New Search for Monochromatic Neutrinos from Dark Matter decay

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Based on arXiv: 1506.02657,

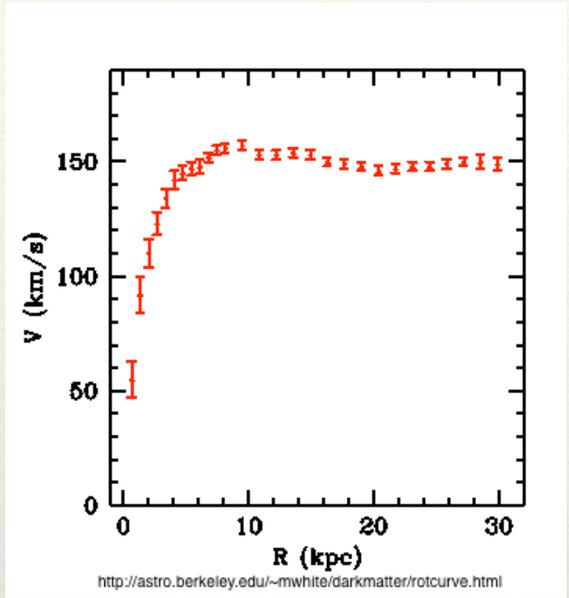
in collaboration with M. Gustafsson and T. Hambye

Menu (aka 'the Outline')

- Searching for Dark Matter
  - Motivations
    - Smoking Guns
- Neutrino Line Search
- Results

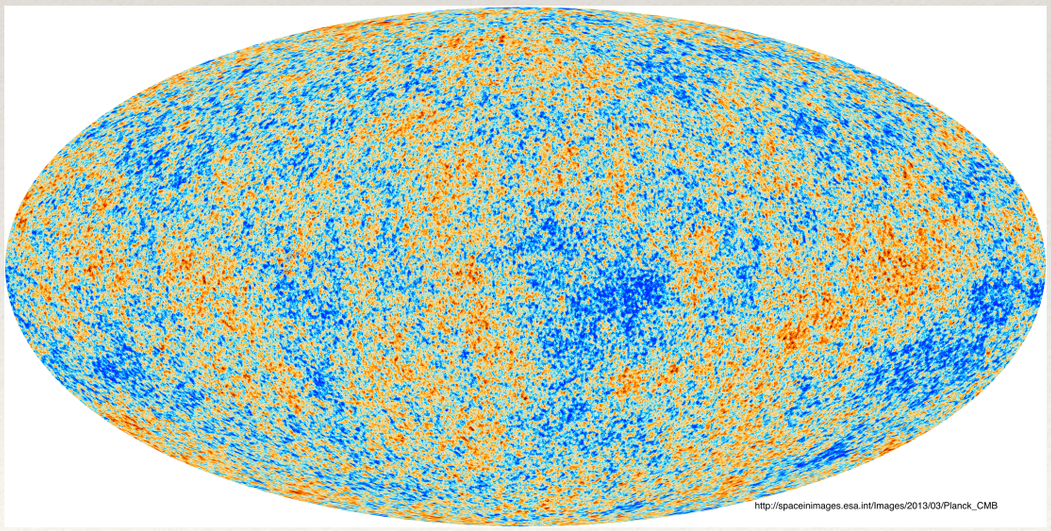
Searching for Dark Matter

Motivations



Rotation Curves

Bullet Cluster



CMB anisotropies

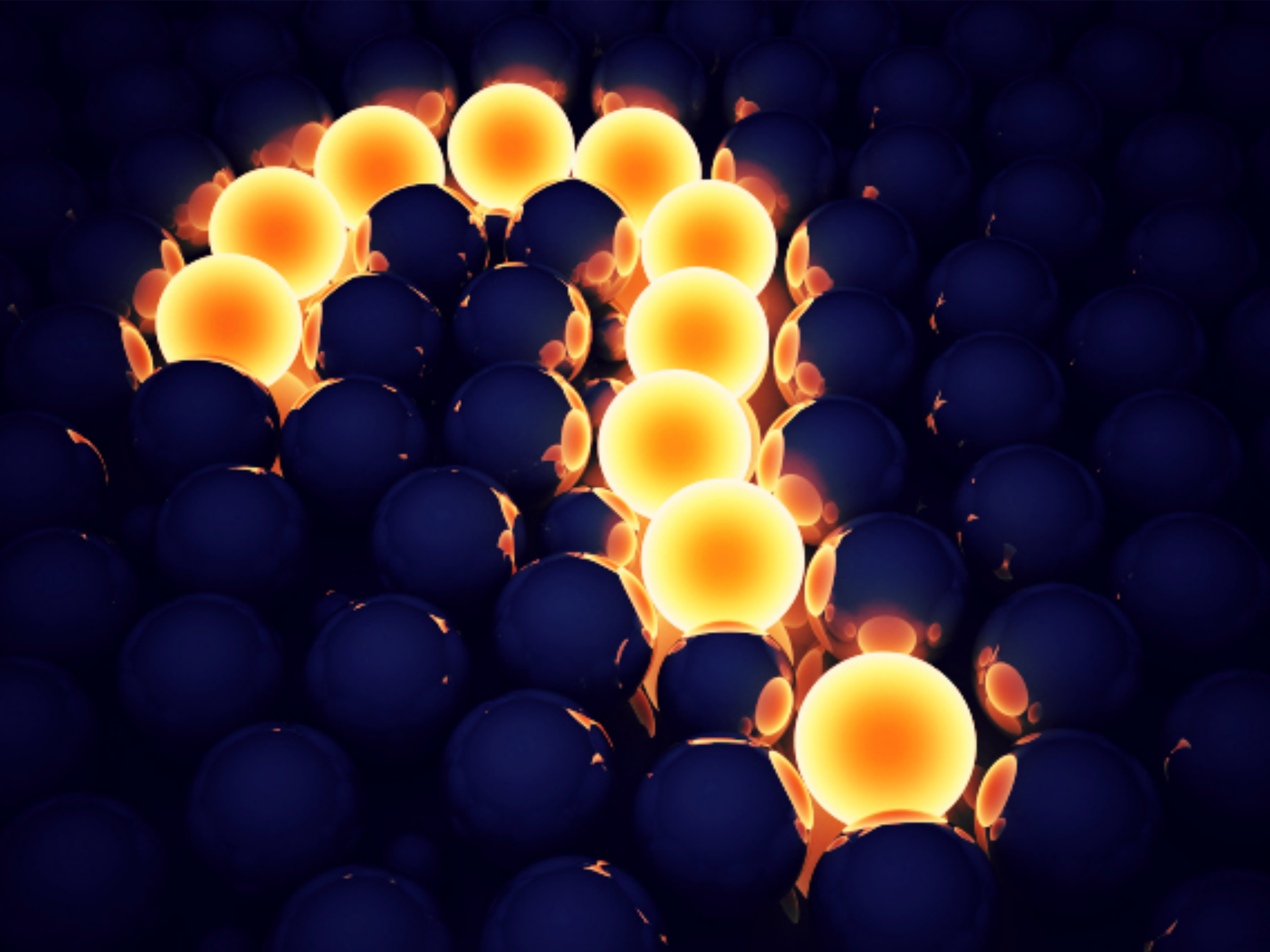
Planck satellite's observations

(arXiv:1502.01589)

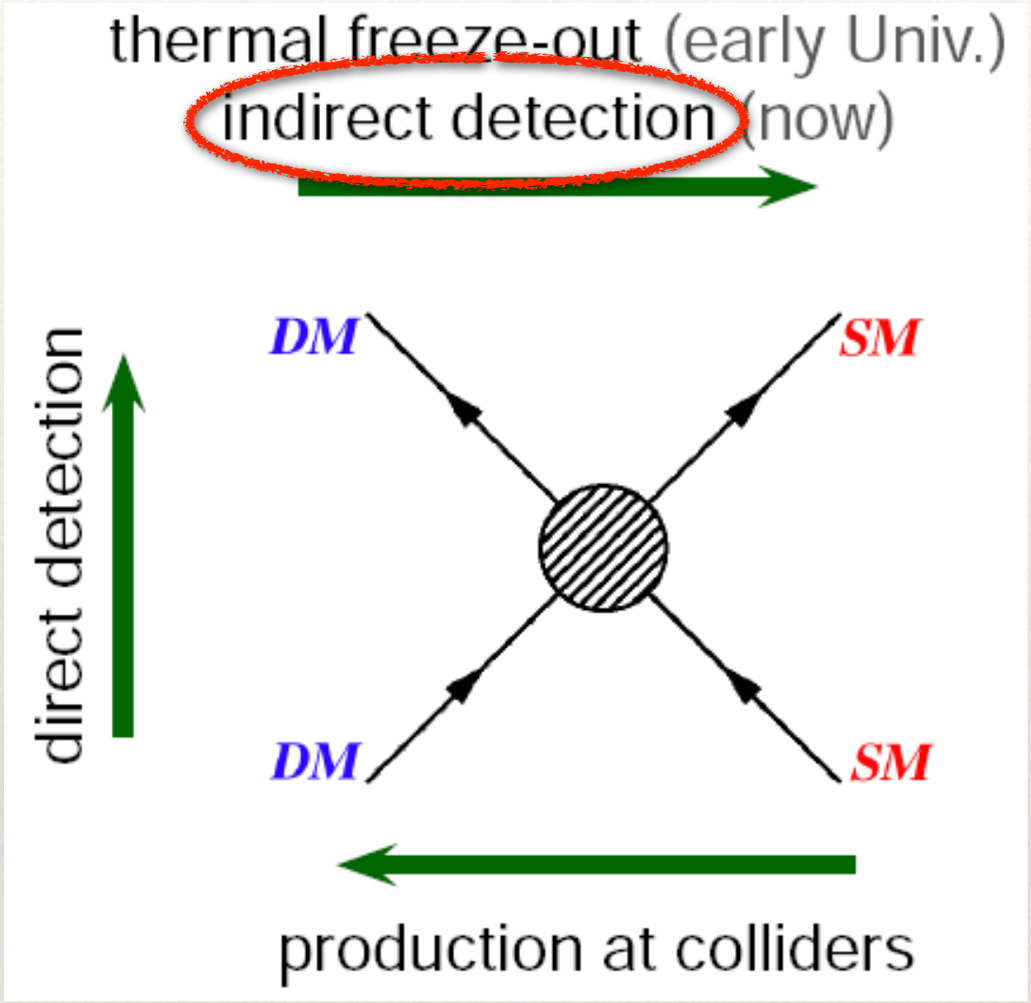
$$\Omega_\Lambda = 0.6844$$

$$\Omega_{matter} = 0.3156$$

$$\Omega_{DM} = 0.2647$$



How to Detect the DM Particle?



