Neutrino telescopes and dark matter detection

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News from the dark

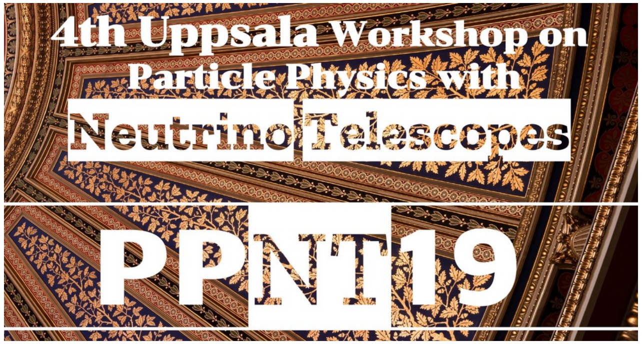
Episode 6: the astroparticle picture

22-24 november 2021, LAPTh Annecy

Some material :

- *PPNT 2019*

https://indico.uu.se/event/600/



- *ICRC 2021*

https://icrc2021.desy.de/

Outline

- *Detection principle*

- *Existing telescopes and projects*

  IceCube – IceCube Gen 2

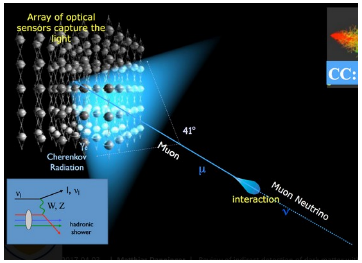
  Antares - KM3Net

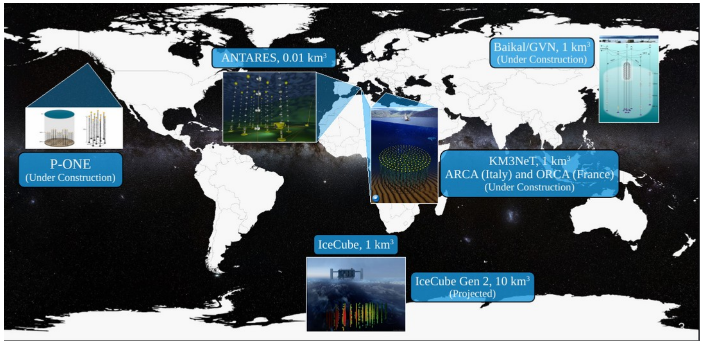
  Baikal

  P-ONE

- *Dark matter detection with neutrinos*

- *Targets:*
  - *Dwarfs - Galaxy clusters*
  - *Galactic center*
  - *Sun*
  - *Earth*

