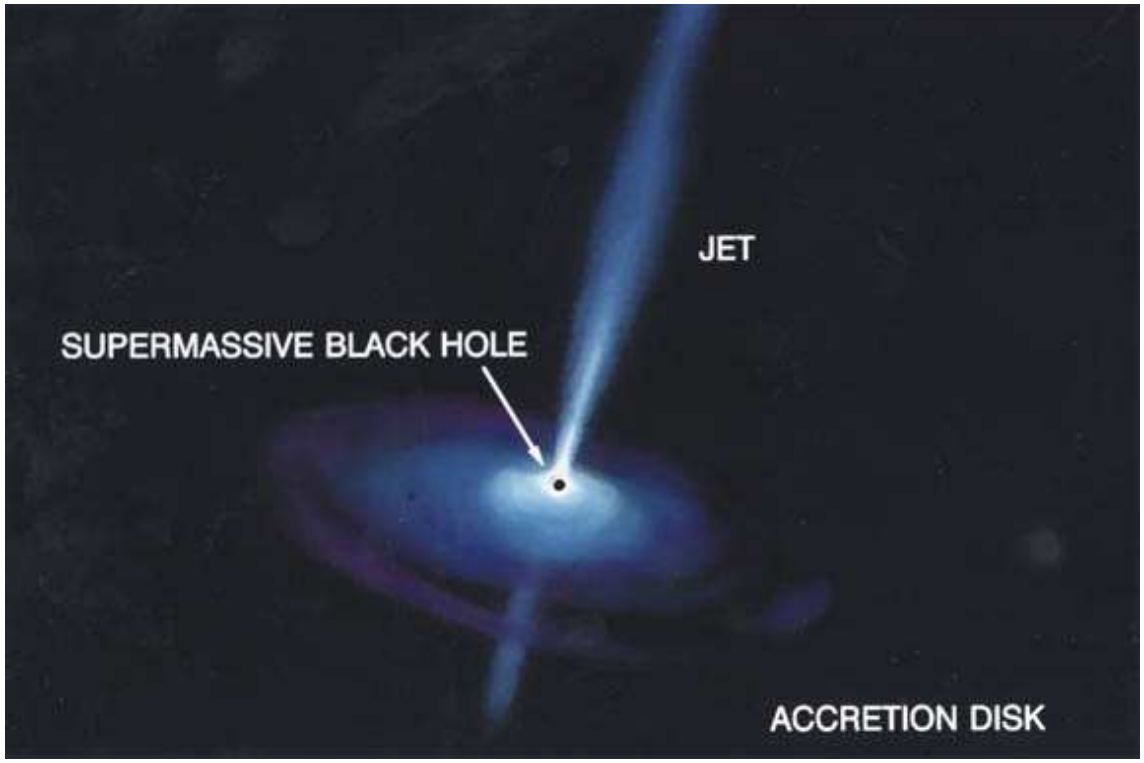
Astroparticle physics news

- The mystery of distant blazars $\Rightarrow$ secondary gamma rays and PeV neutrinos
- IceCube neutrinos: astrophysical or dark matter?
- X-ray line at 3.5 keV? If it's real, what it implies.

(...more or less, in the order from "astro" to "particle".)

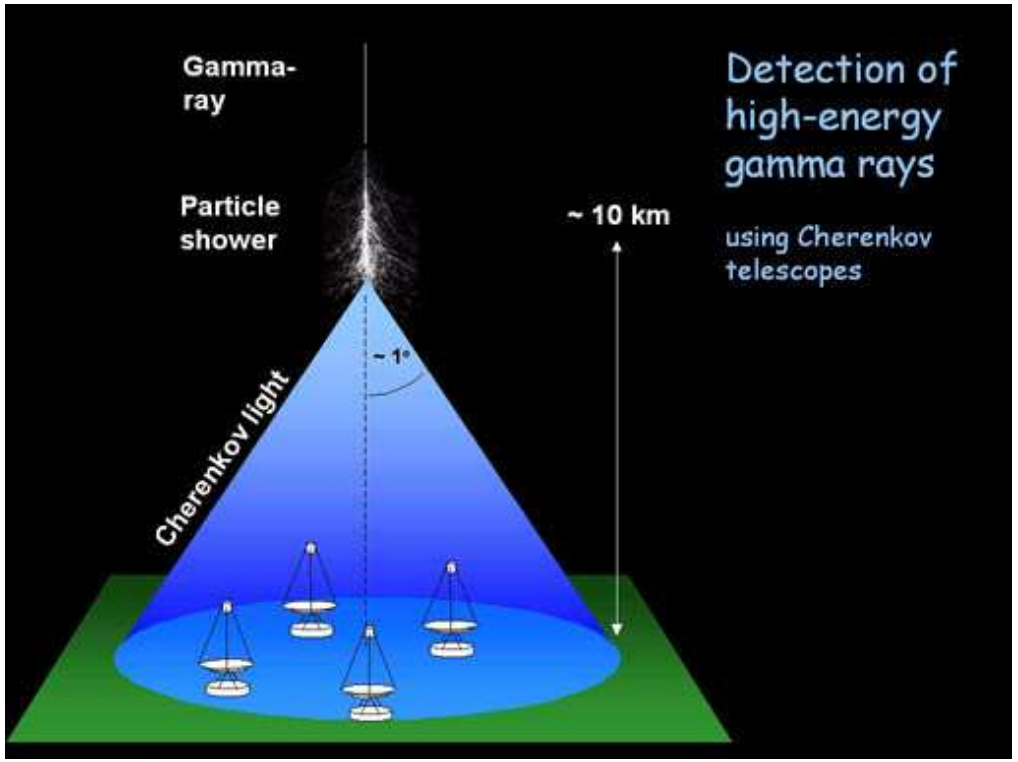
Active galactic nuclei: blazars



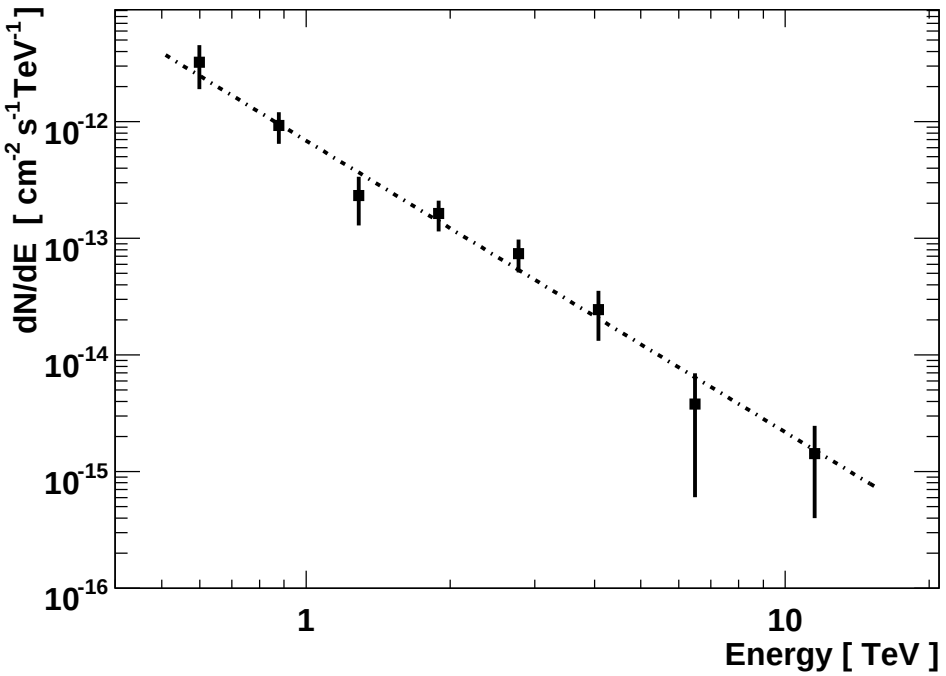
when AGN jet points at Earth, called *blazar*

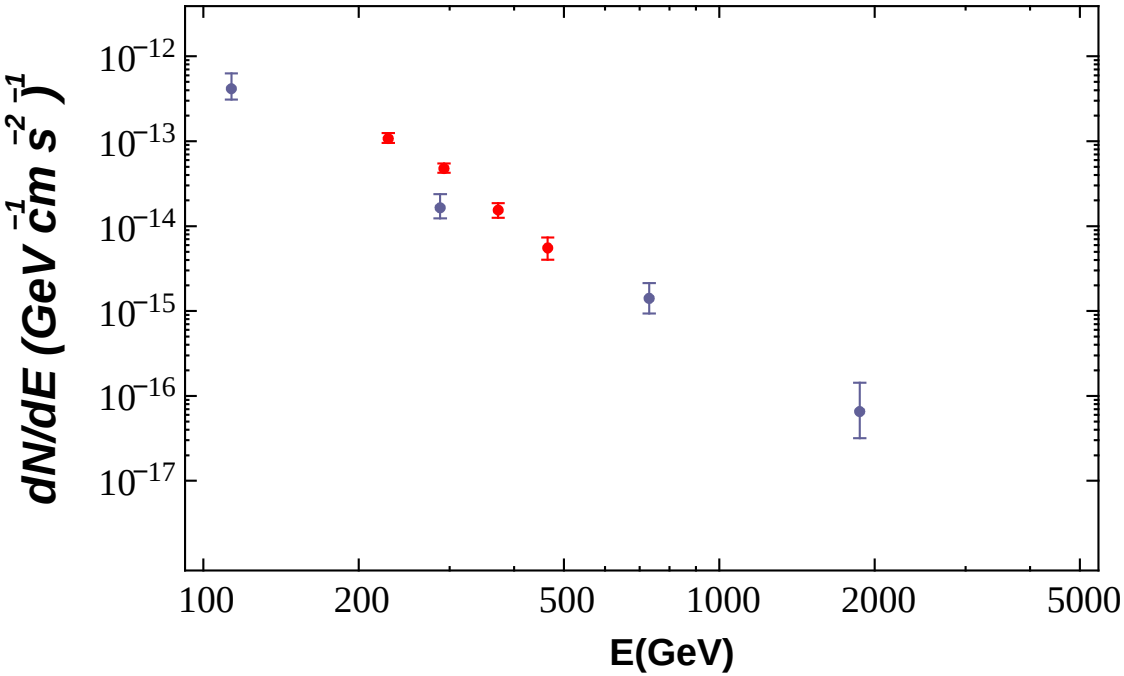
Fermi
Gamma-ray
Space Telescope

Atmospheric Cherenkov Telescopes


Gamma-ray
Particle shower
~ 10 km
~ 1°
Cherenkov light
Detection of high-energy gamma rays
using Cherenkov telescopes

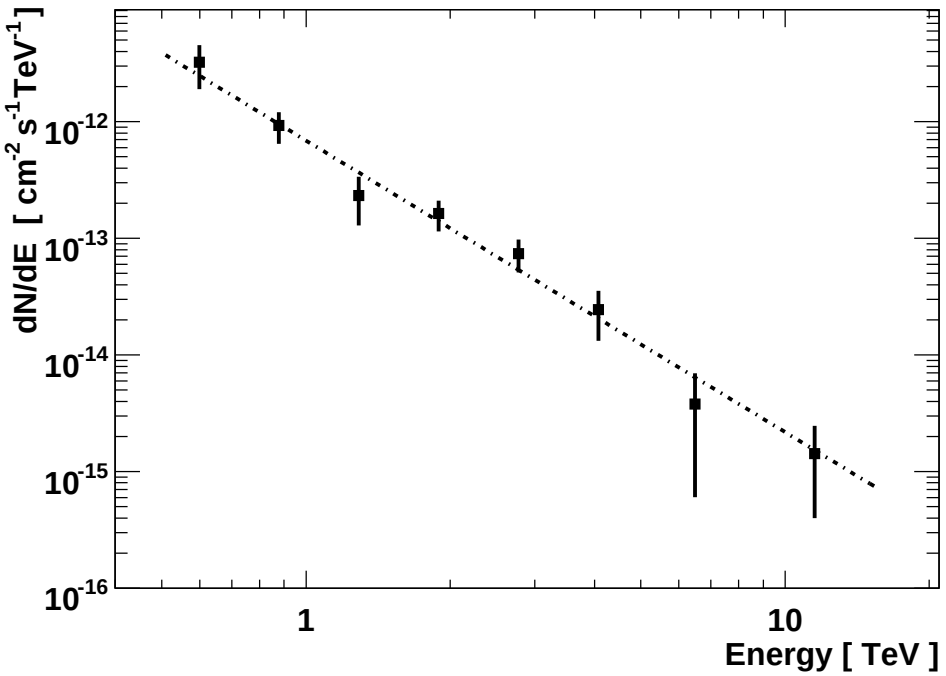
Gamma-ray observations of distant blazars: 1ES 0229+200 ($z = 0.14$) and 3C66A ($z = 0.44$)

