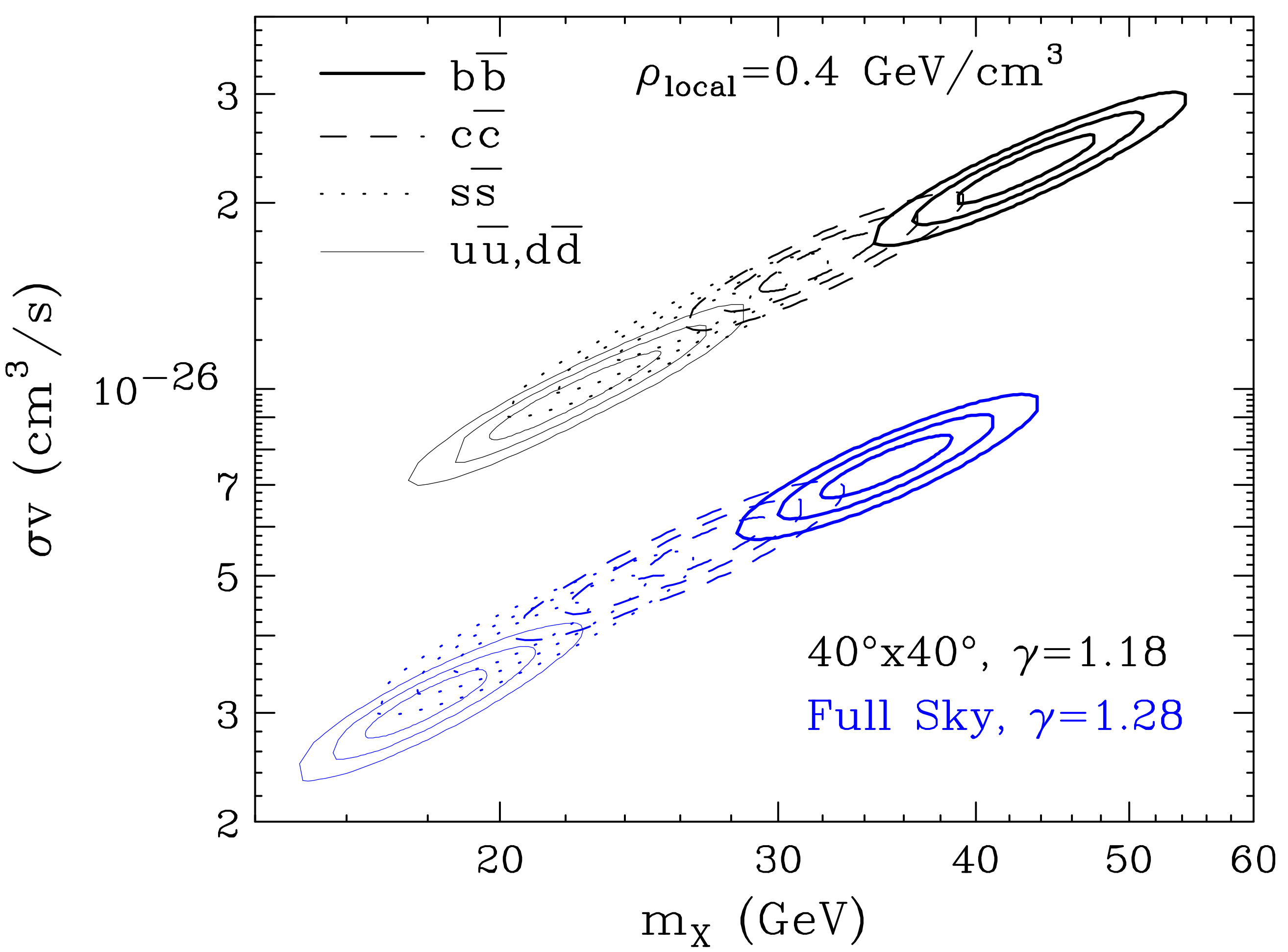
FIG. 4: The spatial templates (in galactic coordinates) for the Galactic diffuse model (upper left), the *Fermi* bubbles (upper right), and dark matter annihilation products (lower), as used in our Inner Galaxy analysis. The scale is logarithmic (base 10), normalized to the brightest point in each map. The diffuse model template is shown as evaluated at 1 GeV, and the dark matter template corresponds to a generalized NFW profile with an inner slope of $\gamma = 1.18$. Red dashed lines indicate the boundaries of our standard Region of Interest (we also mask bright point sources and the region of the Galactic plane with $|b| < 1^\circ$).

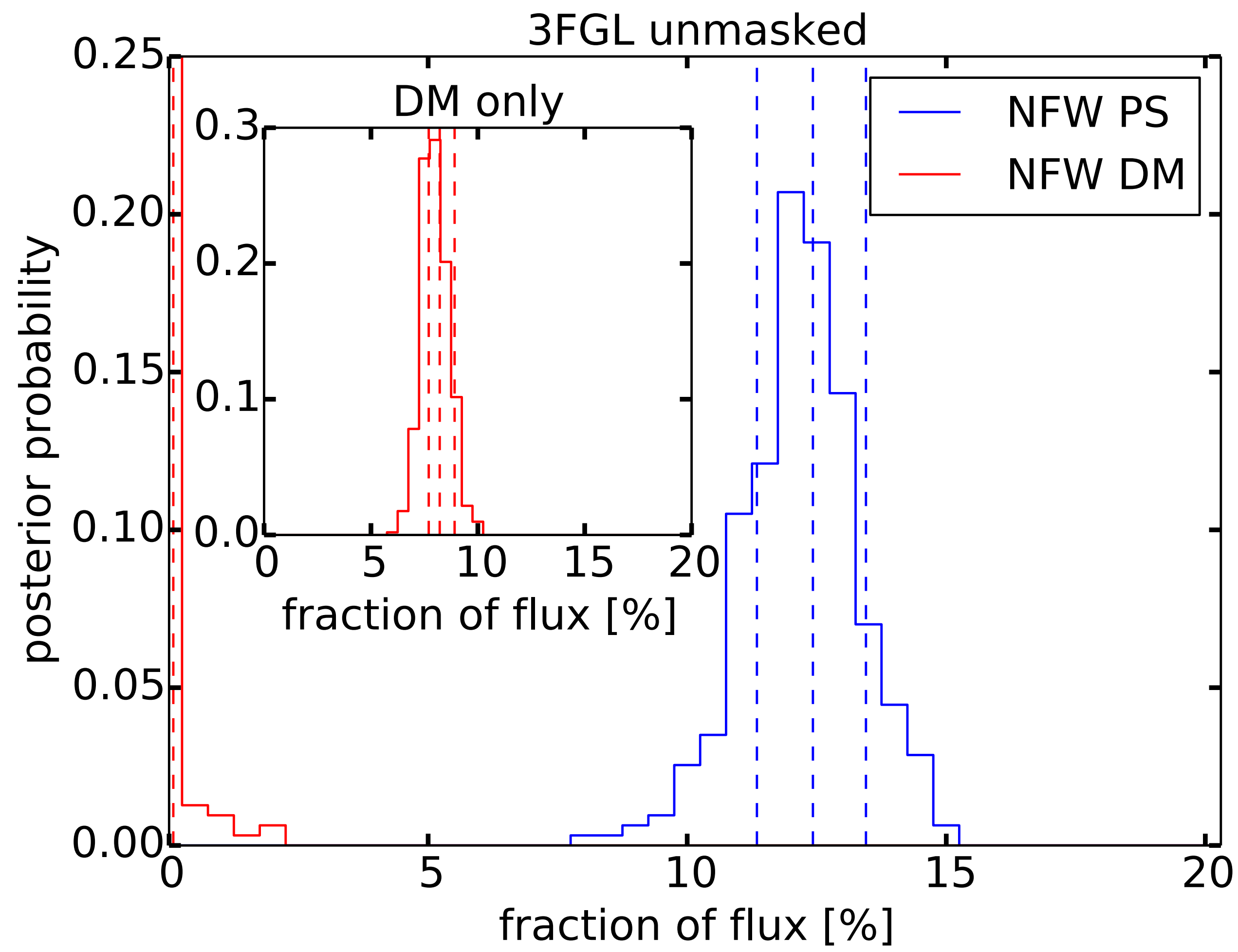
dark matter annihilation?

Daylan et al, arXiv:1402.6703

or unresolved point sources?

S. Lett et al, arXiv:1506.05124v1





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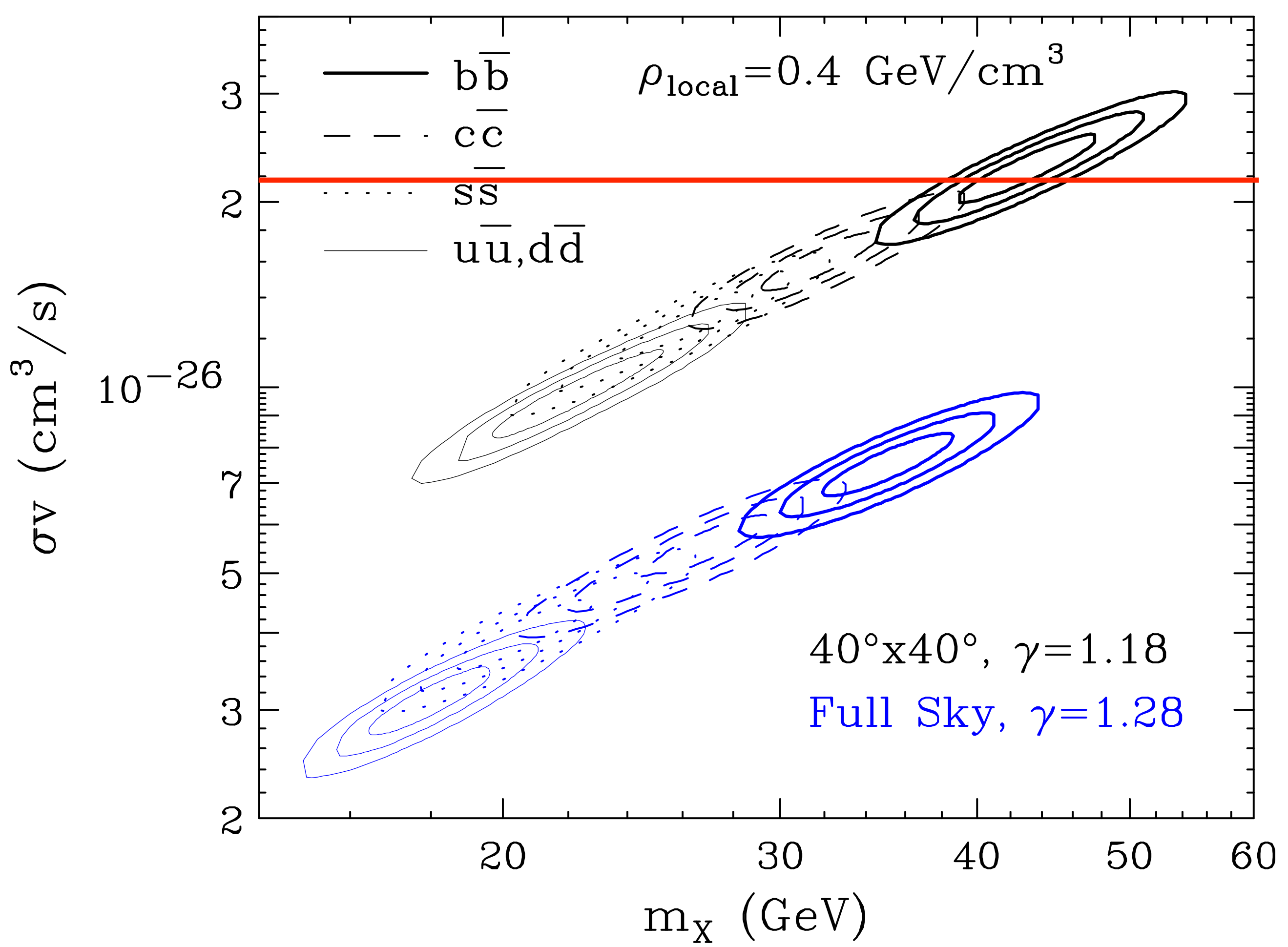
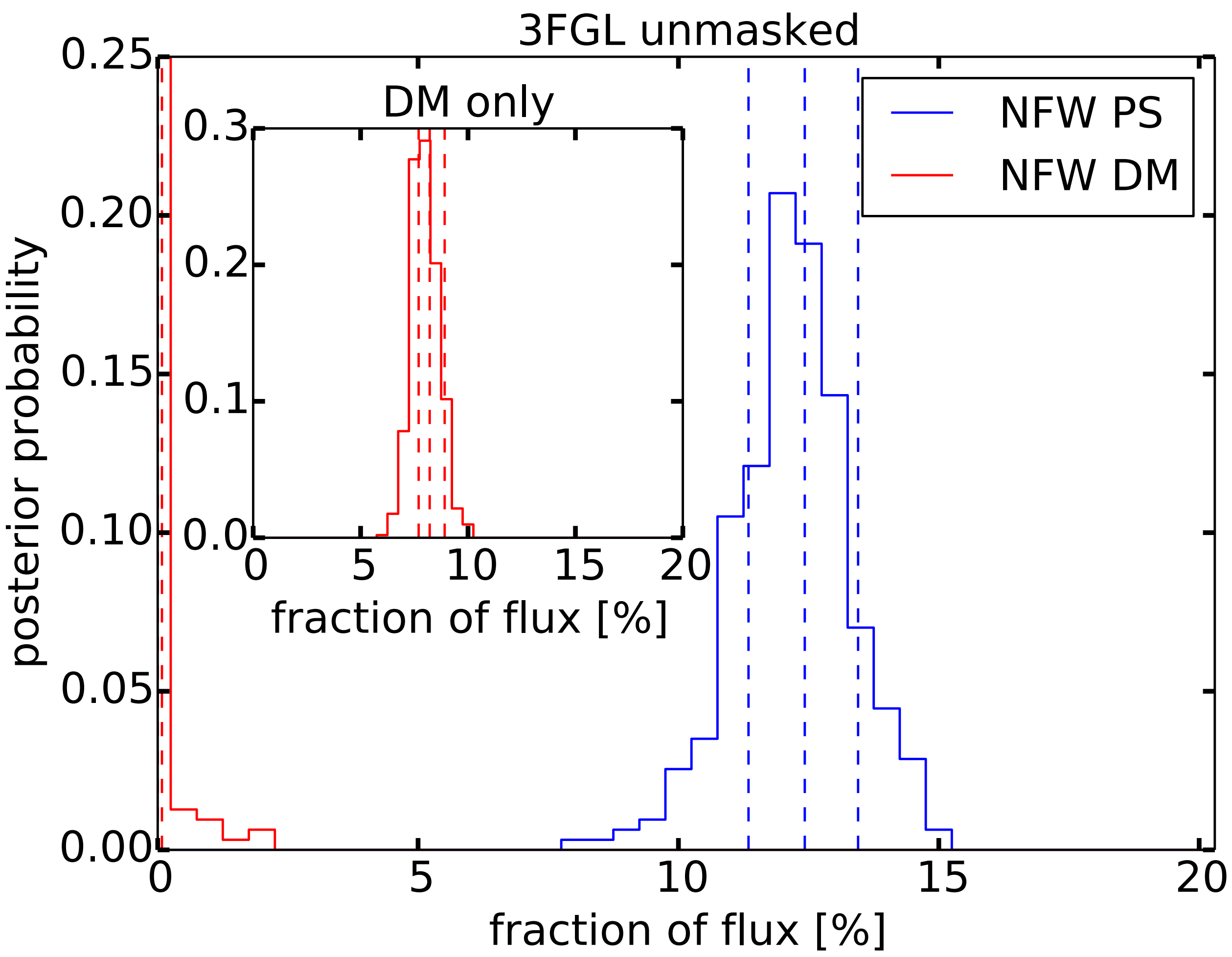
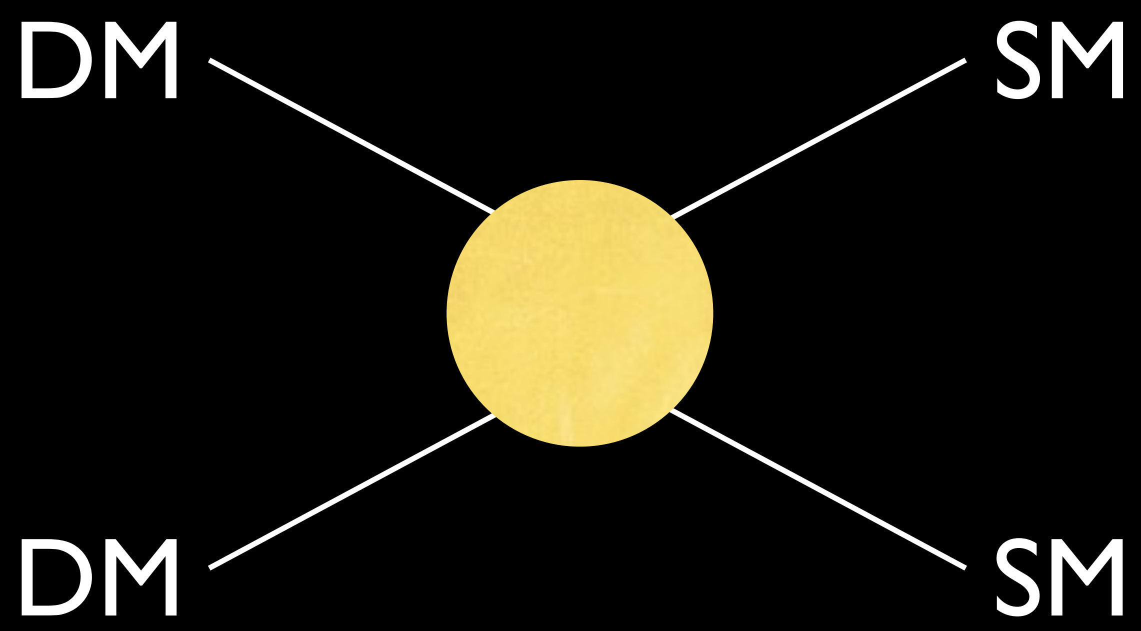




$$\frac{n_{\rm DM}}{s} = 4.4 \times 10^{-10} \frac{\rm GeV}{m_{\rm DM}}$$

Miracles



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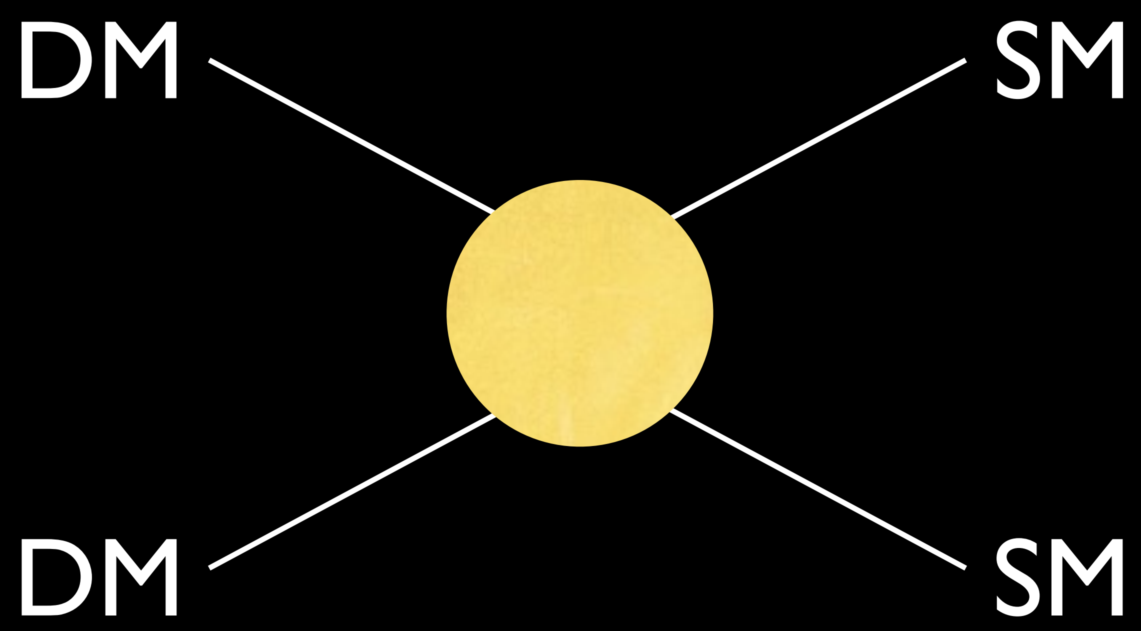

$$\langle \sigma_{2\to 2} v \rangle \approx \frac{\alpha^2}{m^2}$$

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

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

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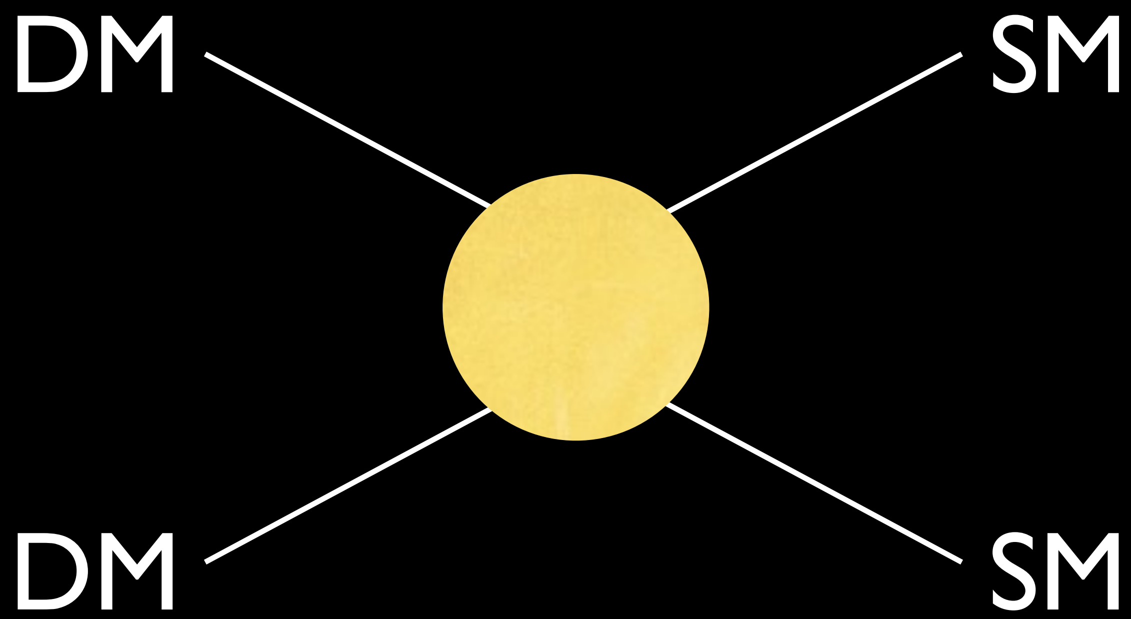

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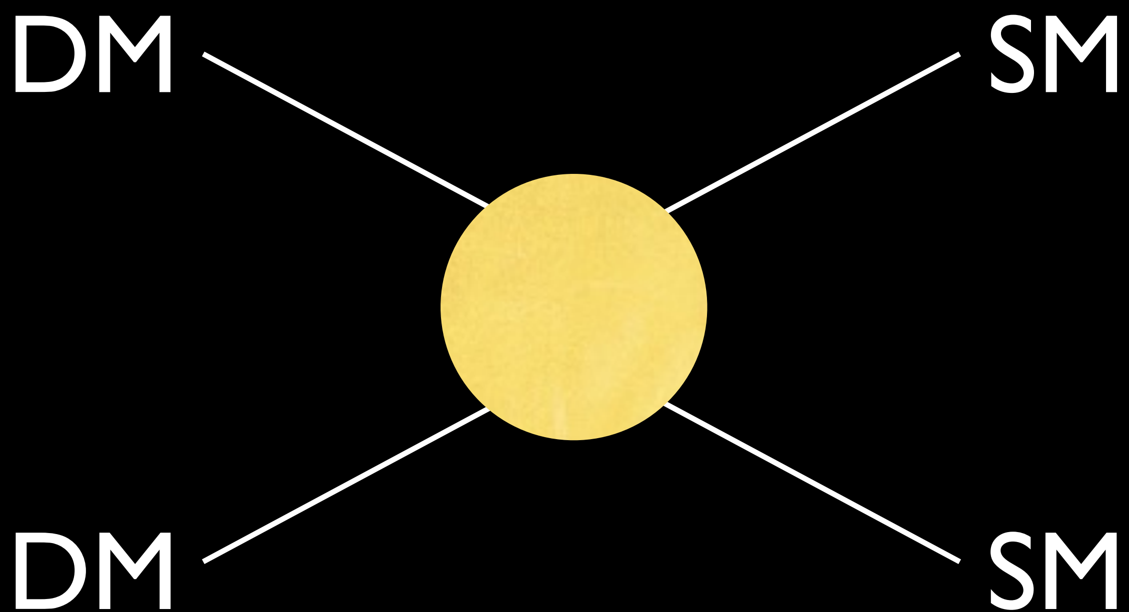

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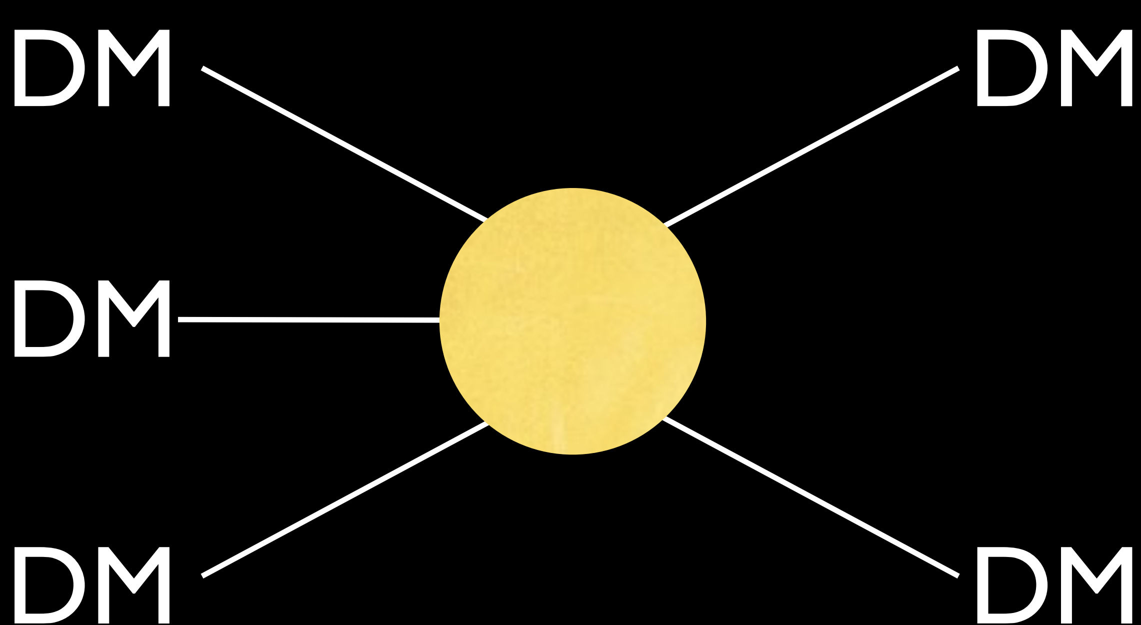

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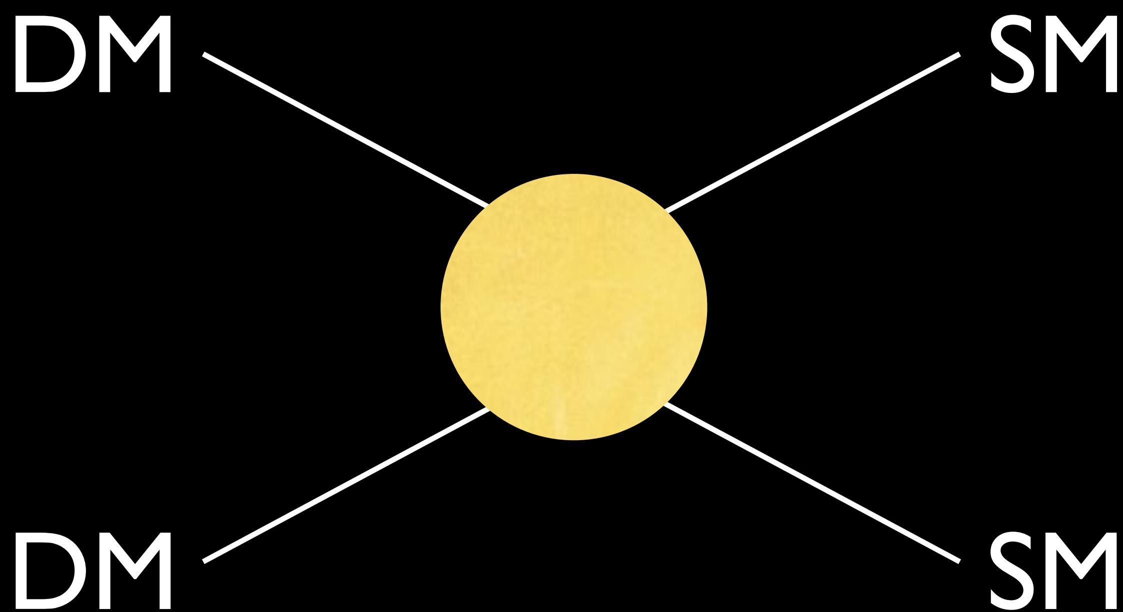

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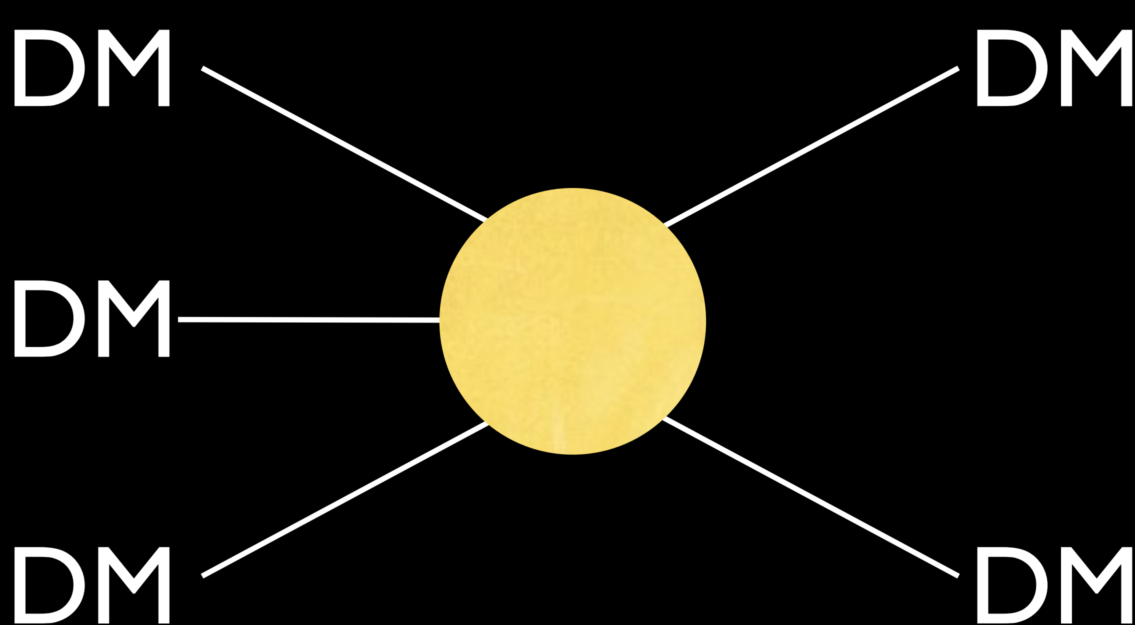


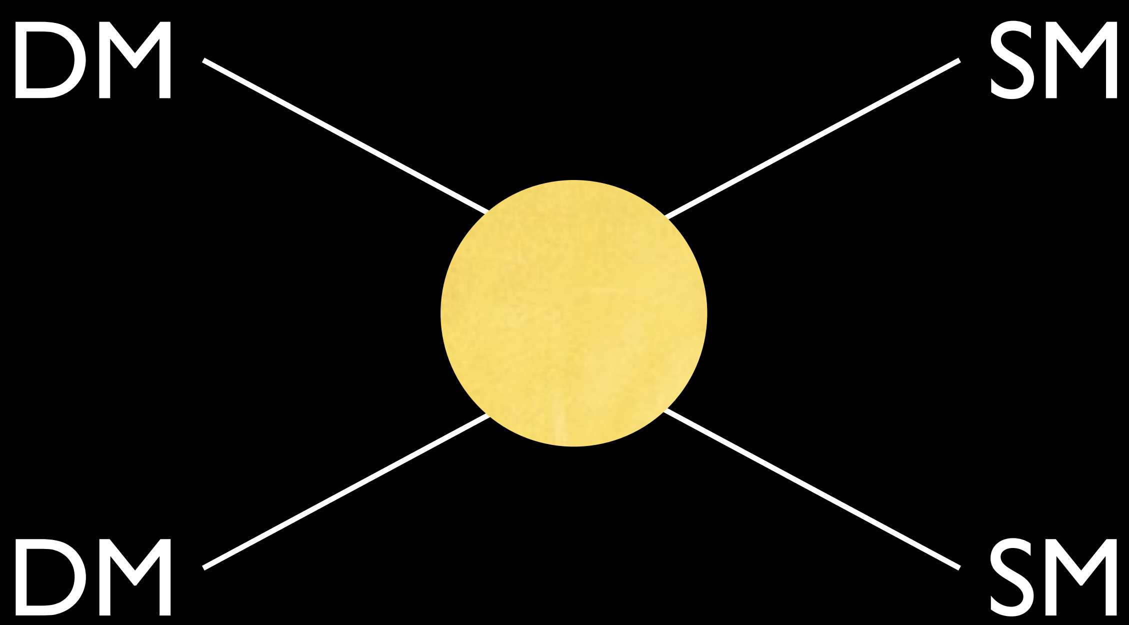
$$\langle \sigma_{3\to 2} v^2 \rangle \approx \frac{\alpha^3}{m^5}$$

$$\alpha \approx 4\pi$$

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

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

Miracles



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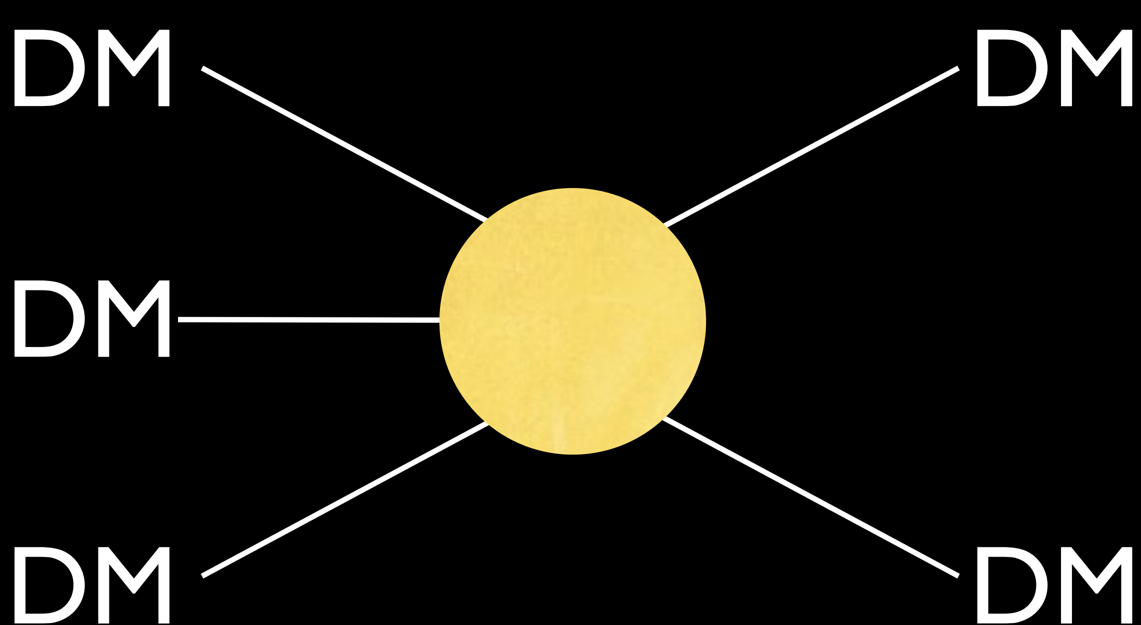
WIMP miracle!



