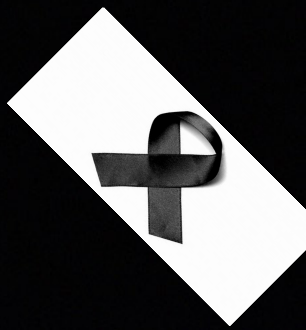
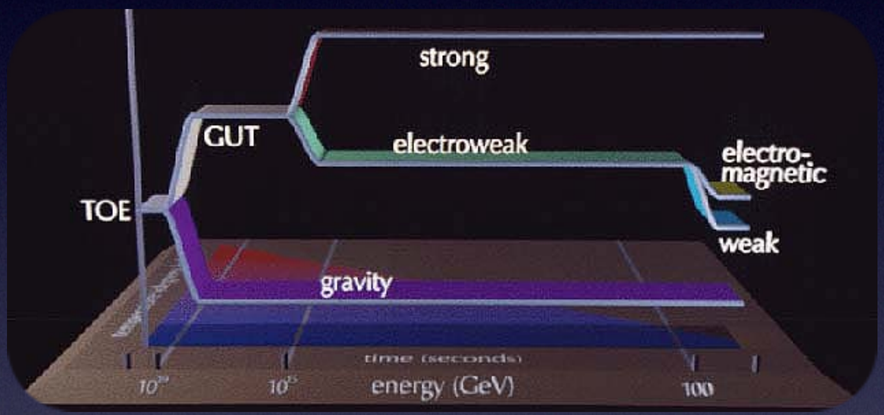
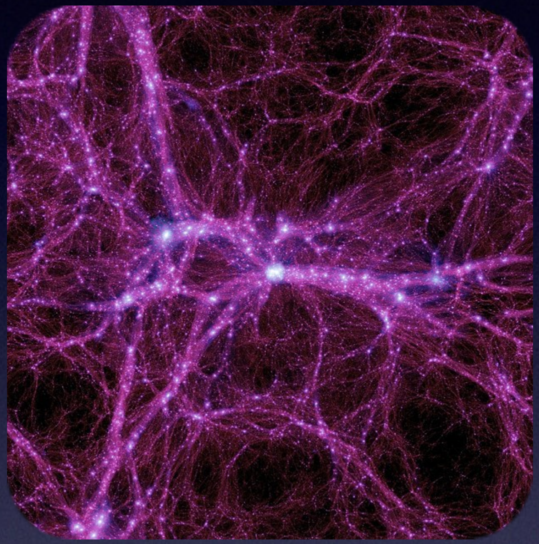
Modeling dark matter



Diary of a dark matter phenomenologist





Yann Mambrini

http://www.ymambrini.com/My_World/Physics.html

université PARIS-SACLAY

LPT Orsay

Dark Side of the Universe Conference, 15-20 December 2015

cnrs dépasser les frontières

Plan

Dark matter from a phenomenological/historical perspective

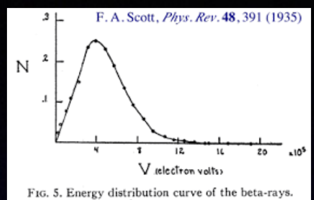
Building a dark matter model with a microscopical approach
the effective approach versus portal cases

Building a dark matter model with an observational approach
FERMI, XMM Newton, ICECUBE

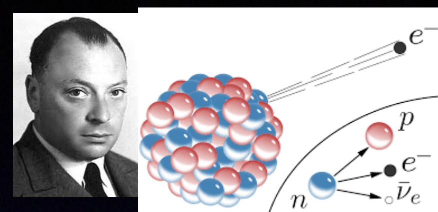
Building a dark matter model with a fundamental approach:
neutrino mass, unification and anomalies

The dark matter case, a neutrino « bis repetita »?

Observation history

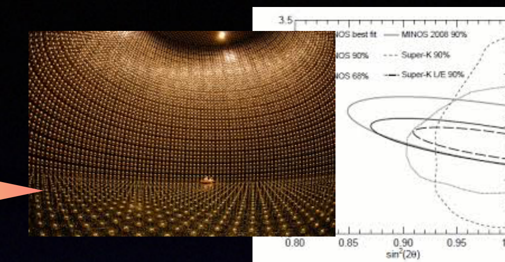


β spectrum
(Hahn - 1911)



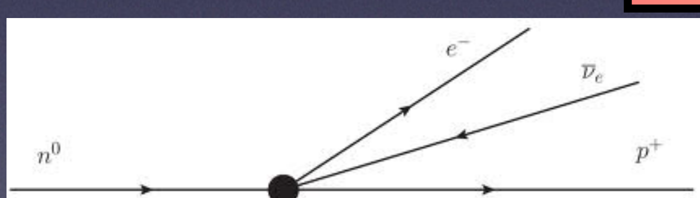
Neutrino hypothesis
(Pauli - 1930)

Neutrino discovery (coupling)
(Cowan-Reynes - 1956)

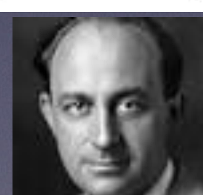


Neutrino nature (mass)
(SuperK - 1998)

Model building history



weak coupling interpretation
(Fermi - 1933)



weak current interpretation
(Standard Model - 1962)

Mass models, SO(10)..
(1974..)

The dark matter case, a neutrino « bis repetita »?

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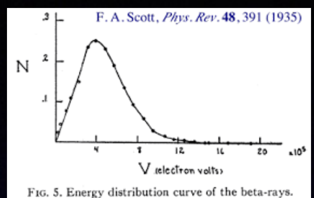

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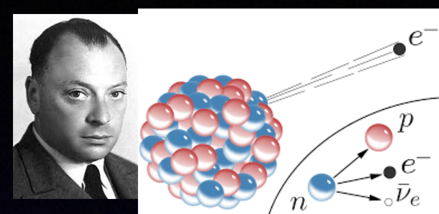

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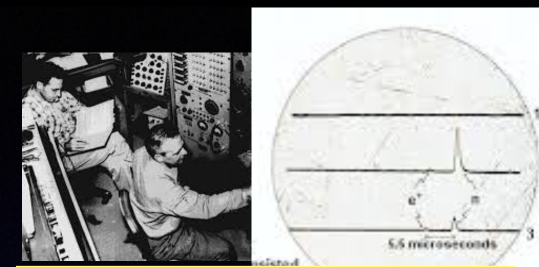

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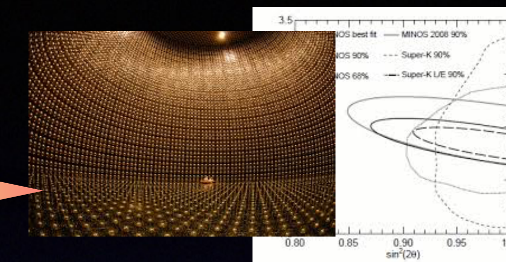

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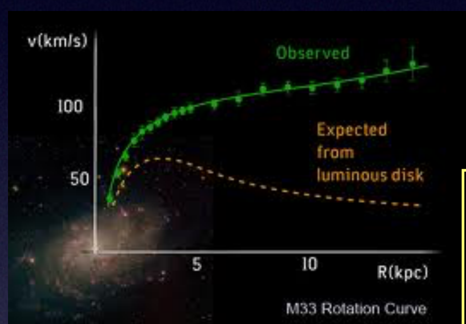
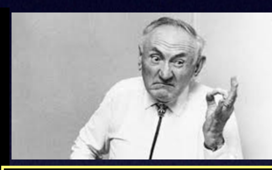
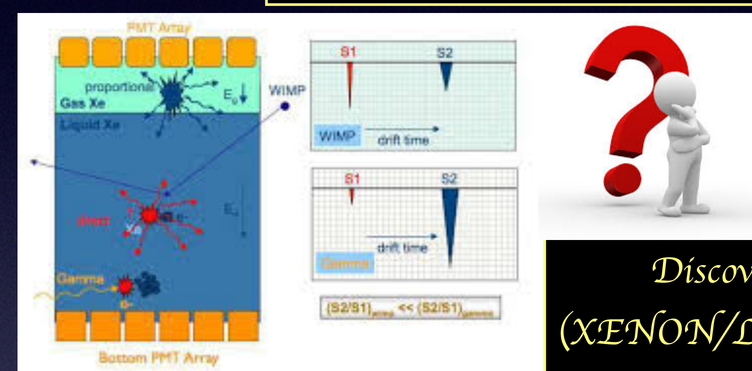
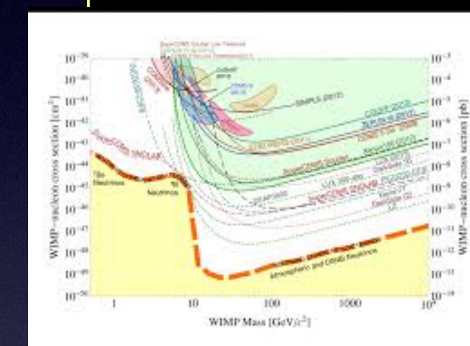




Rotation curves
(Zwicky - 1932)

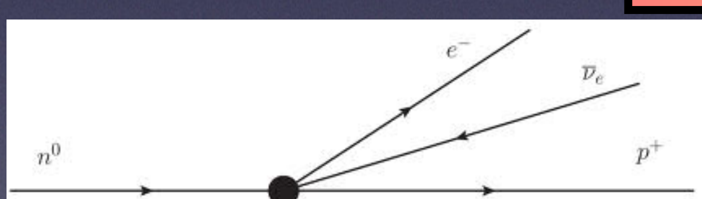


Discovery
(XENON/LZ?? 20??)



DM nature (mass, coupling)

Model building history



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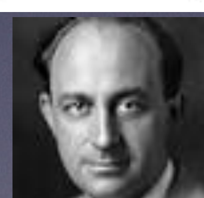

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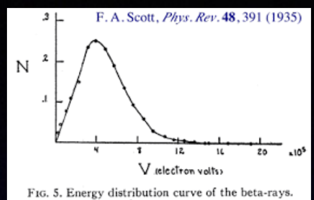

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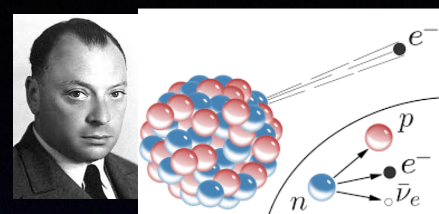

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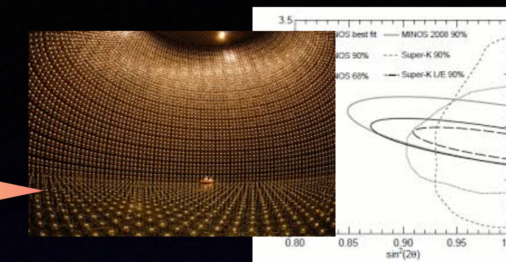

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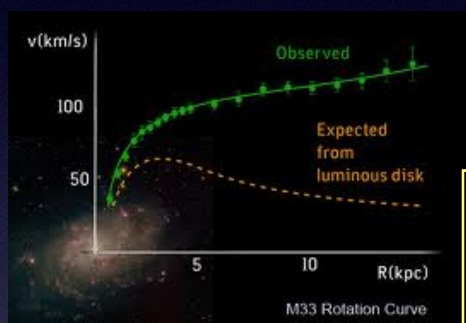

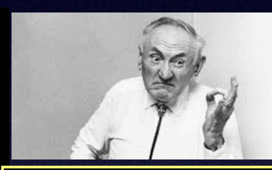

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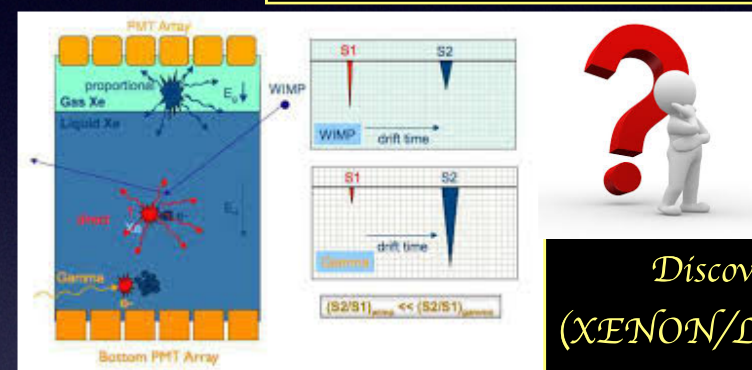
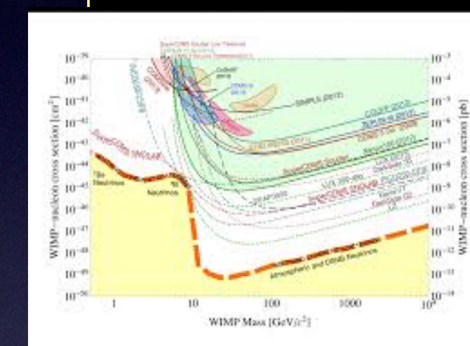


Discovery
(XENON/LZ?? 20??)

[talk of E. Figueroa-Feliciano]



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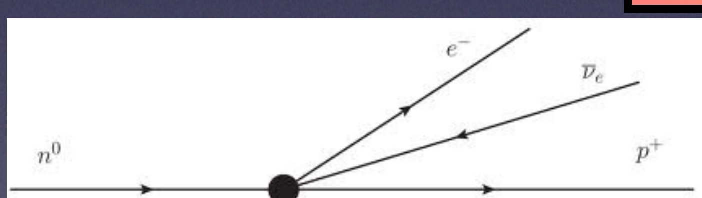

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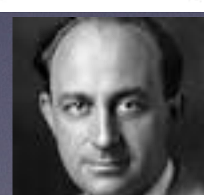

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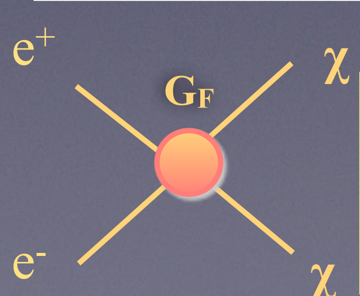
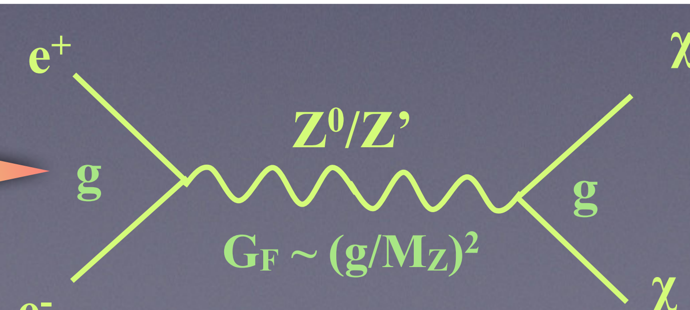
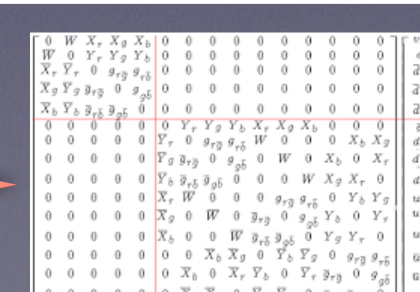


Lee-Weinberg
bound (> 2 GeV)
(Weinberg - 1977)



Z/Z'/Higgs
portal (2010)
no DM bound



SO(10)

1

Building a dark matter model from a microscopic approach

The pure effective approach « a la Fermi »

Enrico Fermi

"Tentativo di una teoria dei raggi β",

Ricerca Scientifica, 1933

TENTATIVO DI UNA TEORIA DEI RAGGI β

Nota (1) di Enrico Fermi

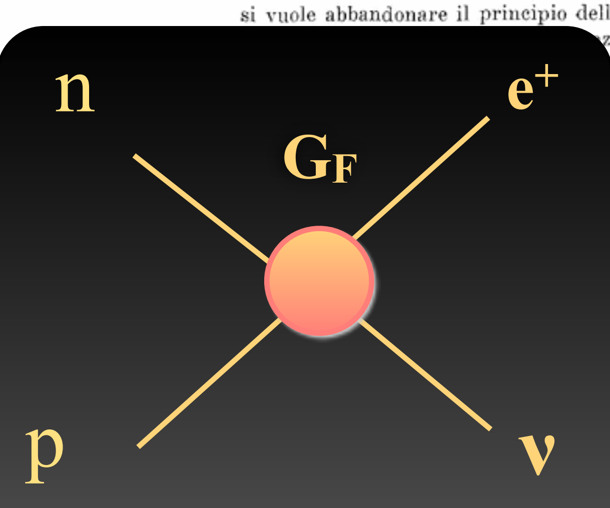
Sunto. - *Si propone una teoria quantitativa dell'emissione dei r... in cui si ammette l'esistenza del « neutrino » e si tratta l'emissione... elettroni e dei neutrini da un nucleo all'atto della disintegrazione... un procedimento simile a quello seguito nella teoria dell'irradi... per descrivere l'emissione di un quanto di luce da un atomo ec... Vengono dedotte delle formule per la vita media e per la forma... spettro continuo dei raggi β, e le si confrontano coi dati sperim...*

Ipotesi fondamentali della teoria.

