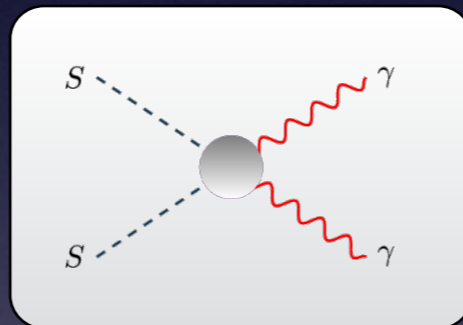


Generating a keV line from annihilating dark matter



Yann Mambrini

LPT Orsay

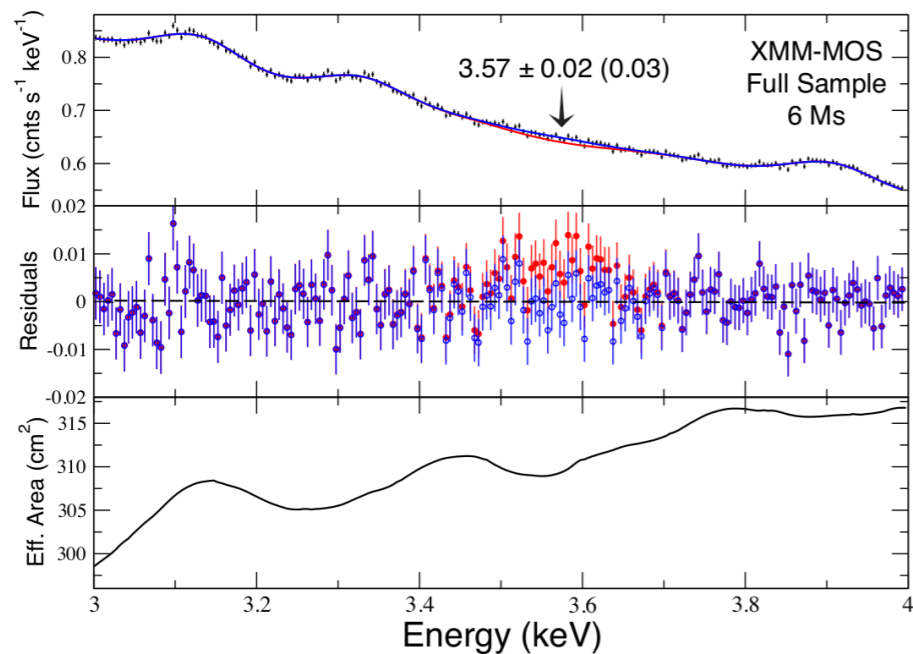


In collaboration with Lucien Heurtier and Emilian Dudas [arXiv :1404.1927](https://arxiv.org/abs/1404.1927)
for the Chalonge Workshop, Meudon Observatory, June the 4th 2014

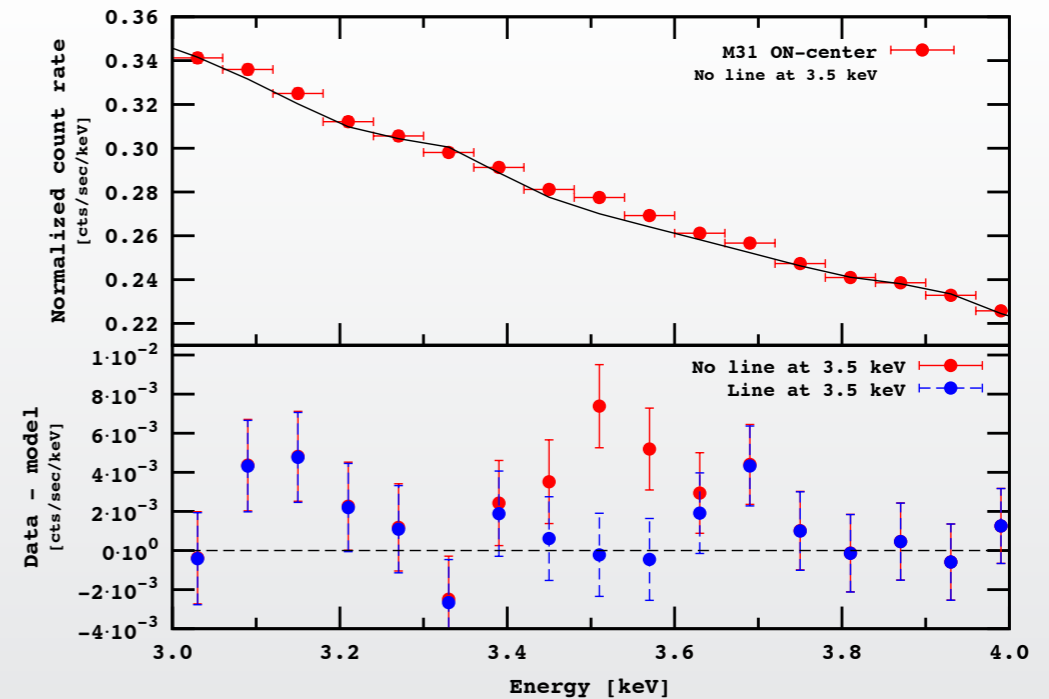
Experimental status



XMM Newton



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



A. Boyarsky, O. Ruchayskiy, D. Iakubovskyi, J. Franse;
<http://arxiv.org/abs/1402.4119>

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

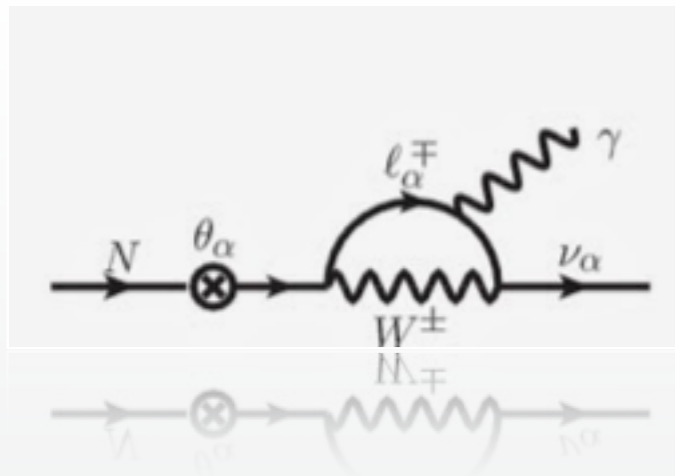
(Perseus, 78 Mpc)

$$\Phi_{\gamma\gamma} = \frac{L}{4\pi D_{pe}^2} = \frac{\rho_{Pe}}{m_{dm}} \times \Gamma(DM \rightarrow \gamma\gamma) \times \frac{(R_{Pe})^3}{3(D_{Pe})^2}$$

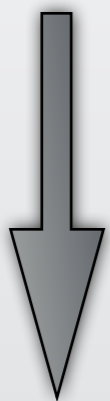
$$\Gamma(DM \rightarrow \gamma\gamma) \simeq 10^{-23} \left(\frac{m_{dm}}{\text{keV}} \right) \Phi_{\gamma\gamma} \text{ cm}^{-2} \text{ s}^{-1}$$

Some decaying/exciting interpretation

Sterile neutrino



$$\Gamma(N \rightarrow \gamma\nu) = 5 \times 10^{-32} \text{ s}^{-1} \left(\frac{\sin \theta}{10^{-10}} \right) \left(\frac{m_N}{\text{keV}} \right)^5$$

