

SM

# INTRODUCTION TO DARK SECTORS, LLPS AND DISCOVERY PHYSICS

ROBERTO FRANCESCHINI, SEPT. 12<sup>th</sup> 2022  
EEFACT WORKSHOP (LNF FRASCATI)



DARK

# Outline

- Ideology of BSM in the 2020s
- What can we probe at  $e^+e^-$
- high-lumi direct probes

# Open questions and shortcomings of the SM

- what is the dark matter in the Universe?
- why QCD does not violate CP?
- how have baryons originated in the early Universe?
- what originates flavor mixing and fermions masses?
- what gives mass to neutrinos?
- why gravity and weak interactions are so different?
- what fixes the cosmological constant?

- ? Need new matter (or even bigger modifications to the SM)
- / Adjusting one SM parameter might do
- ⚙️ Adjusting several SM parameters might do
- EFT Separation of scales as an organizing principle might fail

EACH of these issues one day will teach us a lesson

# Open questions and shortcomings of the SM



- what is the dark matter in the Universe?



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- how have baryons originated in the early Universe?



- what originates flavor mixing and fermions masses?



- what gives mass to neutrinos?

*EFT*



- why gravity and weak interactions are so different?

*EFT*



- what fixes the cosmological constant?



Need new matter (or even bigger modifications to the SM)



Adjusting one SM parameter might do



Adjusting several SM parameters might do

*EFT*

Separation of scales as an organizing principle might fail

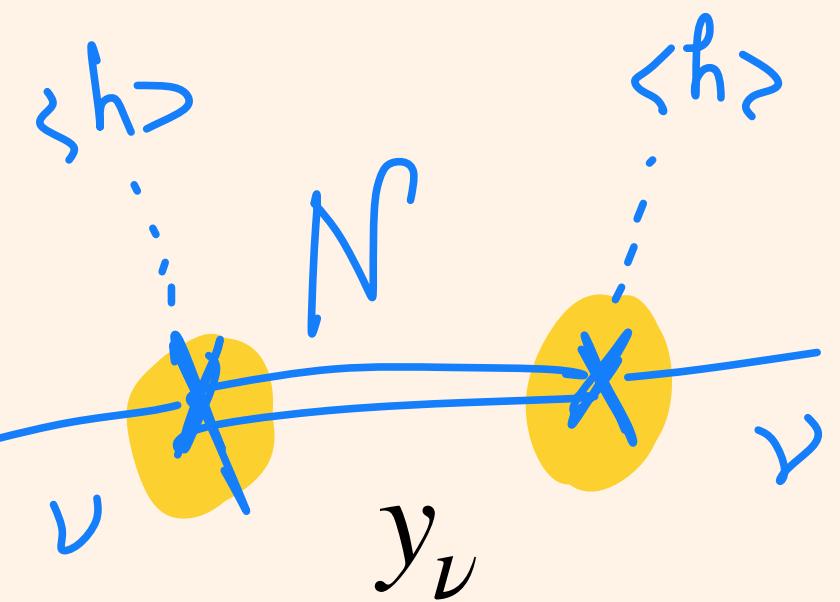


very small mass!

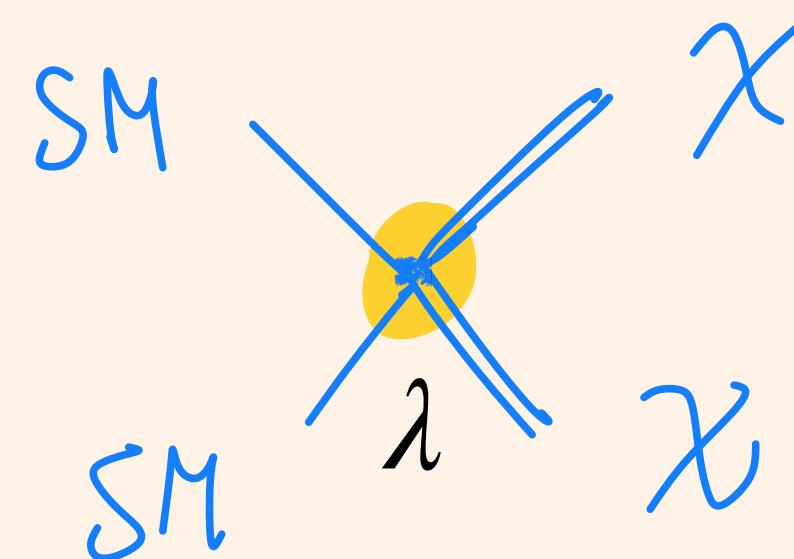
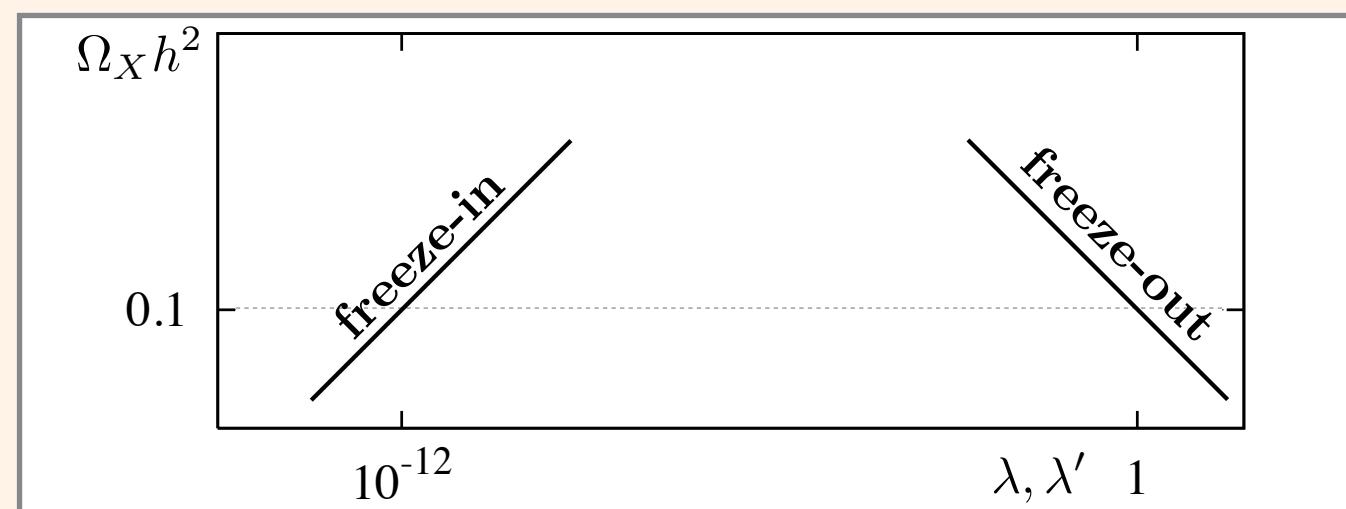
Solutions involve either a small coupling or very high scale, or both.

# Tiny couplings are often needed in models of New Physics

$$m_\nu \simeq \frac{y_\nu^2 v^2}{M}$$



TYPE 1 SEE-SAW

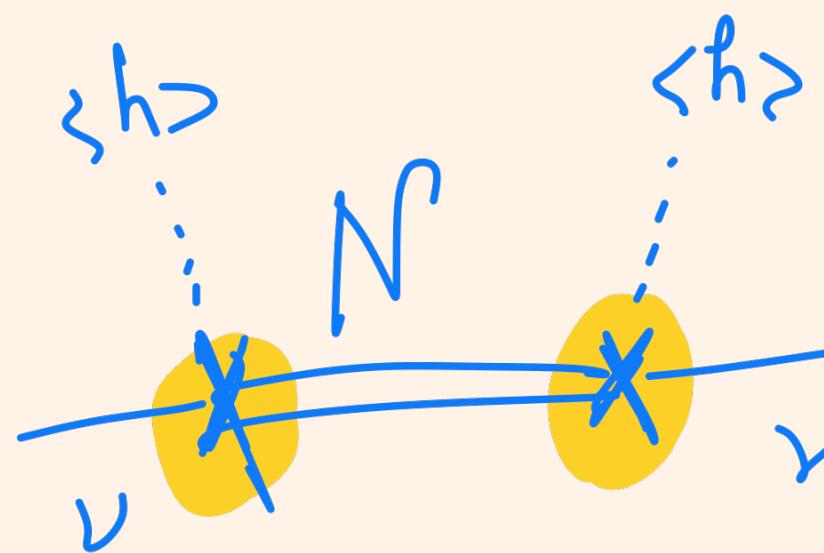
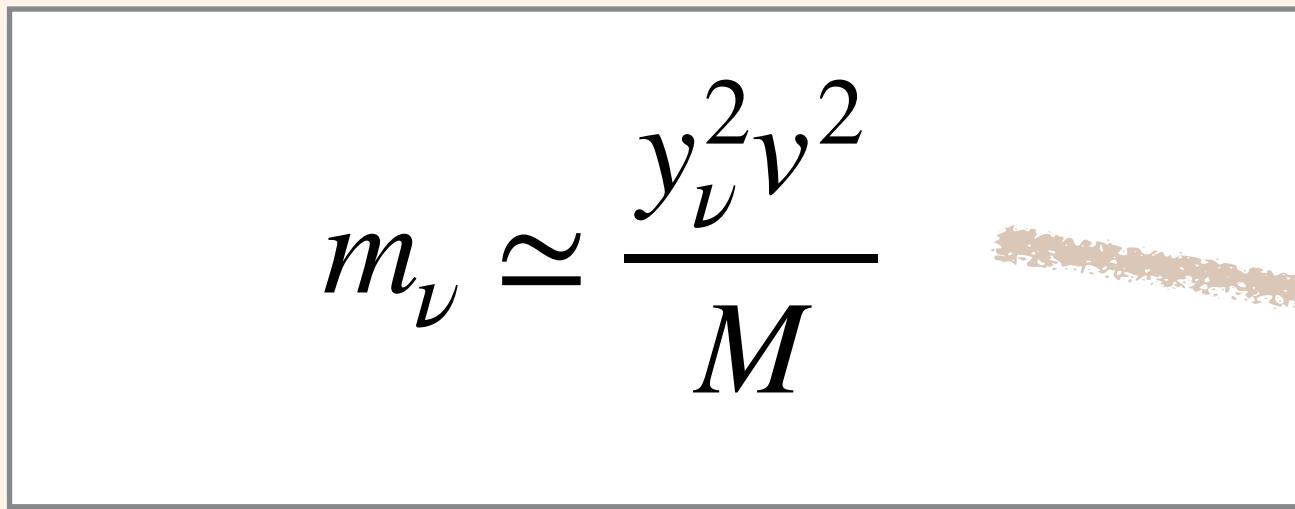


FREEZE-IN DM

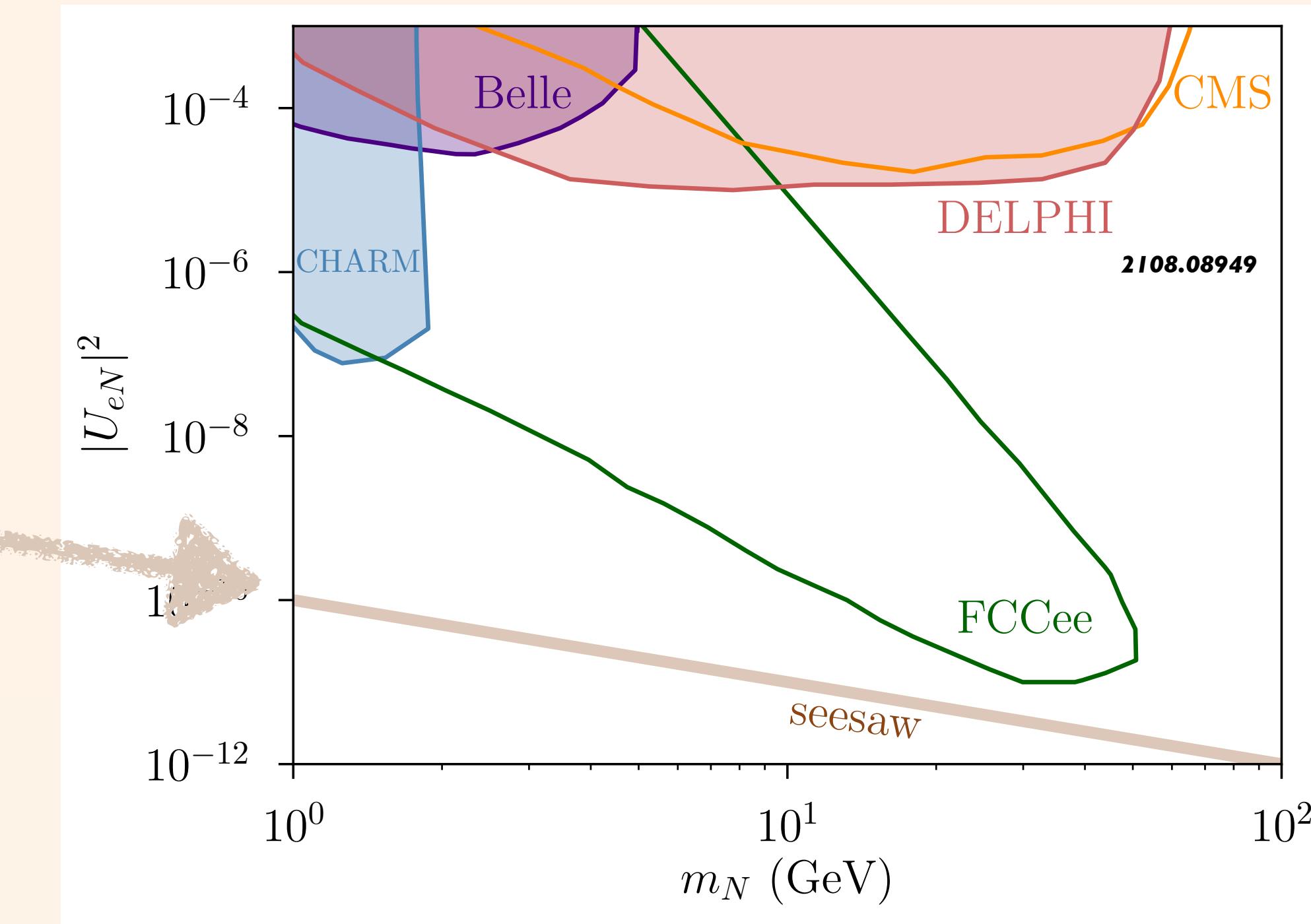
...

