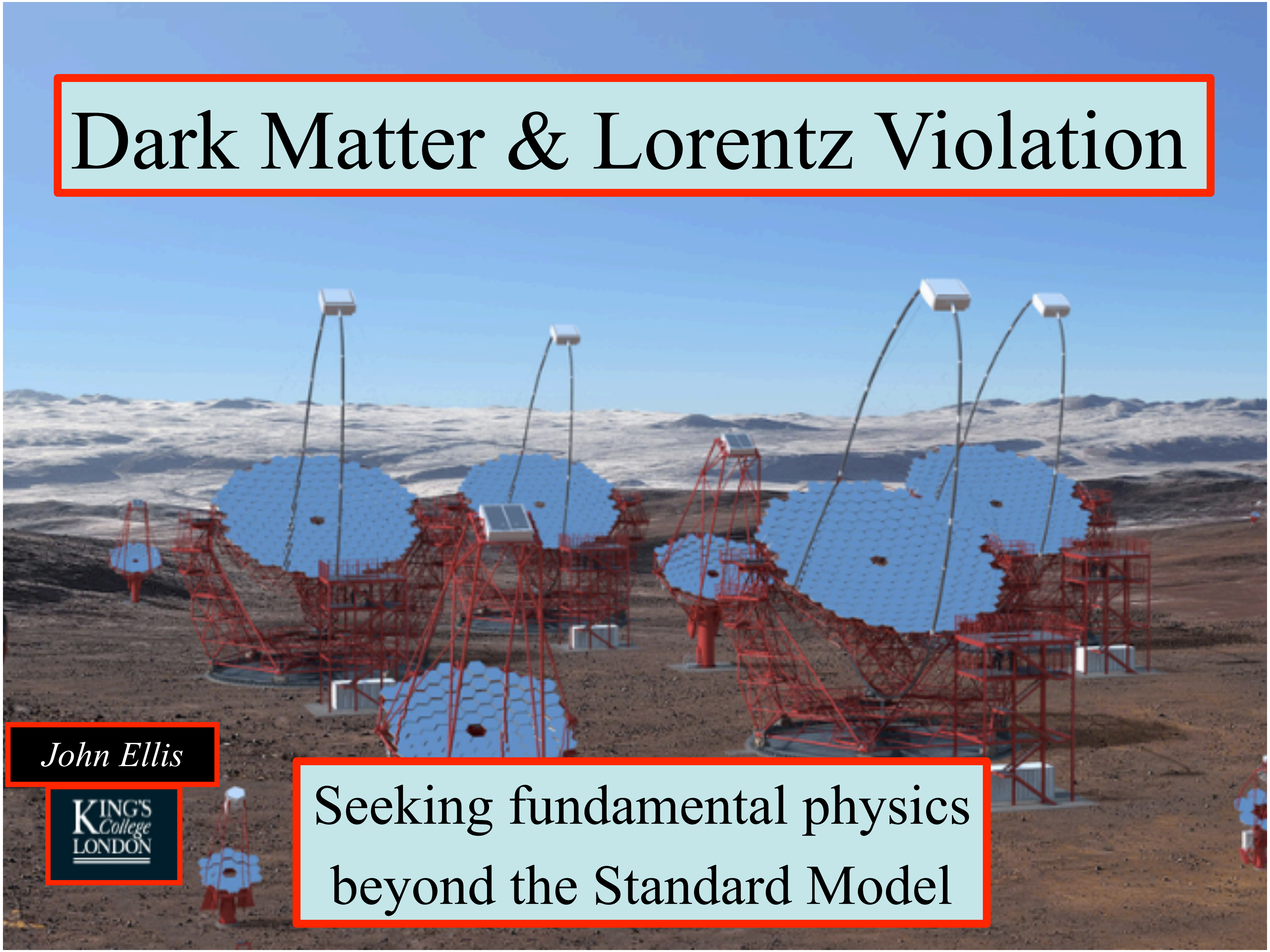
Dark Matter & Lorentz Violation

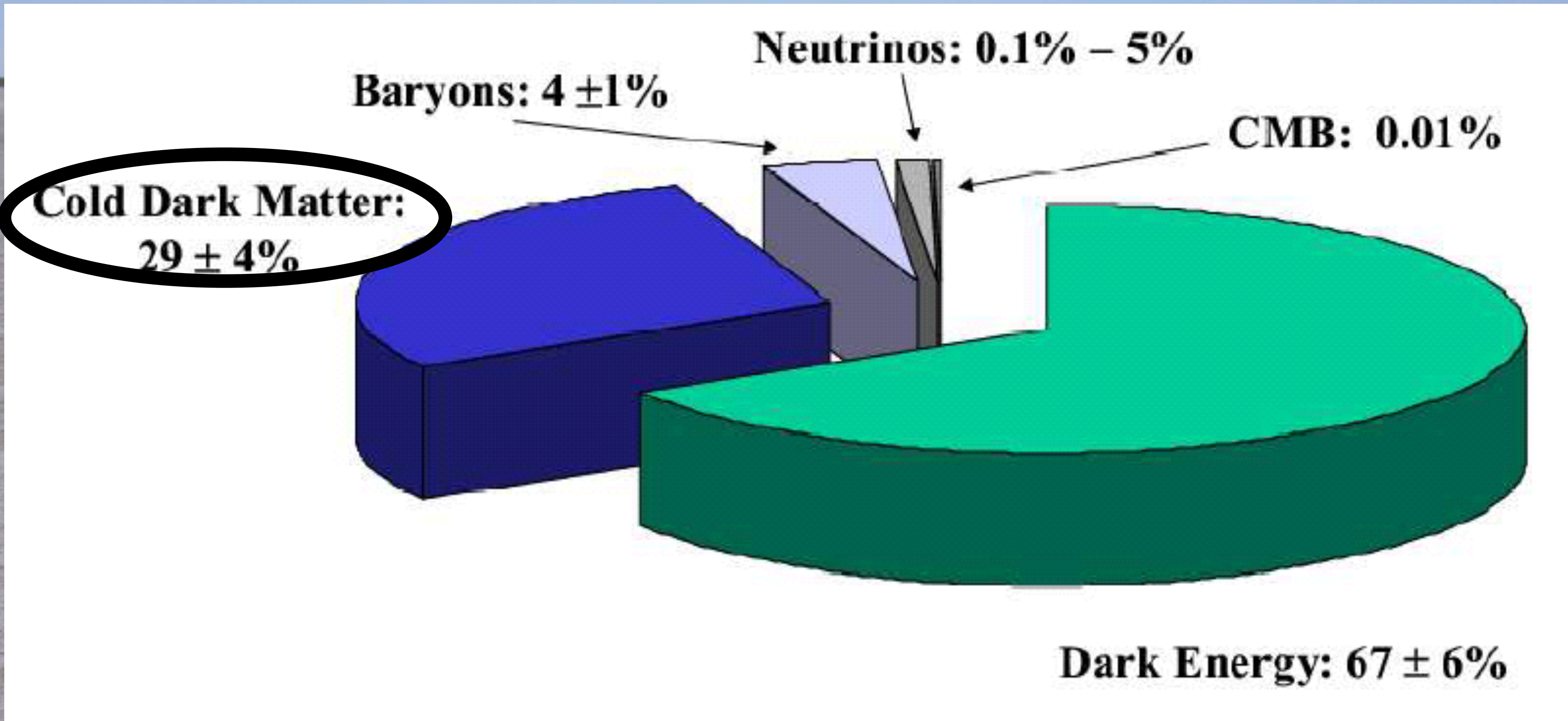


John Ellis

KING'S College LONDON

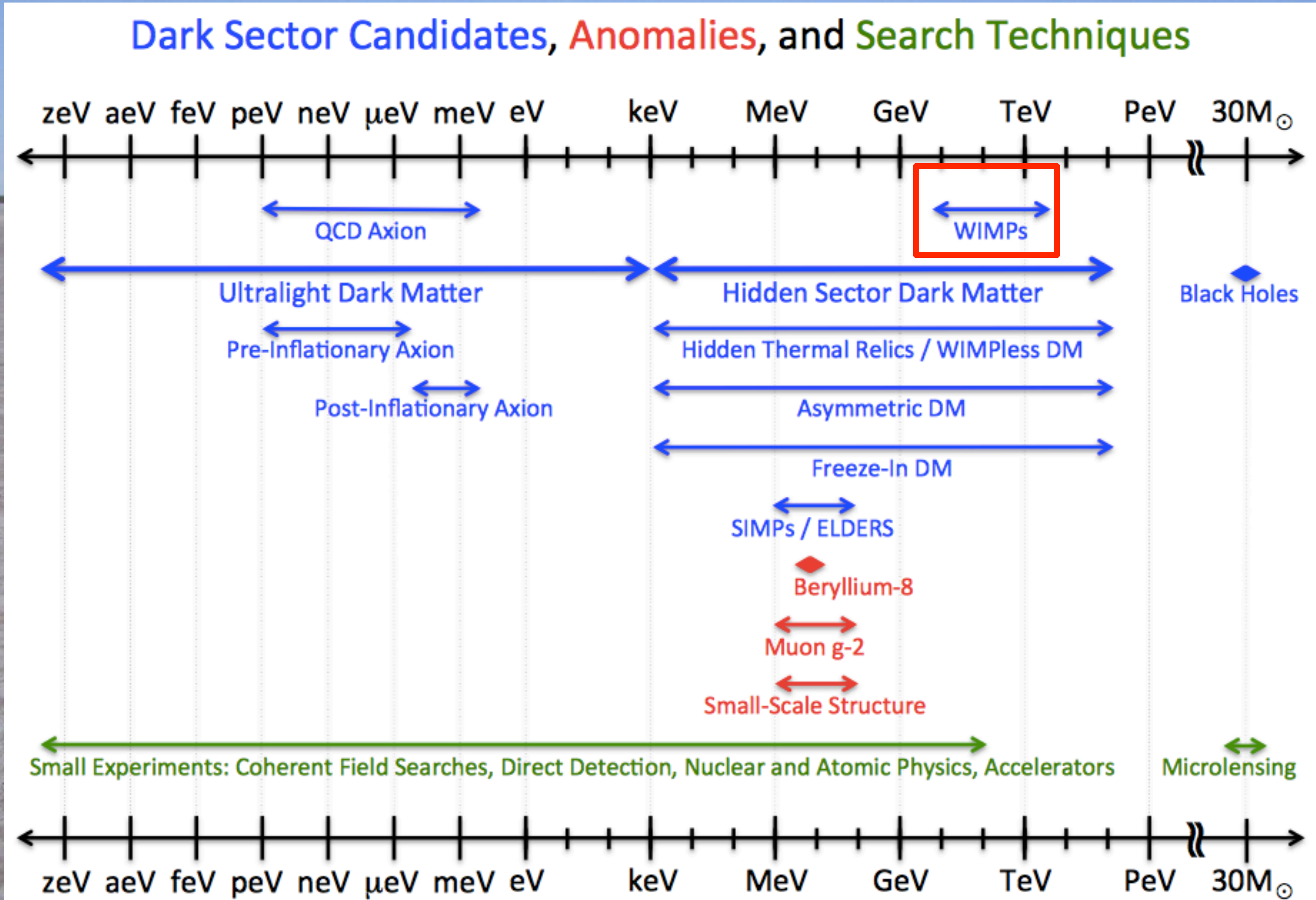
Seeking fundamental physics beyond the Standard Model

Strange Recipe for a Universe



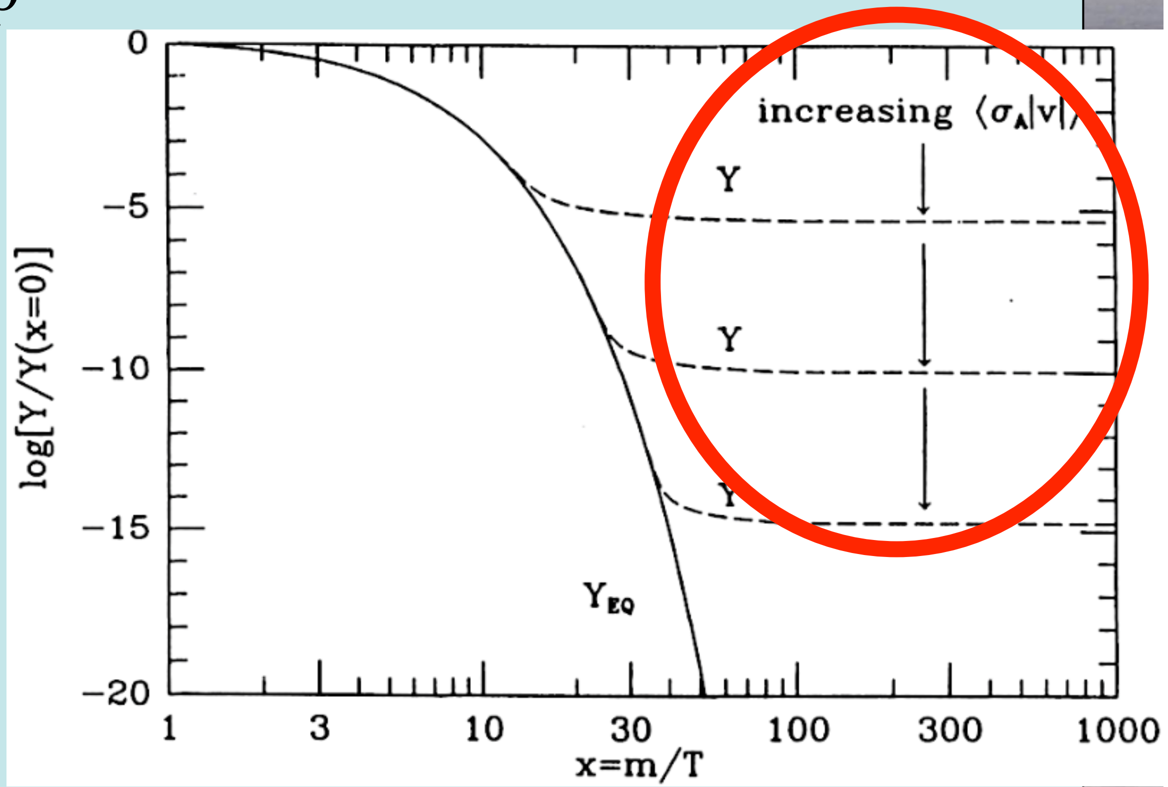
The 'Standard Model' of the Universe indicated by astrophysics and cosmology

Many Candidates for Dark Matter

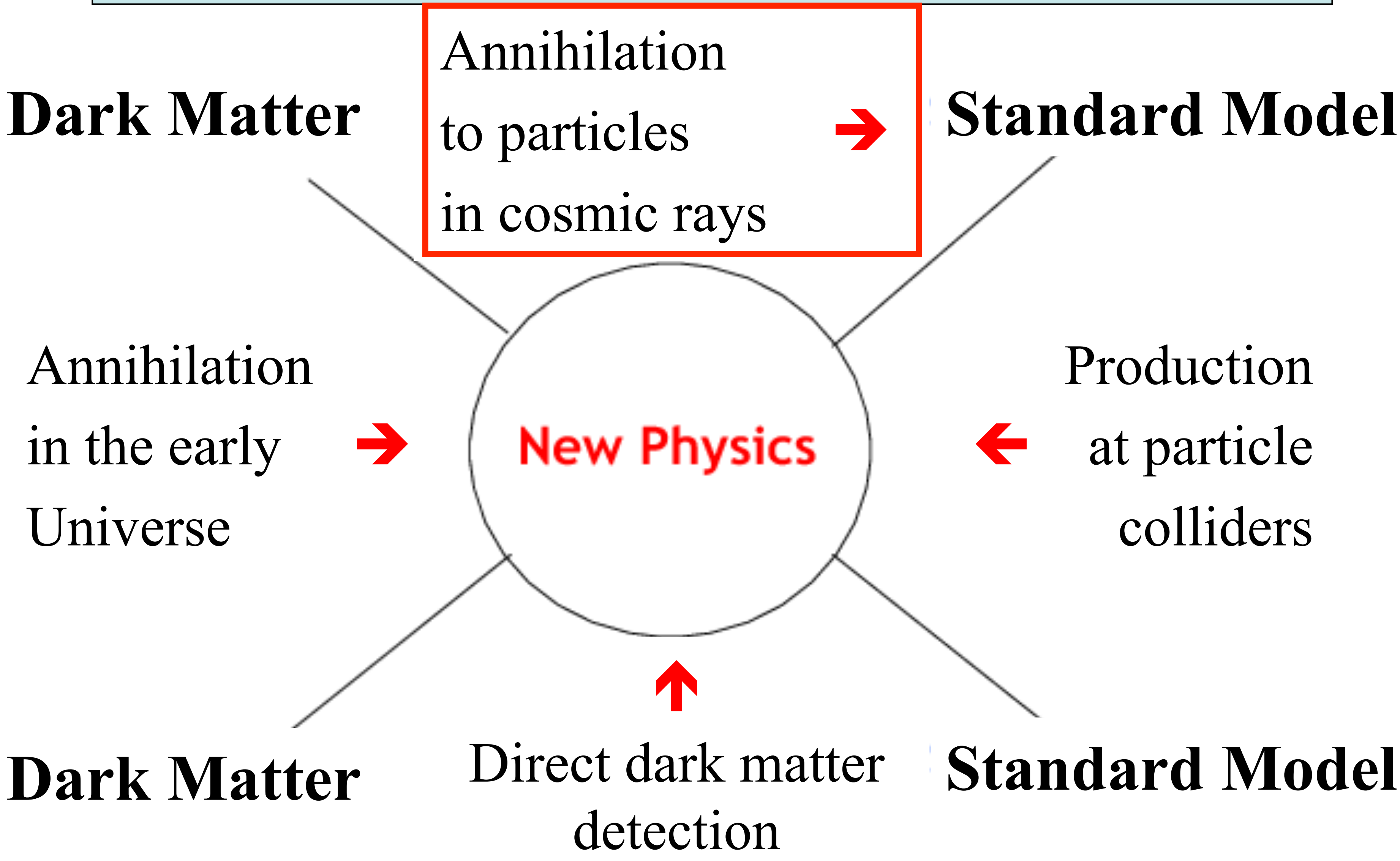


Weakly-Interacting Massive Particles (WIMPs)

- Expected to have been numerous in the primordial Universe when it was a fraction of a second old, full of a primordial hot soup
- Would have cooled down as Universe expanded
- Interactions would have weakened
- WIMPs decoupled from visible matter
- "Freeze-out"
- Larger σ → lower **DM density: OK if σ ~ 3.10^{-26} cm^{2}**



