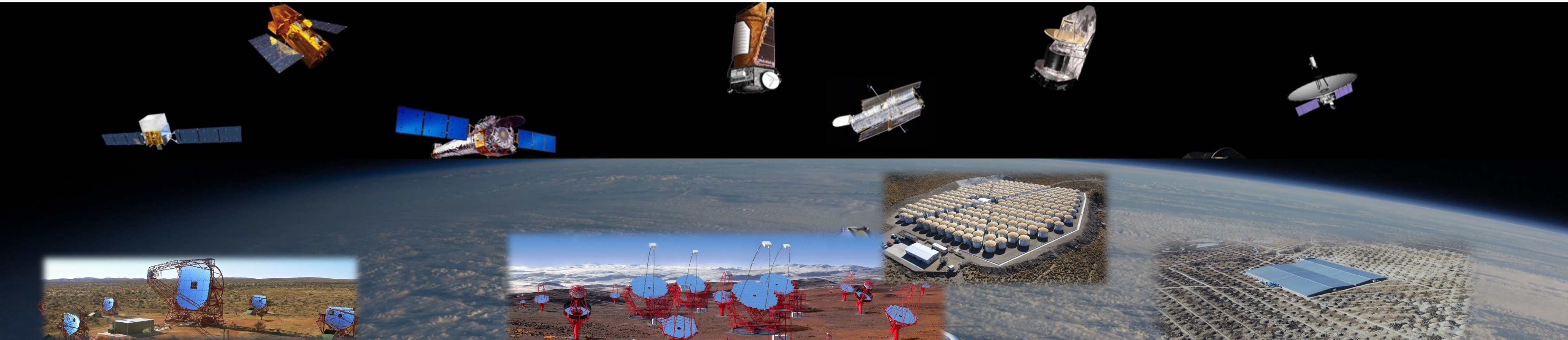
La physique fondamentale par le biais des messagers astrophysiques

Ecole de Gif 2024 - Astronomie Multimessagers

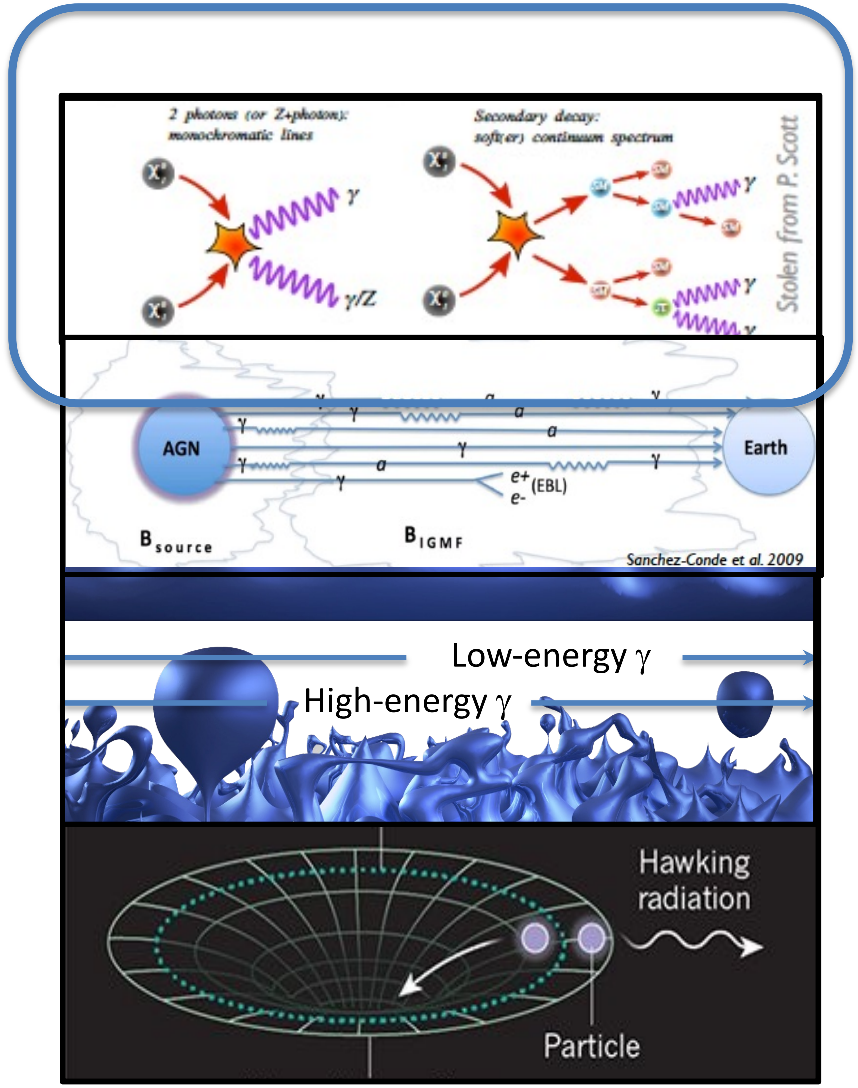
16 sept. 2024 - 20 sept. 2024

Emmanuel Moulin, Irfu, CEA, Université Paris-Saclay



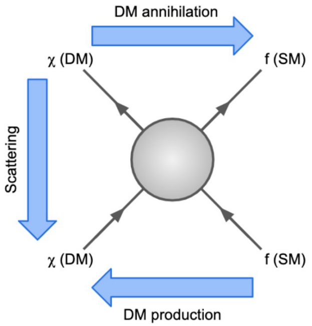
What we discussed so far:

- Dark matter evidences, WIMP paradigm, annihilation/decay
- Dark matter distribution, targets:
  - Galactic Centre, dwarf galaxies, substructures
- Gamma-ray signals /backgrounds
- J-factor estimates/measurements
- Model-independent constraints from GeV-TeV gamma rays
- Neutrino telescope limits



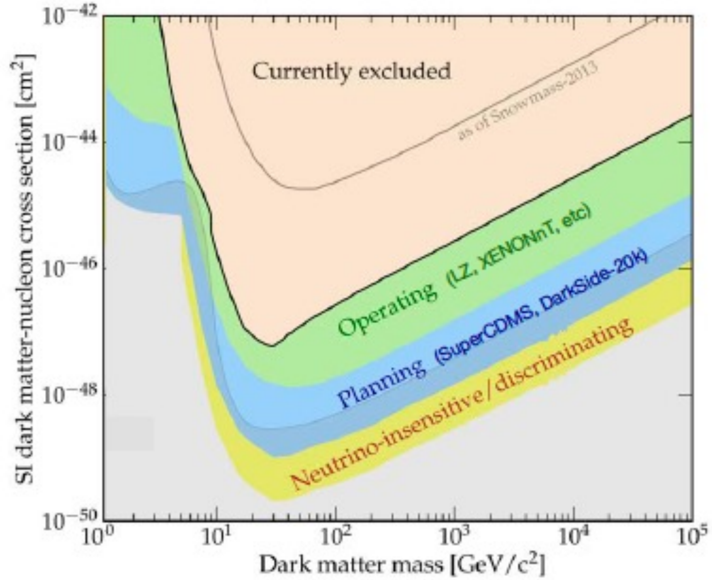
WIMP status

1 GeV – 100 TeV, electroweak couplings with SM



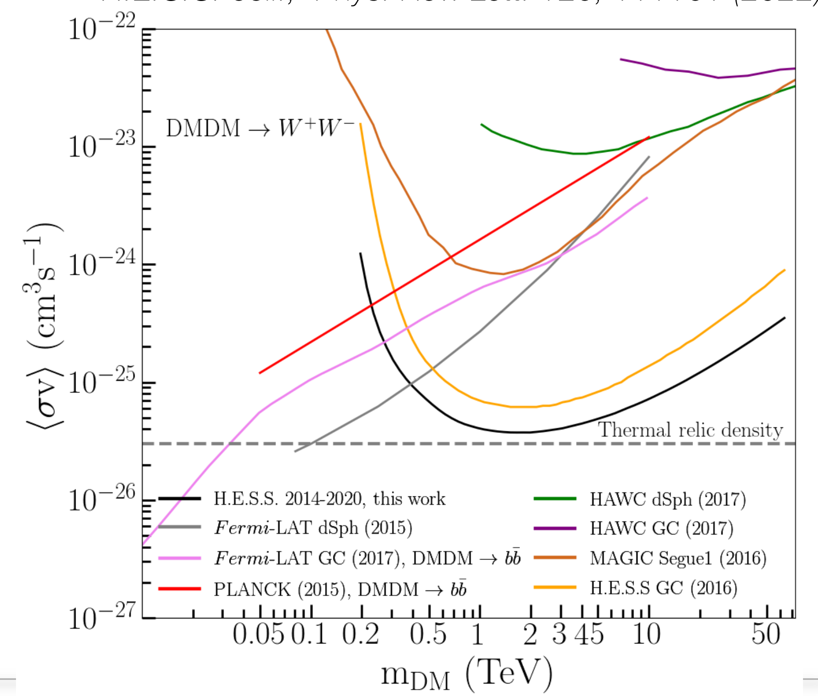
- **No detection (yet) of new weak-scale physics at the LHC**
- **No detection (yet) of WIMPs in direct dark matter searches**

2021 Snowmass Community Study
Chapter 5: Cosmic Frontier



- Strong constraints from direct searches probing cross sections as small as 10^{-47} cm^2 @ 30 GeV

H.E.S.S. coll., Phys. Rev. Lett. 129, 111101 (2022)



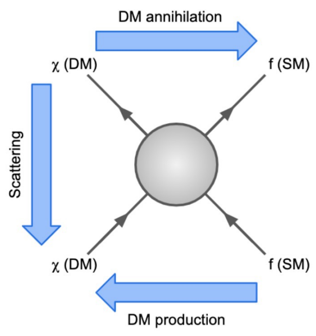
- Strong constraints from VHE gamma rays probing thermal relic TeV DM

- **Some of the simplest thermal WIMP scenarios, e.g., pure higgsinos and winos produce the measured DM abundance not yet detected**

WIMP prospects

2021 Snowmass Community Study
Chapter 5: Cosmic Frontier

1 GeV – 100 TeV, electroweak couplings with SM bosons



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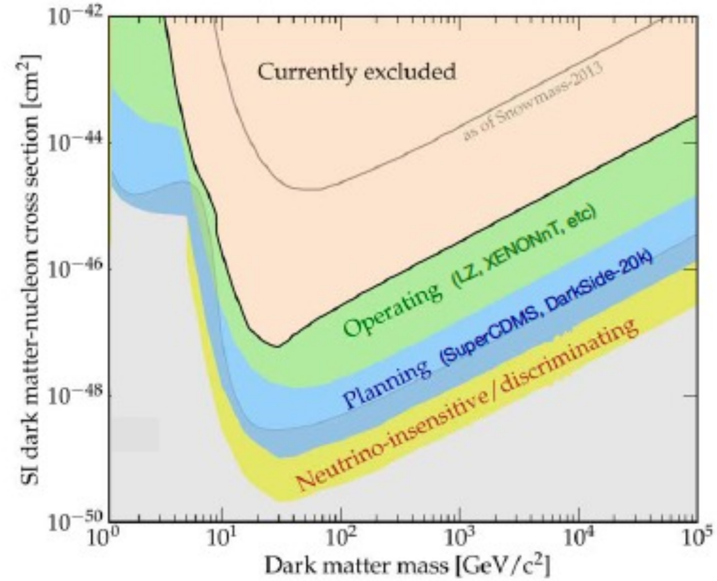
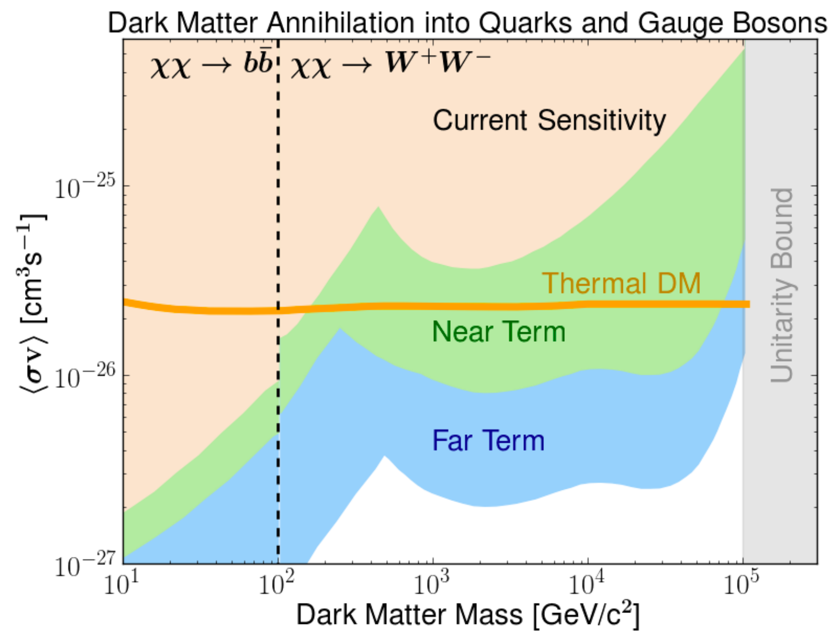


- Strong constraints from direct searches probing cross sections as small as 10^{-47} cm² @ 30 GeV with LZ



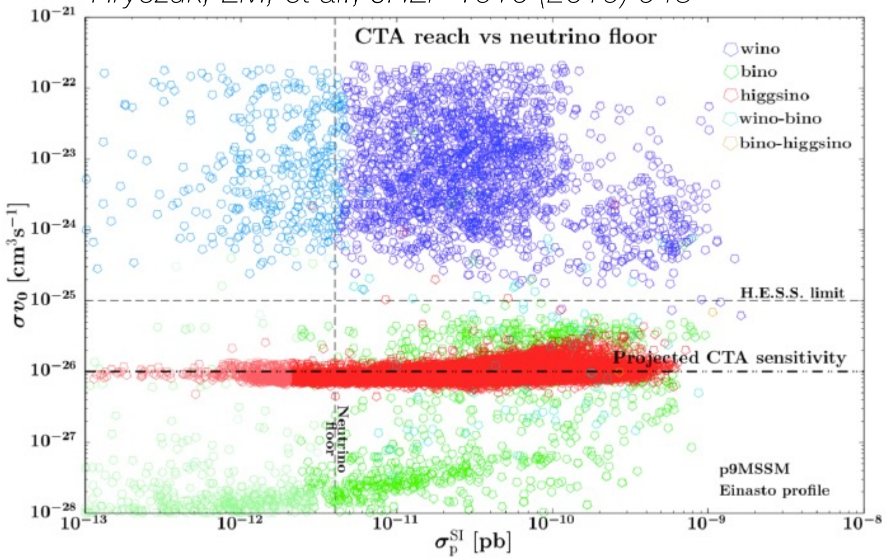
- Strong constraints from gamma-rays

- **Some of the simplest WIMP scenarios, e.g., pure higgsinos and winos produce the measured DM abundance not yet detected**

TeV DM models : Wino and Higgsino

- **Some of the simplest classic WIMP models remain unconstrained - DM could still interact through the W and Z bosons!**

Hryczuk, EM, et al., JHEP 1910 (2019) 043

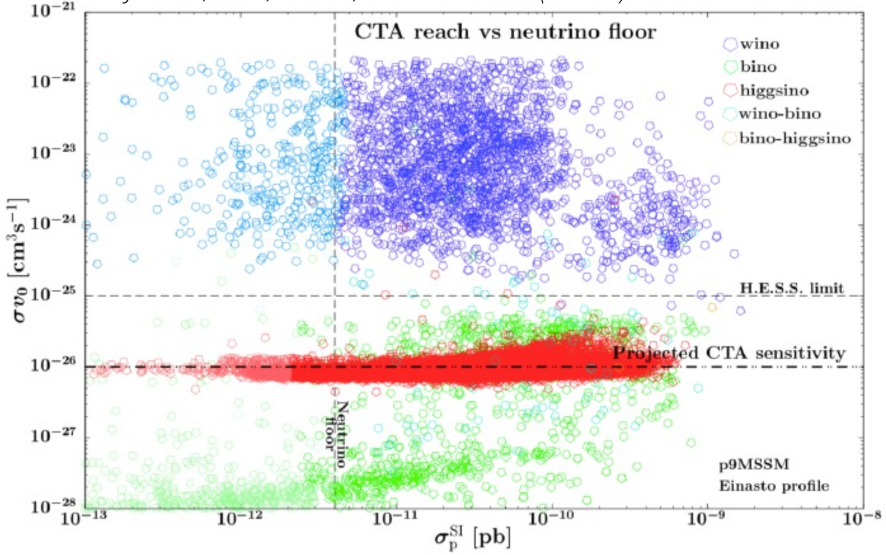


TeV DM models : Wino and Higgsino

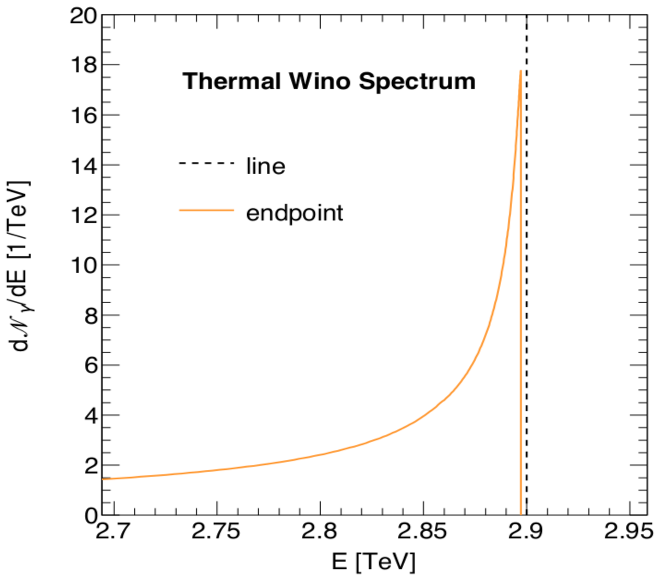
- **Some of the simplest classic WIMP models remain unconstrained - DM could still interact through the W and Z bosons!**

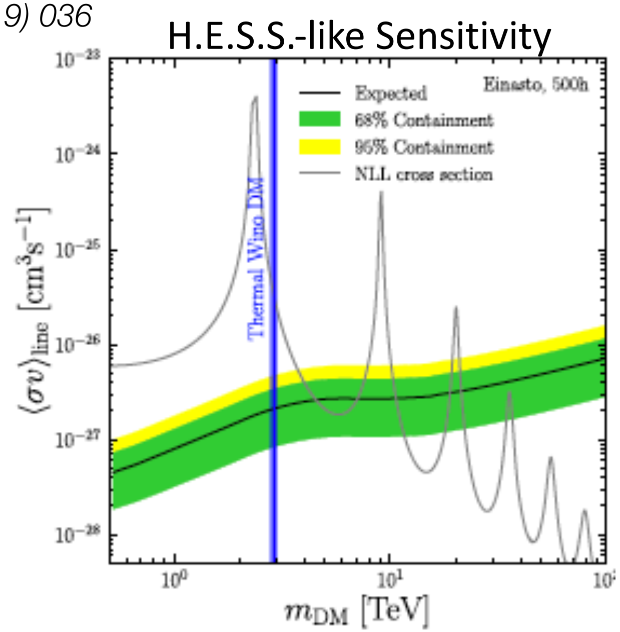
- **Wino/Higgsino show a prominent gamma-ray line (-like) feature in the annihilation spectra**

Hryczuk, EM, et al., JHEP 1910 (2019) 043



Baumgmart, Cohen, EM et al. JHEP 1901 (2019) 036





Montanari, EM, Rodd, PRD107, 043038 (2023)

Strong constraints on Thermal Wino dark matter

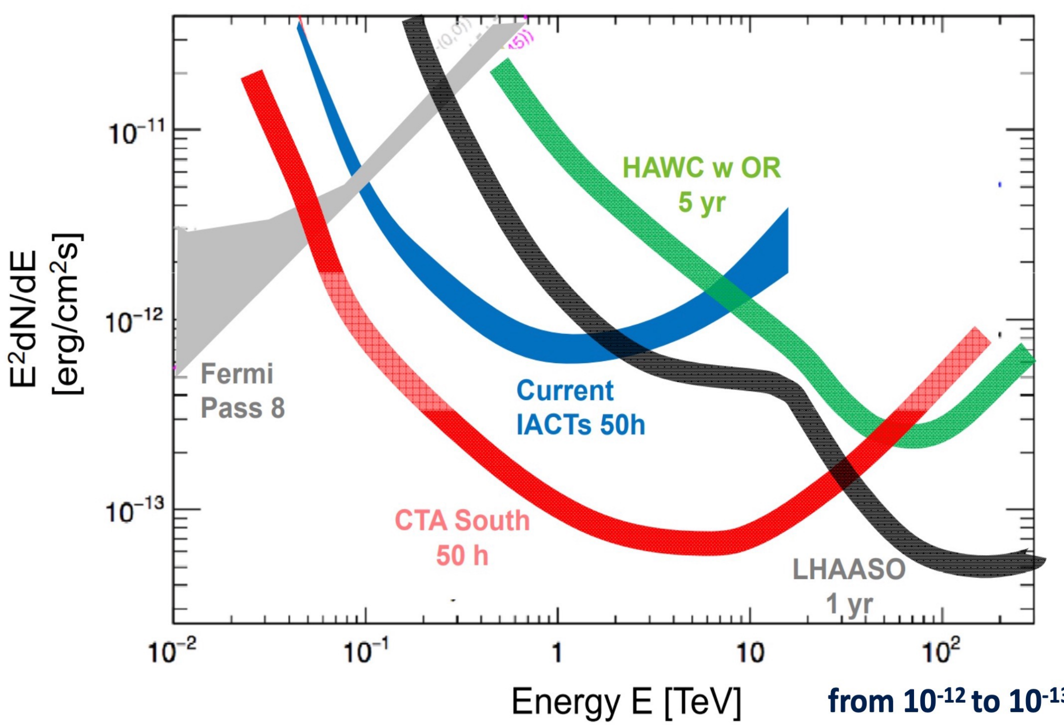
- DM cores up to several kpc excluded at ~2 TeV

  e.g, Rinchiuso, Rodd, EM, et al., PRD 98, 123014 (2018)