# Reach on type-1 see-saw models

Very high-lumi Z-pole



Long-lived signature



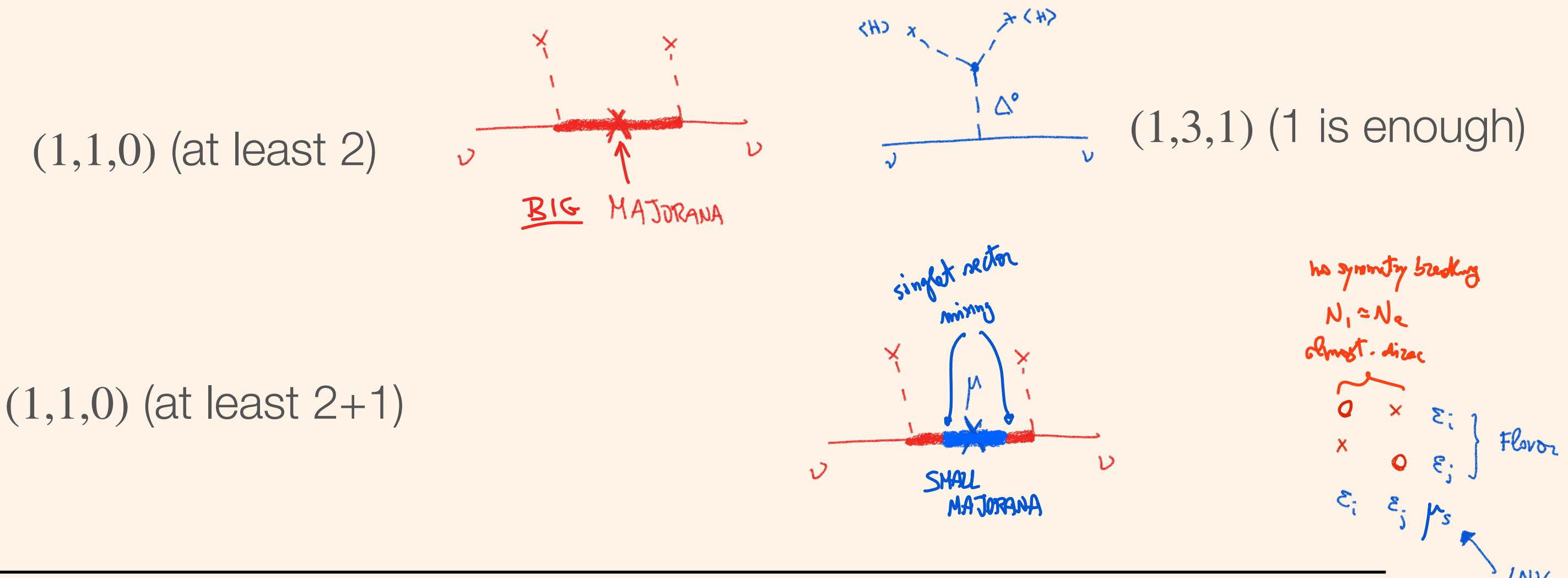
Prototypical:

- depends crucially on lumi (within the mass range that can be probed by the machine)
- suggests a new signature (••)
- there are alternative theoretical models (most of which cannot be probed at the same machine) ↴(ツ) ↵

# A chart of neutrino mass generation mechanisms

*The breaking of lepton number*

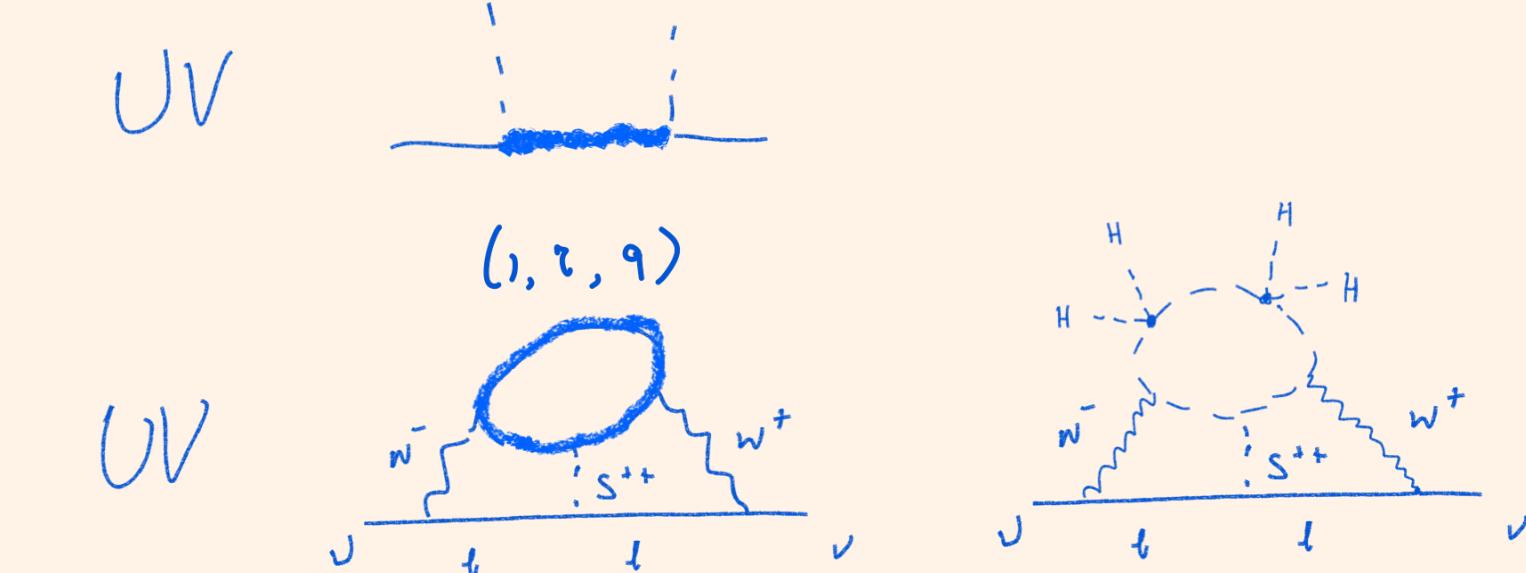
*L – violation*



*L – not accidental*

$$d = 5 \quad (1,2,1/2) \quad \frac{(LH)^2}{\Lambda}$$

$$d = 7 \quad (1,1,2) \quad \frac{(DH\sigma_2 H)^2 S^{--}}{\Lambda^3}$$



*L – gauged, SSB*

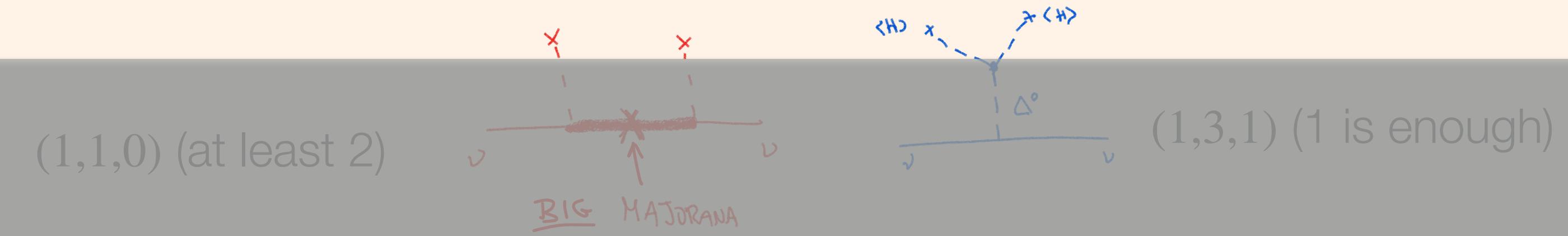
$$SU(3) \otimes SU(2)_L \otimes SU(2)_L \otimes U(1)_{B-L}$$

$$(1,2,1,1), (1,1,2,1), (1,2,2,1), (1,1,1,2),$$

# A chart of neutrino mass generation mechanisms

*The breaking of lepton number*

*L – violation*



**Unlike the situation with SM Higgs boson, which stood apart from other solutions for EWSB, and even had a “no loose theorem” at LHC, we are now in**

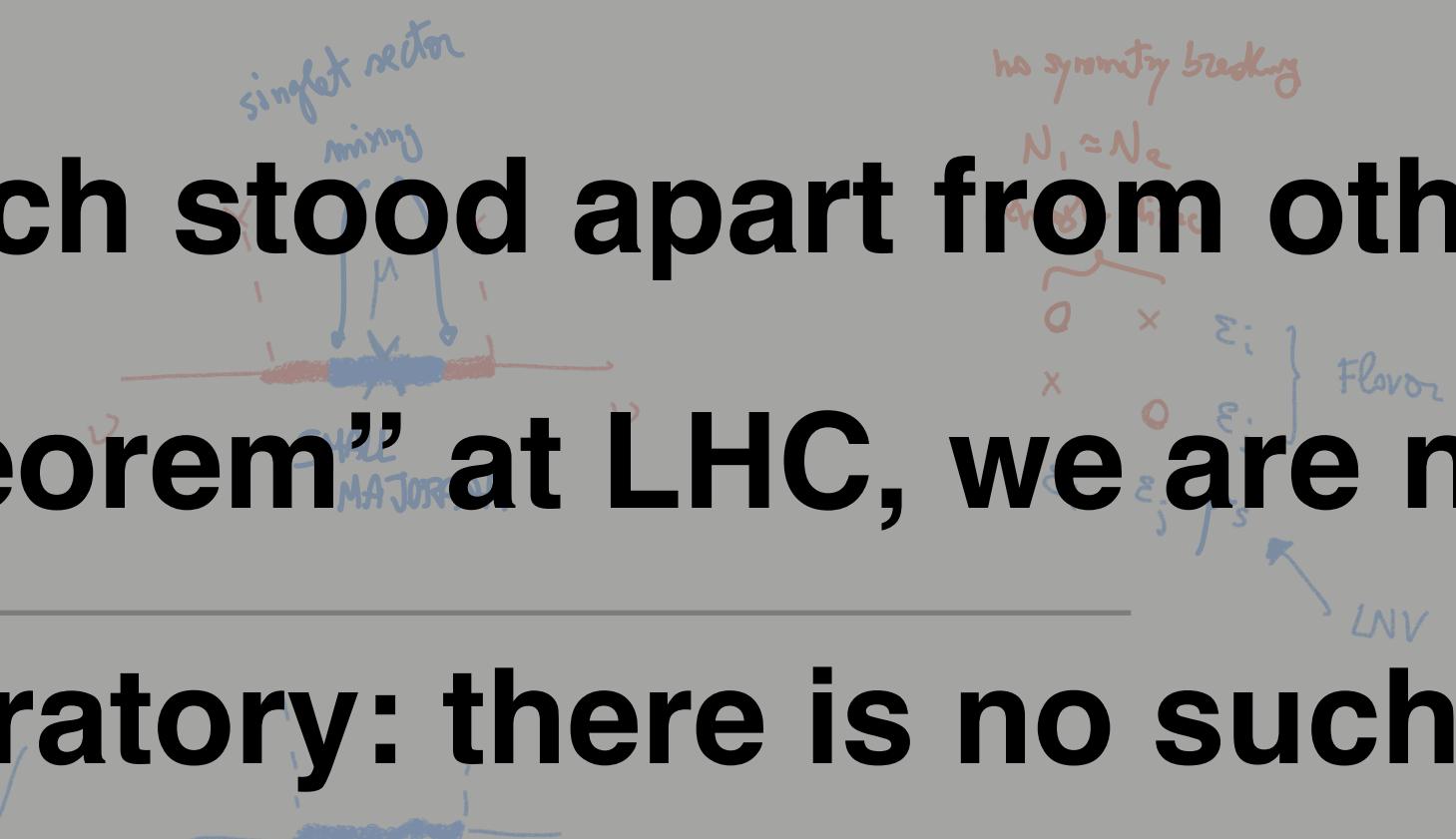
*L – not accidental*      *L – hot accidental*      *L – gauged, SSB*

**a mode of scientific exploration that is truly exploratory: there is no such thing**

as “the” model of new physics.

$$d = 5 \quad (1,2,1/2) \quad \frac{(D\bar{H}\sigma_2 H)^2 S^{--}}{\Lambda} \quad UV$$