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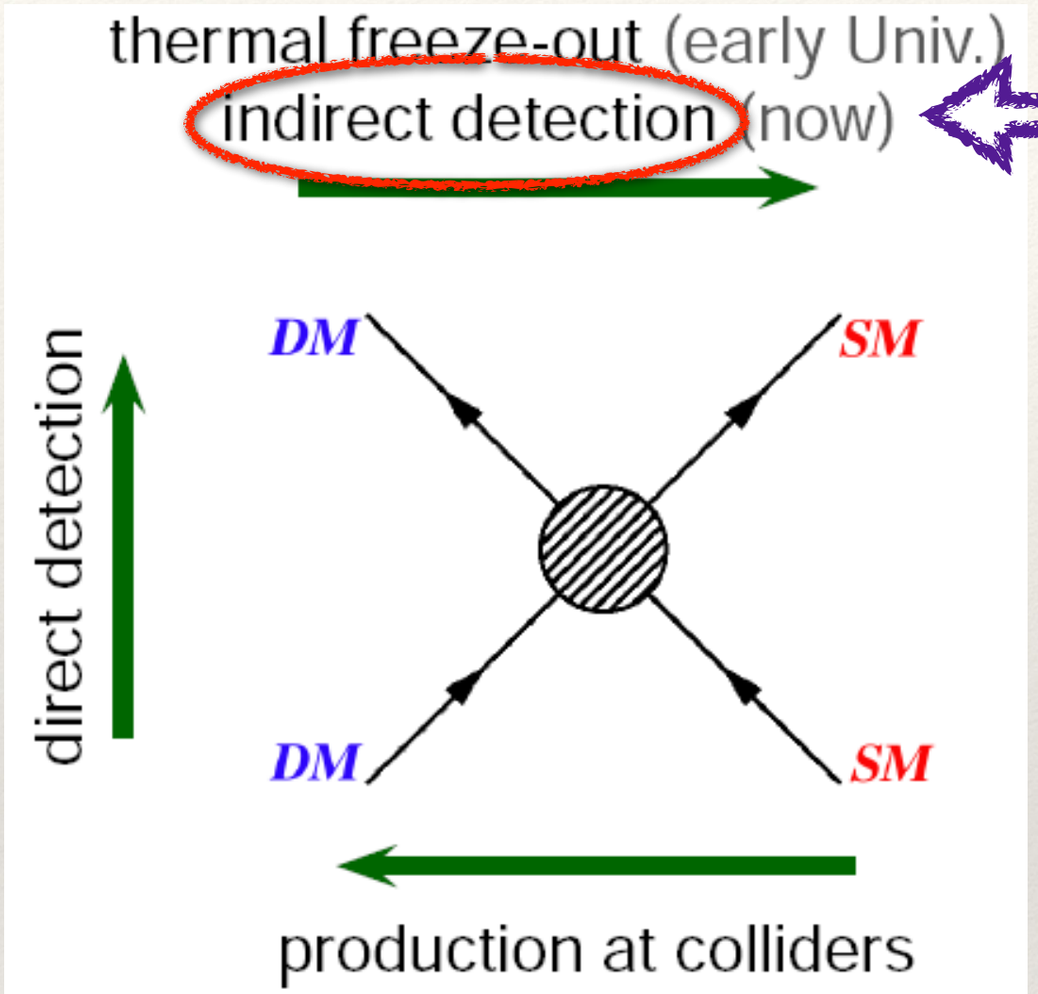
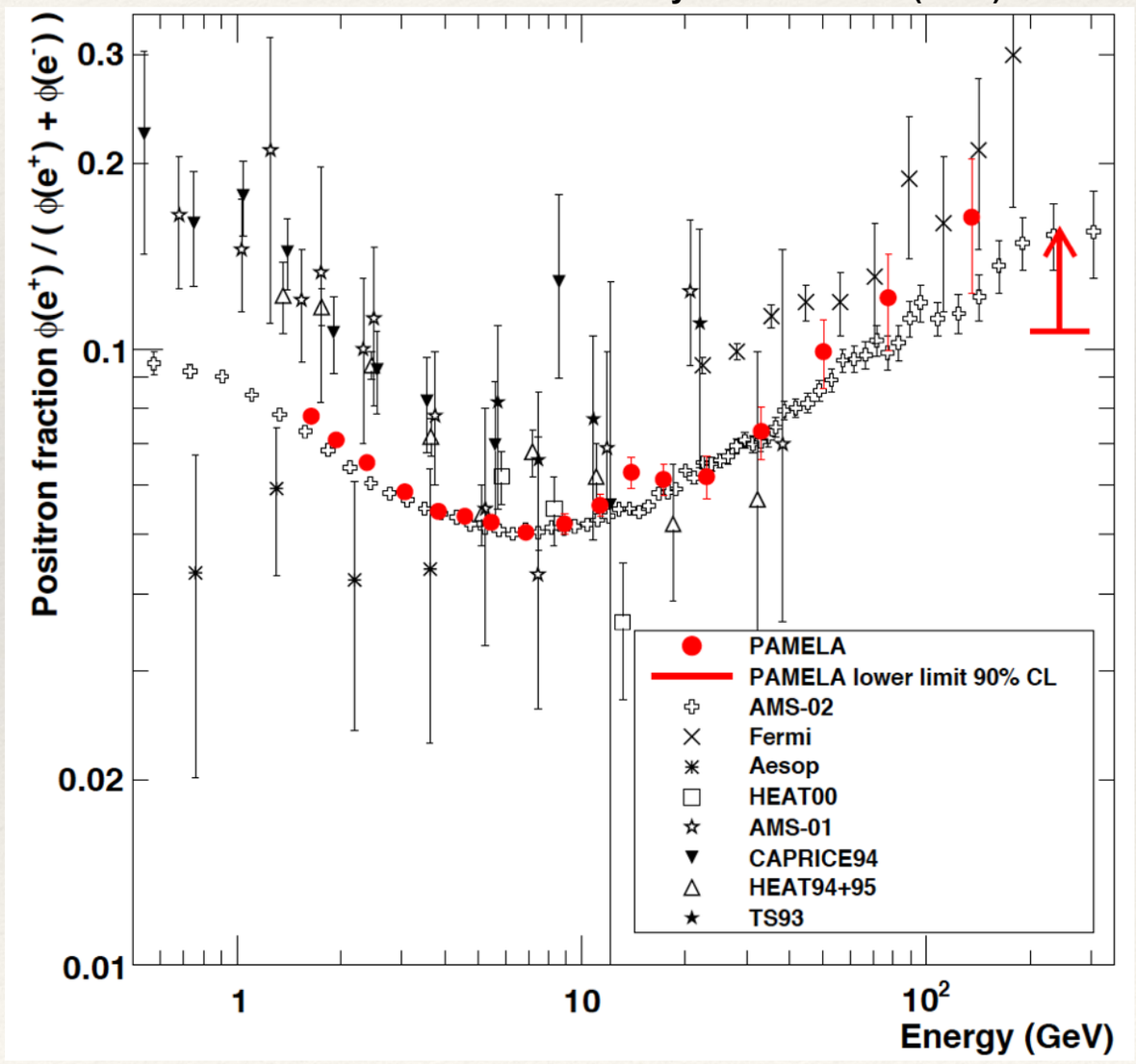


Linked to some observed anomalies in Cosmic Ray Fluxes ?