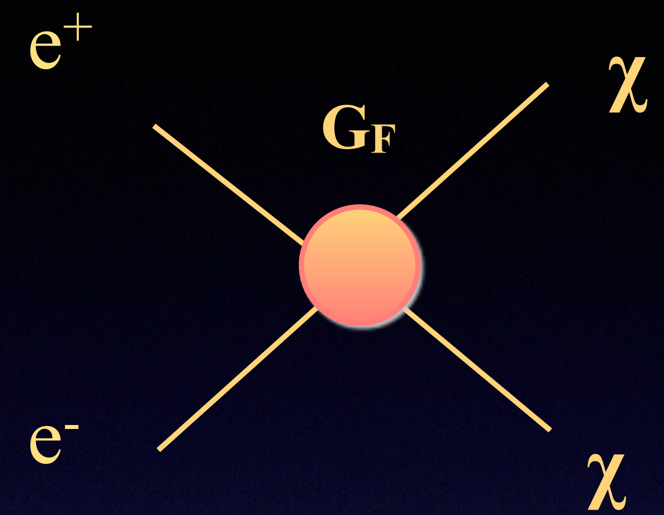
§ 1. Nel tentativo di costruire una teoria degli elettroni nucleari e dell'emissione dei raggi β, si incontrano, come è noto, due difficoltà principali. La prima dipende dal fatto che i raggi β primari vengono emessi dai nuclei con una distribuzione continua di velocità. Se non si vuole abbandonare il principio della conservazione dell'energia, si ...zione dell'energia che si libera ...gga alle nostre attuali possibi... ...sta di Pauli si può p. es. am... ...icella, il così detto « neutrino », ...a dell'ordine di grandezza di ...ette poi che in ogni processo β ...elettrone, che si osserva come ...all'osservazione portando seco ...teoria ci baseremo sopra l'ipo-

...ia degli elettroni nucleari, di... ...e relativistiche delle particelle ...nno una soddisfacente spiega... ...lle vengano legate in orbite di

...cerca Scientifica», 2, fasc. 12, 1933.



$G_F = 10^{-5}\ \mathrm{GeV}^{-2}$



The (Hut-)Lee-Weinberg bound (1977)

$$\langle \sigma v \rangle = G_F^2 m_\chi^2 > 10^{-9}\ \mathrm{GeV}^{-2} \quad \Rightarrow \quad m_\chi > 2\ \mathrm{GeV}$$

LIMITS ON MASSES AND NUMBER OF NEUTRAL WEAKLY INTERACTING PARTICLES

P. HUT

Institute for Theoretical Physics, University of Utrecht, Utrecht, Netherlands

Received 25 April 1977

Volume 39 | 25 July 1977 | Number 4

Cosmological Lower Bound on Heavy-Neutrino Masses

Benjamin W. Lee[a]

Fermi National Accelerator Laboratory,[b] Batavia, Illinois 60510

and

Steven Weinberg[c]

Stanford University, Physics Department, Stanford, California 94305

(Received 13 May 1977)

The present cosmic mass density of possible stable neutral heavy leptons is calculated in a standard cosmological model. In order for this density not to exceed the upper limit of 2×10^{-29} g/cm^3, the lepton mass would have to be *greater* than a lower bound of the order of 2 GeV.

Developing a microscopical approach

On which principle should we extend the microscopic interaction?

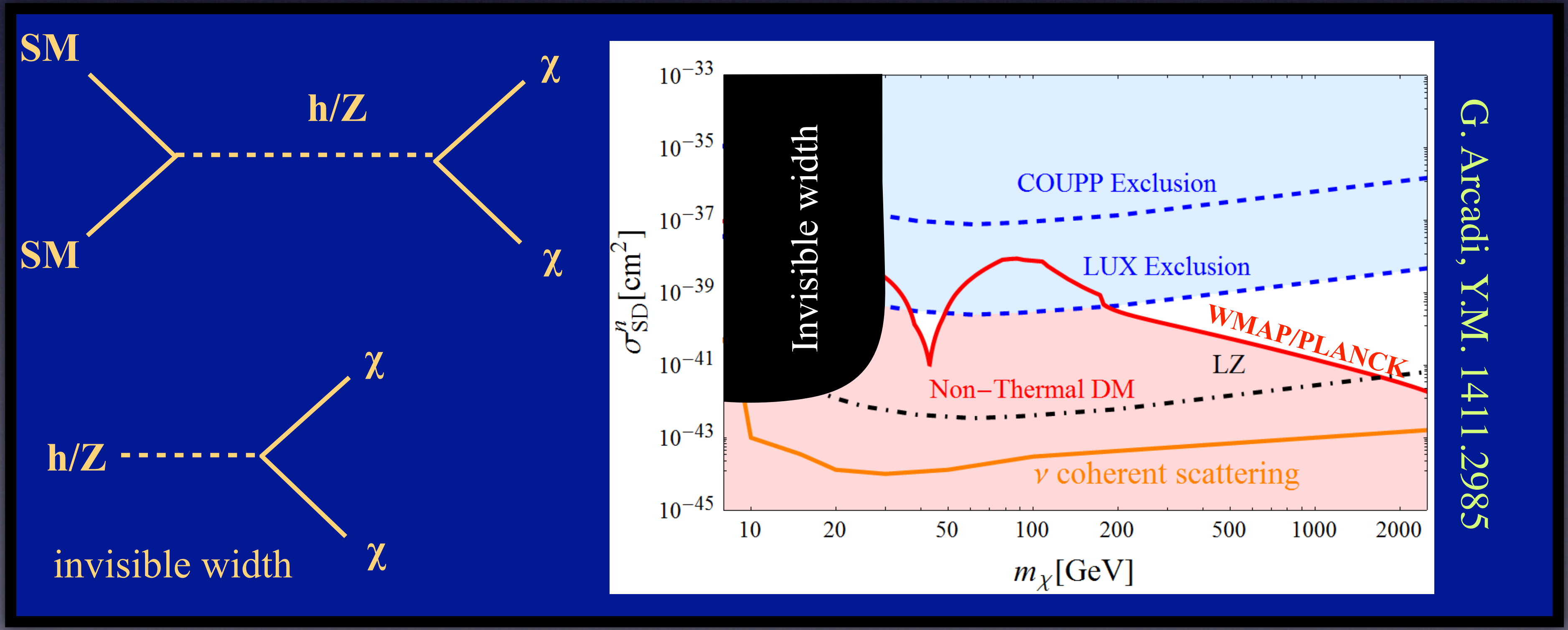
<u>Ockham's razor (*lex parsimoniae*) principle</u> :

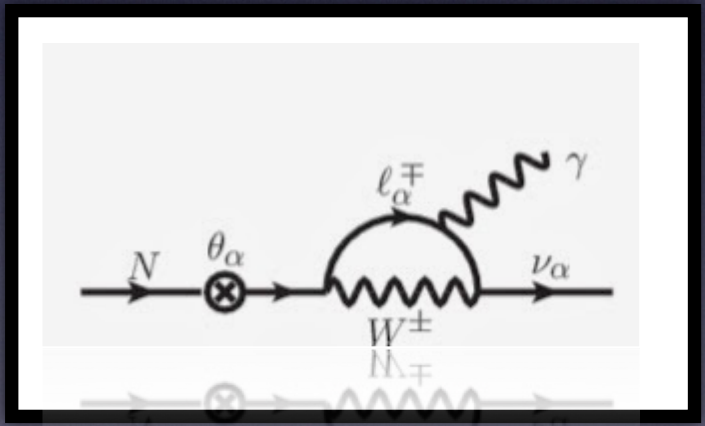
« Pluralitas non est ponenda sine necessitate »

Among competing hypotheses, the one with the fewest assumptions should be selected

(everything should be made as simple as possible..)

Dark matter couple only with the Standard Model (SM) particles : Higgs-portal, Z-portal, sterile neutrino. Consequences on observables are strong: Invisible width of the Higgs/Z, LHC/LEP production in the case of portal models, instability and production of monochromatic photons in the case of sterile neutrino.





Sterile neutrino decay

[See also S. Baek et al. 1311.1035]
[See also P. Ko et al. 1507.06158]

These kind of models already exclude WIMP dark matter (dark matter should be heavier than ~ **200 GeV** [**1 TeV for XENON1T/LZ** 2017-projection] in portal cases or lighter than 10 keV in sterile neutrino cases)

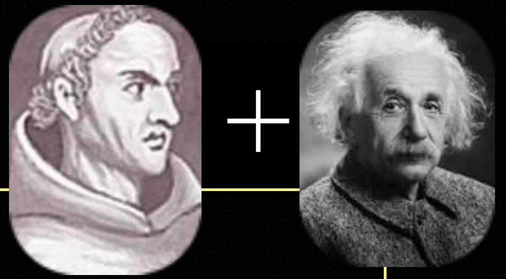
Developing a microscopical approach

Conclusion of the Ockham's razor principle

LHC+WMAP : Invisible Higgs (Z) width
$M\chi < 60$ (30) GeV excluded

LUX + WMAP
$M\chi < 300$ GeV excluded

LHC + LUX + WMAP
$M\chi > 300$ GeV allowed

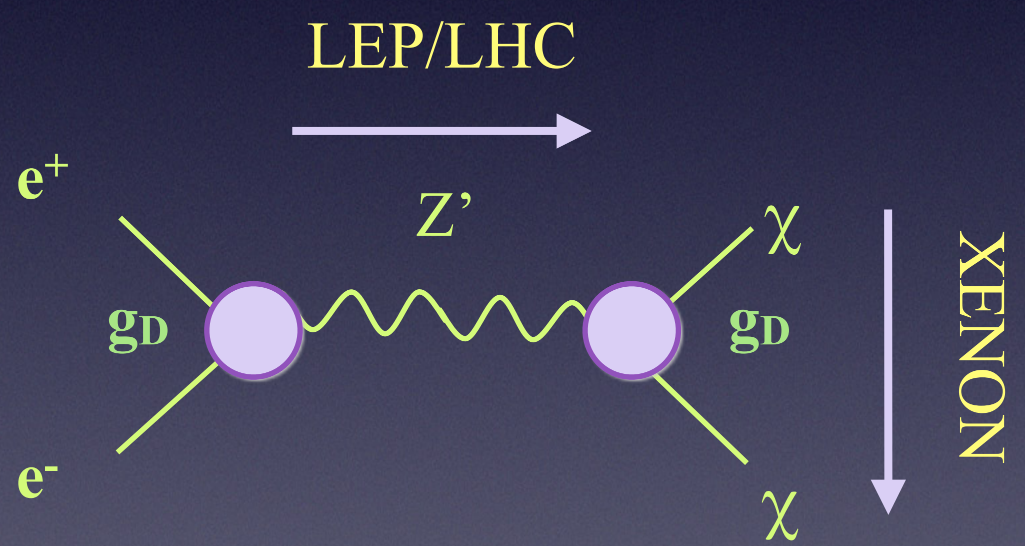


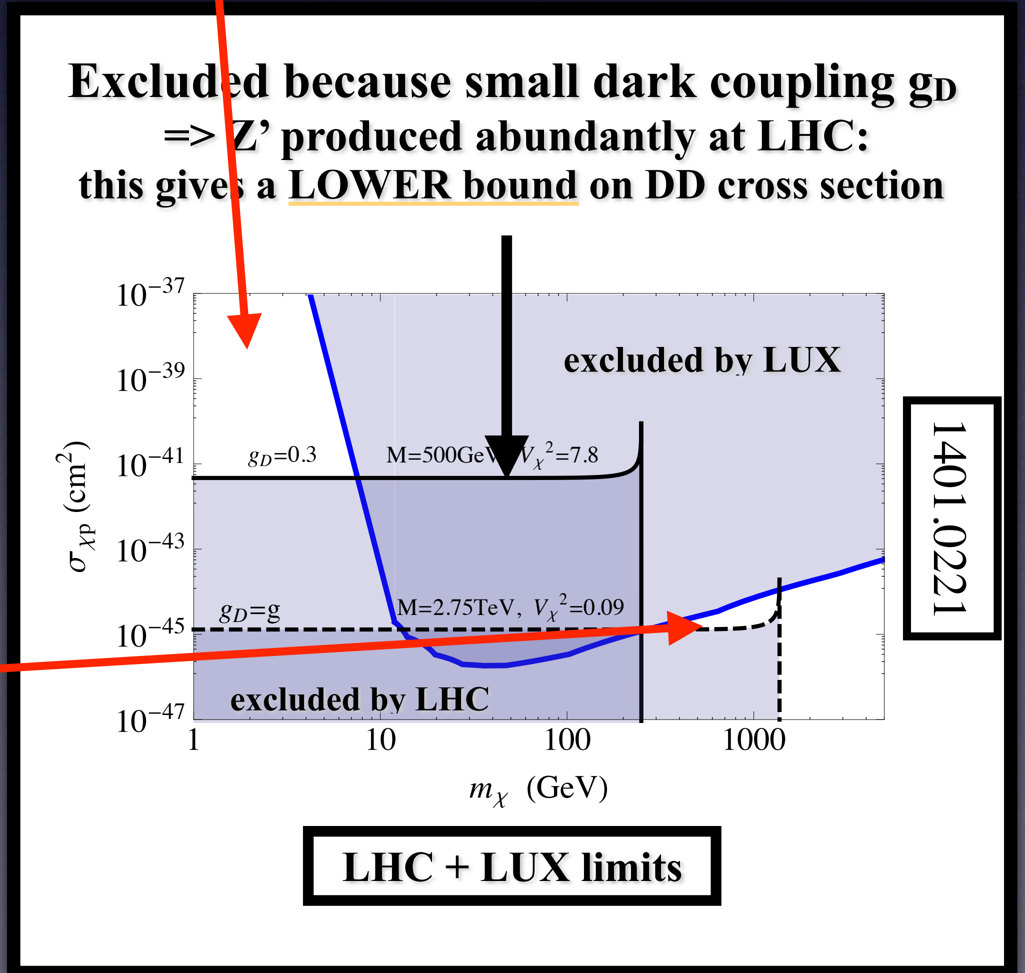
Ockham's razor (*lex parsimoniae*) extended principle :

« Everything should be made as simple as possible.. But not simpler »

Einstein's razor principle (Oxford 1933)

Dark matter couples not only with the Standard Model particles but there exist a dark sector (can be gauged or dynamical) which plays the rôle of the mediator: Z'-portal, supersymmetry or KK modes. Consequences on observables are less strong: no constraints on invisible branching ratio, **light dark matter window is re-opened.**





BUT constraints on non-production of Z'
excludes low values for g_D!
(small g_D means Z' should have been observed).
These kind of models already exclude WIMP dark matter
(dark matter should be heavier than ~ 300 GeV)

See talk of S. Matsumoto for other examples

Developing a microscopical approach

Conclusion of the extended Ockham's razor principle

LHC + LUX (No PLANCK!)