TeV DM models : Wino and Higgsino

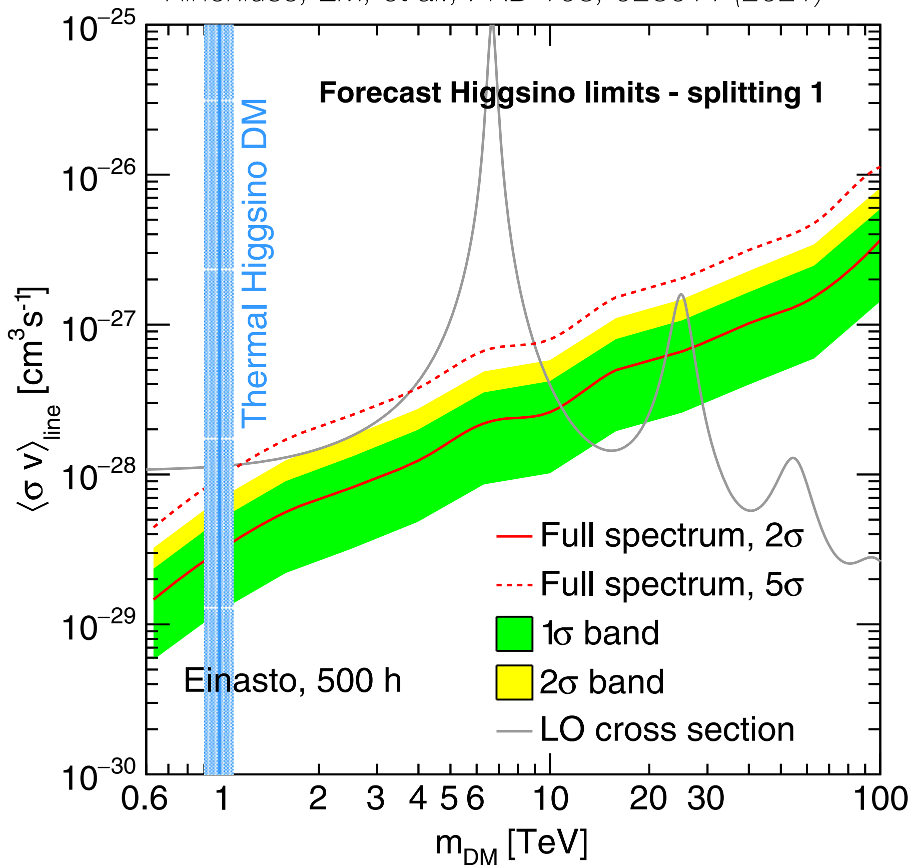
- **Some of the simplest classic WIMP models remain unconstrained - DM could still interact through the W and Z bosons!**

- **Higgsino sentivity forecast with CTA**



from 10^{-12} to 10^{-13} erg/cm^{2}s

Rinchiuso, EM, et al., PRD 103, 023011 (2021)



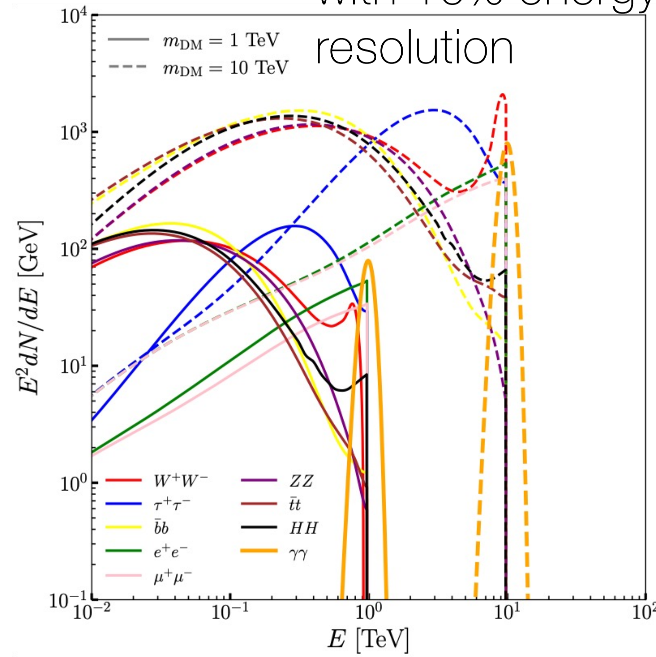
Dark matter line searches

- Gamma-ray line signal from χχ→γγ or χχ→γZ is a very “clean” possible annihilation channel

- No astrophysical lines expected

→ Best prospect for a “smoking gun” indirect signal for DM

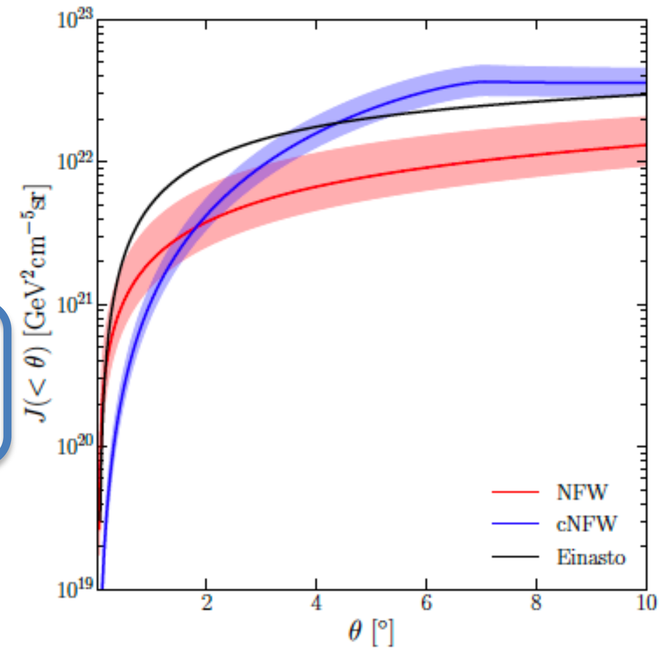
Line spectrum with 10% energy resolution



Dark matter line searches in the GC

- Considering the DM distribution according to a standard Einasto profile with a local DM density of 0.39 GeV/cm^3, the gamma-ray flux in the inner 1 degree around the GC can be estimated as :

$$\Phi_\gamma(>0.1\,\mathrm{TeV}) \simeq 4\times10^{-14}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}\left(\frac{\langle\sigma v\rangle}{2\times10^{-26}\,\mathrm{cm}^3\mathrm{s}^{-1}}\right)\left(\frac{\int_{0.1\,\mathrm{TeV}}\frac{dN}{dE}dE}{0.1}\right)\left(\frac{m_{\mathrm{DM}}}{1\,\mathrm{TeV}}\right)^{-2}$$



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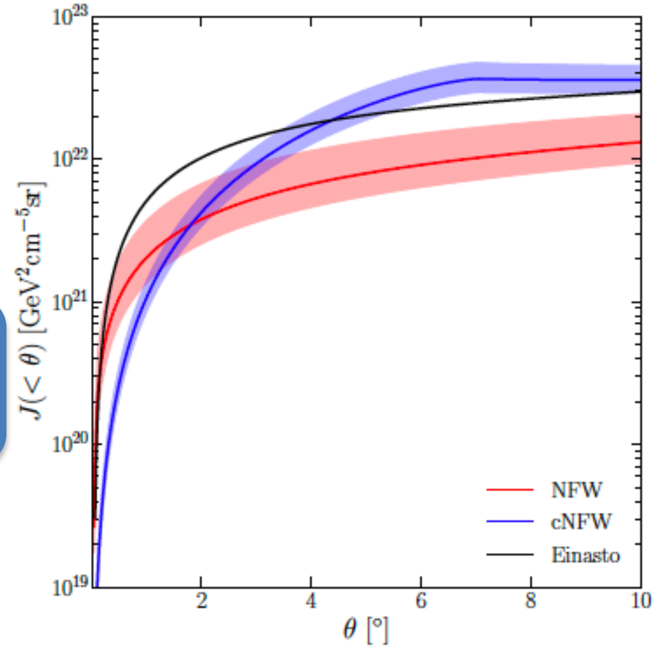

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- Gamma-ray line signal from $\chi\chi\rightarrow\gamma\gamma$ channel :
  $dN/dE = 2\delta(E - m_{DM})$

- Assuming a residual background (assumed to be isotropic)
  $d\Phi_{Res.Bkg.}/dE \simeq 10^{-8}\,\mathrm{TeV^{-1}cm^{-2}s^{-1}sr^{-1}}(E/1\mathrm{TeV})^{-2.3}$
  one can estimate the value of $\langle\sigma v\rangle_{\gamma\gamma}$ for a detection at $n\sigma$ confidence level: the number of gamma rays from DM annihilation exceeds the statistical background

$$N_\gamma^{\mathrm{DM}}/\sqrt{N_{\mathrm{Res.Bkg.}}} \geq n$$

- For an observation time of 100 hours with a constant acceptance of 10^5 m^2 above 100 GeV, one can show that:

$$\langle\sigma v\rangle_{\gamma\gamma} \gtrsim 2n\times10^{-27}\,\mathrm{cm^3s^{-1}}\times\left(m_{\mathrm{DM}}/1\mathrm{TeV}\right)^2$$

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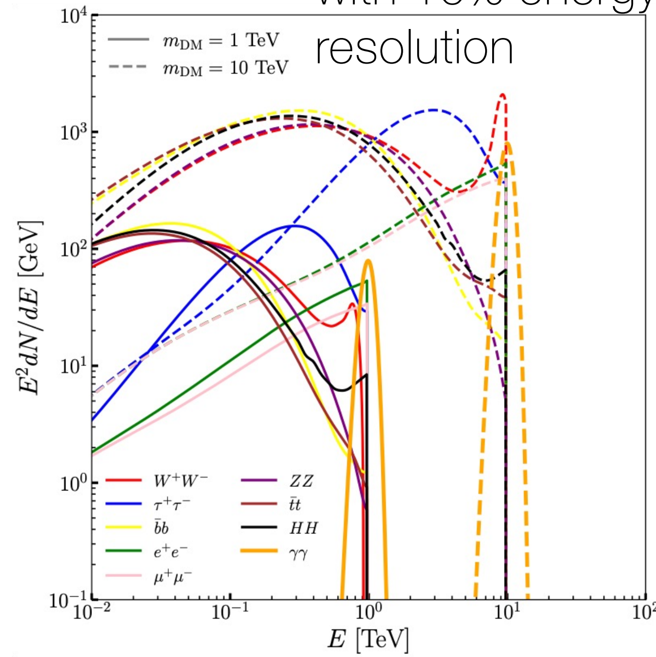
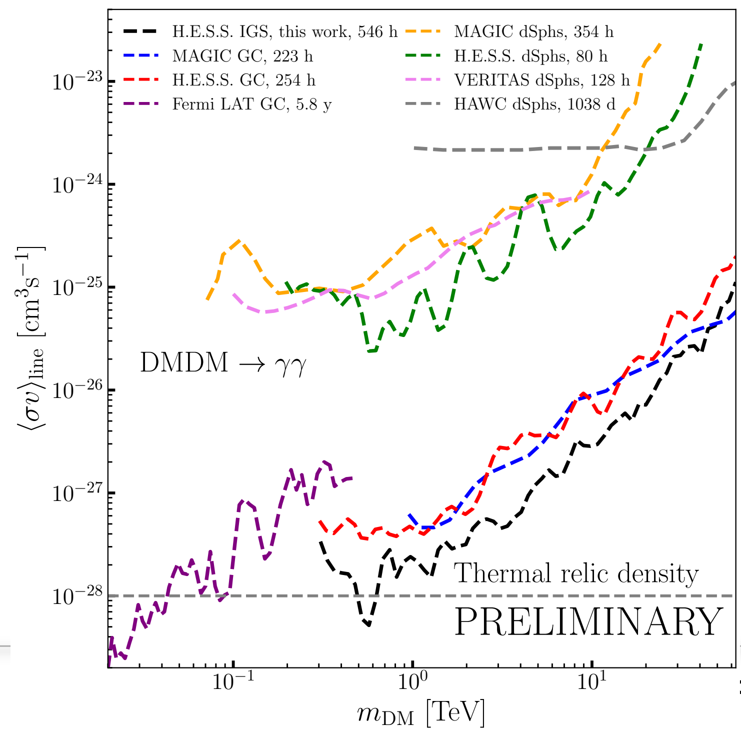


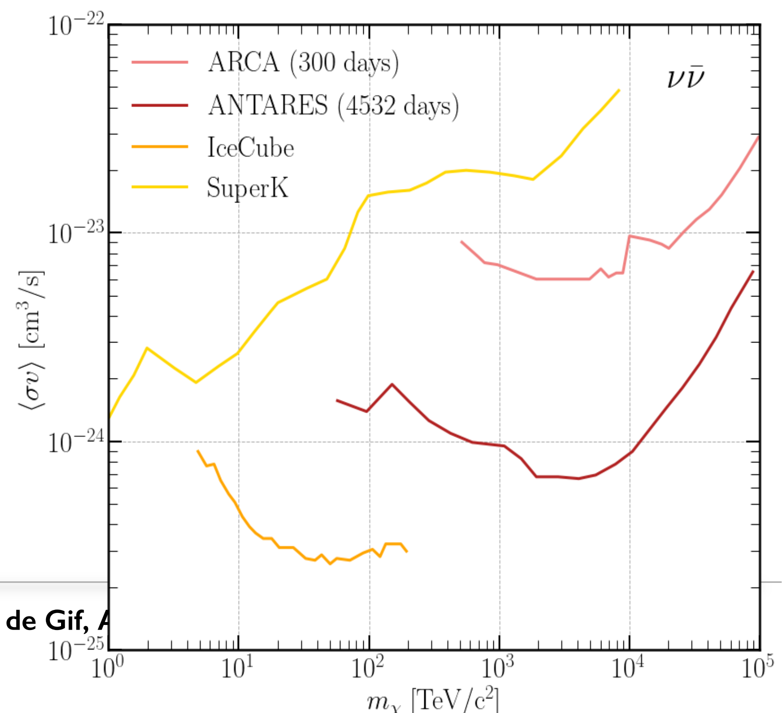
Stringent constraints

- **from Fermi-LAT at sub-TeV**
- **IACTs at > TeV**

EM et al: (H.E.S.S. coll), ICRC2023



Neutrino line in the Galactic Center



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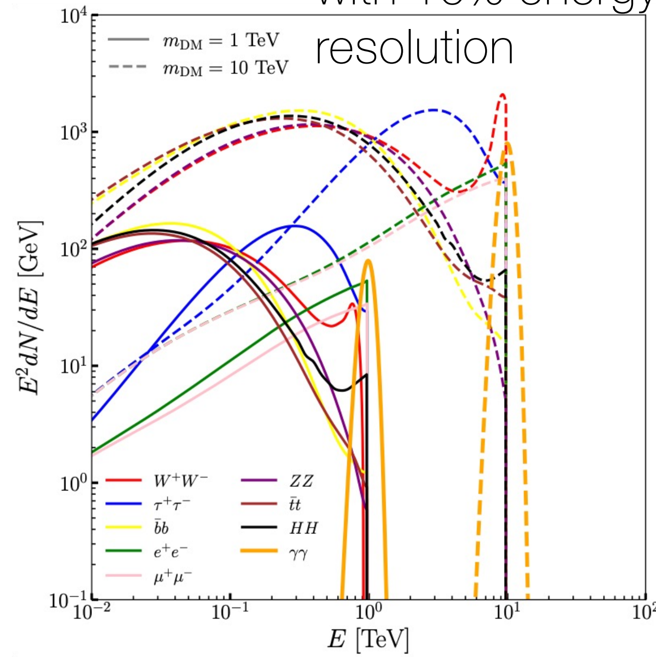

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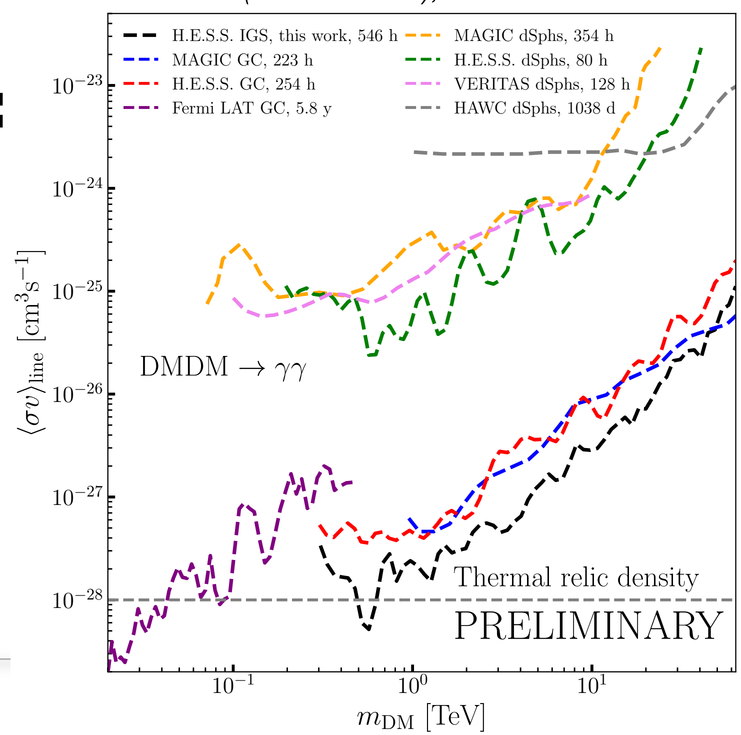
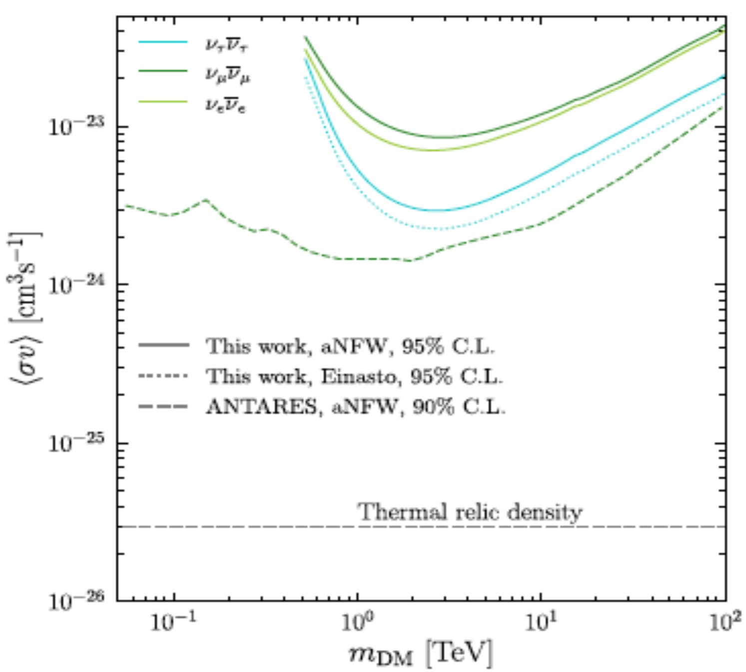


Neutrino line in the Galactic Center

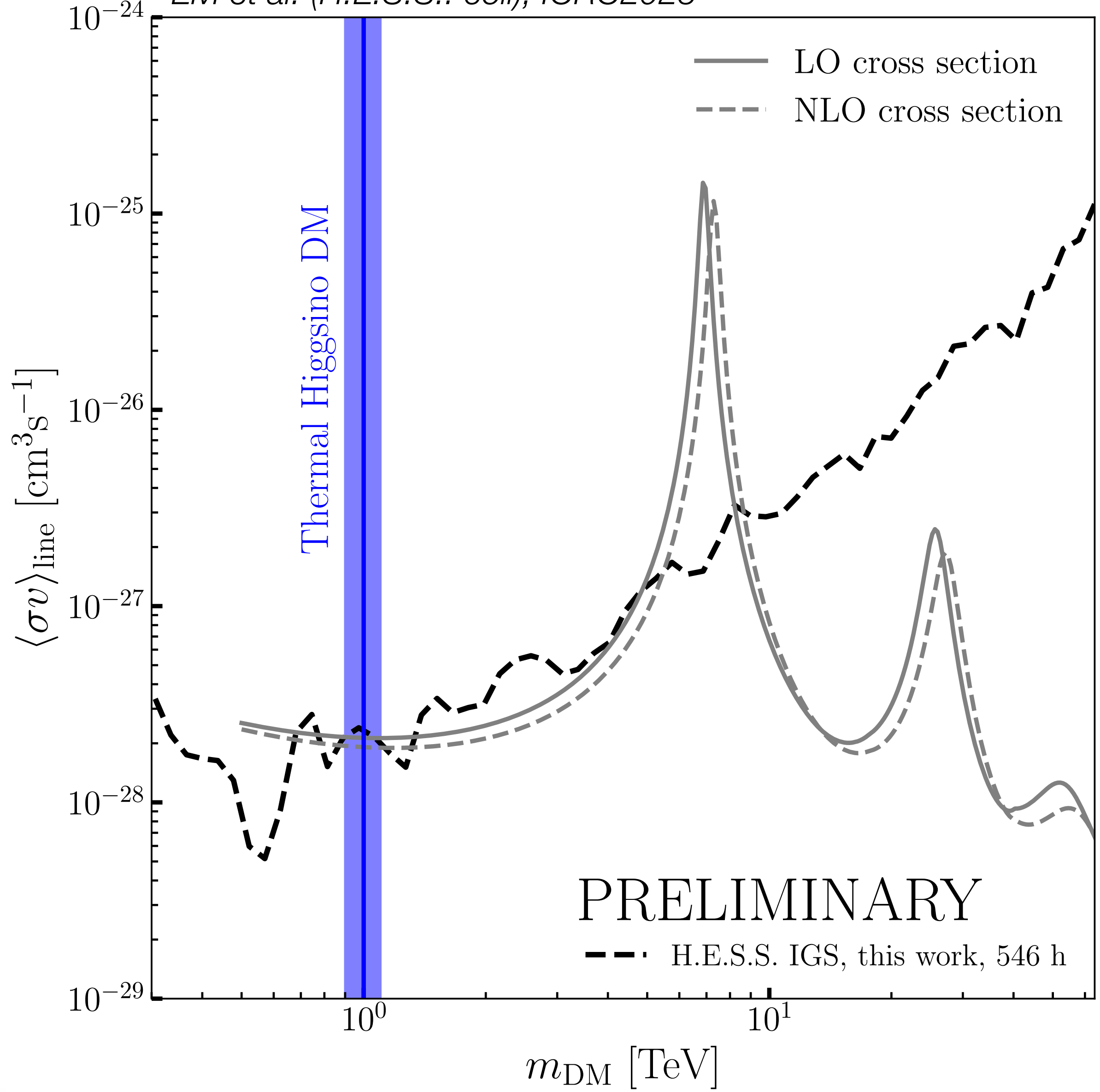


Montanari, EM, Rodd, PRD107, 043038 (2023)