Phys.Rev.Lett. 111 (2013) 081102



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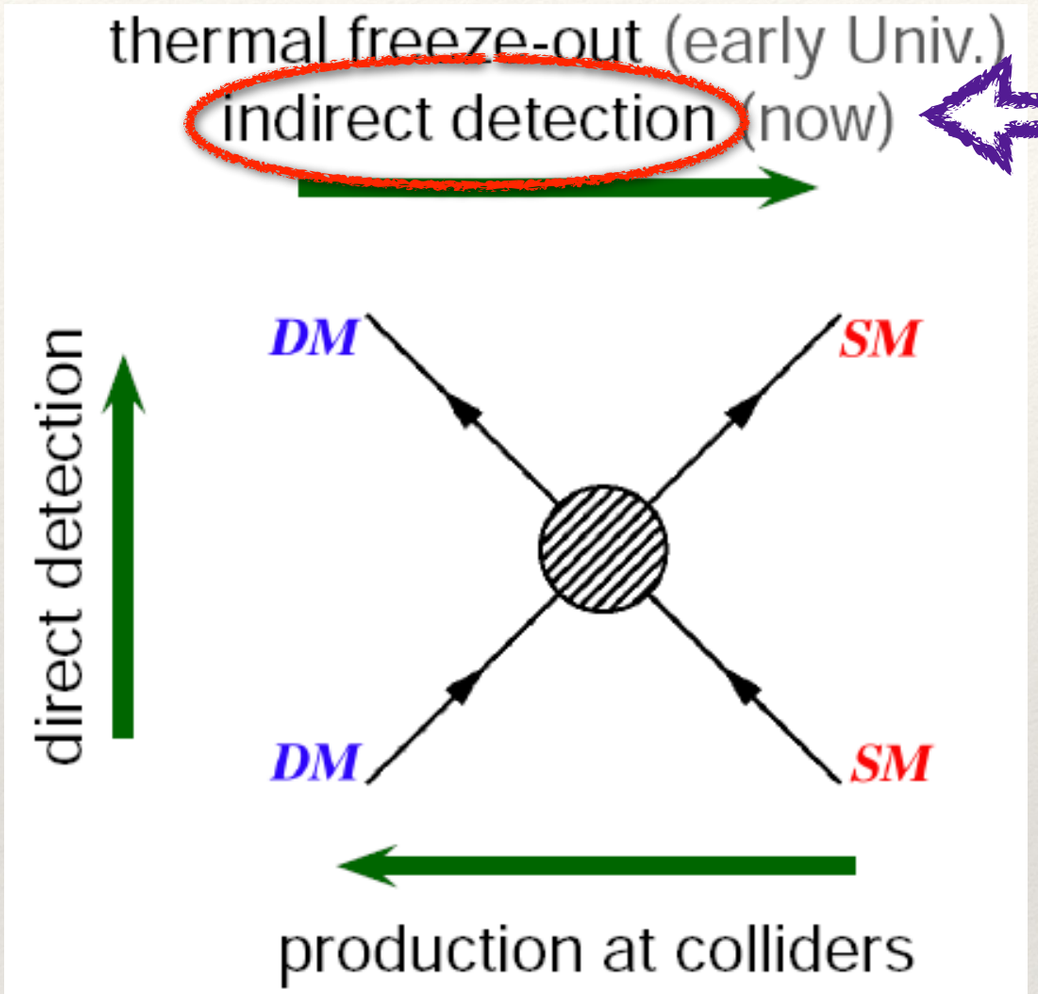

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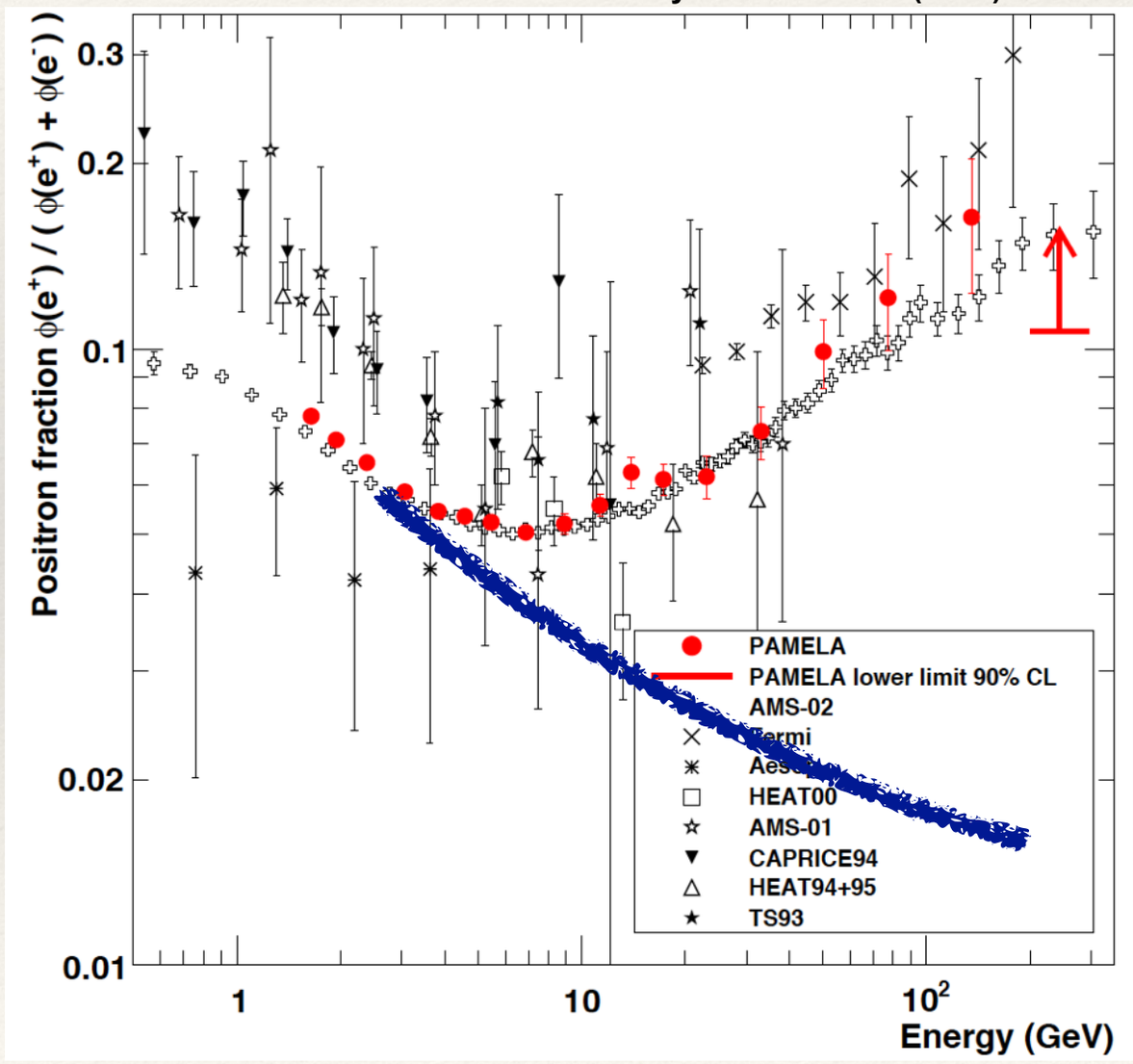
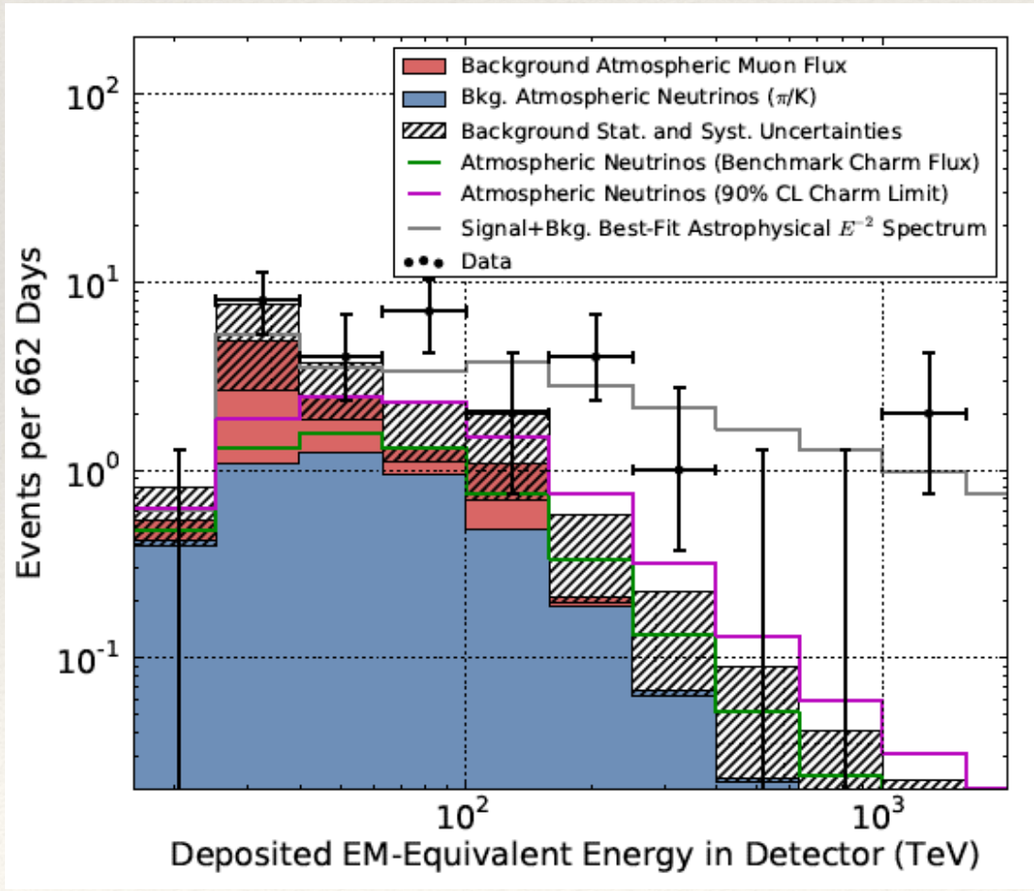


Extraterrestrial Neutrinos

Evidence for High-Energy Extraterrestrial Neutrinos at the IceCube Detector

We report on results of an all-sky search for high-energy neutrino events interacting within the IceCube neutrino detector conducted between May 2010 and May 2012. The search follows up on the previous detection of two PeV neutrino events, with improved sensitivity and extended energy coverage down to approximately 30 TeV. Twenty-six additional events were observed, substantially more than expected from atmospheric backgrounds. Combined, both searches reject a purely atmospheric origin for the twenty-eight events at the 4σ level. These twenty-eight events, which include the highest energy neutrinos ever observed, have flavors, directions, and energies inconsistent with those expected from the atmospheric muon and neutrino backgrounds. These properties are, however, consistent with generic predictions for an additional component of extraterrestrial origin.

IceCube Collaboration
Science **342** (2013) 1242856



Question: Where are those neutrinos actually sourced from?

- Exotic processes,
- supernovae,
- Dark Matter,
- …?