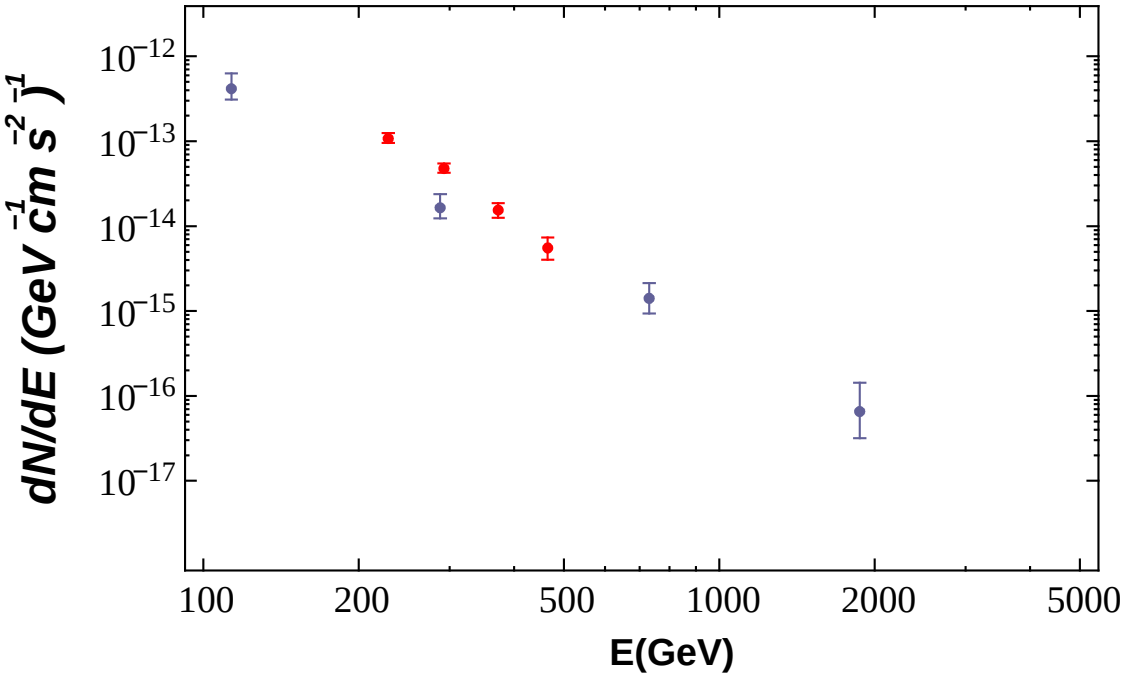




HESS (black), **MAGIC** (blue) and **VERITAS** (red) data points

Gamma-ray observations of distant blazars: 1ES 0229+200 ($z = 0.14$) and 3C66A ($z = 0.44$)

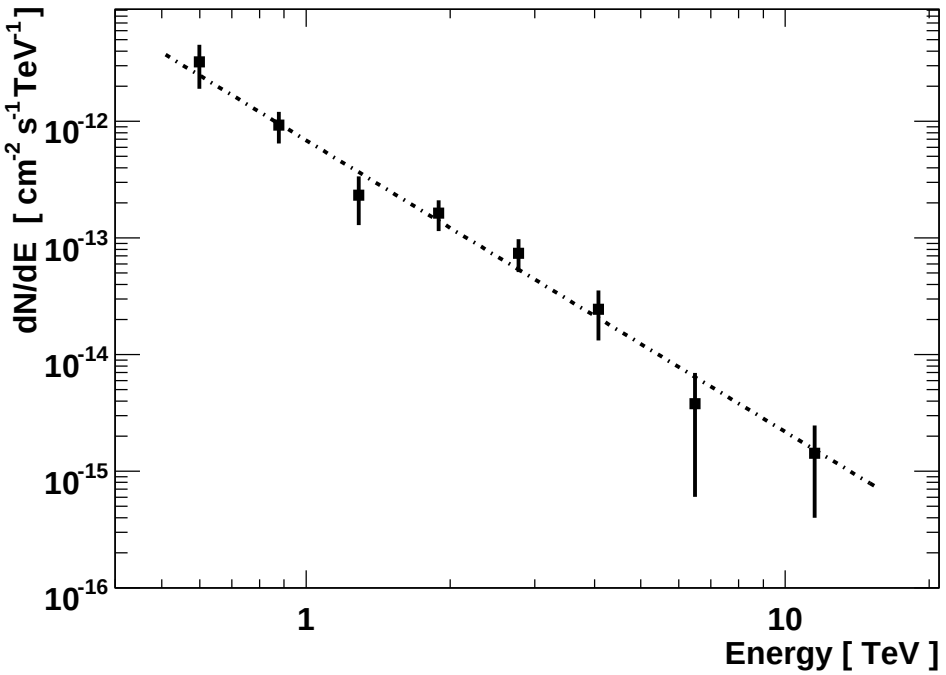


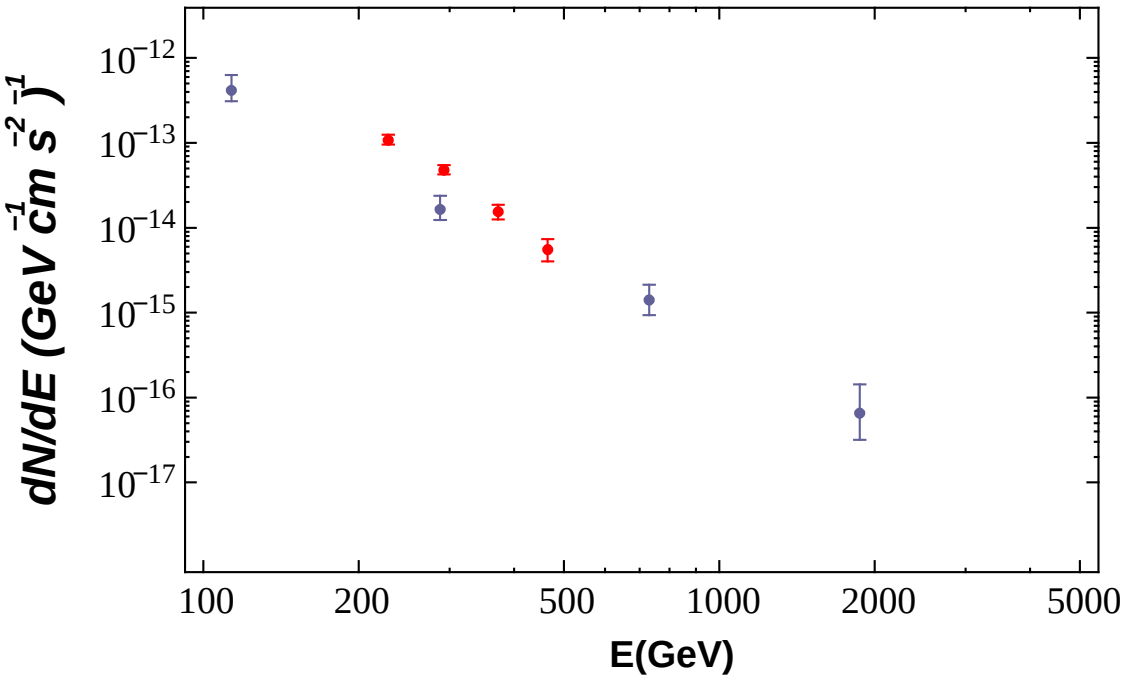


HESS (black), **MAGIC** (blue) and **VERITAS** (red) data points

Theory, e.g., Stecker, et al. (1992): ...*"we predict a sharp cutoff between 0.1 and 1 TeV"*

Gamma-ray observations of distant blazars: 1ES 0229+200 ($z = 0.14$) and 3C66A ($z = 0.44$)





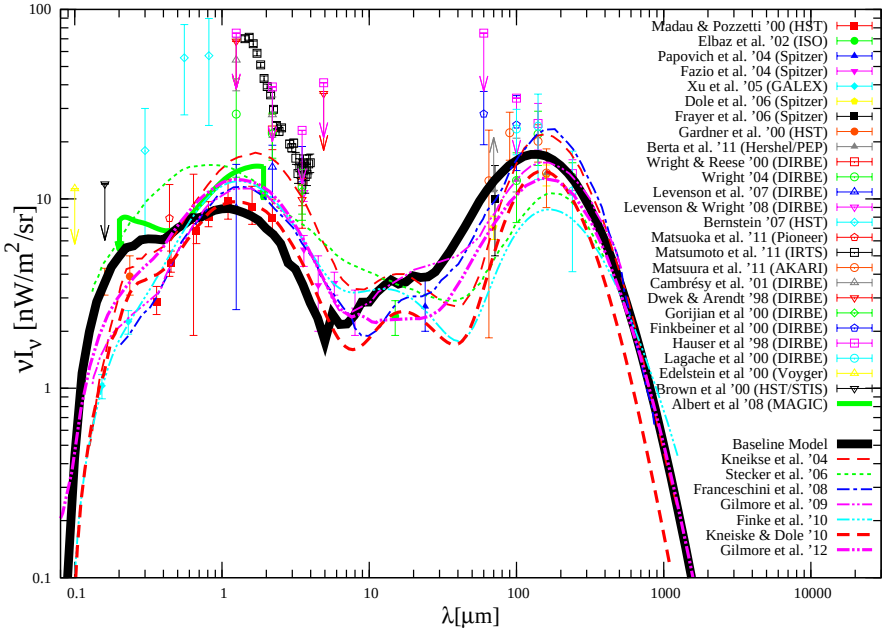
HESS (black), **MAGIC** (blue) and **VERITAS** (red) data points

Theory, e.g., Stecker, et al. (1992): ...*"we predict a sharp cutoff between 0.1 and 1 TeV"*

The data: no signs of absorption due to $\gamma\gamma_{EBL} \to e^+e^-$

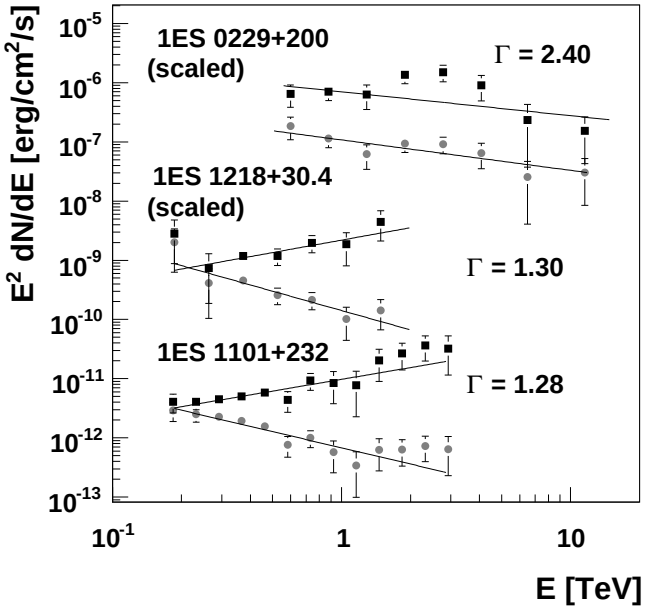
Extragalactic background light (EBL)
(direct and processed starlight)

- intimately connected with star formation history and with dust content of the galaxies
- models uncertain, but *robust lower limits exist* from star counts, especially for UV EBL



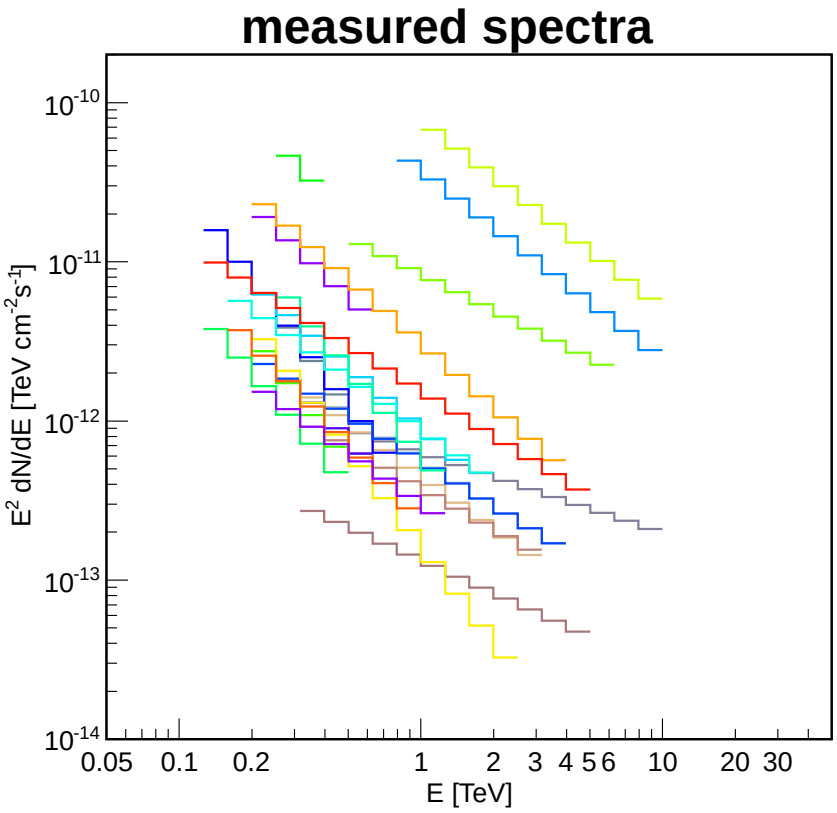
$\gamma\gamma_{EBL} \to e^+e^-$ should degrade the energy of TeV photons