Higgsino dark matter

- Comparing to theoretical line cross section for Higgsinos
  Beneke et al, PLB, 834, 137248 (2022)
- Important contribution to the annihilation spectrum for TeV Higgsino DM comes from the gamma-ray line
  Rinchiuso et al. PRD 103 (2021) 023011
- Thermal Higgsino mass: 1.1 ± 0.1 TeV
- The thermal Higgsino model is probed for the first time

EM et al: (H.E.S.S.. coll), ICRC2023

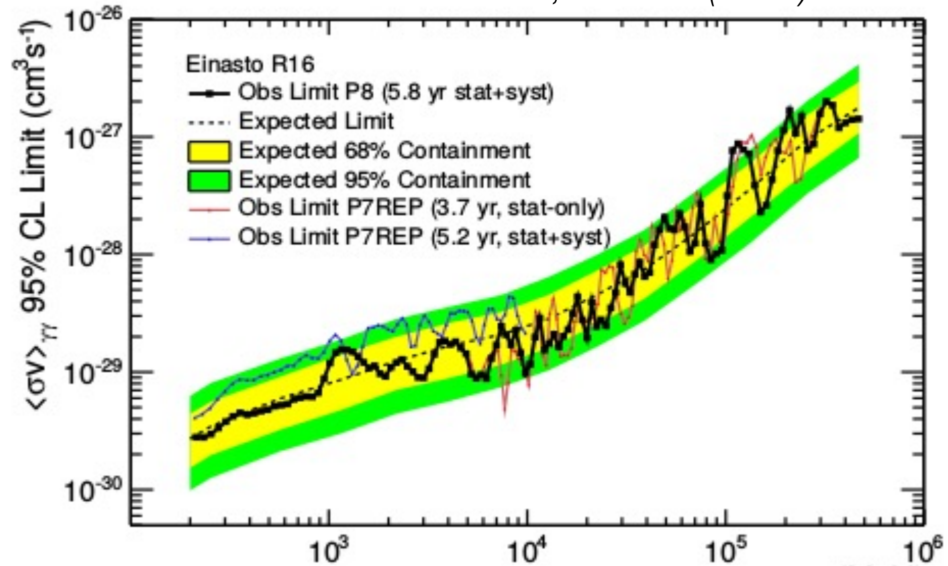


DM line status and prospects

Fermi-LAT gamma lines towards the GC

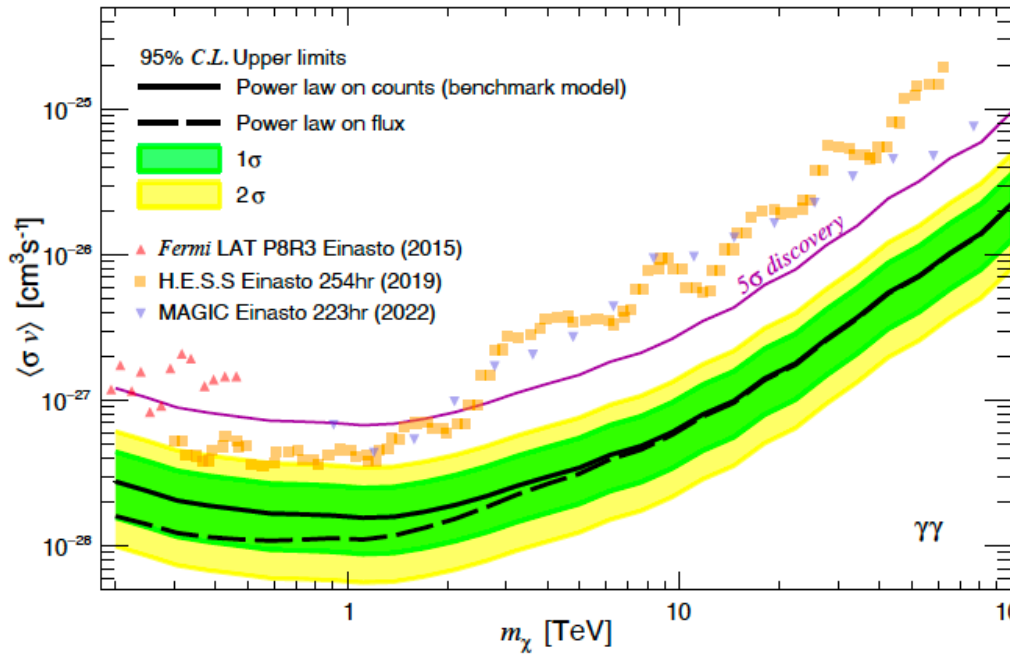
- DM mass range 200 MeV–500 GeV

Fermi-LAT Coll. PRD. 91, 122002 (2015)



Prospects with Galactic Center observations with CTA:

- a total of 500 hours of observation time with a roughly homogeneous exposure over the inner 4°
- A factor of 2-to-10 improvement compared to H.E.S.S./MAGIC



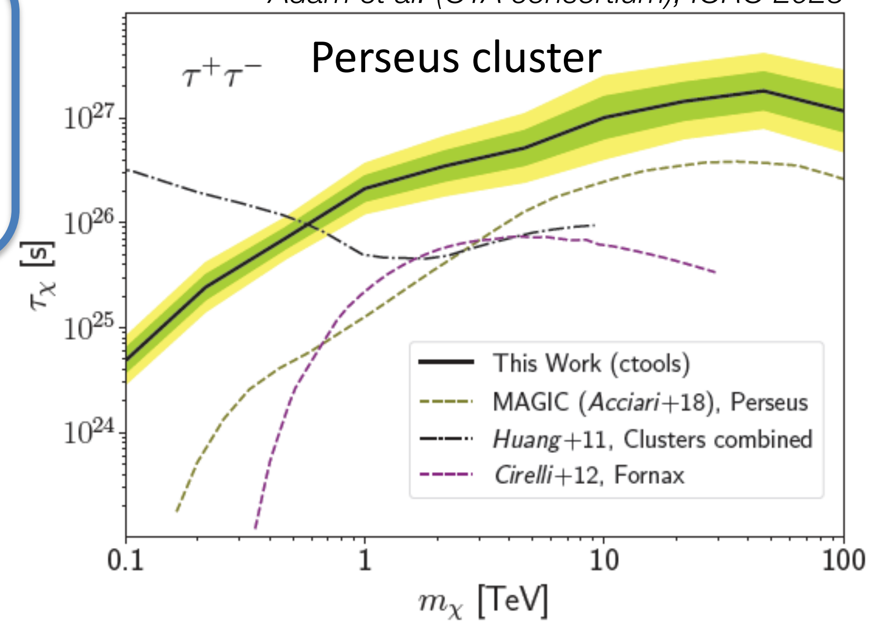
CTA consortium, arXiv:2403.04857

Heavy Decaying Dark Matter

DM $\longrightarrow$ SM SM

- Decaying DM searches target regions of the sky where large volumes can be probed, *i.e.*, galaxy clusters

Adam et al. (CTA consortium), ICRC 2023



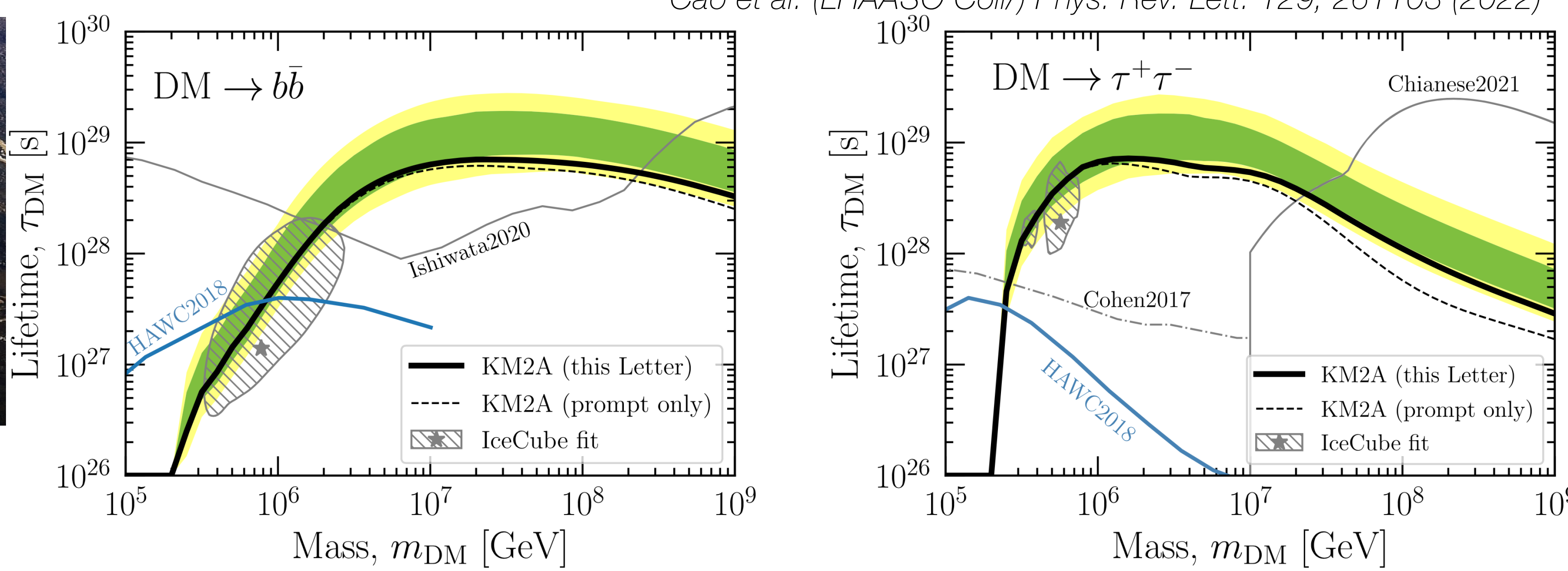
- **> PeV dark matter with wide FoV instruments**

  570 Days of LHAASO Observations

  ~ 15°<b<45°; 30°<l<60°: 0.27 sr

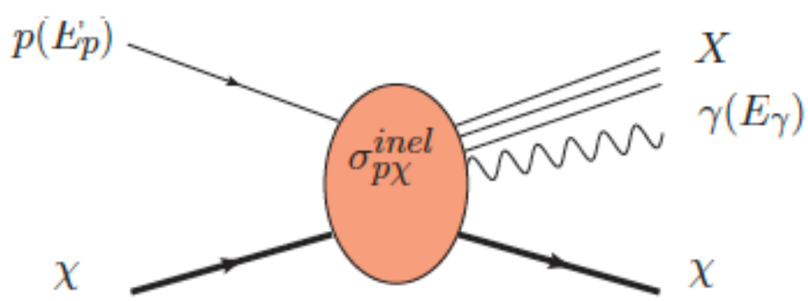
  → Strongest constraints on PeV DM

Cao et al. (LHAASO Coll/) Phys. Rev. Lett. 129, 261103 (2022)



Alternatives to annihilation/decay

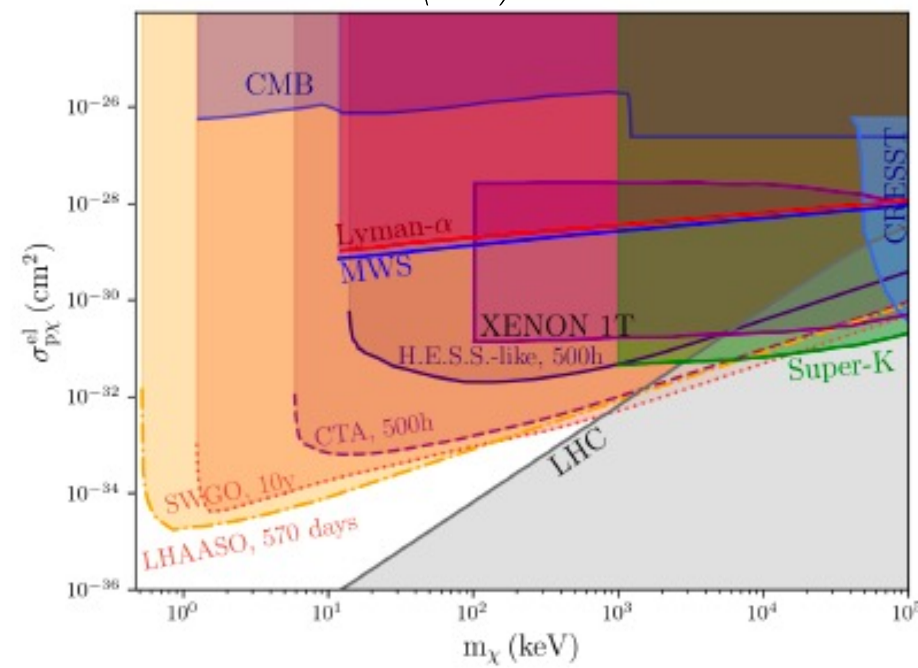
- **Cosmic particle interaction with dark matter**
  - interactions of dark matter with ordinary matter
  - astrophysical sources of high-energy neutrinos, electrons, protons as a particle beam
    - inelastic scattering:
    $\chi + p \rightarrow \chi + p +$ hadronic showers + γ-rays + neutrinos
  - GC harbors both high DM density and hadronic accelerator



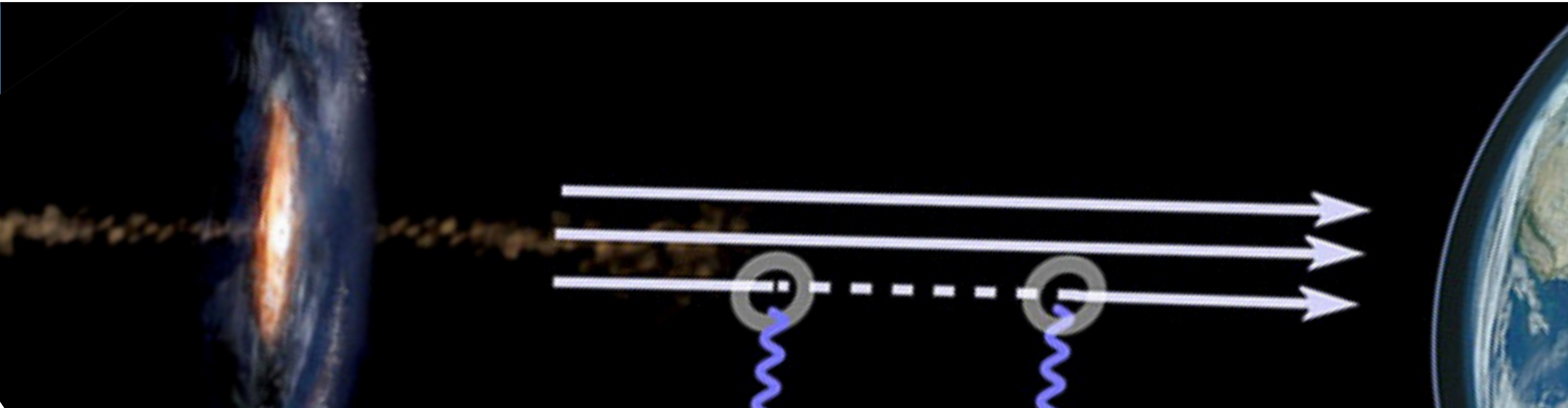
In absence of specific underlying DM models:
the inelastic to the elastic cross section can be related such as $\sigma^{inel}_{p\chi} = 8/3\ \sigma^{el}_{p\chi}$

Broilo, et al. Phys. Rev. D 101 (2020) 074034

Reis et al .JCAP 07 (2024) 012



AXION AND AXION-LIKE PARTICLES



Axions and the strong CP problem

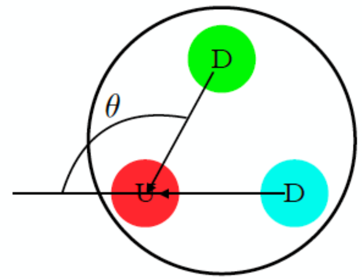
- Strong CP problem : no violation of the CP-symmetry observed in strong interaction

- Axion is by-product of a solution of strong CP problem in QCD:
  - Standard Model involves a parameter θ: one expects θ ~ O(1). When sent to zero it, no violation is expected.

$$\mathcal{L}^{QCD} \subset \frac{\theta \alpha_s}{8\pi} G^a_{\mu\nu} \tilde{G}^{a\mu\nu}$$

- Observable: electric dipole moment of the neutron

  - A classical estimate : $|d_n| \approx 10^{-13}\sqrt{1-\cos\theta}\, e\,\mathrm{cm}$



Classical picture of a neutron

  - A small electric dipole moment of neutron could be explained by approximate CP symmetry of strong interaction.

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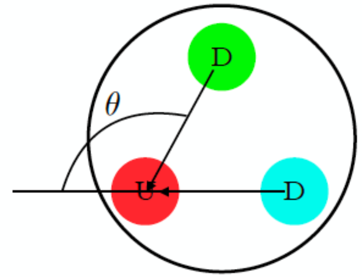
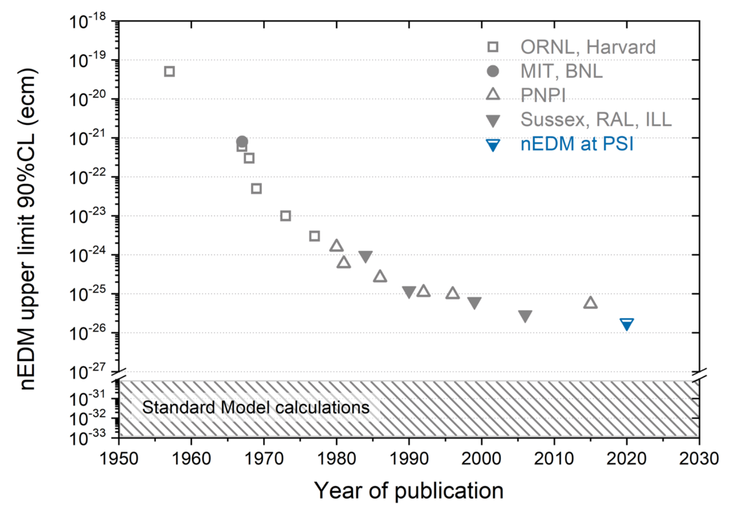


Classical picture of a neutron

- Observable: electric dipole moment of the neutron
  - A classical estimate : $|d_n| \approx 10^{-13}\sqrt{1-\cos\theta}\, e\,\mathrm{cm}$

- Current bound is: $|d_n| \leq 10^{-26} e\,\mathrm{cm}.$
  → why $\theta \leq 10^{-13}$?
  → strong CP problem



Axions and the strong CP problem

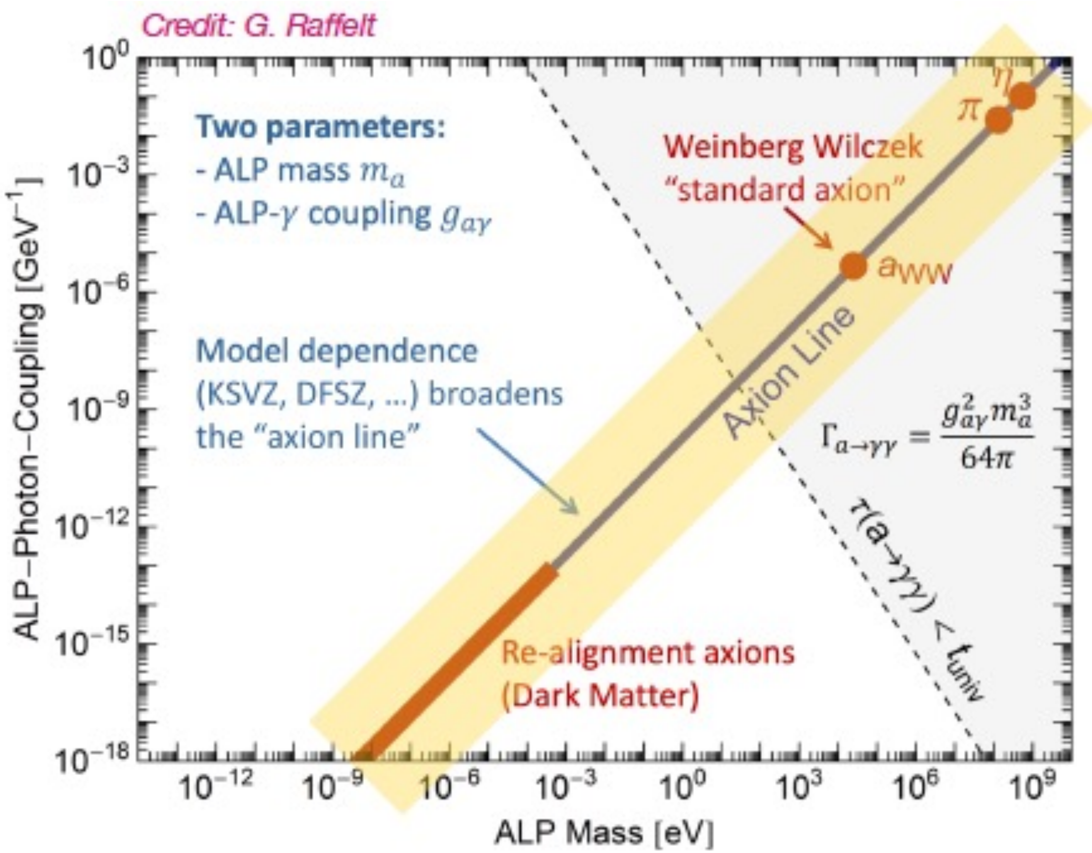
- Strong CP problem : no violation of the CP-symmetry observed in strong interaction