Bets are open…

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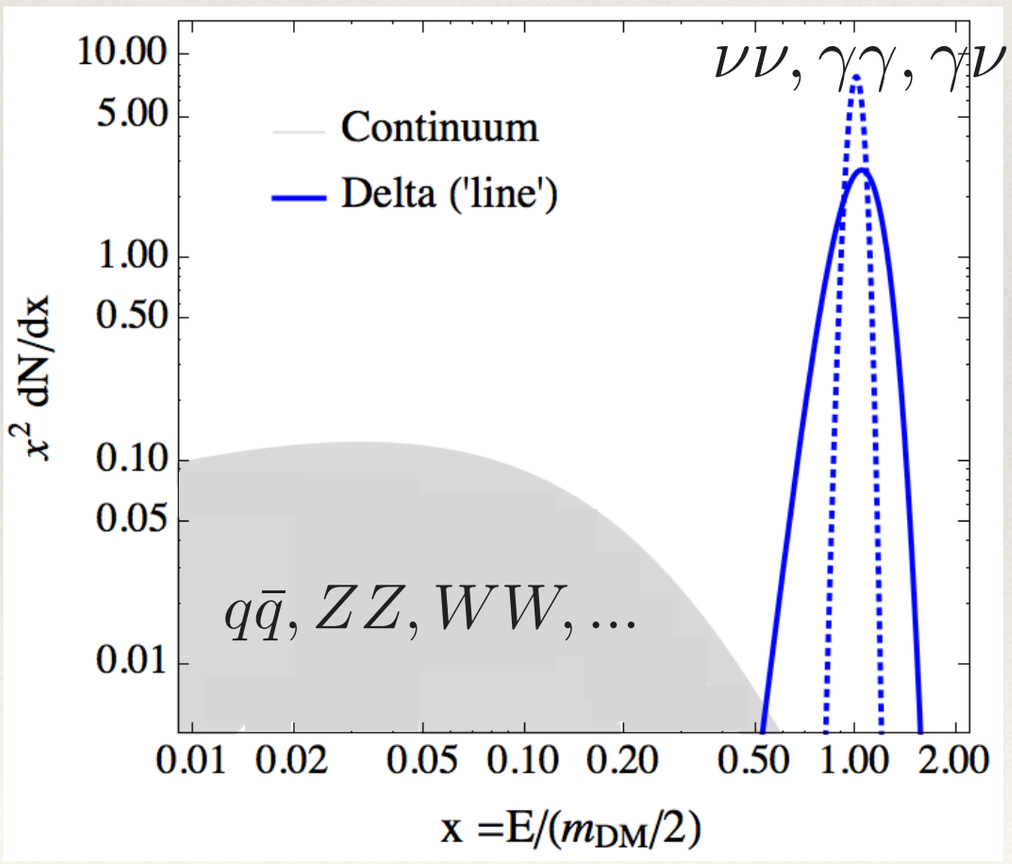
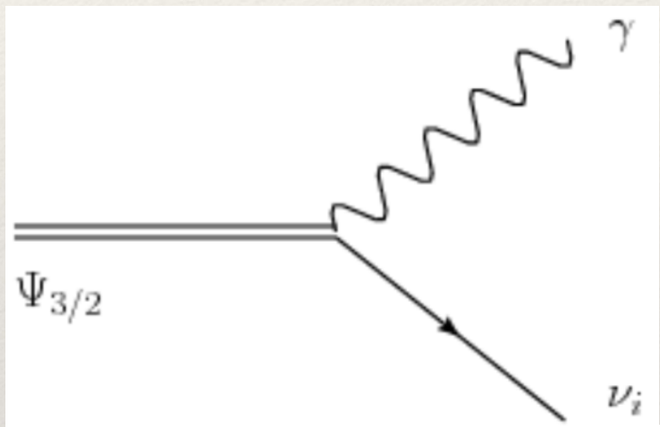
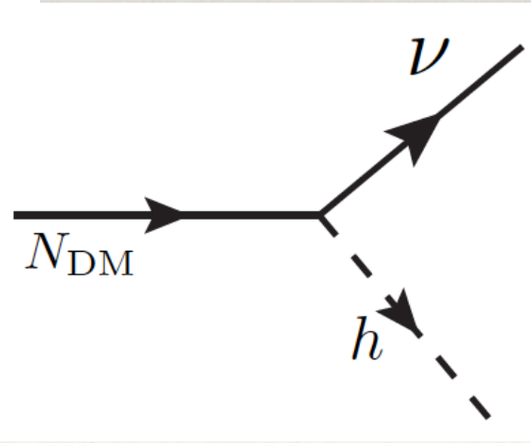
Gamma Lines
Neutrino Lines
(Sharp Spectral Features)

Spectral features





Gravitino decay

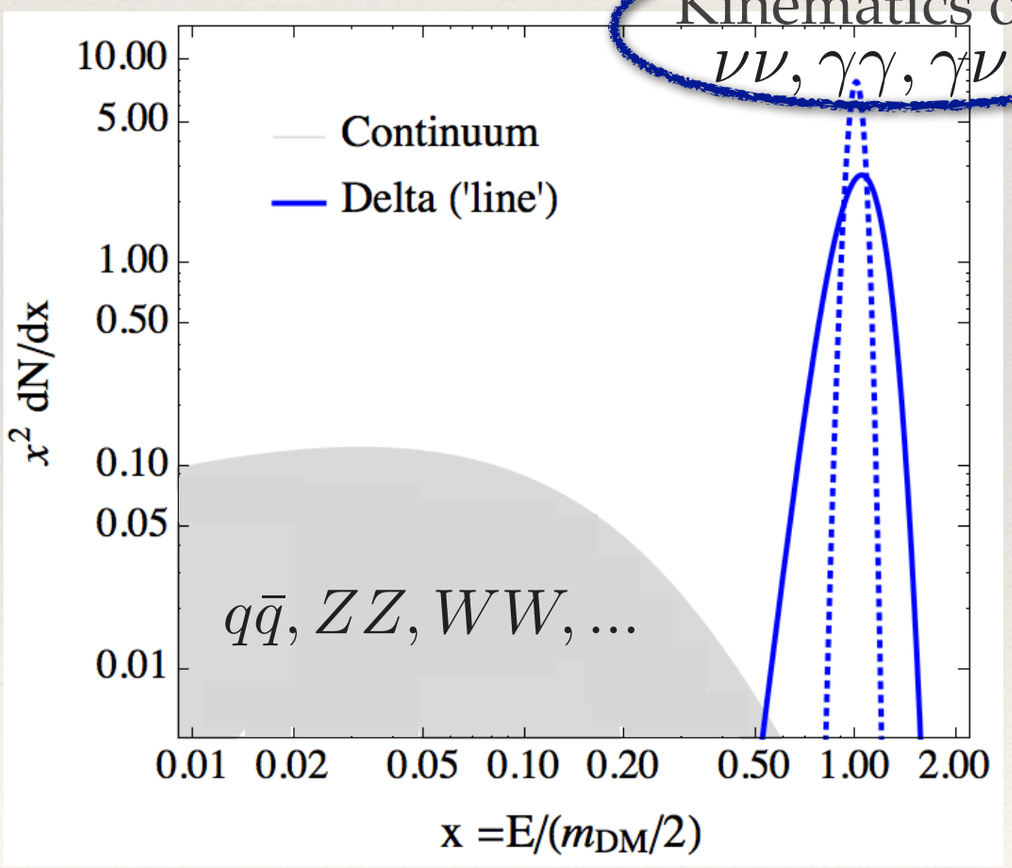


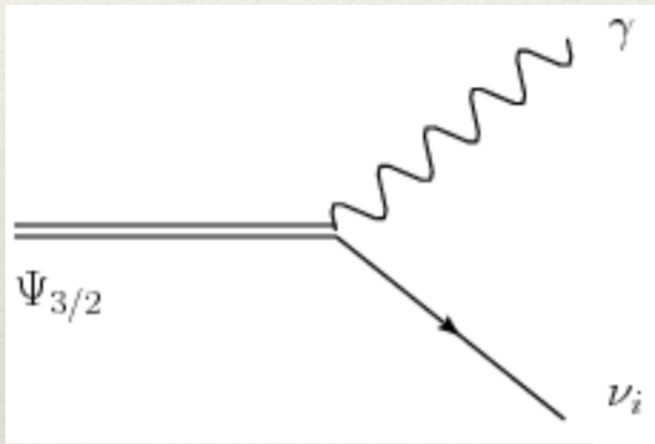
Neutrino See-Saw
Rott, Kohri & Park (2014)

ULB

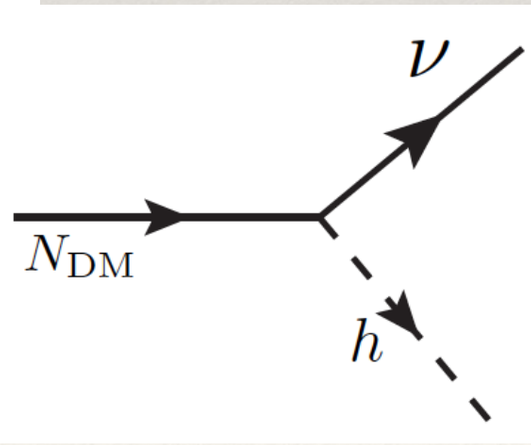
Gamma Lines
Neutrino Lines
(Sharp Spectral Features)