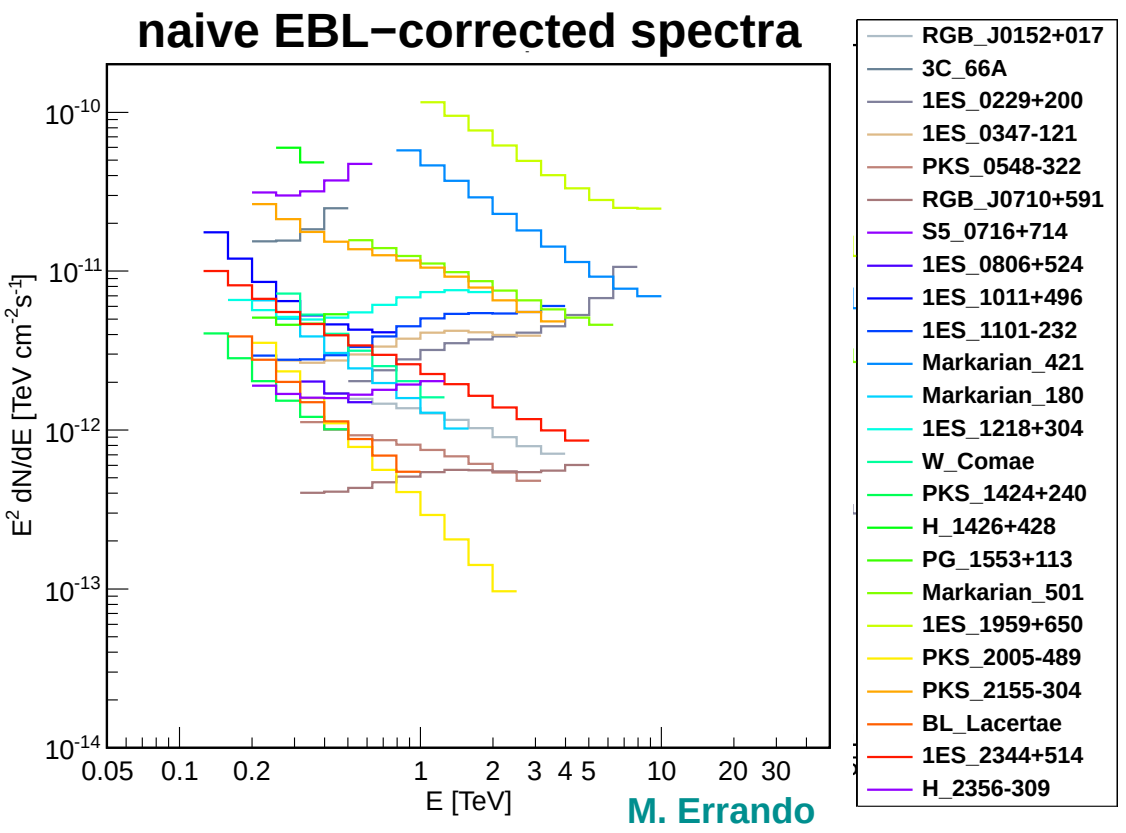
Distant blazars have implausibly hard spectra



Absorption-corrected spectra are extremely hard, $\Gamma < 1.5$, for distant blazars. [Aharonian et al.]

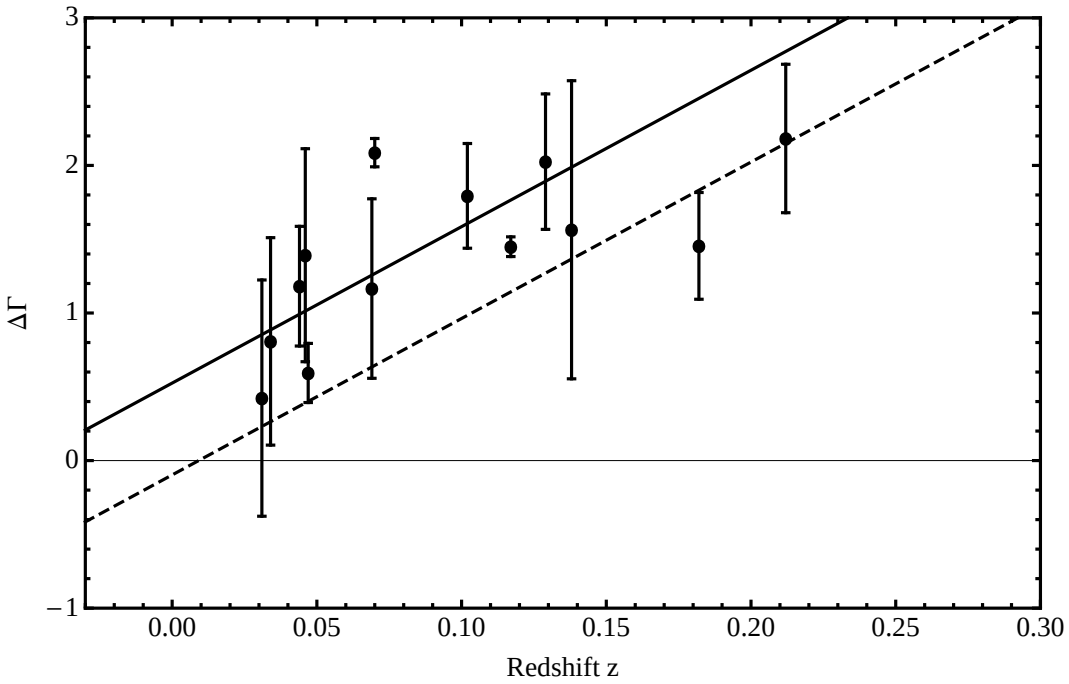
Blazar spectra





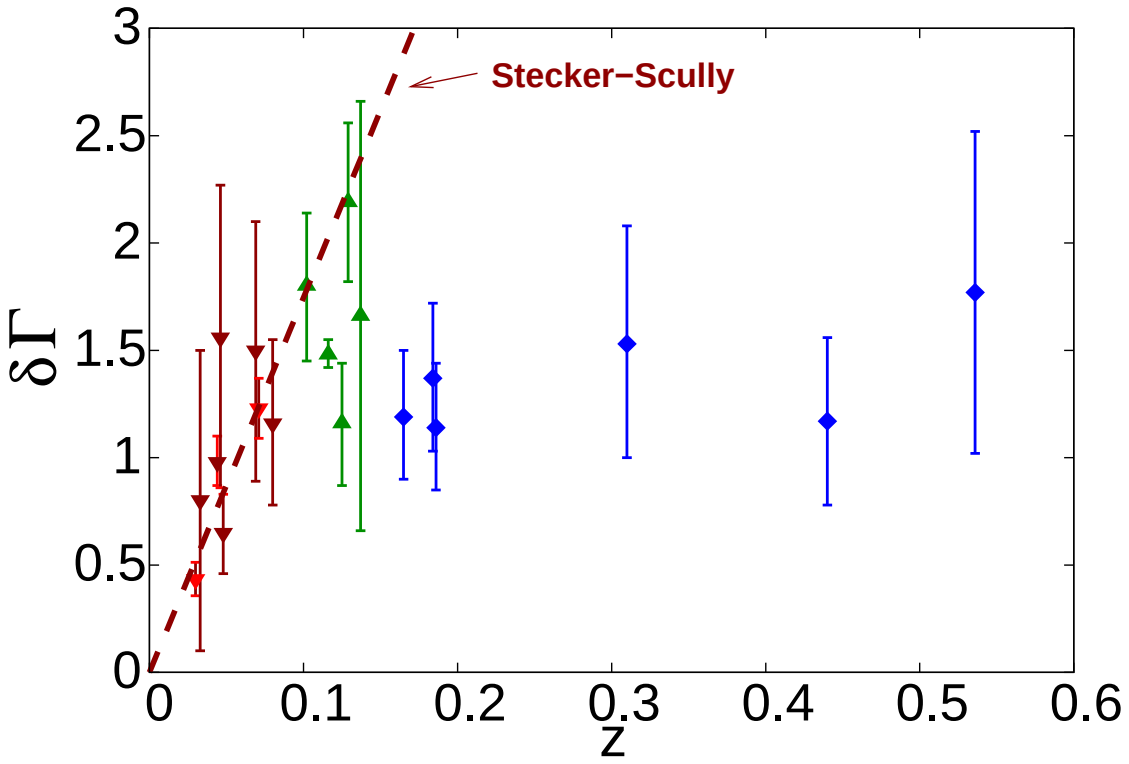
M. Errando

Softening of the spectrum as a function of the redshift



$$\Delta\Gamma = \Gamma_{\rm GeV} - \Gamma_{\rm TeV}$$ [Stecker, Scully]

Distant blazars are different:



$\delta\Gamma = \Gamma_{\rm GeV} - \Gamma_{\rm TeV}$ [Stecker, Scully]

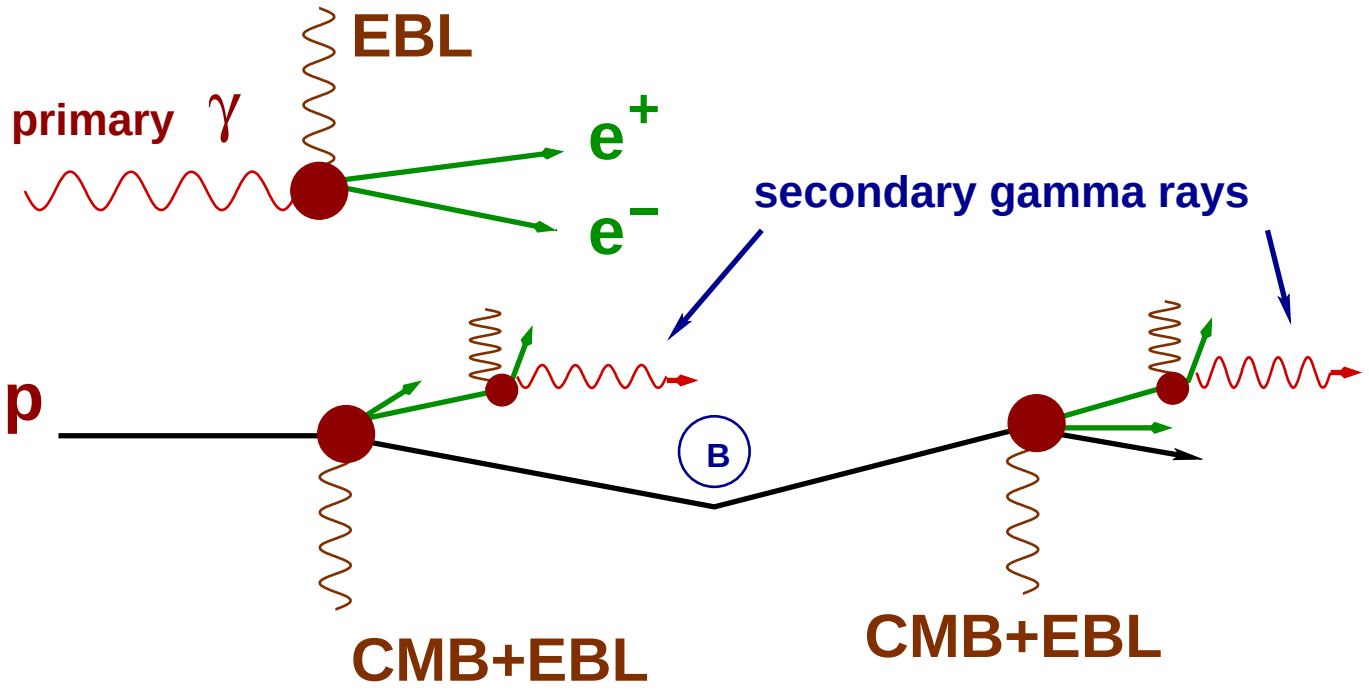
Proposed "new physics" solutions:

The lack of absorption prompted some exotic solutions:

- photons may convert into some hypothetical ***axion-like particles*** that convert back into photons in the galactic magnetic fields
  [Hooper et al.; de Angelis et al.; Simet et al.]
- ***Lorentz invariance violation*** for high-velocity particles may prevent pair production
  [Protheroe et al.]

Is there a more conventional explanation?

AGN produce both cosmic rays and gamma rays



Cosmic rays from AGN

- **No significant attenuation** below GZK cutoff.
  Propagate cosmological distances for $E \lesssim 10^{18}$ eV.
- **Rectilinear propagation** affected only by IGMFs.
  Clusters of galaxies (size R, density n) cause large deflections, but the mean free path of a proton

$$\Lambda \sim 1/(\pi R^2 n) \sim 3 \times 10^3 \mathrm{Mpc}$$

  The mean MFP for linear propagation is of the order of the size of the observed universe.
- **IGMFs are not known:**
  - upper limits: $B < 10^{-9}$ G from non-observation of Faraday rotations
  - lower limits: $B > 10^{-30}$ G if one believes the galactic fields are seed fields amplified by dynamo.

  For magnetic fields $B < 10^{-14}$ G, deflections are smaller than the angular resolution of ACTs.

Secondary gamma rays from cosmic rays along the line of sight?

Gamma-rays produced at the source can attenuate via pair production on EBL for TeV energies: expect **attenuation of TeV γ rays**.

Protons below GZK cutoff interact with EBL, CMB and produce γ rays via
$p\gamma \to pe^+e^-$, $p\gamma \to p\pi^0$: expect **regeneration of TeV γ rays**
Photon backgrounds provide opacity/sink for the former, source for the latter.

What is the scaling of these effects with distance?