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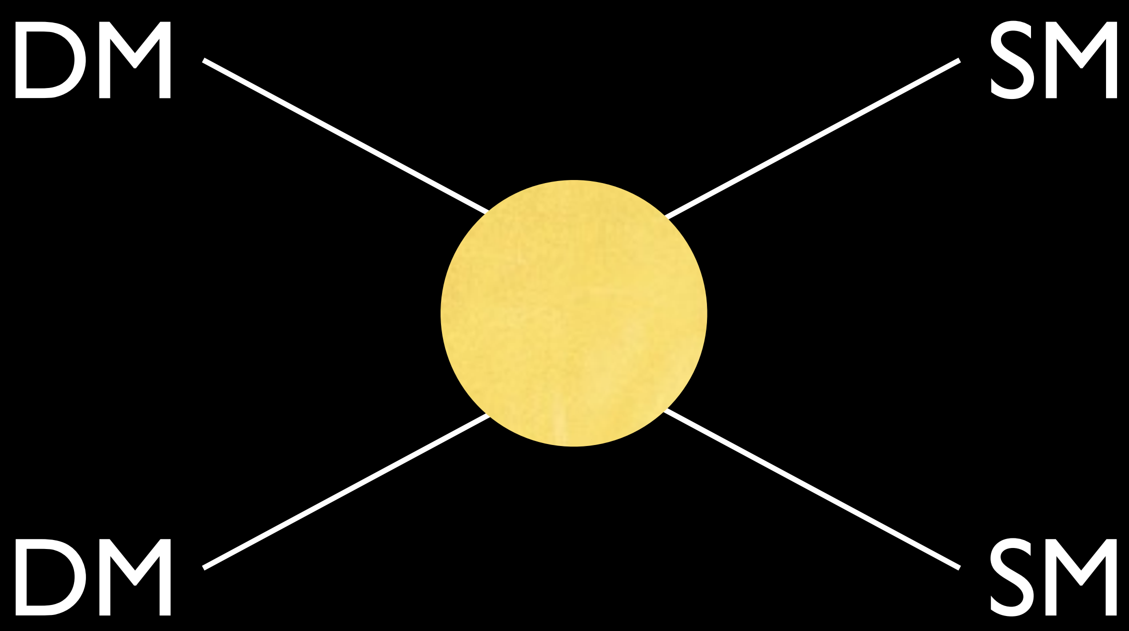

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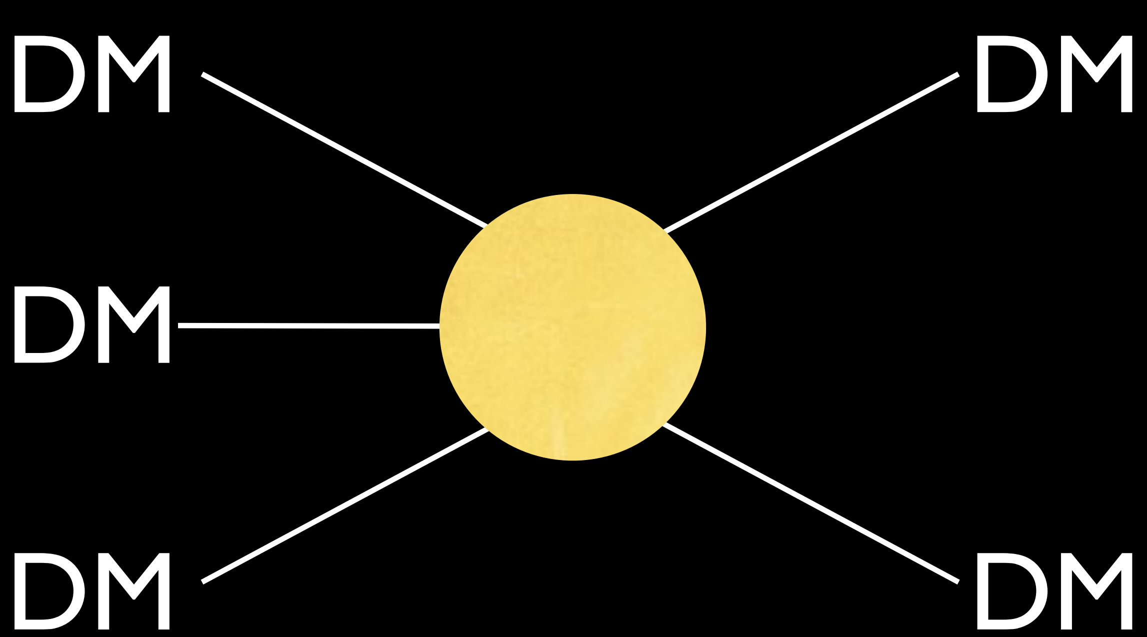

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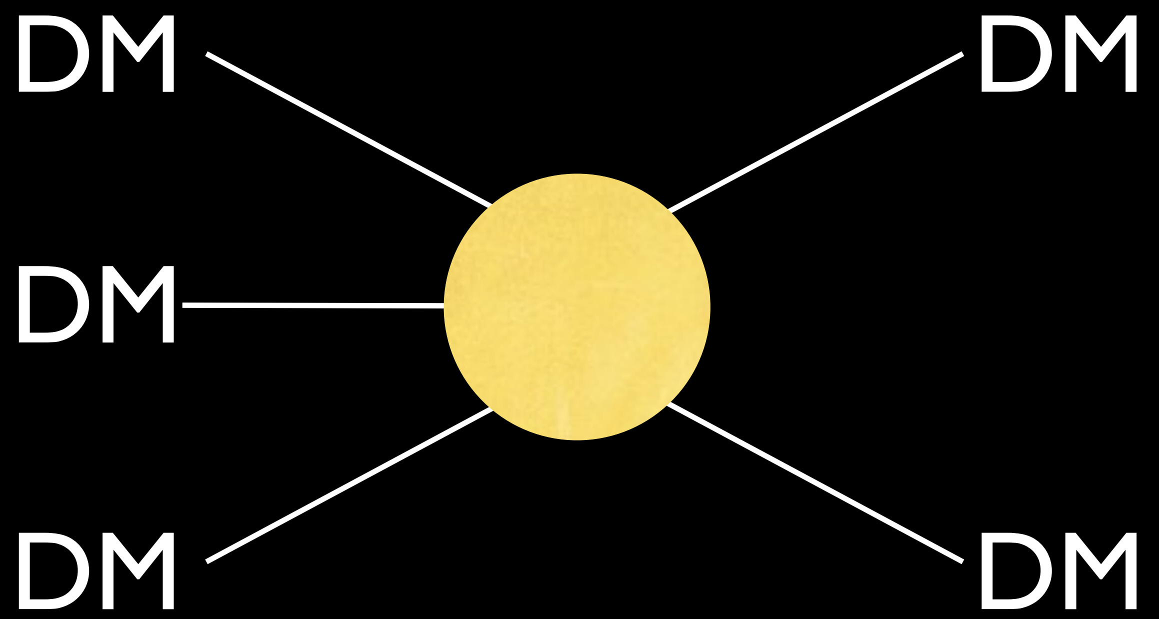
Hochberg, Kuflik, Volansky, Wacker arXiv:1402.5143

SIMP miracle!

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

SIMPlest Miracle

- Not only the mass scale is similar to QCD
- dynamics itself can be QCD! Miracle^3
- DM = pions
- e.g. SU(4)/Sp(4) = S^5



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

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

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

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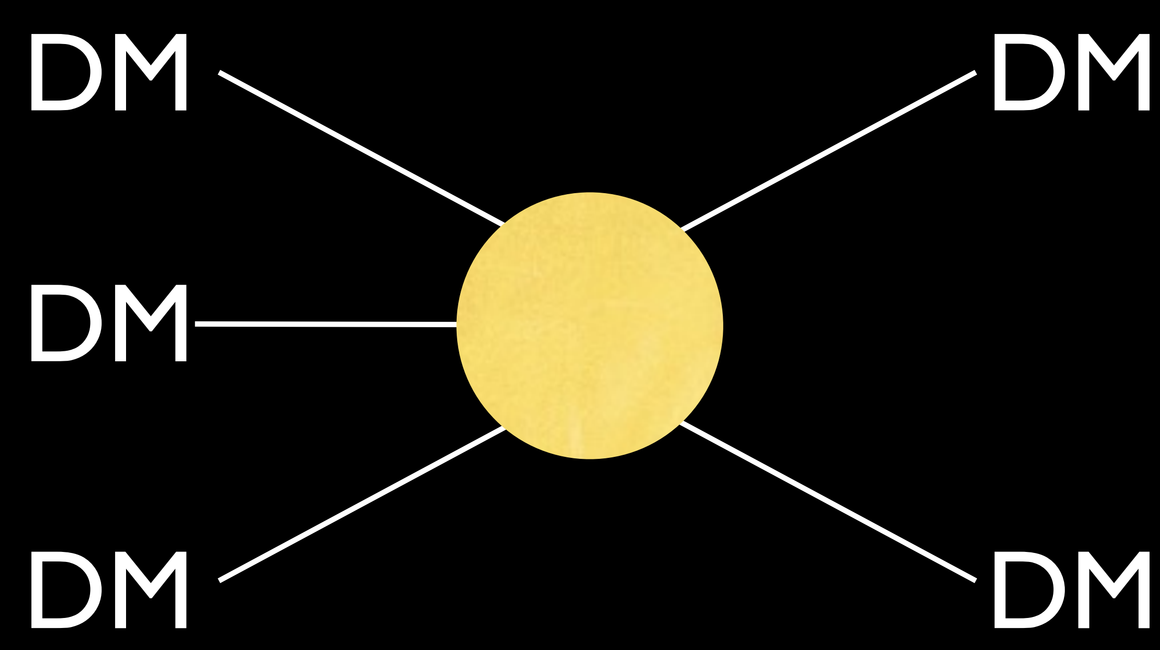

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+HM
arXiv:1411.3727

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

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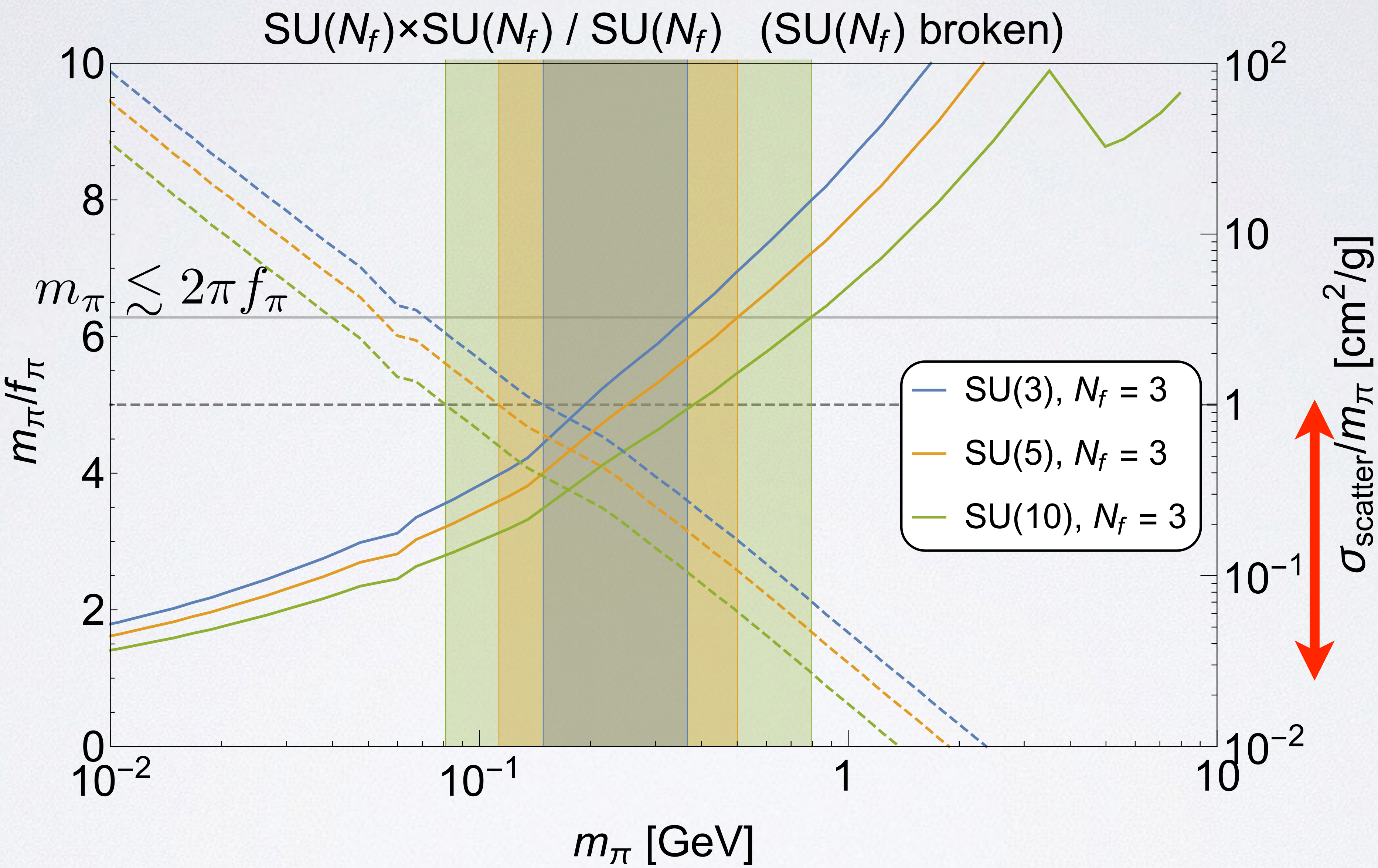
THE RESULTS

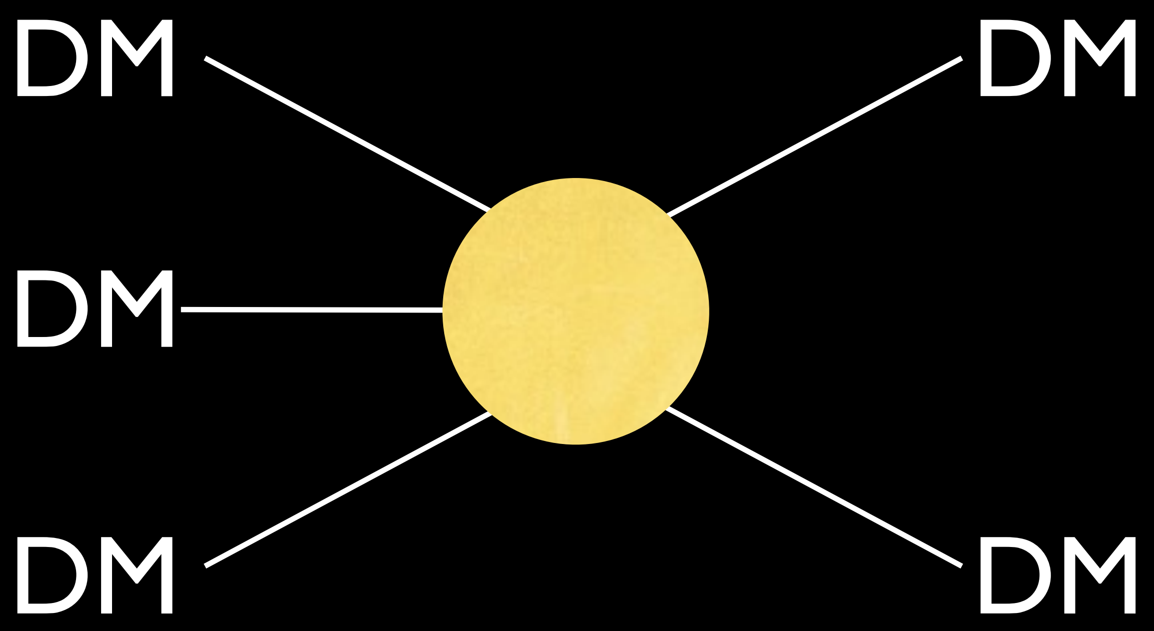


Solid curves: solution to Boltzmann eq. $\dfrac{m_\pi}{f_\pi} \propto m_\pi^{3/10}$

Dashed curves: along that solution $\dfrac{\sigma_{\rm scatter}}{m_\pi} \propto m_\pi^{-9/5}$

communication

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



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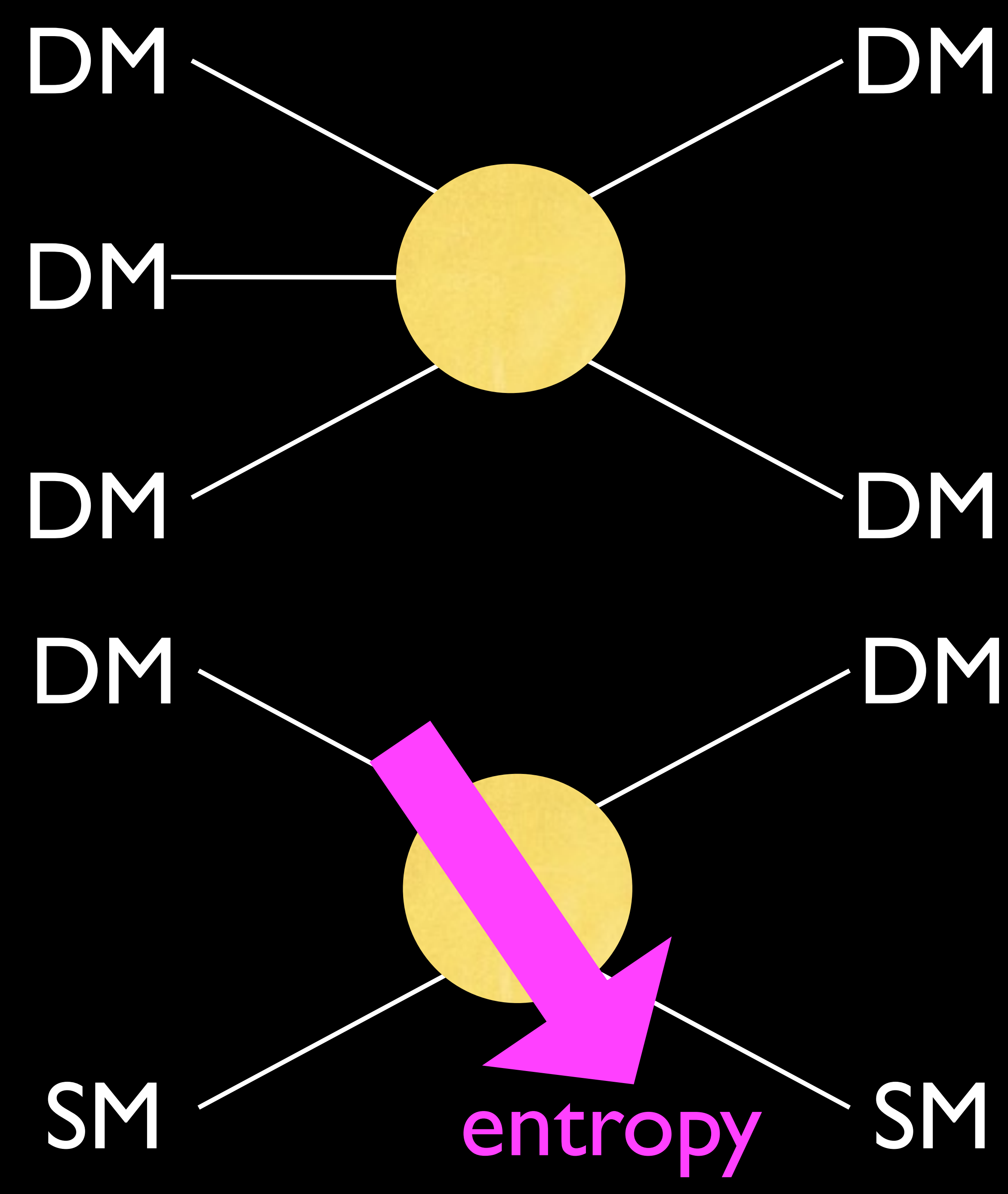
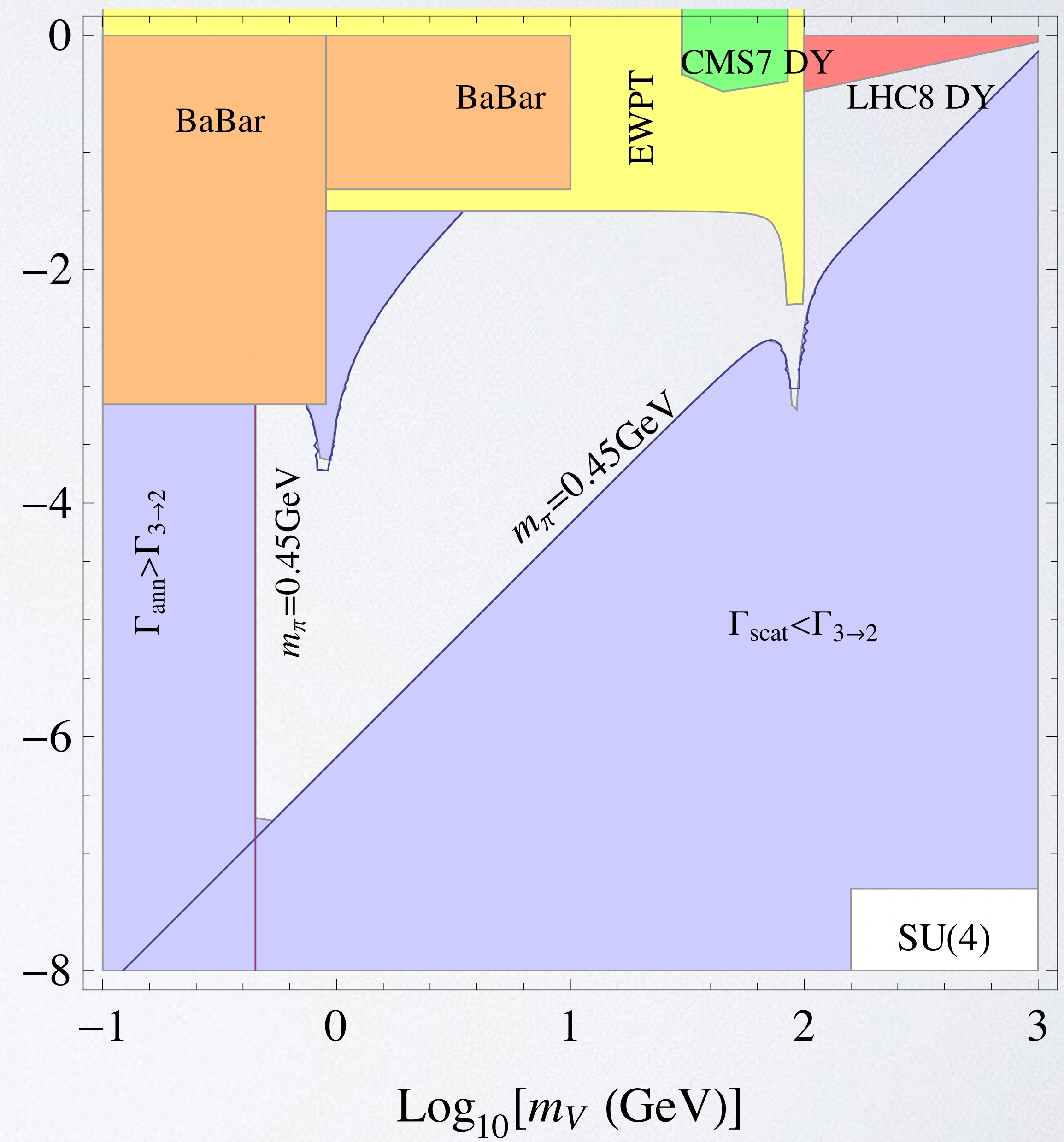


KINETICALLY MIXED U(1)

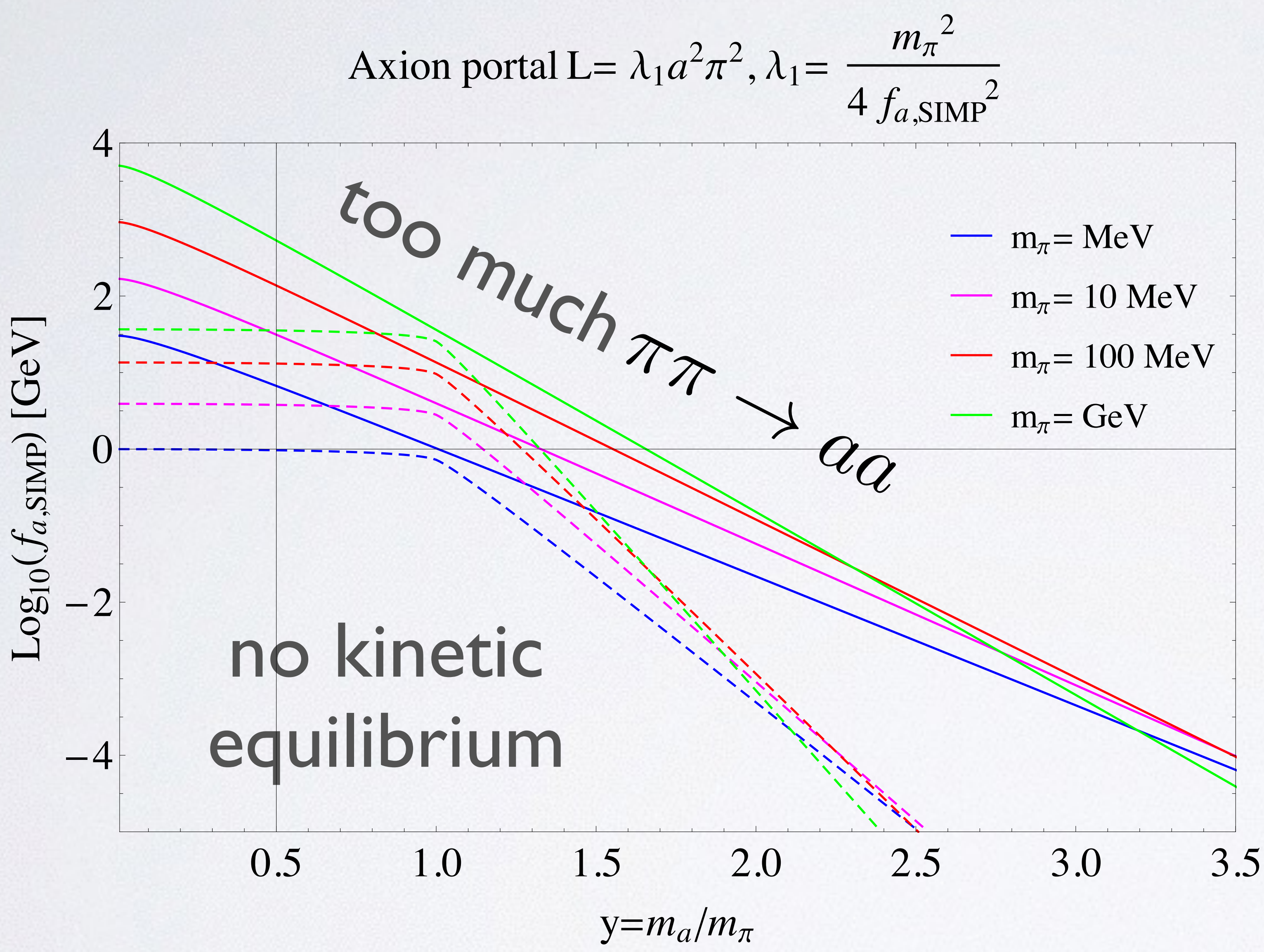
- e.g., SU(4) gauge group with Nf=3
- gauged U(1): $\begin{pmatrix} 1 & & \\ & -1 & \\ & & -1 \end{pmatrix}$
- kinetic mixing induced by:

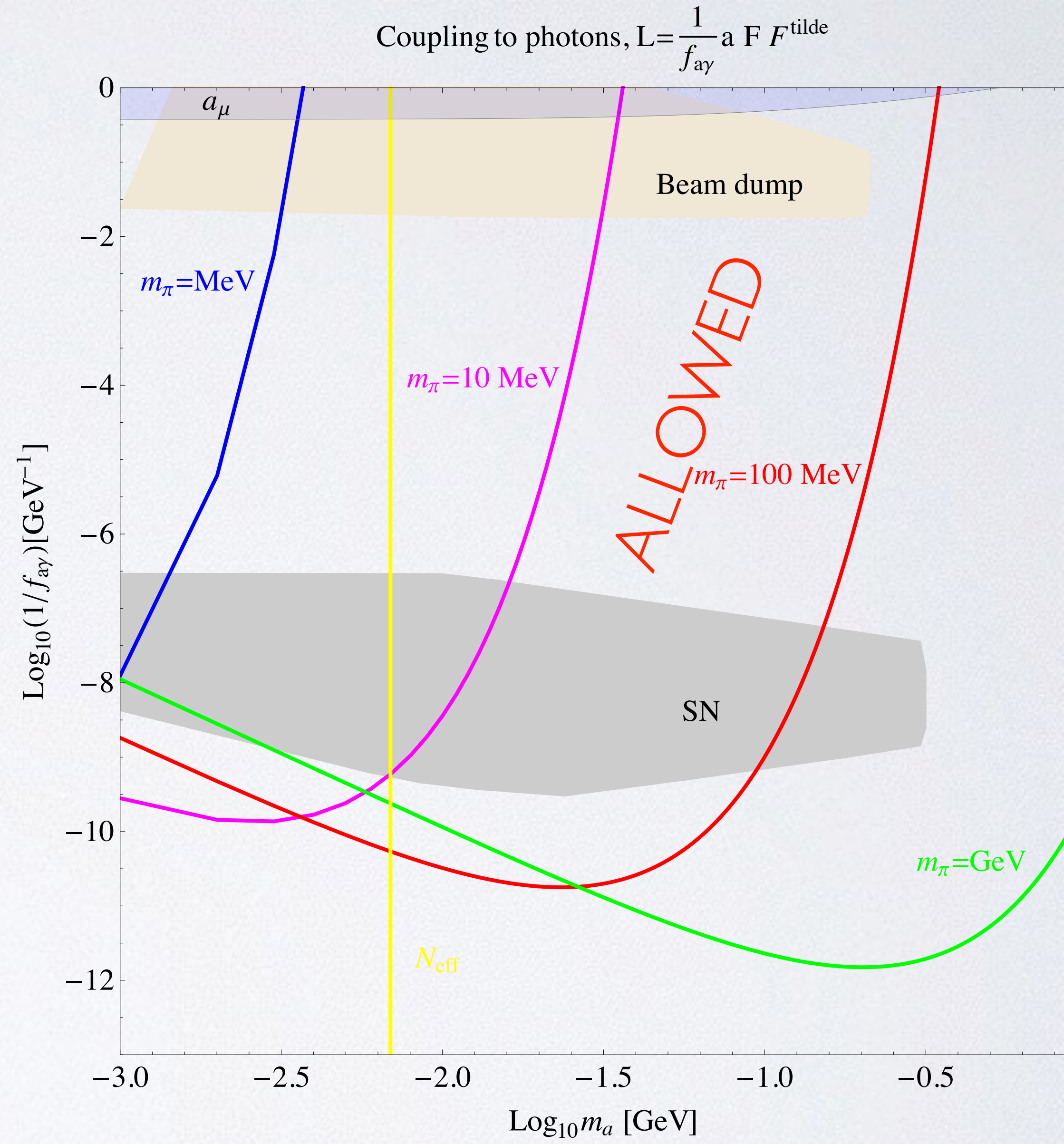
$$\frac{\epsilon_\gamma}{2c_W} B_{\mu\nu} F_D^{\mu\nu}$$

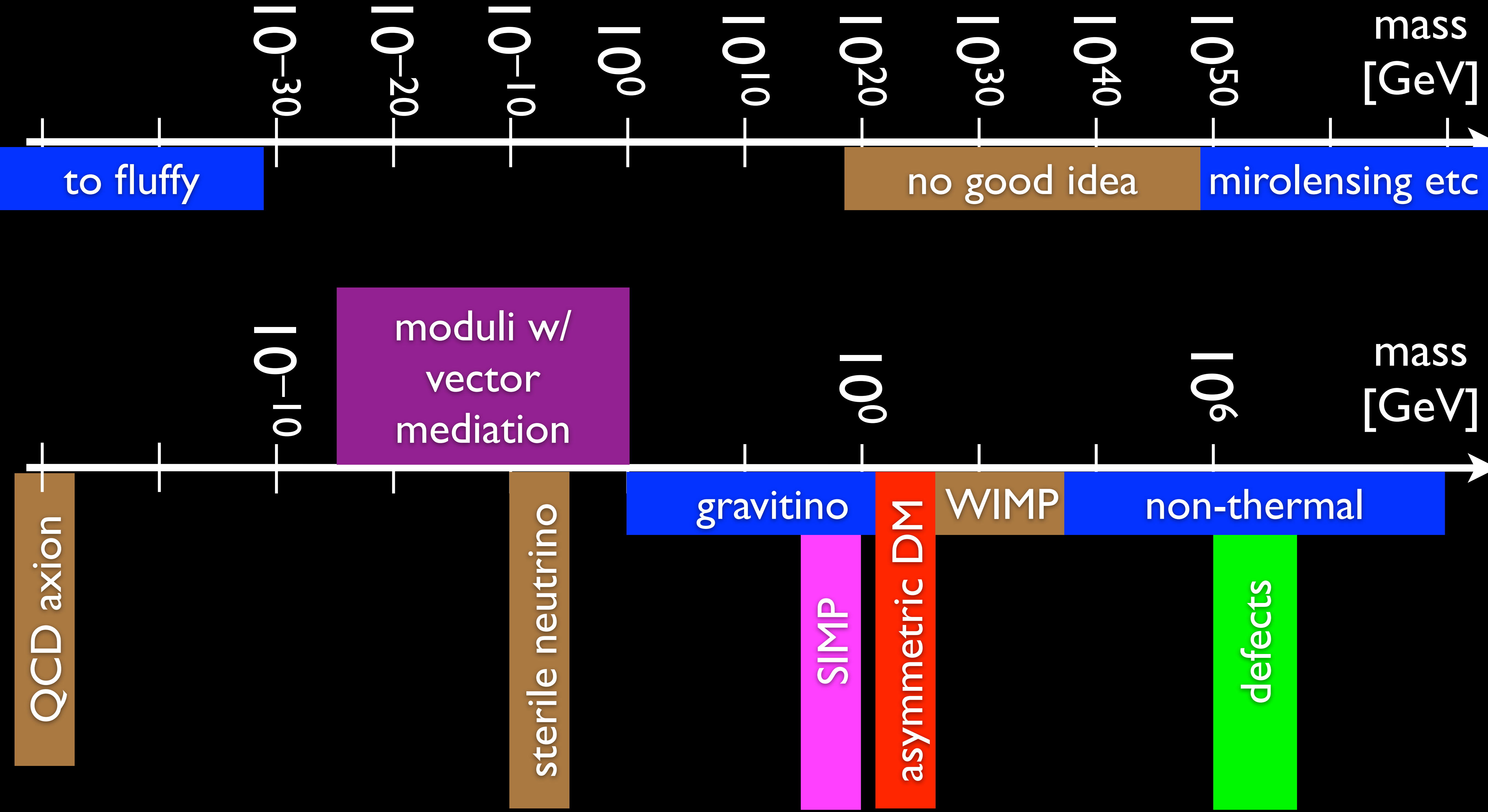


[Lee, Seo 1504.00745]

AXION PORTAL



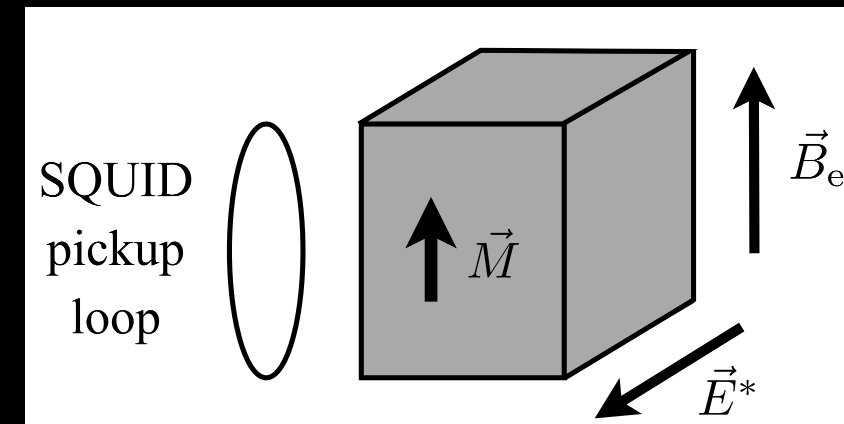




10^{-30}
10^{-20}
10^{-10}
10^{0}
10^{10}
10^{20}
10^{30}
10^{40}
10^{50}
mass [GeV]
to fluffy
no good idea
mirolensing etc
moduli w/ vector mediation
10^{-10}
10^{0}
10^{6}
mass [GeV]
QCD axion
sterile neutrino
gravitino
SIMP
asymmetric DM
WIMP
non-thermal
defects

