BSM Physics with UHECRs

Michael Kachelrieß

NTNU, Trondheim

Fundamental Physics at UHE – Outline:

- Lorentz invariance violation
- ALP effects at UHE
- Top-down models:
  - Superheavy dark matter
  - Topological defects
- Testing new/strong interactions
- Summary

Lorentz invariance violation (LIV):

- motivation: has Planck length $L_{\rm Pl} = \sqrt{\hbar G/c^3}$ any rôle for space-time despite SR?

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  "The elimination of the logical inconsistencies connected with this requires a radical reconstruction of the theory, and...perhaps also the rejection of our ordinary concepts of space and time, modifying them by some much deeper and nonevident concepts. Wer's nicht glaubt, bezahlt einen Thaler."

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$\Rightarrow$ reaction thresholds: changes lower, introduces upper, opens new channels ($\gamma \to 2\gamma$, ...)
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  - Lorentz group kept
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- LIV becomes a priori important, when

$$\frac{m^2}{p^2} \sim \frac{p^{n-2}}{M_{\rm Pl}^{n-2}} \qquad \text{or} \qquad p_{\rm cr} \sim \sqrt[n]{m^2\, M_{\rm Pl}^{n-2}}$$

n	$p_{\rm cr}$ for ν	$p_{\rm cr}$ for e^-	$p_{\rm cr}$ for p
2	$p \sim m_\nu \sim 1\,\text{eV}$	$p \sim m_e$	$p \sim m_p$
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$\Rightarrow$ very low values:

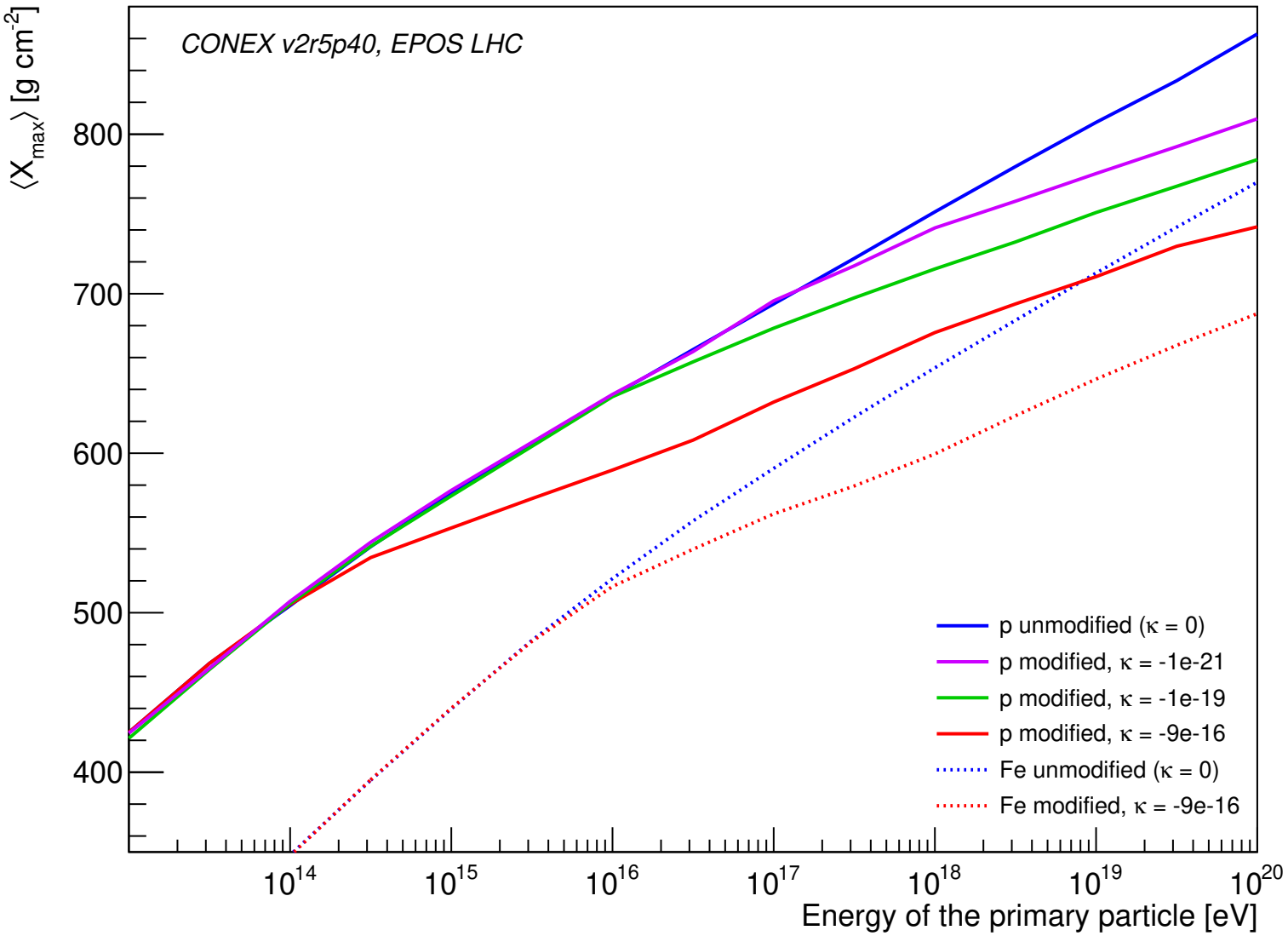
- either tiny pre-factors ("κ")
- or $n \geq 4$ ("$1/M_{\rm Pl}^3$") for QED

Bounds on LIV parameters from UHECRs:

- threshold for GZK may be changed
- GZK photons: upper threshold $E_{\max}$ for $\gamma\gamma \to e^+e^-$ introduced
- if $E_{\max} \ll 10^{20}$ eV, photon fraction too large
- if some UHE photons observed, photon decay $\gamma \to e^+e^-$ can be limited
- now: LIV changes shower evolution

Bounds on κ from EAS:

[*Risse, PAO '22*]



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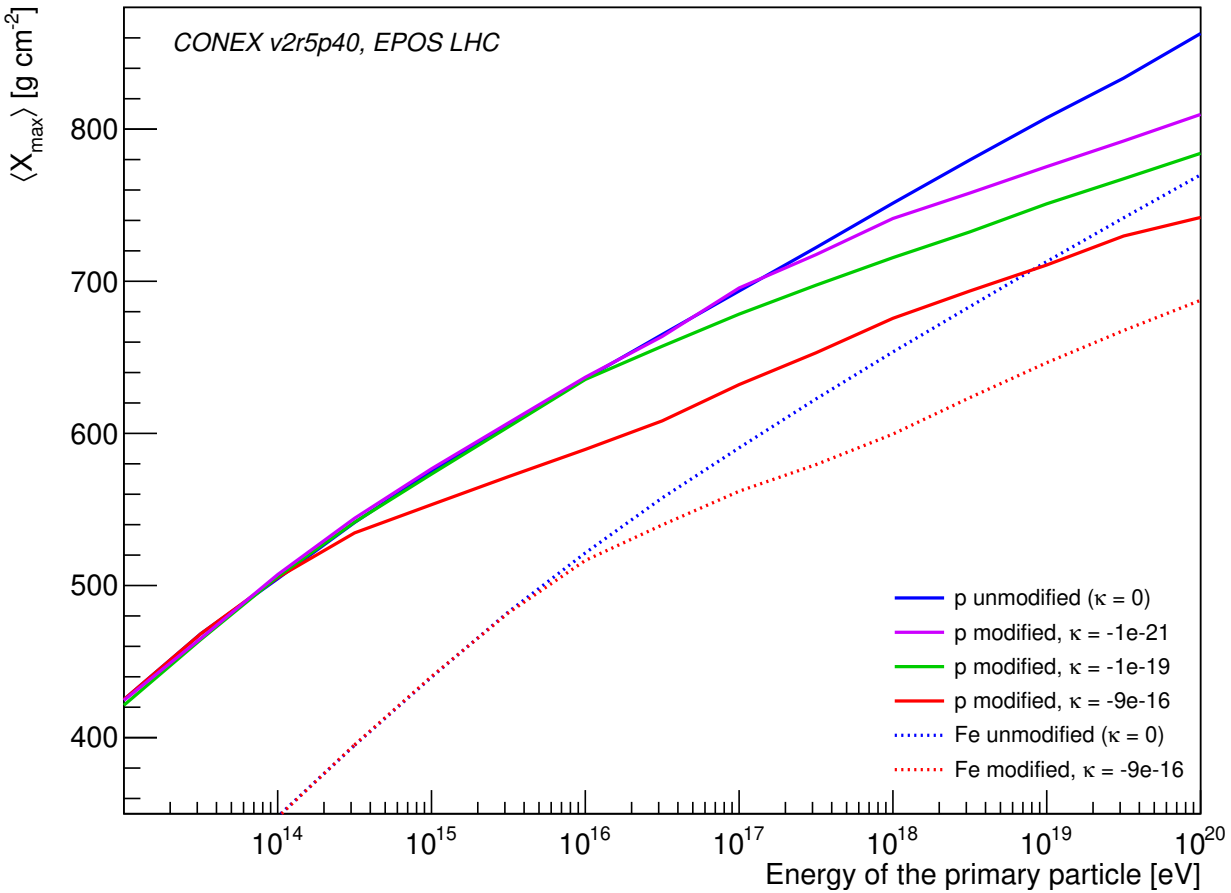
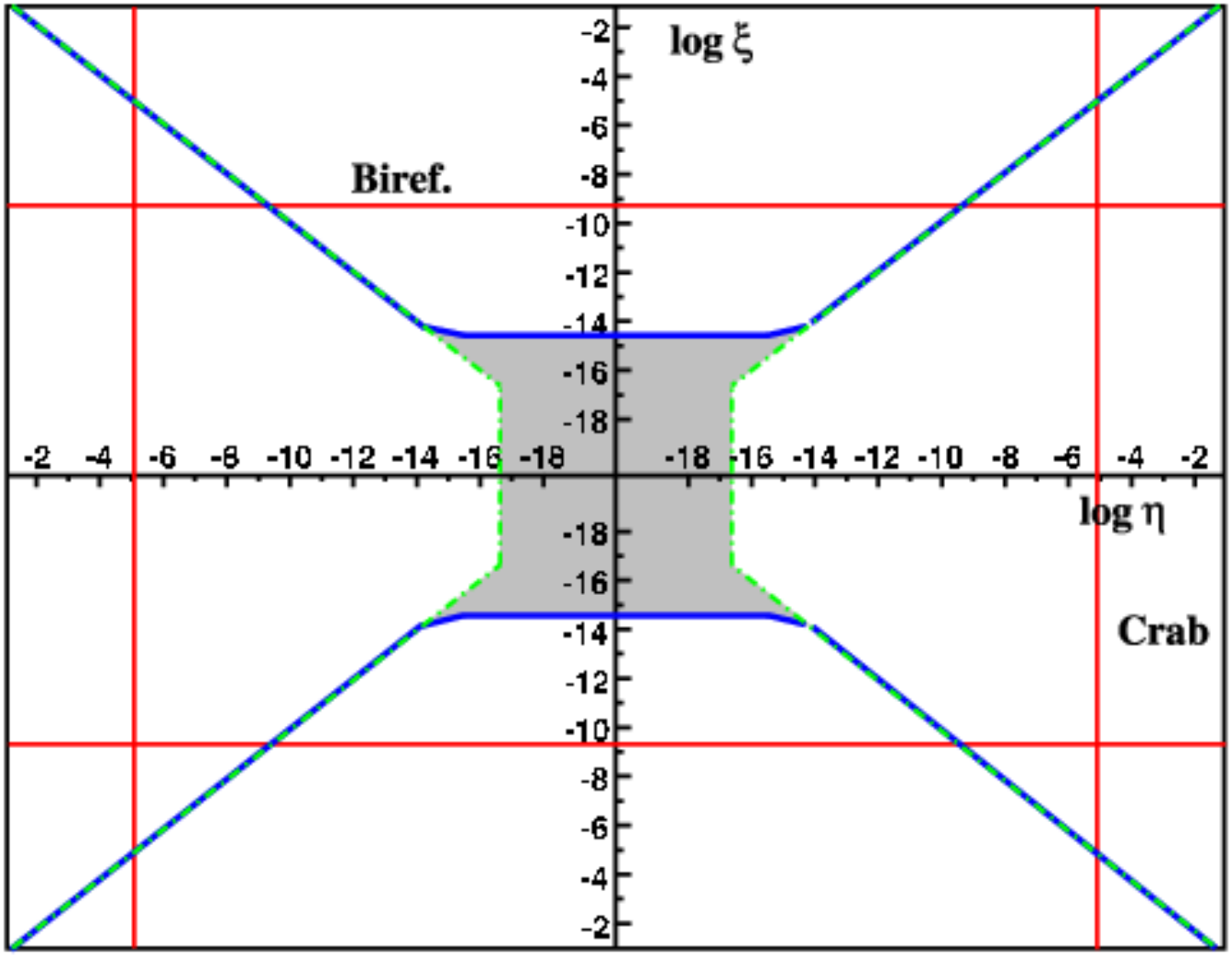
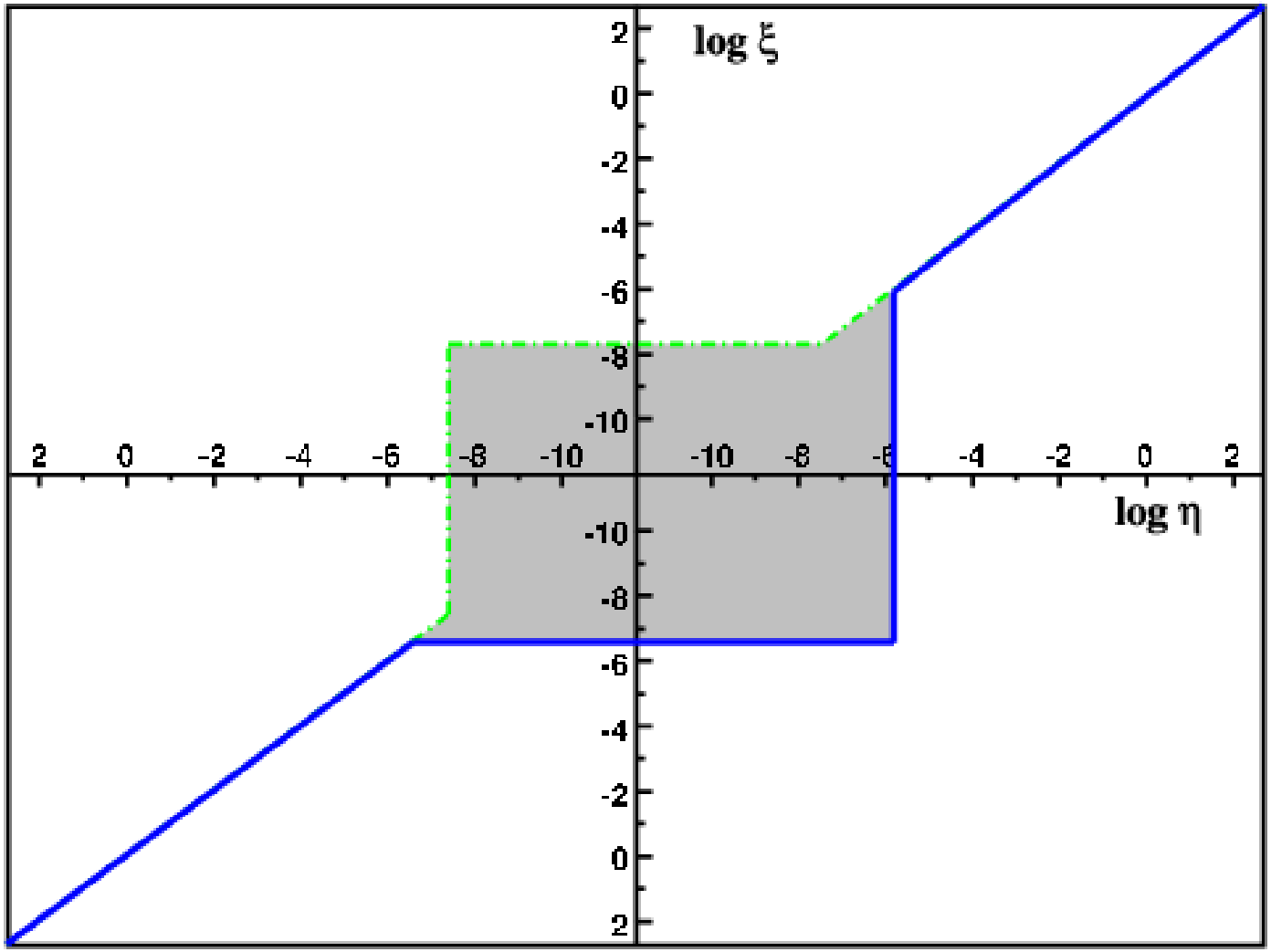


