Search for heavy secluded dark matter with ANTARES

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for the ANTARES Collaboration

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Recap from textbook knowledge: constraints on WIMP parameter space

Indirect searches: annihilation or decay of WIMP$\rightarrow \nu$. Spectra end at $m_{\rm DM} = \mathcal{O}(100)$ TeV.

1. In the **creation** of DM particle from the thermal bath in a 2$\rightarrow$2 process with cross-section σ, unitarity on $\mathcal{S}$ matrix $\Rightarrow \sigma < \frac{1}{p^2}$ (p momentum transfer)
2. Relic density observed today is explained with *freeze-out*. Because of freeze-out, $p \sim M$, or $v \sim 1$ (non-relativistic regime) therefore $\sigma < 1/m^2$.
   Not much momentum left available for kinetic term after having created their mass.
3. $[\Omega_{DM} + \Omega_{baryons} + \Omega_{photons}] \cdot h^2 = 1 \Rightarrow \Omega_{DM} \cdot h^2 < 1$
   In addition, from the Boltzmann equation, $\Omega_{DM} \cdot h^2$ is proportional to $1/\langle \sigma v \rangle$

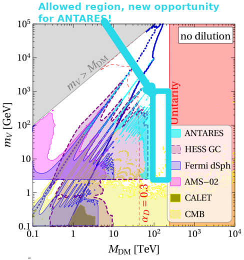
1+2+3 constrain maximum WIMP mass at about 340 TeV [Phys.Rev.Lett. 64 (1990) 615]

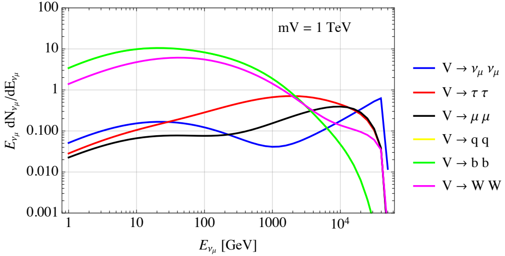
Novel DM scenarios: heavy secluded dark matter

No evidence for WIMP at the GeV-TeV scale; where to search next?

Secluded scenarios can provide dark-matter candidates at and above 10-100 TeV, in line with recent interest for BSM physics in heavy sectors at colliders

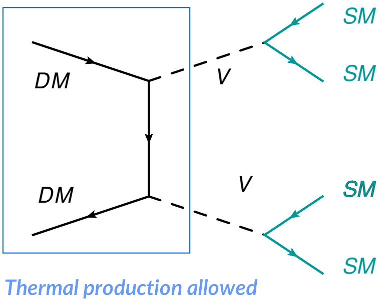
1. Unitarity bound on the dark matter mass naturally evaded with a modified cosmology implying a change of freeze-out point
2. The annihilation spectra of relevance for experiments can be reliably computed from 'boosted' PPPC [F. Sala et al. JCAP 2019 014]

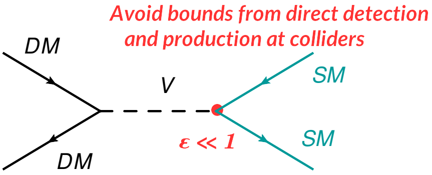




Introduction to secluded dark matter

Secluded dark matter is a DM candidate that interacts with a mediator V (on-shell), itself interacting (weakly) with SM particles.





The ν signal at ANTARES arises from the annihilation of DM pairs into two mediators, then decaying into SM particles that produce νs via decays and showering.

Freeze-out mechanism and relic density

Thermal bath (chemical + thermal equilibrium)

