Beyond the Standard Model with Wide-field Observatories

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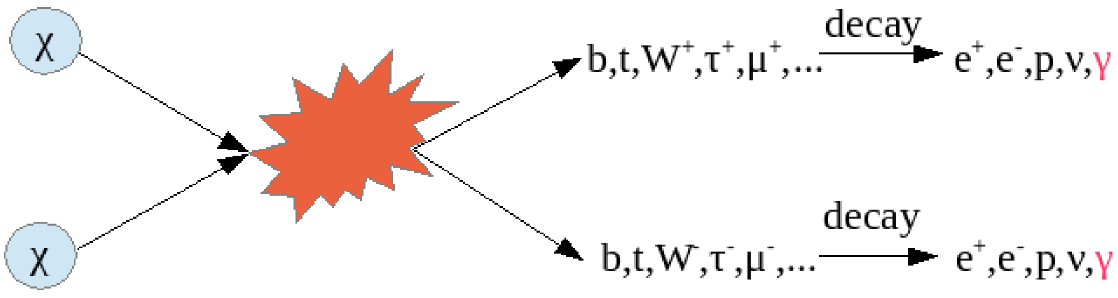
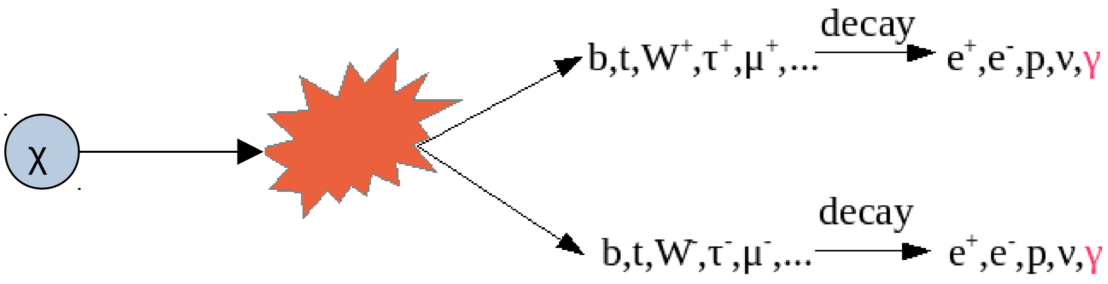
BSM with Southern Wide-FoV Observatory

- Dark Matter
  - Focusing on >TeV WIMPs
    - Motivated by lack of LHC/Fermi-LAT/Direct Detection searches below ~TeV masses
- Primordial Black Holes
- Lorentz Invariance Violation
- Axion-Like-Particles

Dark Matter Annihilation and Decay



$$\frac{dF_\gamma}{dE\,d\Omega} = \frac{1}{4\pi}\frac{\langle\sigma v\rangle}{2M_\chi^2}\frac{dN_\gamma}{dE}\int_{l.o.s.} dx\,\rho(x)^2$$



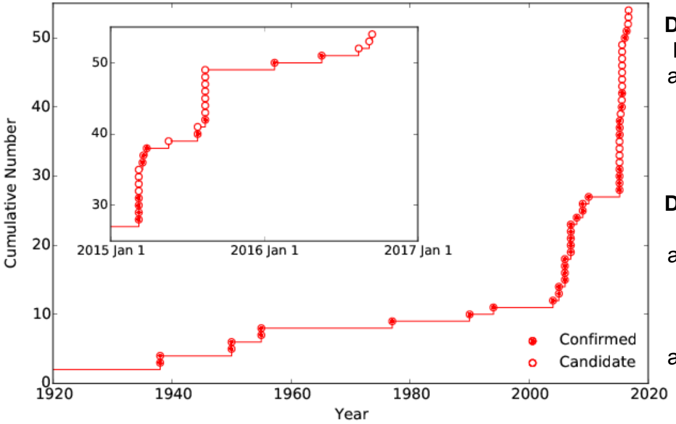
$$\frac{dF_\gamma}{dE\,d\Omega} = \frac{1}{4\pi}\frac{1}{\tau M_\chi}\frac{dN_\gamma}{dE}\int_{l.o.s.} dx\,\rho(x)$$