limit: $-\kappa > -0.6 \times 10^{-20}$

Bounds on dim=5 LIV parameters: $\xi \leftrightarrow e$ and $\eta \leftrightarrow \gamma$



Bounds on dim=6 LIV parameters: $\xi \leftrightarrow e$ and $\eta \leftrightarrow \gamma$



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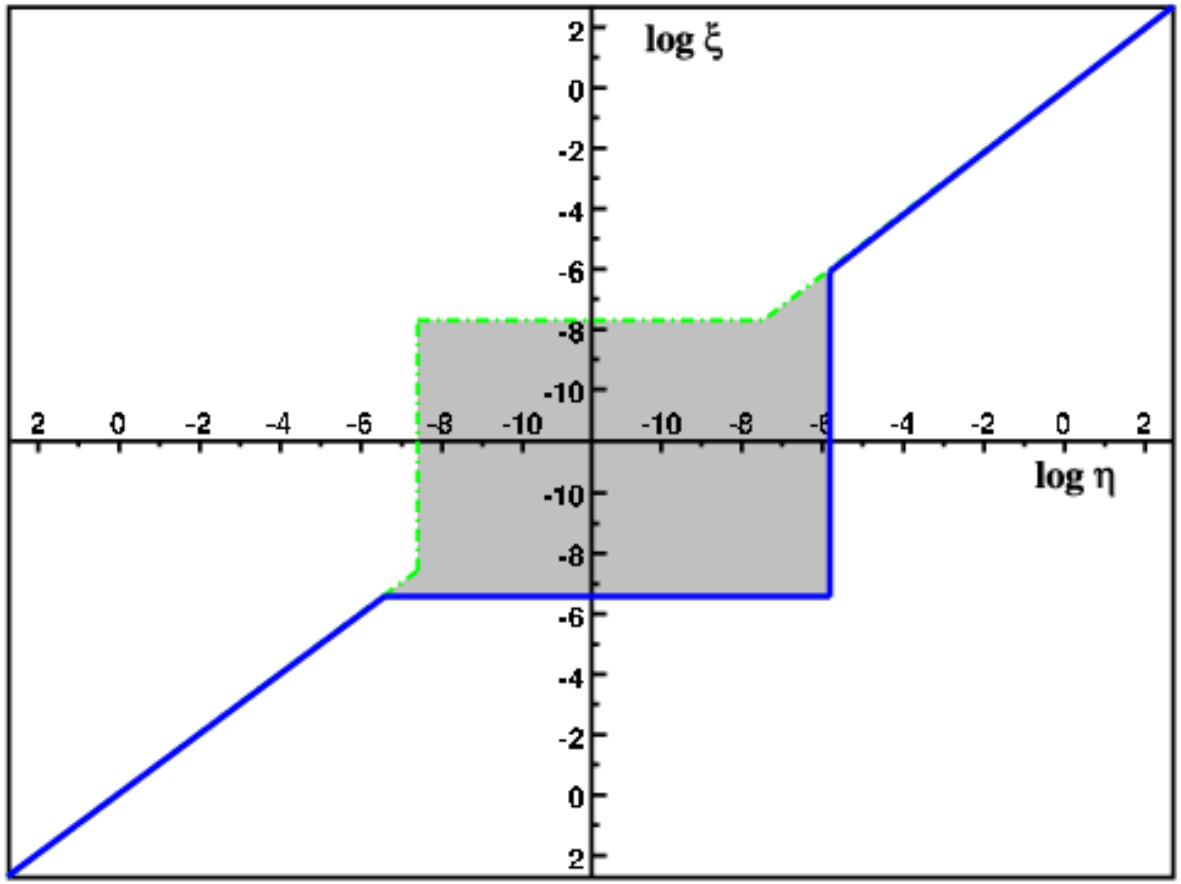
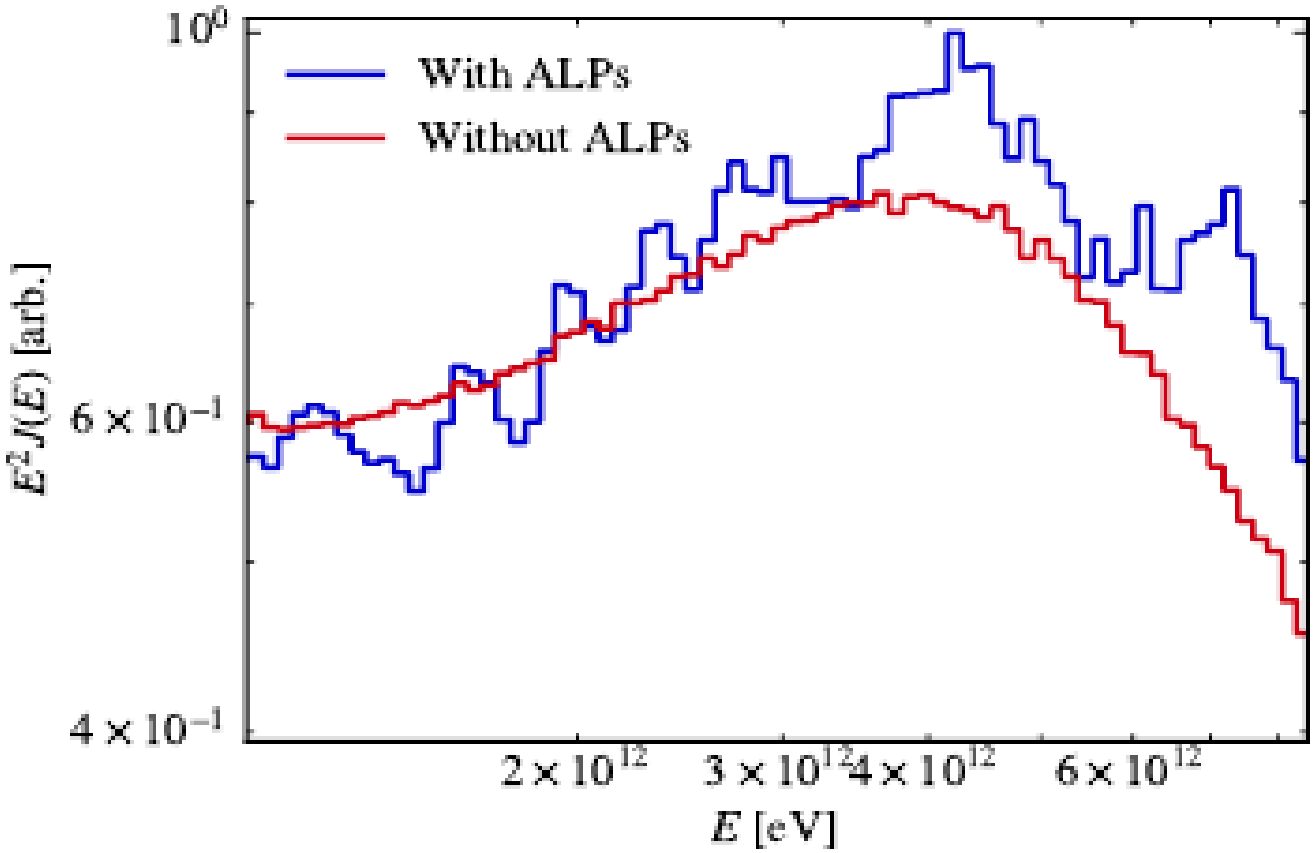


If LIV exists, then probably not of EFT type

ALPs and transparency of the Universe:

- axion-like particles: wiggles + increased m.f.p. of photons



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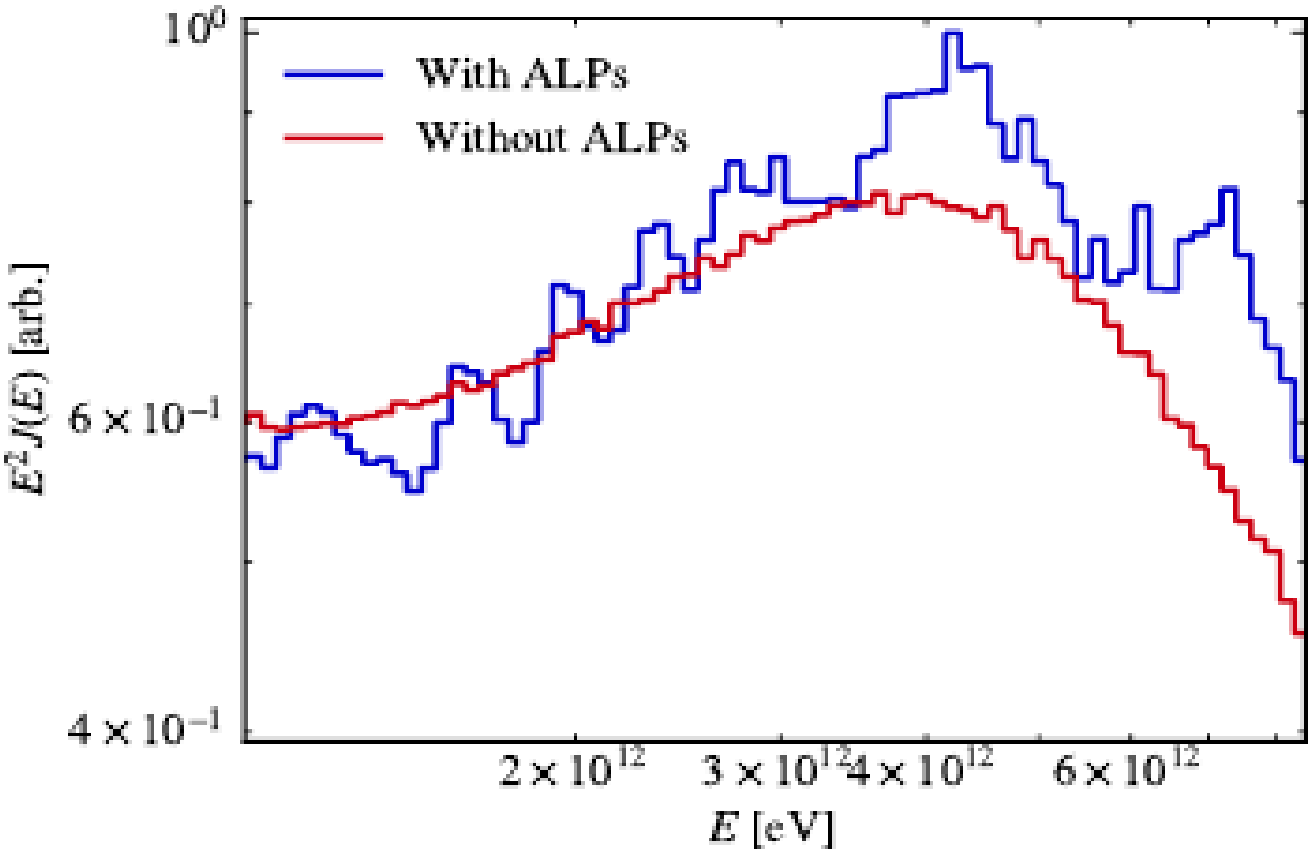

- same parameter range leads to effects for UHE photons [*Troitsky '21*]

Top-Down Models

UHECR primaries are produced by decays of supermassive particle X with $M_X \gtrsim 10^{12}$ GeV.

- topological defects:
  - monopoles [*Hill '83*]
  - cosmic strings [*Ostriker, Thompson, Witten '86*]
  - Q-balls, hybrid defects,...
- superheavy metastable particles [*Berezinsky, MK, Vilenkin '97; Kuzmin, Rubakov '97*]

main properties:

- fragmentation products: mainly photons, neutrinos
- if $X \in$ CDM: Galactic flux dominates
- allows to test high-scale physics: inflation, GUT, ...