Different scaling

$$F_{\text{primary},\gamma}(d) \propto \frac{1}{d^2}\exp\{-d/\lambda_\gamma\} \tag{1}$$

$$F_{\text{secondary},\gamma}(d) = \frac{p\lambda_\gamma}{4\pi d^2}\left[1-e^{-d/\lambda_\gamma}\right] \propto \begin{cases} 1/d, & \text{for } d \ll \lambda_\gamma, \\ 1/d^2, & \text{for } d \gg \lambda_\gamma. \end{cases} \tag{2}$$

$$F_{\text{secondary},\nu}(d) \propto (F_{\text{protons}} \times d) \propto \frac{1}{d}. \tag{3}$$

Different scaling

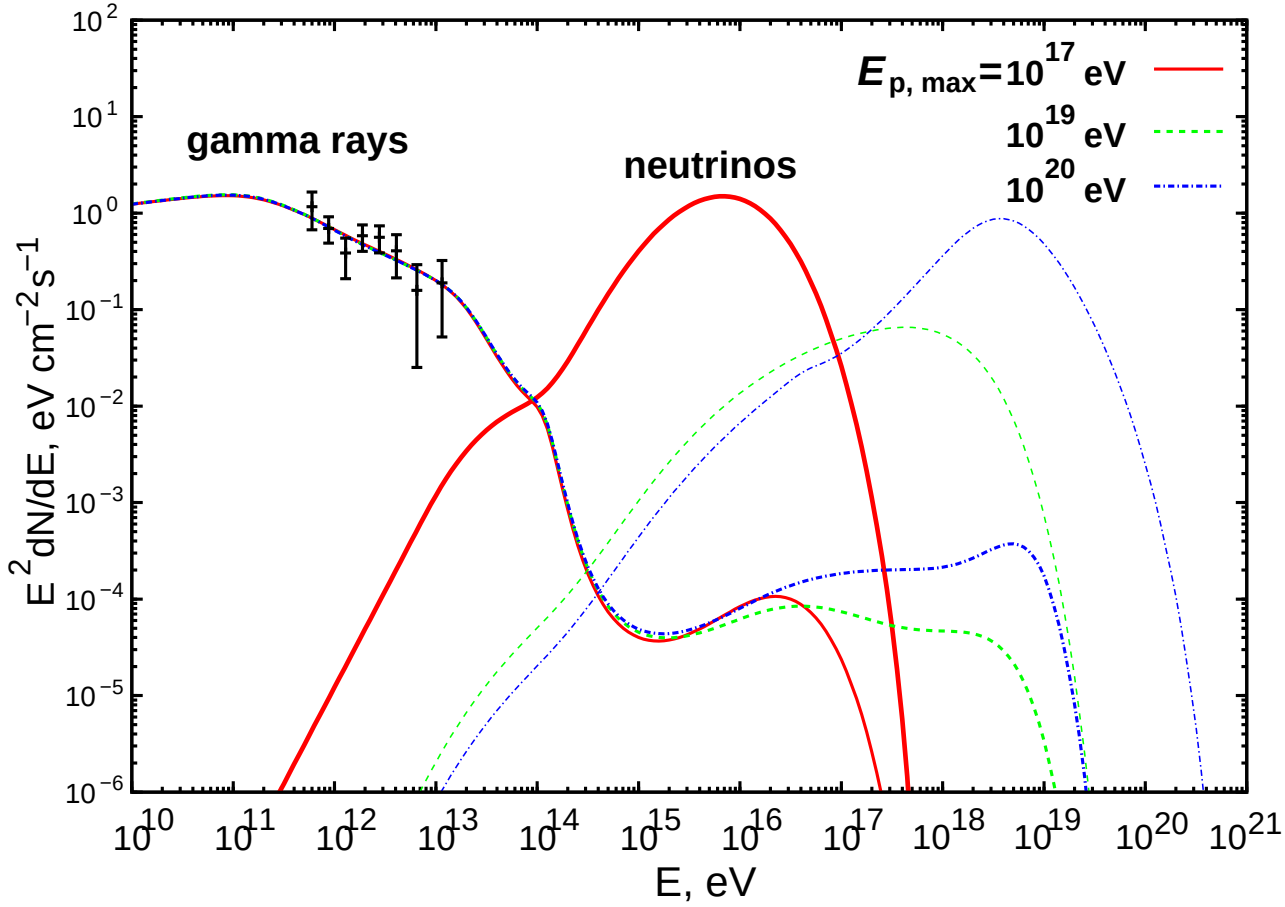
$$F_{\text{primary},\gamma}(d) \propto \frac{1}{d^2}\exp\{-d/\lambda_\gamma\} \tag{1}$$

$$F_{\text{secondary},\gamma}(d) = \frac{p\lambda_\gamma}{4\pi d^2}\left[1-e^{-d/\lambda_\gamma}\right] \propto \begin{cases} 1/d, & \text{for } d \ll \lambda_\gamma, \\ 1/d^2, & \text{for } d \gg \lambda_\gamma. \end{cases} \tag{2}$$

$$F_{\text{secondary},\nu}(d) \propto (F_{\text{protons}} \times d) \propto \frac{1}{d}. \tag{3}$$

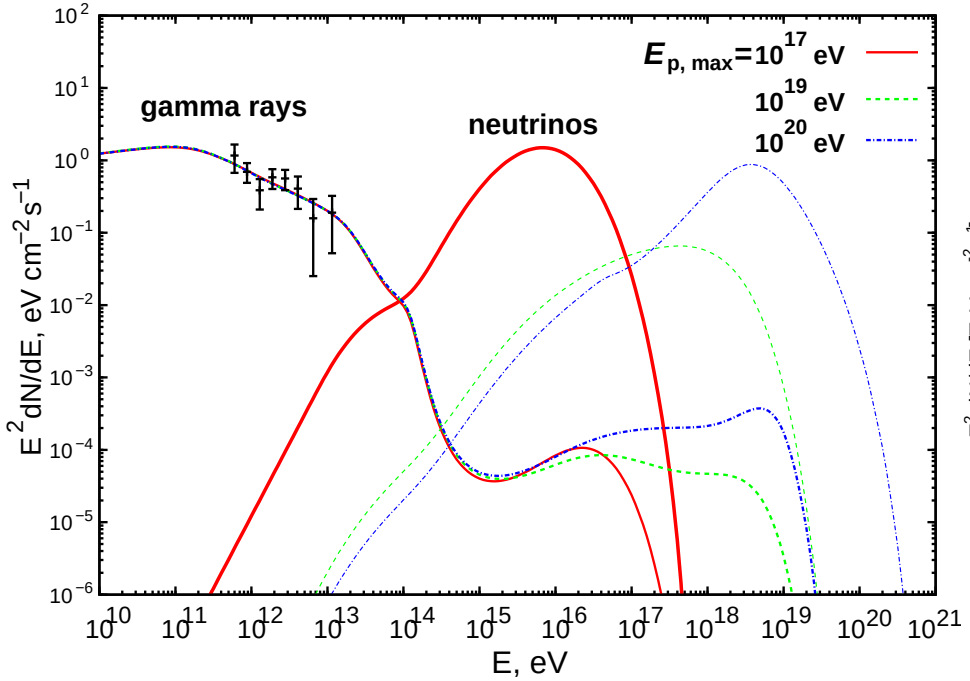
For distant sources, secondary signals win

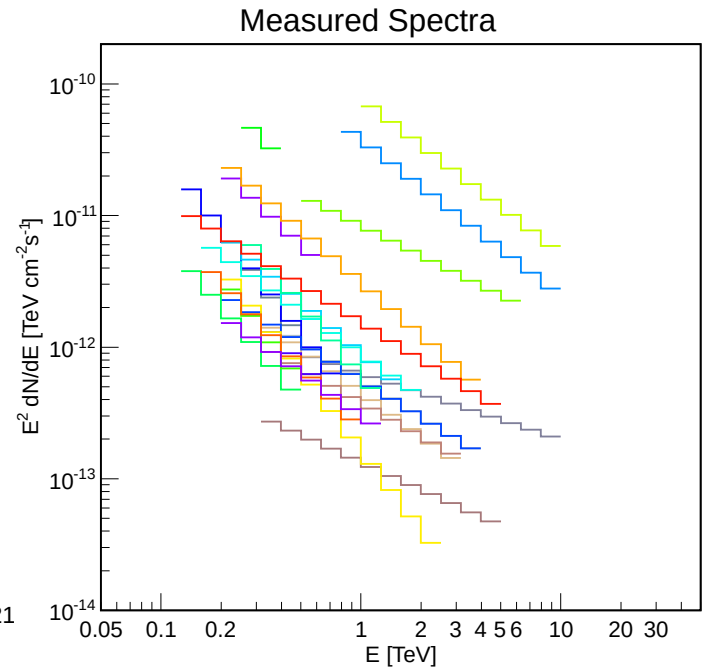
Secondary photons and neutrinos from 1ES0229+200 ($z = 0.14$)



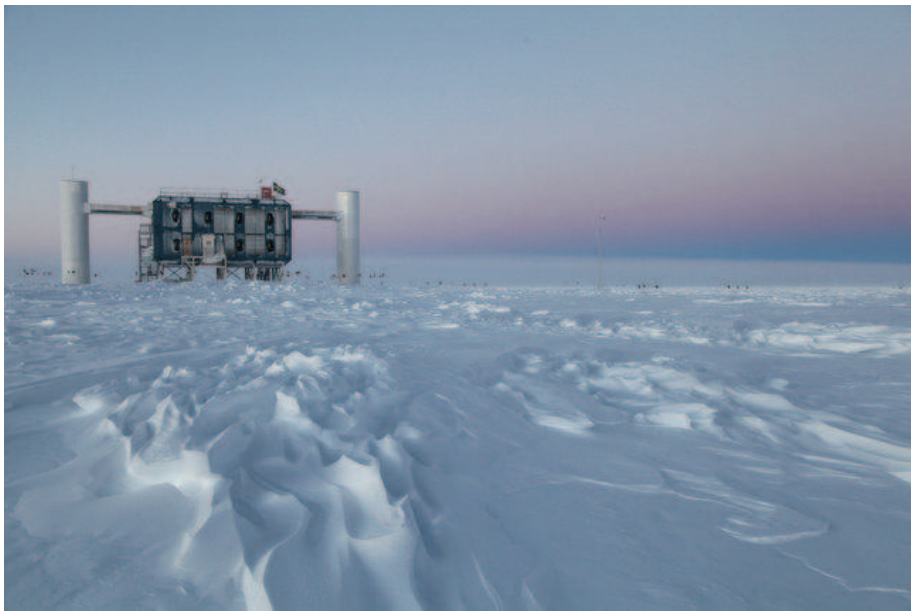
[Essey, Kalashev, AK, Beacom, PRL 104, 141102 (2010)]

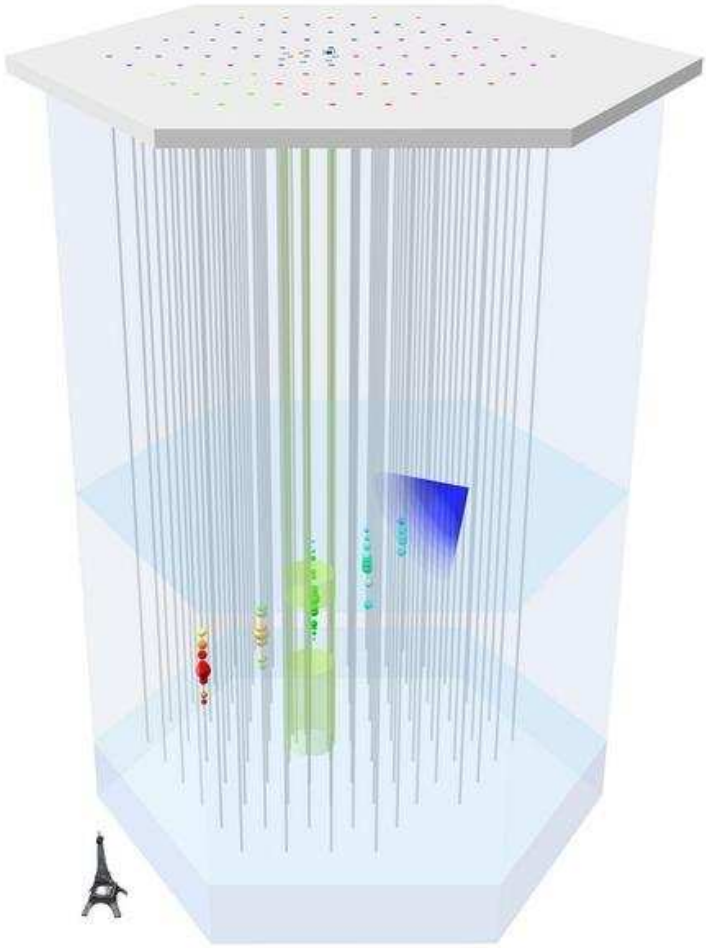
Robust spectral shapes explain the observed universality