Highly Extended DM Objects

- Galaxy Clusters
  - Nearby ones are 2 degrees radius for annihilation
  - Ideal for DM decay searches
- M31 (Andromeda galaxy)
  - >7 degrees radius for annihilation
  - Possibly the best single extragalactic source for annihilation searches
- Galactic center
  - 3-8 degrees radius, with peaked DM profiles for annihilation
  - Cored DM profiles give radius of tens of degrees for annihilation
- For decay, these sizes are ~2x bigger
- Dark matter substructure can make these bigger, too

Southern Dwarf Galaxies

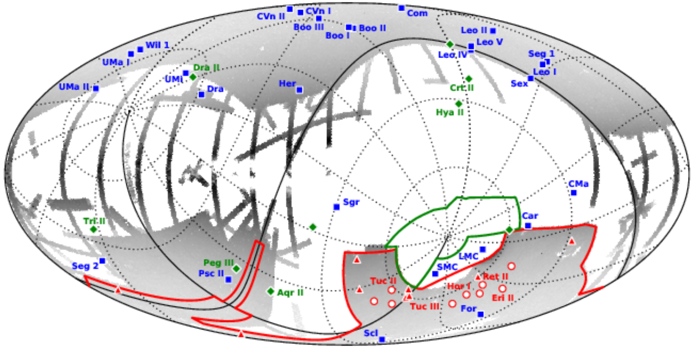
- Dwarf galaxies are high-DM mass, low-luminosity objects
  - Stacked analysis limits DM well
- DES has discovered many new dwarf galaxies (and candidates)
  - All in Southern hemisphere
  - ~half of all known candidates
- LSST (at 30° South) will also find low-brightness objects like dwarfs
  - First science searches in 2021
- Will have lots of new dwarfs to stack
  - But mostly in Southern sky



DES Year 2 Data: Drlica-Wagner+, arXiv:1508.03622

DES Year 1 Data: Bechtol+: arXiv:1503.02584

Koposov+: arXiv:1503.02079



Dwarf Example: Reticulum II

- A particular dwarf galaxy at (ra,dec)=(39°,-54°)
  - Discovered by DES in 2015 – recent discovery
- Possible (though statistically questioned) detection by Fermi-LAT
- May be expected to have the largest annihilation signature among known dwarf galaxies
- If a large-FoV southern observatory had been running, the observation/non-observation at TeV energies would be already banked
  - HESS could (should) look into it, but that takes valuable HESS time

Dark Matter in the Magellanic Clouds

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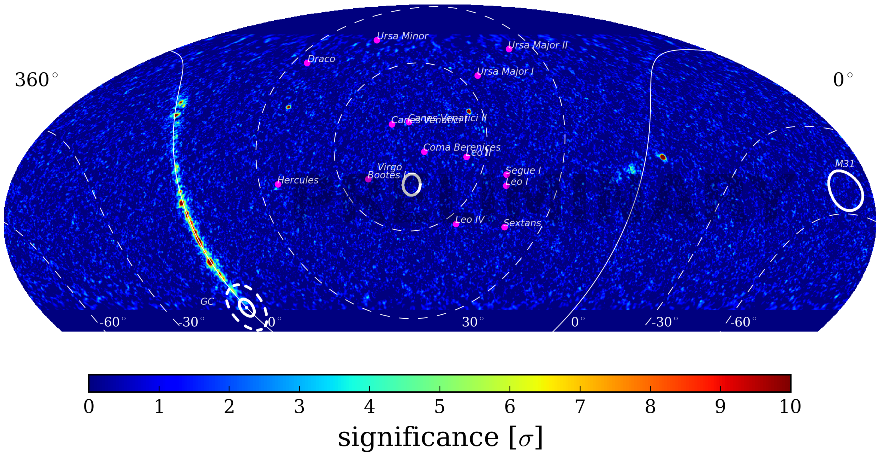
- Looked at by Fermi-LAT
- SMC (Phys. Rev. D 93, 062004 (2016))
  - 60 kpc away, -73 declination
  - Limit within order of magnitude of stacked dwarfs
  - ~3 degrees across
- LMC (Phys. Rev. D 91, 102001 (2015))
  - 50 kpc away, -70 declination
  - Limits as good as stacked dwarfs at low masses
  - 2-4 degrees across
- Some of the best objects for DM searches
  - But need large FoV, southern observatory to see them well

