Dark-Matter Interpretations of the ANITA Anomalous Events

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In collaboration with

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Based on Arxiv: **1902.04584, 1905.13223**

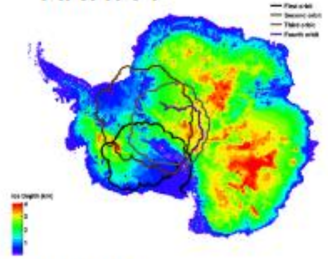
AstroParticle Symposium 2021

ANITA

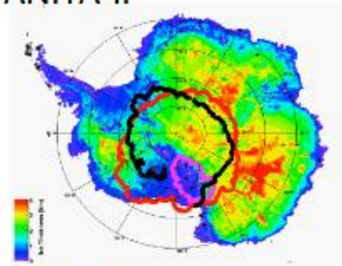
- ANtarctic Impulsive Transient Antenna
  - NASA ultralong duration balloon experiment
- Seeking radio signals from earth-skimming UHE neutrinos
- To this date, 4 flights

ANITA-Lite	ANITA-I	ANITA-II	**ANITA-III**	ANITA-IV
				
2003-2004	2006-2007	2008-2009	2014-2015	2016
18 days, 2 antennas	35 days, 32 antennas	30 days, 40 antennas	22 days, 48 antennas	29 days, 48 antennas
Piggy-back on TIGER	Multi-band, Pol-independent trigger	Multi-band, VPol trigger	Full-band HPol + VPol trigger	Full-band, Lin-Pol trigger
Analyzed	Analyzed	Analyzed	**Recently analyzed**	Analysis Ongoing

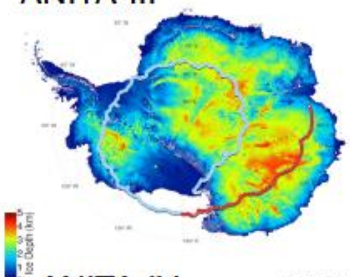
ANITA-I



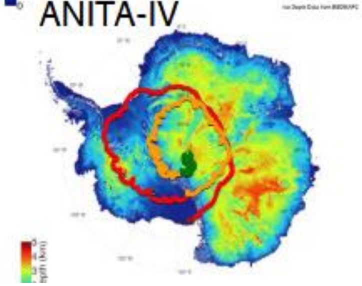
ANITA-II



ANITA-III

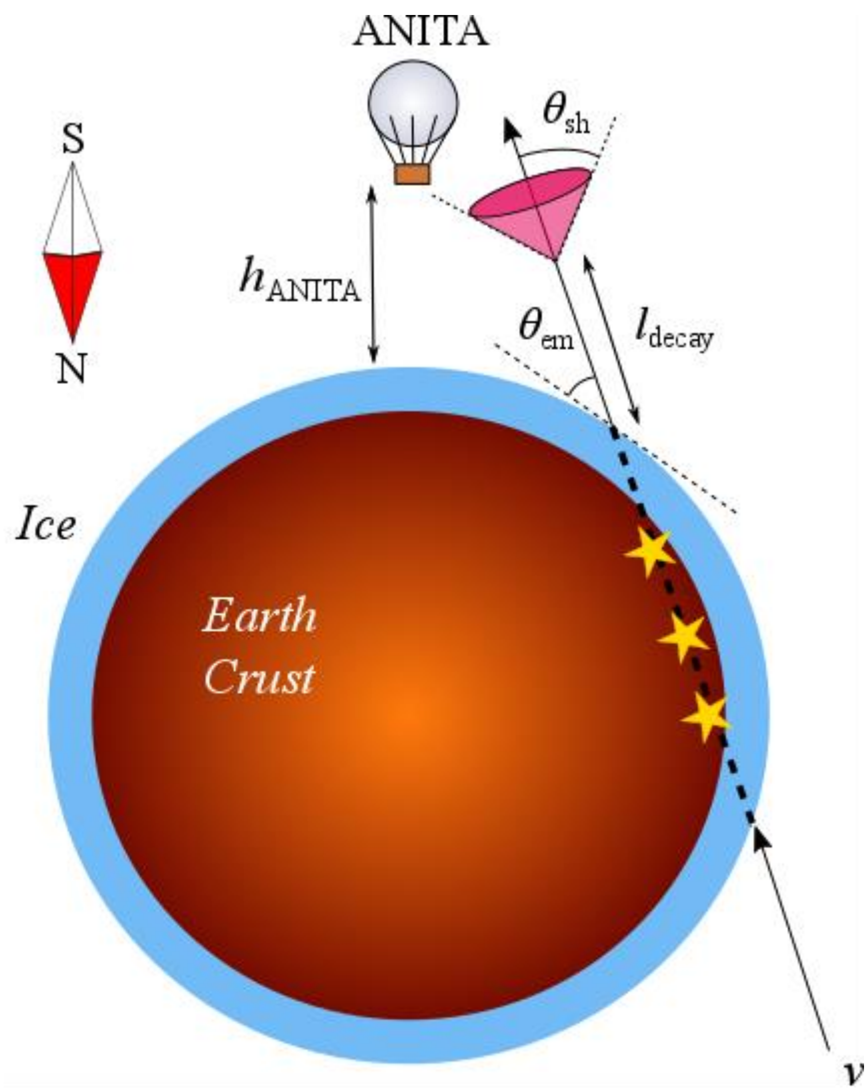


ANITA-IV



Slide from Carsten Rott ©

Upward-propagating EAS



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.

Events Features

ANITA

	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. $282.^\circ 14064$, Dec. $+20.^\circ 33043$	R.A. $50.^\circ 78203$, Dec. $+38.^\circ 65498$
Energy ε_{cr}	$0.6 \pm 0.4\,\mathrm{EeV}$	$0.56^{+0.30}_{-0.20}\,\mathrm{EeV}$
Zenith angle z'/z	$117.^\circ 4 \;/\; 116.^\circ 8 \pm 0.^\circ 3$	$125.^\circ 0 \;/\; 124.^\circ 5 \pm 0.^\circ 3$
Earth chord length ℓ	$5740 \pm 60\,\mathrm{km}$	$7210 \pm 55\,\mathrm{km}$
Mean interaction length for $\varepsilon_\nu = 1\,\mathrm{EeV}$	290 km	265 km
$p_{\mathrm{SM}}(\varepsilon_\tau > 0.1\,\mathrm{EeV})$ for $\varepsilon_\nu = 1\,\mathrm{EeV}$	4.4×10^{-7}	3.2×10^{-8}
$p_{\mathrm{SM}}(z > z_{\mathrm{obs}})$ for $\varepsilon_\nu = 1\,\mathrm{EeV}$, $\varepsilon_\tau > 0.1\,\mathrm{EeV}$	6.7×10^{-5}	3.8×10^{-6}
$n_\tau(1\text{–}10\,\mathrm{PeV}) : n_\tau(10\text{–}100\,\mathrm{PeV}) : n_\tau(> 0.1\,\mathrm{EeV})$	34 : 35 : 1	270 : 120 : 1

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

Possible Interpretations

SM-origin upward-going Extensive Air Showers (EAS) excluded…

Pure SM, downward going

- Downward-going events, interacting with the geomagnetic field [de Vries, Prohira, '19]
- Downward-going events, reflected by sub-layers of the ice sheet [Shoemaker, Kusenko, Munneke, Romero-Wolf, Schroeder, Siegert, '19]

BSM, downward going

- Axionic UHECR reflecting on the ice [Esteban, Lopez-Pavon, Martinez-Soler, Salvado, '19]
- Askaryan emission in the Ice, induced by heavy dark matter [Hooper, Wegsman, Deaconu, Vieregg, '19]

BSM, upward going

- SUSY interpretations [Fox, Sigurdson, Murase *et al., '18*] [Collins, P. S. Bhupal Dev, and Y. Su, '18]
- Sterile neutrino converting in the Earth [Cherry, Shoemaker, '19][Huang, '18]

DM -> SM scattering, upward going

- Dark Matter decaying into leptons [Cline, Gross, Xue '19]

DM -> BSM scattering, upward going

- Dark Matter decaying into RH neutrinos [**LH**, Mambrini, Pierre '19]
- Inelastic Boosted Dark Matter [**LH**, Kim, Park, Shin, '19]

This talk

Events Features

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

IceCube

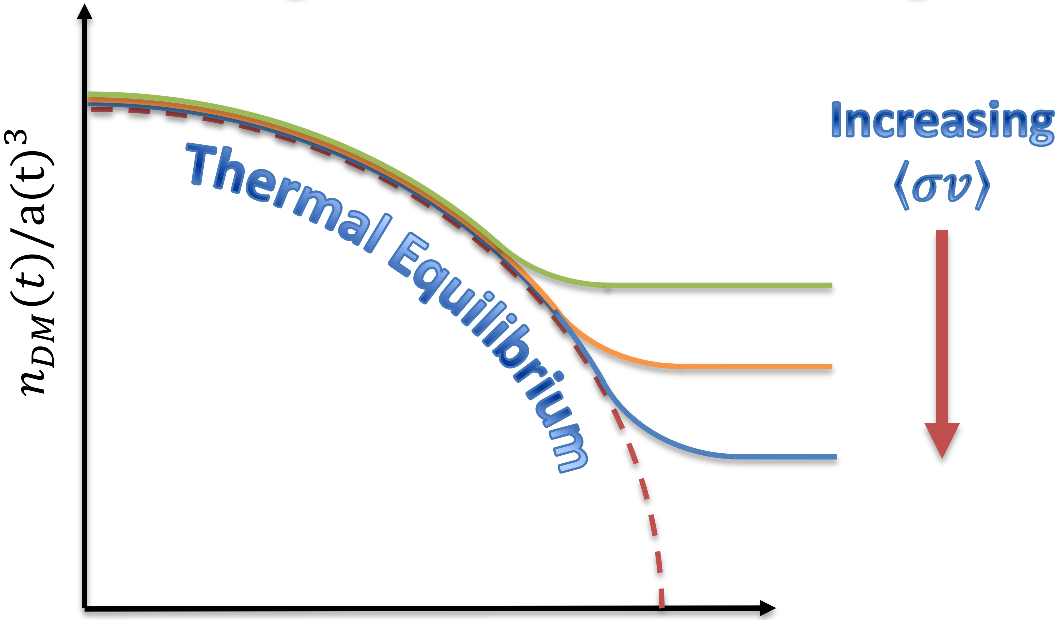
	IceCube-140611	IceCube-140109	IceCube-121205
EHE Northern Track ID	#27	#24	#20
Date & Time (UTC or MJD)	2014-06-11 04:54:24	56666.5	56266.6
Equatorial coordinates (J2000)	R.A. $110\overset{\circ}{.}34 \pm 0\overset{\circ}{.}22$, Dec. $+11\overset{\circ}{.}42 \pm 0\overset{\circ}{.}08$	R.A. $293\overset{\circ}{.}29$,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

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

Why Heavy Dark Matter ?

