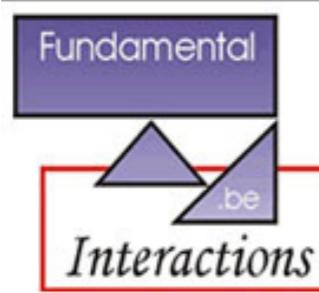


Neutrino and Gamma Lines from Dark Matter Decay

Chaïmae EL AISATI
Antwerpen, December 2015

[Based on: 1506.02657 & 1510.05008]



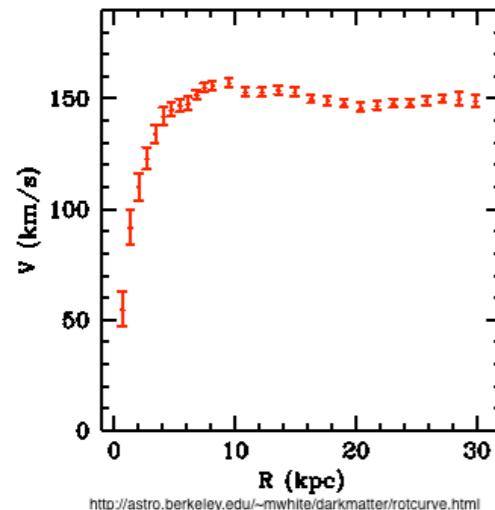
Outline

- ⚡ Motivation
- ⚡ Neutrino lines from DM decay
- ⚡ Correlation w/ Gamma lines & EFT
- ⚡ Summary

Motivation

¿Why do we need DM?

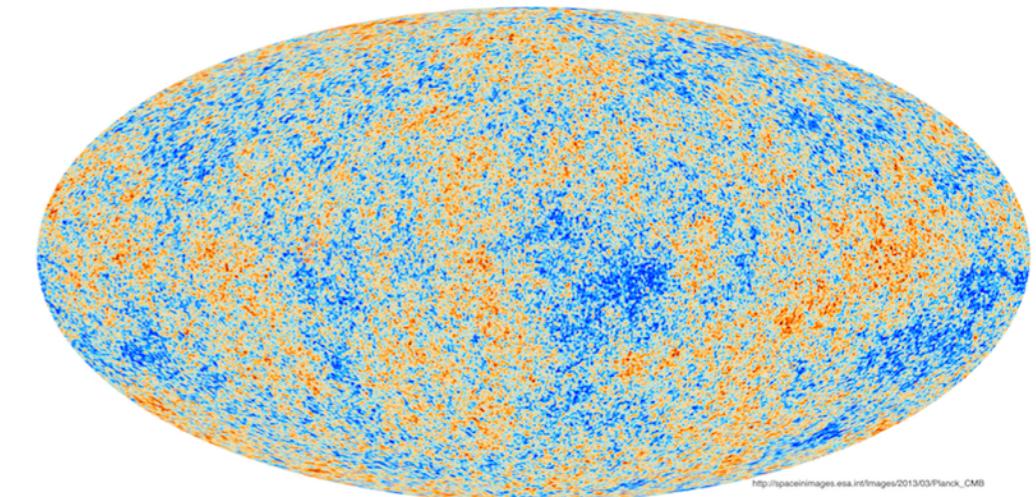
Gravitational evidences for Dark Matter (DM) at all scales



Rotation Curves



Bullet Cluster



CMB anisotropies

BUT ☹ Properties of the DM particle(s?) unknown (except that it has gravitational interactions)

This is why ...

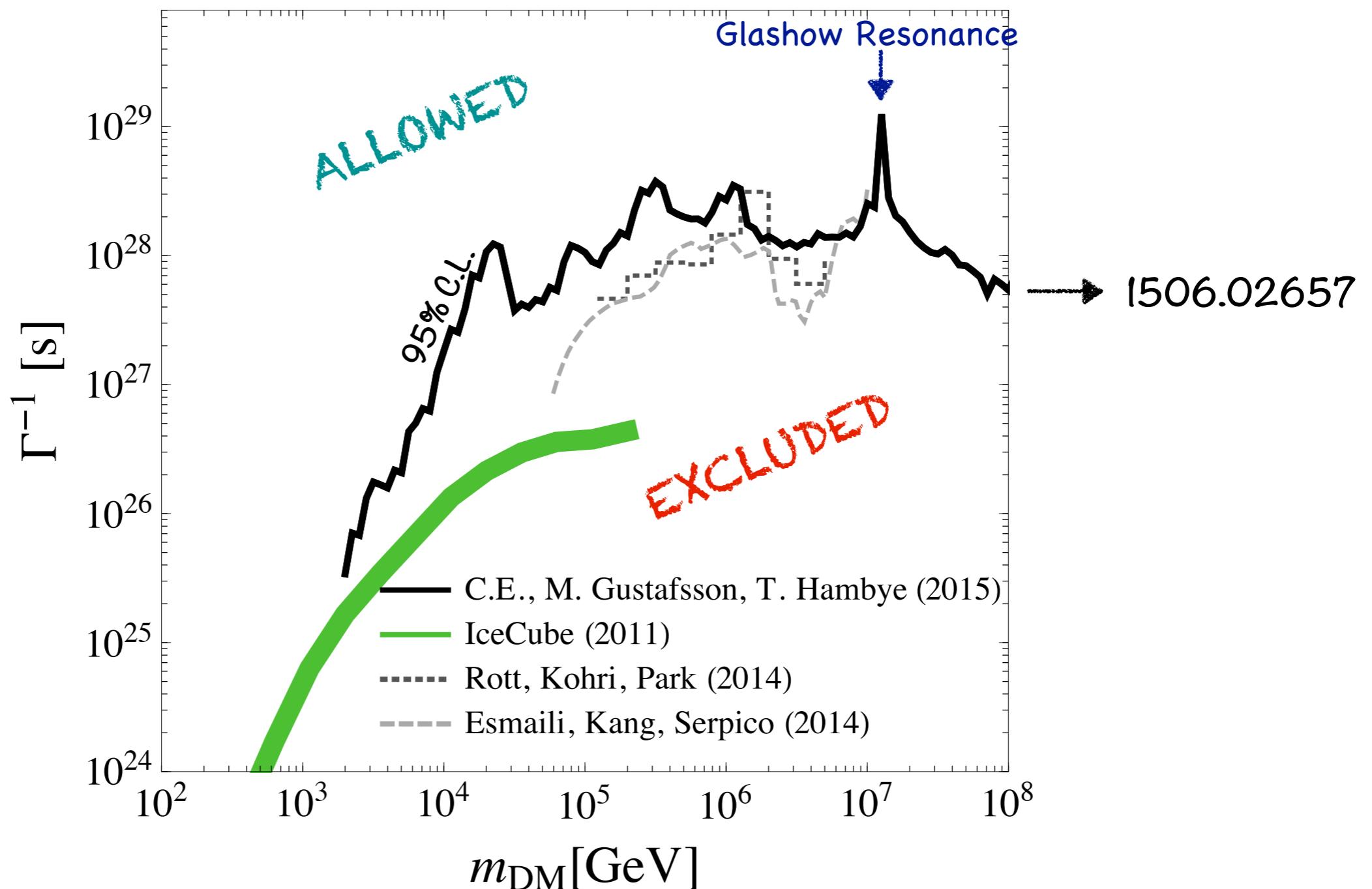
3 main search strategies:

- Production @ colliders (mono-jet, mono-lepton events)
- Direct detection (Xenon, LUX, CDMS, ...)
- Indirect detection (\Leftrightarrow anomalies in CR fluxes)

¿Why γ and ν lines?

- Broad choice of messengers (photons, electrons, positrons, antiprotons, neutrinos,...) to look at in order to (hopefully) find a signal.
- Photons & neutrinos: features basically unaltered, allow to point back to the source (which can e.g. be of great interest for searches in objects that are DM-dominated).
- Scenarios usually considered for probing a signal:
 - Annihilating DM
 - Decaying DM
- : sharp spectral features, such as lines, b/c cannot be explained by astrophysical background.

Status of the limits on \mathcal{V} lines (from DM decay)

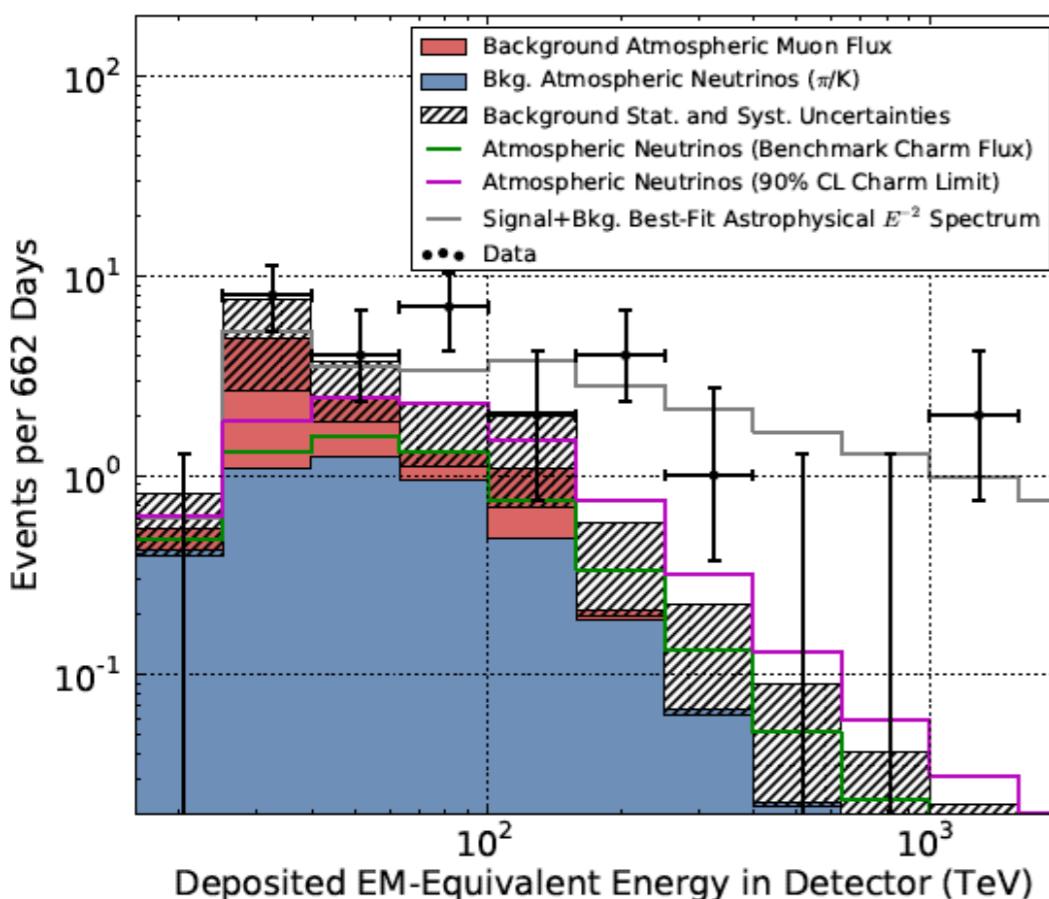


Back in 2013 ...