$M\chi < 10$ GeV allowed $M\chi > 250$ GeV allowed

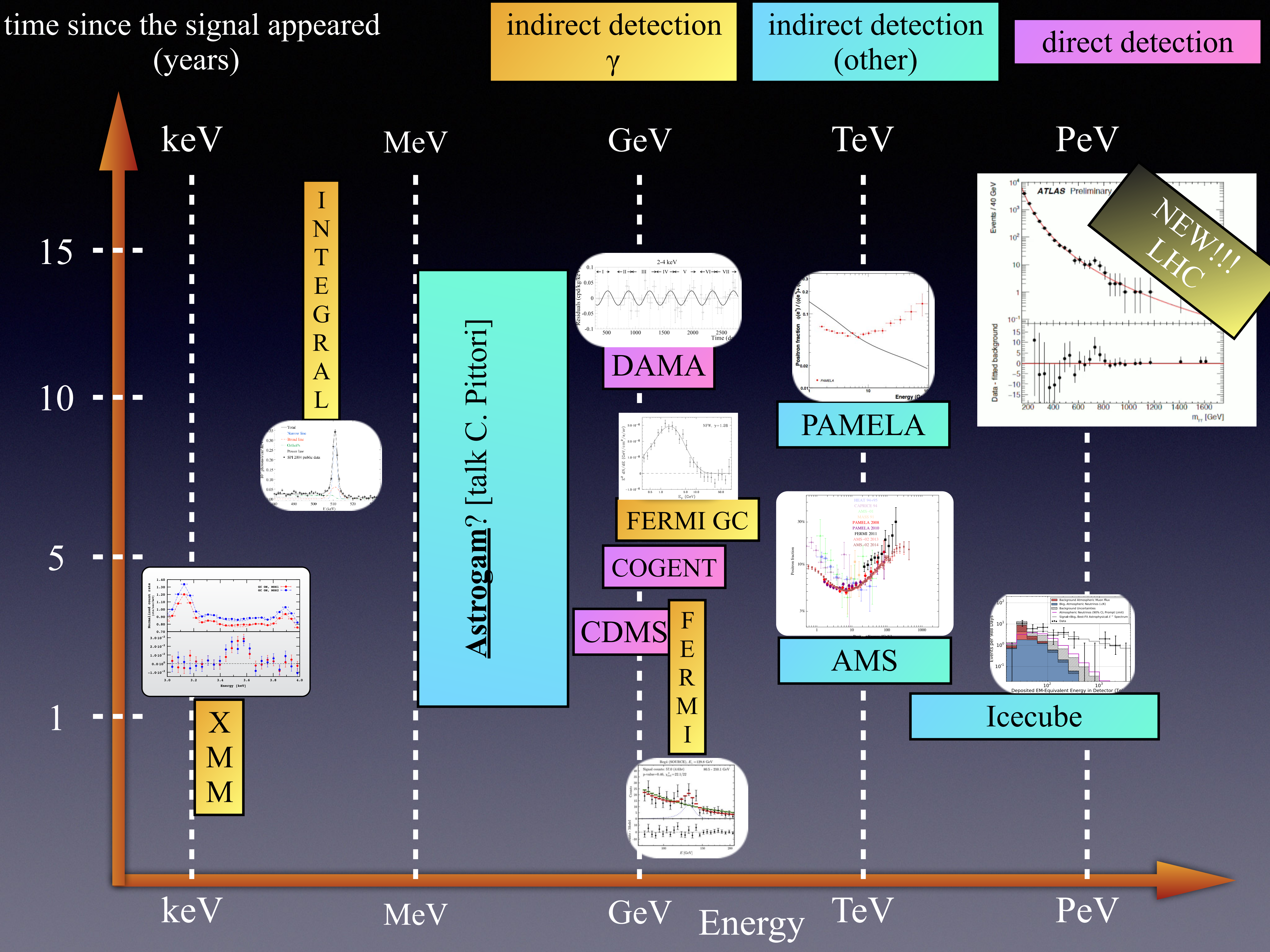
Conclusion of the Ockham's razor principle

LHC + LUX + WMAP

$M\chi > 300$ GeV allowed

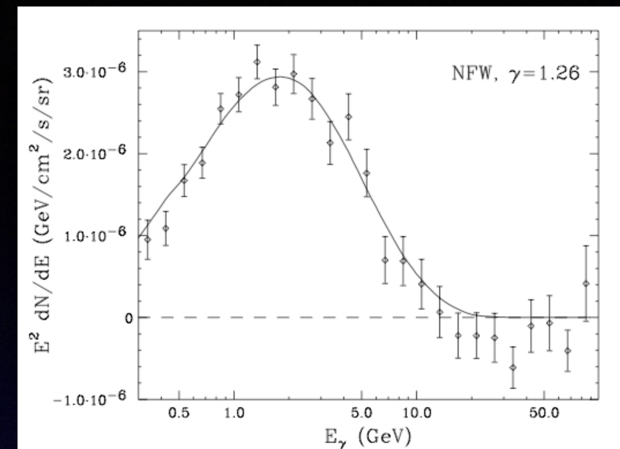
2

Building a dark matter model from observations

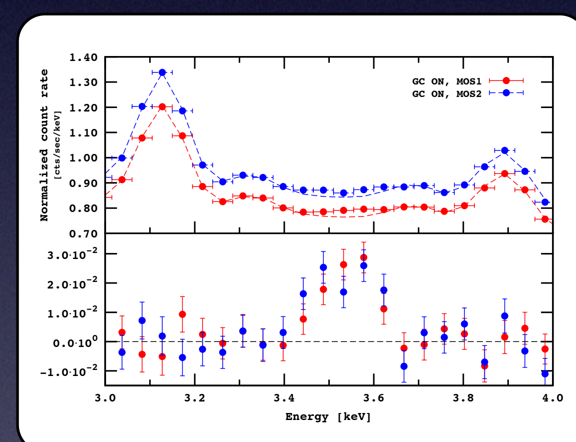


time since the signal appeared (years)
indirect detection γ
indirect detection (other)
direct detection
keV
MeV
GeV
TeV
PeV
15
10
5
1
INTEGRAL
Astrogam? [talk C. Pittori]
DAMA
PAMELA
ATLAS Preliminary
NEW!!! LHC
FERMI GC
COGENT
CDMS
FERMI
AMS
Icecube
XMM
Energy

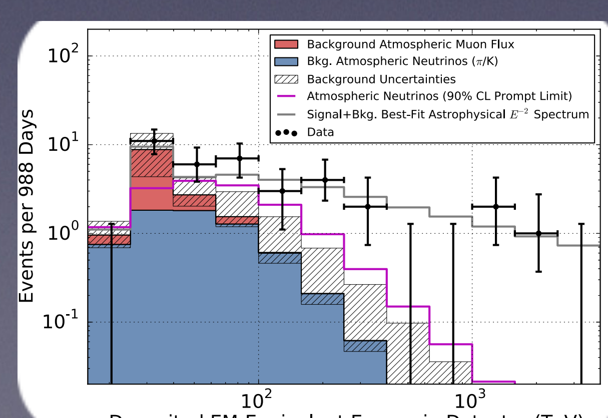
We will illustrate our purpose by 3 recent « signals »



The FERMI galactic center excess

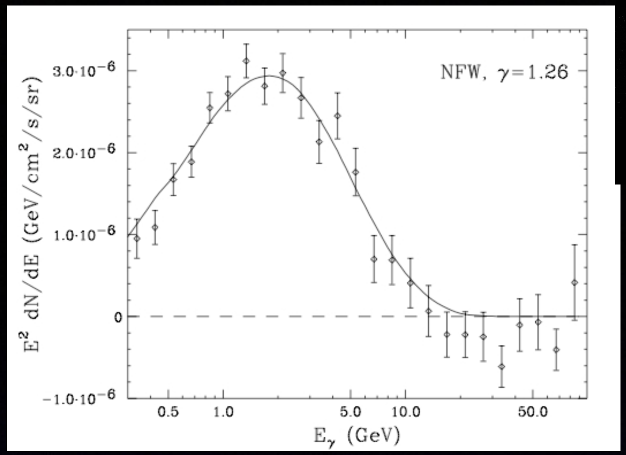


The 3.5 keV line observed by XMM Newton and X-Chandra



The PeV neutrino events measured by IceCube

The GC excess observed by FERMI



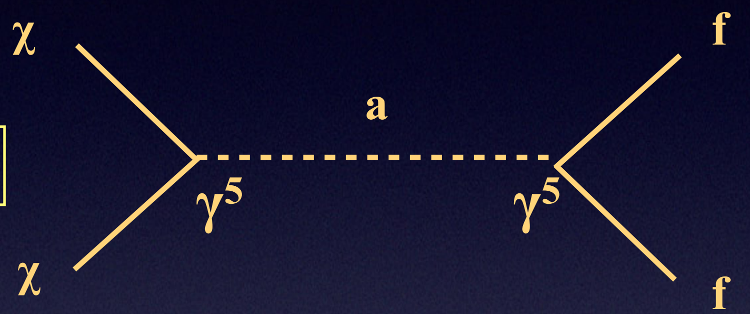
The « coy » dark matter case [Boehm et al. 1401.6458]

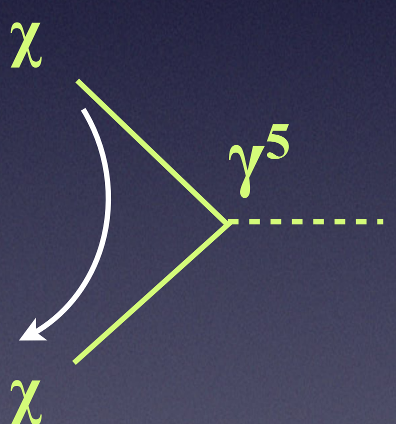
or, can FERMI see something while LUX is blind?

Yes because $(p^2 - m^2)$ is different from $(p^2 + m^2)$

$$\mathcal{L} = -i\frac{g_{DM}}{\sqrt{2}} a\bar{\chi}\gamma^5\chi - i\frac{g_f}{\sqrt{2}} a\bar{f}\gamma^5 f$$

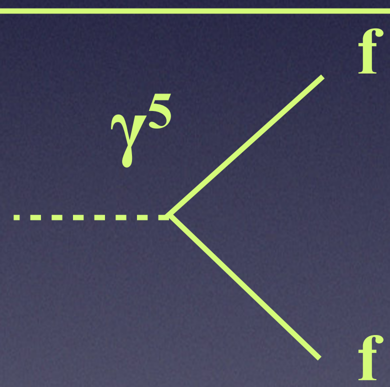
(Ockham's razor extended principle)





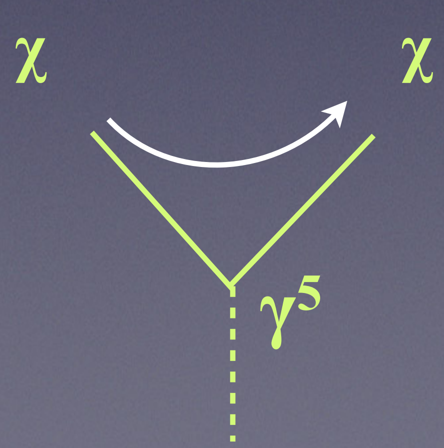
$$|\bar{v}\gamma^5 u|^2 = p^2 + m^2 \ \sim \ 2m^2$$

annihilation



Helicity suppression (Majorana)

$$\langle \sigma v \rangle \propto m_f^2$$



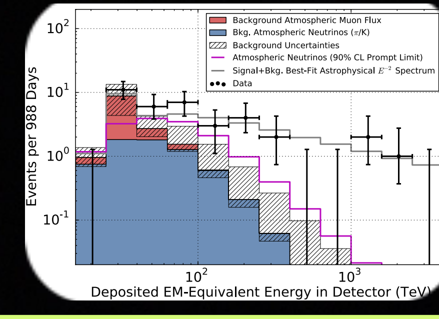
$$|\bar{u}\gamma^5 u|^2 = p^2 - m^2 \ \sim \ v^2$$

scattering

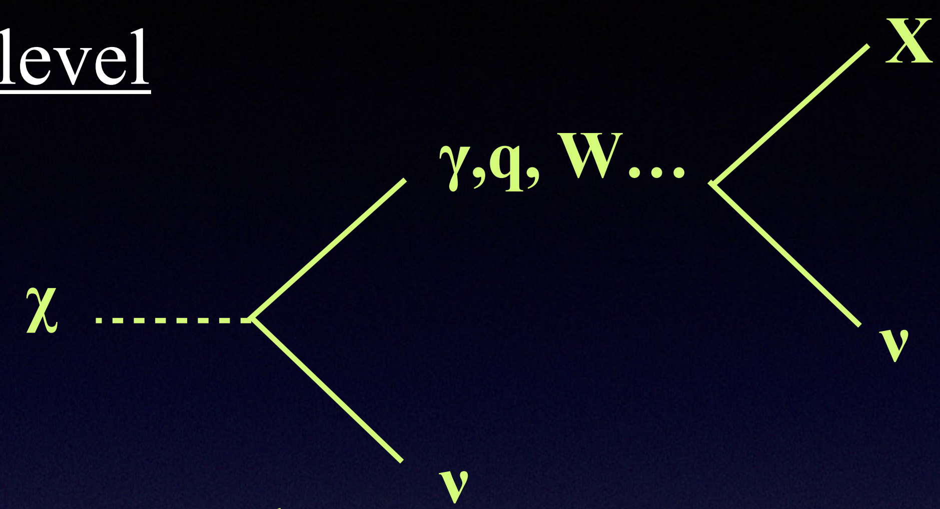
(remark: opposite to the Higgs portal where <σv> is proportional to v^2)

Icecube PeV events [talk of S. Yoshida]

or how to interpret the features of the neutrino high energy spectrum from dark matter perspective?

