A Dark-Matter Interpretation of the ANITA Anomalous Events

In collaboration with

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The dark sector is still quite obscure…

What is Dark Matter?

(One unique particle? A set of particles? Primordial black holes?...)

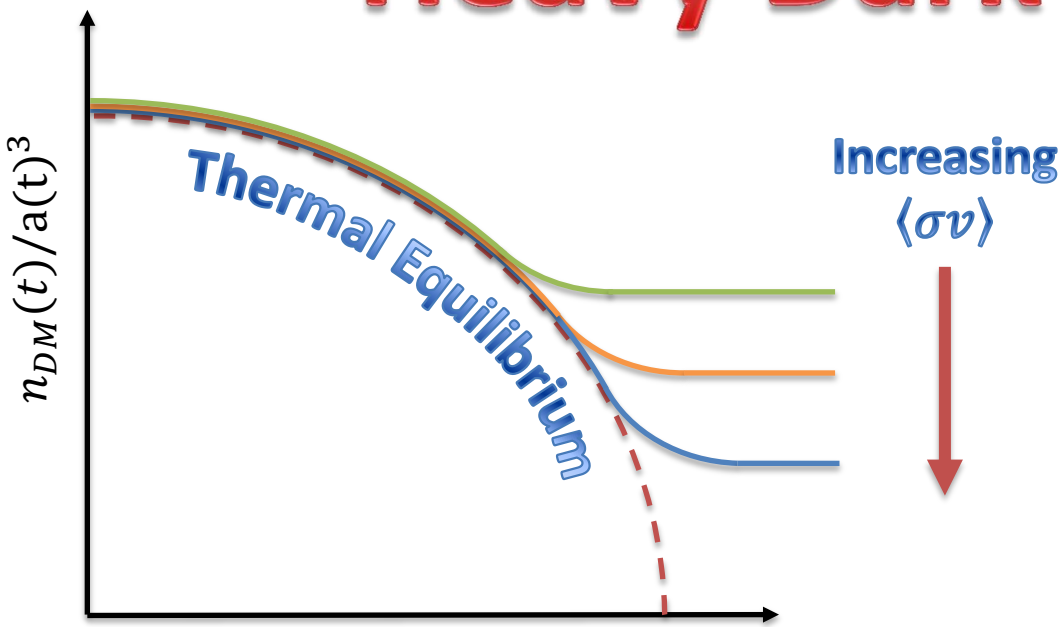
How is it produced?

(Thermal Freeze Out, Non-thermal/Freeze-In, dynamical dark matter , out-of-equilibrium decay …)

What is its mass?

(From micro-eV to … Infinity and beyond!)

Heavy Dark-Matter



Boltzmann Equation

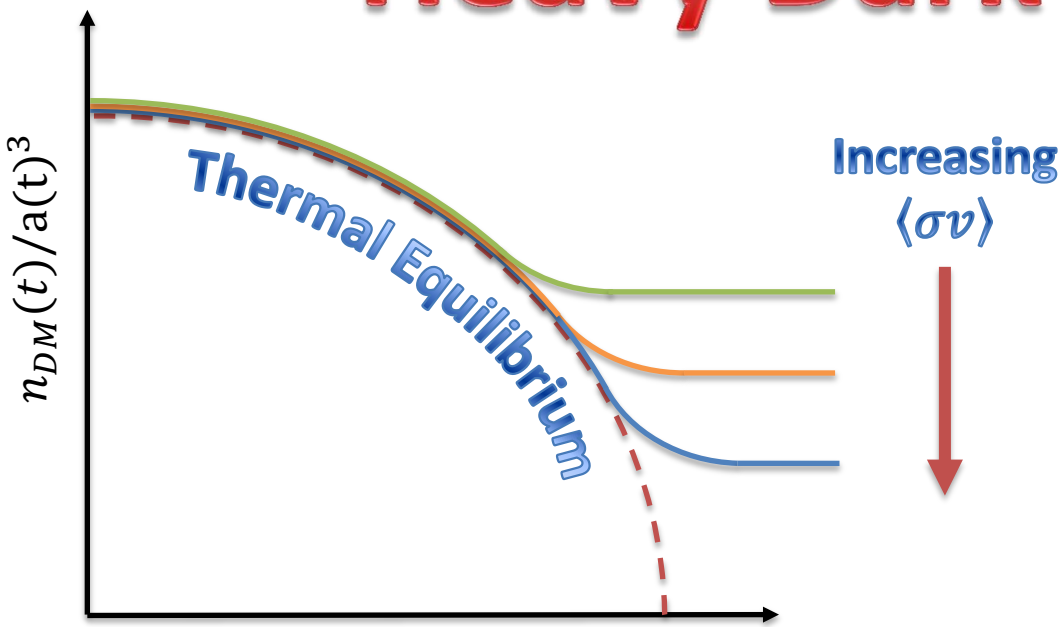
$$\frac{dn_{DM}}{dt} = -\langle\sigma v\rangle\left(n_{DM}^2 - n_{eq}^2\right)$$

Large Mass

Large annihilation cross section

Unitarity bound : $m_{DM} \lesssim O(100)$ TeV

Heavy Dark-Matter



Boltzmann Equation

$$\frac{dn_{DM}}{dt} = -\langle\sigma v\rangle\left(n_{DM}^2 - n_{eq}^2\right)$$

Heavy Dark-Matter (HDM) particles require the use of non-thermal production scenarios

(out-of equilibrium decay of heavy particles, gravitational production…)

Heavy Dark-Matter

How can one detect Heavy Dark-Matter particles ?

No Thermal equilibrium → Low interactions

Large Mass → Low number density

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Annihilation in the Galaxy ? $\propto n_{DM}^2$ Difficult…

Heavy Dark-Matter

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Direct detection ? Difficult…

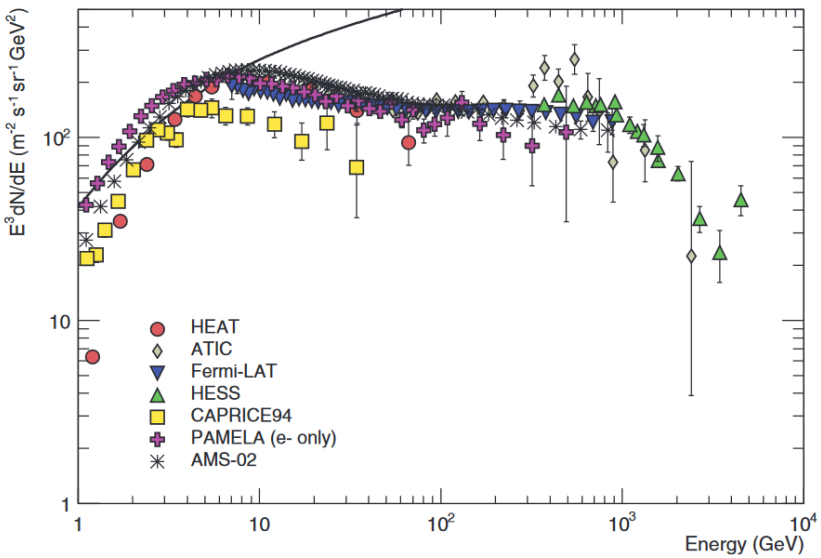
Annihilation in the Galaxy ? $\propto n_{DM}^2$ Difficult…

