



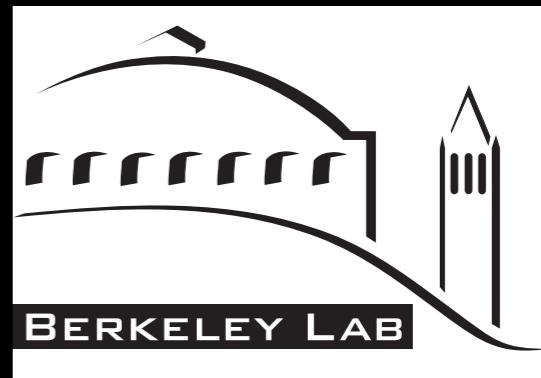
Life after Higgs

— new SUSY breaking &
new dark matter —

Hitoshi Murayama (Kavli IPMU & Berkeley & LBNL)

KAERU workshop, March 26, 2015 @ Kavli IPMU

Hochberg, Kuflik, HM, Volansky, Wacker, arXiv:1411.3727, 1504.xxxx
Hook, HM, arXiv:1503.04880, 1504.xxxx



Key Aspects in Exploring Road to Unification

March 25–26, 2015

@ Kavli IPMU, University of Tokyo, Kashiwa, Japan



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We'd like to celebrate contribution of our dear friend and mentor Kaoru Hagiwara to our field



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Permanent Address: <http://www.scientificamerican.com/article/supersymmetry-and-the-crisis-in-physics/>
Scientific American Volume 310, Issue 5

Supersymmetry and the Crisis in Physics

For decades physicists have been working on a beautiful theory that has promised to lead to a deeper understanding of the universe. Now they are at a crossroads: prove it right in the next year or confront an epochal paradigm shift.

By [Joseph Lykken](#) and [Maria Spiropulu](#)

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At dawn on a summer morning in 2012, we were on our third round of espresso when the video link connected our office at the California Institute of Technology to the CERN laboratory near Geneva. On the monitor we saw our colleagues on the Razor team, one of many groups of physicists analyzing data from the CMS

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Steve Jobs's birthday: Feb. 24, 1955

BIO UPDATED AS OF 2008, by Connie Guglielmo

APPLE PR CONTACTS: Katie Cotton — -redacted- and Steve Dowling: -redacted- or -redacted-

People to contact for comment:

- Apple co-founder Steve Wozniak: -redacted-

- Jon Rubinstein, former head of Apple's iPod division. He's now

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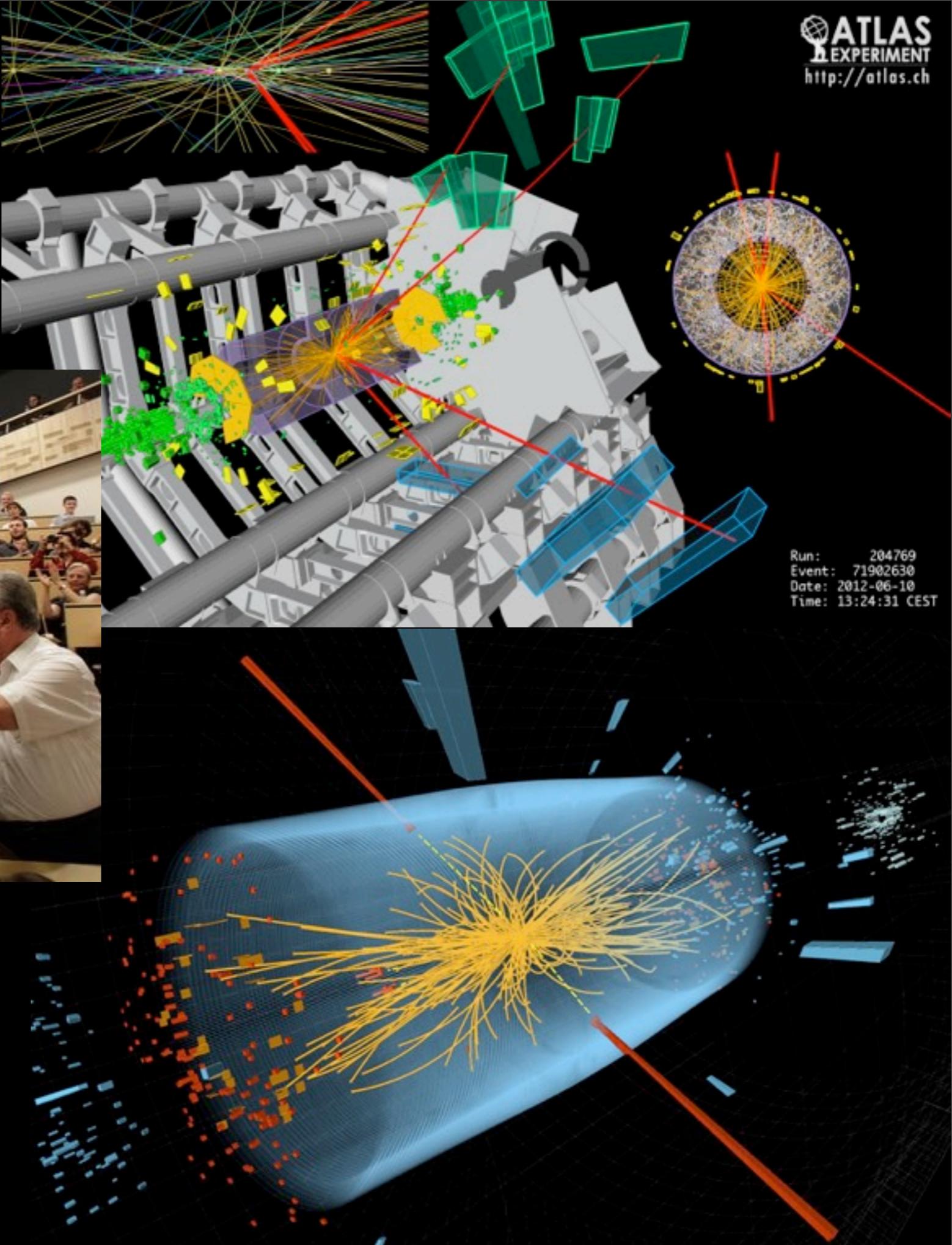
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SUSY



2012.7.4

discovery of Higgs boson



what we learned

- Standard Model looks minimal
- elementary-looking spinless boson exists
- **naturalness problem is real**
- no sign of solution to the naturalness problem e.g., supersymmetry
- Higgs mass is **too heavy for MSSM**

$$\Delta m_h^2 = \frac{3N_c}{4\pi^2} \frac{m_t^4}{v^2} \log \frac{m_{\tilde{t}}^2}{m_t^2}$$

Okada, Yamaguchi, Yanagida
Ellis, Ridolfi, Zwirner
Haber, Hempfling

scalar top mass ≥ 10 TeV preferred

Giudice, Strumia, JHEP08:077

Can we still find SUSY?

- In order for LHC to discovery SUSY, we need some SUSY particles \leq a few TeV
- recent popular idea: *split spectrum*
 - scalars $\geq 10 \text{ TeV}$
 - fermions \leq a few TeV
- well-defined way to achieve it:
 - anomaly mediation
(Giudice, Luty, HM, Rattazzi)
 - support by “*typicality*” (Nomura, Shirai)

Arvanitaki et al
Ibe, Yanagida
Hall Nomura

$$m_{\tilde{f}} \sim \frac{F}{M_{Pl}}, \quad M_i = b_i \frac{\alpha_i}{4\pi} \frac{F}{M_{Pl}}$$



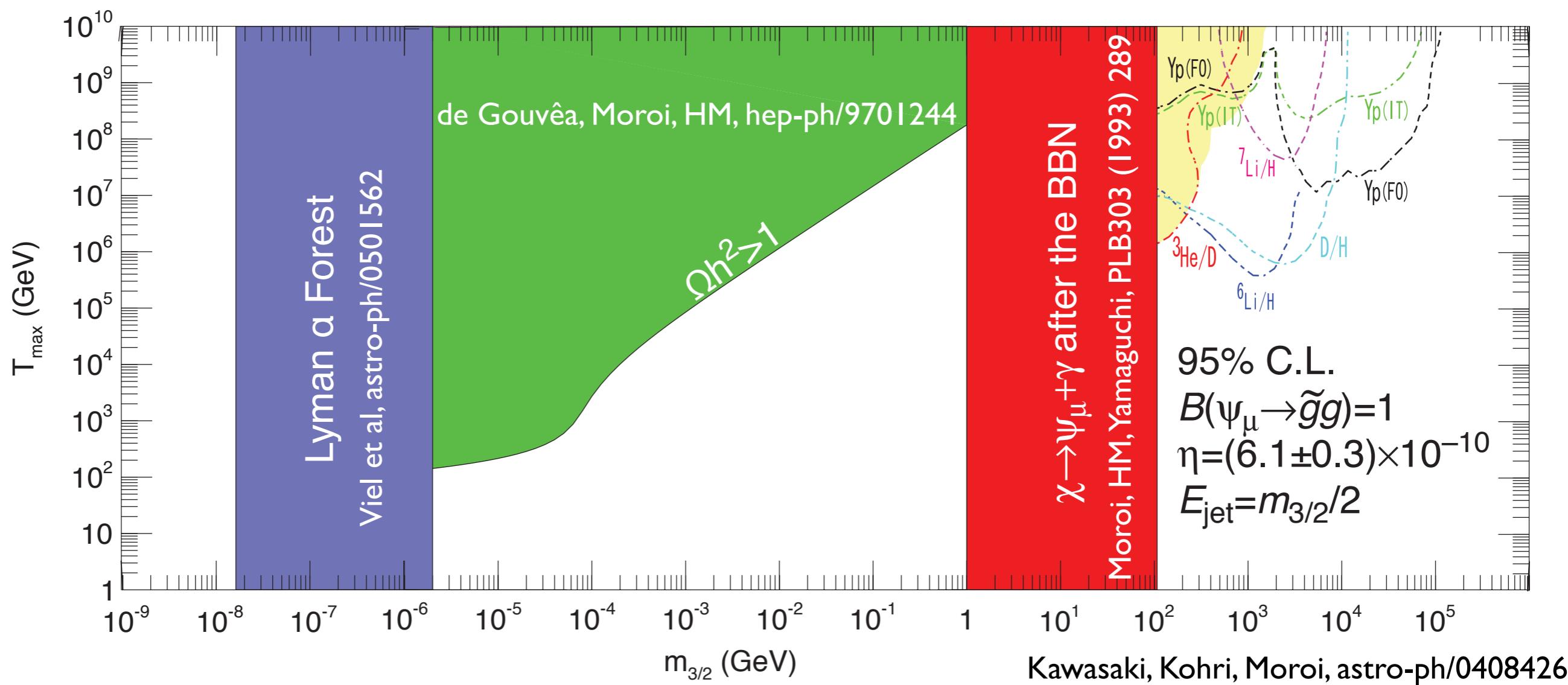
anomaly
mediation

Gravitino problem

- **Gravitinos** produced thermally
- If decays after the BBN, dissociates synthesized light elements
- Hadronic decays particularly bad