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



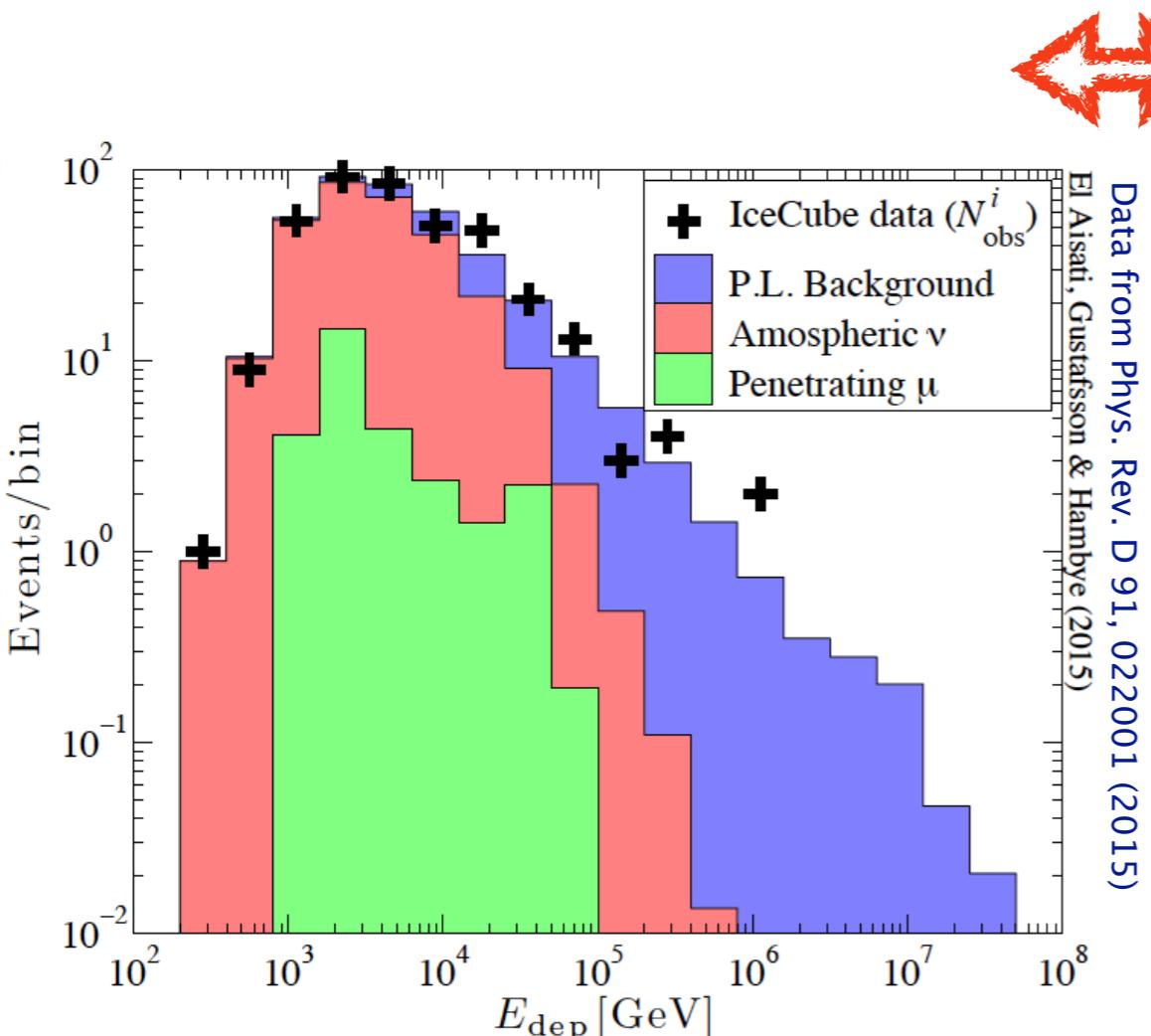
Question: Where are those neutrinos actually sourced from?

Few words on 1506.02657...

New search for monochromatic neutrinos from dark matter decay

Chaïmae El Aisati,^{1,*} Michael Gustafsson,^{2,†} and Thomas Hambye^{1,‡}

¿Could it be that DM left a Smoking Gun in neutrino data?



P-value of the fit = .2

↔ ¿ Is there a bump in the data ?

(If not, what are the limits?)

- 2-year data sample: 200 GeV - 100 PeV
- We allowed the addition of a DM component wrt H_0 , and tested this alternative hypothesis

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

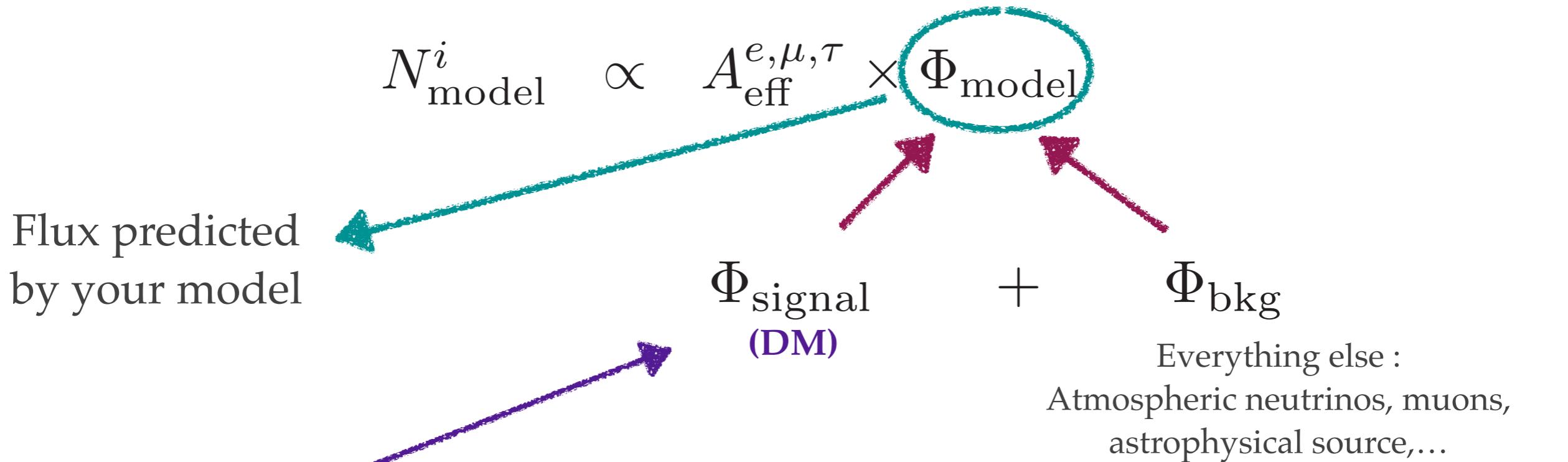
H_1 ↗
↗ H_0

Log-likelihood procedure and
we fitted **energy spectra** $\mathcal{L} = \prod_{\text{bins } i} \frac{(N_{\text{model}}^i)^{N_{\text{obs}}^i}}{N_{\text{obs}}^i!} e^{-N_{\text{model}}^i}$

$$N_{\text{model}}^i = n_{\text{sig}} N_{\text{DM}}^i(m_{\text{DM}}, \tau_0) + n_1 N_{\mu}^i + n_2 N_{\nu}^i + n_3 N_{\text{astro}}^i$$

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

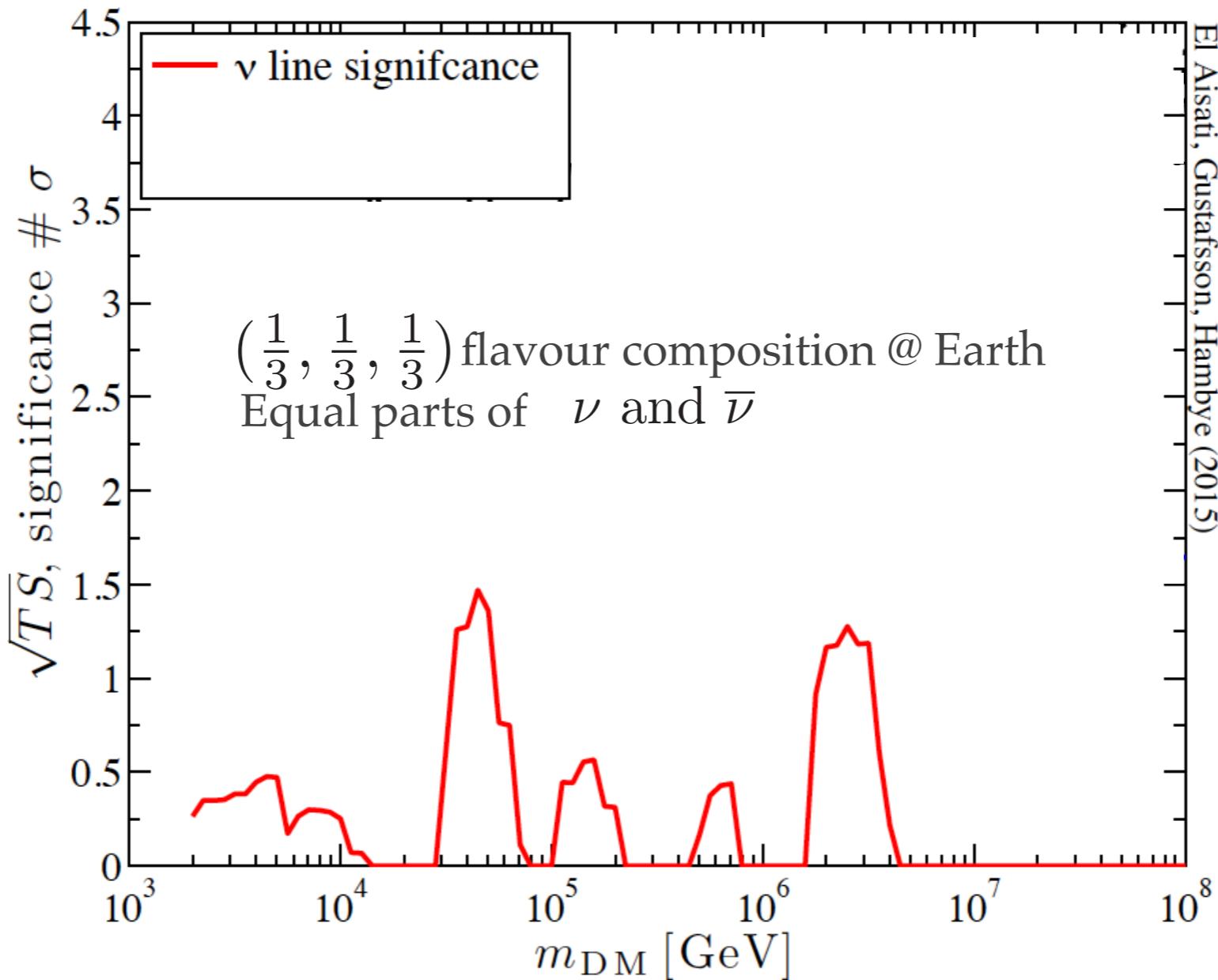
DM Flux Computation



$$\frac{d\phi_{h\alpha}}{dE_\nu d\Omega}(b, l) = \frac{1}{4\pi m_{\text{DM}} \tau_{\text{DM}}} \frac{dN}{dE_\nu} \int_{\text{l.o.s.}} ds \rho_h[r(s, \psi[b, l])] \quad \begin{matrix} \text{(halo,} \\ \text{anisotropic)} \end{matrix}$$

$$\frac{d\phi_{eg}}{dE_\nu d\Omega} = \frac{\Omega_{\text{DM}} \rho_c}{4\pi m_{\text{DM}} \tau_{\text{DM}}} \int_0^\infty dz \frac{c}{H(z)} \left. \frac{dN}{dE} \right|_{E=E_\nu(1+z)} \quad \begin{matrix} \text{'J-factor'} \\ \text{(Extra-Gal.,} \\ \text{isotropic)} \end{matrix}$$