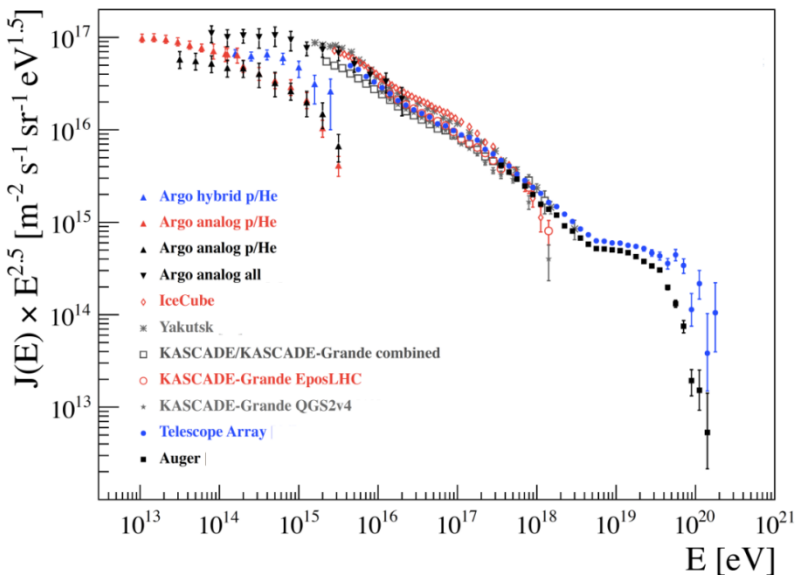
Decay in the Galaxy ? $\propto n_{DM}$ **Maybe ?**

How could we see HDM in the galaxy?

HDM decaying in the galaxy → Boosted decay products propagating …

Large cross section with the CMB, short lifetime, … → Decay products scatter or decay (photons, electrons, protons)





What about neutrinos ?

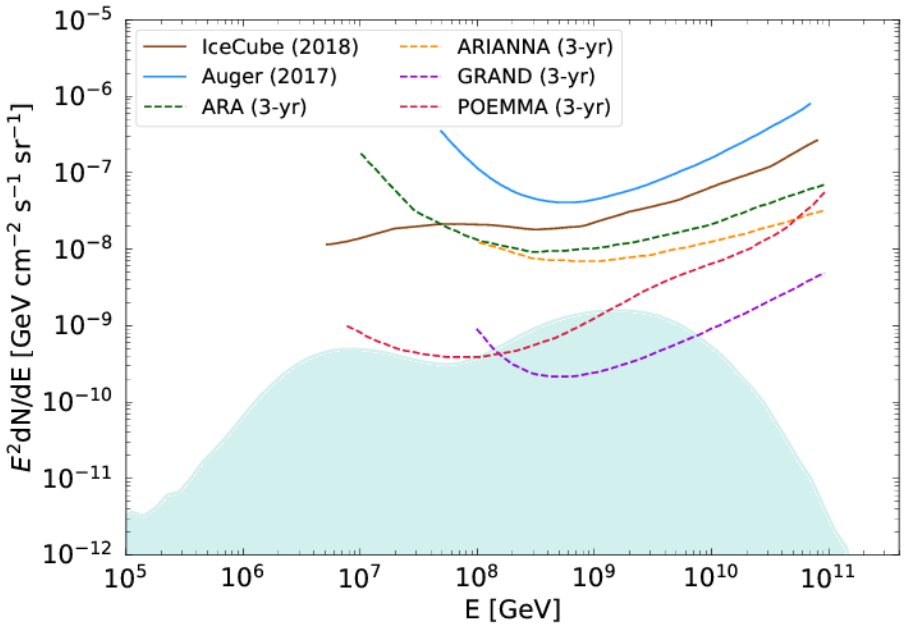
Neutrinos can propagate!

- Cosmogenic neutrinos expected at

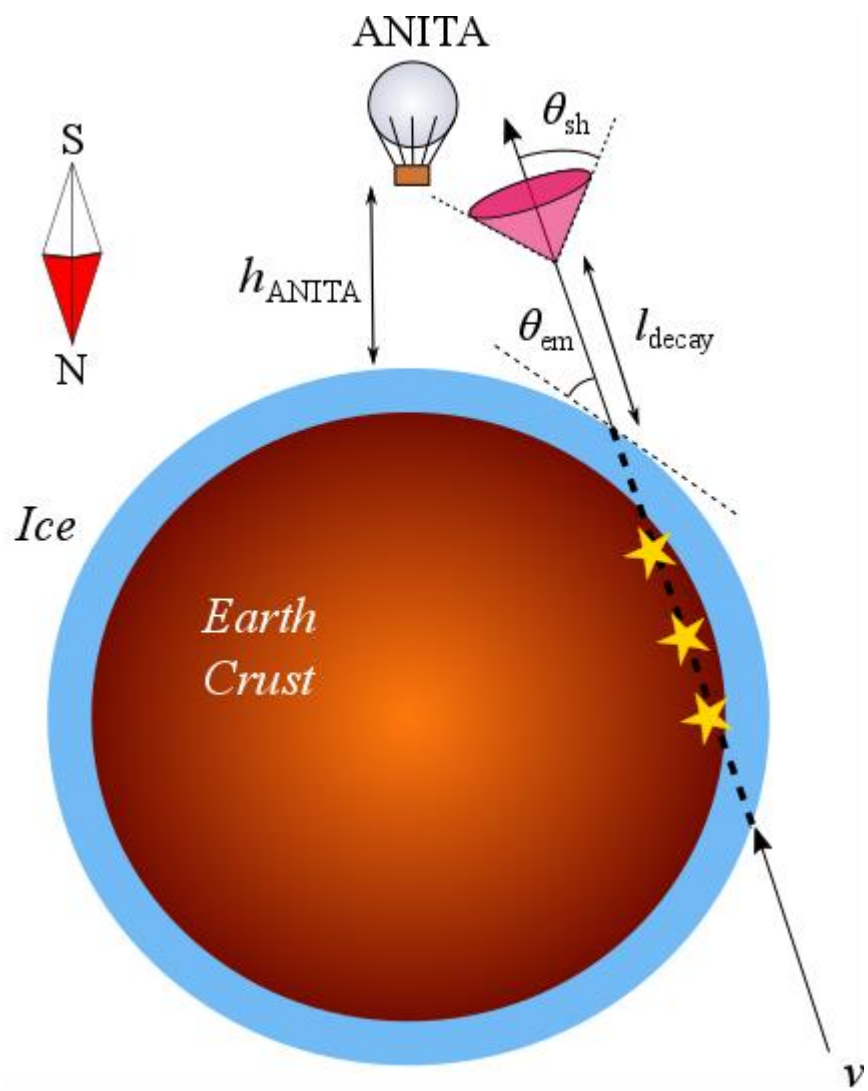
$$E \gtrsim 10^{19-20}\text{eV} \sim 1 - 10 \text{ EeV}$$

- (Very-)Heavy-particle decay might produce signals in neutrino detectors…

- A lot of observatories operating and being built…



The ANITA experiment



Three types of interactions in the SM:

- Charged current: Neutrinos → leptons
- Neutral current : Neutrinos → Neutrinos
- Regeneration: Lepton → Neutrino + sh.