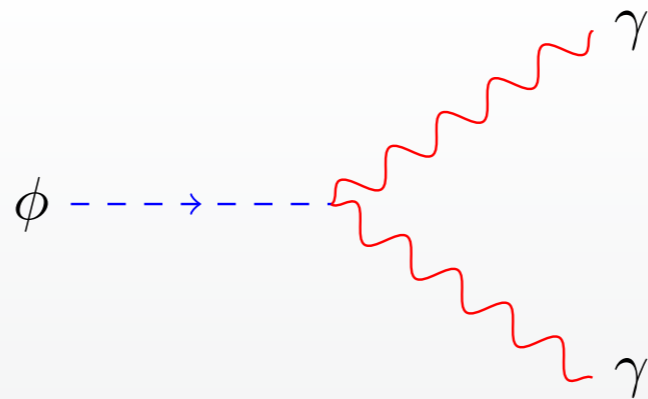


keV $\gamma\gamma$ observation

$$\Gamma \simeq \frac{1}{(2 - 20) \times 10^{27} \text{ s}}$$

arXiv:1403.5837

Axion-like particle



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

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

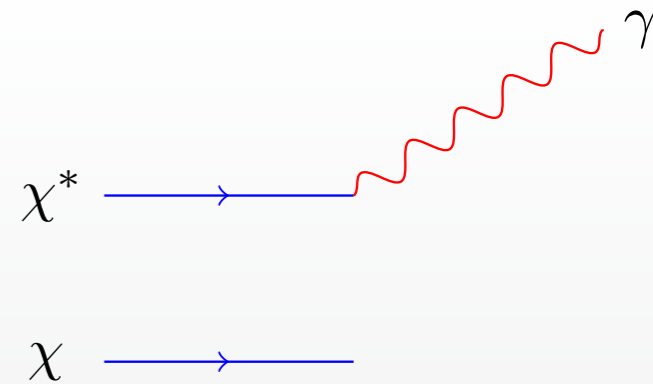


keV $\gamma\gamma$ observation

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

arXiv:1403.0865

Exciting DM



$$\mathcal{L} = \frac{1}{\Lambda} \chi^* \sigma_{\mu\nu} \chi F^{\mu\nu}, \quad \sigma_{\mu\nu} = [\gamma_\mu \gamma_\nu]$$

$$m_{\chi^*} - m_\chi = 3.5 \text{ keV}$$

$$m_\chi \sim 100 \text{ GeV}$$



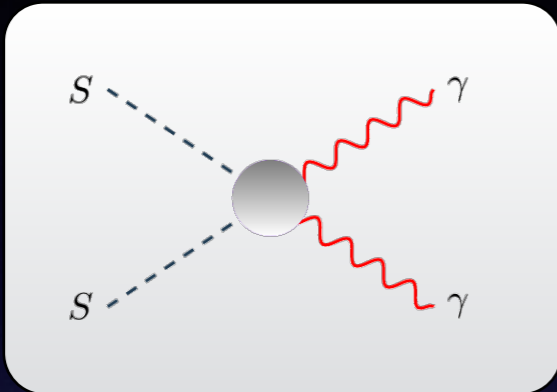
keV $\gamma\gamma$ observation

$$\Lambda \simeq 10^{11} \text{ GeV}$$

arXiv:1404.5446

What about annihilating DM?

Standard belief



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

(Perseus, 78Mpc)

$$L = \int_0^{R_{Pe}} 4\pi r^2 n_{DM}^2 \langle \sigma v \rangle_{\gamma\gamma} = \int_0^{R_{Pe}} 4\pi r^2 \left(\frac{\rho(r)}{m_s} \right)^2 \langle \sigma v \rangle_{\gamma\gamma}$$

$$n_{DM} \simeq \frac{1.49 \times 10^{14} M_{\odot}}{m_s} \frac{3}{4\pi R_{Pe}^3} = 2.6 \times 10^4 \text{ cm}^{-3}$$

$$\phi_{\gamma\gamma} = L / (4\pi D_{Pe}^2) = 1.7 \times 10^{-5} \left(\frac{3.5 \text{ keV}}{m_s} \right)^2 \left(\frac{\langle \sigma v \rangle_{\gamma\gamma}}{10^{-32} \text{ cm}^3 \text{ s}^{-1}} \right) \text{ cm}^{-2} \text{ s}^{-1}$$

+ CMB constraints :

$$\longrightarrow 2 \times 10^{-33} \text{ cm}^3 \text{ s}^{-1} < \langle \sigma v \rangle_{\gamma\gamma} < 8.5 \times 10^{-33} \text{ cm}^3 \text{ s}^{-1}$$

$$\mathcal{L}_{eff} = \frac{S^2}{\Lambda^2} F_{\mu\nu} F^{\mu\nu} \longrightarrow \langle \sigma v \rangle_{\gamma\gamma}^{eff} = \frac{2m_s^2}{\pi\Lambda^4}$$

where Λ represent the scale/masses of the particles running in the loop (charged, LEP/LHC : $\Lambda > 1 \text{ TeV}$)

keV $\gamma\gamma$ observation

Excluded by LEP/LHC..

$$10 \text{ GeV} < \Lambda < 15 \text{ GeV}$$

Conclusion: necessity to build a microscopic model explicitly

From the effective approach to the microscopic one

Enrico Fermi



"Tentativo di una teoria dei raggi β ",

Ricerca Scientifica, 1933

TENTATIVO DI UNA TEORIA DEI RAGGI β

Nota (7) di Enrico Fermi

Sunto. - Si propone una teoria quantitativa dell'emissione dei raggi β in cui si ammette l'esistenza del « neutrone » e si tratta l'emissione degli elettroni e dei neutroni da un nucleo sottile della disintegrazione β con un procedimento analogo a quello seguito nella teoria dell'irradiazione per assorbire l'emissione di un quanta di luce da un atomo eccitato. vengono discusse delle ipotesi per la vita media e per la forma dello spettro continuo dei raggi β , e le si confrontano coi dati sperimentali.

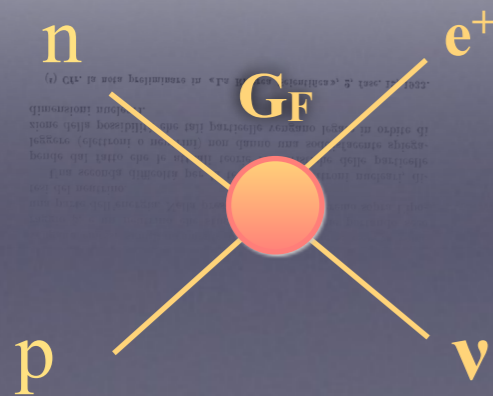
Ipotesi fondamentali della teoria.

§ 1. Nel tentativo di costruire una teoria degli elettroni carichi 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 deve ammettere perciò che una frazione dell'energia che si libera nel processo di disintegrazione è always alle molte altre possibilità di osservazione. Secondo la proposta di Fermi si può p. es. ammettere l'esistenza di una nuova particella, il cui detto « neutrone », emette energia elettrica sulla « massa dell'ordine di grandezza di quella dell'elettrone o minore. Si ammette poi che in ogni processo β vengono emessi simultaneamente un elettrone, che si muove come raggio β , e un neutrone che sfugge all'osservazione portando seco una parte dell'energia. Nella presente teoria si baseranno sopra l'ipotesi del neutrone.

