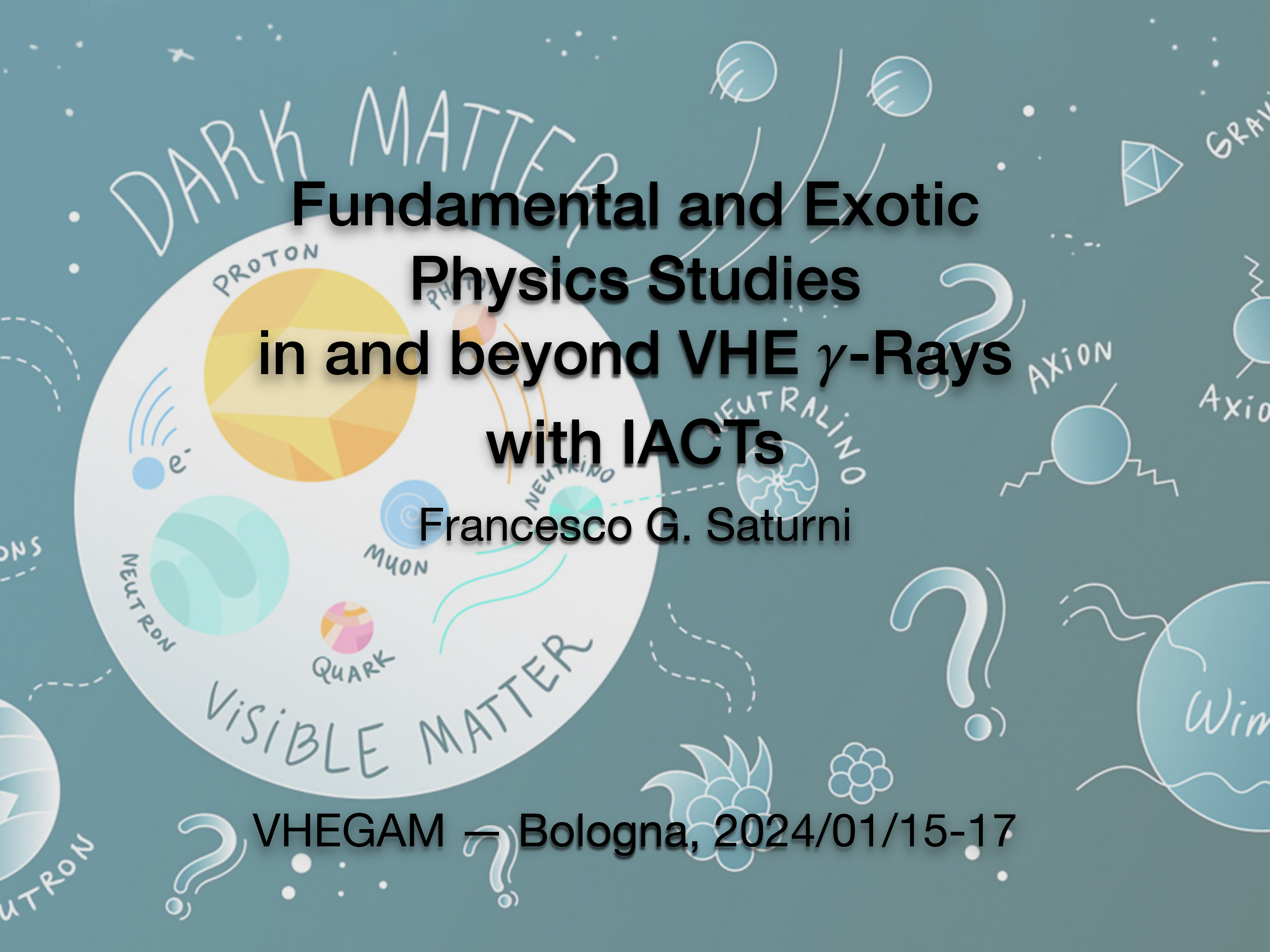


Fundamental and Exotic Physics Studies in and beyond VHE γ-Rays with IACTs

Francesco G. Saturni

VHEGAM — Bologna, 2024/01/15-17

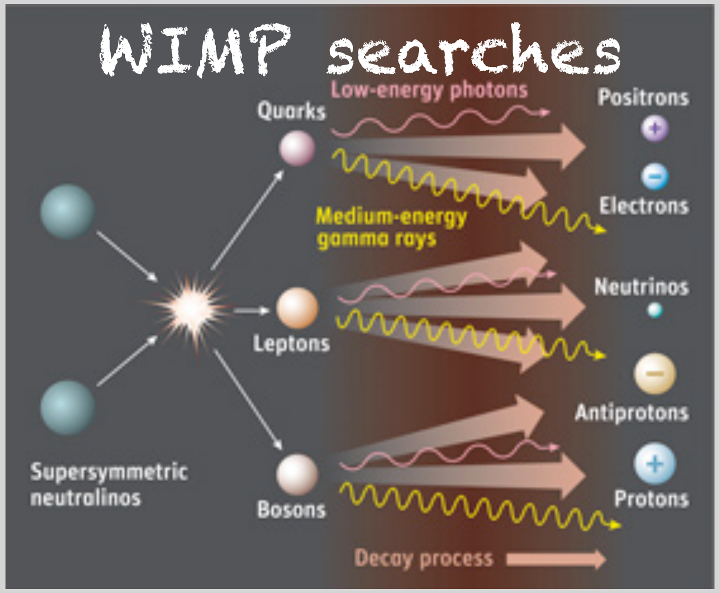
OUTLINE

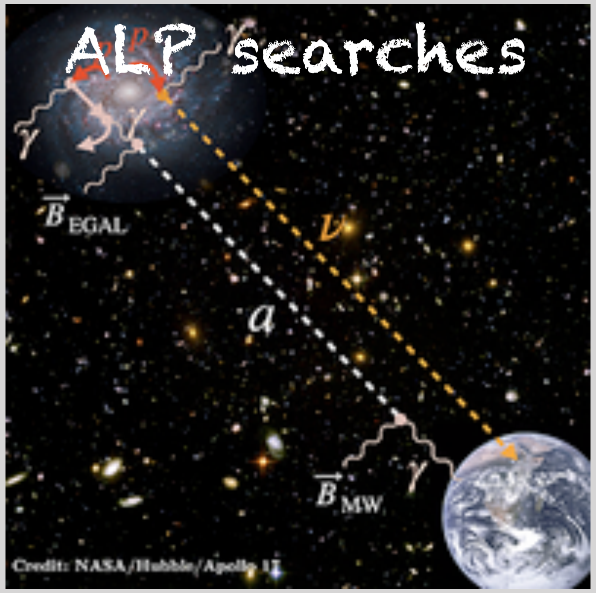
- Overview on fundamental and exotic physics studies with IACTs
- Dark matter searches in VHE γ-rays with IACTs
- IACT fundamental physics studies with γ-rays
- IACT fundamental physics studies beyond γ-rays
- Summary

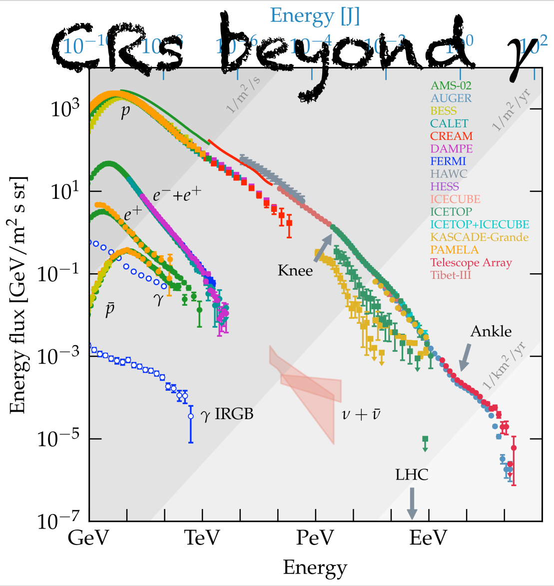
Overview on fundamental and exotic physics studies with IACTs

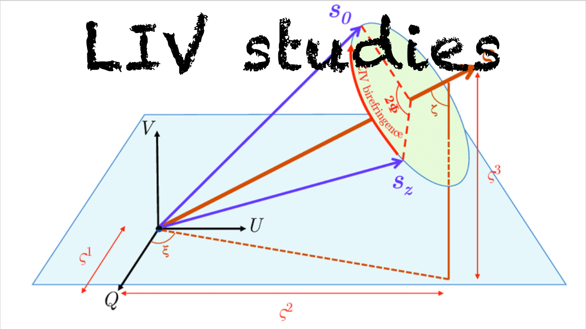
Overview on fundamental and exotic physics studies

- IACTs are a powerful tool for a range of astroparticle, fundamental and exotic physics topics.









Overview on fundamental and exotic physics studies

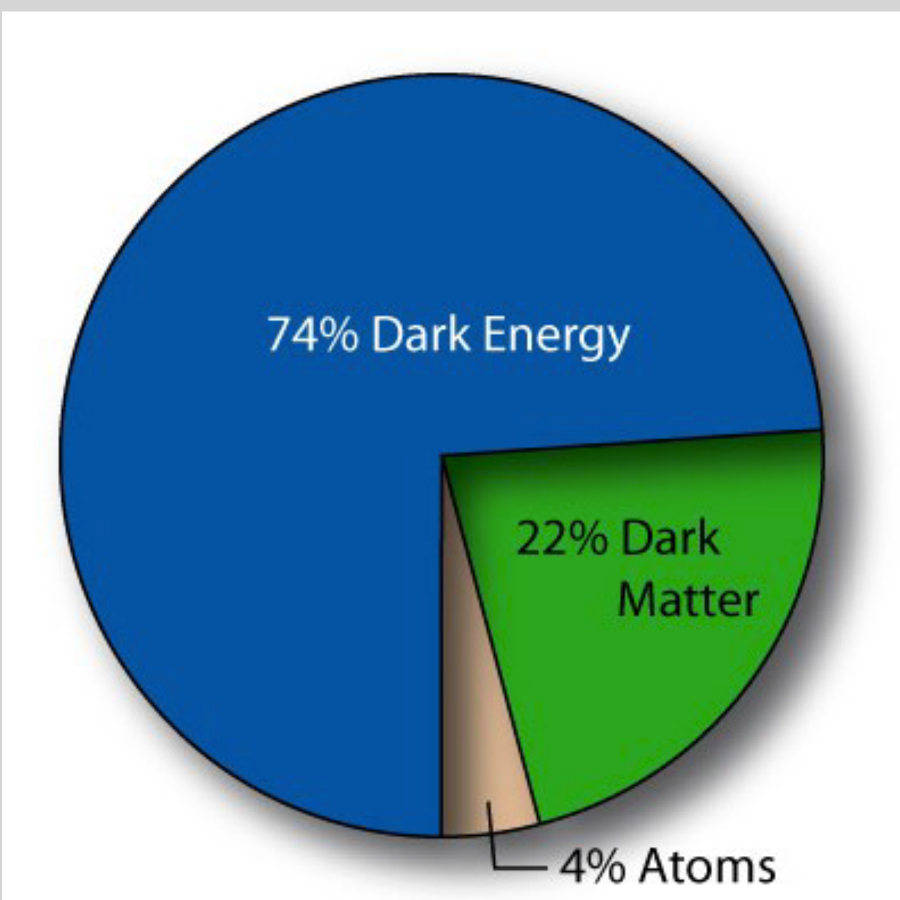
- IACTs are a powerful tool for a range of astroparticle, fundamental and exotic physics topics.

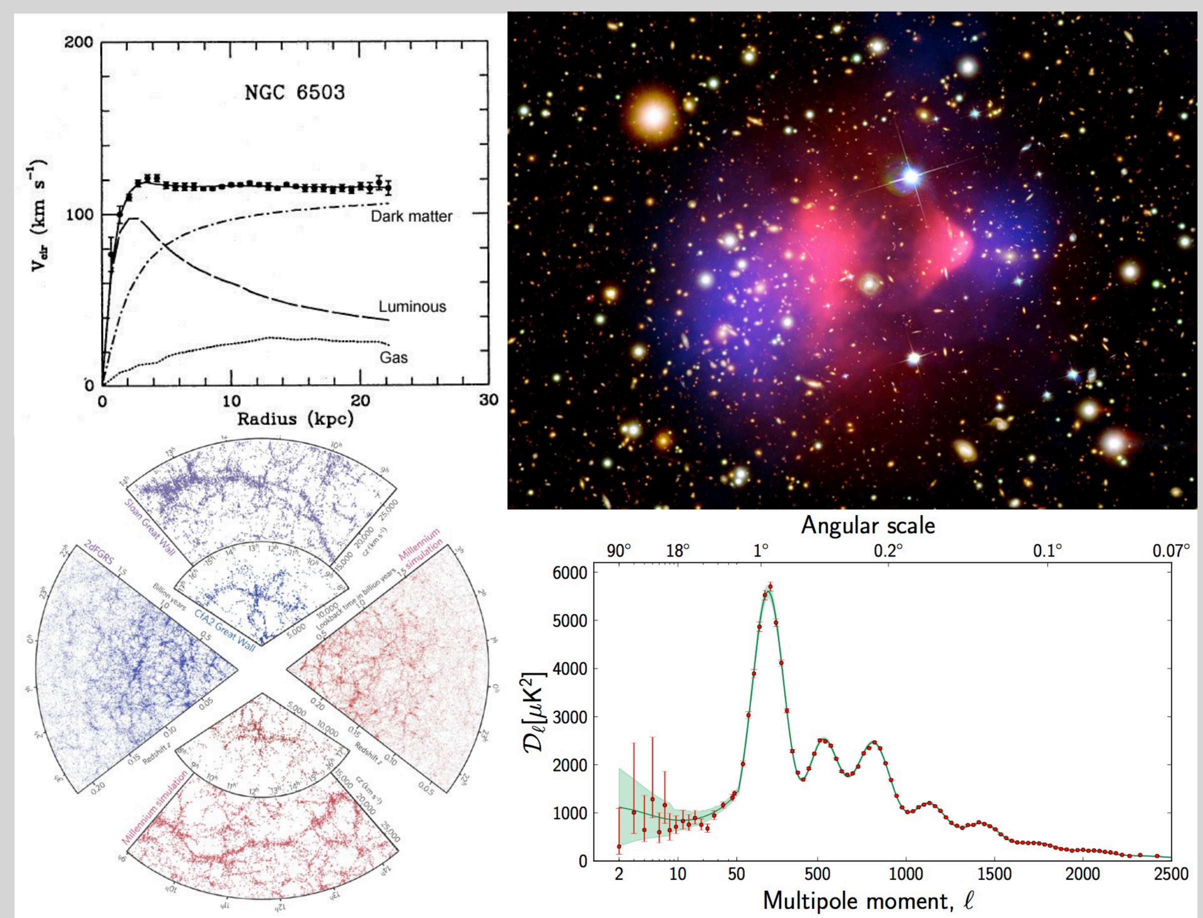
Dark matter searches in VHE γ-rays with IACTs

DM searches in VHE γ-rays with IACTs: WIMPs

- Dark matter (DM) is the major component of the Universe matter content (~22% of the total energy budget);

- its existence only indirectly inferred so far from several astrophysical/cosmological observations.





DM searches in VHE γ-rays with IACTs: WIMPs

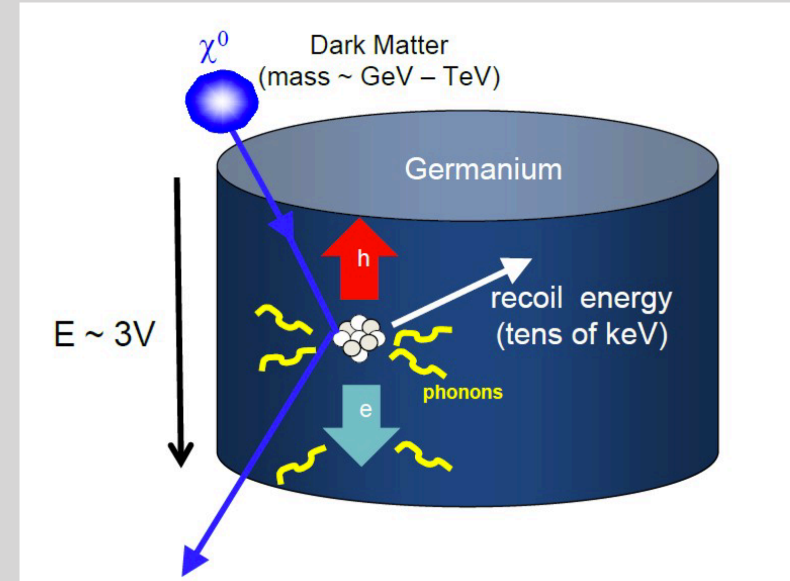
- Paradigm of massive particle DM (WIMPs) characteristics:
  - — large masses (from cosmology)
  - — small cross sections with baryonic matter (from direct detection and production experiments)

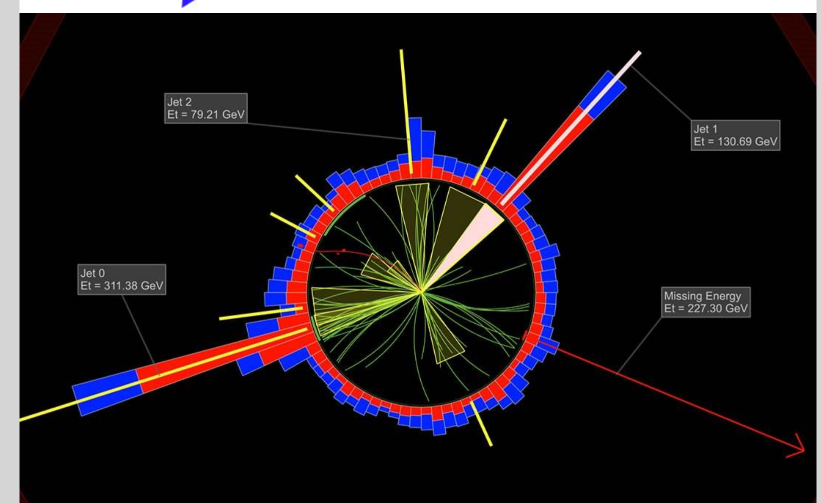
Direct detection

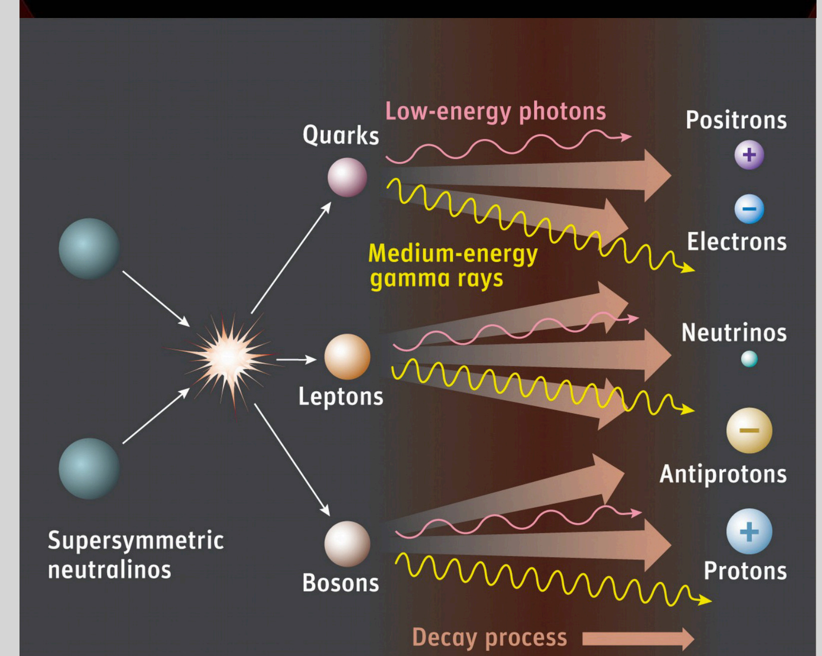
Production

- Cherenkov telescopes look for production of VHE photons from WIMP self-interaction (annihilation or decay).