Searches for WIMP Dark Matter



Nuclear Physics B238 (1984) 453–476

Archetypal WIMP

SUPERSYMMETRIC RELICS FROM THE BIG BANG*

John ELLIS and J. S. HAGELIN

Stanford Linear Accelerator Center, Stanford University, Stanford, California 94305, USA

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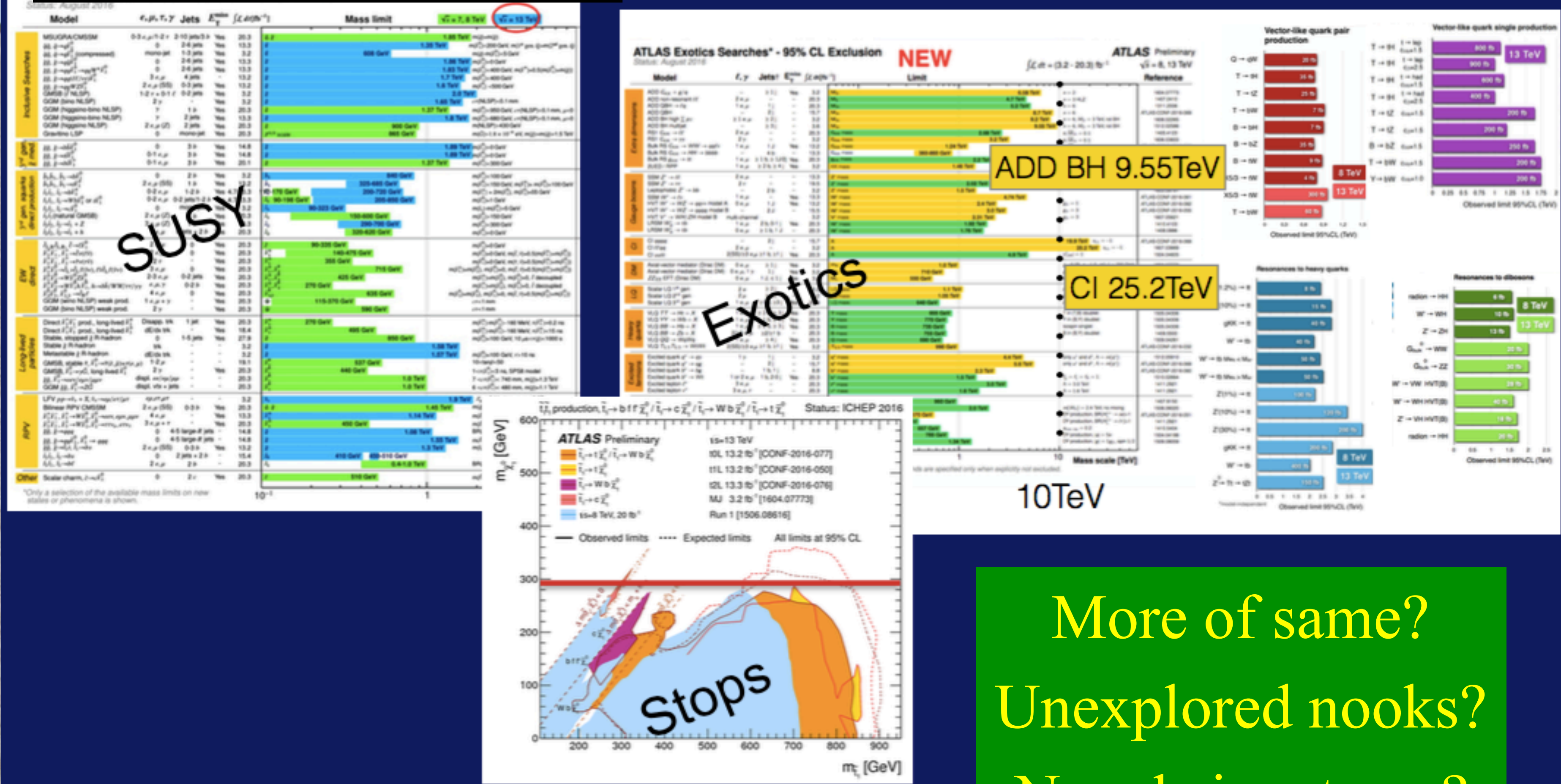
Received 16 September 1983
(Revised 15 December 1983)

We consider the cosmological constraints on supersymmetric theories with a new, stable particle. Circumstantial evidence points to a neutral gauge/Higgs fermion as the best candidate for this particle, and we derive bounds on the parameters in the lagrangian which govern its mass and couplings. One favored possibility is that the lightest neutral supersymmetric particle is predominantly a photino $\tilde{\gamma}$ with mass above $\frac{1}{2}$ GeV, while another is that the lightest neutral supersymmetric particle is a Higgs fermion with mass above 5 GeV or less than O(100) eV. We also point out that a gravitino mass of 10 to 100 GeV implies that the temperature after completion of an inflationary phase cannot be above 10^{14} GeV, and probably not above 3×10^{12} GeV. This imposes constraints on mechanisms for generating the baryon number of the universe.

Nothing (yet) at the LHC

No supersymmetry

Nothing else, either



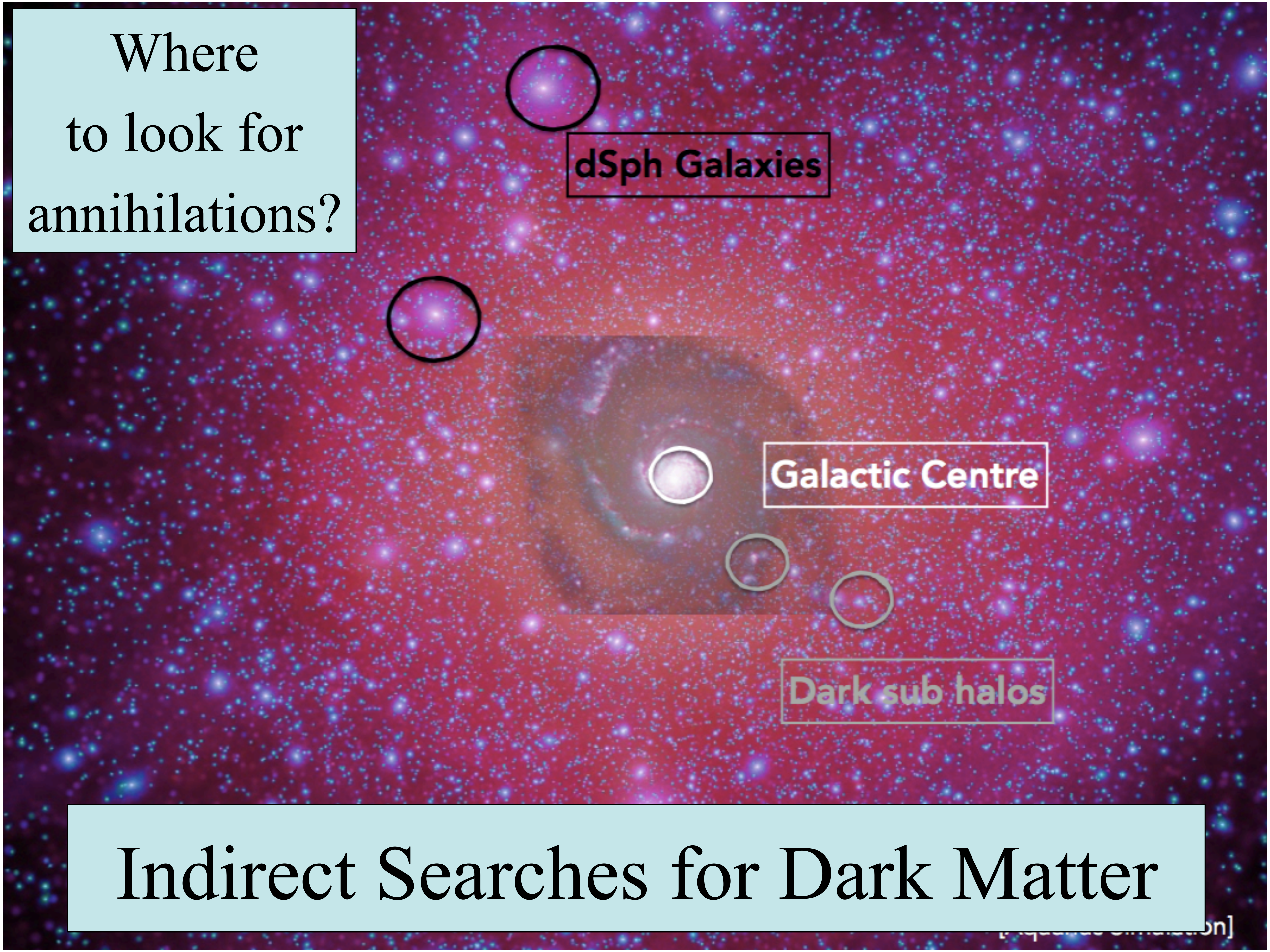
More of same?

Unexplored nooks?

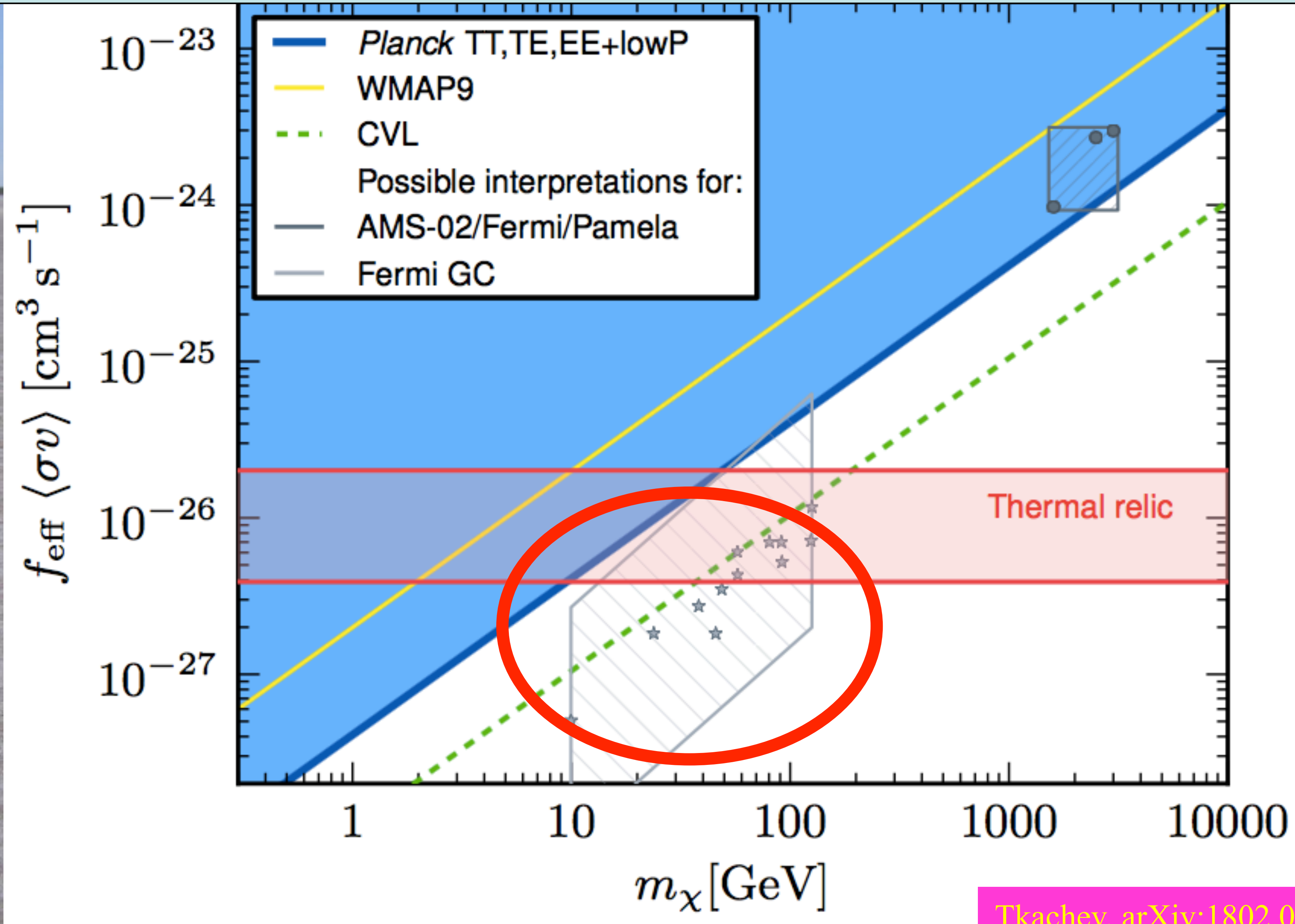
Novel signatures?

Indirect Searches for Dark Matter

Where to look for annihilations?