$\downarrow$

Cooling

Production stops

$\downarrow$

Universe expansion

Freeze-out: annihilation stops

$\downarrow$

Thermal equilibrium stops

DM particles created and annihilated in equilibrium with thermal bath

eg. $\gamma\gamma \leftrightarrow$ DM DM

$\downarrow$

Not enough energy to form DM mass

No longer chemical equilibrium

$\downarrow$

Volumes expand, number density decreases, annihilation rate decreases

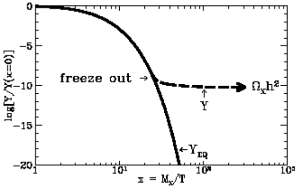
Only elastic scattering

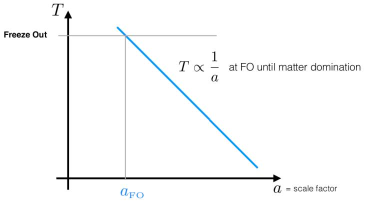
$\downarrow$

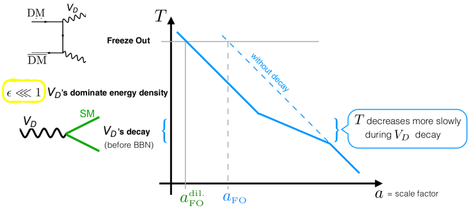
DM in free range propagation

Standard / secluded dark matter freeze-out

Standard cosmological evolution: $\Omega_{\mathrm{DM}} \propto \frac{1}{\sigma v}$.
Secluded: universe at freeze-out is smaller $\Rightarrow$ the same amount of DM is later more diluted $\Rightarrow$ $\sigma v(\mathrm{DM\ DM} \to VV)$ smaller $\Rightarrow$ DM can be heavier



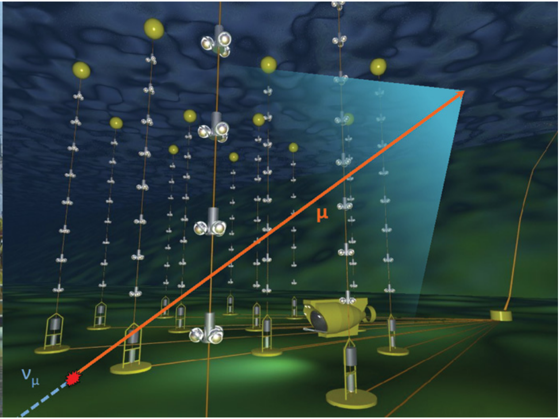




Standard WIMP mass constraint at $m_{\mathrm{DM}} = \mathcal{O}(100)$ TeV [Phys.Rev.Lett. 64 (1990) 615] can be evaded in new cosmological scenario.

The ANTARES neutrino detector: taking data for 13 years → 2021

40 km offshore Toulon, 12 lines, 885 PMTs, 2500 m depth, more than 13 years of operations



Excellent for Southern Hemisphere objects towards high energies!

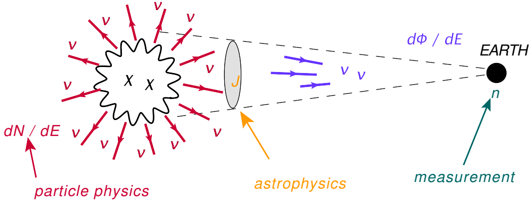
Analysis schema

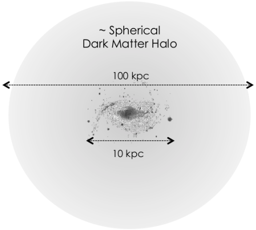
- The annihilation spectra of secluded dark matter into SM particles via mediator V are provided by F. Sala. Final states: $\mu^+\mu^-, \tau^+\tau^-, b\bar{b}, \nu\bar{\nu}$
- Heavy dark matter can be accommodated. DM mass from 3 TeV **to 6 PeV** (yet unexplored above 100 TeV!)
- The mass of the mediator V is unconstrained, provided $m_V \ll m_{\mathrm{DM}}$. Here we considered: 50 GeV, 250 GeV, 1 TeV.
- Analysis method: unbinned likelihood.
- Data is consistent with BG hypothesis. No heavy secluded dark matter in 2007-15 sample.

Results shown at Neutrino2020 [poster #467].

Source: Galactic Centre

Favourable source: (1) largest dark-matter density and (2) in the Southern Hemisphere





$$\Phi = \frac{n}{\mathcal{A}(M_\chi)\, t} = \frac{1}{4\pi} \frac{1}{M_\chi^2} \frac{\langle \sigma v \rangle}{2} \int_0^M \frac{dN}{dE} dE\, J$$

flux = number of events observed / acceptance * lifetime = annihilation rate[1] * average number of particles per collision * source geometry

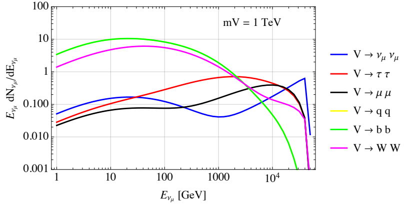
[1] in the above formula: for Majorana self-conjugated WIMPs

Search input and setup

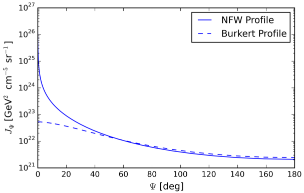
Data set: 9 years (2101.6 days lifetime), two algorithms for track (ν_μ CC) reconstruction.