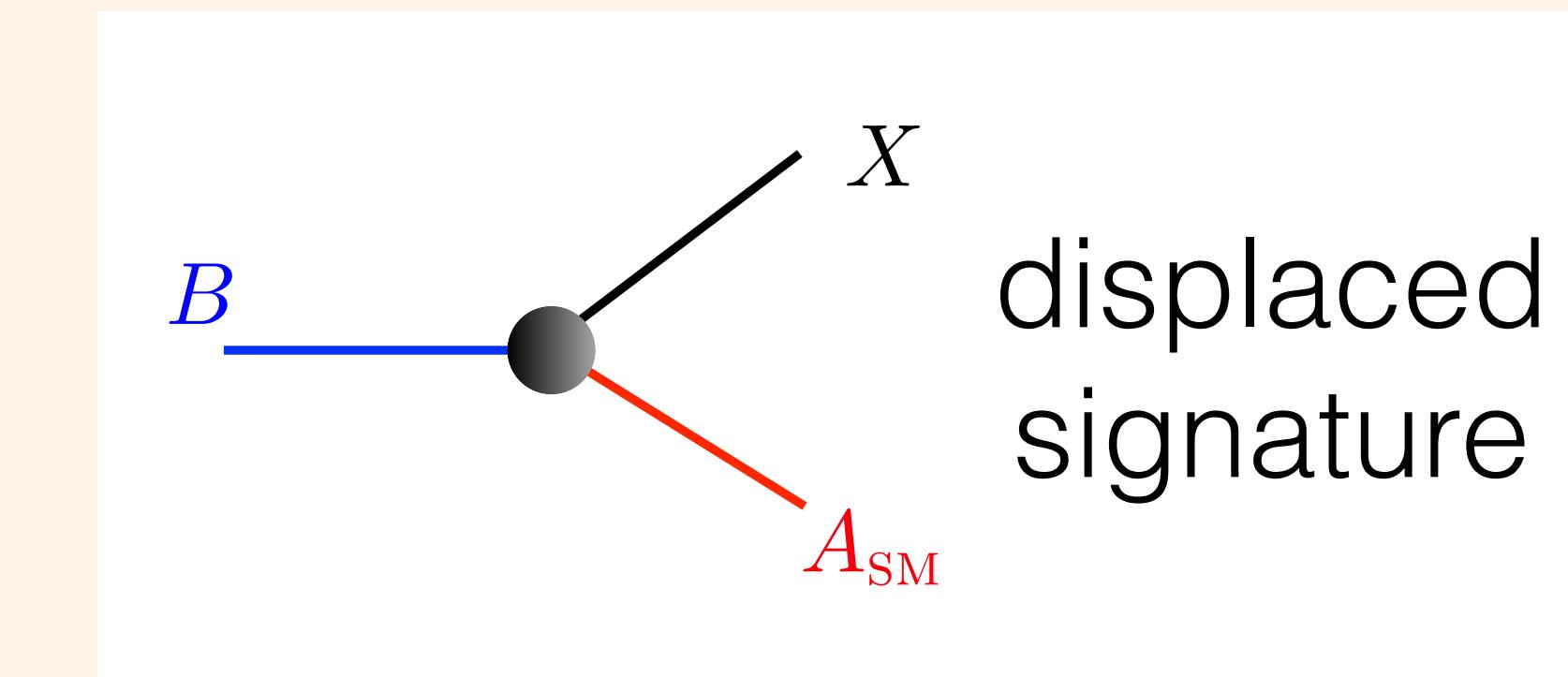
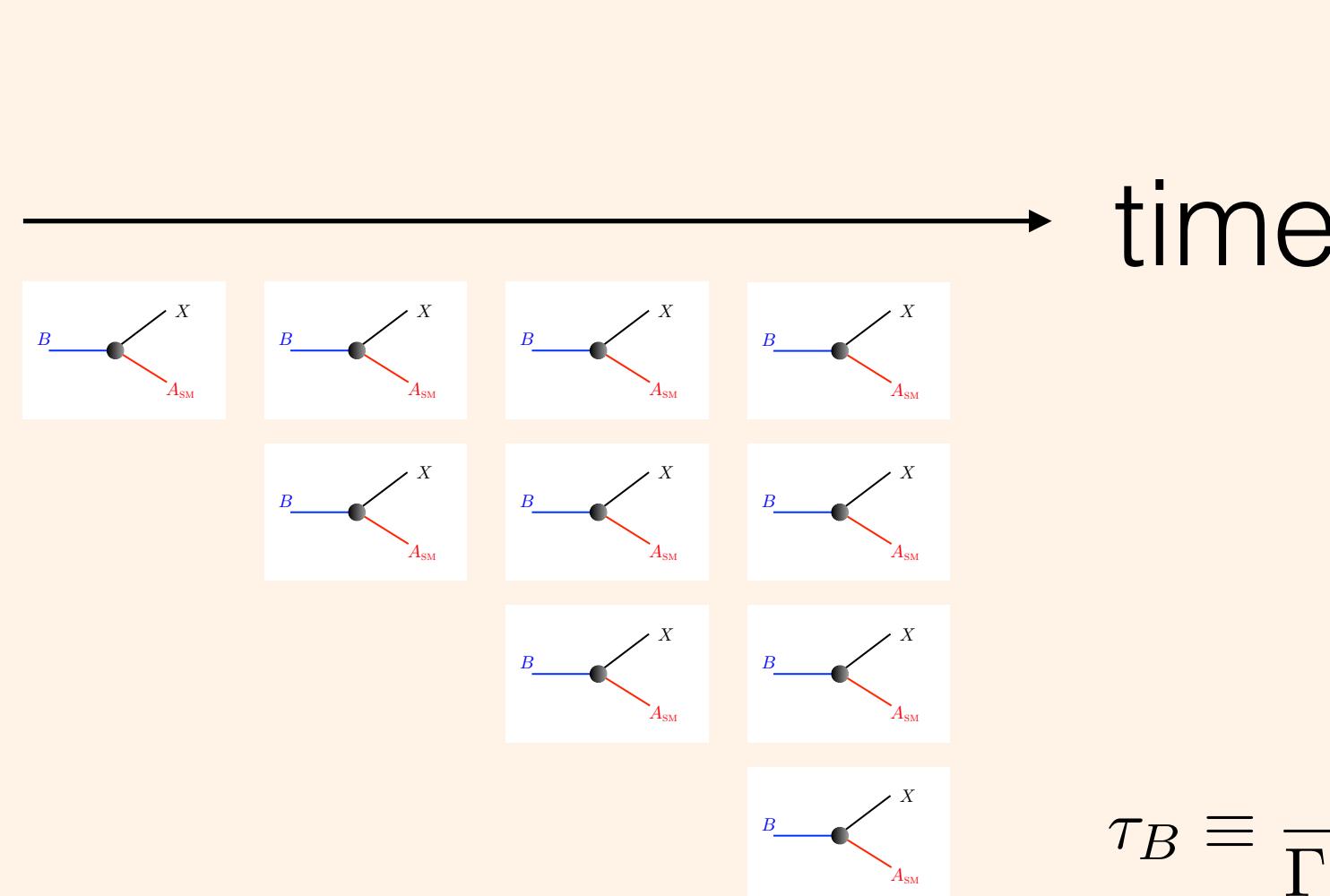
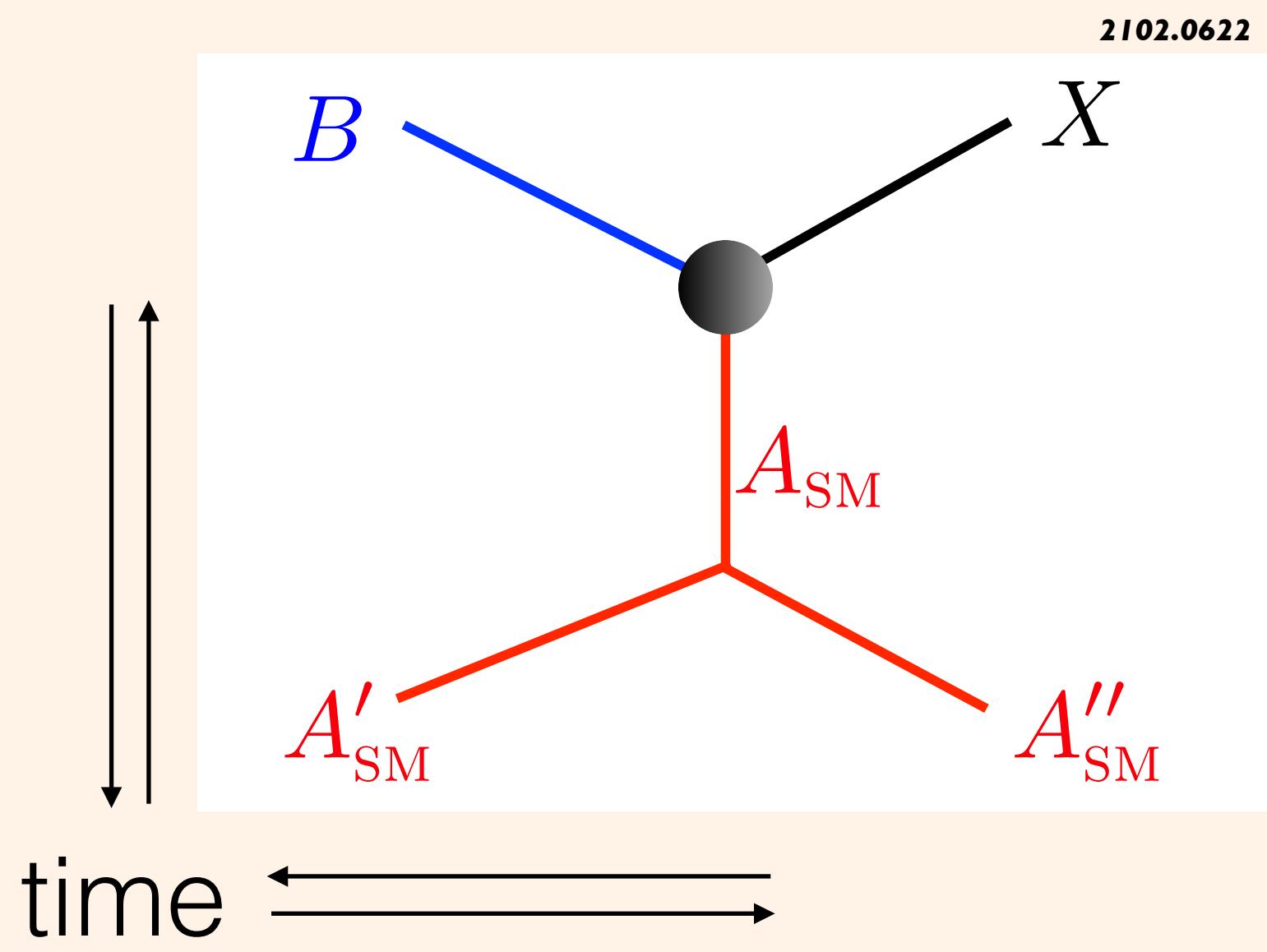
$$d = 7 \quad (1,1,2) \quad \frac{(D\bar{H}\sigma_2 H)^2 S^{--}}{\Lambda^3} \quad UV$$



$$SU(3) \otimes SU(2)_L \otimes SU(2)_L \otimes U(1)_{B-L}$$

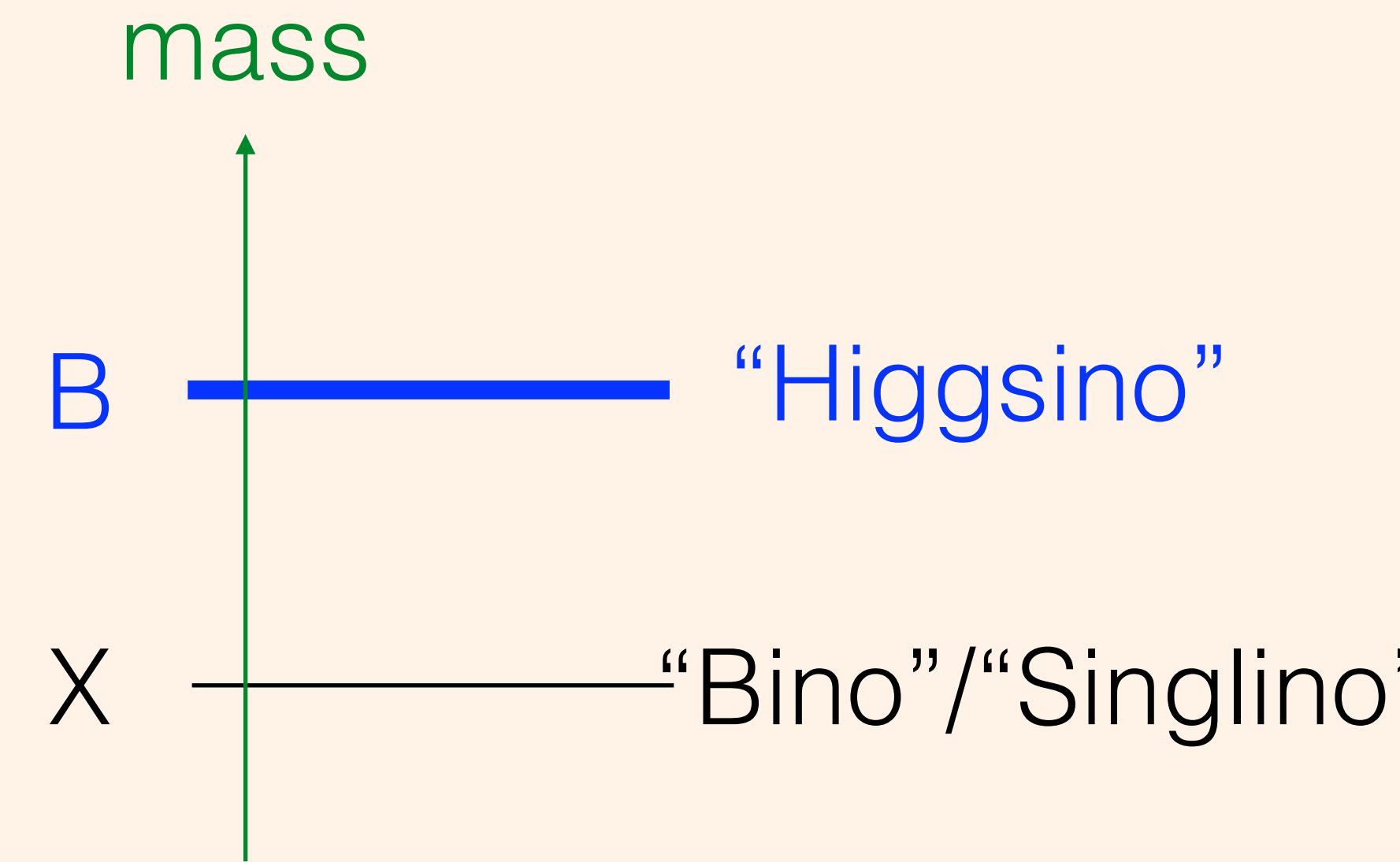
$$(1,2,1,1), (1,1,2,1), (1,2,2,1), (1,1,1,2),$$

# Freeze-in Dark Matter candidates

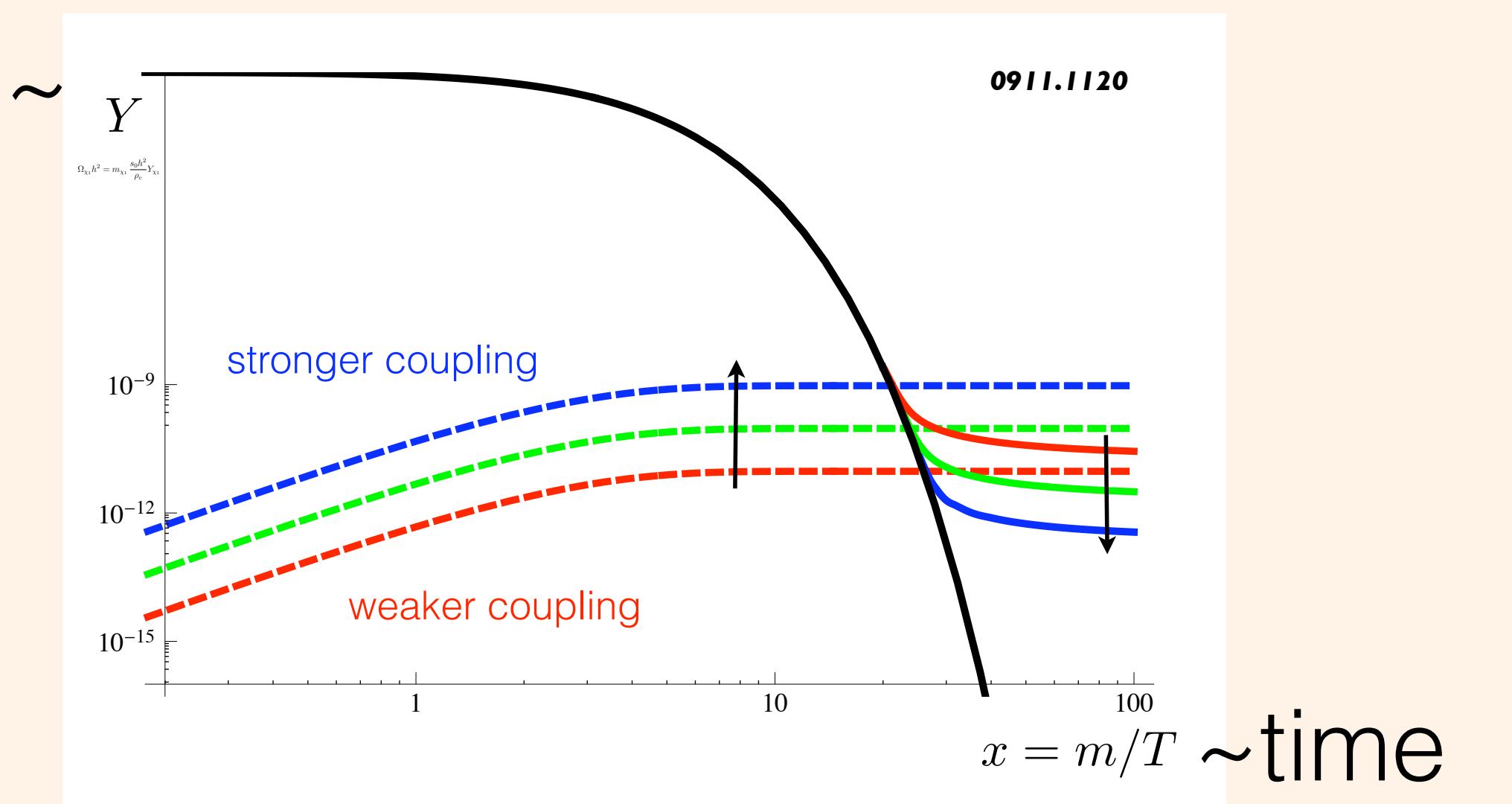


$$\tau_B \equiv \frac{1}{\Gamma_{B \rightarrow A_{\text{SM}} X}} \simeq 3.3 \times 10^3 \text{ m} \left( \frac{g_B}{2} \right) \left( \frac{m_X}{1 \text{ GeV}} \right) \left( \frac{1 \text{ TeV}}{m_B} \right)^2$$