Indirect detection







DM searches in VHE γ-rays with IACTs: WIMPs

- γ-ray fluxes expected from WIMP interactions:

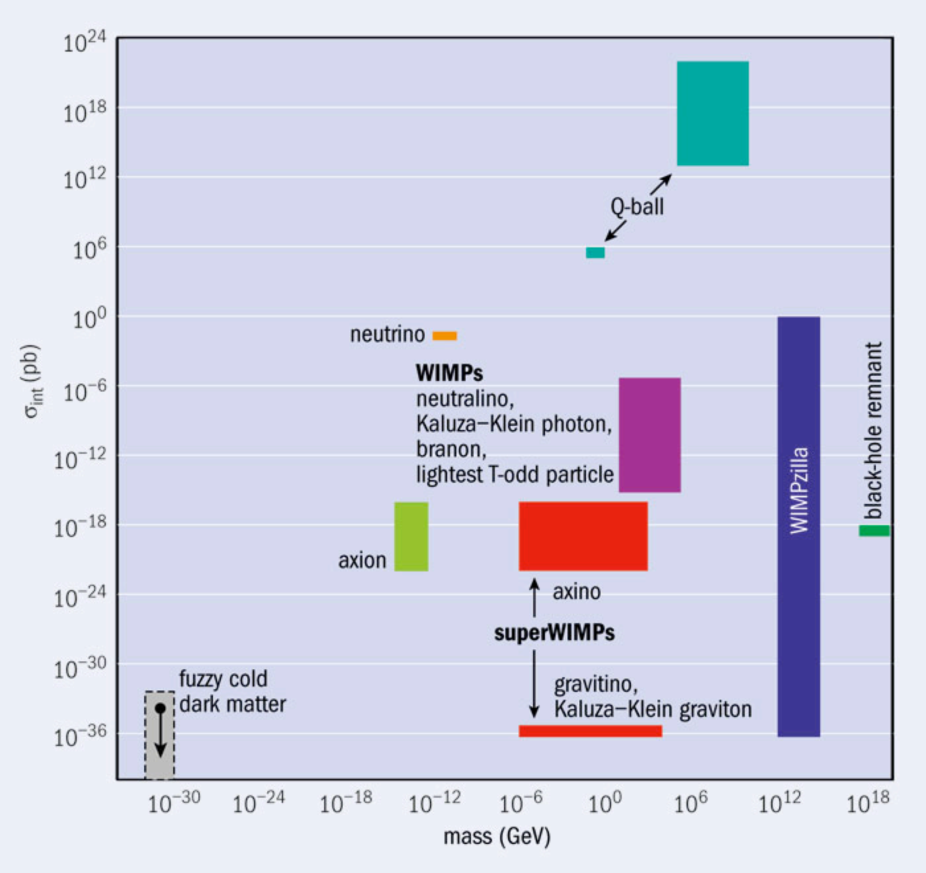
$$\frac{d\Phi_{\rm ann}}{dE_\gamma} = \frac{\langle \sigma_{\rm ann} v \rangle}{8\pi m_\chi^2} \sum_i {\rm BR}_i \frac{dN_\gamma^{(i)}}{dE_\gamma} J(\Delta\Omega)$$

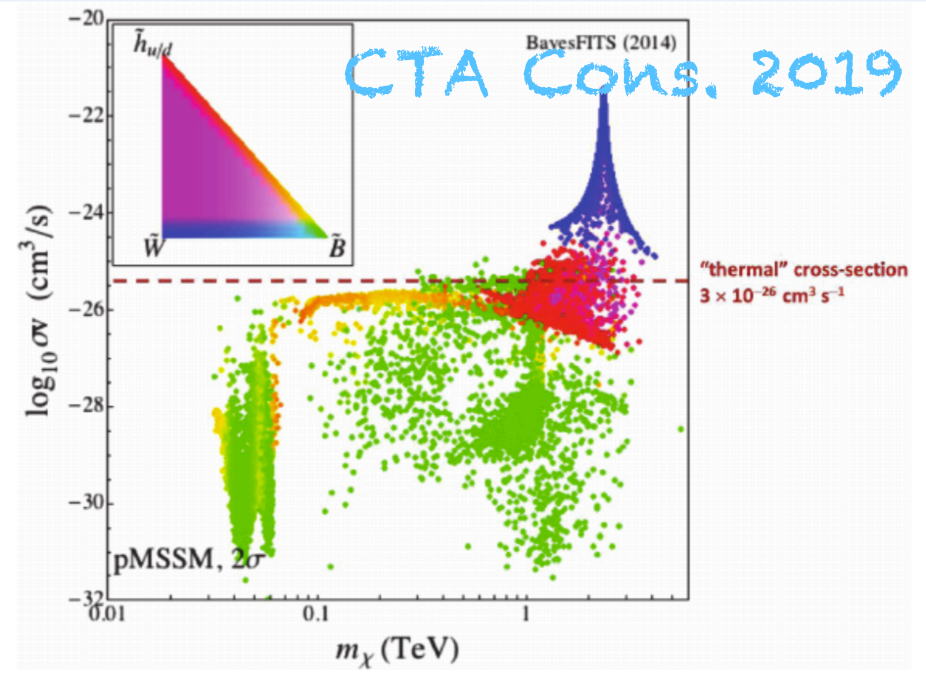
$$\frac{d\Phi_{\rm dec}}{dE_\gamma} = \frac{1}{4\pi m_\chi} \sum_i \Gamma_i \frac{dN_\gamma^{(i)}}{dE_\gamma} D(\Delta\Omega)$$

- The quantities that determine flux intensities are the so-called astrophysical factors *J* and *D*:

$$J(\Delta\Omega) = \int_{\Delta\Omega} d\Omega \int_{\rm l.o.s.} \rho_{\rm DM}^2(\ell;\Omega) d\ell$$

$$D(\Delta\Omega) = \int_{\Delta\Omega} d\Omega \int_{\rm l.o.s.} \rho_{\rm DM}(\ell;\Omega) d\ell$$





DM searches in VHE γ-rays with IACTs: WIMPs

- Several methods available to compute astrophysical factors for WIMP DM halos:

  — empirical models of velocity dispersion
  — likelihood maximization of dynamic equations
  — semi-analytical integrations
  — Bayesian analysis of halo properties
  — MCMC Jeans analysis of halo kinematics

$$\frac{1}{n_*}\left[\frac{d}{dr}\left(n_*\overline{v_r^2}\right)\right]+\frac{2}{r}\beta_{\mathrm{ani}}(r)\overline{v_r^2}=-\frac{G\left[M_{\mathrm{DM}}(r)+M_*(r)\right]}{r^2}$$

- **None of them completely free of biases** that can affect the DM amount determination, and thus the final estimates of the expected γ-ray WIMP DM signal.

DM searches in VHE γ-rays with IACTs: WIMPs

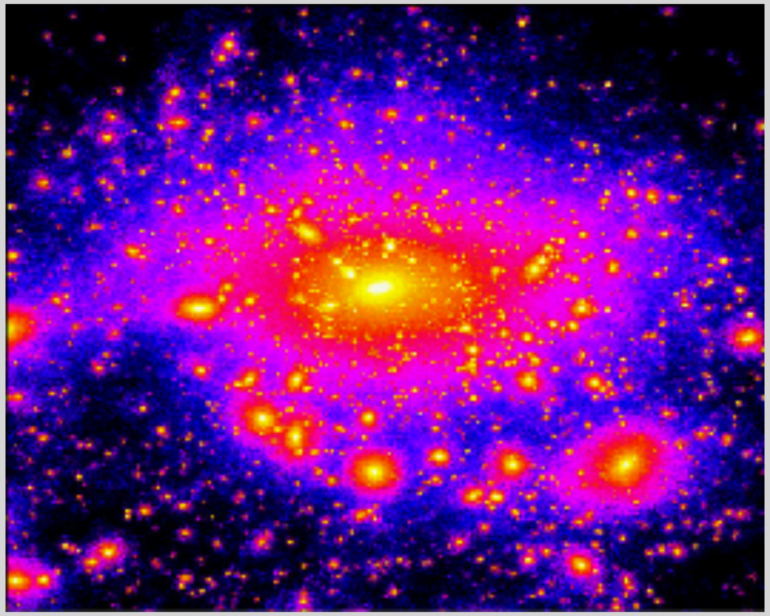
- Main targets for indirect WIMP DM searches:

Galactic Centre (GC) and halo

Dwarf spheroidal galaxies (dSphs)

Galaxy clusters

Dark clumps



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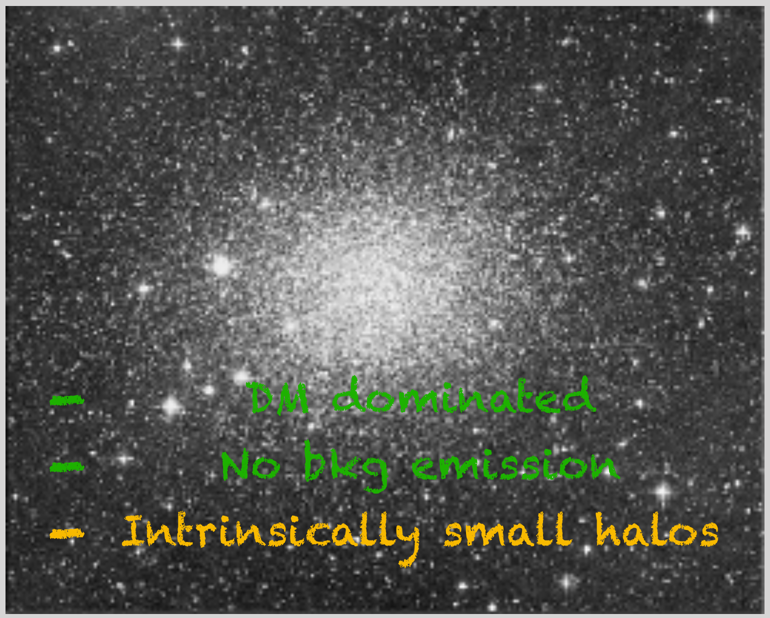

Galaxy clusters

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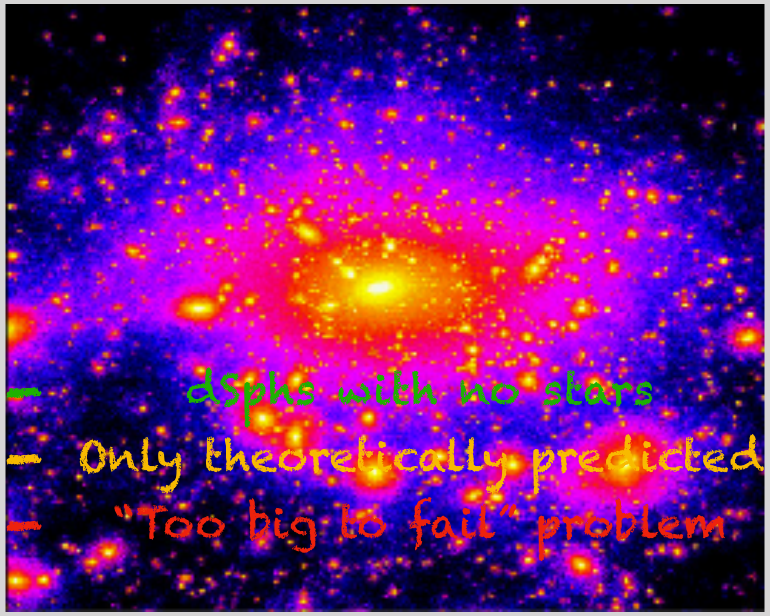
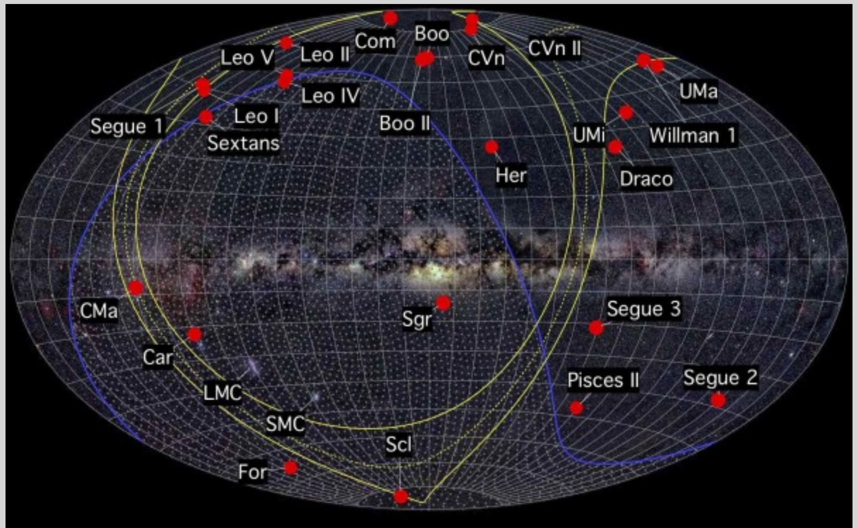
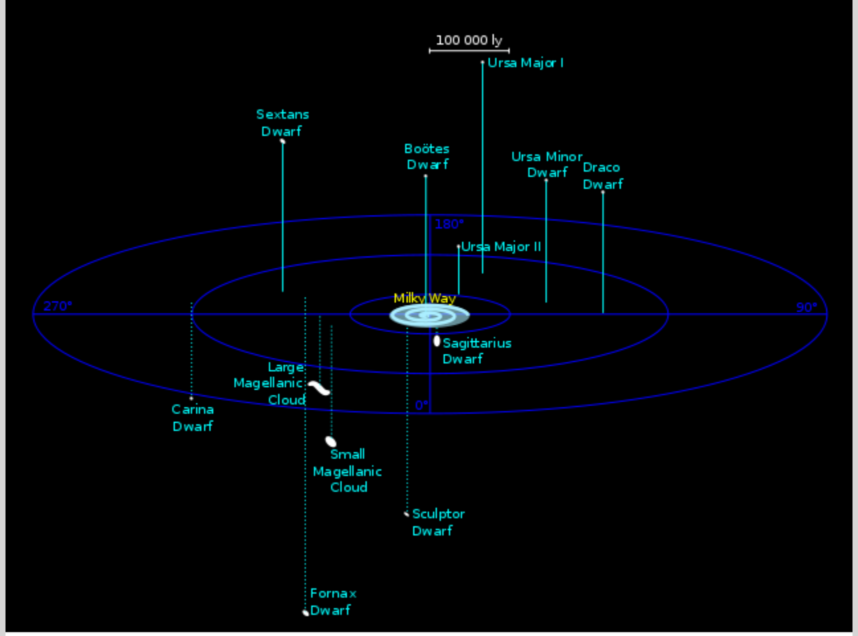


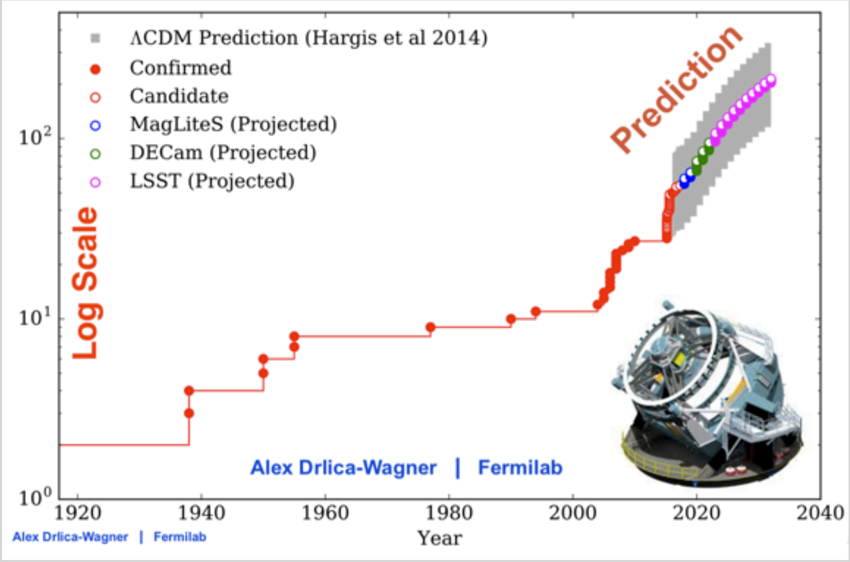
DM searches in VHE γ-rays with IACTs: WIMPs

- Several dSphs already known around the Milky Way, divided in two main categories:
  - **classical** (~100 to ~1000 member stars)
  - **ultra-faint** (<100 member stars)

- Many more to be discovered in the future thanks to telescope technology and performance improvements (e.g., the "Vera C. Rubin" Observatory).

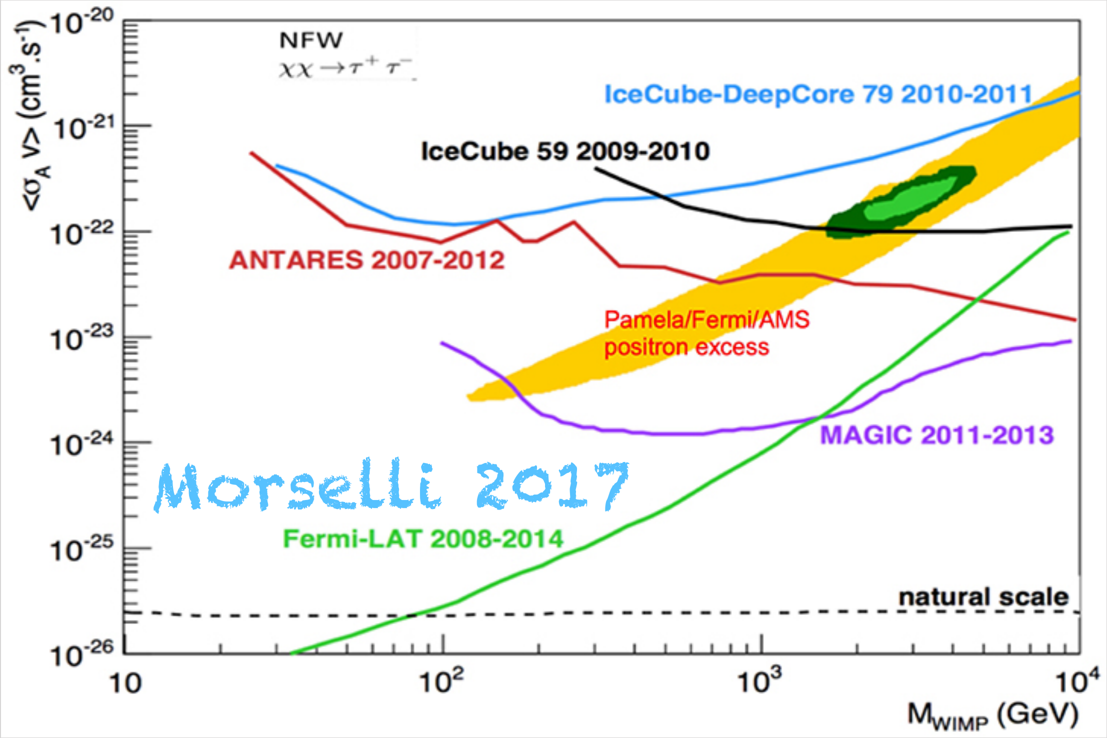


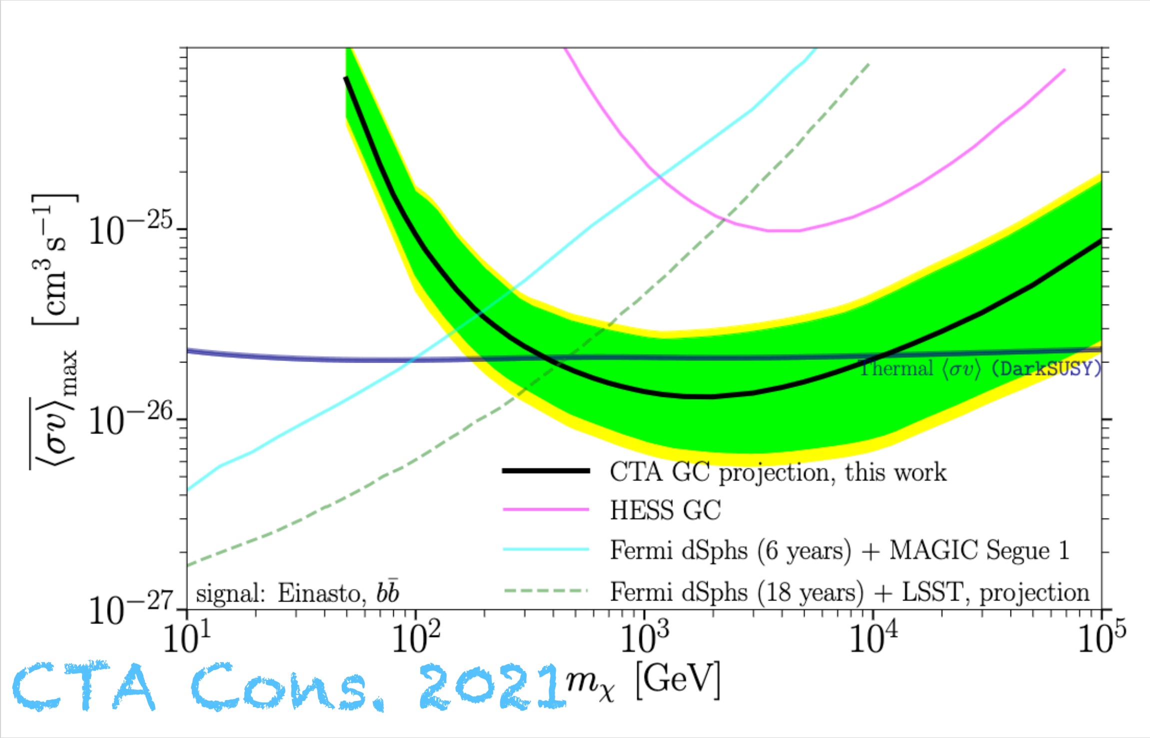


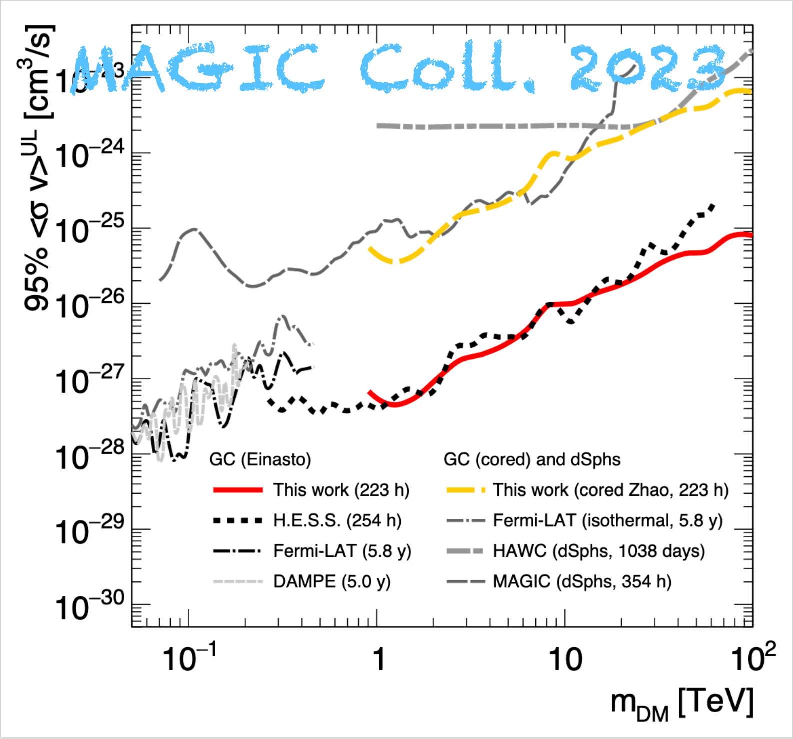


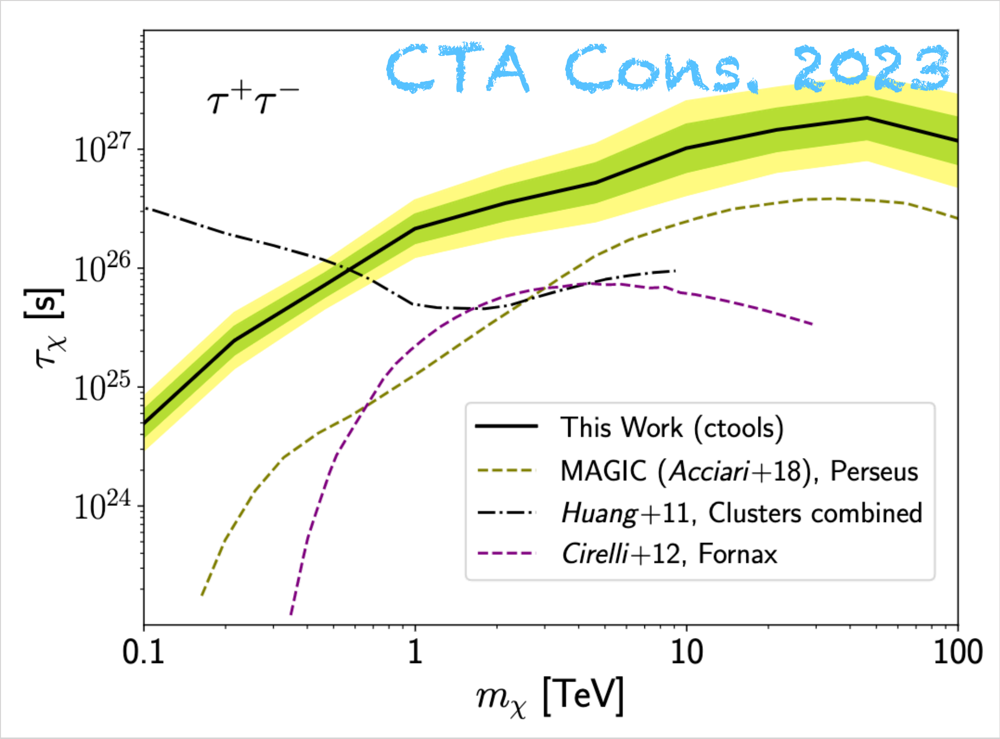
DM searches in VHE γ-rays with IACTs: WIMPs

- Current status of WIMP DM searches in VHE γ-rays:









DM searches in VHE γ-rays with IACTs: WIMPs

- For particle masses >1 TeV, the thermal-relic limit for WIMP annihilation x-sections is not reached yet => **room for improvement with new IACTs**.