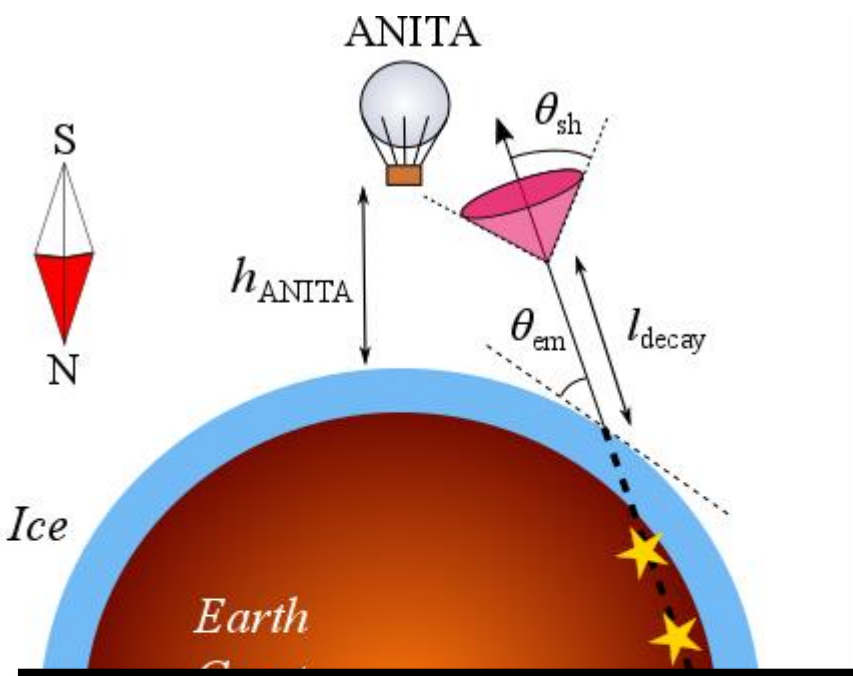
Propagation depends on the particle energy, local density, and particle interactions…

Two anomalous events with emergence angles 27° and 35° and energies O(1)EeV.

At such emergence angles, a SM neutrino cannot cross the Earth.

No astrophysical source identified.

The ANITA experiment



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Property	AAE 061228	AAE 141220
Flight & Event	ANITA-I #3985267	ANITA-III #15717147
Date & Time (UTC)	2006-12-28 00:33:20	2014-12-20 08:33:22.5
Equatorial coordinates (J2000)	R.A. 282.°14064, Dec. +20.°33043	R.A. 50.°78203, Dec. +38.°65498
Energy ε_{cr}	0.6 ± 0.4 EeV	$0.56^{+0.30}_{-0.20}$ EeV
Zenith angle z'/z	117.°4 / 116.°8 ± 0.°3	125.°0 / 124.°5 ± 0.°3
Earth chord length ℓ	5740 ± 60 km	7210 ± 55 km
Mean interaction length for $\varepsilon_\nu = 1$ EeV	290 km	265 km
$p_{SM}(\varepsilon_\tau > 0.1\,\text{EeV})$ for $\varepsilon_\nu = 1$ EeV	4.4×10^{-7}	3.2×10^{-8}
$p_{SM}(z > z_{obs})$ for $\varepsilon_\nu = 1$ EeV, $\varepsilon_\tau > 0.1$ EeV	6.7×10^{-5}	3.8×10^{-6}
n_τ(1–10 PeV) : n_τ(10–100 PeV) : n_τ(> 0.1 EeV)	34 : 35 : 1	270 : 120 : 1

The ANITA experiment

[Fox, Sigurdson, Murase *et al., Nov 18'*]

The SM can't explain ANITA events.

+

A re-analysis of IceCube data

Two upgoing events : energies O(0.01)EeV and emergence angles >30°.

<u>Question:</u> Can both signals have a common origin?

The ANITA experiment

A re-analysis of IceCube data

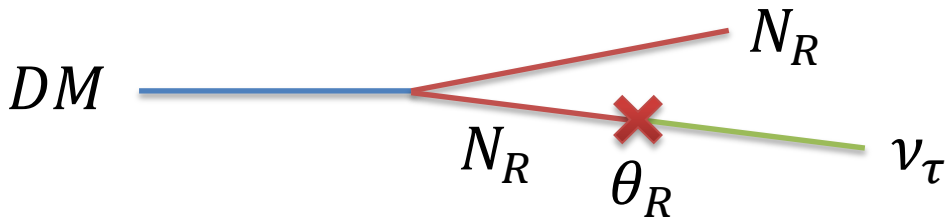
→ two upgoing events : energies O(0.01)EeV and emergence angles >30°.

Property	IceCube-140611	IceCube-140109	IceCube-121205
EHE Northern Track ID	#27	#24	#20
Date & Time (UTC or MJD)	2014-06-11 04:54:24	56666.5	56266.6
Equatorial coordinates (J2000)	R.A. $110.^\circ 34 \pm 0.^\circ 22$, Dec. $+11.^\circ 42 \pm 0.^\circ 08$	R.A. $293.^\circ 29$, Dec. $+32.^\circ 82$	R.A. $169.^\circ 61$, Dec. $+28.^\circ 04$
Zenith angle z	$101.^\circ 42$	$122.^\circ 82$	$118.^\circ 04$
Earth chord length ℓ	2535 km	6910 km	5990 km
As tau: $\varepsilon_{\tau,\mathrm{obs}}$ (median)	70 PeV	13 PeV	12 PeV
Mean interaction length for $\varepsilon_\nu = 1\,\mathrm{EeV}$	340 km	270 km	285 km
$p_{\mathrm{SM}}(\varepsilon_\tau > \varepsilon_{\tau,\mathrm{obs}})$ for $\varepsilon_\nu = 1\,\mathrm{EeV}$	2.2×10^{-4}	3.8×10^{-6}	1.0×10^{-5}
$p_{\mathrm{SM}}(z > z_{\mathrm{obs}})$ for $\varepsilon_\nu = 1\,\mathrm{EeV}$, $\varepsilon_\tau > \varepsilon_{\tau,\mathrm{obs}}$	5.0×10^{-3}	4.5×10^{-5}	1.8×10^{-4}

Question: Can both signals have a common origin?