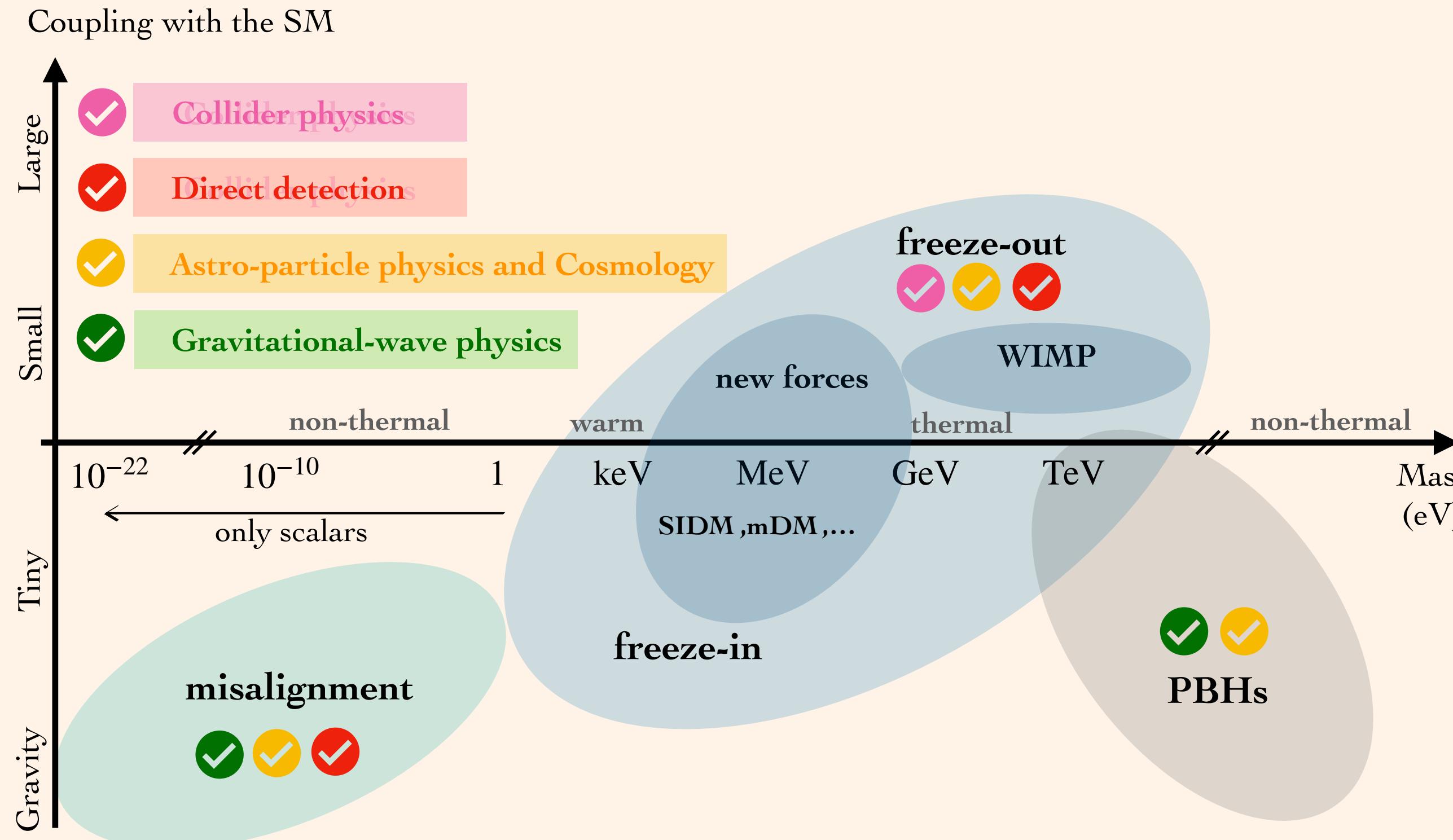
$$\Omega_{\chi_1} h^2 = 0.1 \left( \frac{105}{g_*} \right)^{3/2} \left( \frac{m_{\chi_1}}{10 \text{ keV}} \right) \left( \frac{1 \text{ TeV}}{\mu} \right)^2 \left( \frac{\sum_{ij} g_{A_i} \Gamma_{ij}}{5 \times 10^{-15} \text{ GeV}} \right)$$



Abundance~

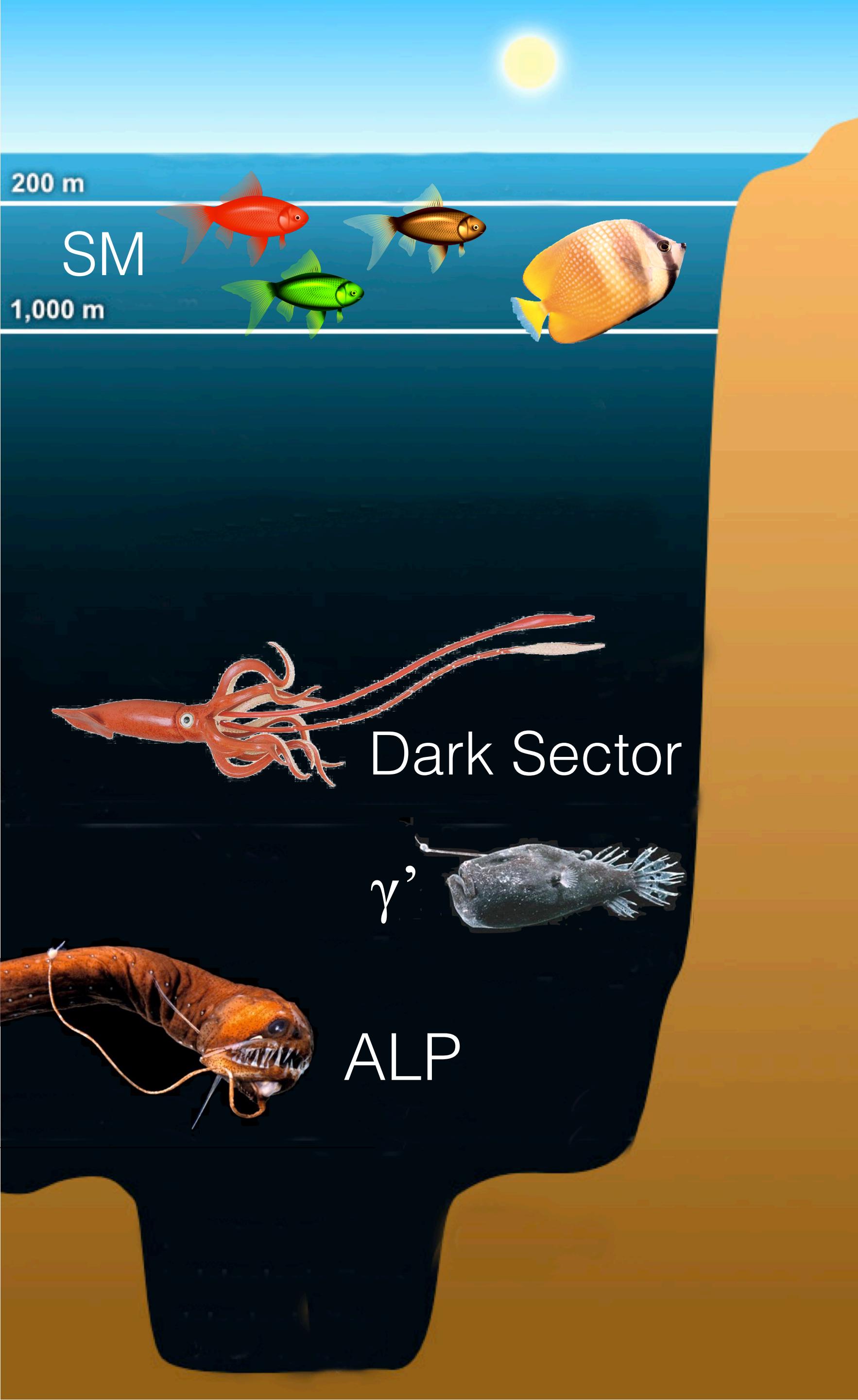


# A chart of Dark Matter candidates



we need to keep the search broad and on multiple fronts

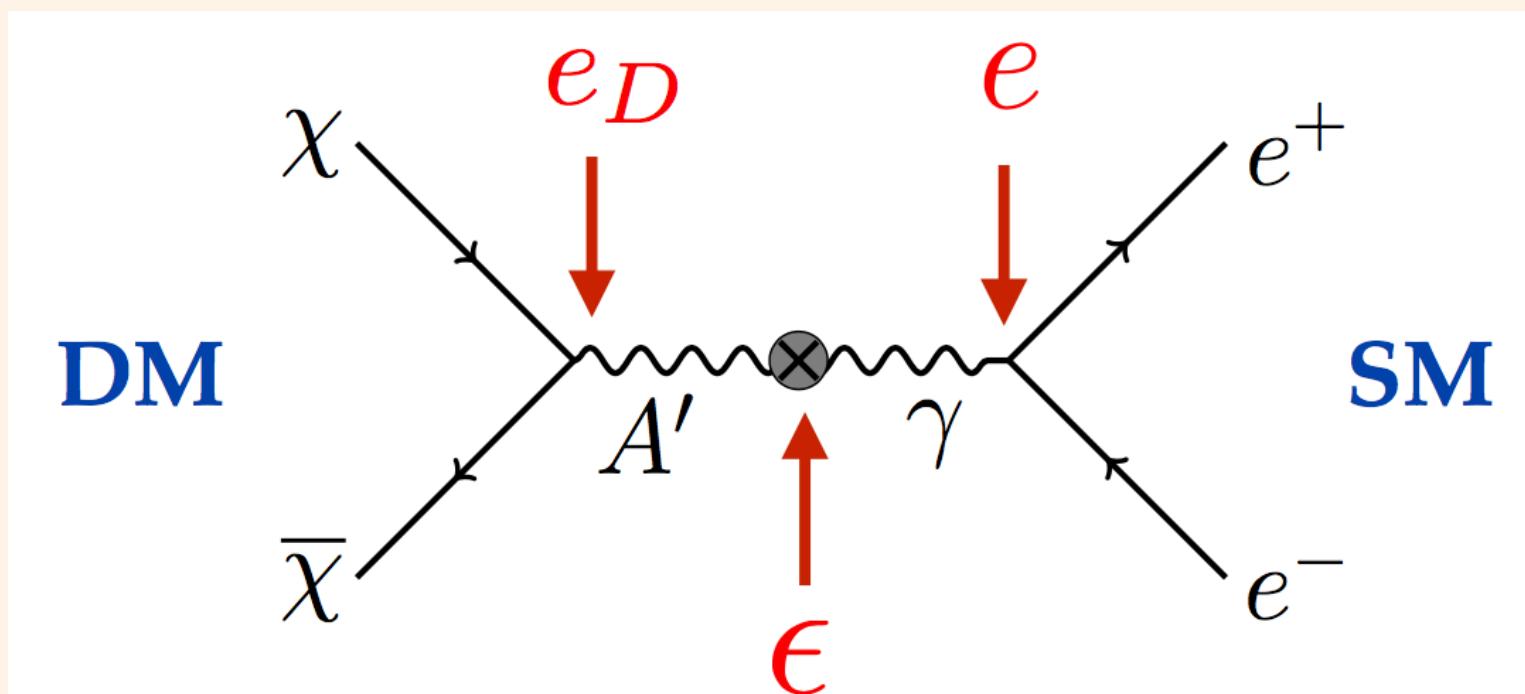
The deeper you look ...  
the larger lumi you need



# The deeper you look ... the larger lumi you need

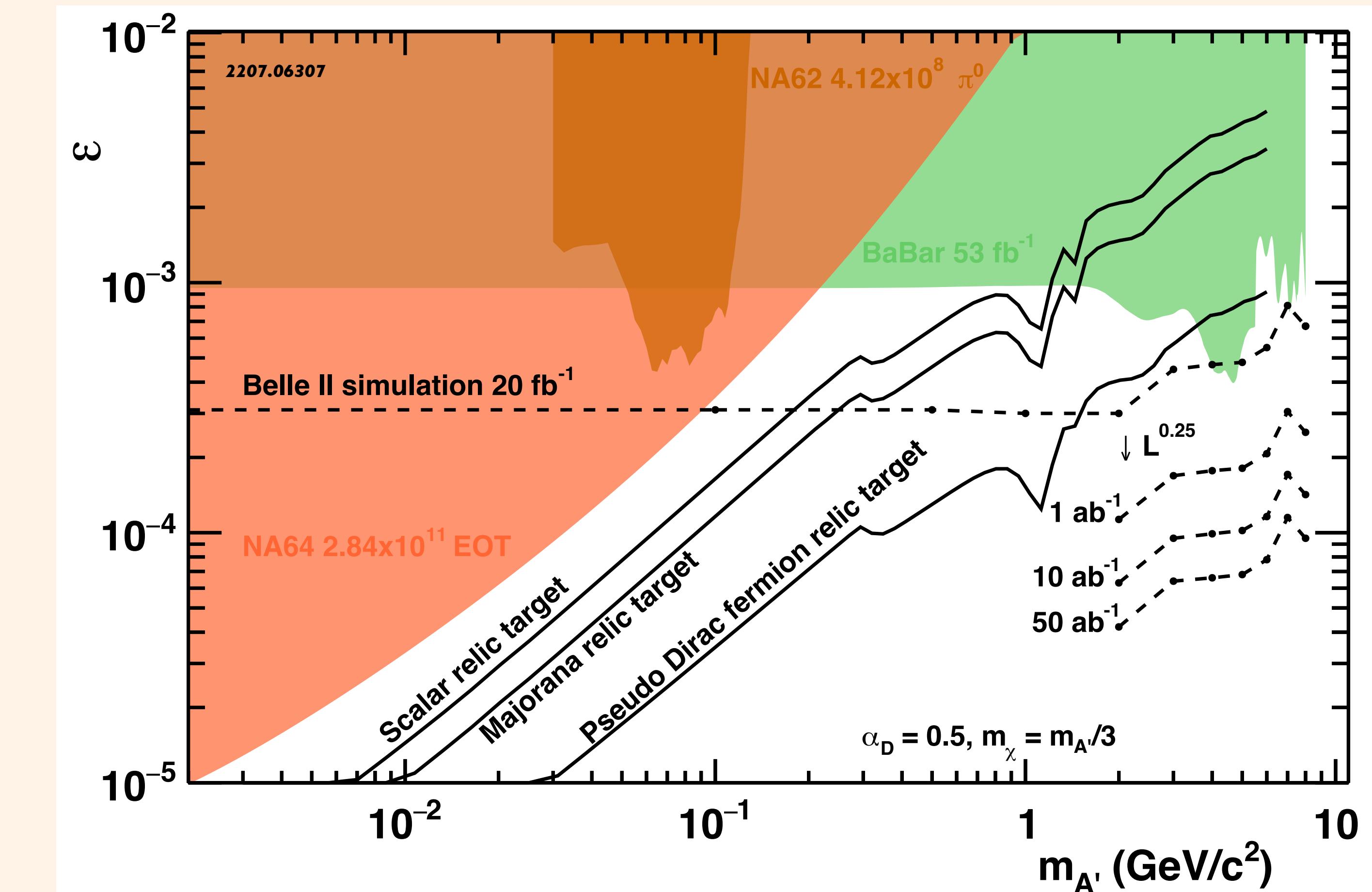
## invisible final states

new gauge interactions for  
thermal equilibrium of sub-  
GeV dark matter



- p-wave annihilation allowed by CMB
- direct detection limits drop below few GeV
- sub-MeV more conflicts with cosmology