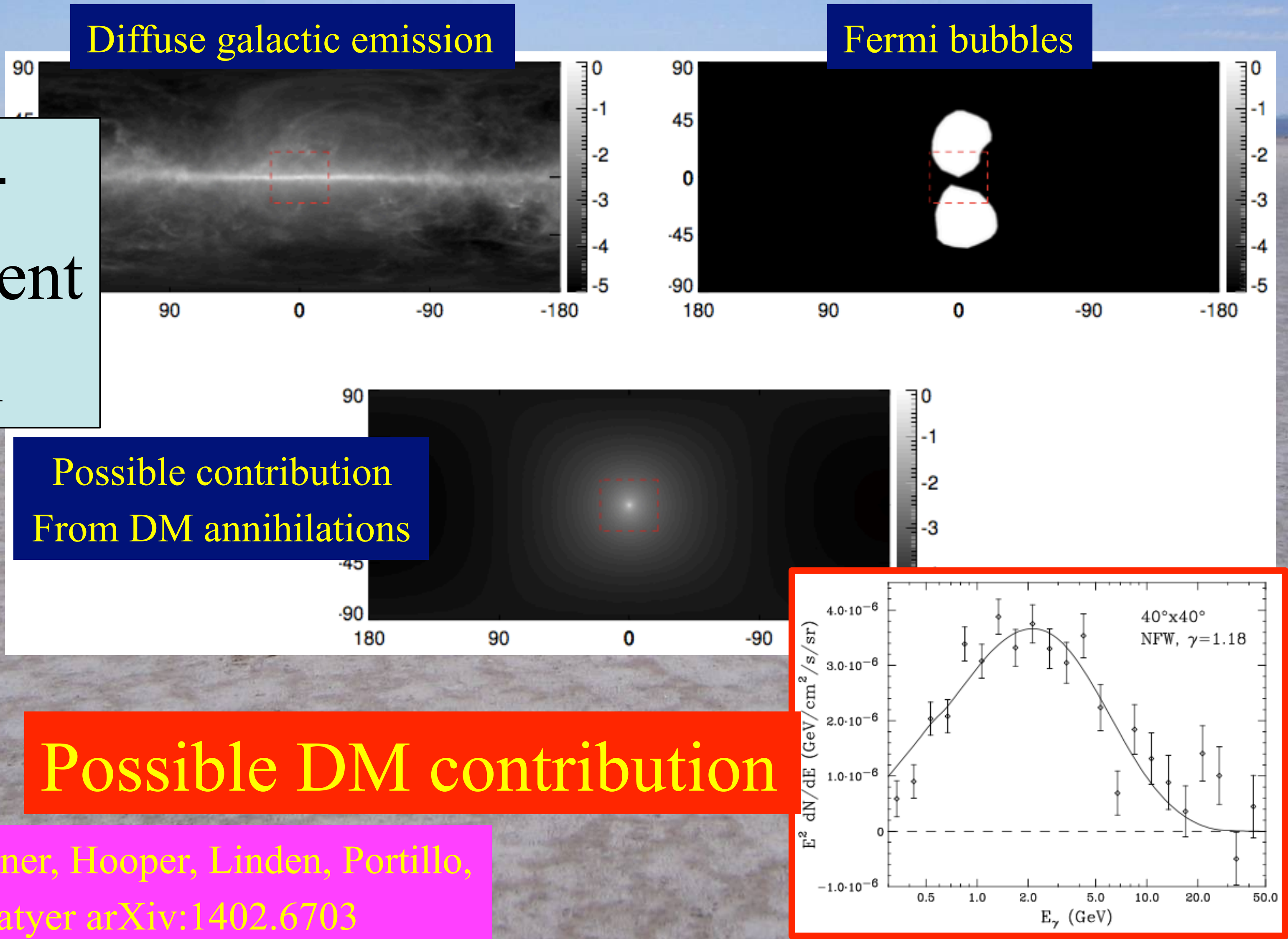
Indirect Constraints on Annihilation



Tkachev, arXiv:1802.02414

Galactic Centre Excess

Multi-Component model



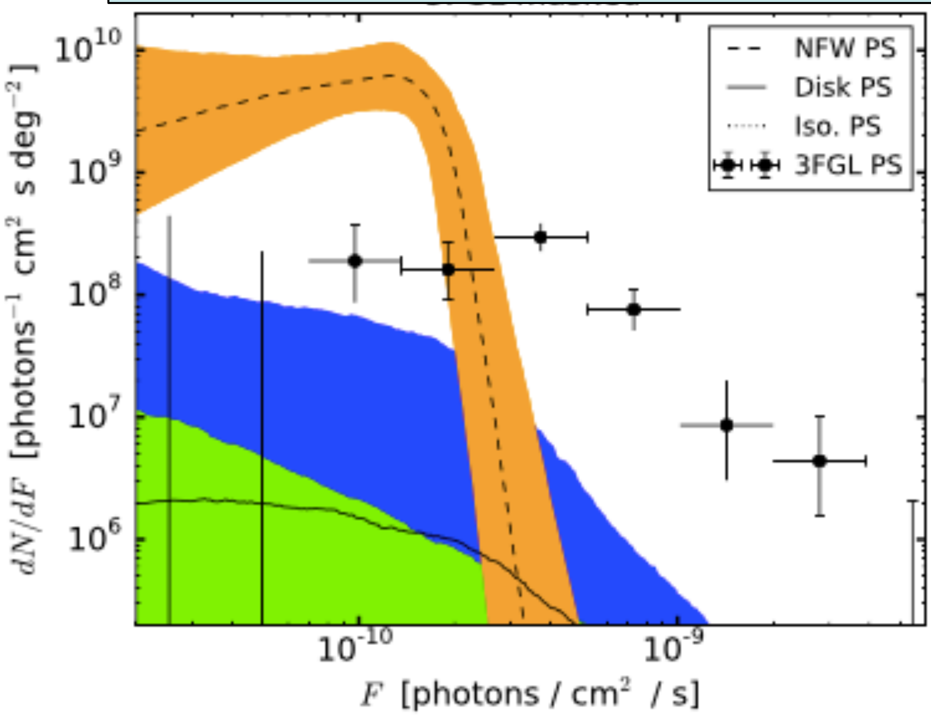
Possible DM contribution

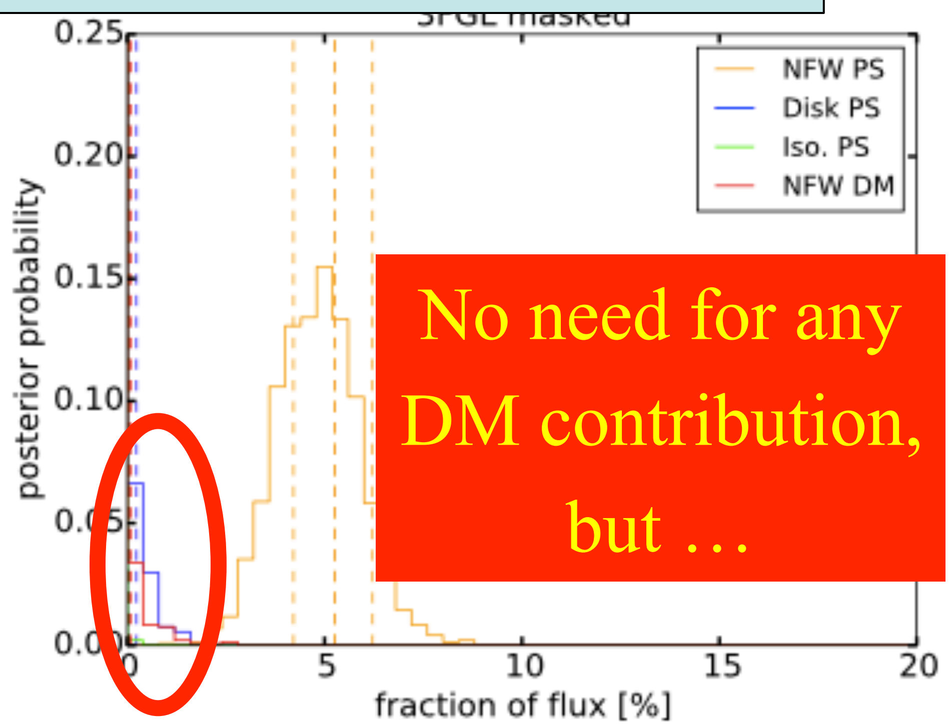
Daylan, Finkbeiner, Hooper, Linden, Portillo, Rodd, Slatyer arXiv:1402.6703

Galactic Centre Excess due to Point Sources?

Possible contribution from unidentified point sources?

Search using measure of non-Poissonian statistics

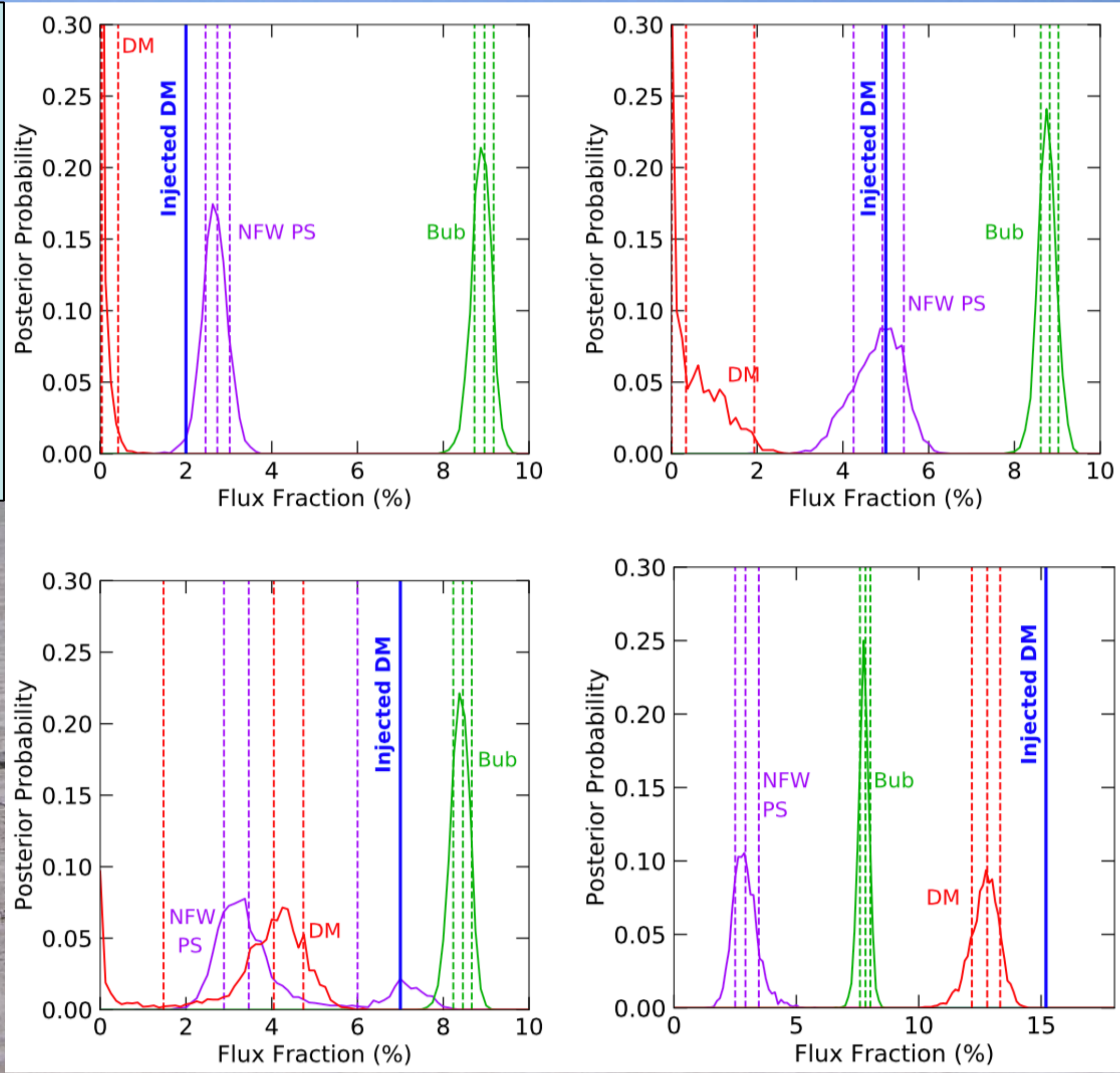




No need for any DM contribution, but …

Lee, Lisanti, Safdi, Slatyer Xue, arXiv:1506.05124

Galactic Centre Excess due to Dark Matter after all?



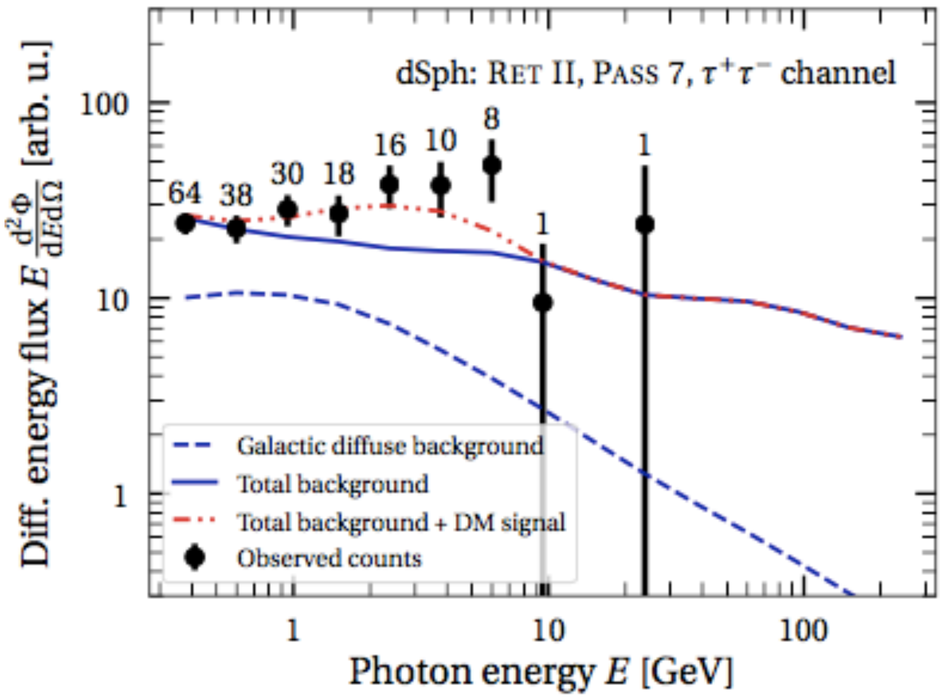
Unmodelled sources in Fermi Bubbles can lead to dark matter signal being misattributed to point sources

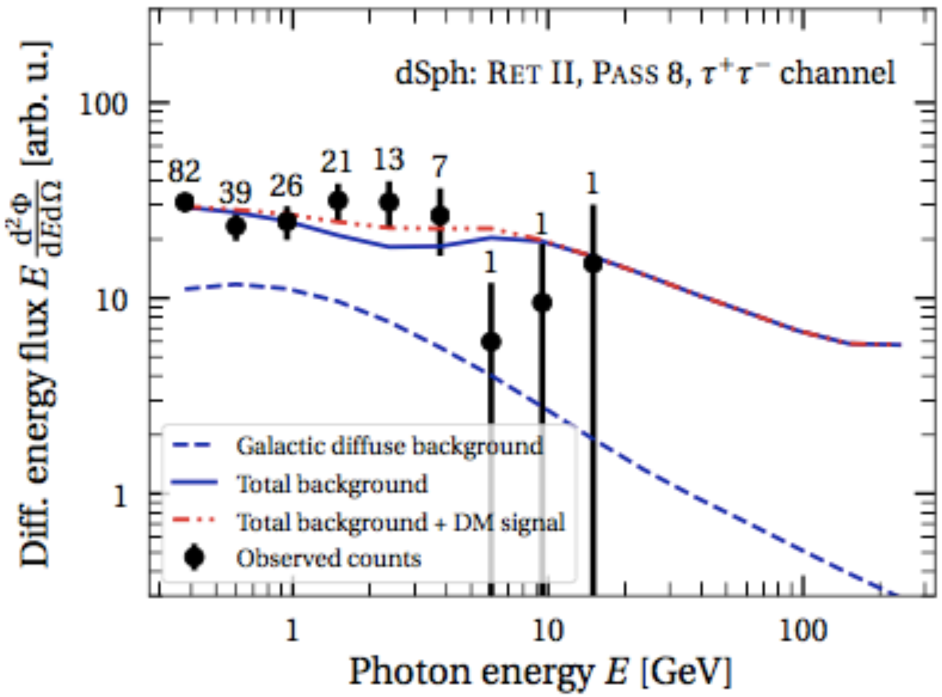
Estimate of DM contribution dependent on templates used

Leane, Slatyer, arXiv:1904.08430

Analysis of Fermi-LAT Data from Reticulum II

Pass 7 of Fermi-LAT data from Reticulum II indicated excess in similar energy range



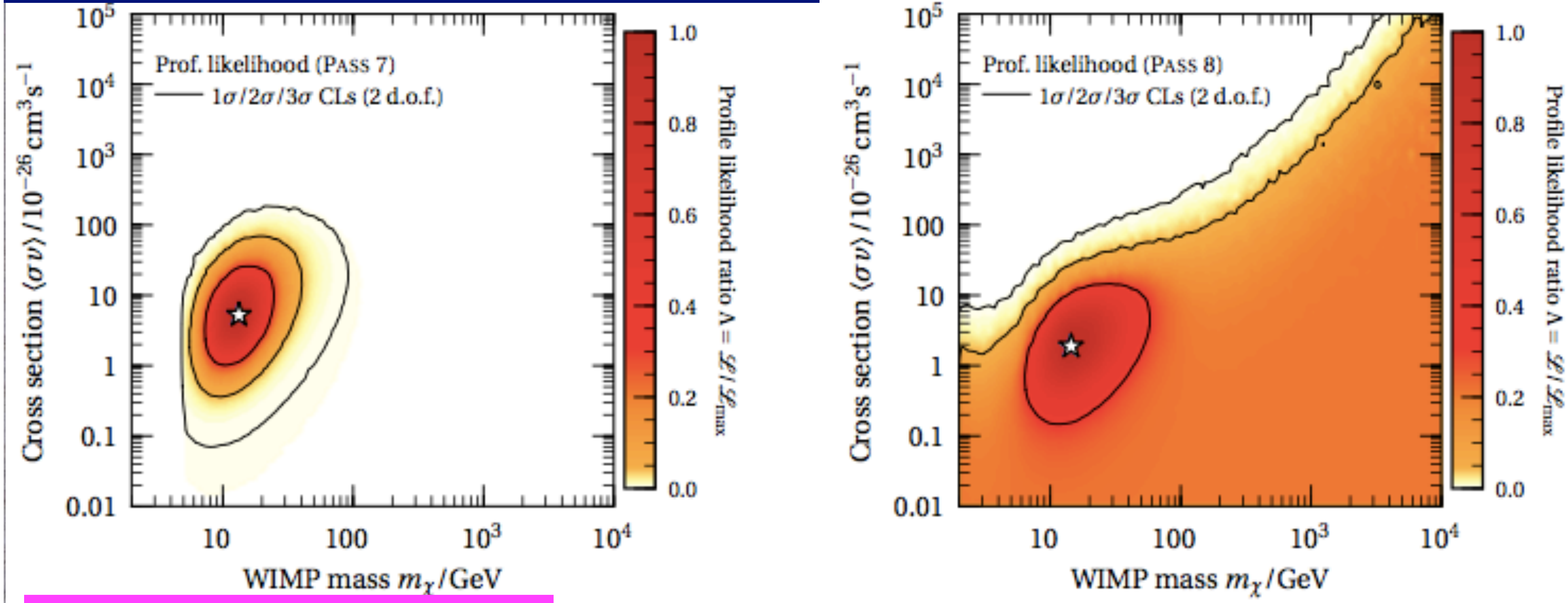


Hoof, Geringer-Sameth, Trotta, arXiv:1812.06986

But less (no) excess in Pass 8 analysis

Analysis of Fermi-LAT Data from Reticulum II

Pass 7 of Fermi-LAT data from Reticulum II indicated excess in similar energy range



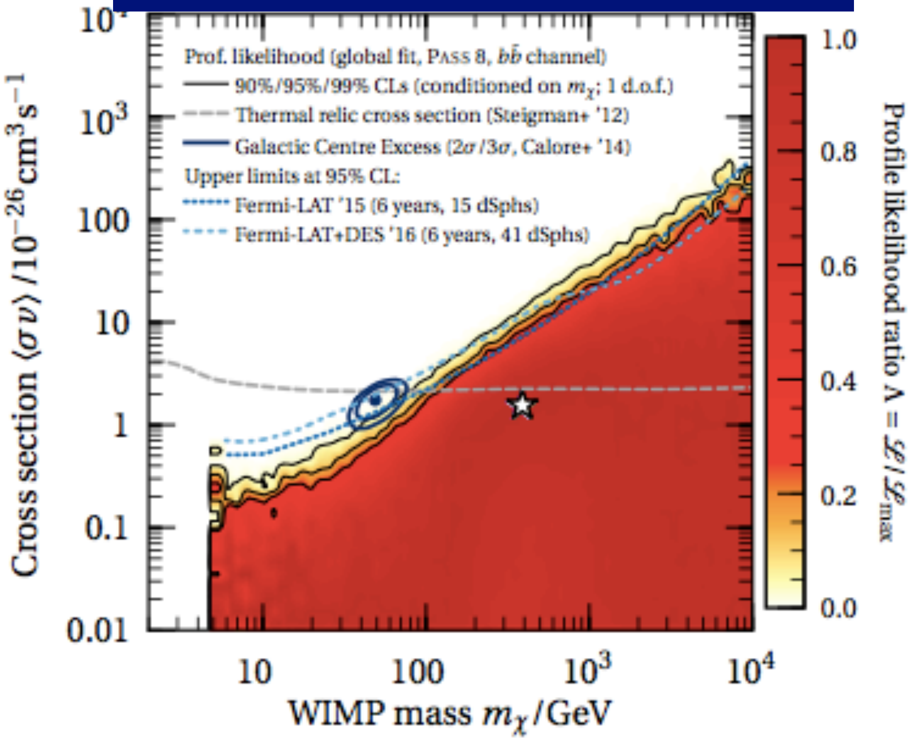
Hoof, Geringer-Sameth, Trotta, arXiv:1812.06986