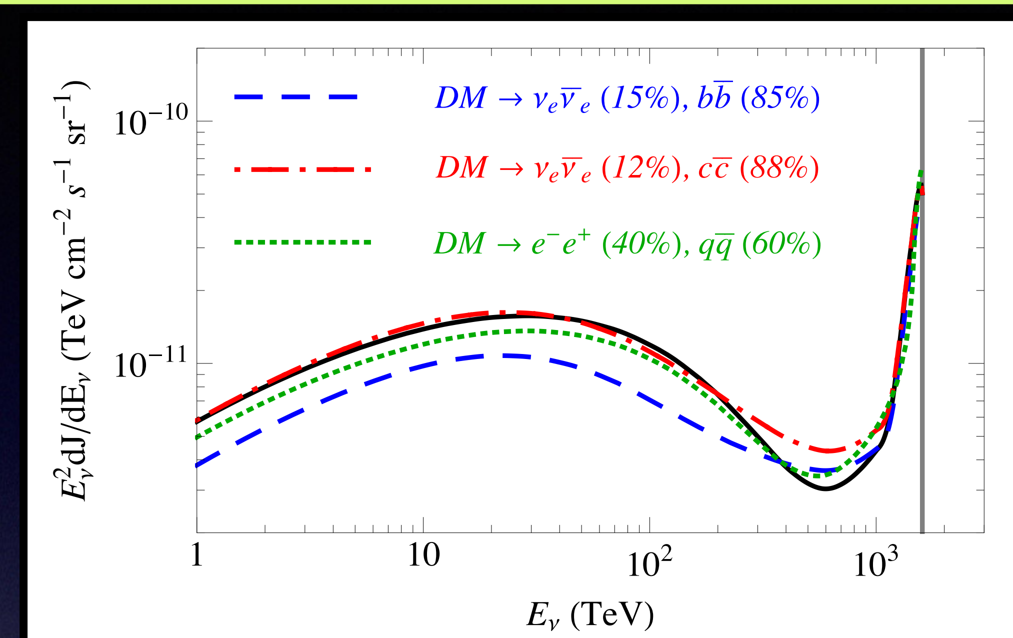


Pure effective level



[C. El Aisati, M. Gustafsson, T. Hambye; 1506.02657]

[C. El Aisati, M. Gustafsson, T. Hambye, T. Scarna; 1510.05008]



[A. Esmaili, P. Serpico; 1308.1105]

Introducing a neutrino sector

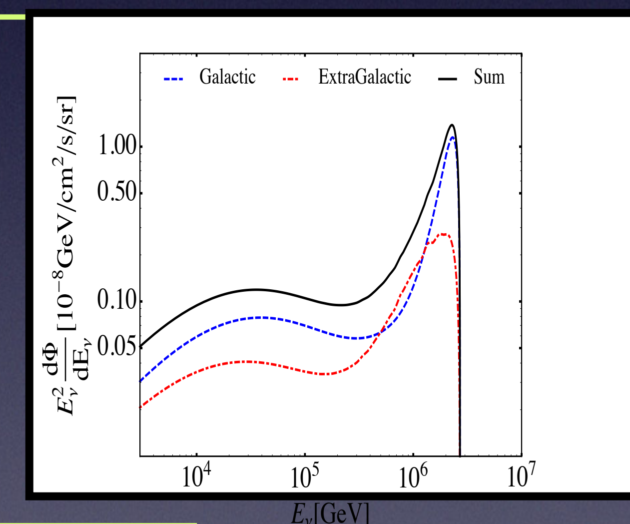
$$\frac{yf}{m_N}\bar{\chi}\Phi H^\dagger L$$

$$\Gamma_3\left(\chi \to \phi h \nu\right) \sim \frac{m_\chi^3}{96\pi^3}\left(\frac{yf}{m_N}\right)^2 \sim \frac{1}{10^{28}\text{sec}}$$

$$\Rightarrow \frac{yf}{m_N} \sim 10^{-36}\text{GeV}^{-1},$$

[P. Ko and Y. Tang; 1508.02500]

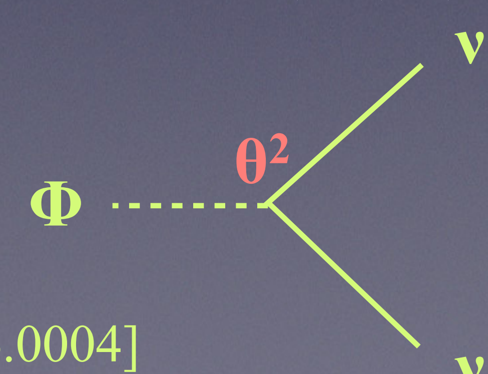
mixing ν_R and the dark matter χ



Introducing a dynamical neutrino sector (+SO(10)..)

$$\mathcal{L}_\nu = -\frac{h}{\sqrt{2}}\bar{\nu}_R^c\Phi\nu_R - \frac{y_{LR}}{\sqrt{2}}\bar{\nu}_L H\nu_R$$

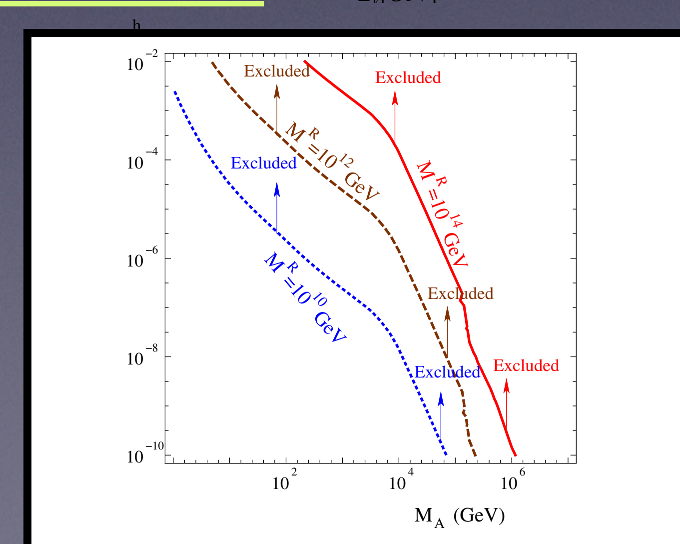
Majoron



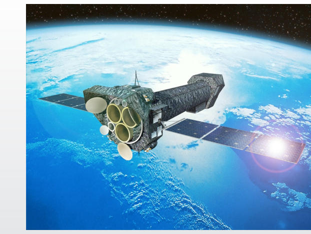
[F. Queiroz, K. Sinha; 1404.1400]

[M. Latanzi, R. Lineros, M. Taoso; 1406.0004]

[E. Dudas, Y.M., K. Olive; 1412.3459]

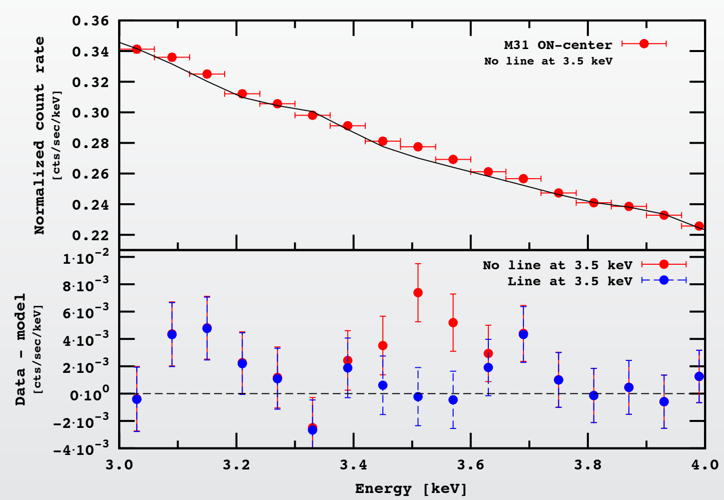


The case of *XMM Newton* signal (2014)



XMM Newton

M31



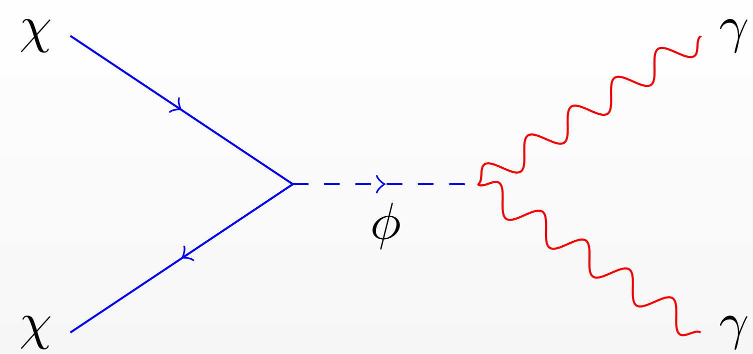
E. Bulbul, M. Markevitch, A. Foster, R. K. Smith, M. Loewenstein, S. W. Randall; http://arxiv.org/abs/1402.2301

$\phi^{obs}_{\gamma\gamma} \simeq 5.2 \times 10^{-5}$ photons cm^{-2} s^{-1} at 3.55 keV

+ [L. Roszkowski et al.; 1403.6503]

BUT important to stay cautious [see the talk of T. Ohashi + papers of Jeltma, Profumo]

Annihilating DM



$$\mathcal{L}_{eff} \supset -\frac{m_s^2}{2} S^2 - \frac{m_\phi^2}{2}\phi^2 - \tilde{m}\phi S^2 + \frac{\phi}{\Lambda} F_{\mu\nu}F^{\mu\nu}$$

$$\langle \sigma v \rangle^{micro}_{\gamma\gamma} = \frac{4 m_s^2 \tilde{m}^2}{\pi \Lambda^2 (4 m_s^2 - m_\phi^2)^2} \,.$$

keV γγ observation

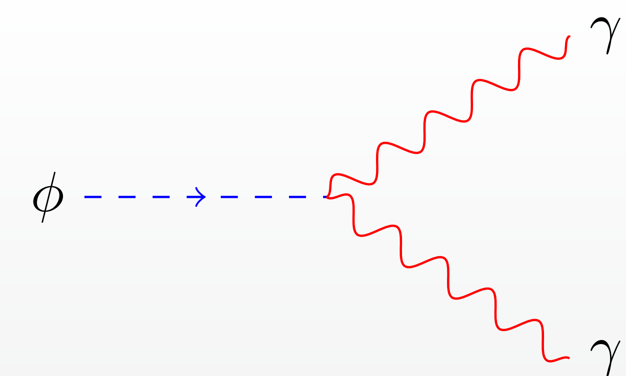
$$300 \text{ keV} \lesssim m_\phi \lesssim 50 \text{ MeV} \,.$$

$$\Lambda \gtrsim 3 \text{ TeV} \qquad [m_\phi \lesssim 50 \text{ MeV}] \,.$$

arXiv:1404.1927

[E. Dudas et al.; 1404.1927]

Axion-like particle



$$\mathcal{L} = \frac{\phi}{\Lambda} F_{\mu\nu}F^{\mu\nu}, \quad F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu$$

$$\Gamma(\phi \to \gamma\gamma) = \frac{m_\phi^3}{8\pi\Lambda^2}$$

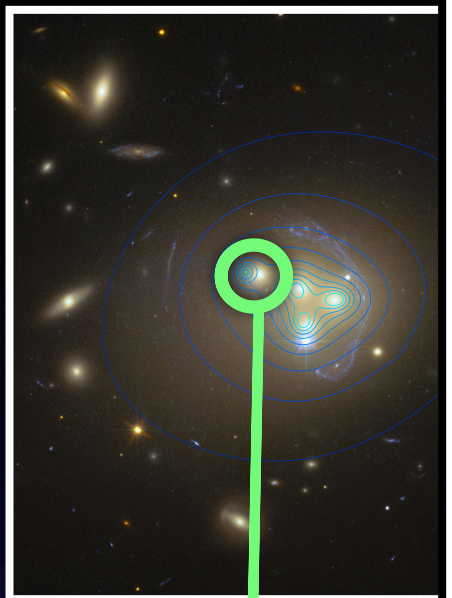
keV γγ observation

$$\Lambda \simeq 5 \times 10^{17} \text{GeV}$$

[J. Jaeckel et al.; 1402.7335]

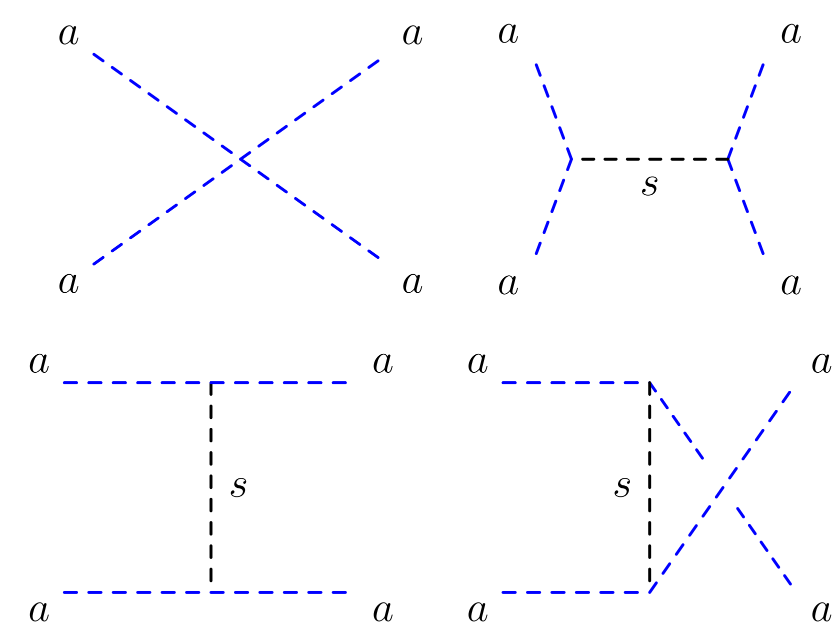
Combining 2 signals: 3.5 keV + SIDM

[Y.M., T. Toma 1506.02032]



$$\mathcal{V}_\Phi = -\mu^2|\Phi|^2 + \frac{\lambda}{4}|\Phi|^4. \qquad \Phi = v + \frac{s+ia}{\sqrt{2}}$$

$$\mathcal{V}_\Phi = \frac{m_s^2}{2}s^2 + \frac{\sqrt{\lambda}}{2\sqrt{2}}m_s s^3 + \frac{\sqrt{\lambda}}{2\sqrt{2}}m_s a^2 s + \frac{\lambda}{16}s^4 + \frac{\lambda}{16}a^4 + \frac{\lambda}{8}a^2 s^2,$$

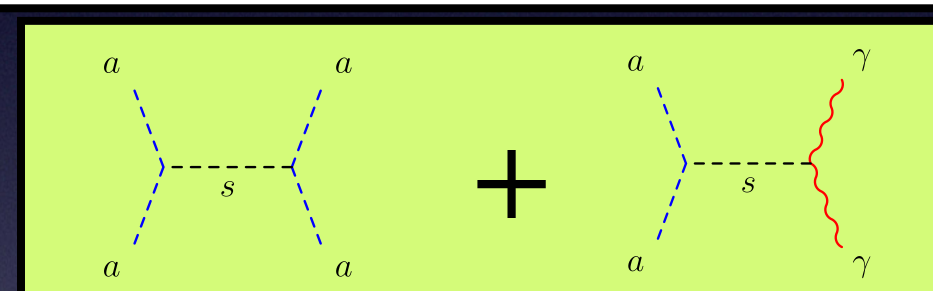


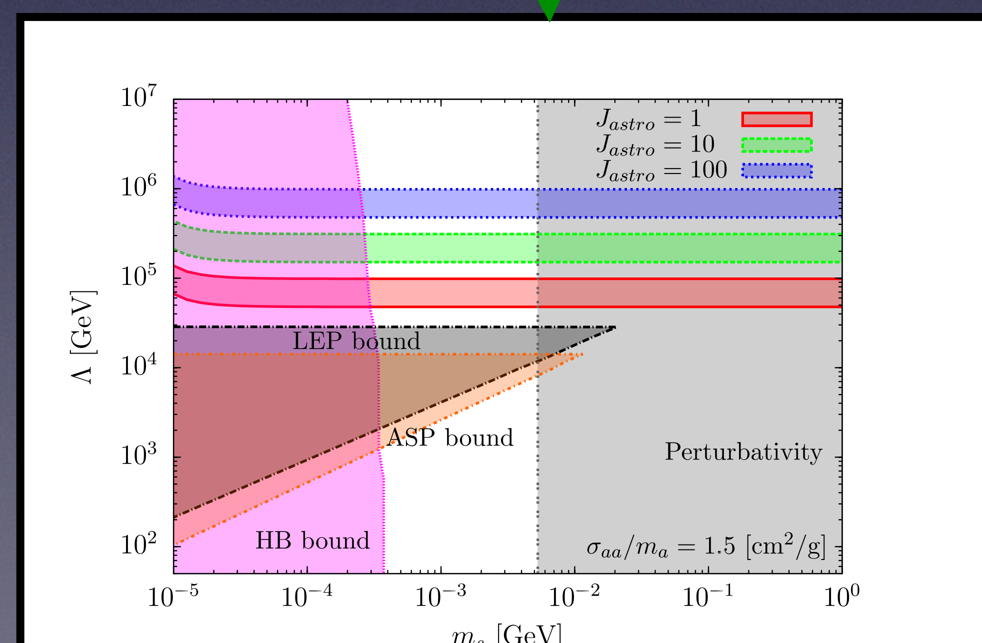
In 2015, Massey *et al.* [1504.03388] found an offset of 1.67 kpc between the center of the halo and its stars. Interpreting as self interacting DM they obtained:

$$\frac{\sigma_{aa}}{m_a} = \frac{\lambda^2 m_a}{32\pi m_s^4\left(1-4\frac{m_a^2}{m_s^2}\right)^2} \simeq \frac{\lambda^2 m_a}{32\pi m_s^4}, \qquad m_s \gg m_a.$$