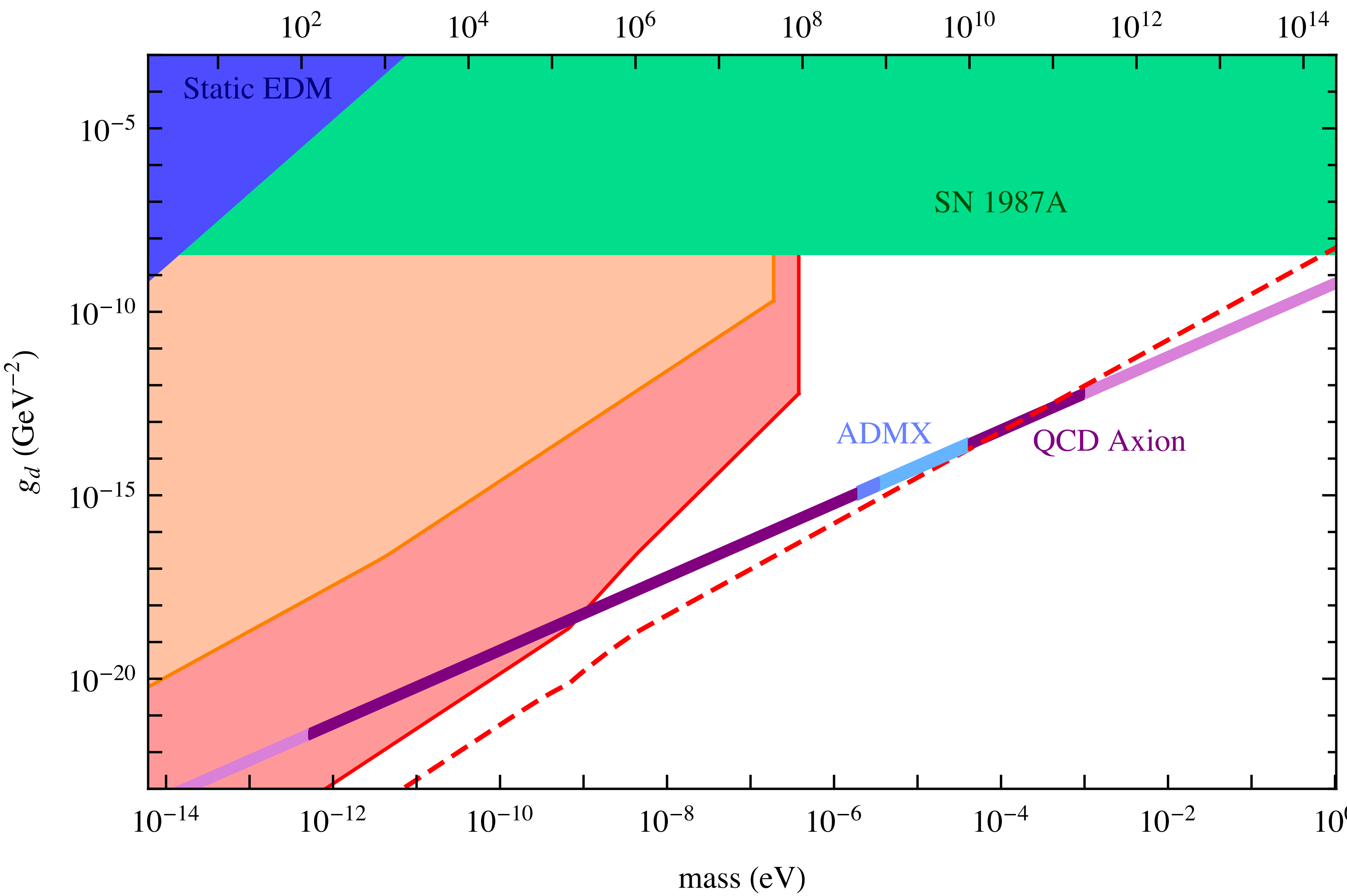
Cosmic Axion Spin Precession

$$H_{eff}(t) = -\vec{\mu}\cdot\vec{B} - \frac{m_u}{m^2_{\rm const}}\sin(m_a t)\times\vec{s}_n\cdot\vec{E}$$



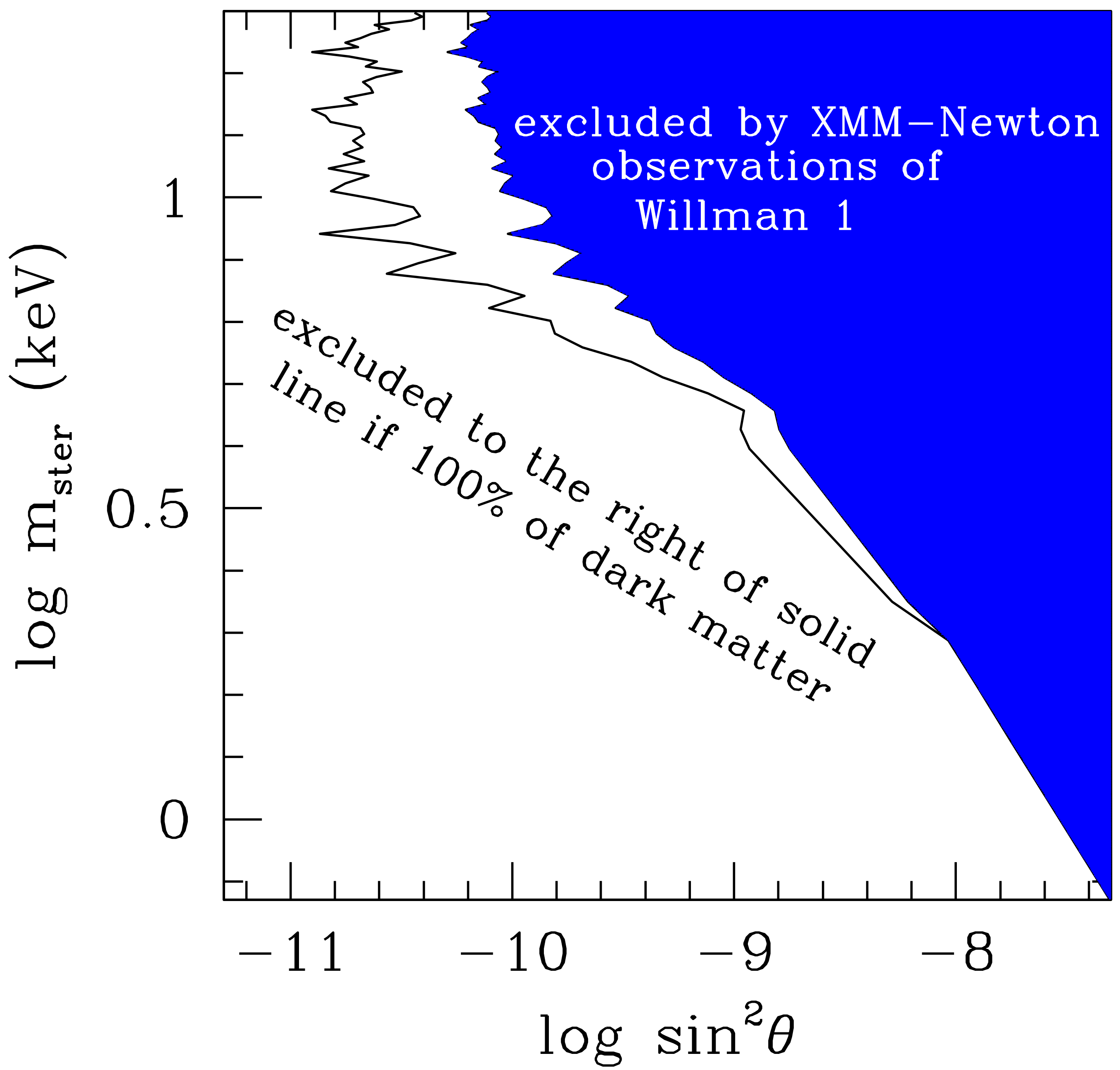
resonance @ $\mu B = m_a$

Budker et al
arXiv:1306.6089

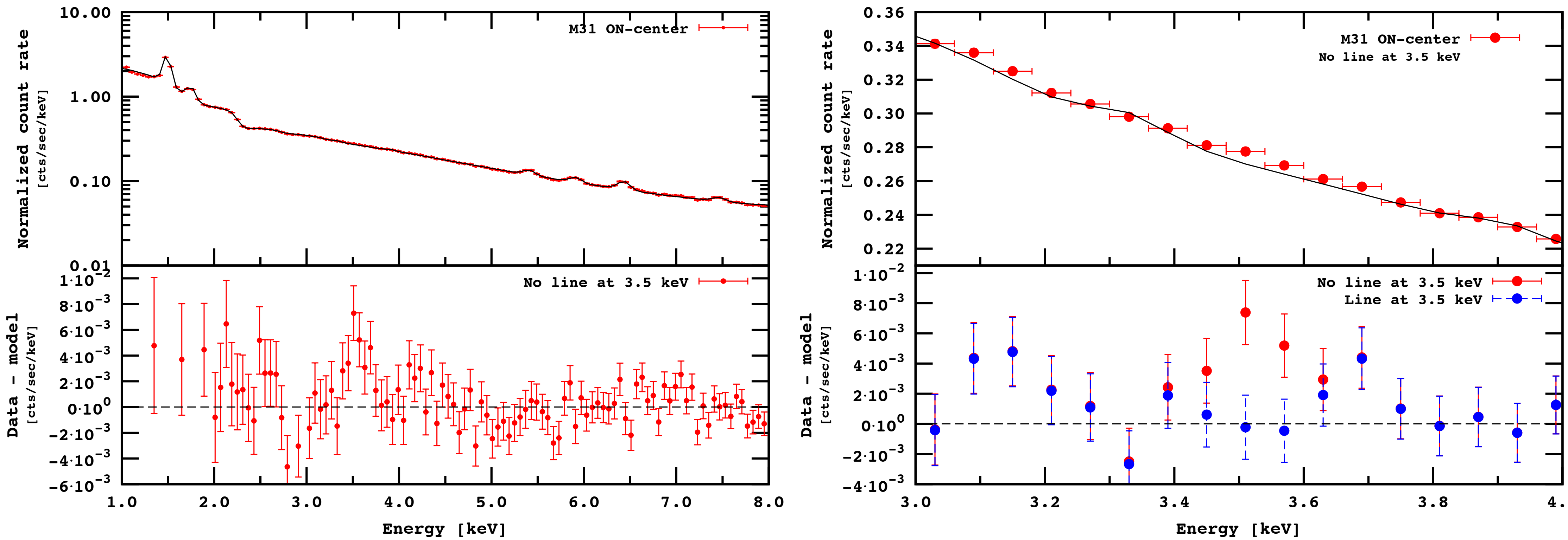


sterile neutrino

Loewenstein & Kusenko (2012)

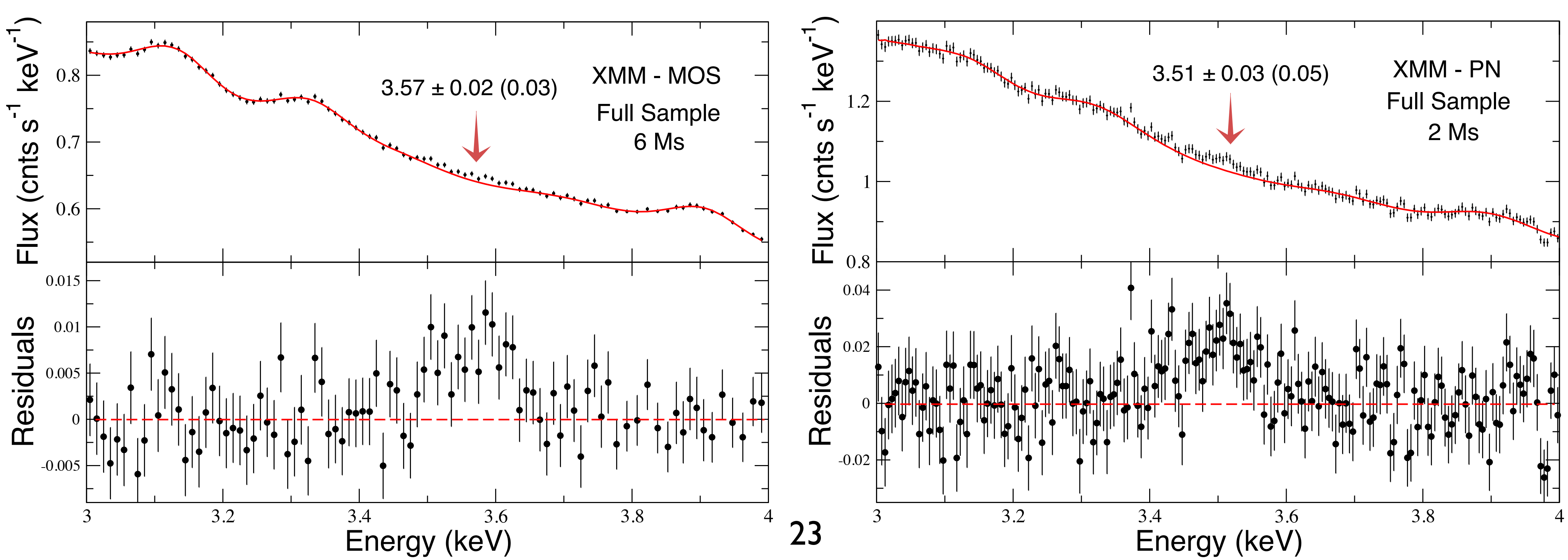


arXiv:1402.4119

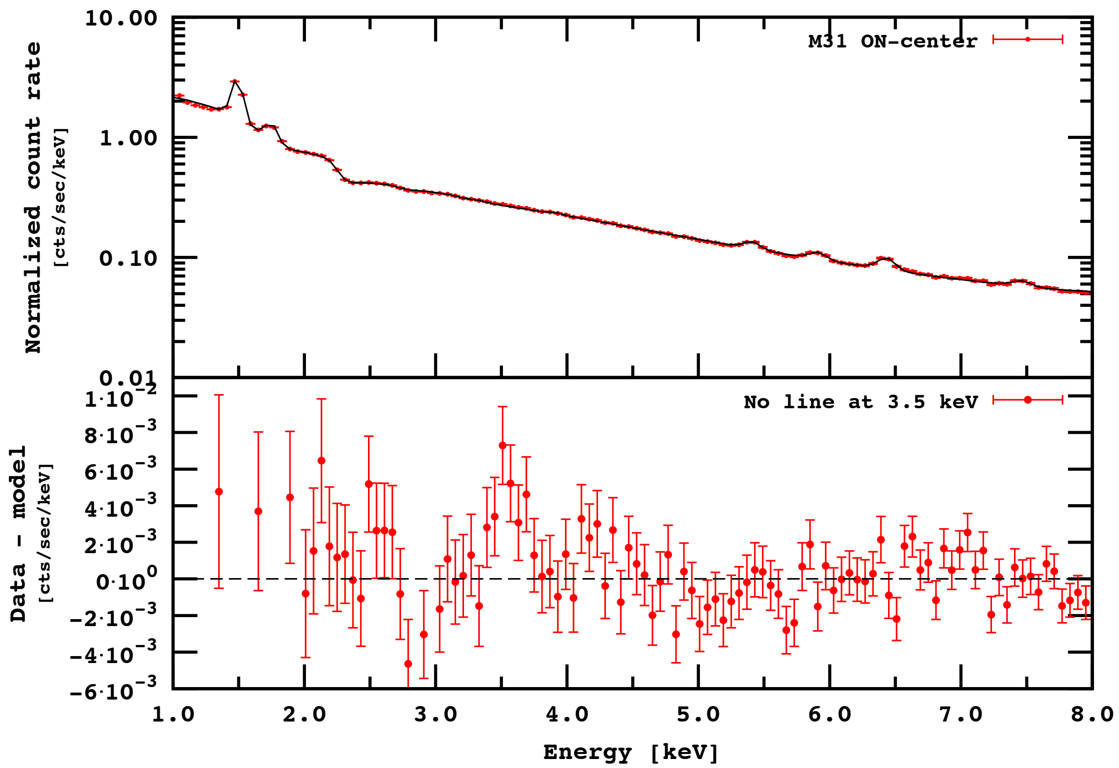


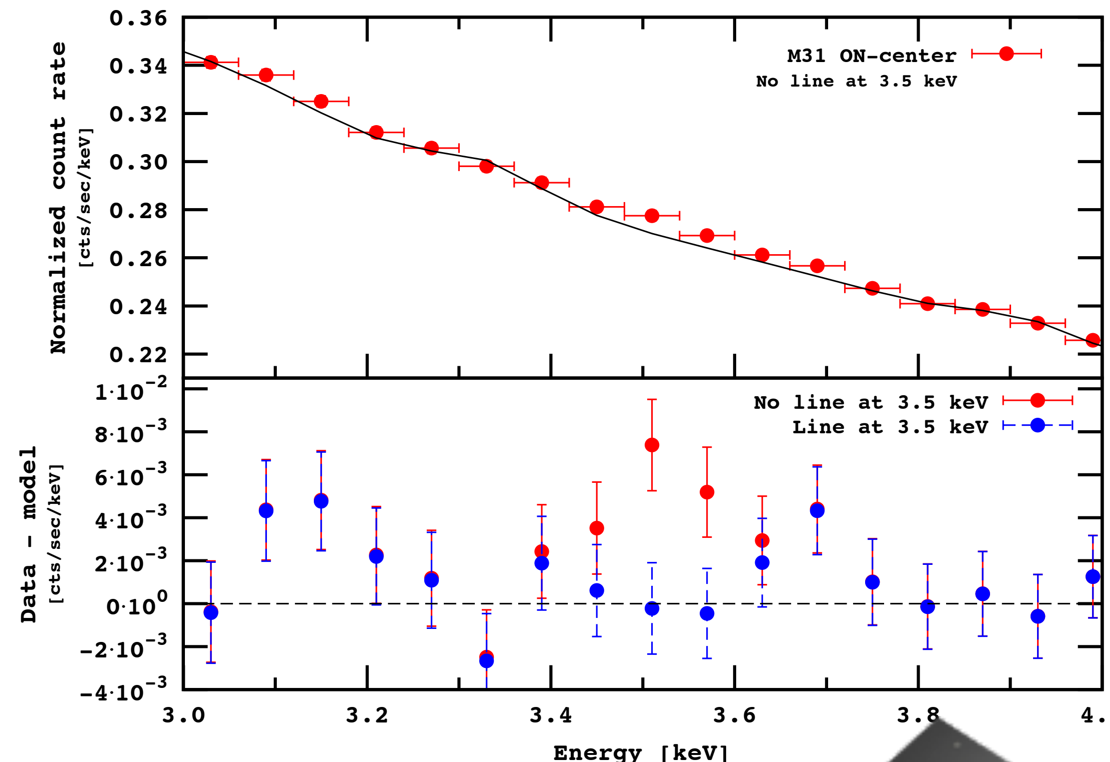
3.5 keV line?

arXiv:1402.2301



arXiv:1402.4119





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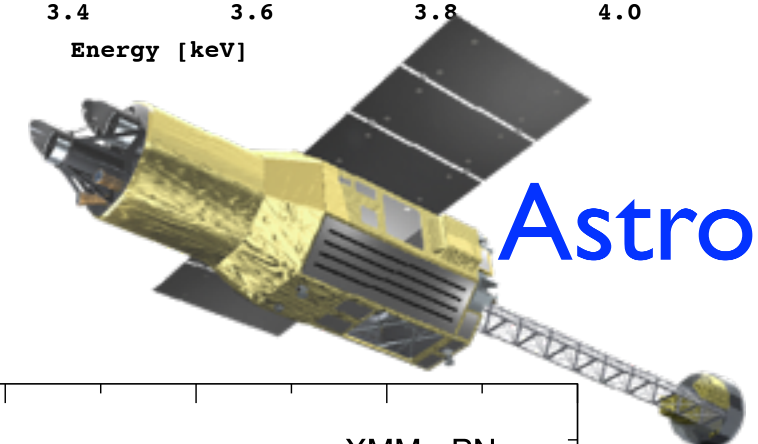
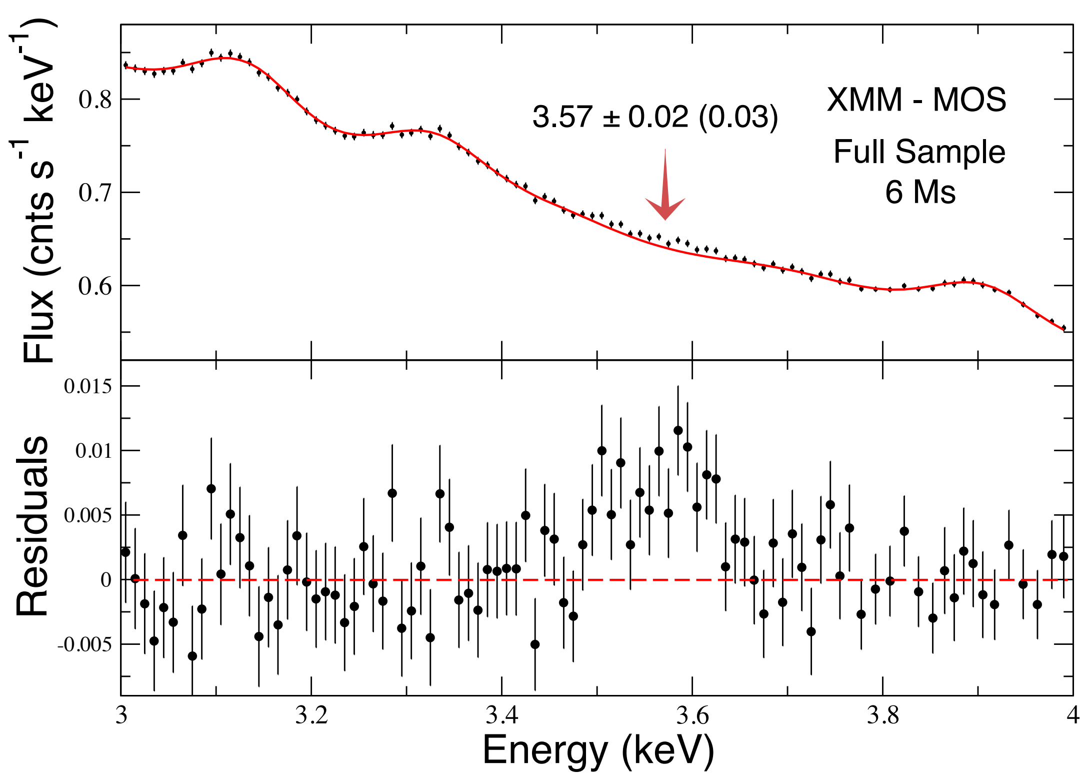
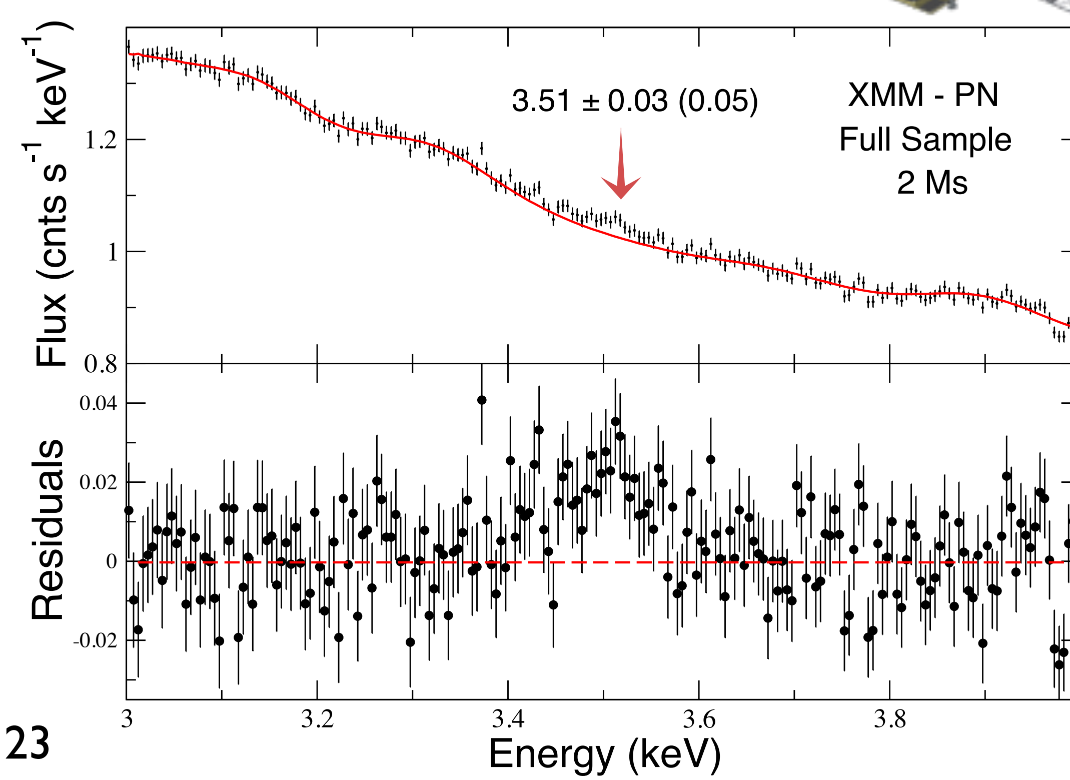


Astro-H

arXiv:1402.2301





Neutrino
our Dad?

beginning of the Universe

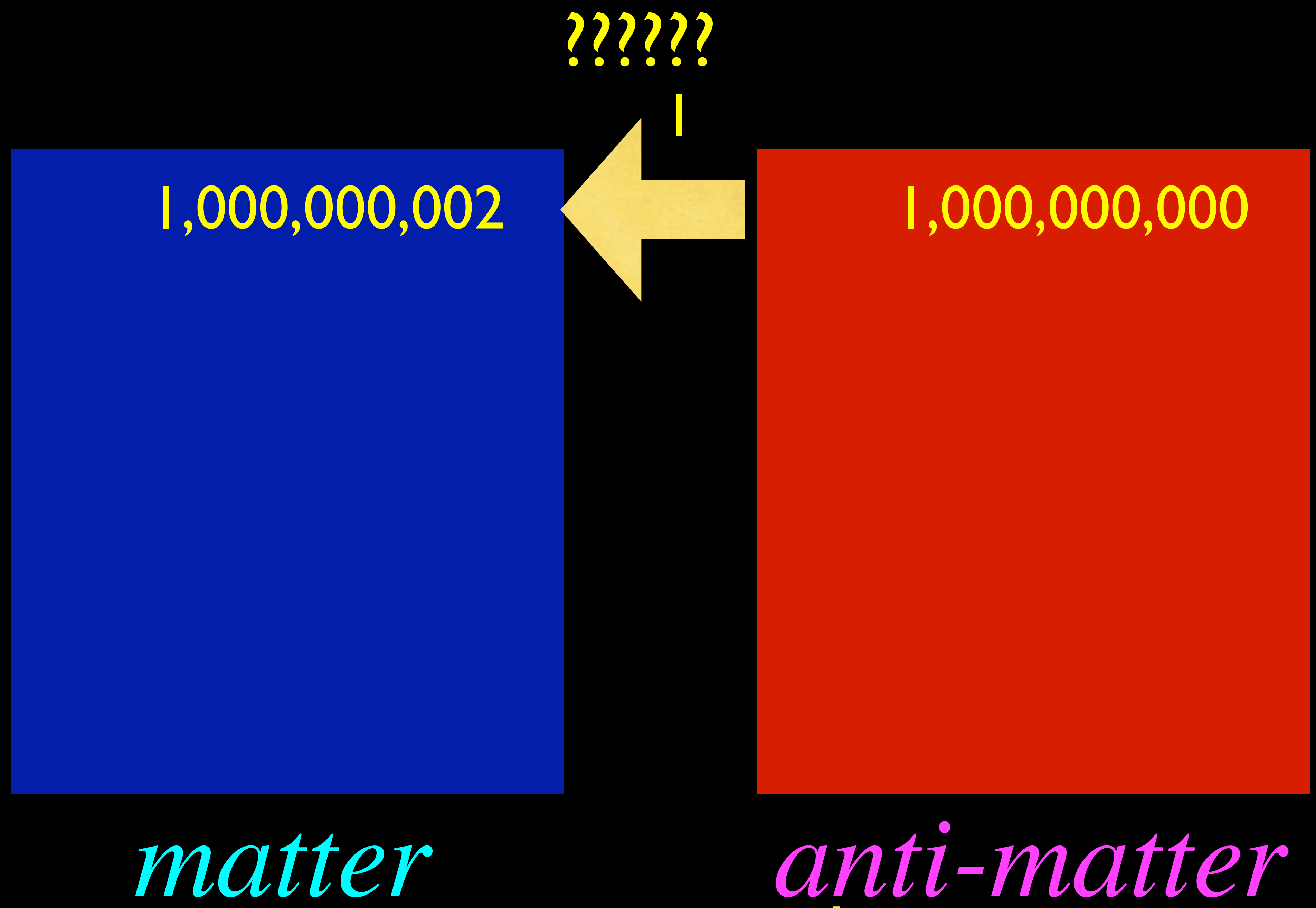
1,000,000,001

1,000,000,001

matter

anti-matter

shortly after



anti-matter needs to convert into matter

Universe now

2

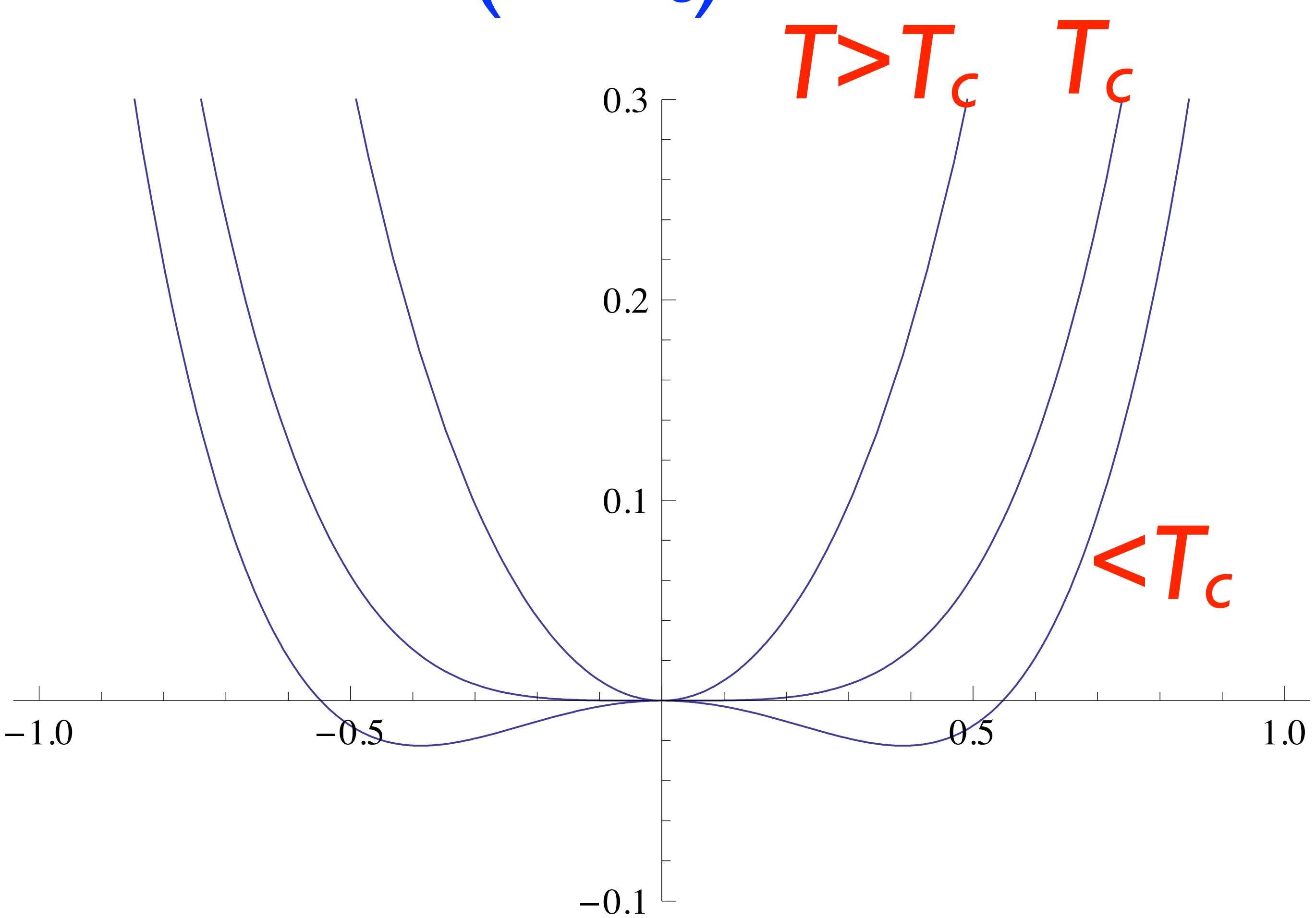
us

matter *anti-matter*

This is how we survived!