A right-handed neutrino interpretation

Consider:



- A right-handed neutrino mixes with the tau neutrino
- A scalar dark-matter particle decays into sterile neutrinos in the galaxy

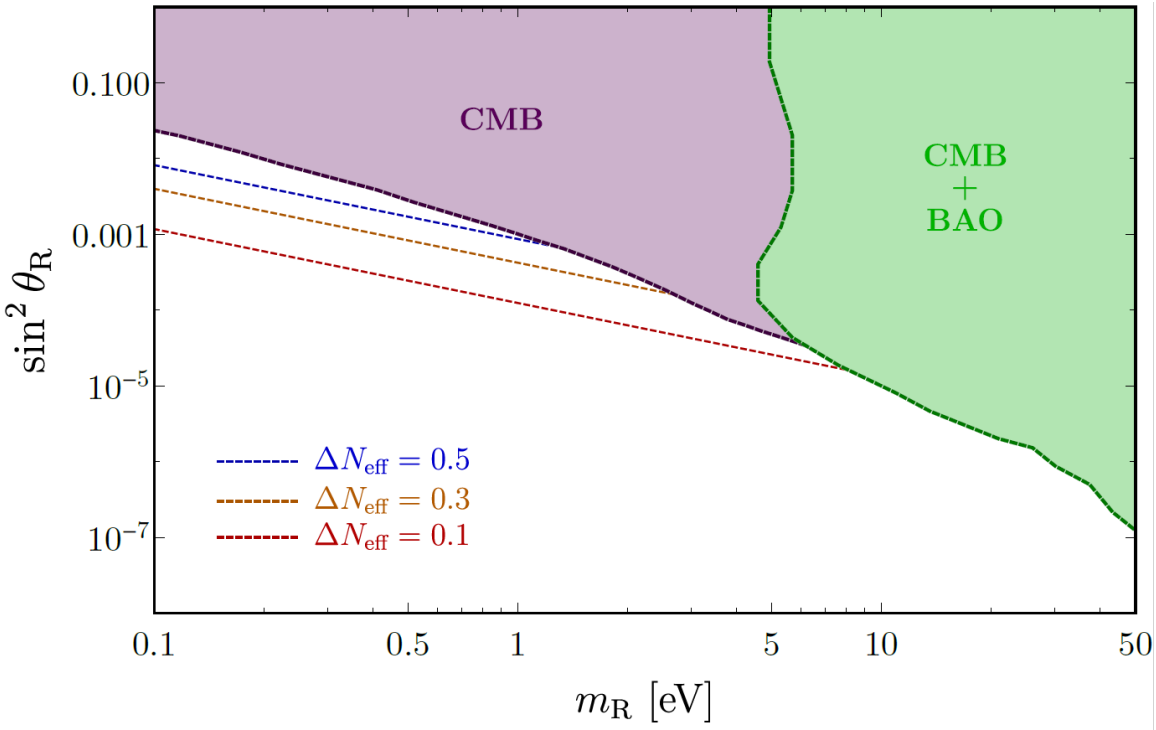
One needs:

→ RH neutrinos sufficiently long lived

→ To satisfy observational bounds (BBN, CMB, direct searches)