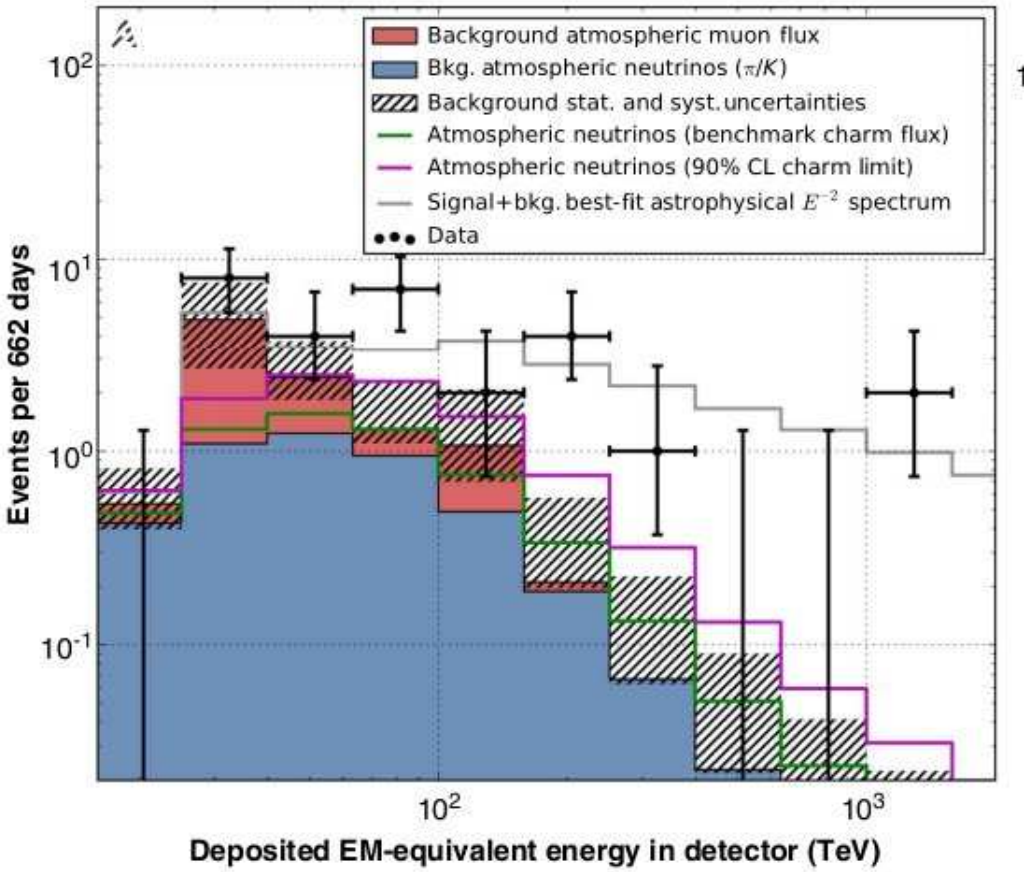


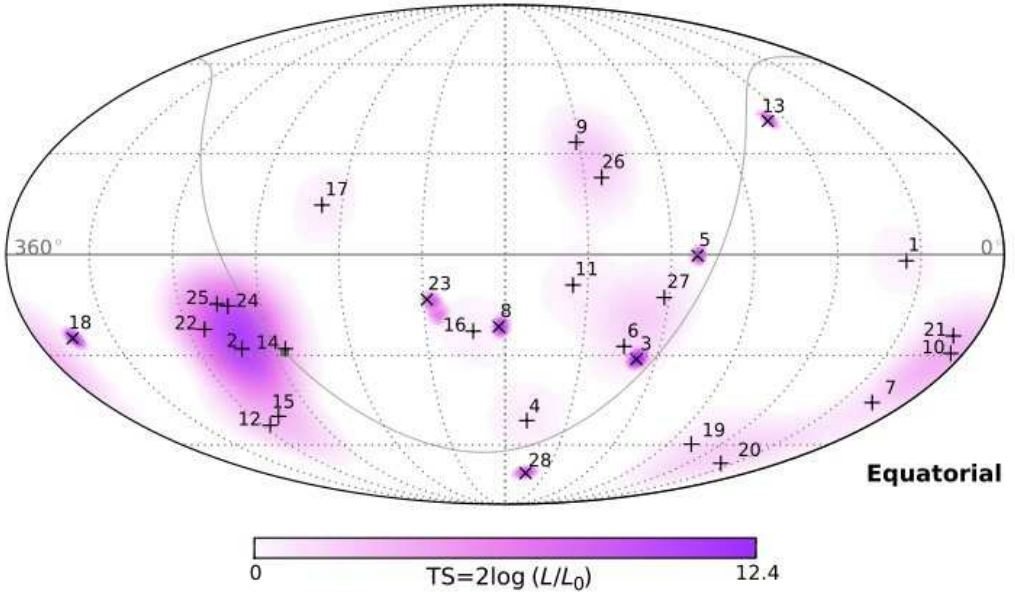
IceCube detector



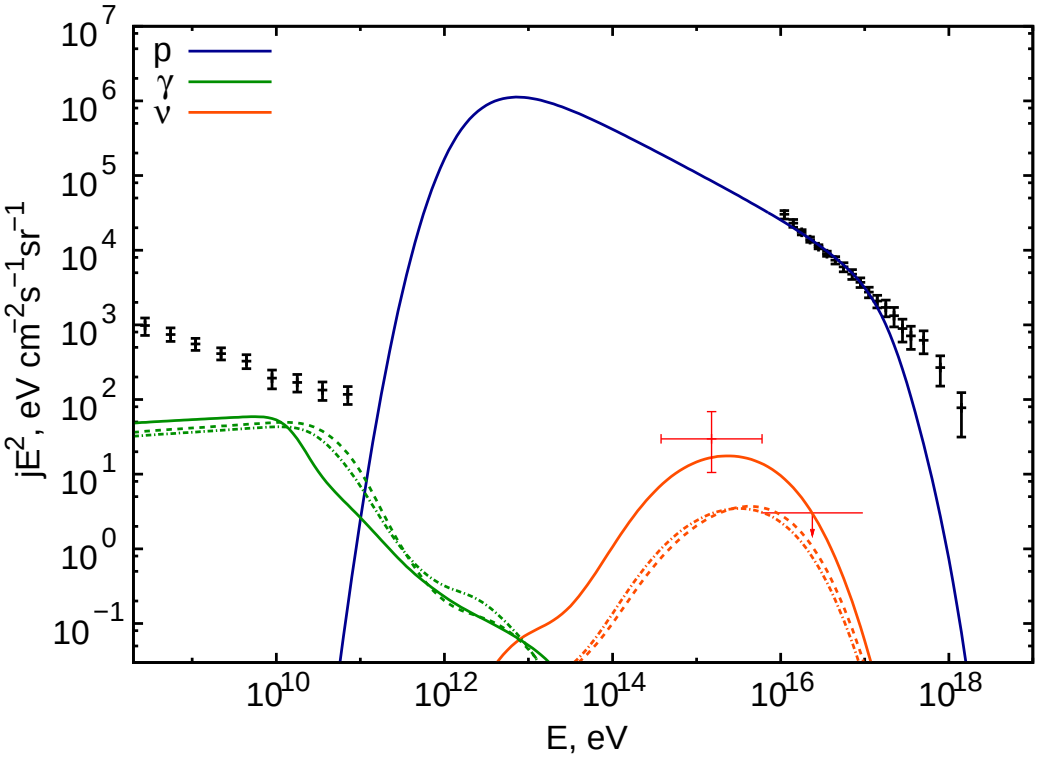


PeV neutrinos discovered by IceCube



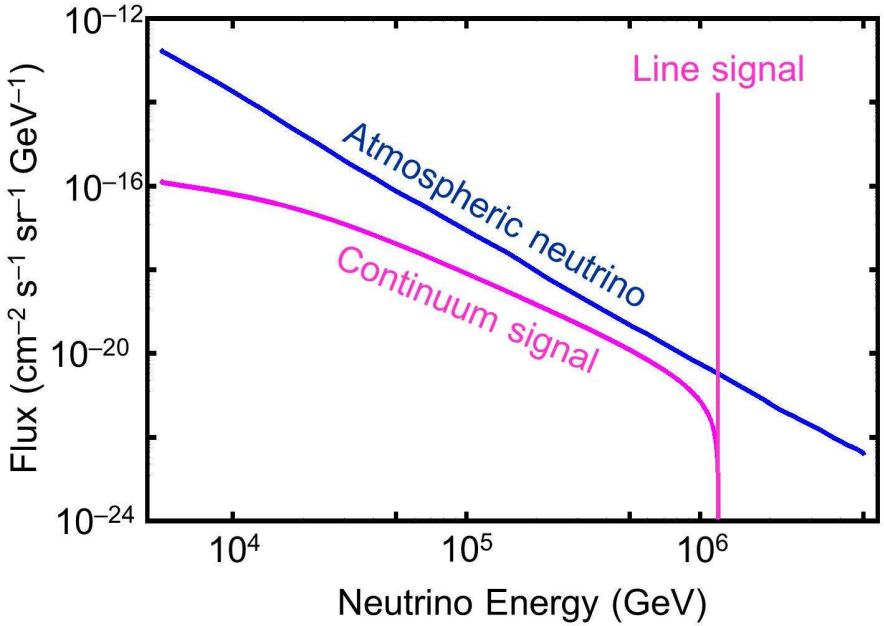


PeV neutrinos discovered by IceCube consistent with secondary spectrum



[Kalashev, Kusenko, Essey, Phys.Rev.Lett. 111 (2013) 041103]

Can the IceCube neutrinos come from decays of heavy dark matter?



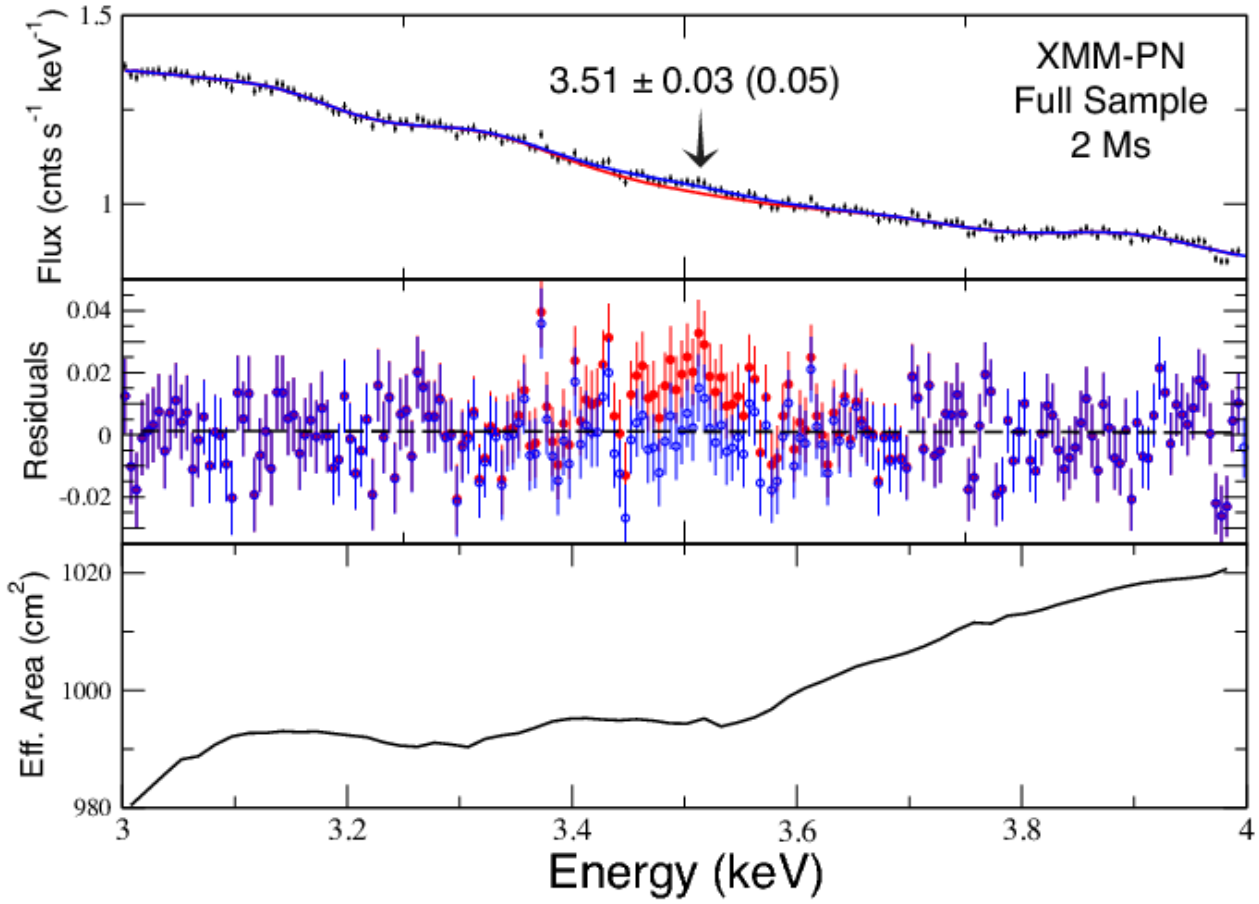
Possible types of DM particles: gravitino with R-partity violation; hidden sector gauge boson; a singlet fermion in an extra dimension; a heavy right-handed neutrino.