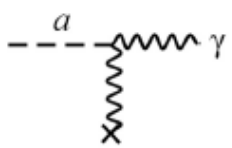
- Axion is by-product of a solution of strong CP problem in QCD:
  - Peccei Quinn Solution: introduce a new field ϕ coupled to GG with a spontaneously broken symmetry at scale f_A
  - CP violating term in QCD Lagrangian is cancelled out by the VEV of ϕ

$$\mathcal{L}^{QCD} \subset \left(\frac{\phi_A}{f_A} - \theta\right)\frac{\alpha_s}{8\pi} G^a_{\mu\nu}\tilde{G}^{a\mu\nu}$$

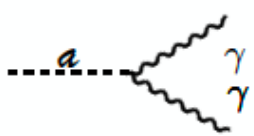
  - QCD axion : $m_A = 5.7 \left(\frac{10^9\,\mathrm{GeV}}{f_A}\right)\mathrm{meV}$

The QCD Axion





Primakoff conversion



Decay

Quick ID:

- **Light** pseudo-scalar particle
- Minimal coupling with **gluons** to solve the strong CP problem
- Production through PQ symmetry breaking at the energy scale
- Viable cold dark matter candidate over a large mass range
- Induced coupling with photons

Axion-Like Particles

- Predicted in several extensions of the standard model
- Phenomenology closely related to that of axions

- Pseudo scalar boson characterized with a two-photon coupling $a\gamma\gamma$
  - As opposed to axions, mass and coupling constant are unrelated
  - Depending on their actual mass and coupling, they can play a role in cosmology as dark matter particles or in dark energy

- ALPs can to explain the current amount of DM with :

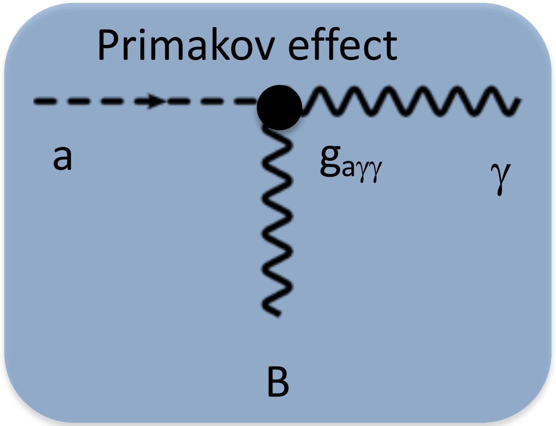
$$g_{a\gamma\gamma} < 10^{-12}\left[\frac{m_a}{1\ \text{neV}}\right]^{1/2}\text{GeV}^{-1}$$ [e.g. Arias et al. 2012]

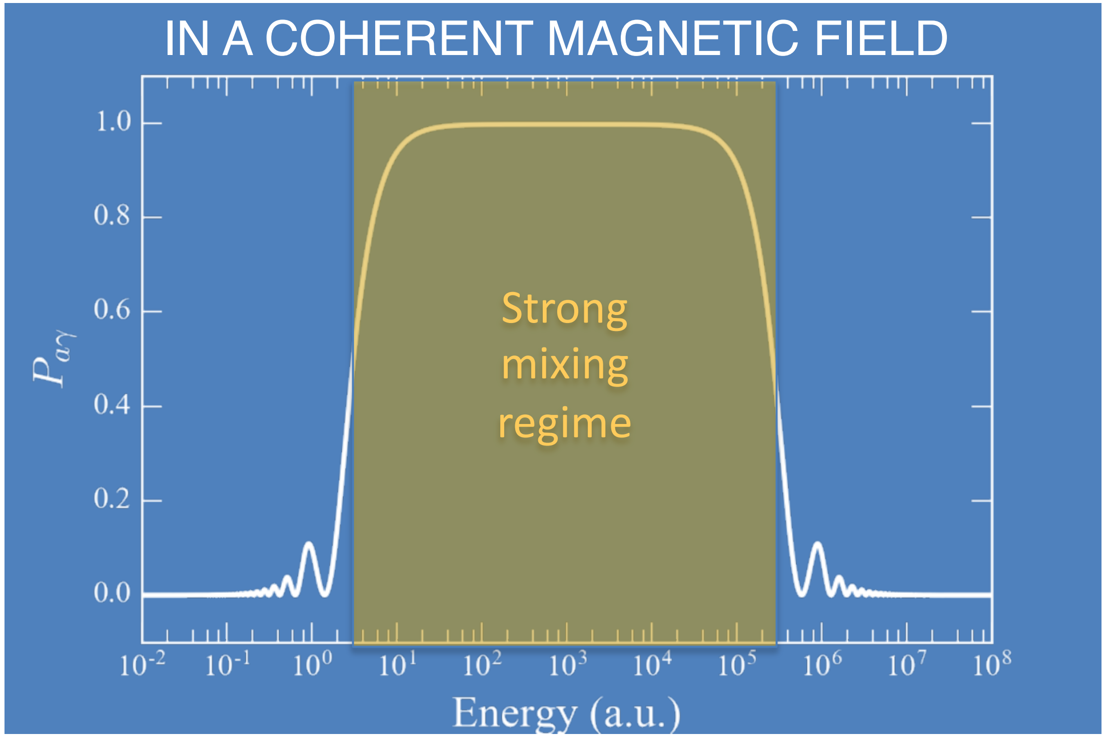
→ ***Very Weakly Interacting Slim Particles - WISPs***

Photon–ALP mixing

$$\mathcal{L}_{\gamma a} = \frac{1}{4} g_{\gamma a} F_{\mu\nu} \tilde{F}^{\mu\nu} \phi_a = -g_{\gamma a} \vec{E} \cdot \vec{B} \phi_a$$

- Consequence of the coupling $a\gamma\gamma$
  $\rightarrow$ photon-ALP oscillation in cosmic magnetic fields along the line of sight





Raffelt & Stodolsky 1988

axions/ALPs do not get absorbed during propagation
$\rightarrow$ might lead to a boost in photon flux

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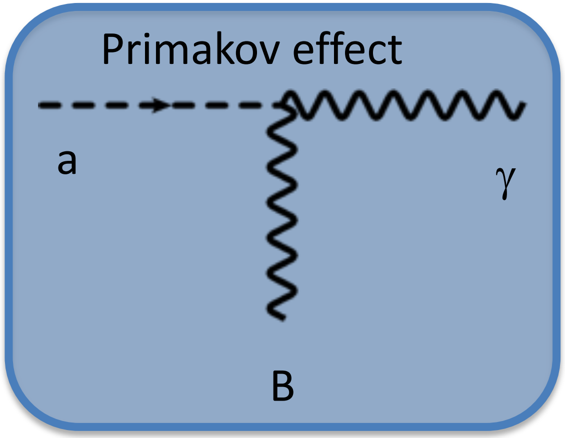
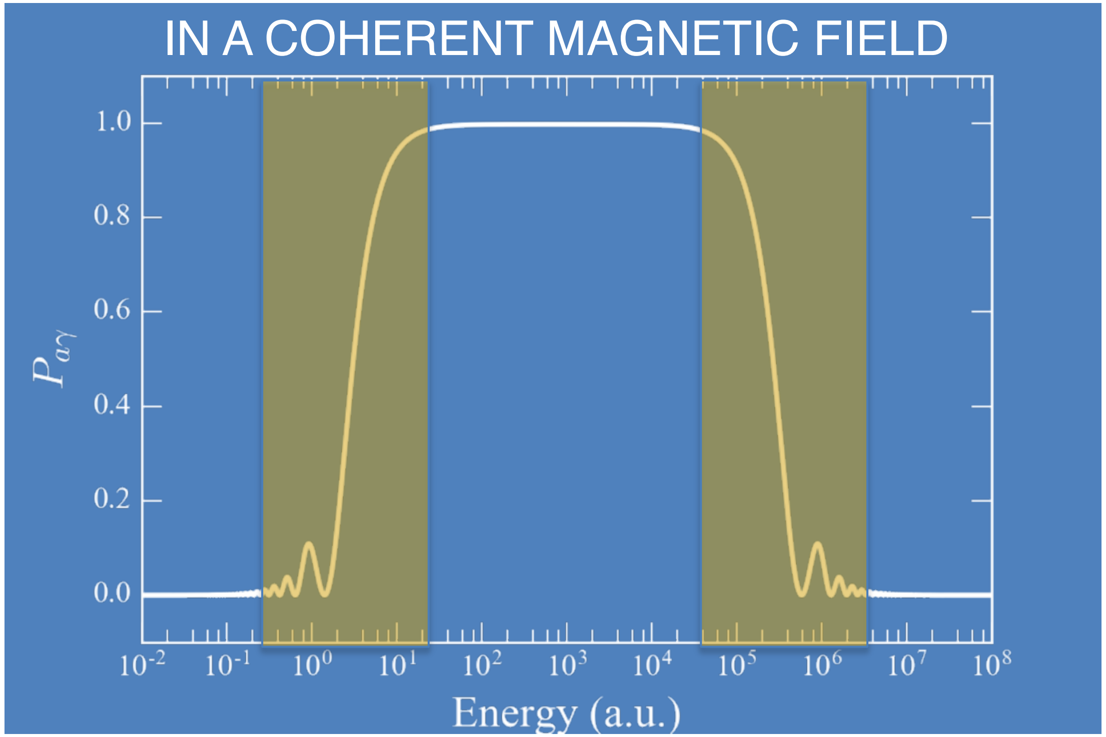




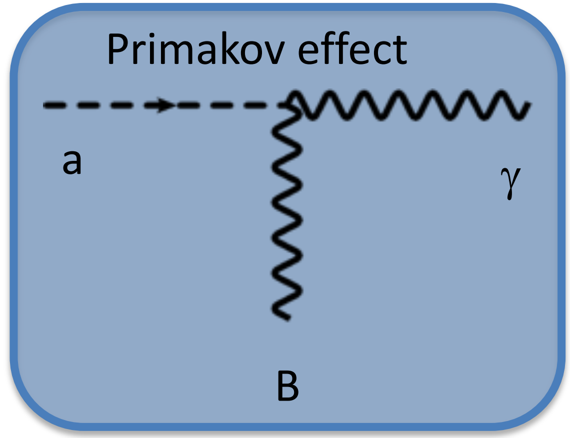
Raffelt & Stodolsky 1988

→ irregularities in energy spectrum around E_{crit} and E_{max}

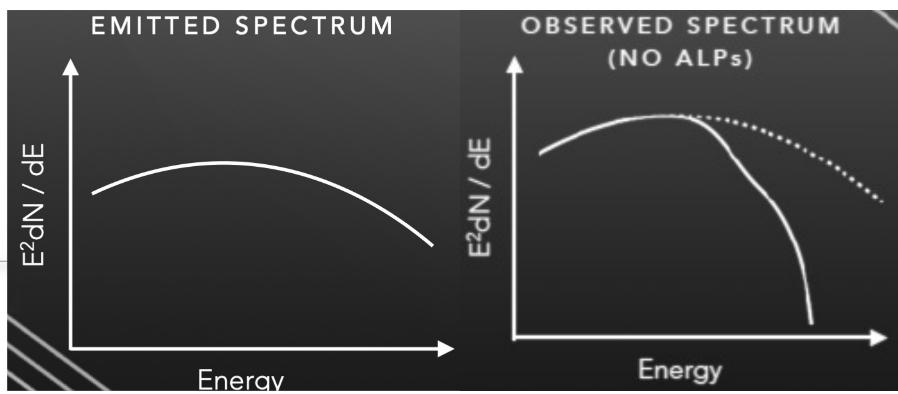
Photon–ALP mixing

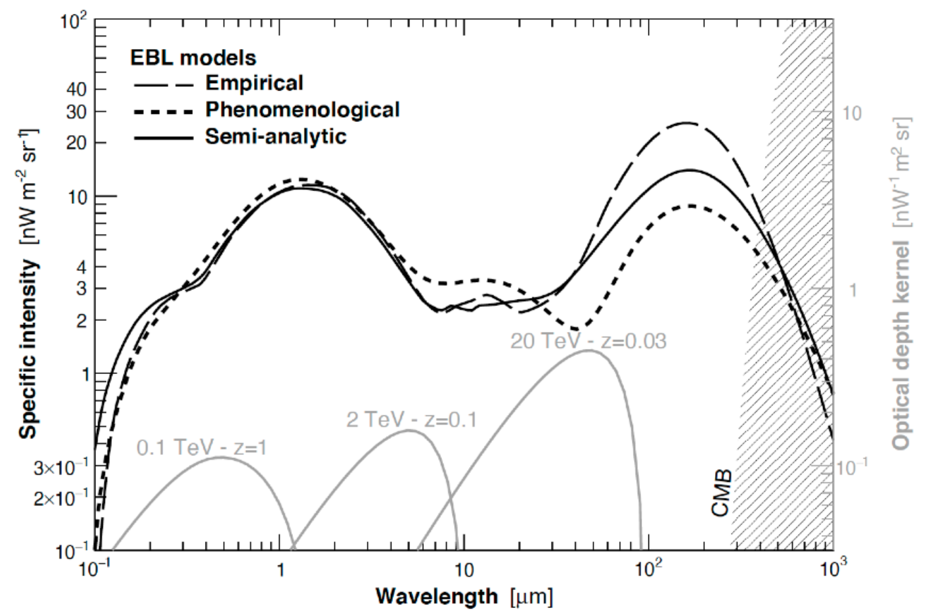
- Consequence of the coupling $a\gamma\gamma$
  $\rightarrow$ photon-ALP oscillation in cosmic magnetic fields along the line of sight

  $\rightarrow$ effect increases with distances: AGN with the beam pointing towards us, i.e., blazars, are the most obvious cases



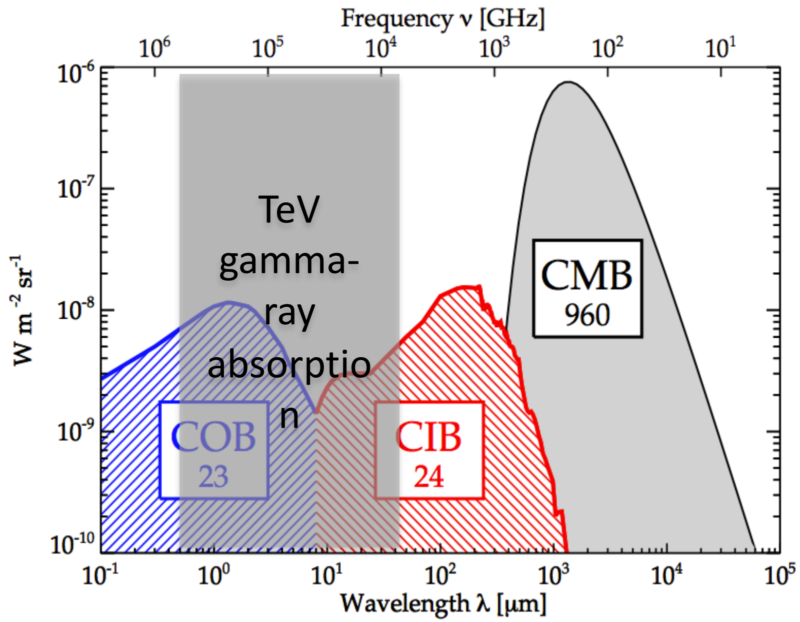
- *Caveat* : absorption of gamma rays on extra background light (a.k.a EBL) due to pair creation
  $\rightarrow$ exponential absorption with optical depth
  $\rightarrow$ gamma-ray flux attenuated

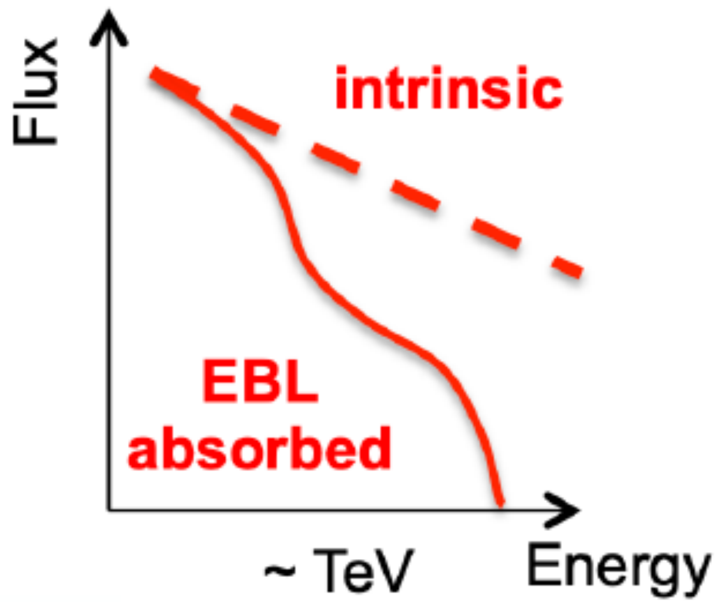




Photon–ALP mixing

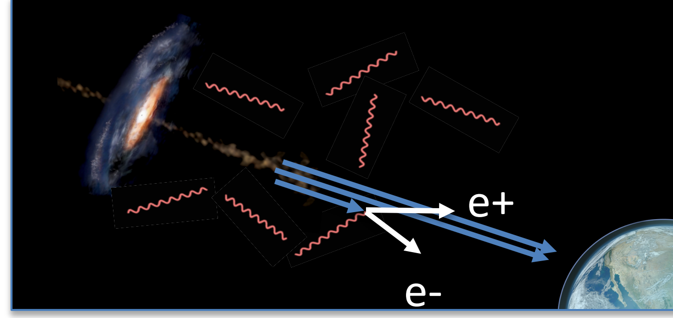
- Caveat : absorption of gamma rays on extra background light (a.k.a EBL) due to pair creation
  → exponential absorption with optical depth
  → gamma-ray flux attenuated



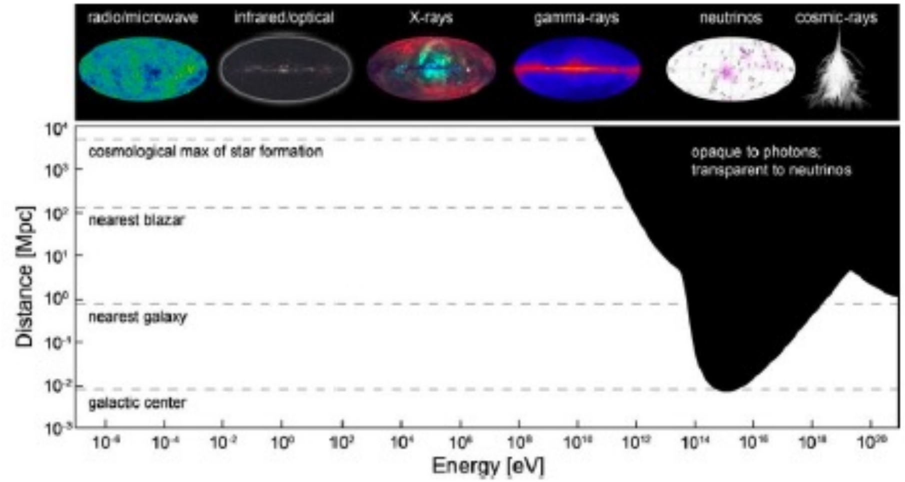


- Observed flux : $\Phi(E_\gamma, z_s) = \Phi(E_\gamma) \times e^{-\tau(E_\gamma, z_s)}$
- Energy-differential flux shows a characteristic EBL cutoff at about $E_{\gamma,\mathrm{cutoff}}(z_s) \sim 800\,(1+z_s)^{-2.4}\,\mathrm{GeV}$

Extra Background Light



- Limits the distances accessible with photons



- Impacts photon spectra (& detectability) of extragalactic γ-ray sources

- Optical depth:

$$\tau(E_0, z_0) = \int_0^{z_0} dz \frac{\partial L}{\partial z}(z) \int_0^{\infty} d\epsilon \frac{\partial n}{\partial \epsilon}(\epsilon, z) \int_{-1}^{1} d\mu \frac{1-\mu}{2} \sigma_{\gamma\gamma}[\beta(E_0, z, \epsilon, \mu)]$$

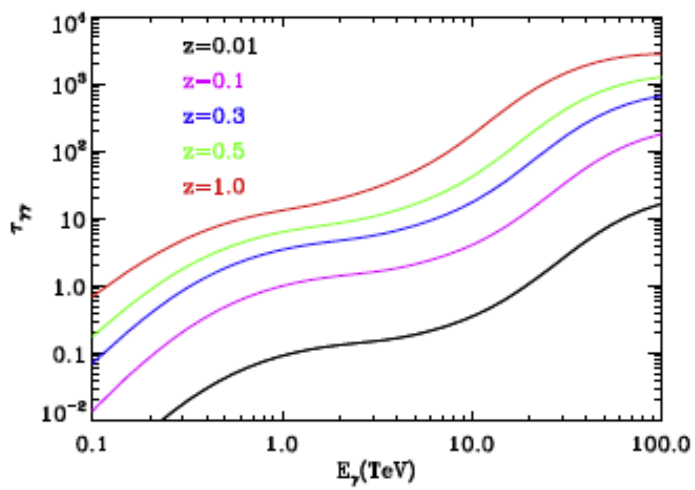
distance element depends on Λ_{CDM} parameters