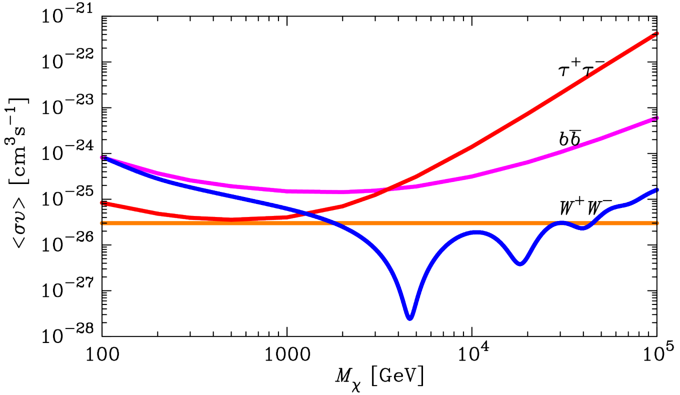
Dark Matter in and Near the Galactic Center

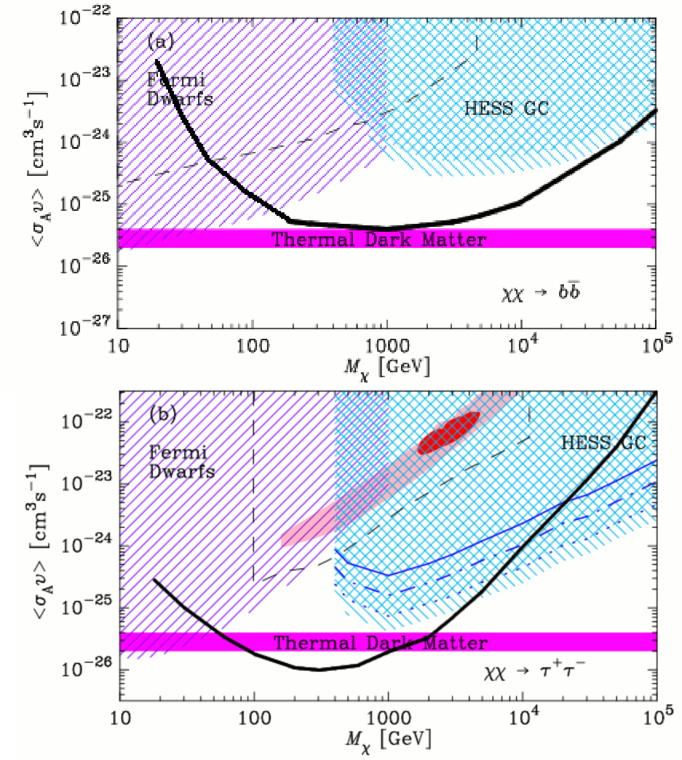
- As much as 1000x more signal expected as from a dwarf galaxy
- Extended over the whole sky, since we are in it
    - But peaked toward galactic center
        - How much peaked is disputed
        - Very extended source
- Also can be large galactic plane backgrounds
    - Less of an issue the higher in energy you go