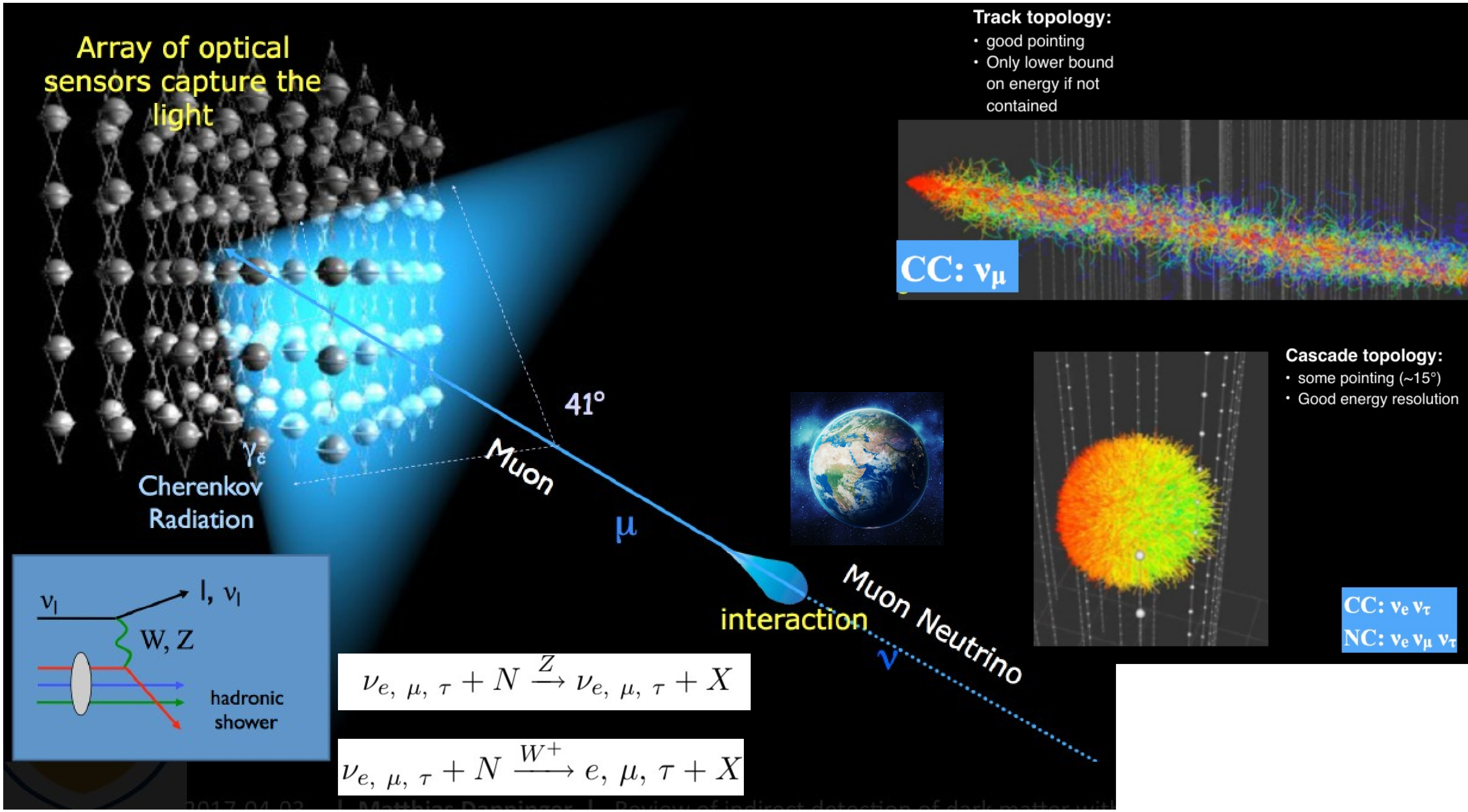




Specific studies:

- *DM annihilation into neutrino*
- *Angular Power Spectrum method*
- *Decaying DM*
- *Secluded DM*
- *Dark Matter neutrino scattering*
- *...*