- In the case of WIMP decay, particle lifetimes >10^{27} s already probed at multi-TeV masses.

Open issues:

1. GC — exact shape of the Milky Way's DM density profile still unknown (cored or cuspy?) => bias in expected signal intensity.
2. GC — high amount of emission from potential contaminants (diffuse bkg, unresolved pt-like sources, Fermi bubbles) => difficult data analysis.
3. dSphs — challenging determination of dSph astrophysical factors (especially for faint targets) => biases in expected signal intensity.
4. dSphs — still missing appropriate general treatment of measurement biases (triaxiality, tidal disruption degree) => biases in expected signal intensity.
5. Clusters — still uncertain estimate of subhalo contribution to DM amount of galaxy clusters => biases in expected signal intensity (DM annihilation only).

DM searches in VHE γ-rays with IACTs: ALPs

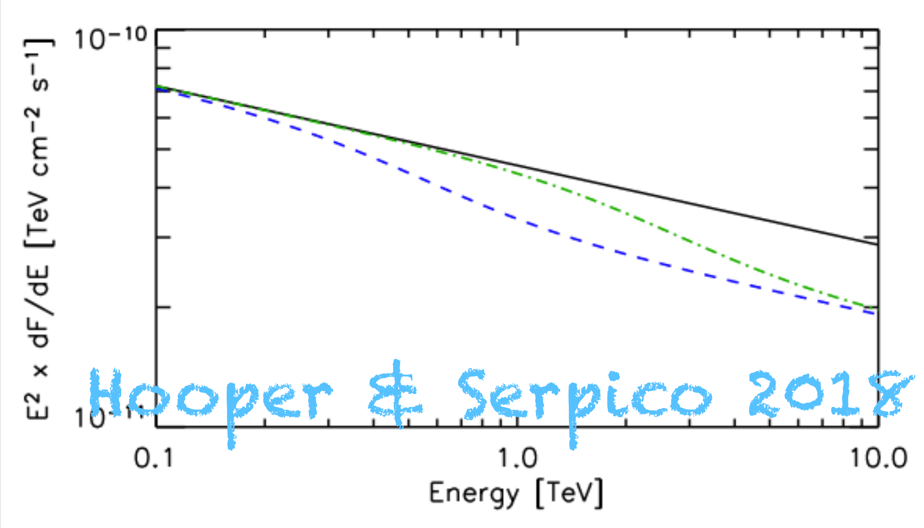
- Another possibility: axion-like particles (ALPs).

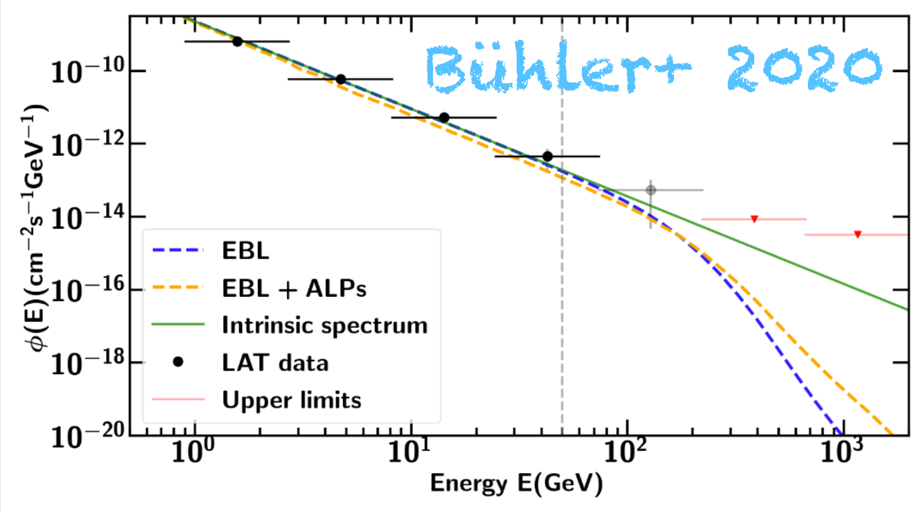
- ALPs are (almost) massless and can convert from/to photons in a magnetic field:

$$P_{\rm osc} = \sin^2(2\theta)\sin^2\left[\frac{g_{a\gamma}Bs}{2}\sqrt{1+\left(\frac{\mathscr{E}}{E_\gamma}\right)^2}\right]$$

- Such oscillations may distort γ-ray spectra:

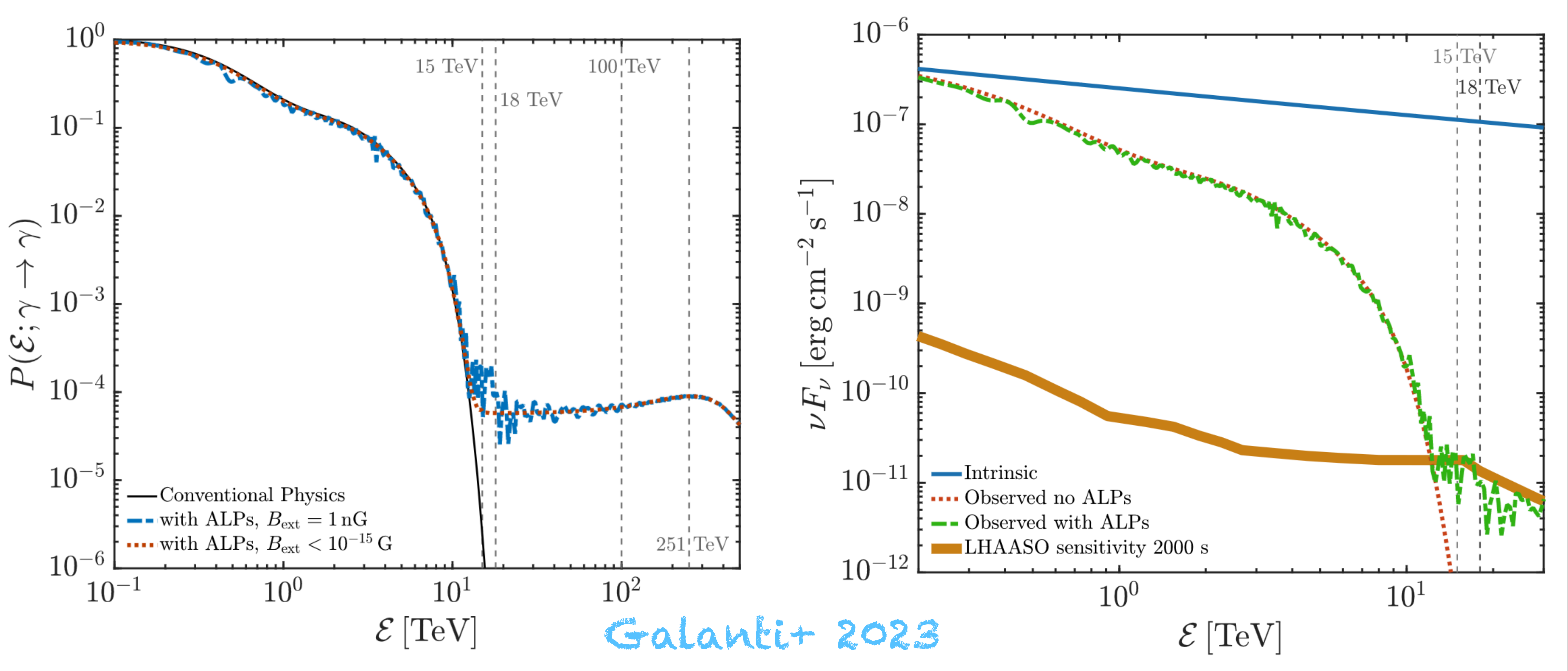
$$F_a\left(E_\gamma\right) = \left[1 - \frac{\mathscr{A}}{1+\left(\mathscr{E}/E_\gamma\right)^2}\right] F_0\left(E_\gamma\right)$$





DM searches in VHE γ-rays with IACTs: ALPs

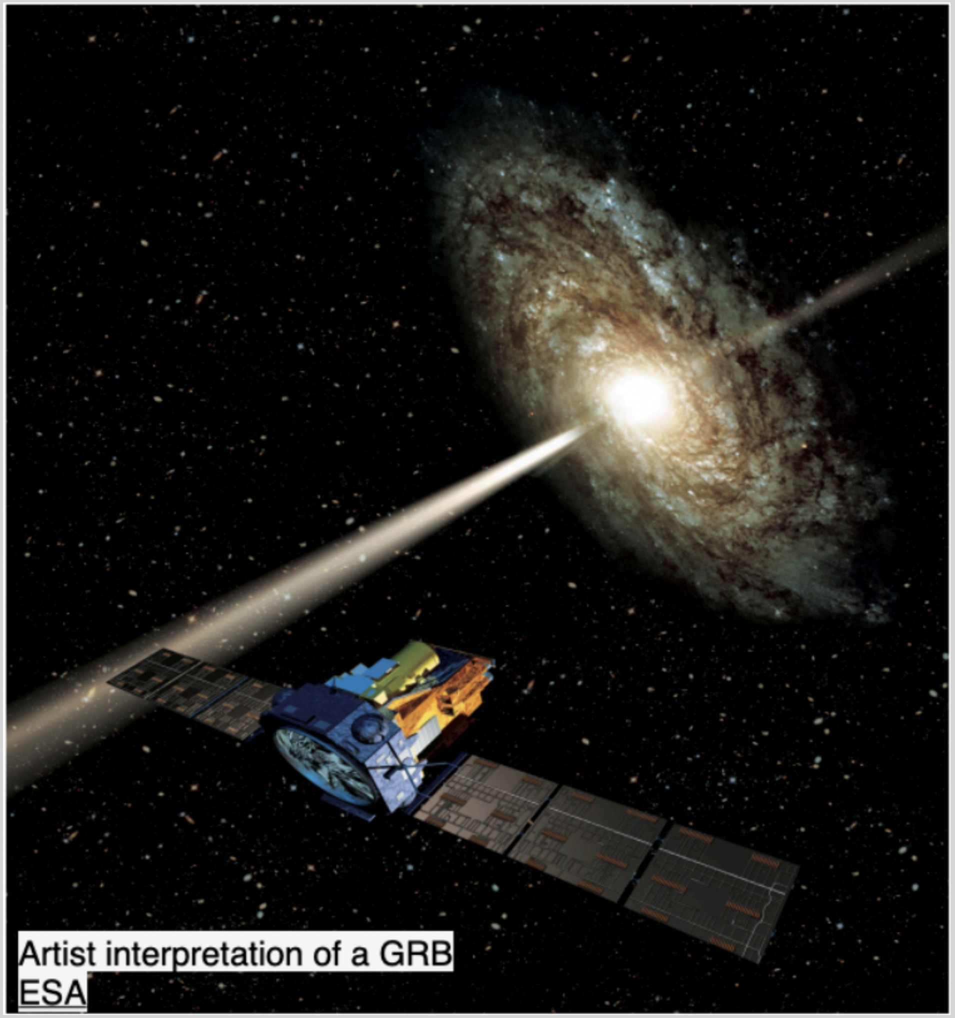
- Photon-ALP coupling can also lead to “photon resurrection” effects (VHE γ-rays “ignoring” the EBL absorption by being transformed to ALPs and vice versa):



DM searches in VHE γ-rays with IACTs: ALPs

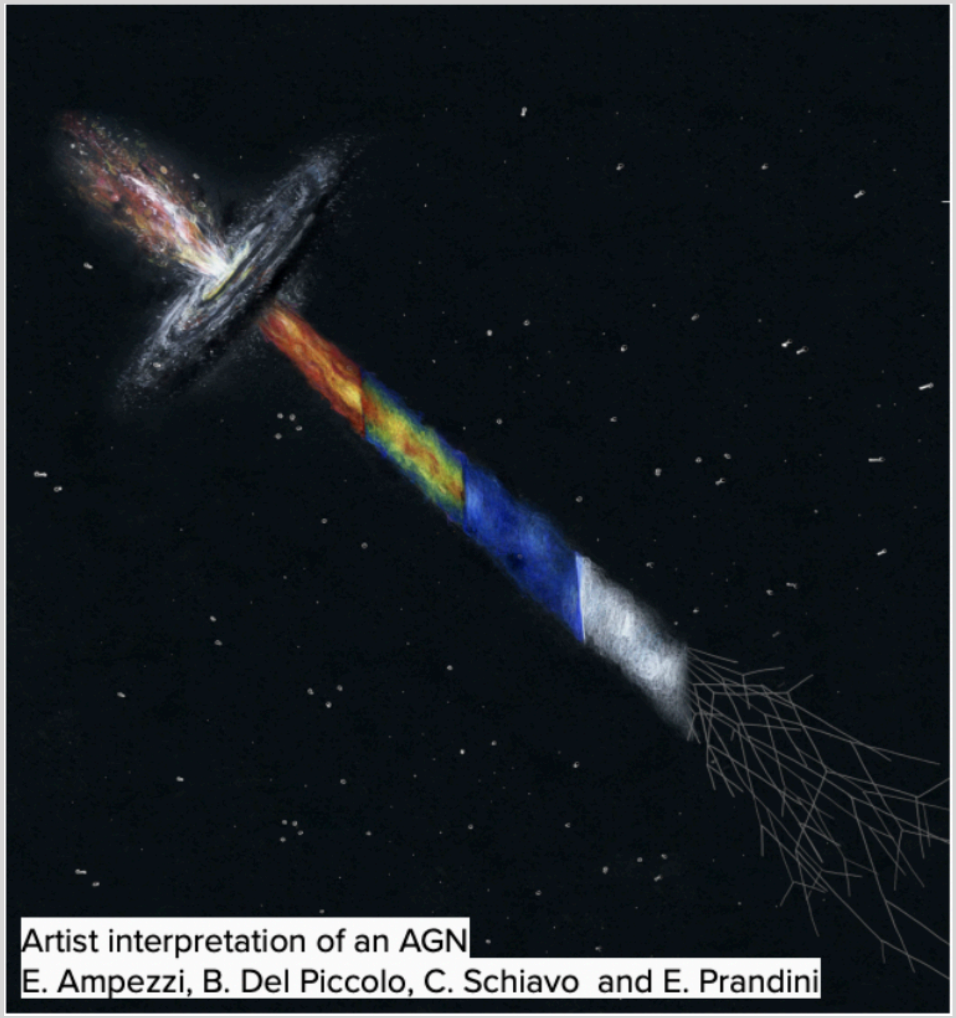
- Main targets for ALP searches:

γ-ray bursts (GRBs)



Artist interpretation of a GRB
ESA

Active galactic nuclei (AGN)



Artist interpretation of an AGN
E. Ampezzi, B. Del Piccolo, C. Schiavo and E. Prandini

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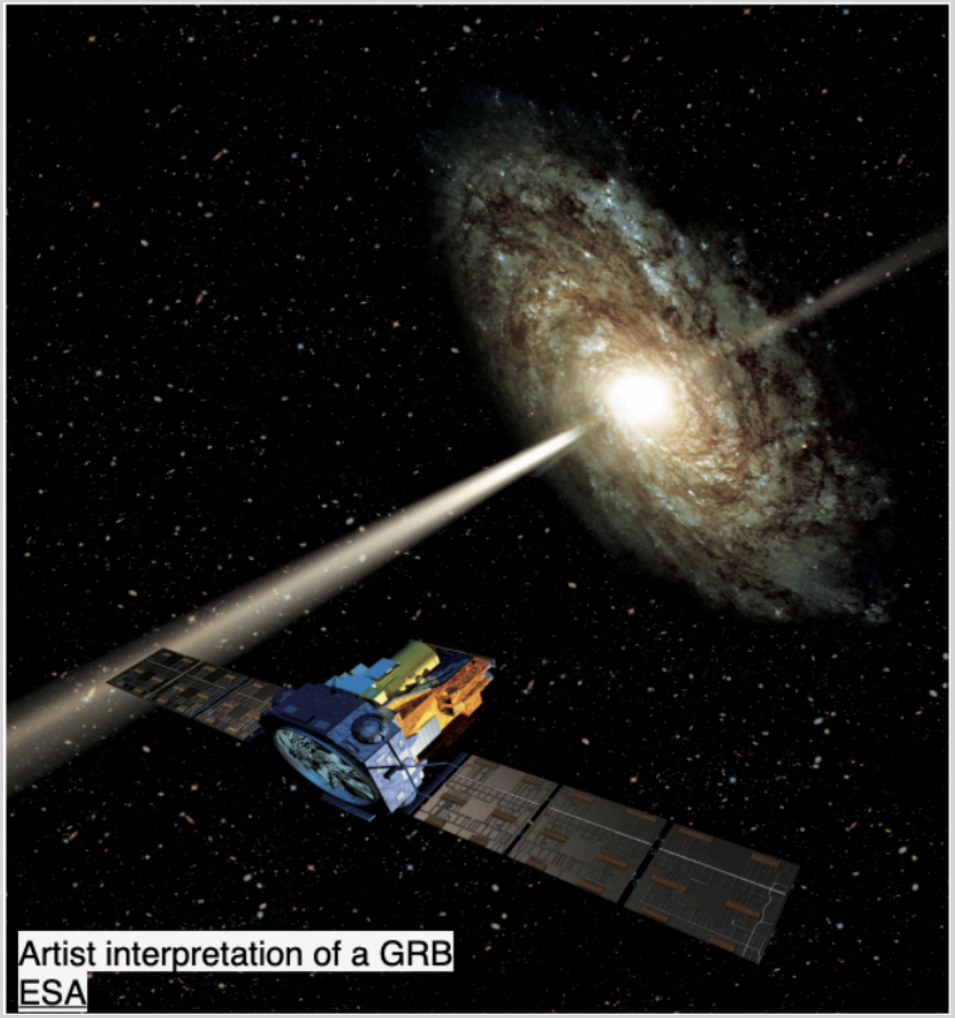
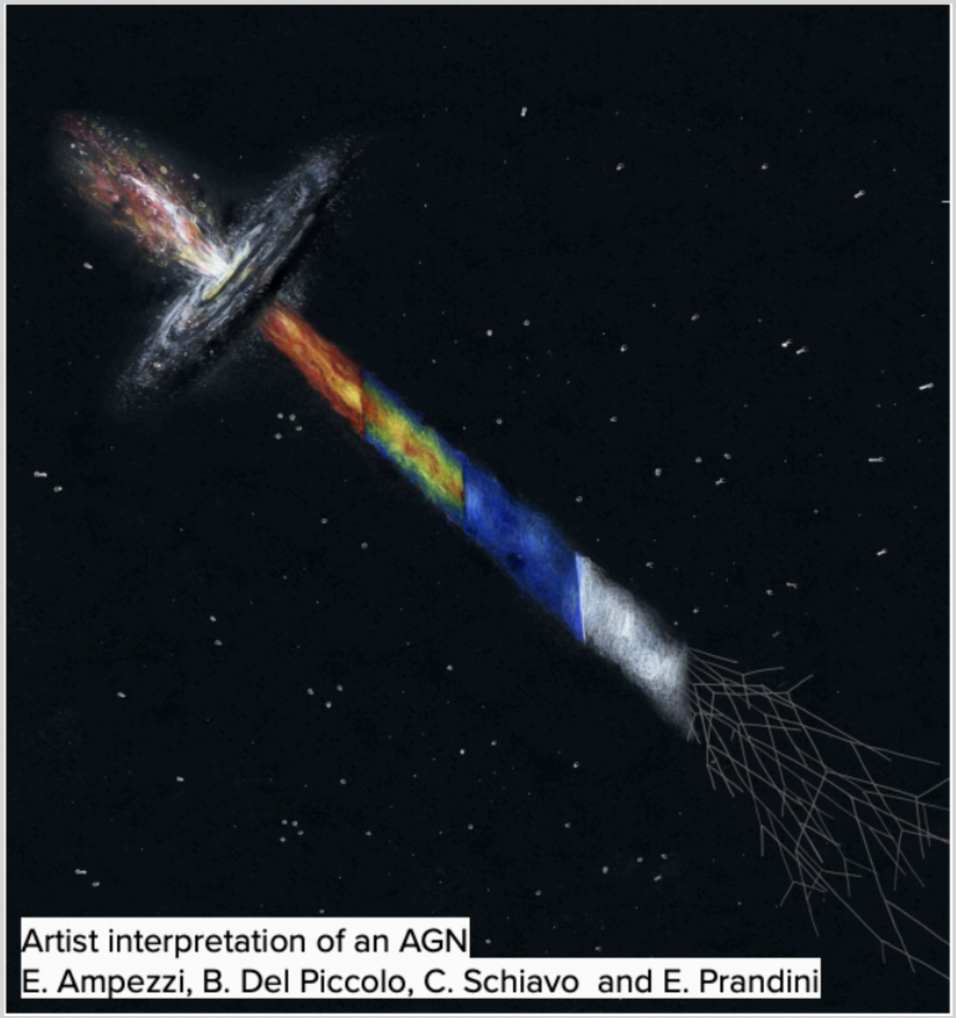


- Potentially nearby
- Transient
- Directional

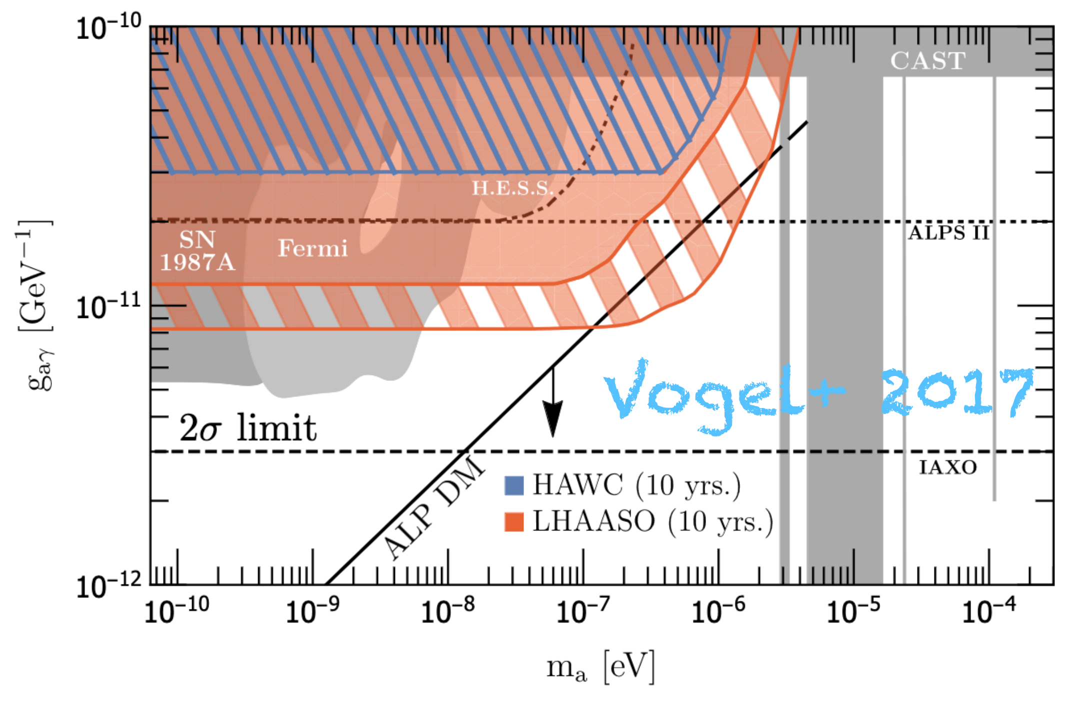
Active galactic nuclei (AGN)