Estimate of Galactic Center Limits with a Southern Wide-field TeV Observatory

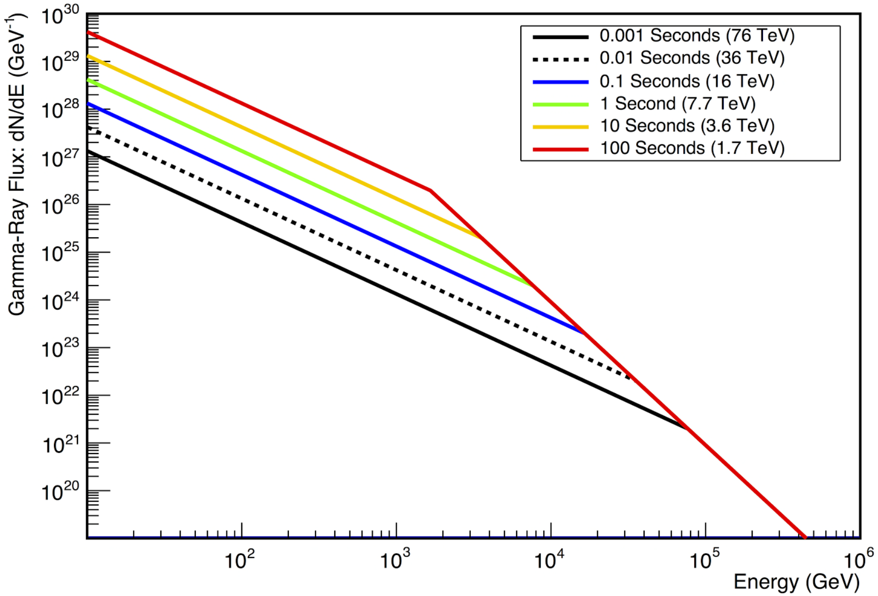
- 5-year limits from HAWC-like detector at -29° S
- Below: at 5200m asl
  - ~2x new 10-year, 254-hour HESS limits
- Right: at 6600m asl
  - As much as 10x better
  - Extends to even lower masses
  - Good overlap with Fermi-LAT limits





Primordial Black Holes (PBHs)

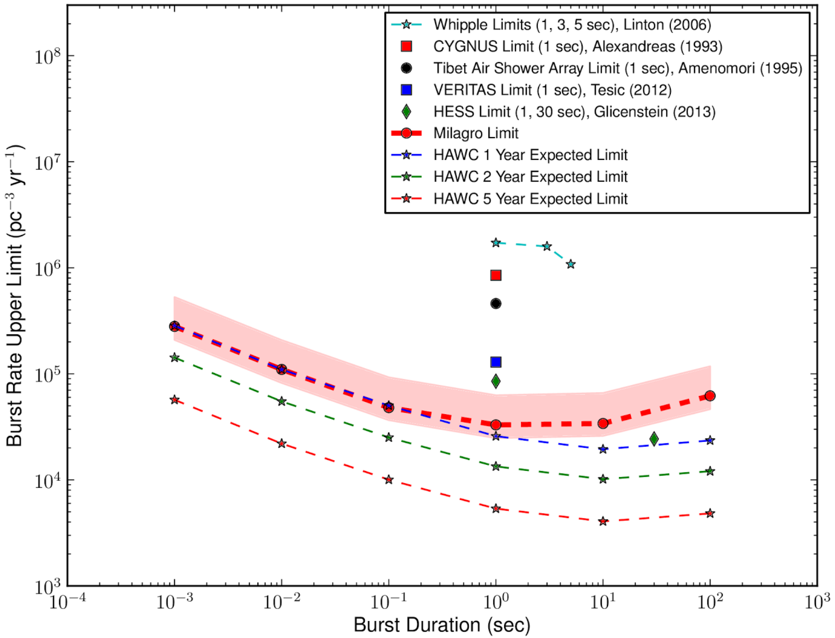
- Black holes from the early universe – a possible dark matter candidate
- Search is like that for GRBs – short, intense burst of gamma rays
- Fluence and spectrum of the burst is a function of the search window
  - As they evaporate, the spectra harden and the fluence decreases
  - The observed fluence of gamma-rays observed depends on the temperature at which it is first observed



Abdo+, ApJ 64, 4 (2015)

Primordial Black Holes (PBHs)

- The large field-of-view and high duty cycle allow for a wide search for PBHs
- The high energy reach enables studies for PBHs up to the highest energies and shortest PBH lifetimes
- Could be detected at any time in any direction
  - Large FoV, high uptime search



Abdo+, ApJ 64, 4 (2015)