$$\frac{n_{3/2}}{s} \sim 10^{-12} \frac{T_{RH}}{10^{10} \text{GeV}}$$

$$m_{3/2}^2 = \frac{1}{3M_{Pl}^2} \left(|F|^2 + \frac{1}{2} D^2 \right)$$

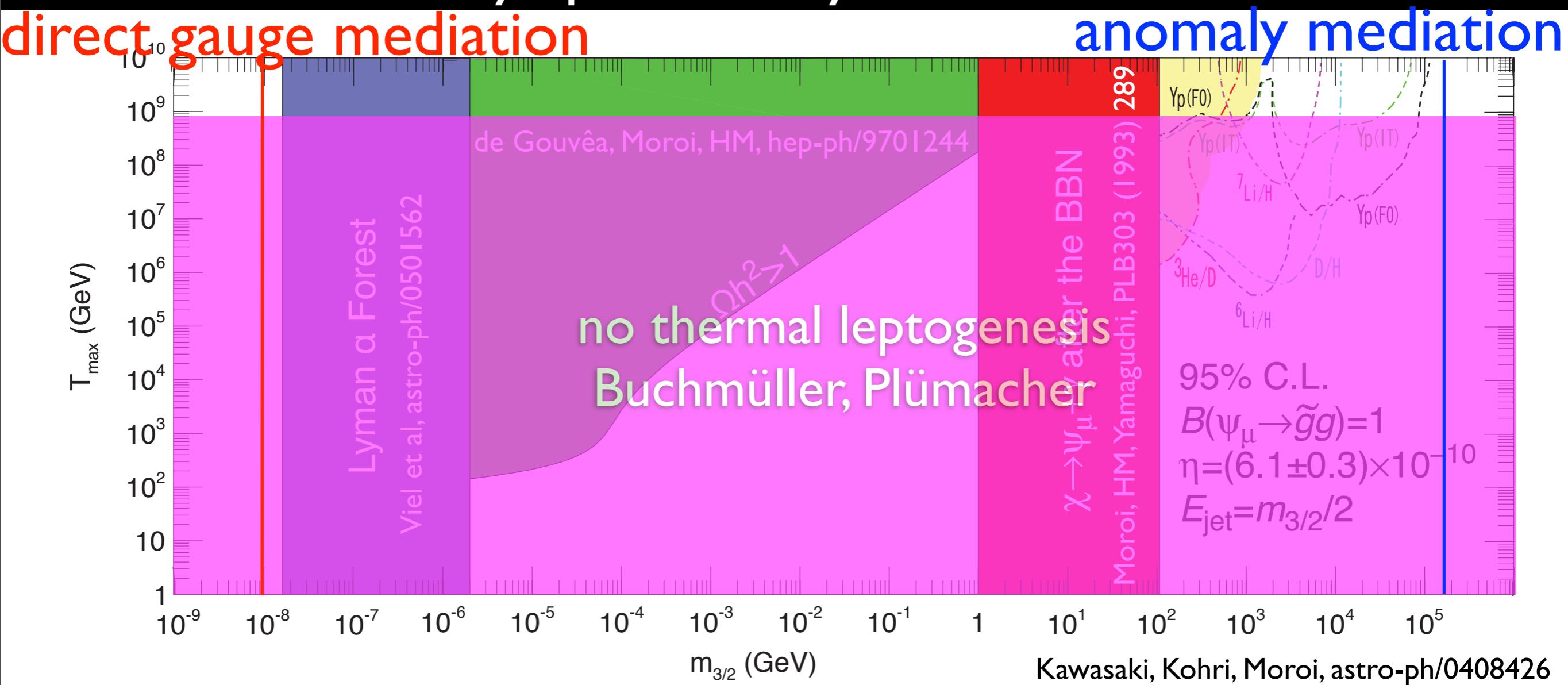


Gravitino problem

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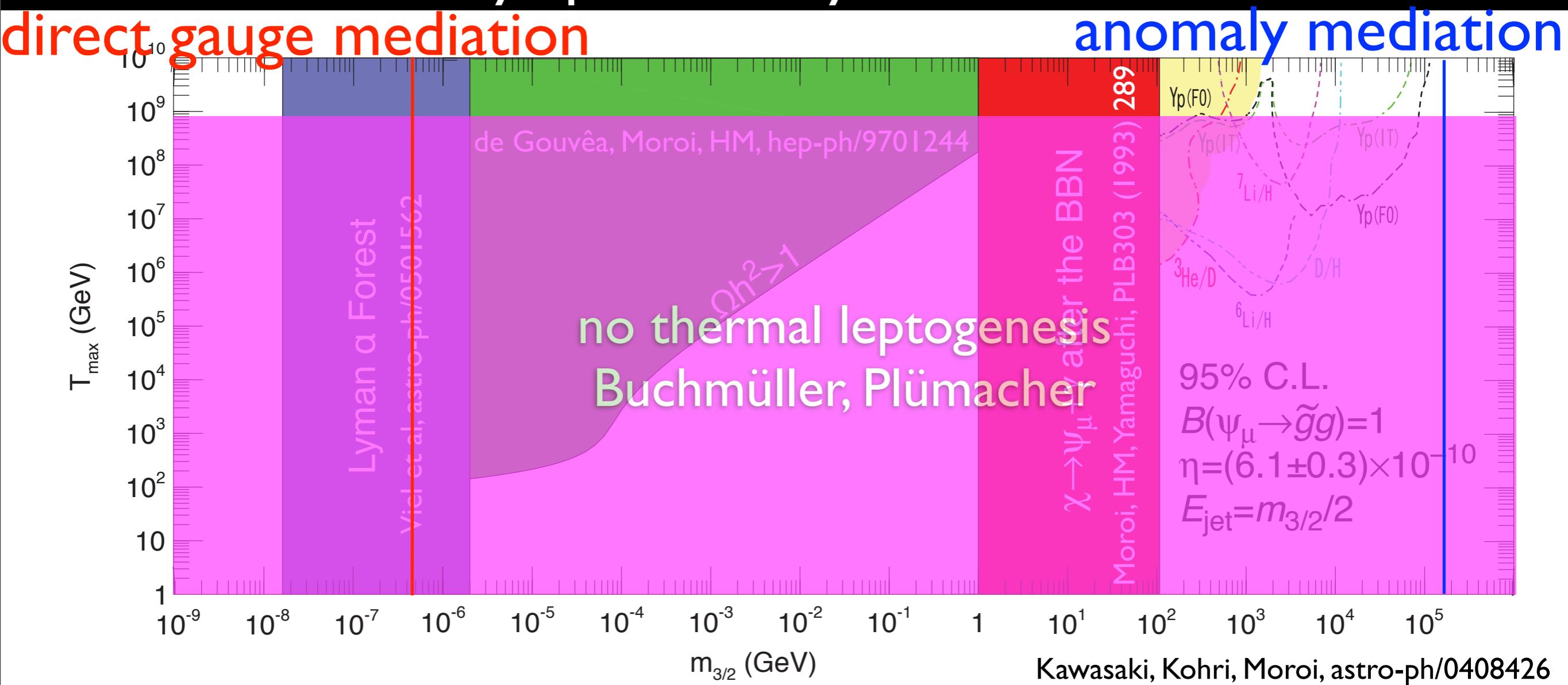


Gravitino problem

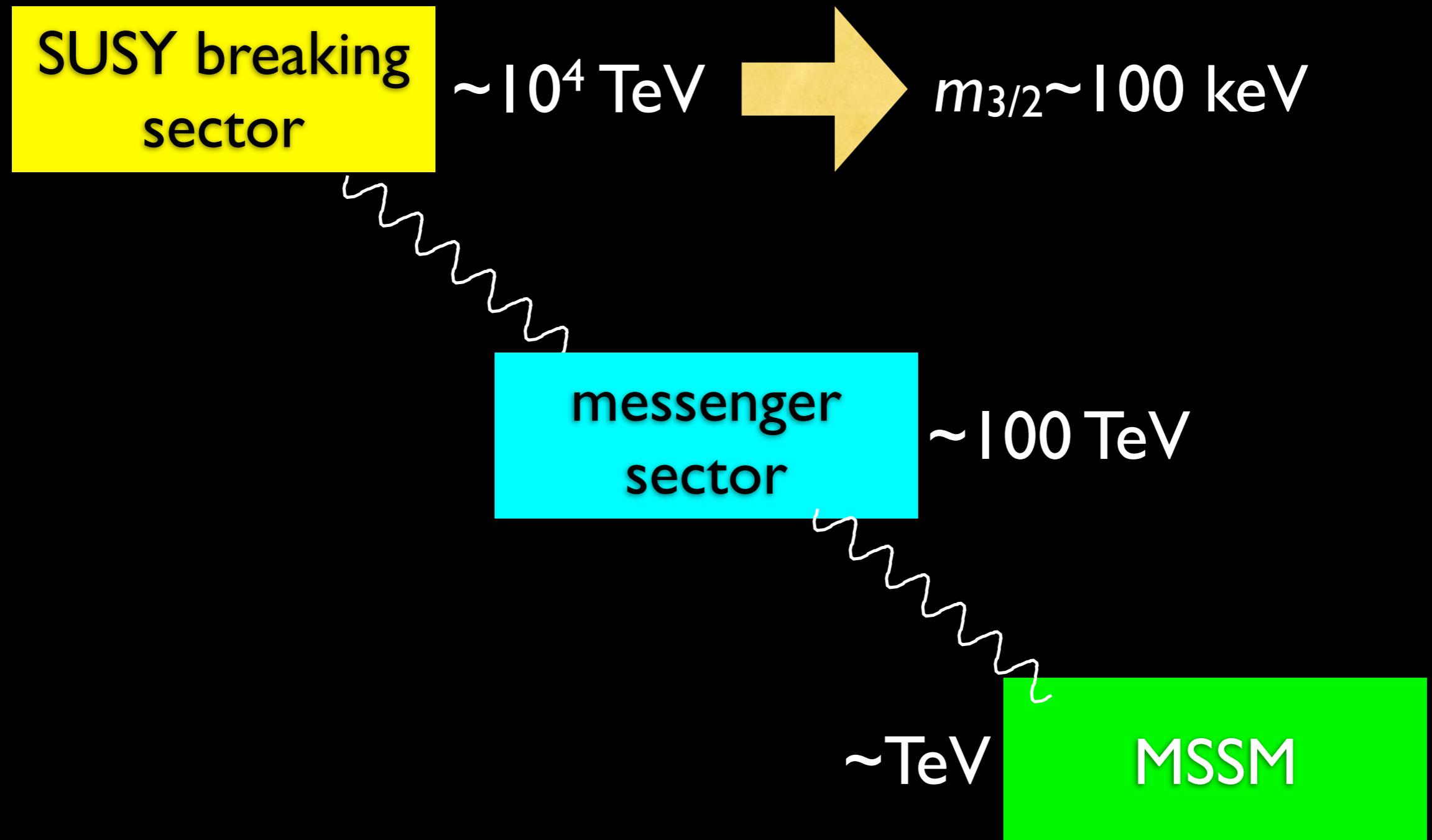
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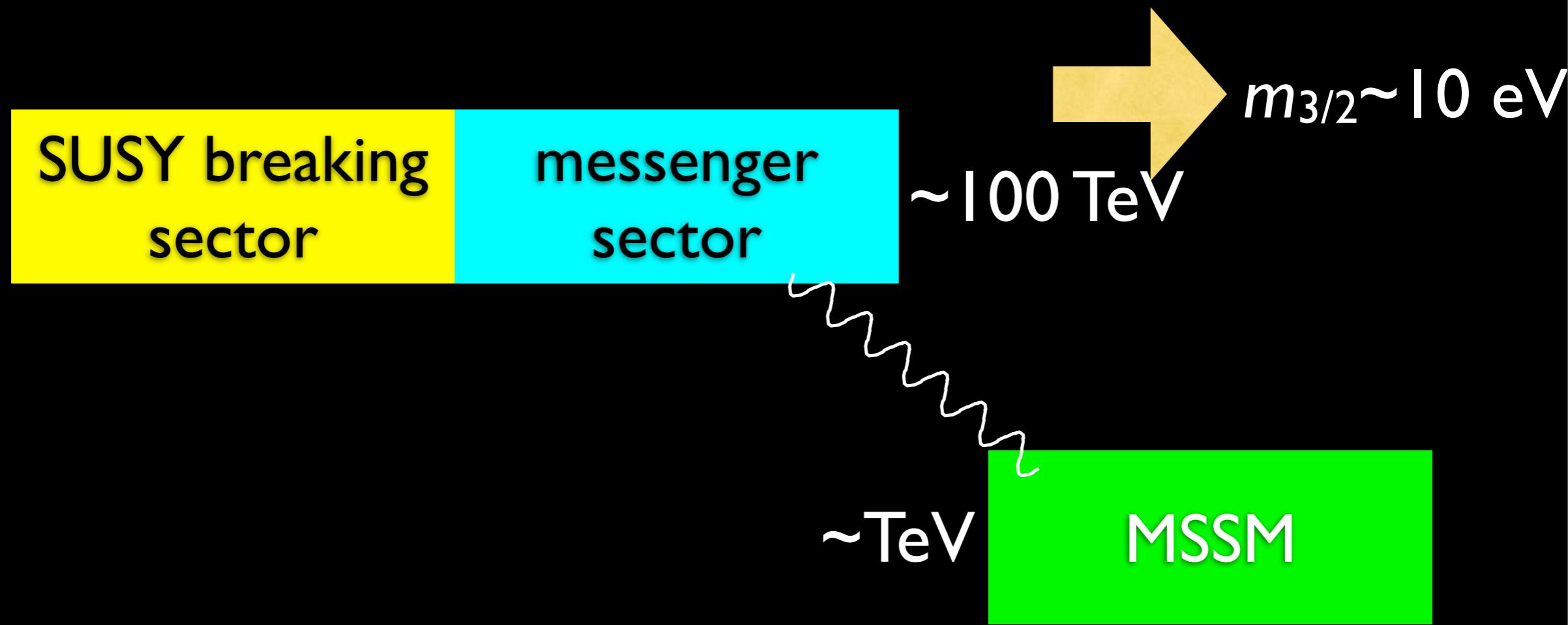