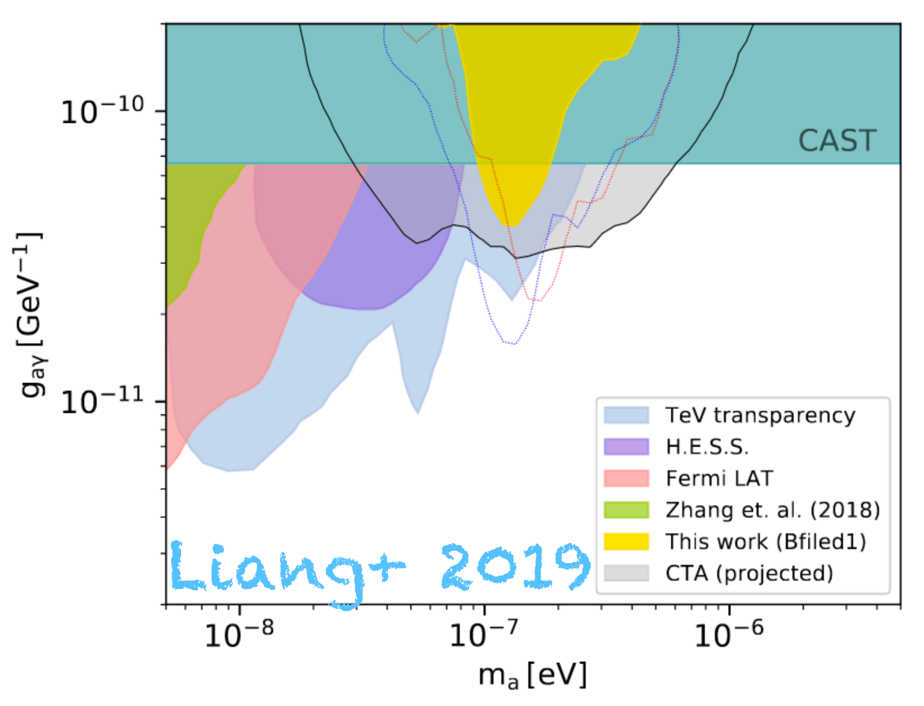


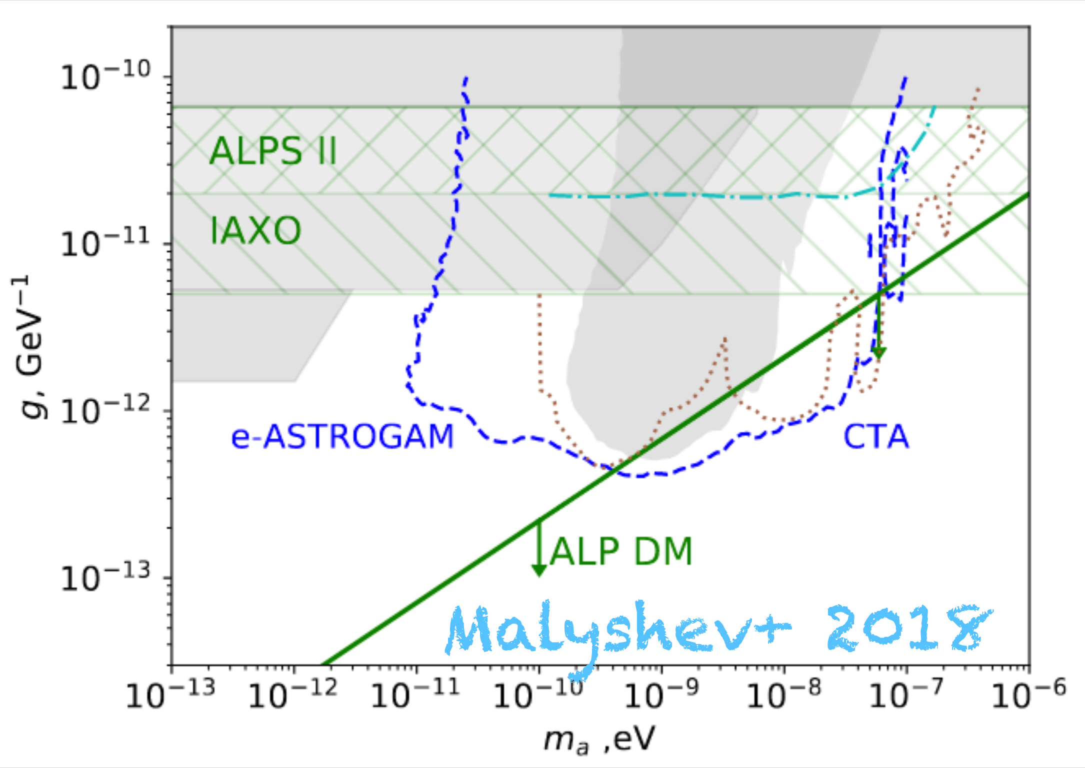
- Hard spectra extended to multi-TeV energies
- Subject to EBL absorption

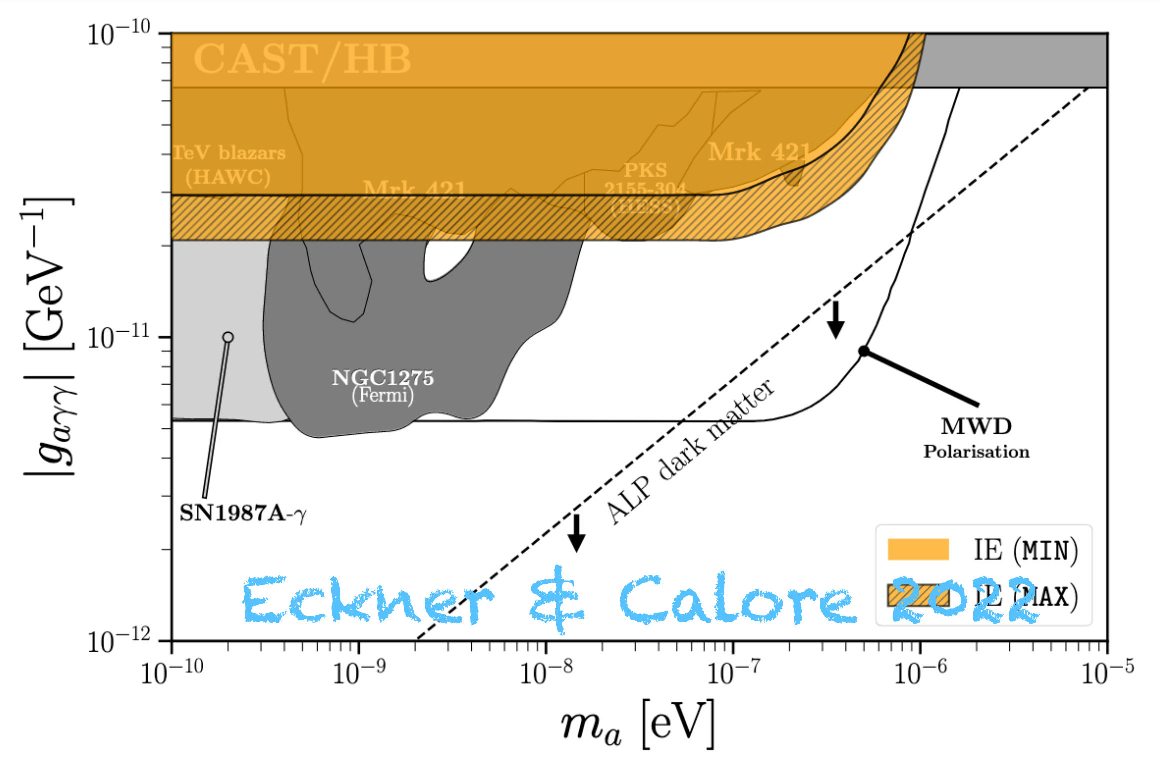
DM searches in VHE γ-rays with IACTs: ALPs

- Current status of ALP searches in VHE γ-rays:





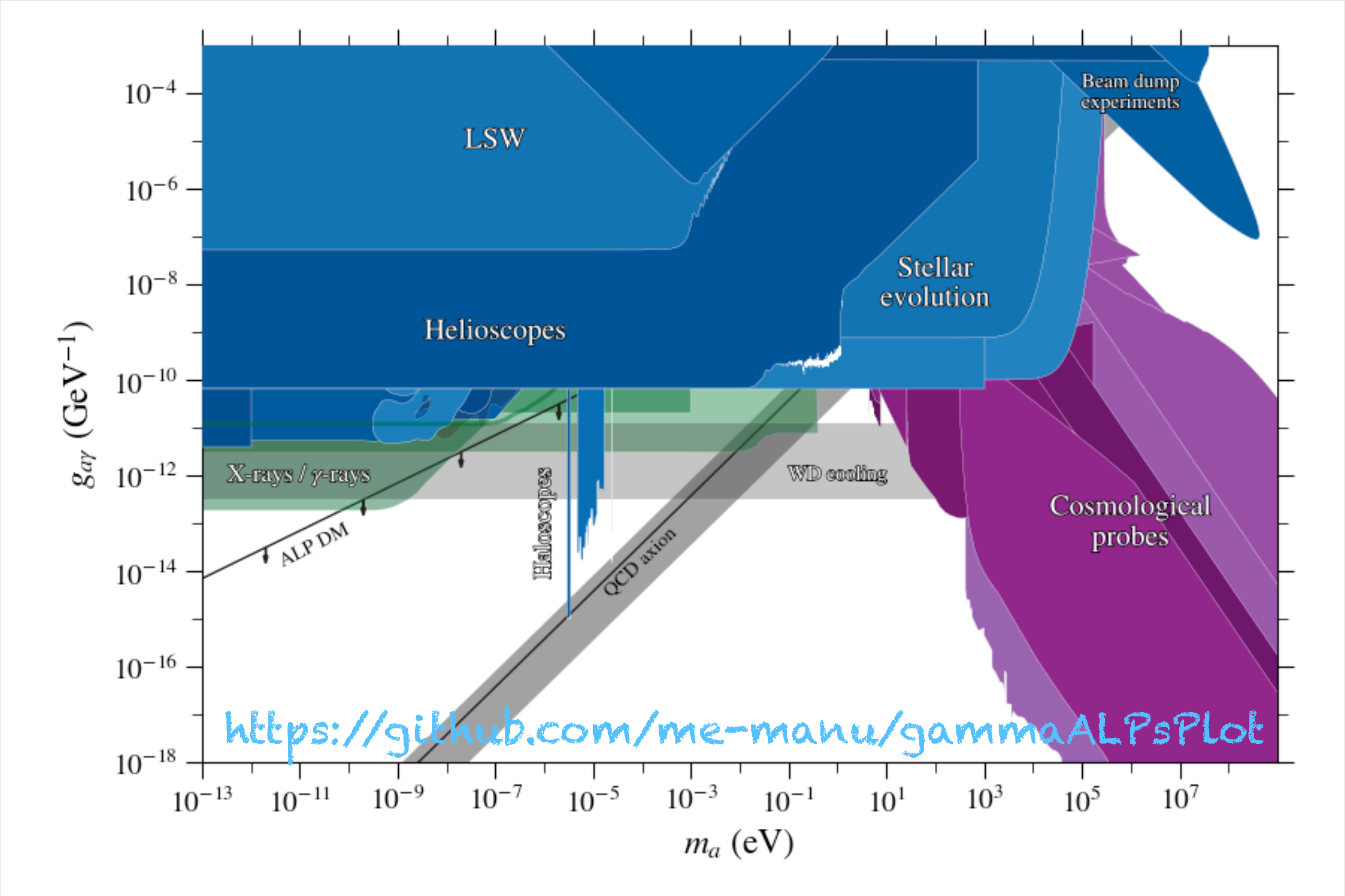




DM searches in VHE γ-rays with IACTs: ALPs

- ALP DM expected to have particle masses between ~10^{-10} eV and ~10^{-7} eV with coupling constants <10^{-12} GeV^{-1} => **room for improvement with new IACTs**.

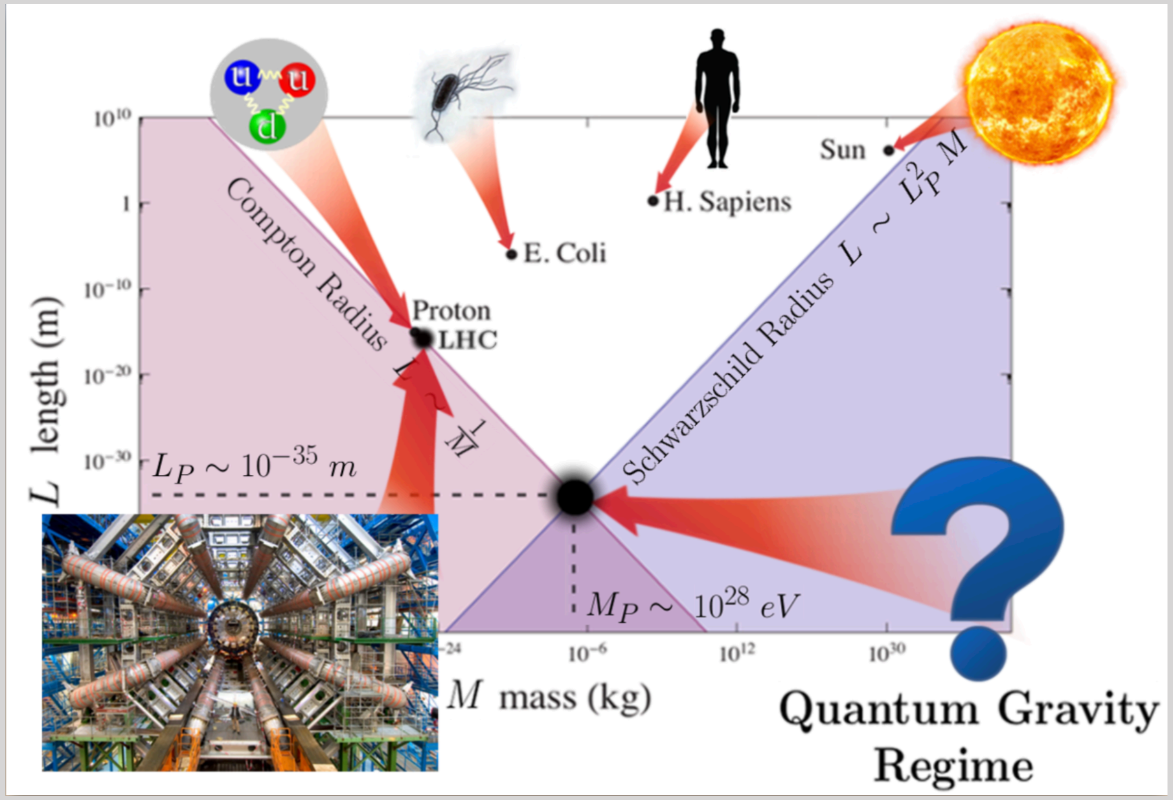
- "Photon resurrection" induced by ALP-photon coupling => **big field to be explored with new IACTs**.



IACT fundamental physics studies with γ-rays

IACT fundamental physics studies with γ-rays: LIV

- Violations of the Lorentz symmetries lie at the heart of the unification between quantum mechanics and general relativity (quantum gravity, QG);



- Lorentz invariance violation (LIV) naturally arises from introducing the Planck length as an additional constant independent of the reference system.

$$\Delta t_n \simeq \pm \frac{n+1}{2}\left(\frac{E_2^n - E_1^n}{E_{\mathrm{QG}}^n}\right) D_n(z)$$

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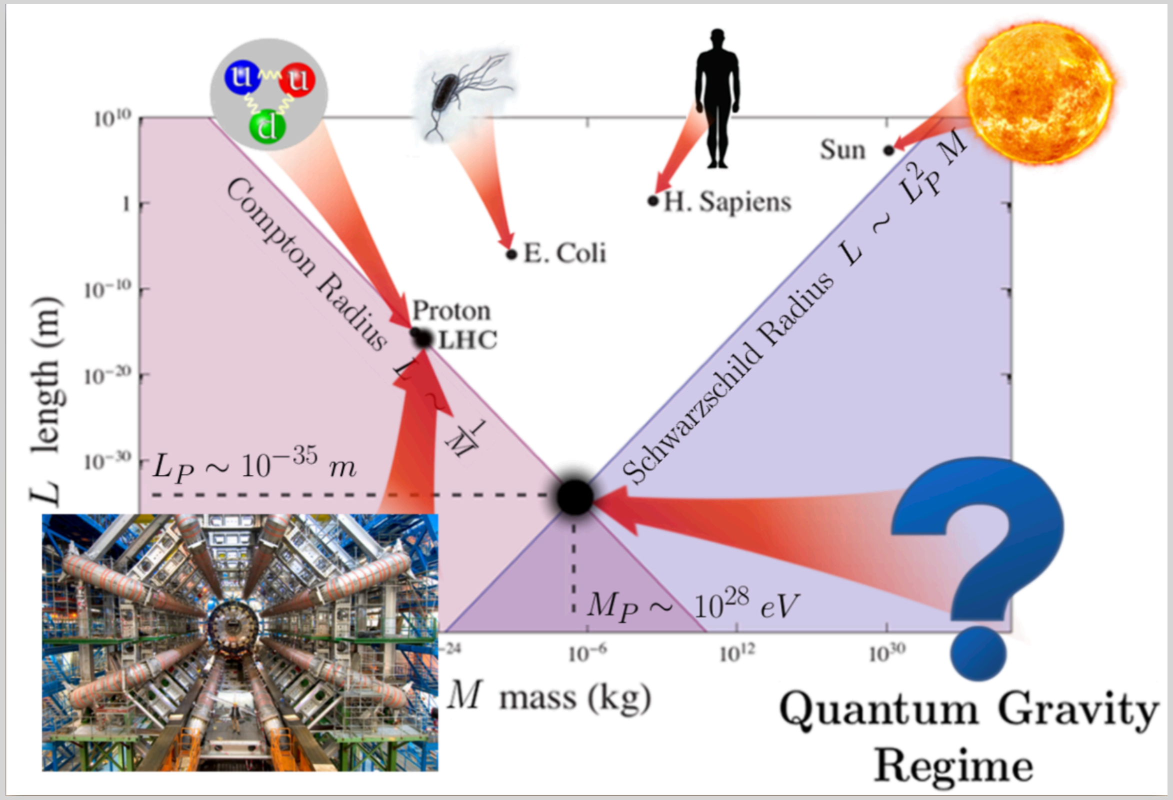

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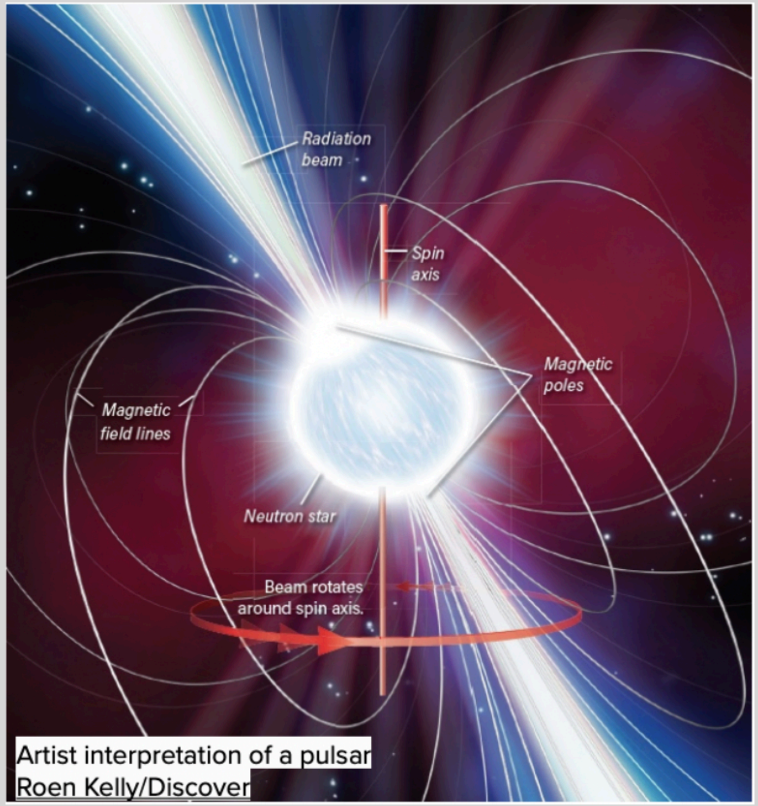
$$\Delta t_n \simeq \pm \frac{n+1}{2}\left(\frac{E_2^n - E_1^n}{E_{\mathrm{QG}}^n}\right) D_n(z)$$

Time variability High energy Long distance

IACT fundamental physics studies with γ-rays: LIV

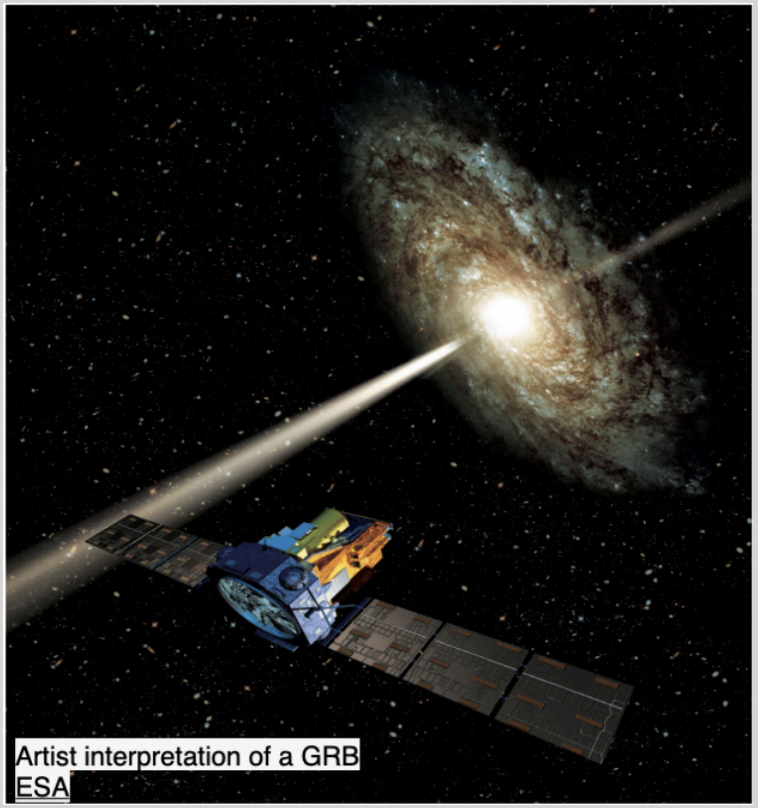
- Main targets for LIV studies:

Pulsars



Artist interpretation of a pulsar
Roen Kelly/Discover

γ-ray bursts (GRBs)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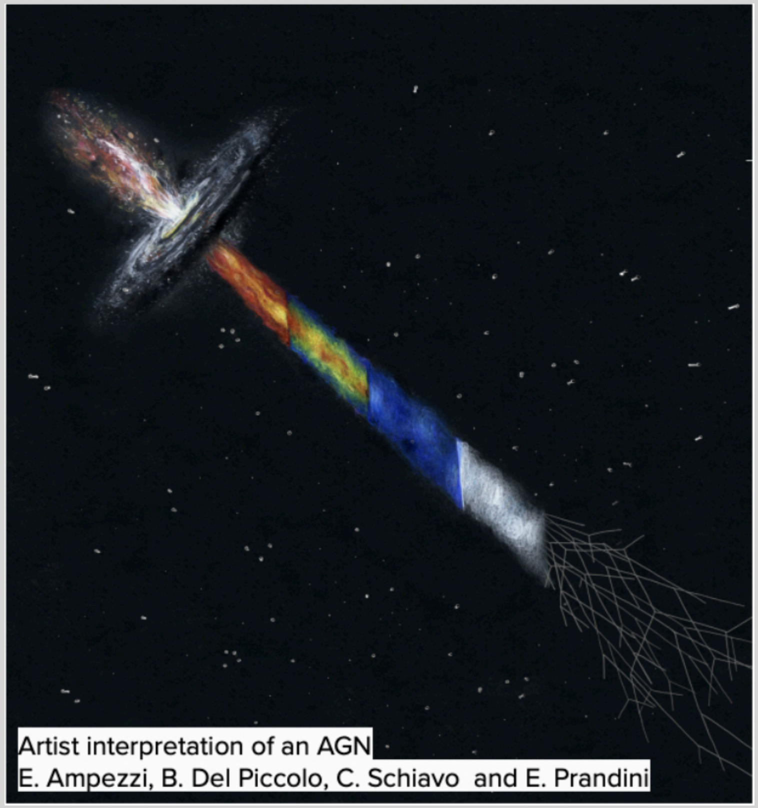
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IACT fundamental physics studies with γ-rays: LIV

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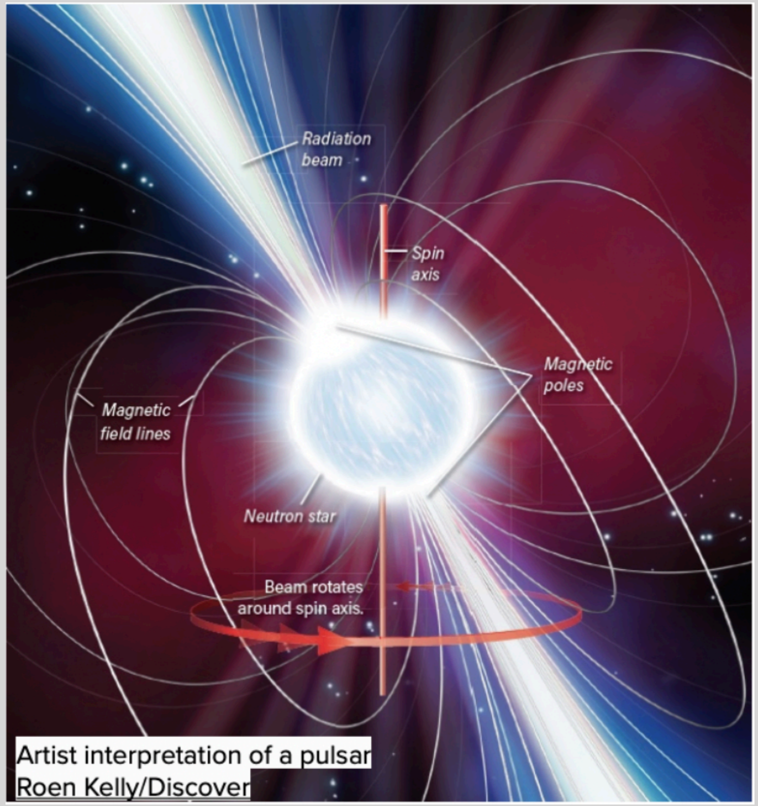
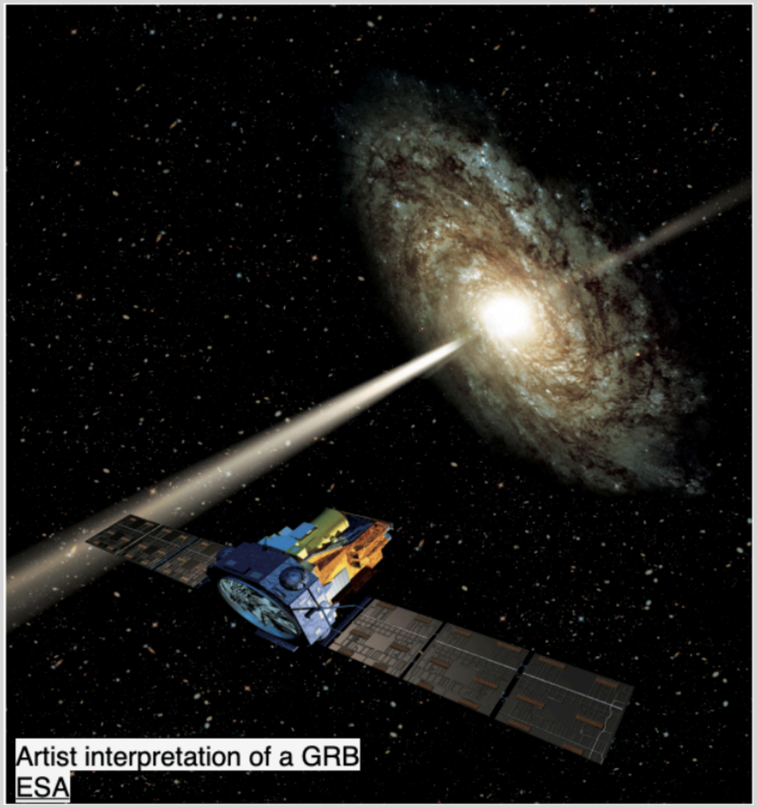


Artist interpretation of a pulsar
Roen Kelly/Discover

- Time variability (a lot)
- High energy
- Short distance

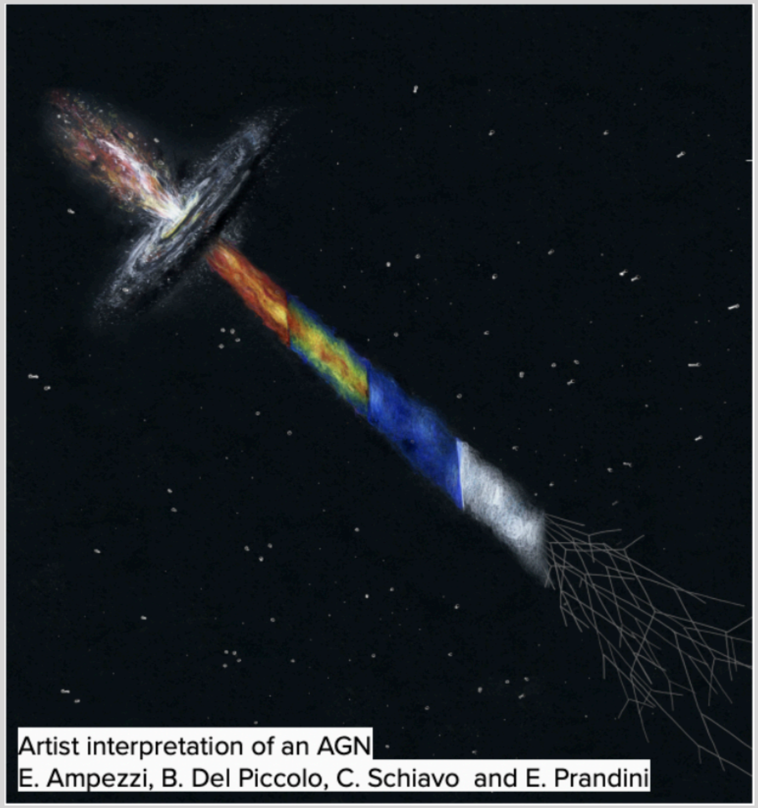
γ-ray bursts (GRBs)



Artist interpretation of a GRB
ESA

- Time variability (prompt emission)
- Not so high energy (EBL absorption)
- Long distance

Active galactic nuclei (AGN)

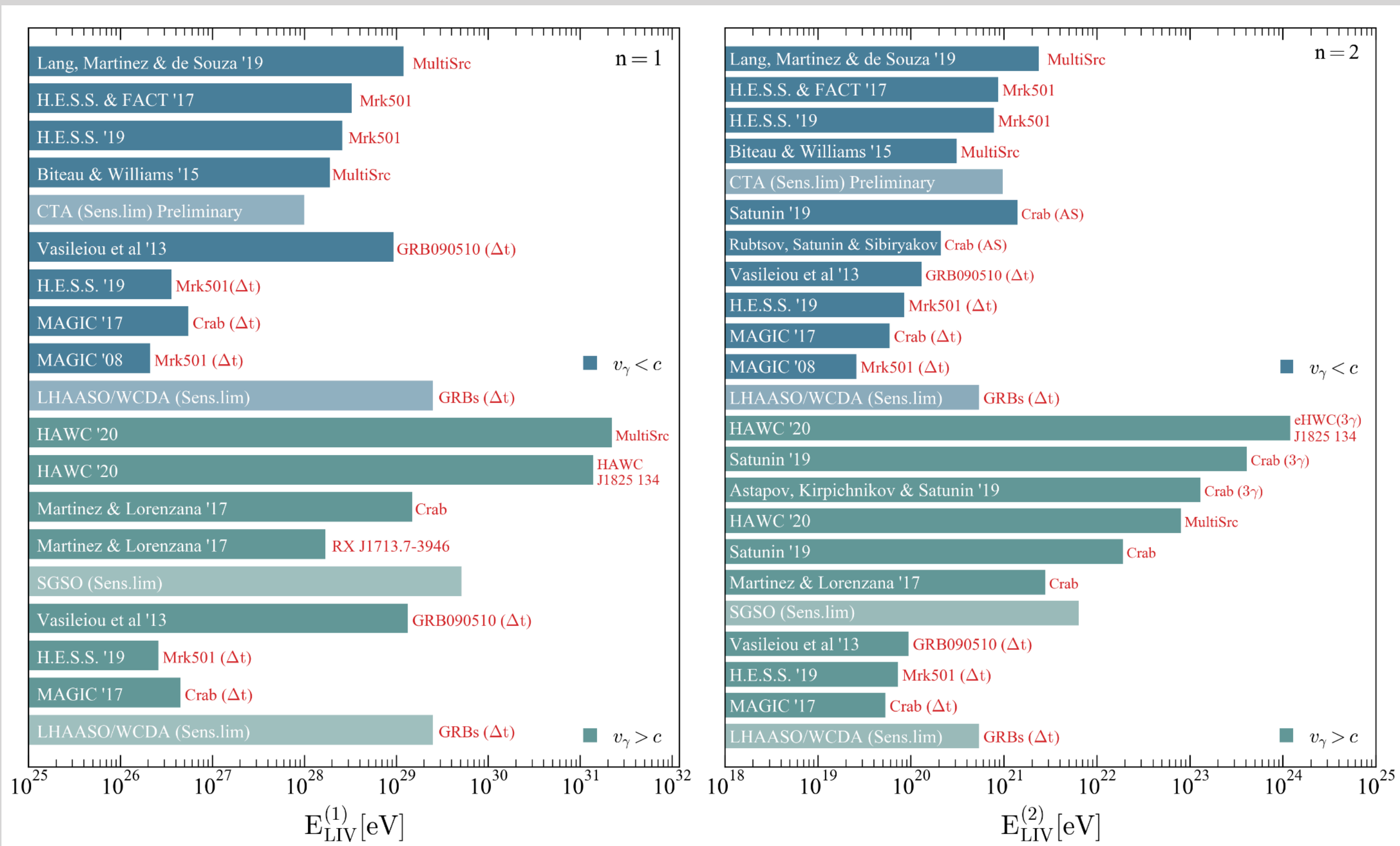


Artist interpretation of an AGN
E. Ampezzi, B. Del Piccolo, C. Schiavo and E. Prandini

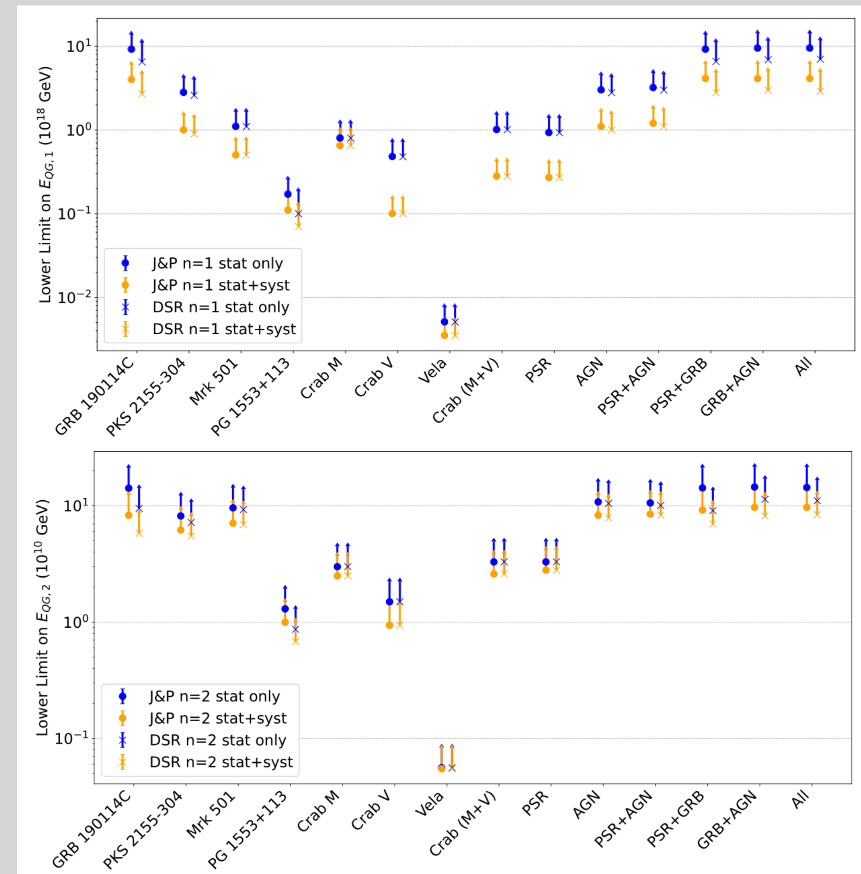
- Time variability (flaring activity)
- Not so high energy (EBL absorption)
- Long distance

IACT fundamental physics studies with γ-rays: LIV

- Current status of LIV studies in VHE γ-rays:



Martínez-Huerta+ 2020



Bolmont+ 2022

	Power-law flux 5σ (3σ) [GeV]	20-TeV cut-off 5σ (3σ) [GeV]	10-TeV cut-off 5σ (3σ) [GeV]
$n = 1$	4.5×10^{20} (1.4×10^{21})	1.8×10^{19} (3.2×10^{19})	4.1×10^{18} (9.1×10^{18})
$n = 2$	5.9×10^{12} (1.2×10^{13})	5.1×10^{11} (9.8×10^{11})	2.7×10^{11} (4.2×10^{11})

Fairbairn+ 2014

redshift z	linear [GeV]	quadratic [GeV]
0.05	2.03×10^{18}	1.61×10^{11}
0.10	1.43×10^{18}	2.21×10^{11}
0.15	1.24×10^{18}	1.23×10^{11}

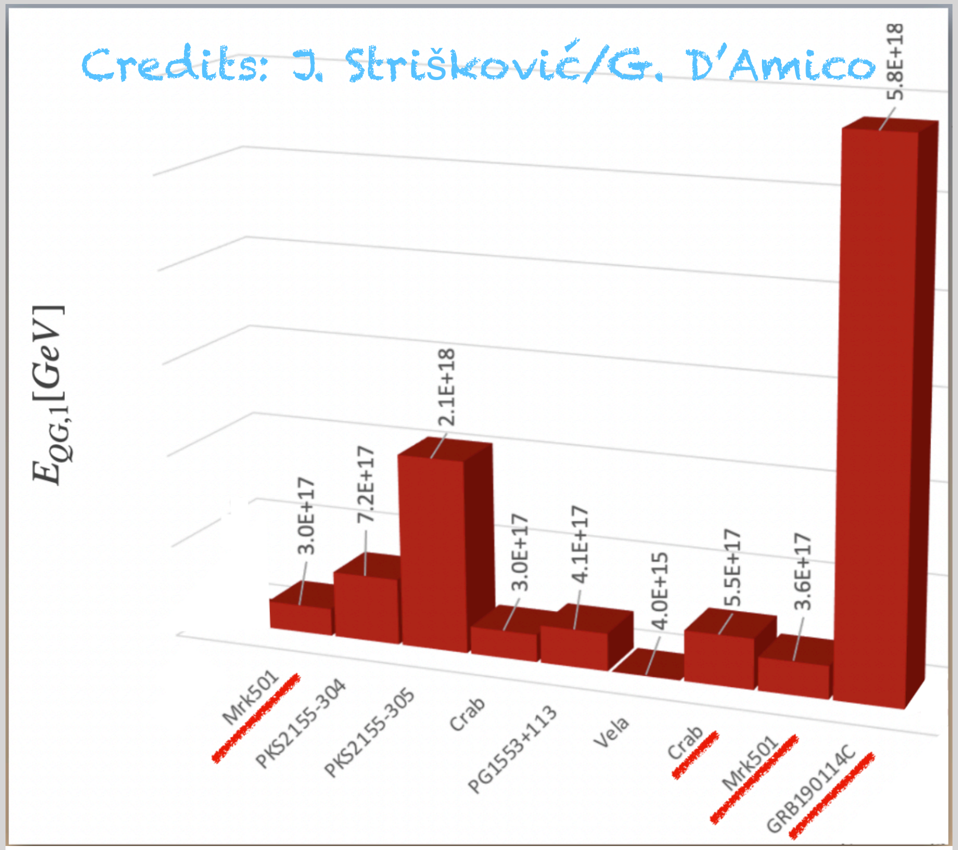
CTA Cons. 2016

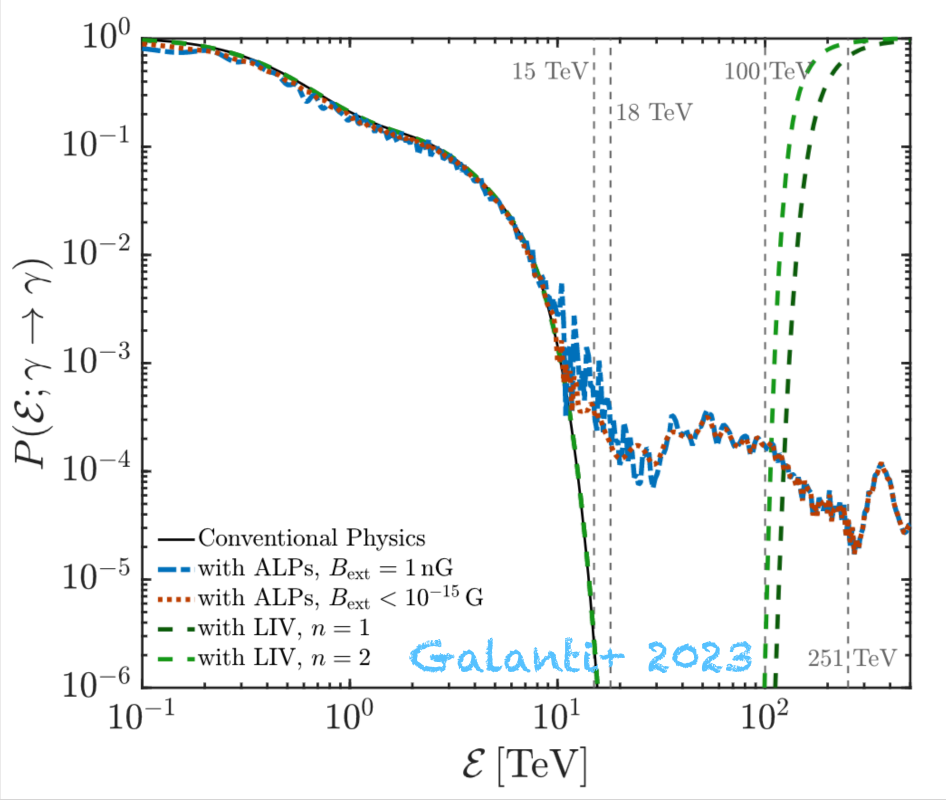
IACT fundamental physics studies with γ-rays: LIV

- Best IACT constraints to QG energies of $>6\times10^{18}$ GeV (linear case) => already very close to the Planck scale ($\sim10^{19}$ GeV).

- Perspectives with next-gen IACTs depend on target class, distance and spectral pars (shape, cut-off).

- **Combination with other exotic physics (e.g., photon resurrection with ALPs) to be explored.**

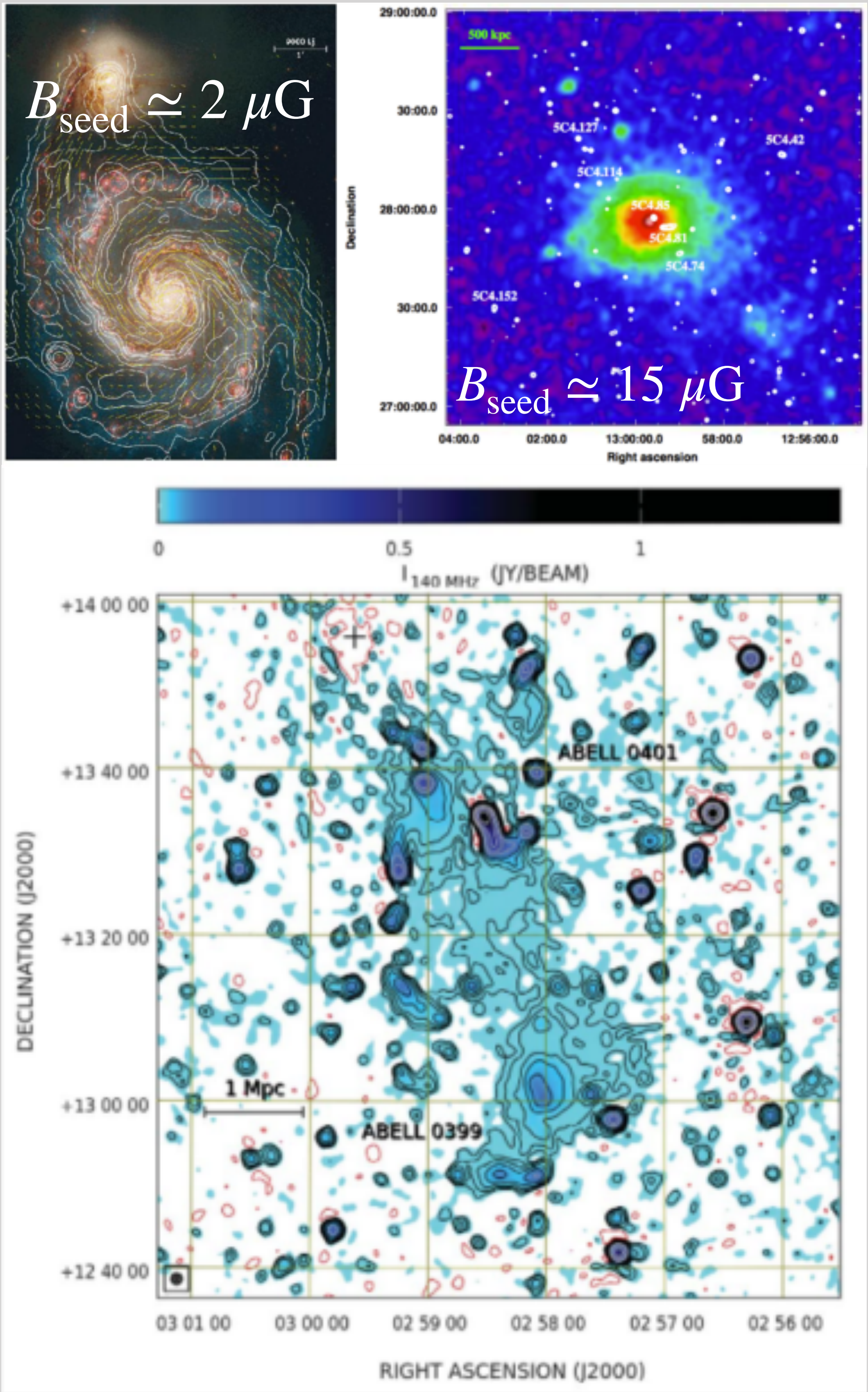




IACT fundamental physics studies with γ-rays: IGMF

- Magnetic fields exist in macroscopic astrophysical objects (galaxies, galaxy clusters), and can be dragged to intergalactic scales through diffusive processes.