Which gives, for ma=3 keV and ms=1 MeV:

$$\sigma_{aa}/m_a \simeq 7\lambda^2 \text{ cm}^2/\text{g}$$



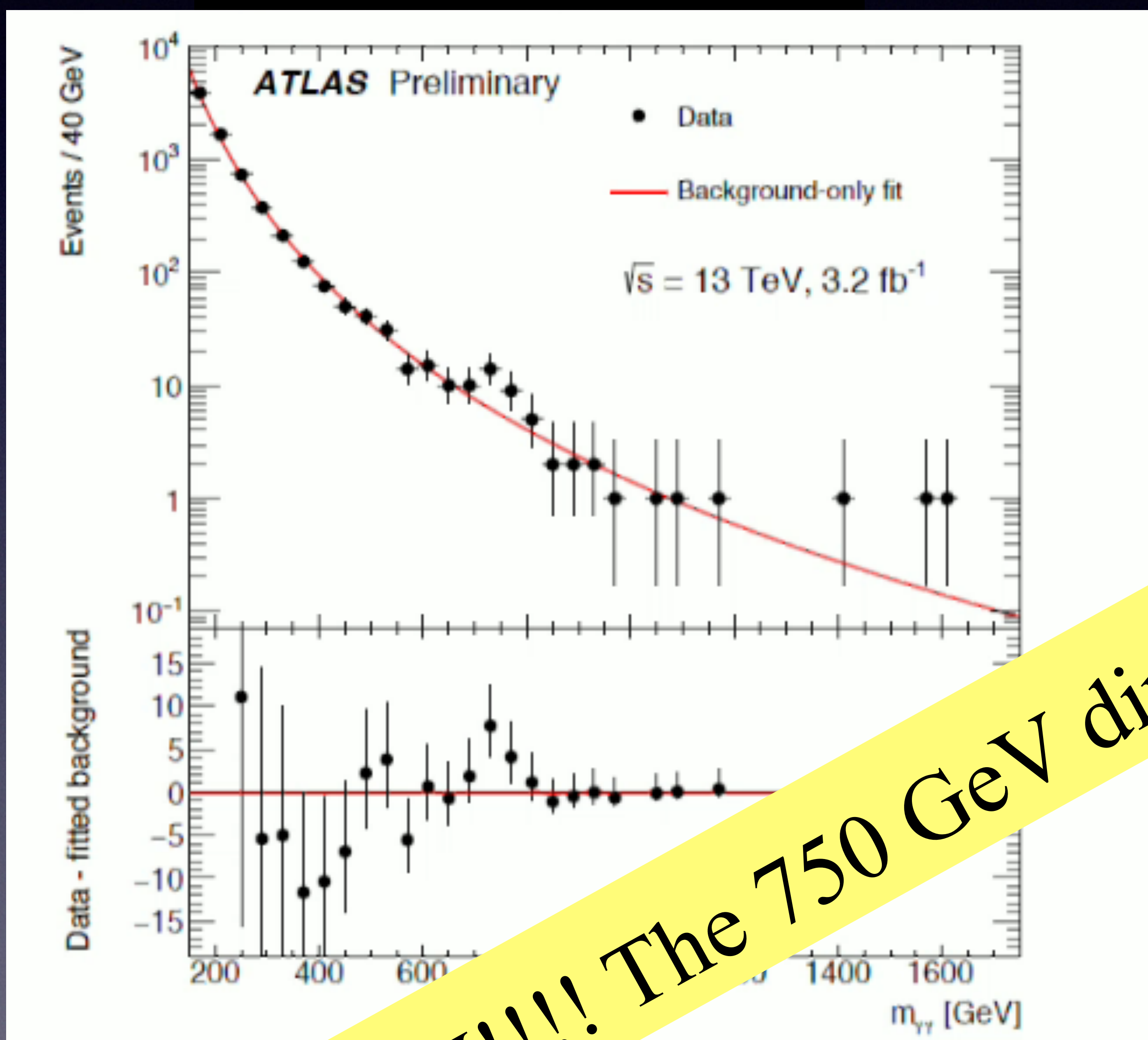


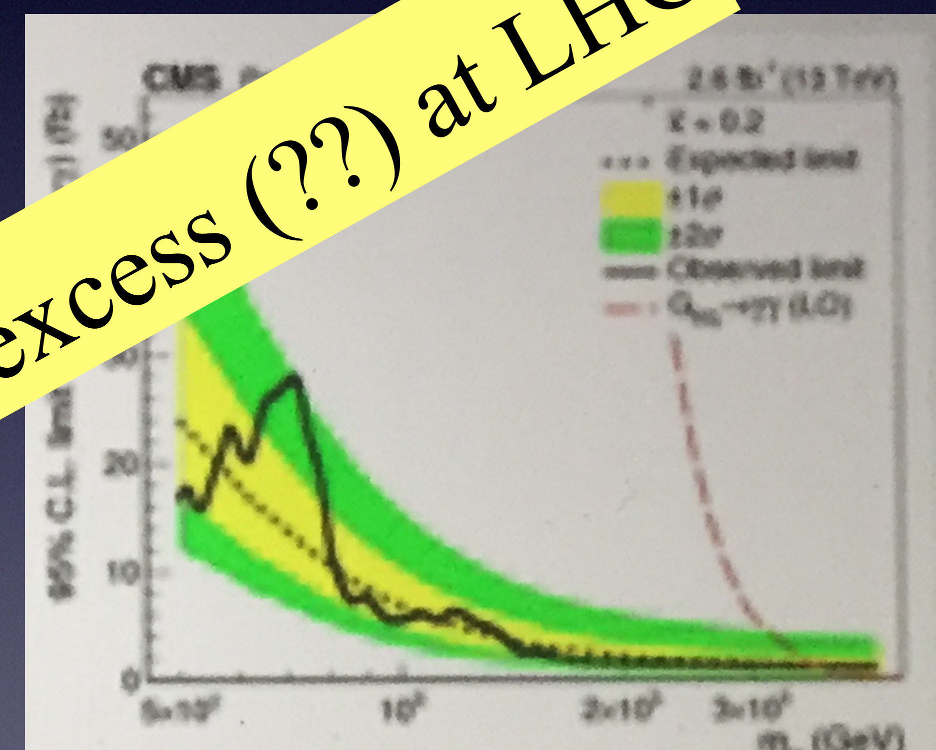
One can do the same exercice for GC excess and 511 keV line Gondola et al. (P. Gondolo et al. 1406.4683

ATLAS
747 GeV
Width of 45 GeV
3.6σ excess (local)
1.9σ excess global

CMS
745 GeV

2.6σ excess (local)
1.2σ excess global



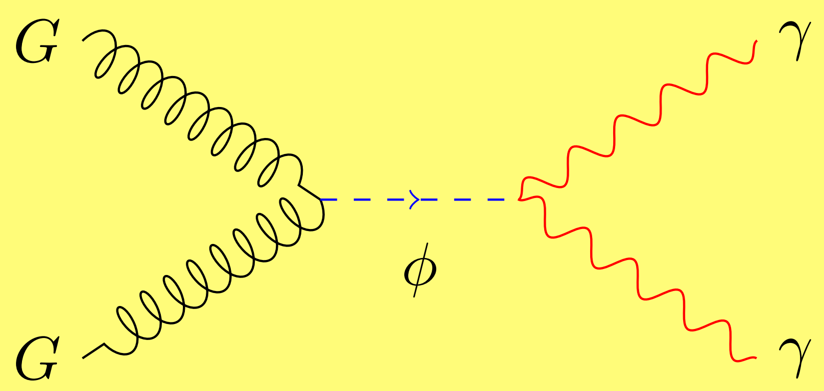


NEW!!!! The 750 GeV diphoton excess (??) at LHC

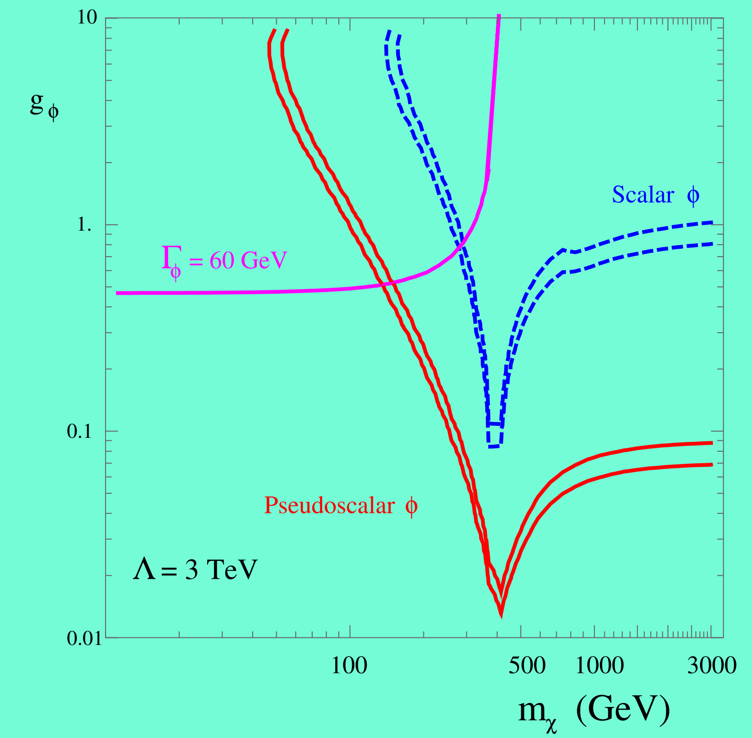
Simplest hypothesis, a (pseudo)scalar Higgs-like particle

$$\mathcal{L}_{0^+} = \frac{c_1}{\Lambda}\phi F_{\mu\nu}F^{\mu\nu} + + \frac{c_2}{\Lambda}\phi W^{\mu\nu}W_{\mu\nu} + \frac{c_3}{\Lambda}\phi G^a_{\mu\nu}G_a^{\mu\nu} + g_\phi \phi\bar{\chi}\chi + m_\psi\bar{\chi}\chi.$$

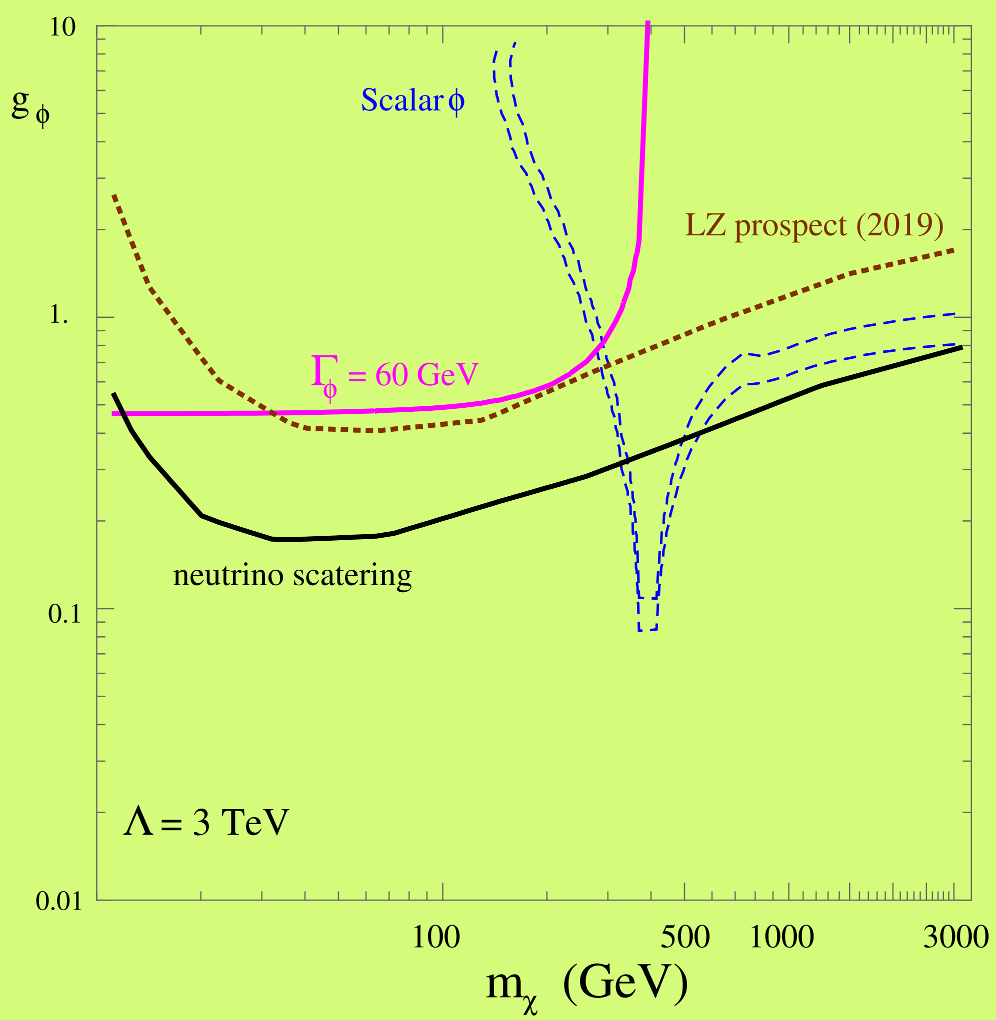
$$\mathcal{L}_{0^-} = \frac{c_1}{\Lambda}\phi F_{\mu\nu}\tilde{F}^{\mu\nu} + + \frac{c_2}{\Lambda}\phi W^{\mu\nu}\tilde{W}_{\mu\nu} + \frac{c_3}{\Lambda}\phi G^a_{\mu\nu}\tilde{G}_a^{\mu\nu} + ig_\phi \phi\bar{\chi}\gamma^5\chi + m_\psi\bar{\chi}\chi.$$



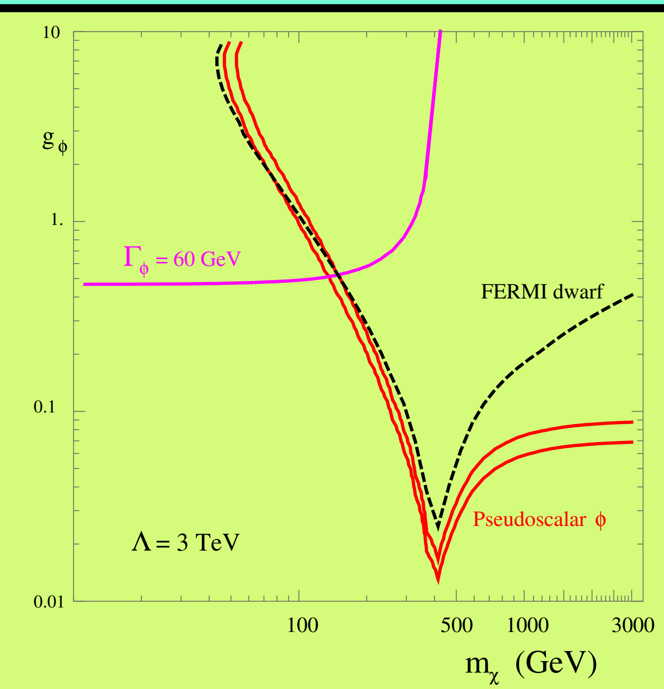
Relic density constraint



Direct detection constraint



Indirect detection constraint



[Y.M., G. Arcadi, A. Djouadi 1512.04913]

Conclusion: a 750 GeV mediator is not exclude by WMAP and PLANCK (extension of the WIMP (wIMP) principle. But hard to see in direct detection or indirect detection experiment (large spectrum).