Detection principle

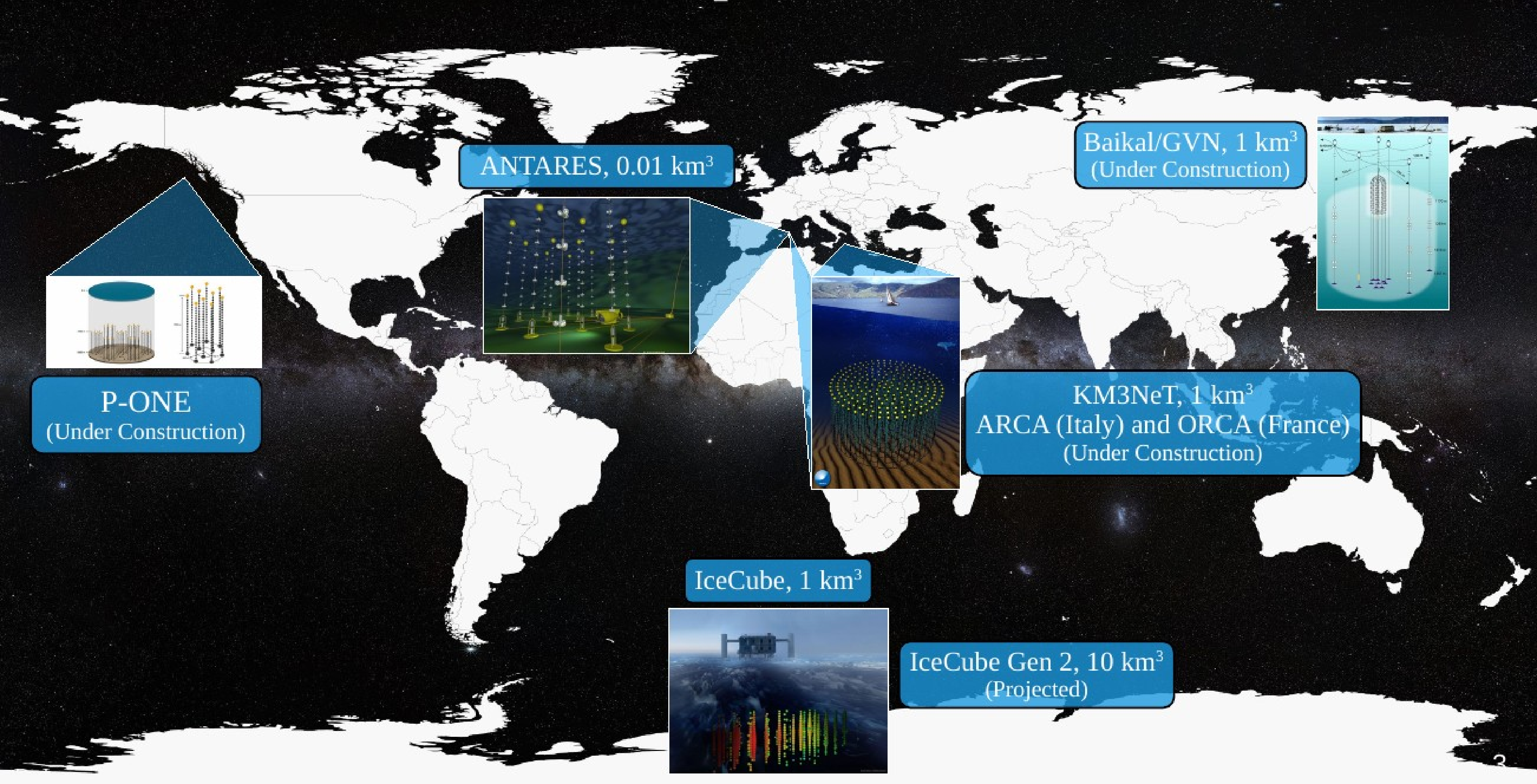


Different topologies depending on specy of the neutrinos and on energy (events inside/outside the instrumental volume)

Collect Cherenkov light of muon coming from muon neutrino interaction in the Earth through charged current