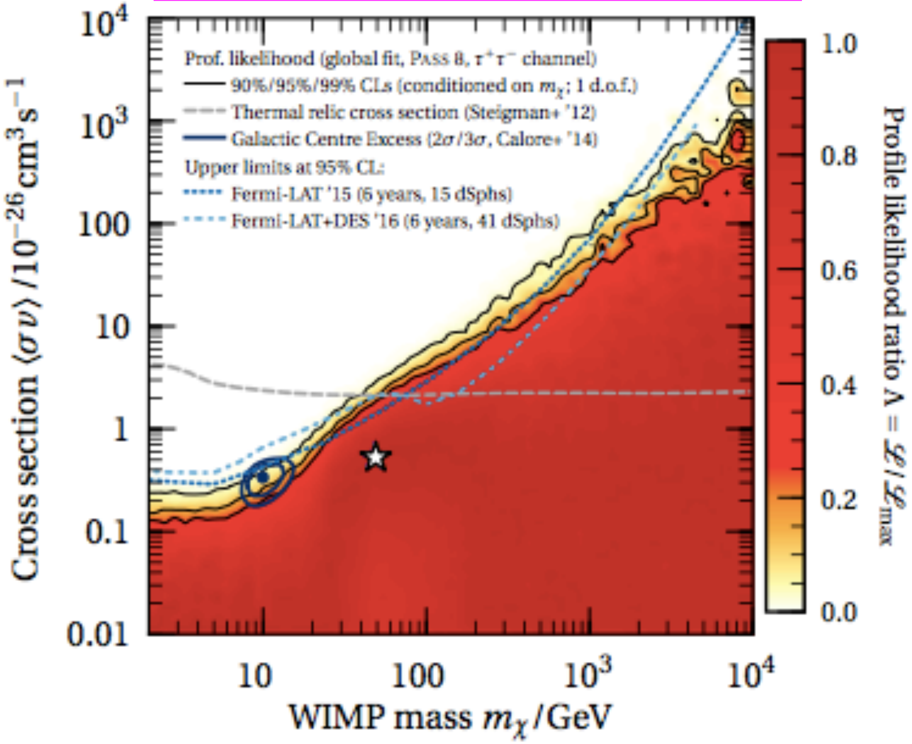
But less (no) excess in Pass 8 analysis

Global Analysis of 27 Dwarf Spheroidal Galaxies

Fits to Fermi-LAT data
in various annihilation scenarios

Hoof, Geringer-Sameth, Trotta,
arXiv:1812.06986





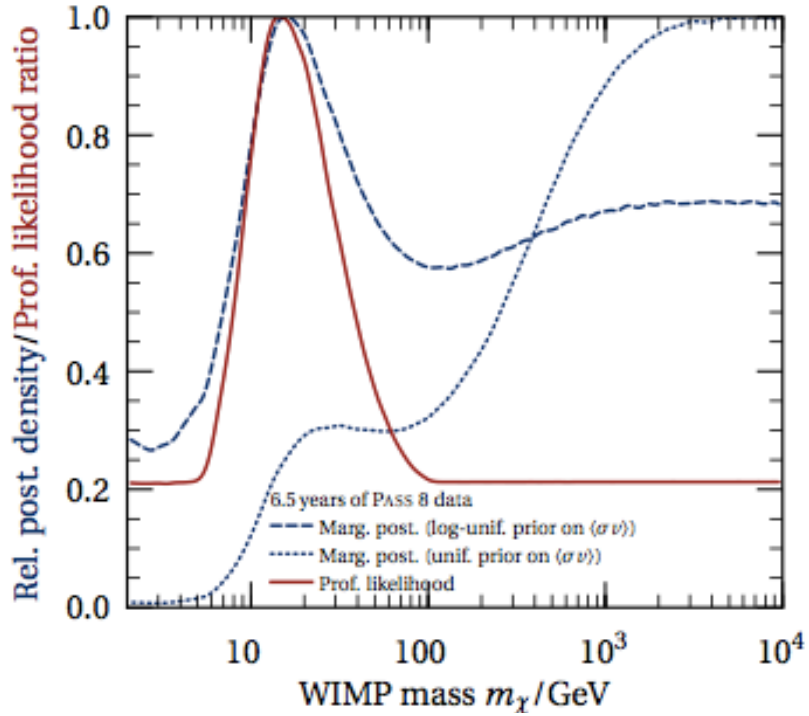
95% exclusion of best fit to galactic centre excess

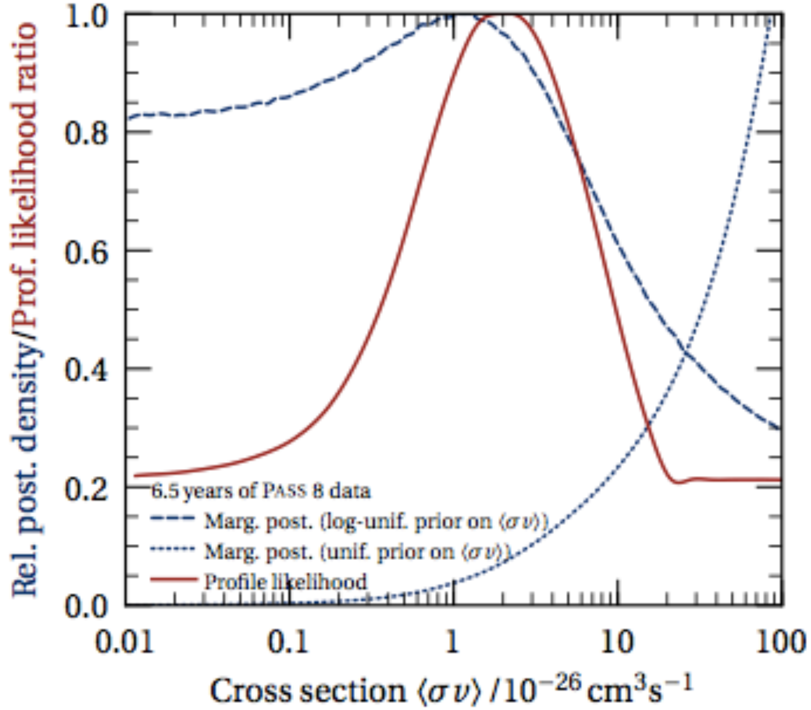
Global Analysis of Dwarf Spheroidal Galaxies

Pass 7 of Fermi-LAT data on 27 dwarf spheroidal galaxies gave interesting indications on mass, σv

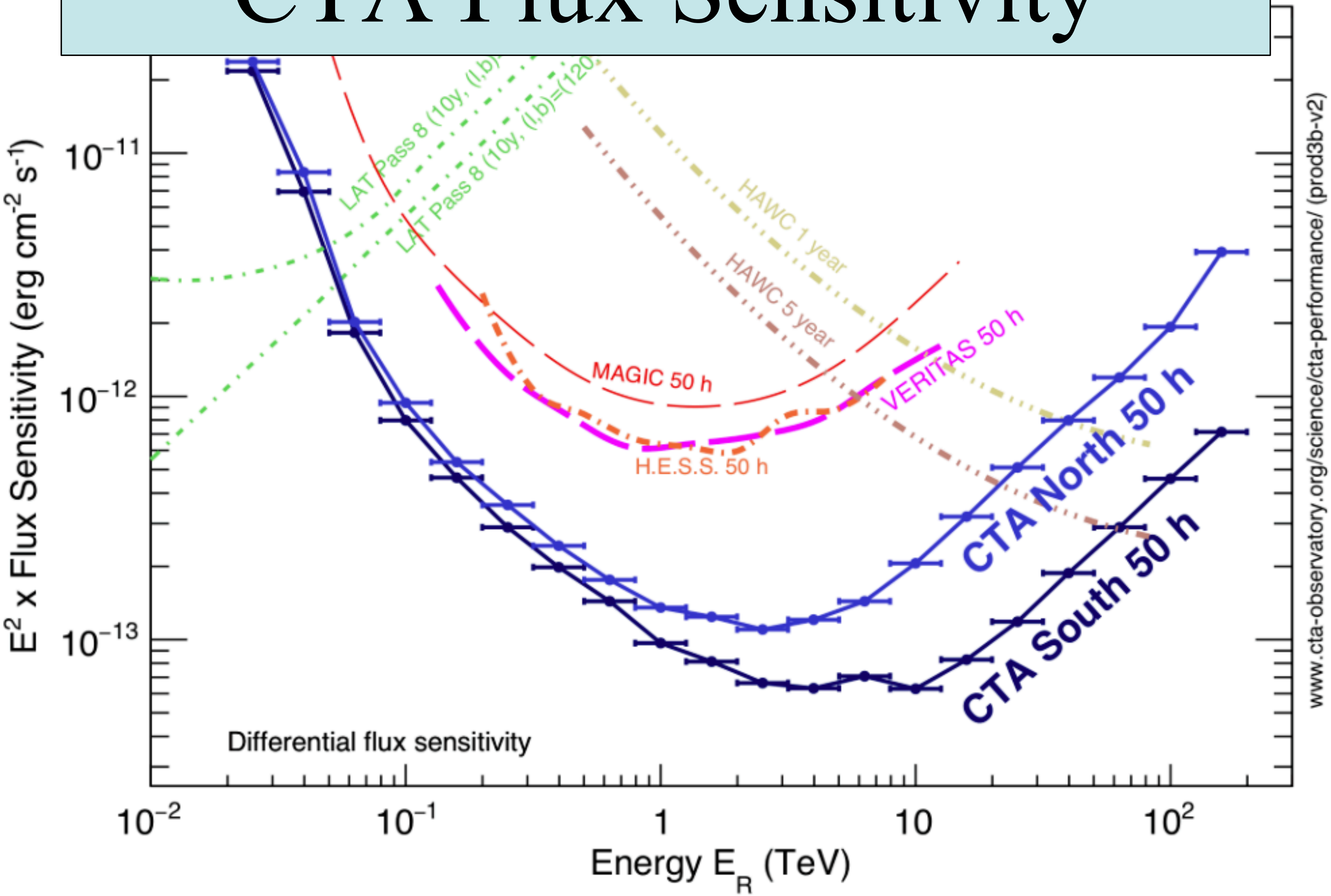
But only weak indications in Pass 8 of Fermi-LAT data

Hoof, Geringer-Sameth, Trotta, arXiv:1812.06986



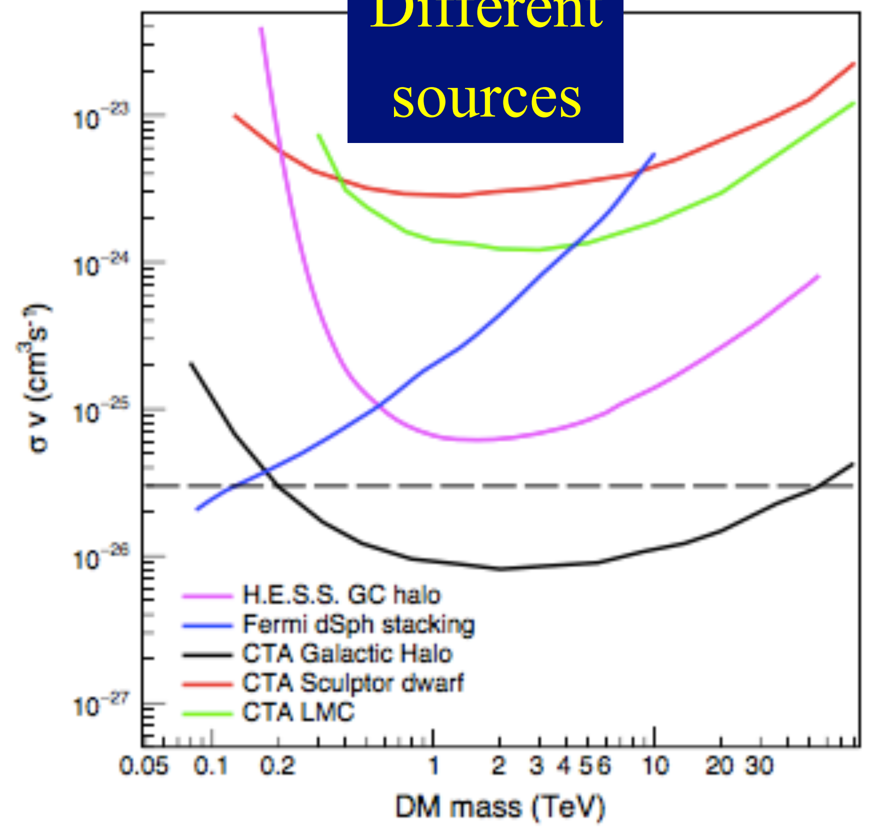


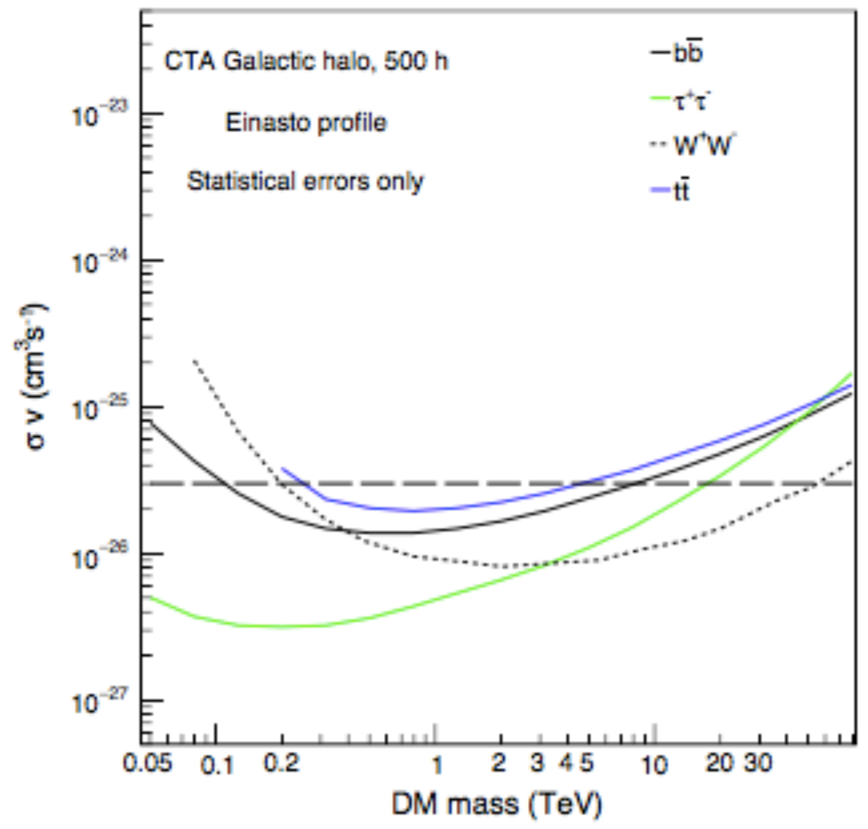
CTA Flux Sensitivity



CTA Sensitivity to DM Annihilations

Different sources

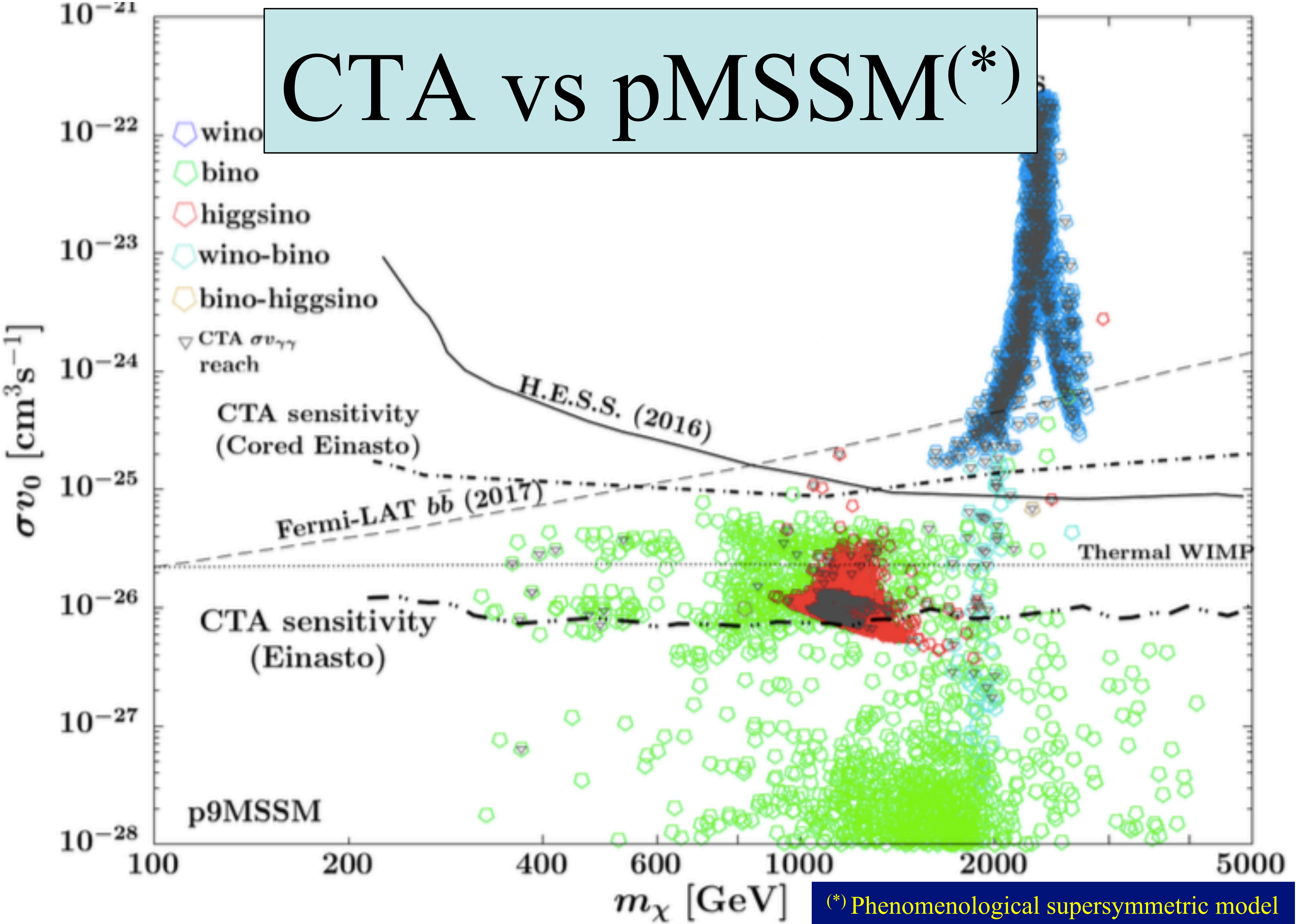




Agudo et al, CTA Astro2020 White Paper

Different annihilation channels

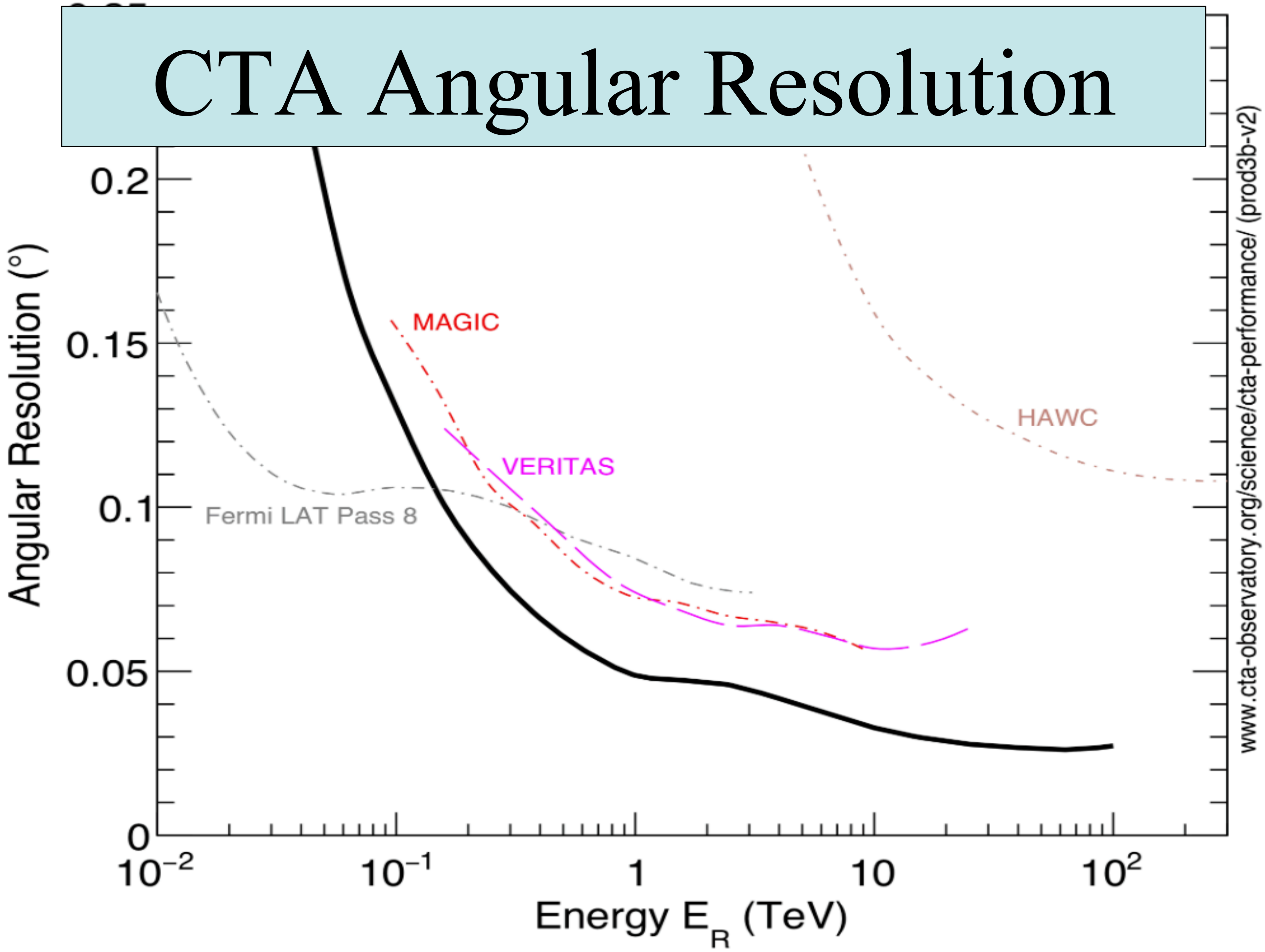
CTA vs pMSSM(*)