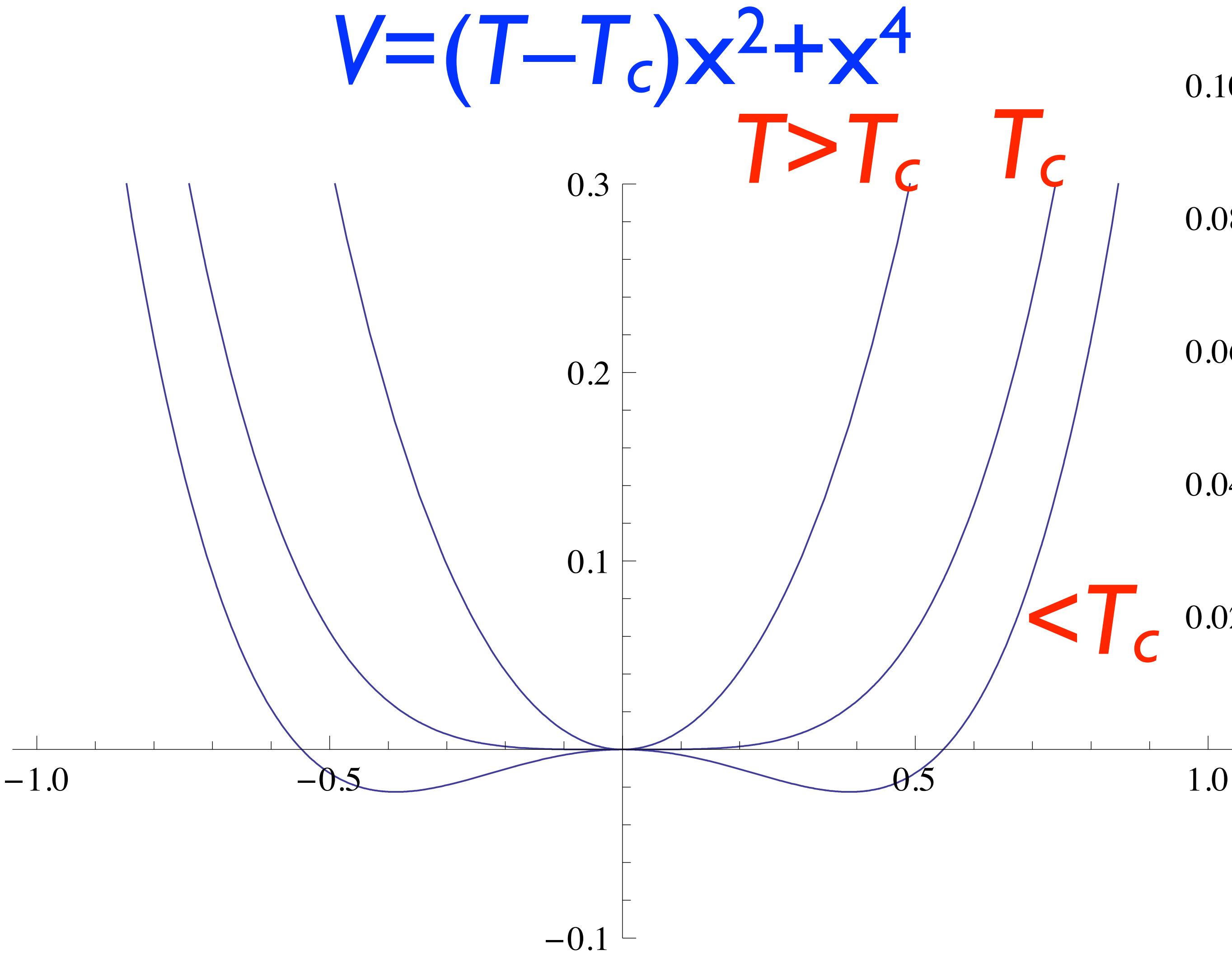
Order of phase transition

$V=(T-T_c)x^2+x^4$

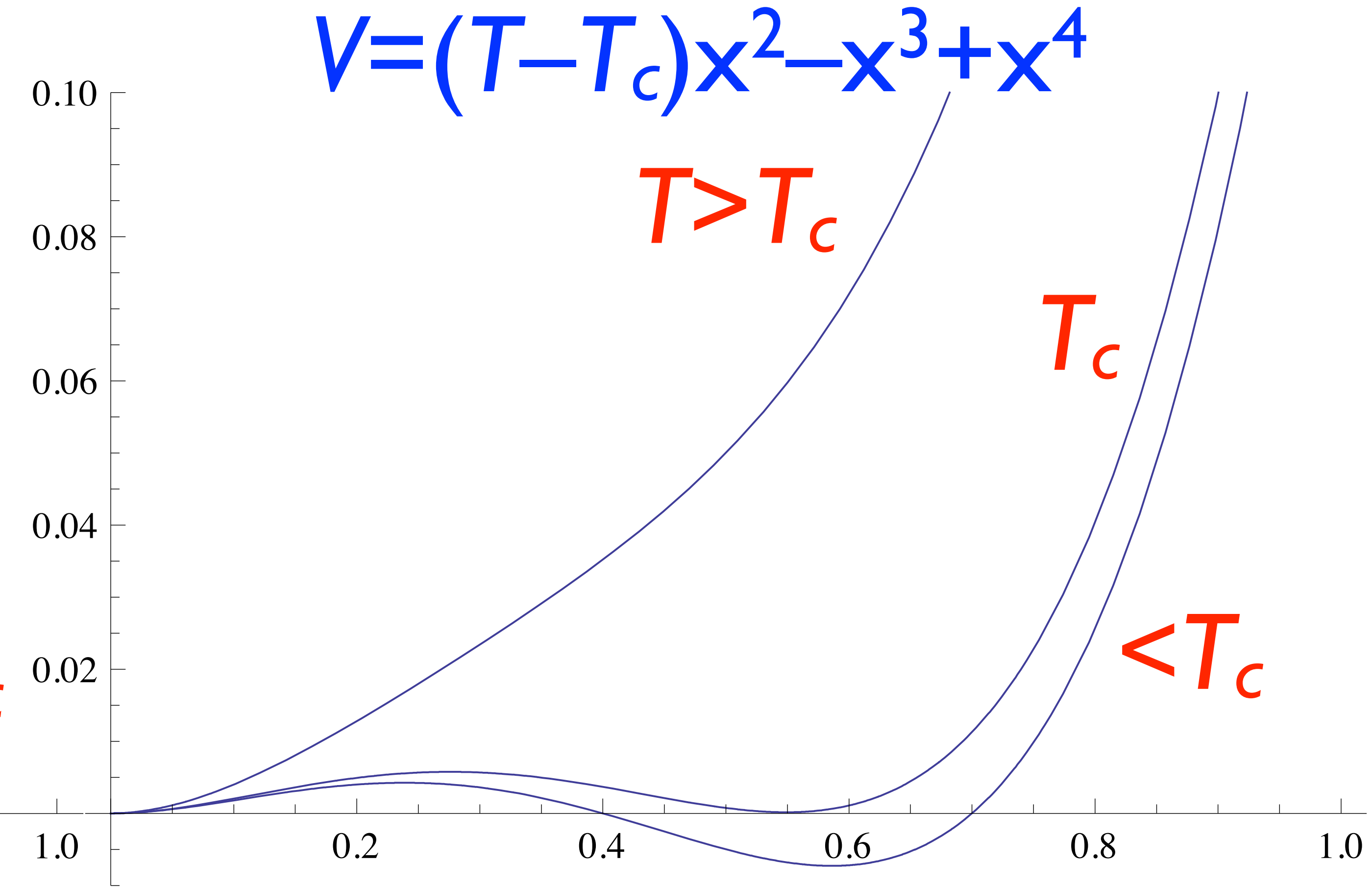


2nd order

Order of phase transition

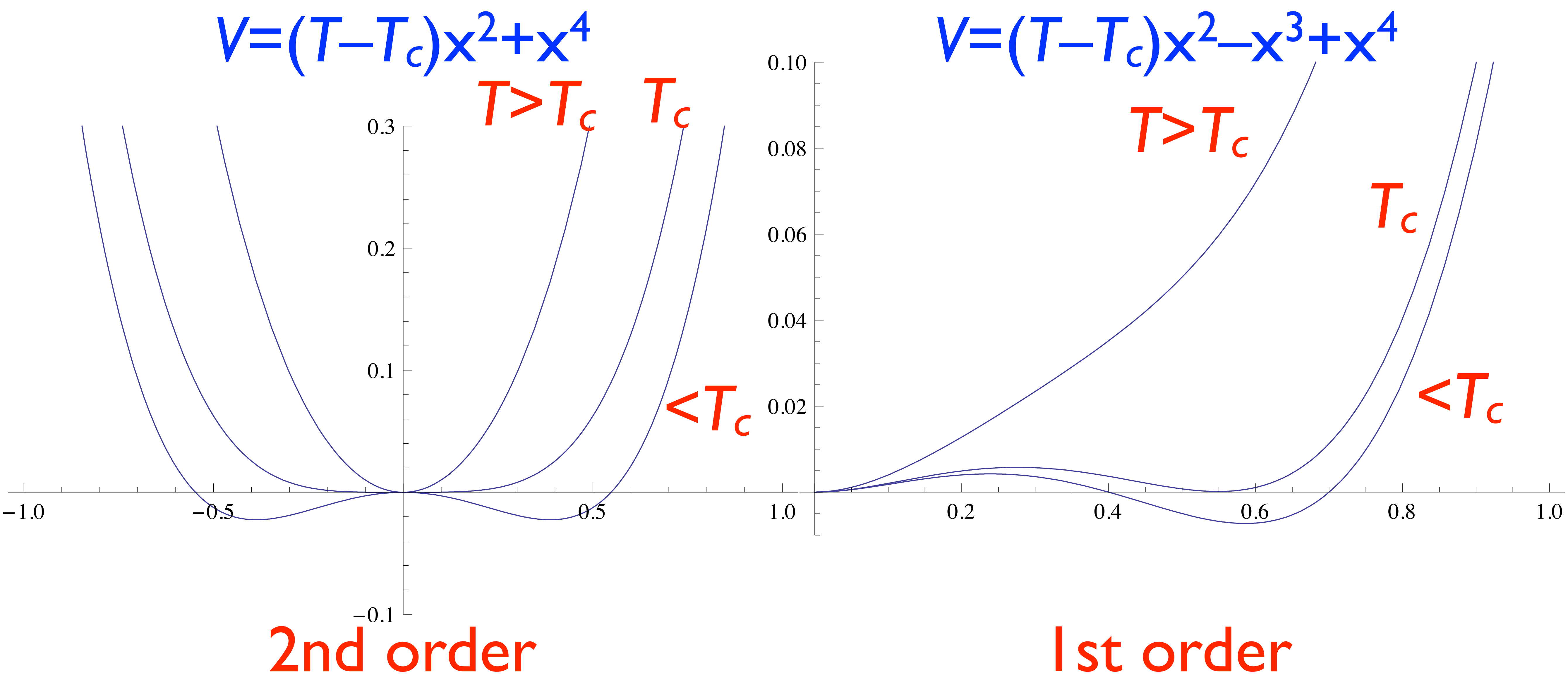


2nd order



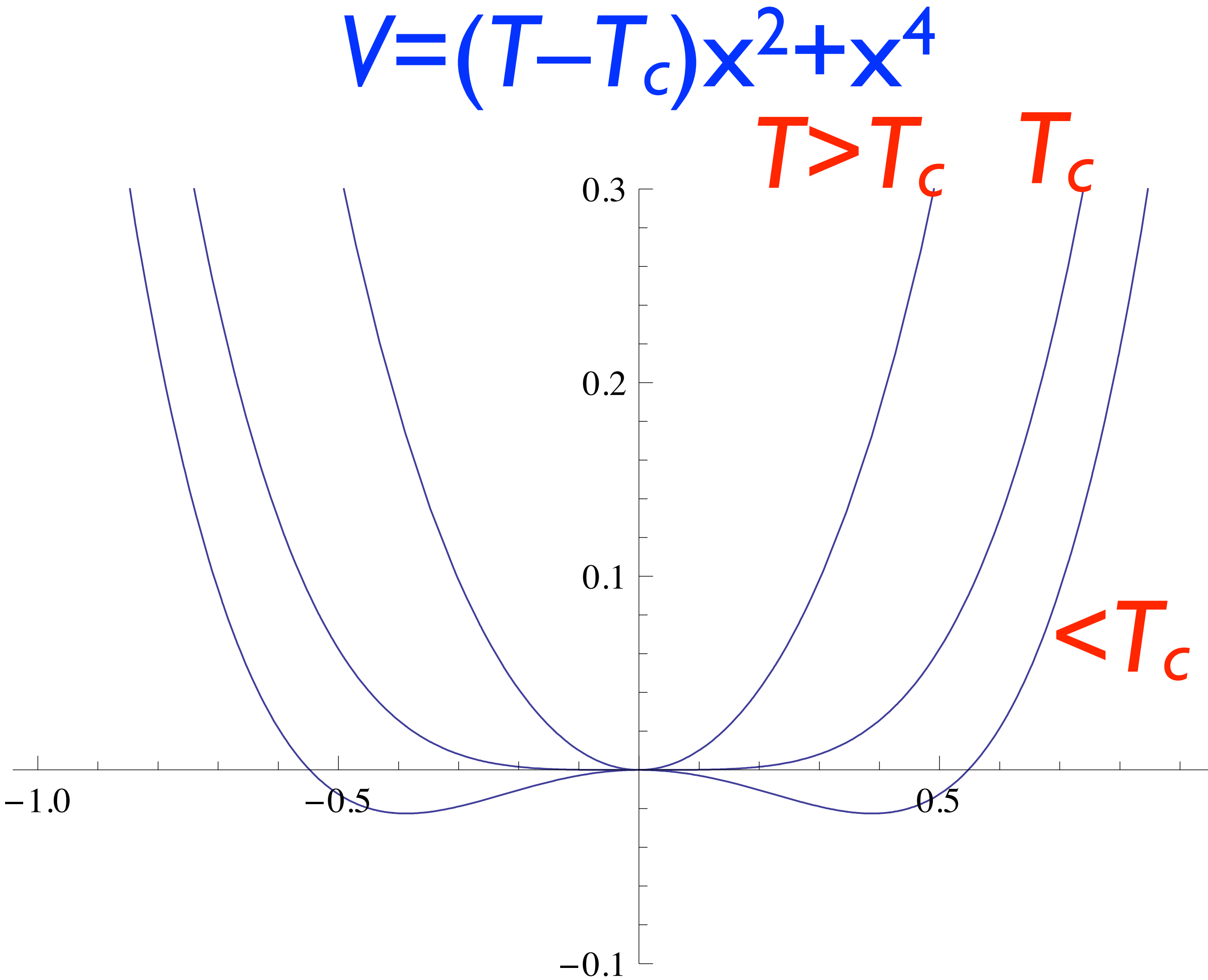
1st order

Order of phase transition

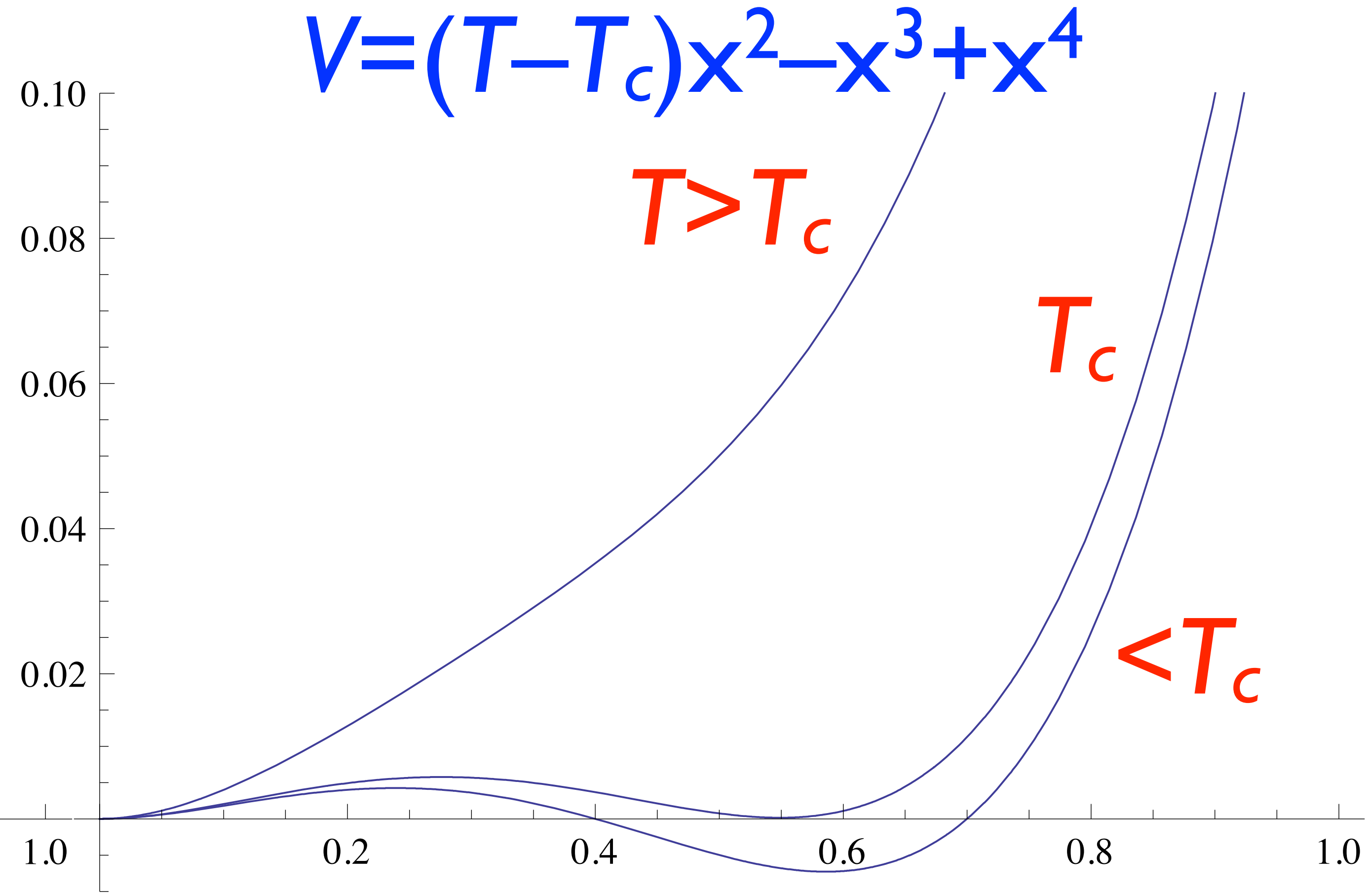


need some modification to Higgs potential
measure Higgs self-coupling ⇒ ILC, FCC

Order of phase transition



2nd order

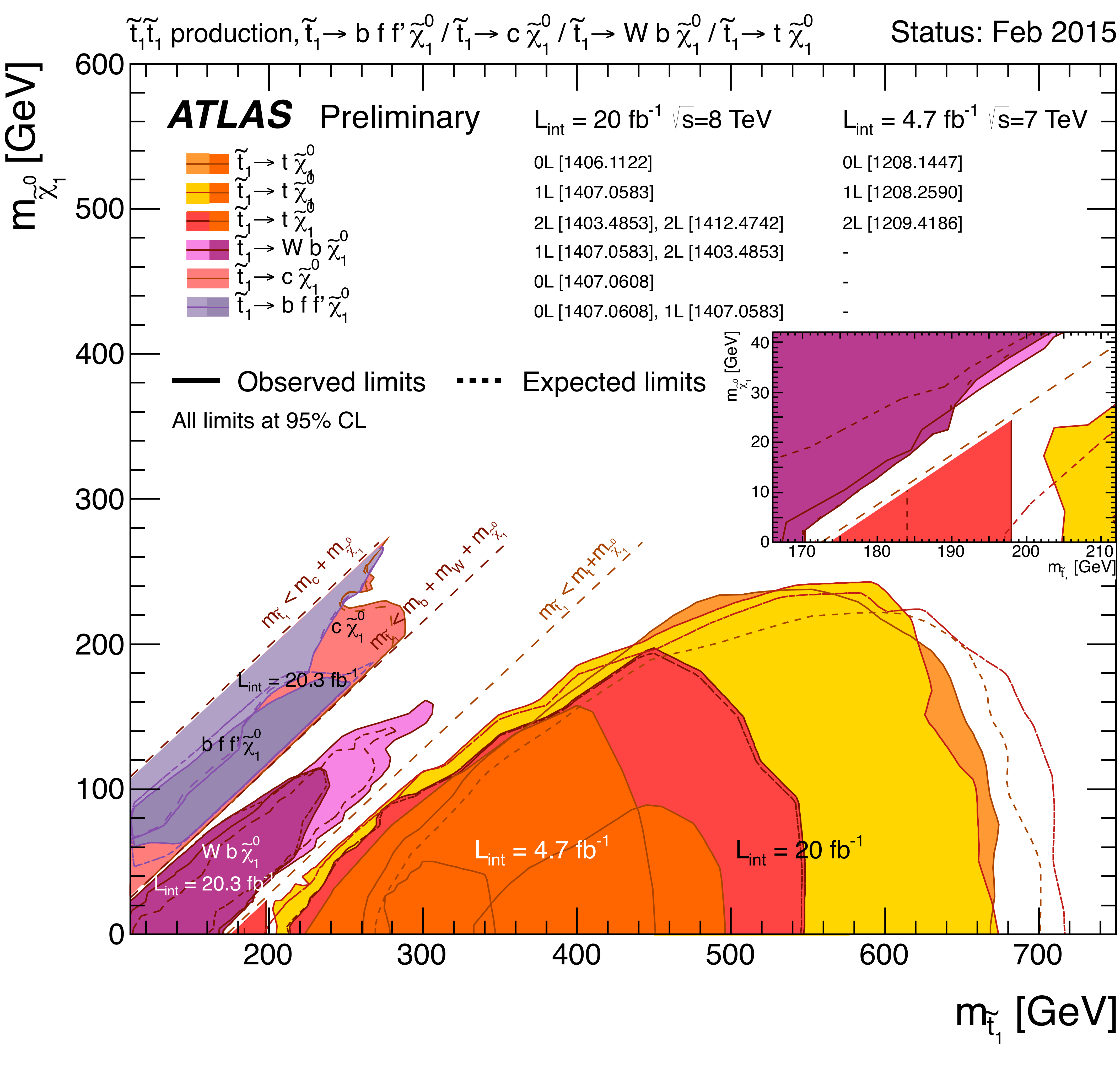


1st order

need some modification to Higgs potential

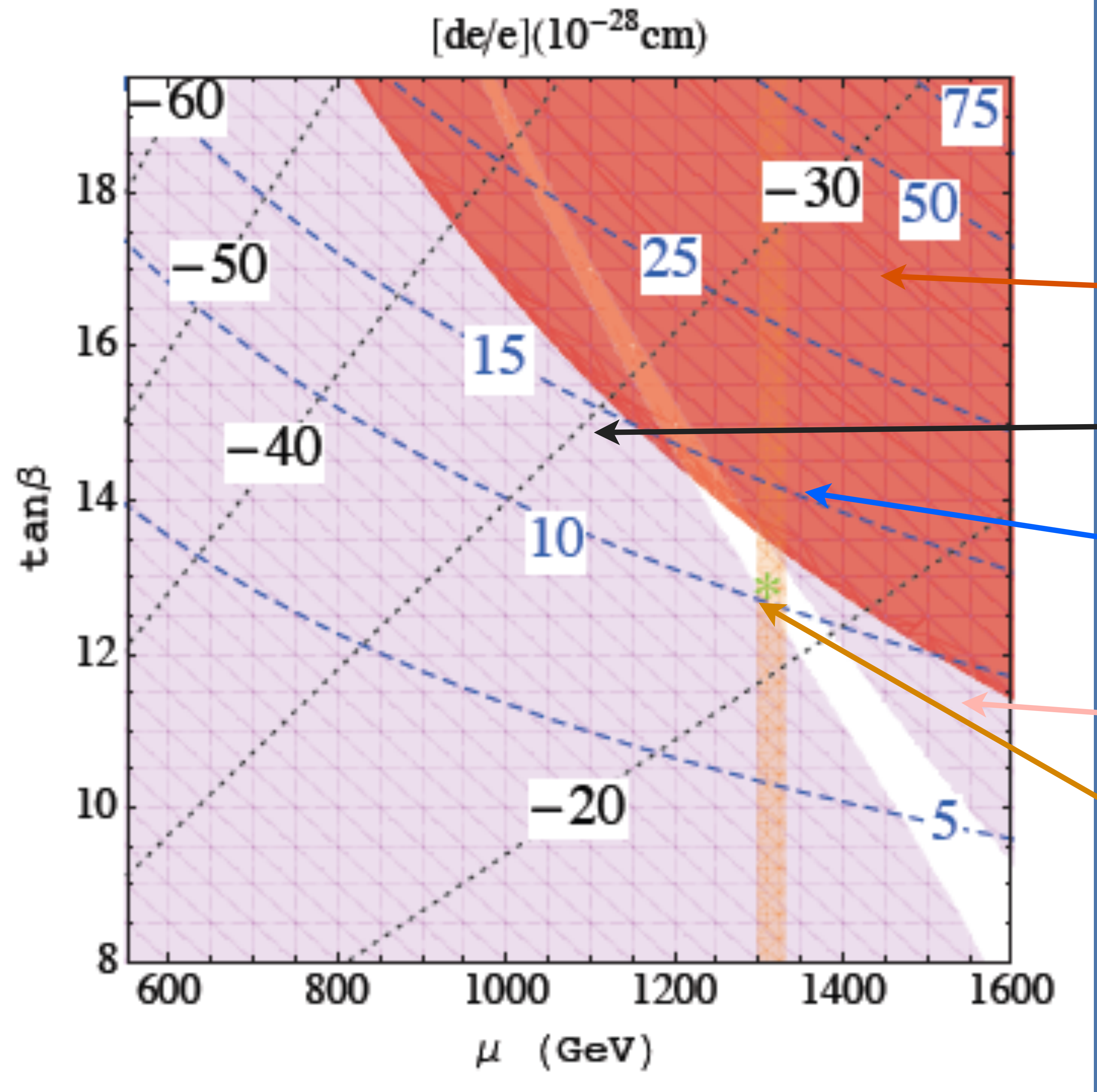
measure Higgs self-coupling ⇒ ILC, FCC

In MSSM, need m(stop)≲160GeV, pratically dead



t̃₁t̃₁ production, t̃₁→ b f f' χ̃⁰₁ / t̃₁→ c χ̃⁰₁ / t̃₁→ W b χ̃⁰₁ / t̃₁→ t χ̃⁰₁
Status: Feb 2015
ATLAS Preliminary
L_int = 20 fb^-1 √s=8 TeV
L_int = 4.7 fb^-1 √s=7 TeV
t̃₁→ t χ̃⁰₁ 0L [1406.1122] 0L [1208.1447]
t̃₁→ t χ̃⁰₁ 1L [1407.0583] 1L [1208.2590]
t̃₁→ t χ̃⁰₁ 2L [1403.4853], 2L [1412.4742] 2L [1209.4186]
t̃₁→ W b χ̃⁰₁ 1L [1407.0583], 2L [1403.4853] -
t̃₁→ c χ̃⁰₁ 0L [1407.0608] -
t̃₁→ b f f' χ̃⁰₁ 0L [1407.0608], 1L [1407.0583] -
Observed limits
Expected limits
All limits at 95% CL
m_t̃₁ < m_c + m_χ̃⁰₁
m_t̃₁ < m_b + m_W + m_χ̃⁰₁
m_t̃₁ < m_t + m_χ̃⁰₁
c χ̃⁰₁
L_int = 20.3 fb^-1
b f f' χ̃⁰₁
W b χ̃⁰₁
L_int = 20.3 fb^-1
L_int = 4.7 fb^-1
L_int = 20 fb^-1
m_χ̃⁰₁ [GeV]
m_t̃₁ [GeV]

Final Results



Open the Heavy Higgs CPV search

Mercury exclusion

Chargino contour

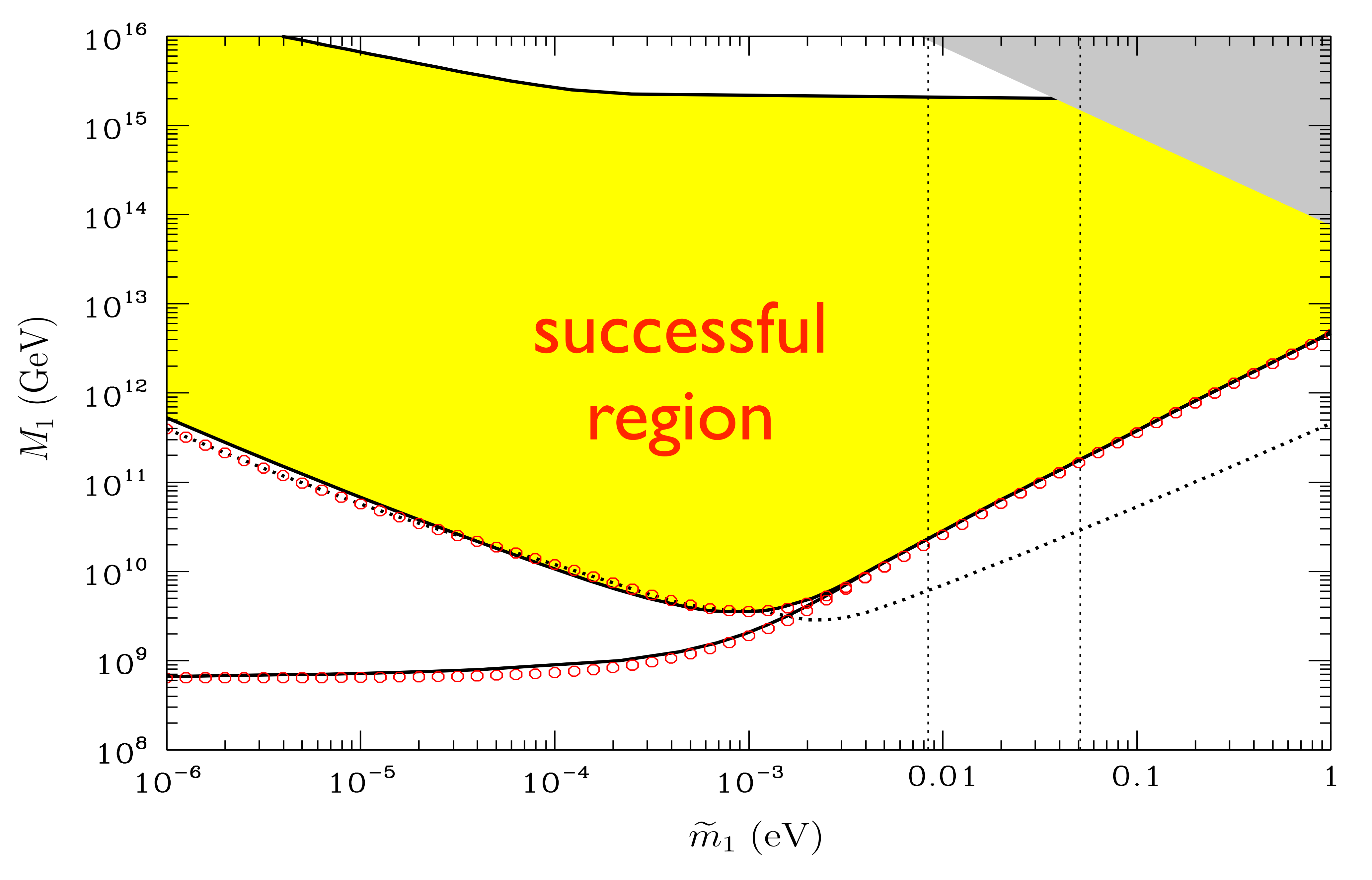
Stau contour

ACME exclusion $|d_e|<8.7\times10^{-29}$ ecm

Preferred by EWBG

LG. Bian, T. Liu, J. S, 1411.6695

Non-trivial success!



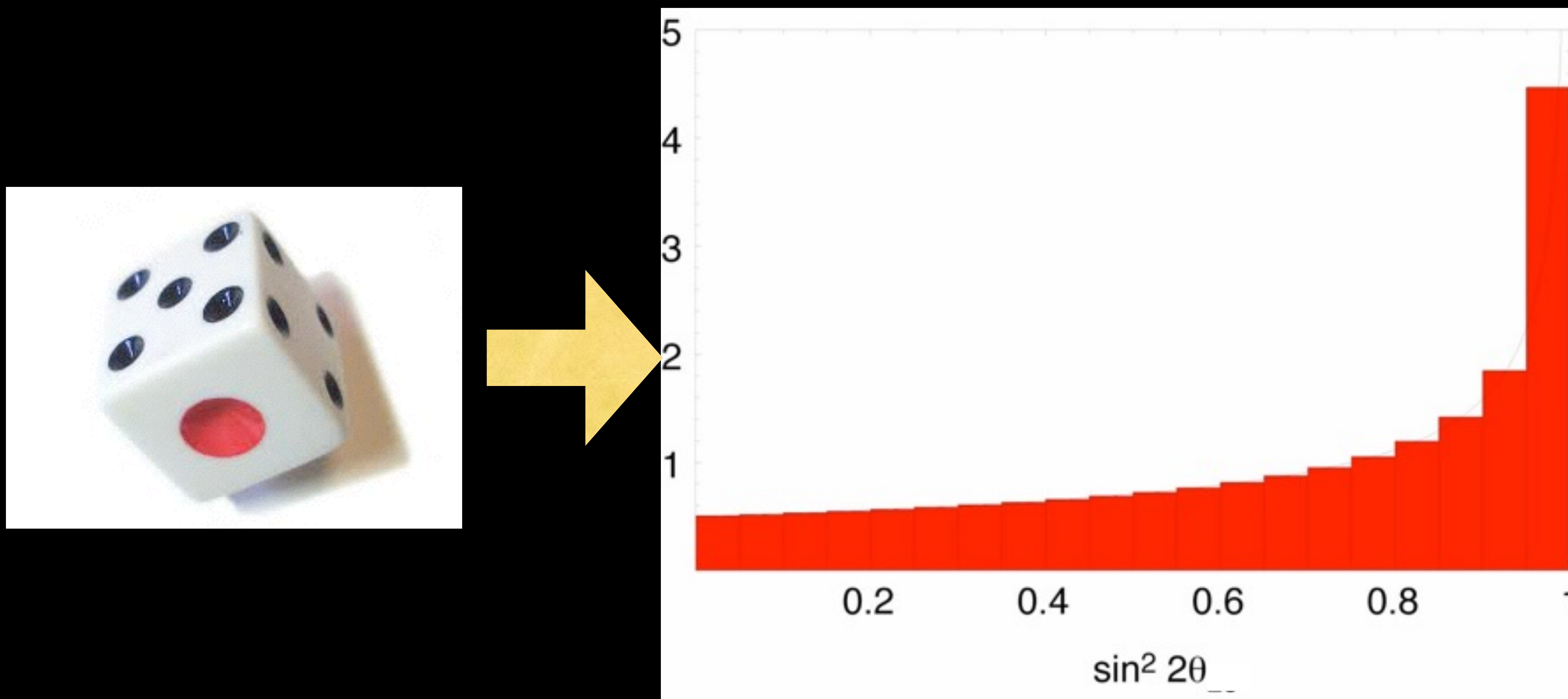
$$\tilde{m}_1 = \frac{(m_D^\dagger m_D)_{11}}{M_1}$$