Una seconda difficoltà per la teoria degli elettroni carichi, dipende dal fatto che le attuali teorie relativistiche delle particelle leggere (elettroni e neutroni) non danno una soddisfacente spiegazione della possibilità che tali particelle vengano legate in orbite di dimensioni nucleari.

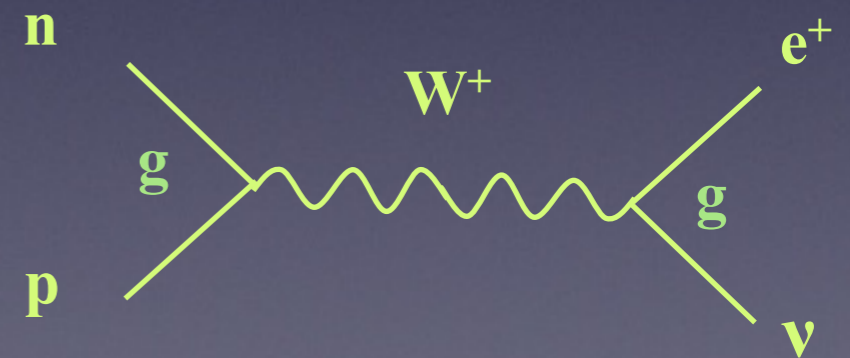
(7) Cfr. la nota precedente in «La Ricerca Scientifica», 2. fasc. 12, 1932.

Renormalizable theory!
and specific signatures
(discovery of charge/
neutral current at CERN)



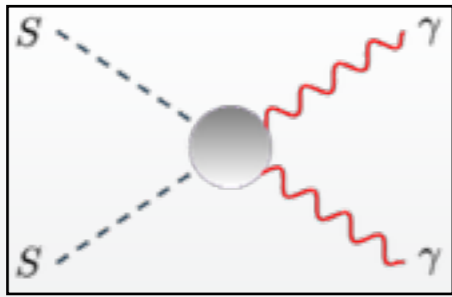
$$G_F = 10^{-5} \text{ GeV}^{-2}$$

microscopic
approach



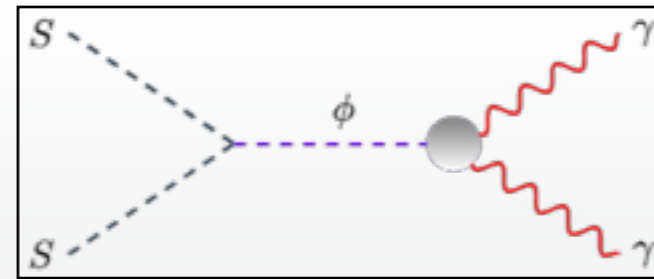
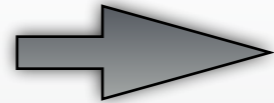
$$G_F \sim (g/M_W)^2$$

Applying the microscopic approach to the keV line



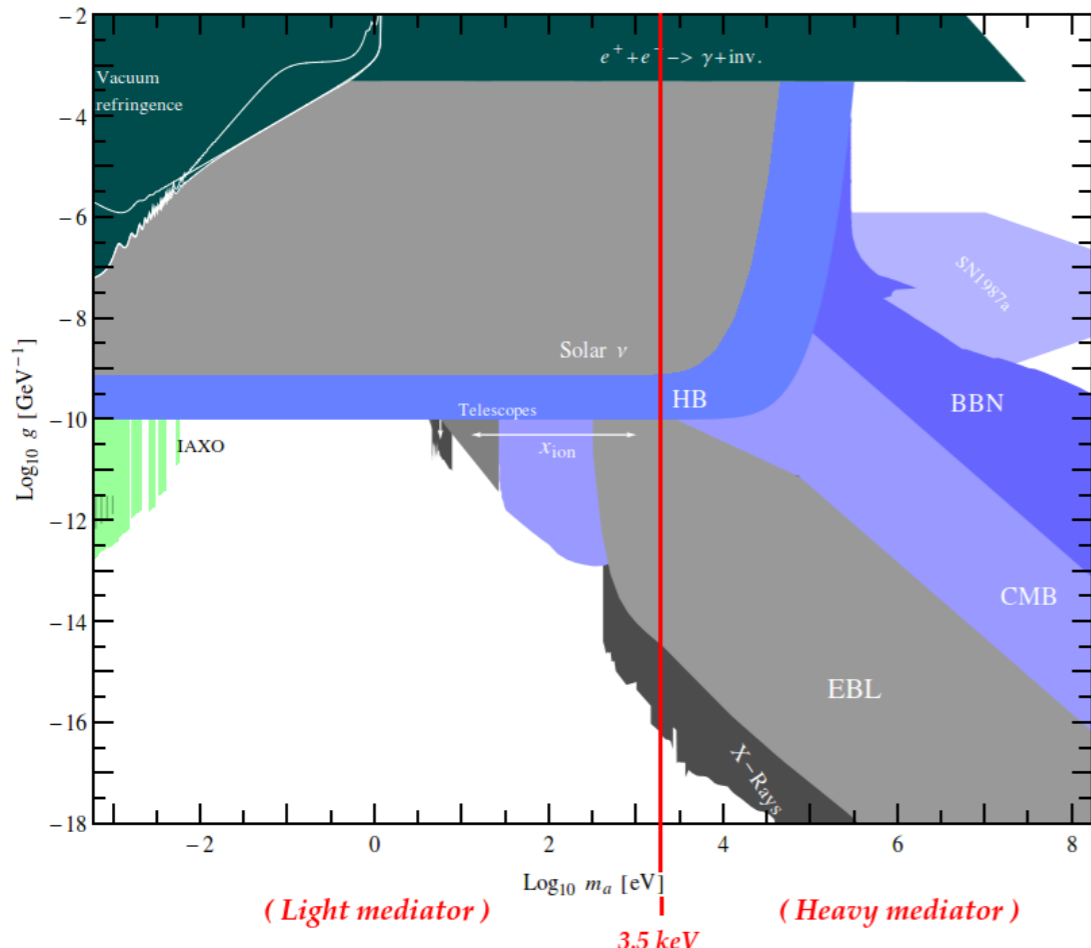
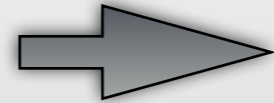
$$\mathcal{L}_{eff} = \frac{S^2}{\Lambda^2} F_{\mu\nu} F^{\mu\nu}$$

$$\langle \sigma v \rangle_{\gamma\gamma}^{eff} = \frac{2m_s^2}{\pi\Lambda^4}$$



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

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



keV $\gamma\gamma$ observation



$$m_\phi \simeq (12.3 - 17.6) \sqrt{\frac{m_s}{3.5 \text{ keV}}} \sqrt{\frac{\tilde{m}}{\Lambda}} \text{ GeV}$$