Particle physics
dependent factors

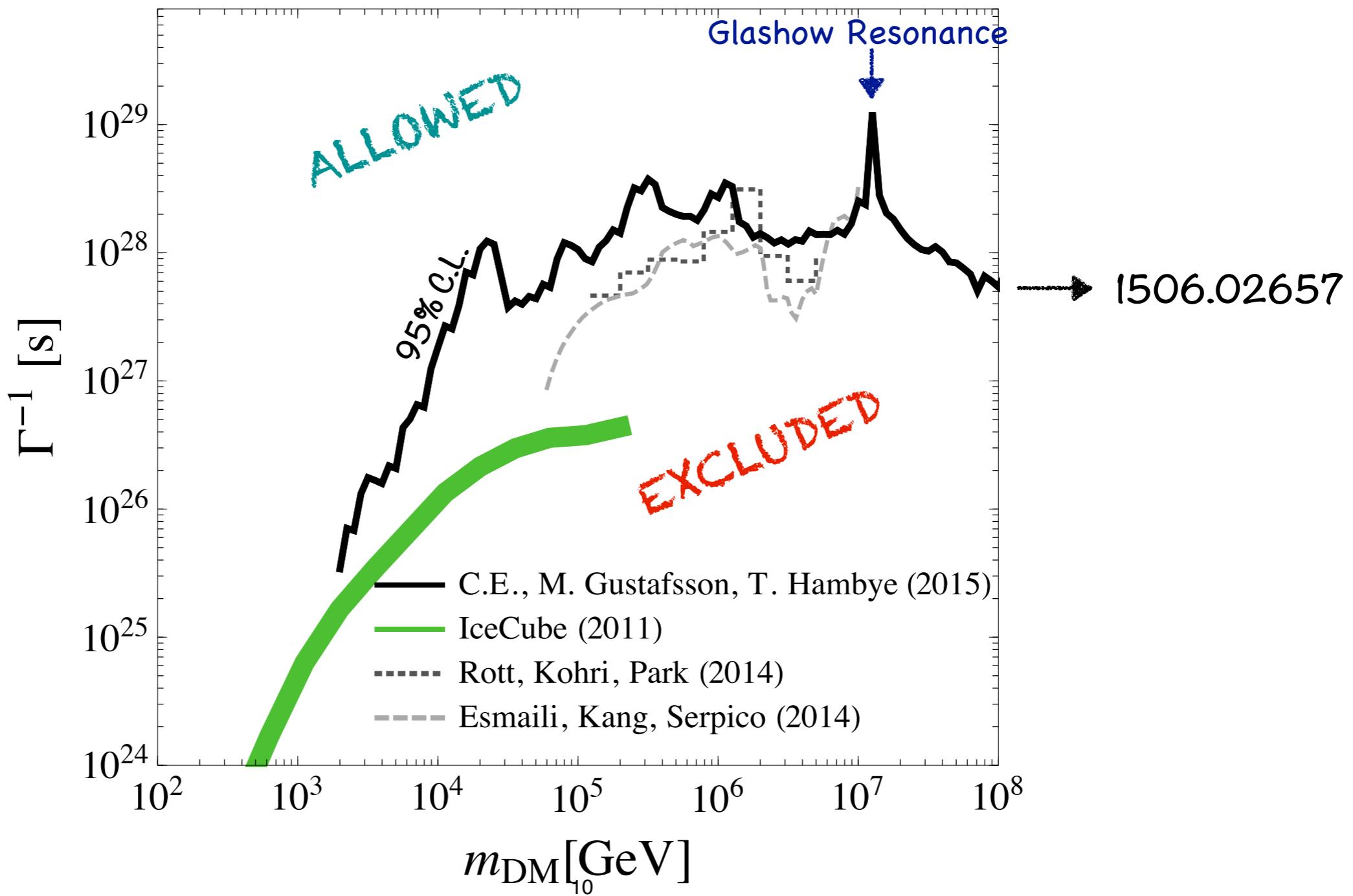


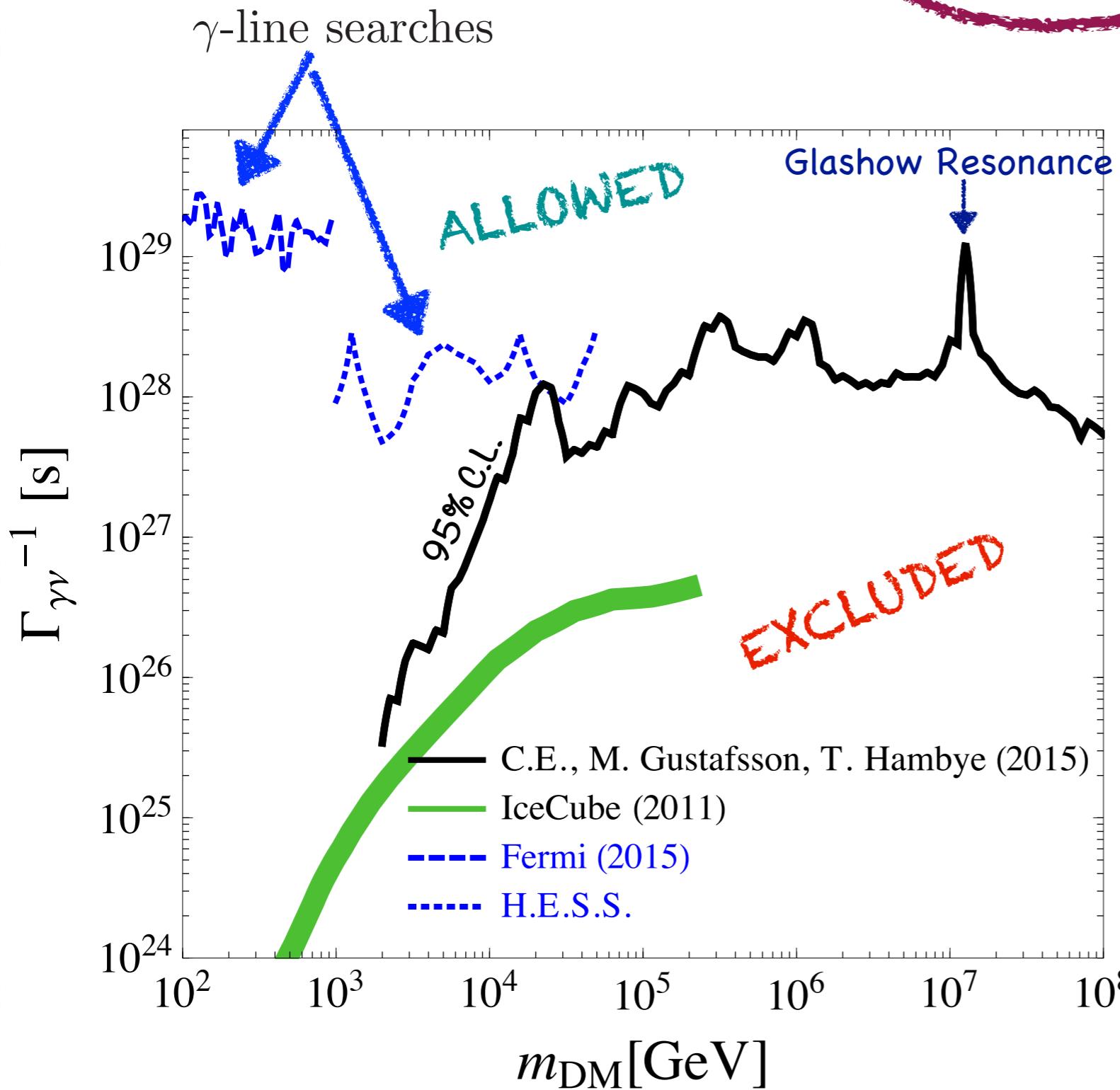
Maximal TS = 2.9 found for 100% ν_e composition @ Earth and DM mass of 45 TeV

Status of the limits on \mathcal{V} lines (continued)

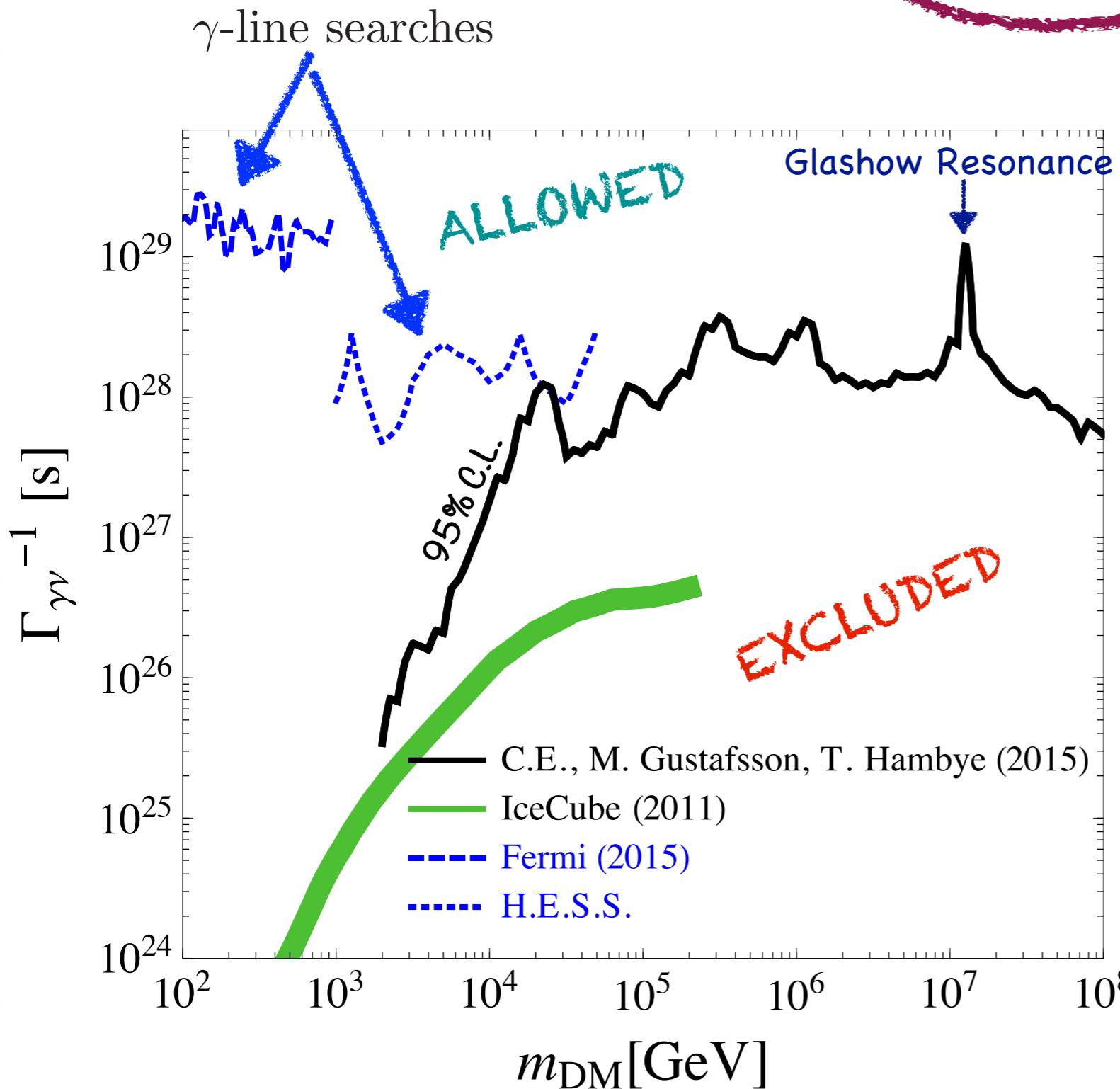
In the end, we did not find any significant line :-)

Still, we improved bounds by more than 1 order of magnitude.



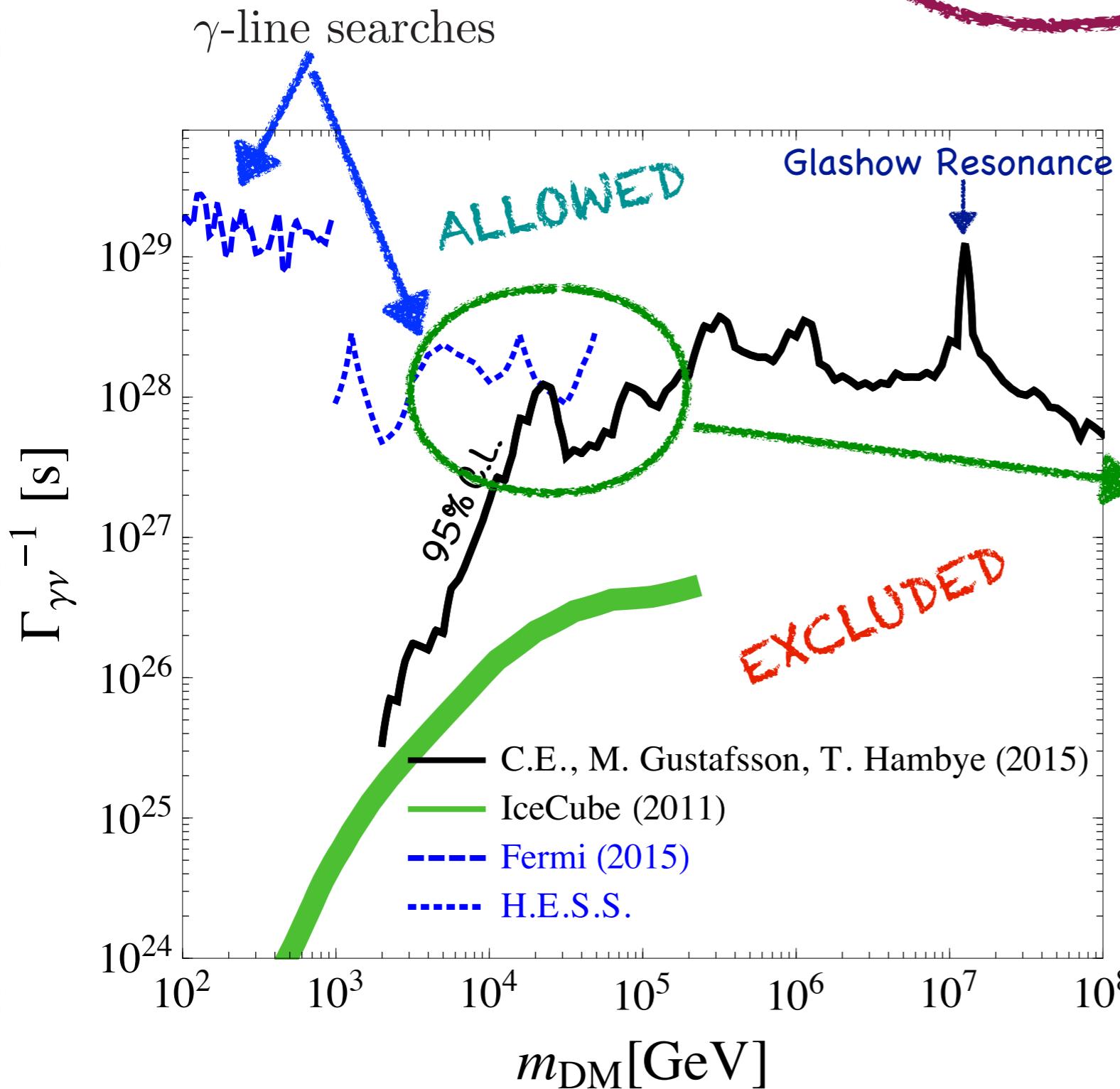
Status of the limits on ν lines + γ lines

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Higher sensitivity than in gamma-ray line searches above 50 TeV masses: advantage of ν -astronomy!