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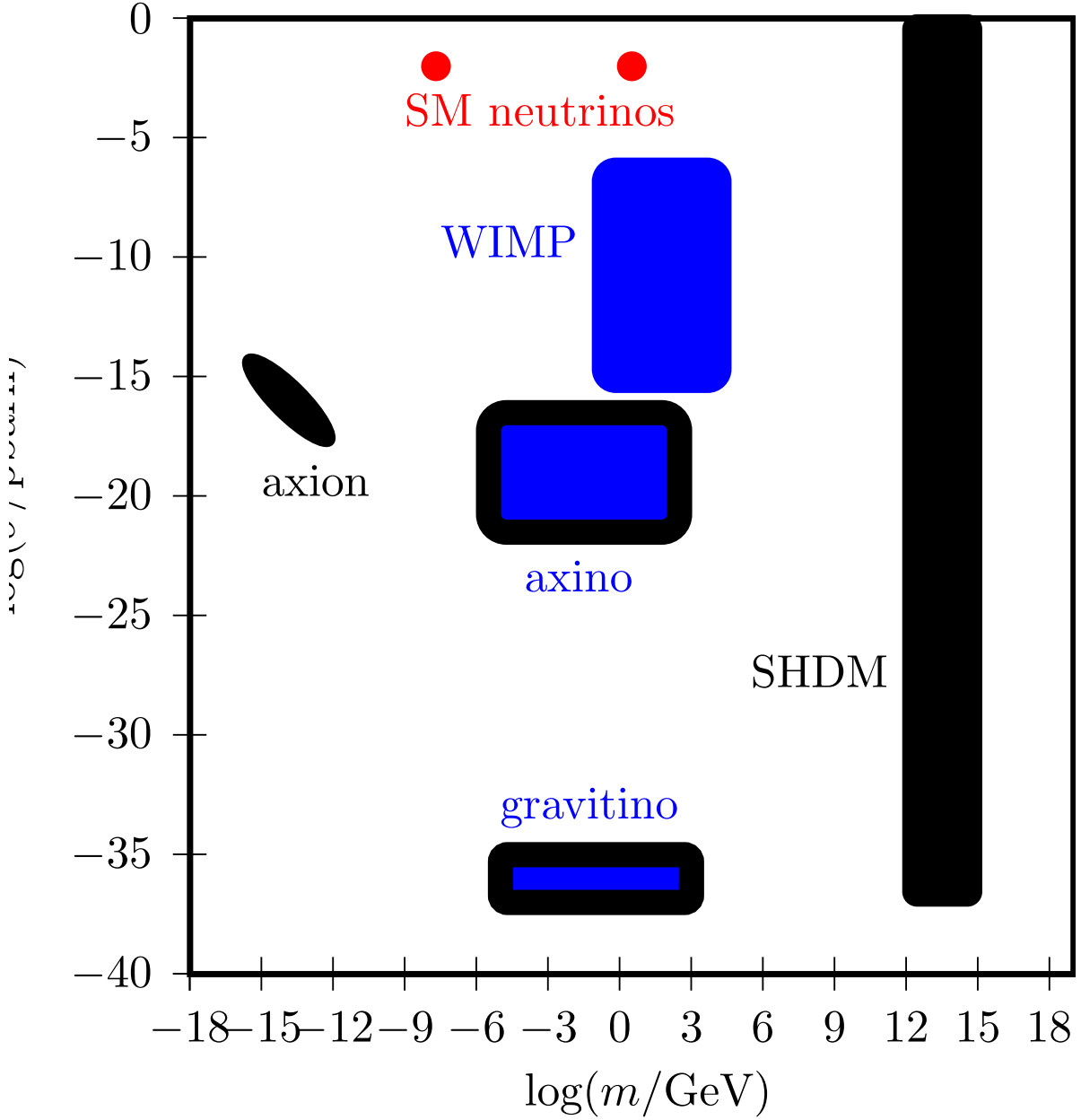
Dark matter candidates with $\Omega \sim 1$:



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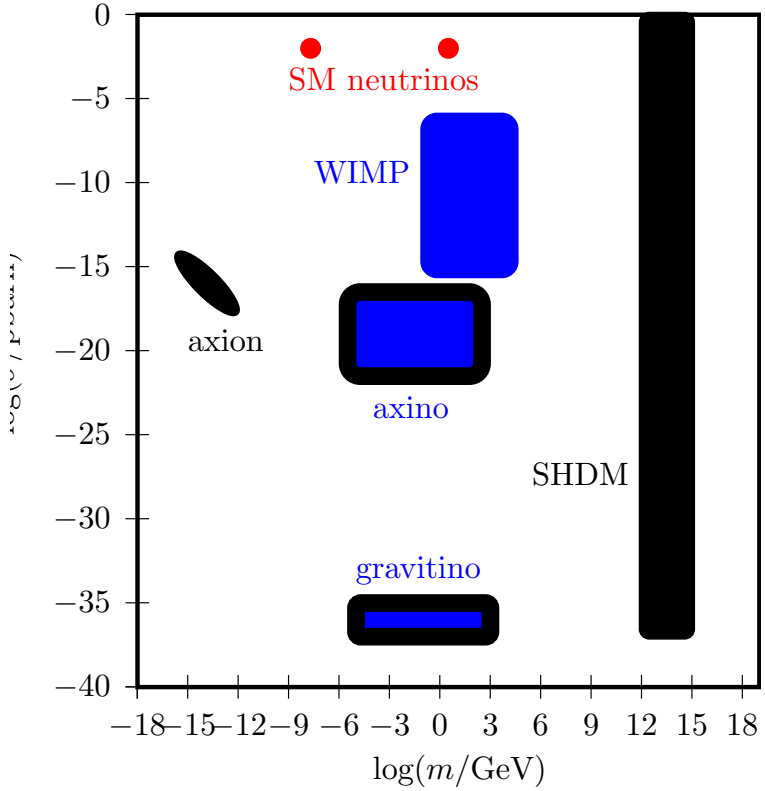
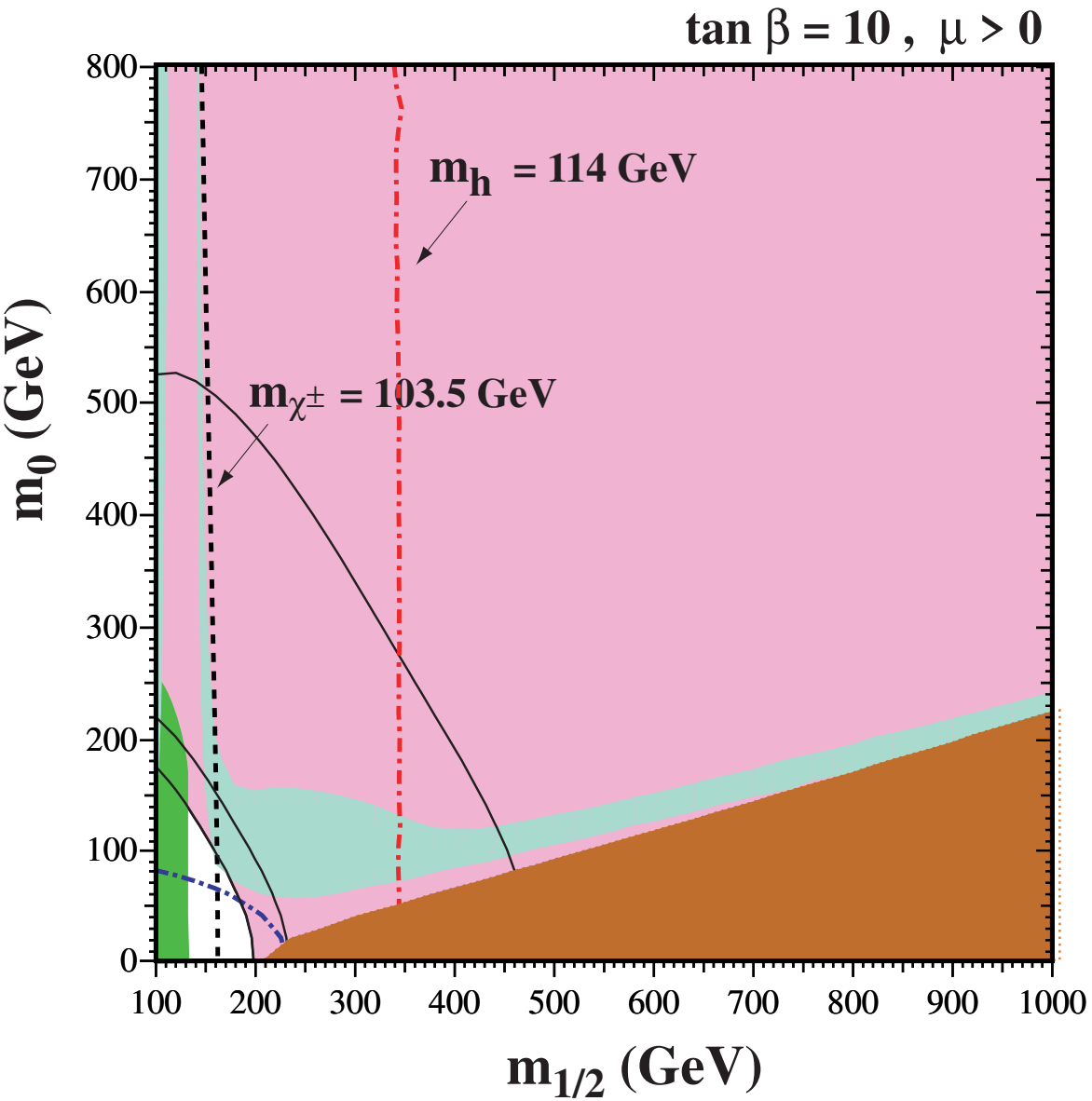


why such a large variation? Different production mechanism

- thermal relics: WIMPs
- misalignement/phase transitions: axions
- gravitational production: superheavy dark matter

WIMP miracle: neutralino DM after LEPII:



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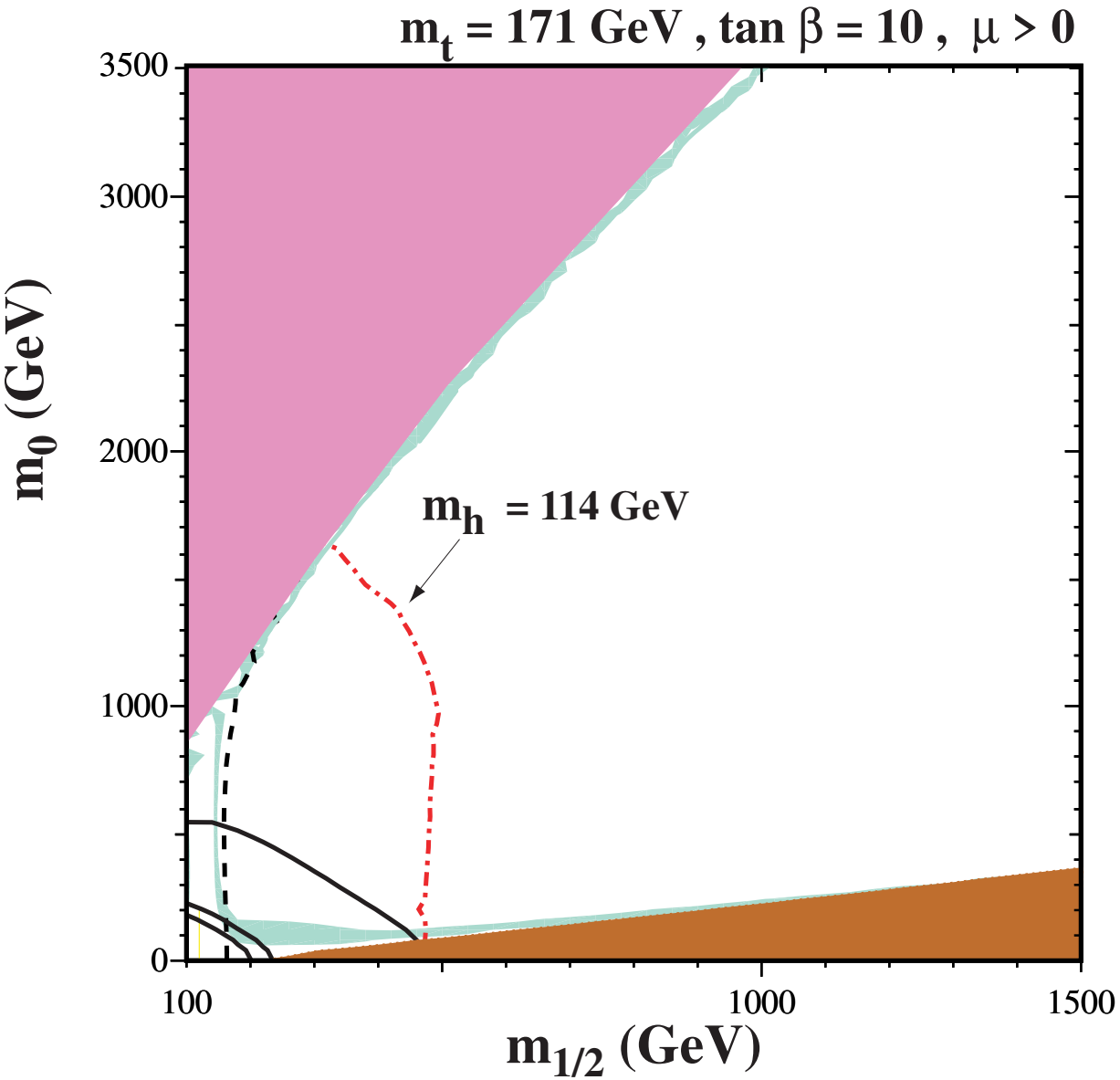

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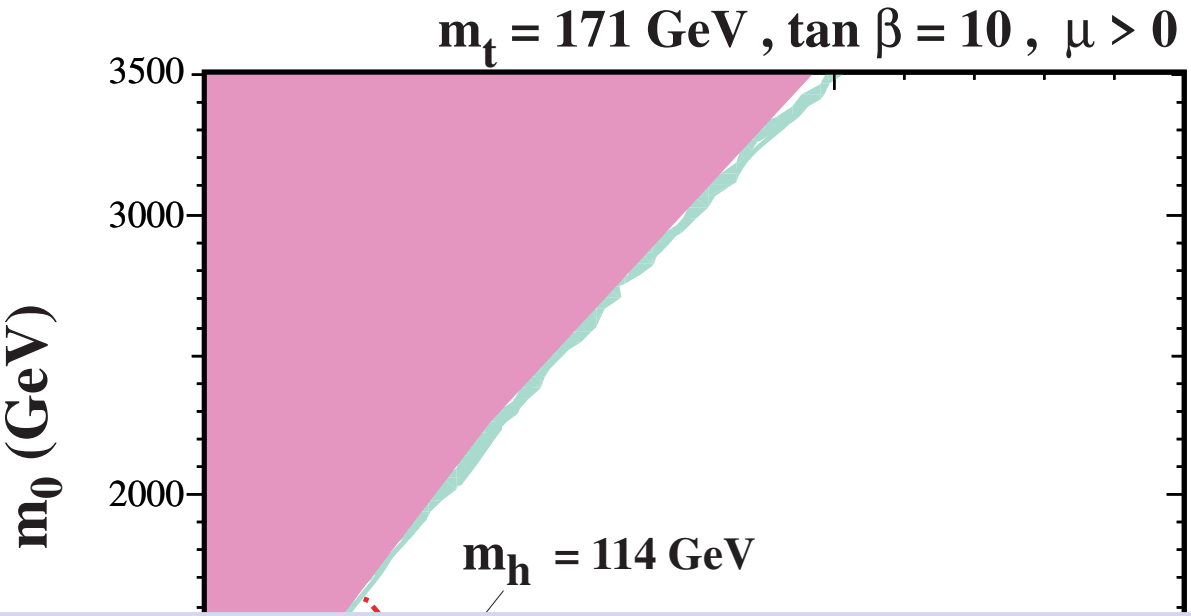
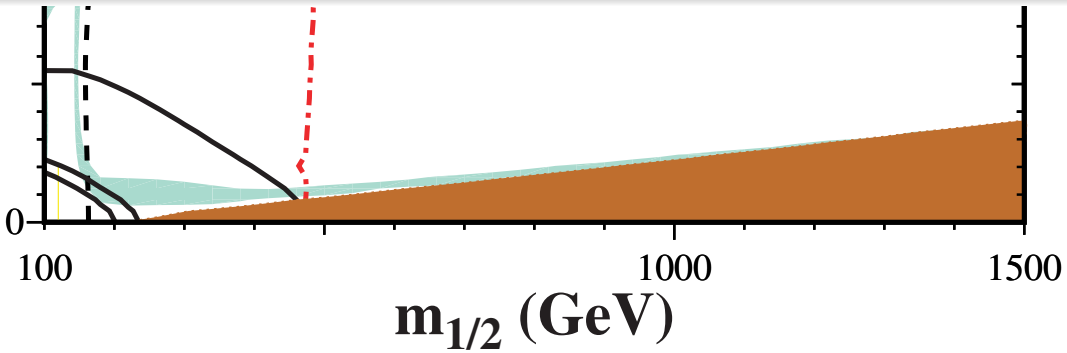