di Bari, Plümacher, Buchmüller

anarchy

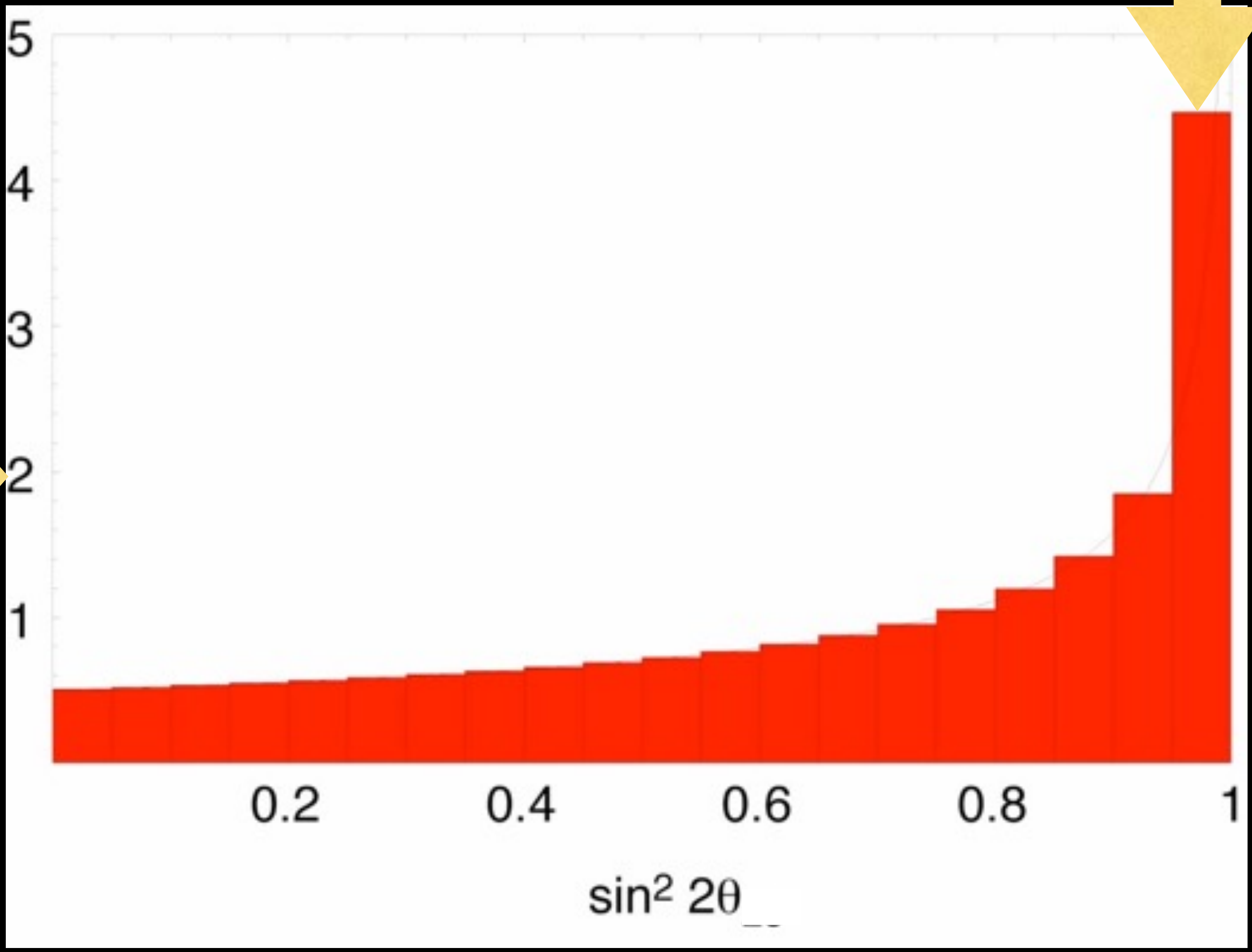
anarchy

anarchy

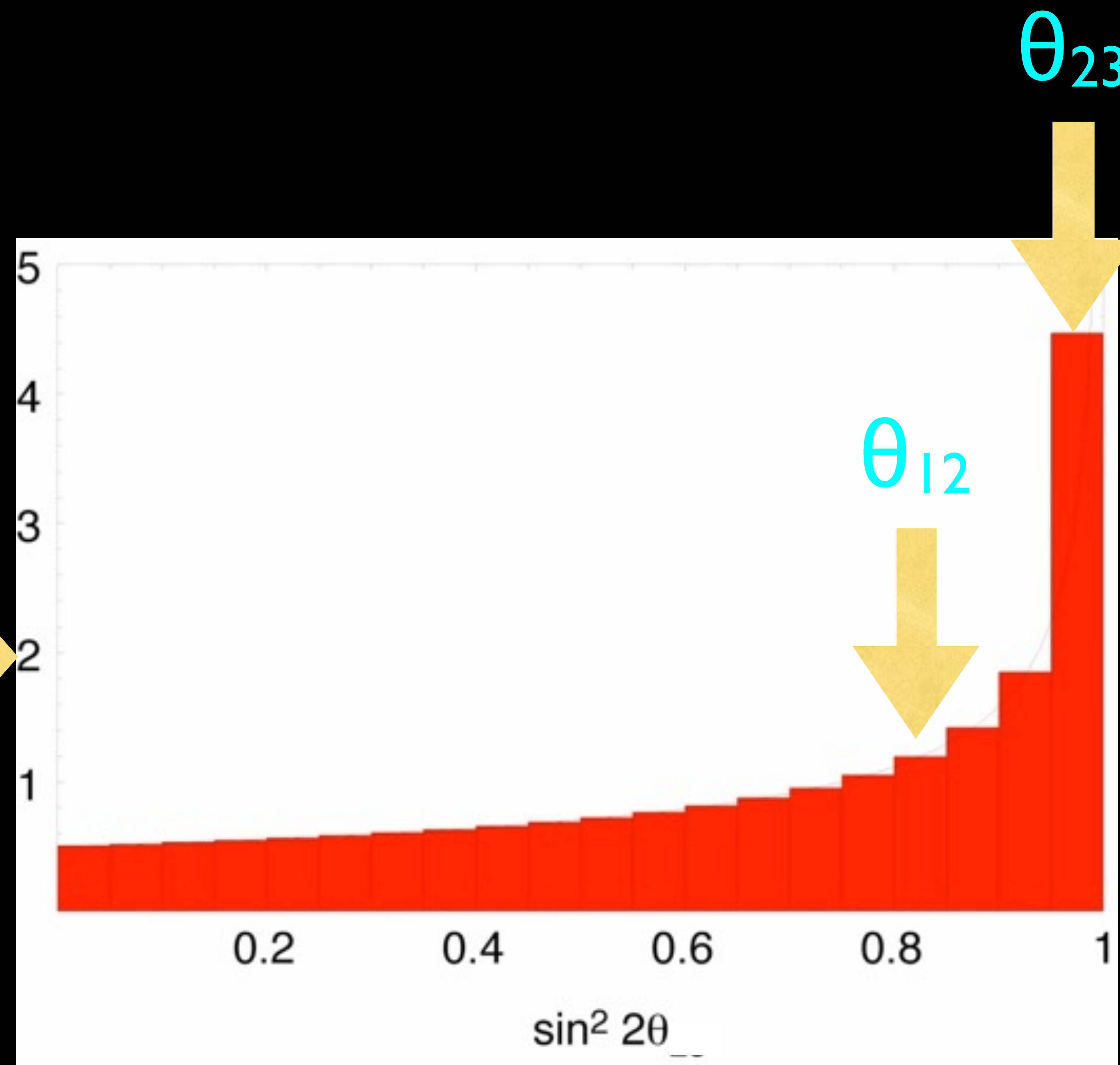


anarchy

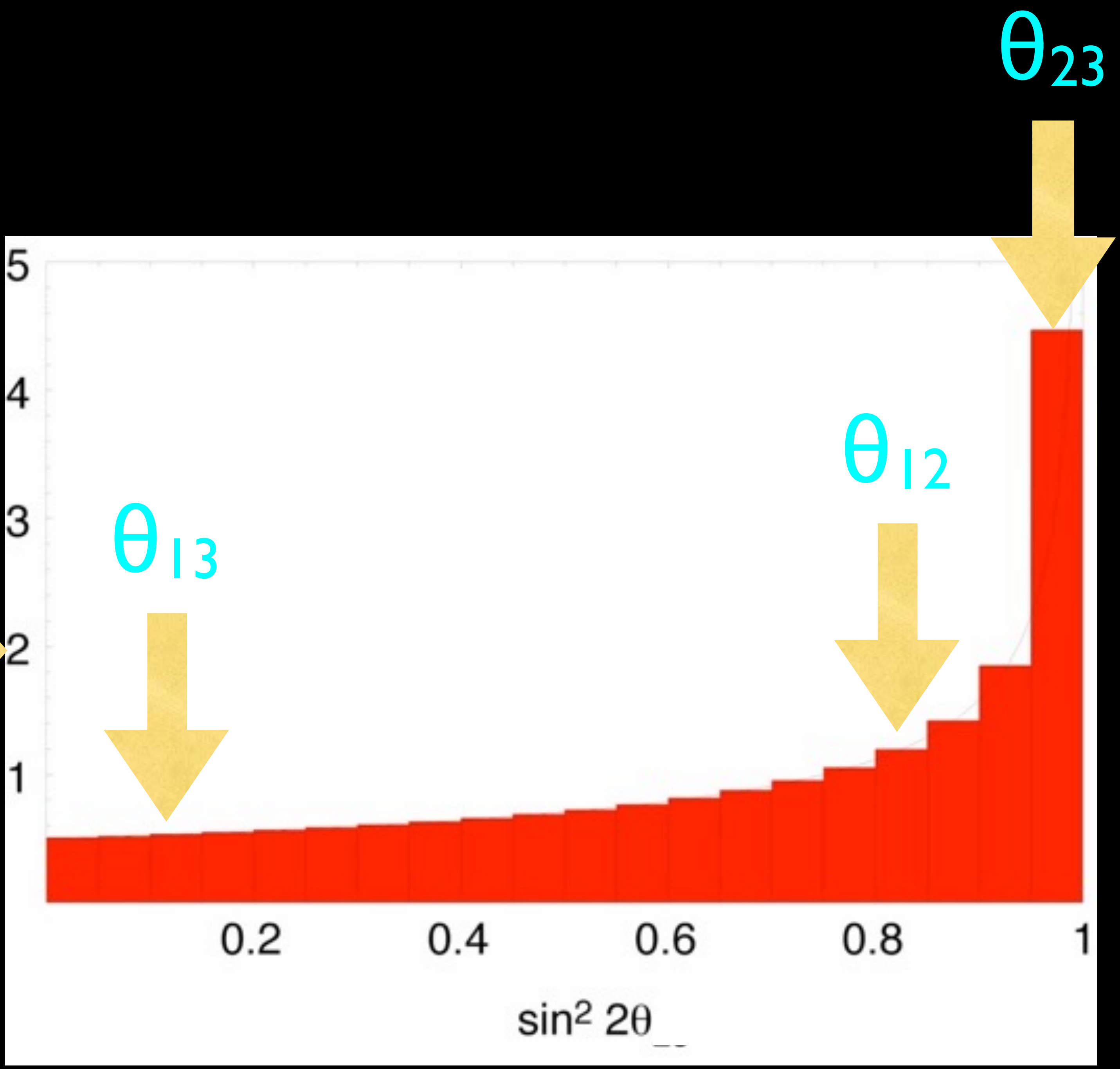
θ_{23}



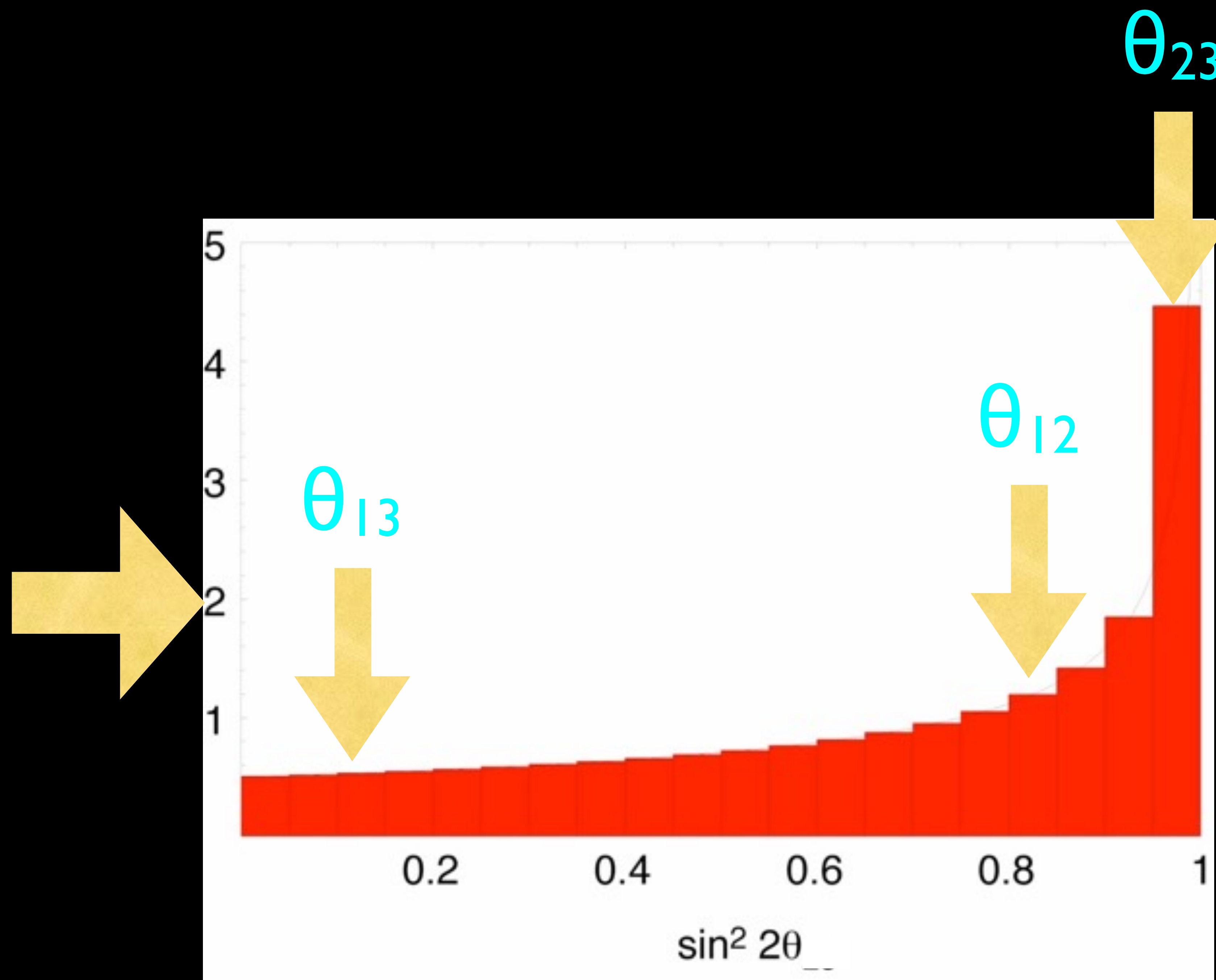
anarchy



anarchy



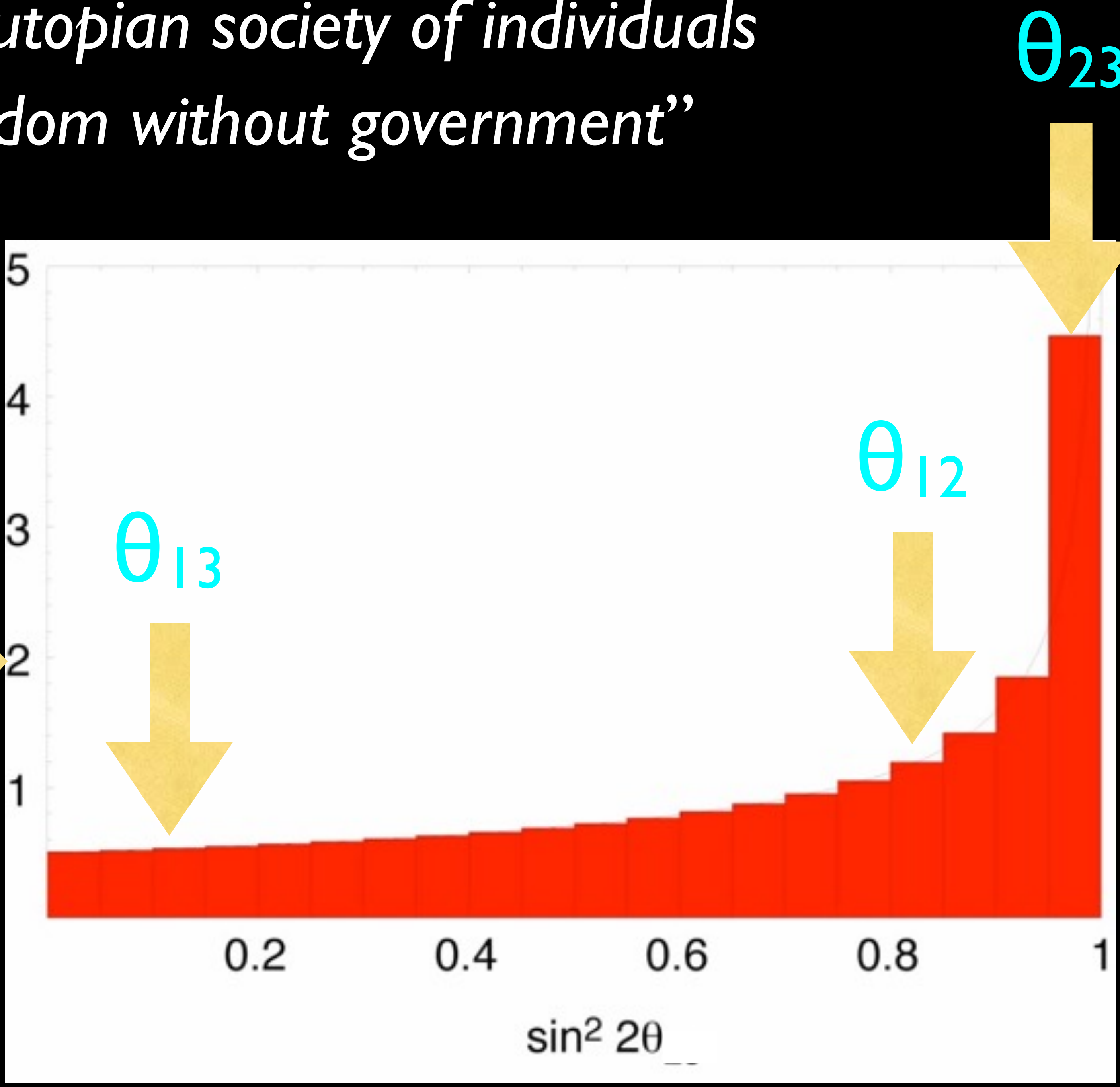
anarchy



Kolmogorov-Smirnov test (de Gouvêa, HM)
nature has 44% chance to choose this kind of numbers

anarchy

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



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anarchy

neutrinos

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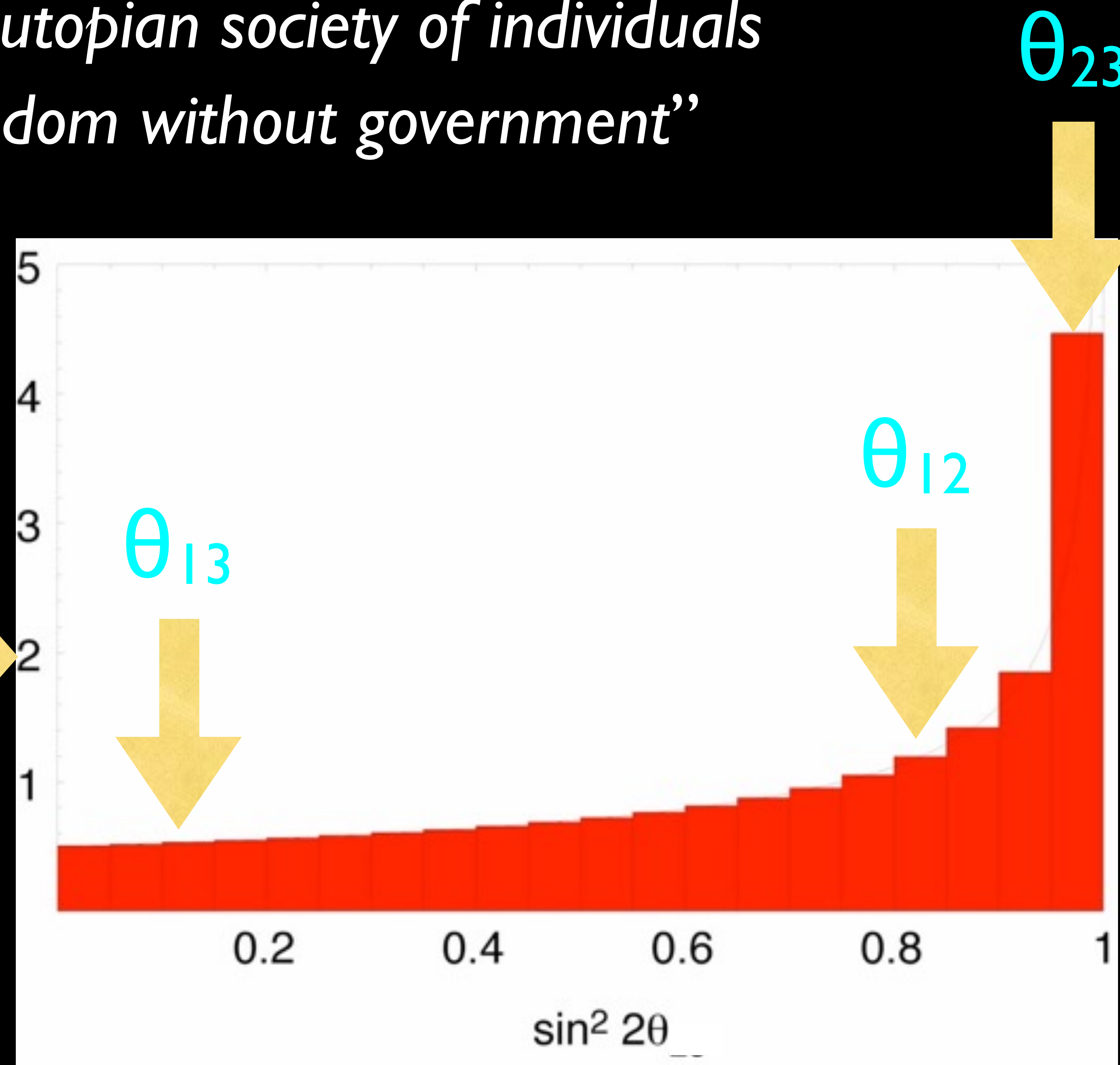

Kolmogorov-Smirnov test (de Gouvêa, HM)

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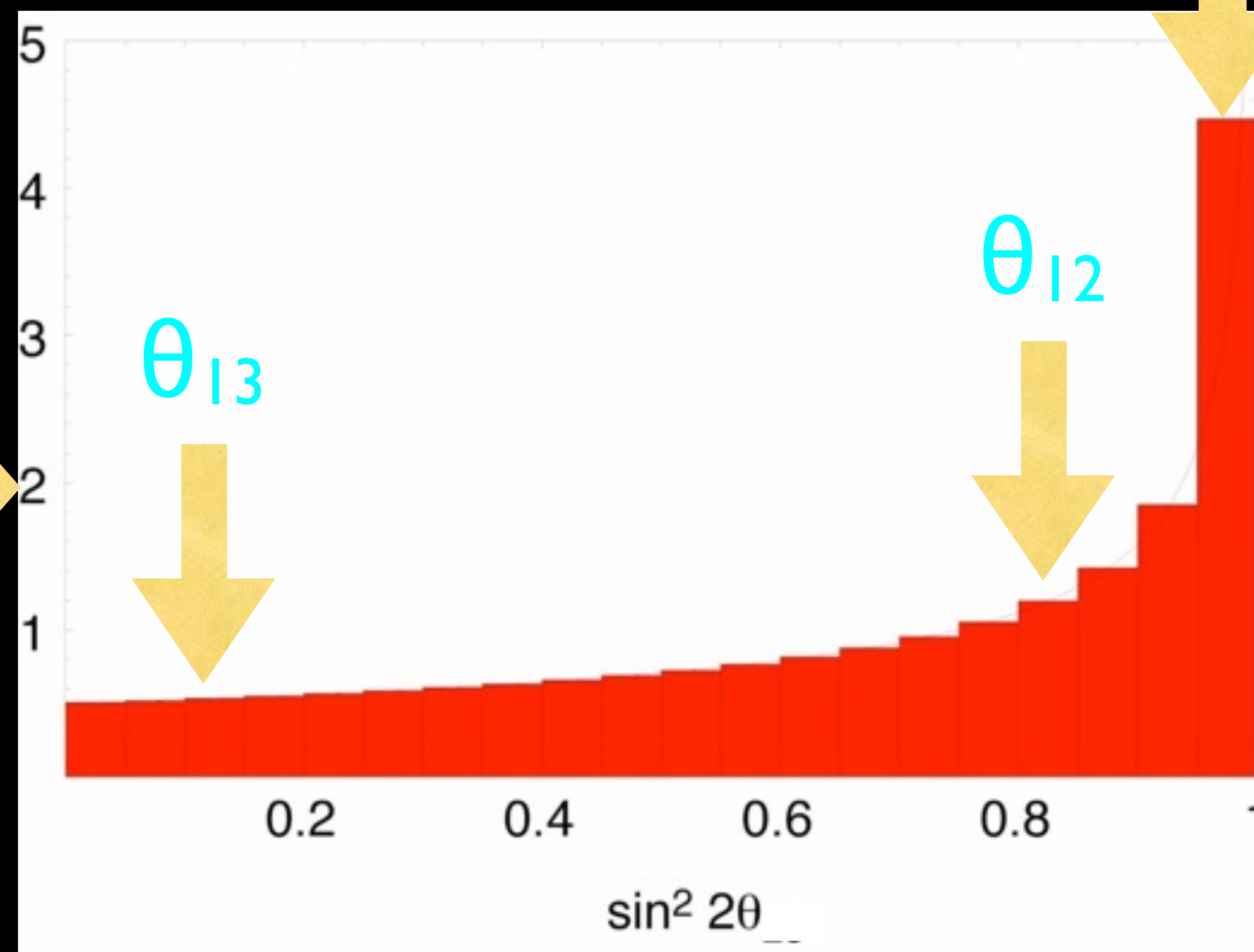
anarchy

neutrinos

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

large mixing

θ_{23}



θ_{13} θ_{12}

Kolmogorov-Smirnov test (de Gouvêa, HM)

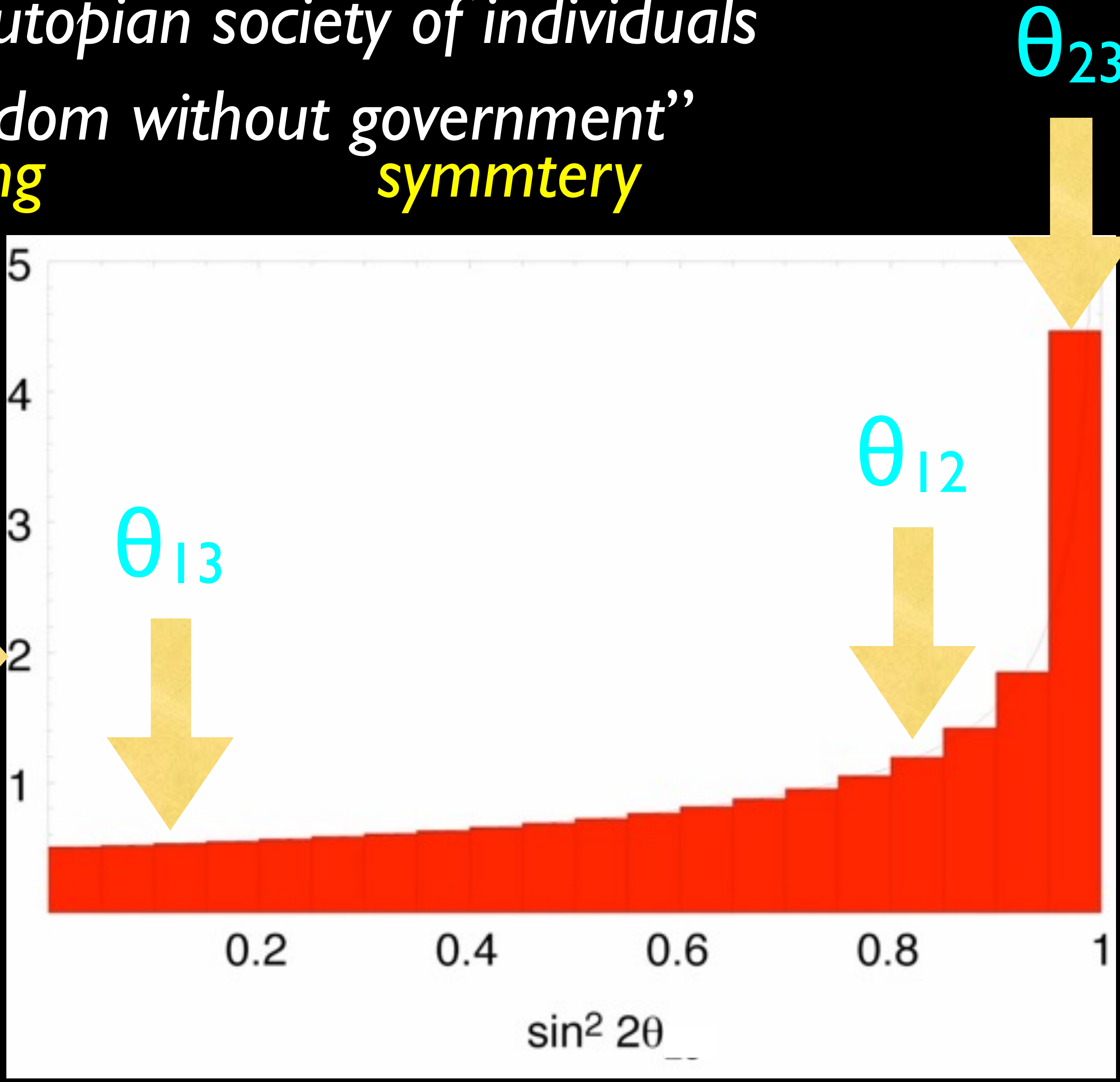
nature has 44% chance to choose this kind of numbers

anarchy

neutrinos

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

large mixing *symmtery*



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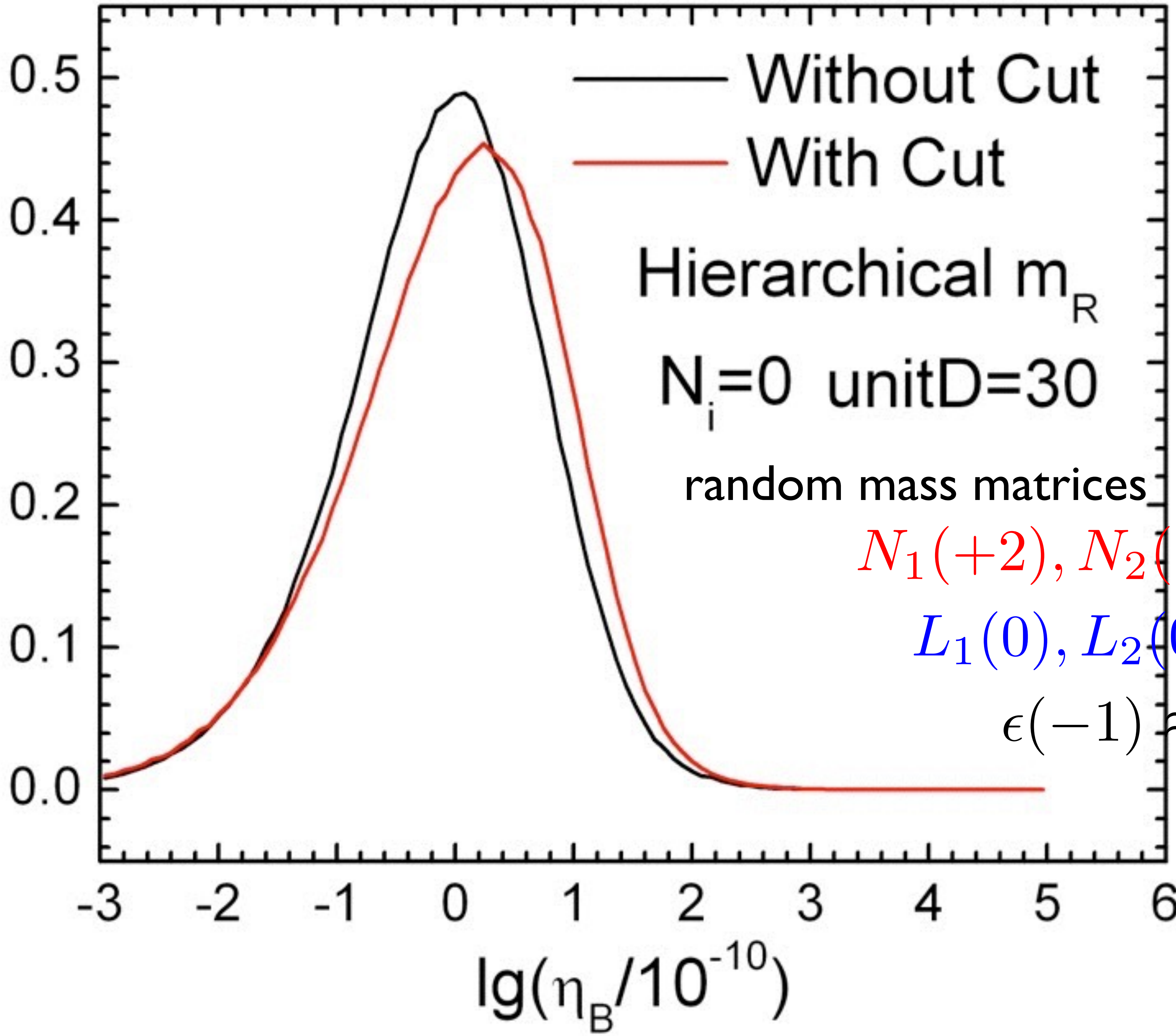


random mass matrices

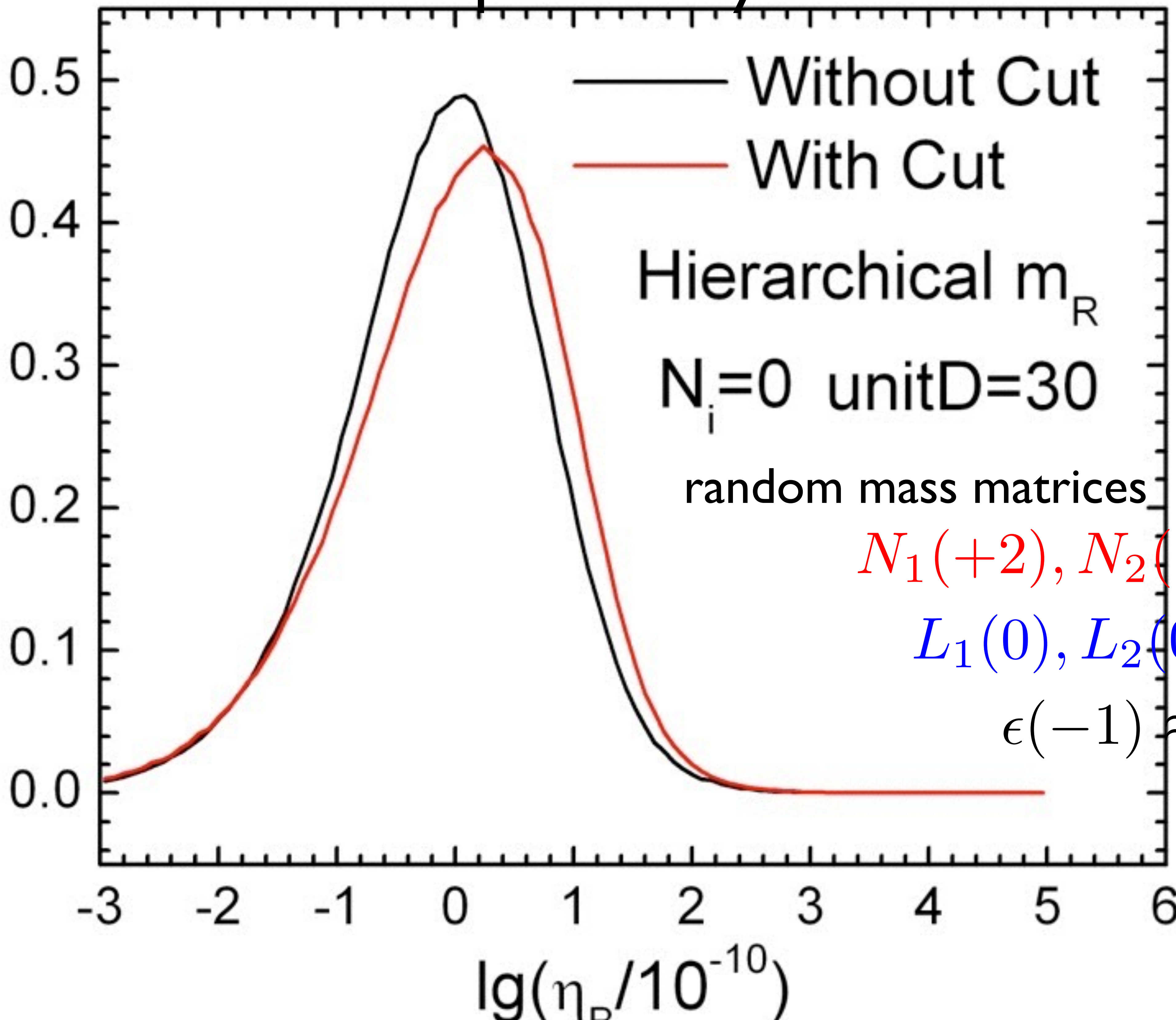
$N_1(+2), N_2(+1), N_3(0)$

$L_1(0), L_2(0), L_3(0)$

$\epsilon(-1) \approx 0.1$

Xiaochuan Lu, HM, arXiv:1405.0547

no direct connection to CP violation in oscillation
but a plausibility test



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How do we test it?

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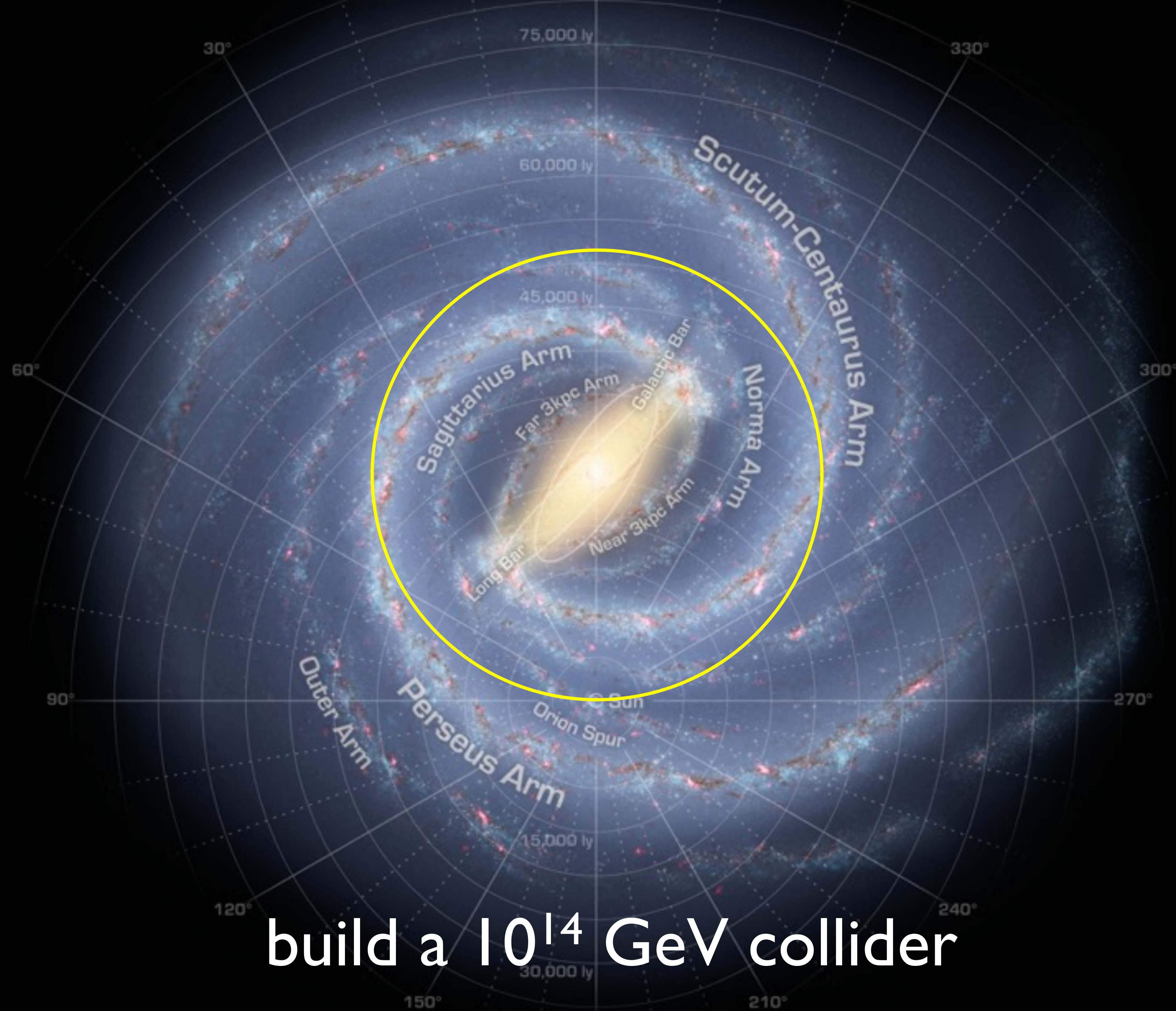
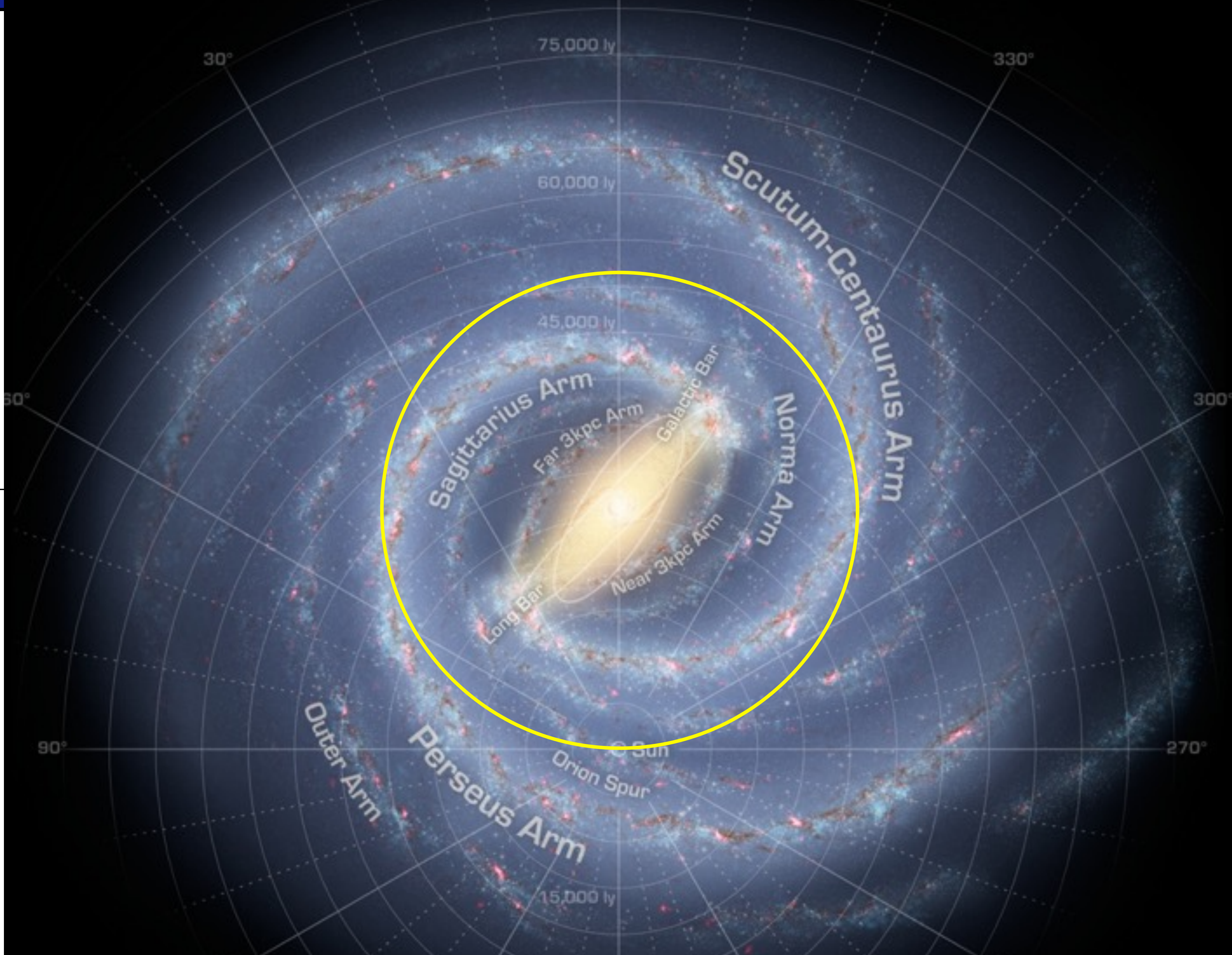


build a 10^{14} GeV collider

How do we test it?



build a 10^{14} GeV collider

indirect evidences

- Are all mixing angles large-ish?
- Is CP violated in neutrino sector?
- Is neutrino Majorana?
- collect archaeological evidences