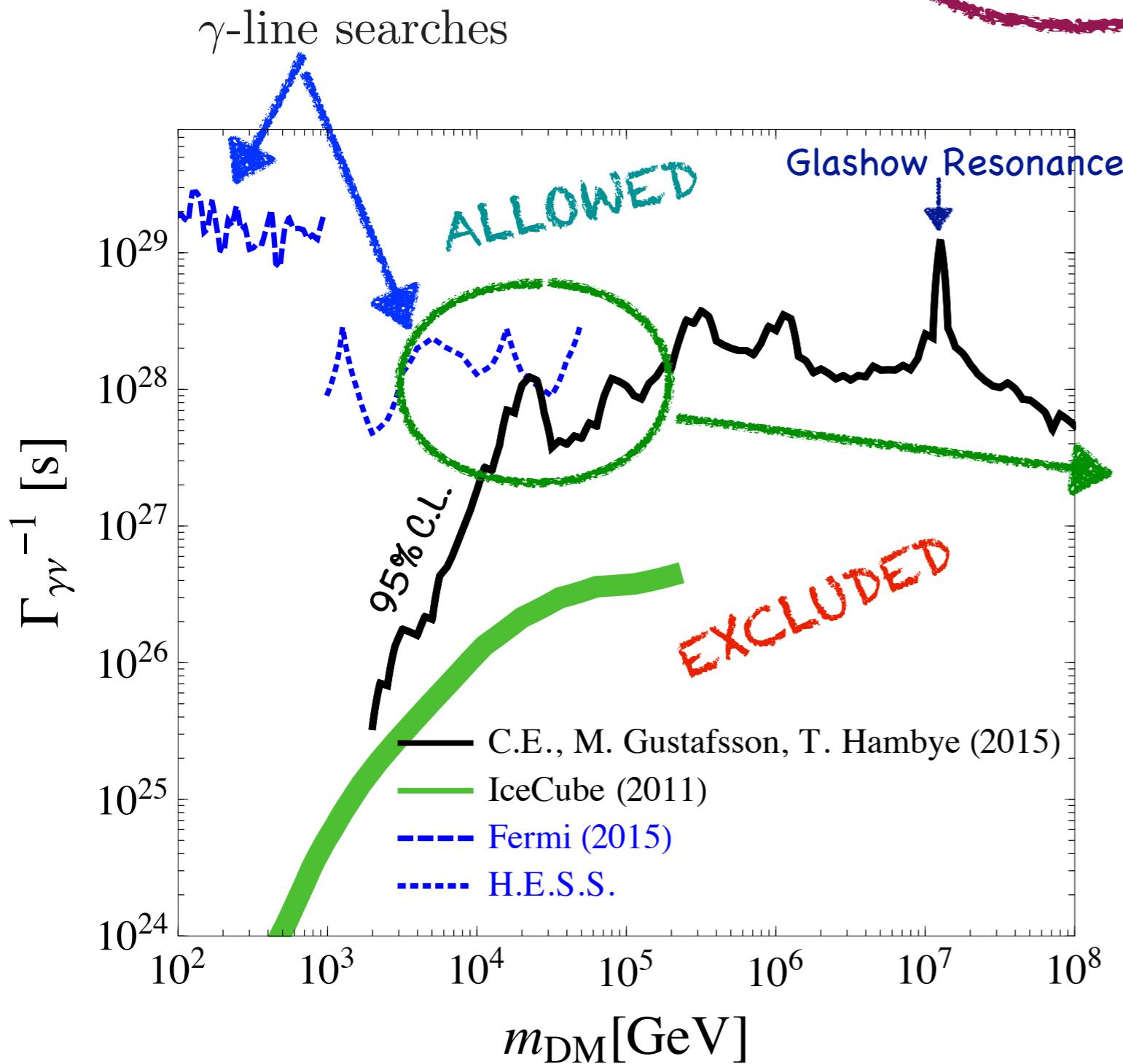
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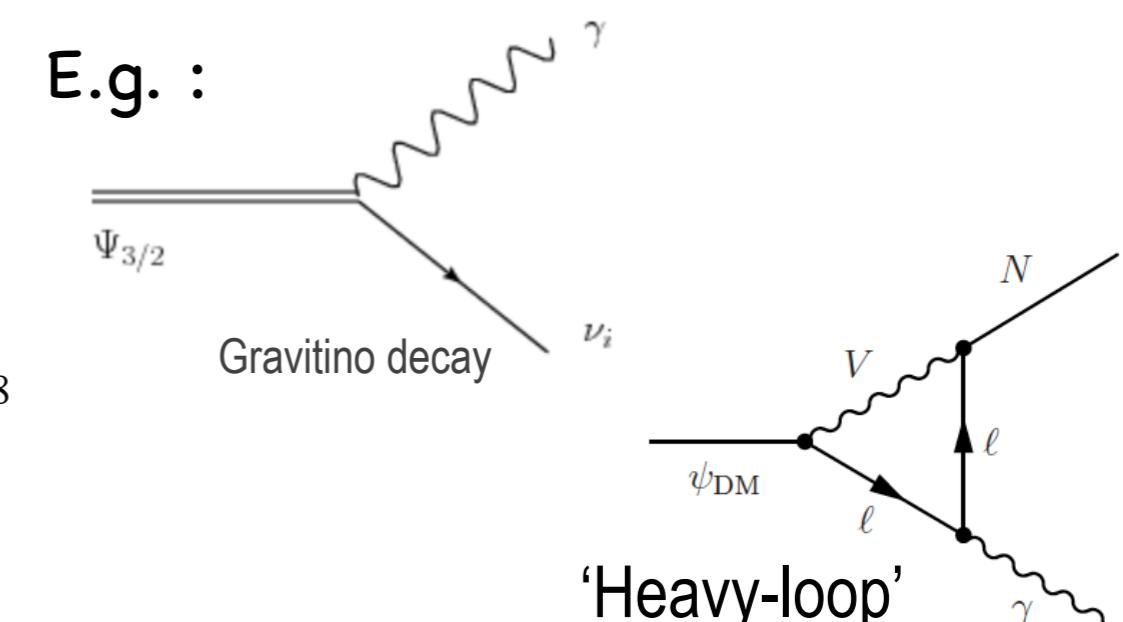
Particularly interesting region for the scenarios producing neutrino & photon-lines!

Status of the limits on ν lines + γ lines



Higher sensitivity than in gamma-ray line searches above 50 TeV masses: advantage of ν -astronomy!

Particularly interesting region for the scenarios producing neutrino & photon-lines!



Garny, Ibarra, Tran, Weniger
(1011.3786)

Question:

- Can we hope to see a “double smoking” gun with present sensitivities?
- Can it be compatible with current CR constraints?

¿What to expect from the EFT approach for the decay into $\nu + \gamma$?

C.E., M. Gustafsson, T. Hambye, T. Scarnà (1510.05008)

- DM neutral => loop suppression
 - Slow decay
- => motivate EFT approach

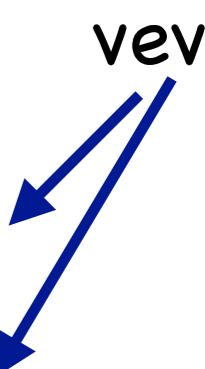
Power expansion $\mathcal{L} = \mathcal{L}_{\text{SM}} + \sum_i c_i \frac{\mathcal{O}_i^{\text{dim5}}}{\Lambda_{UV}} + \sum_i \tilde{c}_i \frac{\mathcal{O}_i^{\text{dim6}}}{\Lambda_{UV}^2} + \dots$

Basis (dim < 7) = “A handful of operators”

(obtained from criteria such as e.g. Lorentz invariance & gauge invariance,
also by the choice of DM’s quantum numbers.)

Dim 5 $\bar{L}\sigma_{\mu\nu}\psi_{\text{DM}}F_Y^{\mu\nu}$
 $\bar{L}\sigma_{\mu\nu}\psi_{\text{DM}}F_L^{\mu\nu}$

Dim 6 $\bar{L}\sigma_{\mu\nu}\psi_{\text{DM}}F_Y^{\mu\nu}\phi$
 $\bar{L}\sigma_{\mu\nu}\psi_{\text{DM}}F_L^{\mu\nu}\phi$
 $D_\mu\bar{L}\gamma_\nu\psi_{\text{DM}}F_Y^{\mu\nu}$
 $D_\mu\bar{L}\gamma_\nu\psi_{\text{DM}}F_L^{\mu\nu}$
 $\bar{L}\gamma_\mu D_\nu\psi_{\text{DM}}F_Y^{\mu\nu}$
 $\bar{L}\gamma_\mu D_\nu\psi_{\text{DM}}F_L^{\mu\nu}$



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 $\bar{L}\sigma_{\mu\nu}\psi_{\text{DM}}F_L^{\mu\nu}\phi$
 $D_\mu \bar{L} \gamma_\nu \psi_{\text{DM}} F_V^{\mu\nu}$

vev



Decay channels:

$\nu\gamma, \nu Z, lW$

$\nu\gamma h, \nu\gamma Z_L, l\gamma W_L, \nu Zh, \nu ZZ_L, lZW_L, lWh, lWZ_L, \nu WW_L$

Some results ...

- By construction, these operators give at least the common decay into $\nu + \gamma \Rightarrow$ mono-energetic particles.
- Gauge inv. \Rightarrow always more monoE neutrinos than gammas ($\nu+Z$ decay)

Operators with a $F_Y^{\mu\nu}$ $\Gamma_\nu/\Gamma_\gamma = \frac{1}{\cos^2 \theta_W} = 1.3$

Operators with a $F_L^{\mu\nu}$ $\Gamma_\nu/\Gamma_\gamma = \frac{1}{\sin^2 \theta_W} = 4.3$

Some results ...

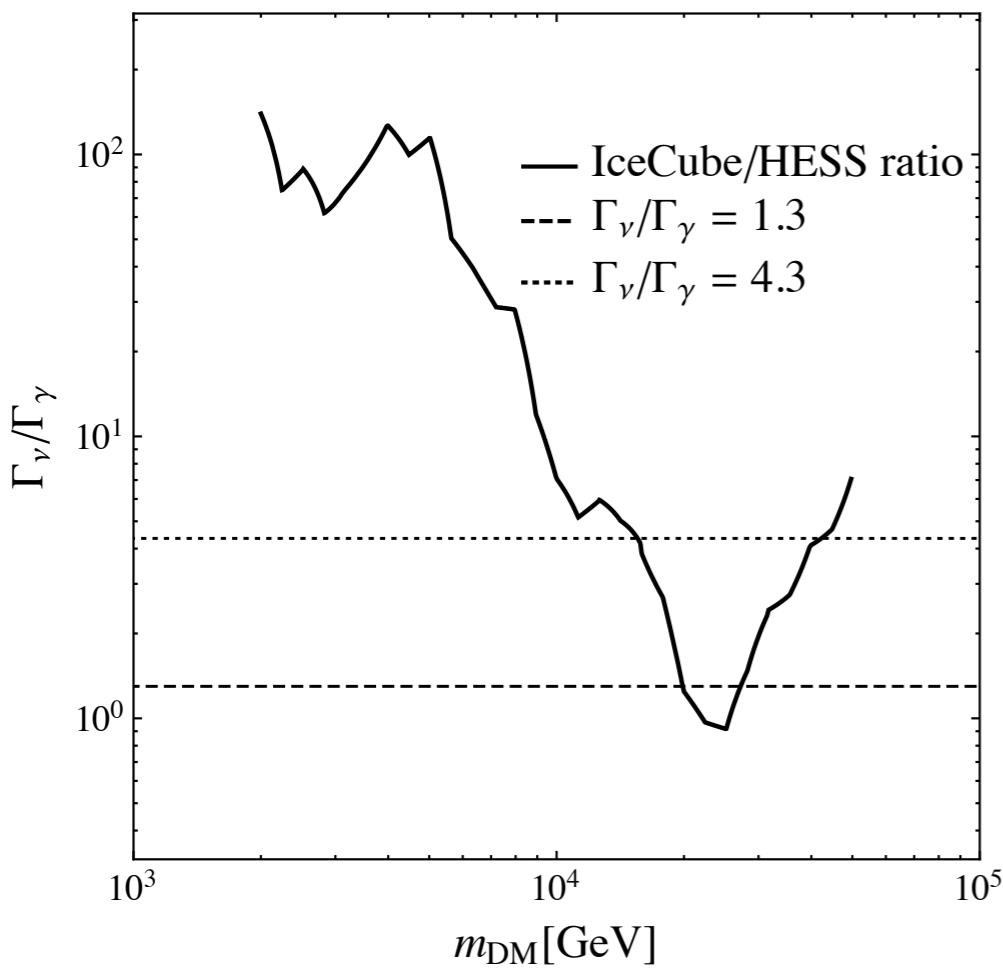
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Operators with a $F_L^{\mu\nu}$

$$\Gamma_\nu/\Gamma_\gamma = \frac{1}{\sin^2 \theta_W} = 4.3$$



- Scaling of 3body decays wrt 2body decays:

$$\frac{m_{DM}^2}{64\pi^2 v_\phi^2}$$

If available, 3-body decay dominate the decay width of the DM at masses > few TeVs.