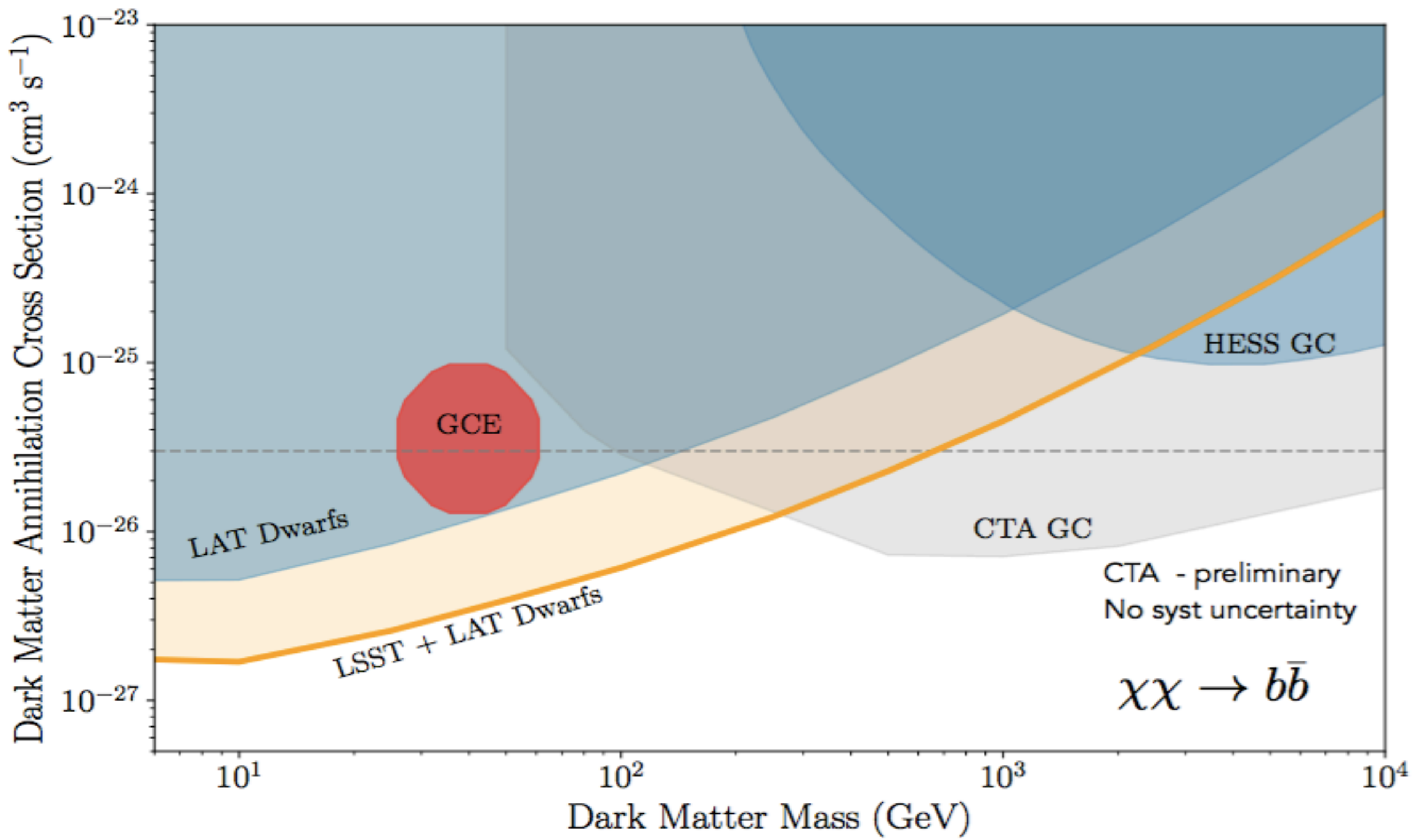
(*) Phenomenological supersymmetric model

Hryczuk, Jodlowski, Moulin, Rinchiuso, Roszkowski, Sessoloa, Trojanowski, arXiv:1905.00315