bulk region excluded after LEPII

- mass degeneracies required too avoid $\Omega_{\chi_o} > \Omega_{\rm CDM}$



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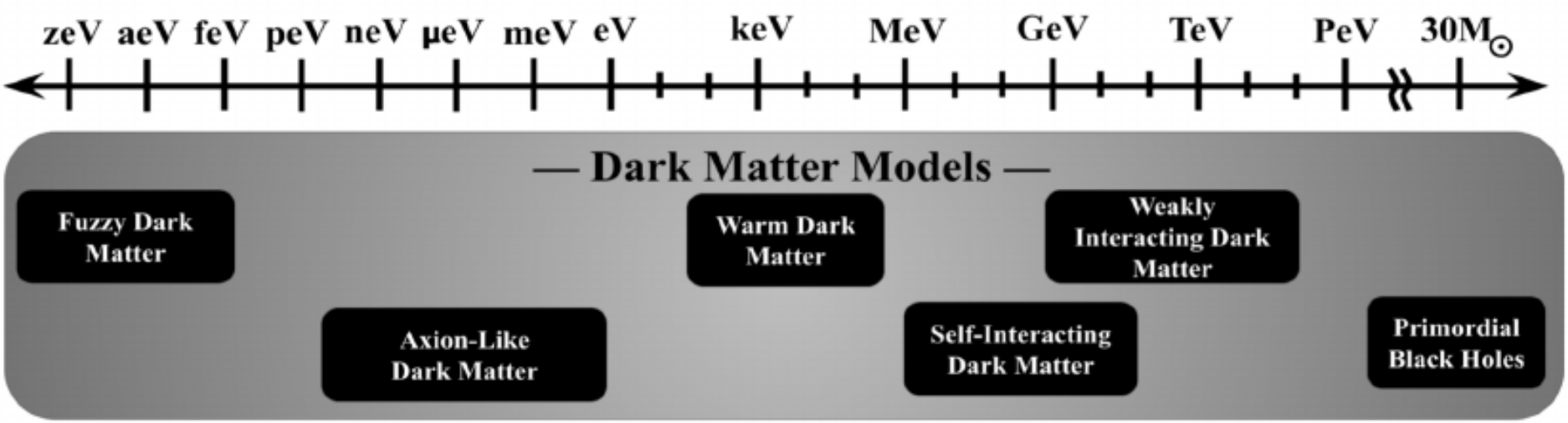

- almost all the $M - \sigma$ plane needs to be explored...

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- In inflationary cosmology, for $M_X \lesssim H_I$:

$$\Omega_X h^2 \sim \left(\frac{M_X}{10^{12}\,\mathrm{GeV}}\right)^2 \frac{T_{RH}}{10^9\,\mathrm{GeV}}$$

[*Kuzmin, Tkachev '98; Chung, Kolb, Riotto '98*]

Signatures of SHDM decays

- fragmentation spectra:
  - slope: flat $dN/dE \propto 1/E^{1.9}$ up to $m_X/2$
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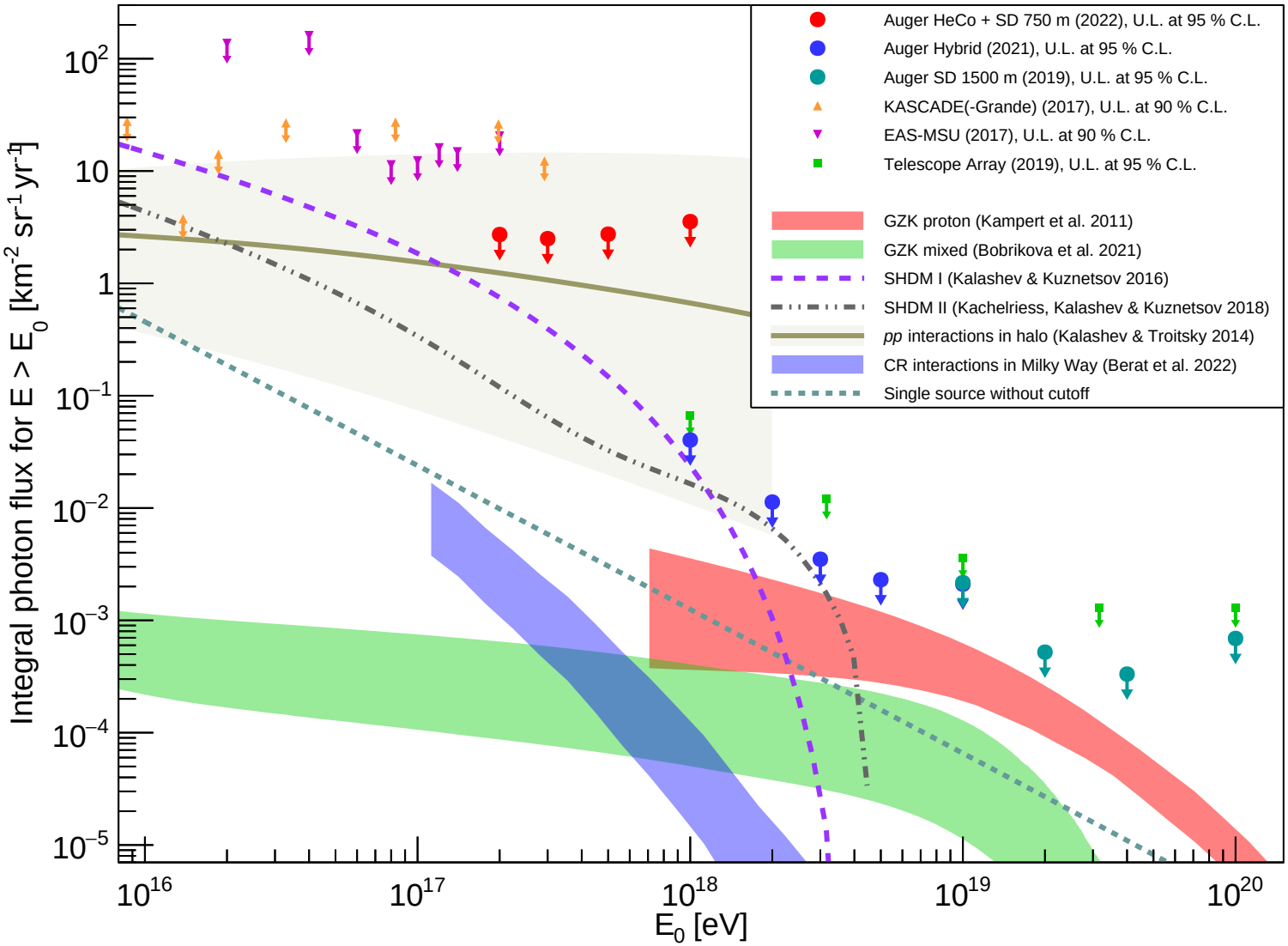
- isocurvature modes: $\delta_X \neq \delta_\gamma$ [*Chung et al. '05*]

Exclusion limits: photons

[PAO '22]



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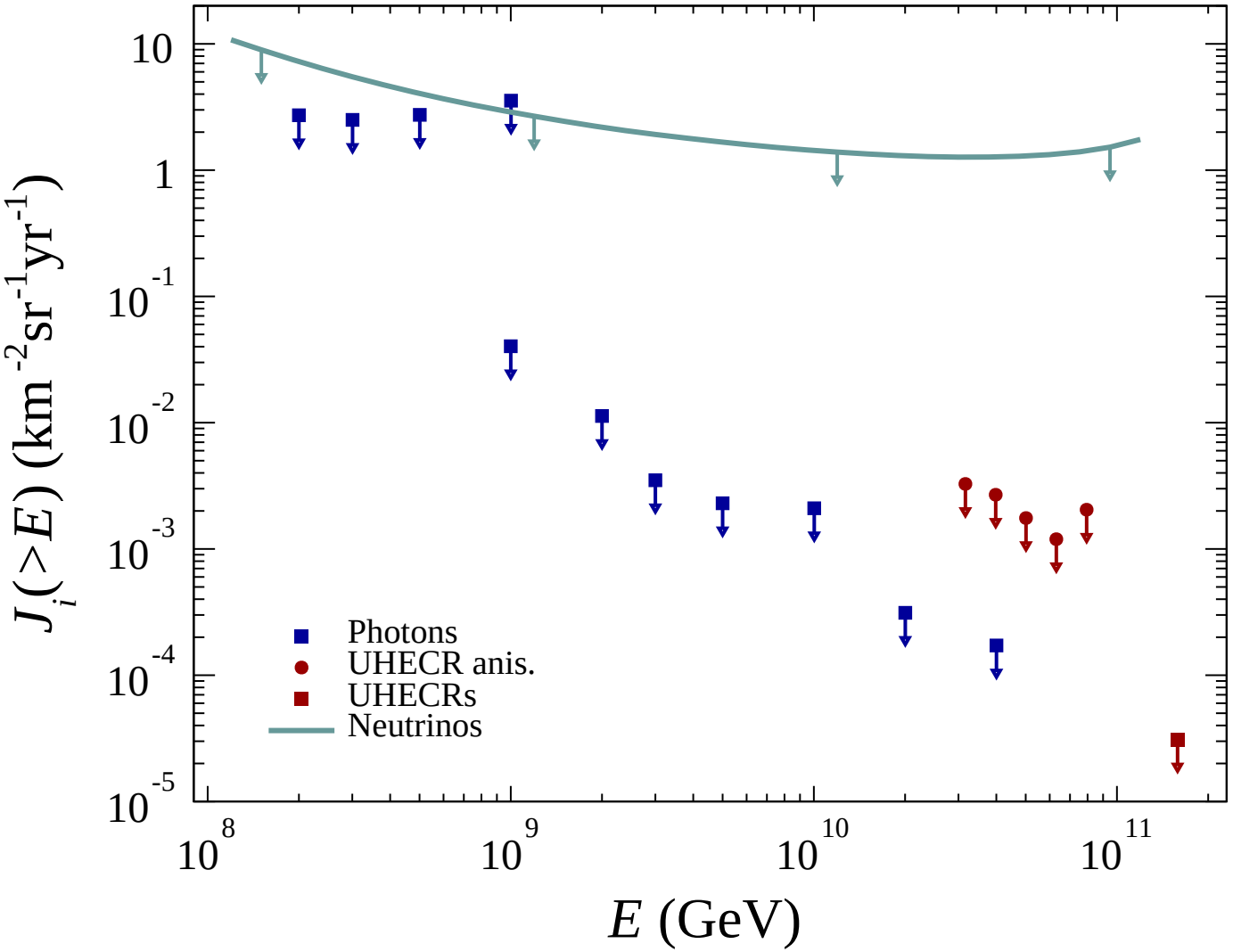

Lifetime:

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  - annihilation $\sigma_{\rm ann} \leq 1/m_X^2 \Rightarrow$ too small flux
  - exception:
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  - global symmetry broken by grav. wormhole effects, $\tau_X \propto \exp(S)$
  - symmetry broken by instanton effects, $\tau_X \propto \exp(4\pi^2/g^2)$
  - discrete symmetries forbid operators with $d < 9$
  - crypton or fractionally charged and confined particle of superstring theories

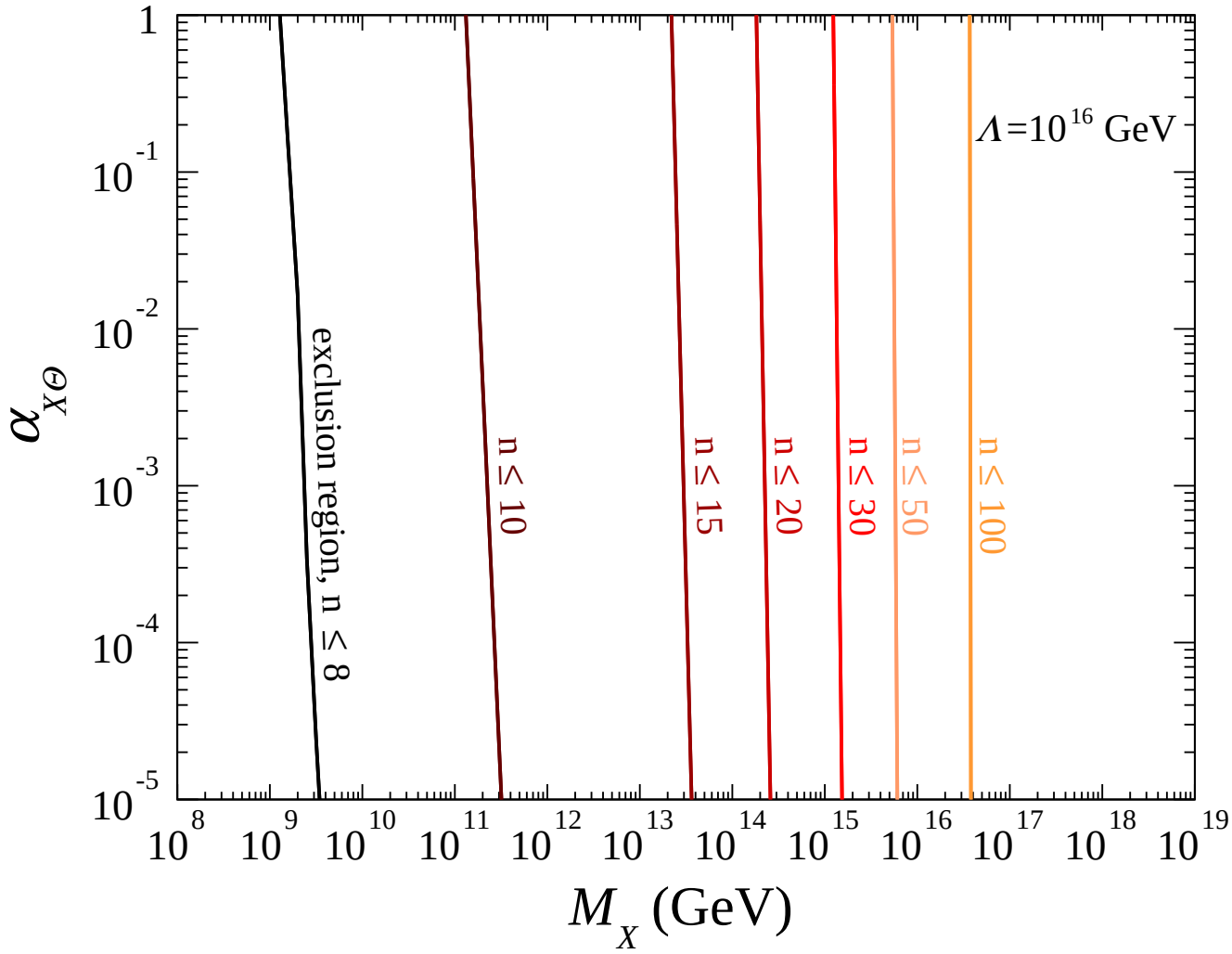
Concrete example:

[PAO '22]

- Pertubative decay via $\mathcal{L} = \frac{g_X}{\Lambda^{n-4}} n(X\psi)$

Concrete example:

[PAO '22]



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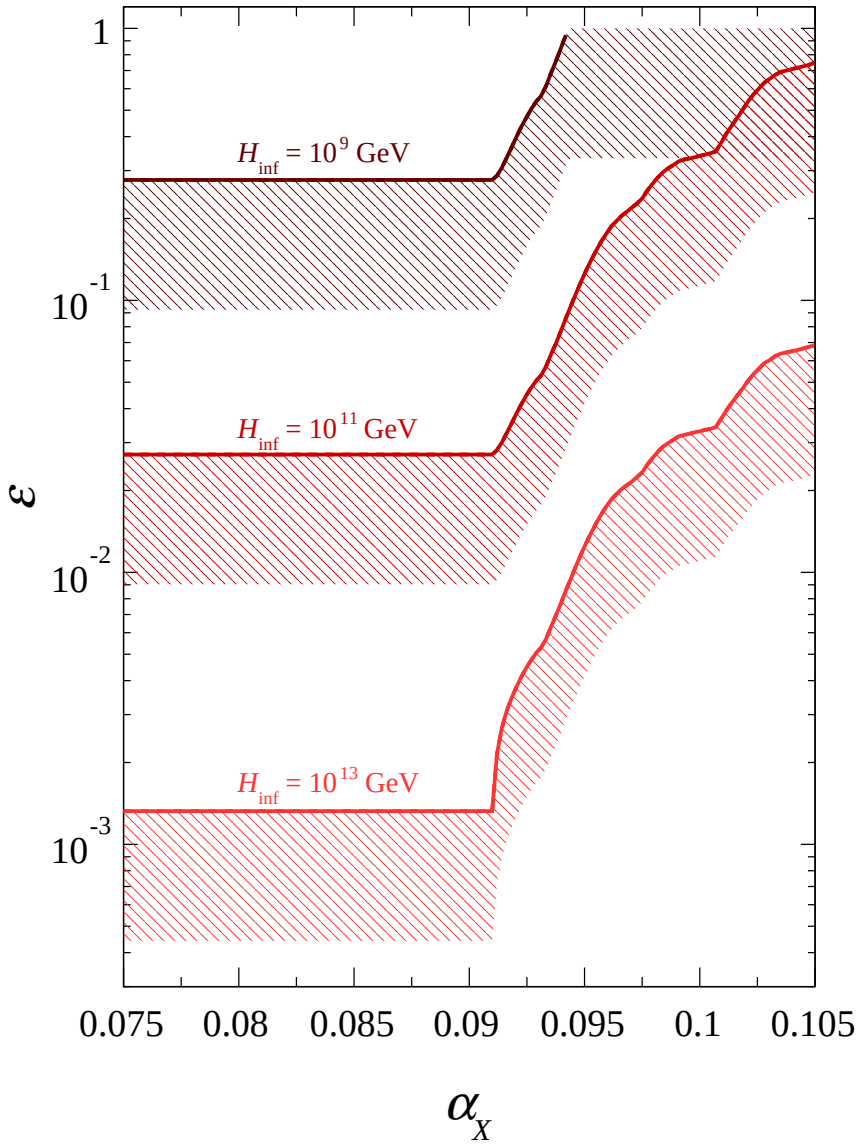
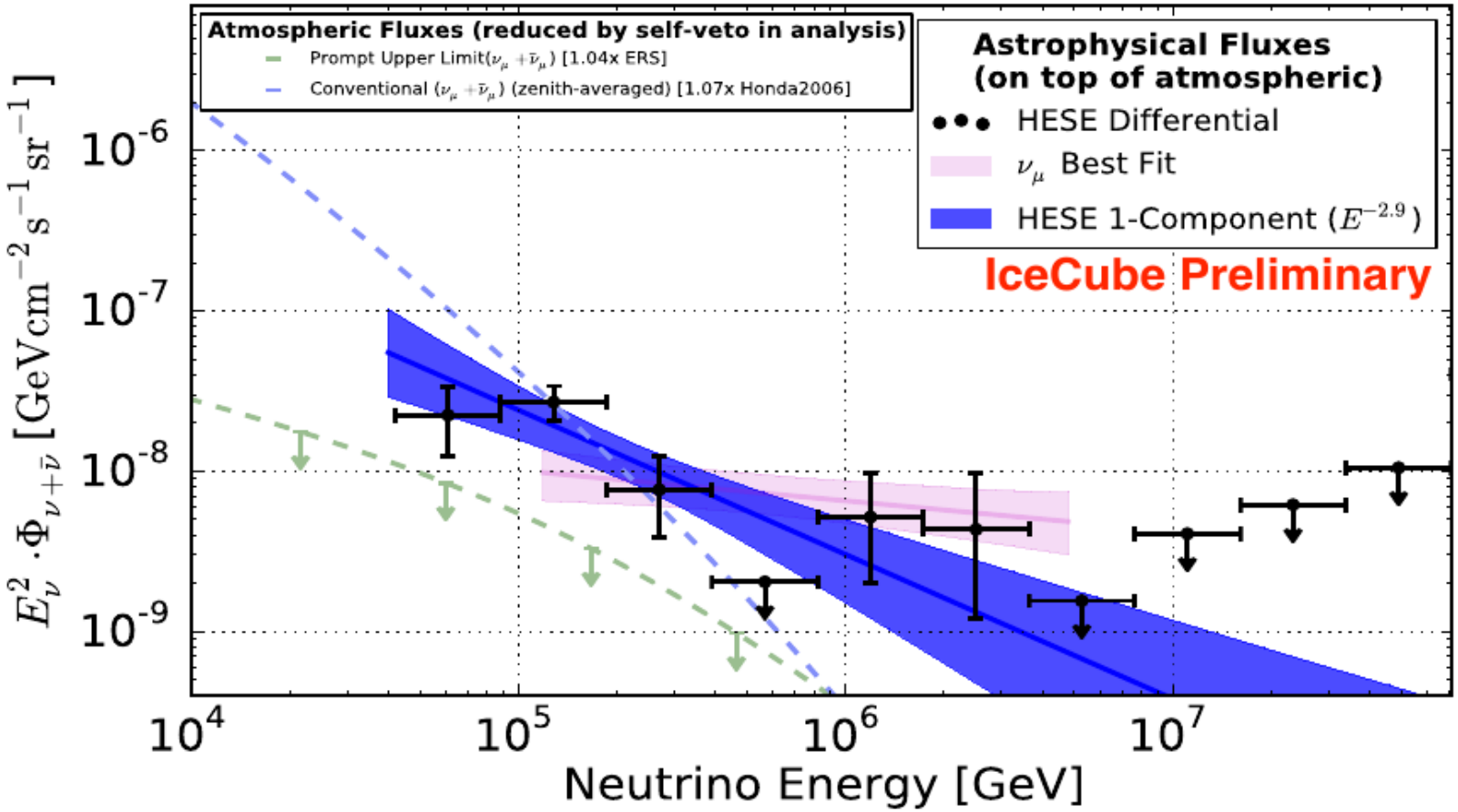
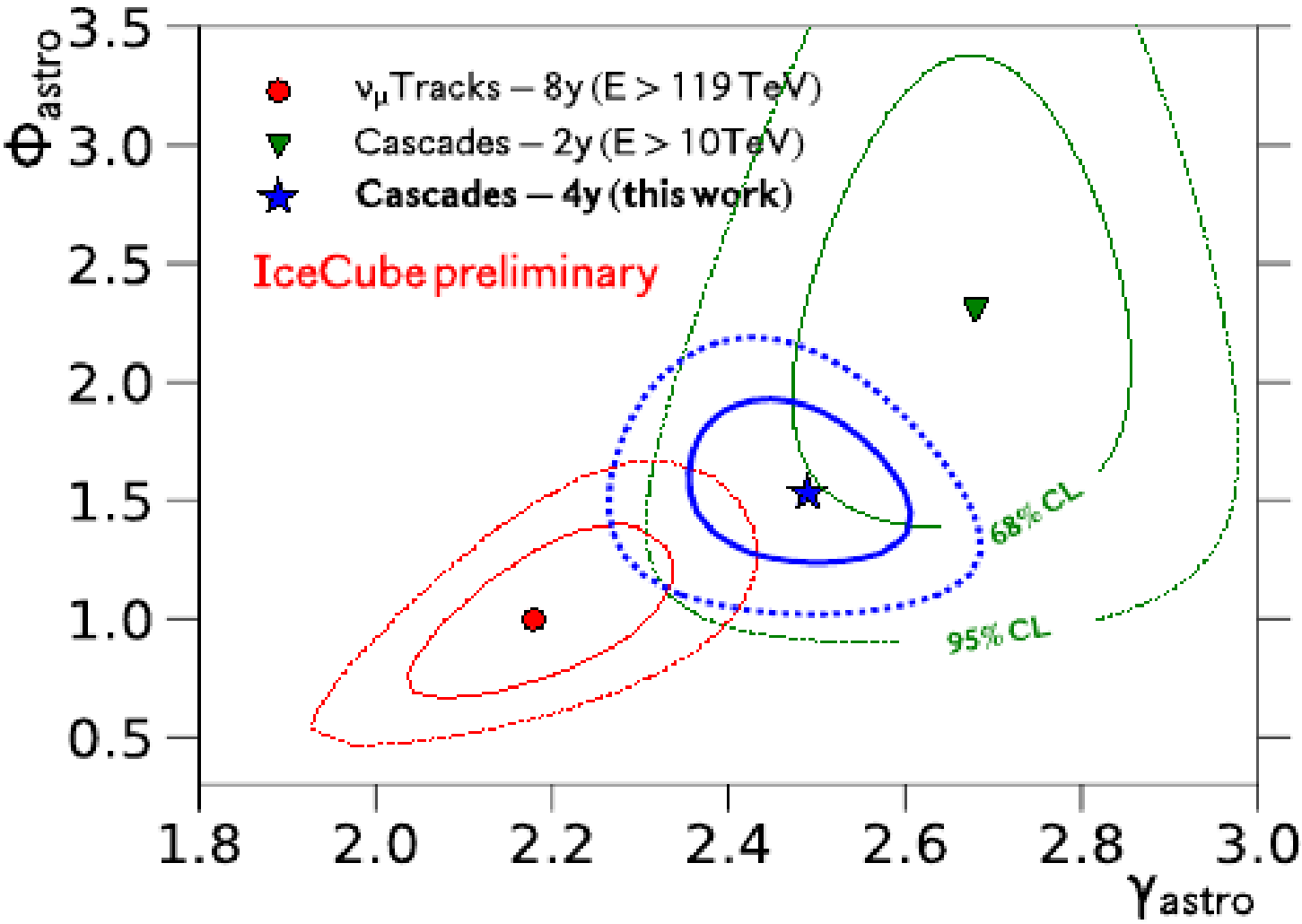


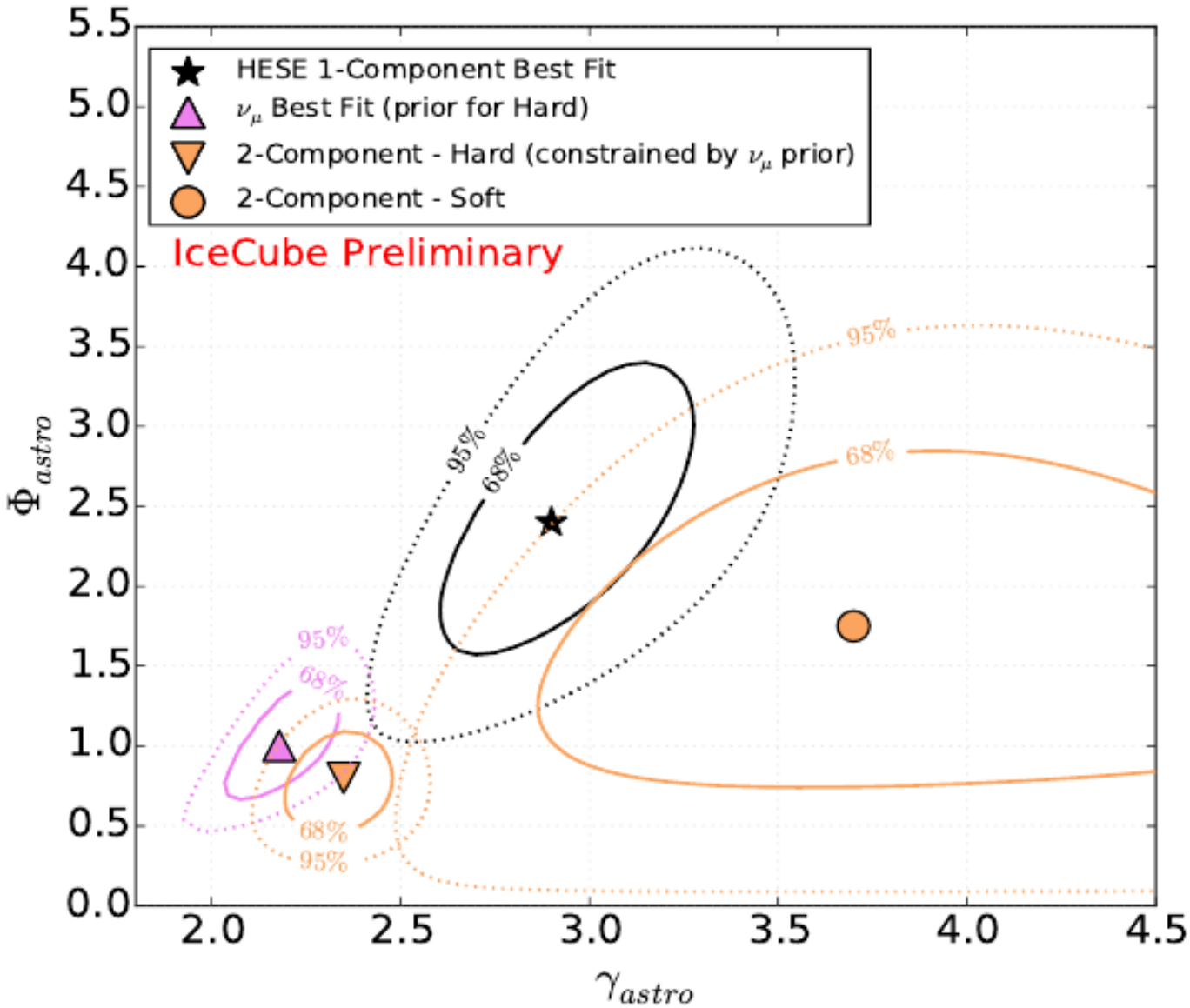
IceCube events: Soft "low-energy" spectrum?