Spectral features





Gravitino decay



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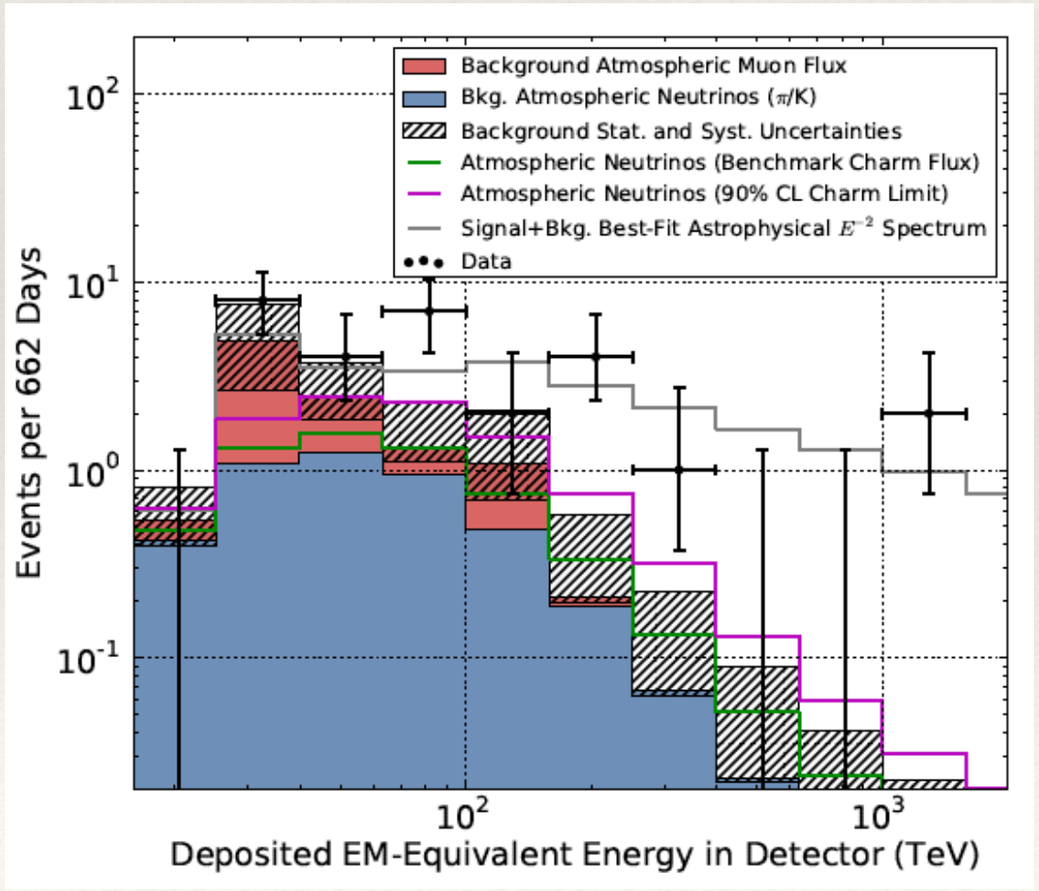

¿Could it be that DM left a Smoking Gun among those extraterrestrial neutrinos?

⟺ ¿ Is there a bump in the signal ?

(If not, what are the limits?)

Neutrino Line Search

How to search for the 'bump'?

- Find a dataset as good as possible
- Define your method
- Get results
- Interpret them

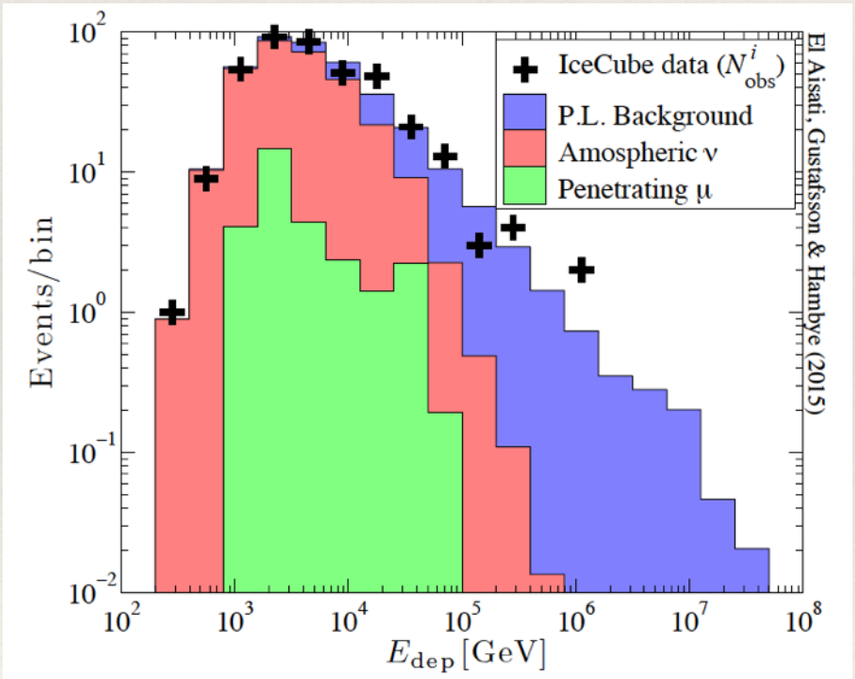

FIG. 1: Deposited energy spectrum from the full sky (black curve) as measured by IceCube. The colored regions show the expected atmospheric muon (bottom green) and neutrino (middle red) fluxes as well as the best-fit astrophysical neutrino power-law background model contribution (top blue).

Data from Phys. Rev. D 91, 022001 (2015)

Data binned in a grid with $N_{\rm bins}$

$$\{N^i_{\rm obs} \quad \text{with} \quad i = 1, ..., N_{\rm bins}\}$$

Then, you want to quantify how your model

$$\{N^i_{\rm mod} \quad \text{with} \quad i = 1, ..., N_{\rm bins}\}$$

compares to data (through a test).

P-value	Weak evidence against the
0.2	NULL hypothesis $\mathbf{H_0}$.

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Statistical Method

Still, does the addition of a line to the Null hypothesis $\mathbf{H_0}$ improve the fit to data by 'much'?

Define the Test Statistic as the ratio of profile LH

$$\mathrm{TS} = 2 \ln \frac{\mathcal{L}(n_{\mathrm{sig}} = n_{\mathrm{sig,best}})}{\mathcal{L}(n_{\mathrm{sig}} = 0)}$$

$\mathbf{H_1}$

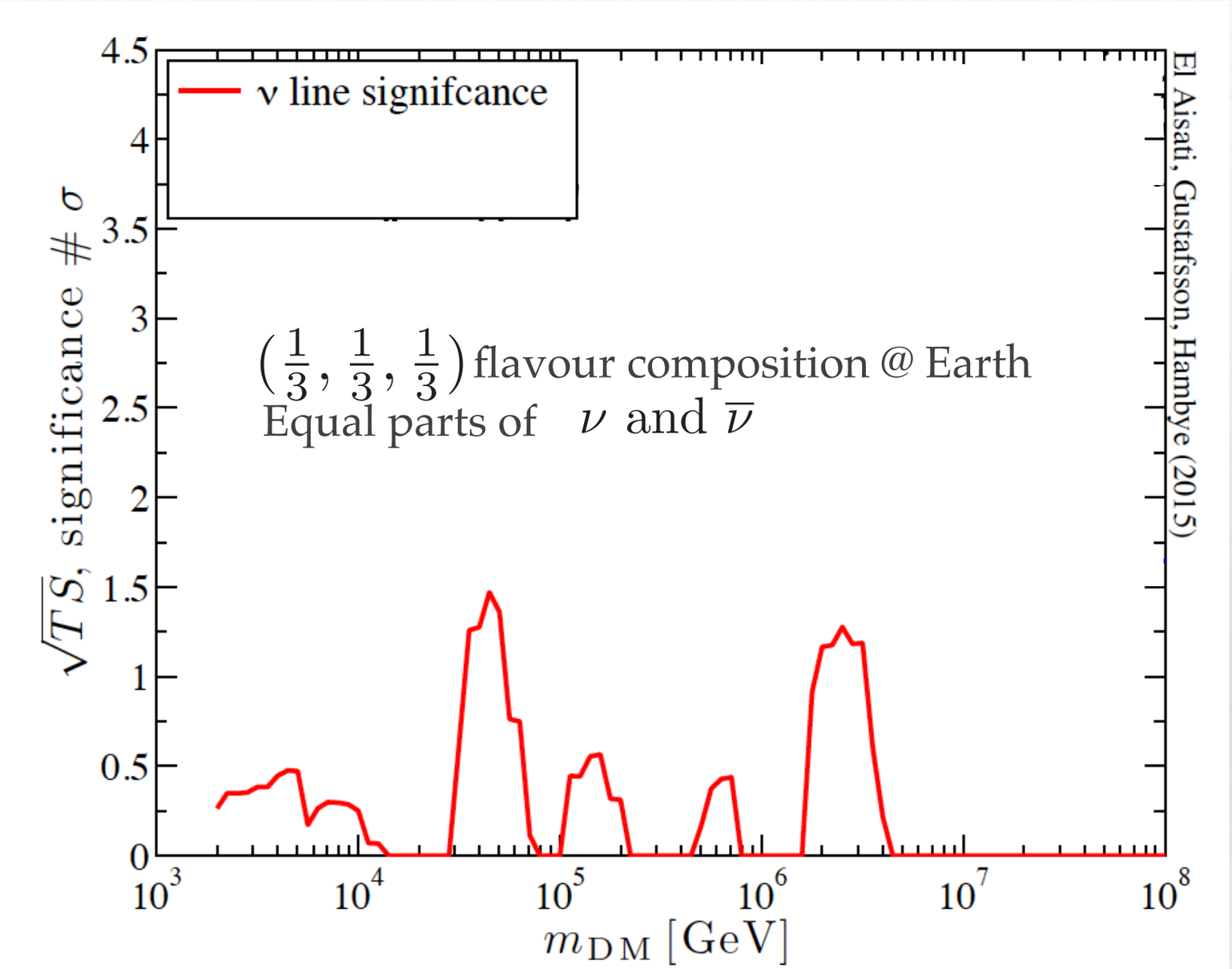
$\mathbf{H_0}$

with likelihood defined as $\mathcal{L} = \prod_{\text{bins } i} \frac{(N^i_{\mathrm{model}})^{N^i_{\mathrm{obs}}}}{N^i_{\mathrm{obs}}!} e^{-N^i_{\mathrm{model}}}$

$$N^i_{\mathrm{model}} = n_{\mathrm{sig}} N^i_{\mathrm{DM}}(m_{\mathrm{DM}}, \tau_0) + n_1 N^i_\mu + n_2 N^i_\nu + n_3 N^i_{\mathrm{astro}}$$

$\sqrt{\mathrm{TS}}$ = the significance (in #'s of σ) for rejecting $\mathbf{H_0}$ in favour of $\mathbf{H_1}$.