Excitement

- CP violation in neutrino sector may be observable with conventional technique

$$P(\nu_\mu \to \nu_e) - P(\bar{\nu}_\mu \to \bar{\nu}_e) = -16 s_{12} c_{12} s_{13} c_{13}^2 s_{23} c_{23}$$

$$\sin\delta \sin\frac{\Delta m_{12}^2 L}{4E} \sin\frac{\Delta m_{13}^2 L}{4E} \sin\frac{\Delta m_{23}^2 L}{4E}$$

Excitement

- CP violation in neutrino sector may be observable with conventional technique

$$P(\nu_\mu \to \nu_e) - P(\bar{\nu}_\mu \to \bar{\nu}_e) = -16 s_{12} c_{12} s_{13} c_{13}^2 \boxed{s_{23}} c_{23}$$
$$\sin\delta \sin\frac{\Delta m_{12}^2 L}{4E} \sin\frac{\boxed{\Delta m_{13}^2} L}{4E} \sin\frac{\boxed{\Delta m_{23}^2} L}{4E}$$

1998
Super-K

Excitement

2002
KamLAND
SNO

- CP violation in neutrino sector may be observable with conventional technique

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Excitement

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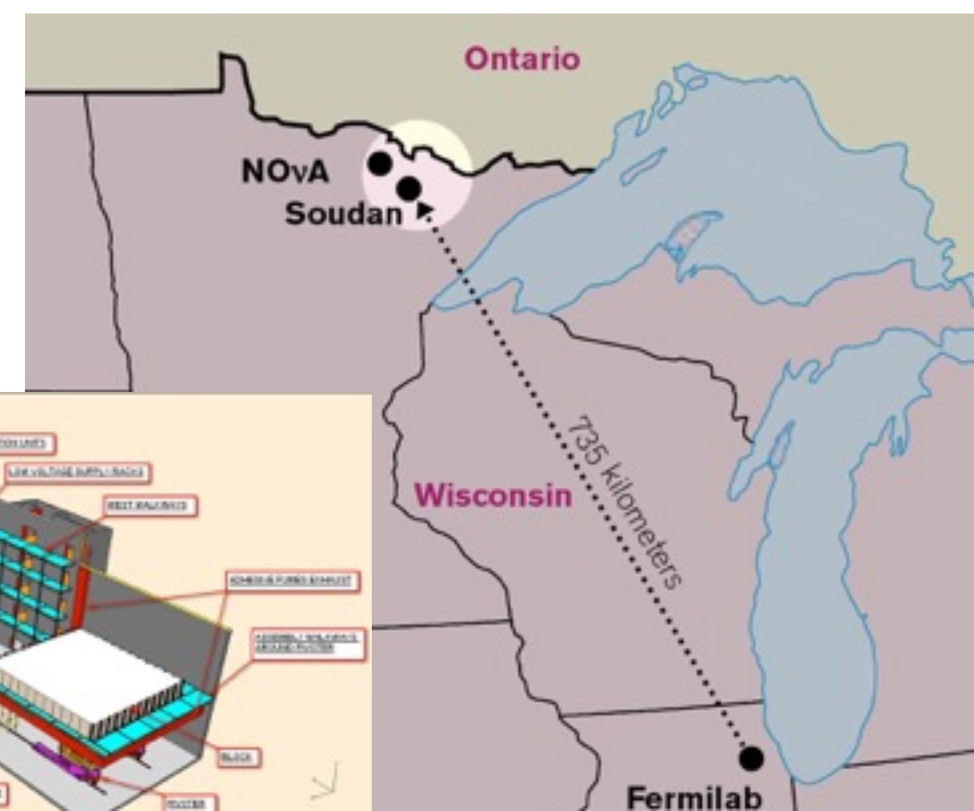

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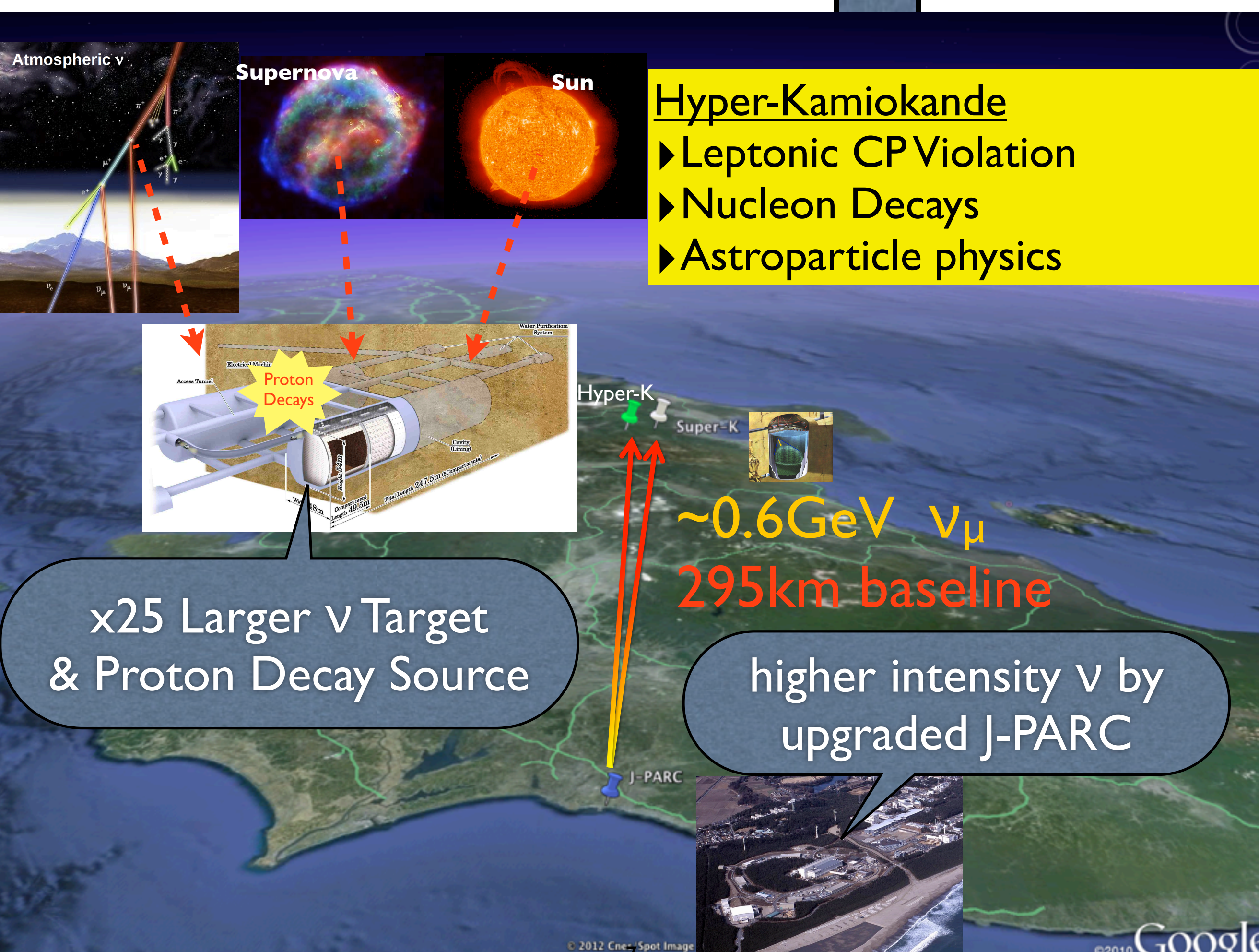

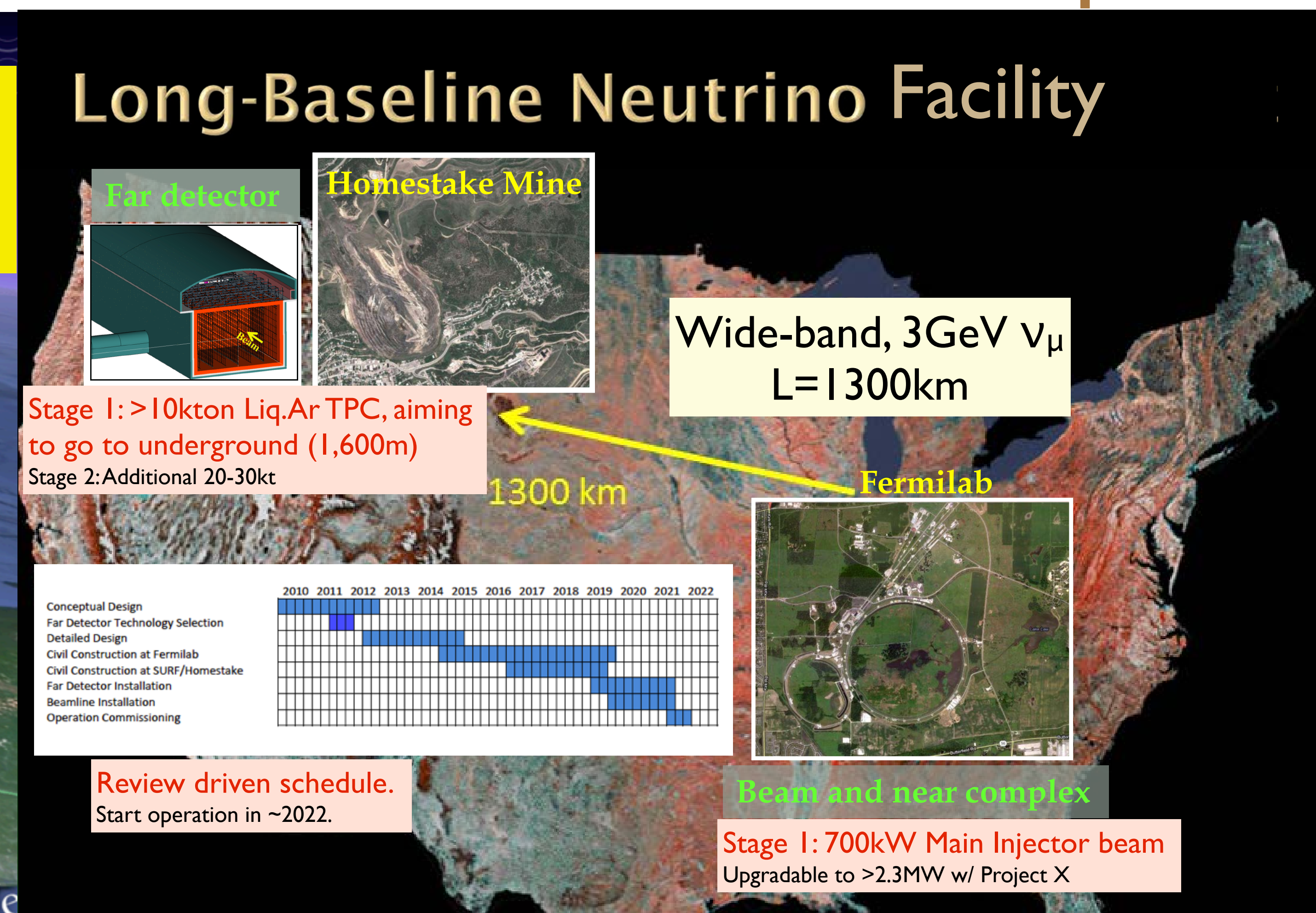

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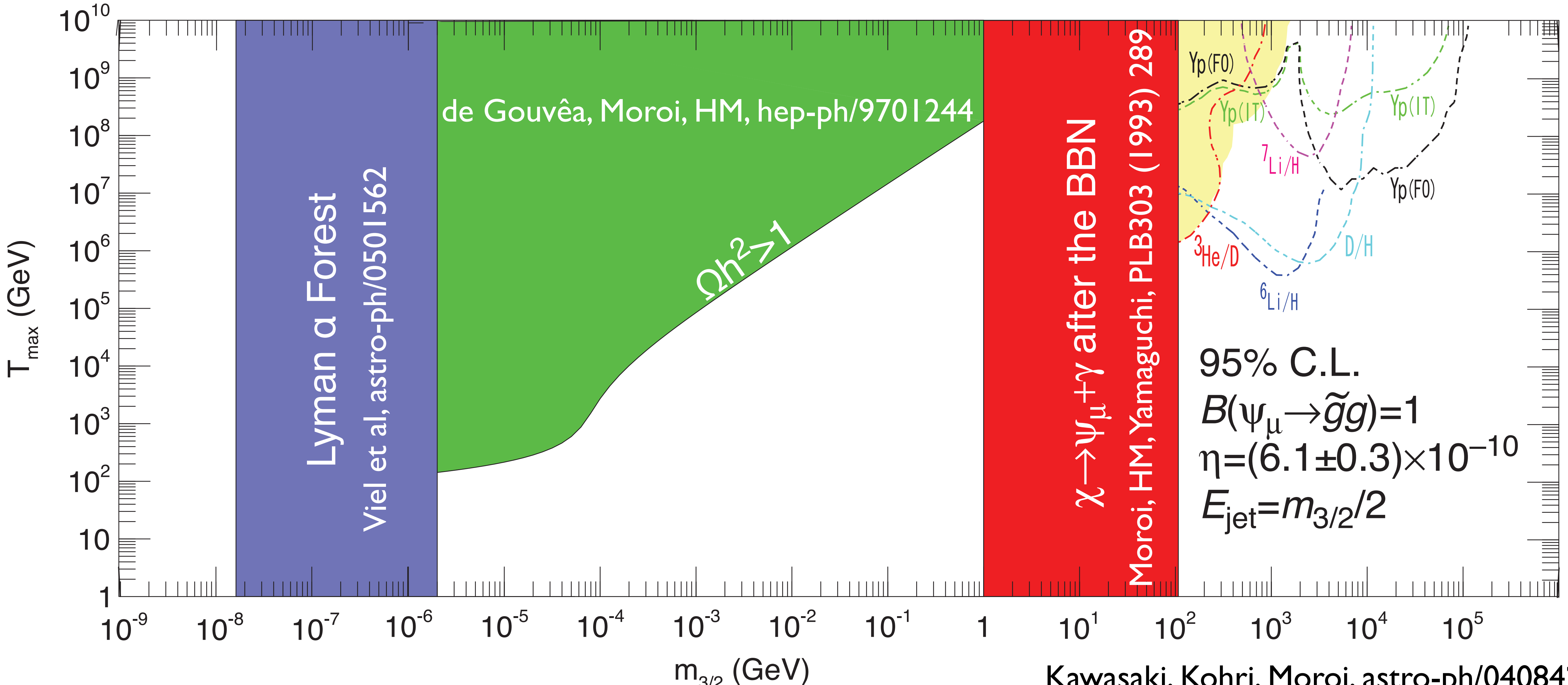

Kawasaki, Kohri, Moroi, astro-ph/0408426

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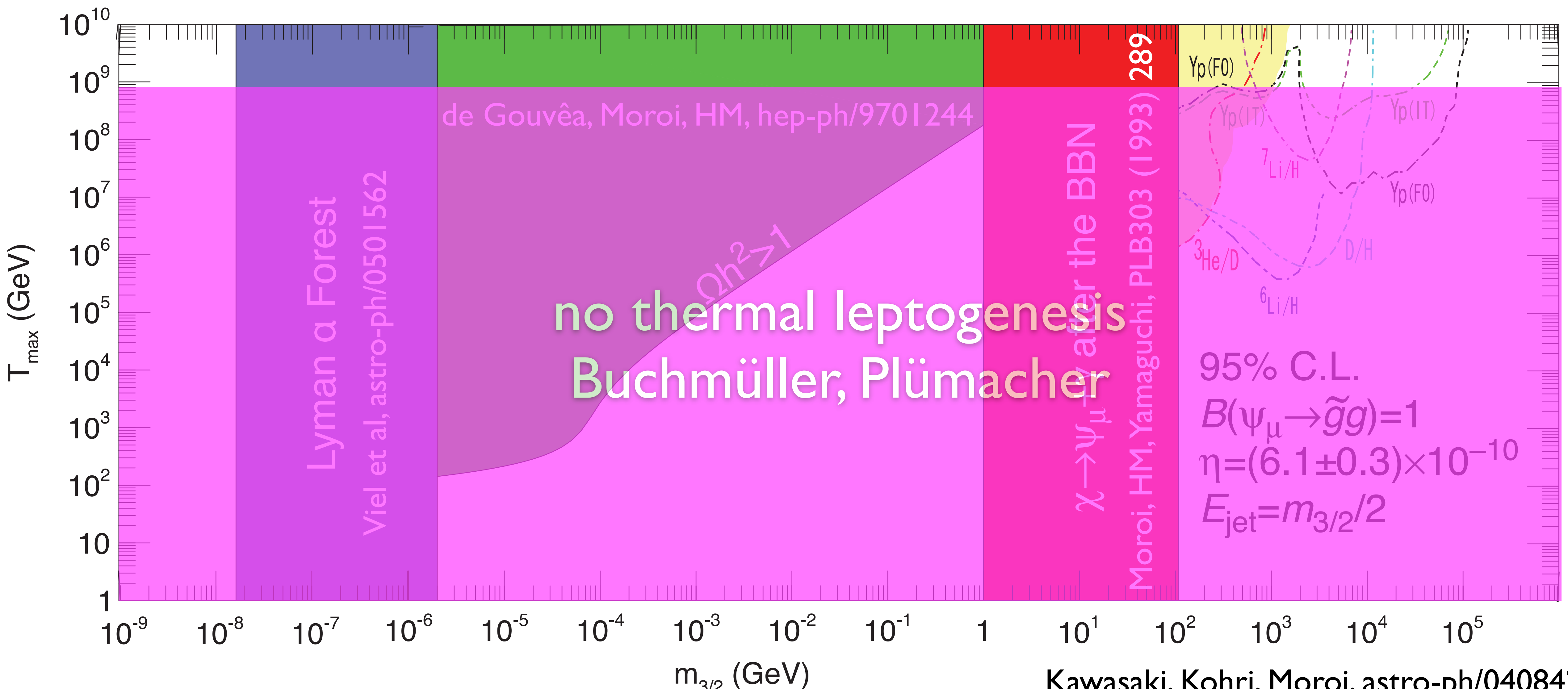

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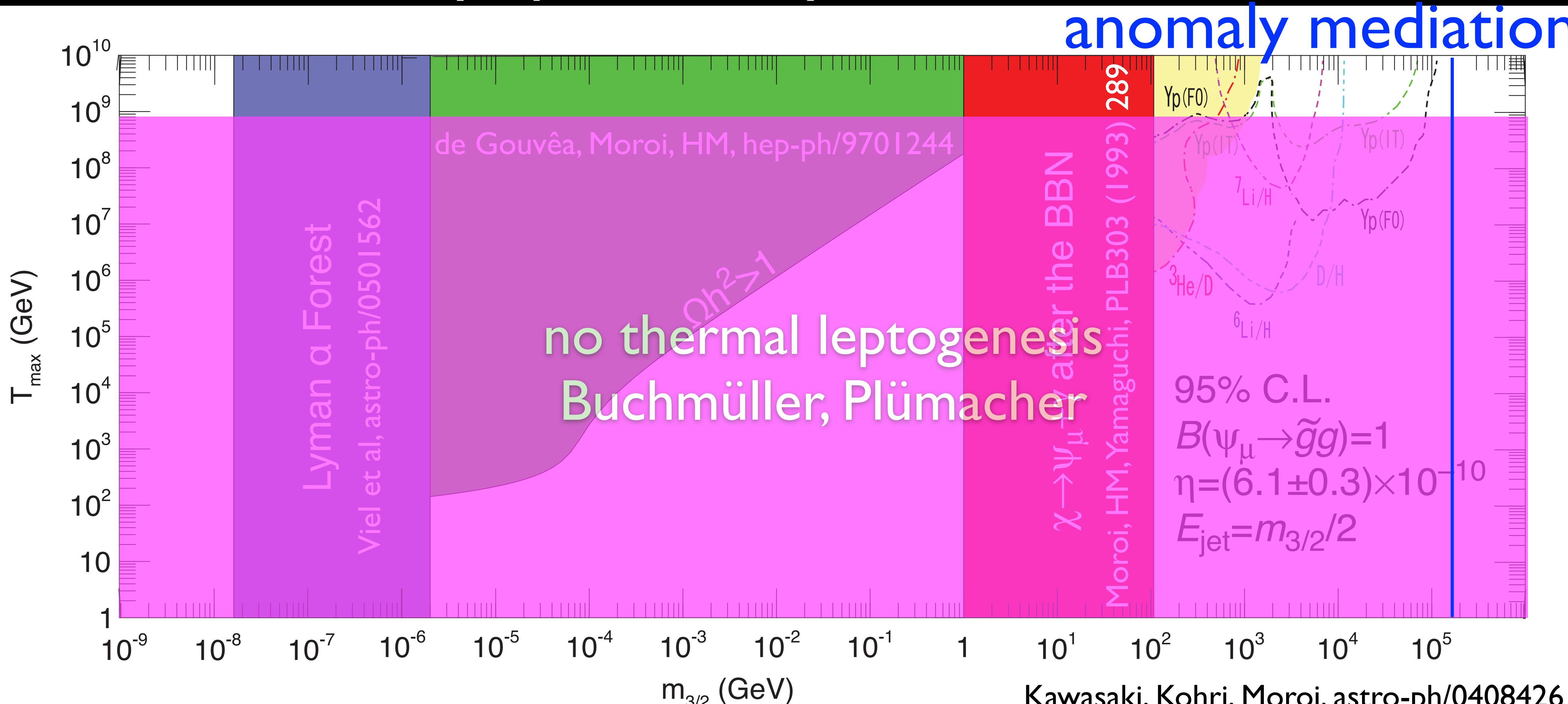

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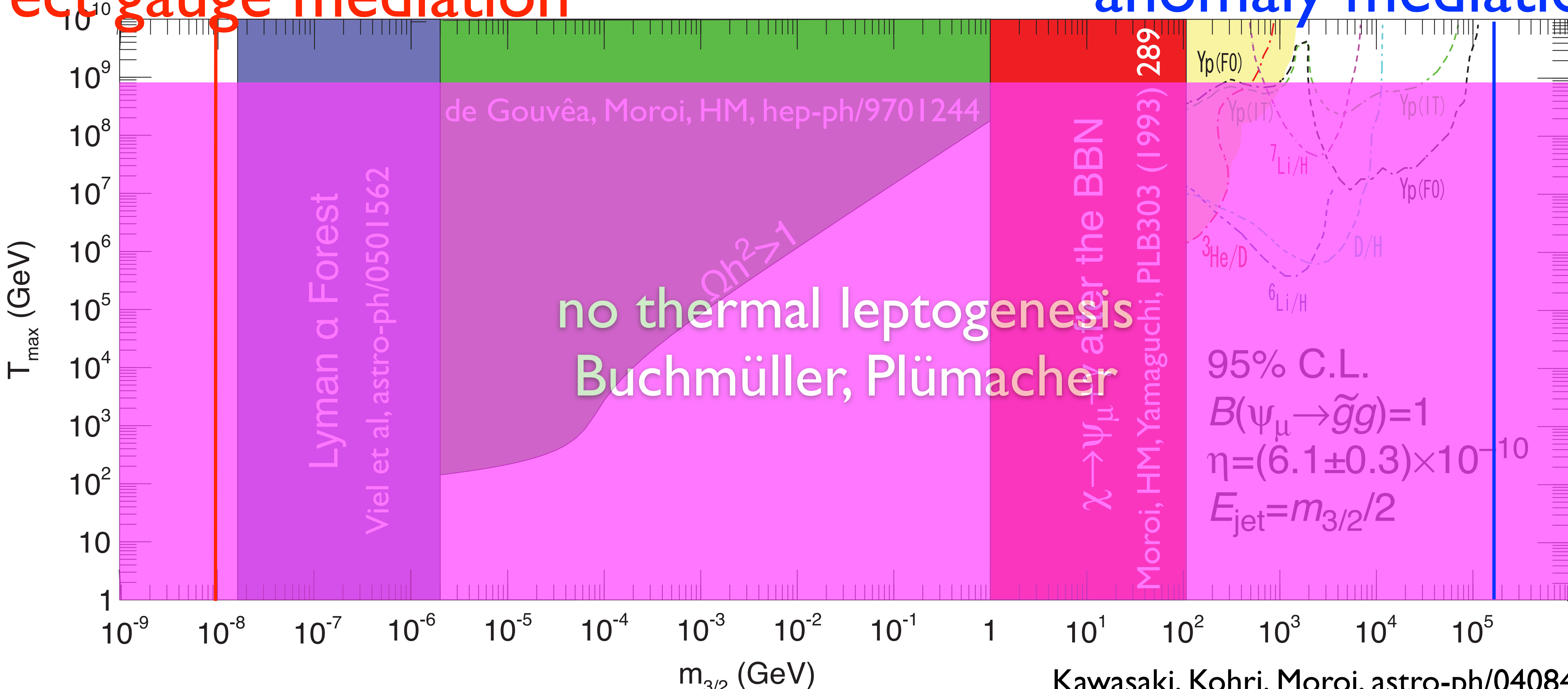
direct gauge mediation

anomaly mediation



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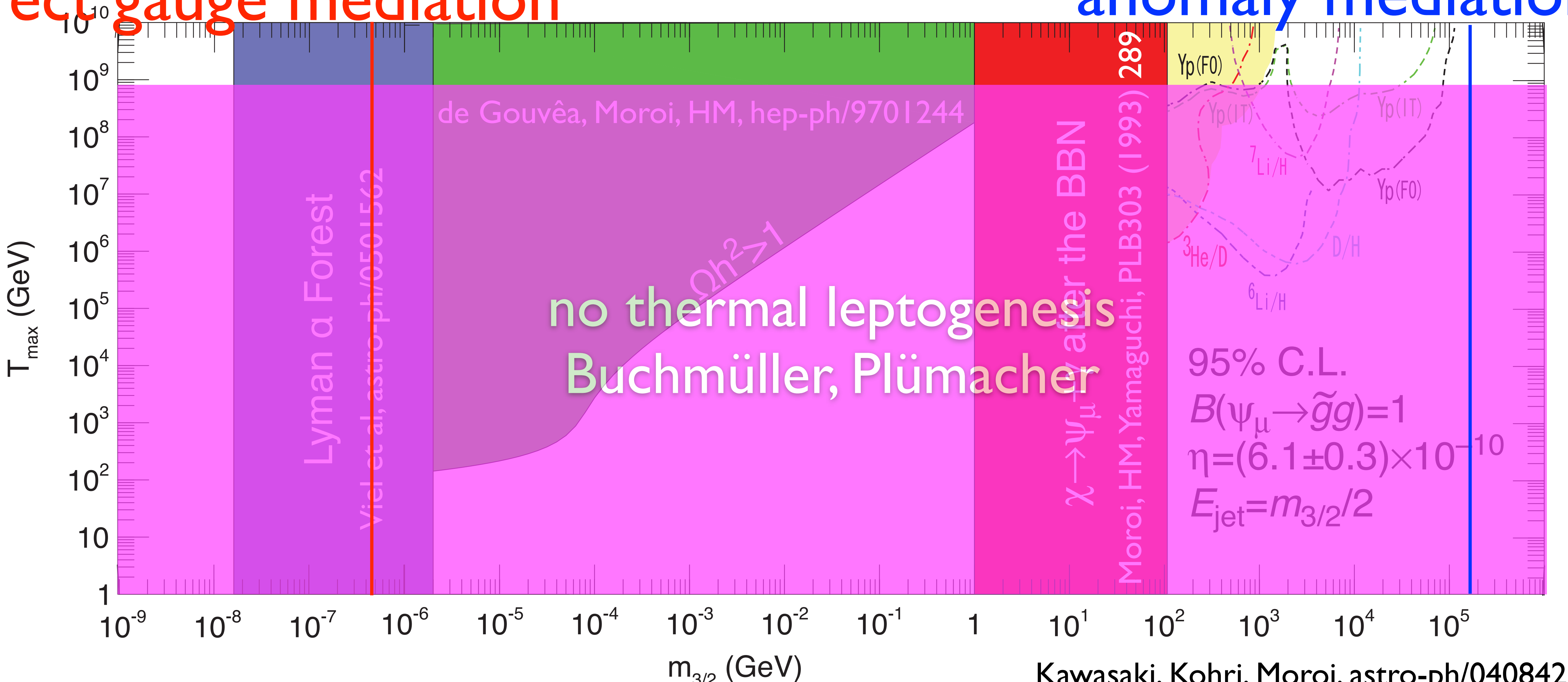
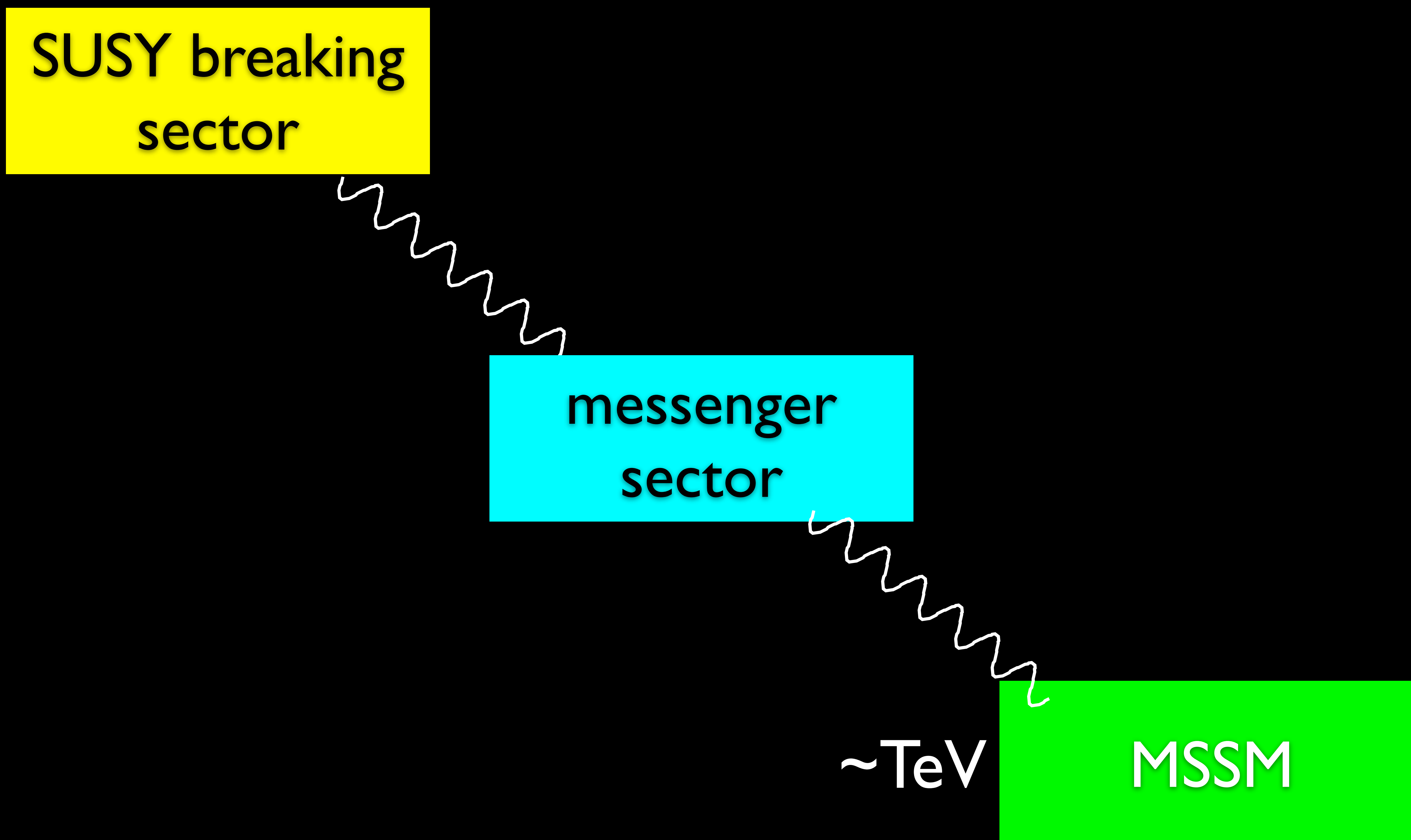


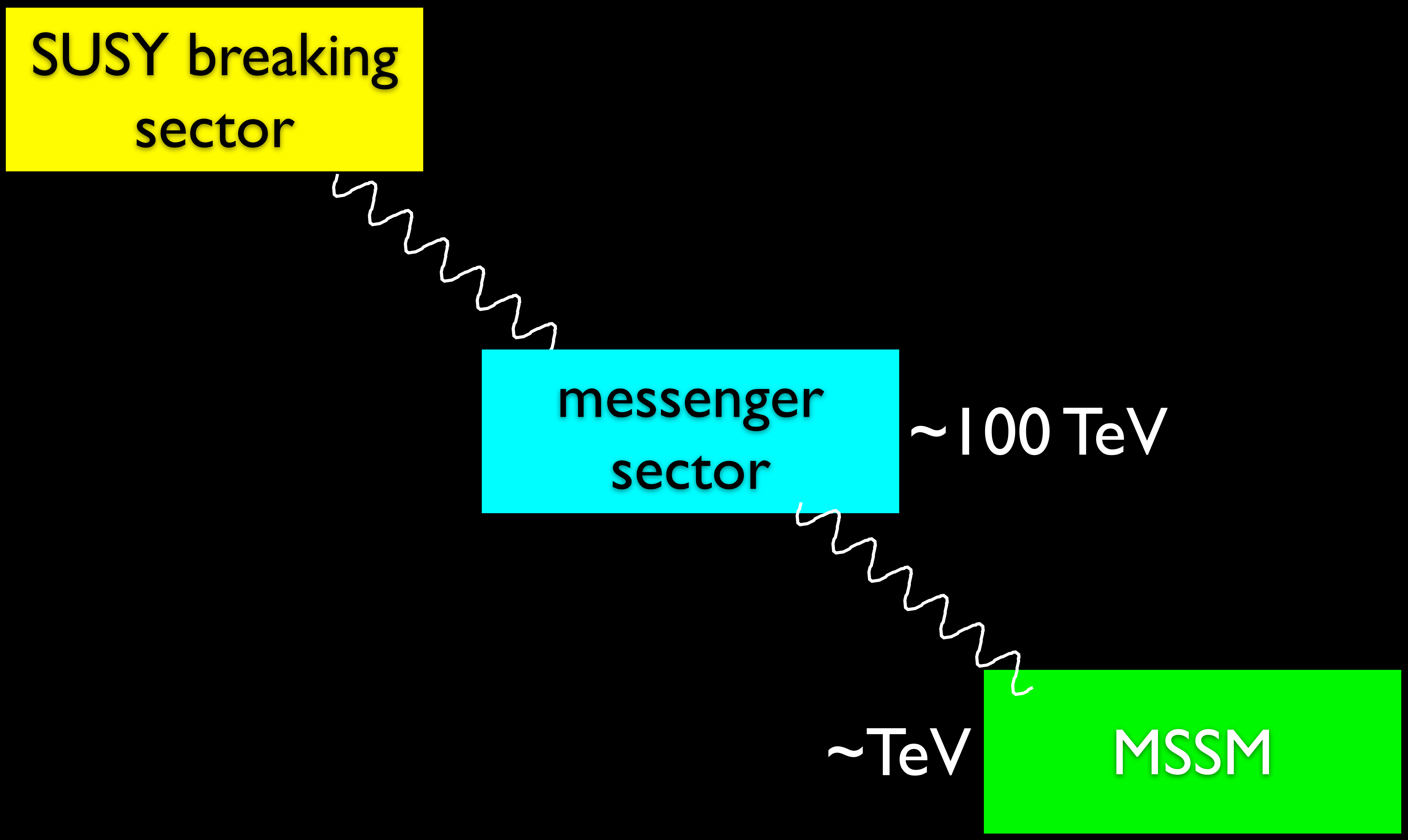
Kawasaki, Kohri, Moroi, astro-ph/0408426

original gauge mediation



Dine, Nelson, Shirman

original gauge mediation



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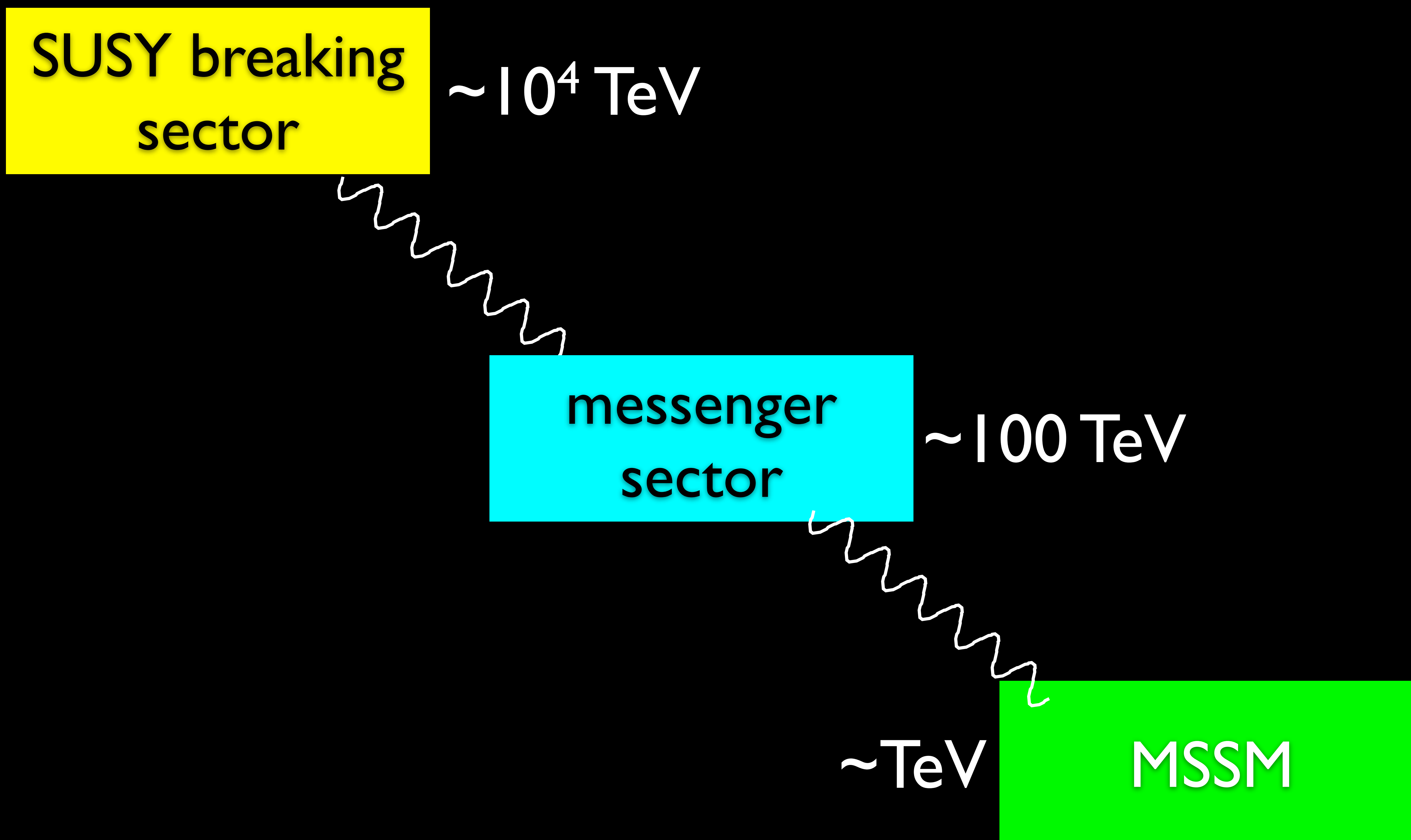