Lorentz Invariance Violation

- Though Lorentz invariance is thought to be a fundamental symmetry, many theories of quantum gravity break the symmetry at high energy
- Parameterize as: $E^2=m^2c^2+p^2c^2(1+\xi_n(pc/M_{pl})^n)$
  - n=1 term violates CPT symmetry
  - n=2 term dominates if CPT is conserved
- Photons' speed becomes energy-dependent
  - c at low energies (where current observatiosn are), but slightly faster or slower at higher energies

Lorentz Invariance Violation: GRBs and AGN

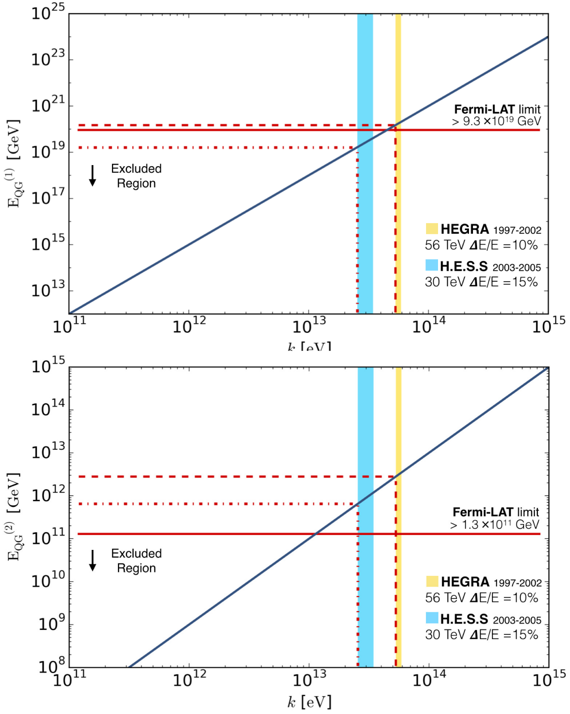
- Long travel distance, short timescale
  - Small speed differential leads to large time differential
  - Would expect to see the high-energy GRB a few seconds before or after the low-energy GRB
  - $(1Gpc)/c-(1Gpc)/(c+10^{-15}c)=100s$
    - 100s probes E_{max}/E_{QG}~10^{-15}
- Need to see a GRB photon in ~TeV range to compete with current limits
  - Requires large uptime, large FoV, high-energy detector to find the GRBs
- Similar analysis can be done with short AGN flares
  - So more observed over FoV, the better to constrain LIV

Lorentz Invariance Violation: Pulsars

- Close travel distance, extremely short timescale
  - Shorter distance than GRBs, so less sensitive to n=1
  - But n=2 is more about energy reach than distance
  - The closer the object, the less EBL attentuation will kill high-energy photons
- Can stack pulsars periods in-phase to get high-significance sources
  - Periods of ~1s (or ms for millisecond pulsars) give very short times
- If LIV were present, the high-energy emission would be later (or earlier) than the low-energy mission
  - Because short timescales, would be sensitive to small delays
- High-uptime observations needed to have lots of periods to stack
  - High-energy observations to get large energy reach
  - The more pulsars in the FoV, the more you can combine to see delays

Lorentz Invariance Violation: High-energy Photons

- LIV is the reason that MeV+ photons don't decay in to e^+e^- in flight
- If LIV is broken at some energy scale, high-energy photons will decay in ~nm
- Observation of even one high-energy photon can constrain LIV
- To observe these photons, need:
  - High energy reach
  - As many sources observed for as much time as possible



Martínez-Huerta & Pérez-Lorenzana, arXiv:1610.00047

Axion-Like Particles

- Axions are hypothetical particles proposed to solve the 'Strong CP' problem in QCD
  - They couple to photons in magnetic fields
  - You can generalize the mass and coupling ($g_{a\gamma}$) to get 'axion like particles' (ALPs)
- Axions and/or ALPs could constitute all or some of the dark matter
- for ALPs, m_a and $g_{a\gamma}$ are independent
  - See B. Berenji+ (2016) arXiv:1602.00091