Constraints on scalars coupling to $\gamma\gamma$

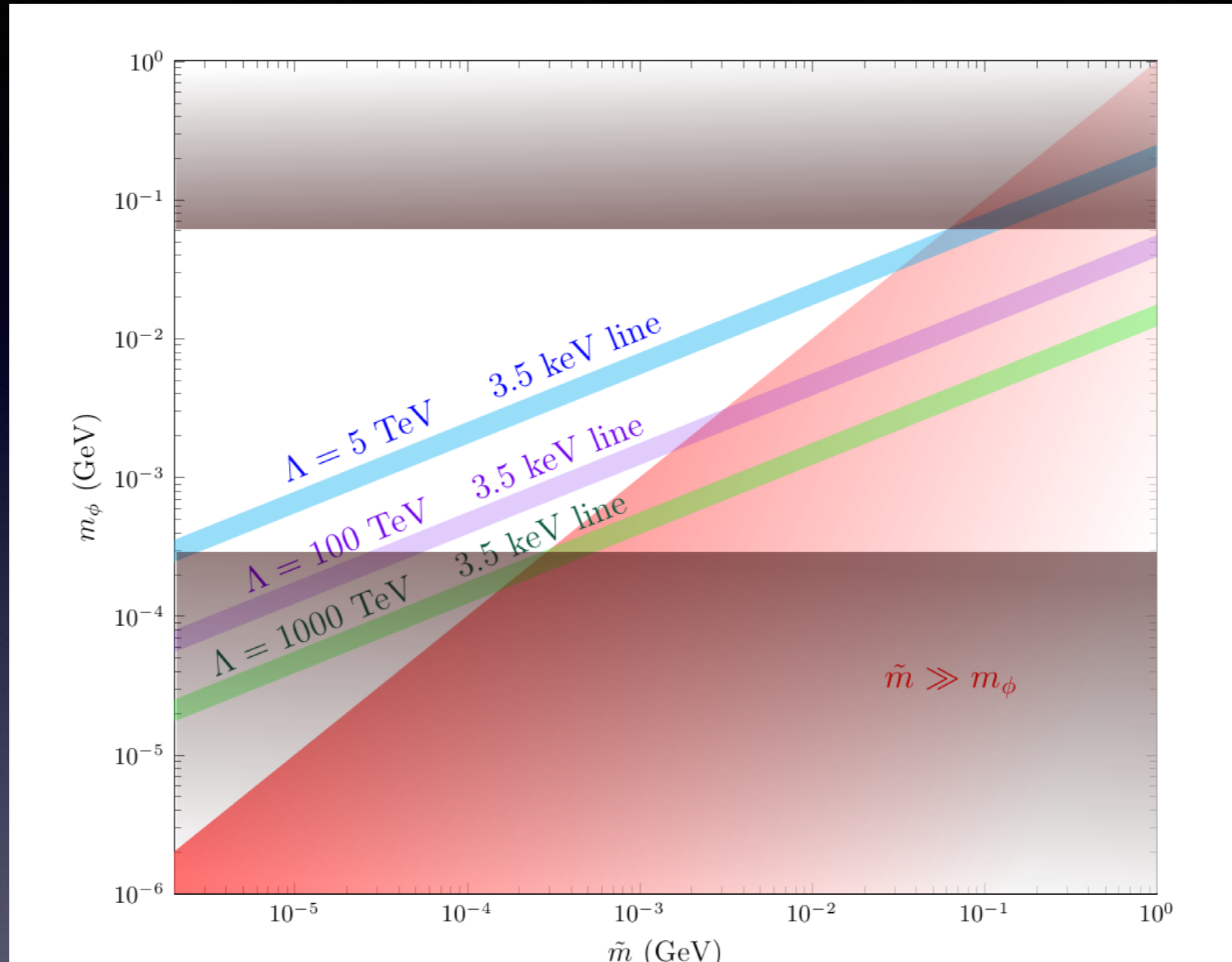
LEP

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

HB star

$$\Lambda \gtrsim 10^{10} \text{ GeV} \quad [m_\phi \lesssim 30 \text{ keV}]$$

Results



A microscopic (UV) construction « à la Higgs »

$$\mathcal{L} = \mathcal{L}_{kin} + \frac{\mu^2}{2}(\sigma^2 + S^2) - \frac{\lambda}{4}(\sigma^2 + S^2)^2 - \bar{\psi}(h_1\sigma + ih_2S\gamma_5)\psi + \frac{\sigma}{\Lambda}F_{\mu\nu}F^{\mu\nu}$$

How to obtain the correct relic abundance?

To respect the flux observed by XMM Newton one needs

$$\langle \sigma v \rangle_{\gamma\gamma} \simeq 10^{-33} \text{ cm}^3 \text{ s}^{-1}$$

However, the averaged annihilation cross section needed to respect WMAP/PLANCK relic density is

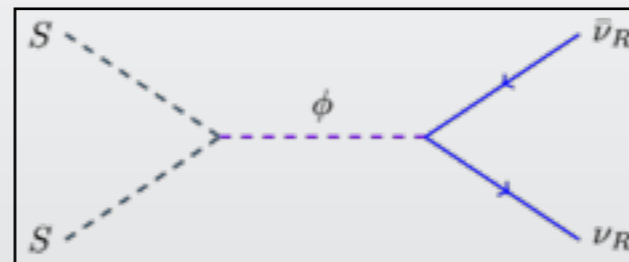
$$\langle \sigma v \rangle \simeq 10^{-26} \text{ cm}^3 \text{ s}^{-1}$$

$$\Omega h^2 \simeq 9.6 \times 10^{-2} \frac{g_{eff}}{g_s(x_f)} \left(\frac{m_s}{1 \text{ eV}} \right)$$

Natural solution is to introduce the right-handed neutrino which couples with Φ

$$-\mathcal{L}_\nu = \frac{M}{2} \nu_R \nu_R + m_D \nu_L \nu_R + \lambda_\nu \phi \nu_R \nu_R + h.c.$$

with $\langle \sigma v \rangle_{\nu\nu} \simeq 10^{-26} \text{ cm}^3 \text{ s}^{-1}$