[Feldstein, AK, Matsumoto, Yanagida (2013)]

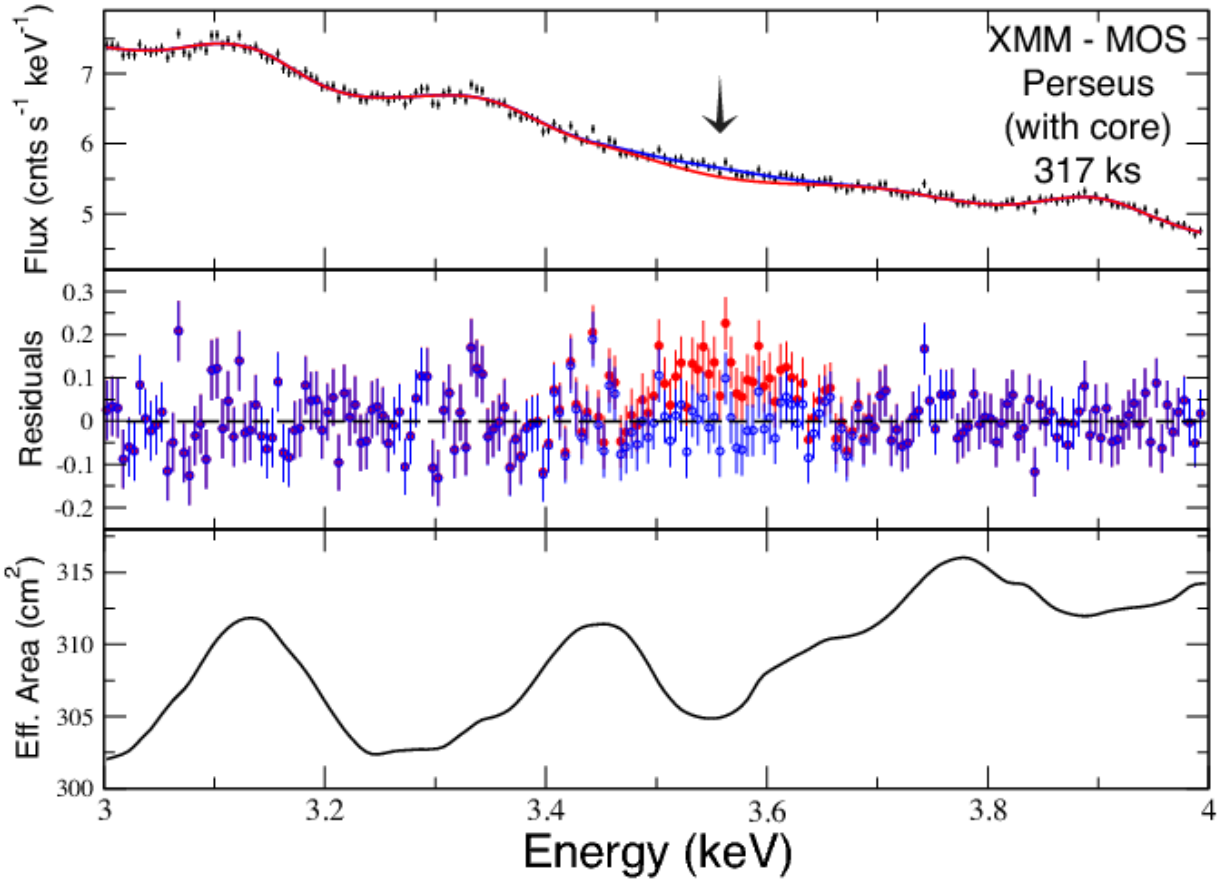
Sterile neutrinos, moduli, and dark matter with a keV mass.

- Dark matter candidates at a keV scale: sterile neutrinos, string/supersymmetry moduli
- Warm or cold, depending on the production scenario
- Particle physics models
- – Sterile neutrinos and an SU(2) singlet Higgs boson
  – Sterile neutrinos and the Split Seesaw
  – String/supersymmetry moduli
- Detection strategy: the search for a keV line

Unidentified line from Bulbul et al.; Boyarsky et al.



Unidentified line from Bulbul et al.; Boyarsky et al.



Neutrino masses and light sterile neutrinos

Discovery of the neutrino masses implies a plausible existence of right-handed (sterile) neutrinos. Most models of neutrino masses introduce sterile states

$$\{\nu_e, \nu_\mu, \nu_\tau, \nu_{s,1}, \nu_{s,2}, \ldots, \nu_{s,N}\}$$

and consider the following Lagrangian:

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \bar{\nu}_{s,a}\left(i\partial_\mu \gamma^\mu\right)\nu_{s,a} - y_{\alpha a} H\, \bar{L}_\alpha \nu_{s,a} - \frac{M_{ab}}{2}\,\bar{\nu}^c_{s,a}\nu_{s,b} + h.c.\,,$$

where H is the Higgs boson and L_α ($\alpha = e, \mu, \tau$) are the lepton doublets. The mass matrix:

$$M = \begin{pmatrix} 0 & D_{3\times N} \\ D^T_{N\times 3} & M_{N\times N} \end{pmatrix}$$

What is the *natural* scale of M?

Seesaw mechanism

In the Standard Model, the matrix D arises from the Higgs mechanism:

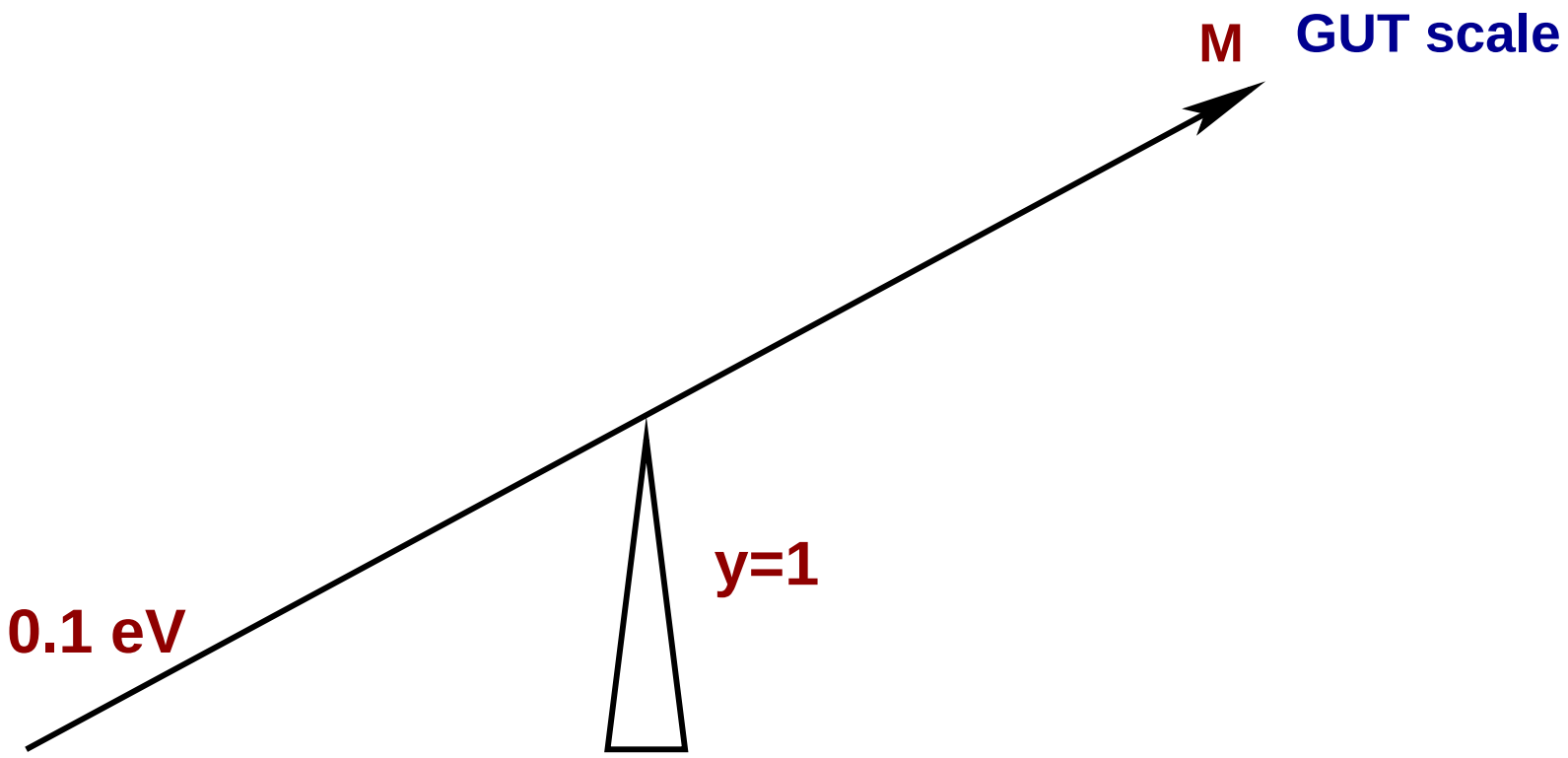
$$D_{ij} = y_{ij}\langle H\rangle$$

Smallness of neutrino masses **does not** imply the smallness of Yukawa couplings. For large M,

$$m_\nu \sim \frac{y^2\langle H\rangle^2}{M}$$

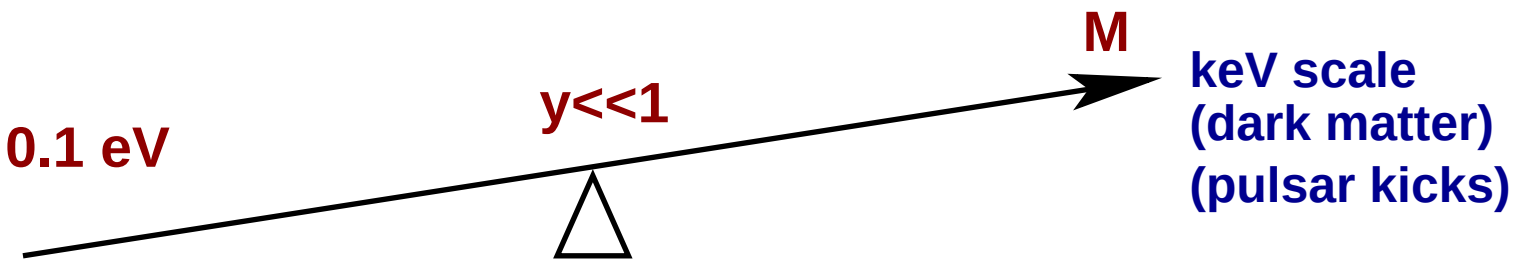
One can understand the smallness of neutrino masses even if the Yukawa couplings are $y \sim 1$ [Gell-Mann, Ramond, Slansky; Yanagida; Glashow; Mohapatra, Senjanović].

Seesaw mechanism



Seesaw mechanism

GUT scale



Various approaches to small Majorana masses

- Just write them down.
  - One sterile keV sterile neutrino, the dark matter candidate **[Dodelson, Widrow]**.
  - Three sterile neutrinos, one with a several keV mass (dark matter) and two degenerate with GeV masses and a keV splitting, νMSM **[Shaposhnikov et al.]**.
- Use **lepton number** conservation as the reason for a small mass **[de Gouvêa]**.
- Use **flavor symmetries**, new gauge symmetries **[Lindner et al.]**
- **Singlet Higgs** (discussed below) at the electroweak scale can generate the Majorana mass. Added bonuses:
  - production from $S \to N N$ at the electroweak scale generates *the right amount* of dark matter.
  - production from $S \to N N$ at the electroweak scale generates *colder* dark matter. A **"miracle"**: EW scale and mass at the keV scale (for stability) $\Rightarrow$ **correct DM abundance**. **[AK; AK, Petraki]**
- **Split seesaw** (discussed below) makes the scale separation natural. Dark matter cooled by various effects. $\Rightarrow$ **democracy of scales**

Sterile neutrinos as dark matter: production scenarios

Production **color coded** by **"warmness" vs "coldness"**:

Sterile neutrinos as dark matter: production scenarios

Production **color coded** by **"warmness" vs "coldness"**:

- **Neutrino oscillations off resonance** [Dodelson, Widrow] No prerequisites; production determined by the mixing angle alone; no way to turn off this channel, except for low-reheat scenarios [Gelmini et al.]

Sterile neutrinos as dark matter: production scenarios

Production **color coded** by **"warmness" vs "coldness"**:

- **Neutrino oscillations off resonance** [Dodelson, Widrow] No prerequisites; production determined by the mixing angle alone; no way to turn off this channel, except for low-reheat scenarios [Gelmini et al.]
- **MSW resonance in $\nu_a \to \nu_s$ oscillations** [Shi, Fuller] Pre-requisite: sizable lepton asymmetry of the universe. The latter may be generated by the decay of heavier sterile neutrinos [Laine, Shaposhnikov]

Sterile neutrinos as dark matter: production scenarios

Production **color coded** by **"warmness" vs "coldness"**:

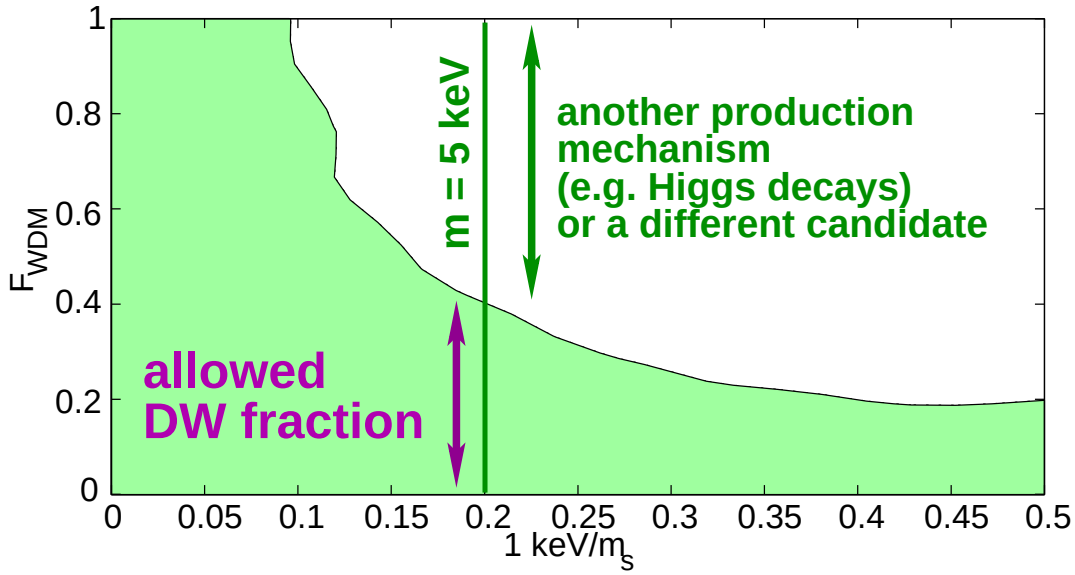
- **Neutrino oscillations off resonance** [Dodelson, Widrow] No prerequisites; production determined by the mixing angle alone; no way to turn off this channel, except for low-reheat scenarios [Gelmini et al.]
- **MSW resonance in $\nu_a \to \nu_s$ oscillations** [Shi, Fuller] Pre-requisite: sizable lepton asymmetry of the universe. The latter may be generated by the decay of heavier sterile neutrinos [Laine, Shaposhnikov]
- **Higgs decays** [AK, Petraki] Assumes the Majorana mass is due to Higgs mechanism. **Sterile miracle: abundance a "natural" consequence of singlet at the electroweak scale**. Advantage: "natural" dark matter abundance