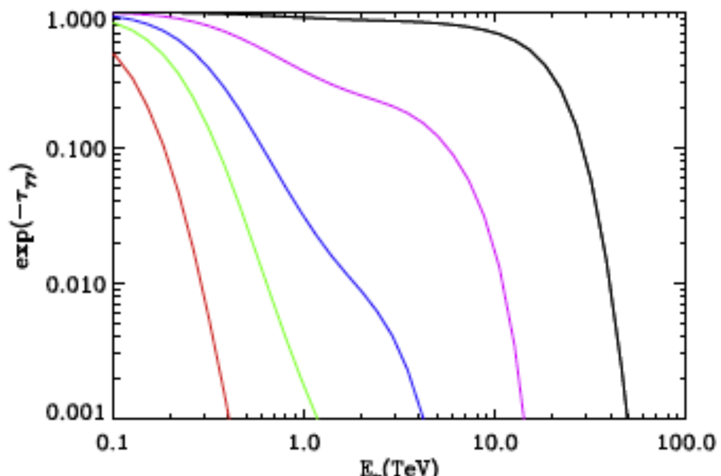
number density of EBL photons

scattering angle

Thomson cross section

- Increases with redshift and energy



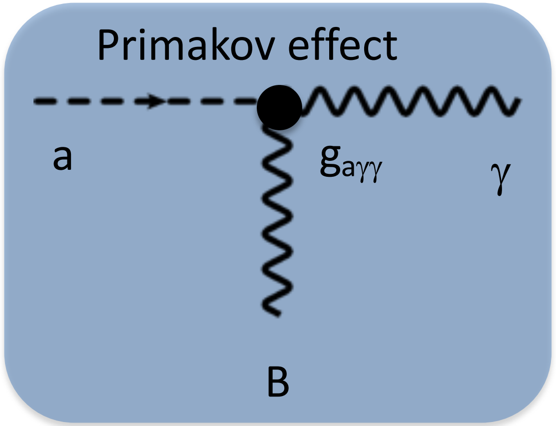


Dwek & Krennrich 2013
arXiv:1209.4661

Photon–ALP mixing

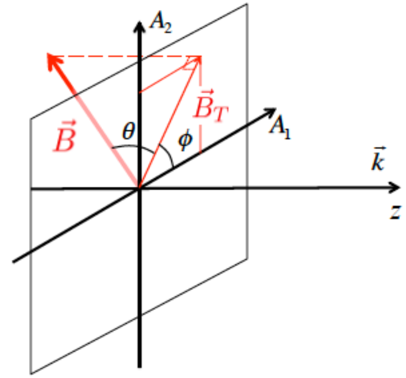
$$\mathcal{L}_{\gamma a} = \frac{1}{4} g_{\gamma a} F_{\mu\nu} \tilde{F}^{\mu\nu} \phi_a = -g_{\gamma a} \vec{E} \cdot \vec{B} \phi_a$$

- Consequence of the coupling $a\gamma\gamma$
  → photon-ALP oscillation in cosmic magnetic fields along the line of sight



- Propagation in magnetic field given by e.o.m:

$$(E - i\partial_z + \mathcal{M})\Psi = 0 \quad \text{with} \quad \Psi = \begin{pmatrix} A_1 \\ A_2 \\ a \end{pmatrix} \quad \text{for } E \gg m_a$$



where M is the mixing matrix depending on the external magnetic field, coupling constant, ALP mass, photon energy, plasma density in medium

Raffelt, Phys.Rept. 198 (1990) 1–113

Photon–ALP mixing

- Coherent magnetic field : uniform orientation and strength
  - Conversion in one domain of size s :

$$P_{\gamma\to a} = \frac{1}{2} \quad \frac{1}{1+\frac{E_c^2}{E^2}} \sin^2\left(\frac{gBs\sin\theta}{2}\sqrt{1+\frac{E_c^2}{E^2}}\right)$$

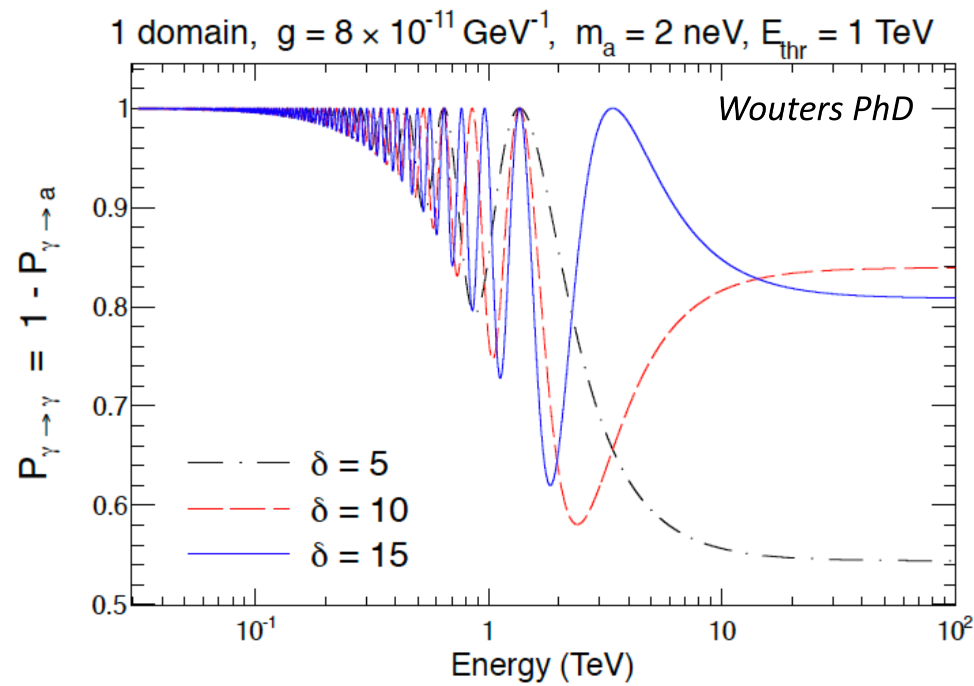
Hochmuth & Sigl, 2007, PRD

$\delta = gBs\sin\theta/2$ strength of the coupling,

- Effect is energy dependent

- Critical energy $$E_c = \frac{m^2}{2gB\sin\theta}$$
  – E << Ec : no conversion
  – E ~Ec : spatial oscillations, energy dependent
  – E >> Ec : spatial oscillations, energy independent

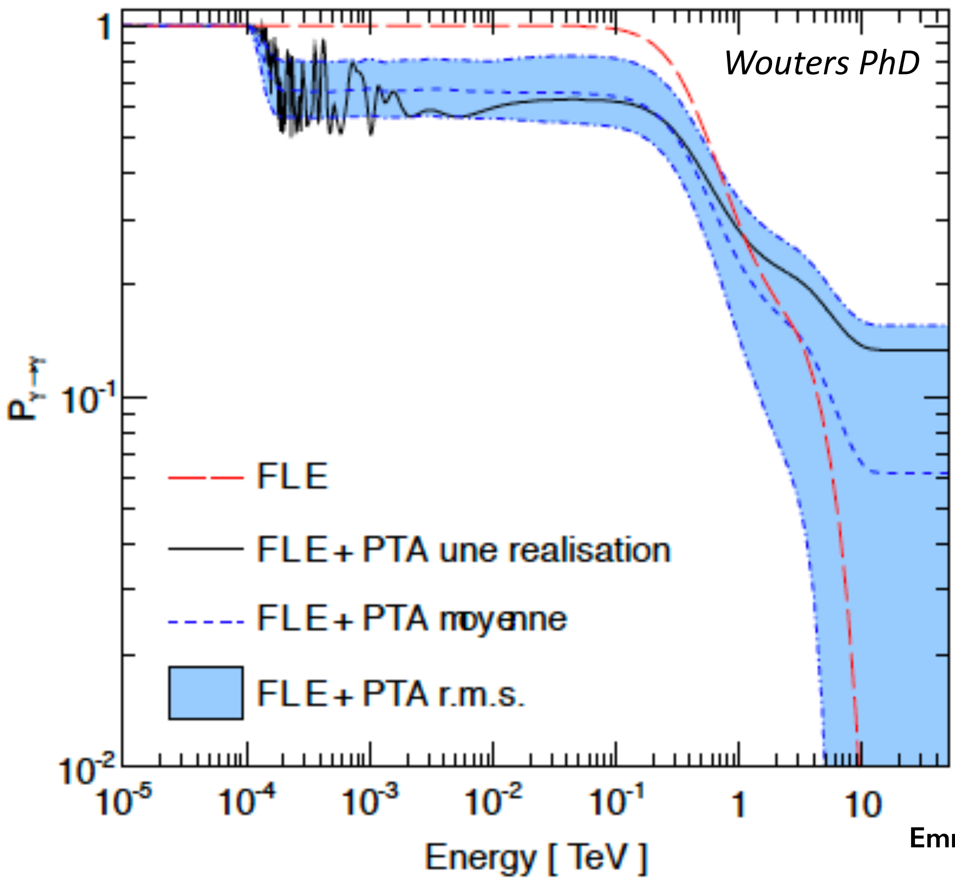
Survival probability of an unpolarized photon as a function of the energy



Photon–ALP mixing

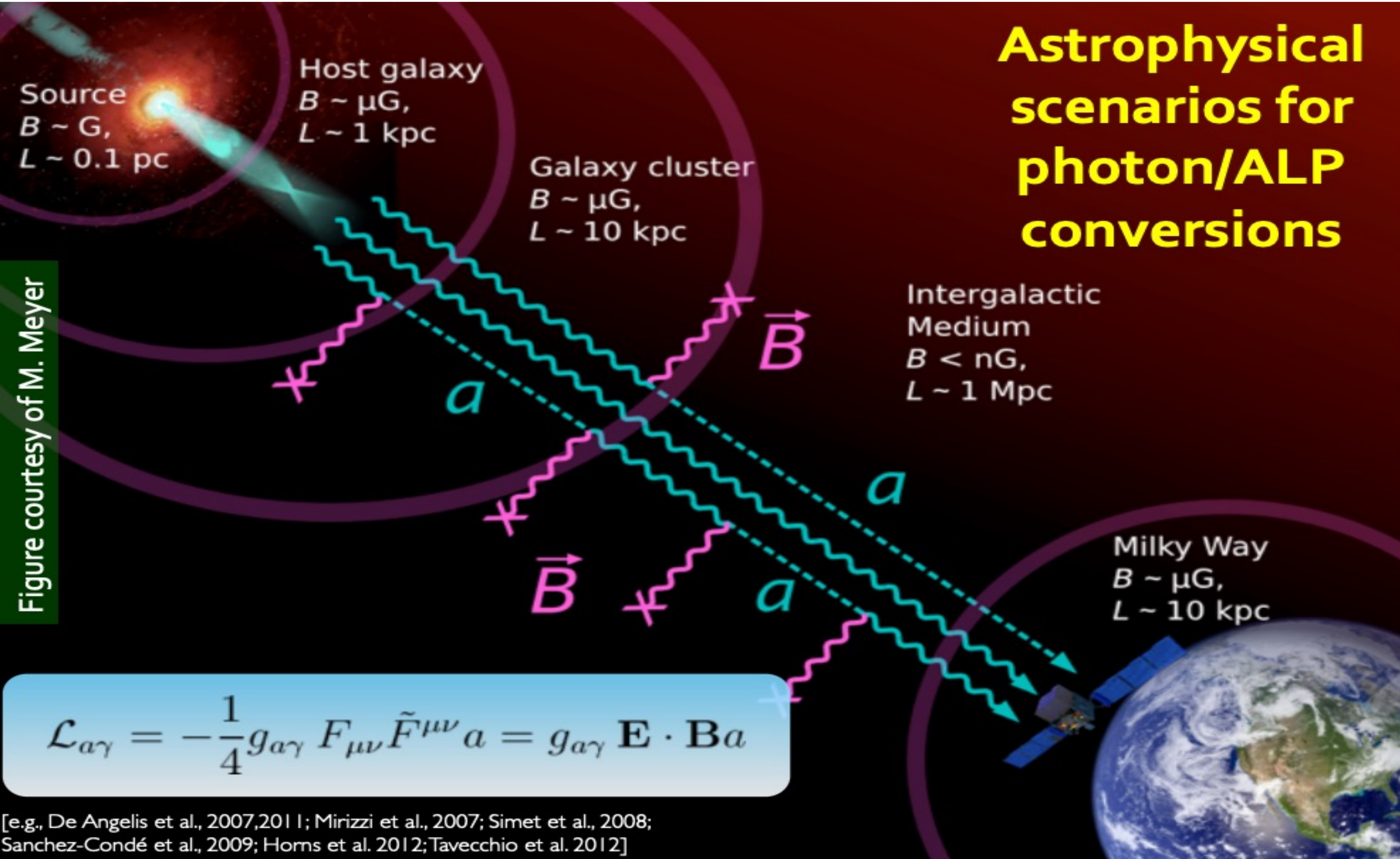
- Astrophysical magnetic fields - Milky-way, Cluster of galaxies
  Intergalactic Magnetic Field : not coherent

- Behavior for average over all possible realizations of B
  - Assuming Kolmogorov turbulence



Search for oscillation pattern in energy-differential spectra

Probing ALPs with gamma rays

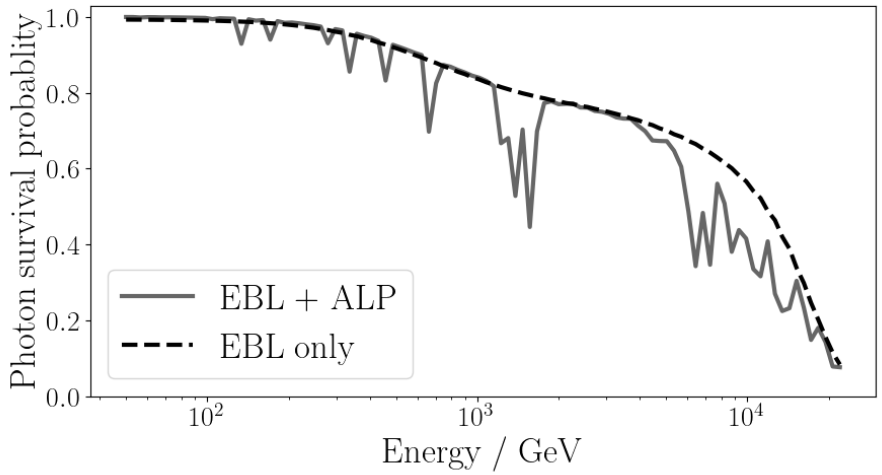


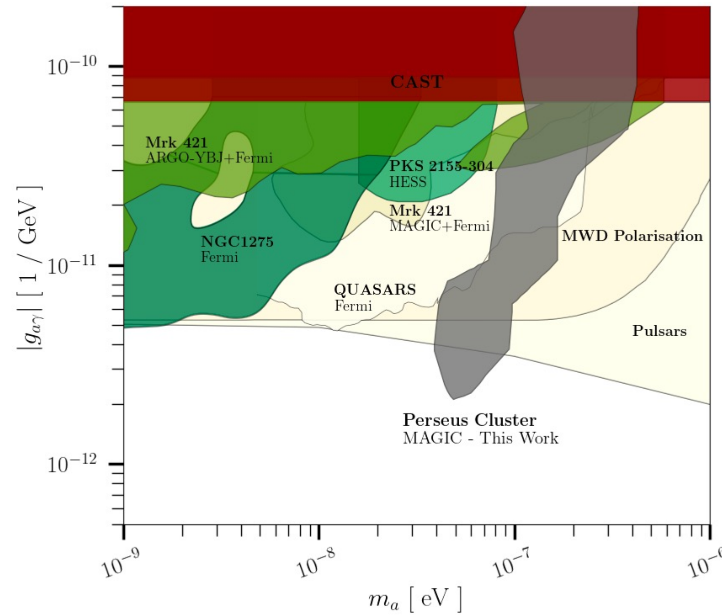
$$\mathcal{L}_{a\gamma} = -\frac{1}{4} g_{a\gamma} F_{\mu\nu} \tilde{F}^{\mu\nu} a = g_{a\gamma} \mathbf{E} \cdot \mathbf{B} a$$

[e.g., De Angelis et al., 2007,2011; Mirizzi et al., 2007; Simet et al., 2008; Sanchez-Condé et al., 2009; Horns et al. 2012; Tavecchio et al. 2012]

Probing ALPs with VHE gamma rays

- Perseus galaxy cluster with MAGIC observations:
  - cluster magnetic field can be estimated





D'Amico et al. ICRC 2023

- The example of M87 with H.E.S.S. data

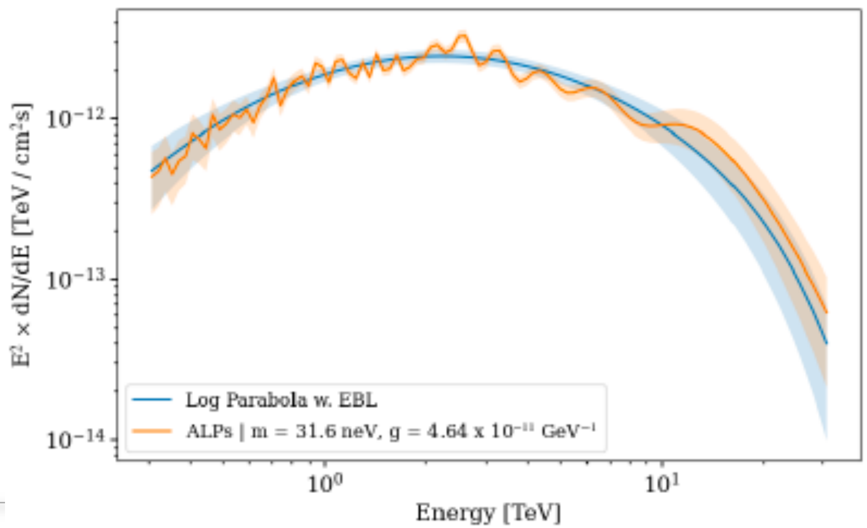


Fig. 6. The No ALPs model of a log parabola with EBL attenuation plotted against the 95th percentile ALP model for the most preferred pixel in our parameter space.

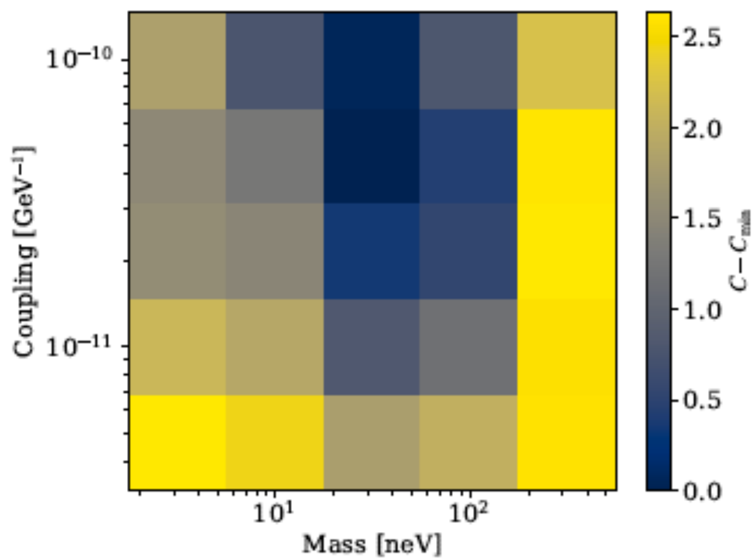
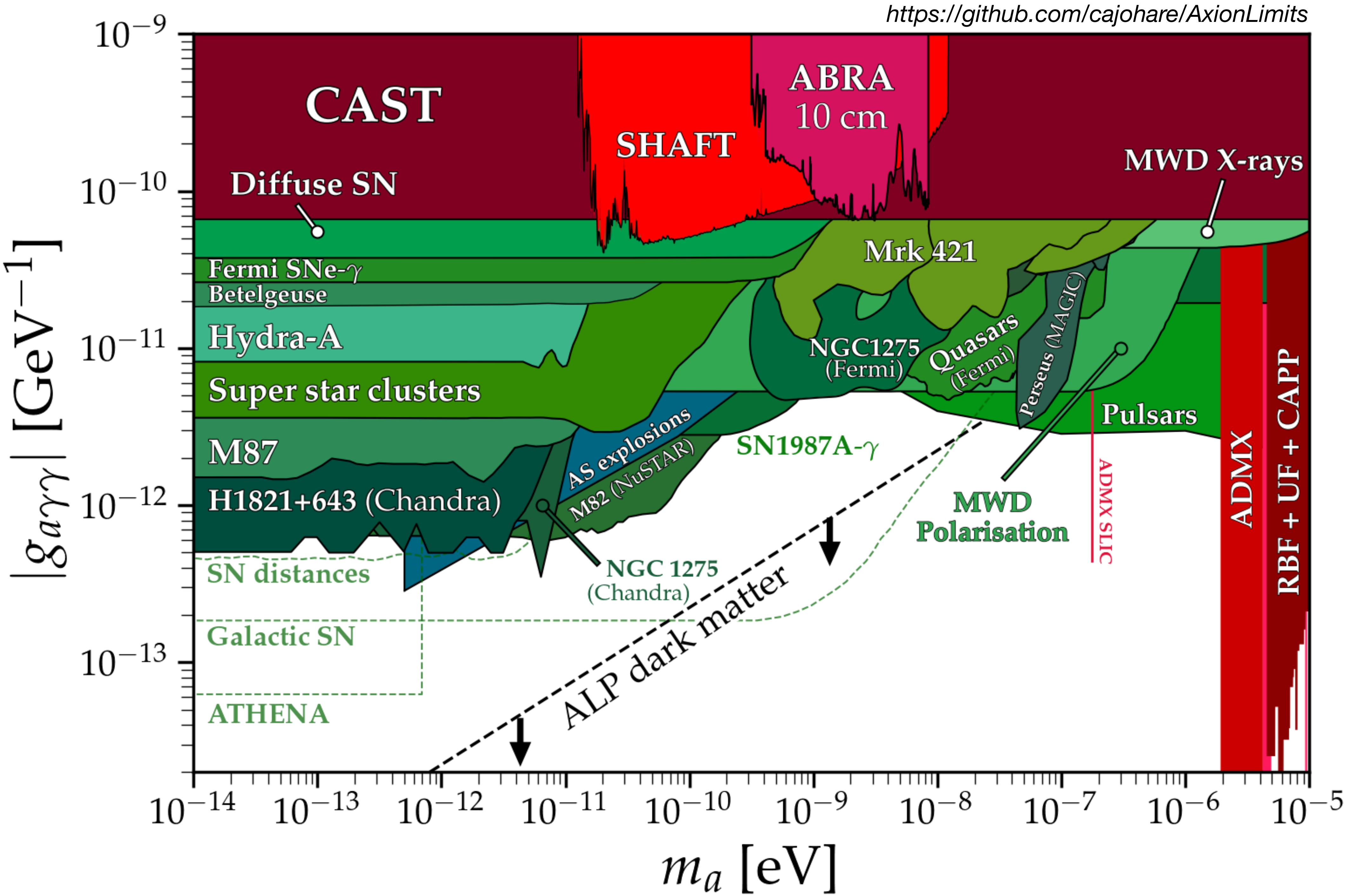


Fig. 7. The Likelihood difference between the most preferred pixel and the deviation of the other pixels from this value.