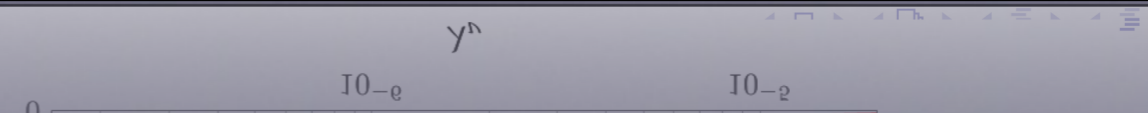
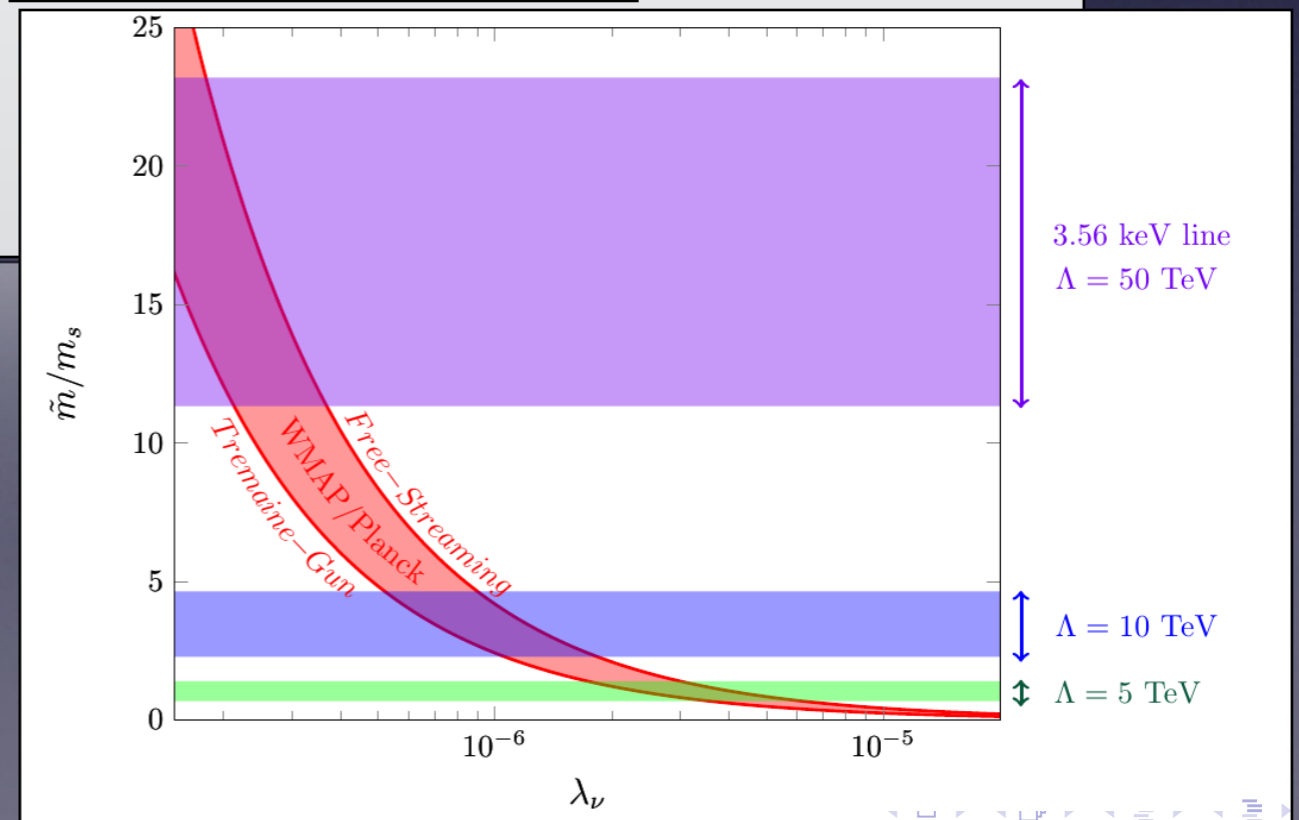


Need to check Tremaine-Gun and Free-streaming bounds

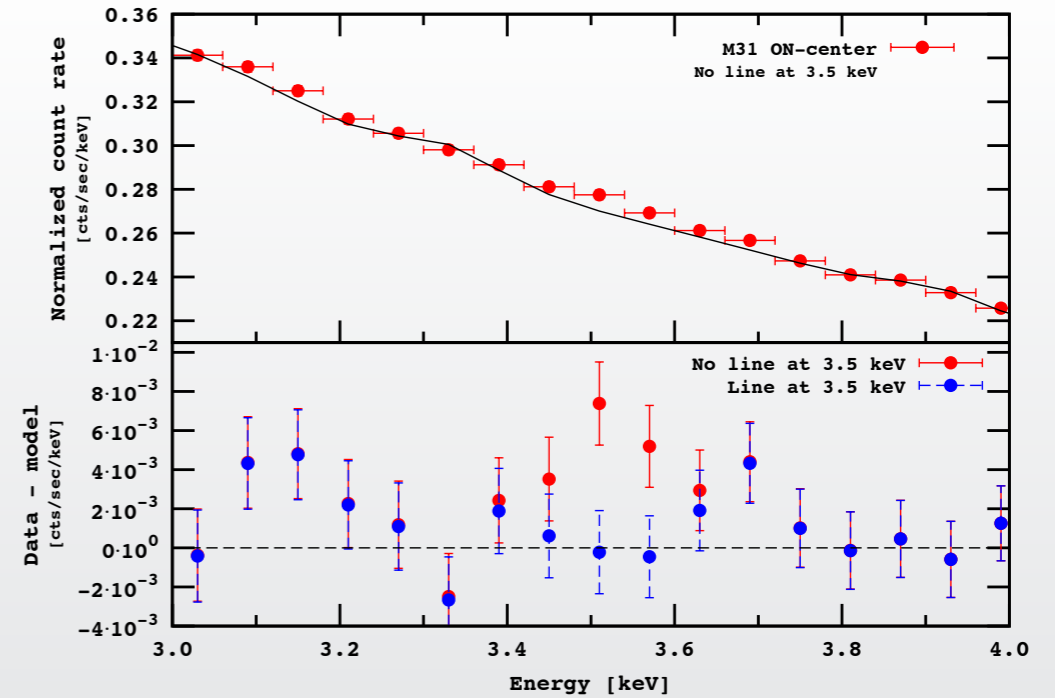
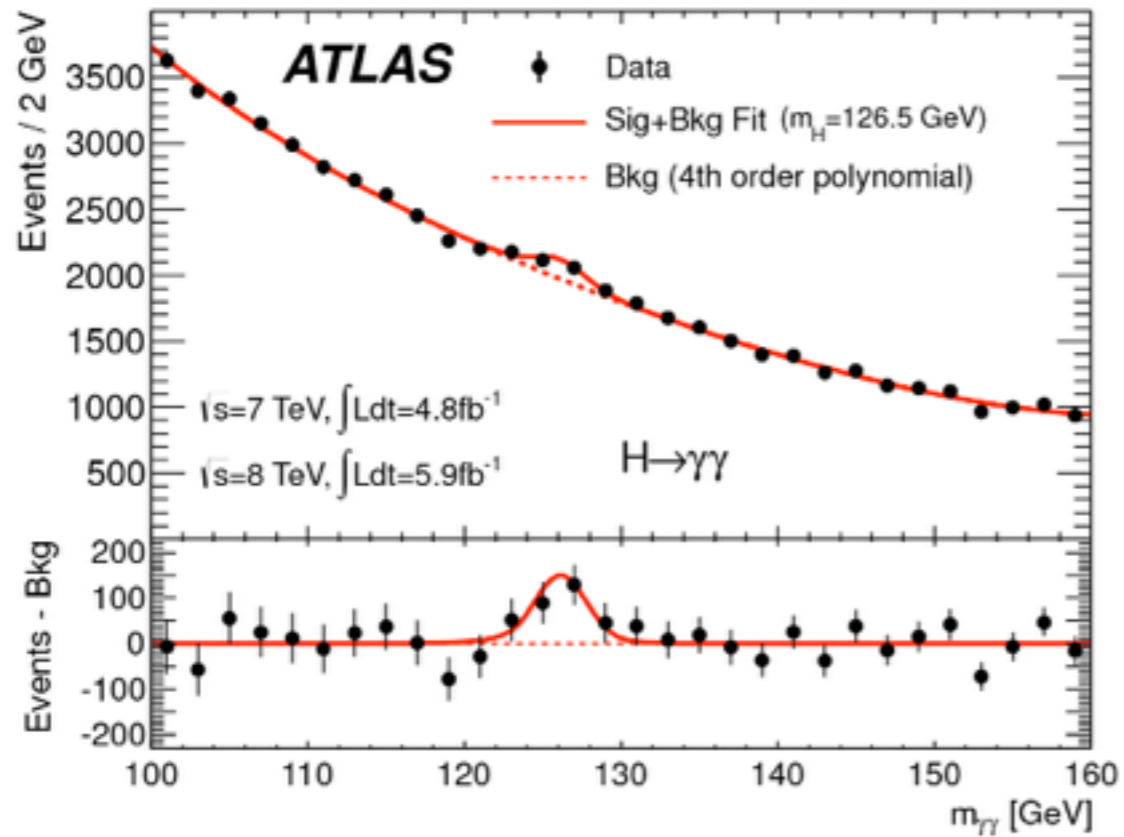
However, there treatment is a little bit more subtle as we have two thermal bath: the Standard Model one (temperature T) and the system Φ - ν_R (temperature T_h) implying in fact

$$\langle \sigma v \rangle_{\nu\nu} \simeq 10^{-28} \text{ cm}^3 \text{ s}^{-1}$$