Dark-matter signal is reproduced with PPPC4[1] and different models for J-Factor[2] as a cluster of events around the source position, searched for with *unbinned likelihood method*.

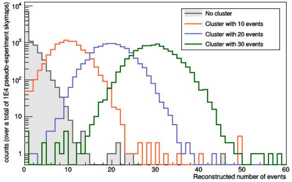
$$\log \mathcal{L}(n_s) = \sum_{i=1}^{N} \log \left[n_s \, S(\psi_i, N^i_{\mathrm{HITS}}) + n_{bg} \, B(\delta_i, N^i_{\mathrm{HITS}}) \right] - n_{bg} - n_s$$



Energy distribution



Morphology



Pseudo-experiments

Background is described with right-ascension shuffled (*blind*) data

[1] http://www.marcocirelli.net/PPPC4DMID.html [2] Burkert [ApJ 1995], NFW [ApJ 1996], McMillan [MNRAS 2017]

Workflow of unbinned analysis

PDFs

Signal: $\psi(\nu, GC)$
BG: $\sin\delta$
in equal solid angle bins

Maximum likelihood: returns n_s

$$\mathcal{L}(n_s) = \prod_{i}^{Nbins} [n_s \mathcal{S}(\psi_i, E_i, q_i) + n_{bg}\mathcal{B}]$$

Poisson

$\mathcal{P}(n_s, \mu)$

Number of events

Neyman statistics

Acceptances

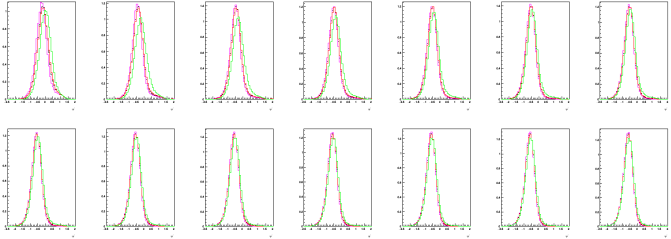
From PPPC
Integrated

Cross-section sensitivities

Limits on $\langle \sigma v \rangle$

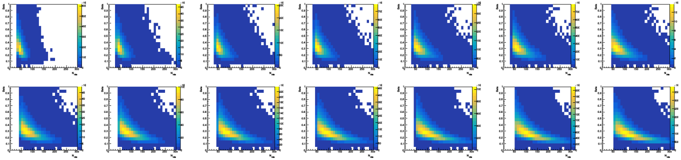
Signal PDFs

Space PDF: distribution around the GC morphology (NFW) folded with detector resolution



x 3 m_V

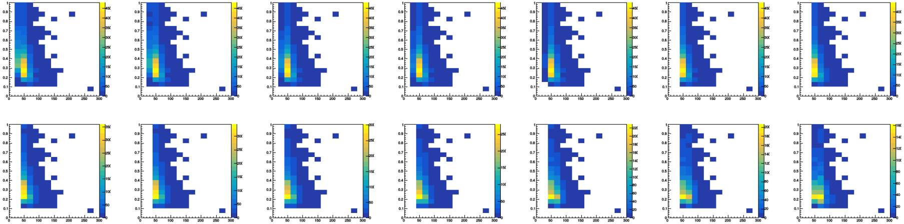
Energy PDF: N_{HITS} : β



x 3 m_V x 5 channels

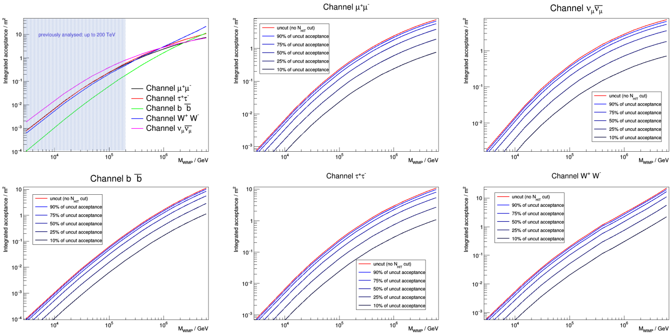
Background

Space PDF: $\sin(\delta)$. Same distribution used for all N_{HIT} cut values, as sky coordinates are independent of energy proxy Energy PDF: N_{HITS} : β