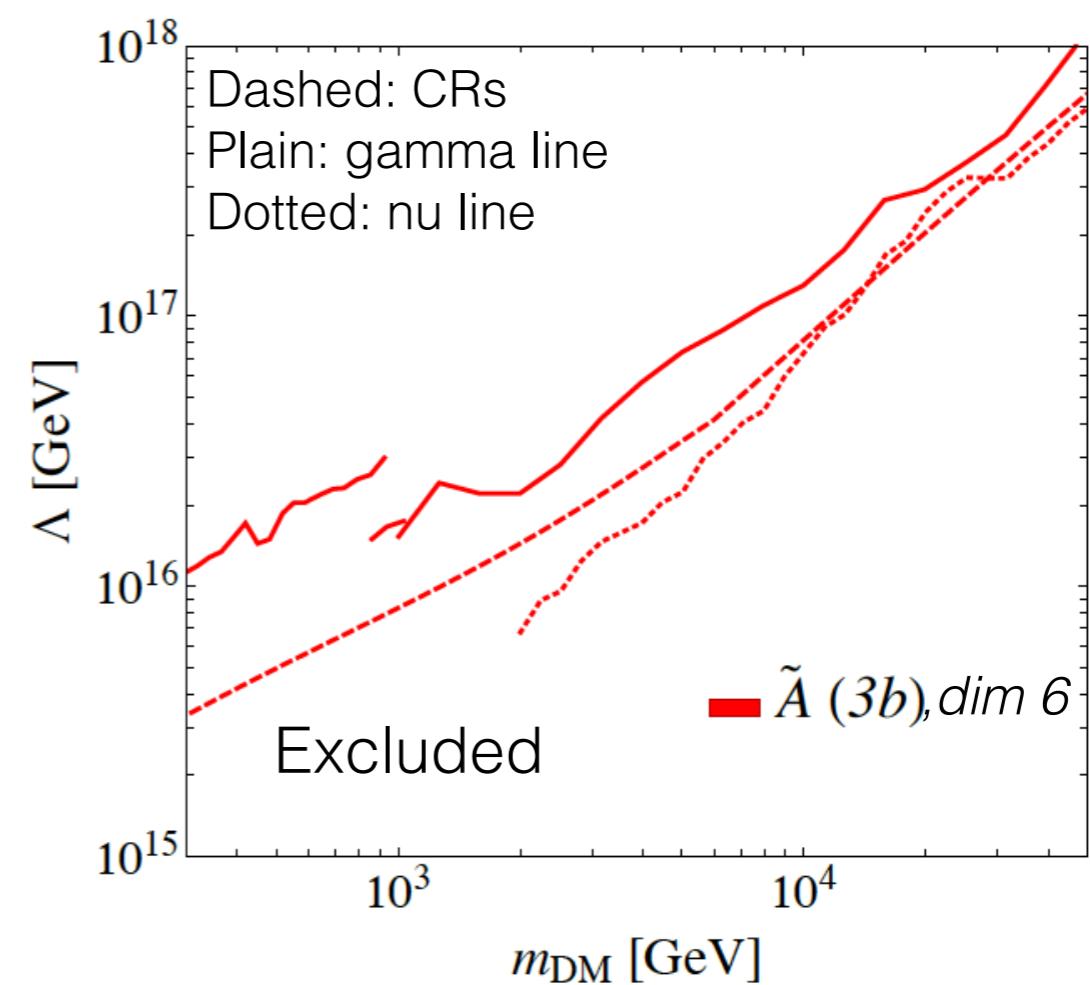
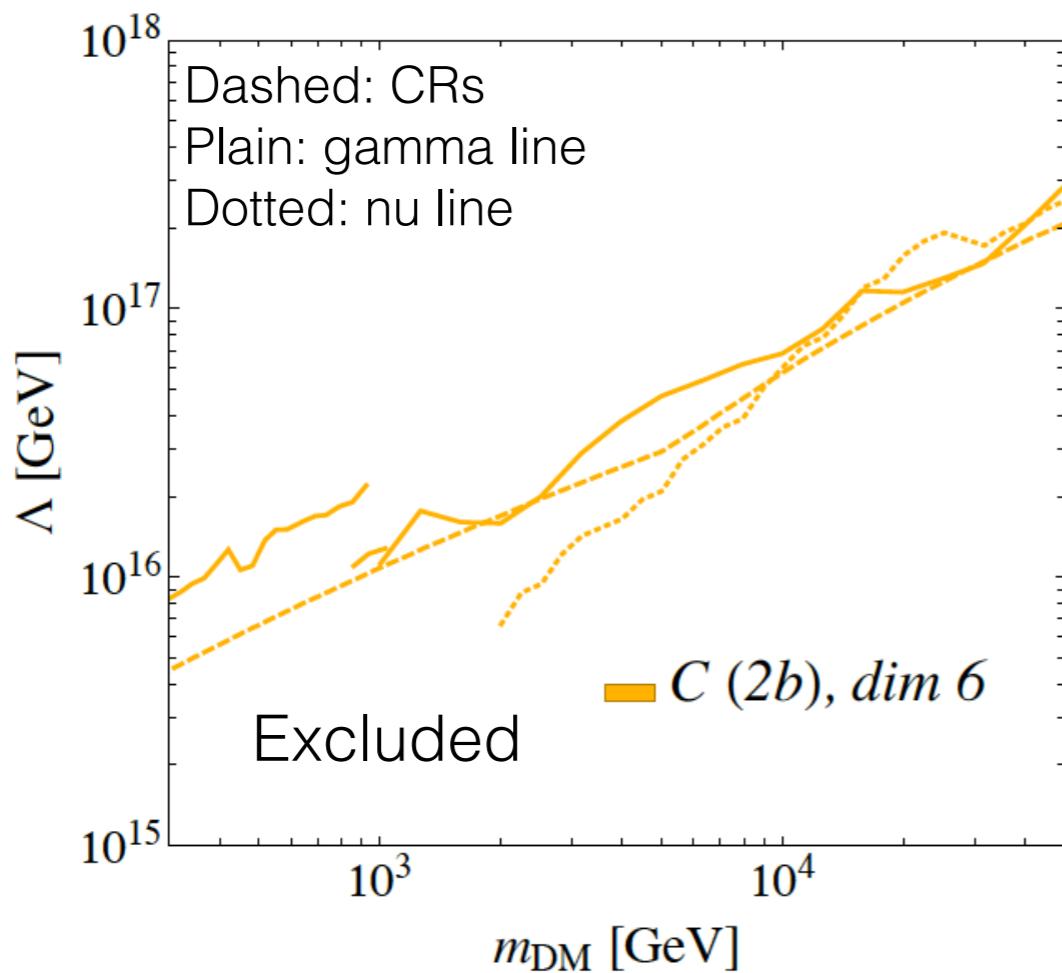


So, in the end, can I hope to see a “double smoking” gun?
(that is also compatible with current CR constraints?)

- Depends on the effective operator and DM field considered
- Depends on the DM mass



E.g.:

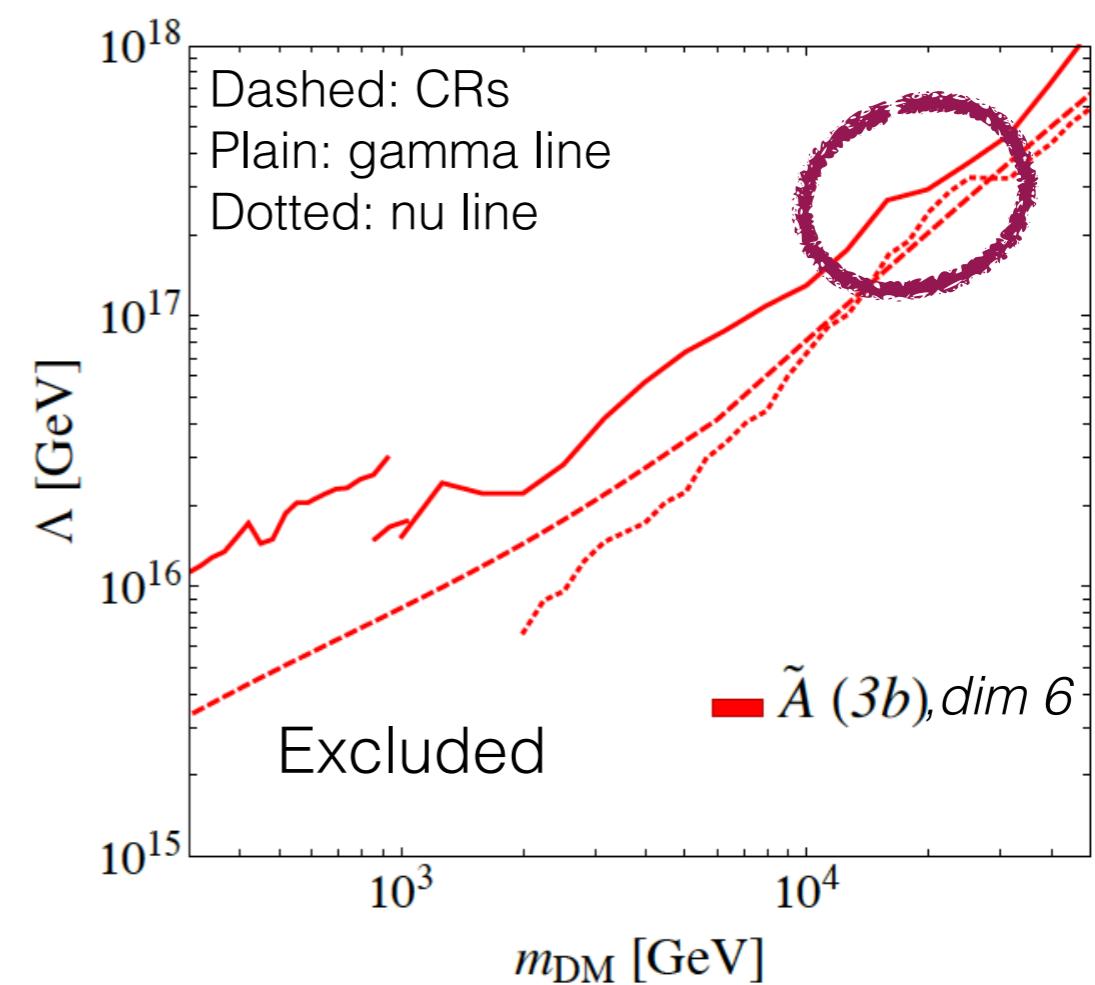
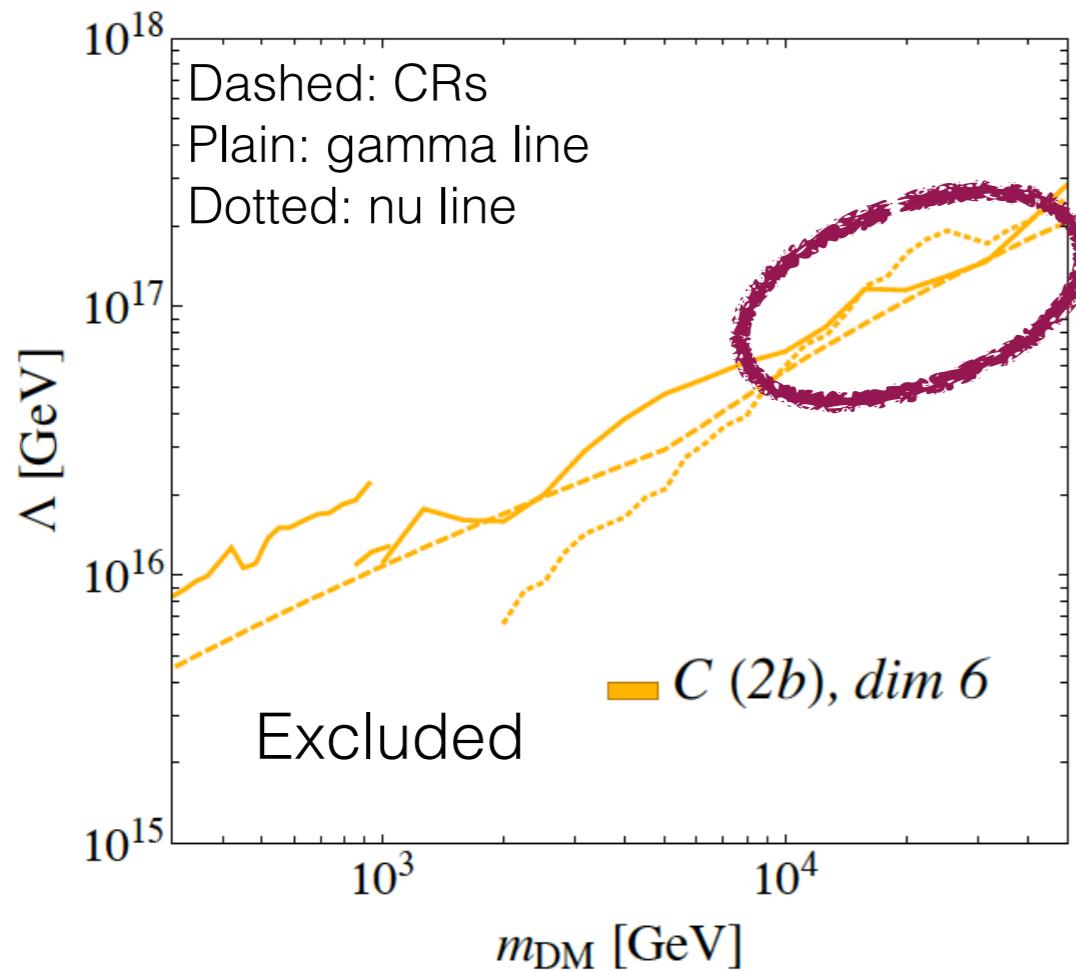