original gauge mediation



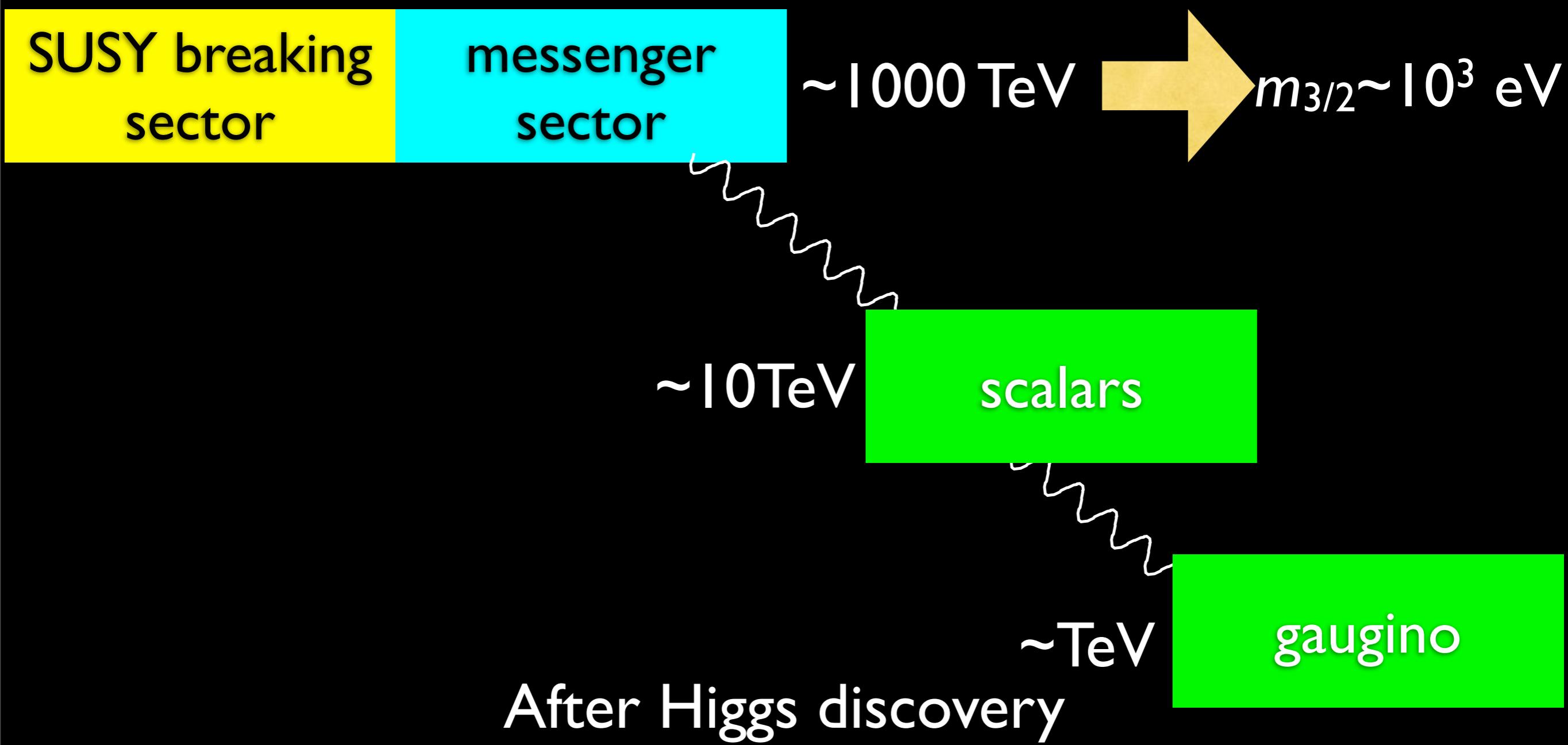
Dine, Nelson, Shirman

direct gauge mediation

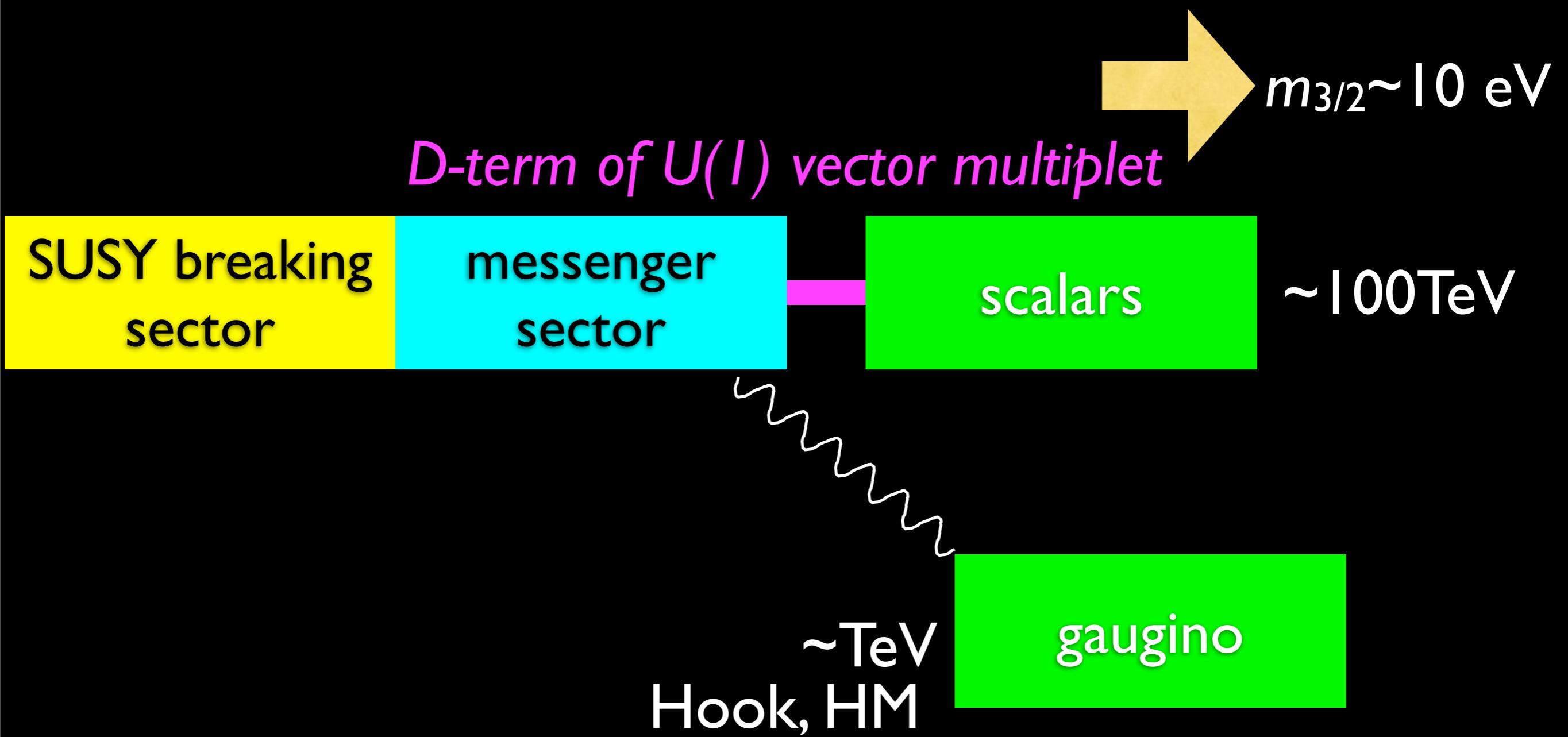


Arkani-Hamed, March-Russell, HM

direct gauge mediation?



vector mediation



$U(1)$ D-term

$$m_{\tilde{f}}^2 = q_f \langle D \rangle > 0$$

- Obviously we need q_f of the same sign for all squarks and sleptons
- then quarks and leptons, too
- anomaly cancellation?
- need **multiplets of negative charges**
- make sure they have **vector-like mass**
- vector-like multiplets act as **messengers**, induce **one-loop gaugino mass**
- split spectrum with tree-level scalar mass!

Nardecchia, Romanino, Ziegler arXiv:0909.3058 for high-scale case

simple: E_6 -like

E_6	27						
$SO(10) \times U(1)_\Psi$	(16, +1)			(10, -2)		(1, +4)	
$SU(5) \times U(1)_X \times U(1)_\Psi$	(10, +1, +1)	(5*, -3, +1)	(1, +5, +1)	(5, -2, -2)	(5*, +2, -2)	(1, 0, +4)	
$SU(5) \times U(1)$	(10, +1)	(5*, +2)	(1, 0)	(5, -2)	(5*, -3)	(1, +5)	

Q, u^c, e^c

L, d^c

ν_R

F

\bar{F}

S

$$Q = \frac{1}{4}(5Q_\psi - Q_\chi)$$

SUSY breaking

$$W = MS(+4)X(-4) + \lambda(X(-4)Y(+4) - \mu^2)$$

- O'Raifeartaigh type
- but *chiral* in U(1) charges!
- generates *D*-term
- messengers 3(5+5*)

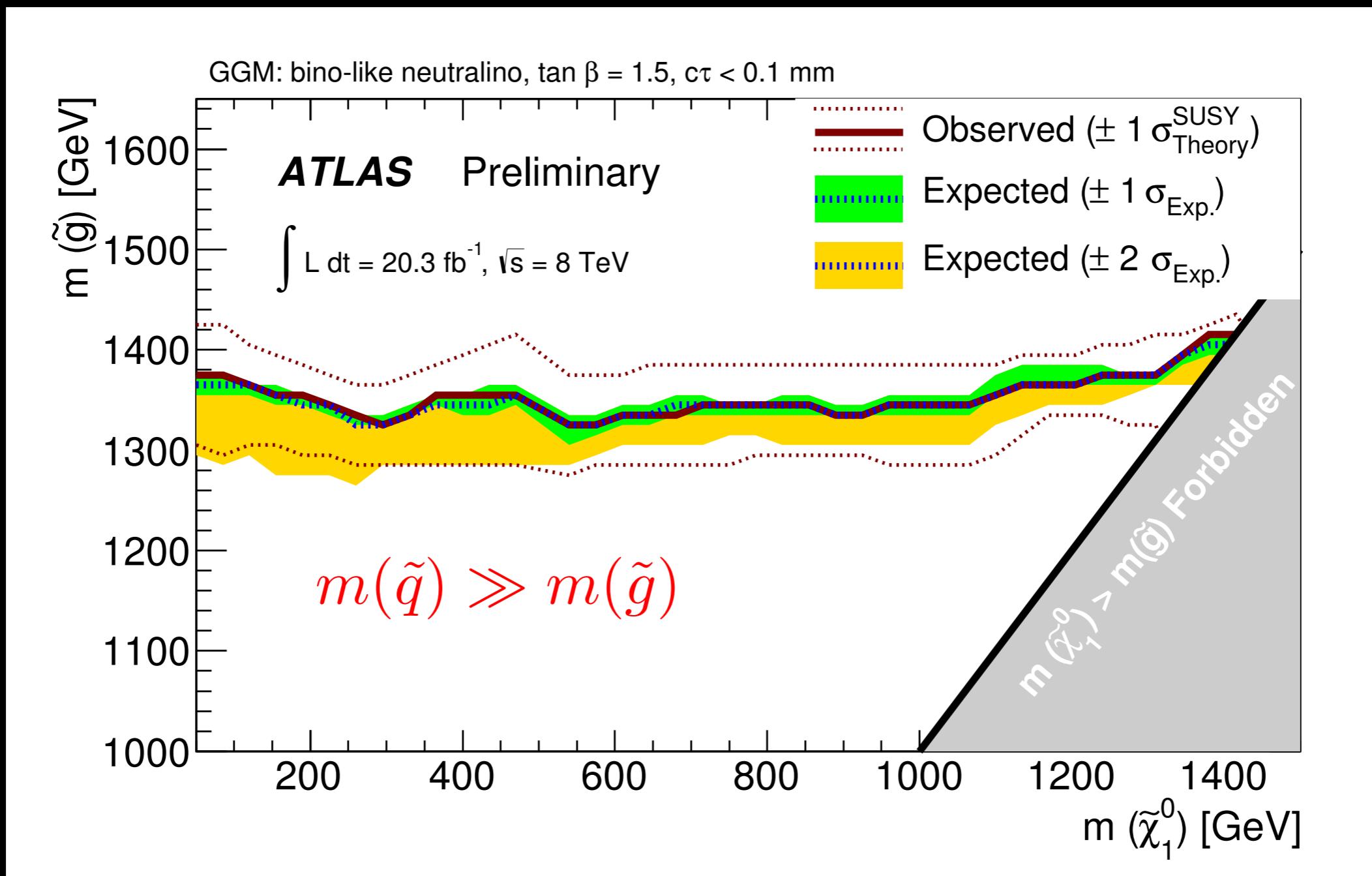
$$D = \frac{4eF_X^*F_X}{16e^2(|X|^2 + |Y|^2)}$$