Integrated acceptances

Acceptance: effective area modulated with source spectrum: $\mathcal{A}(M) = \int_0^M A_{\mathrm{EFF}}(E_\nu) \frac{dN}{dE_\nu} dE_\nu$



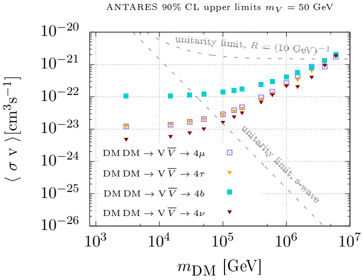
The cut in N_{HIT} is varied between 0 and 200, considering values corresponding to an acceptance fraction 90%, 75%, 50%, 25%, 10%.

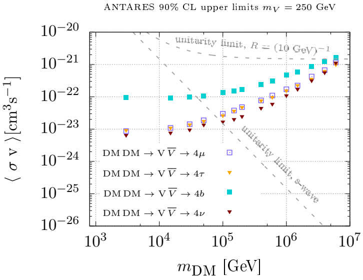
Best N_{HIT} cut used

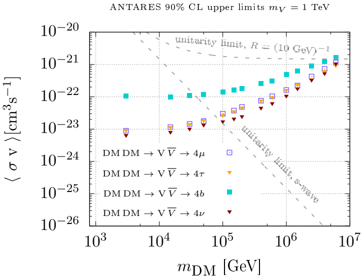
		GeV								PeV				
	m	3	15	30	50	100	150	200	400	600	1	1.5	2.5	4	6
$m_V =$ 50GeV	μ	31	33	35	36	38	39	40	77	82	87	92	97	102	106
	τ	31	33	34	35	37	38	39	74	77	82	86	91	96	99
	b	29	31	32	32	33	34	35	36	37	38	39	40	75	78
	ν	31	34	36	38	40	75	78	86	91	97	102	107	111	113
$m_V =$ 250GeV	μ	31	33	35	36	38	39	40	77	82	87	92	97	102	106
	τ	31	33	34	35	37	38	39	74	77	82	86	91	96	99
	b	29	31	32	32	33	34	35	36	37	38	39	71	75	78
	ν	31	34	36	38	70	75	78	86	91	97	102	107	111	113
$m_V =$ 1TeV	μ	31	33	35	36	38	39	52	77	82	87	92	97	102	106
	τ	31	33	34	35	37	38	39	74	77	82	86	91	96	99
	b	29	31	32	32	33	34	35	36	37	38	39	71	75	78
	ν	31	34	36	38	40	75	78	86	91	97	102	107	111	113

Cross-section limits: unblinded results

Cut optimised per DM mass, mediator mass and channel independently.