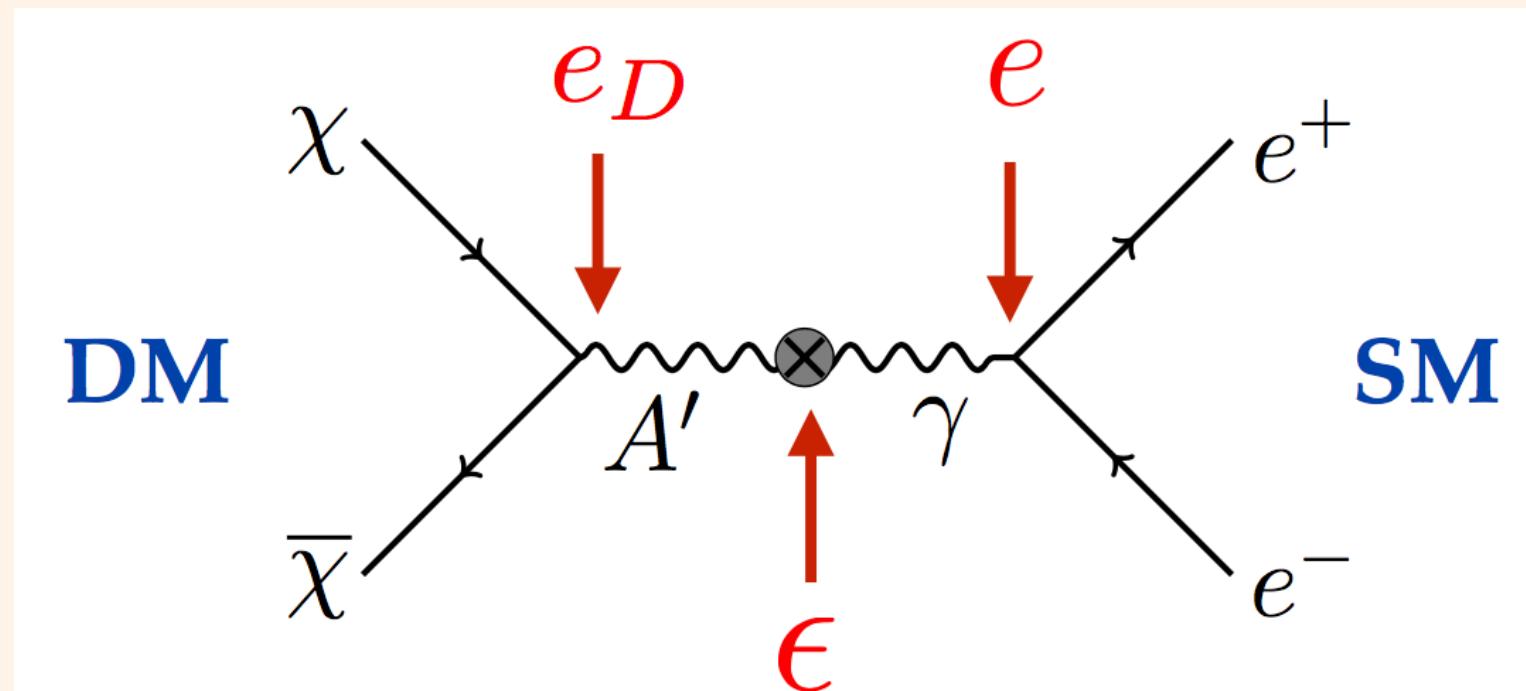
DM in MeV-GeV range (in this class of models)



# The deeper you look... the larger lumi you need

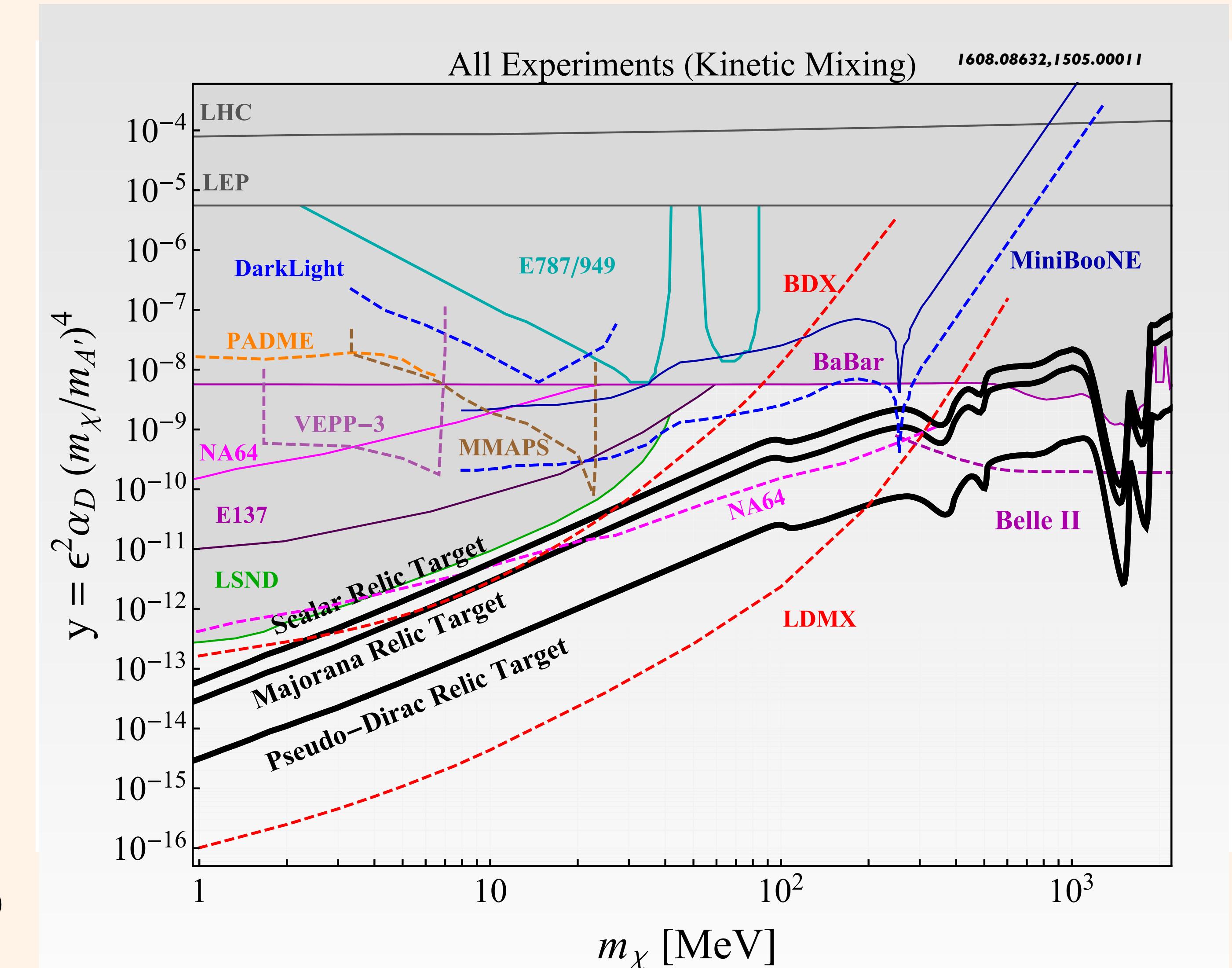
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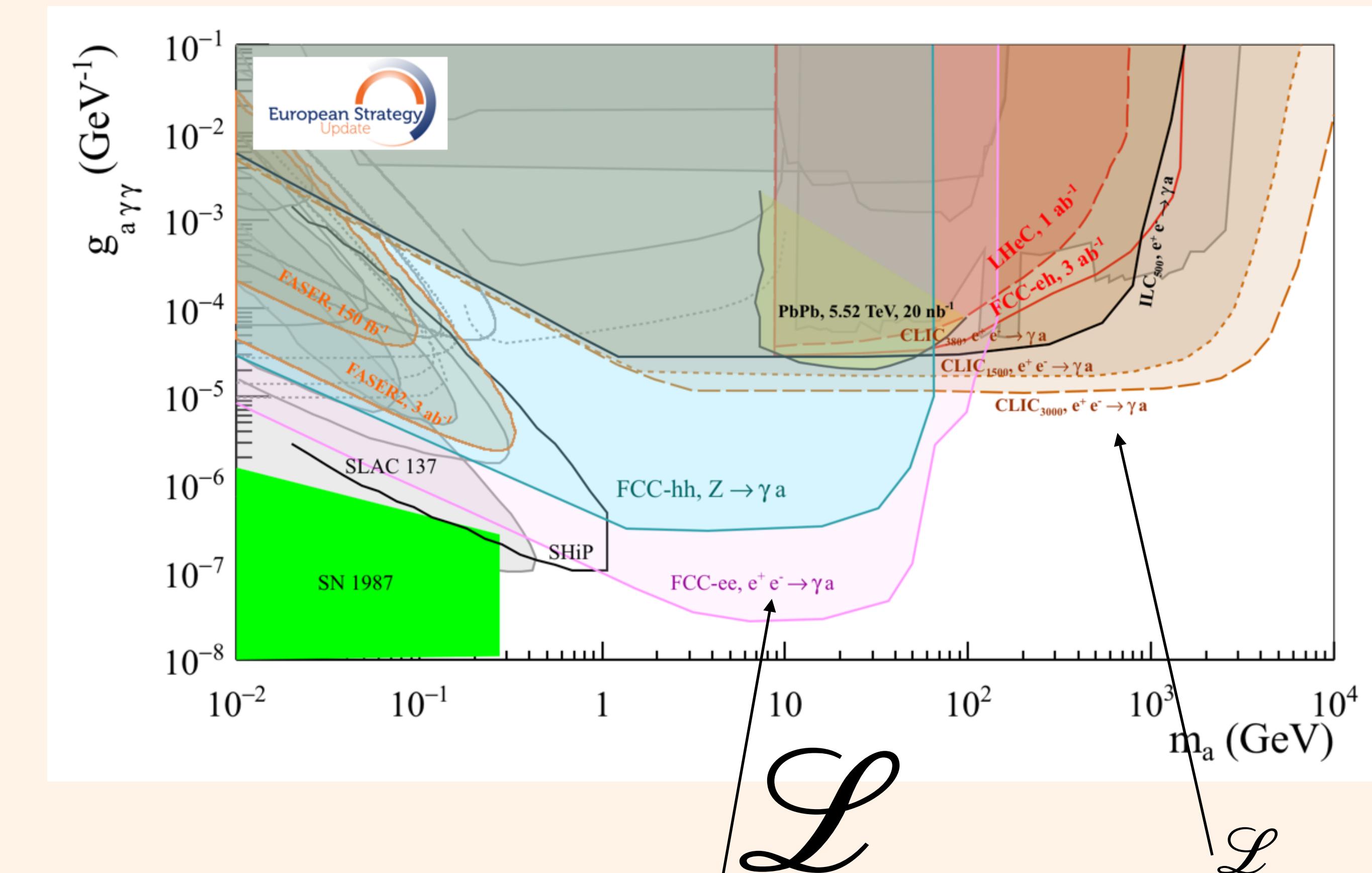
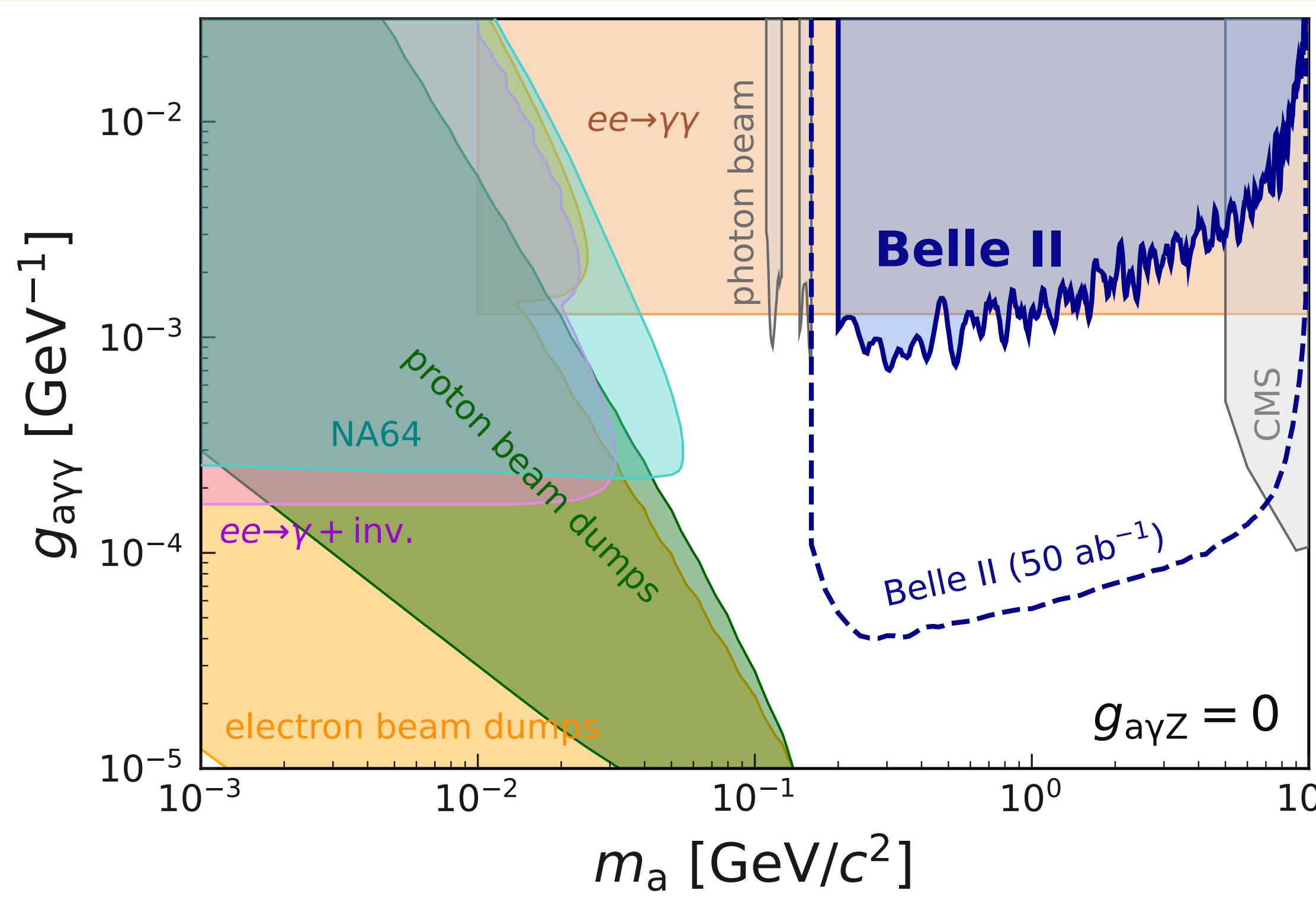
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DM in MeV-GeV range (in this class of models)