$$W = gY\bar{F}F + kS\bar{F}F$$

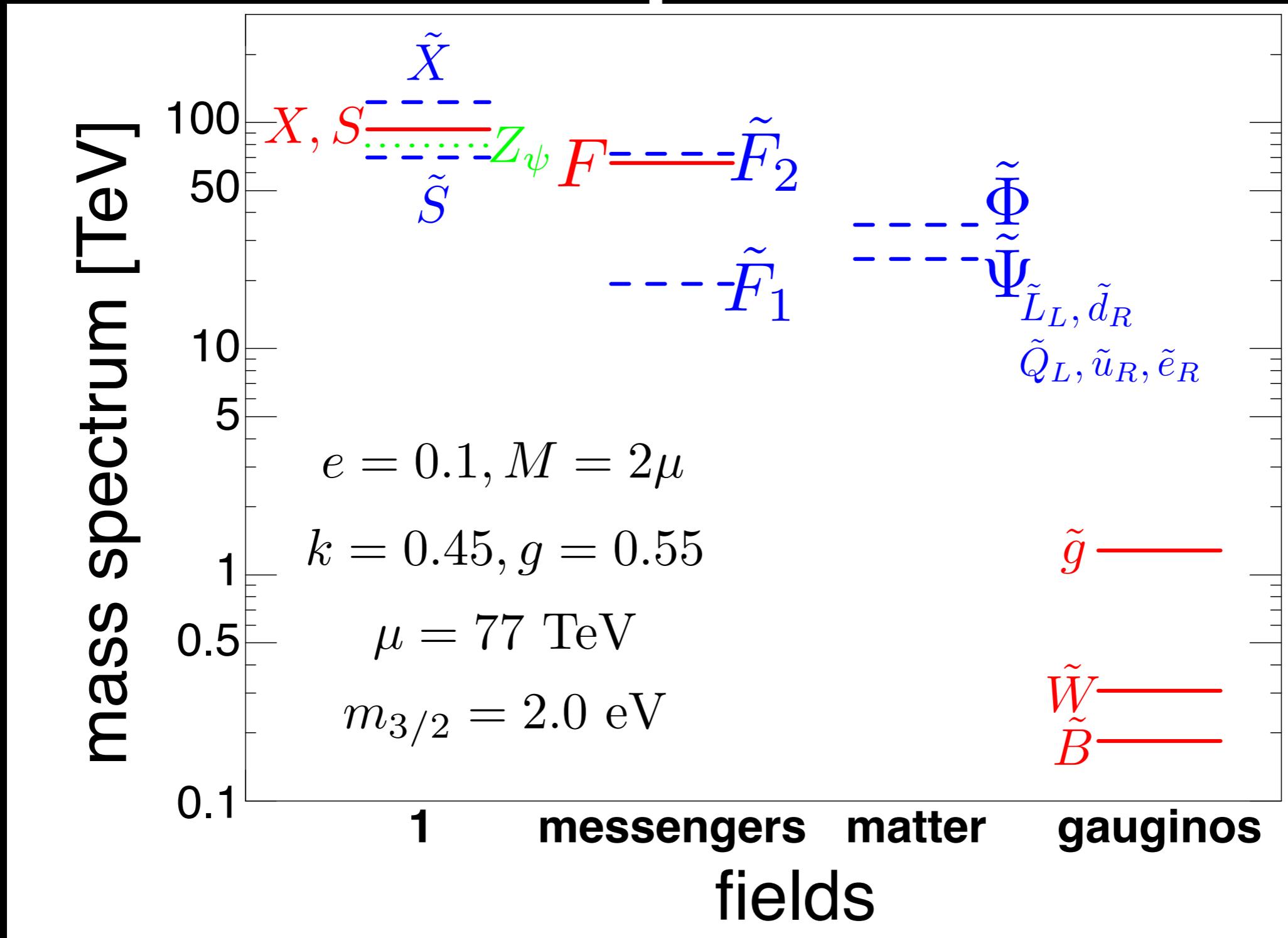
$$(\tilde{F}^*, \tilde{\bar{F}}) \begin{pmatrix} (gY)^2 - 2eD & kF_S \\ kF_S & (gY)^2 - 3eD \end{pmatrix} \begin{pmatrix} \tilde{F} \\ \tilde{\bar{F}}^* \end{pmatrix}$$

- use one pair of doublets as Higgs
- “Solves” μ -problem! $M_{Pl} \rightarrow 100 \text{ TeV}$