Why is ANITA relevant to detect it ?

Super - Heavy Dark Matter



Boltzmann Equation

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

Large Mass

↓

Large annihilation cross section

↓

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

Heavy Dark-Matter

How can one detect Heavy Dark-Matter particles ?

No Thermal equilibrium → Low interactions

Large Mass → Low number density

Heavy Dark-Matter

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Heavy Dark-Matter

How can one detect Heavy Dark-Matter particles ?

No Thermal equilibrium → Low interactions

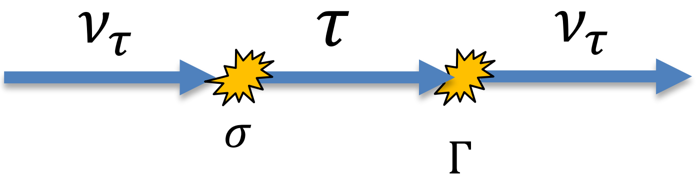
Large Mass → Low number density

→ Direct detection ? Difficult…

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

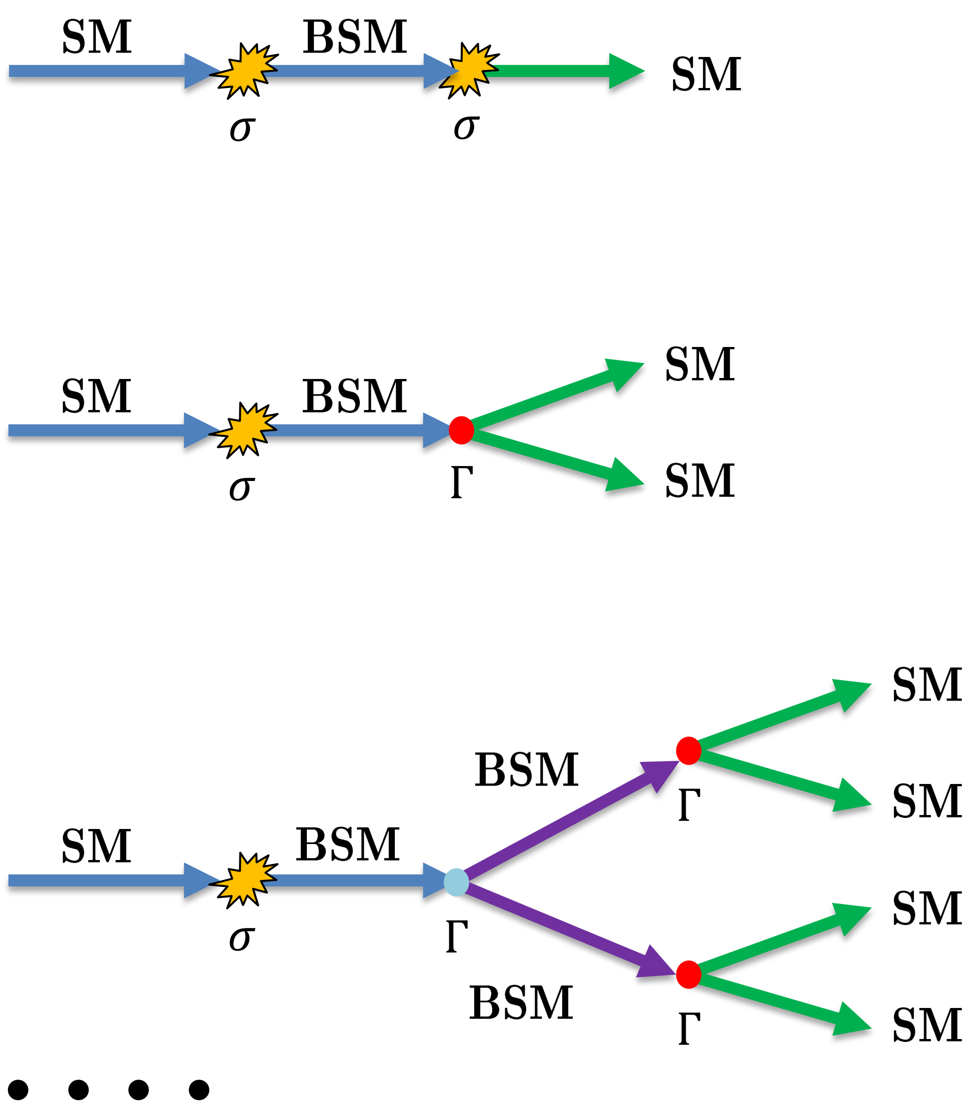
→ Decay in the Galaxy ? $\propto n_{DM}$ **Maybe ?**

BSM interactions and UHECR propagation



- In the SM, neutrinos can interact, regenerate, interact, …

BSM interactions and UHECR propagation



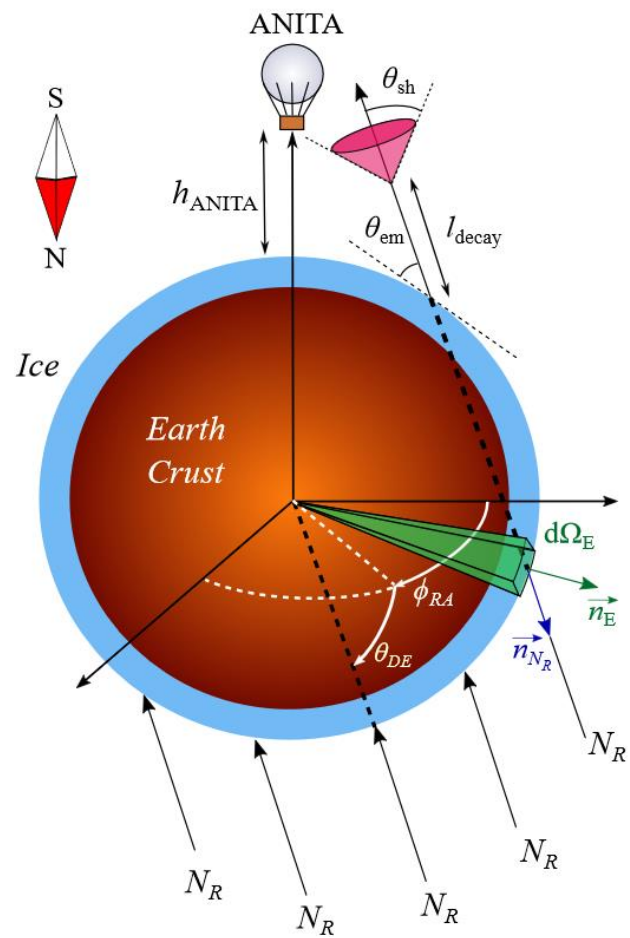
- Energy decreases with the number of interactions
- Energy and angular distributions affected by the interaction topologies…

In a given BSM model :

1. **Identify the relevant interactions;**
2. **Implement the different interaction topologies in a MC simulation;**
3. **Calculate the differential flux when SM particles exit the Earth after propagation**

Challenges for BSM interpretations

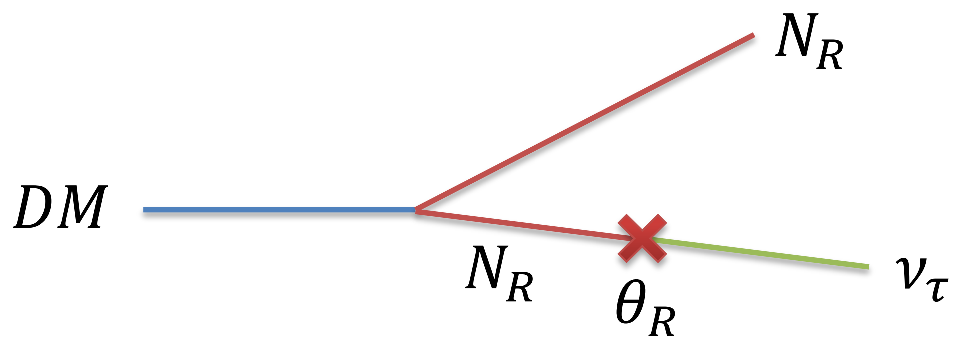
- Understand the total number of events
  1. Incoming Flux
  2. Probability of scattering
  3. Probability that the scatt. Products escape the Earth
  4. Probability that they decay in the low atmmosphere
- Understand the angular distribution of the events
  1. Integrate over incoming particles directions
  2. Integrate over points of impact on the Earth surface
  3. Analyse the results emergence angle per emergence angle



$$\frac{d^2 A_{\rm eff}}{dE_{\rm exit} d\theta_{\rm em}}(E_{\rm exit}, \theta_{\rm em} \mid E_{\rm N}, \theta_{\rm N}, \phi_{\rm N}) = R_{\rm E}^2 \int d\Omega_{\rm E} \vec{n}_{\rm N} \cdot \vec{n}_E$$

$$\times \frac{dP_{\rm exit}}{dE_{\rm exit}}(E_{\rm exit}, \theta_{\rm em} \mid E_{\rm N}, \theta_{\rm N}, \phi_{\rm N}, \theta_{\rm E}, \phi_{\rm E}) \times \int \frac{dP_{\rm decay}}{dl}(l \mid E_{\rm exit}) \times P_{\rm det}(\theta_{\rm sh} | l, \theta_{\rm N}, \phi_{\rm N}, \theta_{\rm E}, \phi_{\rm E}) dl$$

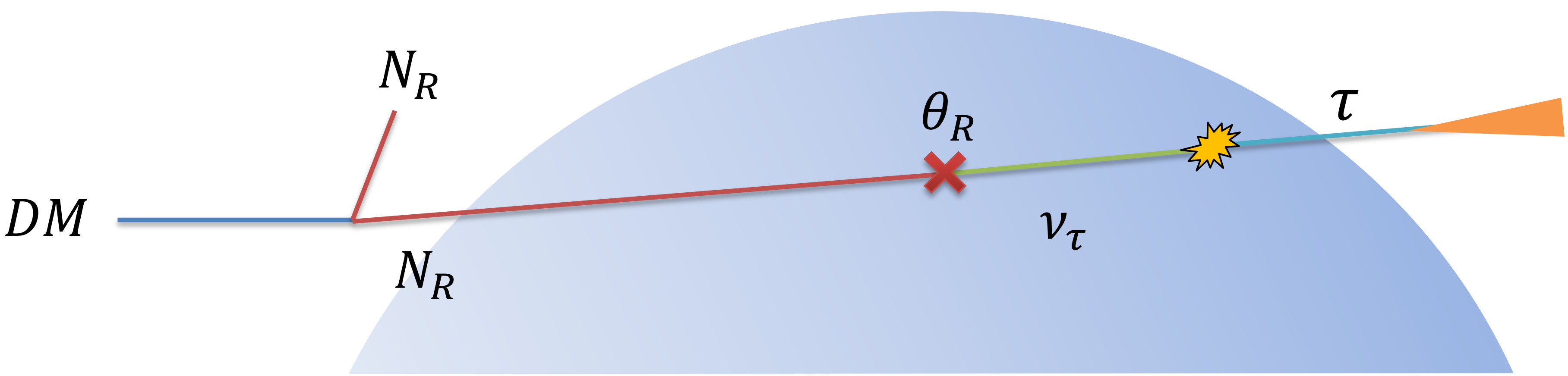
A right-handed neutrino interpretation [LH, Mambrini, Pierre, '19]