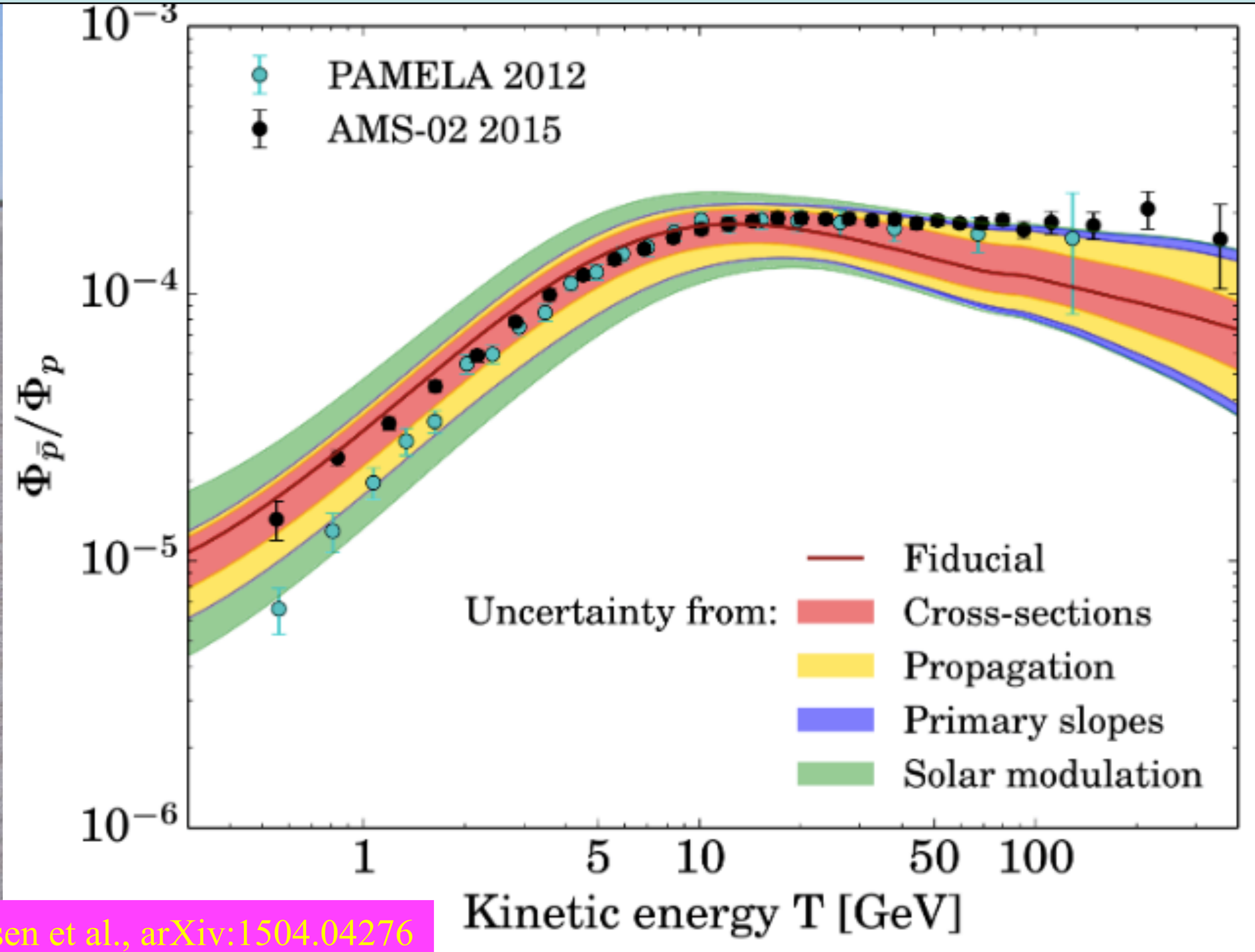
CTA Angular Resolution



Prospective Sensitivity of LSST

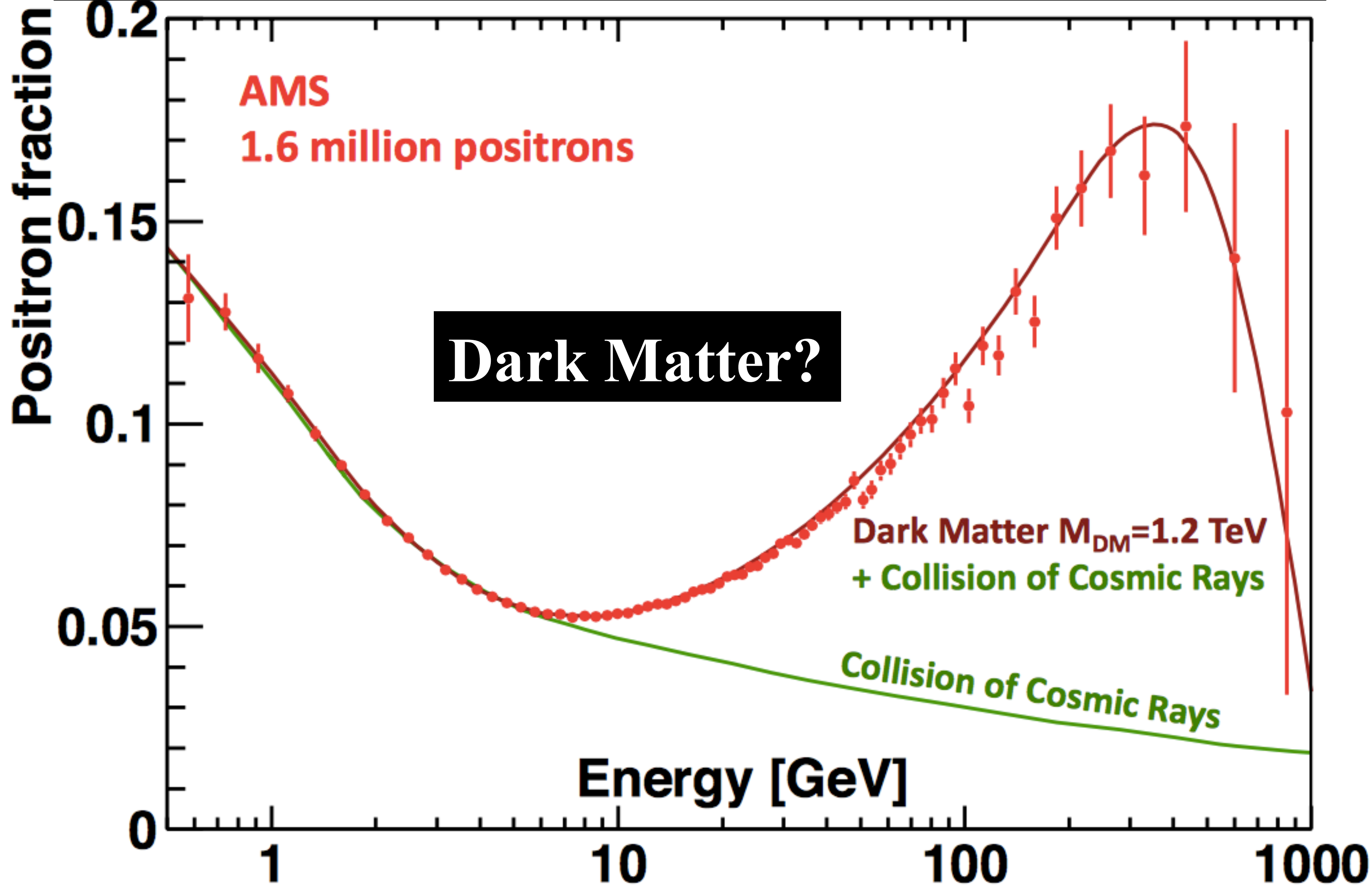


Antiprotons Compatible with Cosmic Rays

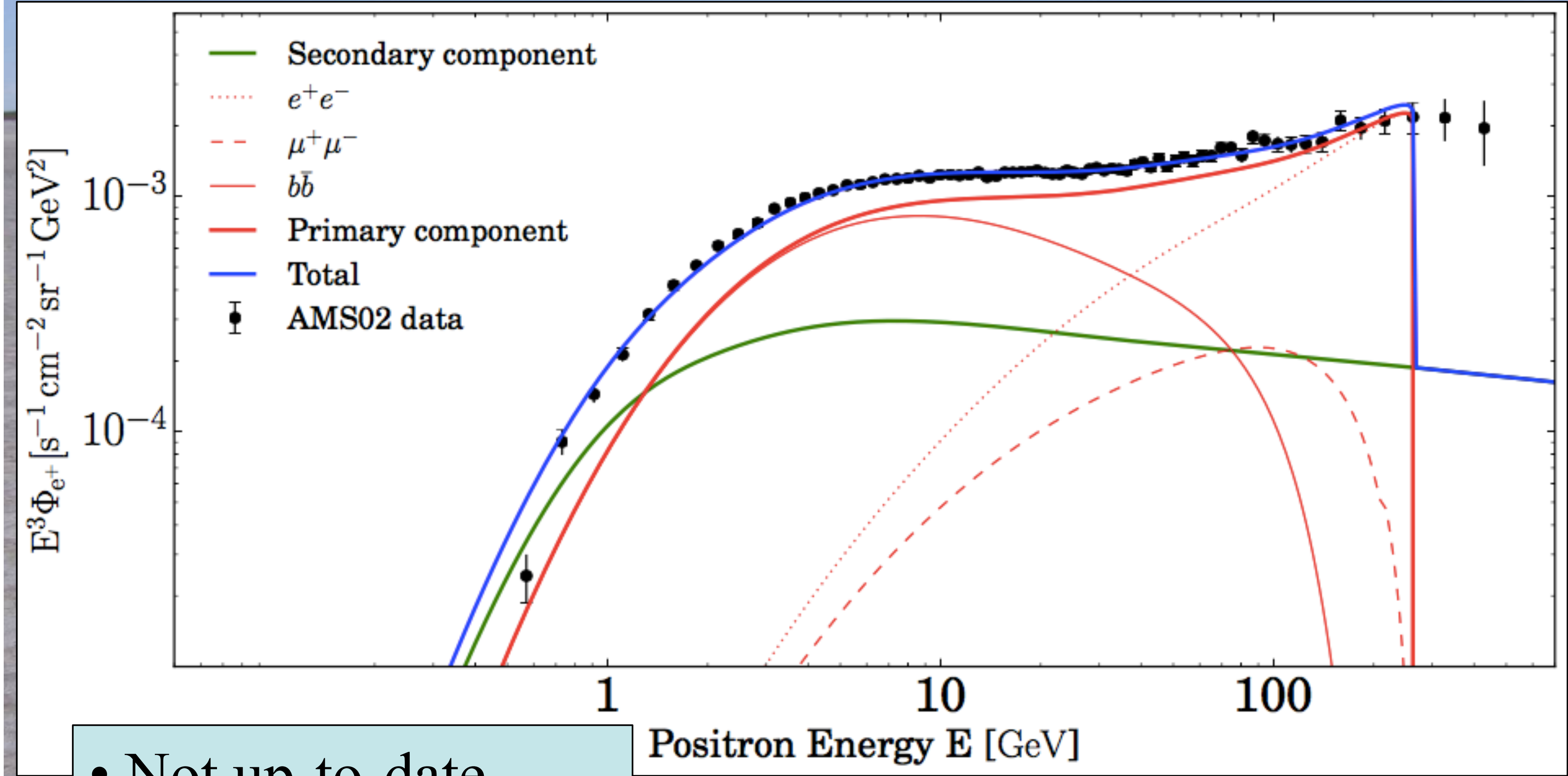


Giesen et al., arXiv:1504.04276

Cosmic-Ray Positrons



Dark Matter Models for e+ Spectrum

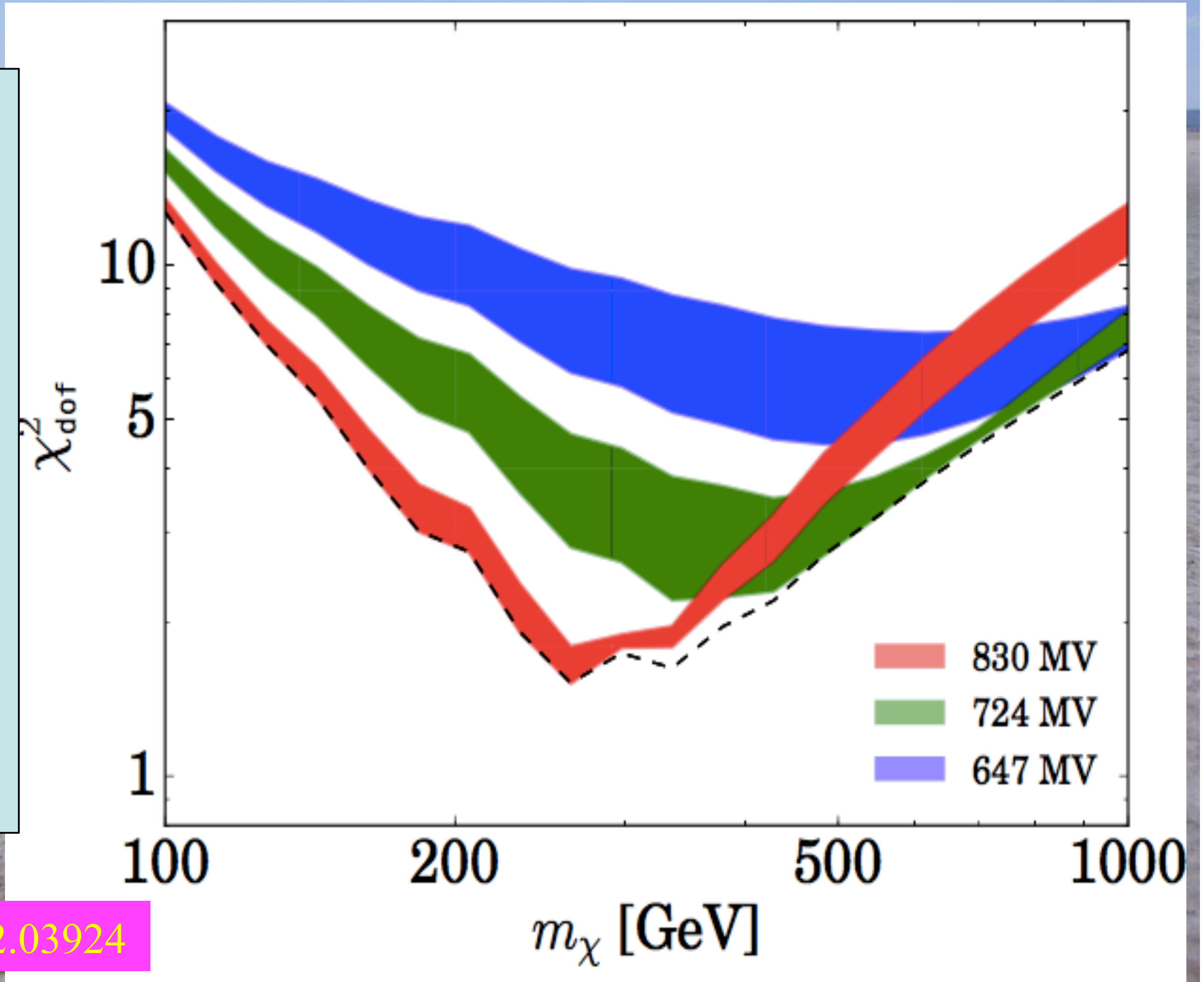


- Not up-to-date
- Illustrates problems

Boudeaud et al., arXiv:1612.03924

Fits to DM Annihilations

- Annihilation mainly into $b\bar{b}$, some admixture of e^+e^-, $\mu^+\mu^-$
- Different cosmic ray models
- Different solar potentials
- **Annihilation σ = 272 × thermal**



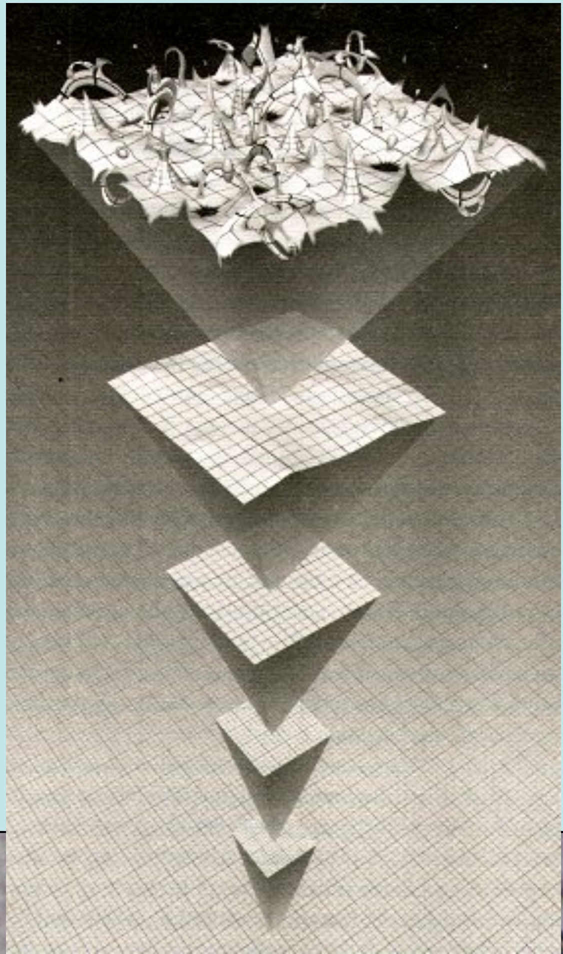
Boudeaud et al., arXiv:1612.03924

Nature of QG Vacuum

- Expect quantum fluctuations in fabric of space-time
- In natural Planckian units:

  $\Delta E, \Delta x, \Delta t, \Delta \chi \sim 1$

- Fluctuations in energy, space, time, topology of order unity
- **Space-time foam**
- **Manifestations?**



Space-Time Foam as a Non-Trivial Medium

- Expect large intrinsic fluctuations at small scales
- Expect back-reaction due to energetic particles
- Non-trivial refractive index
- Effect on propagation that increases with energy:

$$c^2 \mathbf{p}^2 = E^2 \left[1 + \xi E / E_{\mathrm{QG}} + \mathcal{O}(E^2 / E_{\mathrm{QG}}^2) \right] \qquad v = \frac{\partial E}{\partial p} \sim c \left(1 - \xi \frac{E}{E_{\mathrm{QG}}} \right)$$

- Non-critical string model: $\xi = -1$
- $\xi = -1$ needed: avoid Čerenkov radiation *in vacuo*
- Expect: $E_{QG} = O(M_P)$
- Related to $1/M_D$ in non-critical string model

Amelino-Camelia, JE, Mavromatos, Nanopoulos + Sarkar: 1997

Tests of quantum gravity from observations of γ-ray bursts

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* *Theoretical Physics, University of Oxford, 1 Keble Road, Oxford OX1 3NP, UK*
† *Institut de Physique, Université de Neuchâtel, CH-2000 Neuchâtel, Switzerland*
‡ *Theory Division, CERN, CH-1211 Geneva, Switzerland*
§ *Academy of Athens, Chair of Theoretical Physics, Division of Natural Sciences, 28 Panepistimiou Avenue, Athens GR-10679, Greece; Center for Theoretical Physics, Department of Physics, Texas A & M University, College Station, Texas 77843-4242, USA; and Astroparticle Physics Group, Houston Advanced Research Center (HARC), The Mitchell Campus, Woodlands, Texas 77381, USA*

The recent confirmation that at least some γ-ray bursts originate at cosmological distances[1–4] suggests that the radiation from them could be used to probe some of the fundamental laws of physics. Here we show that γ-ray bursts will be sensitive to an energy dispersion predicted by some approaches to quantum gravity. Many of the bursts have structure on relatively rapid timescales[5], which means that in principle it is possible to look for energy-dependent dispersion of the radiation, manifested in the arrival times of the photons, if several different energy bands are observed simultaneously. A simple estimate indicates that, because of their high energies and distant origin, observations of these bursts should be sensitive to a dispersion scale that is comparable to the Planck energy scale ($\sim 10^{19}$ GeV), which is sufficient to test theories of quantum gravity. Such observations are already possible using existing γ-ray burst detectors.

photon energies, any analogous quantum-gravity effect could be distinguished by its different energy dependence: the quantum-gravity effect would increase with energy, whereas conventional medium effects decrease with energy in the range of interest[6].

Equation (1) encodes a minute modification for most practical purposes, as E_{QG} is believed to be a very high scale, presumably of the order of the Planck scale $E_P \approx 10^{19}$ GeV. Even so, such a deformation could be rather significant for even moderate-energy signals, if they travel over very long distances. According to equation (1), a signal of energy E that travels a distance L acquires a 'time delay', measured with respect to the ordinary case of an energy-independent speed c for massless particles:

$$\Delta t \approx \xi \frac{E}{E_{QG}} \frac{L}{c} \qquad (2)$$

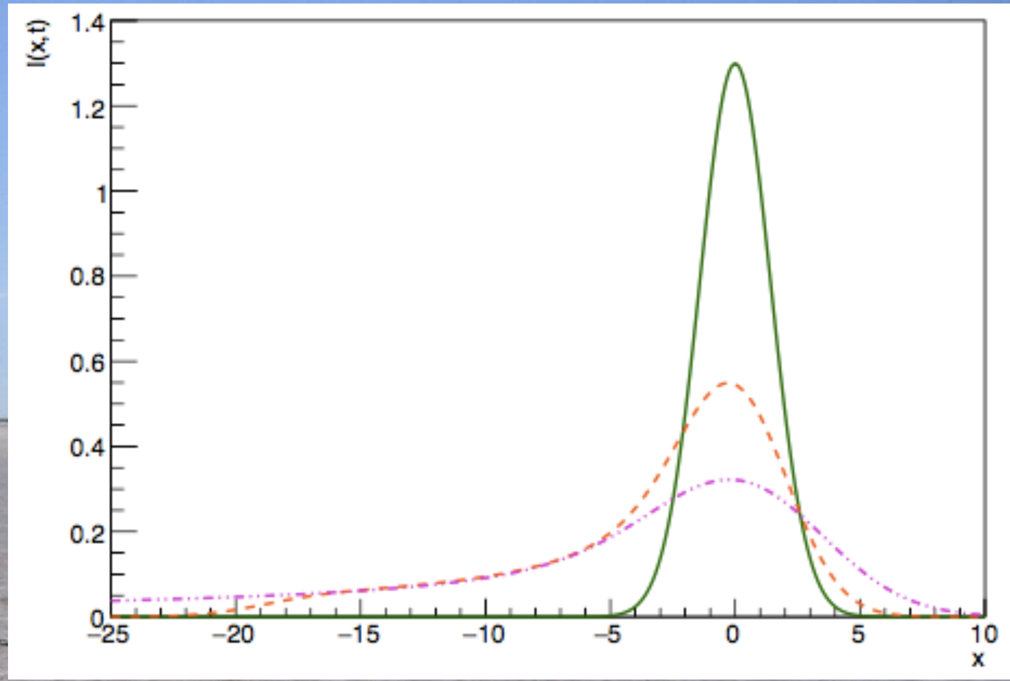
This is most likely to be observable where E and L are large while the interval δt, over which the signal exhibits time structure, is small. This is the case for GRBs, which is why they offer particularly good prospects for such measurements, as we discuss later.

We first review briefly how modified laws for the propagation of particles have emerged independently in different quantum-gravity approaches. The suggestion that quantum-gravitational fluctuations might modify particle propagation in an observable way can already be found in refs 7 and 9. A phenomenological parametrization of the way this could affect the neutral kaon system[9–11] has been already tested in laboratory experiments, which have set lower limits on parameters analogous to the E_{QG} introduced above at levels comparable to E_P (ref. 12). In the case of massless particles such as the photon, which interests us here, the first example of a quantum-gravitational medium effect with which we are familiar occurred in a string formulation of an expanding Robertson–Walker–Friedman

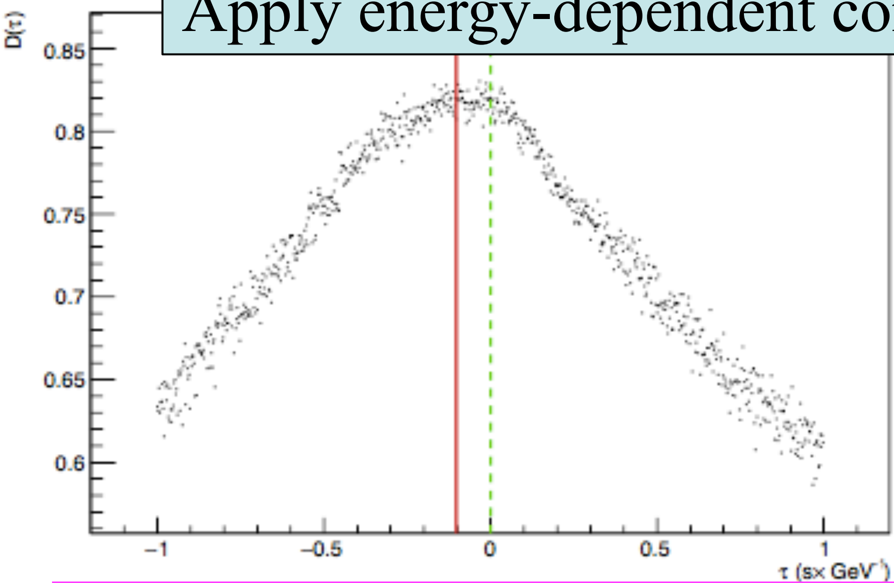
Robust Analysis of Fermi-LAT GRBs

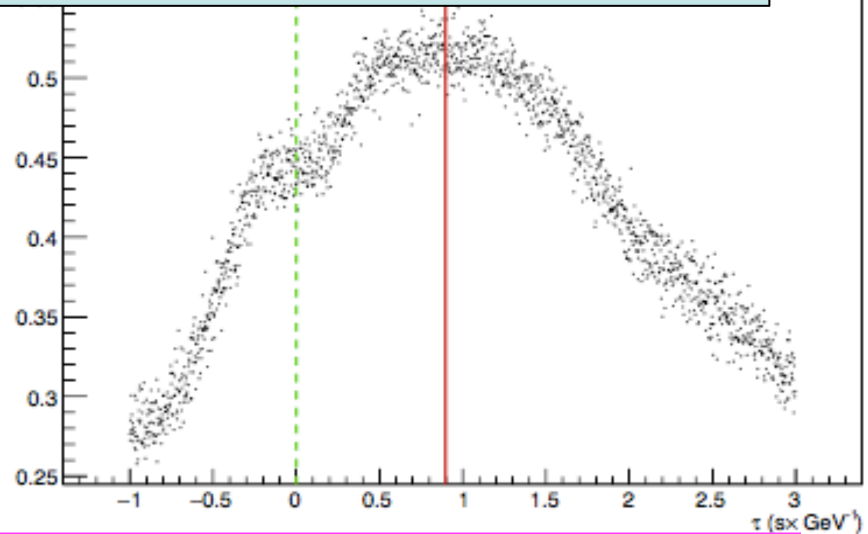
Lorentz violation tends to:

- Smooth out irregularities
- Increase kurtosis
- Increase skewness



Apply energy-dependent correction to maximize irregularities





JE, Konoplich, Mavromatos, Nguyen, Sakharov, Sarkisyan-Grinbaum, arXiv:1807.00189

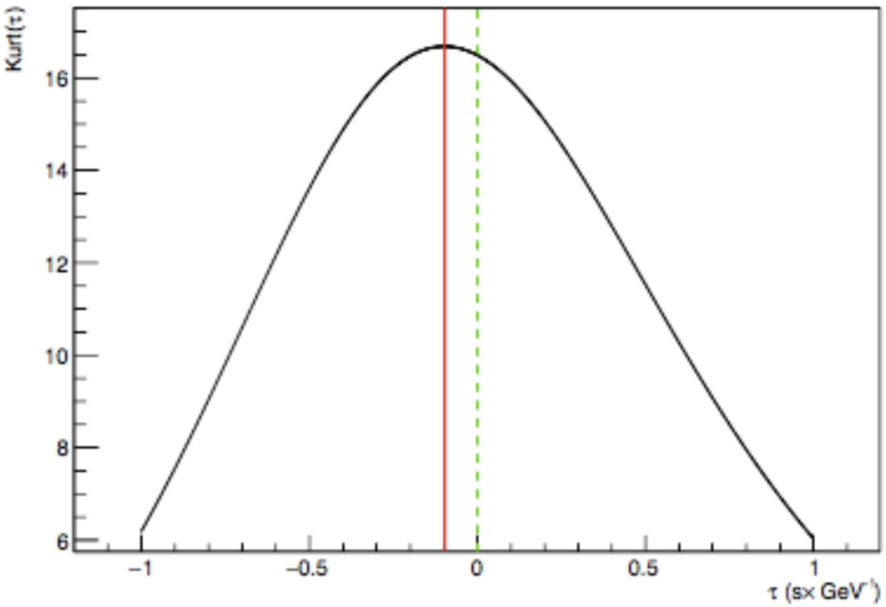
Robust Analysis of Fermi-LAT GRBs

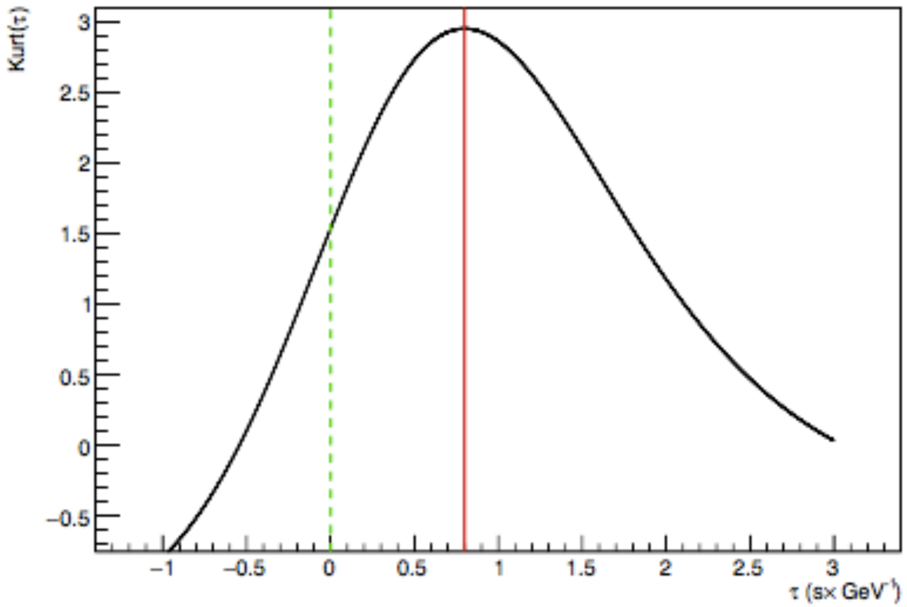
Kurtosis

(larger tails)

$$\mathcal{K}(\tau) = N_W \frac{\sum_{i=0}^{N-1}\left(\left(b_{\mathrm{df}}(E_i,\tau)-\overline{b_{\mathrm{df}}(\tau)}\right)W_i\right)^4}{\left(\sum_{i=0}^{N-1}\left(\left(b_{\mathrm{df}}(E_i,\tau)-\overline{b_{\mathrm{df}}(\tau)}\right)W_i\right)^2\right)^2} - 3$$