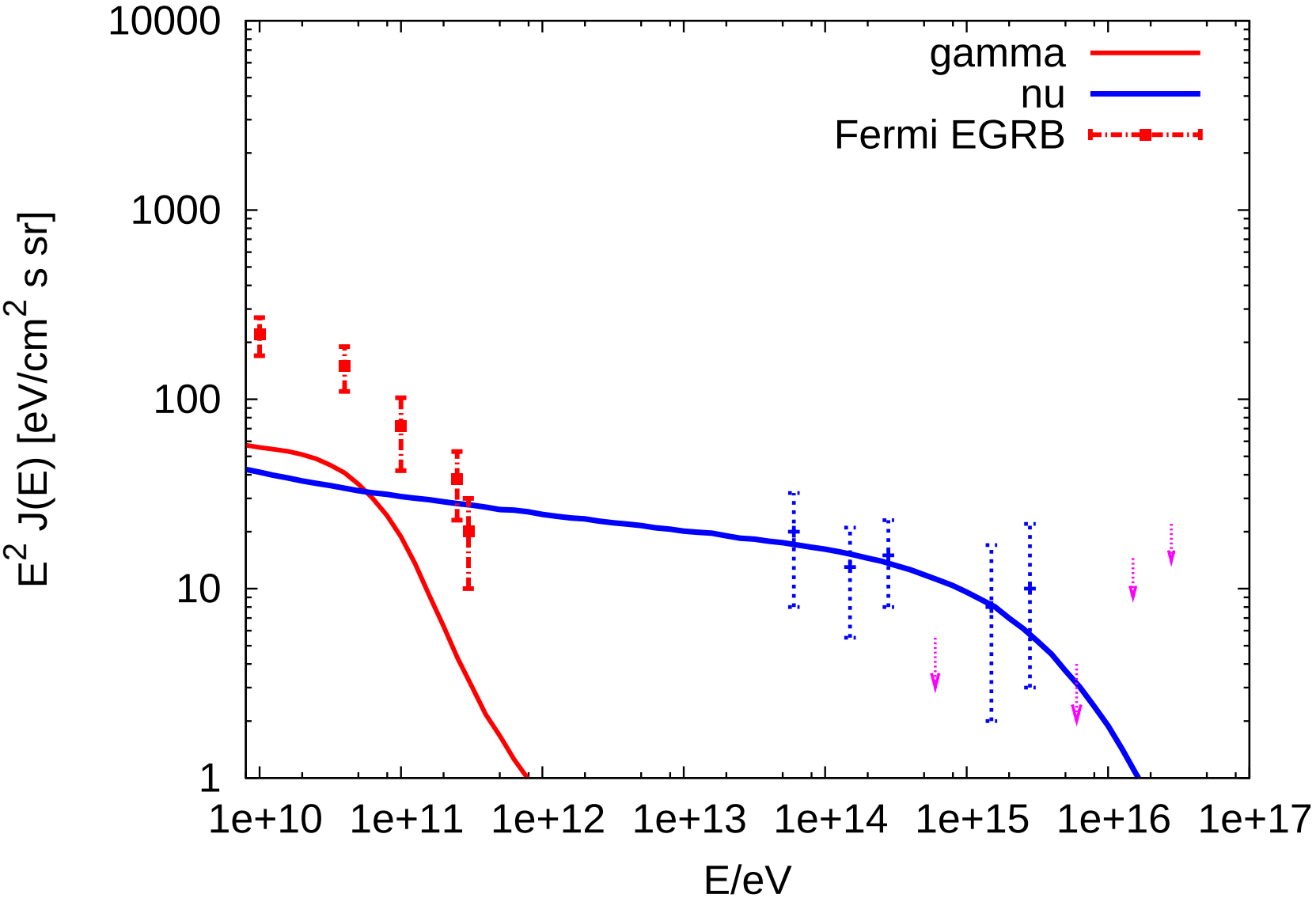
IceCube events: power-law fit of energy spectrum



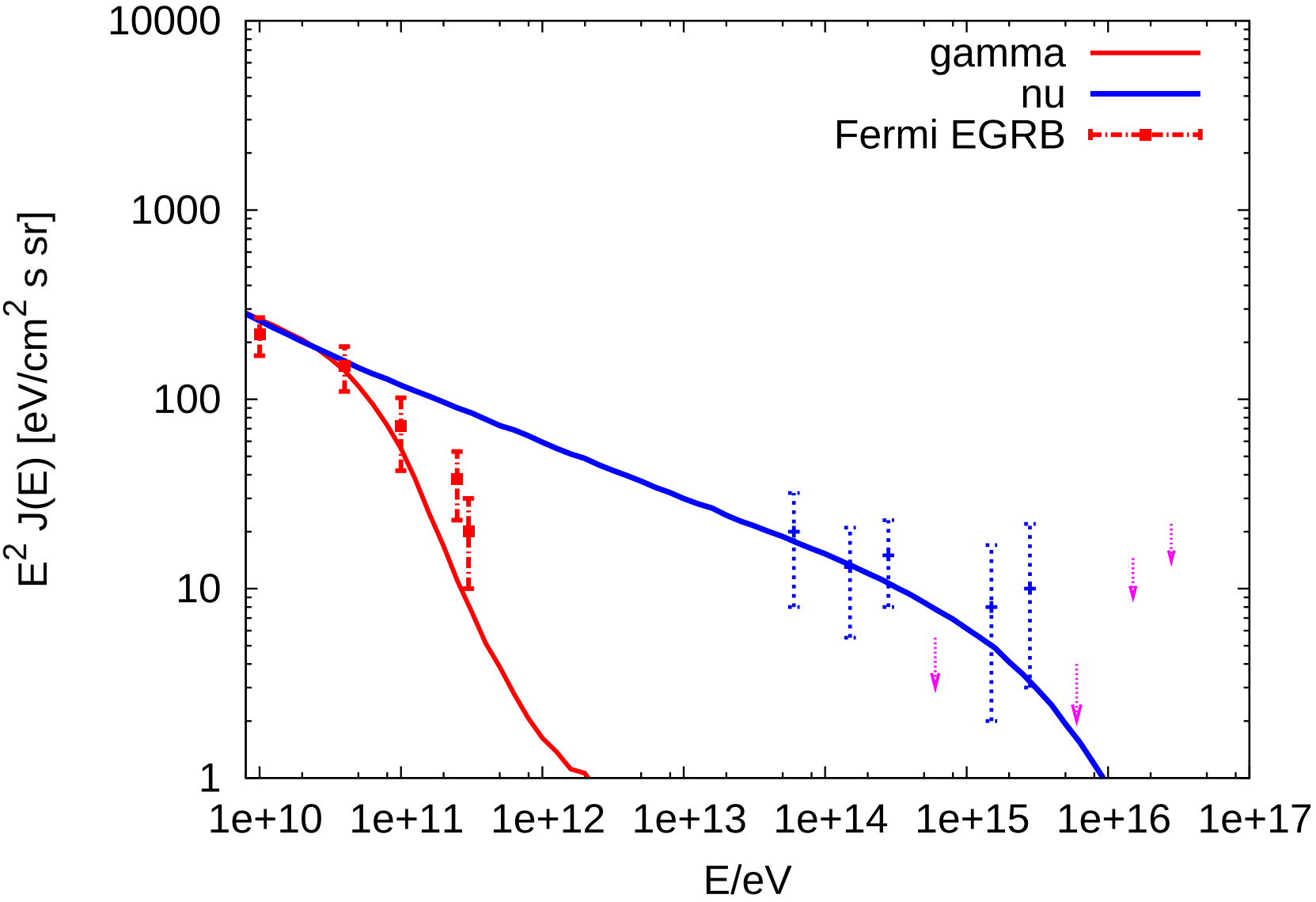
IceCube events: power-law fit of energy spectrum