Required :

- RH neutrino long-lived
- Satisfies cosmo. Bounds (BBN, CMB, direct searches)

Propagation and conversion into tau's



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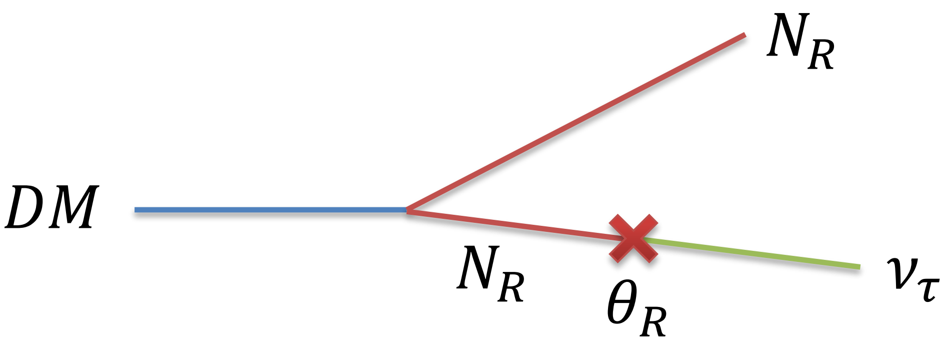

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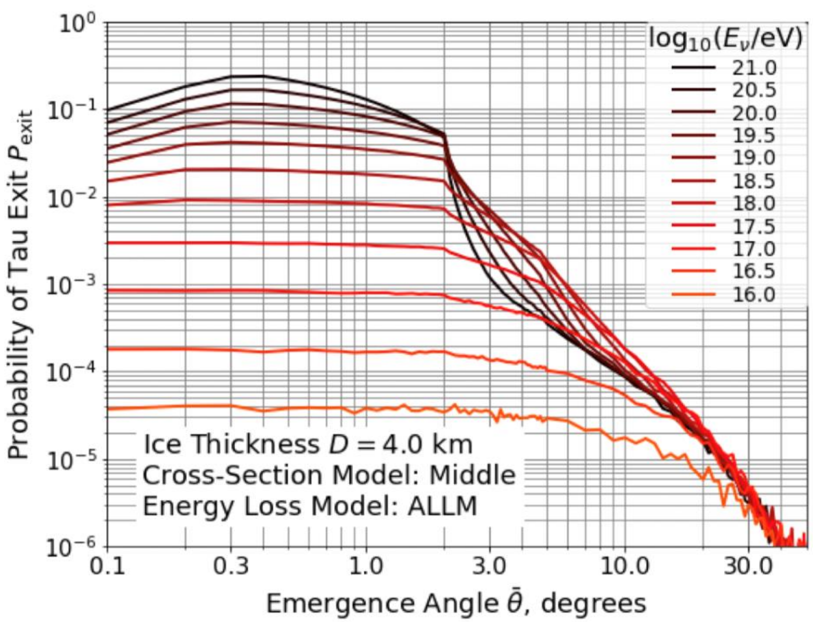
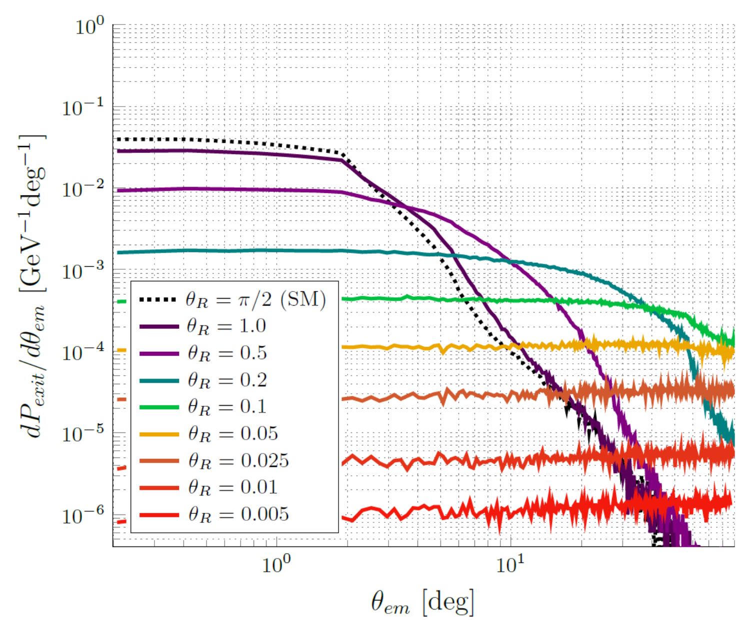


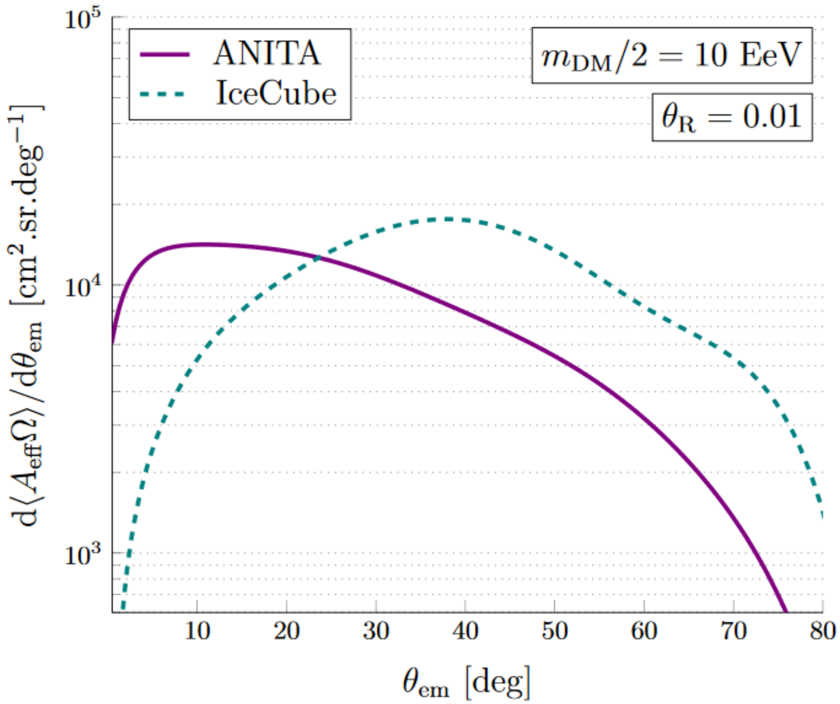
SM [Romero-Wolf *et al.*, Dec 17']

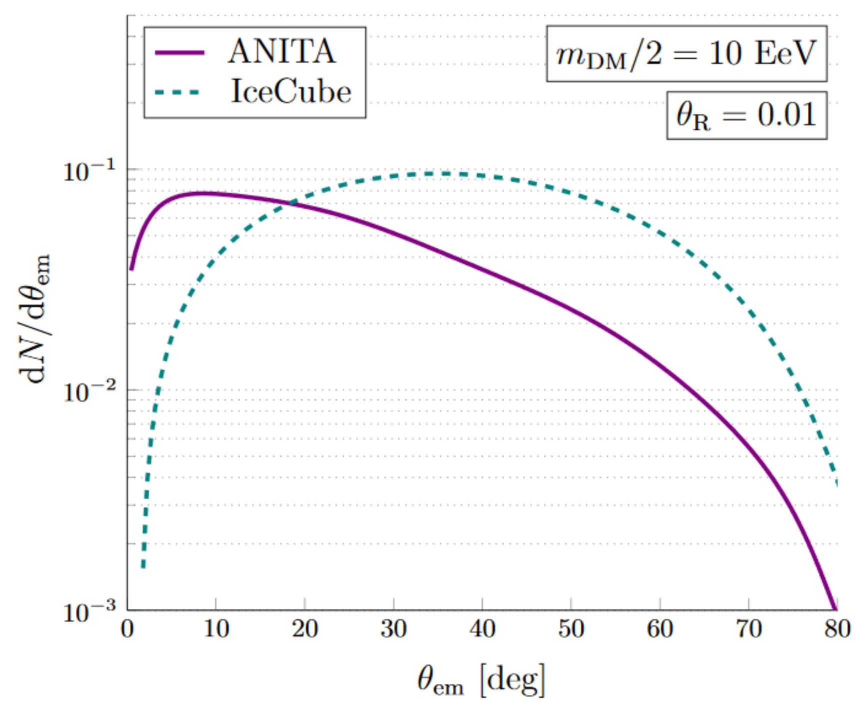


[**LH**, Y. Mambrini, M. Pierre, '19]

ANITA and IceCube detection

[**LH**, Y. Mambrini, M. Pierre, ‘19]