Apply energy-dependent correction to minimize kurtosis





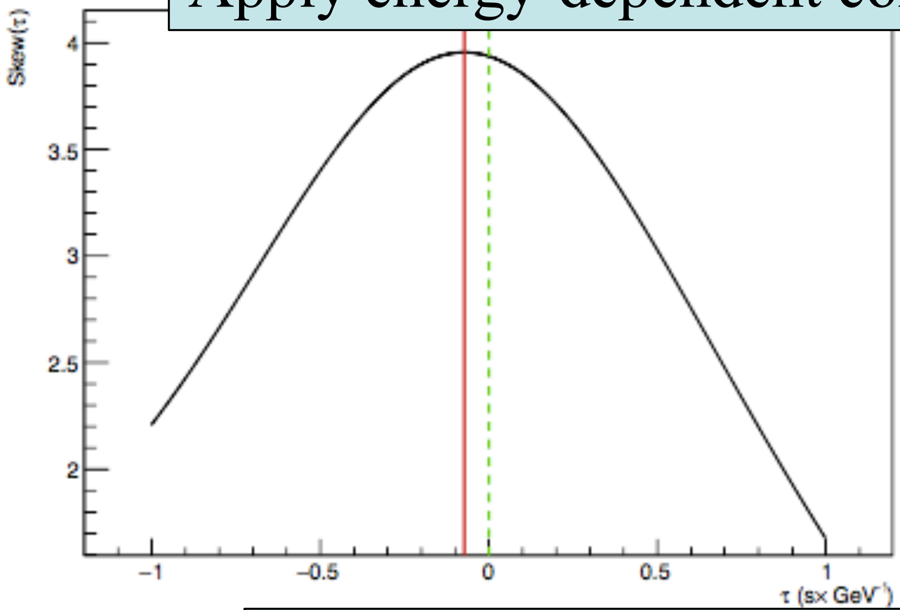
JE, Konoplich, Mavromatos, Nguyen, Sakharov, Sarkisyan-Grinbaum, arXiv:1807.00189

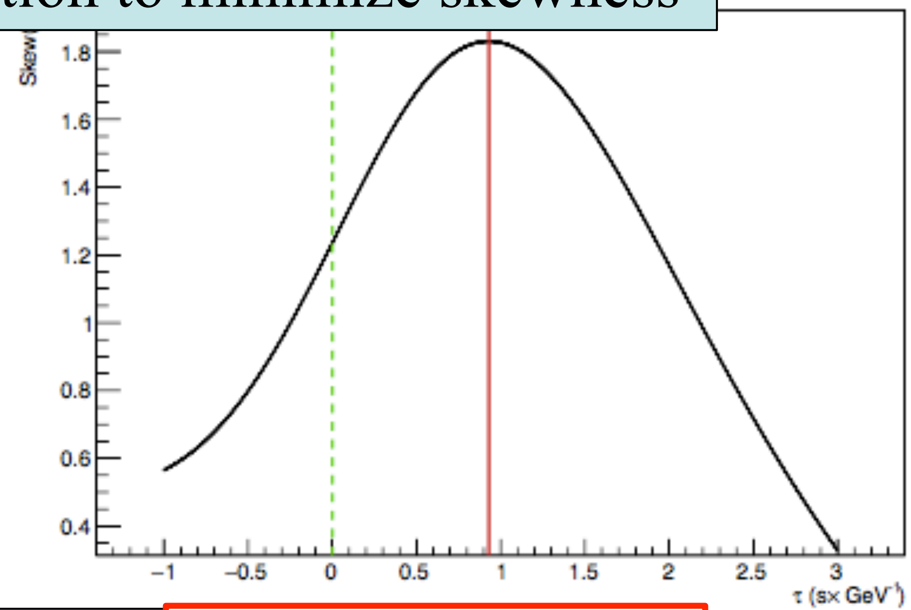
Robust Analysis of Fermi-LAT GRBs

Skewness

$$\mathcal{S}(\tau) = \sqrt{N_W}\,\frac{\sum_{i=0}^{N-1}\left(\left(b_{\rm df}(E_i,\tau) - \overline{b_{\rm df}(\tau)}\right)W_i\right)^3}{\left(\sum_{i=0}^{N-1}\left(\left(b_{\rm df}(E_i,\tau) - \overline{b_{\rm df}(\tau)}\right)W_i\right)^2\right)^{3/2}}$$

Apply energy-dependent correction to minimize skewness

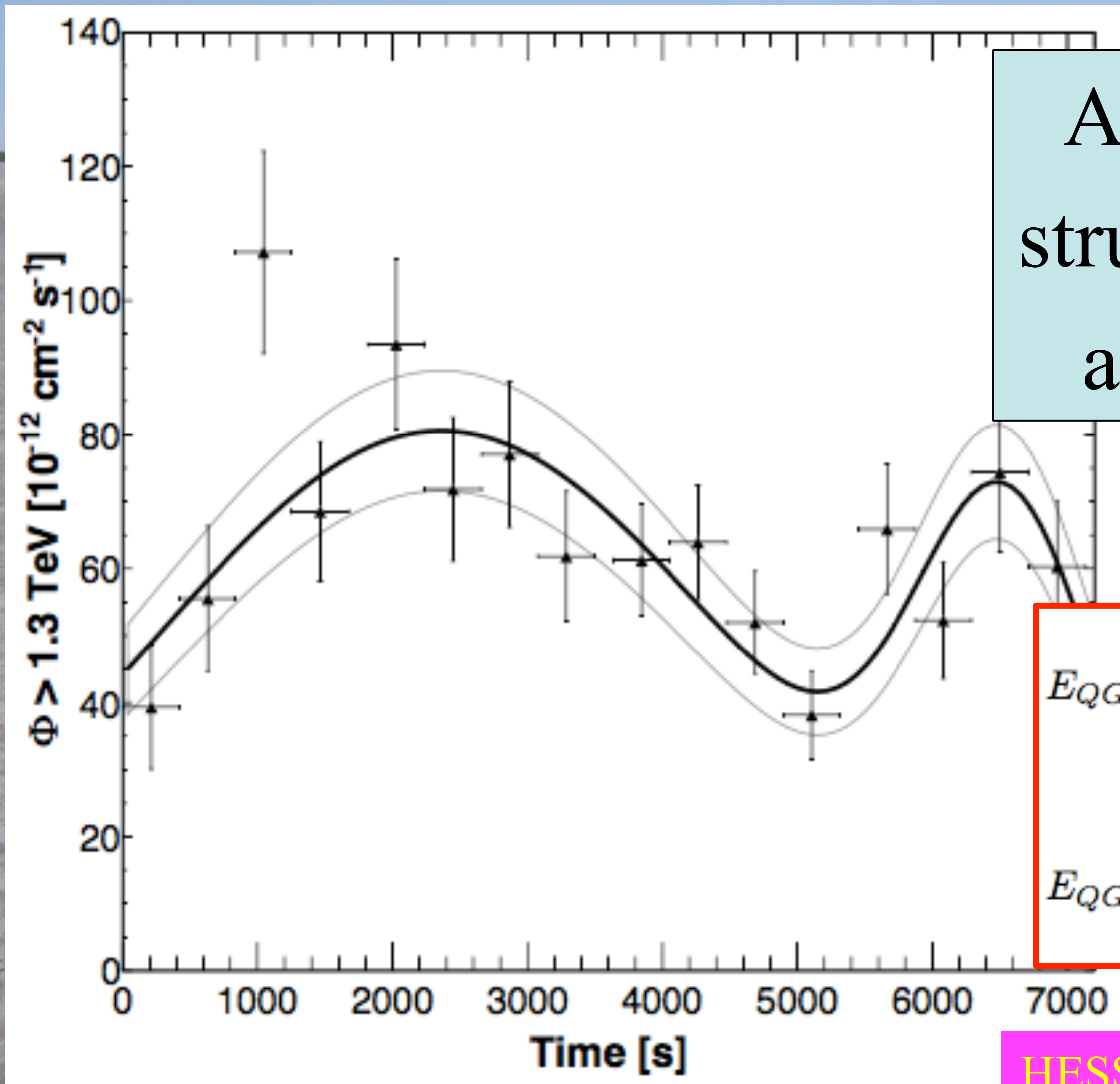




Combined analysis using 8 GRBs: $M_1 \geq 2.4 \times 10^{17}$ GeV

JE, Konoplich, Mavromatos, Nguyen, Sakharov, Sarkisyan-Grinbaum, arXiv:1807.00189

HESS Analysis of Markarian 501



Analysis of temporal structure of γ emissions at different energies

$$E_{QG,1} > \begin{cases} 3.6 \times 10^{17}\ \text{GeV} & \text{(subluminal)}, \\ 2.6 \times 10^{17}\ \text{GeV} & \text{(superluminal)}, \end{cases}$$

$$E_{QG,2} > \begin{cases} 8.5 \times 10^{10}\ \text{GeV} & \text{(subluminal)}, \\ 7.3 \times 10^{10}\ \text{GeV} & \text{(superluminal)}. \end{cases}$$

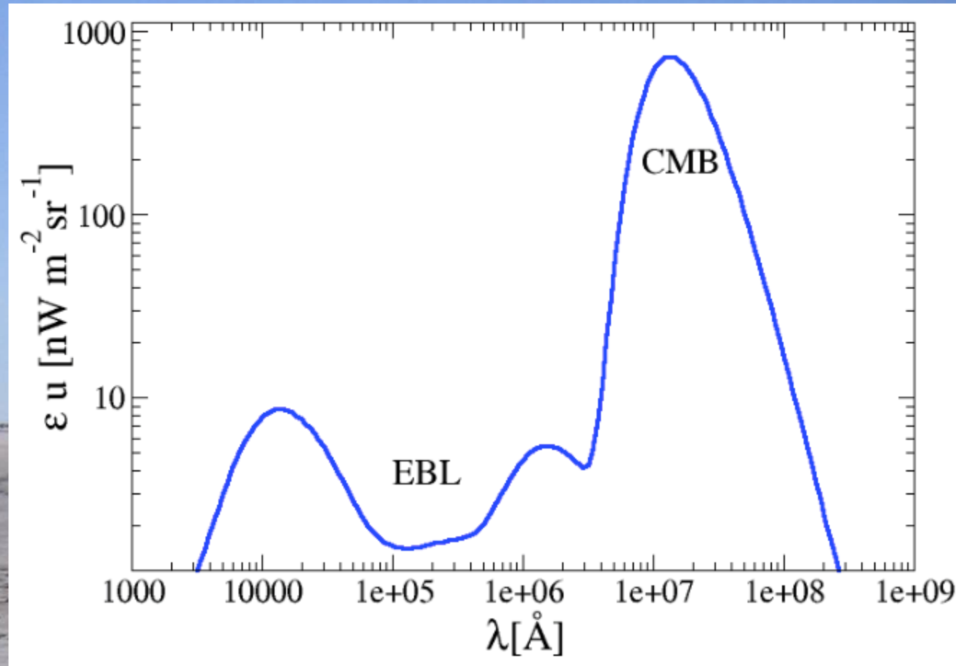
HESS Collaboration, arXiv:1901.05209

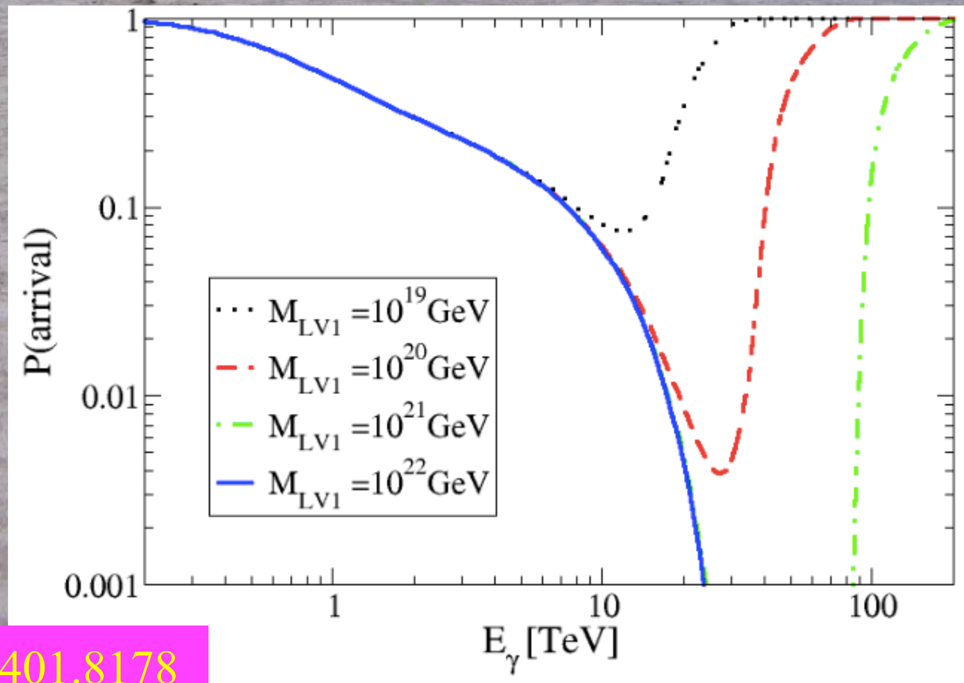
Possible Effect on γ Spectrum

- Expect absorption due to e^+e^- production in collisions with γ background
- Reduced absorption if Lorentz violation via modified (E, p) dispersion relation for γ

Kifune, astro-ph/9904164

Protheroe & Meyer, astro-ph/0005349



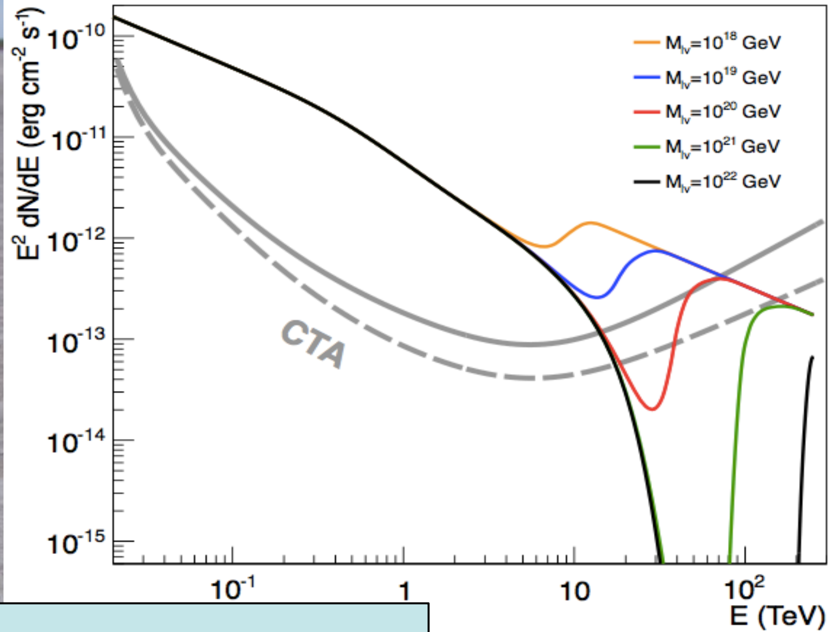


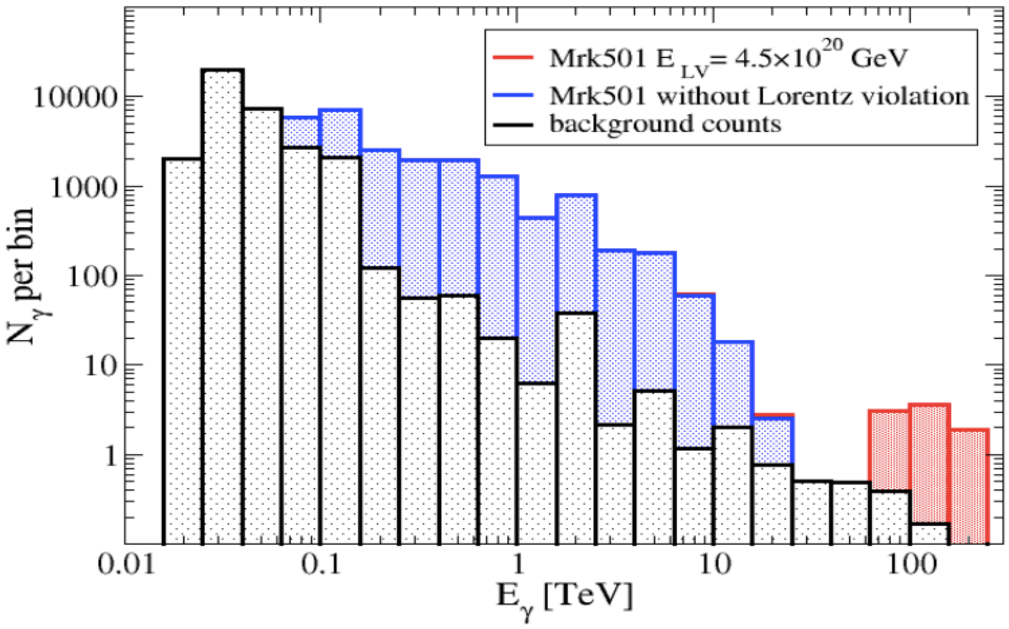
Fairbairn, Nilsson, JE, Hinton, White, arXiv:1401.8178