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E.g.:





TAKE AWAY MESSAGES

- These are times for major improvements in neutrino-line searches. They are now reaching gamma-line searches sensitivities in a broad part of the parameter space.
- Opens the way for probing ‘double smoking gun’ scenarios
- We studied such a scenario, namely DM decay into $\nu + \gamma$ using EFT.
- Double smoking guns (for a decaying DM) could be seen in the 10–50 TeV DM mass range.
- CRs induced by effective operators are a tool to help discriminate among operators

*i*Thank you for your attention!

Convolution with the detector's response function:

$$\frac{dN_\alpha}{dE_\nu d\Omega dE' d\cos\theta' d\phi'} = \frac{d(\phi_h + \phi_{eg})_\alpha}{dE_\nu d\Omega} \cdot A_{\text{eff},\alpha} \cdot T \cdot D_{\text{eff},\alpha}$$

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

$D_{\text{eff},\alpha}$ the dispersion function

E' the 'reconstructed' energy variable

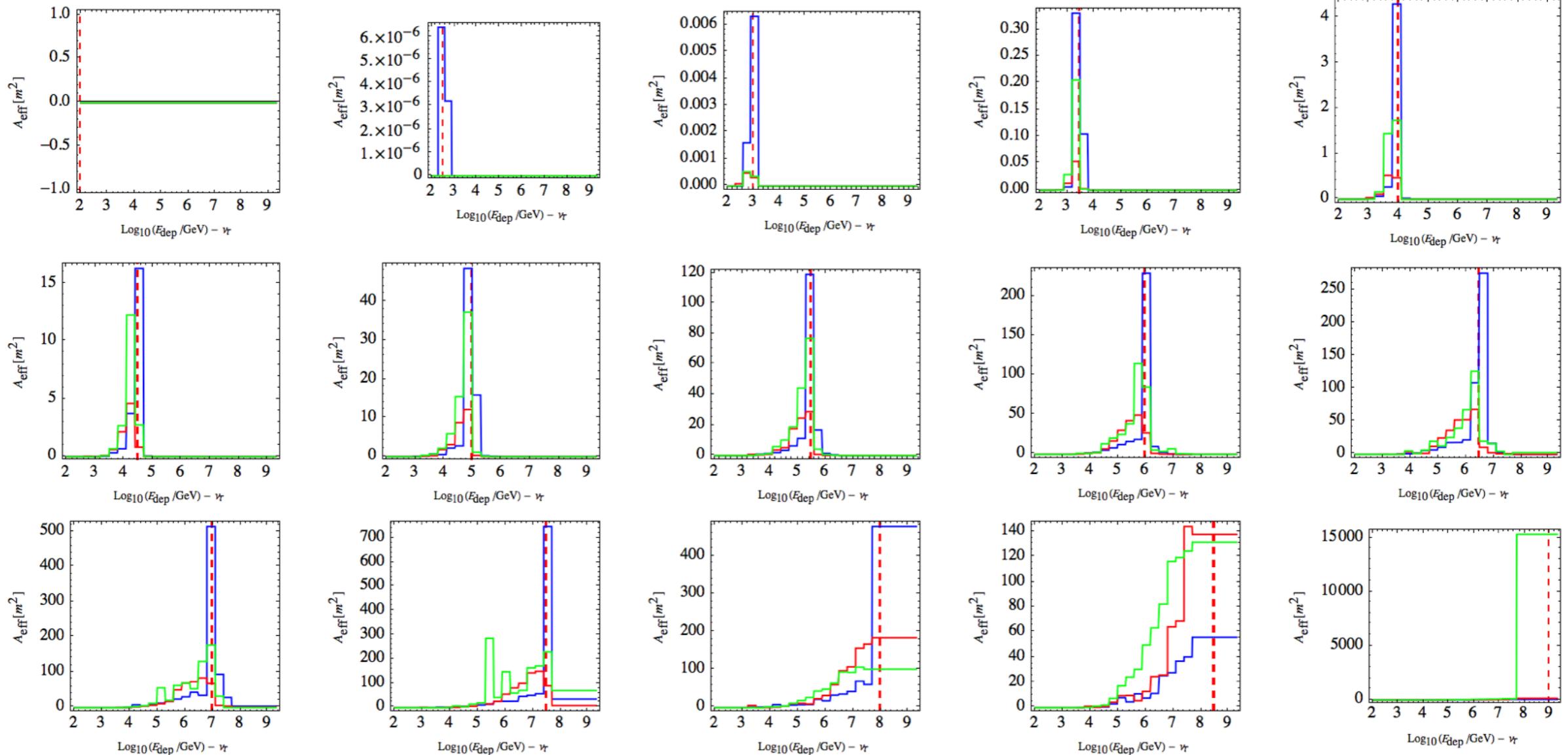
(θ', ϕ') solid angle.

Flavour composition

and then integrate

$$N_{\text{DM}}^i(m_{\text{DM}}, \tau_{\text{DM}}) = \int_{\Delta_i E'} dE' \int_{\Delta\theta'(t)} d\cos\theta' \int_{\Delta\phi'(t)} d\phi' \int dE \int_{4\pi} d\Omega \sum_{\alpha=e, \mu, \tau, \bar{e}, \bar{\mu}, \bar{\tau}} P_\alpha \frac{dN_\alpha}{dE_\nu d\Omega dE' d\cos\theta' d\phi'}$$

Reconstruction of lines @ different energies

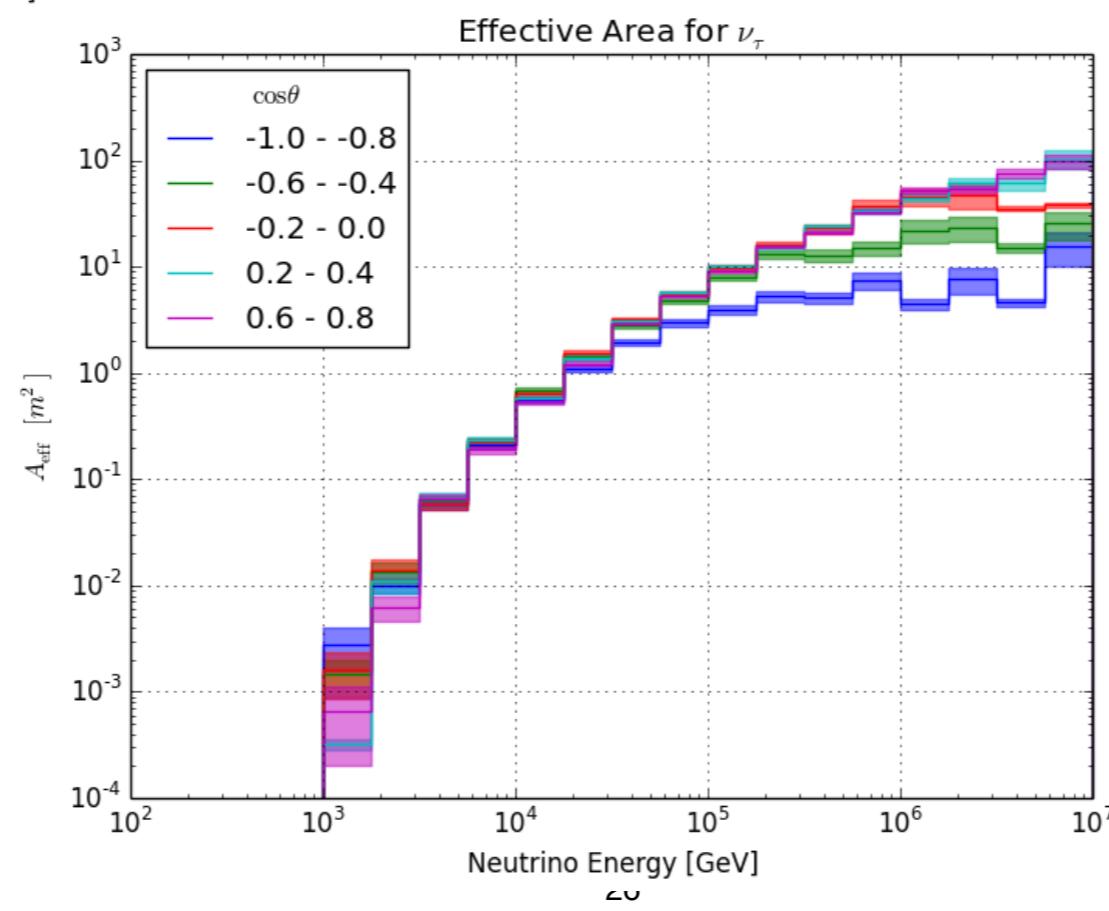
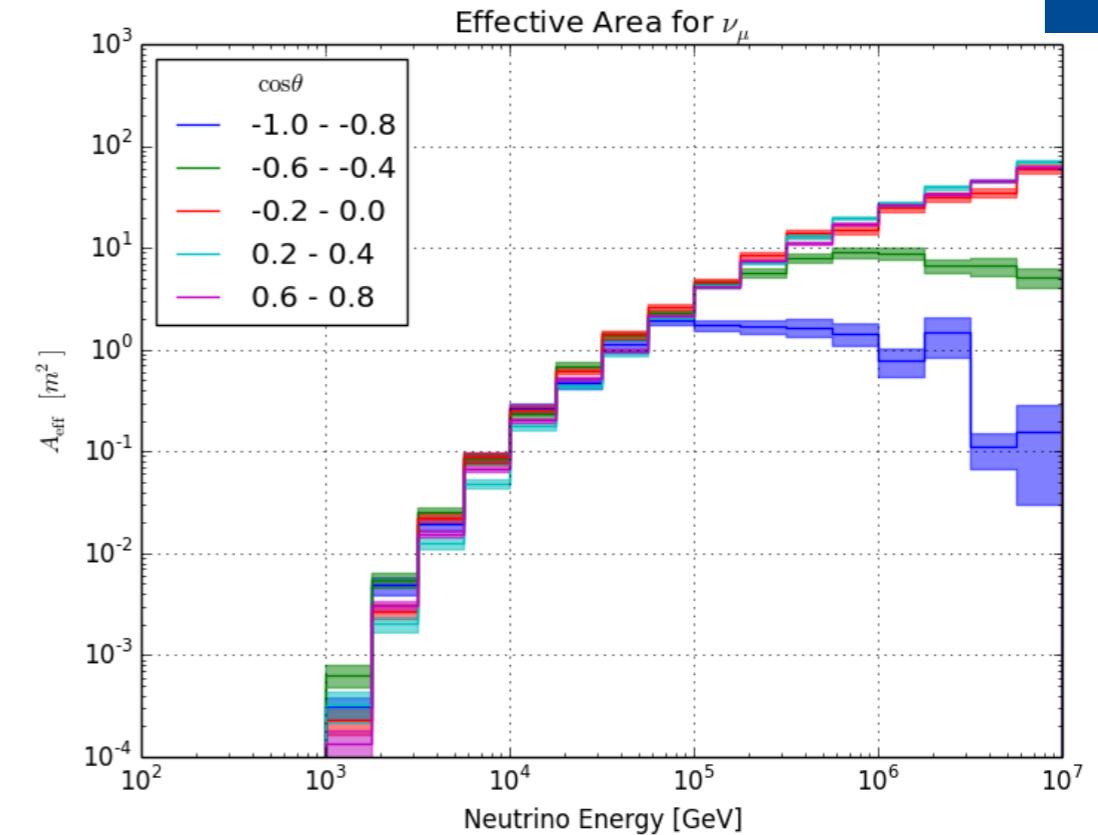
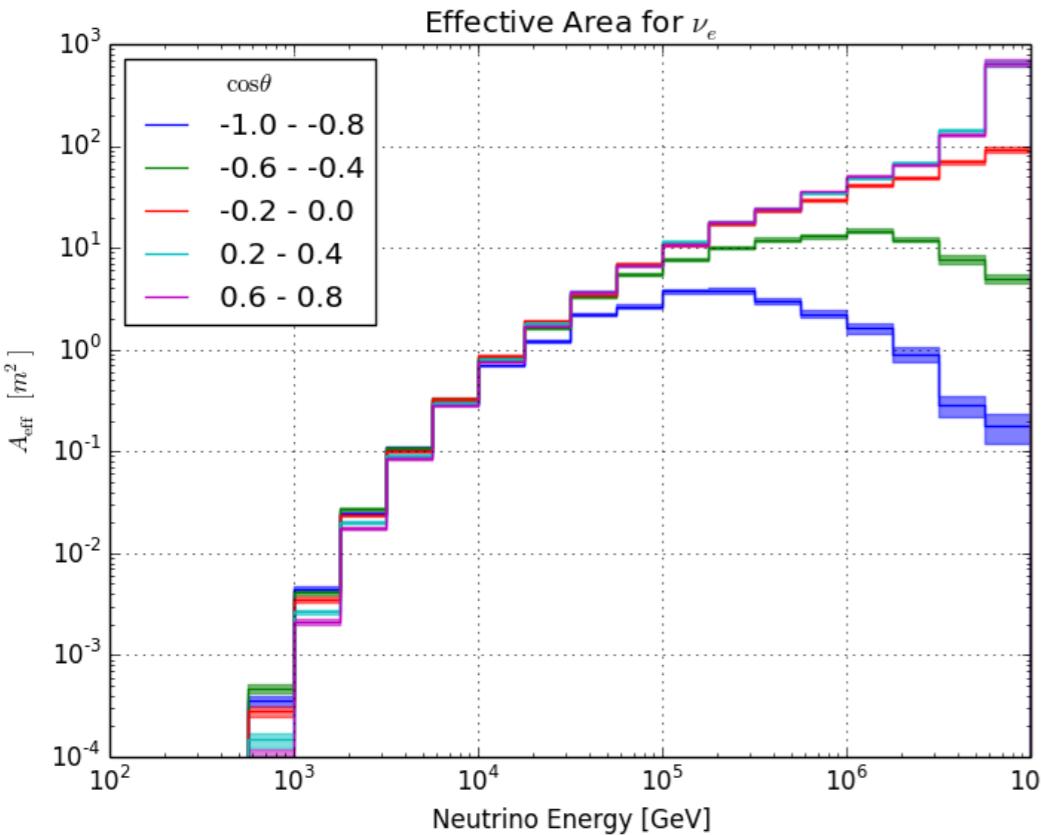