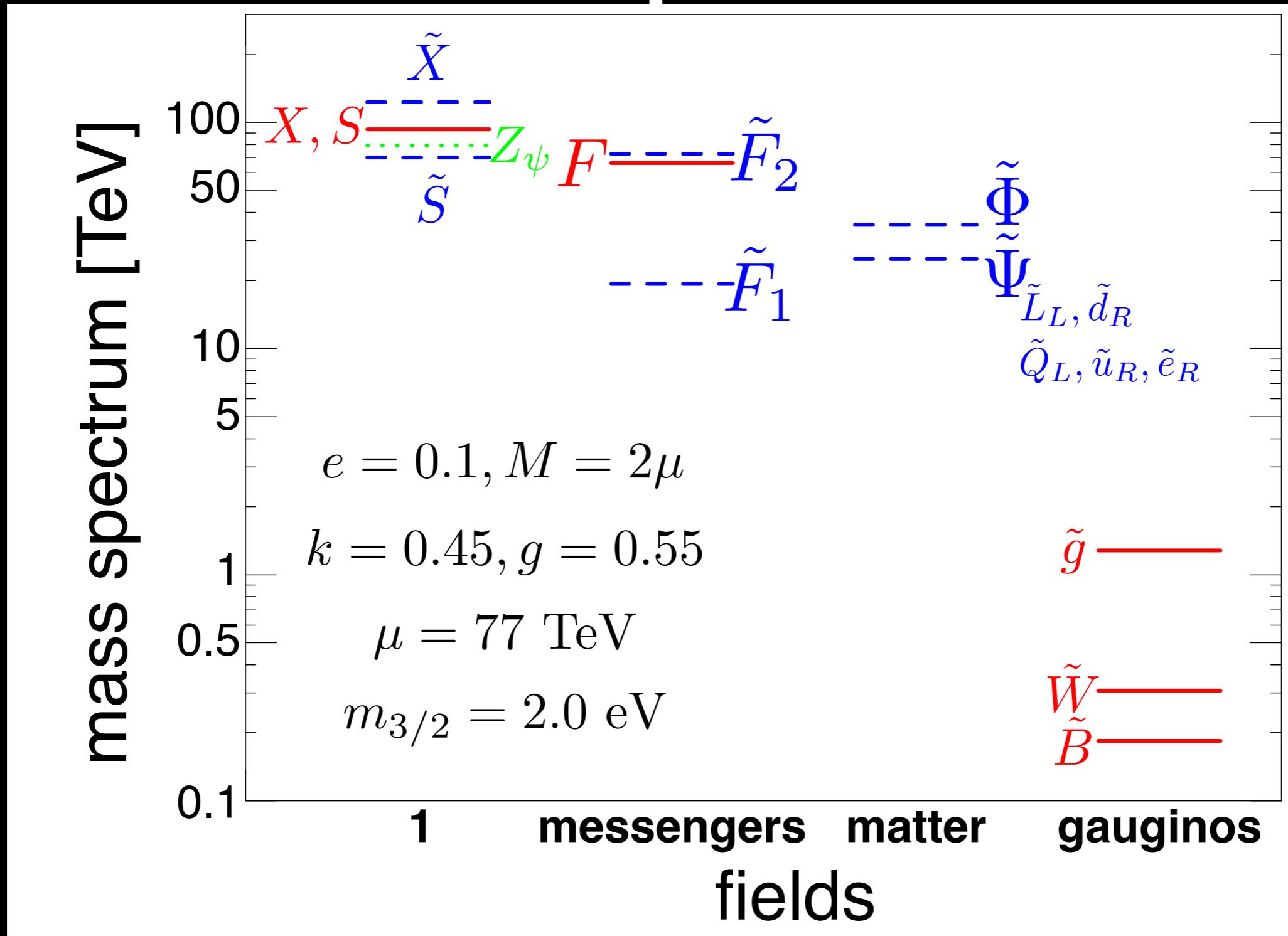
$E_{\text{miss}} + 2 \text{ photons}$



mass spectrum

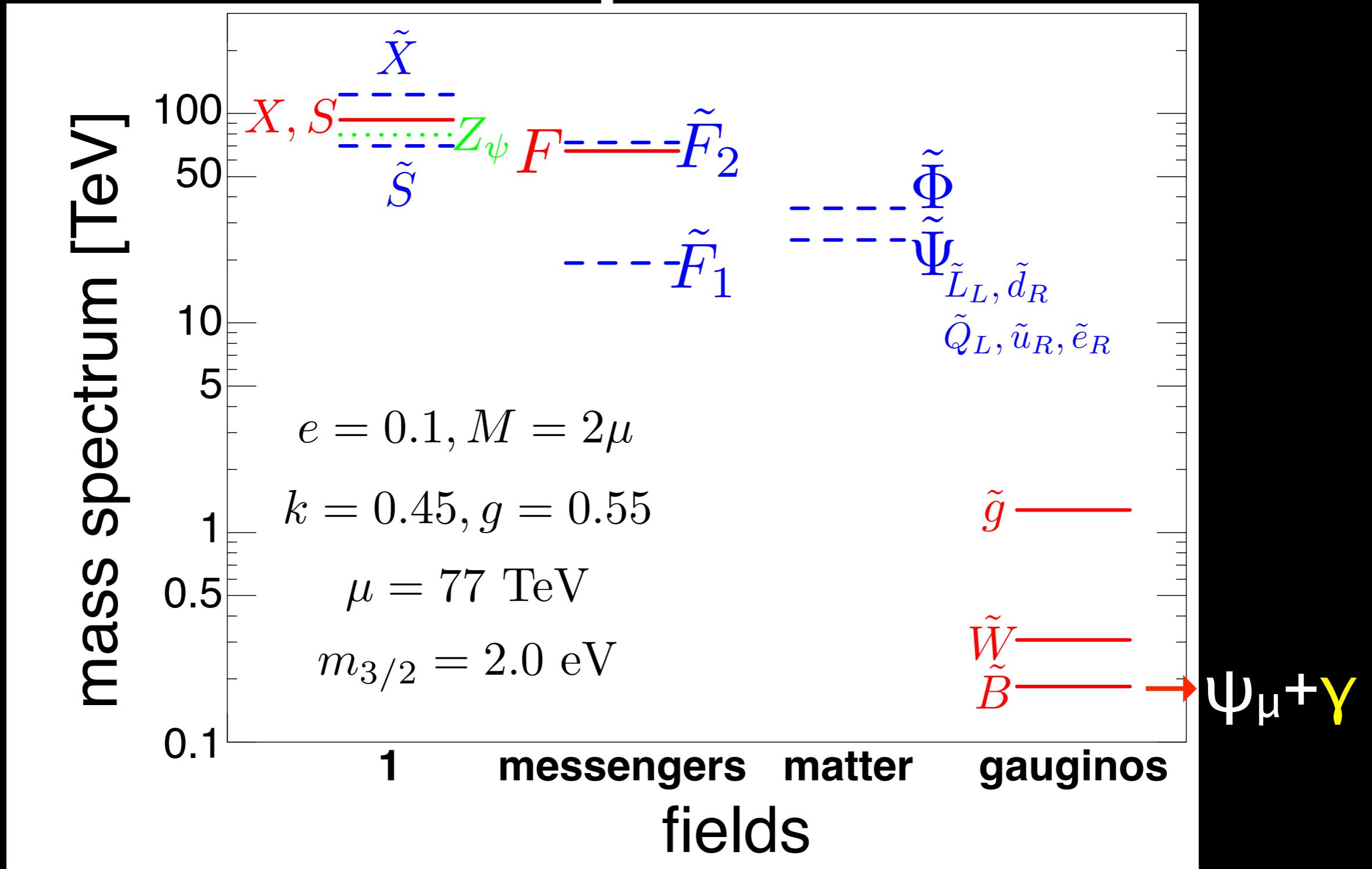


mass spectrum



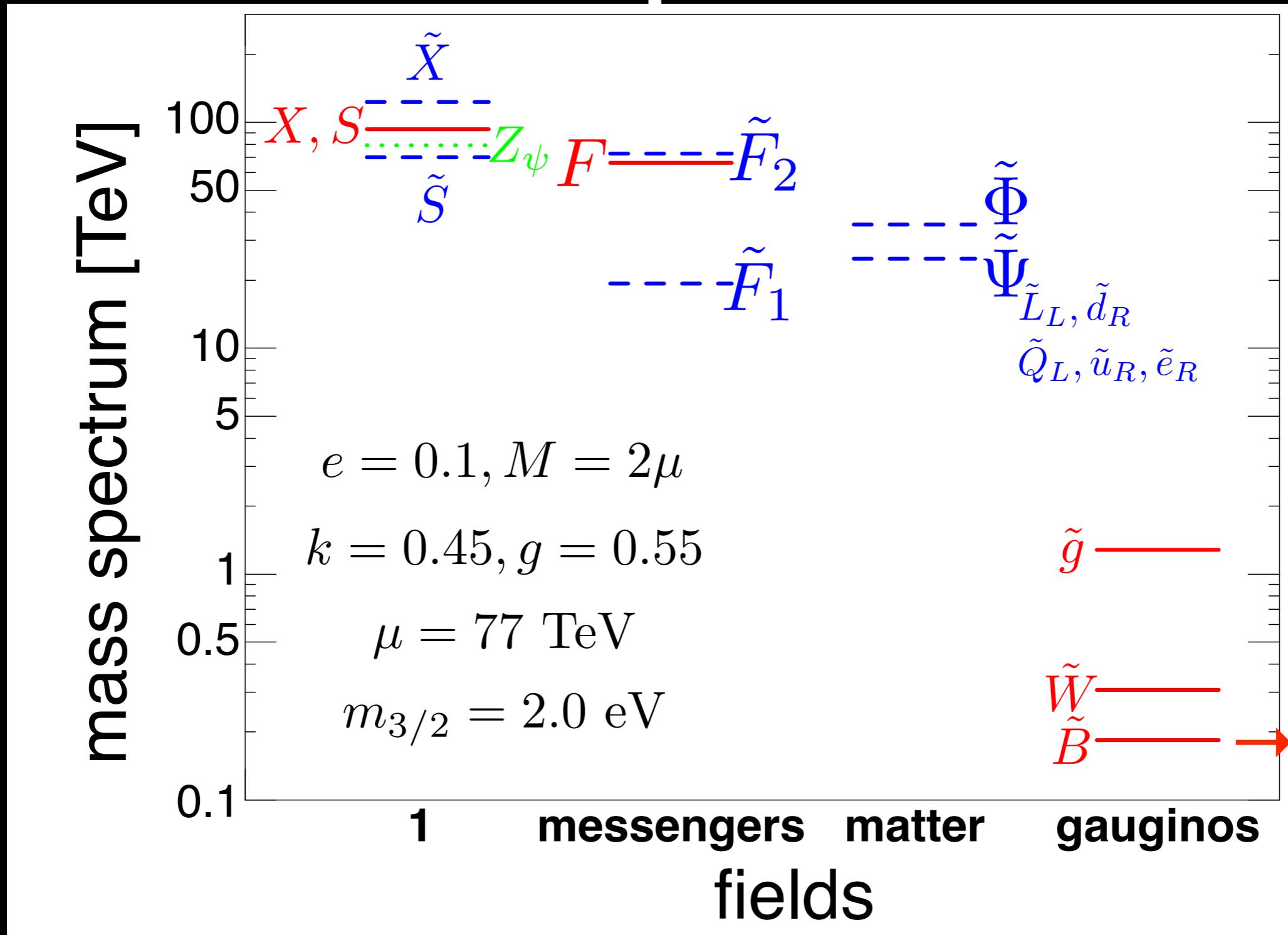
$$M_1 : M_2 : M_3 = \frac{12}{5} \alpha_1 : 2\alpha_2 : 3\alpha_3$$

mass spectrum



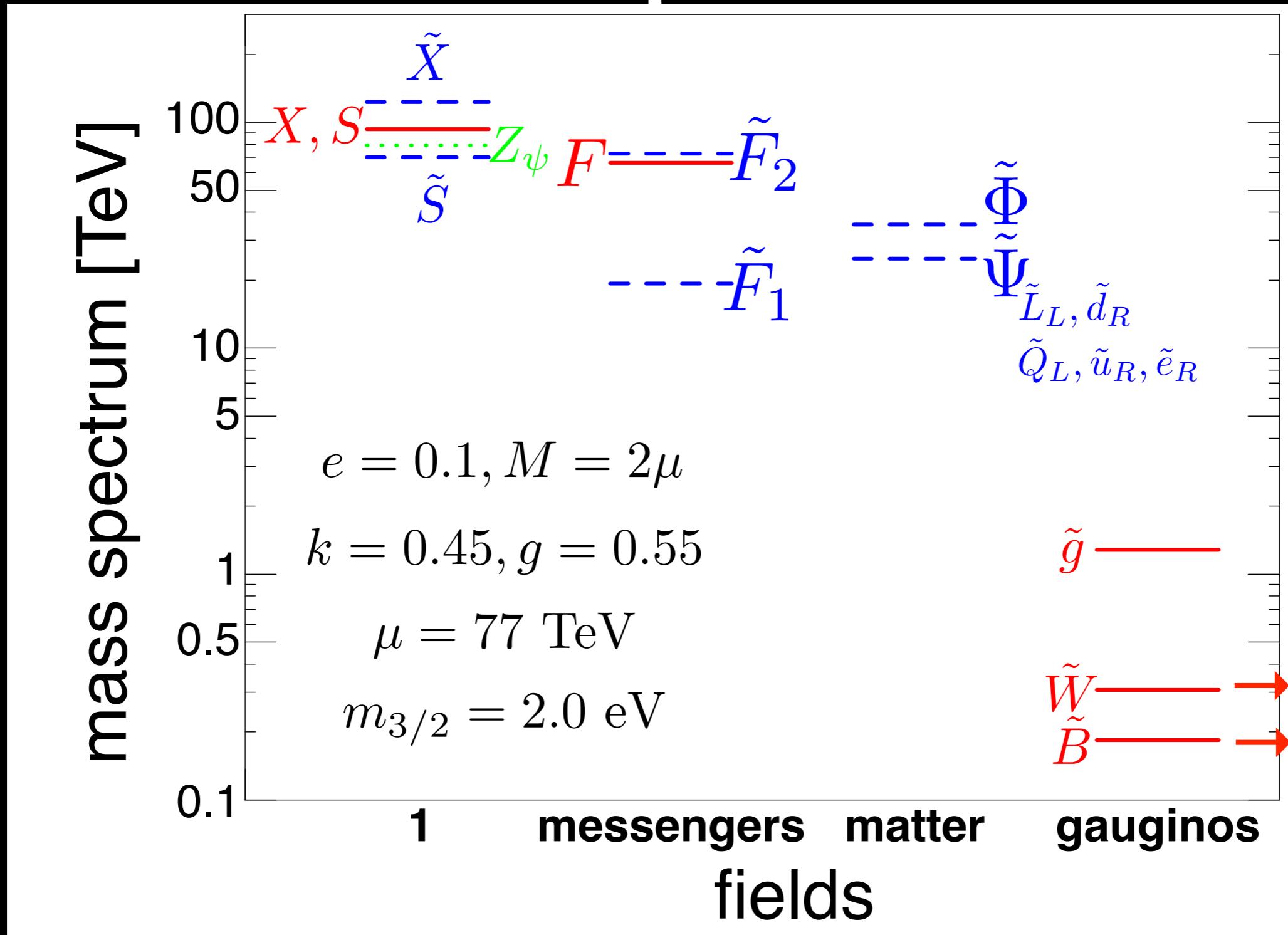
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mass spectrum



$$M_1 : M_2 : M_3 = \frac{12}{5} \alpha_1 : 2\alpha_2 : 3\alpha_3$$

mass spectrum



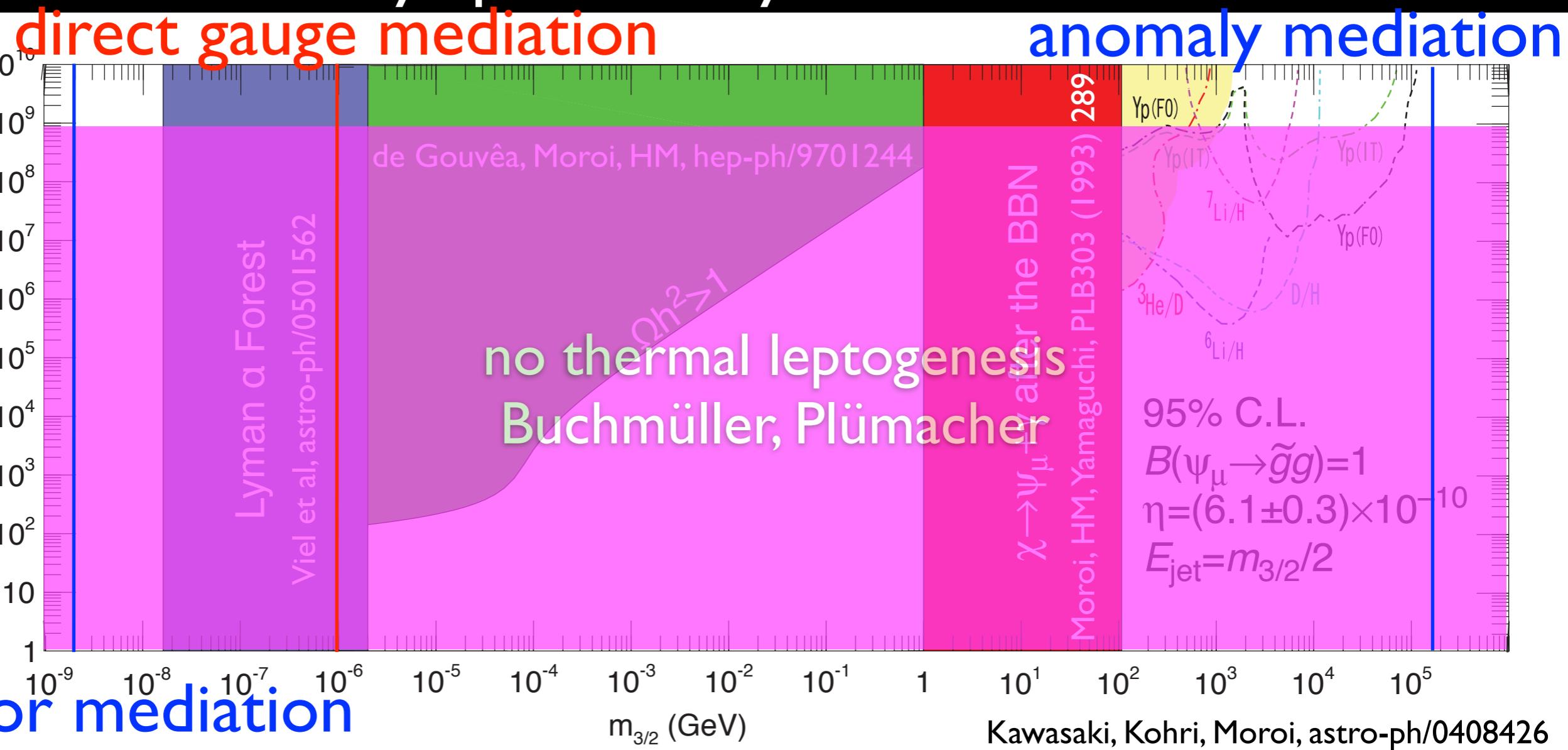
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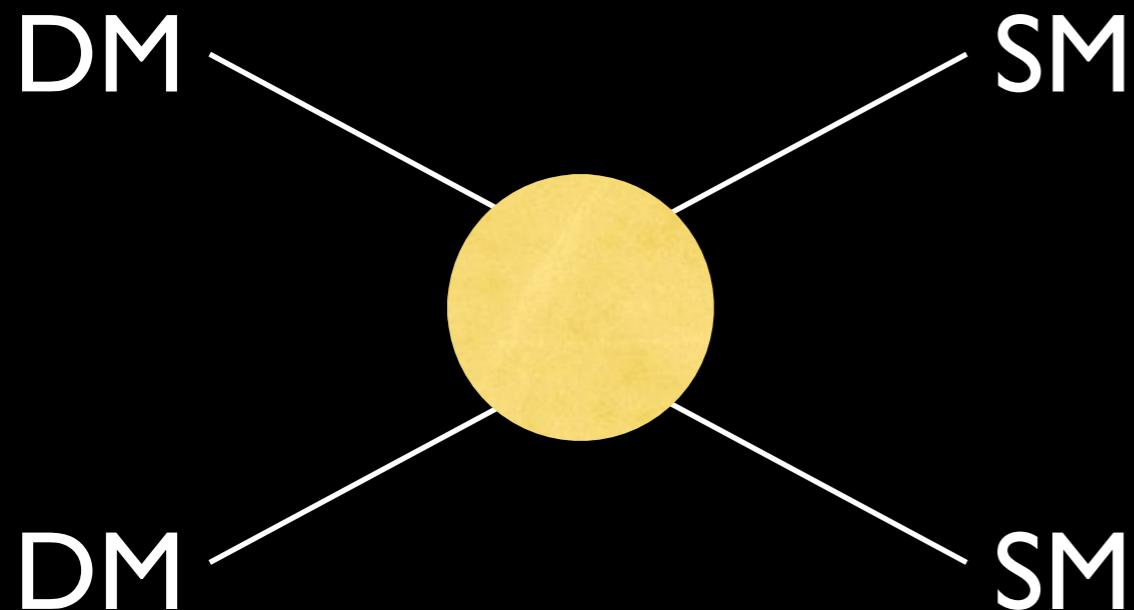
consistent cosmology