- Most of intergalactic magnetic field (IGMF) models assume pre-existing seeds of either astrophysical or cosmological origin.



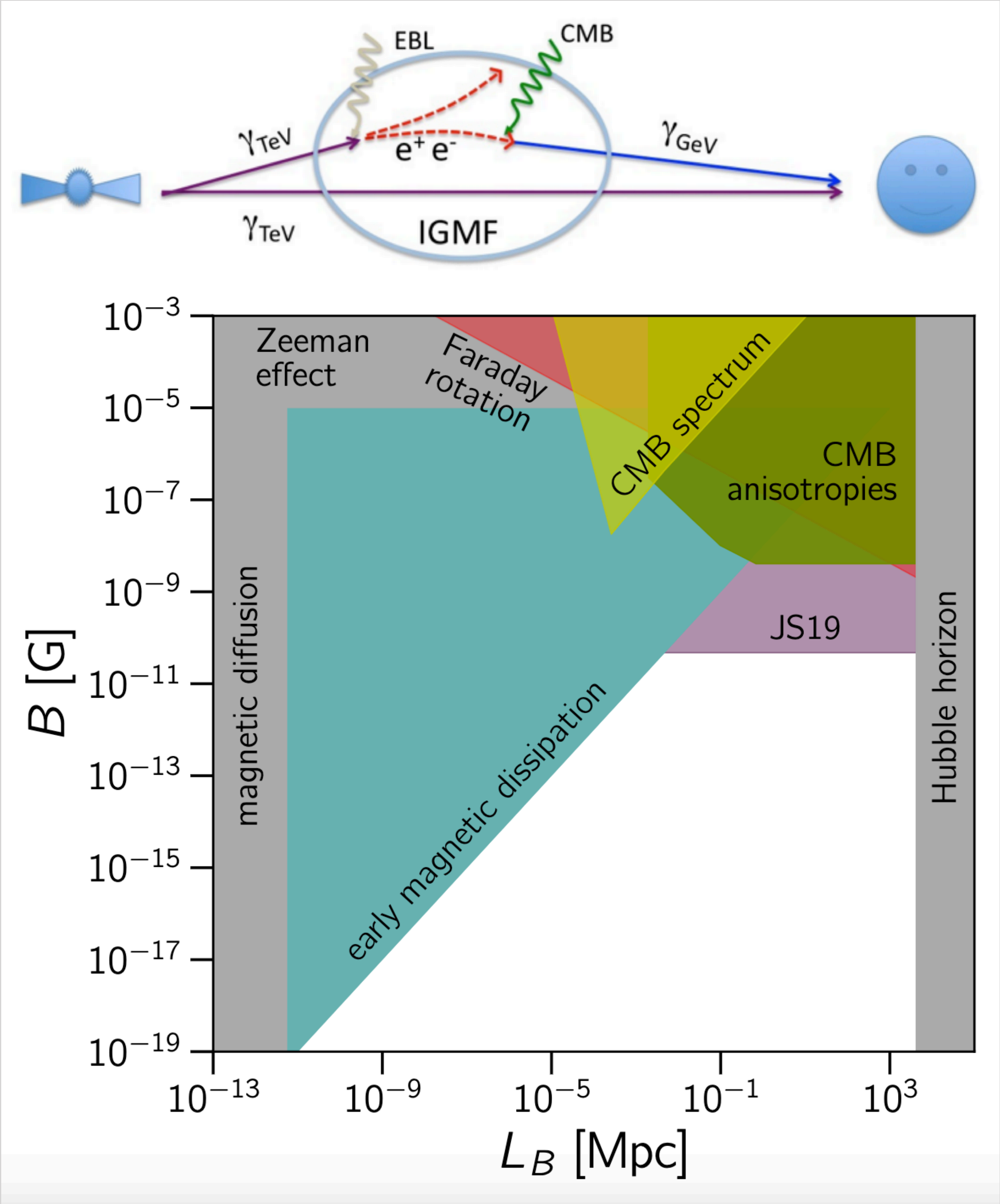
See also Paolo's talk!

IACT fundamental physics studies with γ-rays: IGMF

- IGMF characterized by
  — field strength;
  — correlation length.

- Physical process:
  — reprocessing TeV photons in the GeV band.

- Measurable effects:
  — extended emission;
  — echo emission;
  — spectral features.



Batista & Saveliev 2021

See also Paolo's talk!

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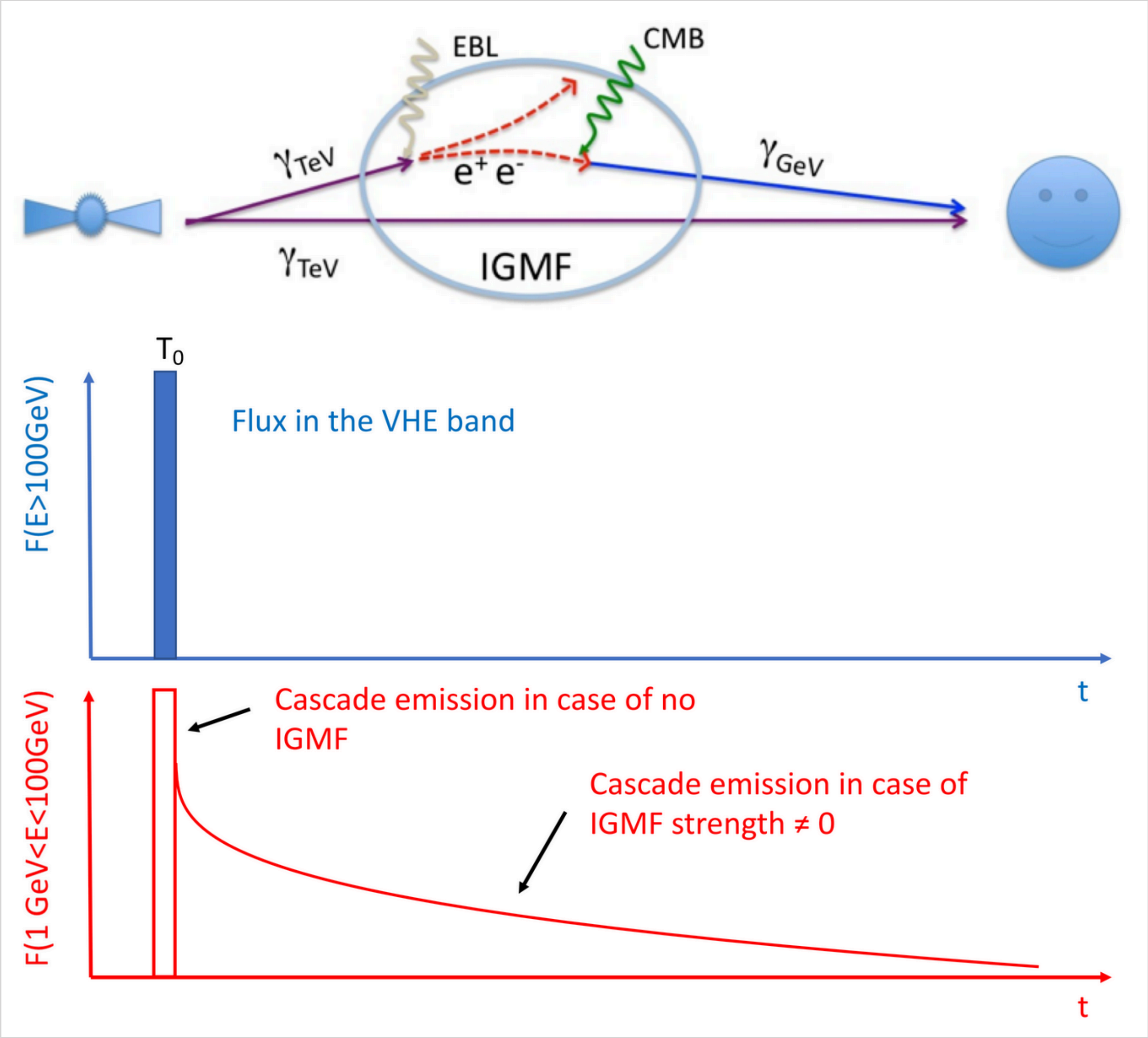


$$E_\gamma \simeq 70 \left(\frac{E'_{\gamma_0}}{10\ \mathrm{TeV}}\right)^2 \mathrm{GeV} \qquad F_\gamma \simeq \frac{t}{t+\Delta t} F_\gamma^{(0)}$$

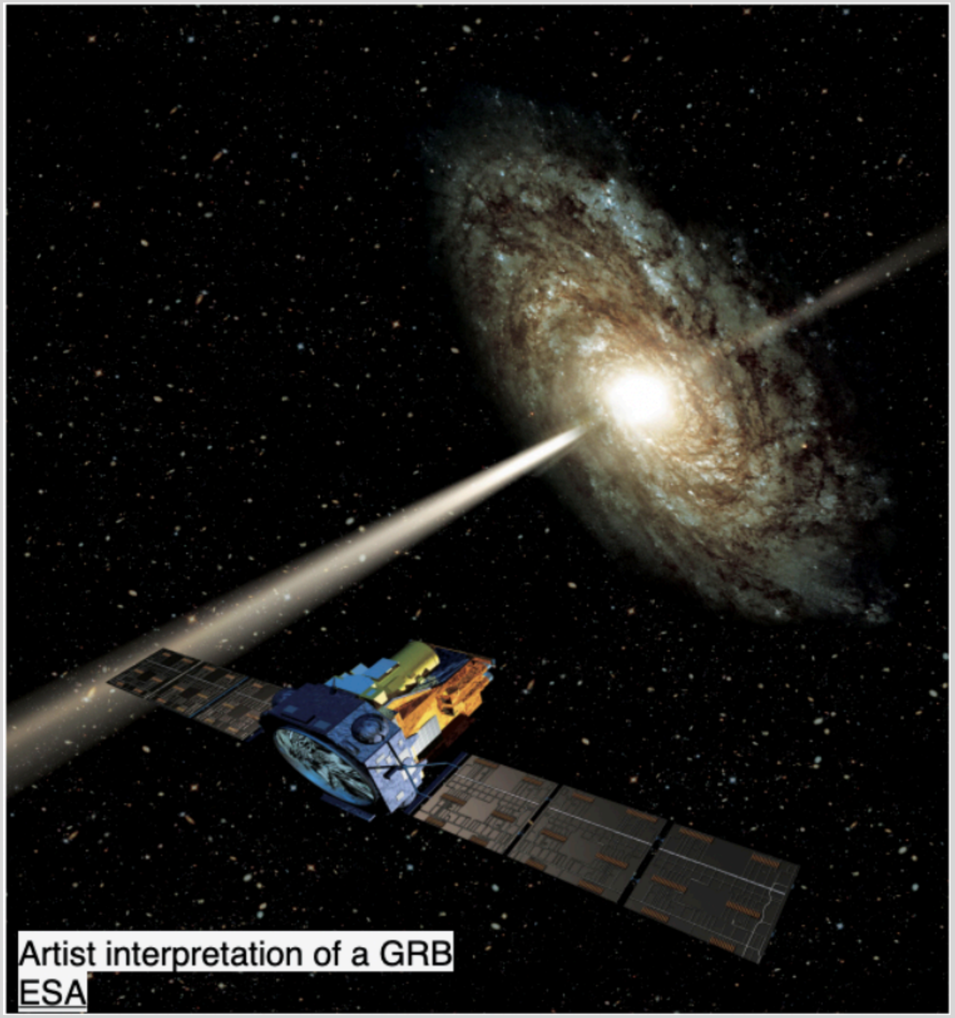
$$\frac{\Delta t}{10^4\ \mathrm{s}} \simeq K_{\lambda D}\left(1-\tau^{-1}\right)(1+z)^{\delta_{\lambda D}}\left(\frac{E_\gamma}{0.1\ \mathrm{TeV}}\right)^{\alpha_{\lambda D}}\left(\frac{B}{10^{-18}\ \mathrm{G}}\right)^2\left[1+\left(\frac{\lambda_B}{10^3\ \mathrm{pc}}-1\right)H_{\lambda D}\right]$$

See also Paolo's talk!

IACT fundamental physics studies with γ-rays: IGMF

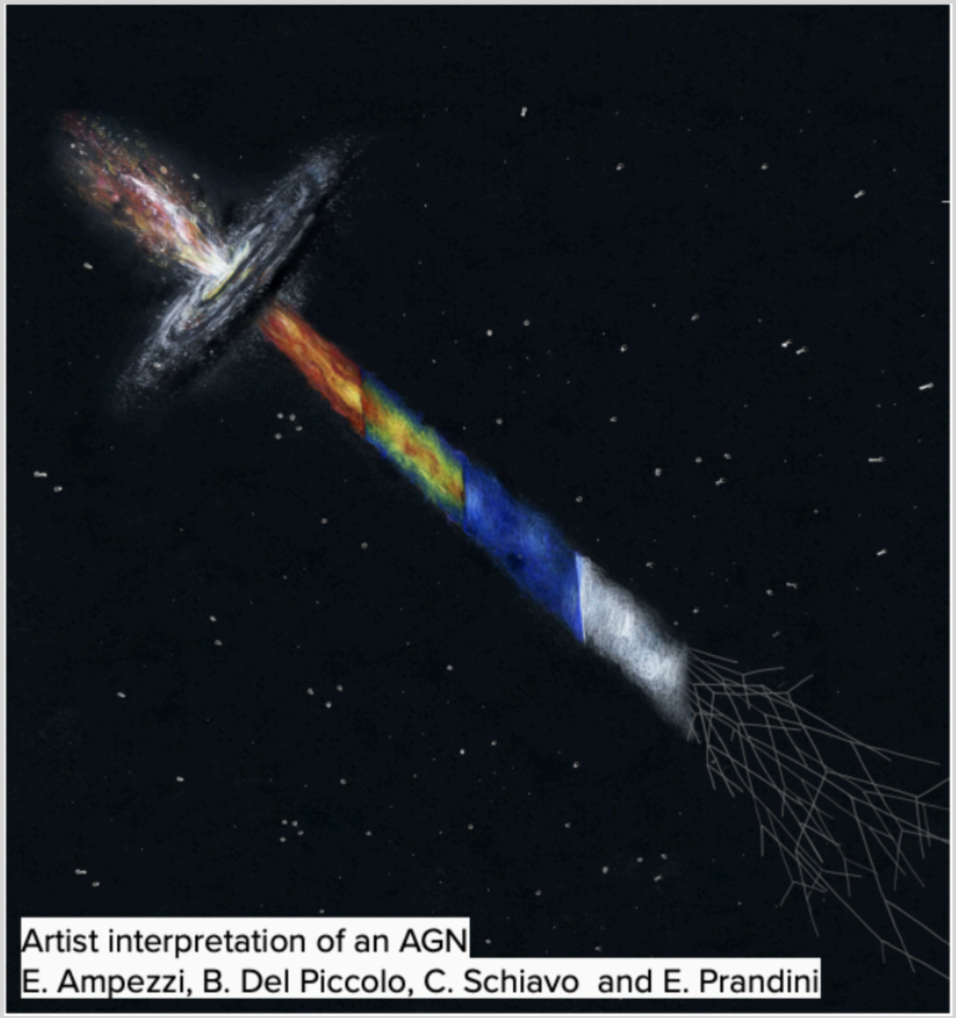
- Main targets for IGMF studies:

γ-ray bursts (GRBs)



Artist interpretation of a GRB
ESA

Active galactic nuclei (AGN)



Artist interpretation of an AGN
E. Ampezzi, B. Del Piccolo, C. Schiavo and E. Prandini

See also Paolo's talk!

IACT fundamental physics studies with γ-rays: IGMF

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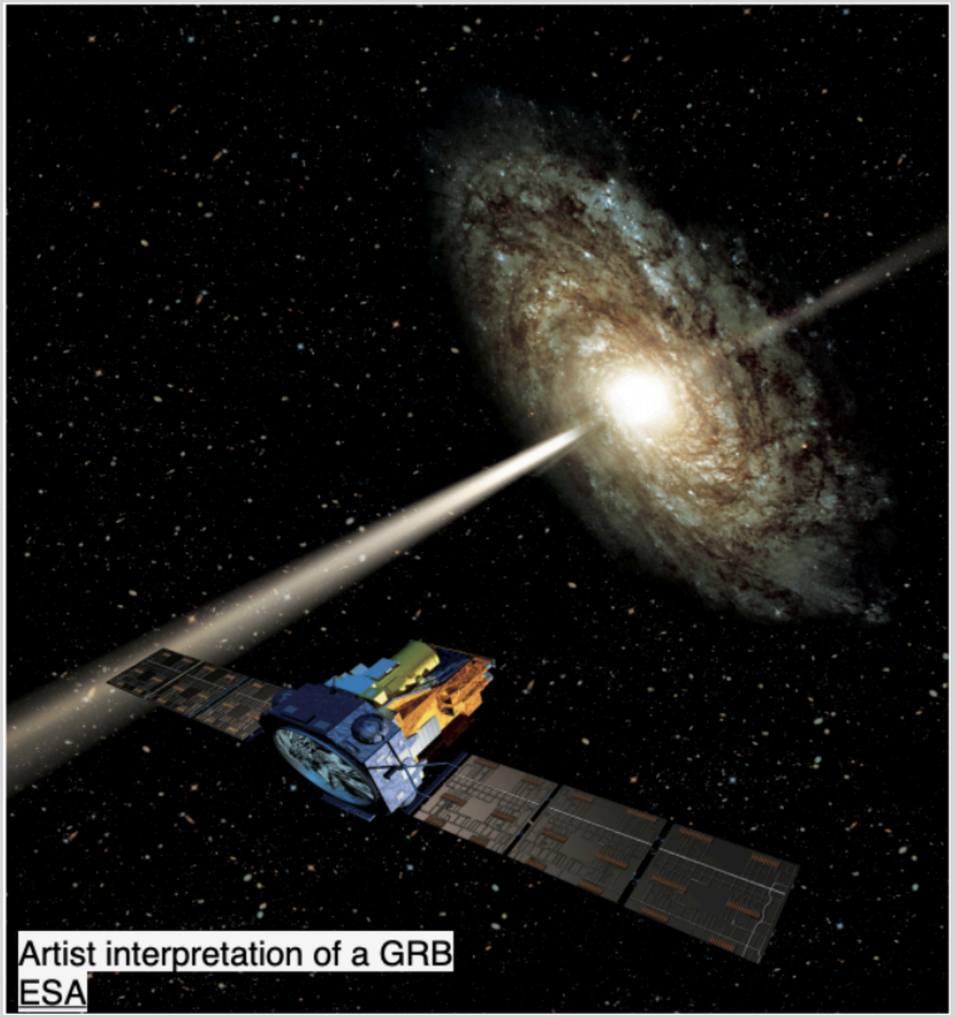
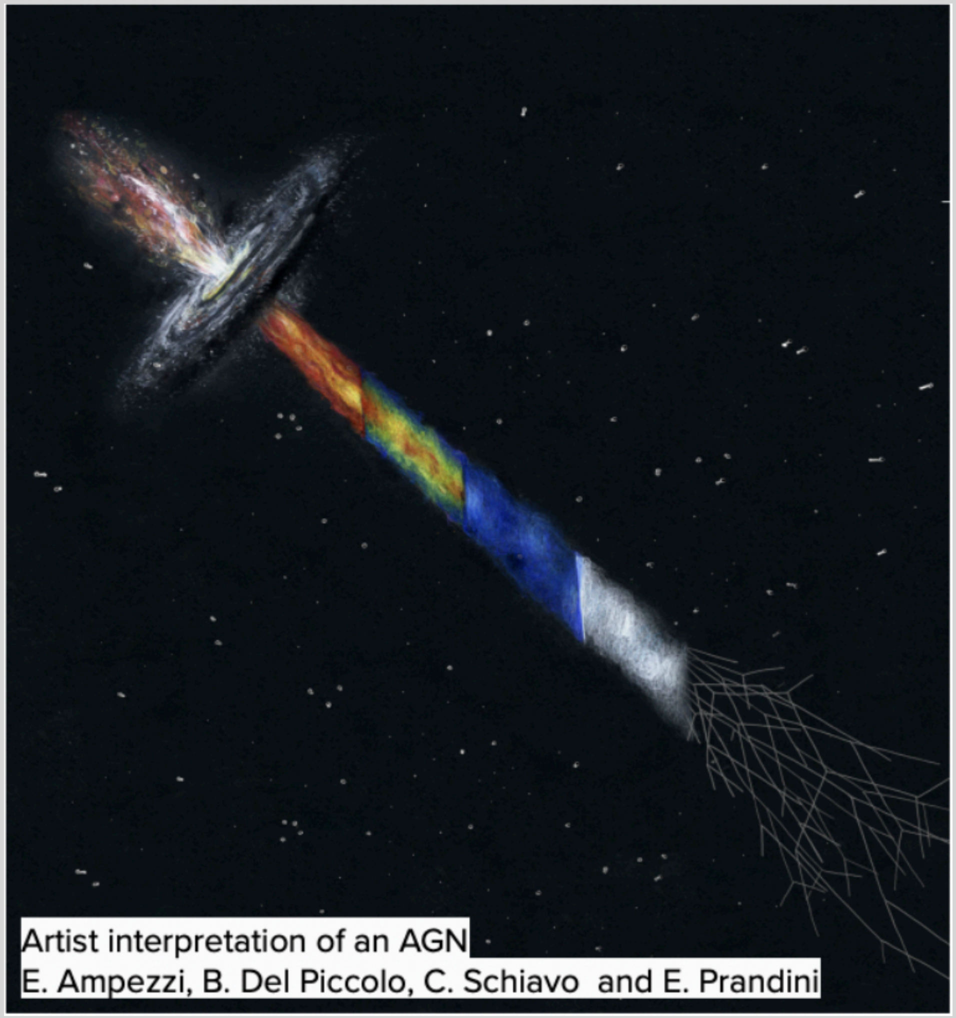