Line Search Results



Maximal TS =2.9 found for 100% ν_e composition @ Earth and DM mass of 45 TeV

No line detected

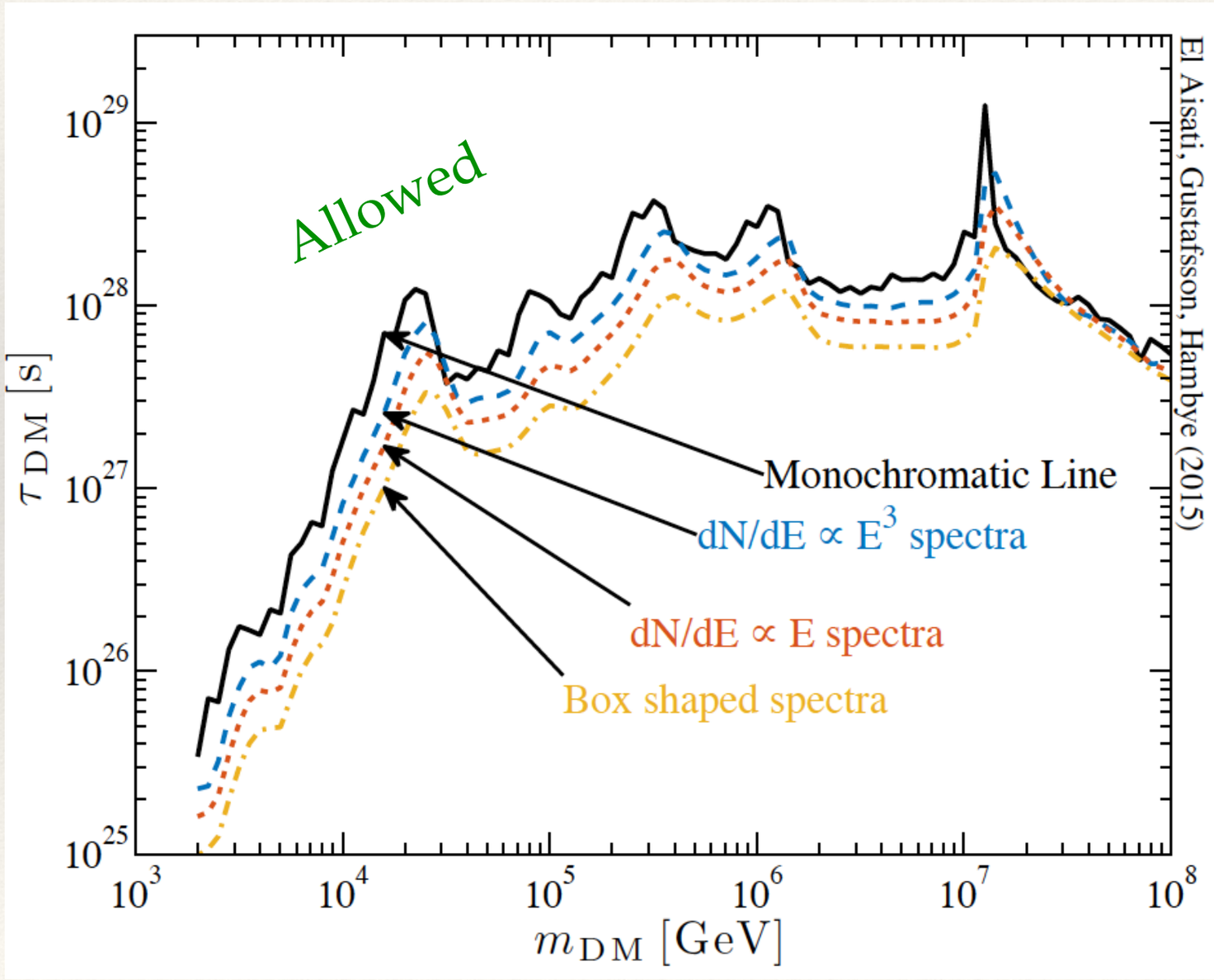
Constrain the signal

LR method

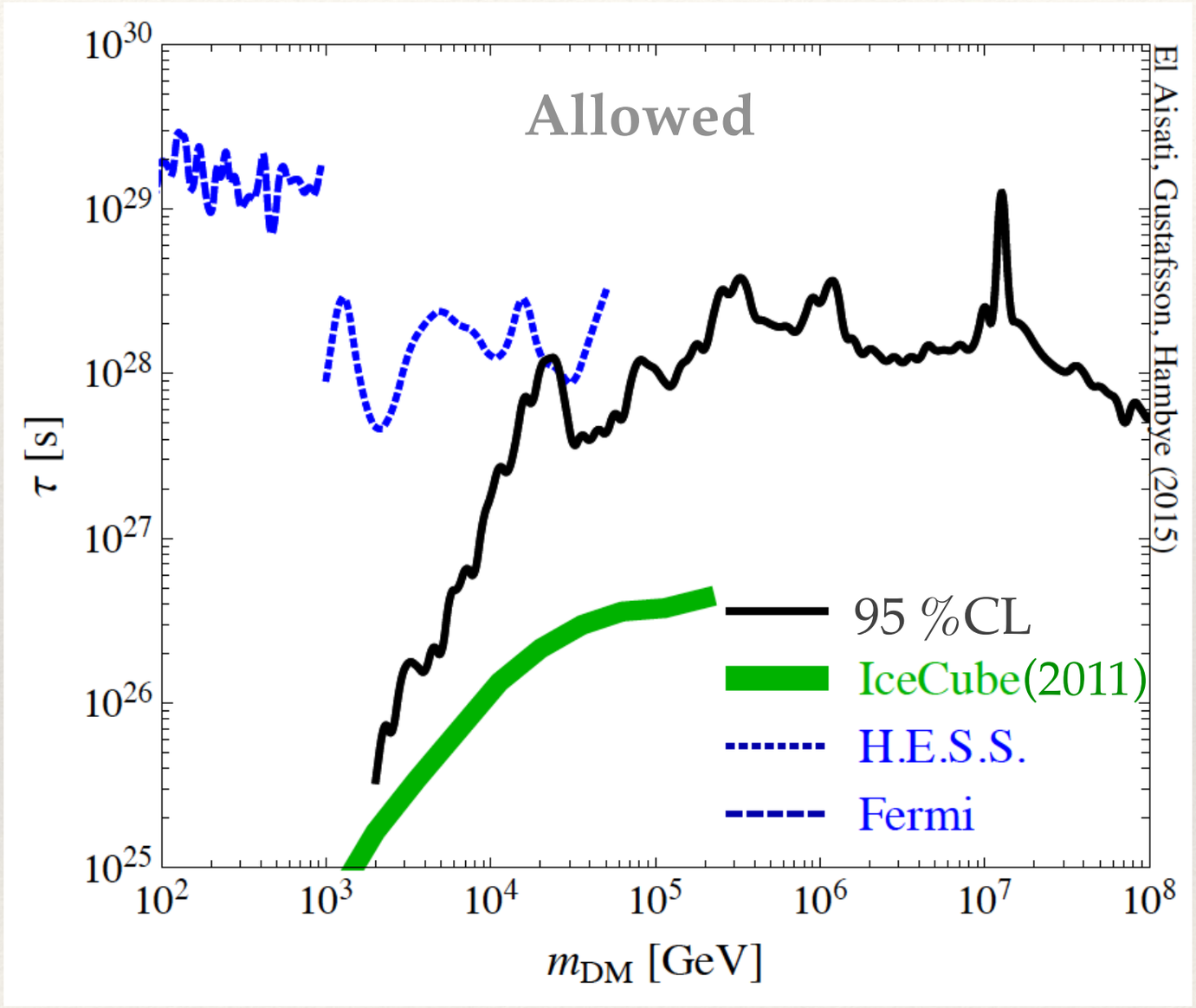
Other line-like features

Spectrum normalised to 1 particle per decay

$$\frac{\mathrm{d}N}{\mathrm{d}E} = \frac{2^{n+1}(n+1)}{m_{\mathrm{DM}}} \left(\frac{E}{m_{\mathrm{DM}}}\right)^n \Theta(m_{\mathrm{DM}} - 2E)$$



Conclusions



- No significant line detected.
- Improved bounds by more than an order of magnitude.
- Higher sensitivity than in gamma-ray line searches above 50 TeV masses.
- Neutrinos can be a great tool for DM searches.

(In progress : extension to annihilation scenario)

¡Thank you for your attention!