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

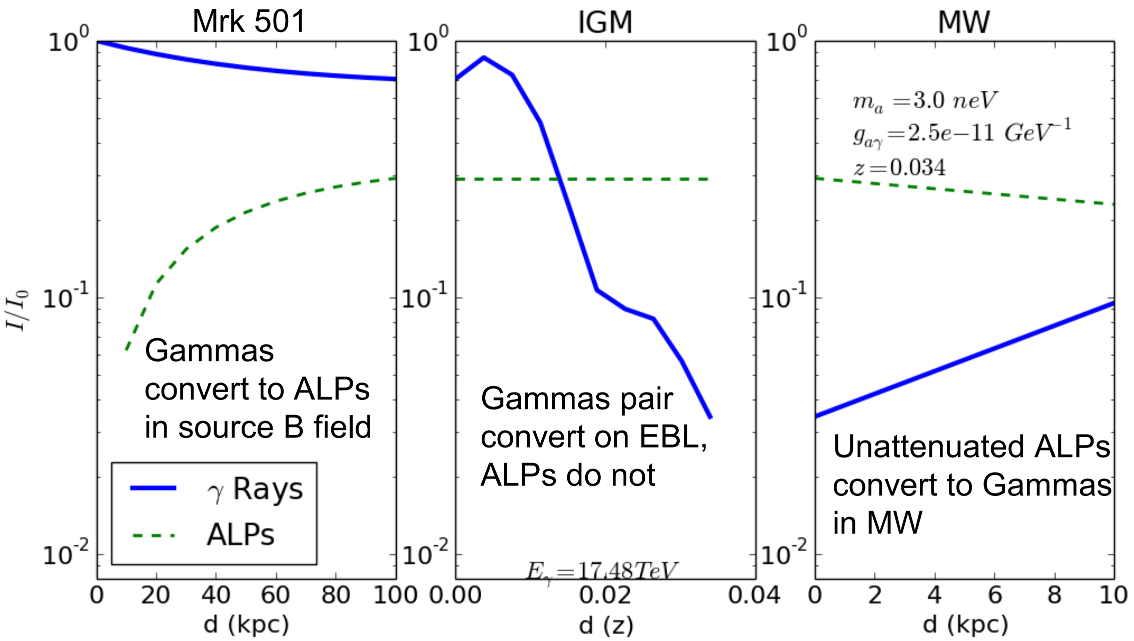
$$m_a \approx 6\ \mu\text{eV} \left(\frac{f_a}{10^{12}\ \text{GeV}} \right)^{-1}$$

$= 6\ \mu\text{eV}\ g_{a\gamma}$

Thanks to A. Albert

Constraining Axion-Like Particles

- Instead of gamma rays attenutating from the EBL, you see emission at higher energies due to gammas converting to ALPs and back again