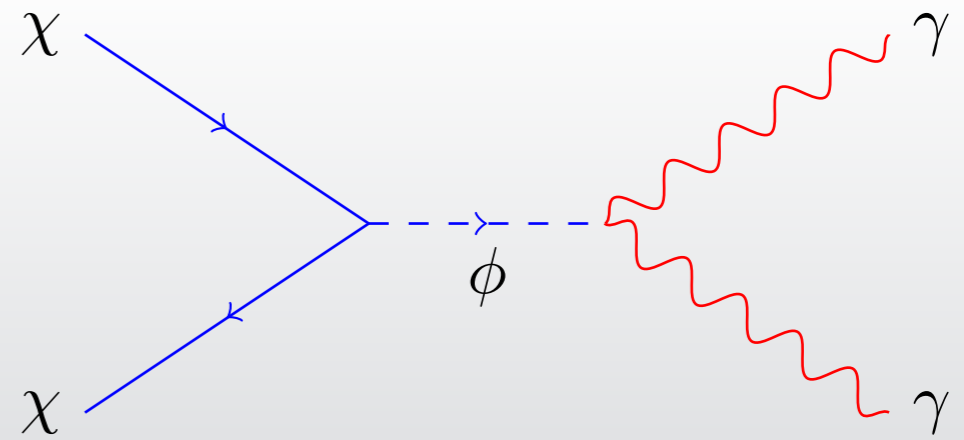
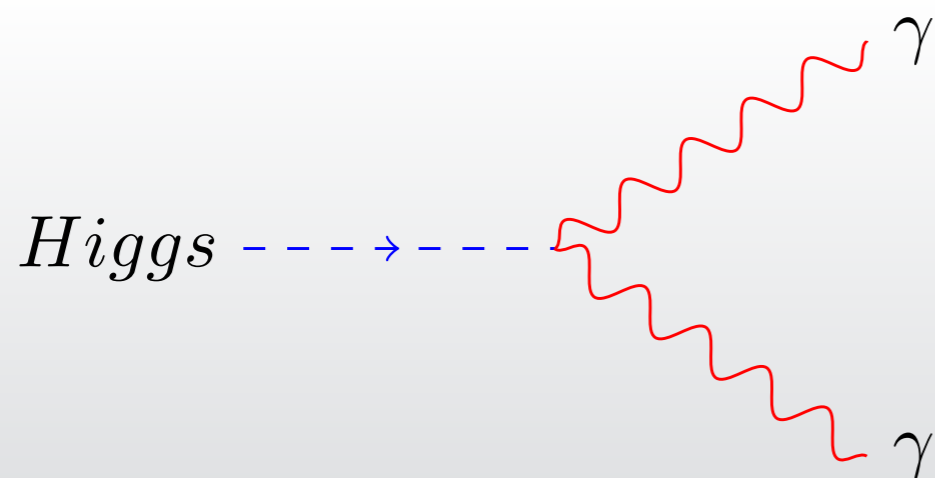
for $M_\Phi = 3.5 \text{ keV}$