Back Up Slides

DM Flux Computation

$$N^i_{\rm model} \propto A^{e,\mu,\tau}_{\rm eff} \times \Phi_{\rm model}$$

Flux predicted by your model

$$\Phi_{\rm signal} + \Phi_{\rm bkg}$$

$\Phi_{\rm signal}$ **(DM)**

$\Phi_{\rm bkg}$: Everything else : Atmospheric neutrinos, muons, astrophysical source,…

$$\frac{{\rm d}\phi_{{\rm h}\alpha}}{{\rm d}E_\nu {\rm d}\Omega}(b,l) = \frac{1}{4\pi\, m_{\rm DM}\, \tau_{\rm DM}} \frac{{\rm d}N}{{\rm d}E_\nu} \int_{\rm l.o.s.} {\rm d}s\ \rho_{\rm h}[r(s,\psi[b,l])] \quad \text{(halo, anisotropic)}$$

$$+$$

$$\frac{{\rm d}\phi_{\rm eg}}{{\rm d}E_\nu\, d\Omega} = \frac{\Omega_{\rm DM}\rho_{\rm c}}{4\pi m_{\rm DM}\tau_{\rm DM}} \int_0^\infty {\rm d}z\ \frac{c}{H(z)}\ \frac{{\rm d}N}{{\rm d}E}\bigg|_{E=E_\nu(1+z)} \quad \text{(Extra-Gal., isotropic)}$$

$\int_{\rm l.o.s.} {\rm d}s\ \rho_{\rm h}[r(s,\psi[b,l])]$: ‘J-factor’

Particle physics dependent factors

Once you have the fluxes, you just need to convolve them with the detector's response function:

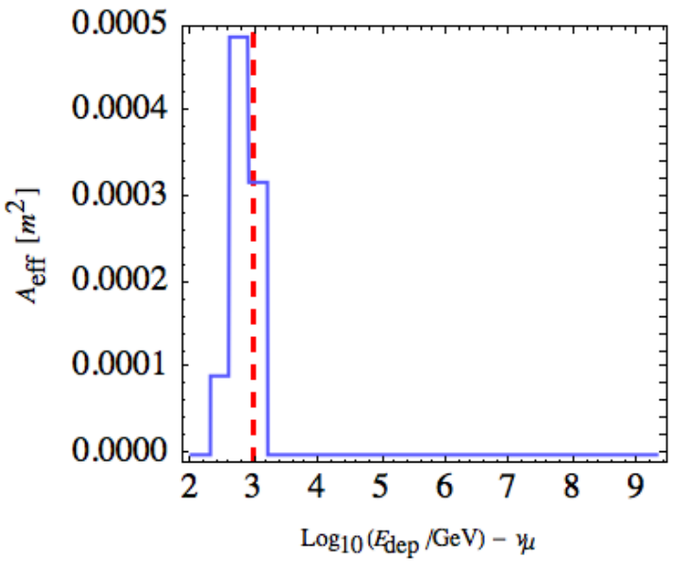
$$\frac{\mathrm{d}N_\alpha}{\mathrm{d}E_\nu \mathrm{d}\Omega \mathrm{d}E' \mathrm{d}\cos\theta' \mathrm{d}\phi'} = \frac{\mathrm{d}(\phi_\mathrm{h}+\phi_\mathrm{eg})_\alpha}{\mathrm{d}E_\nu \mathrm{d}\Omega} \cdot A_{\mathrm{eff},\alpha} \cdot T \cdot D_{\mathrm{eff},\alpha}$$

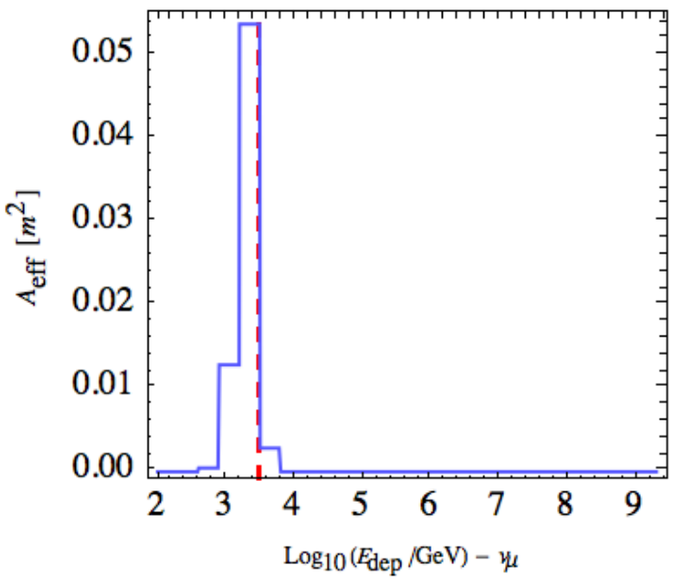
with $\alpha \in \{e, \mu, \tau, \bar{e}, \bar{\mu}, \bar{\tau}\}$
T the exposure time
E_ν the 'true' energy variable
Ω solid angle
$D_{\mathrm{eff},\alpha}$ the dispersion function
E' the 'reconstructed' energy variable
(θ', ϕ') solid angle.

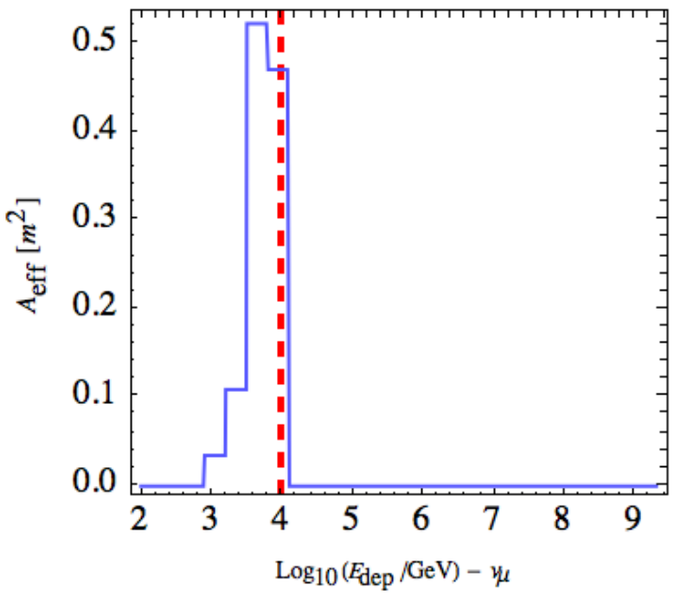
and then integrate

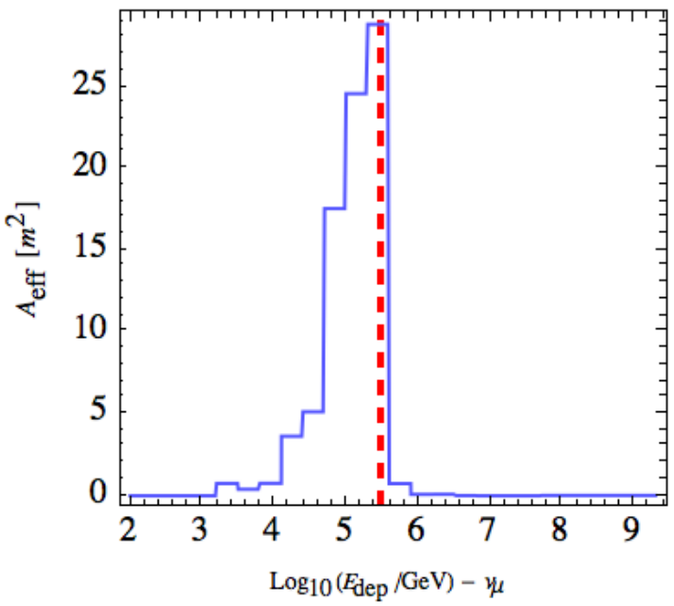
Flavour composition

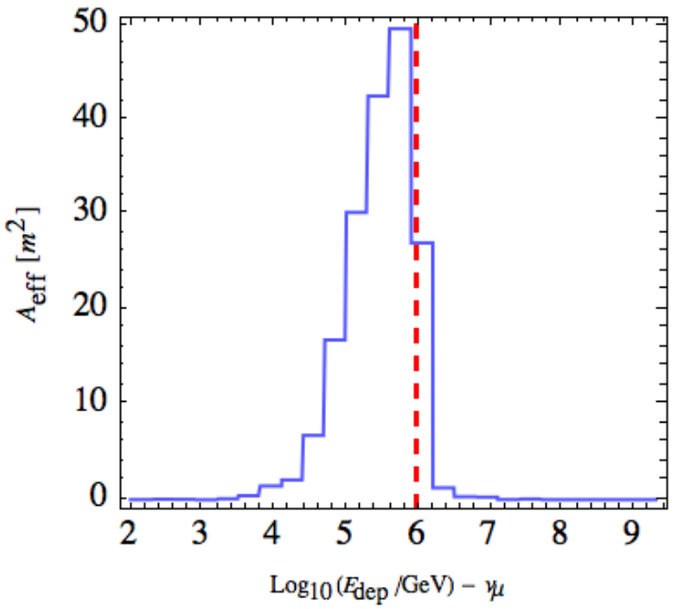
$$N^i_\mathrm{DM}(m_\mathrm{DM}, \tau_\mathrm{DM}) = \int_{\Delta_i E'} \mathrm{d}E' \int_{\Delta\theta'(t)} \mathrm{d}\cos\theta' \int_{\Delta\phi'(t)} \mathrm{d}\phi' \int \mathrm{d}E \int_{4\pi} \mathrm{d}\Omega \sum_{\substack{\alpha=e,\mu,\tau,\\ \bar{e},\bar{\mu},\bar{\tau}}} P_\alpha \frac{\mathrm{d}N_\alpha}{\mathrm{d}E_\nu \mathrm{d}\Omega \mathrm{d}E' \mathrm{d}\cos\theta' \mathrm{d}\phi'}$$

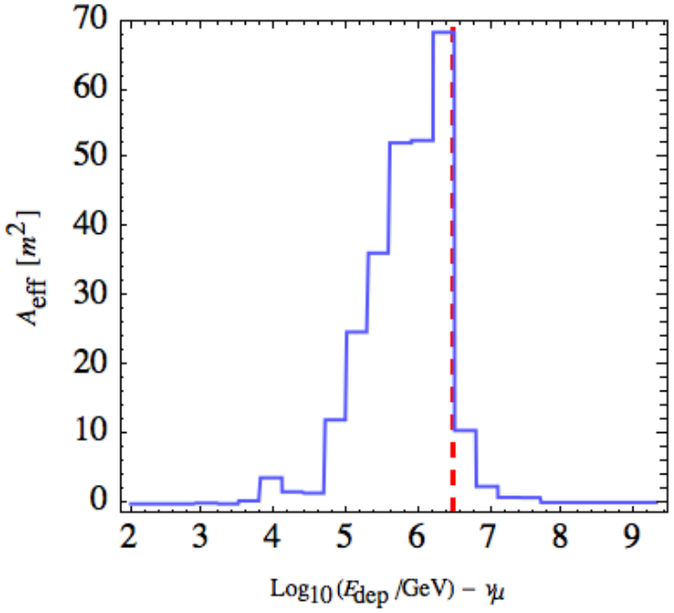

0.0005
0.0004
0.0003
0.0002
0.0001
0.0000
$A_{\text{eff}}\ [m^2]$
2 3 4 5 6 7 8 9
$\text{Log}_{10}(E_{\text{dep}}/\text{GeV}) - \gamma_\mu$