Muon track, typical events for DM searches

Neutrino Telescopes around the World



From Daniel Lopez Coto @ ICRC2021

Size evolution

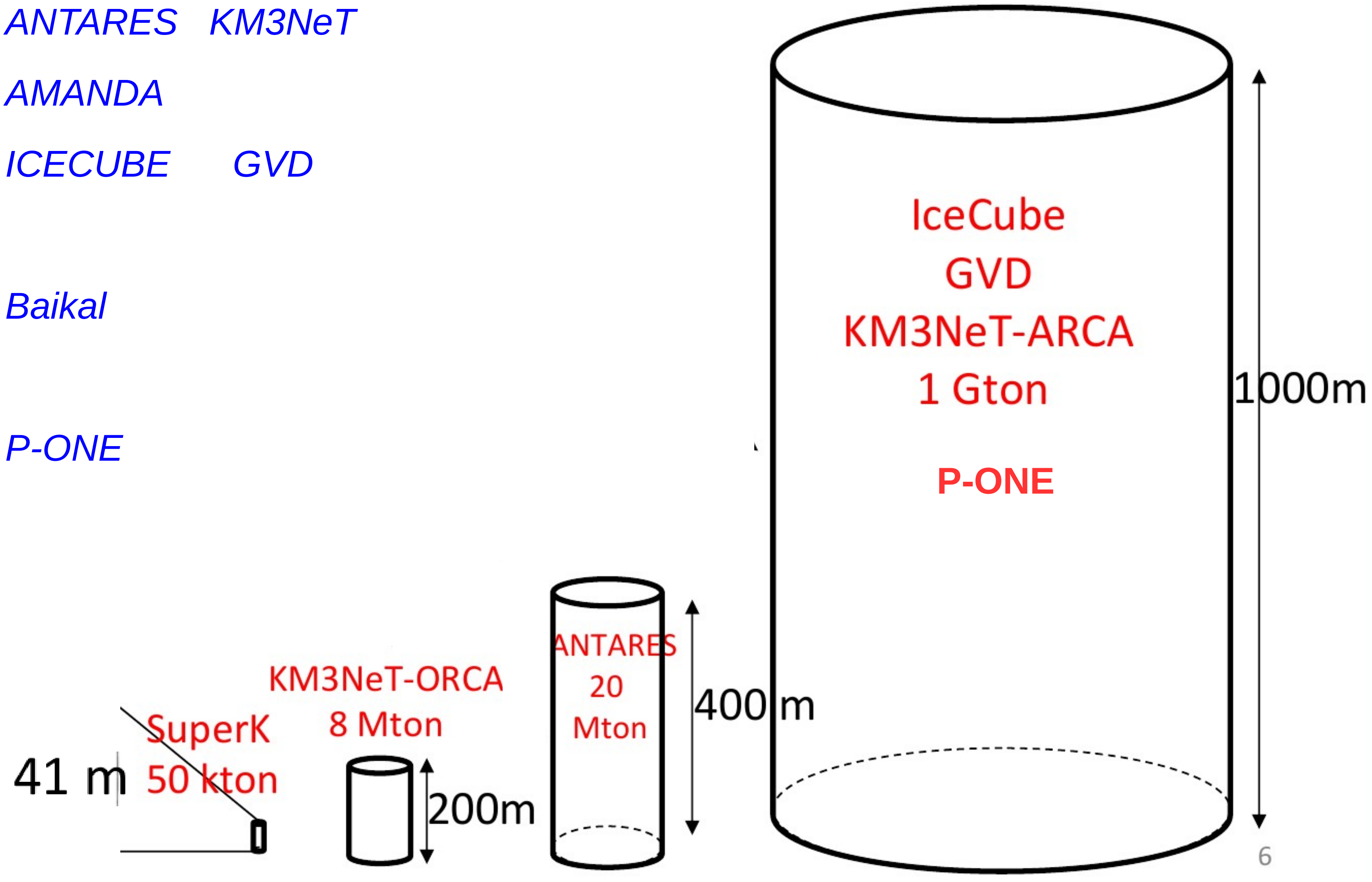
ANTARES   KM3NeT

AMANDA

ICECUBE   GVD