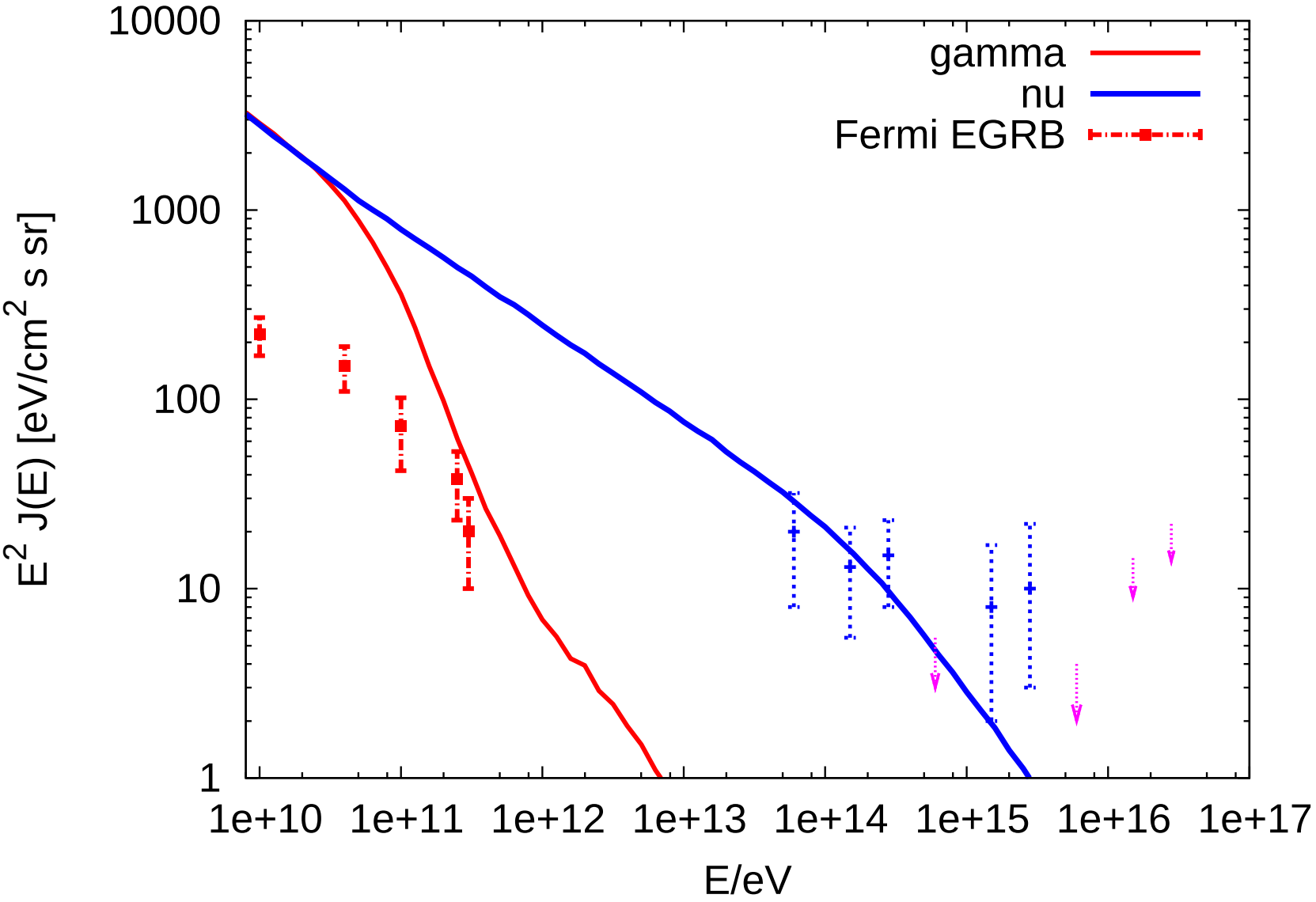
Cascade limit: $\alpha = 2.1$



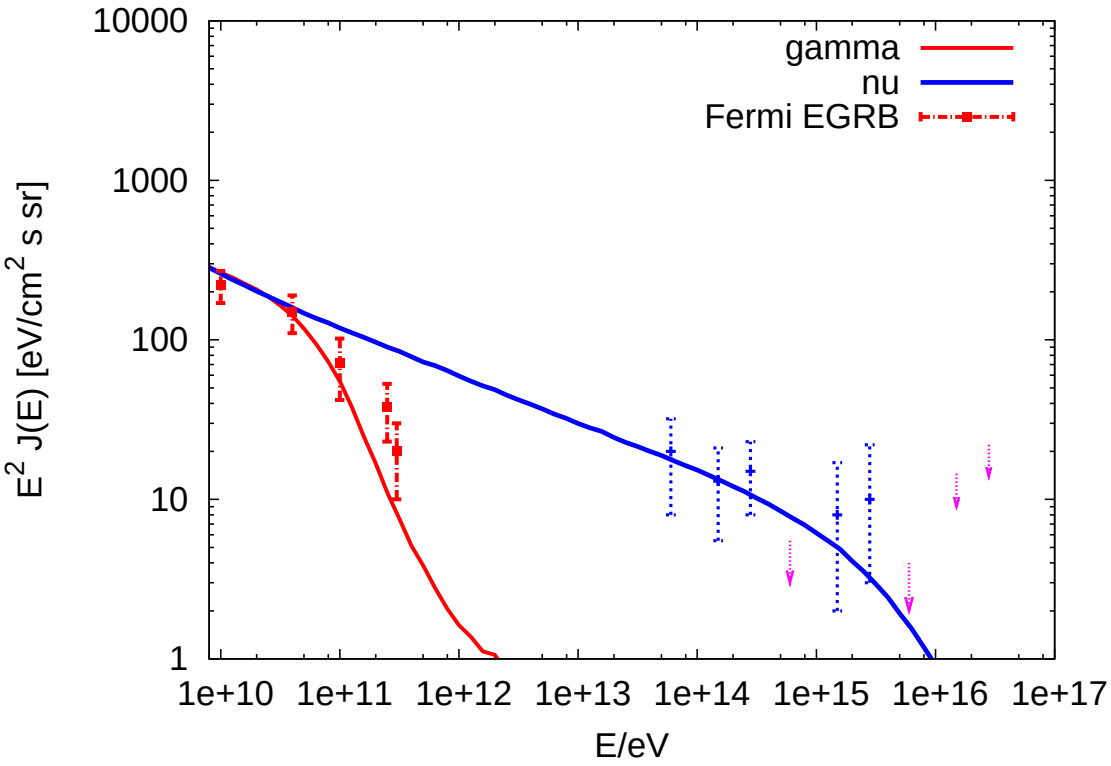
Cascade limit: $\alpha = 2.3$



Cascade limit: $\alpha = 2.5$



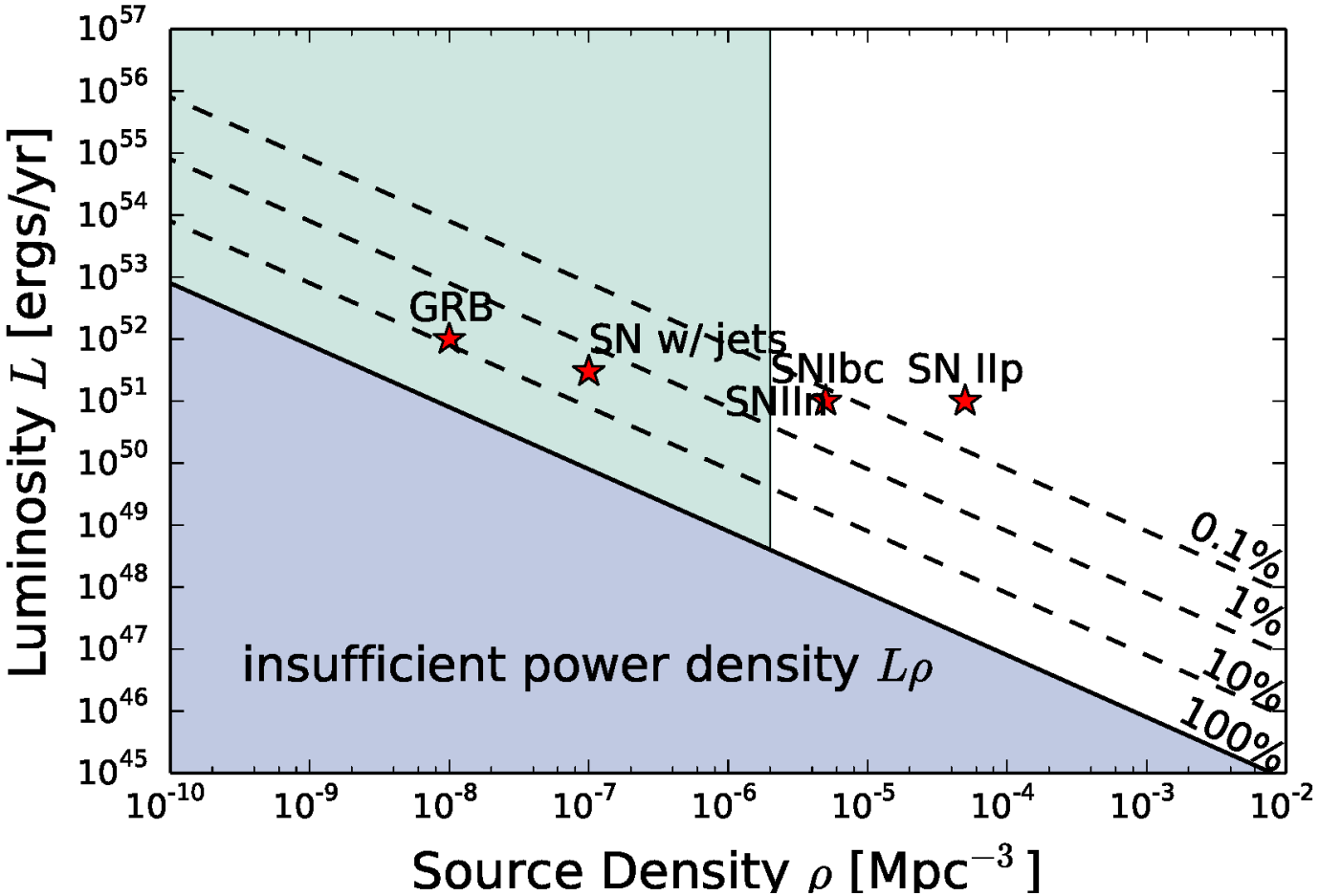
Cascade limit:



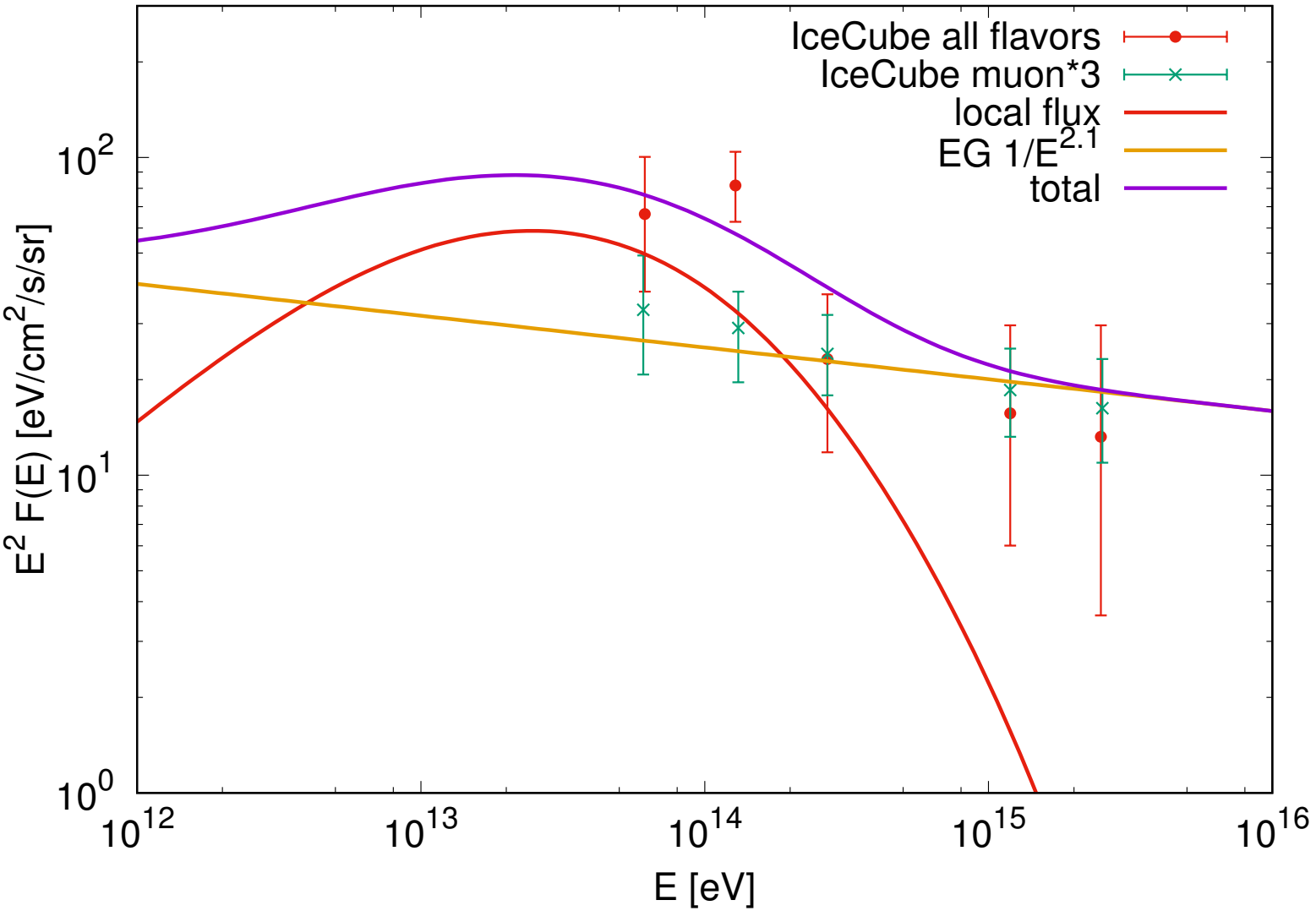
Slope $\alpha \gtrsim 2.2$

- requires "hidden sources" or
- Galactic origin

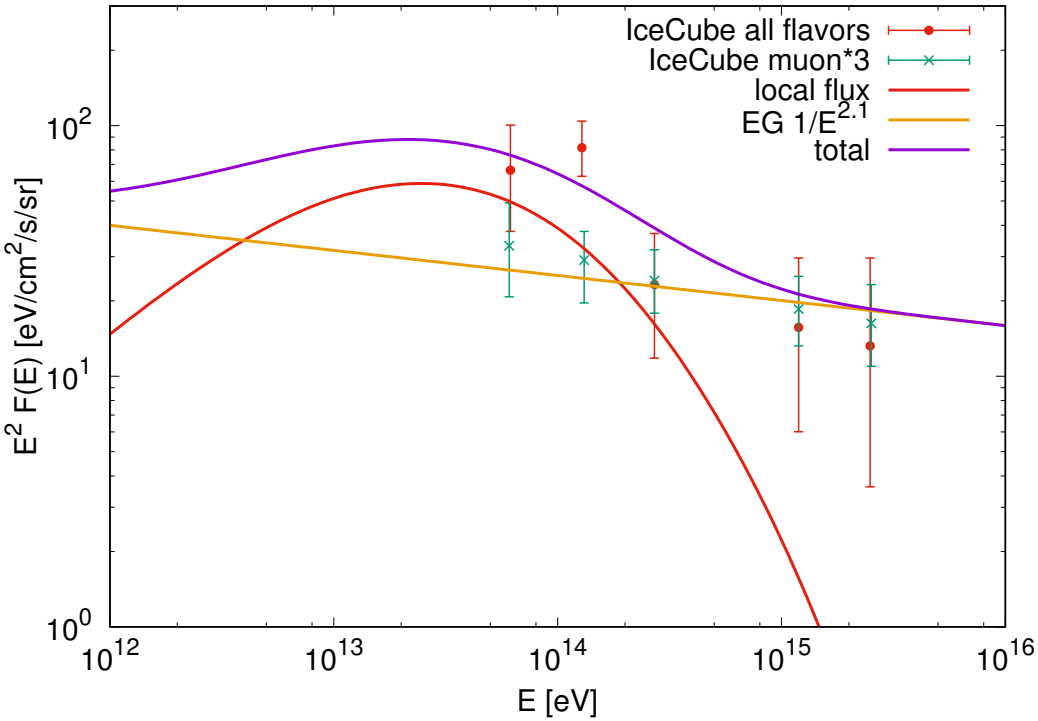
IceCube searches for sources: transient sources



Galactic origin?

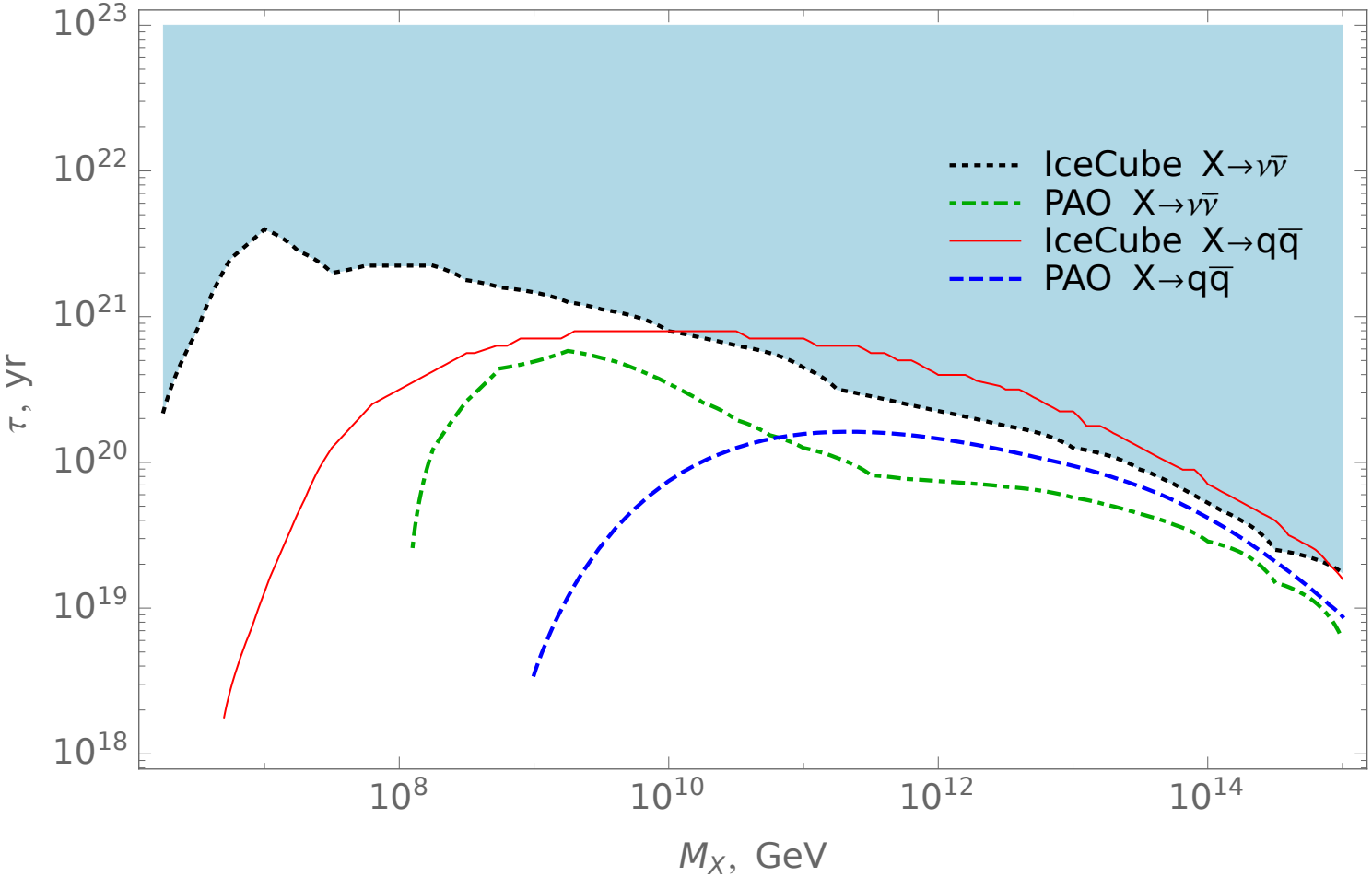


Galactic origin?