Blue: e-neutrinos

Green: mu-neutrinos

Red: Tau-neutrinos

Effective Areas

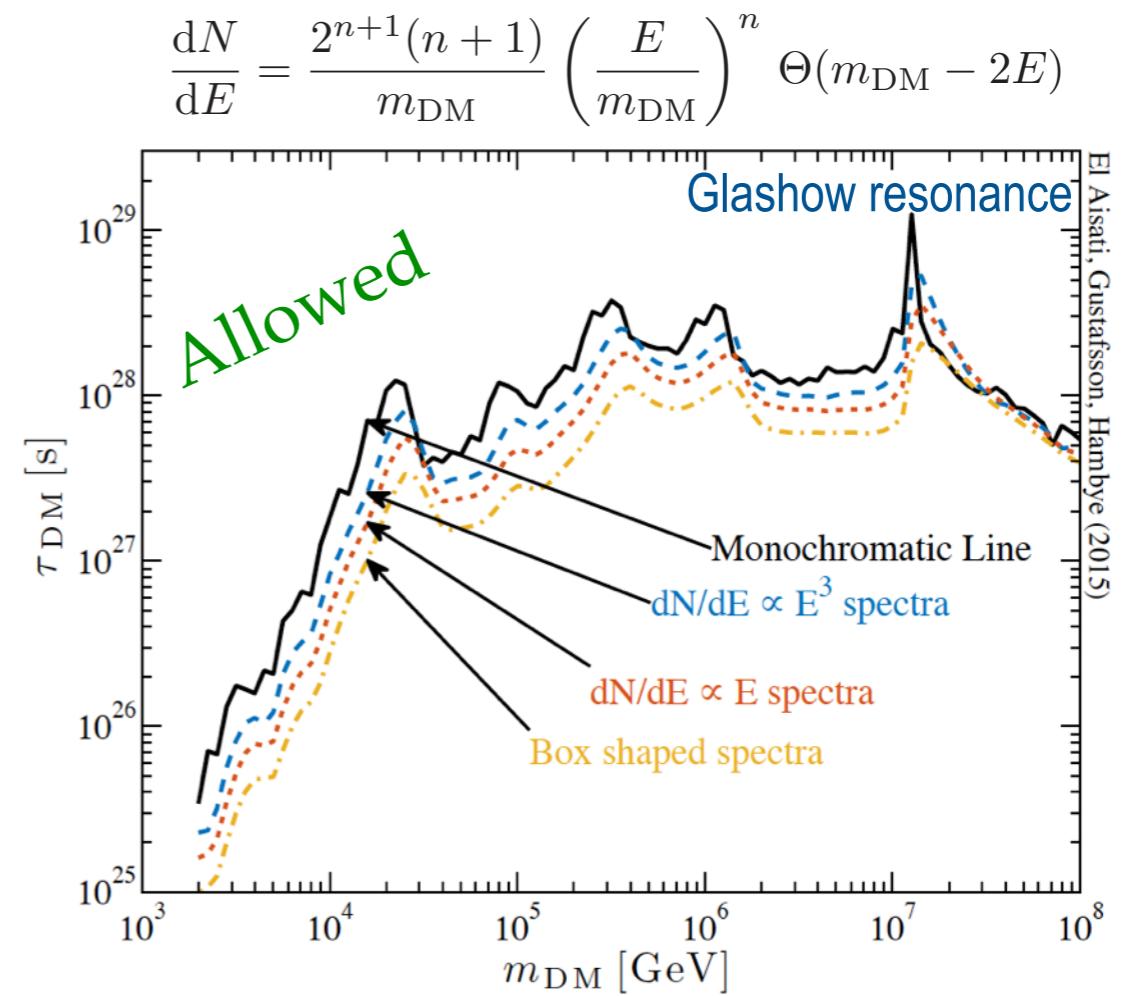
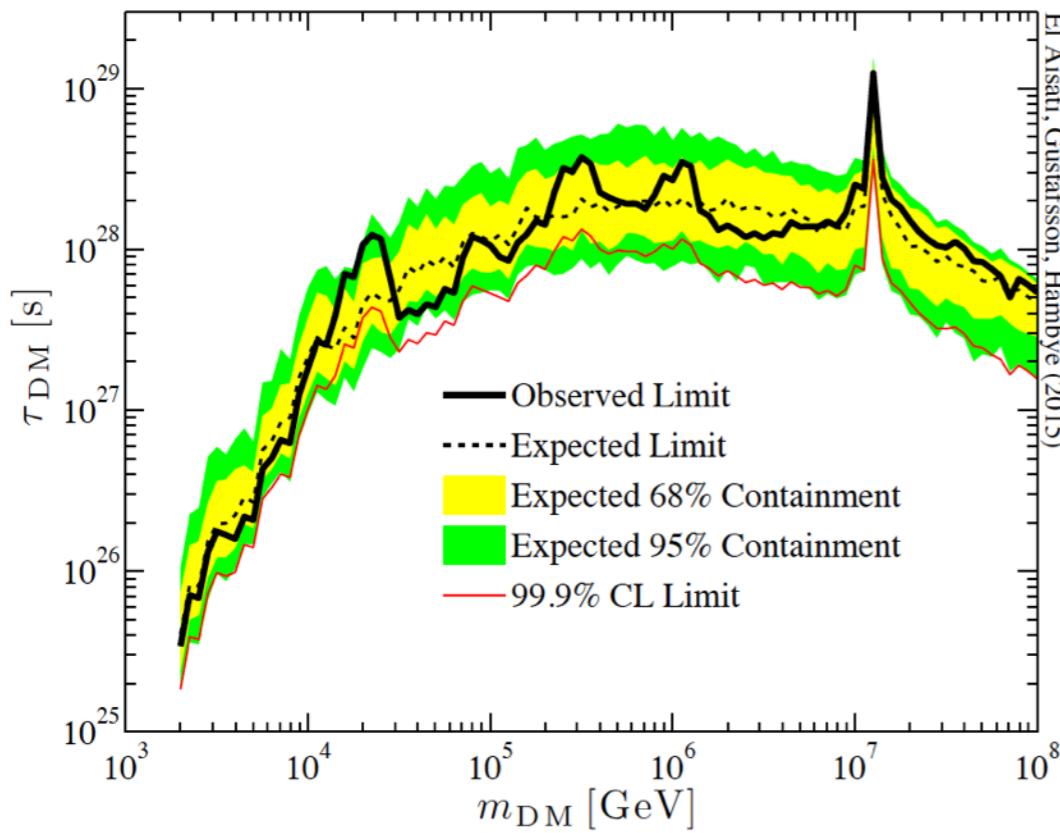