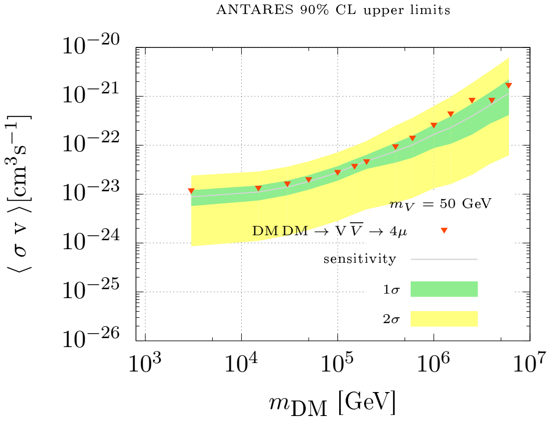


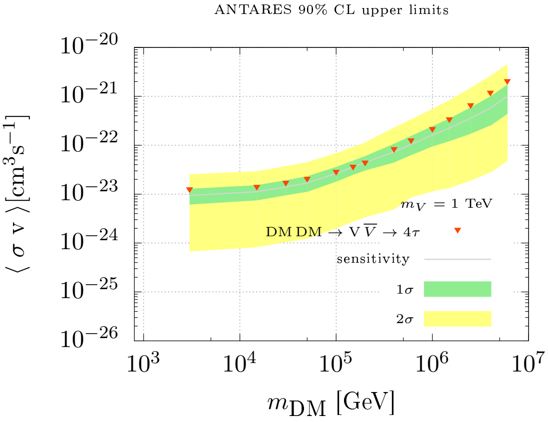




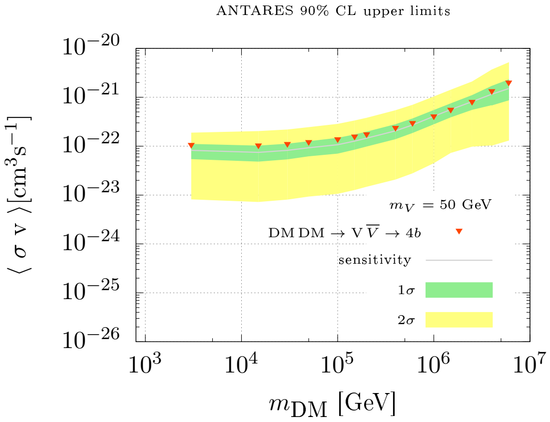
- Note! As usual limits are raised to be = sensitivities in this case of underfluctuations.
- First-time DM limits above 100 TeV, even if not strongly constraining.

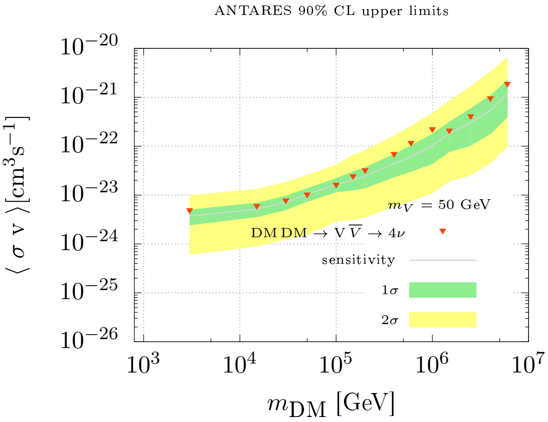
Cross-section limits per channel, $m_V = 50$ GeV (light mediator)





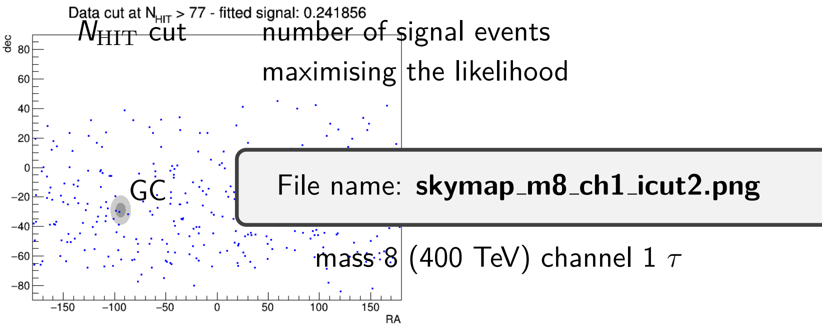
Cross-section limits per channel, $m_V = 50$ GeV (light mediator) (cont.)