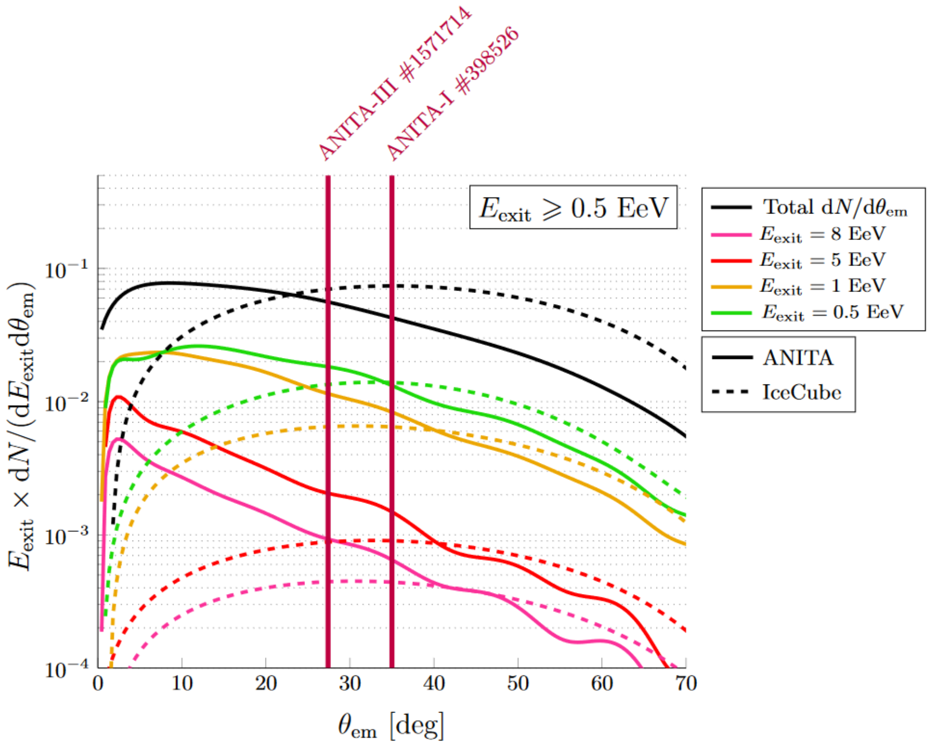


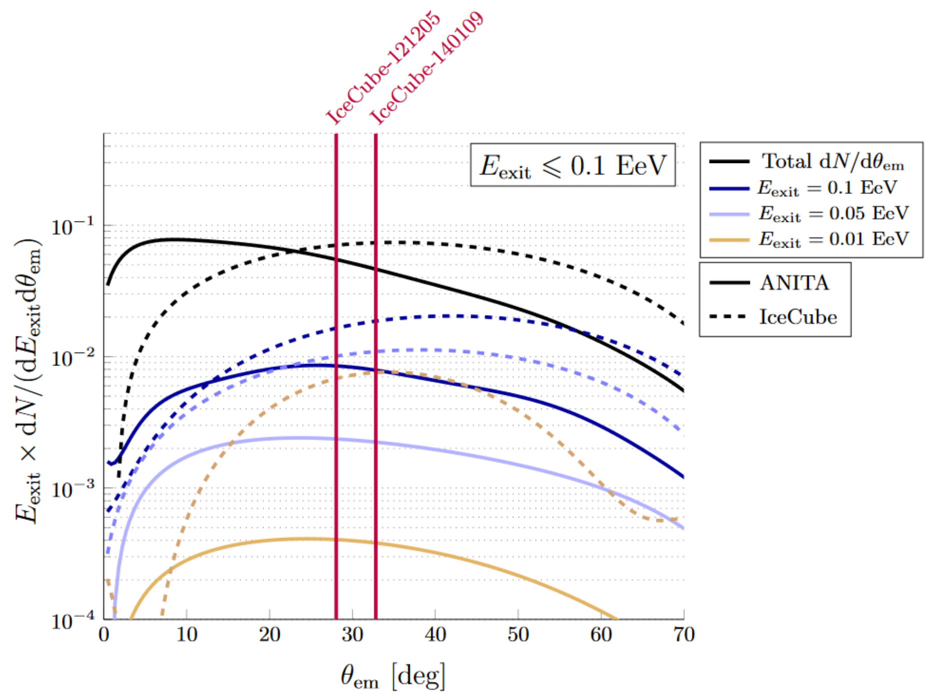


$$N_{\rm tot}^{\rm ANITA} \simeq 3.03 \left(\frac{\theta_R}{0.01}\right)^2 \left(\frac{10^{23}{\rm s}}{\tau_{\rm DM}}\right)\left(\frac{T_{\rm exp}}{85.5\ {\rm days}}\right)\left(\frac{20\ {\rm EeV}}{m_{\rm DM}}\right)^{0.67} \quad [\ \theta_R \lesssim 0.025\,;\ m_{\rm DM} > 2\ {\rm EeV}\ ]$$

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

ANITA/IceCube detection





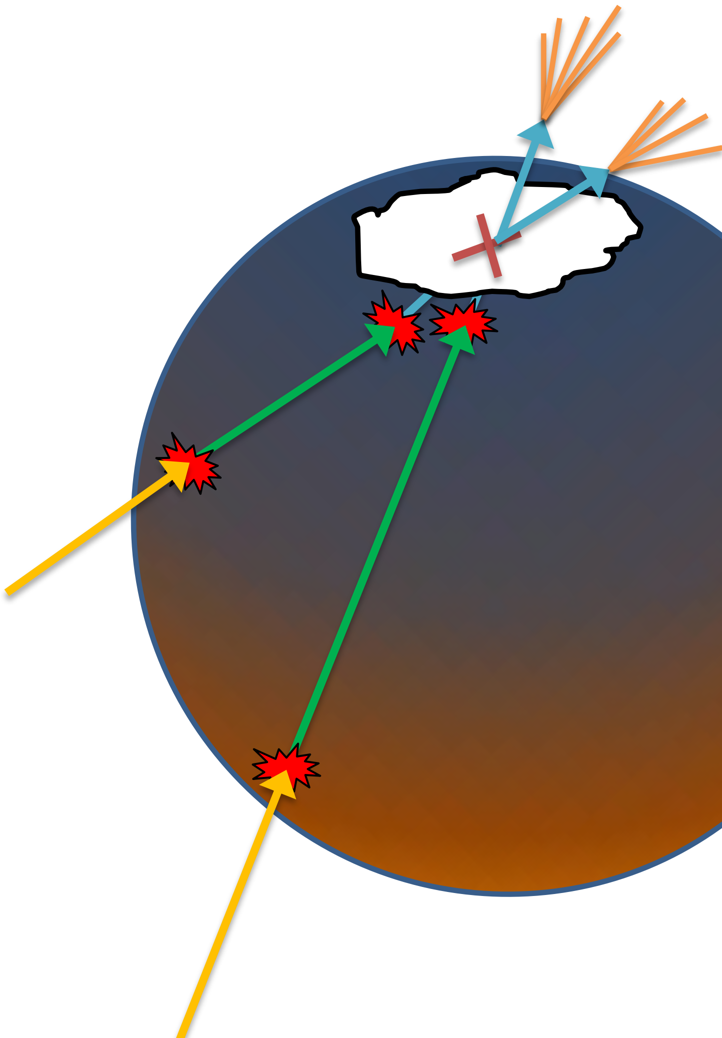
Energies > 0.5 EeV : Favour an ANITA detection at angles ~ 30°

Energies < 0.5 EeV : Favour an IceCube detection at angles ~ 30°

Perfect complementarity between the two collaborations detection !

[**LH**, Y. Mambrini, M. Pierre, ‘19]

How to get a better angular distribution?



Assuming a tau escapes the Earth and produces the EAS

↓

Need to produce it (very) close to the surface in order to let it escape

↓

Relatively small volume in which scattering (or decay) should take place

↓

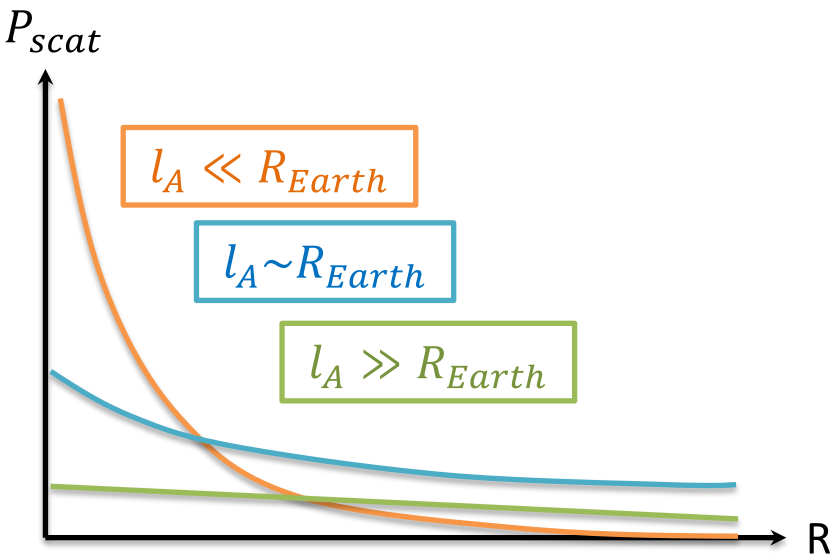
Need to push up the scattering cross section

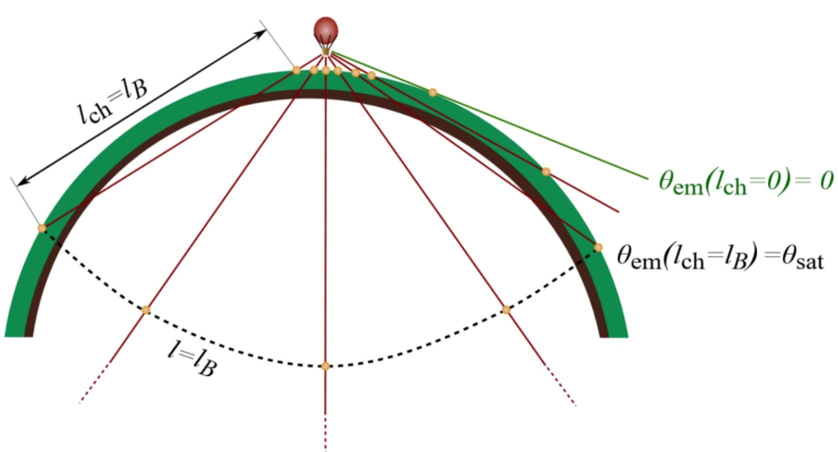
↓

Earth relatively opaque at large angles…

A translucent Earth makes it better!

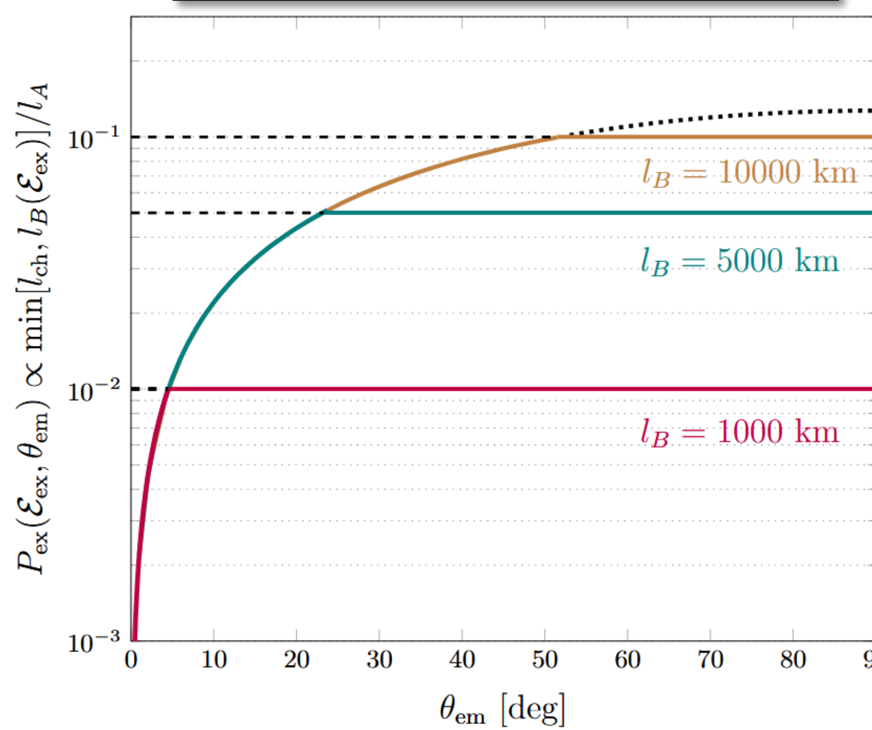
If some dark particle decays into hadrons → No need for propagating EW particles through the Earth !