# The deeper you look ... the larger lumi you need

**prompt(ish) visible final states**  $e^+e^- \rightarrow \gamma + \gamma\gamma$



# The deeper you look... the larger lumi you need

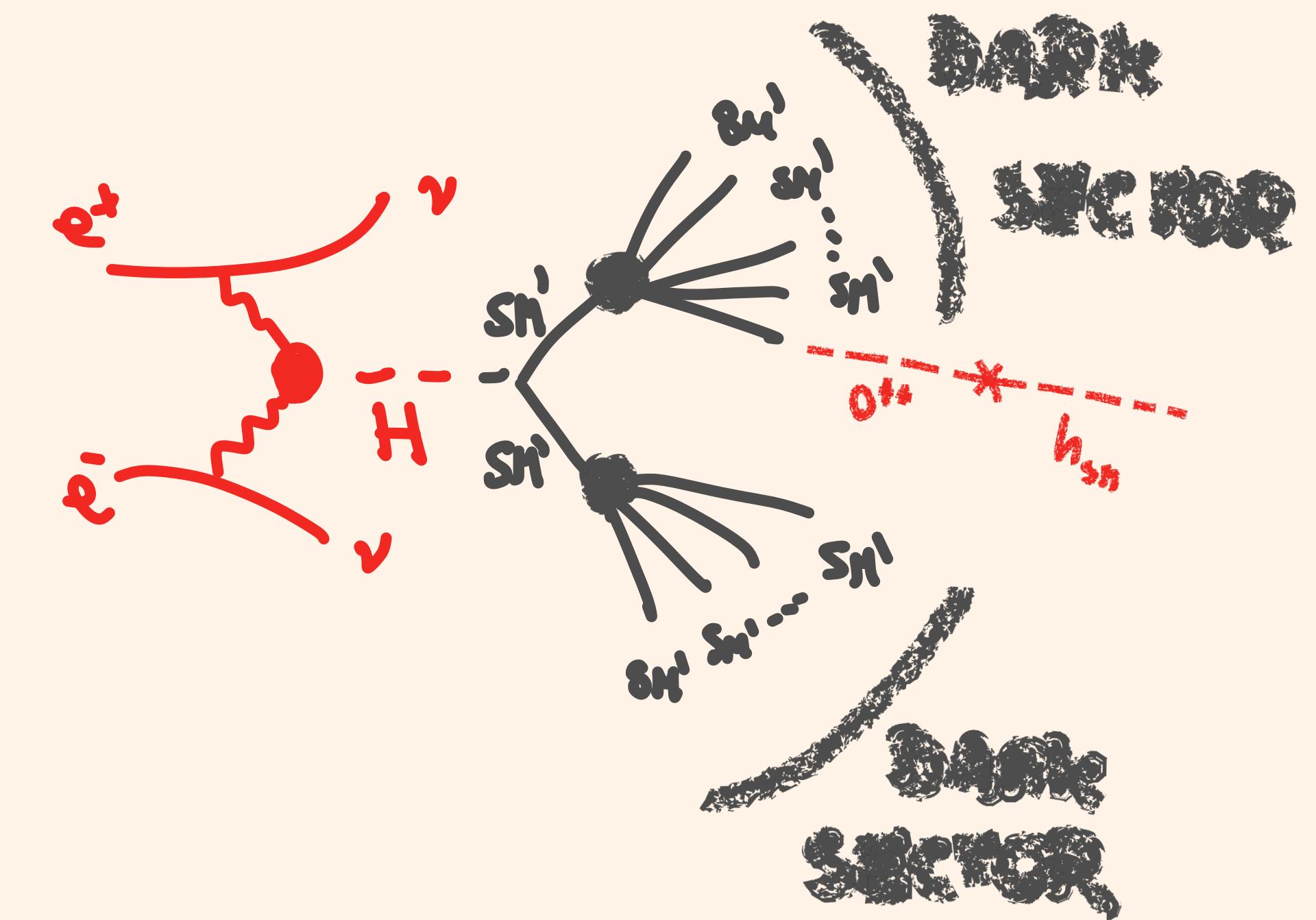
## long-lived visible signatures

A whole sector “mirrors” the SM in order to explain (at least in part) the lightness of Higgs boson.

The coupling between the SM and the mirror sector needs to be somewhat suppressed to accomplish the task (e.g. stabilize the weak scale)

$$e^+e^- \rightarrow H \nu\nu \quad H \rightarrow LLP LLP \quad \dots \quad LLP \rightarrow bb$$

“Neutral Naturalness” scenarios: Folded SUSY, fraternal Twin Higgs, ...



# The deeper you look ... the larger lumi you need

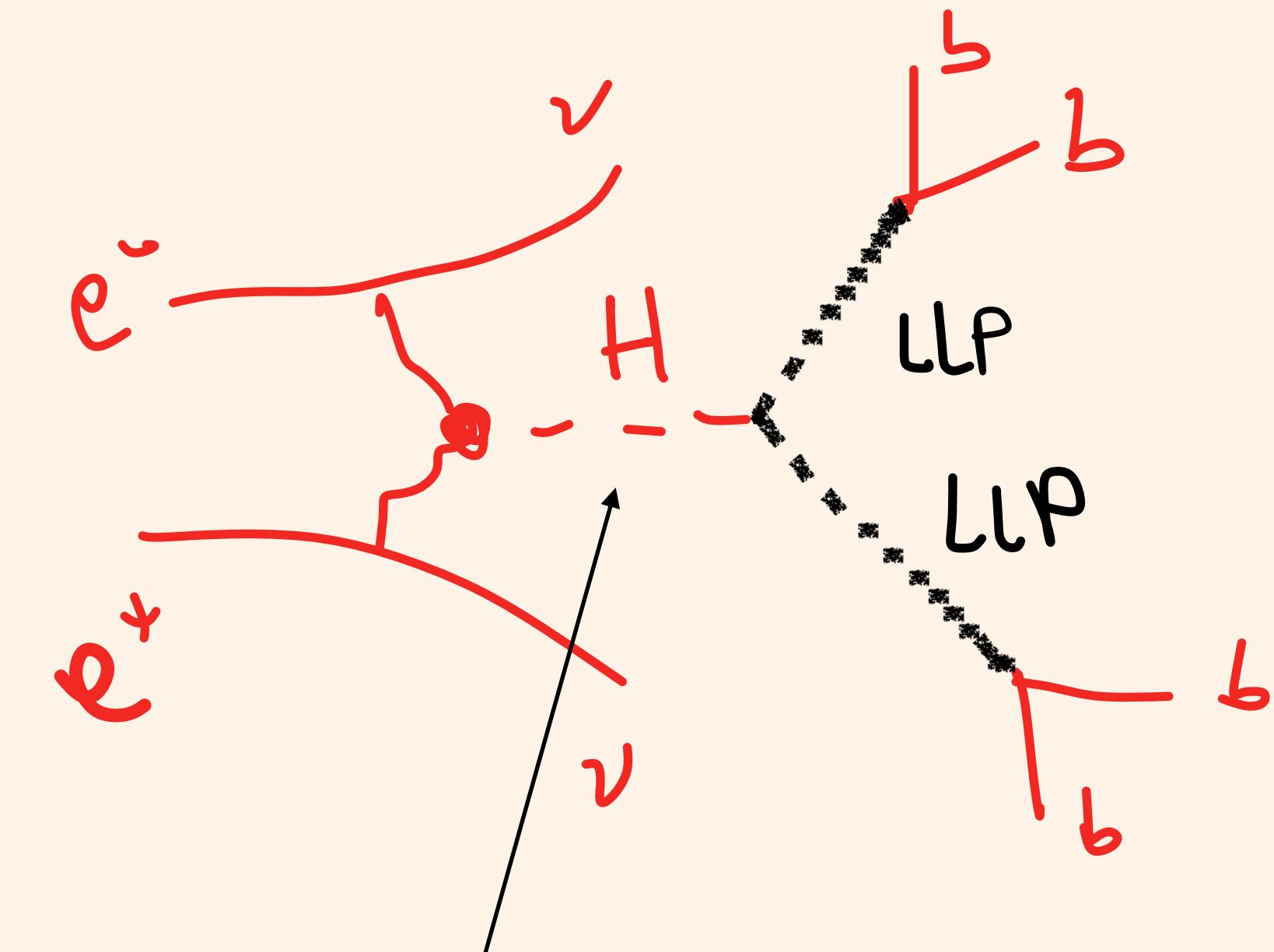
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$$e^+ e^- \rightarrow H \nu \bar{\nu} \quad H \rightarrow LLP \text{ LLP} \xrightarrow{c\beta\gamma\tau_0} LLP \rightarrow b\bar{b}$$

“Neutral Naturalness” scenarios: Folded SUSY, fraternal Twin Higgs, ...