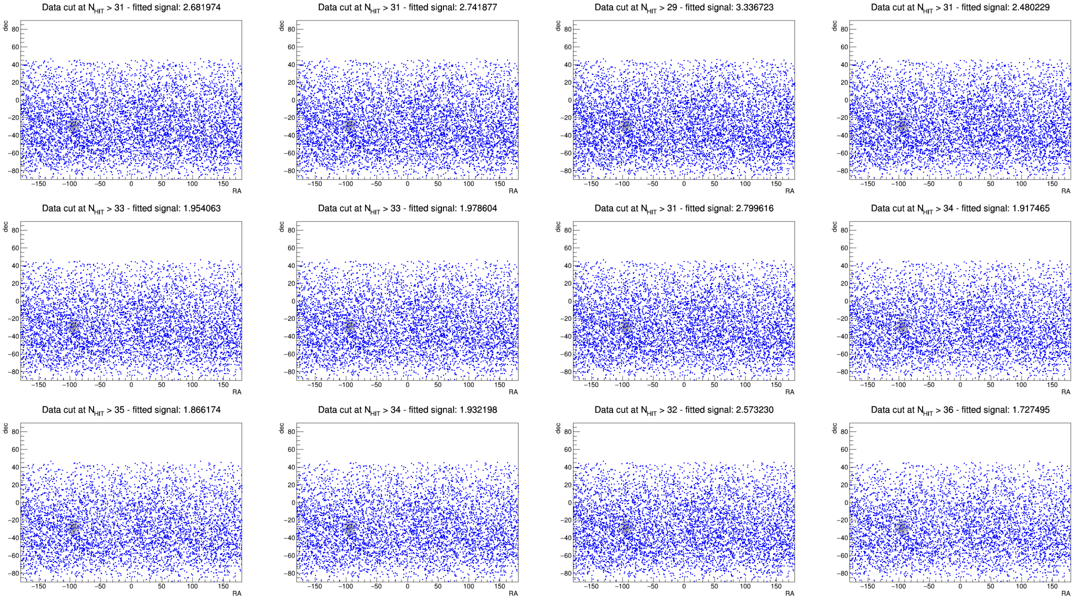




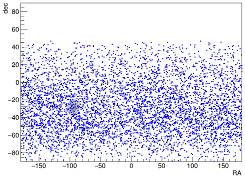
Unblinded skymaps

Here follow the unblinded skymaps with N_{HIT} cut dependent on m_{DM}, m_V, channel. To guide the eye, a 5° and 10° region around the position of the Galactic centre is marked with gray areas. How to read the unblinded result:

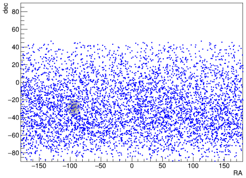



Data cut at N_{HIT} > 31 - fitted signal: 2.681974
Data cut at N_{HIT} > 31 - fitted signal: 2.741877
Data cut at N_{HIT} > 29 - fitted signal: 3.336723
Data cut at N_{HIT} > 31 - fitted signal: 2.480229
Data cut at N_{HIT} > 33 - fitted signal: 1.954063
Data cut at N_{HIT} > 33 - fitted signal: 1.978604
Data cut at N_{HIT} > 31 - fitted signal: 2.799616
Data cut at N_{HIT} > 34 - fitted signal: 1.917465
Data cut at N_{HIT} > 35 - fitted signal: 1.866174
Data cut at N_{HIT} > 34 - fitted signal: 1.932198
Data cut at N_{HIT} > 32 - fitted signal: 2.573230
Data cut at N_{HIT} > 36 - fitted signal: 1.727495
dec
RA

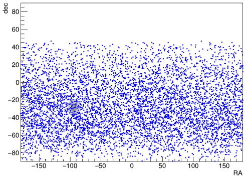
Data cut at $N_{HIT} > 36$ - fitted signal: 1.744167



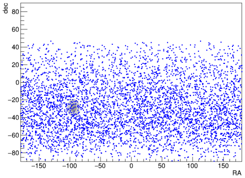
Data cut at $N_{HIT} > 35$ - fitted signal: 1.819361



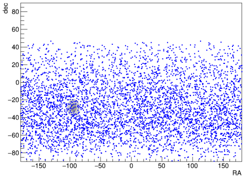
Data cut at $N_{HIT} > 32$ - fitted signal: 2.460980



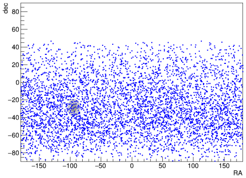
Data cut at $N_{HIT} > 38$ - fitted signal: 1.621305



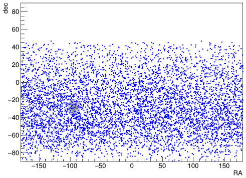
Data cut at $N_{HIT} > 38$ - fitted signal: 1.605004



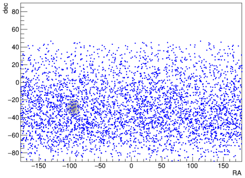
Data cut at $N_{HIT} > 37$ - fitted signal: 1.690475



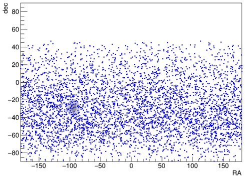
Data cut at $N_{HIT} > 33$ - fitted signal: 1.986072



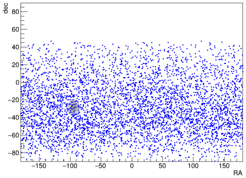
Data cut at $N_{HIT} > 40$ - fitted signal: 1.494109



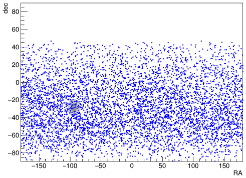
Data cut at $N_{HIT} > 39$ - fitted signal: 1.547029



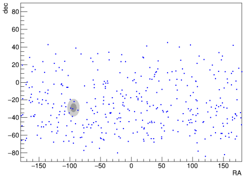
Data cut at $N_{HIT} > 38$ - fitted signal: 1.579418