Conclusion of the observational model building

In the experimental data approach, evading the classical WIMP bound, some work is needed concerning the primordial Universe physics (reheating, WIMPZILLA, freeze-in..)

3

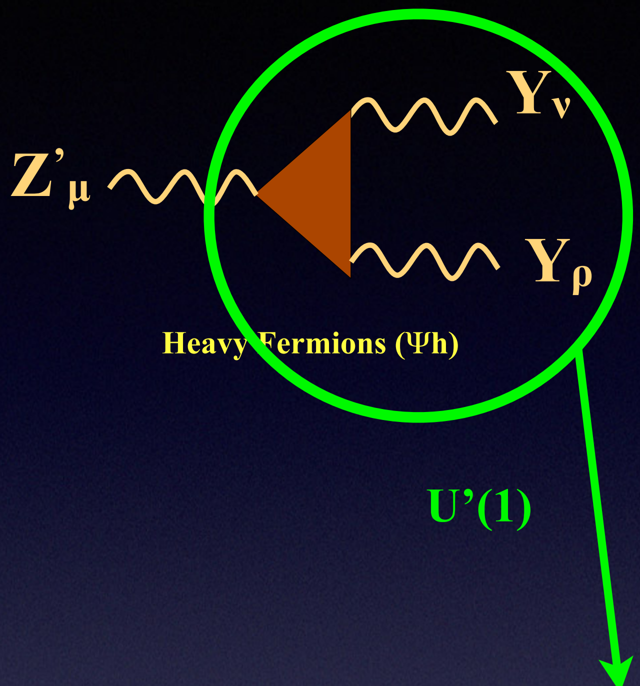
Building a dark matter model from fundamental principles

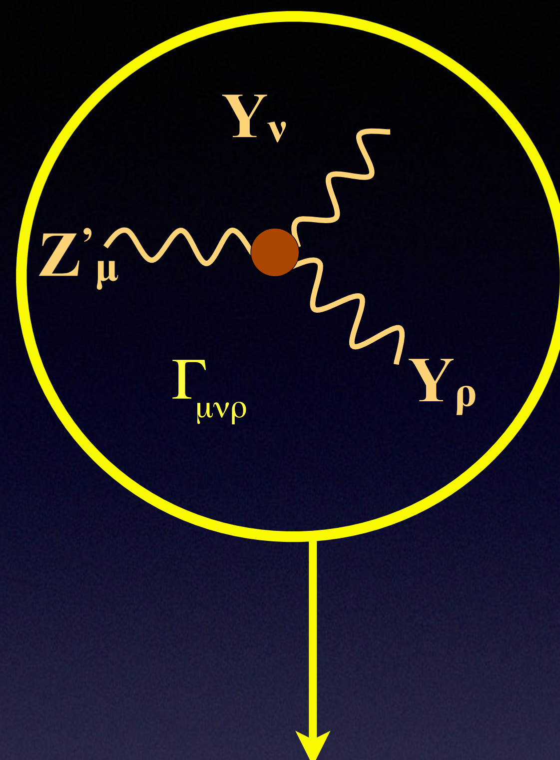
Supersymmetry
Supergravity
String-inspired (KKLT) scenario
Extra-dimension..
the dark matter candidate (neutralino, gravitino, sneutrino, singlino..) comes as a « bonus »

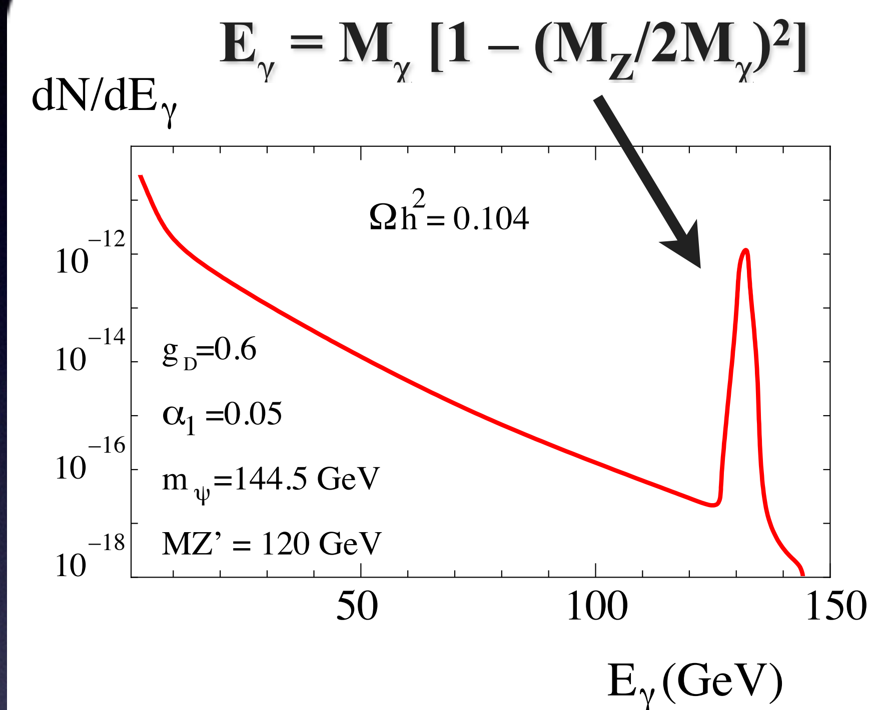
Monochromatic signal from anomaly cancelation

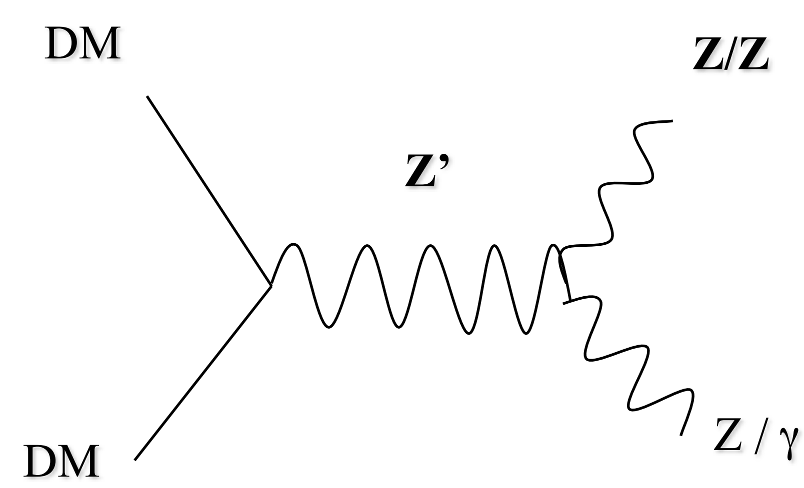
[Y.M; 0909.5053]

[Jackson, Servant, Taoso, et al. 0912.0004]







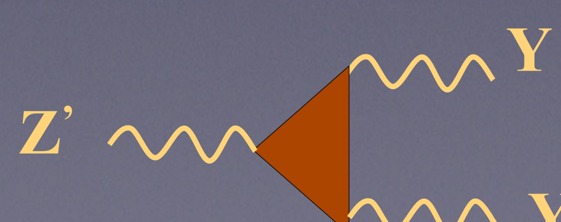


$$\mathcal{L} \to \mathcal{L} + \lambda \epsilon^{\mu\nu\rho\sigma} F^Y_{\mu\nu} F^Y_{\rho\sigma} + \mathcal{L}'$$

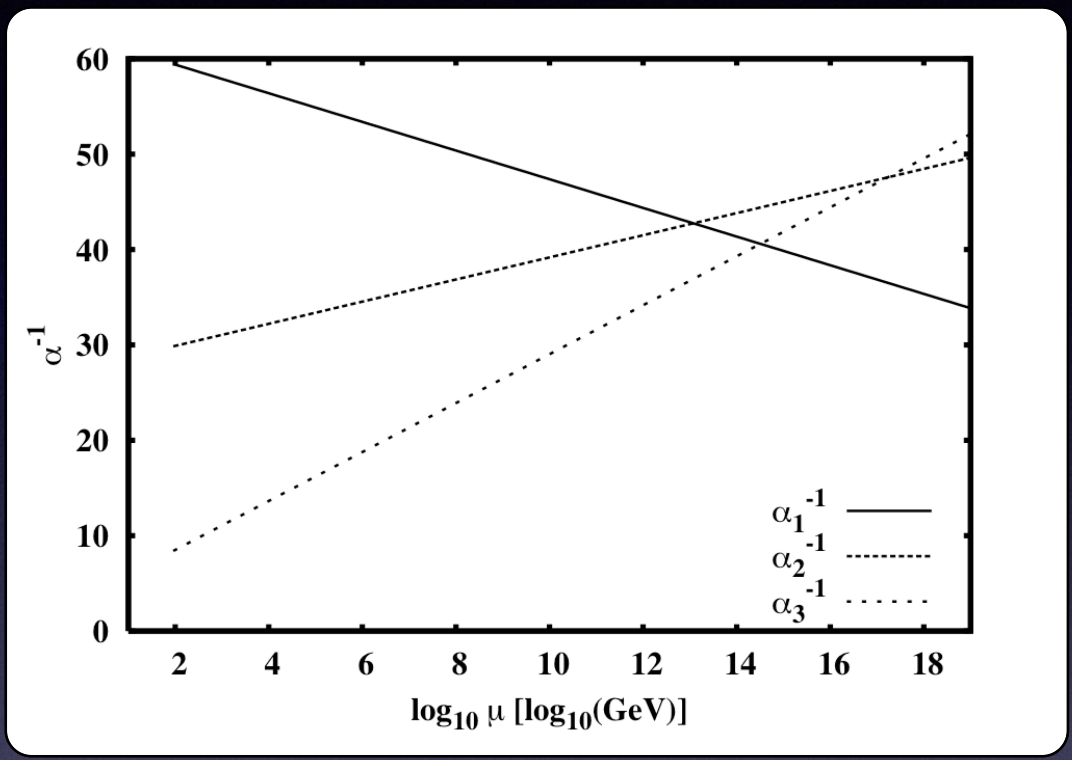
$$\mathcal{L} = F^{Y\,\mu\nu} F^Y_{\mu\nu} - (\partial_\mu a - M_{Z'} Z_\mu)^2 - i\bar{\Psi}\gamma^\mu D_\mu \Psi$$

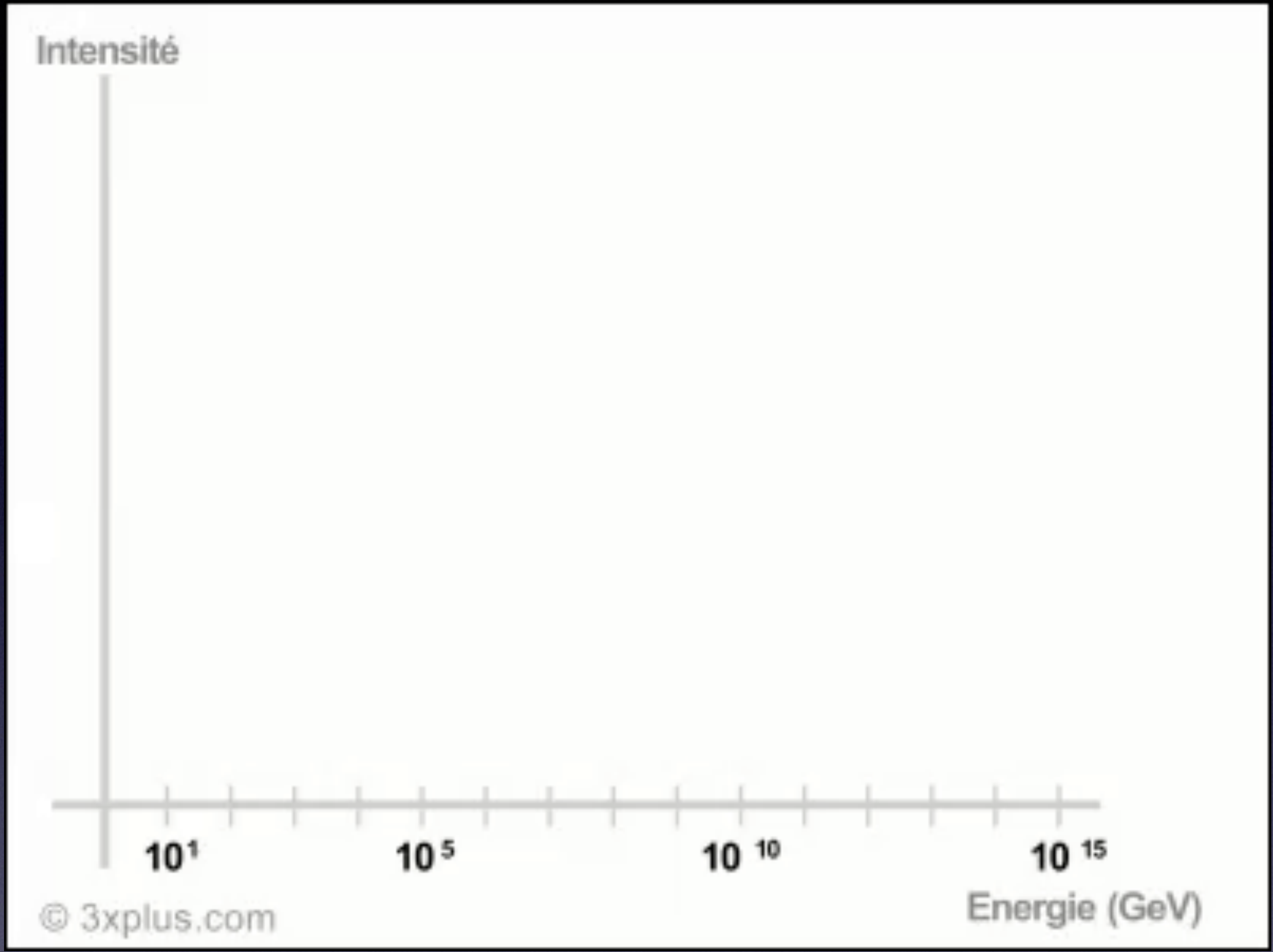
[Stuckelberg phase]

$$\mathcal{L}' = B\ a\epsilon^{\mu\nu\rho\sigma} F^Y_{\mu\nu} F^Y_{\rho\sigma} + C\ \epsilon^{\mu\nu\rho\sigma} Z'_\mu Y_\nu F^Y_{\rho\sigma}$$

$\delta\ \mathcal{L}'$ = - δ ()