A right-handed neutrino interpretation

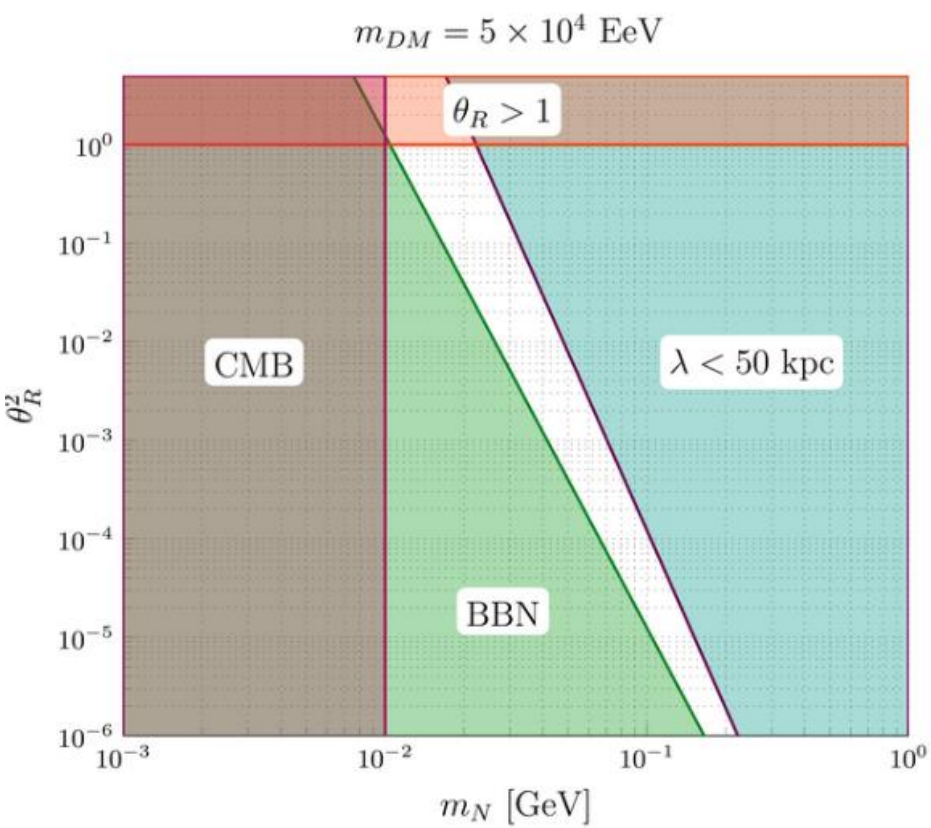
$m_R < 10$ eV or $m_R \sim 0.1$ GeV

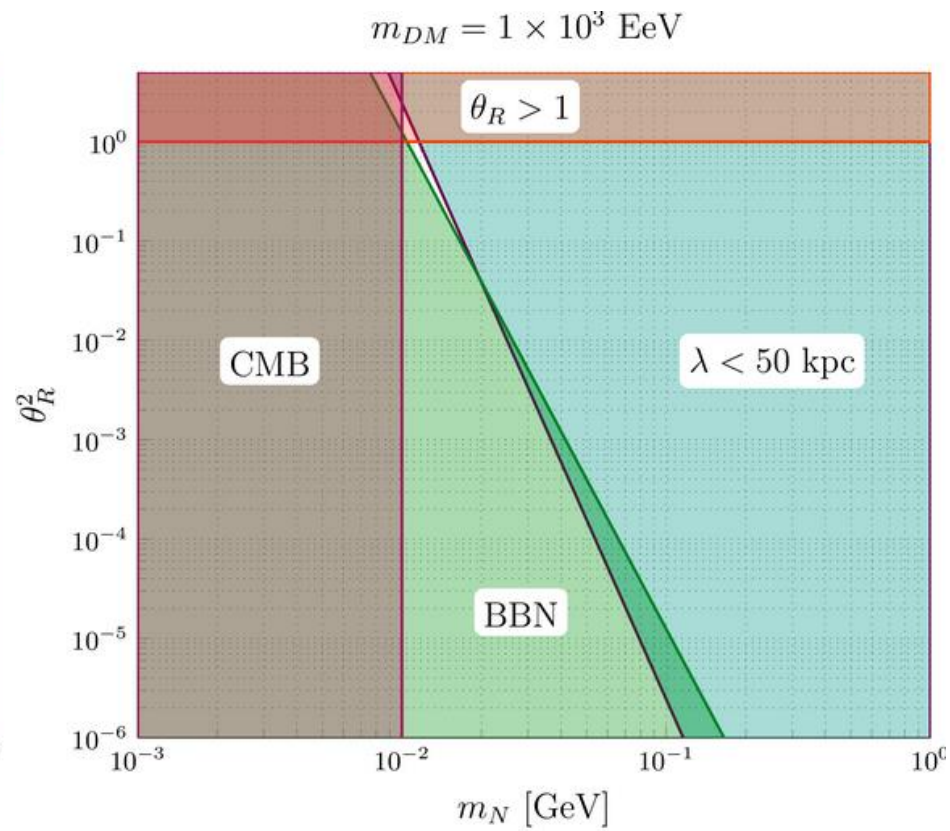


$m_R < 10$ eV → $m_{DM} \sim 10$ EeV

A right-handed neutrino interpretation

$$m_R < 10 \text{ eV or } m_R \sim 0.1 \text{ GeV}$$



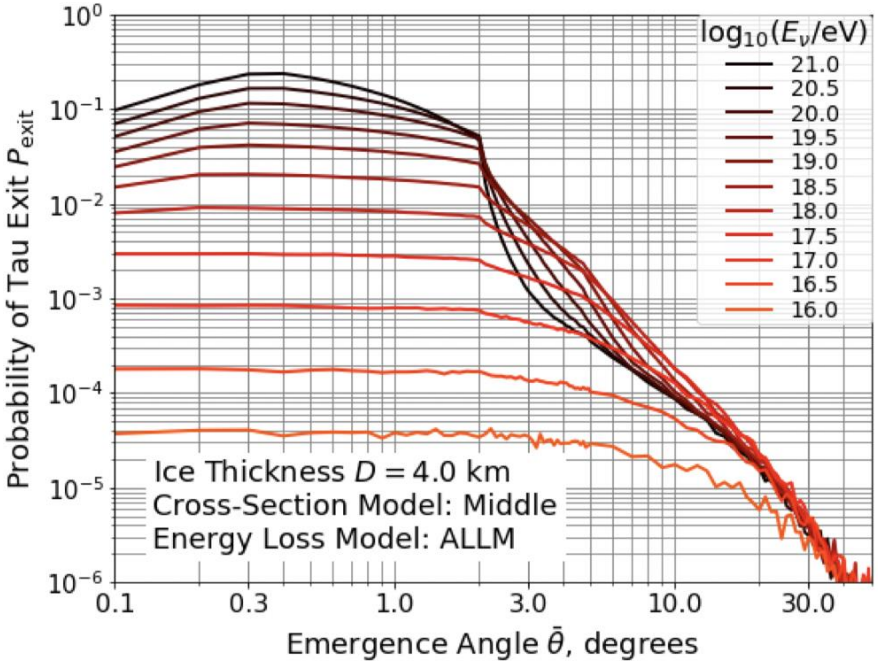


$m_R \sim 0.1$ GeV → $m_{DM} \gtrsim 10^3$ EeV $= 10^{12}$GeV

Approaches the inflaton mass…

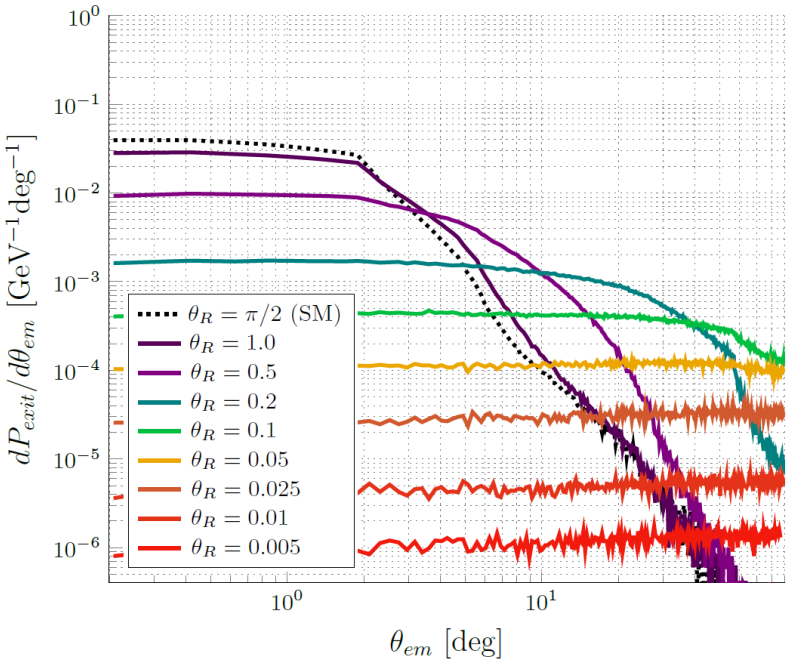
A right-handed neutrino interpretation

Propagation and conversion into tau's



SM

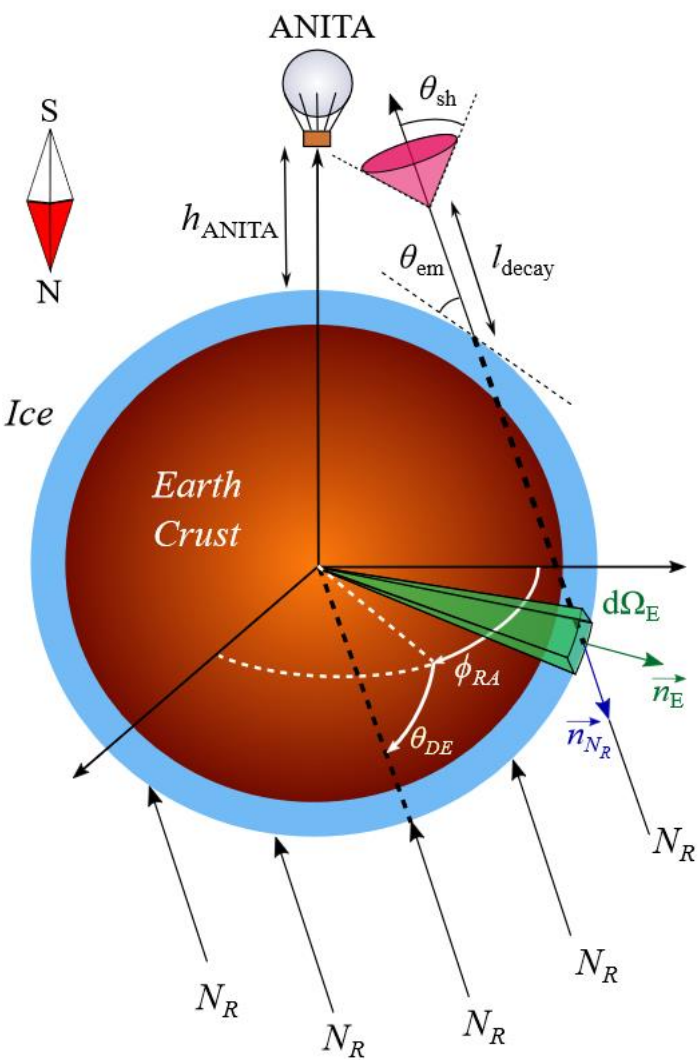
[Romero-Wolf *et al.*, Dec 17']