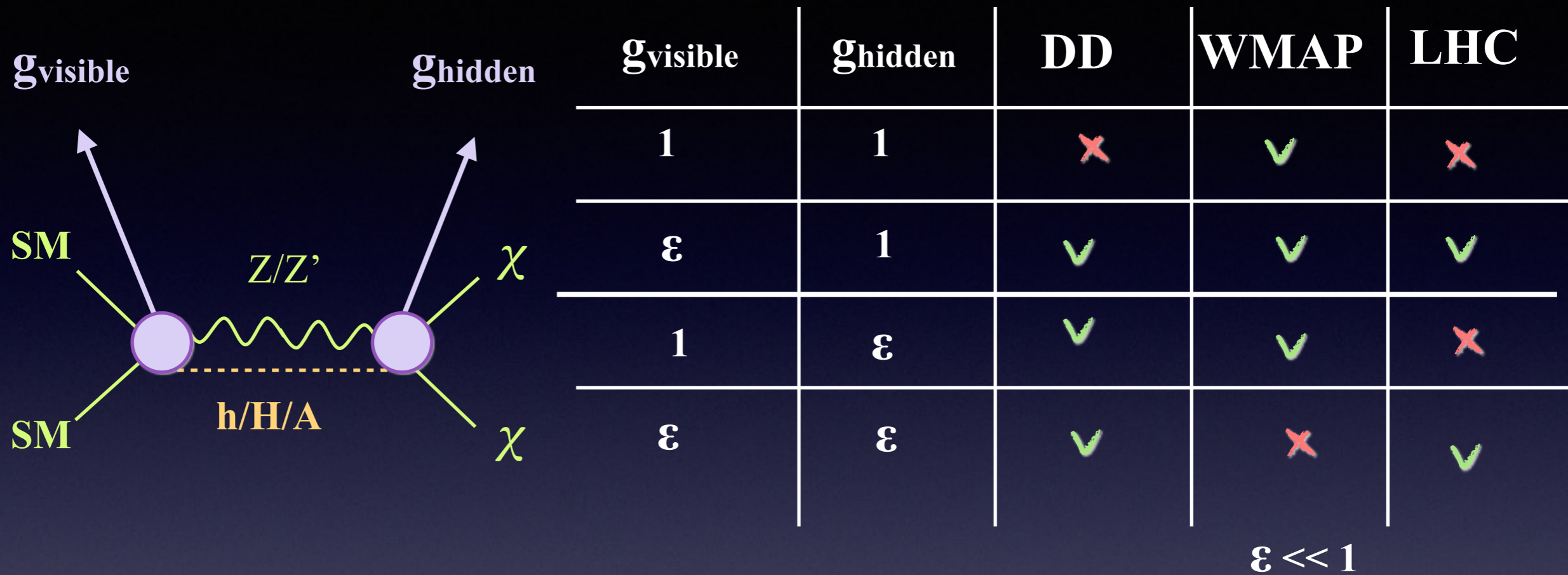
Possible accelerator signatures



A. Boyarsky, O. Ruchayskiy, D. Iakubovskiy, J. Franse; <http://arxiv.org/abs/1402.4119>



Status of combined dark matter searches



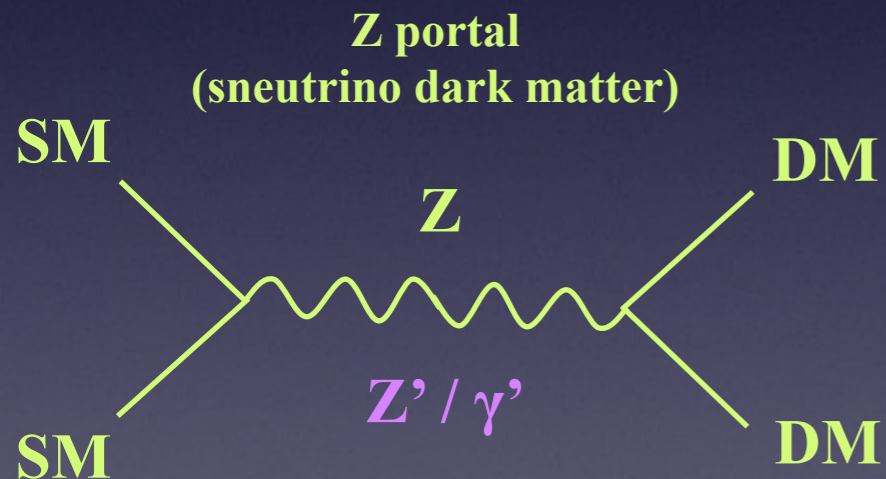
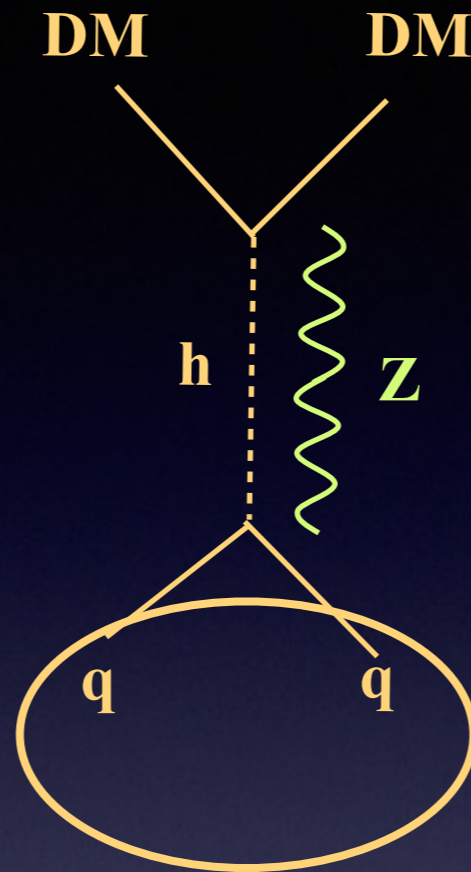
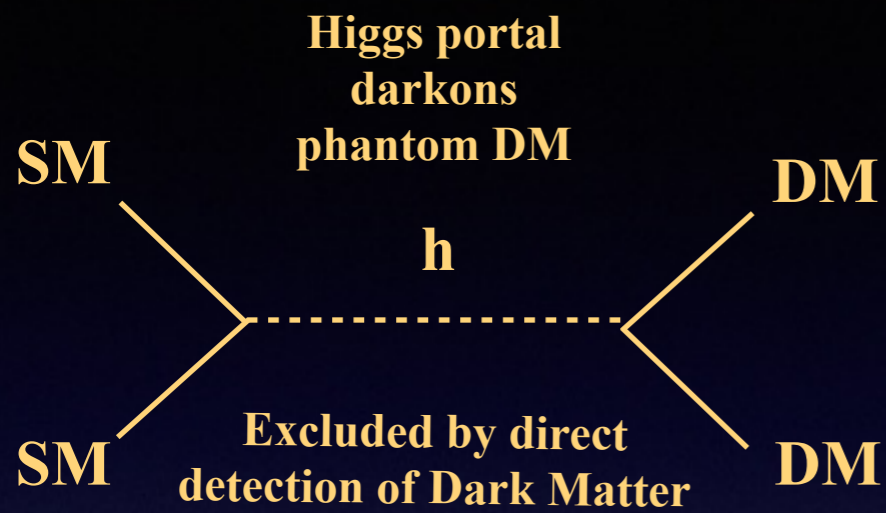
Tendencies:

Large g_{visible} is strongly constrained by LHC

Large g_{hidden} is strongly constrained by DD experiments

Small g_{visible} and g_{hidden} are strongly constrained by WMAP (overabundance)

What are the possible mediators?

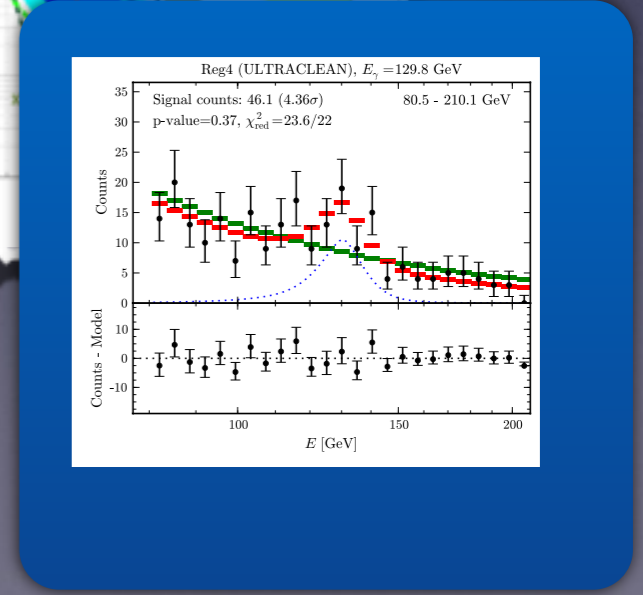
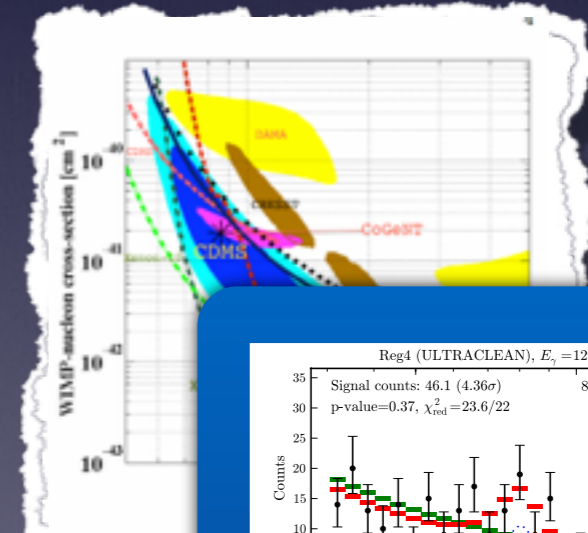
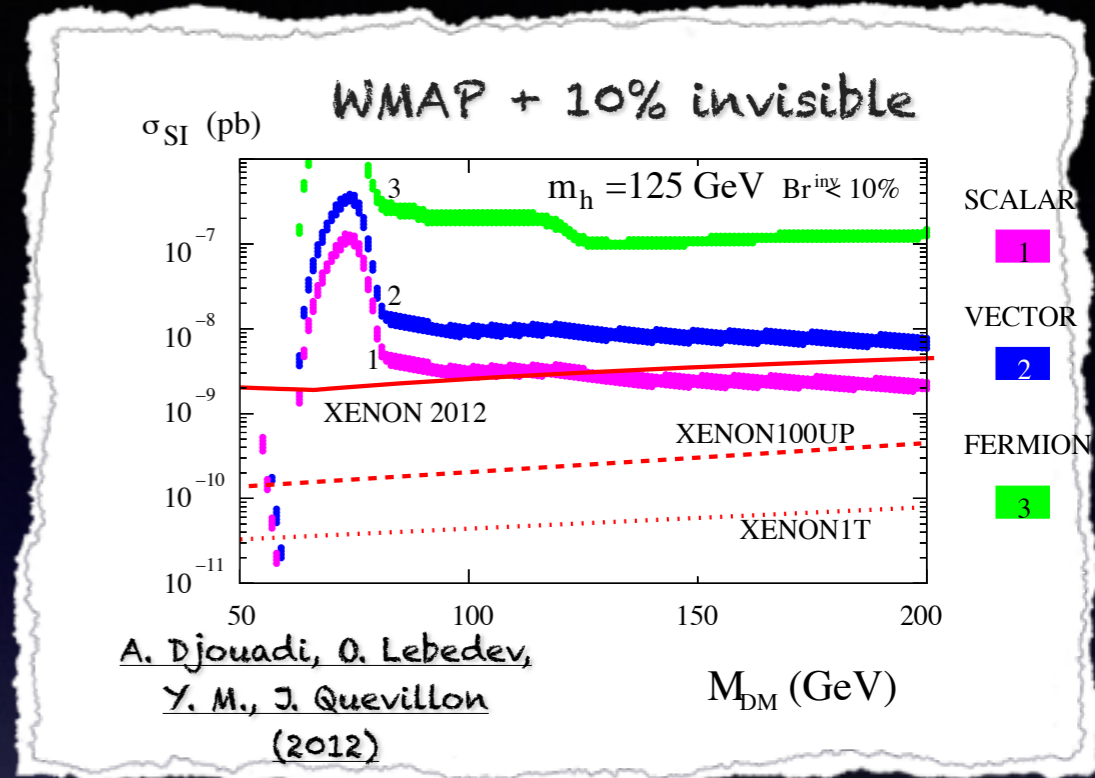