Deriving limits

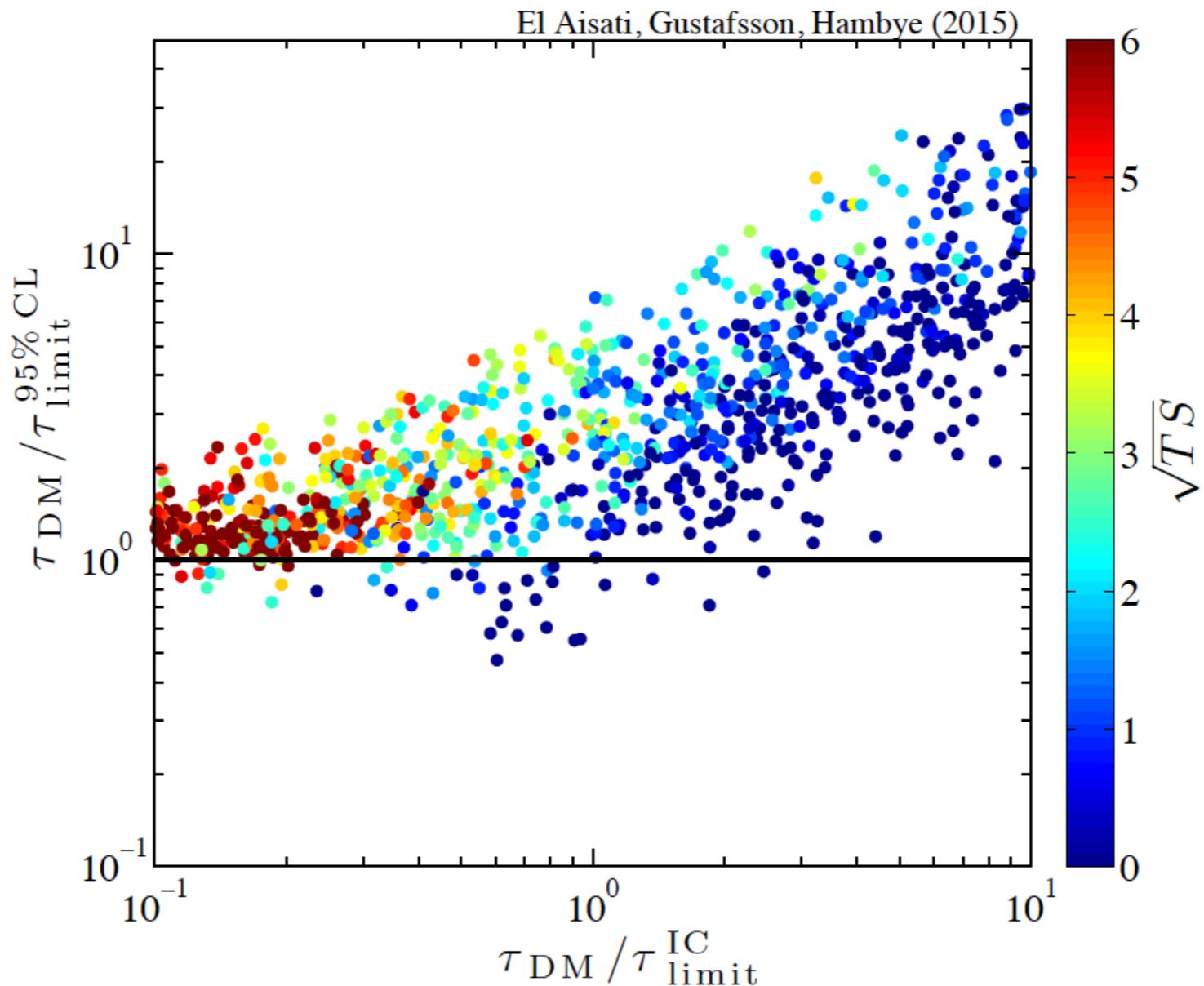
$$TS = 2 \ln \frac{\mathcal{L}(n_{\text{sig}} = n_{\text{sig,best}}, \hat{\theta})}{\mathcal{L}(n_{\text{sig}} = n_{\text{limit}}, \hat{\theta})}$$

(Profile Likelihood)

Keep DM lifetimes
that give $TS < 2.71$ (95% C.L.)



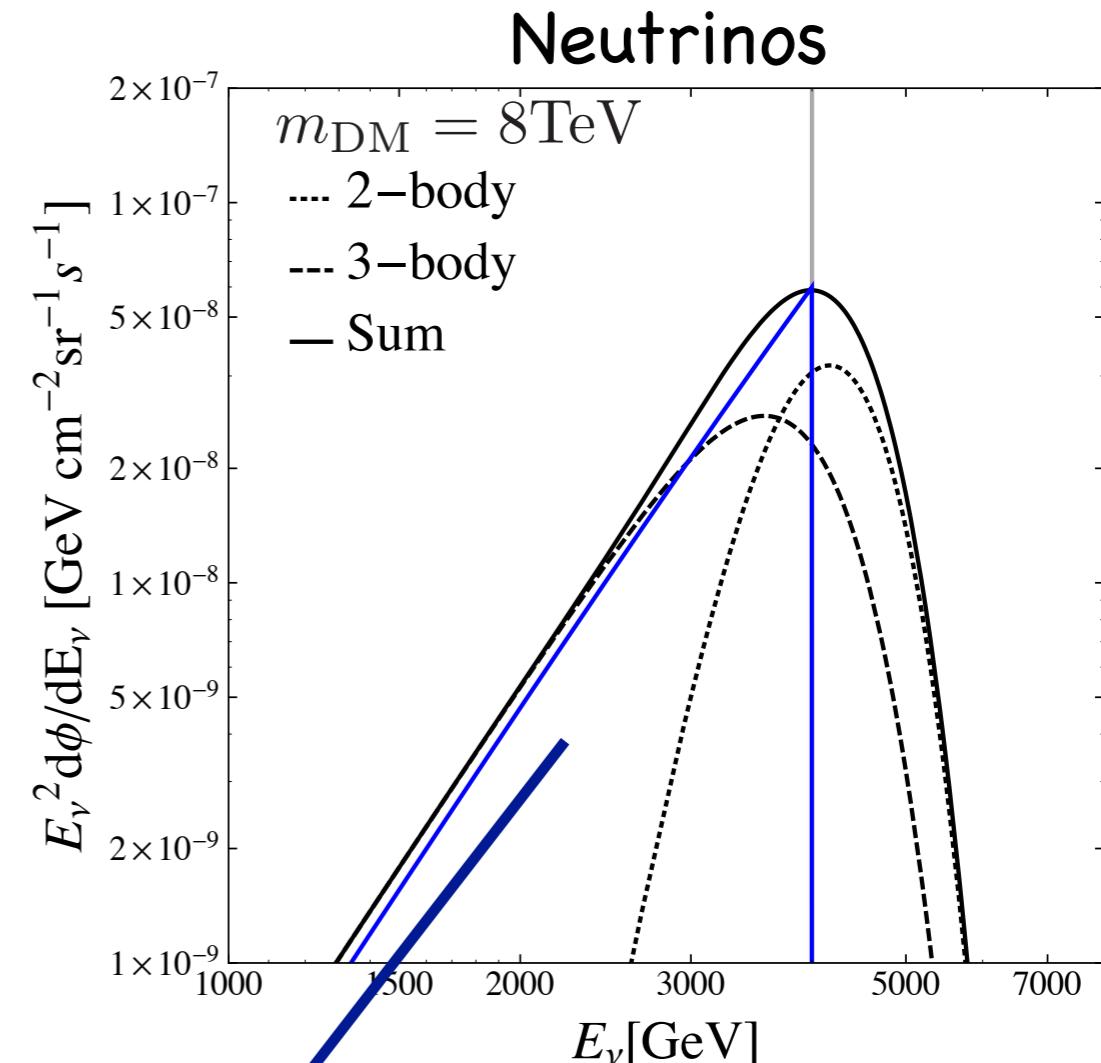
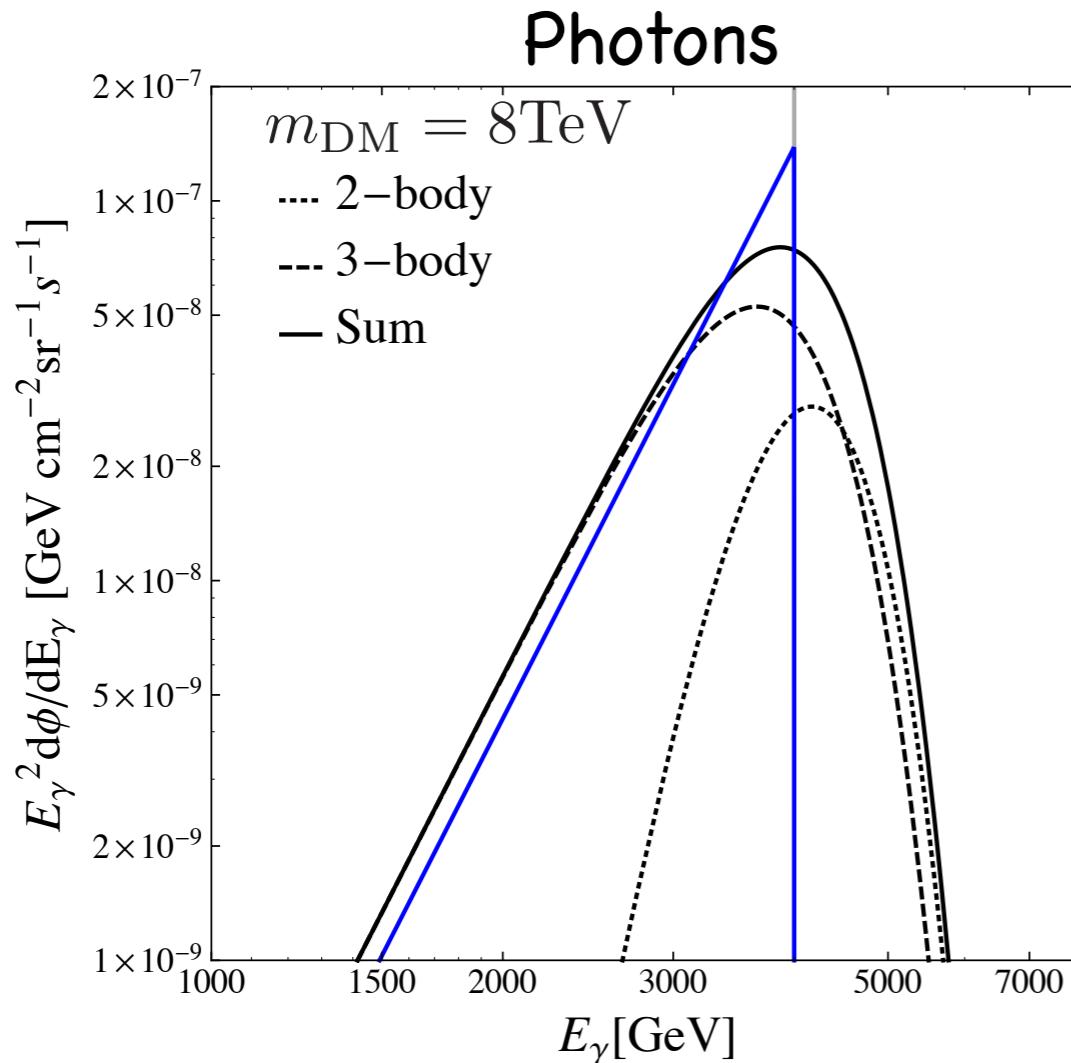
Statistical coverage



<i>DM field n-plet, Y</i>	<i>Operator</i>	<i>Prediction</i>	
		$R_{\nu/\gamma}$	$R_{\gamma/CR}$
1 0	\mathcal{O}_H^{1Y}	1.3	A
	\mathcal{O}_H^{1L}	4.3	E
2 -1	$\mathcal{O}^{(5)Y}, \mathcal{O}^{2Y}, \mathcal{O}^{3Y}$	1.3	A
	$\mathcal{O}^{(5)L}, \mathcal{O}^{2L}, \mathcal{O}^{3L}$	4.3	E
3 0	\mathcal{O}_H^{1Y}	1.3	A
	$\mathcal{O}_H^{1L,a}$	4.3	C
	$\mathcal{O}_H^{1L,d}, \mathcal{O}_H^{1L,f}$	4.3	D
	$\mathcal{O}_H^{1L,c}, \mathcal{O}_H^{1L,e}$	4.3	E
3 -2	$\mathcal{O}_{\tilde{H}}^{1Y}$	1.3	A
	$\mathcal{O}_{\tilde{H}}^{1L,e}$	4.3	C
	$\mathcal{O}_{\tilde{H}}^{1L,b}, \mathcal{O}_{\tilde{H}}^{1L,d}$	4.3	D
	$\mathcal{O}_{\tilde{H}}^{1L,c}$	4.3	E
	$\mathcal{O}_{\tilde{H}}^{1L,f}$	4.3	F
4 -1	$\mathcal{O}^{(5)L}, \mathcal{O}^{2L}, \mathcal{O}^{3L}$	4.3	D
5 0	\mathcal{O}_H^{1L}	4.3	D
5 -2	$\mathcal{O}_{\tilde{H}}^{1L}$	4.3	D

Other line-like features

$$\begin{aligned} \bar{L}\sigma_{\mu\nu}\psi_{\text{DM}}F_Y^{\mu\nu}\phi \\ \bar{L}\sigma_{\mu\nu}\psi_{\text{DM}}F_L^{\mu\nu}\phi \end{aligned}$$



$\nu\gamma h, \nu\gamma Z_L, l\gamma W_L$

$$\frac{dN}{dE_\gamma} = \frac{64}{m_{\text{DM}}} \left(\frac{E_\gamma}{m_{\text{DM}}} \right)^3 \Theta \left(\frac{m_{\text{DM}}}{2} - E_\gamma \right)$$

$\nu\gamma h, \nu\gamma Z_L, \nu Zh, \nu ZZ_L, \nu WW_L$

$$\frac{dN}{dE_\nu} = \frac{32}{m_{\text{DM}}} \left(1 - \frac{2E_\nu}{3m_{\text{DM}}} \right) \left(\frac{E_\nu}{m_{\text{DM}}} \right)^2 \Theta \left(\frac{m_{\text{DM}}}{2} - E_\nu \right)$$

This type of spectrum can also be looked/searched for.

Some results ...

¿What about other Cosmic Rays?

They also provide upper limits on DM's decay widths.