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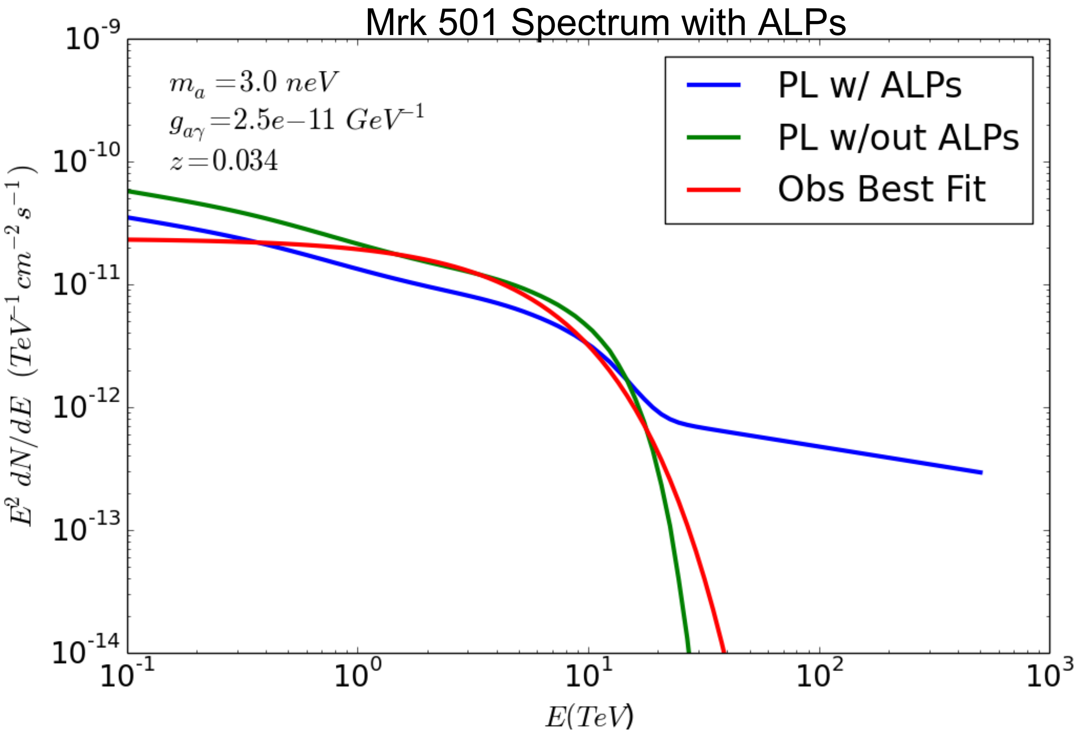

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Constraining Axion-Like Particles

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- To search for a lack of an EBL cutoff, need to look at high energy
- Source-to-source variation makes it difficult to determine a lack of a cutoff from any single source
  - Need to observe many sources
  - Wide FoV enables us to find these AGN at high energies
    - Can determine lack of a cutoff
  - IACTs can follow-up to determine further spectral information

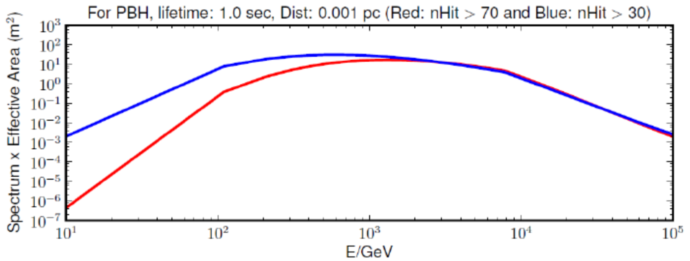
Summary

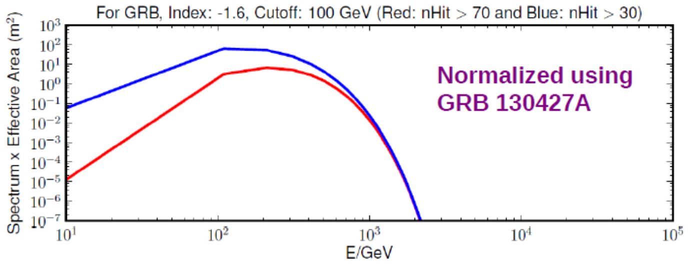
- Wide FoV helps with extended sources, multiple stacked sources
  - Also have data banked for when new sources are discovered
- Large uptime + wide FoV helps with finding transients and short flares
- High energy reach probes *many* objects in largely-unexplored regime
- All of these have highly-motivated BSM physics motivations