SM + RH neutrinos and mixing angle

[**LH**, Y. Mambrini, M. Pierre, '19]

Effective Area Calculation



$$\frac{\mathrm{d}^2 A_{\mathrm{eff}}}{\mathrm{d}E_{\mathrm{exit}}\mathrm{d}\theta_{\mathrm{em}}}(E_{\mathrm{exit}}, \theta_{\mathrm{em}} \mid E_{\mathrm{N}}, \theta_{\mathrm{N}}, \phi_{\mathrm{N}})$$

$$= R_{\mathrm{E}}^2 \int \mathrm{d}\Omega_{\mathrm{E}} \vec{n}_{\mathrm{N}} \cdot \vec{n}_E$$

$$\times \frac{\mathrm{d}P_{\mathrm{exit}}}{\mathrm{d}E_{\mathrm{exit}}}(E_{\mathrm{exit}}, \theta_{\mathrm{em}} \mid E_{\mathrm{N}}, \theta_{\mathrm{N}}, \phi_{\mathrm{N}}, \theta_{\mathrm{E}}, \phi_{\mathrm{E}})$$

$$\times \int \frac{\mathrm{d}P_{\mathrm{decay}}}{\mathrm{d}l}(l \mid E_{\mathrm{exit}}) \times P_{\mathrm{det}}(\theta_{\mathrm{sh}} | l, \theta_{\mathrm{N}}, \phi_{\mathrm{N}}, \theta_{\mathrm{E}}, \phi_{\mathrm{E}}) \mathrm{d}l$$

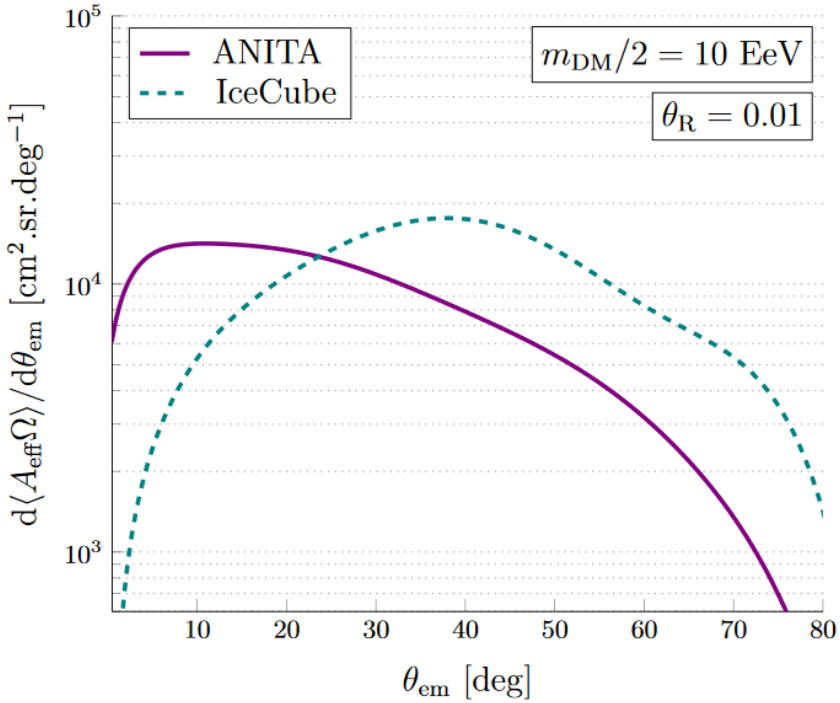
ANITA and IceCube detection

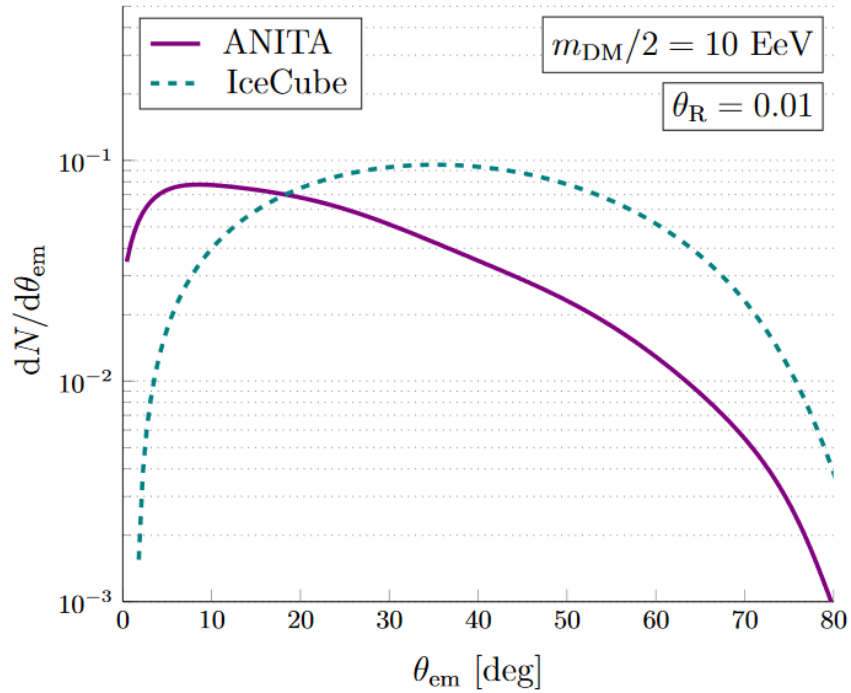
Simulate the detection probability of a shower for IceCube and ANITA

- IceCube : Fiducial volume of $(1km)^3$ under the Earth surface

- ANITA : shower must be produced in the low atmosphere, within a cone of around 1.5° away from the detector