0.05
0.04
0.03
0.02
0.01
0.00
$A_{\text{eff}}\ [m^2]$
2 3 4 5 6 7 8 9
$\text{Log}_{10}(E_{\text{dep}}/\text{GeV}) - \gamma_\mu$


0.5
0.4
0.3
0.2
0.1
0.0
$A_{\text{eff}}\ [m^2]$
2 3 4 5 6 7 8 9
$\text{Log}_{10}(E_{\text{dep}}/\text{GeV}) - \gamma_\mu$


25
20
15
10
5
0
$A_{\text{eff}}\ [m^2]$
2 3 4 5 6 7 8 9
$\text{Log}_{10}(E_{\text{dep}}/\text{GeV}) - \gamma_\mu$


50
40
30
20
10
0
$A_{\text{eff}}\ [m^2]$
2 3 4 5 6 7 8 9
$\text{Log}_{10}(E_{\text{dep}}/\text{GeV}) - \gamma_\mu$


70
60
50
40
30
20
10
0
$A_{\text{eff}}\ [m^2]$
2 3 4 5 6 7 8 9
$\text{Log}_{10}(E_{\text{dep}}/\text{GeV}) - \gamma_\mu$

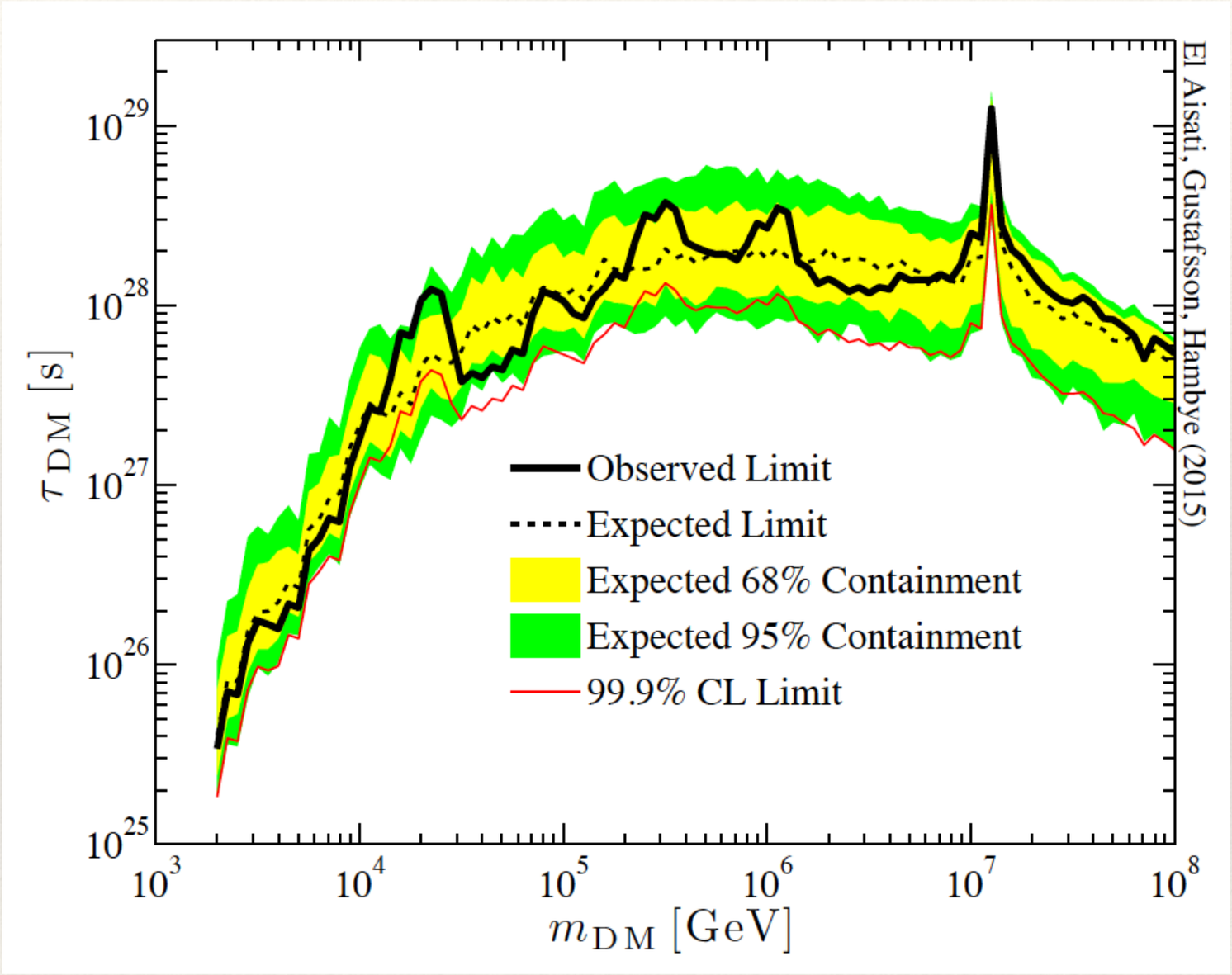
Constraining the line with a TS

ULB

$$\mathrm{TS} = 2 \ln \frac{\mathcal{L}(n_{\mathrm{sig}} = n_{\mathrm{sig,best}}, \hat{\theta})}{\mathcal{L}(n_{\mathrm{sig}} = n_{\mathrm{limit}}, \hat{\hat{\theta}})}$$

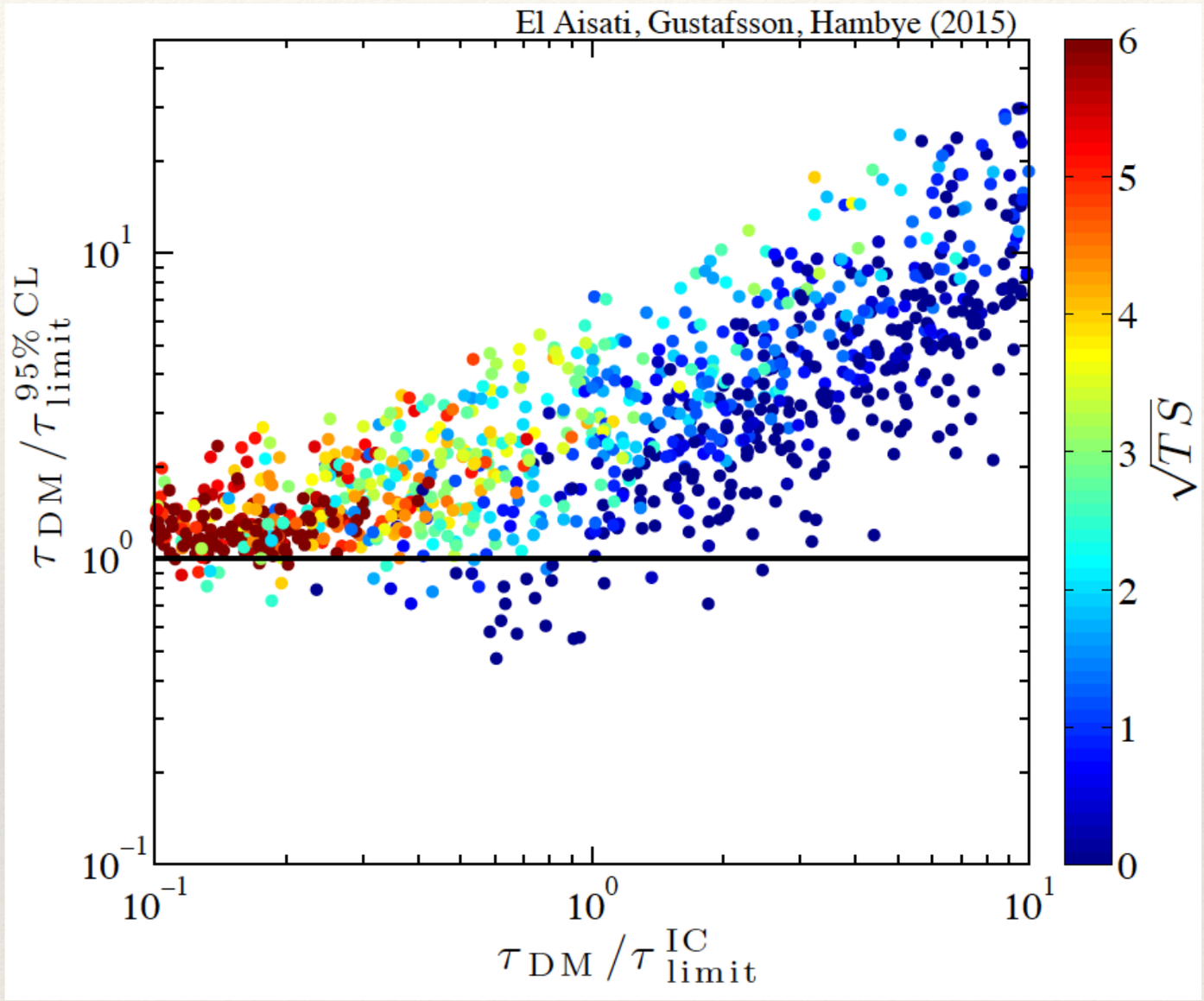
95% C.L. when TS < 2.71

DM decay



talk about robust limit, show

Statistical Coverage



Coverage = 93%

101 masses tested