Sterile neutrinos as dark matter: production scenarios

Production **color coded** by **"warmness" vs "coldness"**:

- **Neutrino oscillations off resonance** [Dodelson, Widrow] No prerequisites; production determined by the mixing angle alone; no way to turn off this channel, except for low-reheat scenarios [Gelmini et al.]
- **MSW resonance in $\nu_a \to \nu_s$ oscillations** [Shi, Fuller] Pre-requisite: sizable lepton asymmetry of the universe. The latter may be generated by the decay of heavier sterile neutrinos [Laine, Shaposhnikov]
- **Higgs decays** [AK, Petraki] Assumes the Majorana mass is due to Higgs mechanism. **Sterile miracle: abundance a "natural" consequence of singlet at the electroweak scale**. Advantage: "natural" dark matter abundance
- **Split seesaw**: [AK, Takahashi, Yanagida]
  Two production mechanisms, **cold** and **even colder**.
  Advantage: "naturally" low mass scale

Lyman-α bounds on Dodelson-Widrow production



[Boyarsky, Lesgourgues, Ruchayskiy, Viel]

Free-streaming properties: [Boyanovsky; Petraki]

New scale or new Higgs physics?

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \bar{N}_a \left(i\partial_\mu \gamma^\mu\right) N_a - y_{\alpha a} H\, \bar{L}_\alpha N_a - \frac{M_a}{2}\, \bar{N}^c_a N_a + h.c.\,,$$

To explain the pulsar kicks and dark matter, one needs $M \sim$ **keV**. Is this a new fundamental scale? Perhaps. Alternatively, it could arise from the Higgs mechanism:

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \bar{N}_a \left(i\partial_\mu \gamma^\mu\right) N_a - y_{\alpha a} H\, \bar{L}_\alpha N_a - h_a\, S\, \bar{N}^c_a N_a + V(H,S)$$

$$M = h\langle S\rangle$$

Now $S \to NN$ decays can produce sterile neutrinos.

For small h, the sterile neutrinos are out of equilibrium in the early universe, but S is in equilibrium. There is a new mechanism to produce sterile dark matter at $\boldsymbol{T \sim m_S}$ from decays $\boldsymbol{S \to NN}$:

$$\boldsymbol{\Omega_s = 0.2 \left(\frac{33}{\xi}\right) \left(\frac{h}{1.4 \times 10^{-8}}\right)^3 \left(\frac{\langle S \rangle}{\tilde{m}_S}\right)}$$

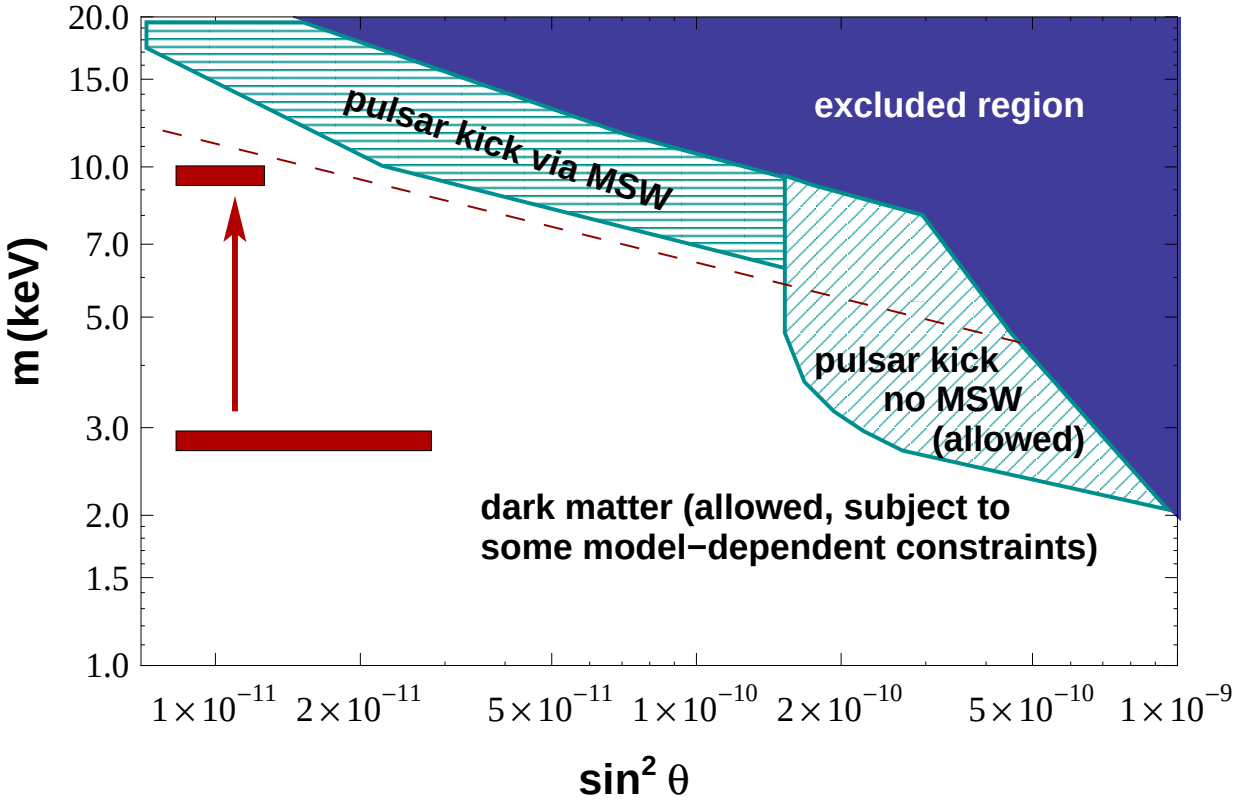
Here ξ is the dilution factor due to the change in effective numbers of degrees of freedom.

$\boldsymbol{\langle S \rangle \sim 10^2\,\mathrm{GeV}}$ (EW scale)
$\boldsymbol{M_s \sim \mathrm{keV}}$ (for stability) $\boldsymbol{\Rightarrow h \sim 10^{-8}}$

$$\boldsymbol{\Rightarrow \Omega \approx 0.2}$$

The sterile neutrino momenta are red-shifted by factor $\boldsymbol{\xi^{1/3} > 3.2}$. [AK, Petraki]

Cooling changes the clustering properties

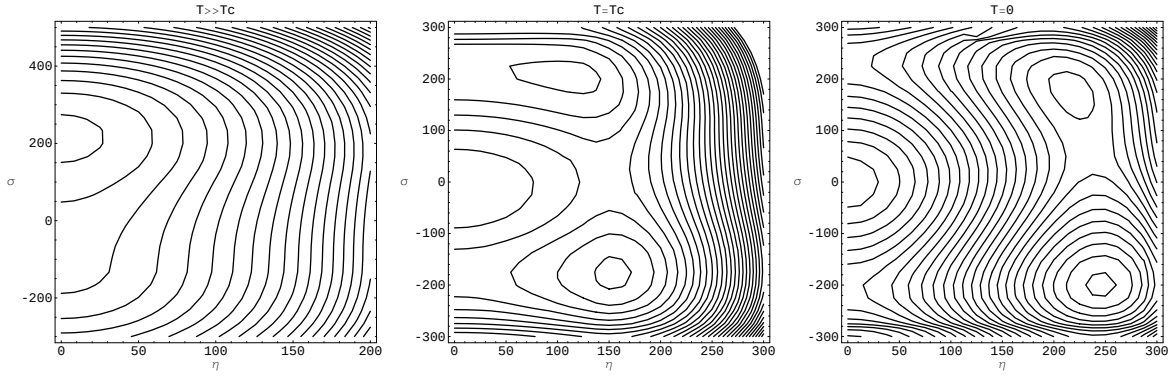


[AK, PRL **97**:241301 (2006); Petraki, AK, PRD 77, 065014 (2008); Petraki, PRD 77, 105004 (2008)]

Implications for the EW phase transition and the LHC

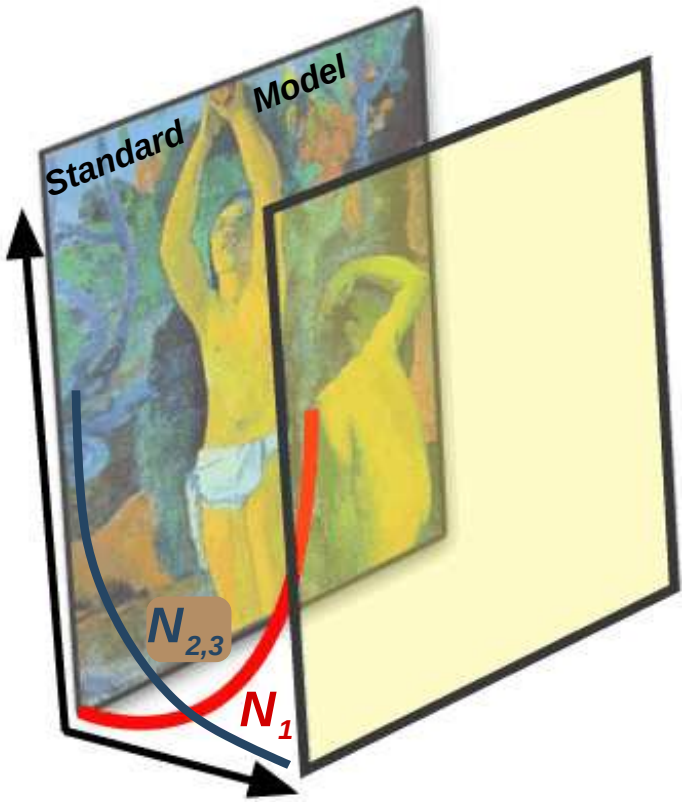
One may be able to discover the *singlet Higgs* at the LHC [Profumo, Ramsey-Musolf, G. Shaughnessy; Davoudiasl et al.; O'Connell et al.; Ramsey-Musolf, Wise]

The presence of S in the Higgs sector changes the nature of the electroweak phase transition [AK, Petraki]

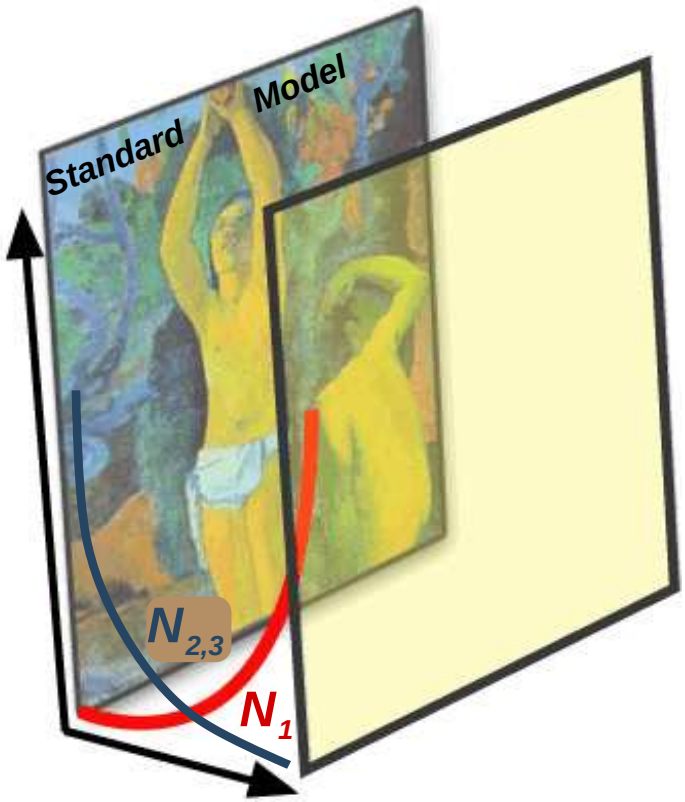


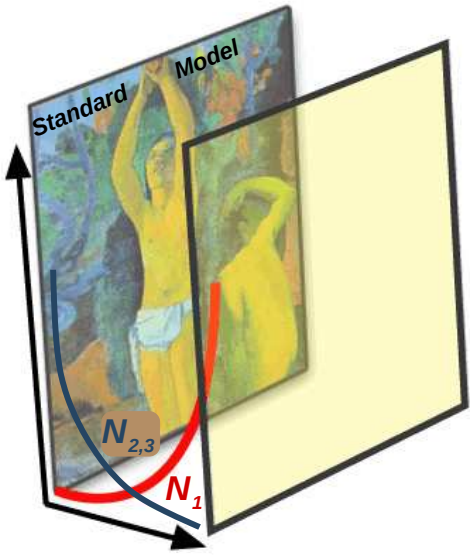
First-order transition, CP in the Higgs sector $\Longrightarrow$ **electroweak baryogenesis**

Split seesaw



Split seesaw





Standard Model on $z = 0$ brane. A Dirac fermion with a bulk mass m:

$$S = \int d^4x\, dz\, M \left(i\bar{\Psi}\Gamma^A \partial_A \Psi + m\bar{\Psi}\Psi \right),$$

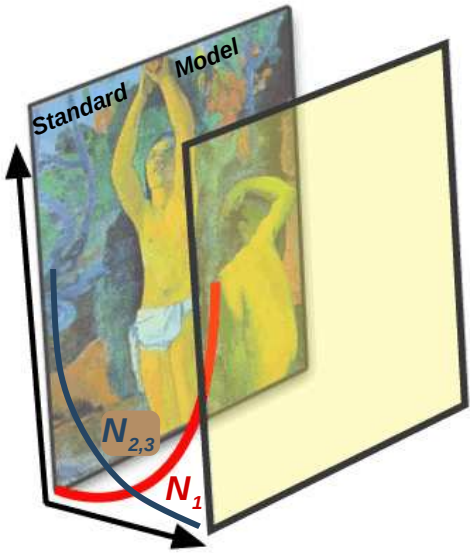
The zero mode: $(i\Gamma^5\partial_5 + m)\Psi^{(0)} = 0$. behaves as $\sim \exp(\pm mz)$. The 4D fermion:

$$\Psi_R^{(0)}(z,x) = \sqrt{\frac{2m}{e^{2m\ell}-1}} \frac{1}{\sqrt{M}} e^{mz} \psi_R^{(4D)}(x).$$

Also, a U(1)$_{(B-L)}$ gauge boson in the bulk, $(B-L) = -2$ Higgs ϕ on the SM brane. The VEV $\langle\phi\rangle \sim 10^{15}$GeV gives right-handed neutrinos heavy Majorana masses.