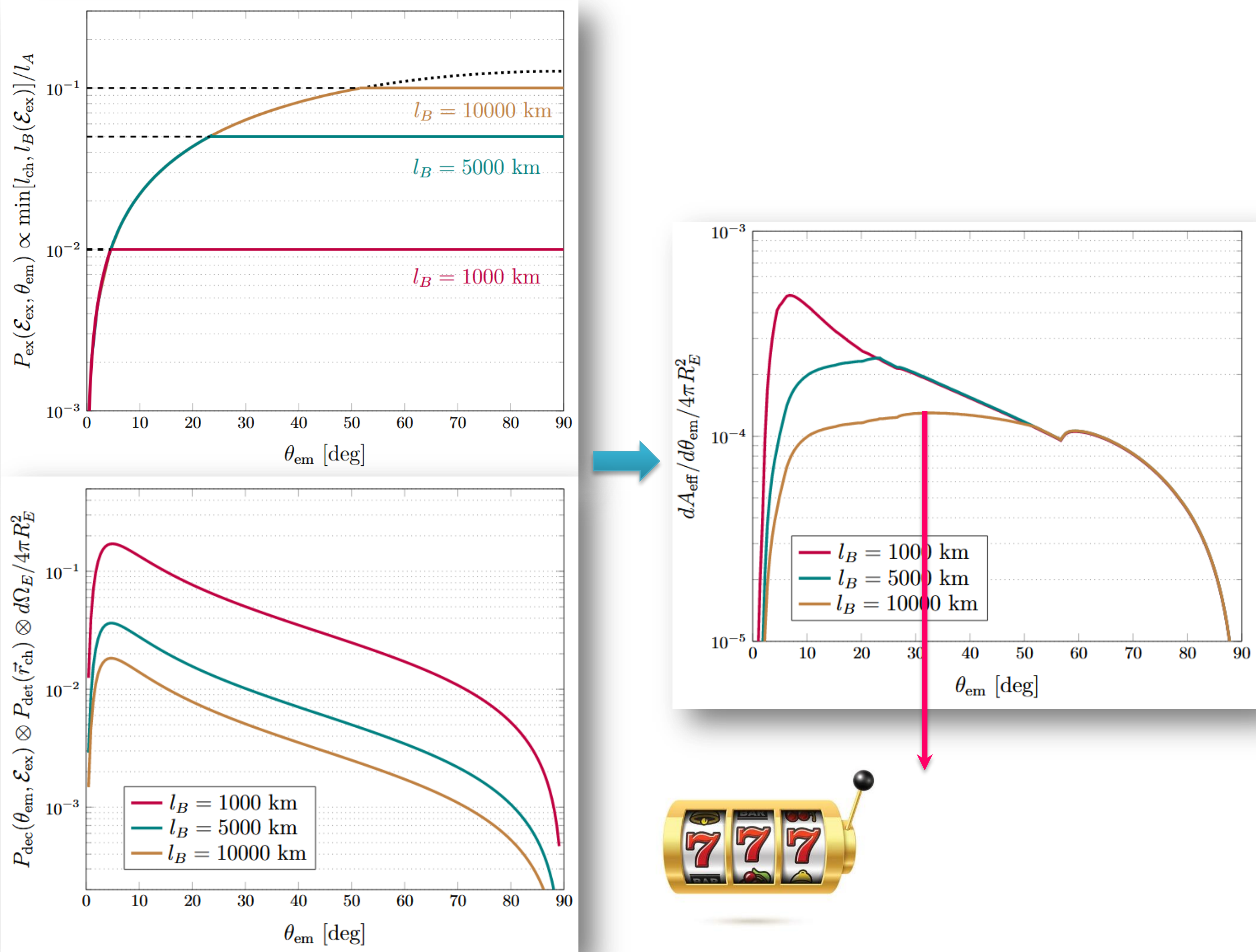




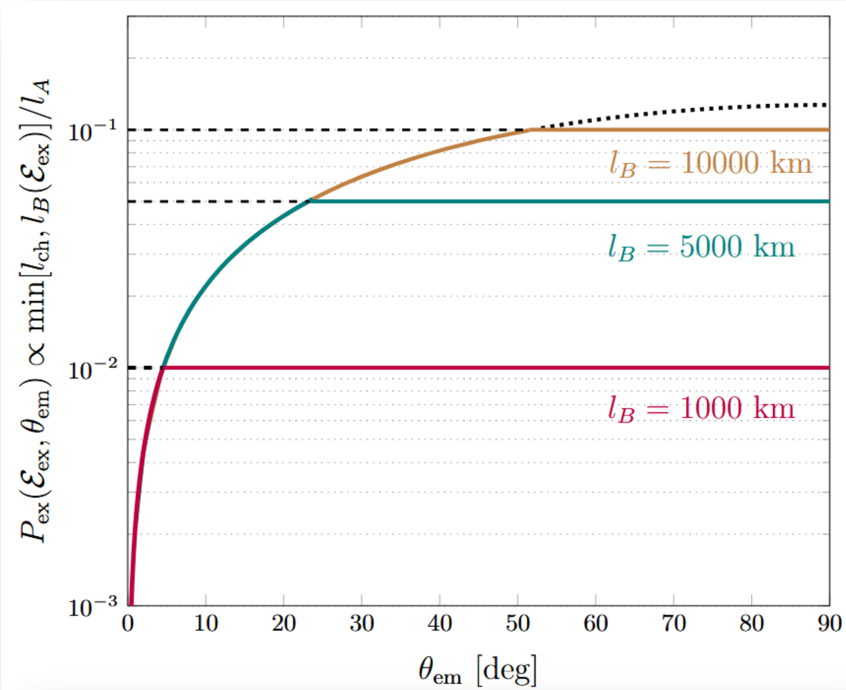
$$A \xrightarrow{\sigma_{AN}} B \xrightarrow{\Gamma_B} \bar{q}q$$

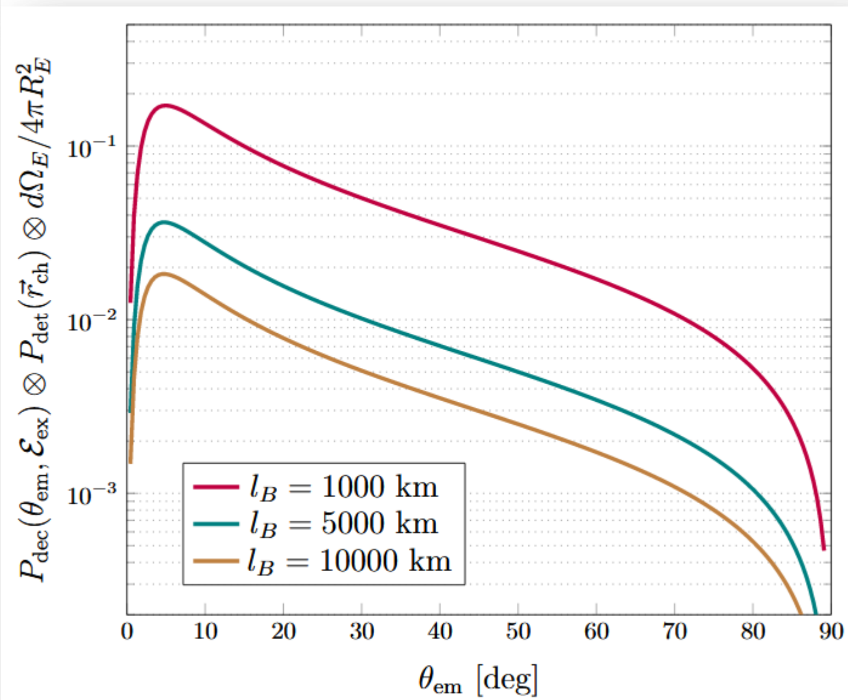
$$P_{ex}(\theta_{em}, \mathcal{E}_{ex}) \propto \frac{\min[l_{ch}, l_B(\mathcal{E}_{ex})]}{l_A}$$

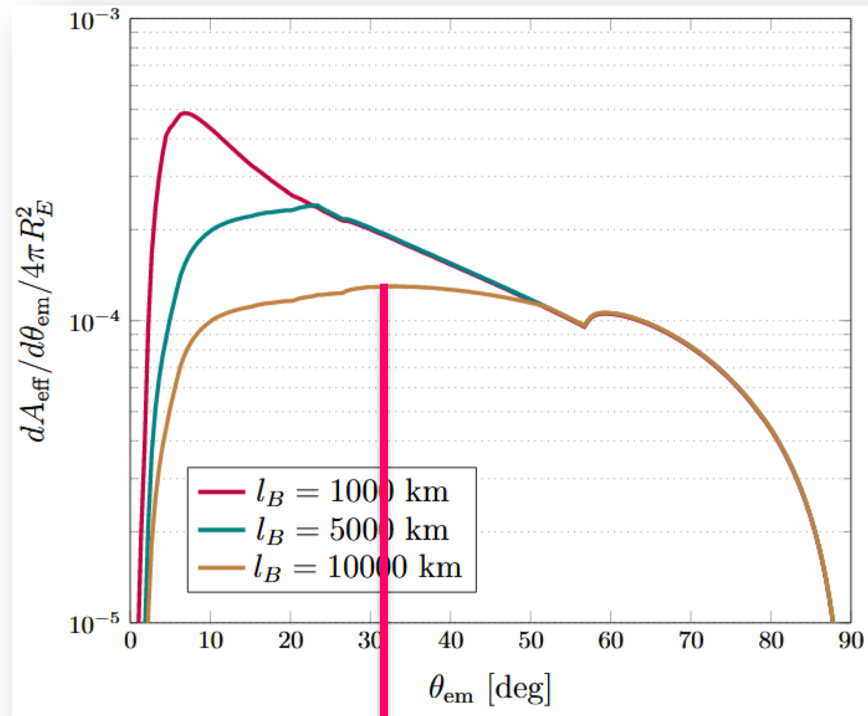




$P_{ex}(\mathcal{E}_{ex}, \theta_{em}) \propto \min[l_{ch}, l_B(\mathcal{E}_{ex})]/l_A$
$l_B = 10000$ km
$l_B = 5000$ km
$l_B = 1000$ km
θ_{em} [deg]
$P_{dec}(\theta_{em}, \mathcal{E}_{ex}) \otimes P_{det}(\vec{r}_{ch}) \otimes d\Omega_E/4\pi R_E^2$
$l_B = 1000$ km
$l_B = 5000$ km
$l_B = 10000$ km
θ_{em} [deg]
$dA_{eff}/d\theta_{em}/4\pi R_E^2$
$l_B = 1000$ km
$l_B = 5000$ km
$l_B = 10000$ km
θ_{em} [deg]