ANITA and IceCube detection



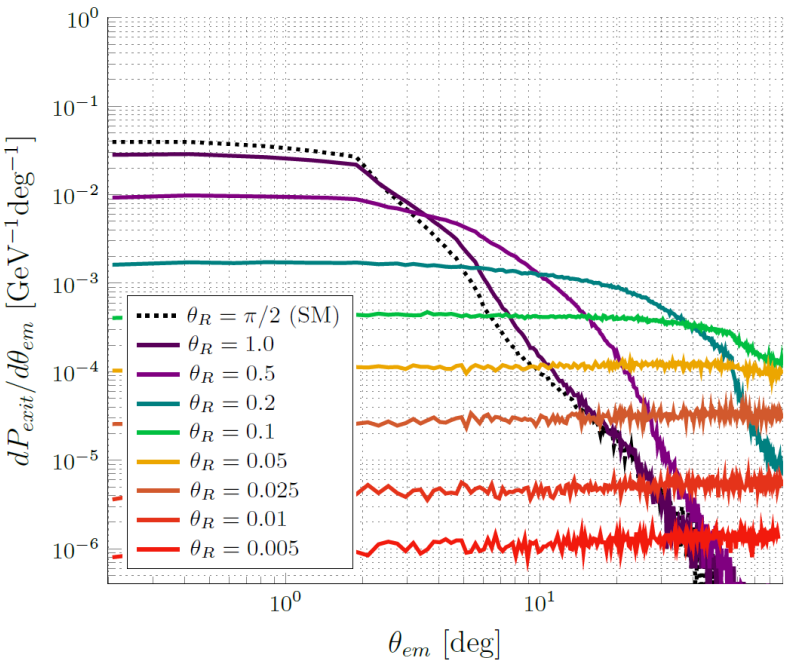


$$N_{\rm tot}^{\rm ANITA} \simeq 3.03 \left(\frac{\theta_R}{0.01}\right)^2 \left(\frac{10^{23}\mathrm{s}}{\tau_{\rm DM}}\right) \left(\frac{T_{\rm exp}}{85.5\ \mathrm{days}}\right) \left(\frac{20\ \mathrm{EeV}}{m_{\rm DM}}\right)^{0.67} \qquad [\ \theta_R \lesssim 0.025\,;\ m_{\rm DM} > 2\ \mathrm{EeV}\ ]$$

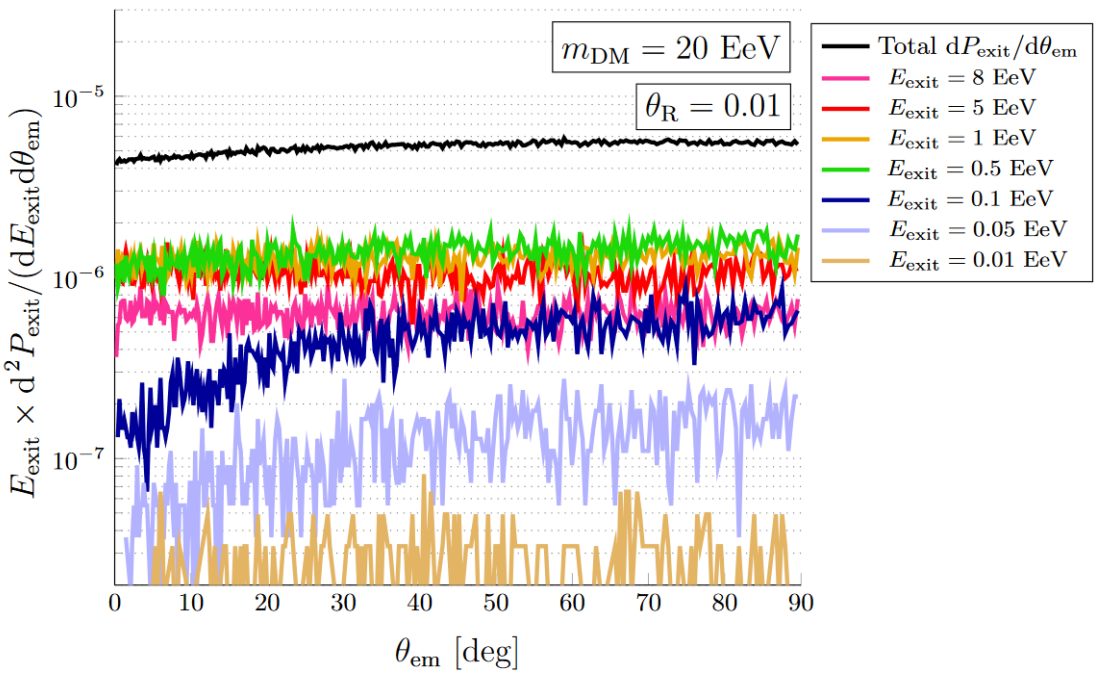
$$N_{\rm tot}^{\rm IceCube} \simeq 3.65 \left(\frac{\theta_R}{0.01}\right)^2 \left(\frac{10^{23}\mathrm{s}}{\tau_{\rm DM}}\right) \left(\frac{T_{\rm exp}}{3142.5\ \mathrm{days}}\right) \left(\frac{20\ \mathrm{EeV}}{m_{\rm DM}}\right)^{0.70} \qquad [\ \theta_R \lesssim 0.025\,;\ m_{\rm DM} > 2\ \mathrm{EeV}\ ]$$