Excluded by direct detection of Dark Matter

Falk, Olive, Srednicki (1994)

**Z' portal
Hidden photon
(mirror dark matter)**

**Not excluded
Can explain excess observed by CRESST/
CoGENT/DAMA
or FERMI monochromatic line**



Conclusions

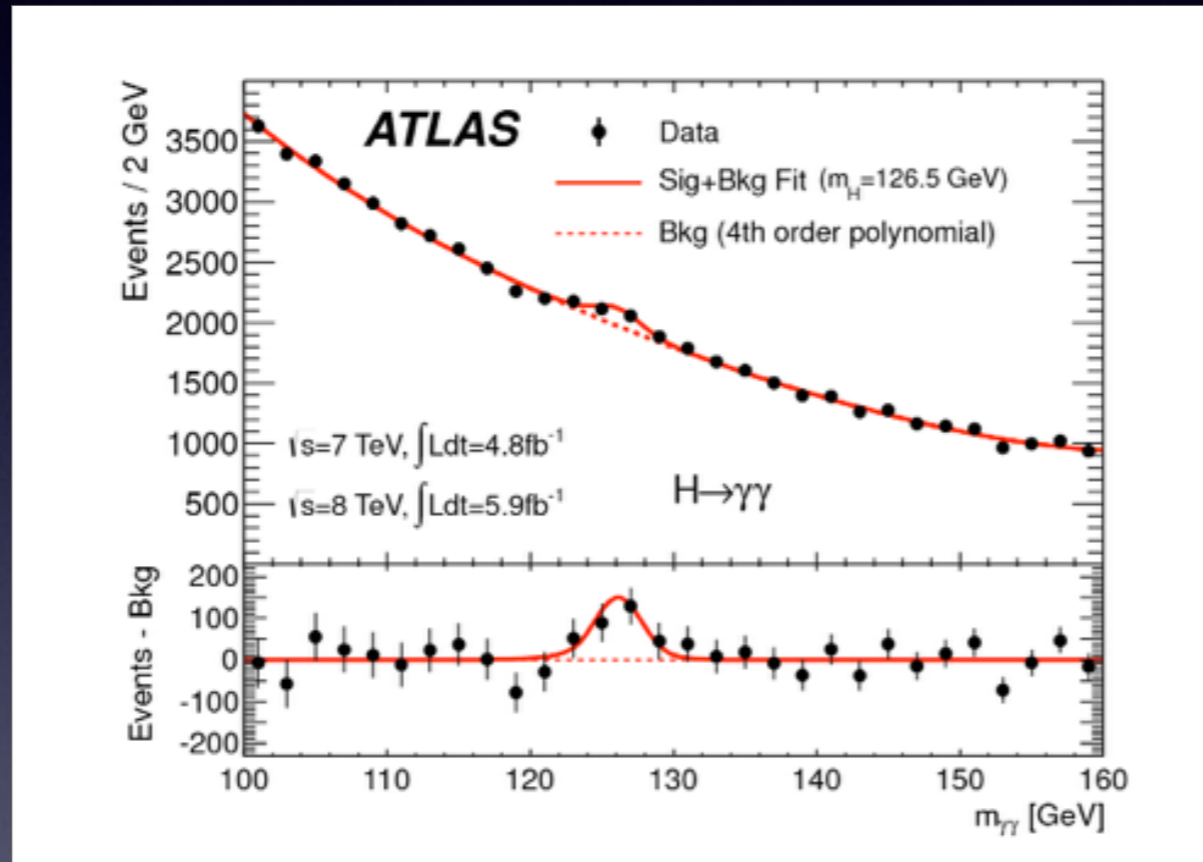
A lot of possibilities from particle physics to explain the 3.5 keV monochromatic line

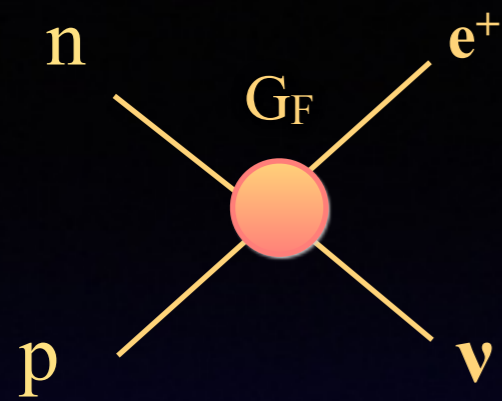
Annihilating as well as decaying dark matter possesses suitable candidates

Be careful when abusing effective approaches

Interesting accelerators signatures

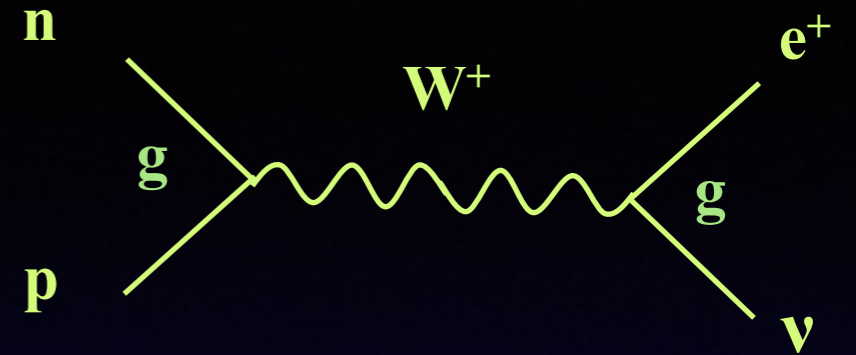
Example of dynamical (spontaneous) realization





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

microscopic
approach



$$G_F \sim (g/M_W)^2$$

1 : "Tentativo di una teoria dei raggi β ", *Ricerca Scientifica*, 1933
In collaboration with Lucien Heurtier and Emiliano Dudas
 arXiv :1404.1927