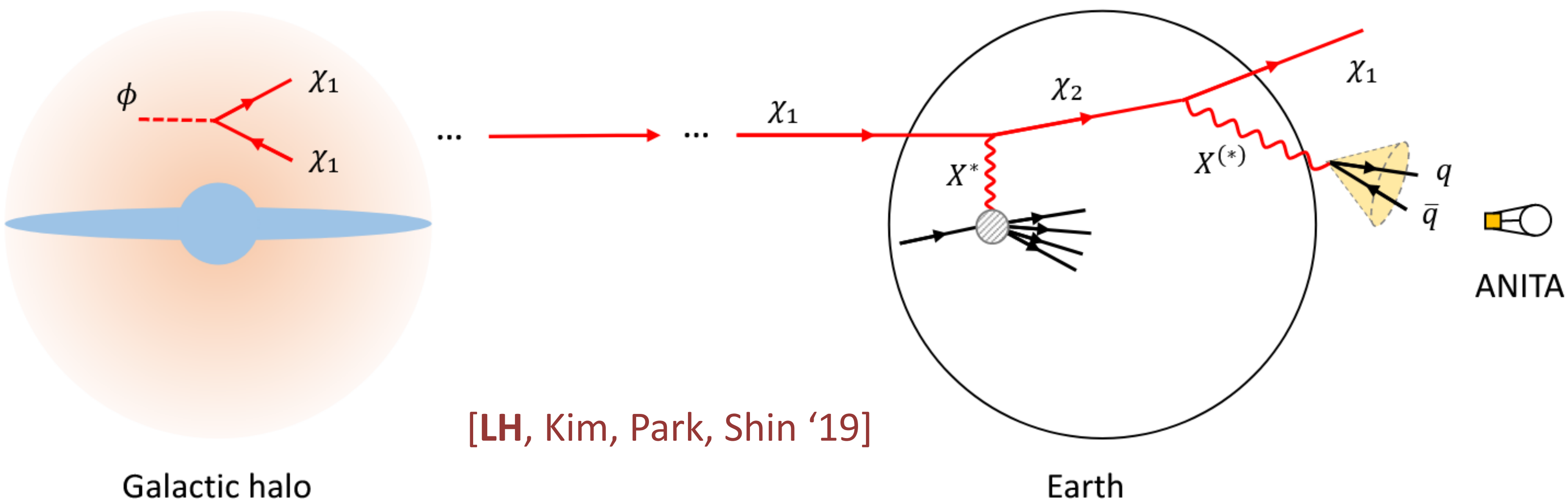
$\theta_{max} \sim 30°$

Inelastic Boosted Dark Matter

$$\mathcal{L}_{\rm int} \supset y_\phi \phi \bar{\chi}_1 \chi_1 - \frac{\epsilon}{2} F_{\mu\nu} X^{\mu\nu} + (g_{12} \bar{\chi}_2 \gamma^\mu \chi_1 X_\mu + \text{h.c.})$$

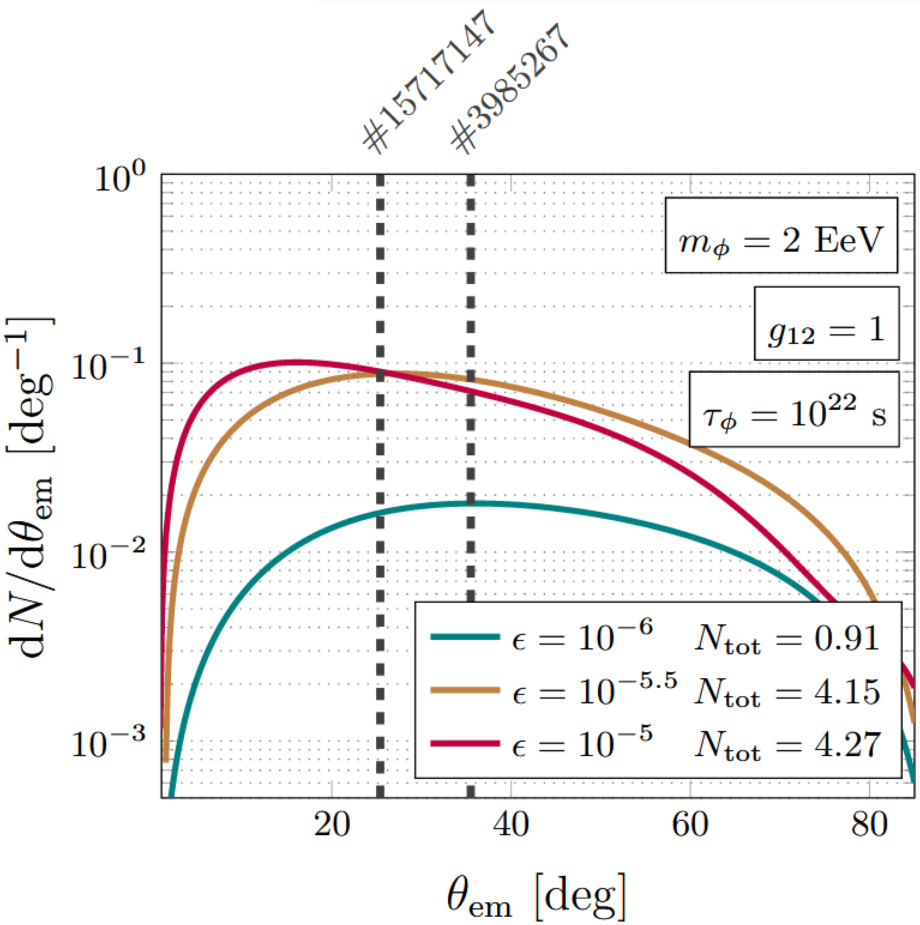
[Kim, Park, Shin 1702.02944][Kim, Park, Shin 1612.06867][Giudice, Kim, Park, Shin, 1712.0712]

Super-heavy DM — Light, boosted DM — $U(1)_X$ −charged dark sector

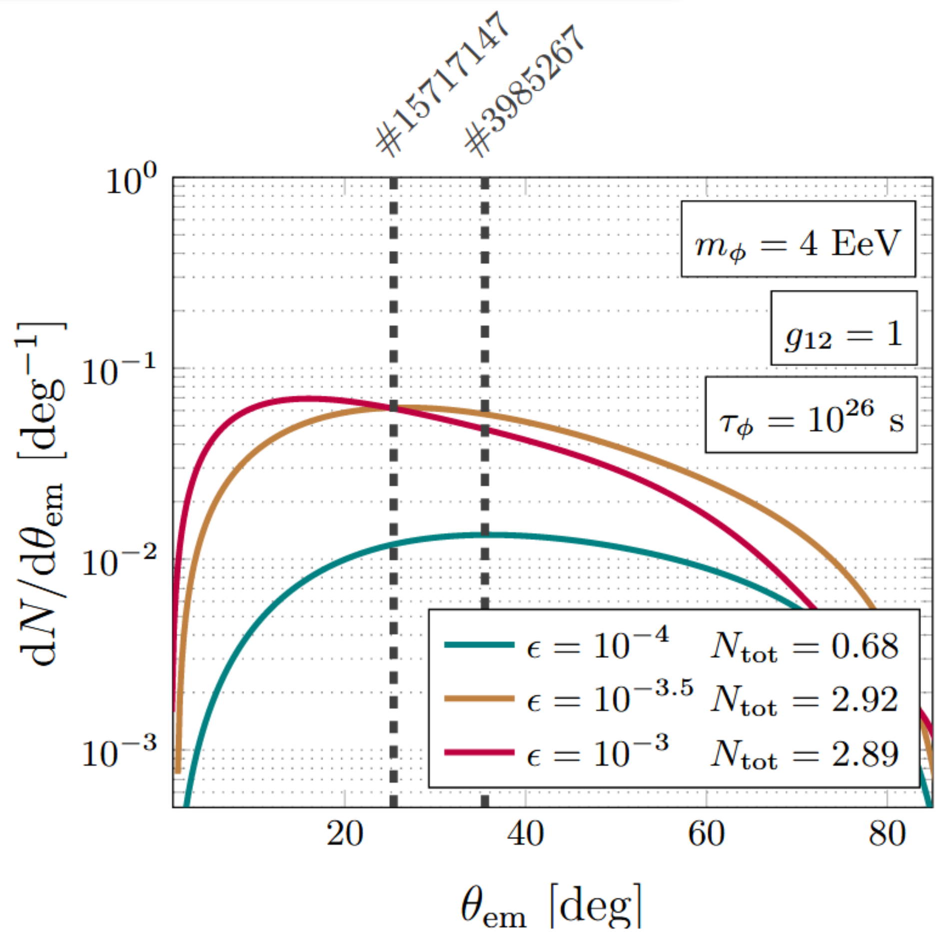


[**LH**, Kim, Park, Shin '19]

On-shell: $m_2 > m_1 + m_X,\ m_X = 0.5$ GeV,
$m_\phi = 2$ EeV,
Off-shell: $m_2 = 2.5$ GeV, $m_1 = 2$ GeV, $m_X = 2$ GeV,
$m_\phi = 4$ EeV.