Differential Exit Probability

Total Exit Probability

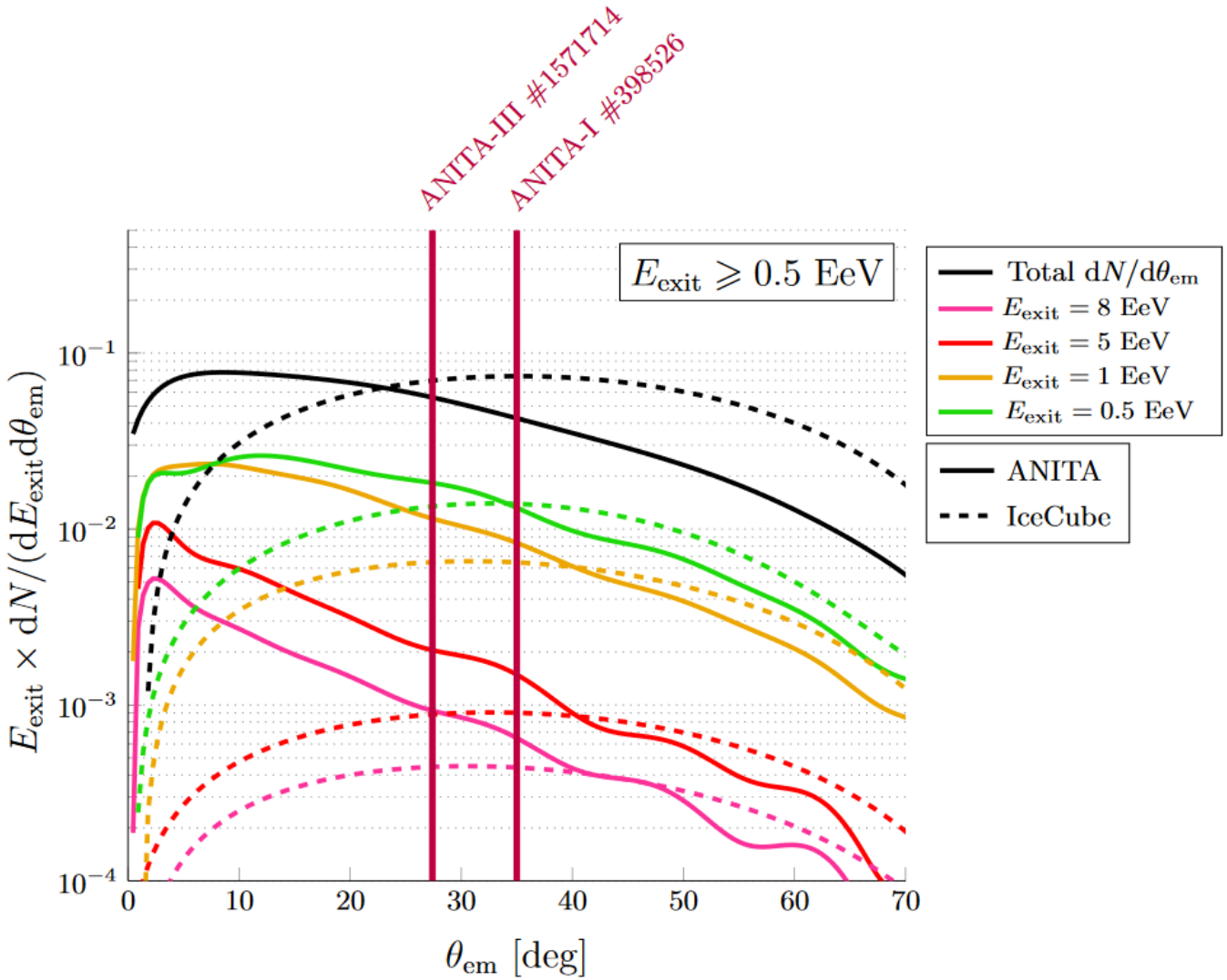


Diff. Exit Probability



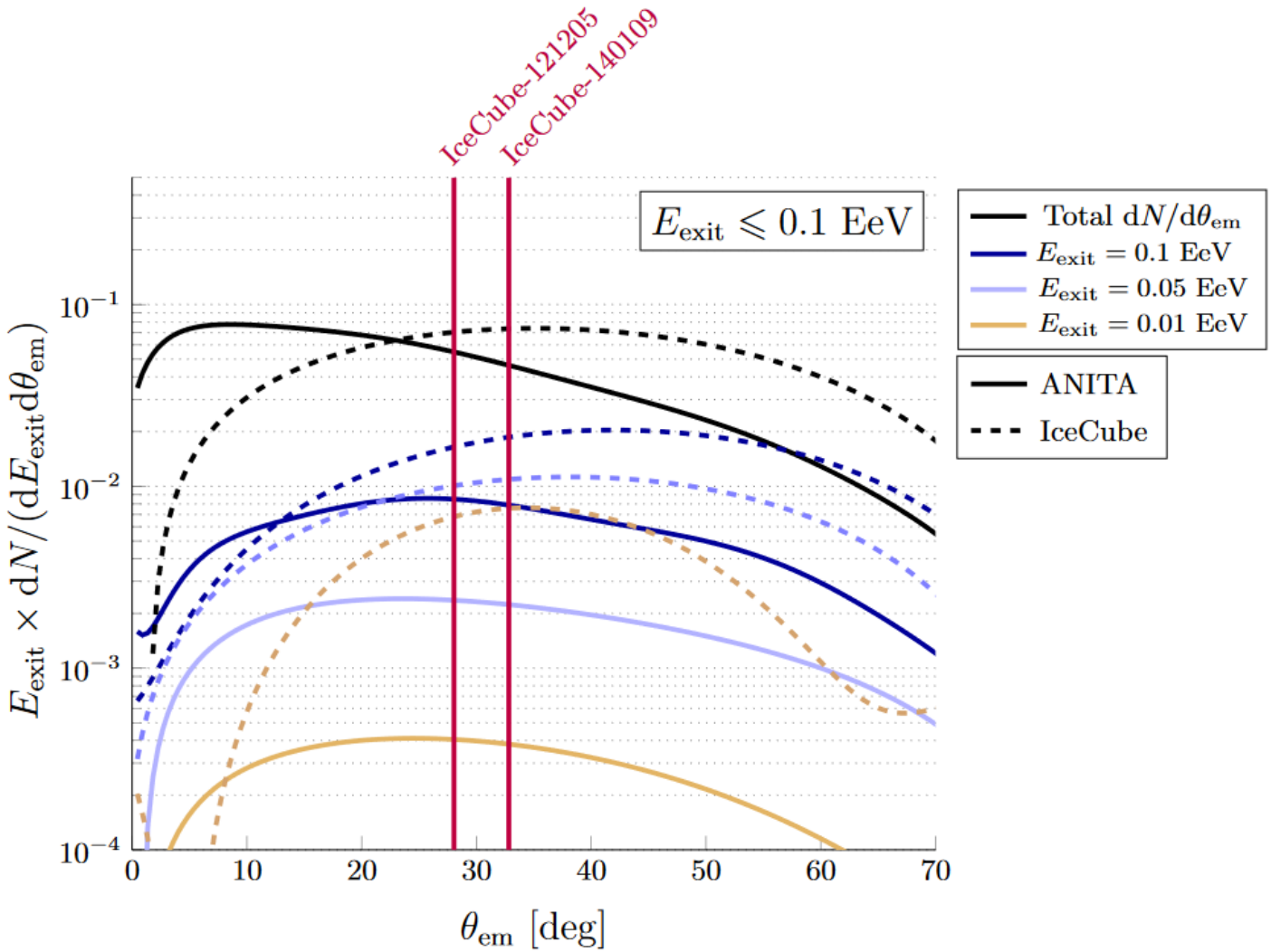
→ Access to the energy distribution per emergence angme of the predicted events

ANITA detection



[**LH**, Y. Mambrini, M. Pierre, '19]

IceCube detection



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Conclusion

- A dark matter of mass as large as $\gtrsim$ 1-10EeV decaying indirectly into neutrinos might lead to interesting signatures in the neutrino sector.
- The presence of a BSM sector modifies the way the neutrinos can propagate in the Earth
- A dark scalar decaying into right-handed neutrinos can explain the recent measurements of both IceCube and ANITA
- Given this model, a dark matter mass of mass >1-10 EeV predicts a perfect complementarity between the two collaborations.