- reheating after inflation often produces too many gravitinos: totally harmless
- thermal leptogenesis
- verified tunneling to SUSY vacuum OK
- gravitons thermalize and become warm dark matter: within Lyman- α limit

what about cold dark matter?
axion?

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

Miracles

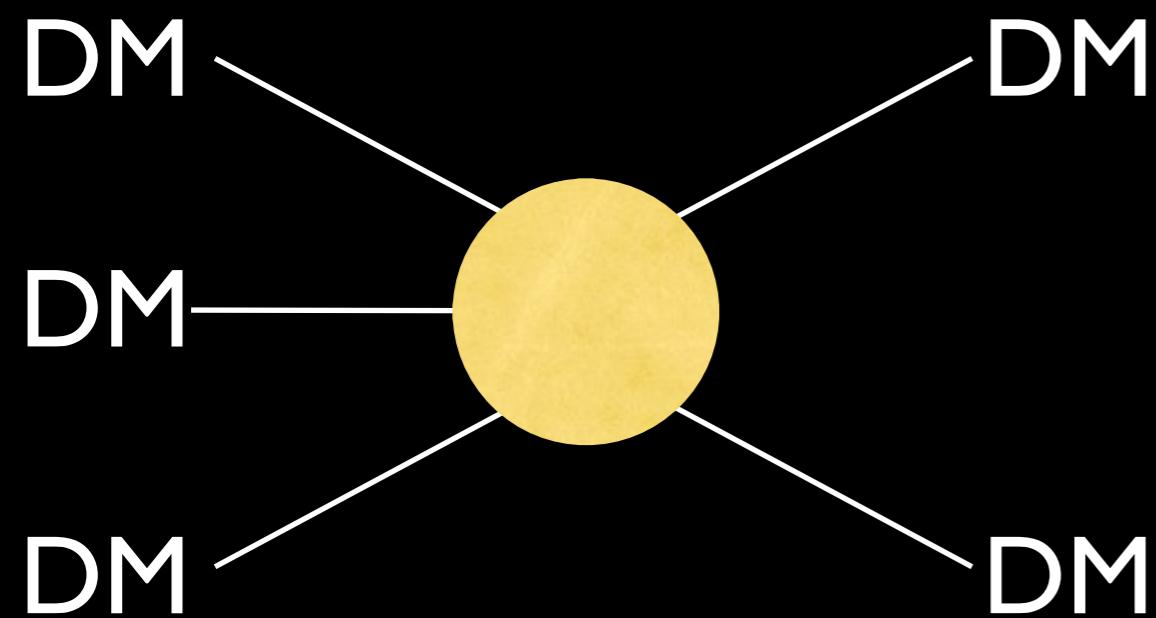


$$\langle \sigma_{2 \rightarrow 2} v \rangle \approx \frac{\alpha^2}{m^2}$$

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

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

WIMP miracle!



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

$$\alpha \approx 4\pi$$

Hochberg, Kuflik,
Volansky, Wacker

$m \approx 300 \text{ MeV}$ arXiv:1402.5143

SIMP miracle!

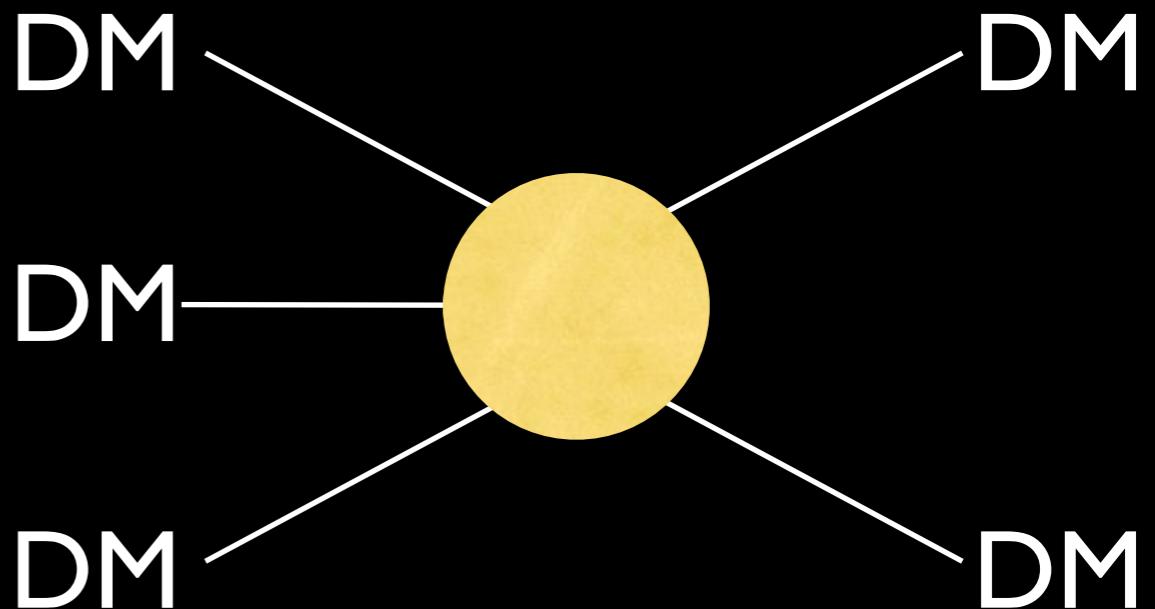
$$\frac{n_{\text{DM}}}{s} = 4.4 \times 10^{-10} \frac{\text{GeV}}{m_{\text{DM}}}$$