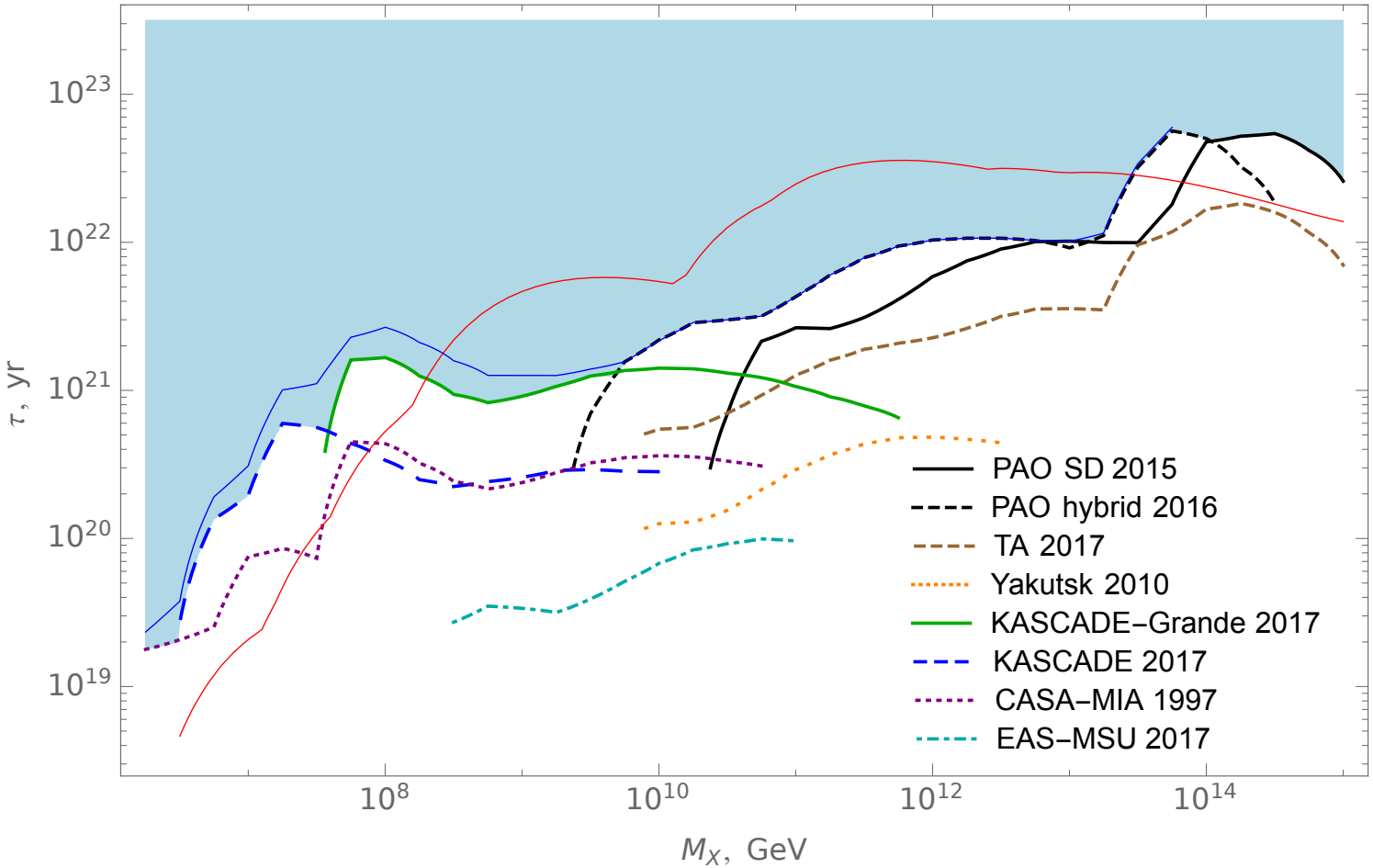
- possible sources:
  - extended CR halo [*Taylor, Gabici, Aharonian '14*]
  - extended nearby CR sources [*Andersen, MK, Semikoz '17, Bouyahiaoui, MK, Semikoz '21*]
  - heavy dark matter [*Feldstein et al. '13, Esmaili, Serpico '13,...*]

Exclusion plots for $X \to \bar{\nu}\nu$: neutrino constraints



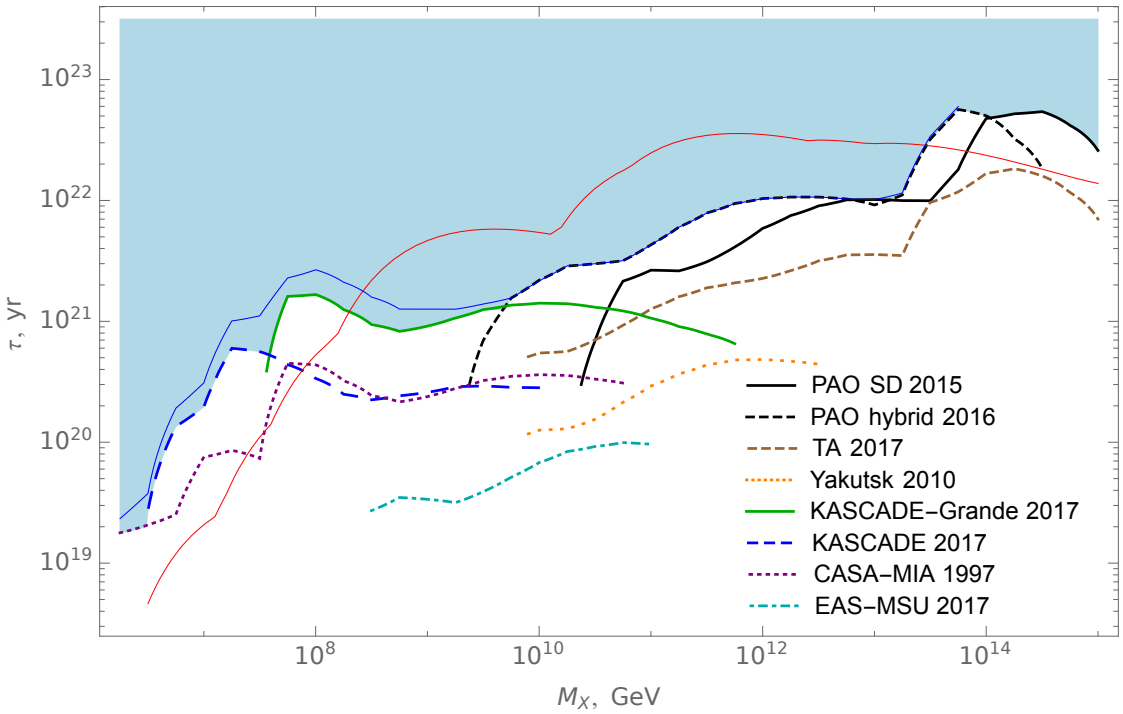
[*MK, Kalashev, Kuznetsov '18*]

Exclusion plots for $X \to \bar{\nu}\nu$: gamma constraints



[*MK, Kalashev, Kuznetsov '18*]

Exclusion plots for $X \to \bar{\nu}\nu$: constraints



[*MK, Kalashev, Kuznetsov '18*]

- significant contribution from only leptonic decay still possible

Topological defect models

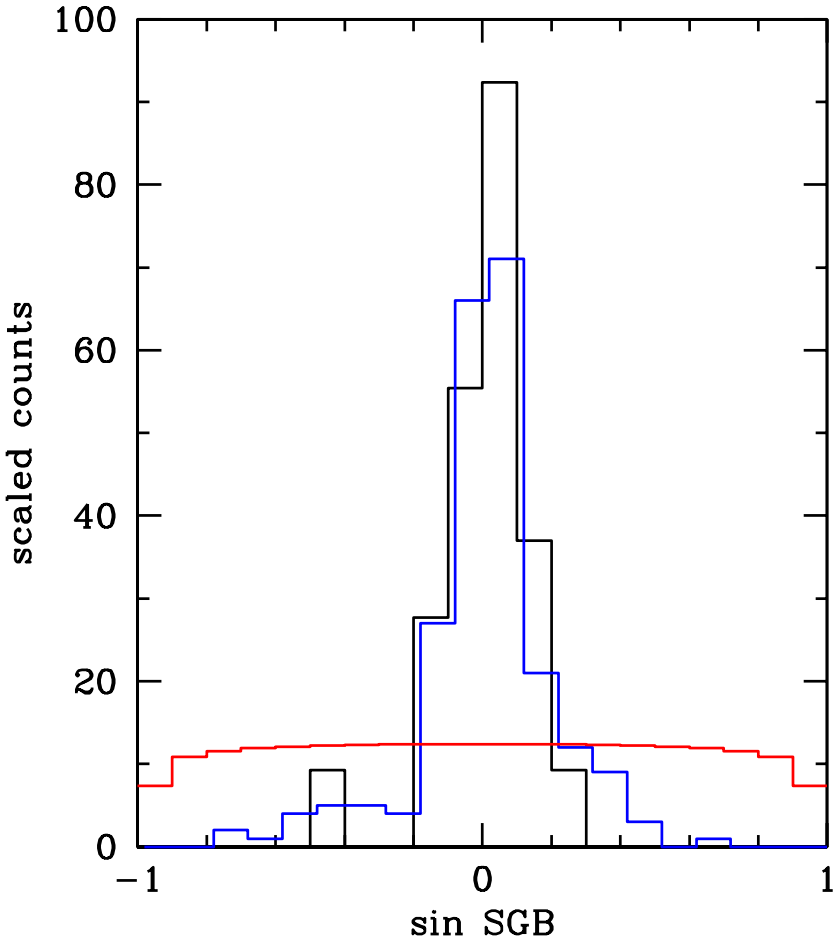
+ "generic" in SUSY-GUTs
+ produced during reheating
+ source of primordial perturbations

- typical density: one per horizon/correlation length
- main energy loss low-energy radiation?

LSS anomalies:

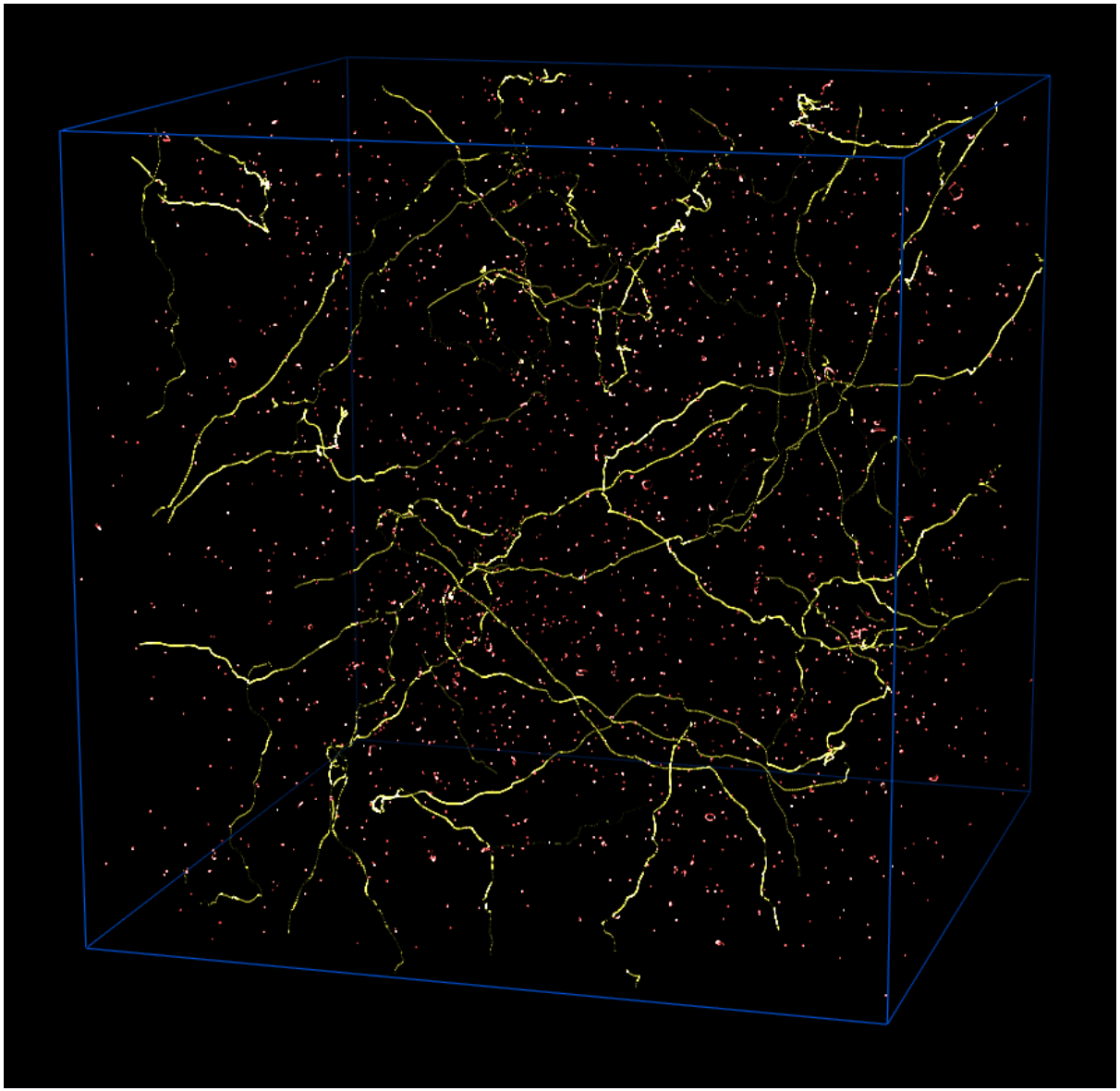
[*Peebles '22*]

- bulk flows & kinematic dipoles (radio galaxies,) too large?
- deviations from homogeneity on too large scales?



Topological defect models

[*Allen, Shellard '06*]



- box $2ct$
- matter epoch
- scaling regime

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favourable models for UHECRs:

- monopole-antimonopole pairs
- hybrid defects: cosmic necklaces

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- hybrid defects: cosmic necklaces
  - $G \to H \otimes U(1) \to H \otimes Z_2$
  - monopoles $M \sim \eta_m / e$ connected by strings $\mu_s \sim \eta_s^2$
  - parameter $r = M/(\mu d)$:
  - $r \ll 1$ normal string dynamics
  - $r \gg 1$ non-rel. string network:

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  - $r \gg 1$ non-rel. string network: $\Rightarrow$ strongly reduced photon, increased neutrino fluxes

Testing new/strong interactions

- New effects in strong interactions:
  - BFKL, colour glass effects
  - chiral phase transition, strange fireballs, ...
- Large extra dimensions
- Deviations from weak interactions:
  - NS neutrino interactions
  - sterile neutrinos
- ...

Summary

- strong limits on ETF-like LIV
- topological defects are generic prediction of (SUSY-) GUTs
- SHDM is an interesting DM candidate
  - probes inflation & GUT physics
  - photon & neutrino searches most promising
- ν-telescopes: strong limits on sterile neutrinos and NSI