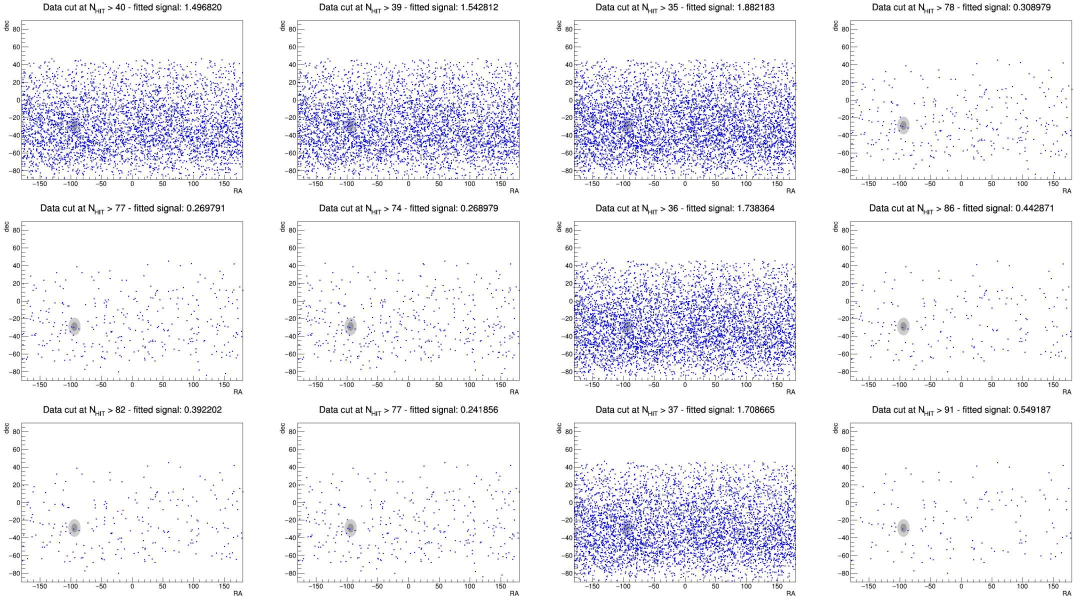


Data cut at $N_{HIT} > 34$ - fitted signal: 1.963197

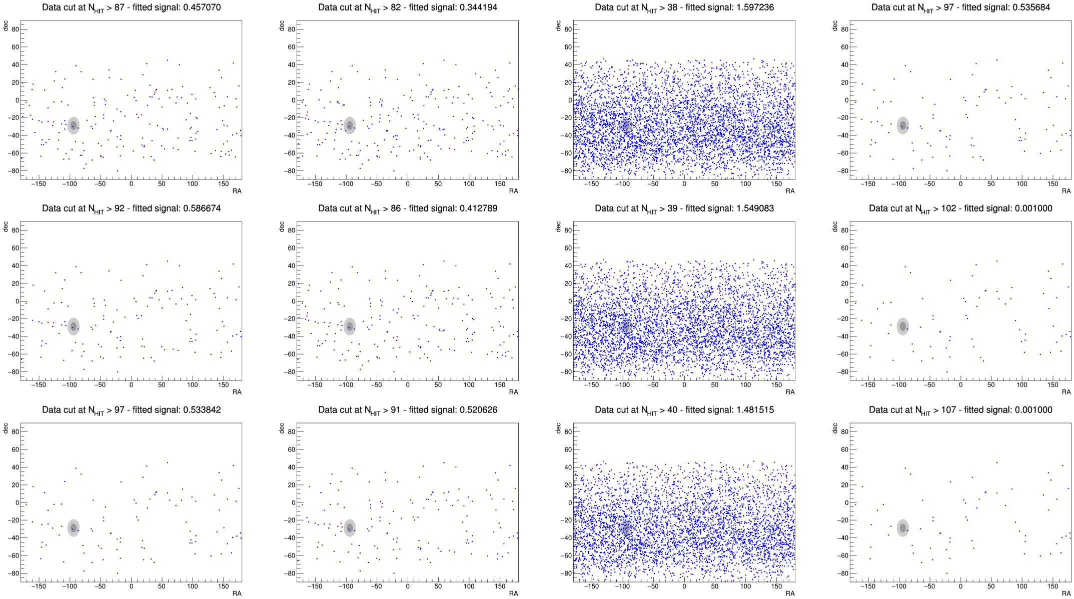


Data cut at $N_{HIT} > 75$ - fitted signal: 0.324076

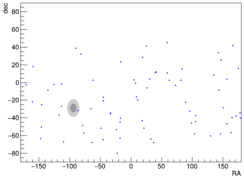




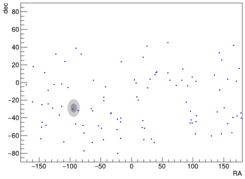
Data cut at $N_{HIT} > 40$ - fitted signal: 1.496820
Data cut at $N_{HIT} > 39$ - fitted signal: 1.542812
Data cut at $N_{HIT} > 35$ - fitted signal: 1.882183
Data cut at $N_{HIT} > 78$ - fitted signal: 0.308979
Data cut at $N_{HIT} > 77$ - fitted signal: 0.269791
Data cut at $N_{HIT} > 74$ - fitted signal: 0.268979
Data cut at $N_{HIT} > 36$ - fitted signal: 1.738364
Data cut at $N_{HIT} > 86$ - fitted signal: 0.442871
Data cut at $N_{HIT} > 82$ - fitted signal: 0.392202
Data cut at $N_{HIT} > 77$ - fitted signal: 0.241856
Data cut at $N_{HIT} > 37$ - fitted signal: 1.708665
Data cut at $N_{HIT} > 91$ - fitted signal: 0.549187
dec
RA


Data cut at N_{HIT} > 87 - fitted signal: 0.457070
Data cut at N_{HIT} > 82 - fitted signal: 0.344194
Data cut at N_{HIT} > 38 - fitted signal: 1.597236
Data cut at N_{HIT} > 97 - fitted signal: 0.535684
Data cut at N_{HIT} > 92 - fitted signal: 0.586674
Data cut at N_{HIT} > 86 - fitted signal: 0.412789
Data cut at N_{HIT} > 39 - fitted signal: 1.549083
Data cut at N_{HIT} > 102 - fitted signal: 0.001000
Data cut at N_{HIT} > 97 - fitted signal: 0.533842
Data cut at N_{HIT} > 91 - fitted signal: 0.520626