SIMPlest Miracle

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

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

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

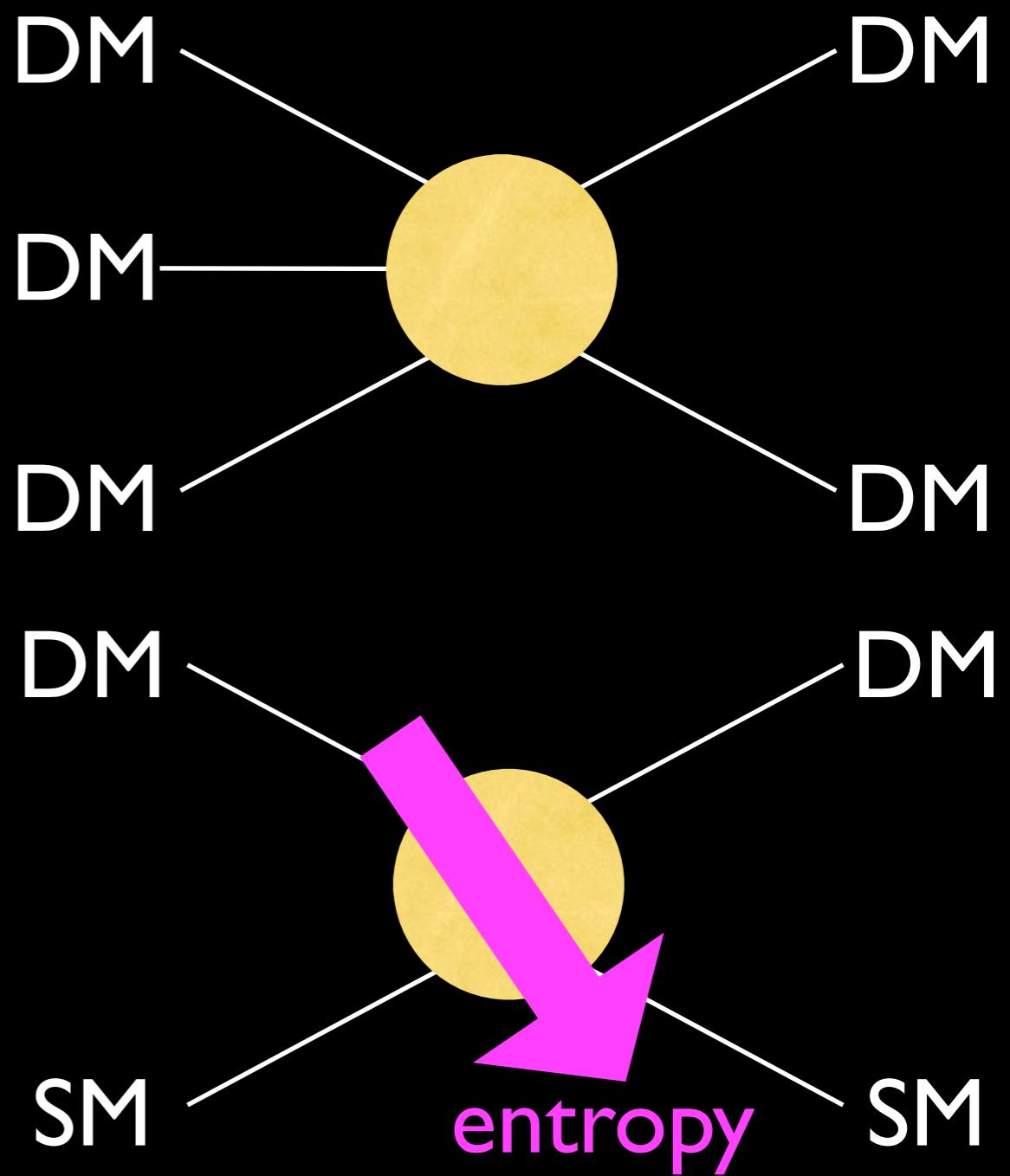


+HM

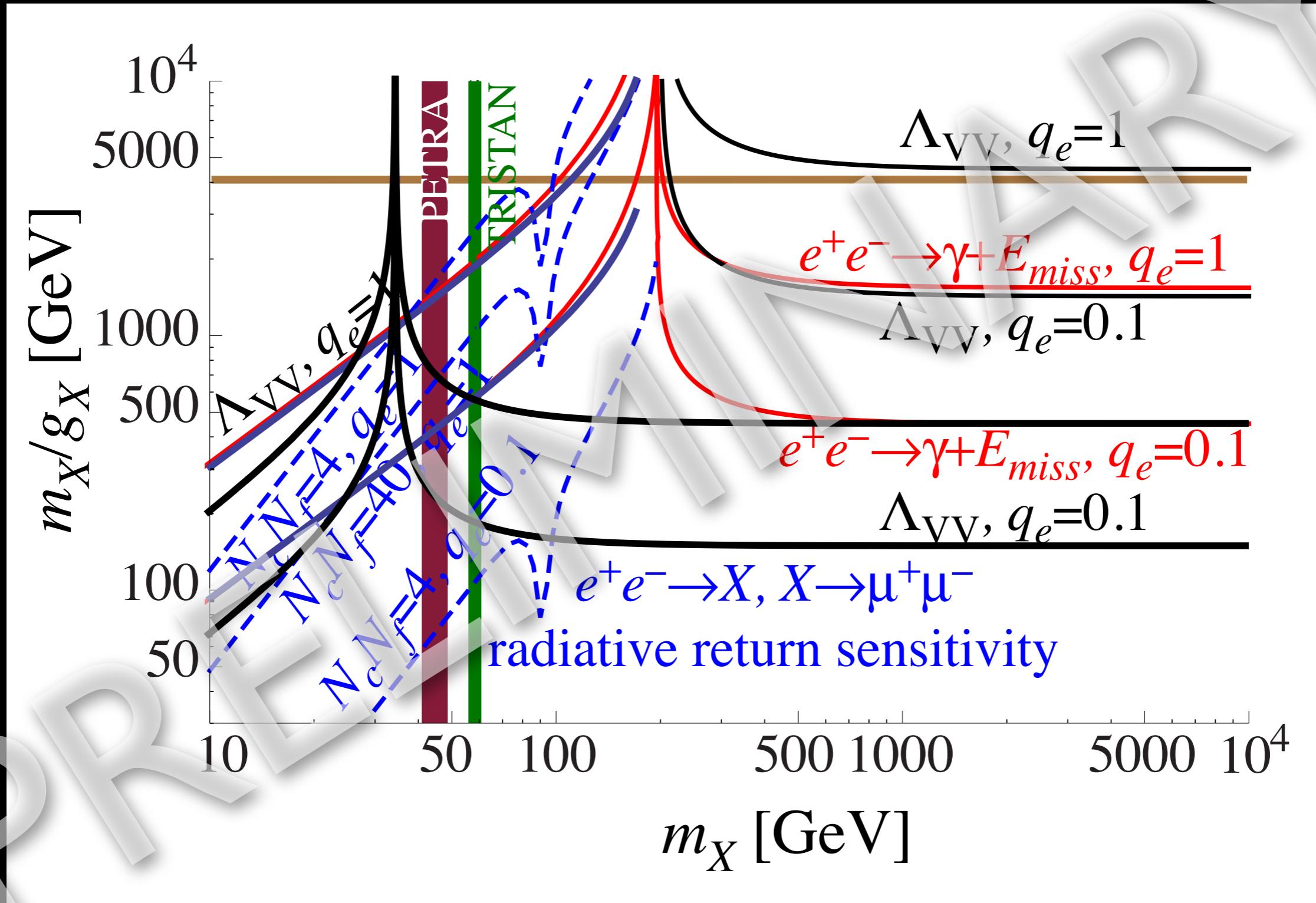
arXiv:1411.3727

communication

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



vector exchange



a light Z' missed??? $g_X \sim 0.003 - 0.03$

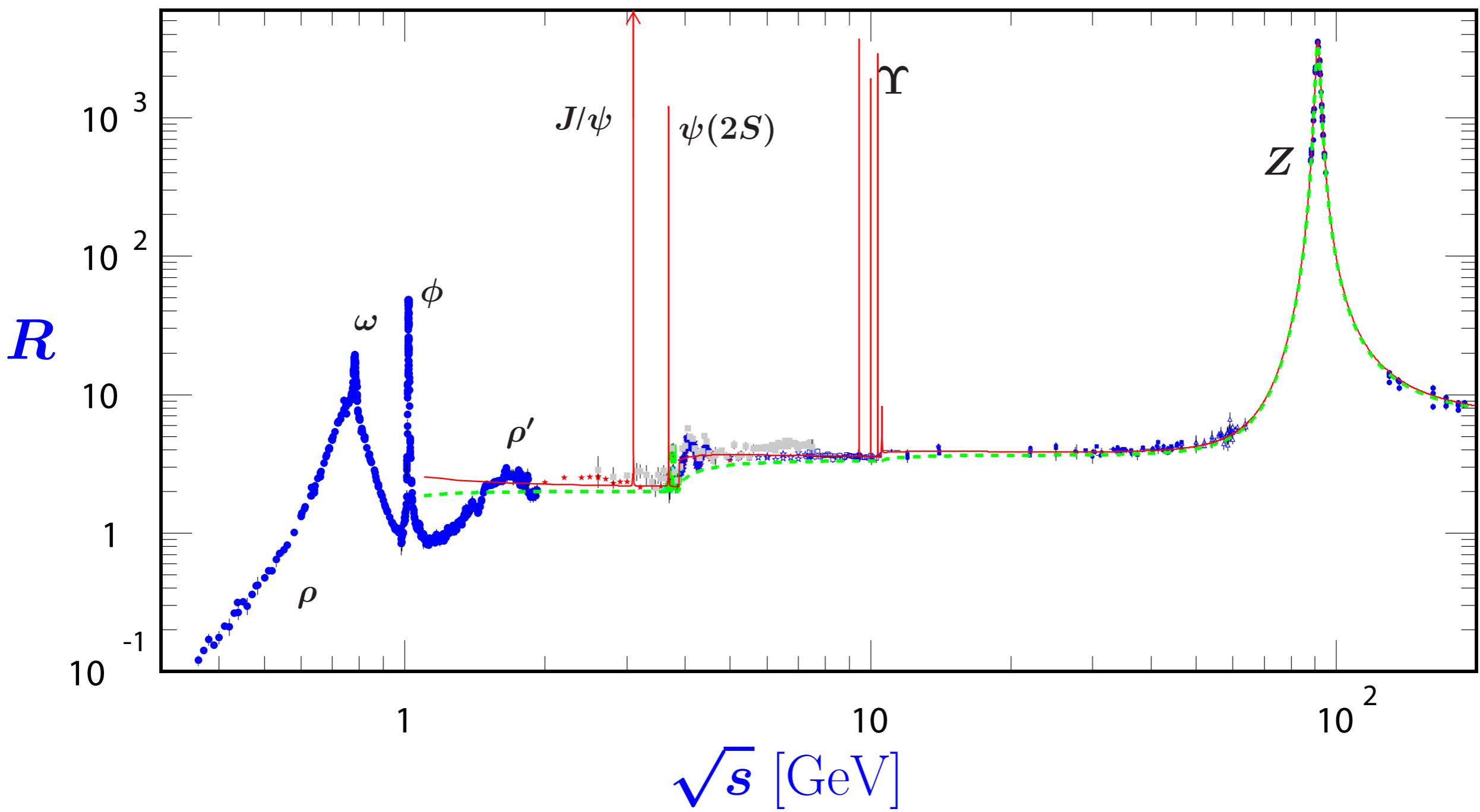
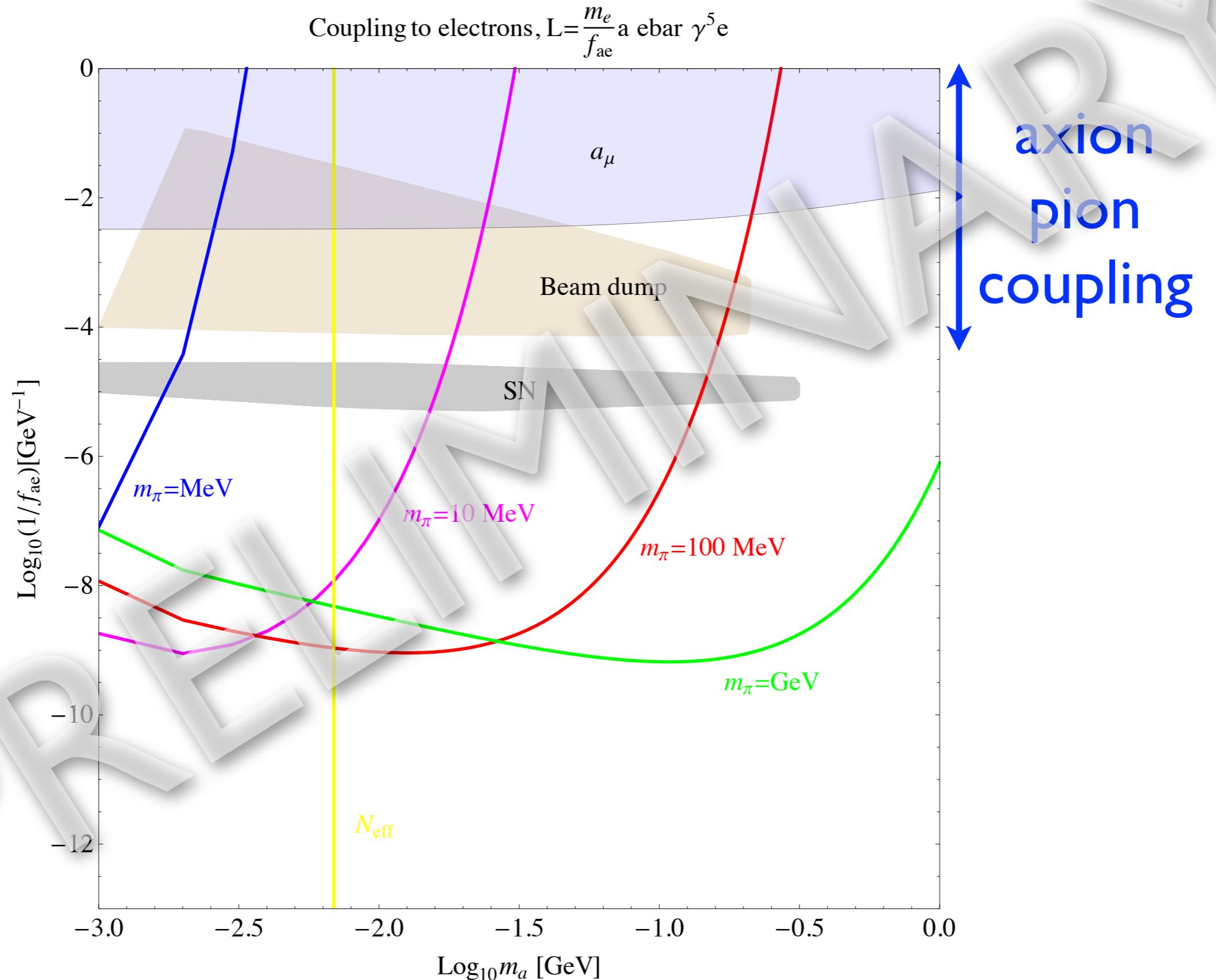


Figure 46.6: World data on the total cross section of $e^+e^- \rightarrow \text{hadrons}$ and the ratio $R(s) = \sigma(e^+e^- \rightarrow \text{hadrons}, s)/\sigma(e^+e^- \rightarrow \mu^+\mu^-, s)$. $\sigma(e^+e^- \rightarrow \text{hadrons}, s)$ is the experimental cross section corrected for initial state radiation and electron-positron vertex loops, $\sigma(e^+e^- \rightarrow \mu^+\mu^-, s) = 4\pi\alpha^2(s)/3s$. Data errors are total below 2 GeV and statistical above 2 GeV. The curves are an educative guide: the broken one (green) is a naive quark-parton model prediction, and the solid one (red) is 3-loop pQCD prediction (see “Quantum Chromodynamics” section of this *Review*, Eq. (9.7) or, for more details, K. G. Chetyrkin *et al.*, Nucl. Phys. **B586**, 56 (2000) (Erratum *ibid.* **B634**, 413 (2002)). Breit-Wigner parameterizations of J/ψ , $\psi(2S)$, and $\Upsilon(nS)$, $n = 1, 2, 3, 4$ are also shown. The full list of references to the original data and the details of the R ratio extraction from them can be found in [[arXiv:hep-ph/0312114](https://arxiv.org/abs/hep-ph/0312114)]. Corresponding computer-readable data files are available at <http://pdg.lbl.gov/current/xsect/>. (Courtesy of the COMPAS (Protvino) and HEPDATA (Durham) Groups, May 2010.)

PDG 2014

“axion” exchange



Life after Higgs

- requiring rethinking on past prejudices
- SUSY breaking mechanism
 - split spectrum (anomaly mediation)
 - vector mediation (new!)
- dark matter
 - SIMP instead of WIMP (new!)
 - Z' , MeV-scale “axion”

Kaoru's conditions

- No reminiscence or pleasantries
- no discussions of past collaborations
- real science
- Forward-looking

Now some
personal reminiscence...

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Invited talk given at Conference: [C92-02-18](#) (Tsukuba Workshop: JLC 1992:265-283)
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Published in [Phys.Rev. D47 \(1993\) 56-81](#)
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HELAS: HELicity Amplitude Subroutines for Feynman diagram evaluations

K. Hagiwara¹, J. Kanzaki¹, H. Murayama² and I. Watanabe³

Version 3.0 (1 Jan 2000)

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I\$\$\$\$\$ → IXXXXX

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Chapter 1

Introduction

HELAS¹² (HELicity Amplitudes Subroutines) is a set of FORTRAN77 subroutines which enable us to compute the helicity amplitudes of an arbitrary tree-level Feynman diagram with a simple sequence of CALL SUBROUTINE statements.