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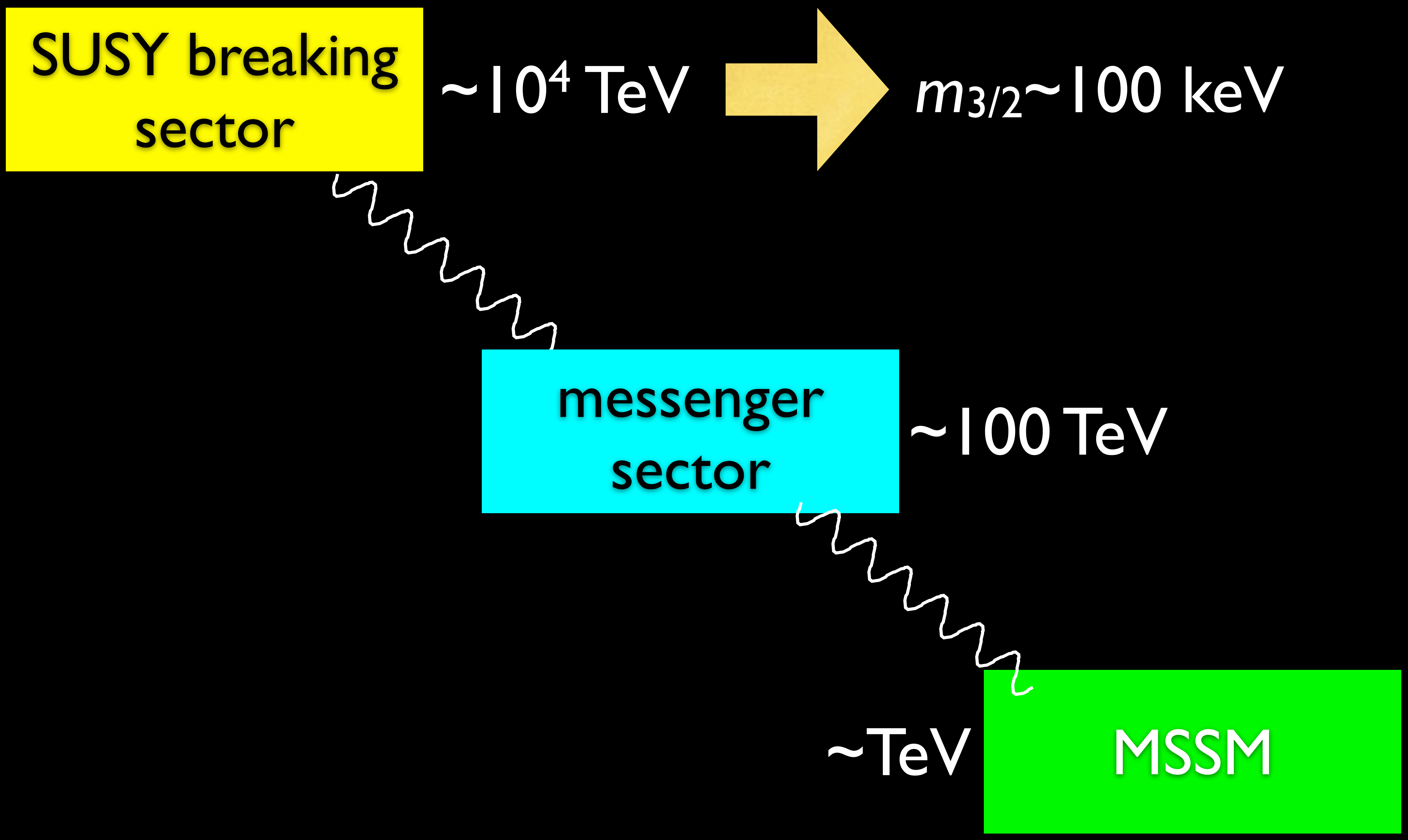

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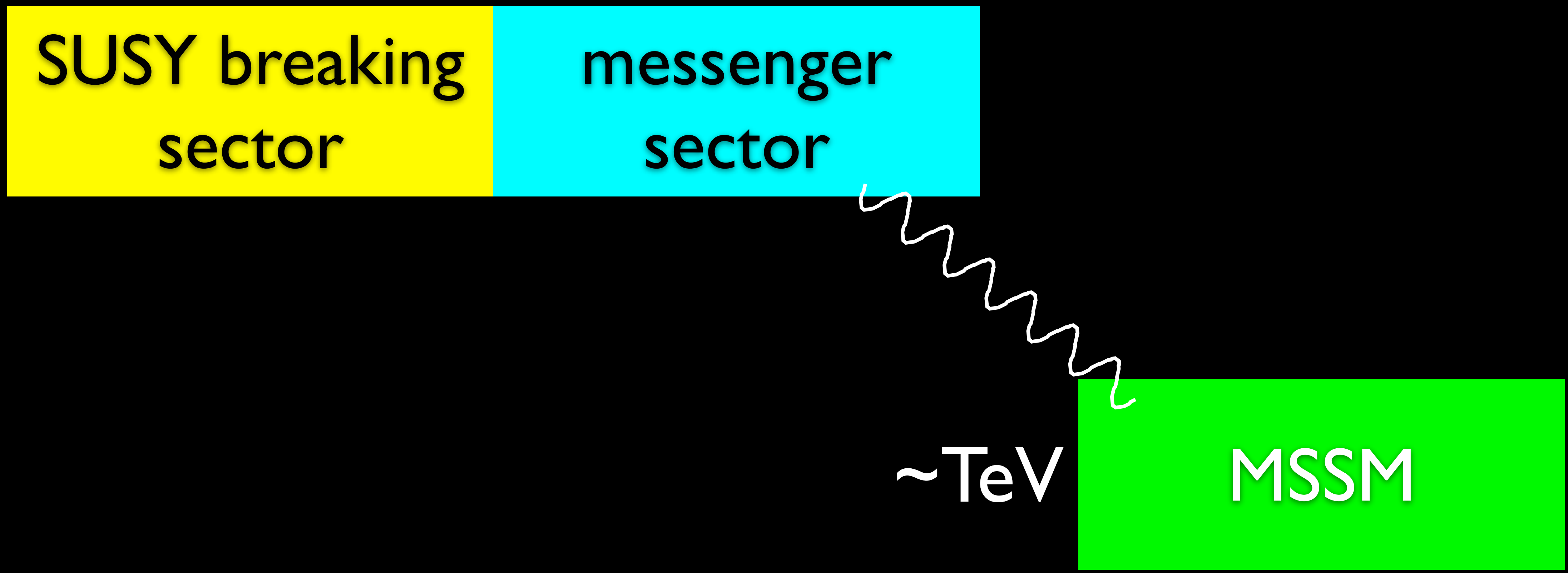

Arkani-Hamed, March-Russell, HM

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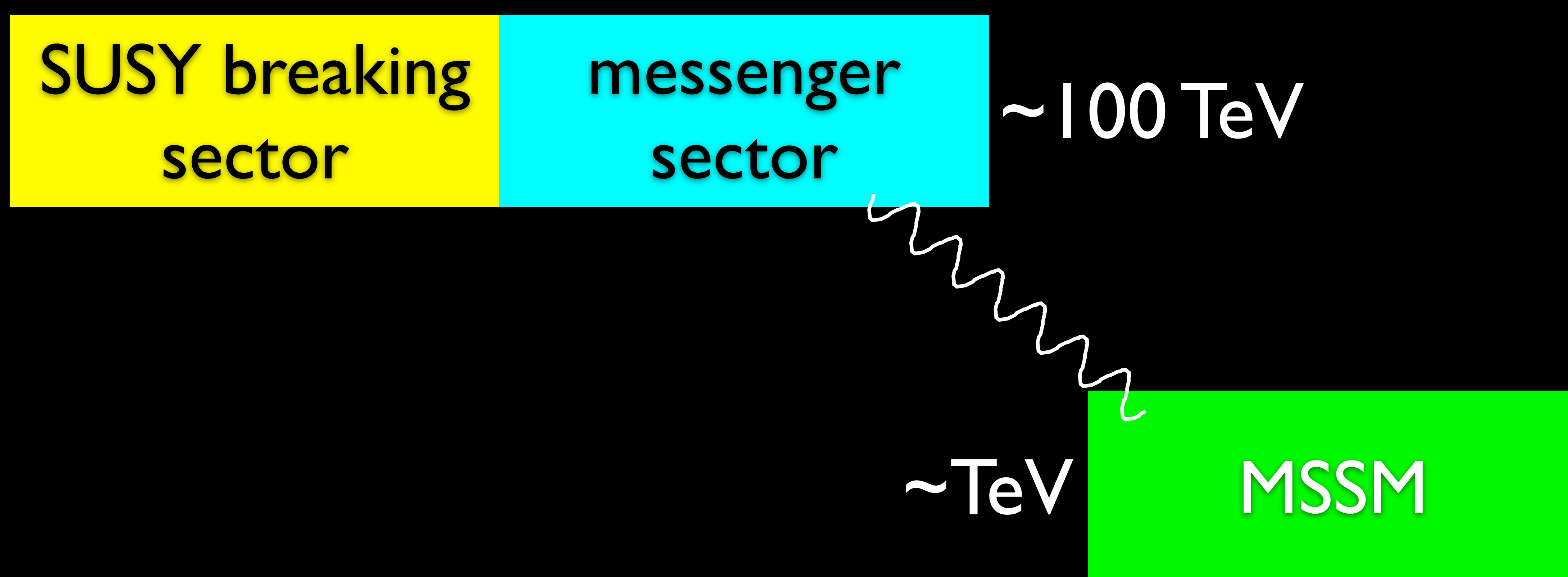

Arkani-Hamed, March-Russell, HM

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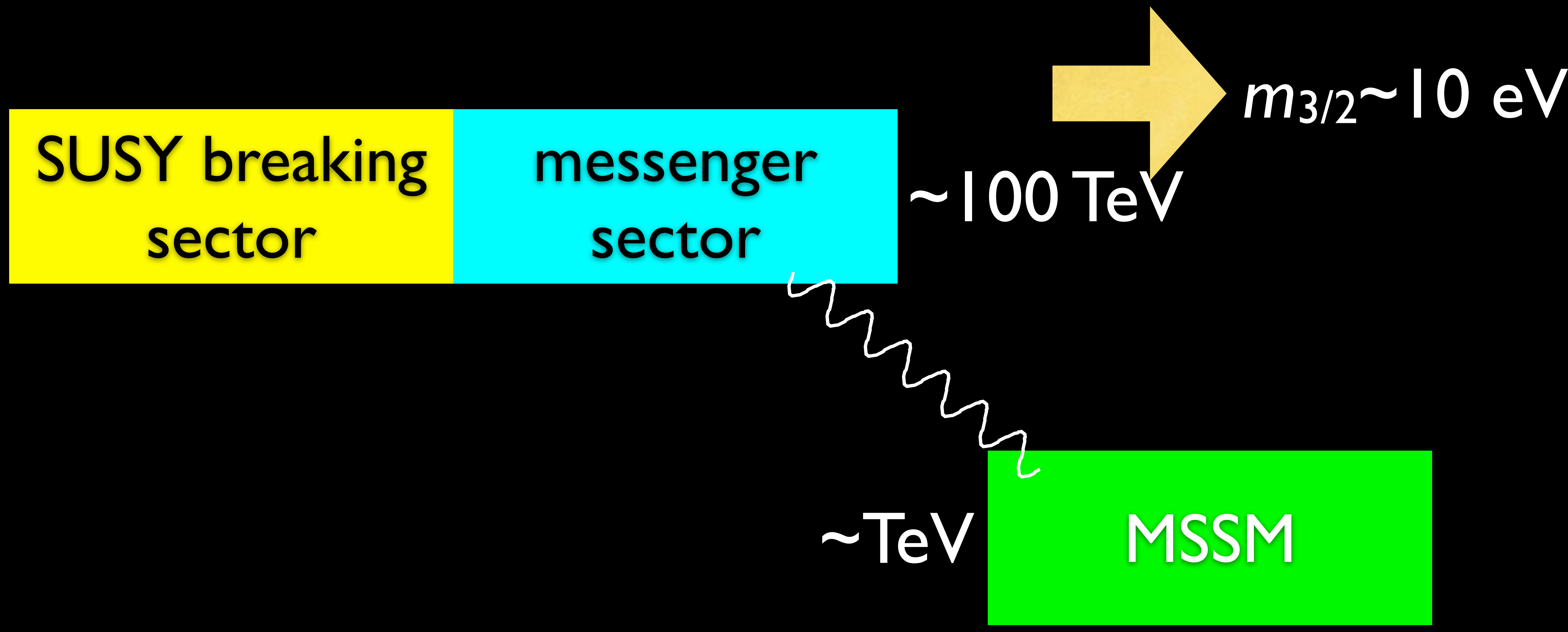
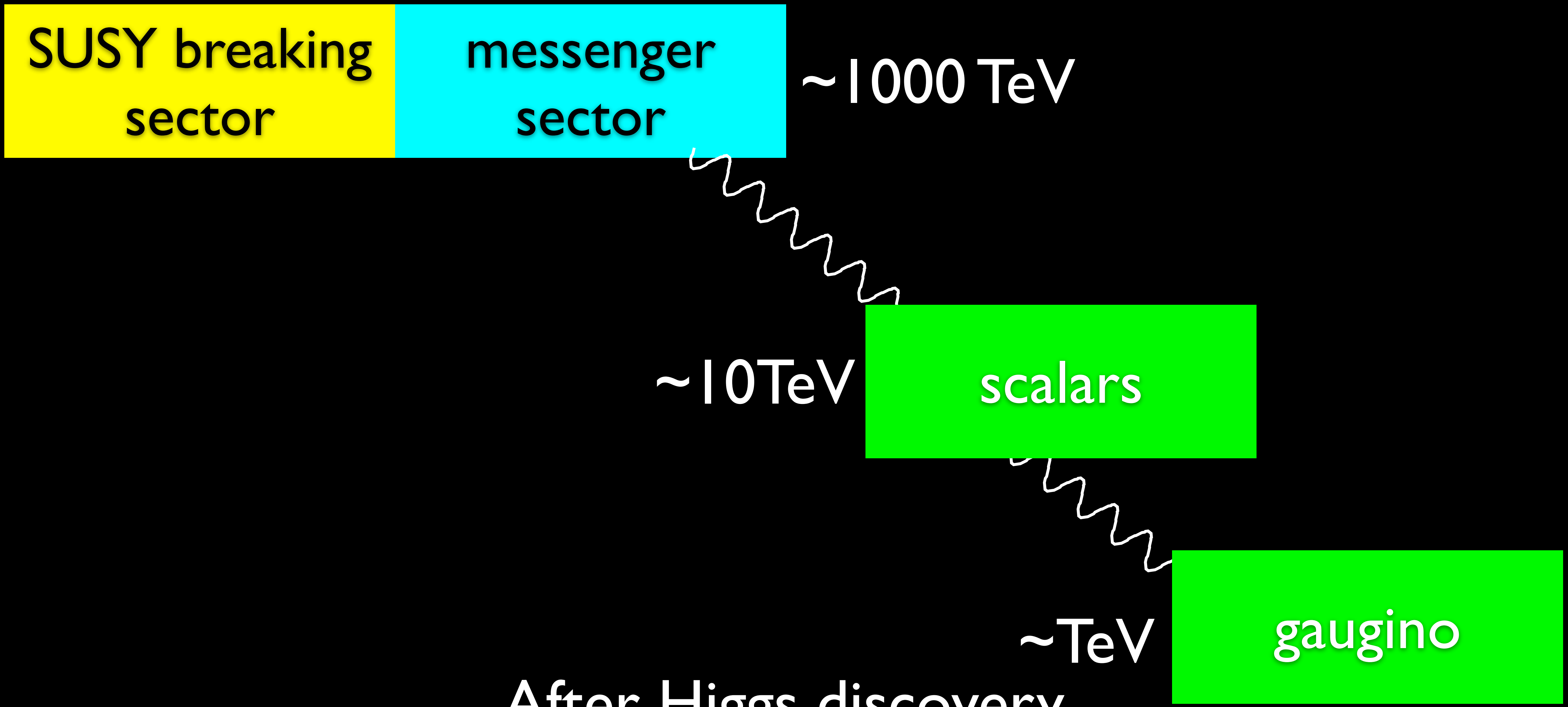


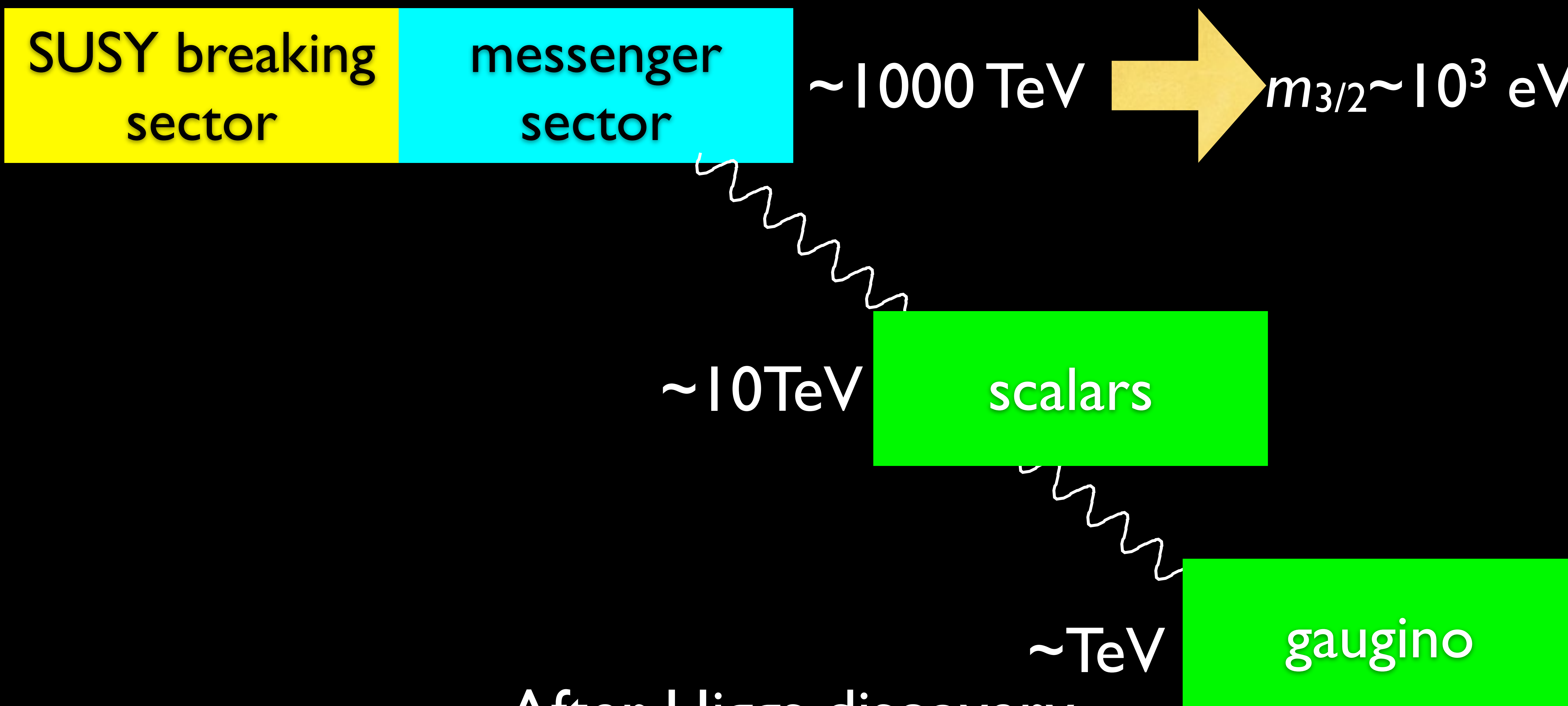
Arkani-Hamed, March-Russell, HM

direct gauge mediation?



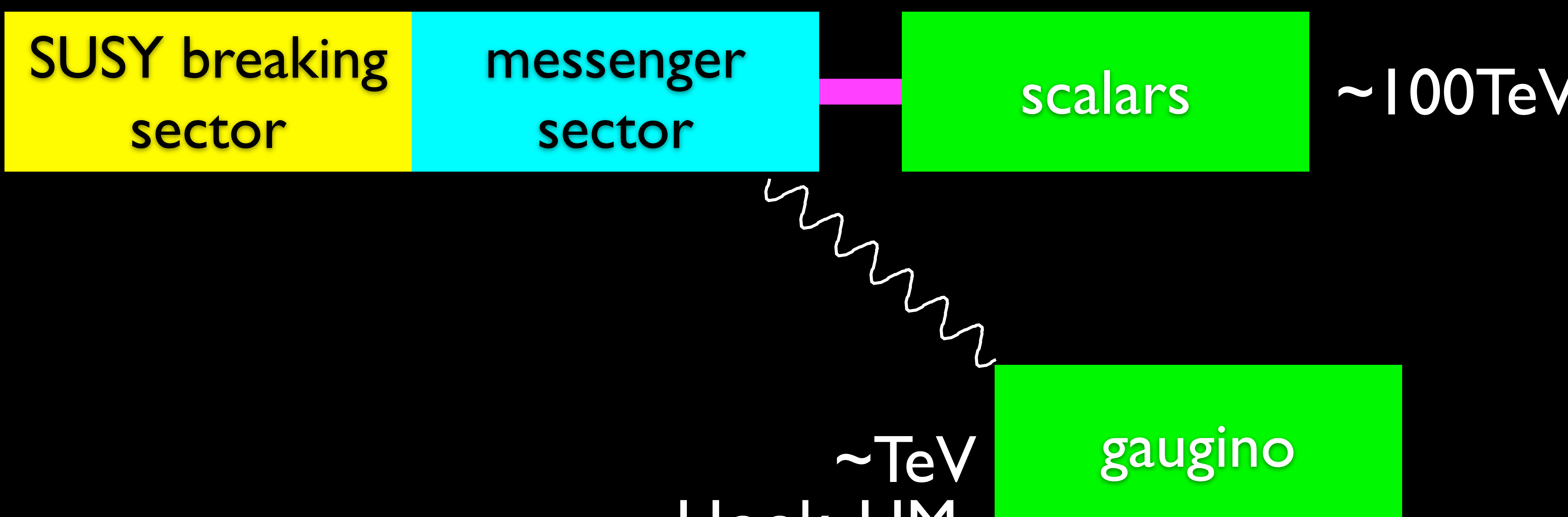
After Higgs discovery

direct gauge mediation?



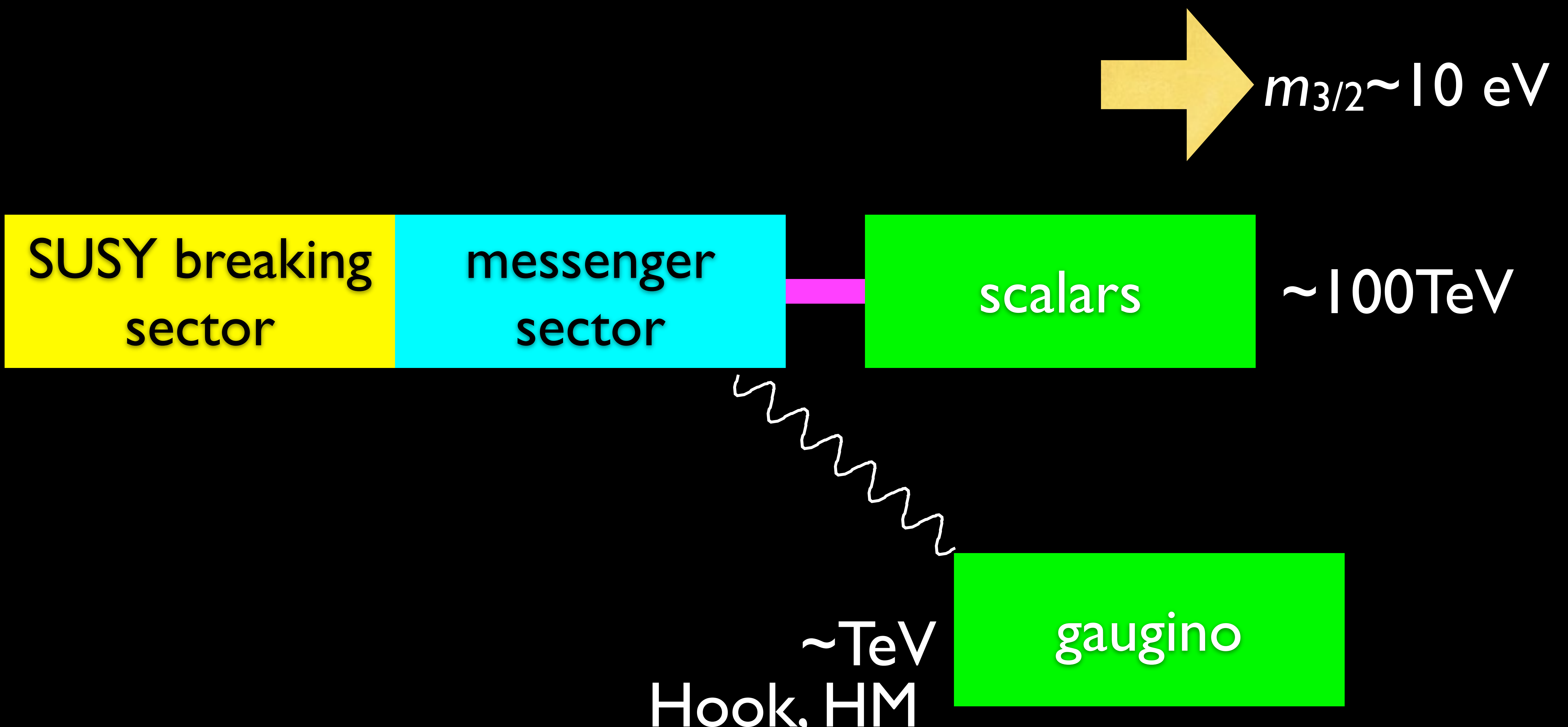
After Higgs discovery

vector mediation



Hook, HM

vector mediation



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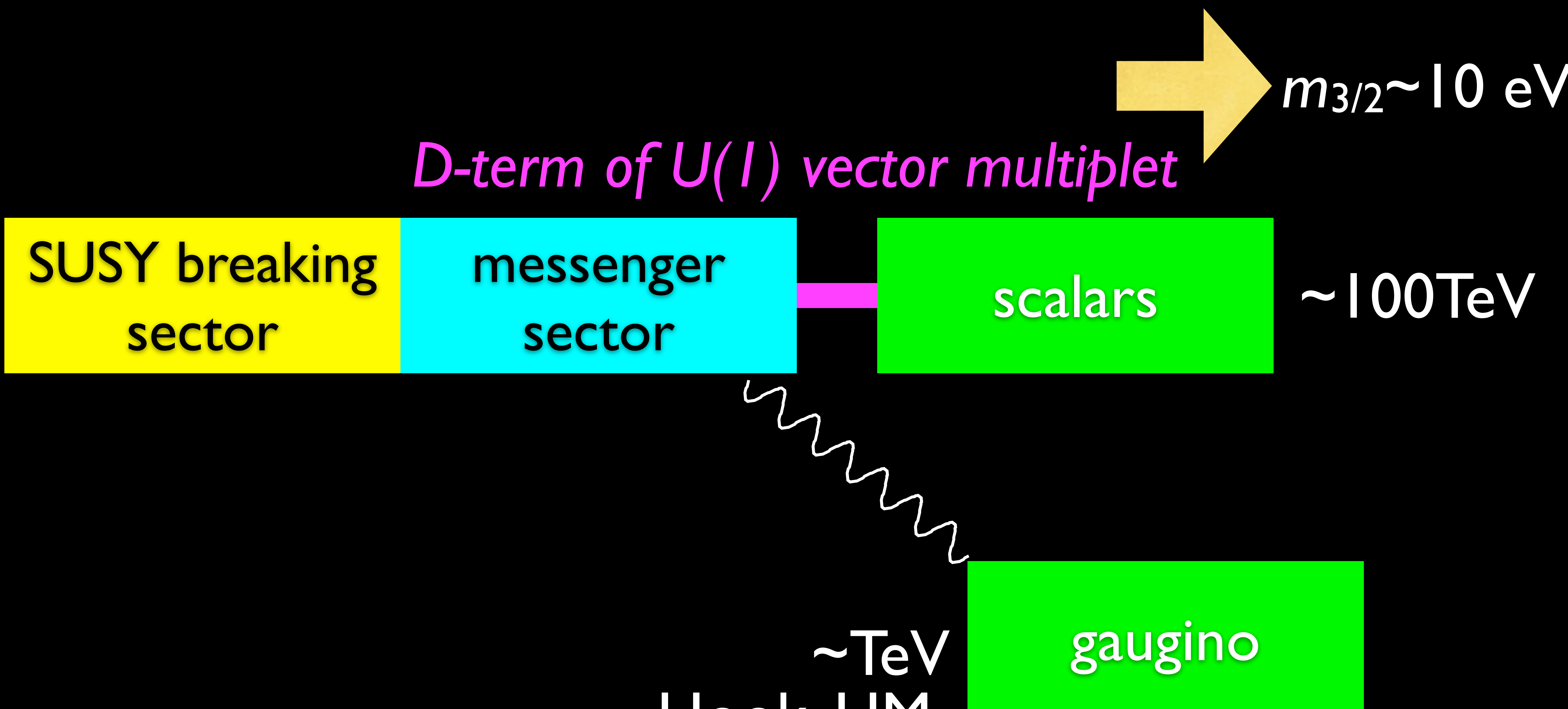
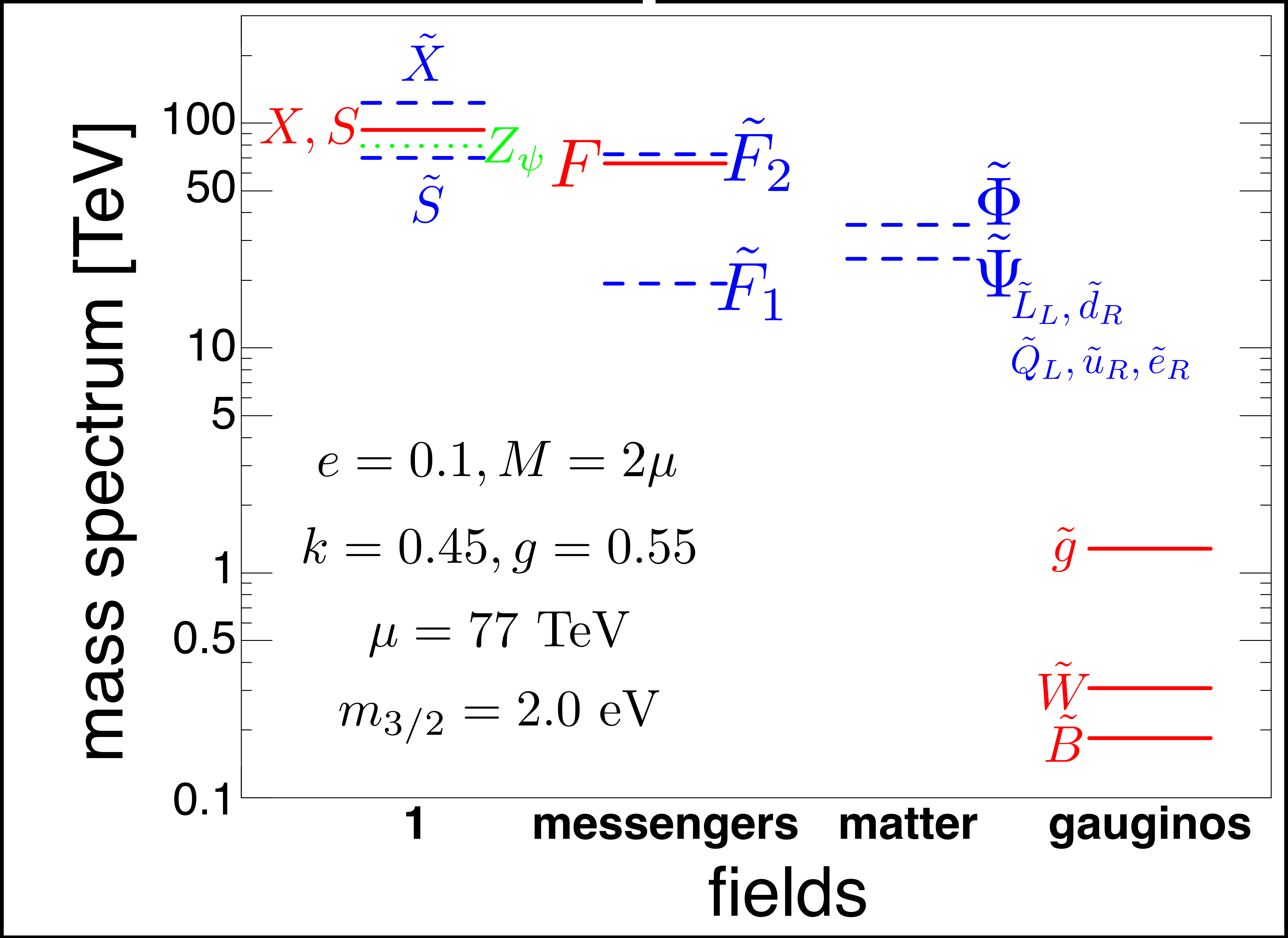


Hook, HM

mass spectrum



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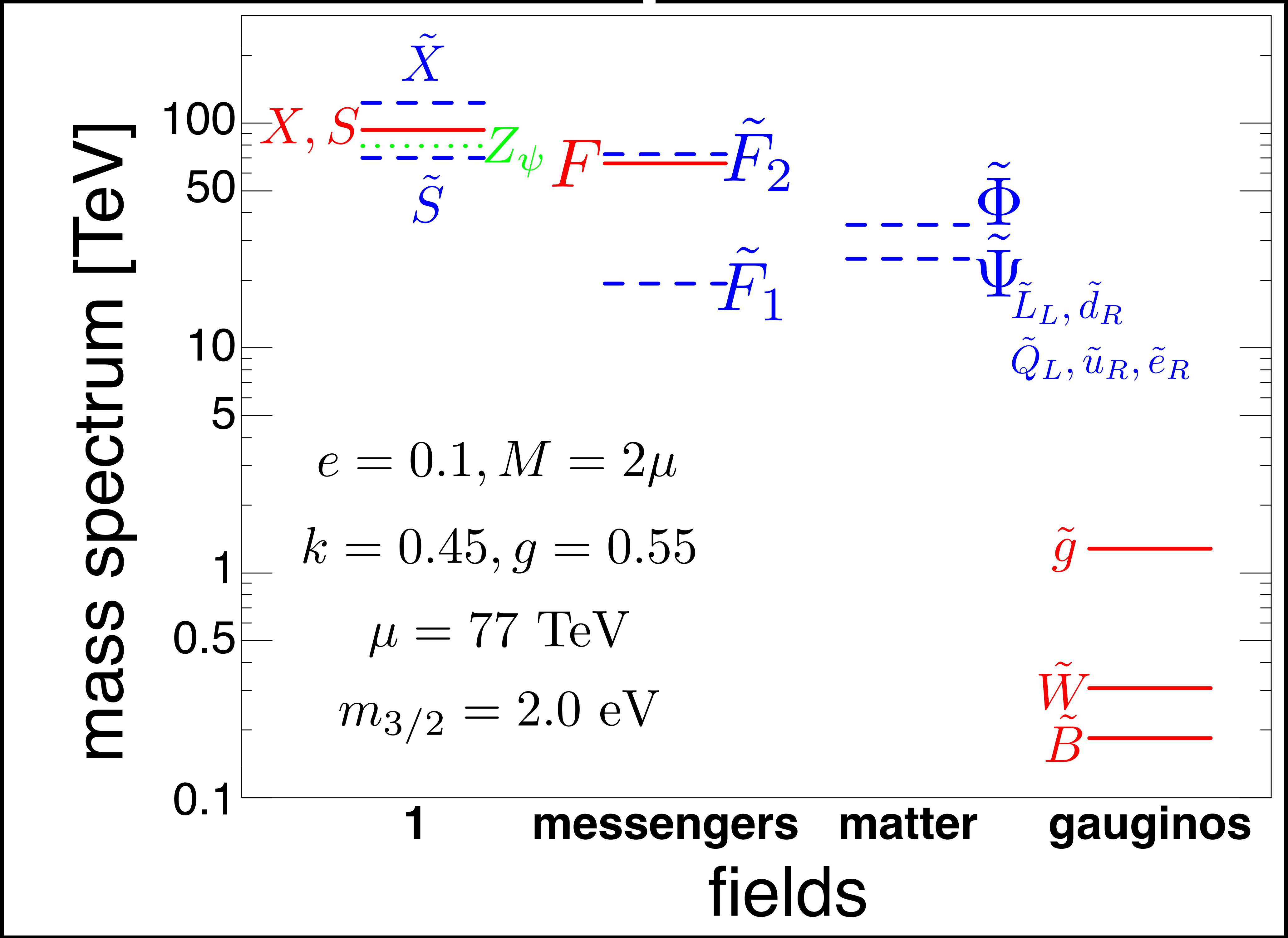