On-shell scenario



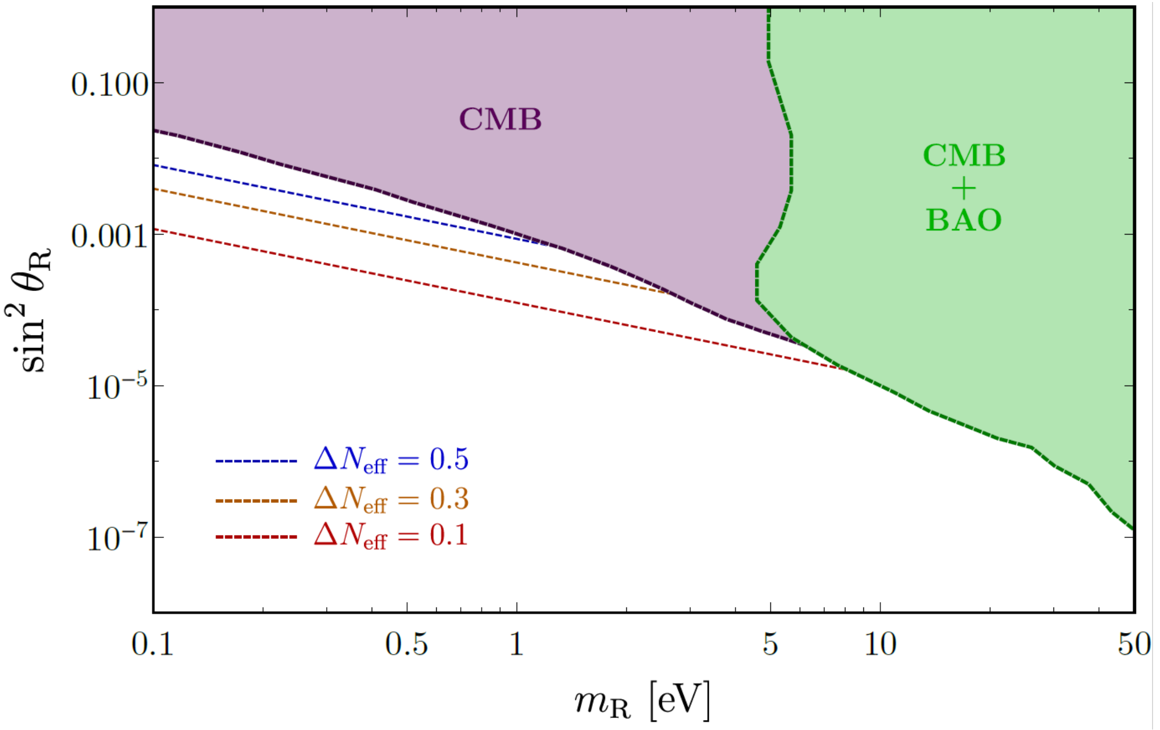
Off-shell scenario

Conclusion

- The presence in the galaxy of a metastable **super-heavy dark matter** particle might lead to interesting signatures accessible to UHECR searches.
- The presence of a **BSM sector modifies the way UHECRs propagate** through the Earth.
- This modification can lead to **non-trivial energy distributions** of the events produced in various detectors.
- A dark **scalar decaying into right-handed neutrinos** can explain the recent measurements of **both IceCube and ANITA**. A dark-matter mass >1-10 EeV predicts a **perfect complementarity** between the two collaborations.
- On the other hand, models of **inelastic boosted dark matter**, where incoming particles are able to up-scatter within the dark sector before decaying into hadrons, **can lead to a clean angular distribution for the ANITA** events.
- The **Earth's volume can act as a gigantic beam –dump detector** which is promising for the search of heavy new physics.

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

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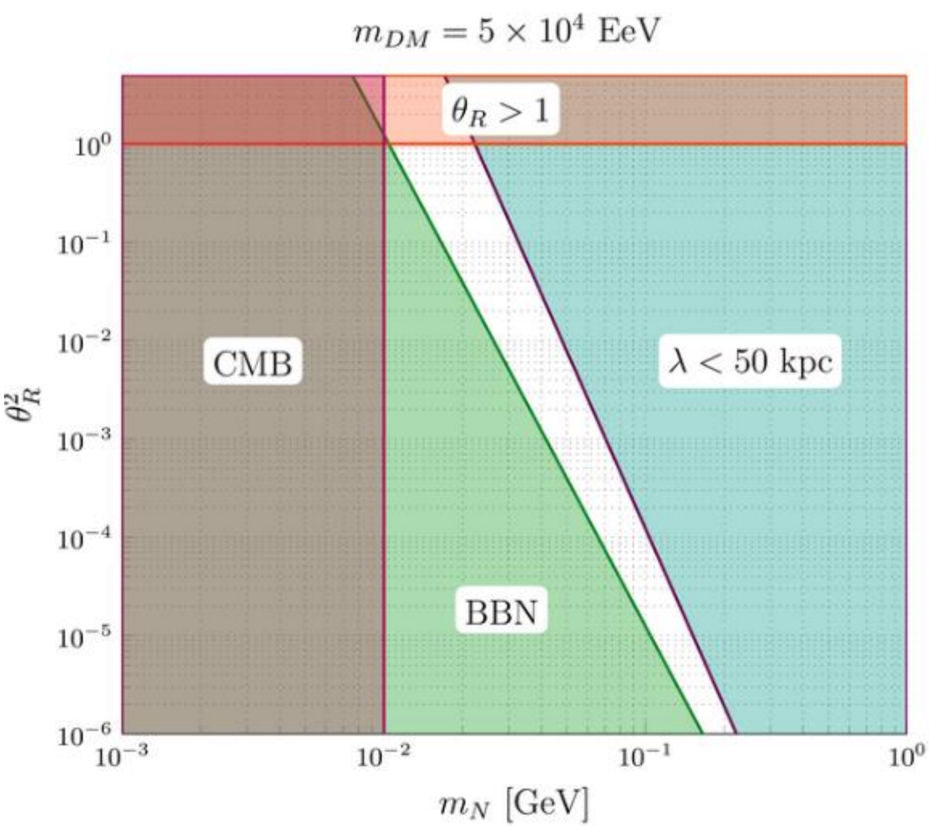
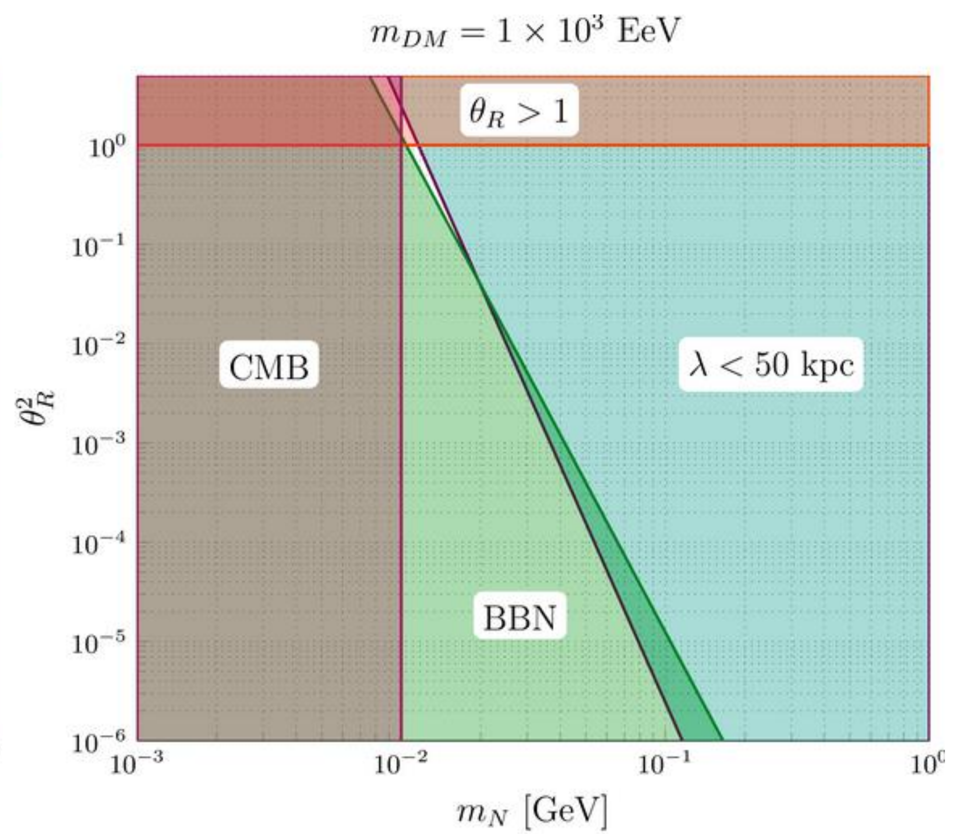