- Transient sources (disentanglement between prompt & cascade emission)
- Transient & directional

Active galactic nuclei (AGN)

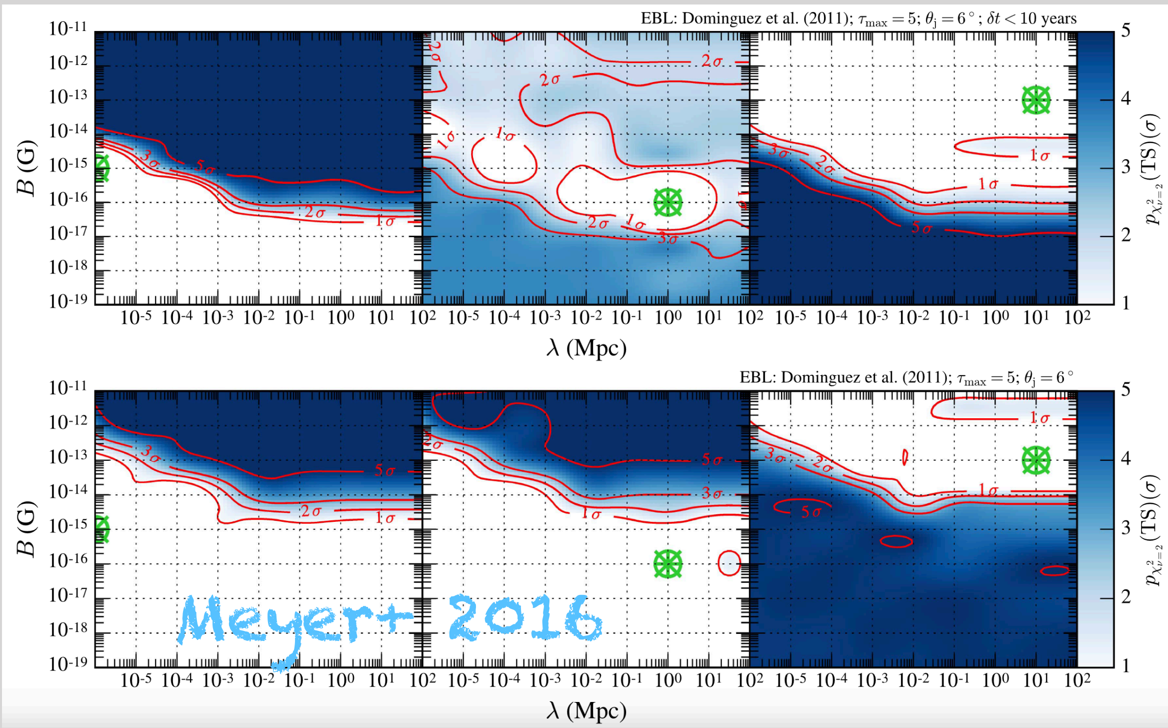


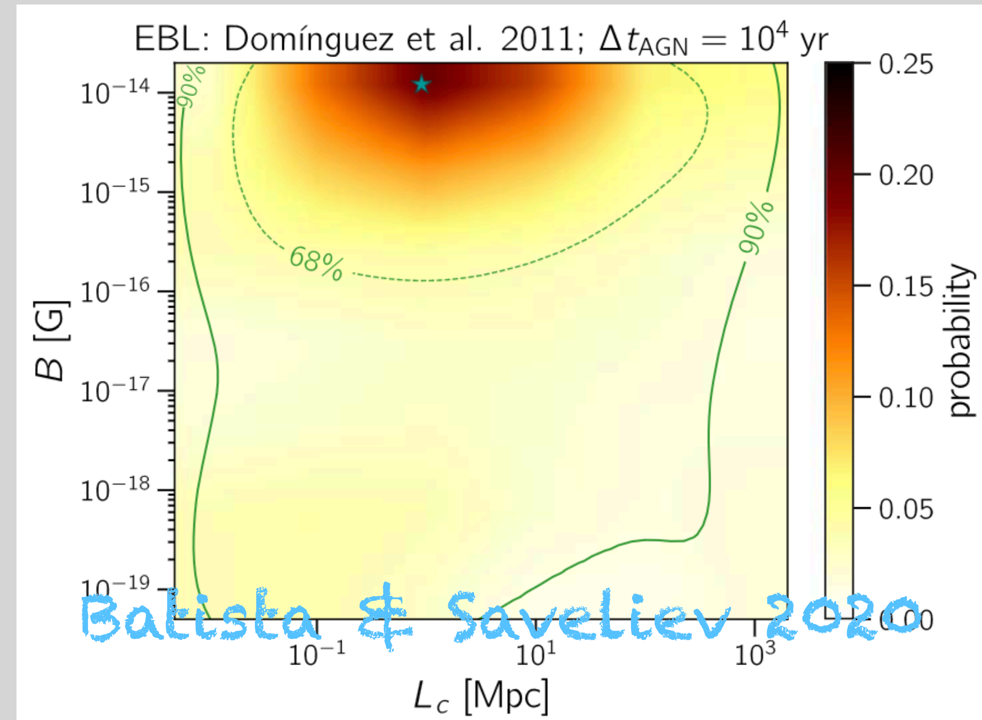
- Steady sources (possibility to detect the extended emission)
- Difficulty to disentangle intrinsic & cascade emission in the GeV domain

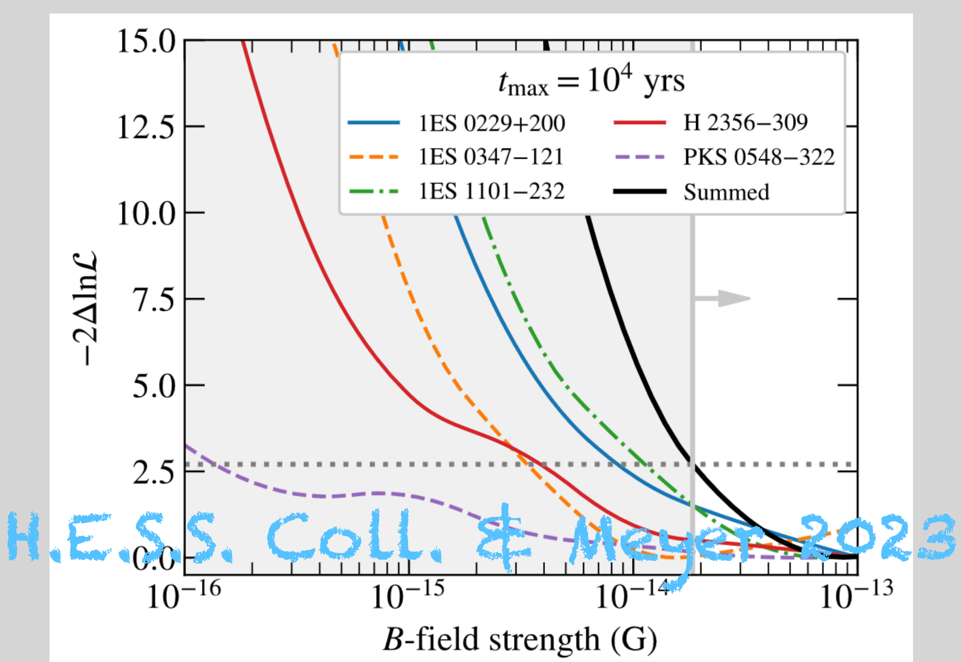
See also Paolo's talk!

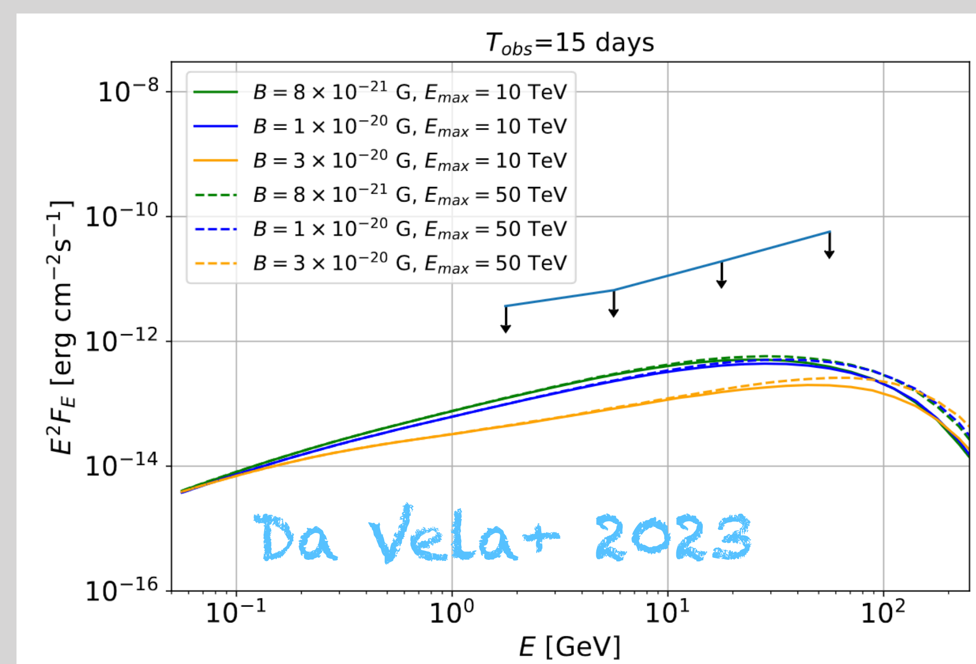
IACT fundamental physics studies with γ-rays: IGMF

- Current status of IGMF studies in VHE γ-rays:









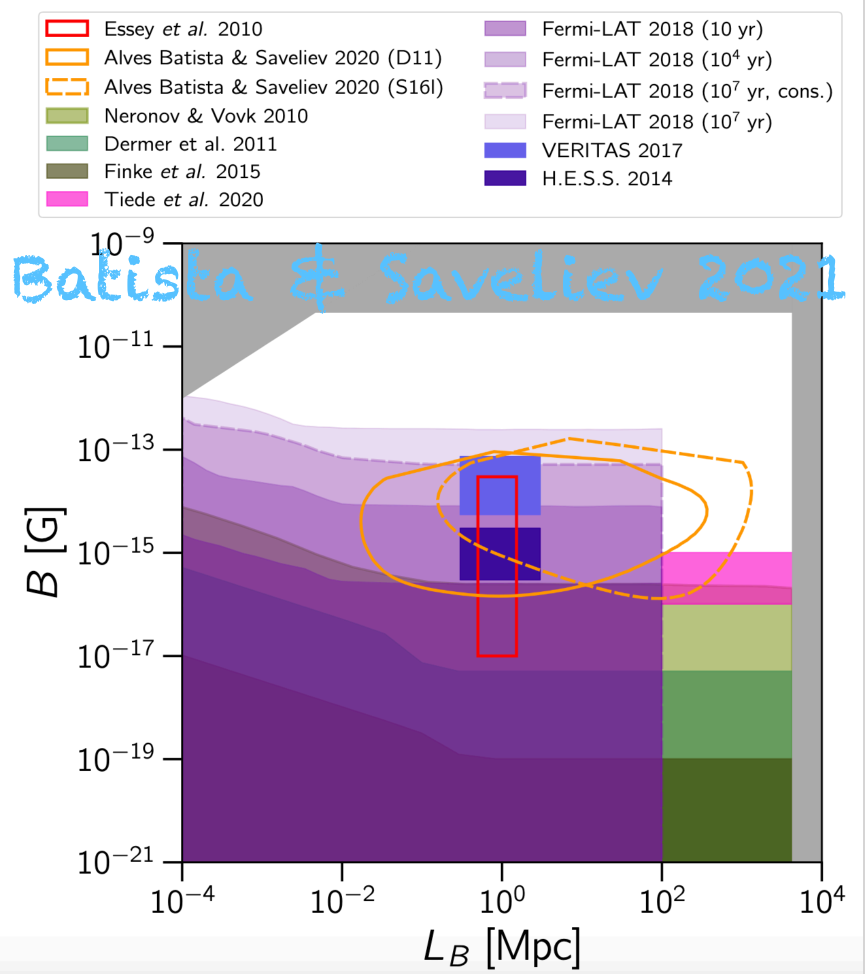
See also Paolo's talk!

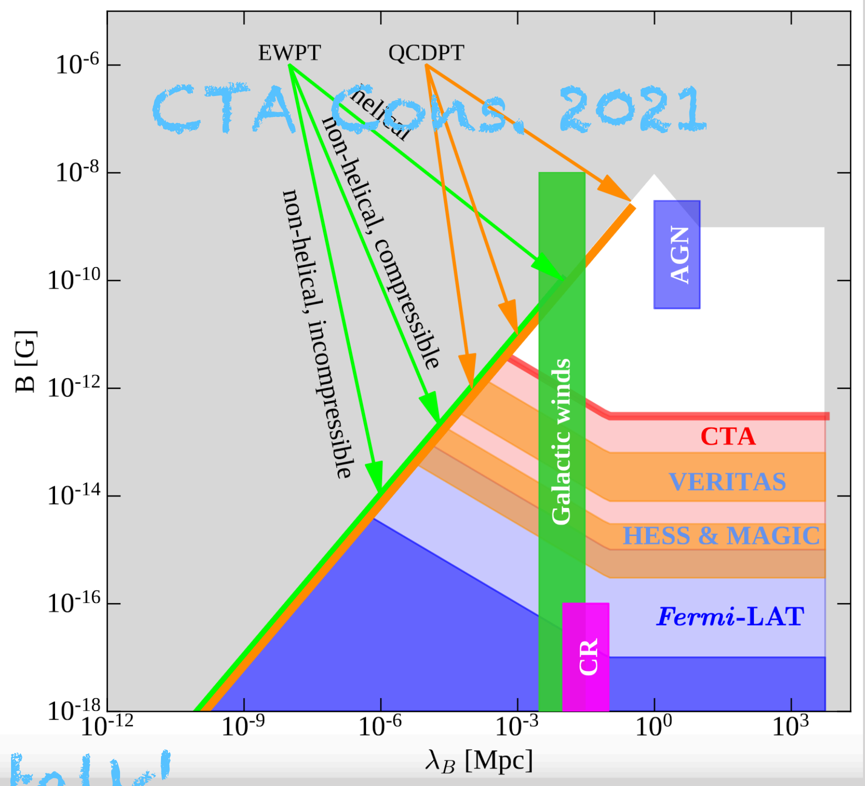
IACT fundamental physics studies with γ-rays: IGMF

- IGMF parameter space rapidly closing due to the intense research activity in this field.

- GRBs kicking in the game (e.g. GRB190114C and especially GRB221009A) => **potential best targets for new IACTs.**

- **Observe extended cascade emission from AGN with improved IACT angular resolution.**





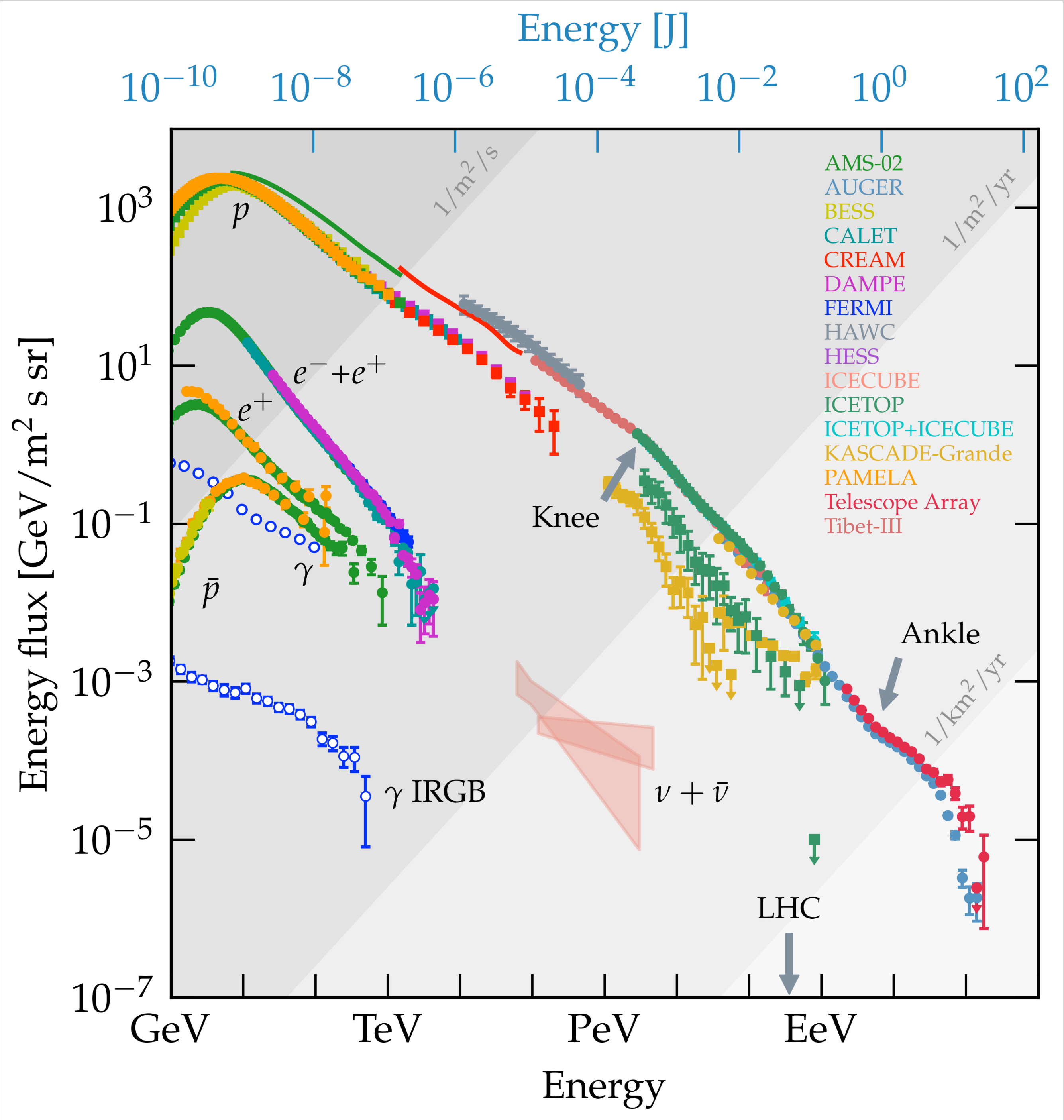
See also Paolo's talk!

IACT fundamental physics studies beyond γ-rays

IACT fundamental physics studies beyond γ-rays

- The origin of cosmic rays (CRs) is still one of the most important open questions in astrophysics;

- Supernova remnants (SNRs) can account for CRs up to ~3 PeV; for higher energies, AGN mechanisms are required.



IACT fundamental physics studies beyond γ-rays

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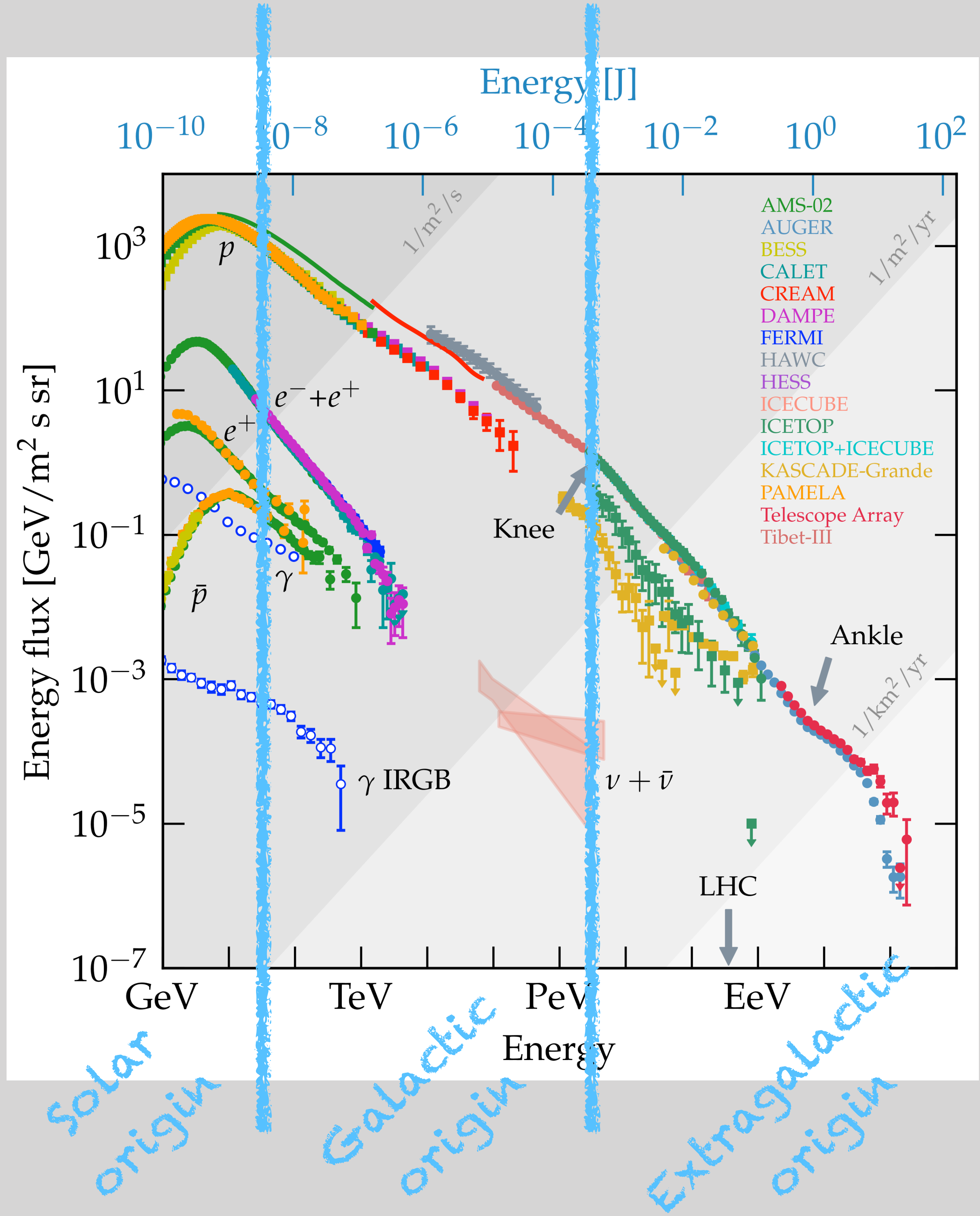
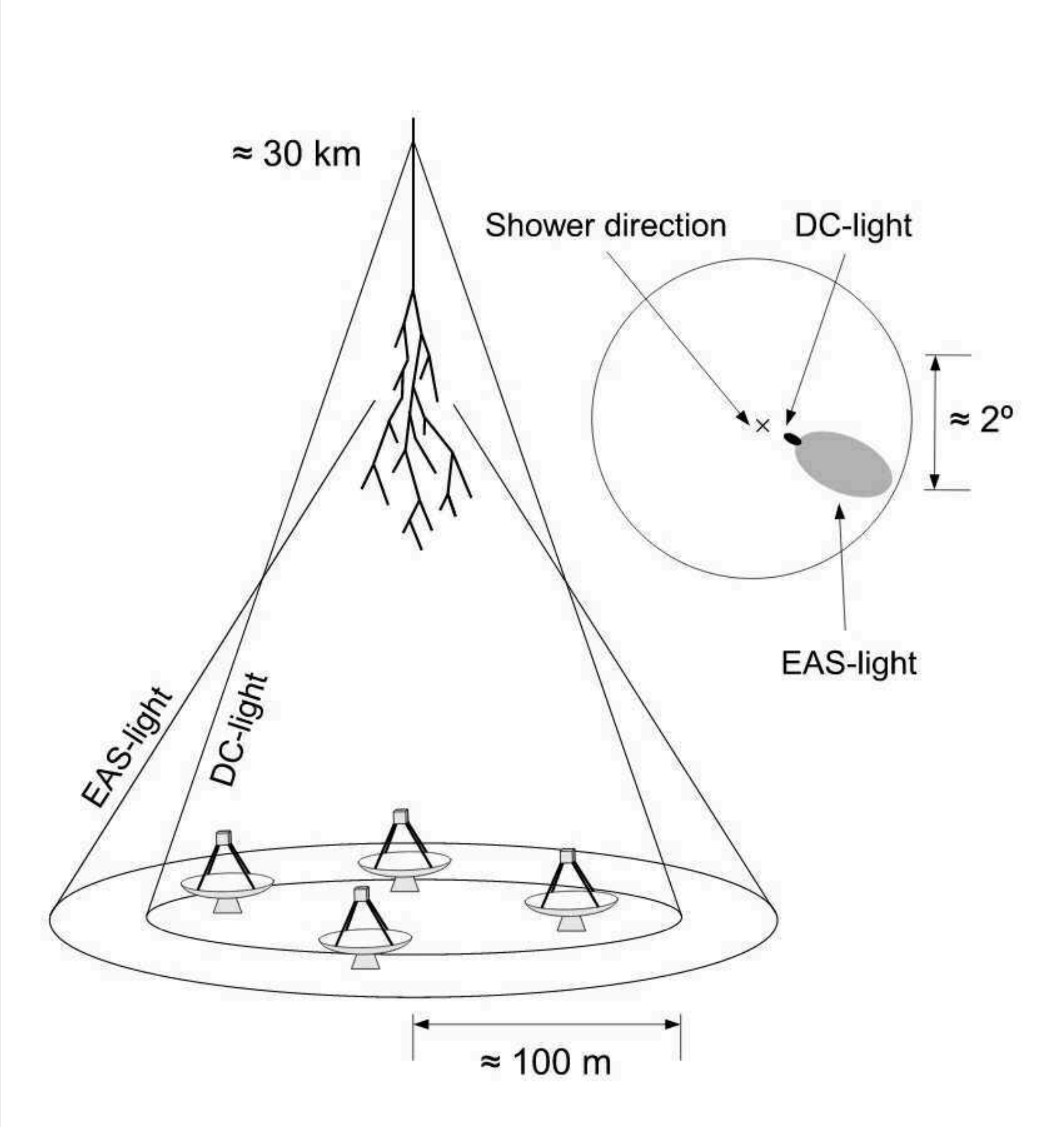