[AK, Takahashi, Yanagida]

Split seesaw



Effective Yukawa coupling and the mass are suppressed:

$$M^{(R)}_{d=4} = M^{(R)}_{d=5}\left(\frac{2m_i}{M(e^{2m_i\ell}-1)}\right),$$

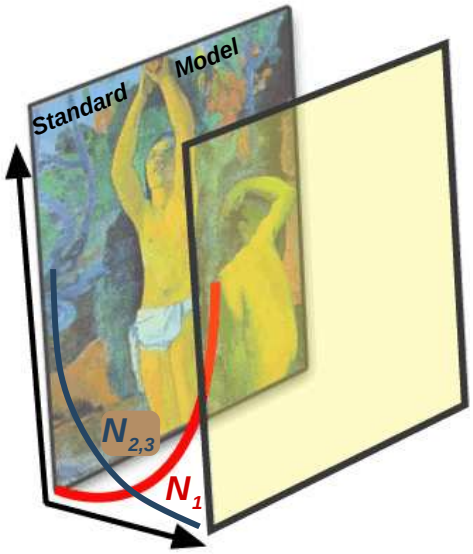
$$y_{d=4} = y_{d=5}\sqrt{\frac{2m_i}{M(e^{2m_i\ell}-1)}}$$

successful seesaw relation unchanged:

$$m_\nu \sim \frac{y^2_{d=4}\langle H\rangle^2}{M^{(R)}_{d=4}} = \frac{y^2_{d=5}\langle H\rangle^2}{M^{(R)}_{d=5}}$$

[AK, Takahashi, Yanagida]

Split seesaw: economical, natural extension of SM



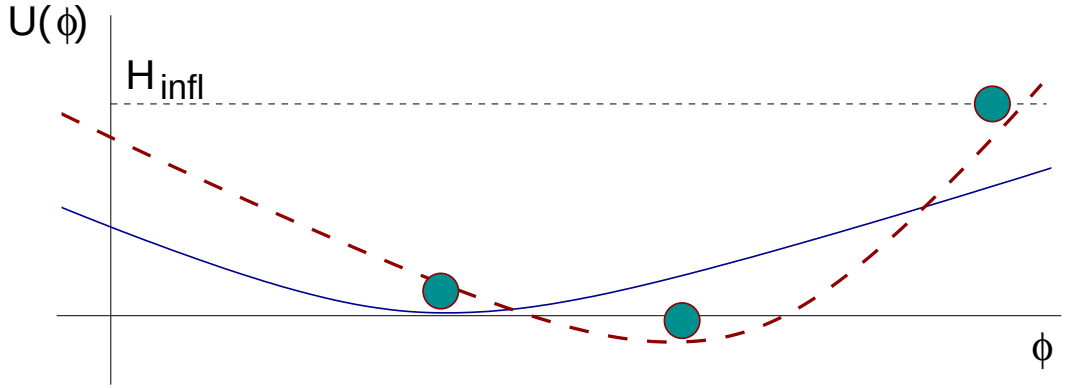
- Democracy of scales: small difference in the bulk masses m_i results in exponentially large splitting between the sterile neutrino masses.
- An rather minimal model: SM augmented by three right-handed singlets can explain
  - observed **neutrino masses**
  - **baryon asymmetry** (via leptogenesis)
  - **dark matter**

  if, for example
  $M_1 = 5\,\mathrm{keV}$ or $M_1 = 17\,\mathrm{keV}$, and
  $M_{2,3} \sim 10^{15}\mathrm{GeV}$

[AK, Takahashi, Yanagida]

An alternative DM at a keV scale: string/supersymmetry moduli

- Expansion of the universe breaks supersymmetry: the effective potential acquires terms of the form $-cH^2\phi^2$, where c is of order one
- on average, each degree of freedom carries a non-zero energy in the de Sitter universe.



1. the minimum of the effective potential during inflation is displaced, for a light field, by a large amount ($\sim M_{\rm Pl}$)
2. at the end of inflation, the field is not necessarily in the minimum of either de Sitter or flat effective potential

Moduli problem

Oscillating scalar field is a cosmological equivalent of matter. The field starts oscillating when $H \sim m_\phi$, and the temperature is

$$T_\phi \sim (90/\pi^2 g_*)^{1/4} \sqrt{M_{\rm Pl} m_\phi}.$$

The density to entropy ratio is

$$\frac{\rho_\phi}{s} \sim \frac{m_\phi^2 \phi_0^2/2}{(2\pi^2/45) g_* T_\phi^3} \sim \mathbf{10^5\,GeV} \left(\frac{m_\phi}{\rm keV}\right)^{1/2} \left(\frac{\phi_0}{M_{\rm Pl}}\right)^2 .$$

...to be compared with dark matter:

$$\frac{\rho_{\rm DM}}{s} = 0.2\,\frac{\rho_{\rm c}}{s} = \mathbf{3 \times 10^{-10}\,GeV},$$

bad discrepancy. Moreover, the universe with so much dark matter forms only one form of structures: black holes.

The density to entropy ratio is can be small enough in those (superhorion-size) patches that have $\phi_0 \ll M_{\rm Pl}$:

$$\frac{\rho_\phi}{s} \sim \frac{m_\phi^2 \phi_0^2/2}{(2\pi^2/45) g_* T_\phi^3} \sim 10^{-9}\,{\rm GeV} \left(\frac{m_\phi}{\rm keV}\right)^{1/2} \left(\frac{\phi_0}{10^{-7} M_{\rm Pl}}\right)^2 .$$

The density to entropy ratio is can be small enough in those (superhorion-size) patches that have $\phi_0 \ll M_{\rm Pl}$:

$$\frac{\rho_\phi}{s} \sim \frac{m_\phi^2 \phi_0^2/2}{(2\pi^2/45) g_* T_\phi^3} \sim 10^{-9}\,{\rm GeV} \left(\frac{m_\phi}{\rm keV}\right)^{1/2} \left(\frac{\phi_0}{10^{-7} M_{\rm Pl}}\right)^2 .$$

Can life exist in those parts of the universe where $\Omega_{DM}/\Omega_{baryon} \gg 1$?

The density to entropy ratio is can be small enough in those (superhorion-size) patches that have $\phi_0 \ll M_{\rm Pl}$:

$$\frac{\rho_\phi}{s} \sim \frac{m_\phi^2 \phi_0^2/2}{(2\pi^2/45) g_* T_\phi^3} \sim 10^{-9}\,{\rm GeV} \left(\frac{m_\phi}{\rm keV}\right)^{1/2} \left(\frac{\phi_0}{10^{-7} M_{\rm Pl}}\right)^2 .$$

Can life exist in those parts of the universe where $\Omega_{DM}/\Omega_{baryon} \gg 1$?

Structures start forming at $T_{\rm eq} \sim 10^5\,{\rm GeV} \left(\frac{m_\phi}{\rm keV}\right)^{1/2} \left(\frac{\phi_0}{M_{\rm G}}\right)^2$. and only black holes emerge, unless $\mathbf{\Omega_{\rm DM}/\Omega_{\rm baryon} < 10}$. **[Tegmark, Aguirre, Rees, Wilczek]**

The density to entropy ratio is can be small enough in those (superhorion-size) patches that have $\phi_0 \ll M_{\rm Pl}$:

$$\frac{\rho_\phi}{s} \sim \frac{m_\phi^2 \phi_0^2/2}{(2\pi^2/45) g_* T_\phi^3} \sim 10^{-9}\,{\rm GeV} \left(\frac{m_\phi}{\rm keV}\right)^{1/2} \left(\frac{\phi_0}{10^{-7} M_{\rm Pl}}\right)^2 .$$

Can life exist in those parts of the universe where $\Omega_{DM}/\Omega_{baryon} \gg 1$?

Structures start forming at $T_{\rm eq} \sim 10^5\,{\rm GeV} \left(\frac{m_\phi}{\rm keV}\right)^{1/2} \left(\frac{\phi_0}{M_{\rm G}}\right)^2$. and only black holes emerge, unless $\mathbf{\Omega_{\rm DM}/\Omega_{\rm baryon} < 10}$. **[Tegmark, Aguirre, Rees, Wilczek]**

Anthropic selection favors the maximal allowed value ϕ_0, which corresponds to dark matter density close to the observed $\mathbf{\Omega_{\rm DM}/\Omega_{\rm baryon}}$.

The density to entropy ratio is can be small enough in those (superhorion-size) patches that have $\phi_0 \ll M_{\rm Pl}$:

$$\frac{\rho_\phi}{s} \sim \frac{m_\phi^2 \phi_0^2/2}{(2\pi^2/45) g_* T_\phi^3} \sim 10^{-9}\,{\rm GeV} \left(\frac{m_\phi}{\rm keV}\right)^{1/2} \left(\frac{\phi_0}{10^{-7} M_{\rm Pl}}\right)^2 .$$

Can life exist in those parts of the universe where $\Omega_{DM}/\Omega_{baryon} \gg 1$?

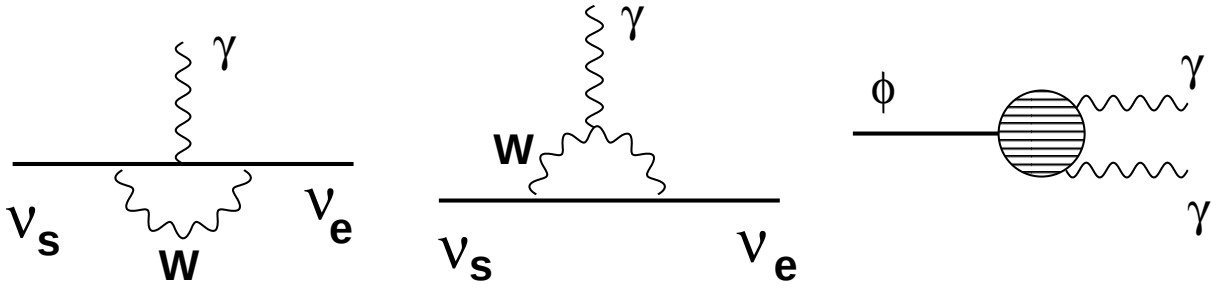
Structures start forming at $T_{\rm eq} \sim 10^5\,{\rm GeV} \left(\frac{m_\phi}{\rm keV}\right)^{1/2} \left(\frac{\phi_0}{M_{\rm G}}\right)^2$. and only black holes emerge, unless $\mathbf{\Omega_{\rm DM}/\Omega_{\rm baryon} < 10}$. **[Tegmark, Aguirre, Rees, Wilczek]**

Anthropic selection favors the maximal allowed value ϕ_0, which corresponds to dark matter density close to the observed $\mathbf{\Omega_{\rm DM}/\Omega_{\rm baryon}}$.

Anthropic solution to moduli problem $\Rightarrow$ correct amount of dark matter.
[AK, Loewenstein, Yanagida]

Radiative decays of sterile neutrinos and moduli

Sterile neutrino in the mass range of interest have lifetimes **longer than the age of the universe**, but they do decay:



Photons have energies $m/2$: X-rays. Concentrations of dark matter emit X-rays.
[Abazajian, Fuller, Tucker; Loewenstein et al., others]

Can one distiguish between sterile neutrinos and moduli? Not from the spectrum.
However, **moduli make a very cold dark matter**, while
sterile neutrios can have a measurable free-streaming length.

Conclusions: many exciting news

- The IceCube discovery of PeV neutrinos may be able to confirm our understanding of secondary particle production from blazars.

- It can also point to decays of heavy dark matter particles!

- Dark matter at a keV mass scale is viable, well-motivated, and hinted by the recent X-ray data.