Data cut at N_{HIT} > 40 - fitted signal: 1.481515
Data cut at N_{HIT} > 107 - fitted signal: 0.001000
dec
RA

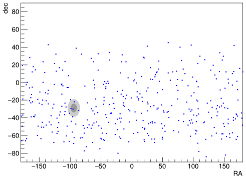
Data cut at N_{HIT} > 102 - fitted signal: 0.001000



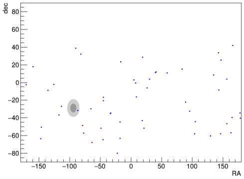
Data cut at N_{HIT} > 96 - fitted signal: 0.547118



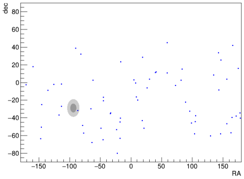
Data cut at N_{HIT} > 75 - fitted signal: 0.217702



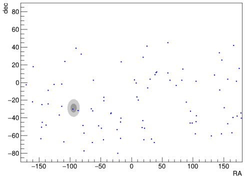
Data cut at N_{HIT} > 111 - fitted signal: 0.001000



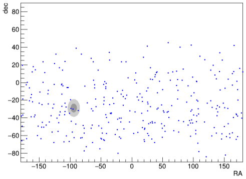
Data cut at N_{HIT} > 106 - fitted signal: 0.001000



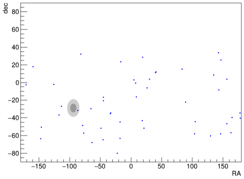
Data cut at N_{HIT} > 99 - fitted signal: 0.504235



Data cut at N_{HIT} > 78 - fitted signal: 0.208932



Data cut at N_{HIT} > 113 - fitted signal: 0.001000



Take-home message

1. No WIMP yet found encourages the exploration of new scenarios
2. Physics beyond the SM is searched in heavy sectors at colliders: heavy DM
3. Heavy DM can be accommodated in secluded scenarios which evade unitarity bound thanks to the presence of mediator $V \rightarrow$ modified cosmology
4. Mediator decays inside the GC and produces fluxes of SM particles observable in telescopes
5. ANTARES can exploit its view of the GC up to high energies
6. Data 2007-15 is consistent with background. No trace of heavy dark matter. Limits are however rather weak in the PeV energy range.
7. Results shown at Neutrino2020 [poster #467]; corresponding publication in preparation.