Backup

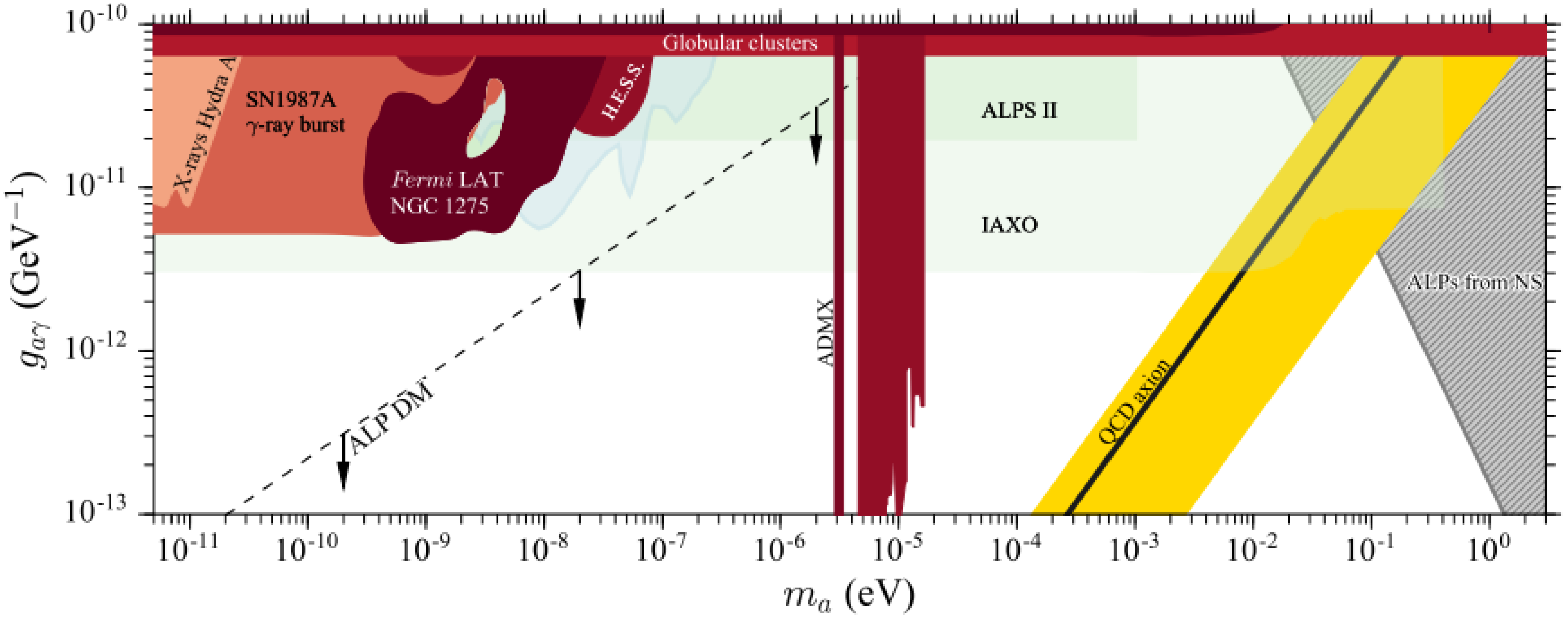
PBH

- How do we know if it's a GRB or a PBH?
  - Energy spectrum
  - Time behavior





Gamma-ray Bursts (GRB)	PBH Bursts (pBHB)
Detected at cosmological distances	Unlikely to be detected outside our Galaxy
Most GRBs show hard-to-soft evolution	Soft-to-hard evolution is expected from pBHB
Hadrons are not expected from GRBs	Hadronic bursts may reach earth
Gravitational Wave signal is expected	No gravitational wave signal is expected
Time duration can range from fraction of second to few hours	Time duration of the burst is most likely less than few seconds
Fast Rise Exponential Decay (FRED) light curve	Exponential Rise Fast Fall (ERFF) light curve
X-ray, optical, radio afterglows are expected	No multi-wavelength afterglow is expected
Multi-peak time profile	Single-peak time profile



Phys. Rept. 636, 1 (2016)

Figure 26: Current status of the limits imposed on the ALP parameter space by different experiments and targets. Limits derived with LAT observations are shown as dark red (NGC 1275 in the Perseus galaxy cluster [271]) and gray hatched (neutron stars [253]) regions. Limits from other experiments are shown in red. The parameter space where ALPs could explain a low γ-ray opacity is shown in light blue. The parameter space where ALPs could explain hints for a low γ-ray opacity are shown in blue. Sensitivity estimates for future laboratory experiments are shown in green. The QCD axion line is shown in yellow. ALP parameters below the dashed line could account for all the DM. See Refs. [272, 273] and references therein.