Gauge coupling unification



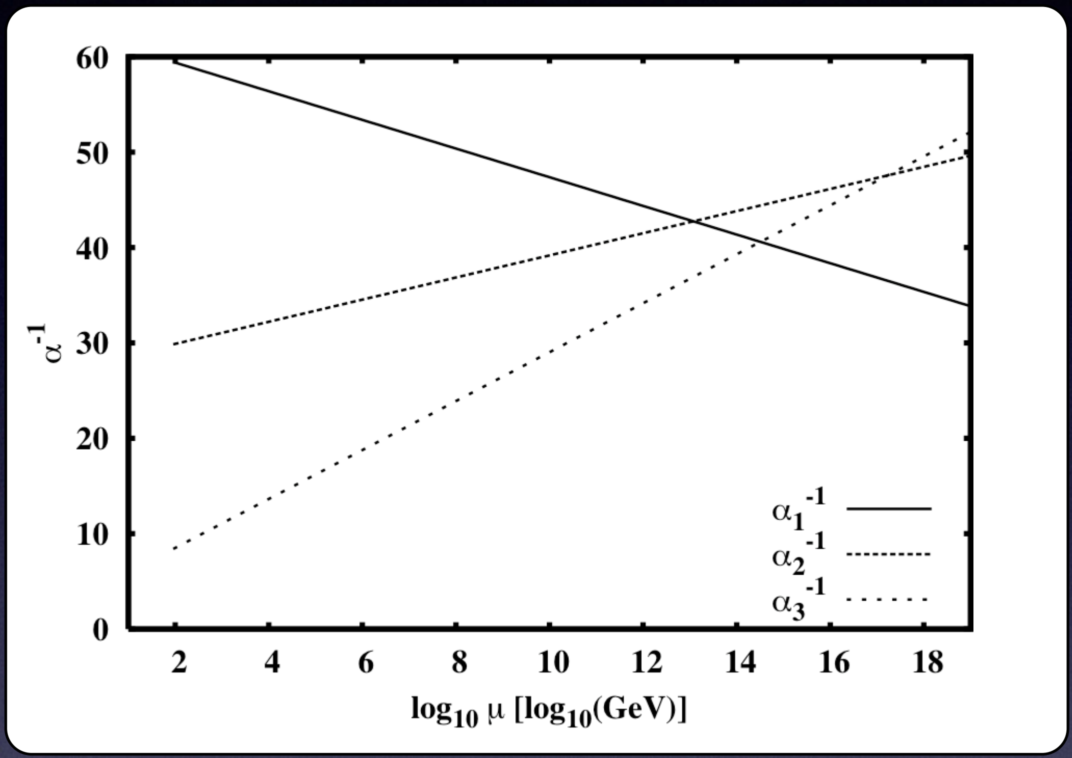


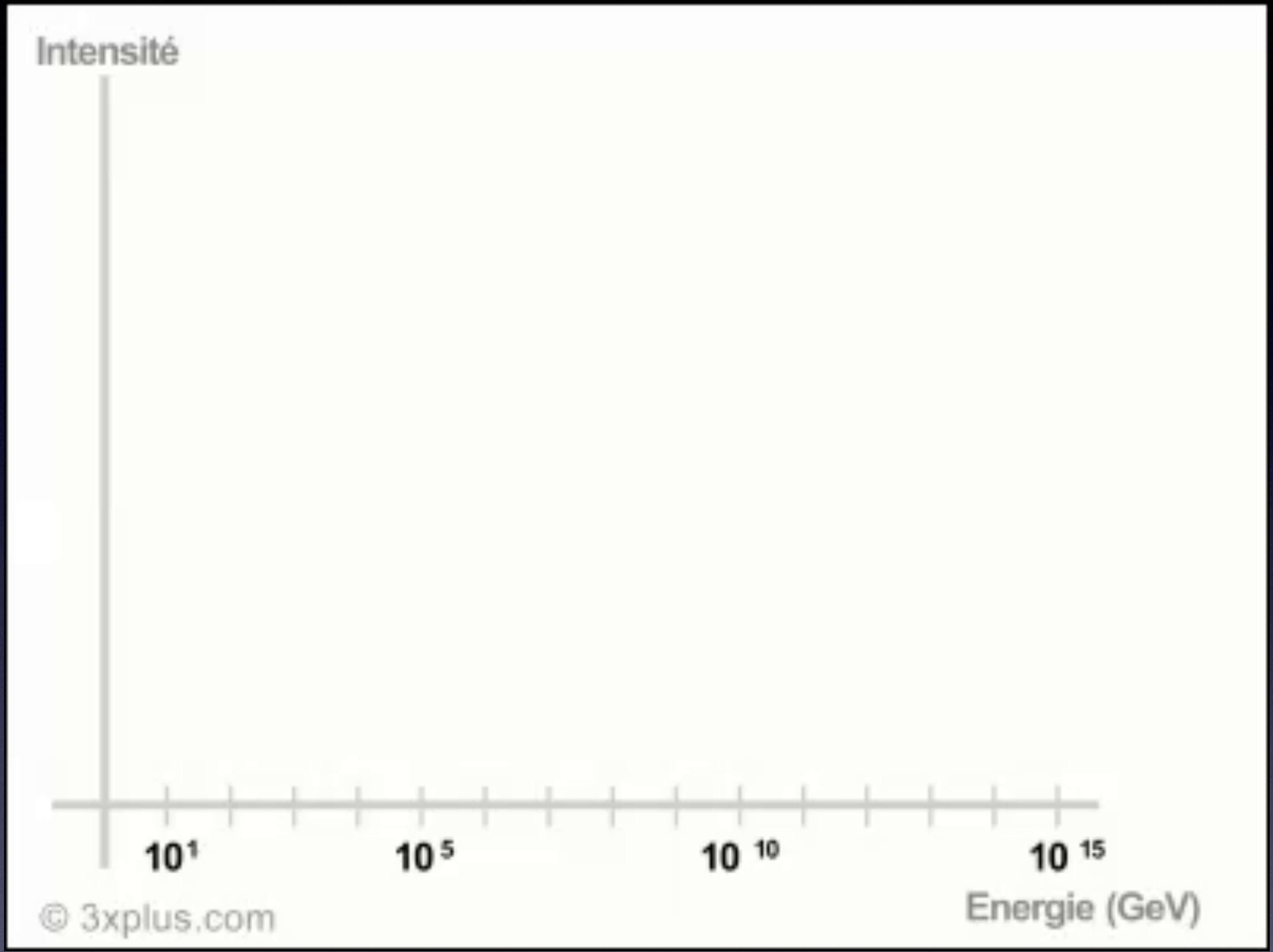
First motivation for GUT-like models

Two medications: modifying the **particle content** (SUSY) or the **gauge structure** (GUT), or **both** (SUSY-GUT)

Care should be taken concerning the proton decay in GUT models as electrons and quarks belong to **same multiplets**

Gauge coupling unification





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Example of SO(10)

[talk of K. Olive]

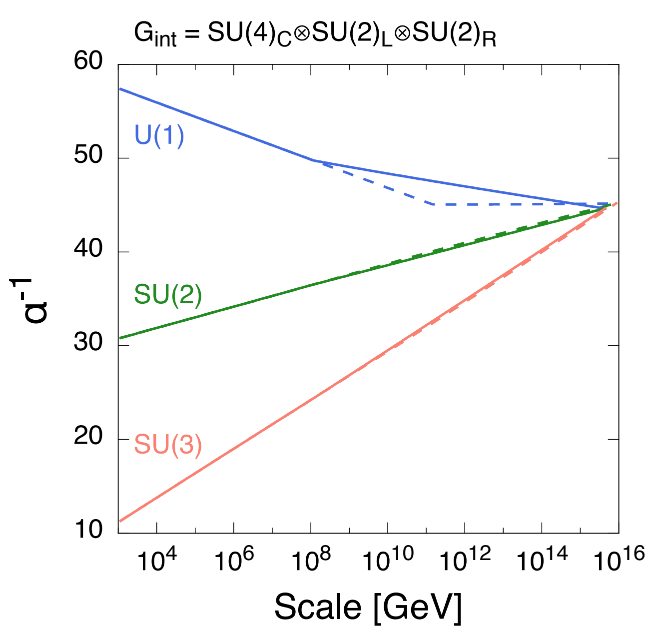
« Did anybody read on the front page of Times that matter is decaying? »

Woody Allen, 1980

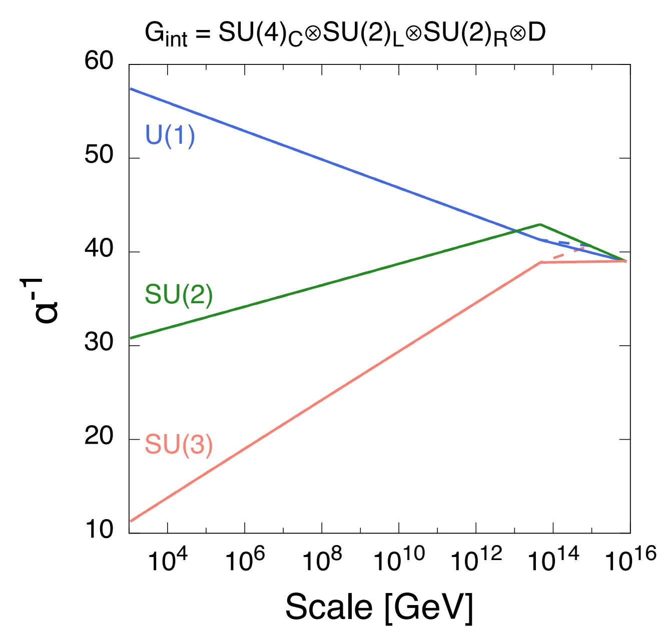
$$\mathrm{SO}(10) \longrightarrow G_{\mathrm{int}} \longrightarrow G_{\mathrm{SM}} \otimes \mathbb{Z}_N$$

$$\mathcal{L}_Y = \frac{g}{2}\mathbf{16}_L.\mathbf{16}_L.\mathbf{10} + \frac{h}{2}\mathbf{16}_L.\mathbf{16}_L.\mathbf{126}$$

$$M^R = h\langle\mathbf{126}\rangle$$



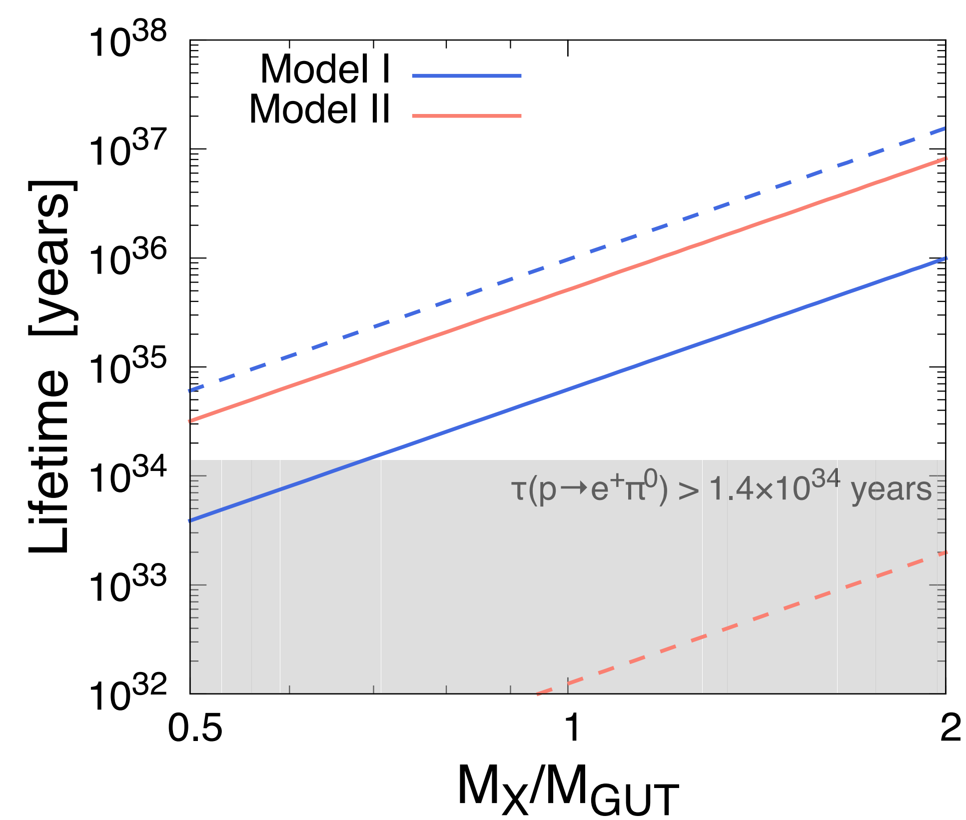
(a) Model I

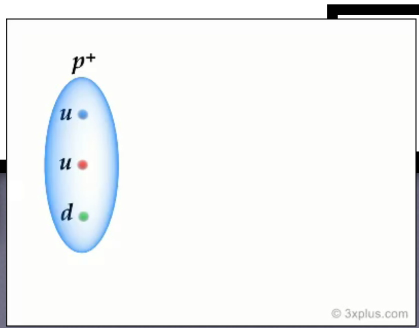


(b) Model II

without dark matter

with dark matter





proton lifetime

[M. Frigerio, T. Hambye; 0912.1546]

[N. Nagata et al.; 1502.06929,1509.00809,1512.02184]

[C. Arbelaez et al.; 1509.06313]