Simulation of Markarian 501

Fit to spectrum

$$\frac{dN_{501}}{dE} = 5.78 \cdot 10^{-12} \left(\frac{E}{1\ \mathrm{TeV}}\right)^{-2.72} \mathrm{cm}^{-2}\,\mathrm{s}^{-1}\,\mathrm{TeV}^{-1}$$





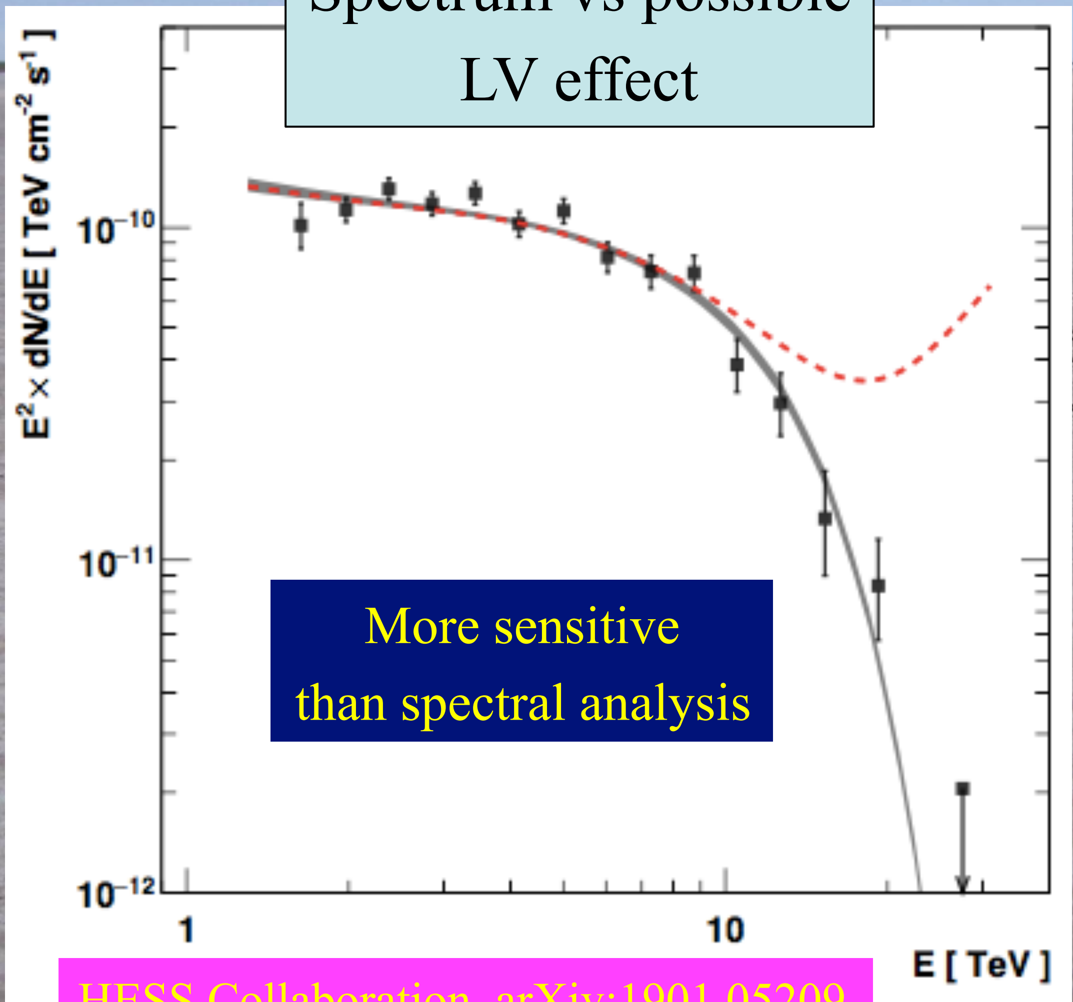
CTA sensitivity

	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})

Fairbairn, Nilsson, JE, Hinton, White, arXiv:1401.8178

HESS Analysis of Markarian 501

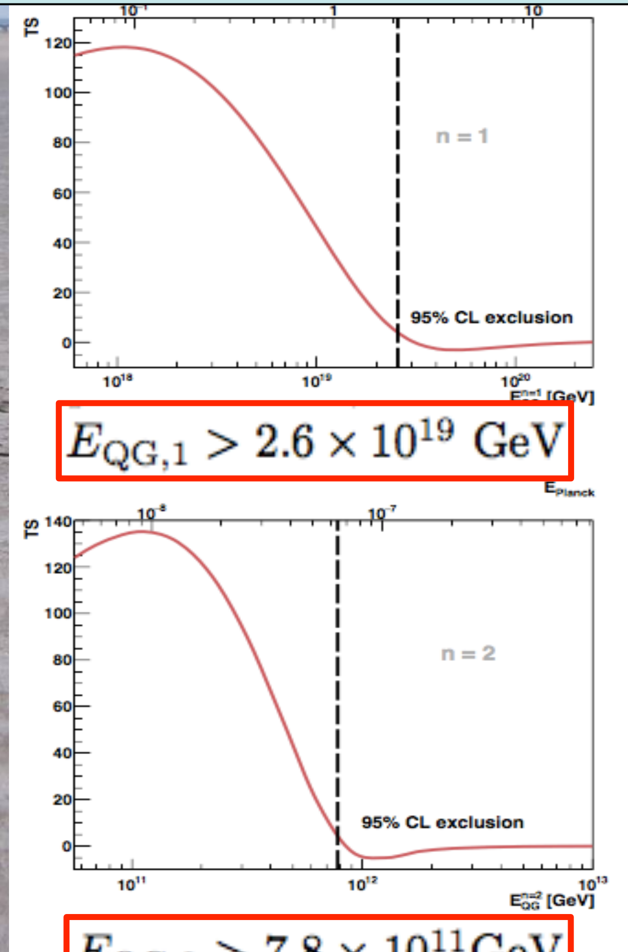
Spectrum vs possible LV effect



More sensitive than spectral analysis

HESS Collaboration, arXiv:1901.05209

Lower limits on LV scale

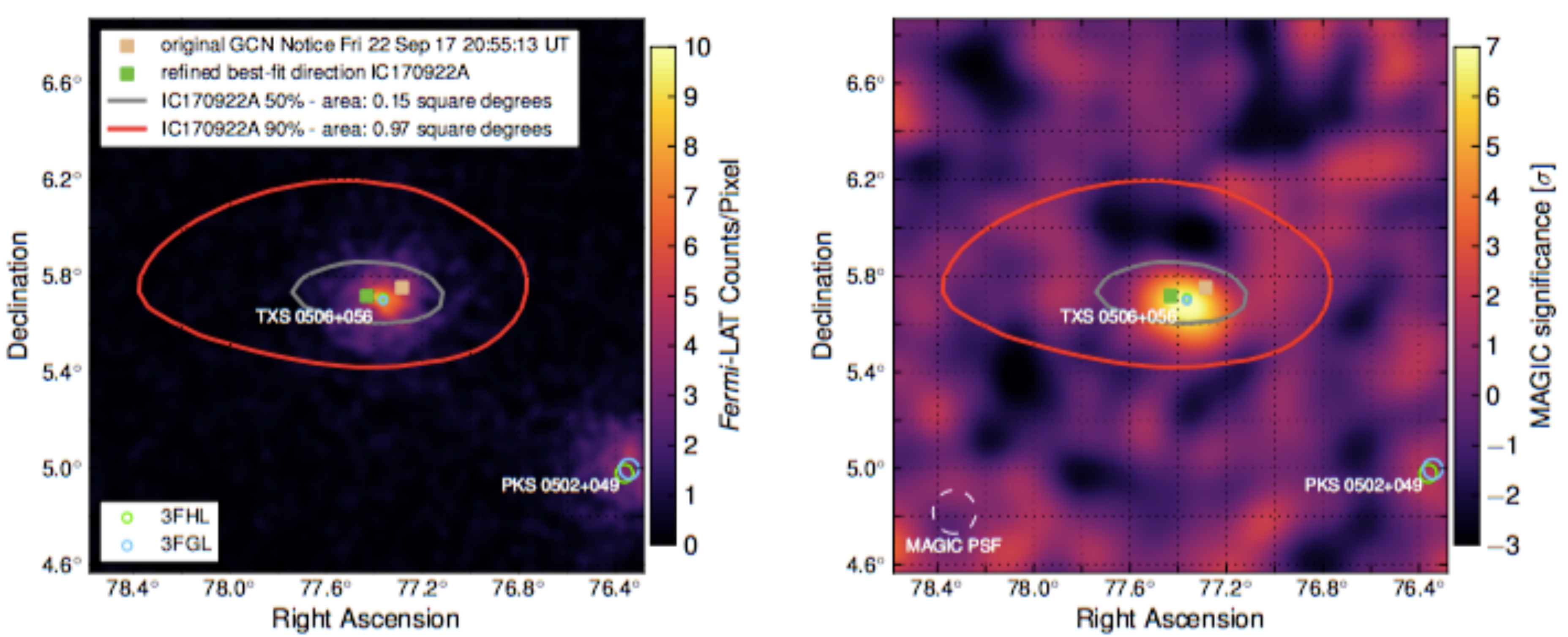


$E_{QG,1} > 2.6 \times 10^{19}$ GeV

$E_{QG,2} > 7.8 \times 10^{11}$ GeV

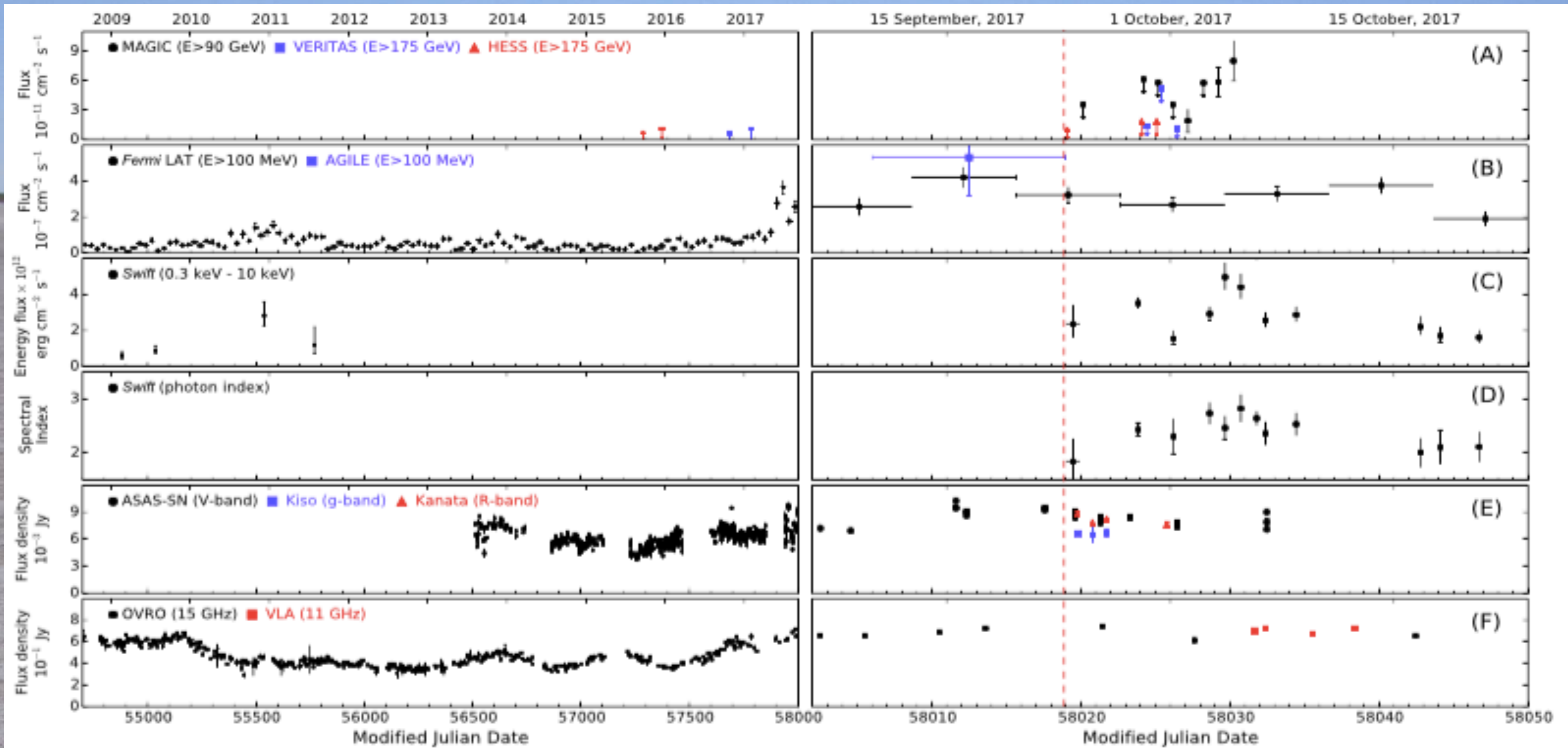
Multimessenger Observations of Blazar TXS 0506+056

IceCube-170922A vs *Fermi*-LAT, MAGIC



IceCube, *Fermi*-LAT, MAGIC, *AGILE*, ASAS-SN, HAWC, H.E.S.S, *INTEGRAL*, Kanata, Kiso, Kapteyn, Liverpool telescope, Subaru, *Swift*/*NuSTAR*, VERITAS, and VLA/17B-403 teams
arXiv:1807.08816

Electromagnetic Follow-up to IC170922



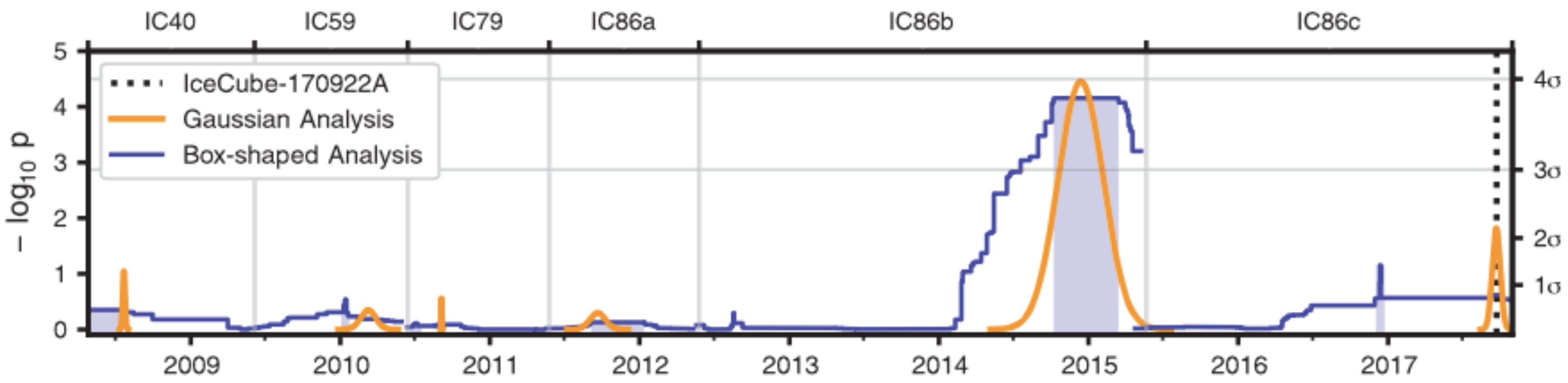
γ-ν coincidence: most sensitive limits on Lorentz violation in neutrino propagation

$$M_1 \gtrsim \frac{H_0^{-1}}{\Delta t} E \int_0^{z_{\rm src}} \frac{(1+z)}{\sqrt{\Omega_\Lambda + \Omega_M (1+z)^3}} dz \approx 3 \times 10^{16}\ \mathrm{GeV}$$

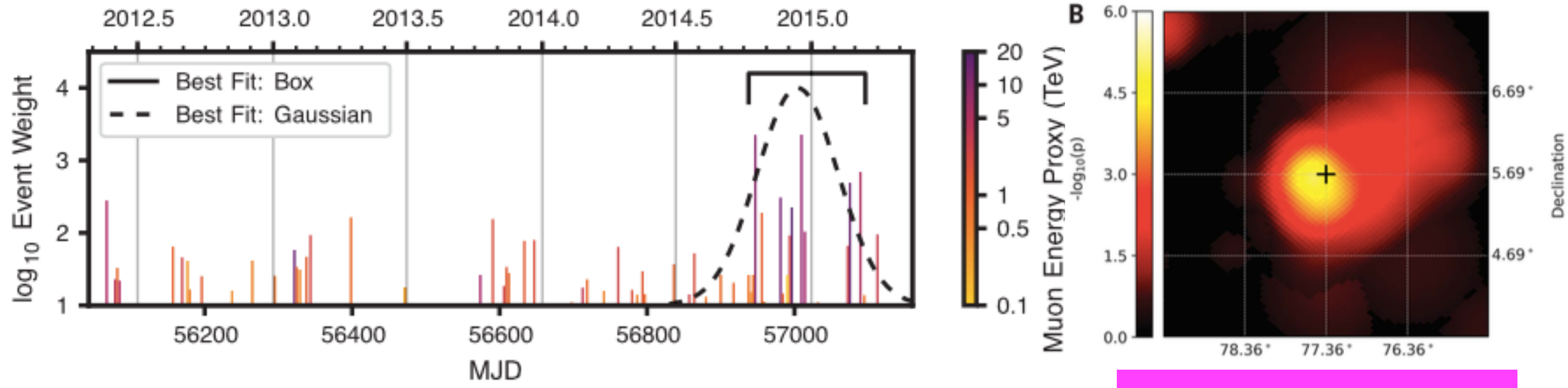
$$M_2 \gtrsim \left[\frac{3}{2} \frac{H_0^{-1}}{\Delta t} E^2 \int_0^{z_{\rm src}} \frac{(1+z)^2}{\sqrt{\Omega_\Lambda + \Omega_M (1+z)^3}} dz \right]^{1/2} \approx 10^{11}\ \mathrm{GeV}$$

JE, Mavromatos, Sakharov, Sarkisyan-Grinbaum, arXiv:1807.05155

Earlier Neutrino Burst from TXS 0506+056



More multimessenger observations possible in future with CTA?



IceCube Collaboration

Summary

- CTA has great prospect for particle physics as well as astrophysics
- Searches for products of dark matter annihilations complement accelerator searches
- Violent events in the Universe provide probes of extreme conditions beyond reach of accelerators
- Astro**particle** physics has a bright future!