It is easy to write down a FORTRAN program to calculate the helicity amplitudes of a given process by calling HELAS subroutines. For instance, the helicity amplitudes of the process $W^+W^- \rightarrow t\bar{t}$ can be evaluated by the following program with just 11 lines. First, the two incoming (W^+ and W^-) and the two outgoing (t and \bar{t}) particle wavefunctions are calculated by calling the following 4 subroutines:

```
CALL VXXXXX(PWM,WMASS,NHWM,-1 , WM)
CALL VXXXXX(PWP,WMASS,NHWP,-1 , WP)
CALL OXXXXX(PT ,TMASS,NHT ,+1 , FO)
CALL IXXXXX(PTB,TMASS,NHTB,-1 , FI)
```

Second, the 4 Feynman diagrams of Fig. 1 (see page 9) are calculated with the following 6 lines:

```
CALL J3XXXX(FI,FO,GAU,GZU,ZMASS,ZWIDTH , J3)
CALL VVVXXX(WP,WM,J3,GW , AMPS)
CALL FVIXXX(FI,WM,GWF,0.,0. , FVI)
CALL IOVXXX(FVI,FO,WP,GWF , AMPT)
CALL HIOXXX(FI,FO,GCHT,HMASS,HWIDTH , HTT)
CALL VVSXXX(WM,WP,HTT,GWPH , AMPH)
```

Finally, the helicity amplitudes are obtained by adding the above sub-amplitudes

$$\text{AMP} = \text{AMPS} + \text{AMPT} + \text{AMPH}.$$

The meaning of each line will become clear in the next chapter (Sect. 2.3).

Even the program to compute the helicity amplitudes of the process $e^-e^+ \rightarrow e^-\bar{\nu}_e W^+Z$, which has 80 Feynman diagrams, has only 65 lines of CALL sentences (see Appendix B.6 for a sample program). This compactness of the helicity amplitude programs is the main advantage of using HELAS.

Another advantage of the HELAS system is that it is very easy to allow external heavy particles to decay into light quarks and leptons without loosing the spin correlation. This is achieved simply by replacing the relevant external wavefunction subroutine by a sequence

¹This name has nothing to do with the ancient Greek ‘Ελλας’ since Greek is completely Greek to us.

²[helásu] means *to decrease* in Japanese. Does HELAS decrease your tasks?

```
CALL IXXXX(PTB,TMASS,NHTB,-1 , FI)
```

Second, the 4 Feynman diagrams of Fig. 1 (see page 9) are calculated with the following 6 lines:

```
CALL J3XXX(FI,FO,GAU,GZU,ZMASS,ZWIDTH , J3)
CALL VVVXXX(WP,WM,J3,GW , AMPS)
CALL FVIXXX(FI,WM,GWF,0.,0. , FVI)
CALL IOVXXX(FVI,FO,WP,GWF , AMPT)
CALL HIOXXX(FI,FO,GCHT,HMASS,HWIDTH , HTT)
CALL VVSXXX(WM,WP,HTT,GWPH , AMPH)
```

Finally, the helicity amplitudes are obtained by adding the above sub-amplitudes

```
AMP = AMPS + AMPT + AMPH.
```

The meaning of each line will become clear in the next chapter (Sect. 2.3).

Even the program to compute the helicity amplitudes of the process $e^-e^+ \rightarrow e^-\bar{\nu}_e W^+ Z$, which has 80 Feynman diagrams, has only 65 lines of `CALL` sentences (see Appendix B.6 for a sample program). This compactness of the helicity amplitude programs is the main advantage of using `HELAS`.

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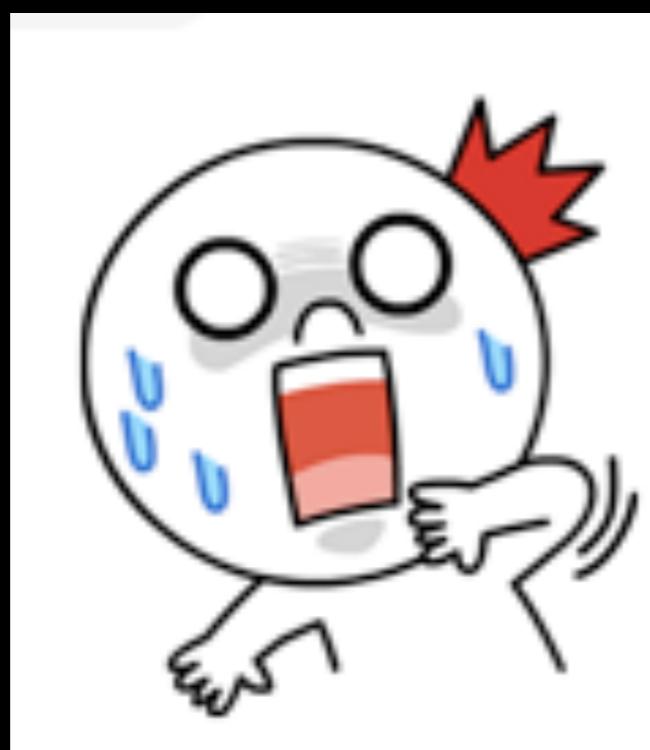
Miyazawa

Sugawara

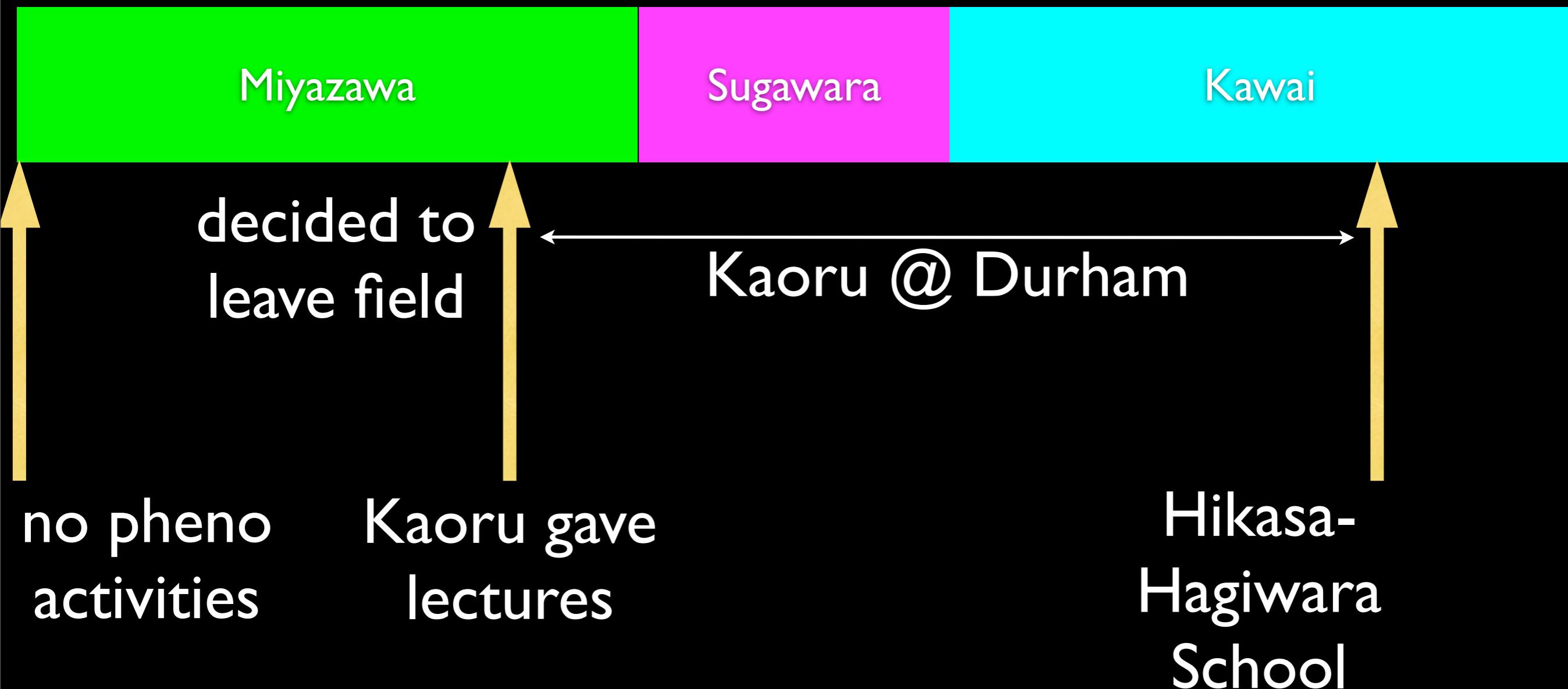
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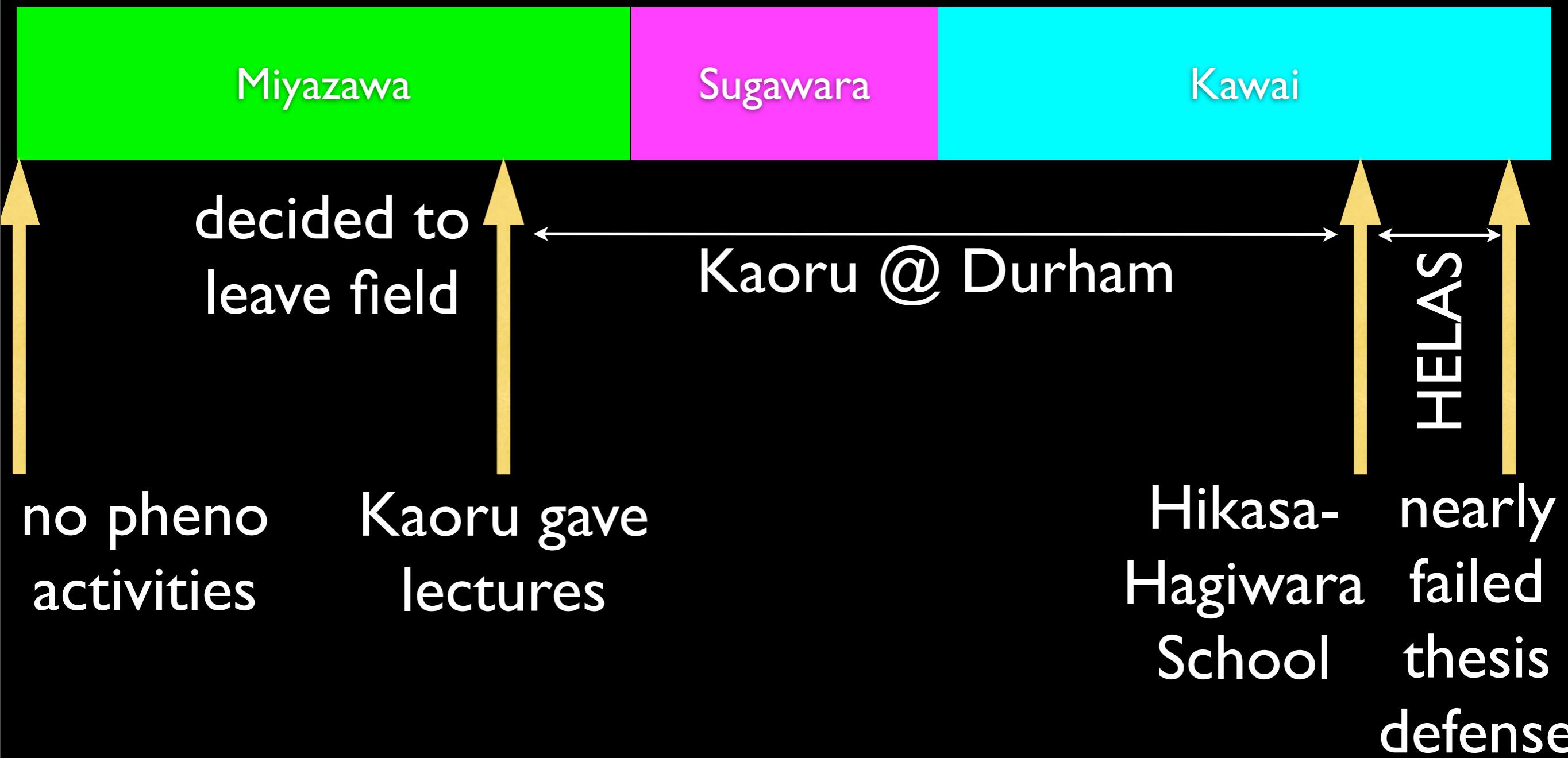


no pheno
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Kaoru gave
lectures

Hikasa-
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**Thank you, Kaoru,
I'm eternally grateful!**