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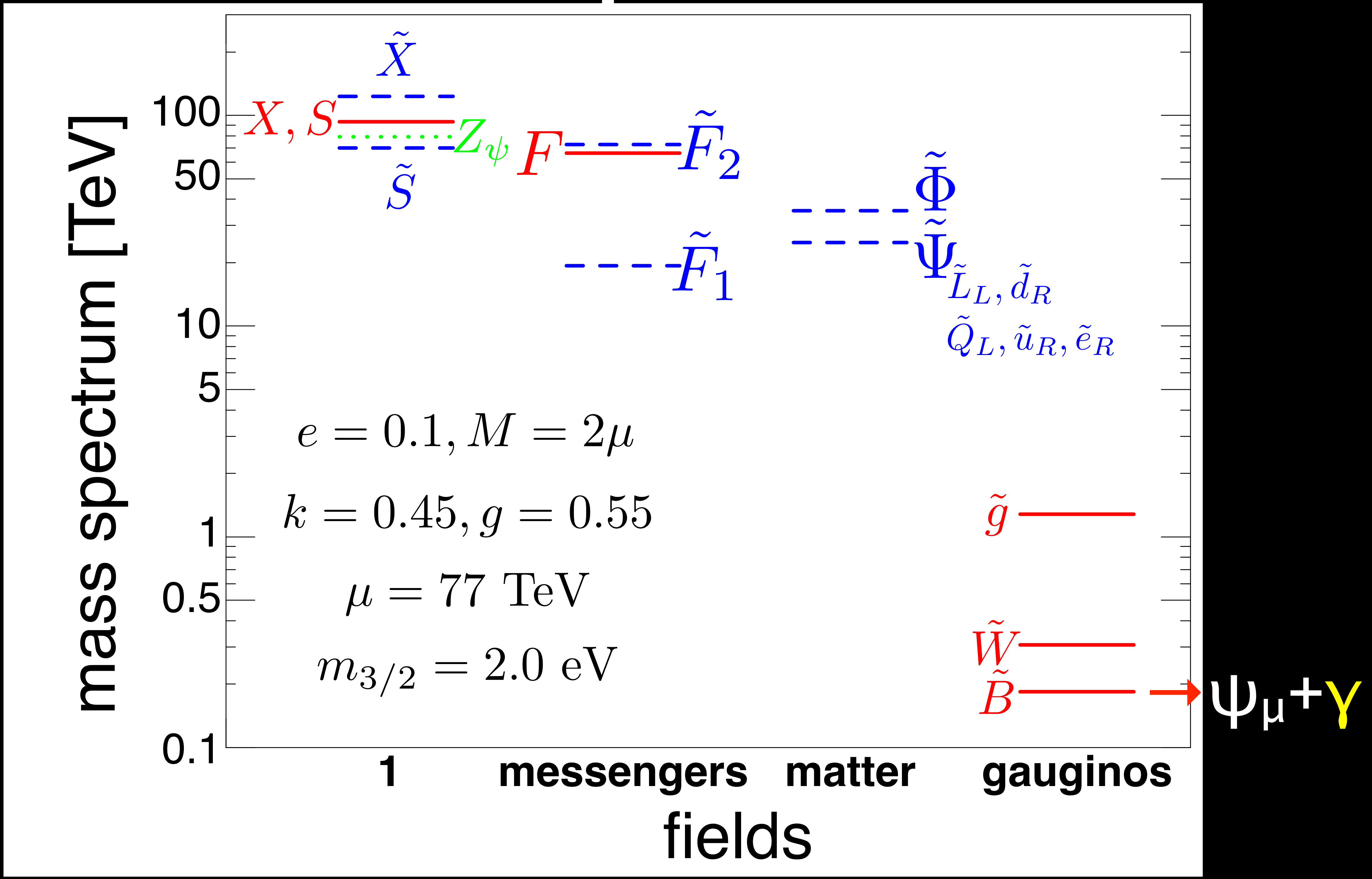

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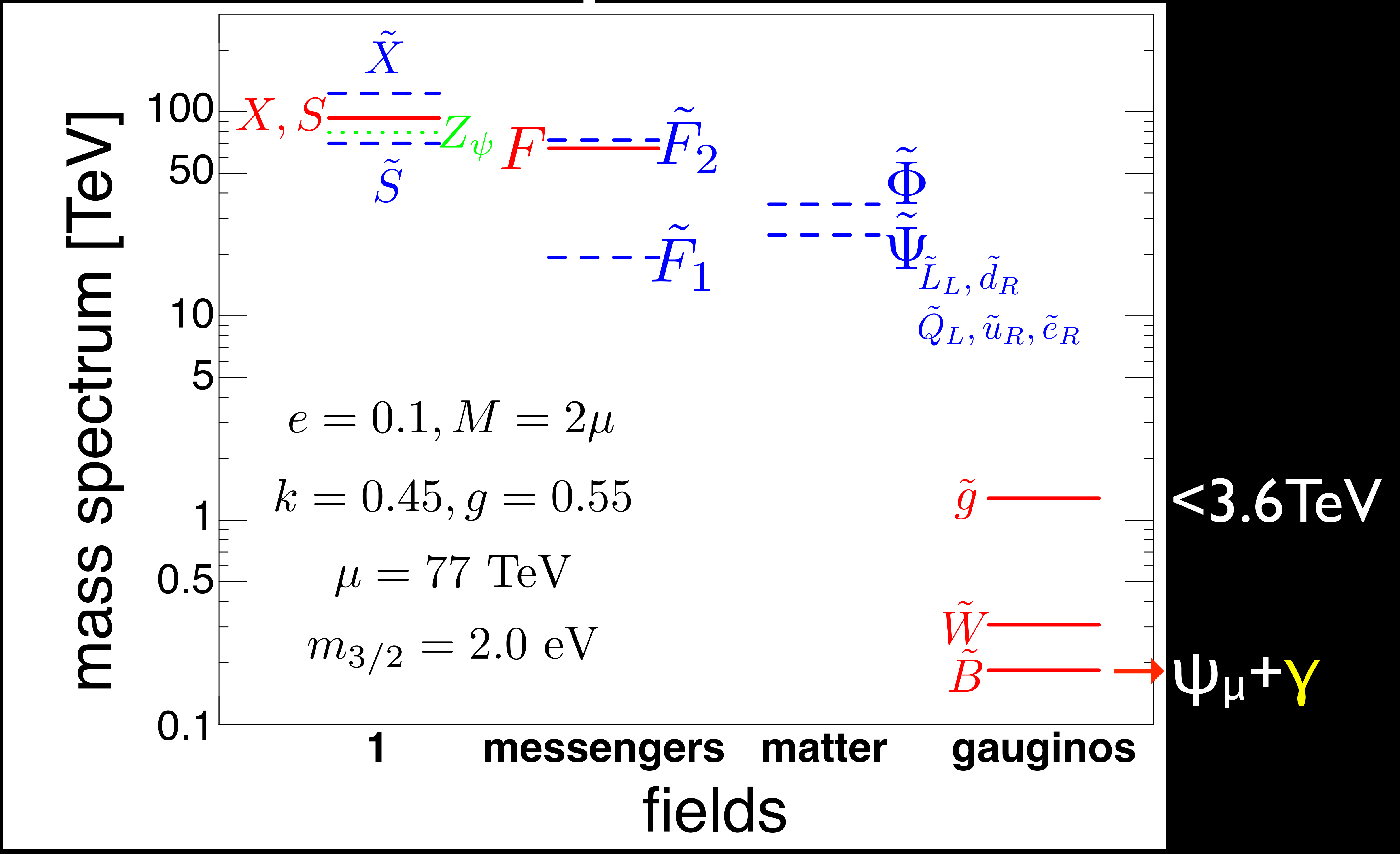

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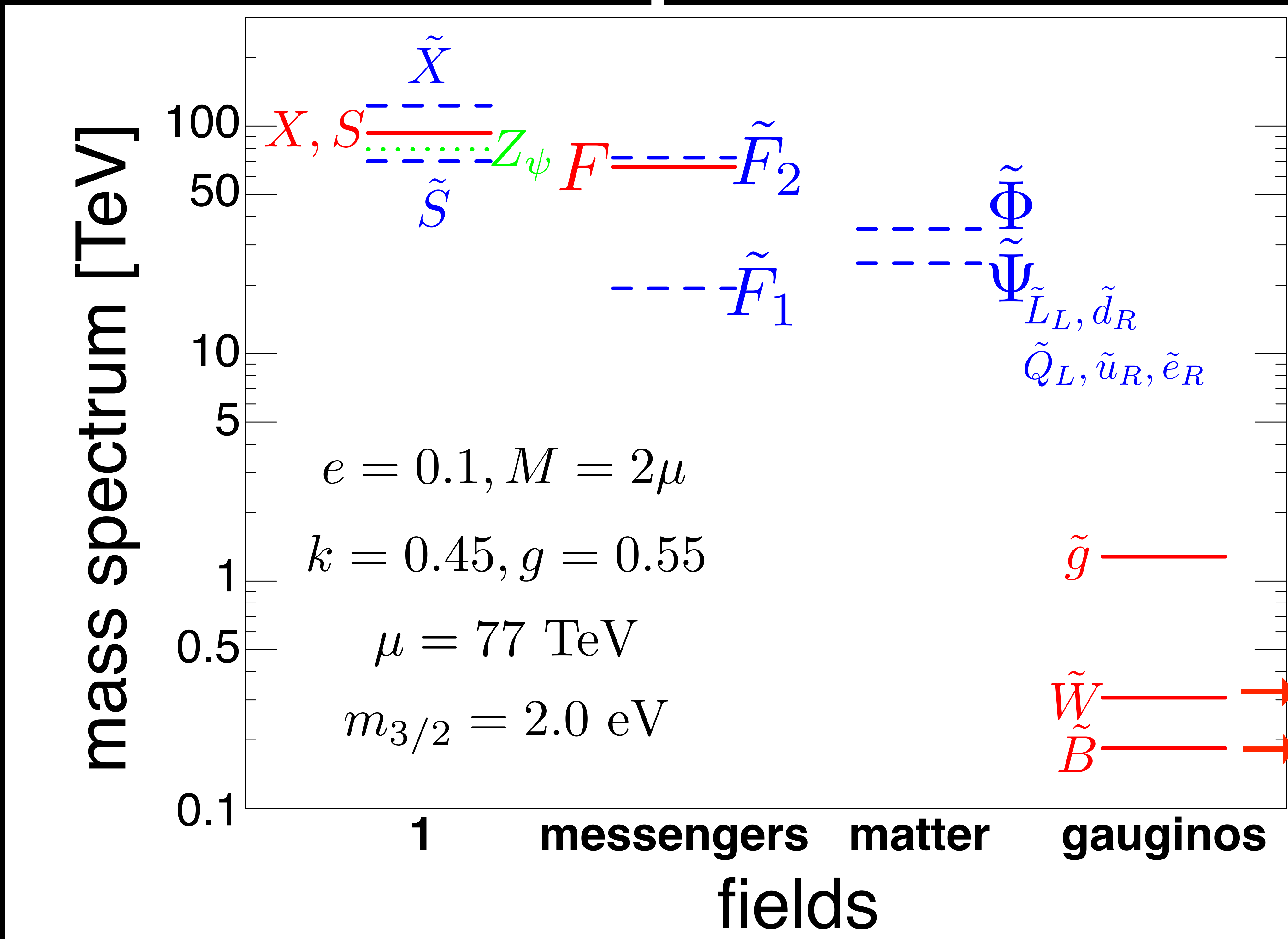

<3.6TeV

ILC1000

$\psi_\mu + \gamma$

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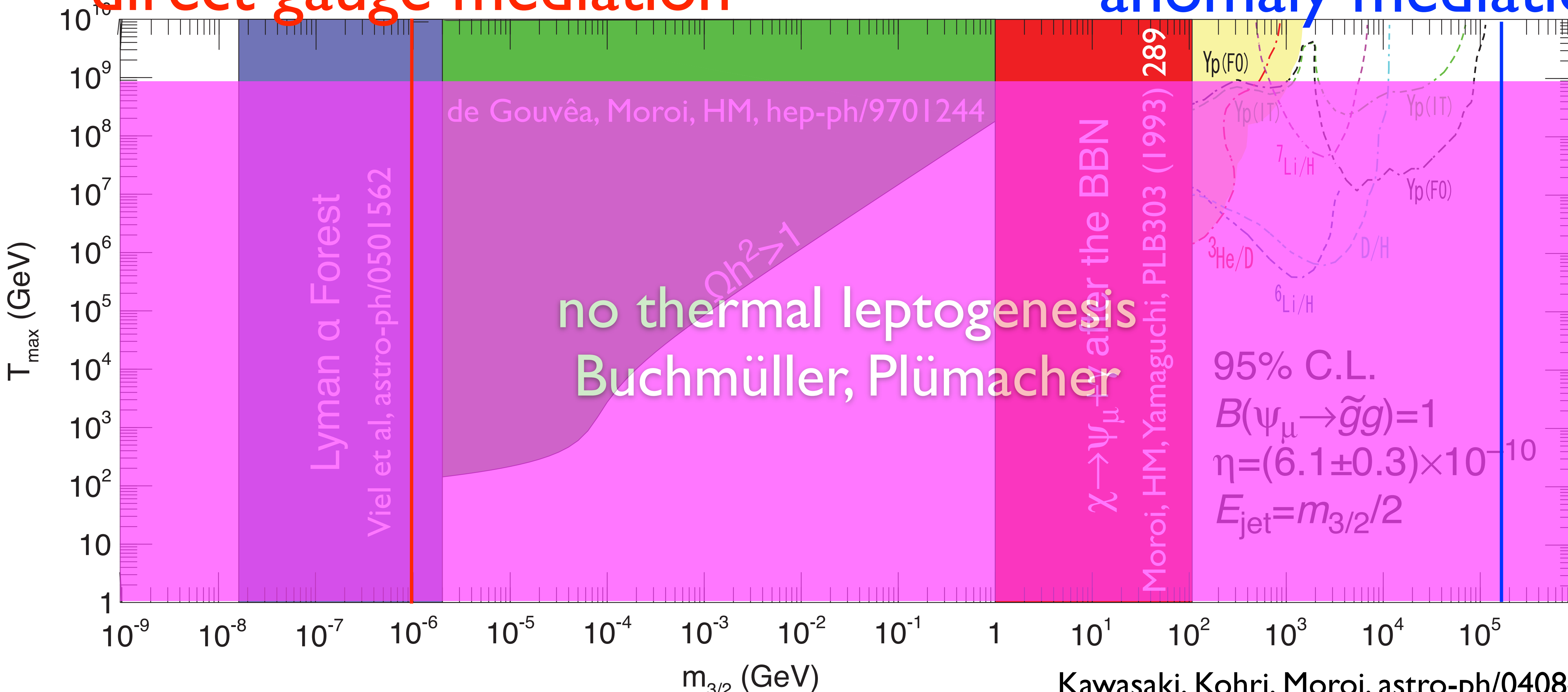

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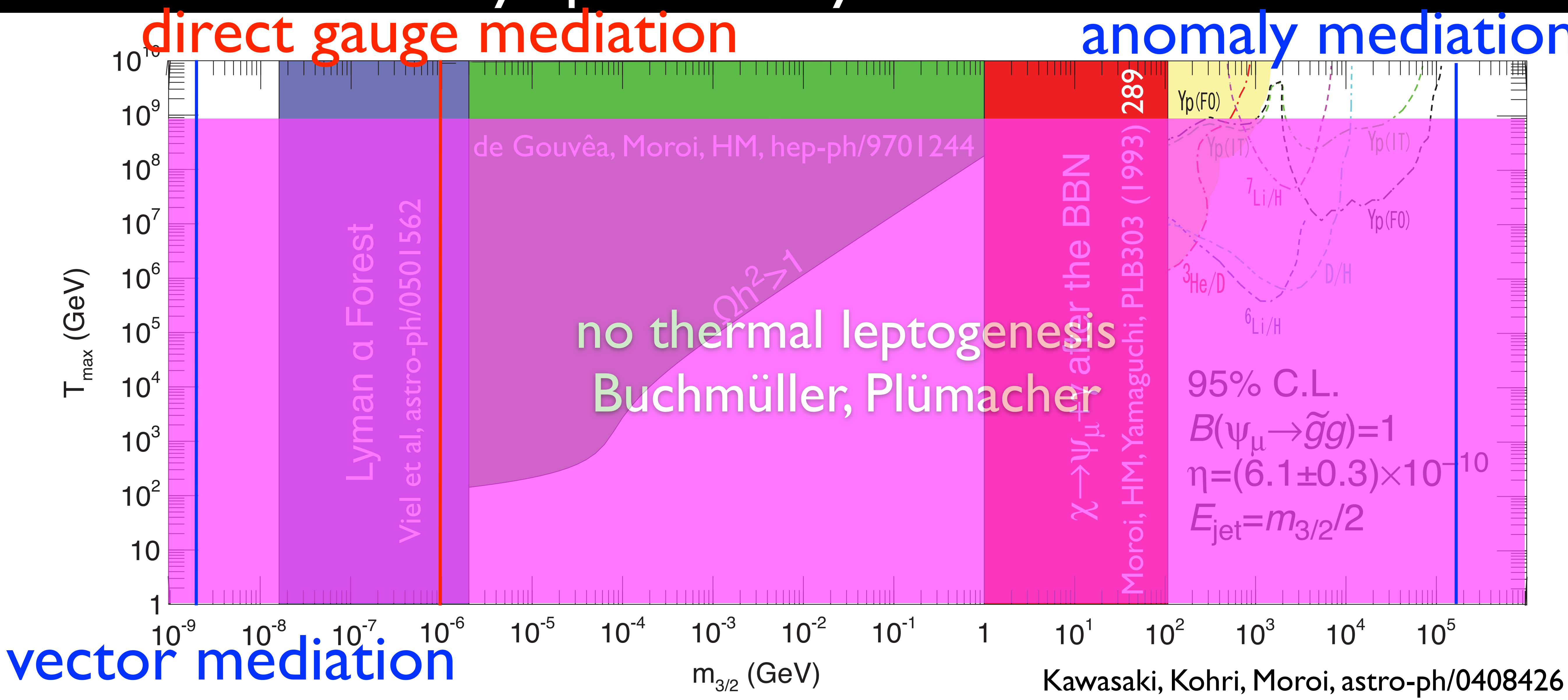

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moduli

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- moduli mass expected to be comparable to the gravitino mass
- modulus coherent oscillation can be dark matter (de Gouvêa, HM, Moroi, hep-ph/9701244)

$$\phi_0 \approx \left(\frac{T_{eq}^2 M_{Pl}^3}{m_\phi} \right)^{1/4} = (3 \times 10^{11} \mathrm{GeV}) \left(\frac{\mathrm{eV}}{m_\phi} \right)^{1/4}$$

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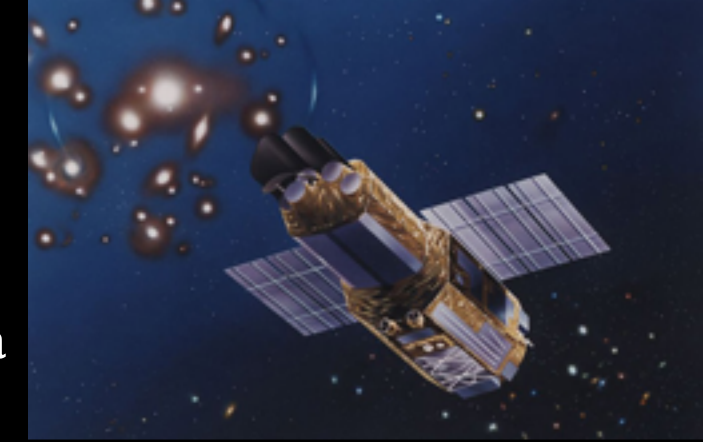
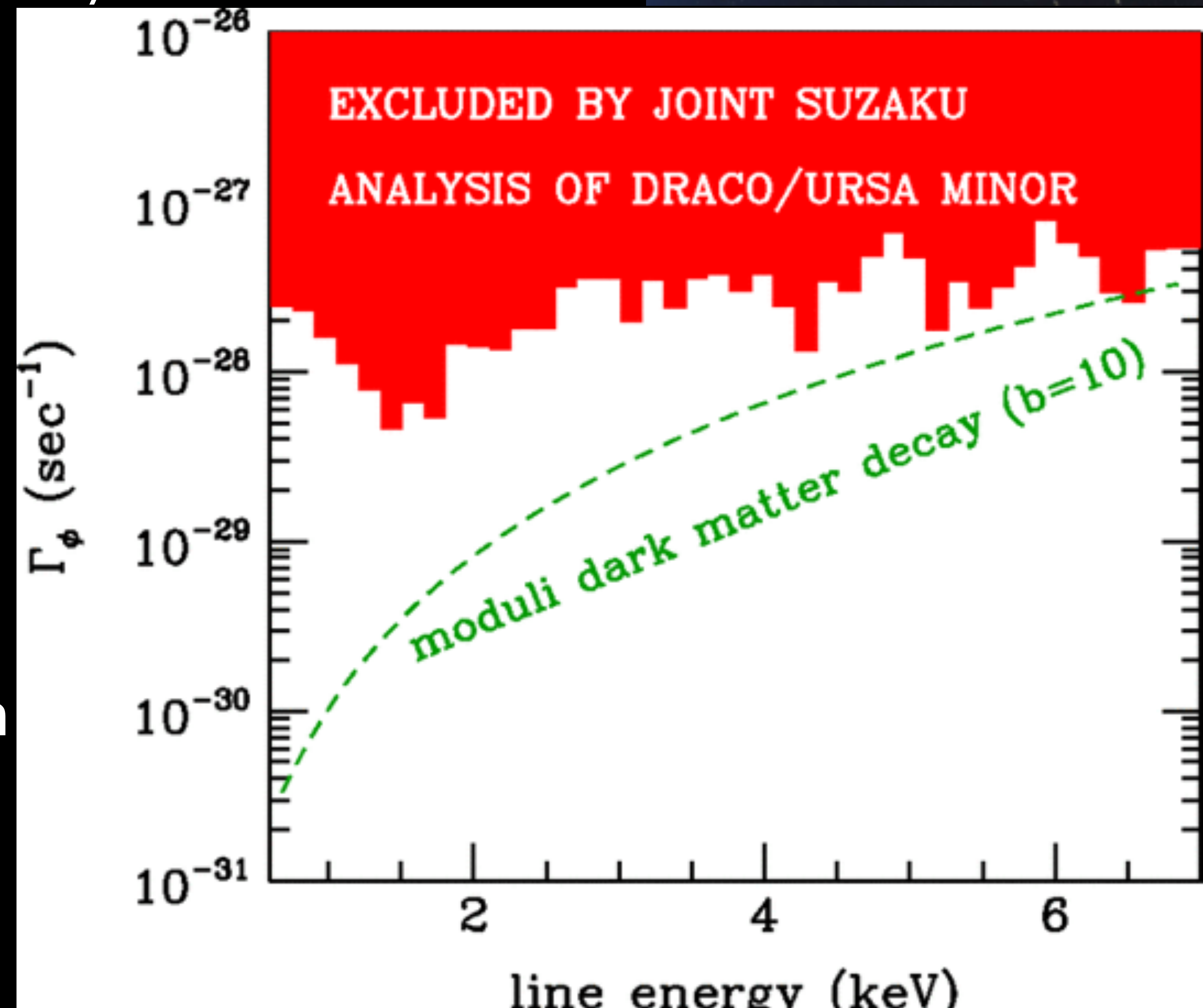


moduli

Kusenko, Lowenstein, Yanagida
Phys. Rev. D 87, 043508



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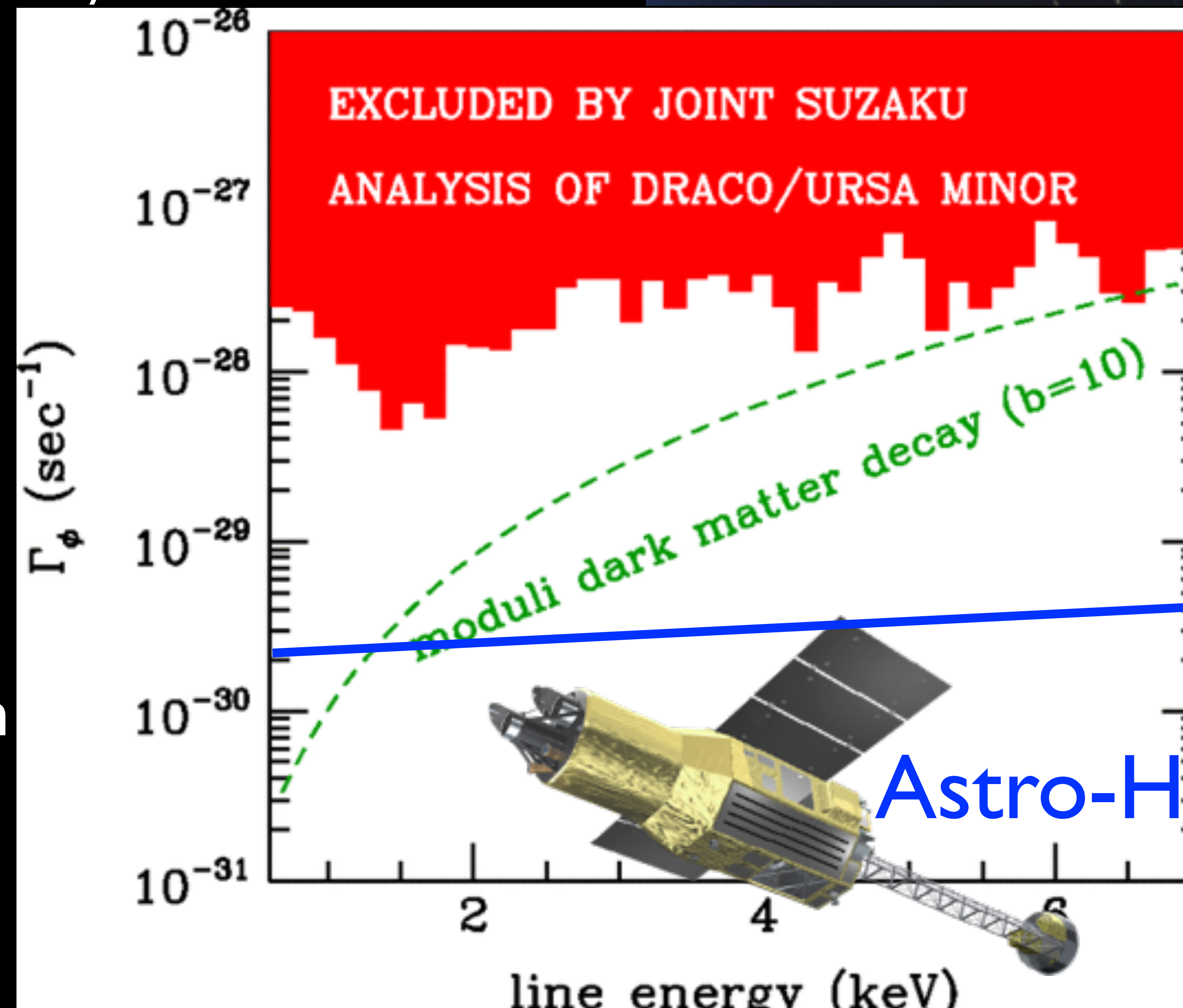

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inVisibles

neutrinos, dark matter & dark energy physics

Meet Visibles


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Dark Energy

It's Λ, forget it!

It's Λ, forget it!

It's Λ, forget it!

- think about a theorist during inflation
- argues for anthropic view and discourage measuring *w*
- misses the opportunity to predict $n_s \neq 1$, end of inflation
- the effect was a few percent
- You'll be sorry if you didn't

SuMIRe

Subaru Measurement of Images and Redshifts

- Subaru: 8.2 m, excellent seeing 0.6”

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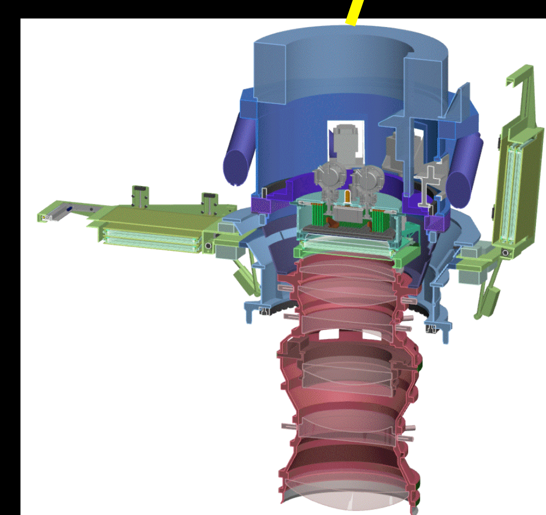

HSC

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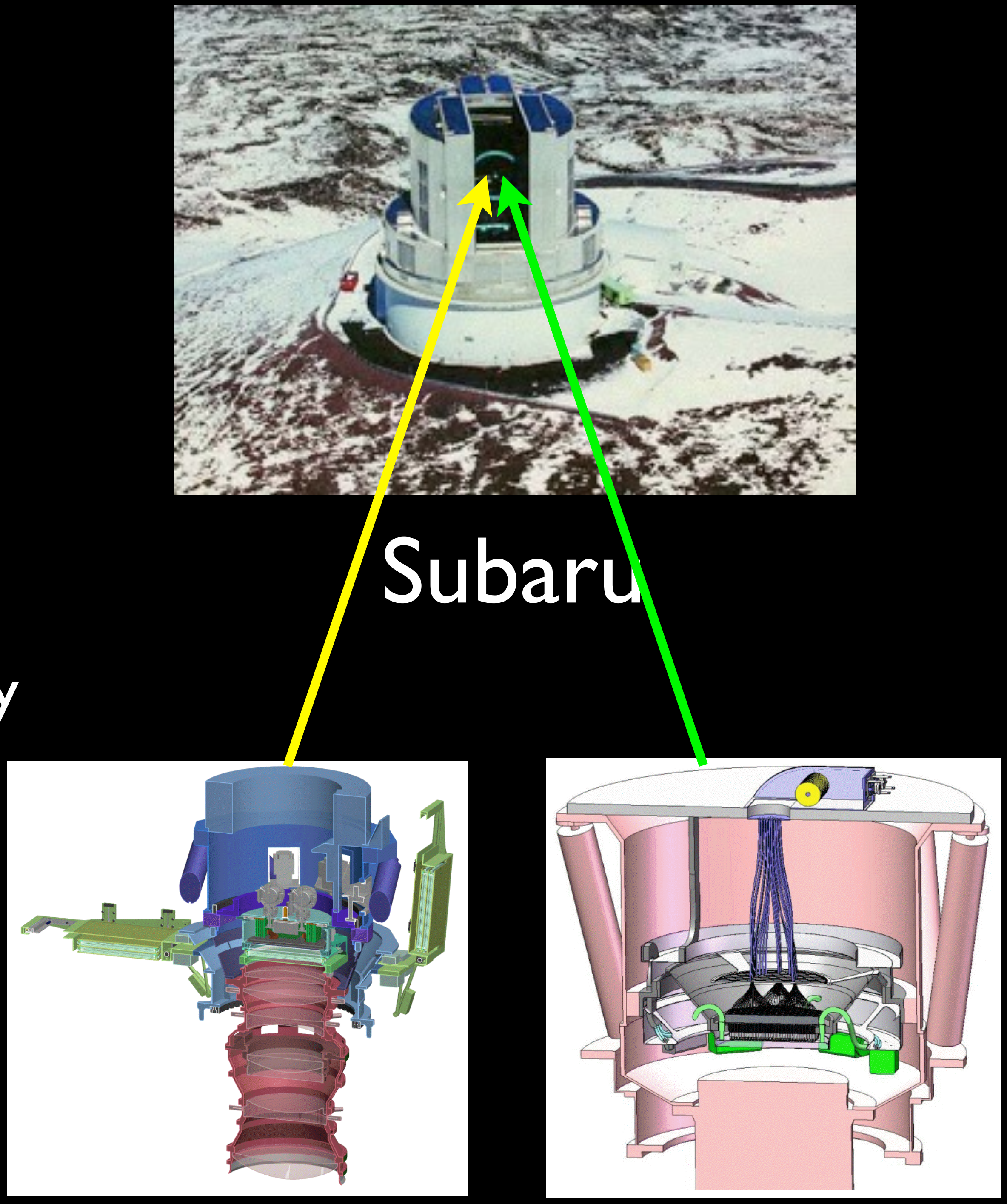

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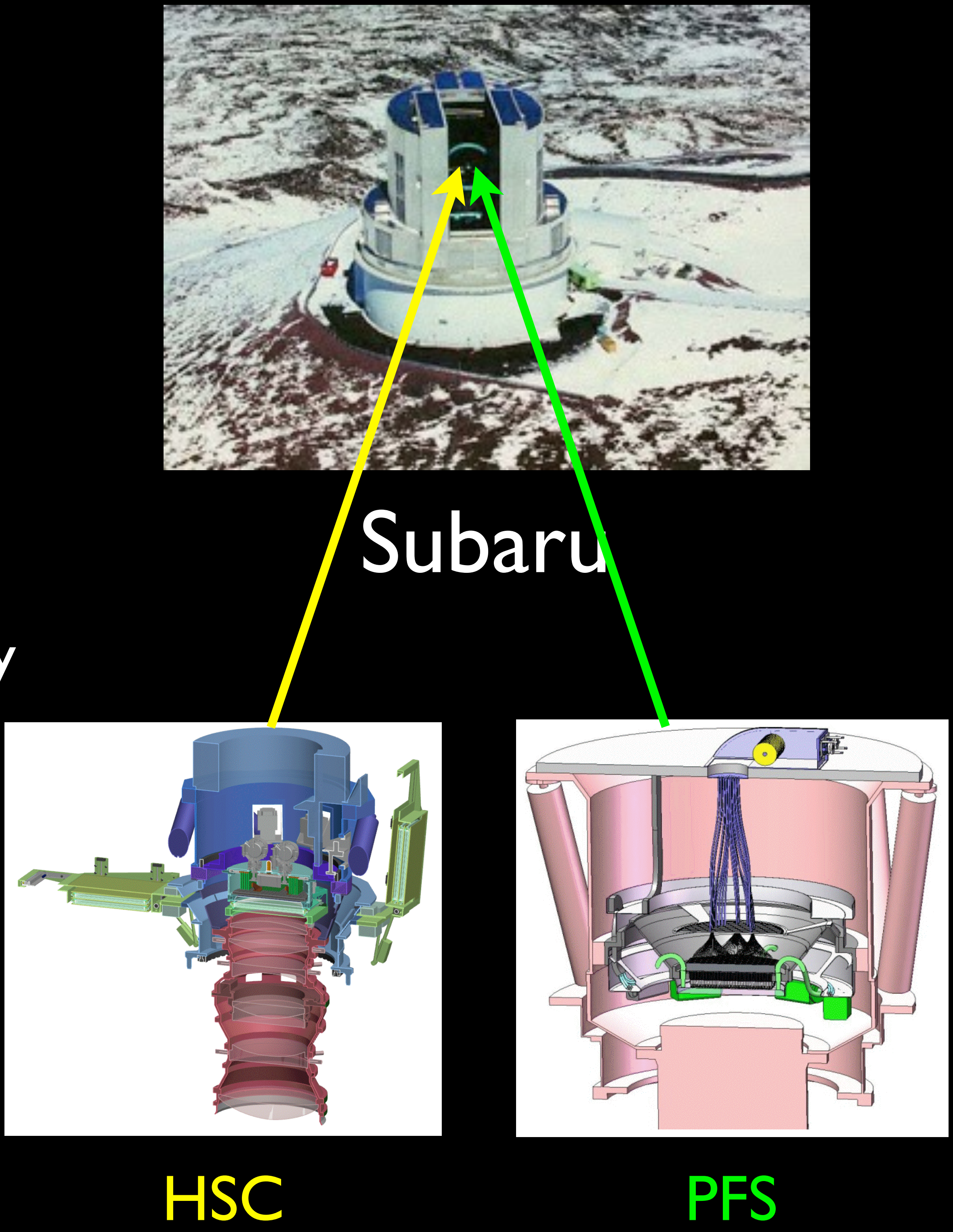
- imaging & spectroscopy on the same telescope: SDSS on powerful 8.2m!



model-independent