R. Cecil et al. ICRC 2023

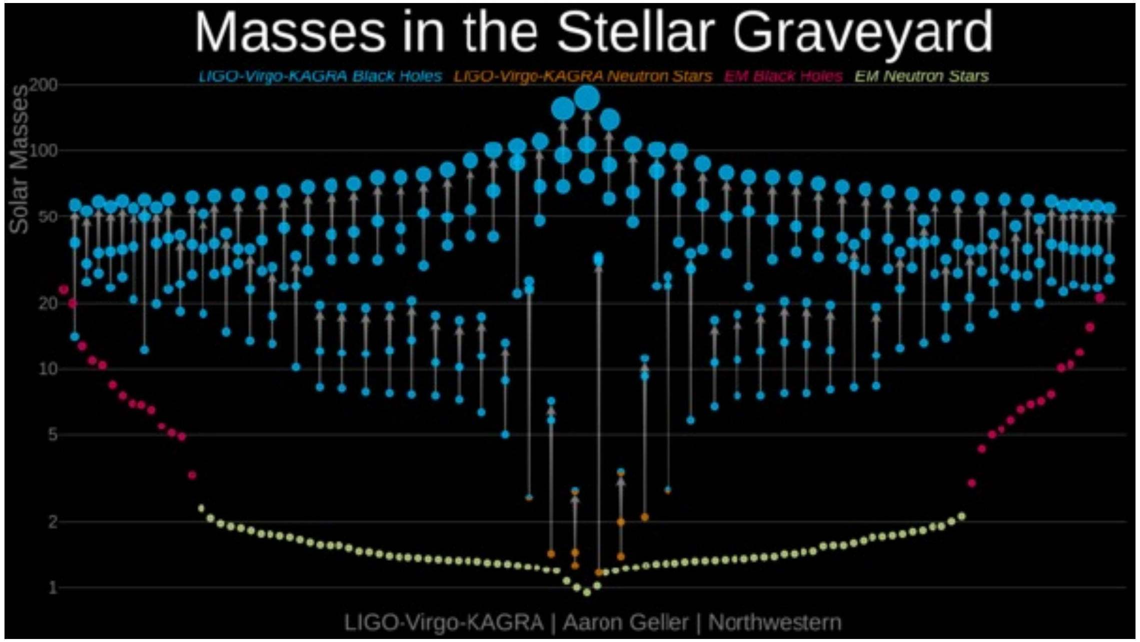
High-energy astrophysics limits

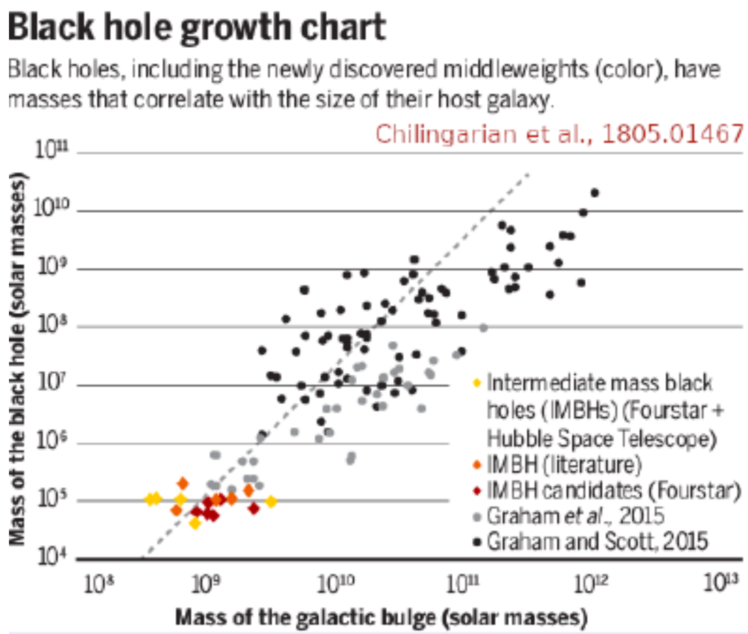


PRIMORDIAL BLACK HOLES

Observed black holes

- Stellar black holes : BHs originated in the explosion of massive stars/supernovae, ~ 3 – 100 $M_\odot$
- Intermediate mass black holes (IMBH) New class of recently discovered BHs, ~ 10^2 – 10^6 $M_\odot$
- Supermassive black holes (SMBH) : BHs at the center of galaxies, ~ 10^6 – 10^9 $M_\odot$





Observed black holes

- Stellar black holes : BHs originated in the explosion of massive stars/supernovae, ~ 3 – 10^2 $M_\odot$
- Intermediate mass black holes (IMBH) New class of recently discovered BHs, ~ 10^2 – 10^6 $M_\odot$

2015 : 1st ever observation of merging BHs by LIGO/VIRGO

~90 events detected in total today (GWTC-3)

majority of the events are BHs of ~20 Msun mass

→ Unexpectedly high masses! Did LIGO detect Primordial black holes?

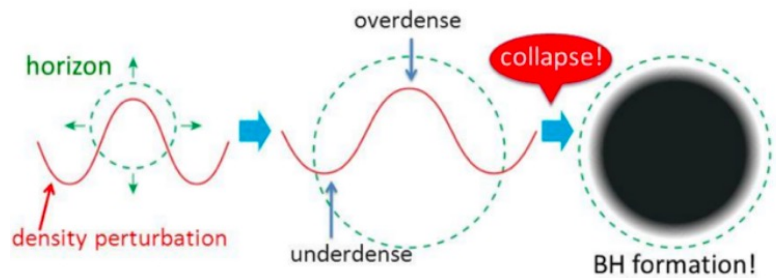
- If primordial BHs forms binaries – much more events should be seen by LIGO/VIRGO
  https://arxiv.org/abs/1603.08338 ; https://arxiv.org/abs/1709.06576 ; https://arxiv.org/abs/1709.09007
- "Eliminating the LIGO bounds on primordial black hole dark matter"
  https://arxiv.org/pdf/2008.10743.pdf

Did LIGO detected dark matter in form of ~20 Msun BHs? Probably not, but too early to draw firm conclusions!

PBH in a nutshell

- Black holes created during the early universe :
  - collapse of large primordial overdensities

  Zeldovich & Novikov 67, Carr & Hawking 74, Carr 75…



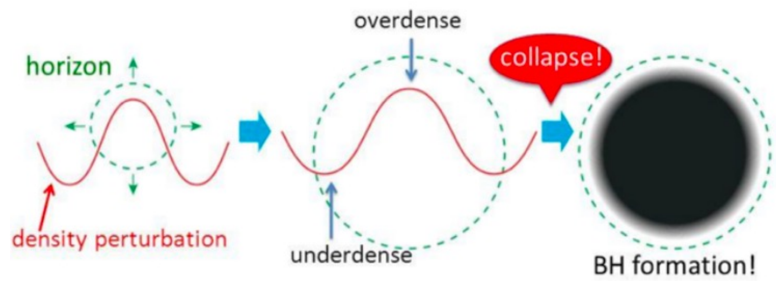
Kawasaki, et al. PRD D. ***87****, 063519 (2012)*

- The resulting BH inherits the mass corresponding to the Hubble radius at the time of collapse tc, i.e. Hubble horizon at time t, ct, same order as Schwarzschild radius ~ GM/c^2,

$$M_{PBH} = M_H(t_f) \simeq \frac{c^3}{G} t_f \quad \longrightarrow \quad M_{\rm i}(t_{\rm f}) \sim 10^{15}\,{\rm g}\left(\frac{t_{\rm f}}{10^{-23}\,{\rm s}}\right)$$

PBH in a nutshell

- Black holes created during the early universe :
  - collapse of large primordial overdensities



*Kawasaki, et al. PRD D. **87**, 063519 (2012)*

- For PBH formed in the radiation-dominated area: $M_\mathrm{i}(t_\mathrm{f}) \sim 10^{15}\,\mathrm{g}\left(\frac{t_\mathrm{f}}{10^{-23}\,\mathrm{s}}\right)$

(Possible formation of BHs with smaller masses due to incomplete collapse or to other formation channels : phase transitions, collapse of cosmic strings, domain walls)

- PBH mass bounds:
  - *lower limit* : the mass enclosed within the Hubble horizon at the formation time t_f from the big bang: $M_\mathrm{min} \sim 0.1\,\mathrm{g}$
  - *upper limit* : PBH should form before the onset of BBN for them not to spoil the baryon-to-photon ratio $M_\mathrm{BBN} \sim M(t_\mathrm{f} \approx 1\,\mathrm{s}) \sim 10^5\,M_\odot$

PBH in a nutshell

$$M_i(t_f) \sim 10^{15}\,\mathrm{g}\left(\frac{t_f}{10^{-23}\,\mathrm{s}}\right)$$

- Age of the Universe t_U =10 Gyr $\rightarrow$ $M \sim 10^{15}$ g
  - The PBHs with masses $M \lesssim 10^{15}$ g would have been completely evaporated since the Big Bang by now
- Some of which with $M \sim 10^{15}$g would be evaporating today in bursts of short, intense transient emissions of gamma rays
- More massive, stable counterparts to these evaporating PBHs are a candidate for some of the DM density of the universe

Black hole evaporation

- Hawking temperature $T_H = 1/(4\pi/G_N M_{BH}) \simeq 1.06 \times (10^{16}\ g/M_{BH})\ MeV$,

Hawking '74

- Expected particle yield per unit time and energy from a nonrotating black hole with mass MBH and corresponding Hawking temperature T_H

$$\frac{d^2N_k}{dE_k dt} = \frac{1}{2\pi} \frac{\Gamma_k(E_k, M_{BH}, m)}{e^{E_k/T_{BH}} - (-1)^{2s}}$$

Γ (Ek,MBH,m) is the particle-dependent gray-body factor and Ek indicates the energy of the emitted particle k of mass m and spin s

  - *Note that the emission is not exactly black-body but depends upon the spin and charge of the emitted particle, the average energy for neutrinos, electrons and photons being $4.22T_{BH}$, $4.18T_{BH}$ and $5.71T_{BH}$, respectively.*
  - *All of the black holes that we know exist (Stellar-mass, supermassive) have temperatures much smaller than the CMB temperature (~2.7 K); since no heat can flow from a colder to a hotter "body", massive black holes do not evaporate*

Black hole evaporation

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- Expected particle yield per unit time and energy from a nonrotating black hole with mass MBH and corresponding Hawking temperature T_H

$$\frac{d^2N_{\rm k}}{dE_{\rm k}dt} = \frac{1}{2\pi}\frac{\Gamma_{\rm k}(E_{\rm k}, M_{\rm BH}, m)}{e^{E_{\rm k}/T_{\rm BH}} - (-1)^{2s}}$$

Γ (Ek,MBH,m) is the particle-dependent gray-body factor and Ek indicates the energy of the emitted particle k of mass m and spin s

- From Stefan-Boltzmann law and change of mass one can show that an (approximate) BH lifetime is

$$\tau(M) \sim \frac{G^2M^3}{\hbar c^4} \sim 10^{64}\left(\frac{M}{M_\odot}\right)^3\ {\rm yr}$$

Black hole evaporation

- Hawking temperature $T_{\mathrm{H}} = 1/(4\pi/G_N M_{\mathrm{BH}}) \simeq 1.06 \times (10^{16}\ \mathrm{g}/\mathrm{M_{BH}})\ \mathrm{MeV}$.

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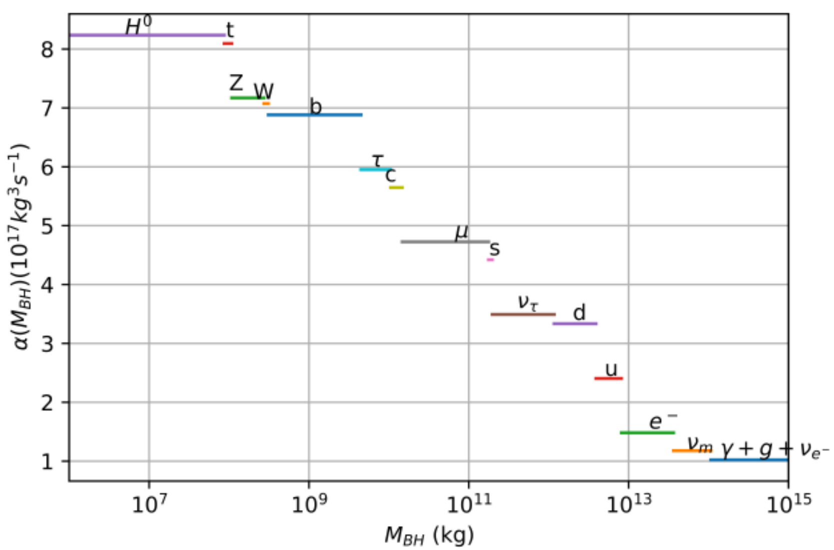
$$\frac{d^2N_{\mathrm{k}}}{dE_{\mathrm{k}}dt} = \frac{1}{2\pi}\frac{\Gamma_{\mathrm{k}}(E_{\mathrm{k}}, M_{\mathrm{BH}}, m)}{e^{E_{\mathrm{k}}/T_{\mathrm{BH}}} - (-1)^{2s}}$$

- Accounting for the SM degrees of freedom gives :



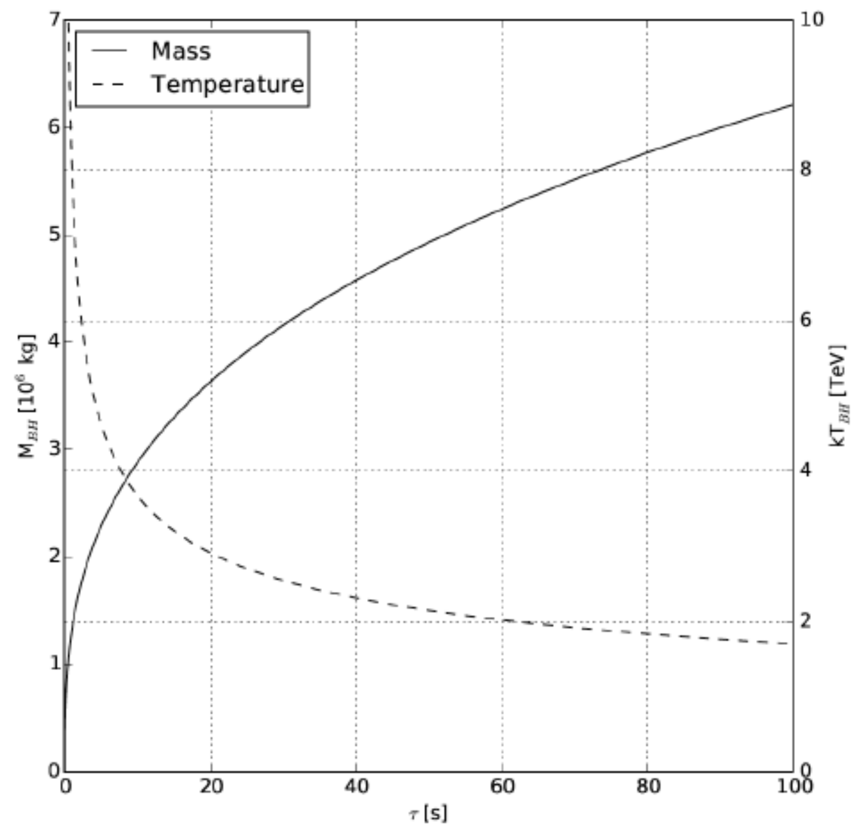


Figure 6: Black hole mass and temperature for the final 100 seconds of the BH evaporation lifetime (τ is the remaining time). The decrease of mass and the increase of temperature accelerate as $\tau \to 0$.

Search for photon bursts from PBH evaporation

- Final-stage emission searches for high-energy photon bursts expected before ~10^{15} g mass PBHs « completely » evaporate
  → look for cluster of N_{obs} photons

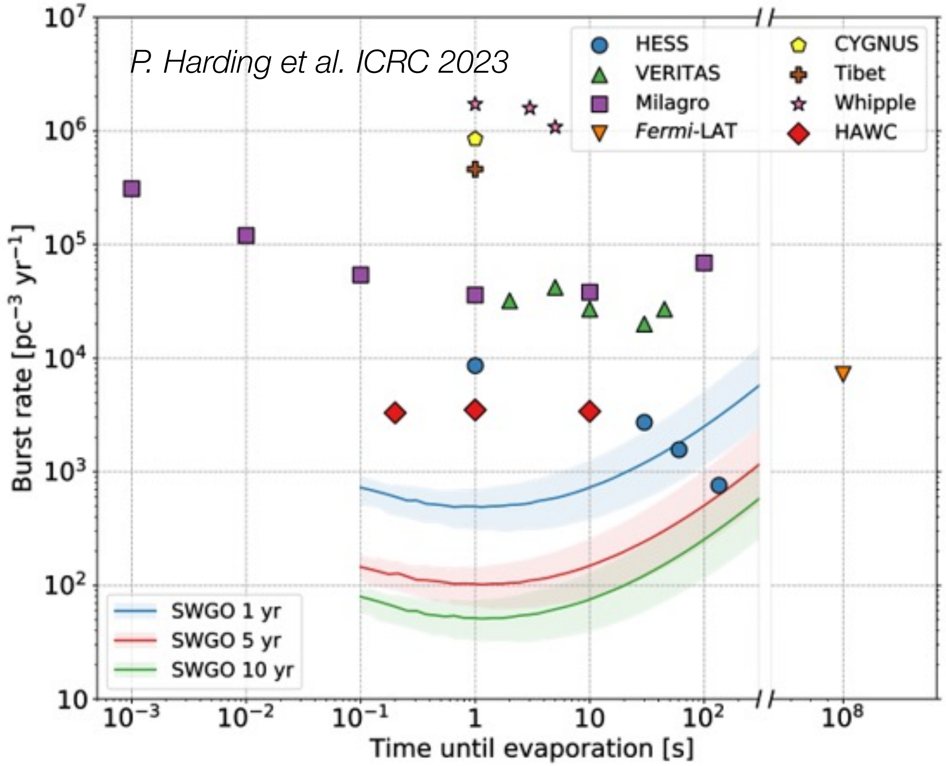
- Expected rate of cluster of N_{obs} observed photons:

$$R(N_{obs}) = \int d\Omega \int_0^\infty dr\, r^2 \dot{\rho}_{PBH} \mathcal{P}(N_{obs}|\lambda)$$

  - Ω solid angle of observations
  - r distance of the PBH
  - λ the expected number of photons
  - $\dot{\rho}_{\rm PBH}$: PBH evaporation rate per unit volume

Search for photon bursts from PBH evaporation

- Final-stage emission searches for high-energy photon bursts expected before $\sim 10^{15}$ g mass PBHs « completely » evaporate



- The number of cluster of N_{obs} observed photons in a time T and solid angle Ω is therefore:

$$N_{cluster}(N_{obs}) = \dot{\rho}_{PBH}\, T\, \Omega \frac{(r_0\sqrt{N_0})^3}{2} \frac{\Gamma(N_{obs}-3/2)}{\Gamma(N_{obs}+1)}$$

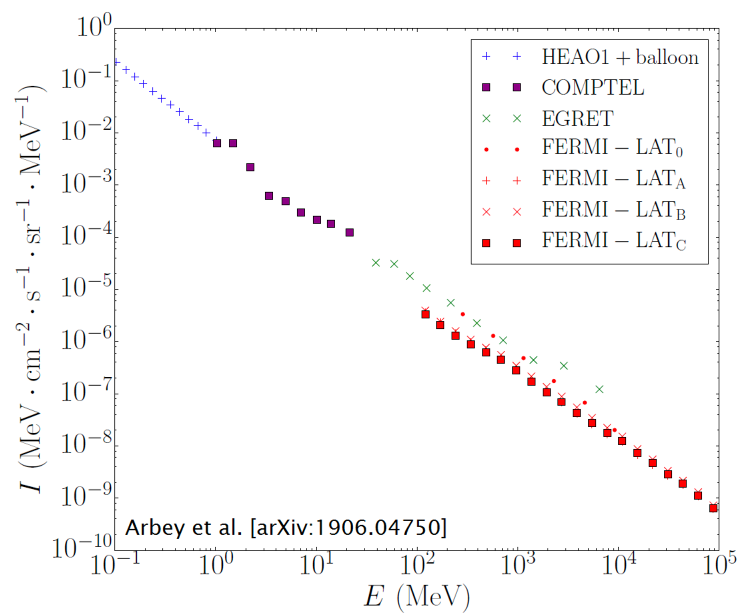
for isotropic evaporation rate

with N_0 is the expected number of photons seen by the detedctor for a PBH evaporation at distance r_0

Isotropic gamma ray background (IGRB) constraints

Diffuse background +

- Active galactic nuclei
- Gamma ray bursts
- DM annihilation/decay?
- Hawking radiation?



The IGRB as measured by HEAO1+balloon, COMPTEL, EGRET and FERMI-LAT missions.