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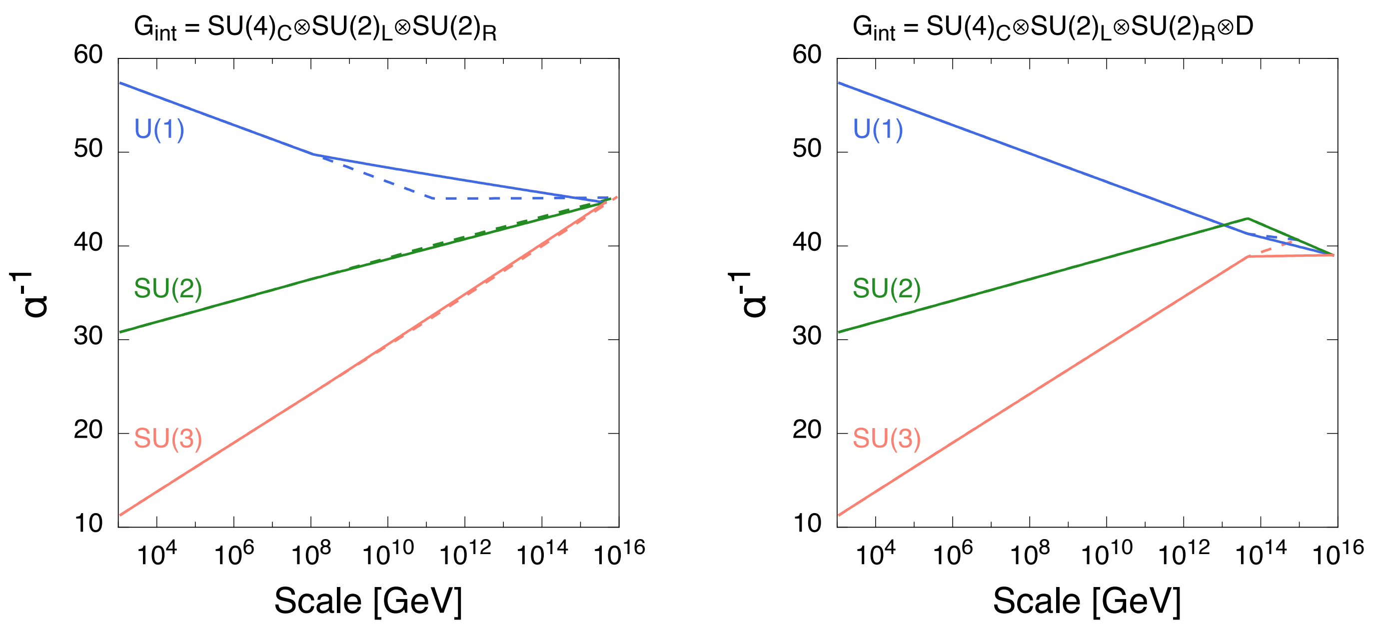
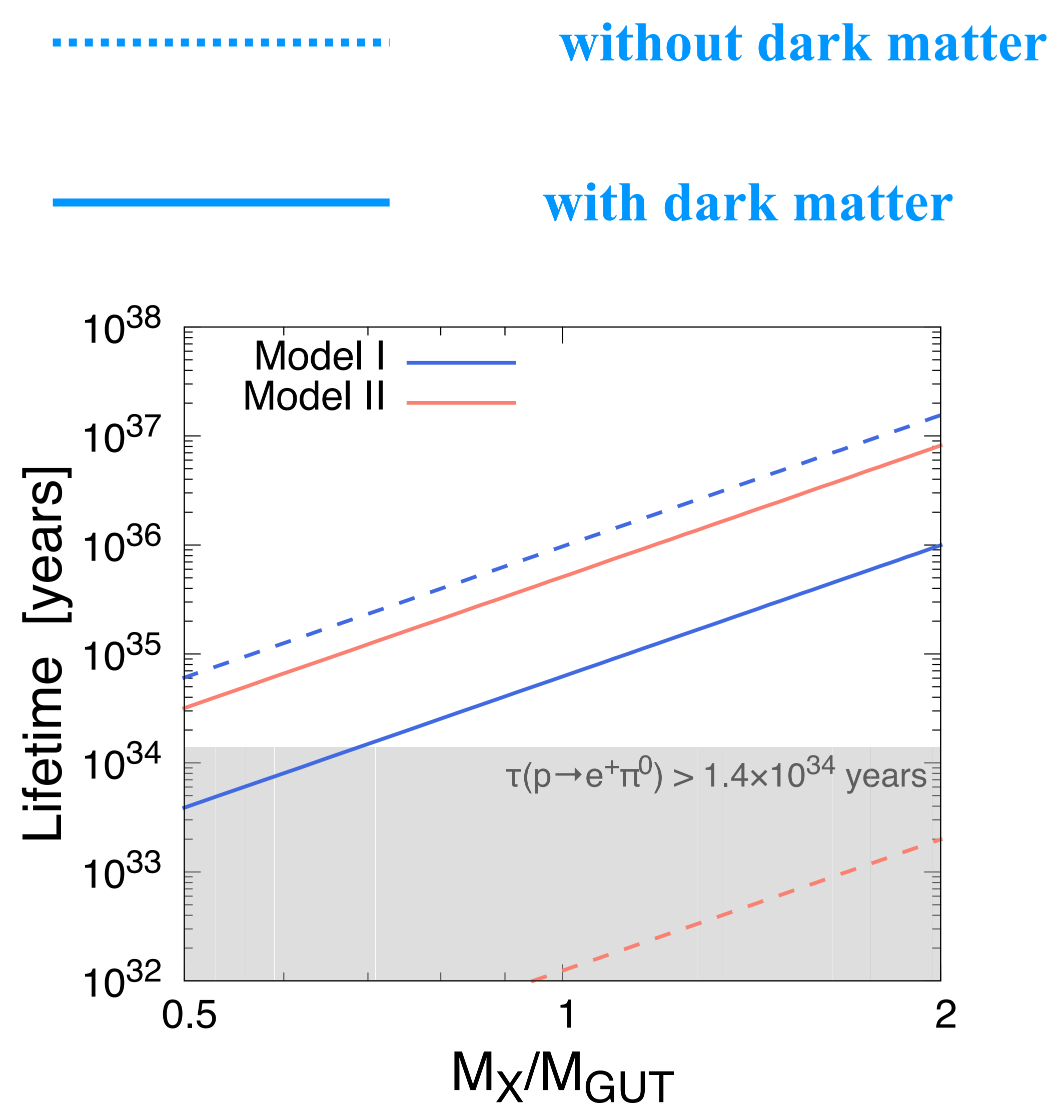
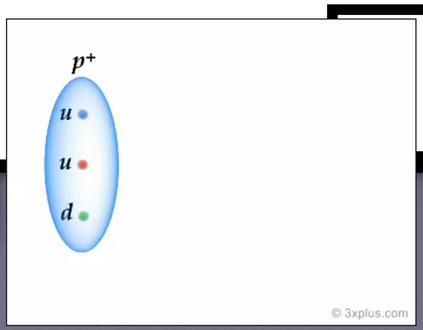


(a) Model I (b) Model II



proton lifetime



[M. Frigerio, T. Hambye; 0912.1546]

[N. Nagata et al.; 1502.06929,1509.00809,1512.02184]

[C. Arbelaez et al.; 1509.06313]

Conclusion

Building a dark matter model with a microscopical approach

Mass of dark matter > 200 GeV or < 10 GeV

Building a dark matter model with an observational approach

Need of non-thermal scenarios

Building a dark matter model with a fundamental approach

Elegant but difficulties to respect all the parallel constraints generated by the construction

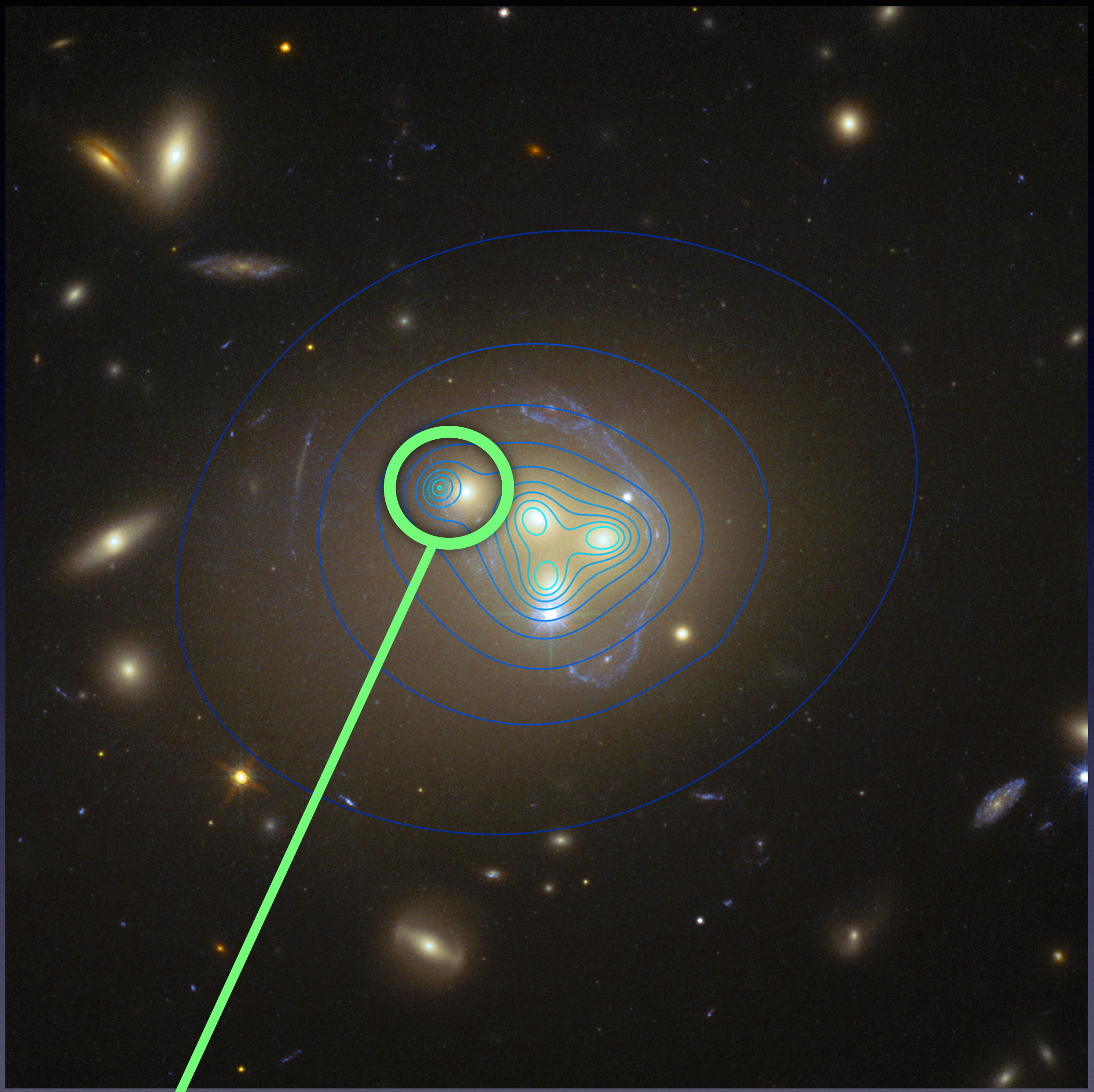
Conclusion of the microscopic approach

Introducing a dark force (Z’) and relaxing the thermal equilibrium gives rise to models evading at the same time the Lee-Weinberg and unitarity bound. It re-open the low mass widow, excluded by Higgs/Z portal.

BUT, the non-observation at the LHC of any resonance (!!) exclude light messengers

The WIMP scale (1-300 GeV) is disfavored by direct detection experiments in the WIMP framework

The case Abell 3827 : first observation?



ESO 146-5 (ESO 146-IG 005) is the designation given to a group of interacting giant elliptical galaxies in the center of the Abell 3827 cluster. The group is well noted due to their strong gravitational lensing effect.

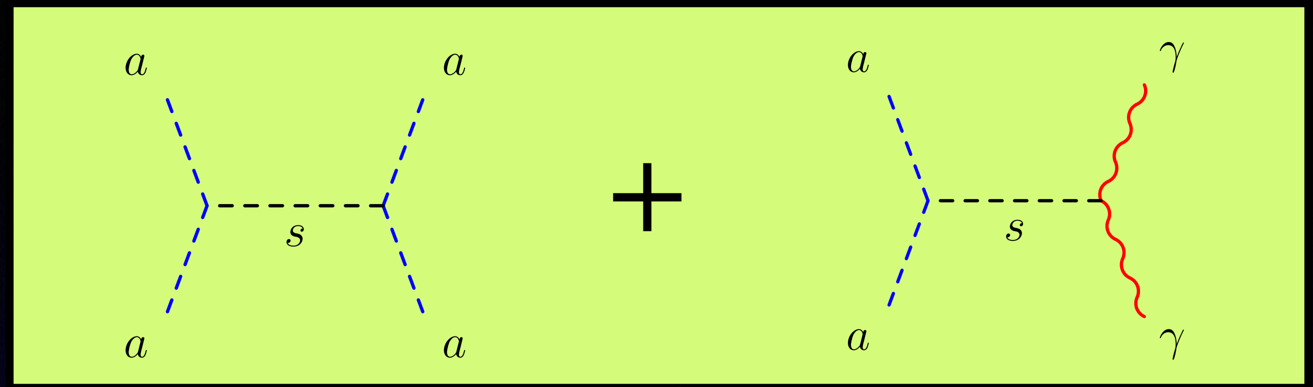
This group of interacting galaxies was found 1.4 billion light years away in the center of Abell 3827. A huge halo of stars is surrounding their interacting nuclei.

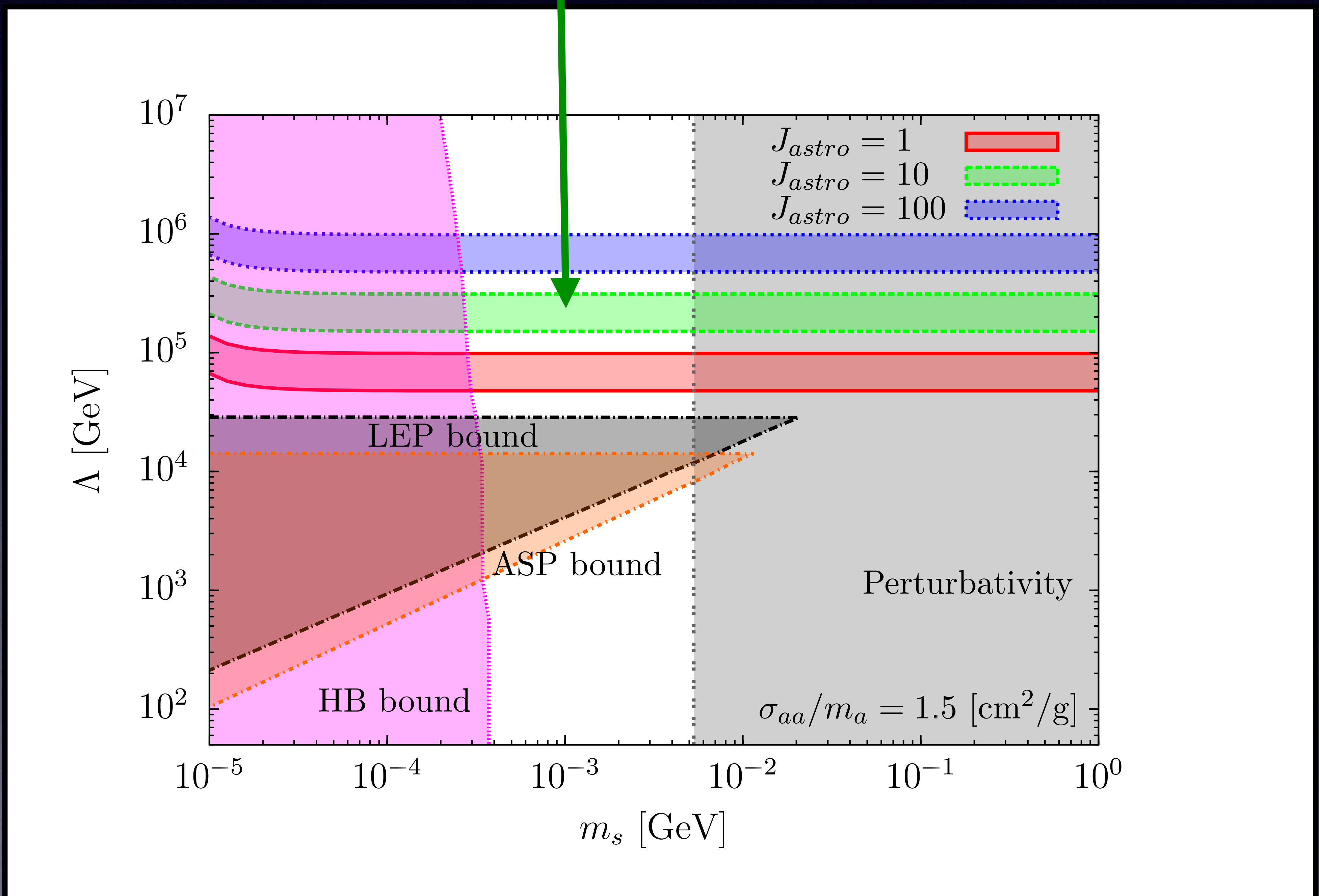
In 2015, Massey *et al.* [1504.03388] found an offset of 1.67 kpc between the center of the halo and its stars. Interpreting as self interacting DM they obtained:

$$\sigma/m \sim (1.7 \pm 0.7) \times 10^{-4} \left(\frac{t_{\rm infall}}{10^9 \ {\rm yrs}}\right)^{-2} {\rm cm}^2/{\rm g}.$$

Massey *et al.* obtained a *lower limit* because the clusters have interacted

Combining XMM and SIDM [Y.M., T. Toma; 1506.02032]





Summary on the old-school bounds:

Lee-Weinberg bound (1977)

$$\langle \sigma v \rangle = G_F^2 m_\chi^2 > 10^{-9} \text{ GeV}^{-2} \quad \Rightarrow \quad m_\chi > 2 \text{ GeV}$$

BUT non-valid as soon as we suppose an extra mediator
(Z' lighter then the Z for instance => $G'_F > G_F$

Cowsik-McClelland bound (1972)

$$\Omega_\nu h^2 = \frac{\rho_\nu}{\rho_0^c} h^2 = \frac{n_\nu \, m_\nu}{10^{-5} \text{ GeV cm}^3} \simeq \frac{m_\nu}{92 \text{ eV}} \quad \Rightarrow \quad m_\nu \lesssim 9 \text{ eV}$$

BUT be careful to the extra degrees of freedom
(dark radiation)

Unitarity bound

$$m_\chi \lesssim 340 \text{ TeV}$$

BUT thermal production has been imposed
(FIMP or WIMPZILLA do not enter in this game)