IACT fundamental physics studies beyond γ-rays

- Main techniques for CR studies:
  — standard analysis with different reconstruction techniques;
  — direct Cherenkov (DC) light detection with cut-based or template fitting analysis.

- Choice of targets does not matter for hadrons, and for leptons only requirement is to be free of γ-ray sources (ZA < 35° for both).



H.E.S.S. Coll. 2007

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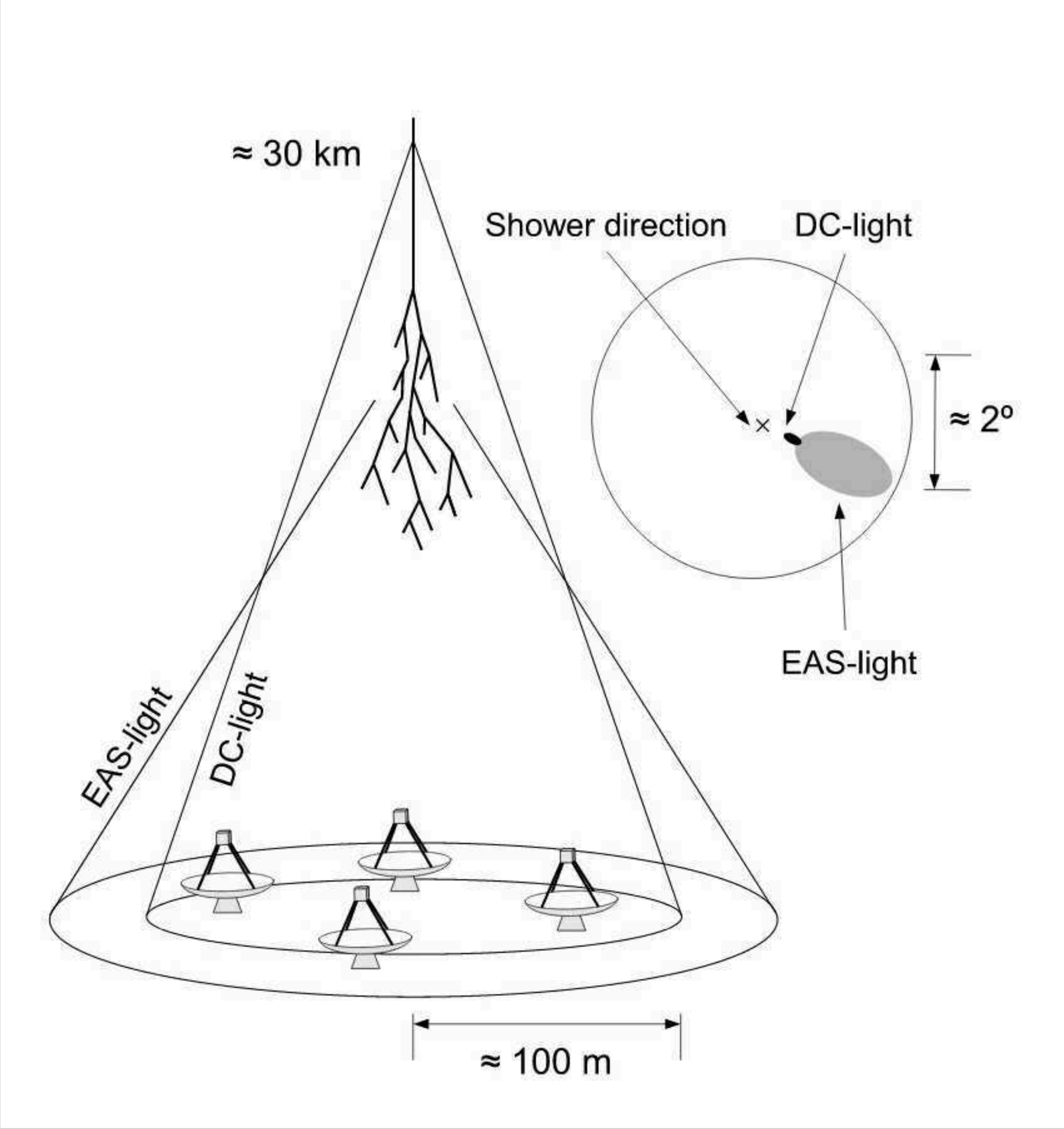
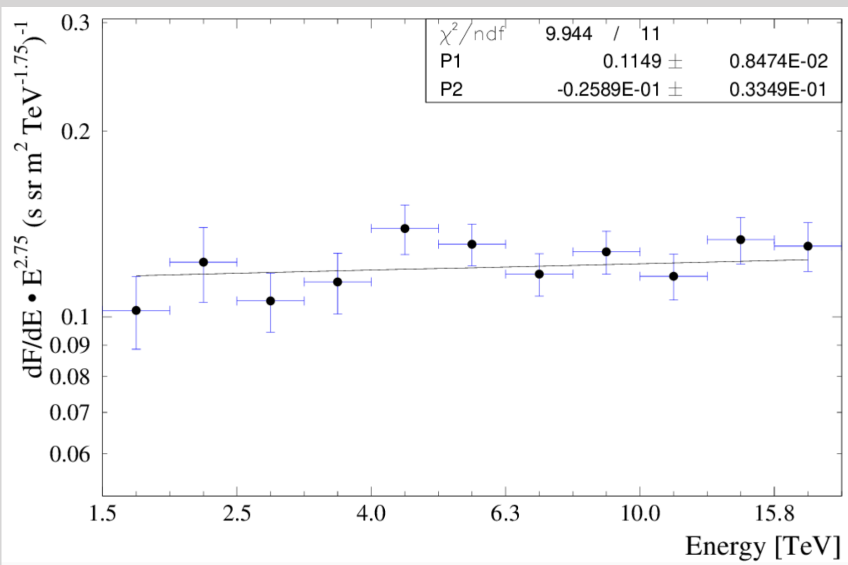


H.E.S.S. Coll. 2007

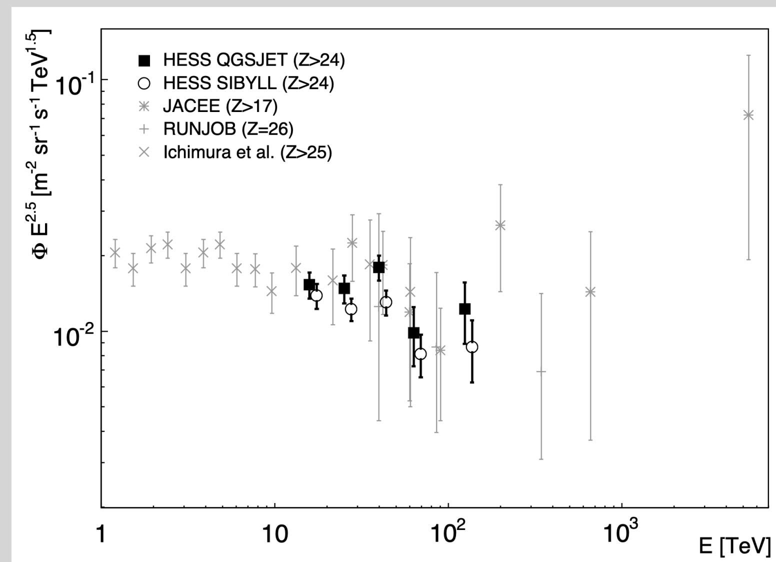
IACT fundamental physics studies beyond γ-rays

- Status of CR studies in VHE:

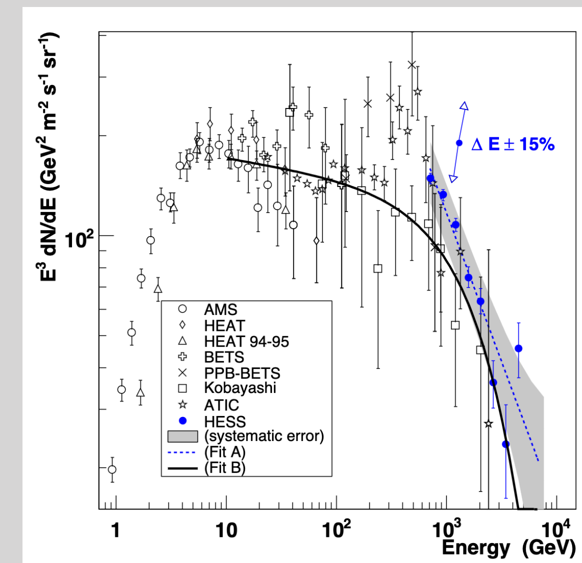
Protons	Iron nuclei	Electrons



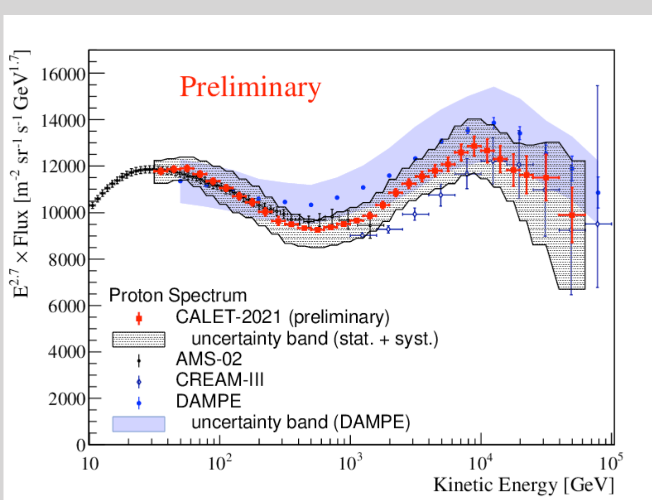
HEGRA Coll. 1999



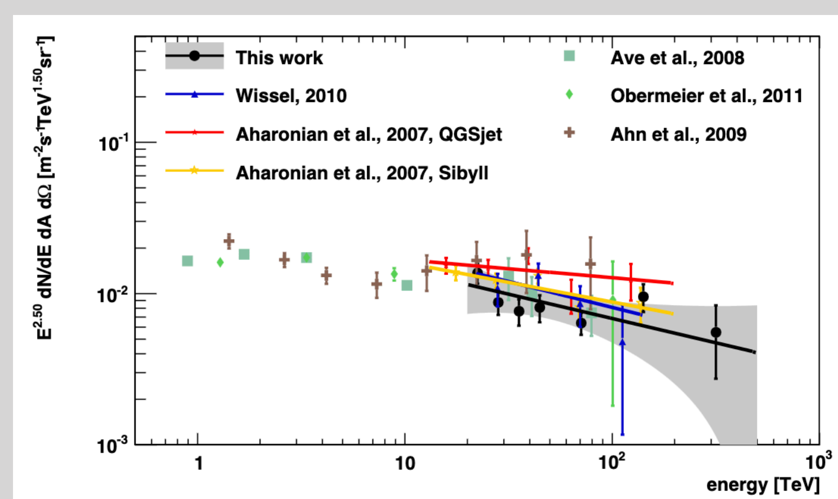
H.E.S.S. Coll. 2007



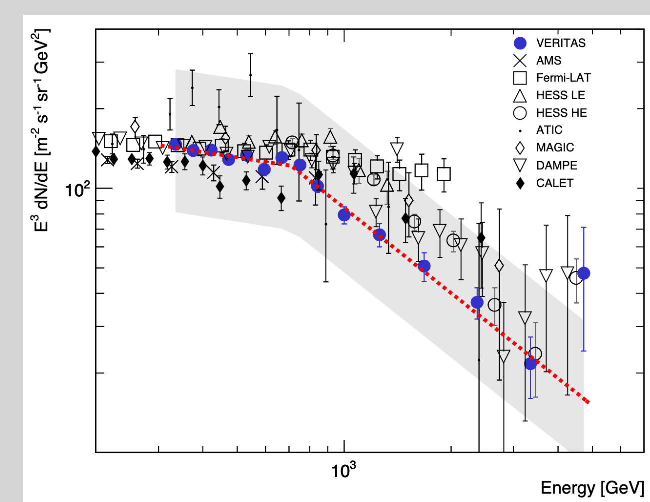
H.E.S.S. Coll. 2008



CALET Coll. 2021



VERITAS Coll. 2018a

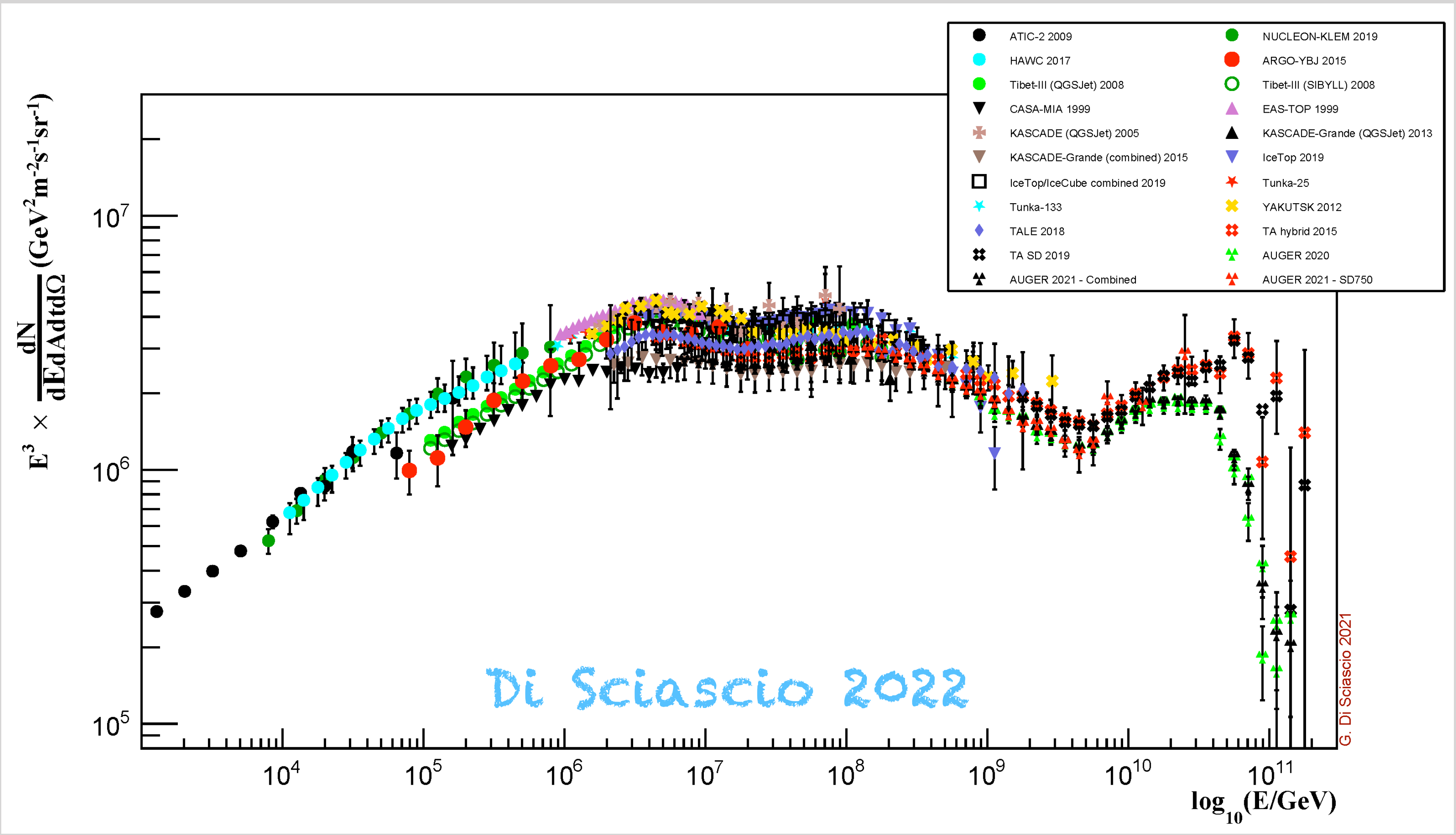


VERITAS Coll. 2018b

IACT fundamental physics studies beyond γ-rays

- CR studies with Cherenkov light detection underway since decades.

- Other than the most abundant CRs (protons, electrons, iron), **other species can be studied** (Cherenkov light $\propto Z^2$).



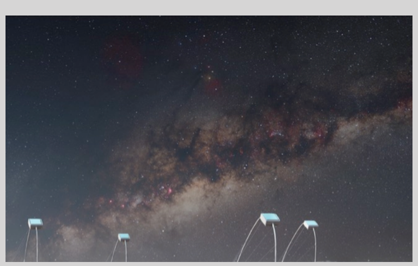
Summary

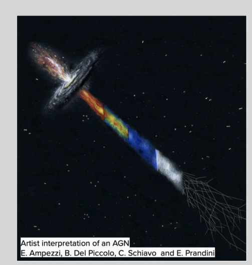
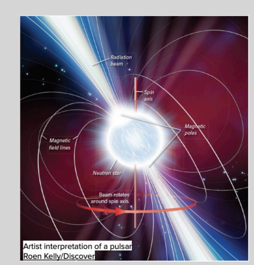
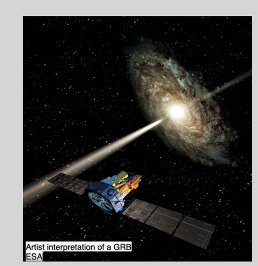
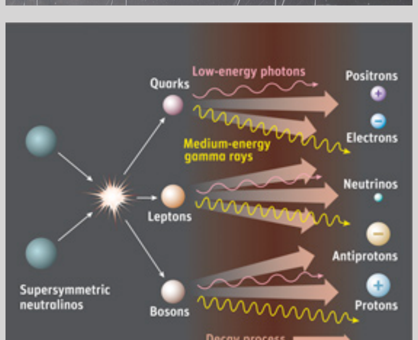
Summary

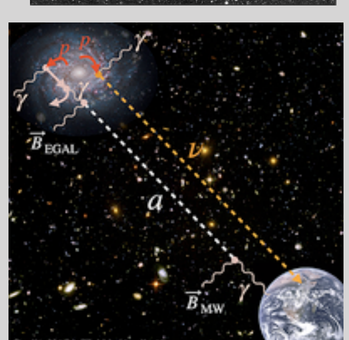
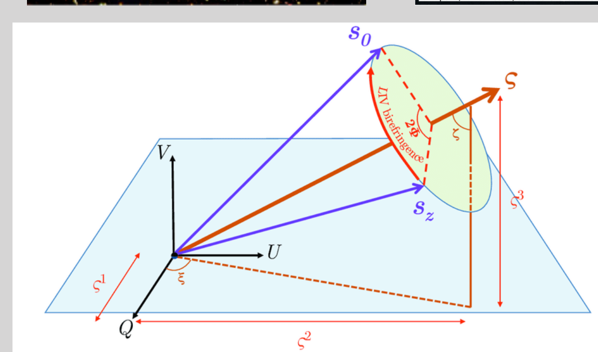
- Many topics of astroparticle/fundamental/exotic physics still to be explored in detail with Cherenkov observations;

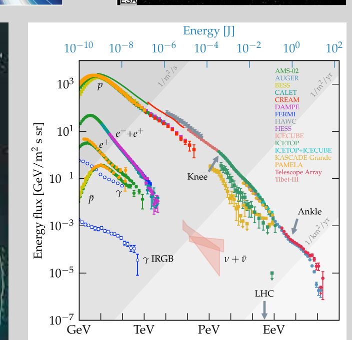
- several open aspects to be investigated for better understanding of the physical aspects and improvement of the analysis techniques;

- big fields still open at reach of next-generation IACTs.





Thank you!

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