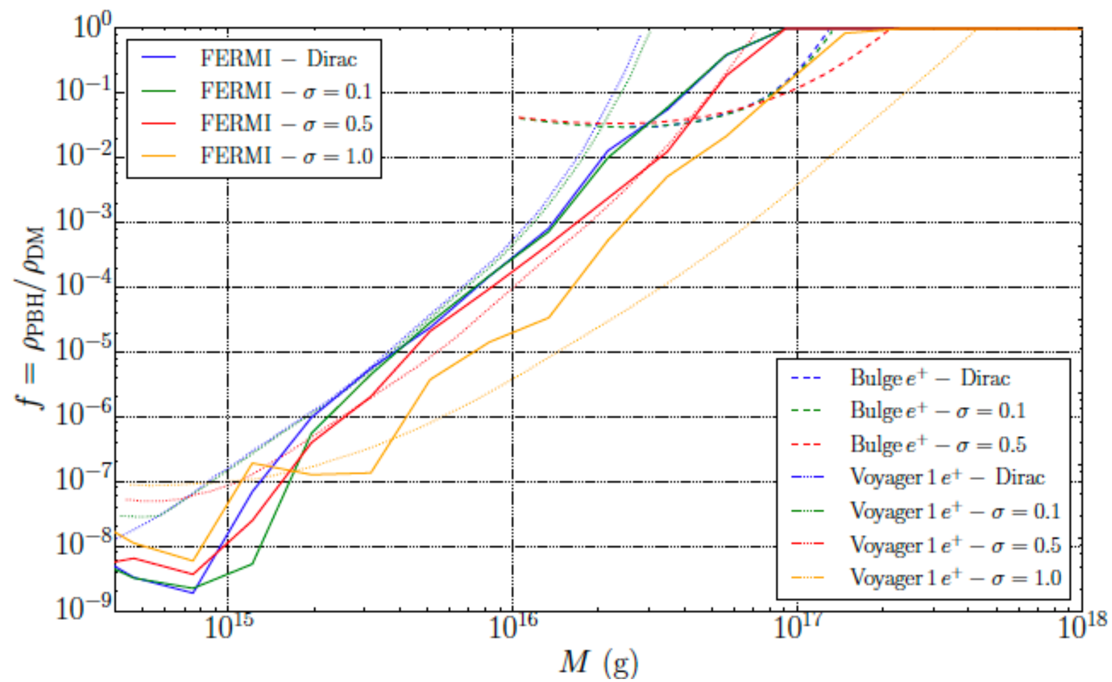
- Flux estimation for BHs

$$I \approx \frac{1}{4\pi} E \int_{t_{\min}}^{t_{\max}} (1+z(t)) \frac{\mathrm{d}^2 n}{\mathrm{d}t\mathrm{d}E}((1+z(t))E)\mathrm{d}t$$

$$\approx \frac{1}{4\pi} E \int_{t_{\min}}^{t_{\max}} (1+z(t))$$

$$\times \int_{M_{\min}}^{M_{\max}} \left[\frac{\mathrm{d}n}{\mathrm{d}M} \frac{\mathrm{d}^2 N}{\mathrm{d}t\mathrm{d}E}(M,(1+z(t))E)\,\mathrm{d}M \right] \mathrm{d}t$$

Arbey et al. arxiv:1906.04750



- Limits for monochromatic mass functions as well as log-normal mass functions with different gaussian width

PBH searches with keV/MeV photons

- PBHs with masses $10^{16} – 10^{21}$ g are poorly constrained and can make all dark matter :
  - Hawking temperature of such black holes is in keV-MeV range
- Expected particle yield per unit time and energy from a nonrotating black hole with mass M_{BH} :

$$\frac{d^2 N_{\rm k}}{dE_{\rm k} dt} = \frac{1}{2\pi} \frac{\Gamma_{\rm k}(E_{\rm k}, M_{\rm BH}, m)}{e^{E_{\rm k}/T_{\rm BH}} - (-1)^{2s}} .$$

Hawking 1974

INTEGRAL [ESA]

XMM-Newton [ESA]

- Expected energy-differential gamma-ray flux

$$\frac{d^2\Phi_\gamma}{dE_\gamma}(\Delta\Omega) = \frac{1}{4\pi}\int_{\Delta\Omega} d\Omega \int_{\rm LOS} ds \frac{f_{\rm pbh}\,\rho_{\rm DM}(r(s,d,\theta))}{M_{\rm pbh}} \frac{d^2 N_\gamma}{dE_\gamma dt}$$

$$D(\Delta\Omega) = \int_{\Delta\Omega}\int_{\rm LOS} \rho_{\rm DM}(r(s,d,\theta))\, ds\, d\Omega.$$

Framework similar to standard decaying DM:
– the strength ~ D-factor; the spectrum is hard in keV-MeV bands
– best targets : dSphs, GC, clusters...

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  - Hawking temperature of such black holes is in keV-MeV range
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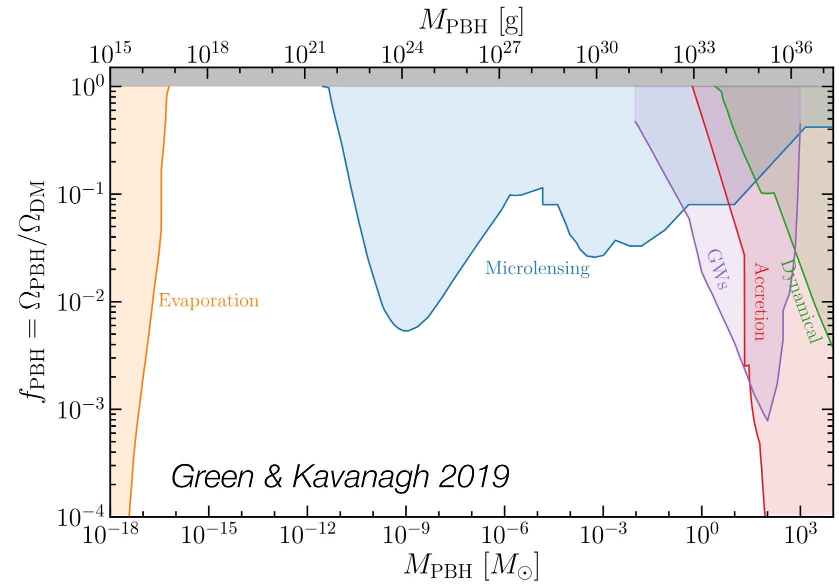
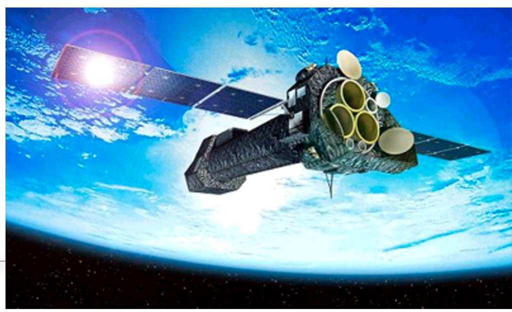
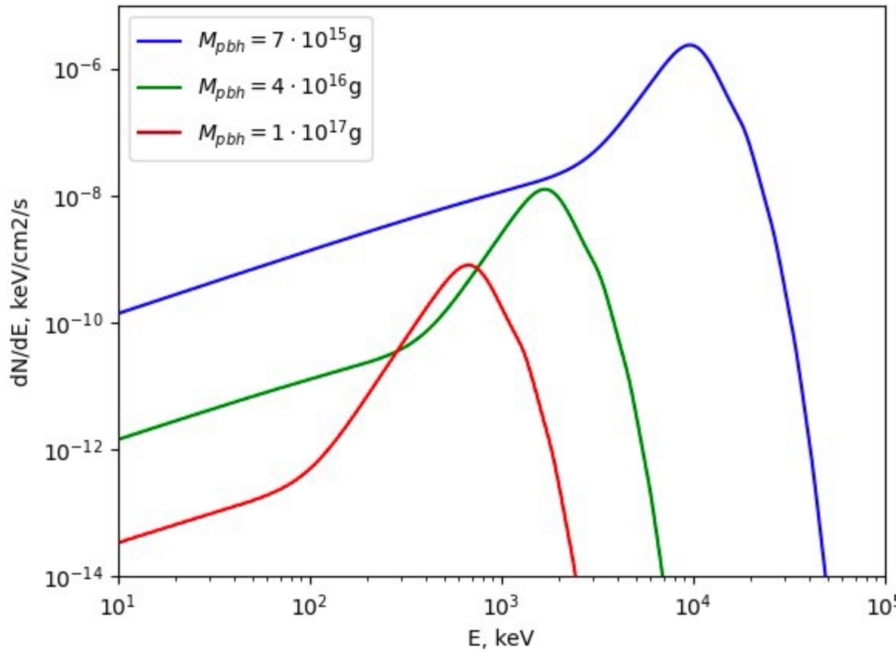


$$\frac{d^2\Phi_\gamma}{dE_\gamma}(\Delta\Omega) = \frac{1}{4\pi}\int_{\Delta\Omega} d\Omega \int_{\rm LOS} ds \frac{f_{\rm pbh}\,\rho_{\rm DM}(r(s,d,\theta))}{M_{\rm pbh}} \frac{d^2N_\gamma}{dE_\gamma dt}$$



XMM-Newton [ESA]

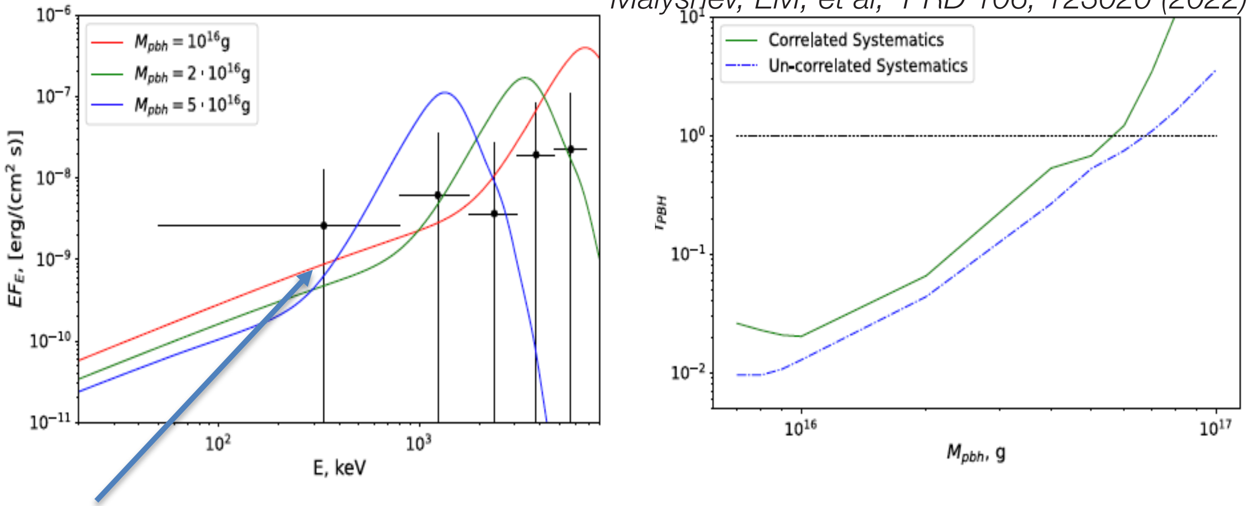
INTEGRAL [ESA]



PBH searches with keV/MeV photons

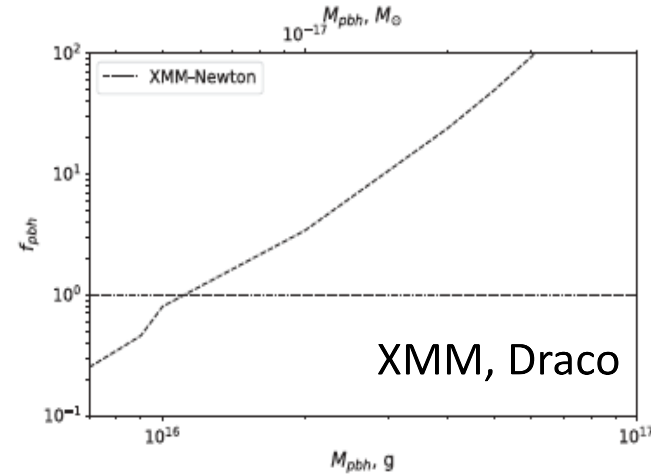
- ~3 Ms XMM observations of Draco
- **MeV Galactic diffuse emission**
  - INTEGRAL SPI observations of the inner Milky Way between 2002/11 and 2021/10

Malyshev, EM, et al, PRD 106, 123020 (2022)



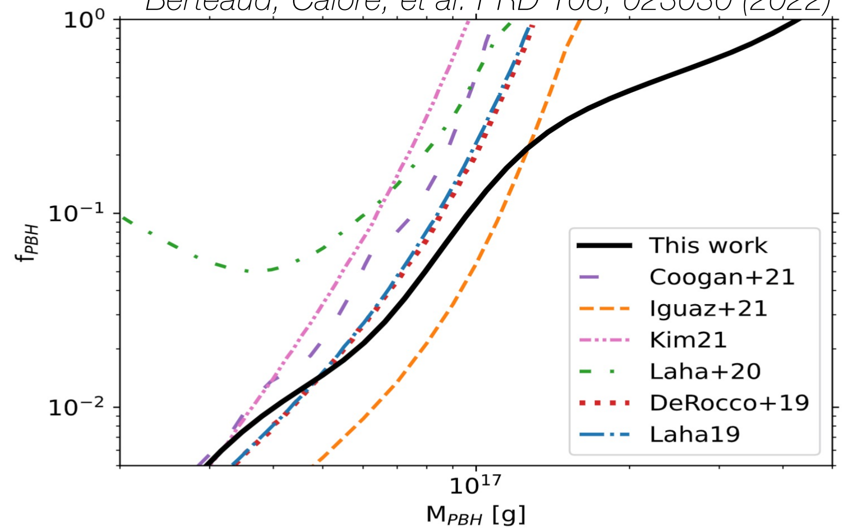
Residual INTERGAL/SPI background
from ON/OFF observartion pairing to minimize the effects of the time-dependent background variability

$$\frac{d^2\Phi_\gamma}{dE_\gamma dt} = \frac{f_{\rm pbh}}{4\pi M_{\rm pbh}} \frac{d^2N_\gamma}{dE_\gamma dt} \sum_{\rm i} (D_{\rm ON,i} - \alpha_i D_{\rm OFF,i})$$

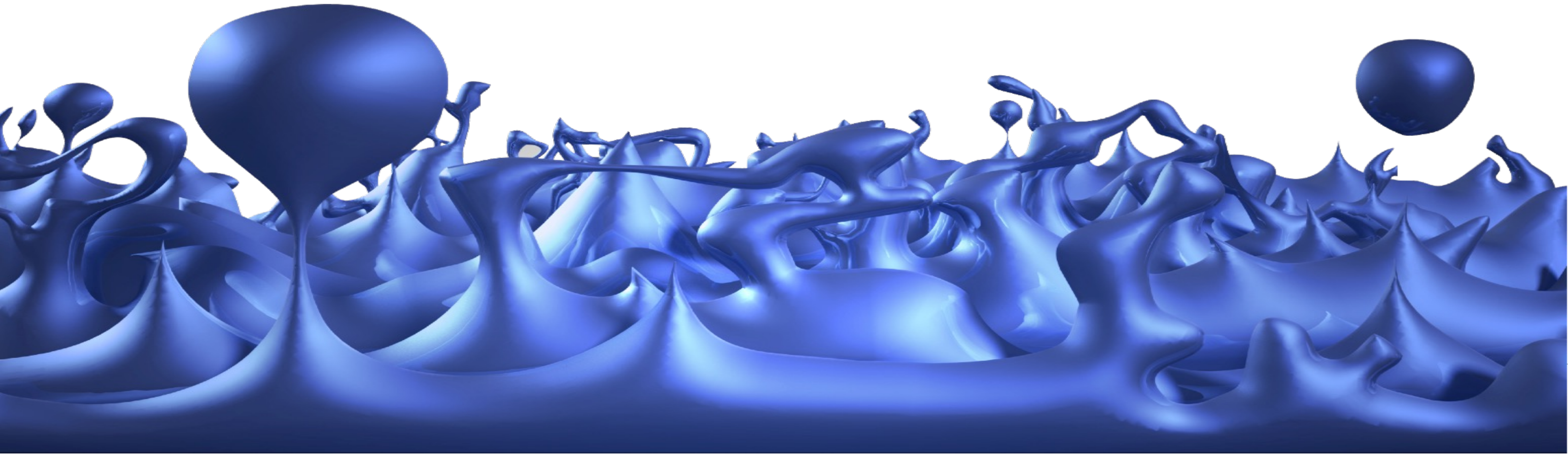


- Backgound template modelling appraoch
  - ICS of electrons off the interstellar radiation field
  - unresolved sources
  - nuclear lines, …

Berteaud, Calore, et al. PRD 106, 023030 (2022)



LORENTZ INVARIANCE VIOLATION SEARCHES AT VERY HIGH ENERGIES



Modified dispersion relation

$$l_P = \sqrt{\frac{\hbar G}{c^2}} \approx 1.6 \times 10^{-35} \text{ m},$$

$$m_P = \sqrt{\frac{\hbar c}{G}} \approx 2.18 \times 10^{-8} \text{ kg},$$

$$E_P = m_P c^2 \approx 1.22 \times 10^{19} \text{GeV}$$

- Lorentz invariance is central in modern physics theories

- However close to Planck energy $E_{Pl} = \sqrt{\hbar c^5 / G} \approx 1.22 \times 10^{19}$ GeV
some quantum gravity models (QG) predict that spacetime fluctuations modify photon propagation in vacuum according to their energy $\rightarrow$ Lorentz invariance violation (LIV)

- LIV induced effects can be introduced in a model-independent way in the standard dispersion relation of photons :

$$E^2 = p^2 c^2 \times \left[1 \pm \sum_{n=1}^{\infty} \left(\frac{E}{E_{QG,n}}\right)^n\right]$$

  - Subluminal or superluminal LIV $\rightarrow$ +/-
  - Experiments are only sensitive to n = 1, 2

  Note that E_{QG} is often compared to E_{Pl} , but could be very different from it

$\rightarrow$ Photon speed depends on their energy

Search for time delays

- Considering only the linear (n = 1) or quadratic (n = 2) term, it can be shown that the group velocity of photons acquires a dependence on their energies :

$$v_g(E) = \frac{\partial E}{\partial p}$$

- From $E^2 \simeq p^2c^2 \times \left[1 \pm \left(\frac{E}{E_{QG}}\right)^n\right]$, one gets $E = pc\left[1 \pm \frac{1}{2}\left(\frac{E}{E_{QG}}\right)^n\right]$

  with first-order Taylor expansion.

- Therefore : $v_g(E) = \frac{\partial E}{\partial p} = c\left[1 \pm \frac{1}{2}\left(\frac{E}{E_{QG}}\right)^n\right] \pm \frac{pc}{2E_{QG}^n}\frac{\partial E^n}{\partial E}\frac{\partial E}{\partial p}$

With E ~pc ($E \ll E_{QG}$), $\frac{\partial E}{\partial p} = c\left[1 \pm \frac{1}{2}\left(\frac{E}{E_{QG}}\right)^n\right]\left[1 \mp \frac{n}{2}\left(\frac{E}{E_{QG}}\right)^n\right]^{-1}$

Neglecting the 2n-order term, one shows that

$$v_g(E) = \frac{\partial E}{\partial p} = c\left[1 \pm \frac{n+1}{2}\left(\frac{E}{E_{QG}}\right)^n\right]$$

Search for time delays

- As Universe is expanding, the expansion has to be taken into account when calculating the delay (Jacob & Piran, 2008)
- The time delay between two photons of energies E_h and E_l is therefore :

$$\Delta t_n \simeq s_\pm \frac{n+1}{2} \frac{E_h^n - E_l^n}{E_{QG}^n} \int_0^z \frac{(1+z')^n}{H(z')} dz'$$

with $H(z) = H_0 \sqrt{\Omega_m (1+z)^3 + \Omega_\Lambda}$

Note that other models it can have different redshift dependence.