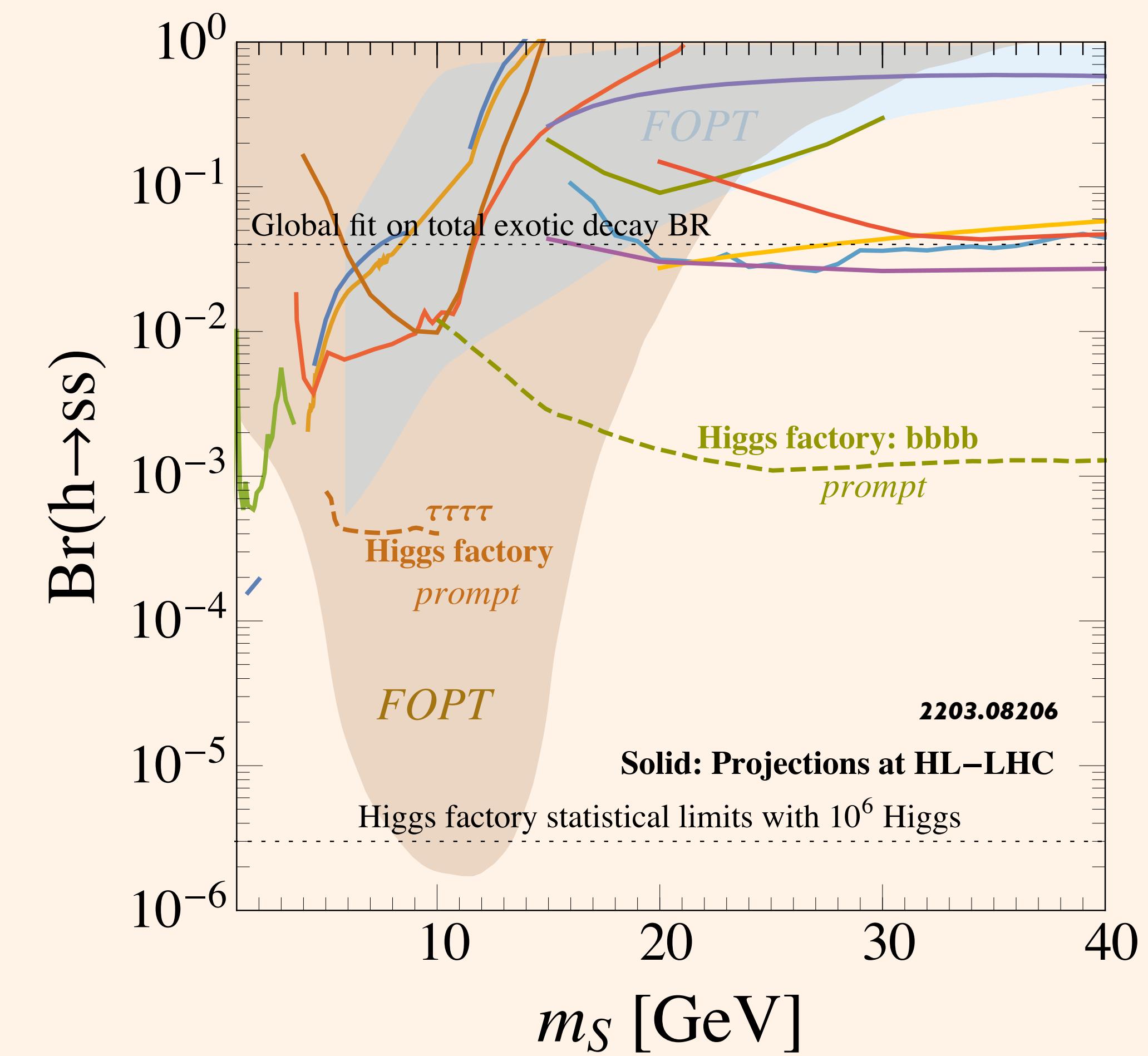


$m_H = 125, 200, 400, 600, 800, 1000 \text{ GeV}$

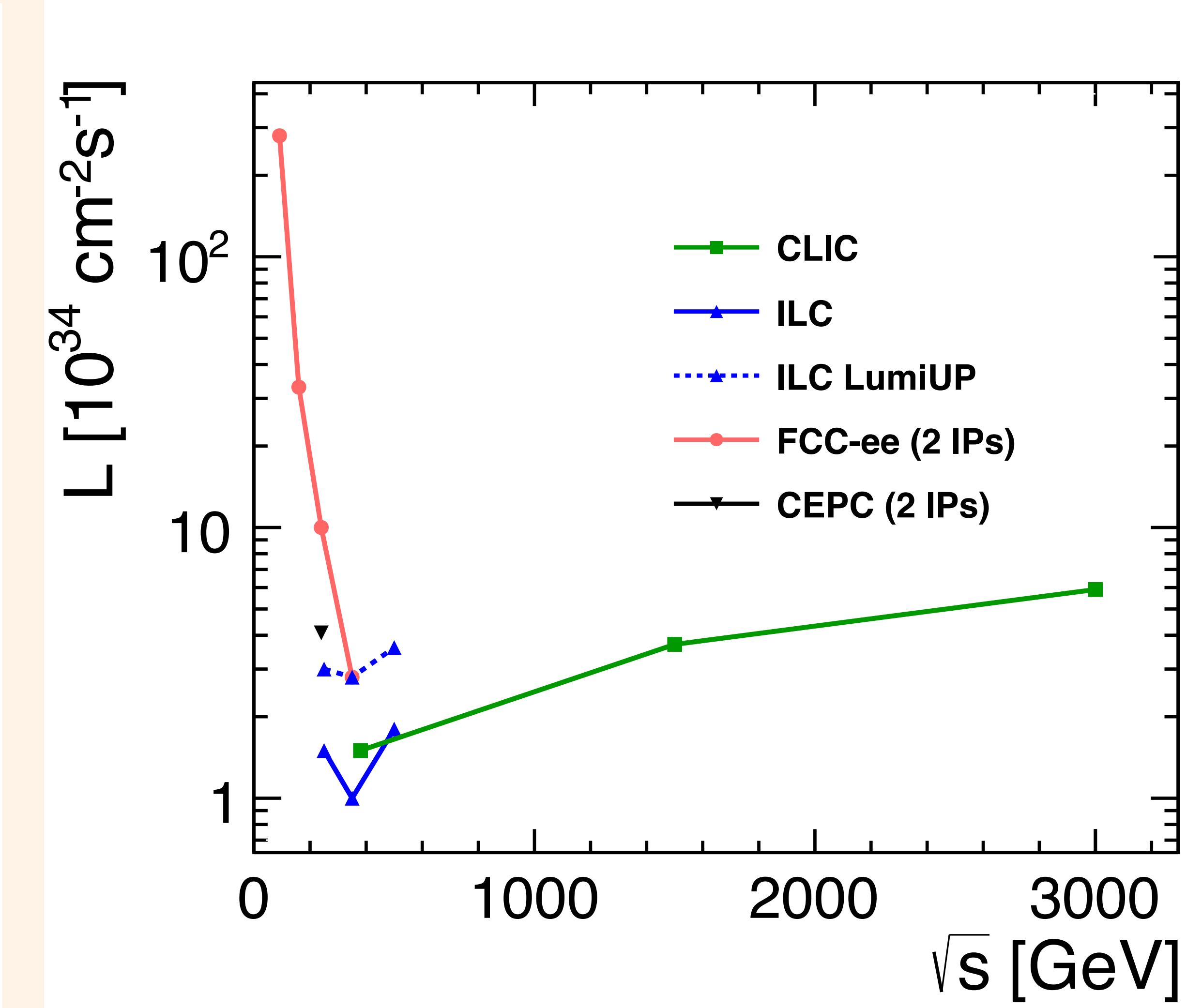
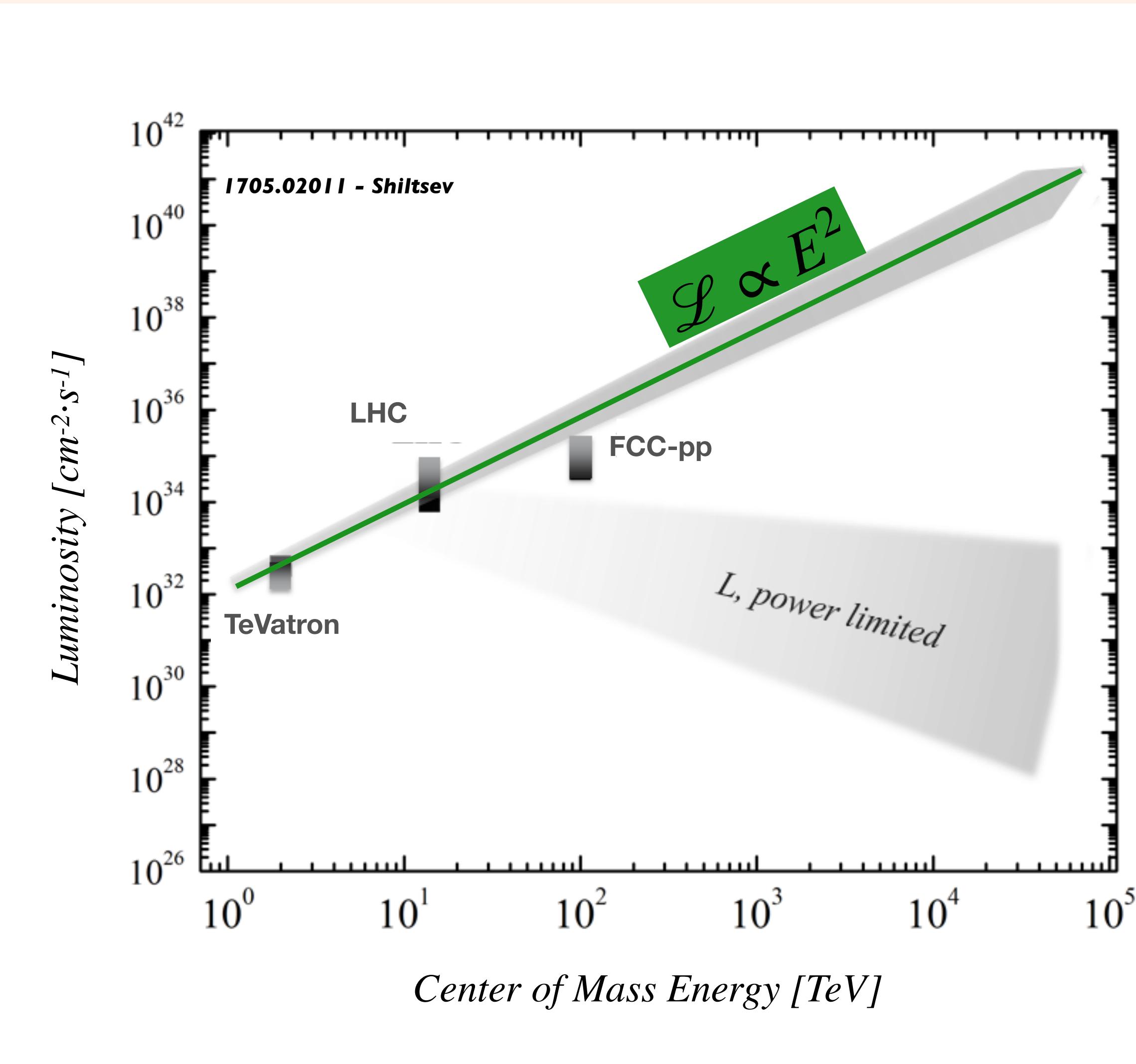
# The deeper you look... the larger lumi you need

other possible LLP origins may include the realization of one Sakharov condition for baryogenesis: an out-of-equilibrium phase of the Universe during a 1st order Phase Transition at the weak scale

$$h \rightarrow S_{LLP} S_{LLP}$$

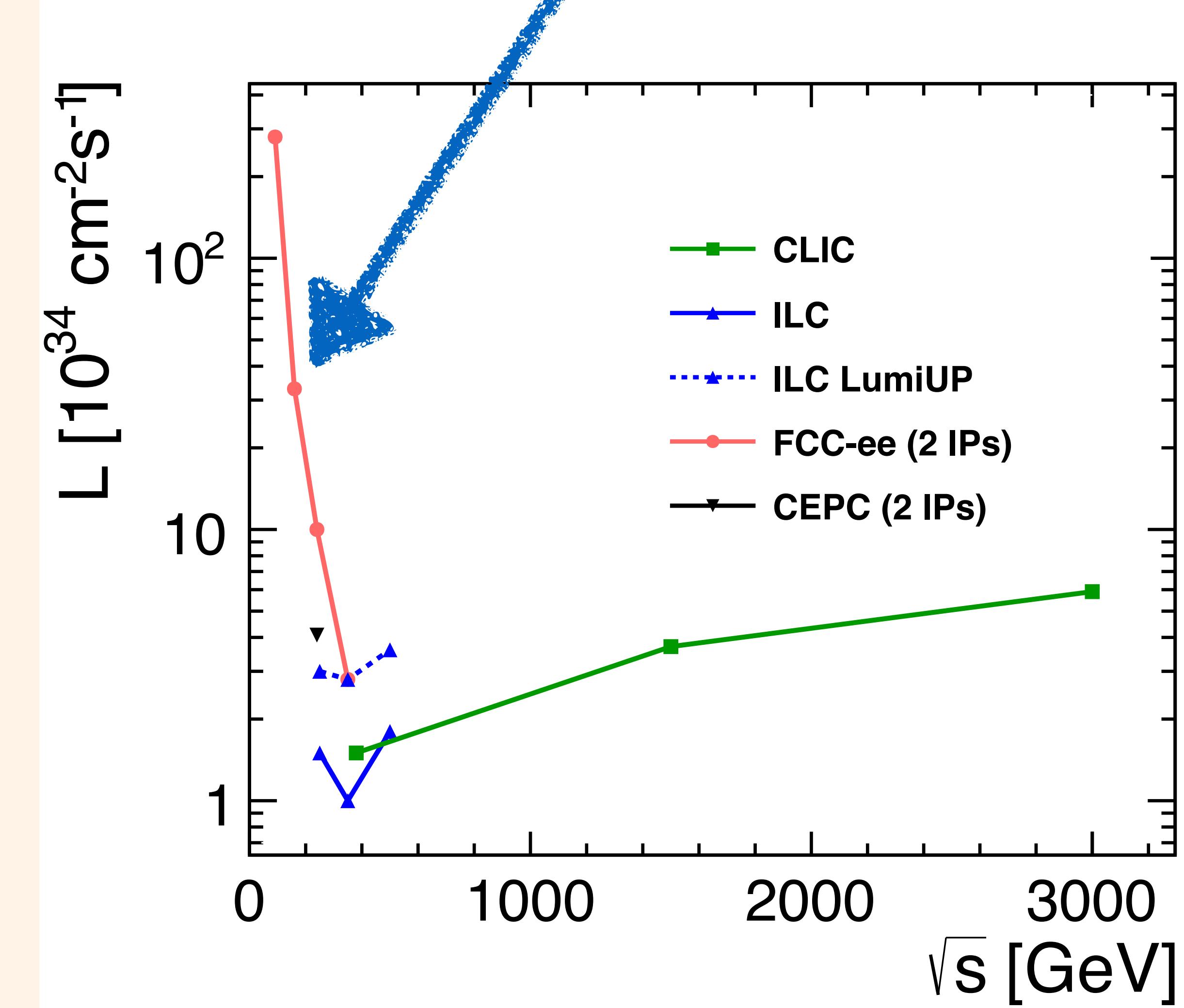
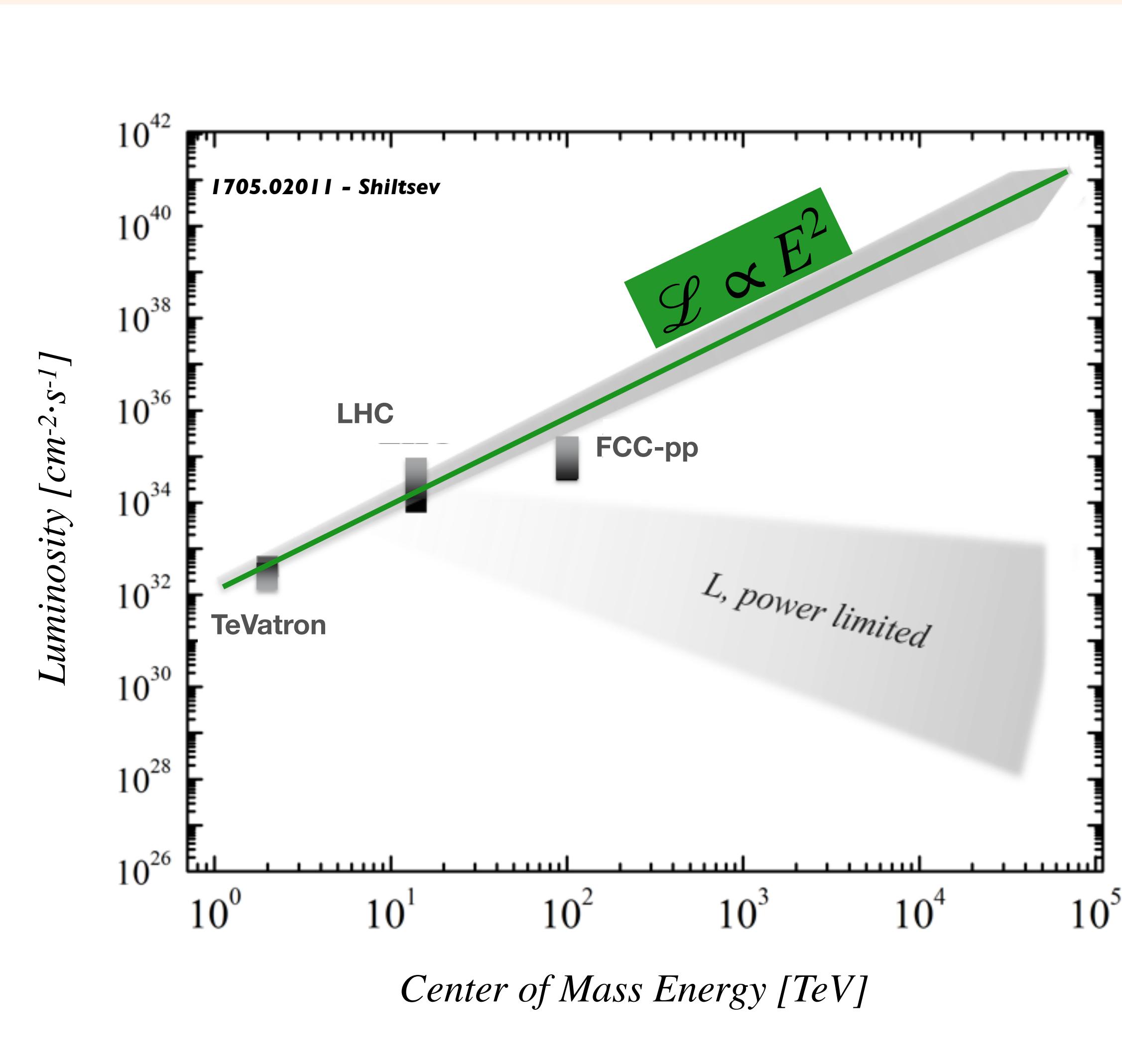