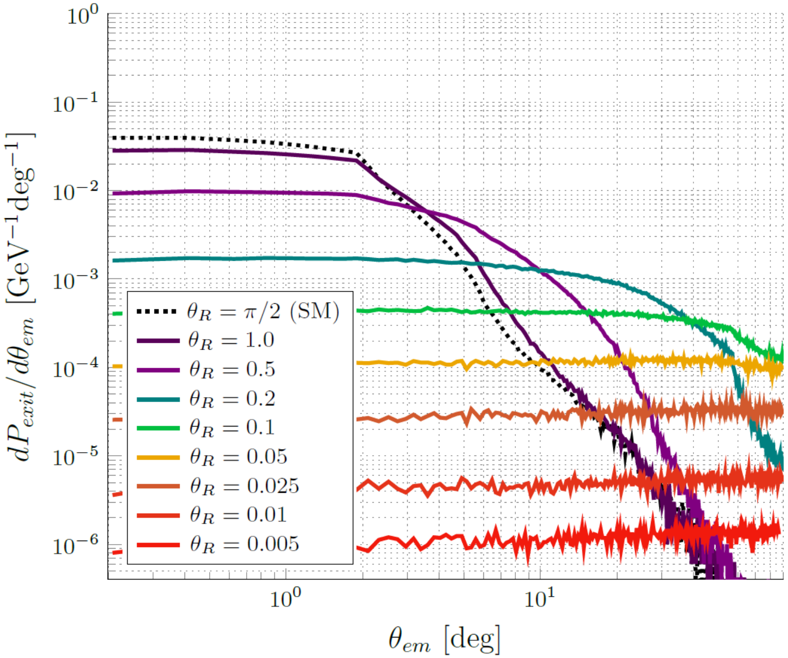


$m_R \sim 0.1$ GeV → $m_{DM} \gtrsim 10^3$ EeV $= 10^{12}$GeV

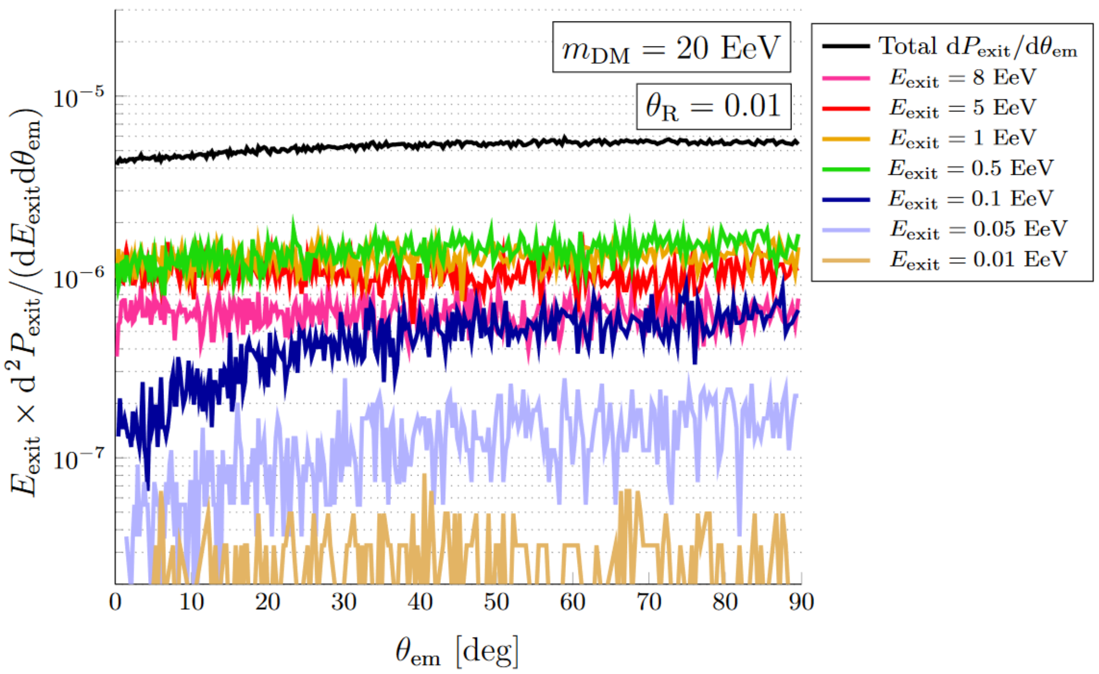
Approaches the inflaton mass…

Differential Exit Probability

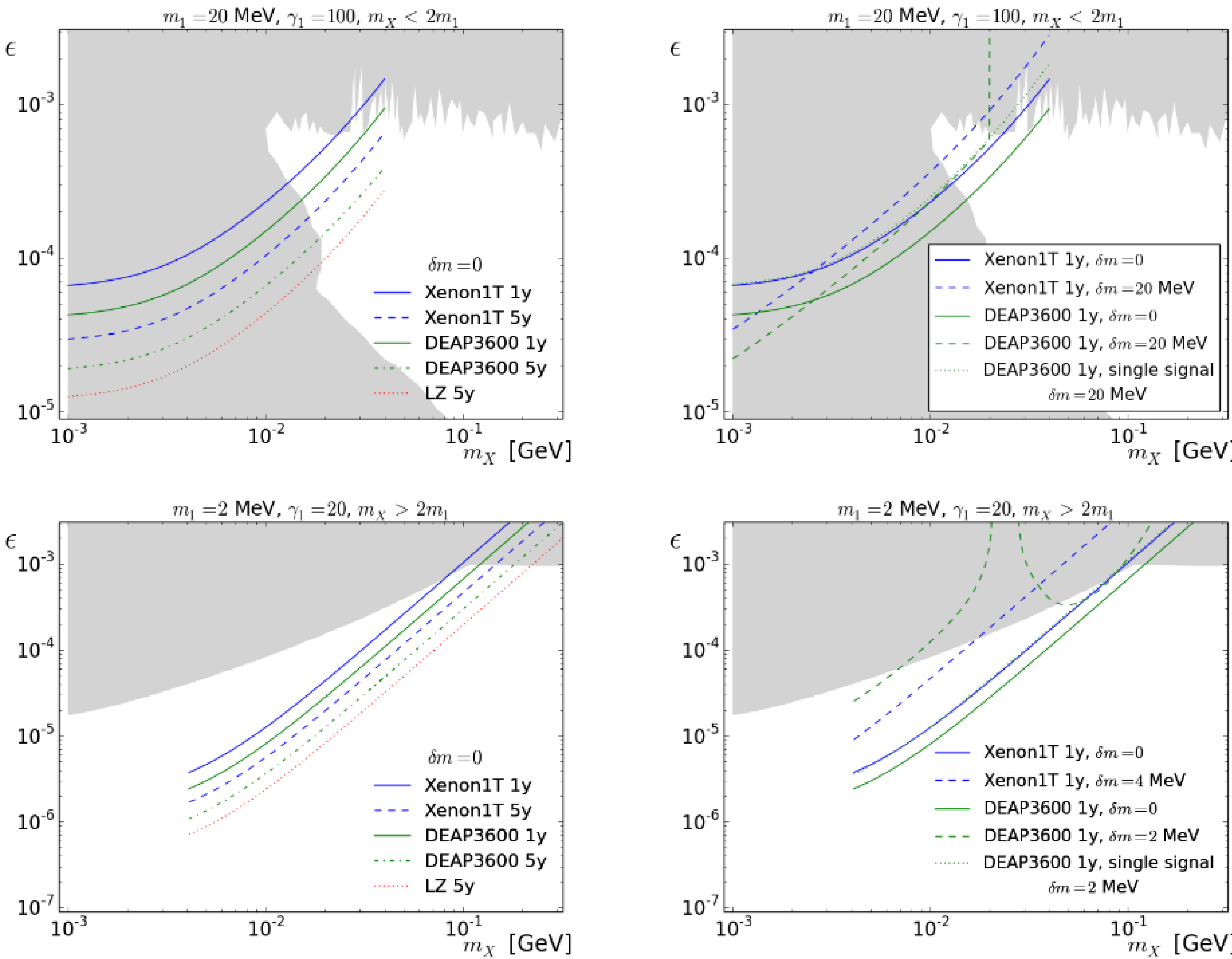
Total Exit Probability



Diff. Exit Probability

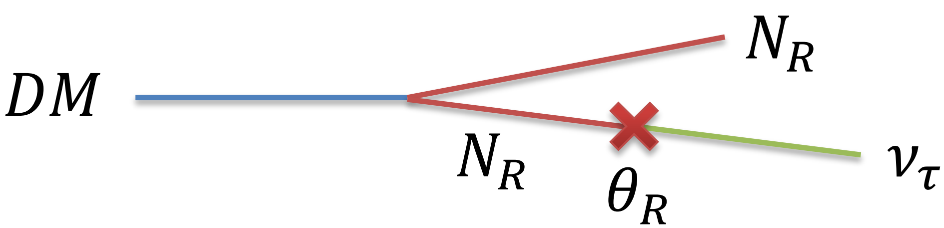


→ Access to the energy distribution per emergence angme of the predicted events



$m_1 = 20$ MeV, $\gamma_1 = 100$, $m_X < 2m_1$
ϵ
10^{-3}
10^{-4}
10^{-5}
10^{-3}
10^{-2}
10^{-1}
m_X [GeV]
$\delta m = 0$
Xenon1T 1y
Xenon1T 5y
DEAP3600 1y
DEAP3600 5y
LZ 5y
$m_1 = 20$ MeV, $\gamma_1 = 100$, $m_X < 2m_1$
Xenon1T 1y, $\delta m = 0$
Xenon1T 1y, $\delta m = 20$ MeV
DEAP3600 1y, $\delta m = 0$
DEAP3600 1y, $\delta m = 20$ MeV
DEAP3600 1y, single signal
$\delta m = 20$ MeV
$m_1 = 2$ MeV, $\gamma_1 = 20$, $m_X > 2m_1$
10^{-6}
10^{-7}
$\delta m = 0$
Xenon1T 1y
Xenon1T 5y
DEAP3600 1y
DEAP3600 5y
LZ 5y
$m_1 = 2$ MeV, $\gamma_1 = 20$, $m_X > 2m_1$
Xenon1T 1y, $\delta m = 0$
Xenon1T 1y, $\delta m = 4$ MeV
DEAP3600 1y, $\delta m = 0$
DEAP3600 1y, $\delta m = 2$ MeV
DEAP3600 1y, single signal
$\delta m = 2$ MeV

A right-handed neutrino interpretation [LH, Mambrini, Pierre, '19]



Required :

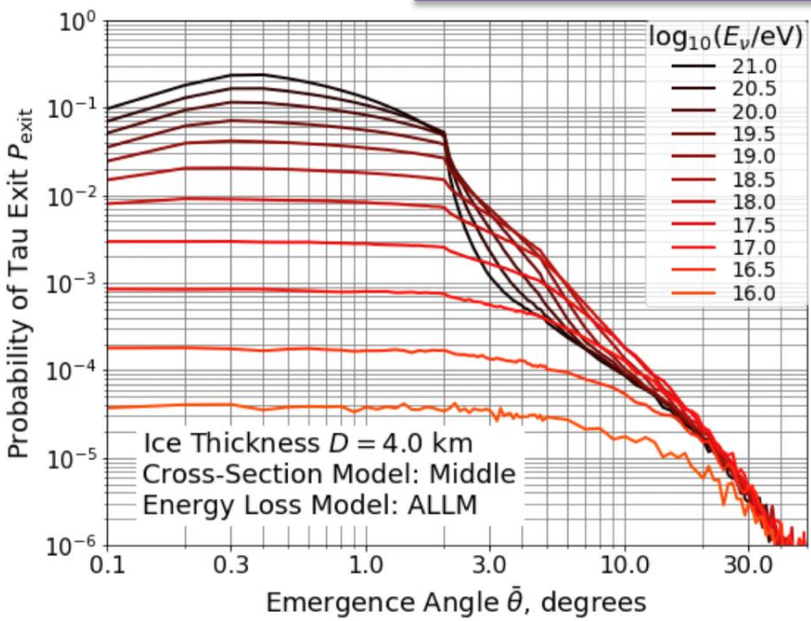
- RH neutrino long-lived
- Satisfies cosmo. Bounds (BBN, CMB, direct searches)

$m_R < 10\ \mathrm{eV}$ → $m_{DM} \gtrsim 1\ \mathrm{EeV}$

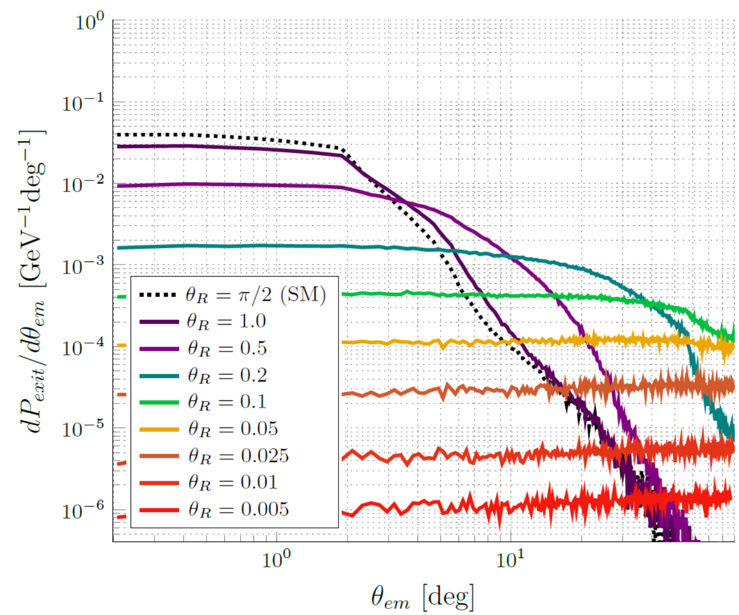
$m_R \sim 0.1\ \mathrm{GeV}$ → $m_{DM} \gtrsim\ 10^3\ \mathrm{EeV} = 10^{12}\mathrm{GeV}$

Approaches the inflaton mass…

Propagation and conversion into tau's



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



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