- For subluminal effect, the two photons are assumed to be emitted at the same time, the photon arrives first

Search for time delays

- As Universe is expanding, the expansion has to be taken into account when calculating the delay (Jacob & Piran, 2008)
- The time delay between two photons of energies E_h and E_l is therefore :

$$\Delta t_n \simeq s_\pm \frac{n+1}{2} \frac{E_h^n - E_l^n}{E_{QG}^n} \int_0^z \frac{(1+z')^n}{H(z')} dz'$$

with $H(z) = H_0 \sqrt{\Omega_m (1+z)^3 + \Omega_\Lambda}$

<u>CMB+lensing/BAO (2018):</u>
$H0$[kms−1Mpc−1]
= 67.66 ± 0.42
Ωm = 0.3111 ± 0.0056
ΩΛ = 0.6889 ± 0.0056

- *Note that time delays are expected from source intrinsic effect, plasma effect, photon interaction with dark mattter, cascade in the IGMF, …*

<u>→ For source intrinsic effect :</u> Population studies (all sources) or
Full modeling of source intrinsic effects

Astrophysical sources for time delay searches

$$\Delta t_n \simeq s_\pm \frac{n+1}{2} \frac{E_h^n - E_l^n}{E_{QG}^n} \int_0^z \frac{(1+z')^n}{H(z')} dz'$$

Energy difference

Distance parameter

- Need for sources that are
  - Distant
  - Variable or transient
  - Energetic

- Candidates:
  - Gamma-Ray Bursts (GRBs)
  - Flaring Active Galactic Nuclei (AGNs)
  - Pulsars (PSRs)

Astrophysical sources for time delay searches

$$\Delta t_n \simeq s_\pm \frac{n+1}{2} \frac{E_h^n - E_l^n}{E_{QG}^n} \int_0^z \frac{(1+z')^n}{H(z')} dz'$$

Energy difference

Distance parameter

Caveats:

A measured lag is the combination of lags from different origins : expected and some hypothetical ones:

- source effect : delays due to emission and acceleration mechanisms at the source
- source plasma effect
- cascade in IGMF
- …

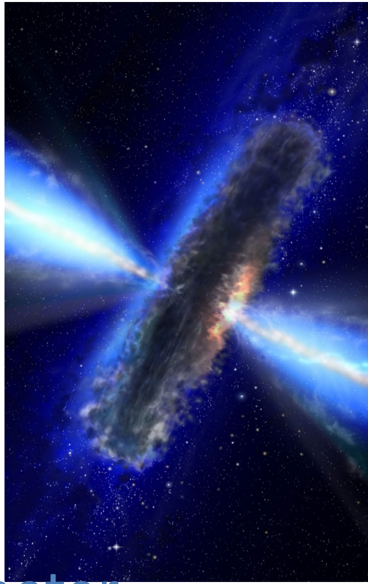
Careful estimates needed

Example : flaring AGN

$$\Delta t_n \simeq s_\pm \frac{n+1}{2} \frac{E_h^n - E_l^n}{E_{QG}^n} \int_0^z \frac{(1+z')^n}{H(z')} dz'$$

Energy difference

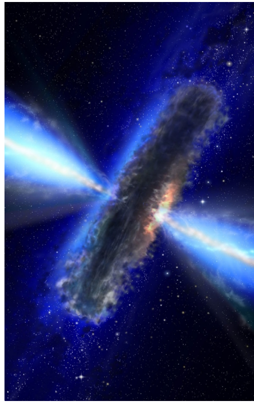
Distance parameter



Blazars

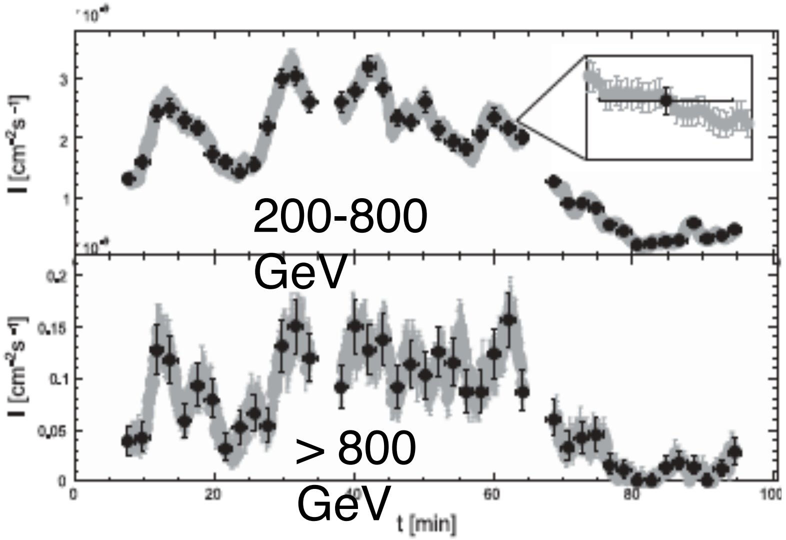
- Jet close to the line-of-sight
- High variability (flares)

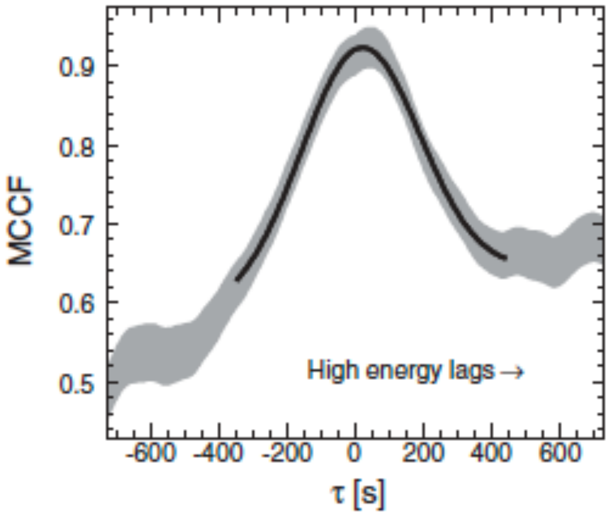
👍 Good statistics with IACTs
👍 High variability (O(min))
👍 Distant sources
👎 Flares happen randomly
👎 Hints of intrinsic temporal effects
👎 Details of emission mechanisms poorly understood



Example : PKS 2155-304 flare in 2006

- z = 0.116 (~490 Mpc)
- 2006 flare :
  - Very high flux➔~14 Crab; High statistics➔~10000 photons
- Time lag between two light curves with the modified cross correlation function





- *Best-fit function peaks at 20 s*
- *Error on the measured time delay is determined by propagating the flux errors via simulations:*
- *cross correlation peak distribution : mean of 25s and a rms of 28s*

→ *Time lag not significant*

- The best limit obtained by HESS is currently EQG = 2.1 x 10^{18} GeV with the Big flare of PKS 2155 (n = 1, 95% CL)
- Stronger limits obtained on E_{QG} are of ~10E_{Pl} for individual GRBs

Modified pair cross section

- A Modified Dispersion Relation can also induce a modified photon kinematics, which can lead to modifications of the $\gamma\gamma$ interaction cross-section
    - change in the energy threshold of the γγ → e+e– pair production reaction
- Cosmic opacity for VHE γ rays (E > 10 TeV) that result from the interaction with the extragalactic background light can be strongly reduced

- Let's rewrite the modified relation for photons as
    - The term $m_\gamma^2 \equiv -E_\gamma^3/E_{\mathrm{LIV}}$ acts as an effective mass term for photons

$$E_\gamma^2 = p_\gamma^2 c^2 - \frac{E_\gamma^3}{E_{\mathrm{LIV}}}$$

- Assuming the same MDR, the minimum energy of the soft target photons that allow the pair-production reaction is

Fairbarn 2014

$$\epsilon_{th} = \frac{(m_e c^2)^2}{E_\gamma}\left[1 \pm \frac{1}{4}\left(\frac{E_\gamma}{E_{LIV}}\right)^{n+2}\right]$$

Modified pair cross section

- A Modified Dispersion Rrelation can also induce a modified photon kinematics, which can lead to modifications of the $\gamma\gamma$ interaction cross-section

Fairbarn 2014

$$\epsilon_{th} = \frac{(m_e c^2)^2}{E_\gamma} \left[1 \pm \frac{1}{4} \left(\frac{E_\gamma}{E_{LIV}} \right)^{n+2} \right]$$

  - superluminal case (-): the threshold is lowered and photons undergo a stronger absorption leading to steeper energy spectra
  - subluminal case (+): higher threshold leading to a reduction of VHE photon absorption and less attenuated energy spectra

- Accounting for propagation over cosmological distances :

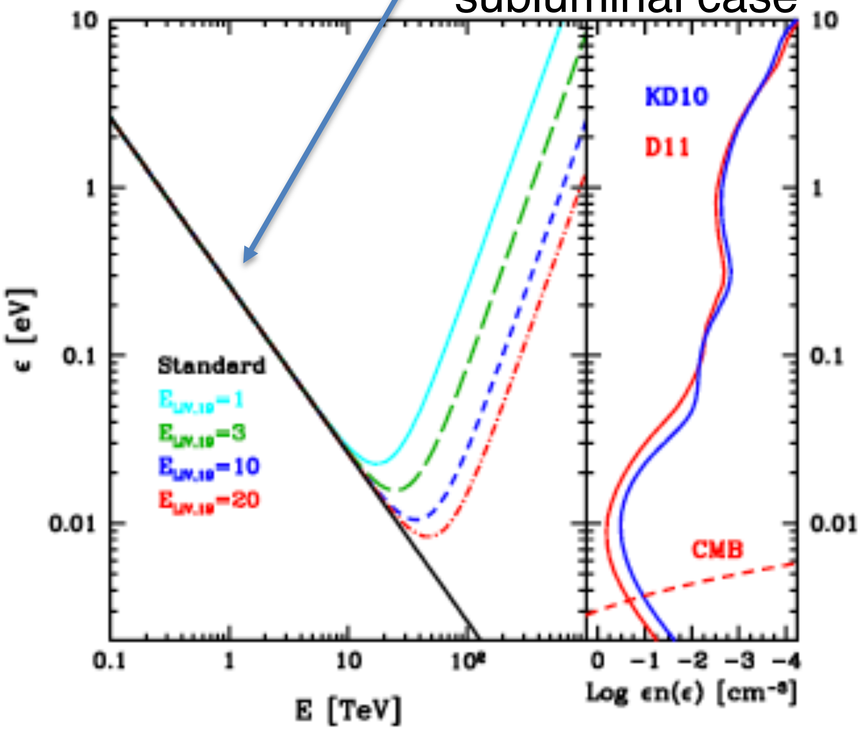
$$\epsilon_{th} \longrightarrow \frac{\epsilon_{th}}{1+z}$$

Modified pair cross section and opacity

Standard value (i.e. w/o LIV)

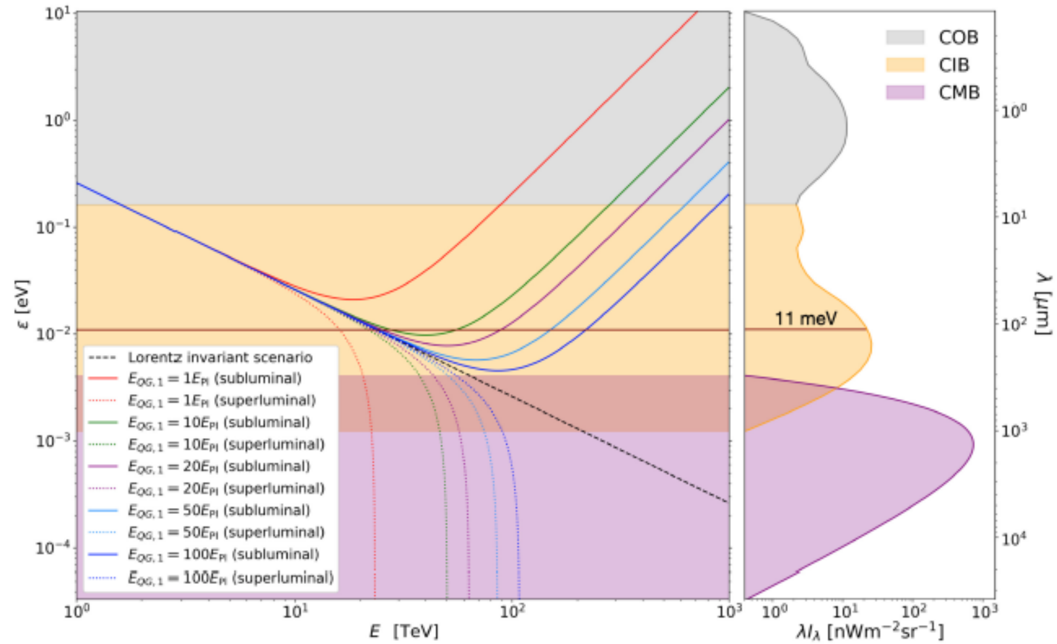
$$\epsilon_{\rm min} = m_e^2 c^4 / E_\gamma \simeq \ 0.26 / E_{\gamma,\rm TeV} \ \rm eV.$$

subluminal case



Tavecchio&Bonnoli A&A 585, A25 (2016)

EBL models from Dominguez 2011 and Kneiske 2010

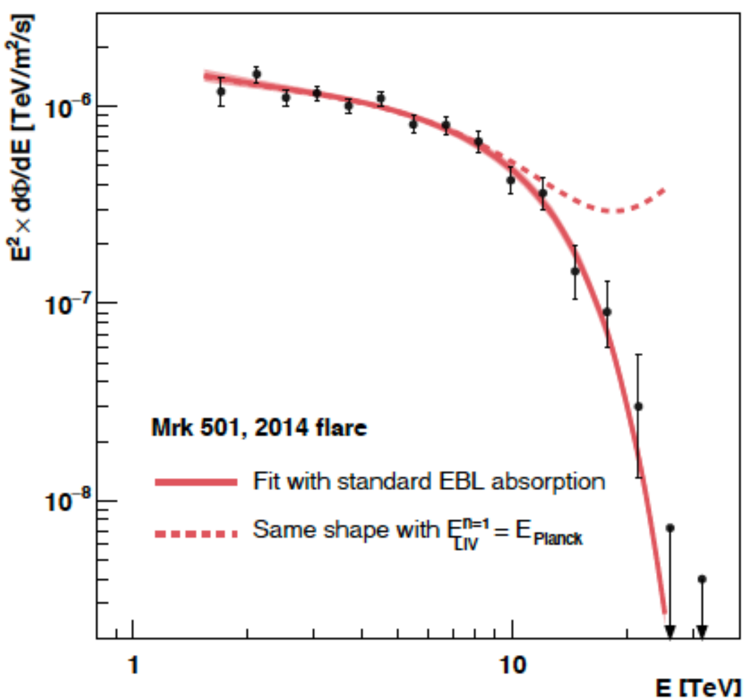


Evolution of the background photon energy threshold versus
gamma-ray energy E (here noted E) for LIV effects (n=1) at z =0.
Right: spectral energy distribution of target photon fields: optical (COB), infrared (CIB) and CMB.

Astrophysical sources for LIV-induced modified pair cross section searches

- An ideal source to test possible modifications of the γ-ray opacity induced by LIV should be a bright emitter above 20–30 TeV
  → Flaring blazars may display hard and bright TeV emission
  →“extreme” BL Lacs

- The example of Mkr 501 flare:



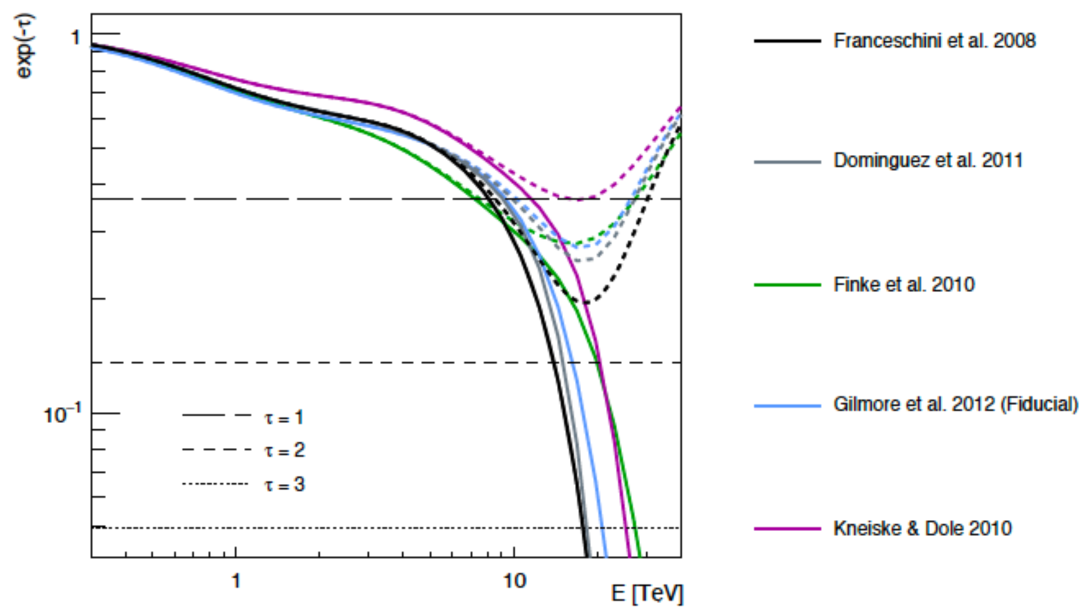
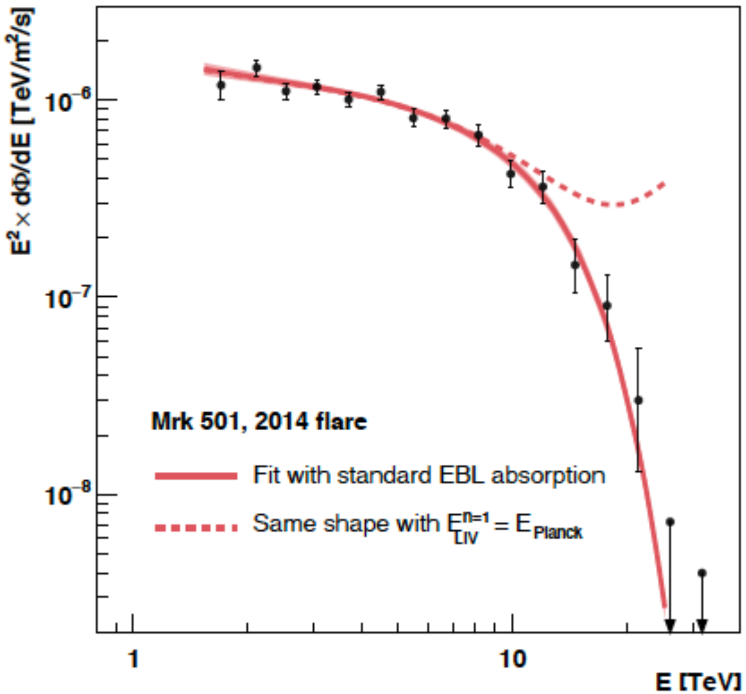


FIGURE 7.9 – *Courbes d'atténuation en considérant le redshift de Mrk 501 ($z = 0.034$) pour différents modèles d'EBL récents, dans le cas standard (ligne pleine) et en présence de LIV à l'échelle de Planck et avec $n = 1$ (lignes pointillées).*

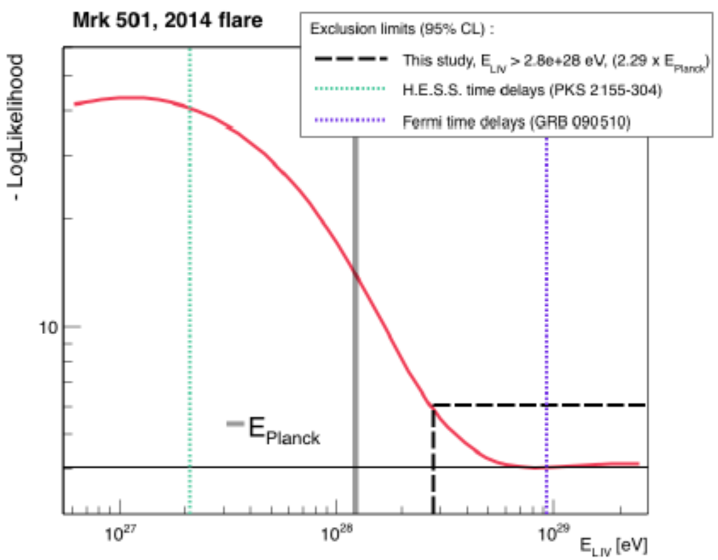
H.E.S.S. observations of 2014 Mkr 501 flare



$$\Phi_{\rm obs}(E_\gamma) = \Phi_0 \frac{E_\gamma}{E_0}^{-\alpha} \times \exp\left[-\tau_{\rm Fr08}(E_\gamma, z = 0.034, E^n_{\rm LIV})\right]$$

$$\tau(E_\gamma, z_s) = \int_0^{z_s} dz \frac{dl}{dz} \int_0^2 d\mu \frac{\mu}{2} \int_{\epsilon_{\rm seuil}}^{\infty} d\epsilon \frac{dn_{\rm EBL}}{d\epsilon}(\epsilon, z)\, \sigma_{\gamma\gamma}\left[\beta(E_\gamma(1+z), \epsilon, \mu)\right]$$

LIV effect encoded in ε and in the pair production cross. section

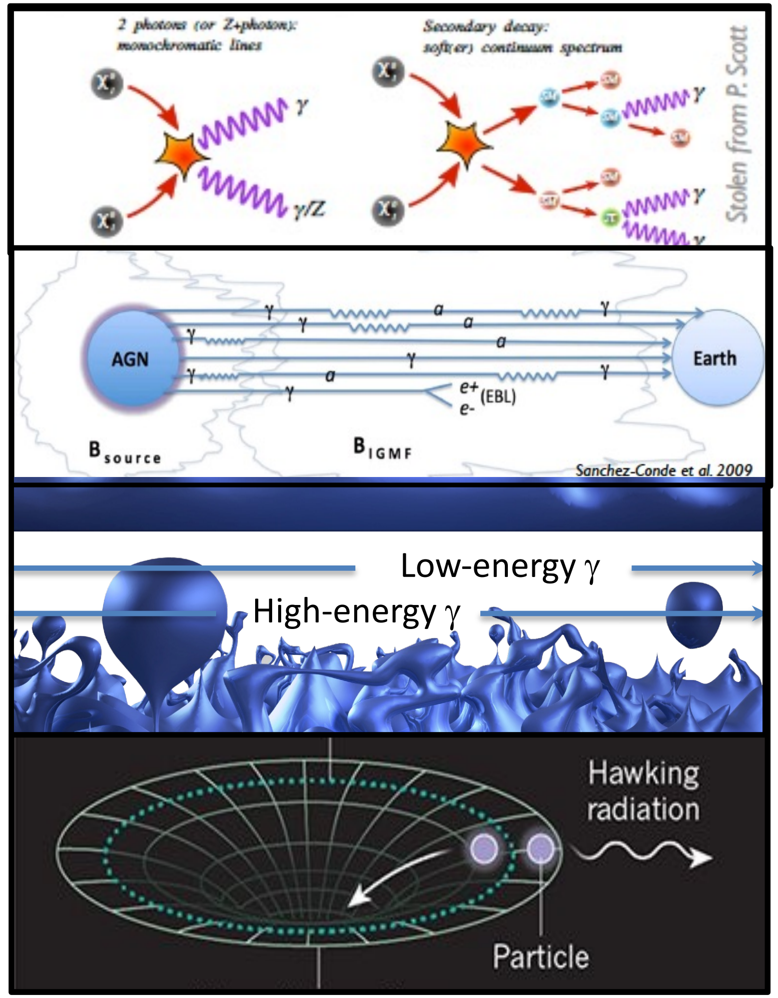


- $E_{LIV} >$ 2.3 E_{pl} for n=1 (95% C.L.)
- Stronger constaints obtained from time delay searches with GRB 090510

« Fundamental physics » in the context of multi-messenger astronomy

No conclusive identification of DM, but enormous progress in astrophysical sensitivity

- WIMP paradigm dominated the searches for decades
  - Still alive, but not alone! WIMP exploration will continue
  - Limitations in our understanding of the 'background' (aka astrophysics)
- Alternative candidates gain more and more attention
  - Rich pheno with ~PeV decaying DM, ALP, PBH, …



BSM physics can also manifest as apparent violations of laws/symmetries of the SM:

- ALPs/LIV may alterate the apparent transparency of the universe
- LIV may induce a modified dispersion relation of photons

End

Thank you for your attention!

For further questions do not hesitate to get in touch with me
emmanuel.moulin@cea.fr