# The larger lumi you need



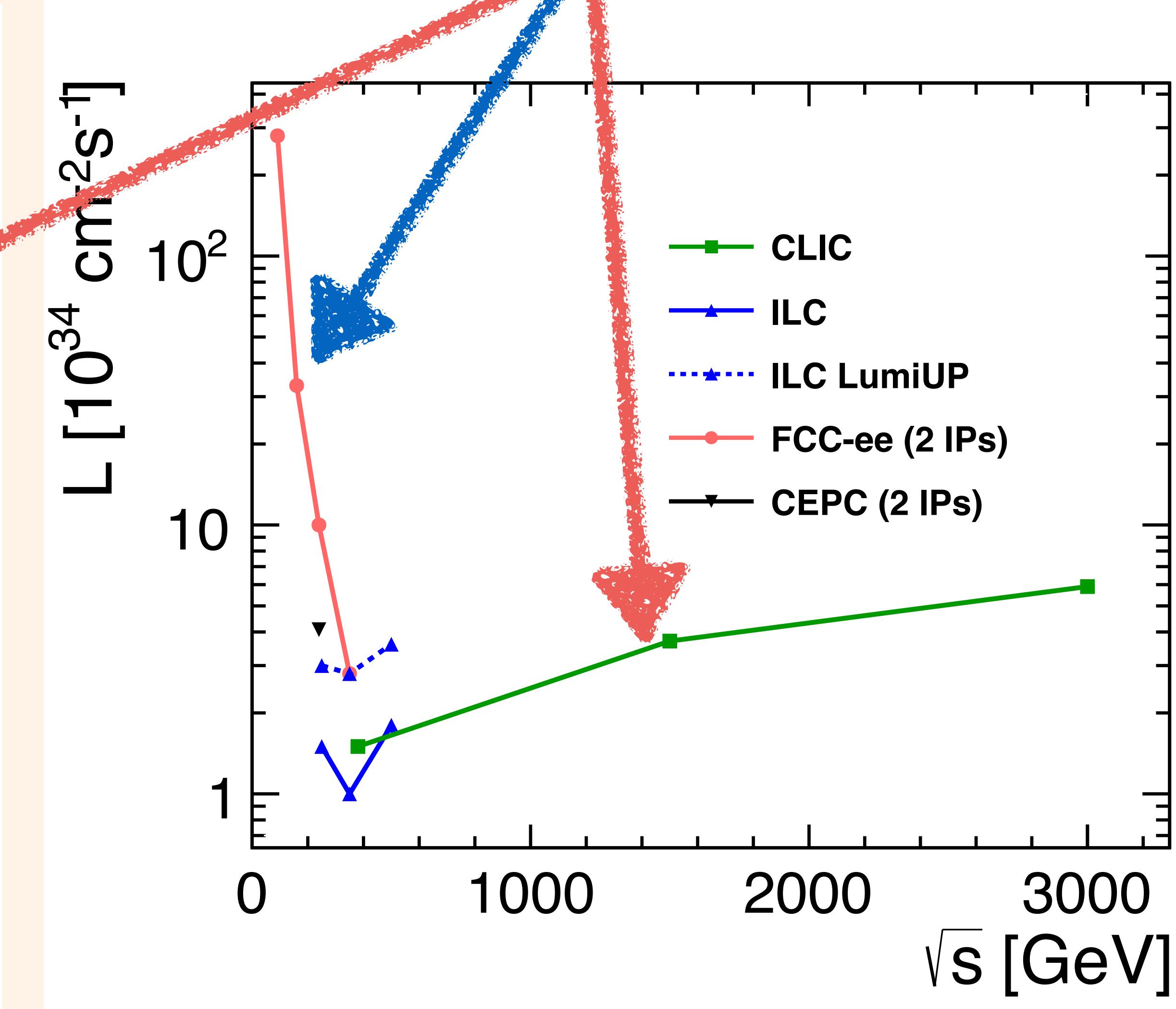
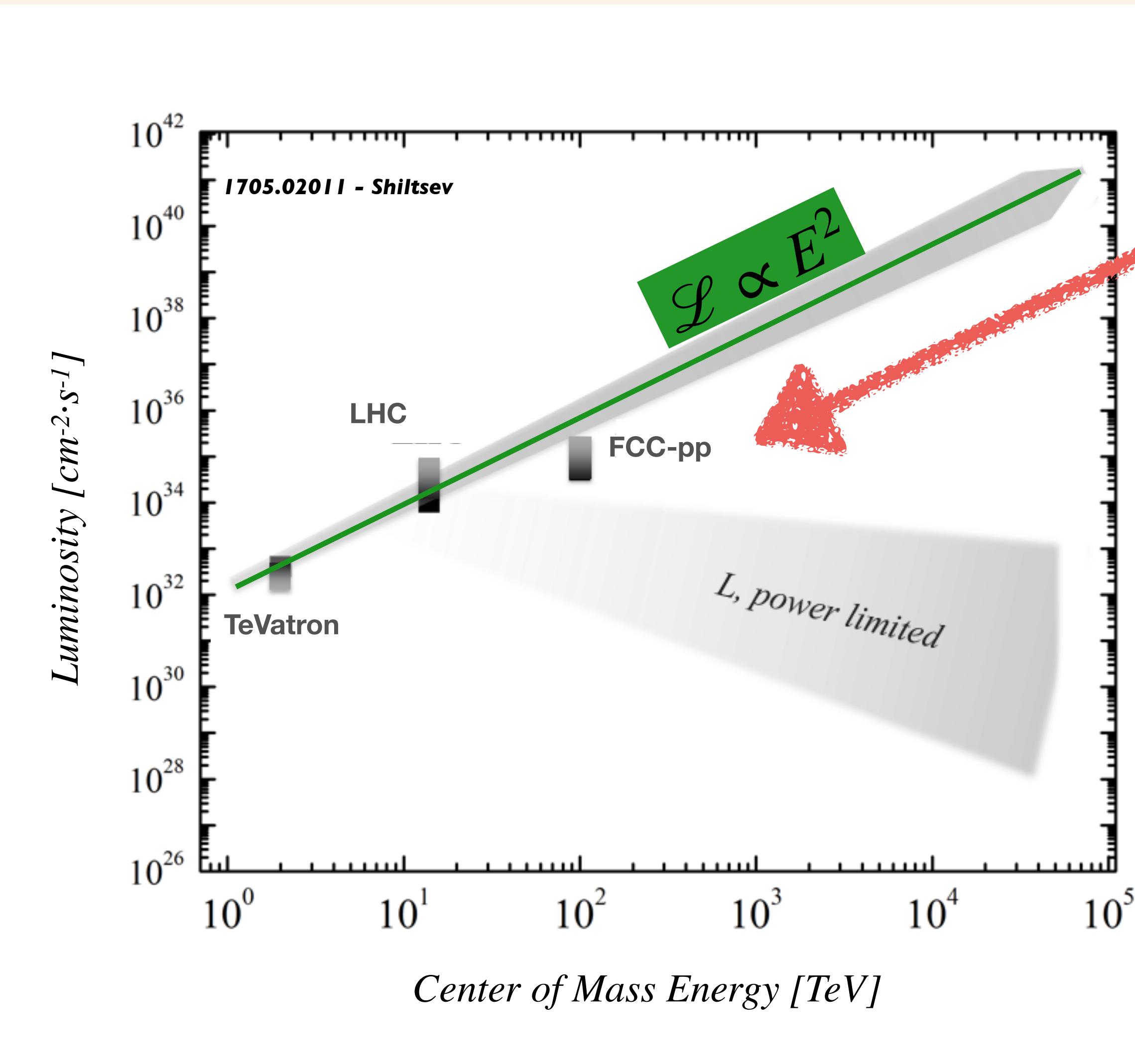
# The larger lumi you need

Luminosity falls  
too fast



# The larger lumi you need

Luminosity is not growing fast enough



The

# Luminosity per Power

Shiltsev@eeFACT22

ot  
ugh

Circular ee

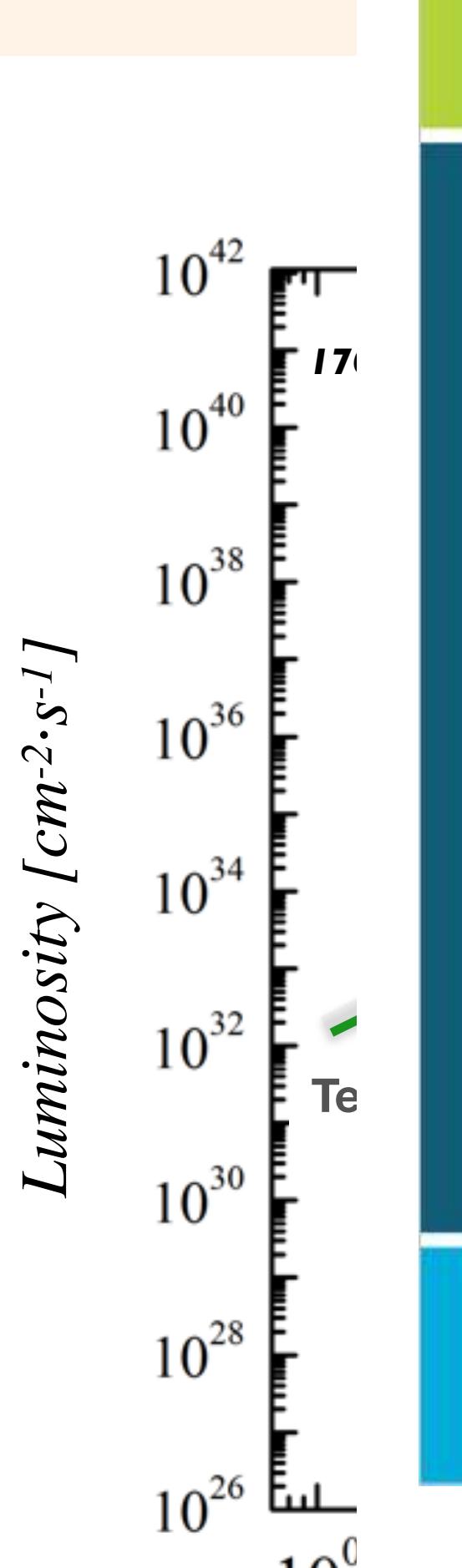
ERL based ee

Linear ee

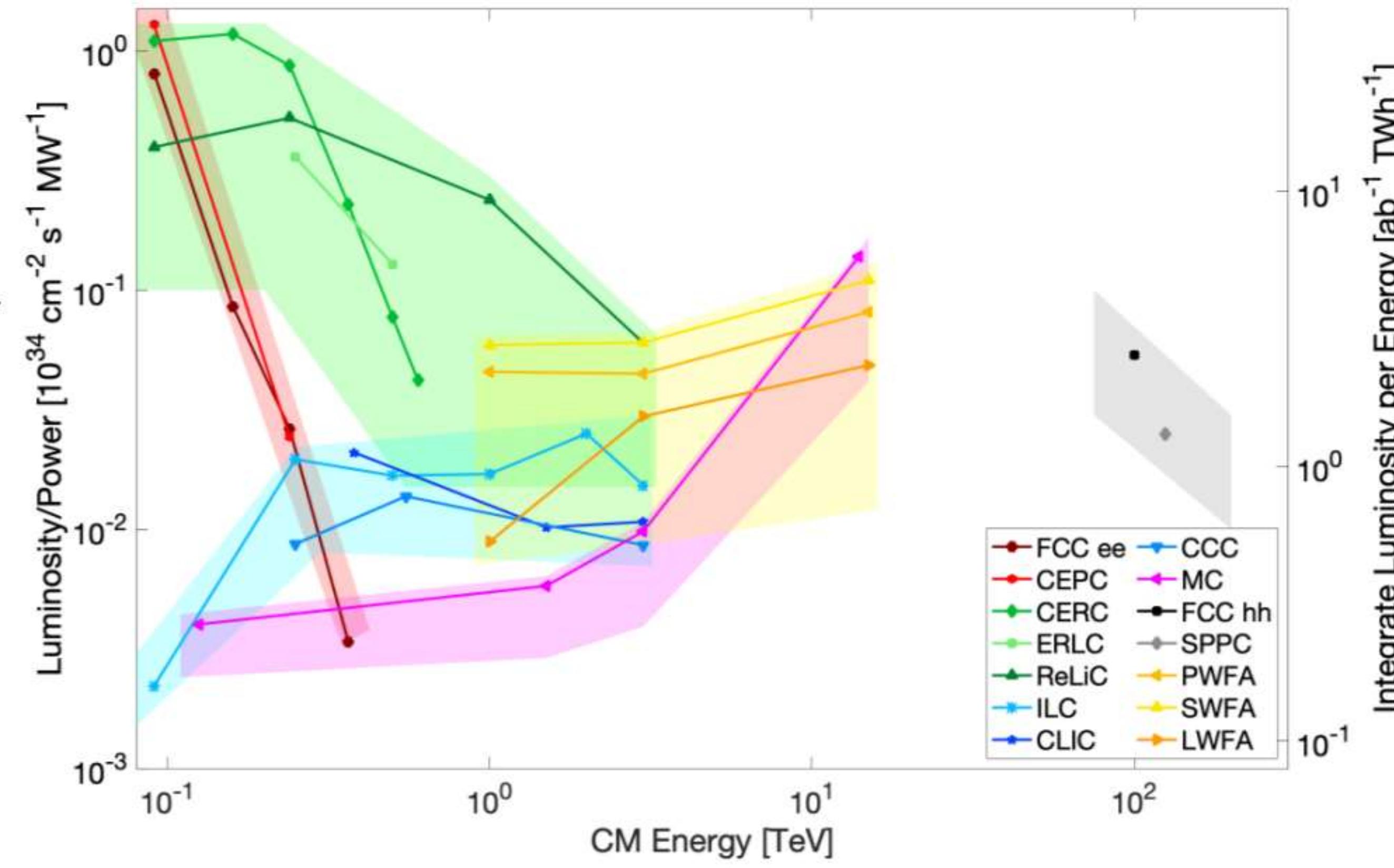
Muon coll

Wakefield

Hadron pp



- Figure-of-merit Peak Luminosity (per IP) per Input Power and Integrated Luminosity per TWh.
- Integrated luminosity assumes 10<sup>7</sup> seconds per year.
- The luminosity is per IP.
- Data points are provided to the ITF by proponents of the respective machines.
- The bands around the data points reflect approximate power consumption uncertainty for the different collider concepts.



Once again: luminosity and power consumption values have not been reviewed by ITF - we used proponents' numbers.



# Conclusions

- lots of motivations for BSM out there!
- Dark Matter suggests a whole dark sector may exist
- other issues may find a solution in scenario featuring a somewhat secluded sector  $\Rightarrow$ suggestive of small couplings (for baryogenesis, Higgs and weak scale, neutrino and flavor patterns ... )
- luminosity is a key parameter to gain sensitivity to these scenarios at  $e^+e^-$  machines

Thank you!