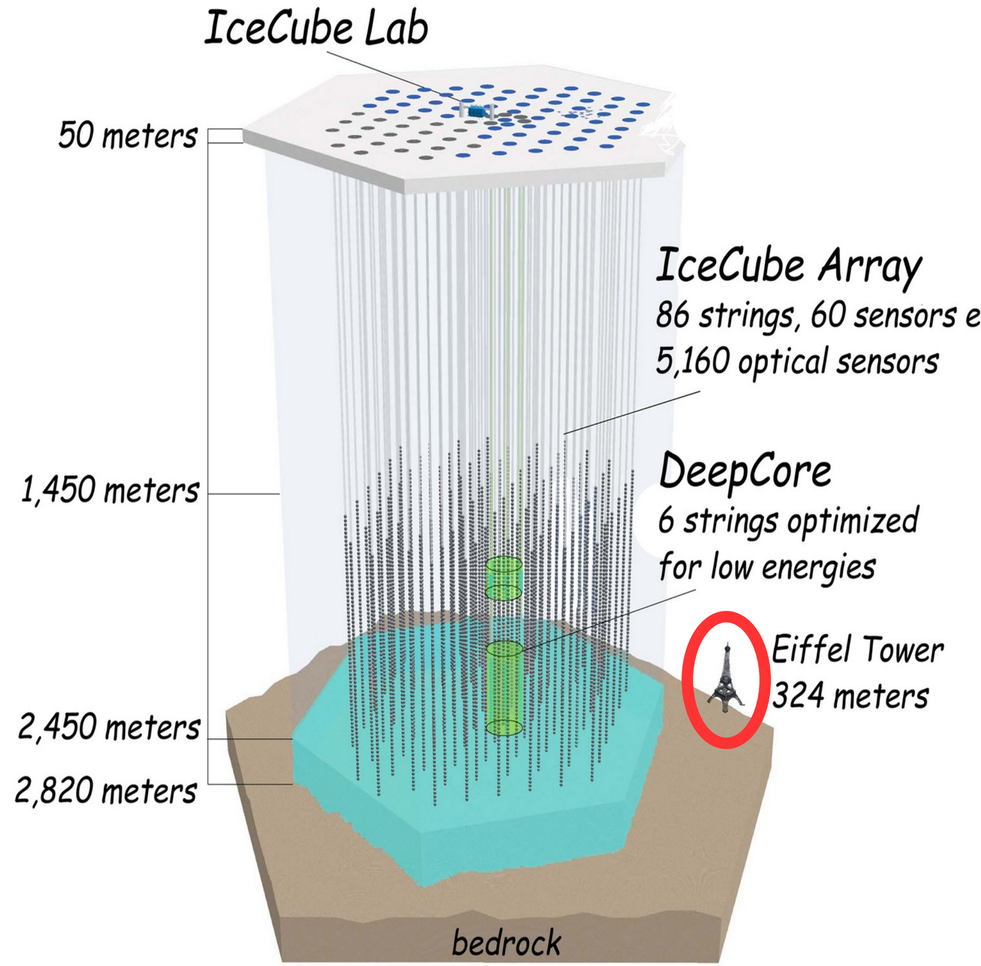
Baikal

P-ONE



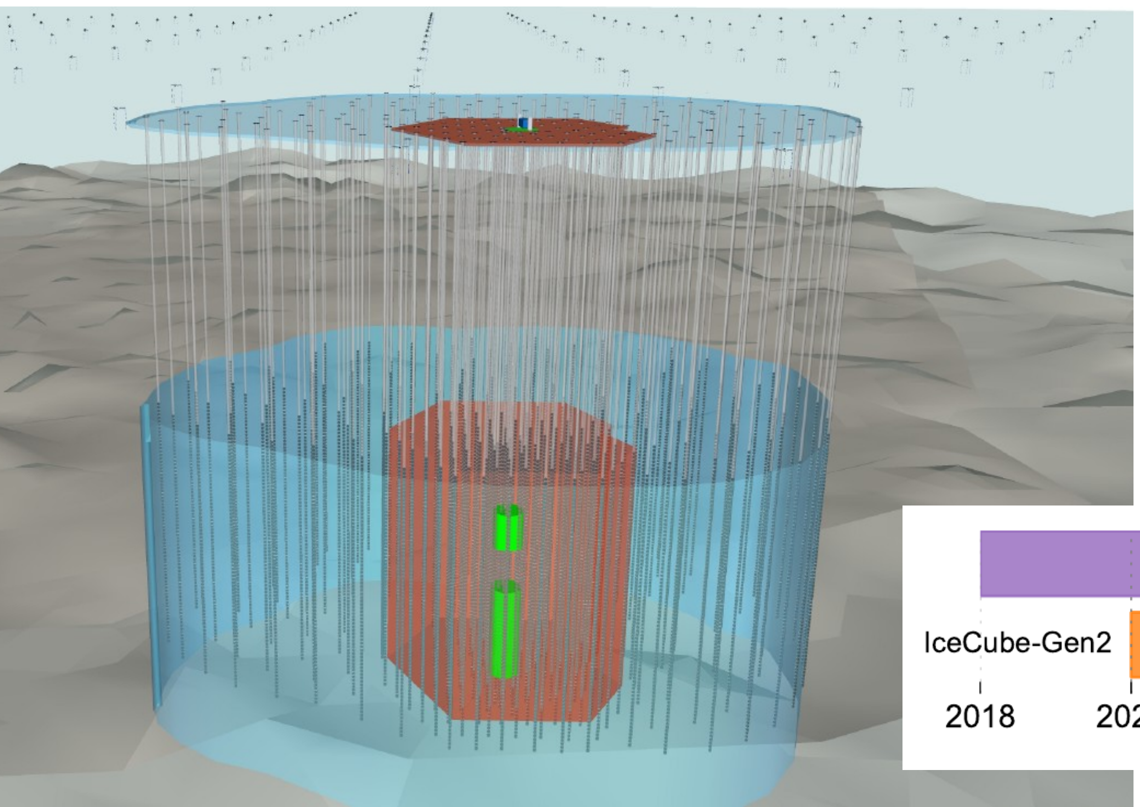
From Paschal Coyle @ ICRC2021

(Amanda) Icecube – Icecube GEN2

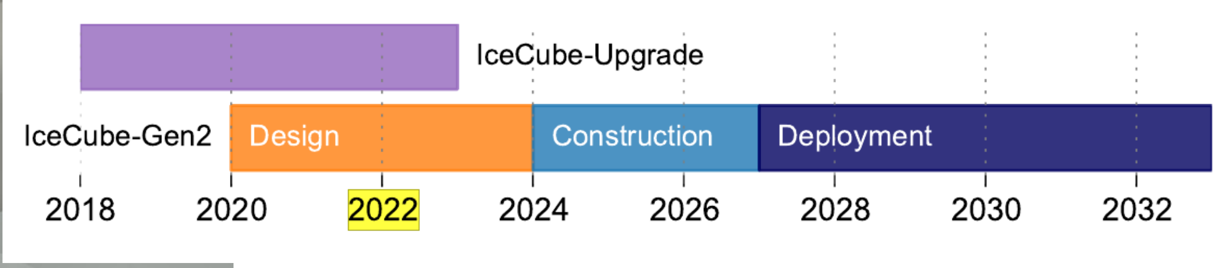


ICECUBE GEN 2 10 km^3

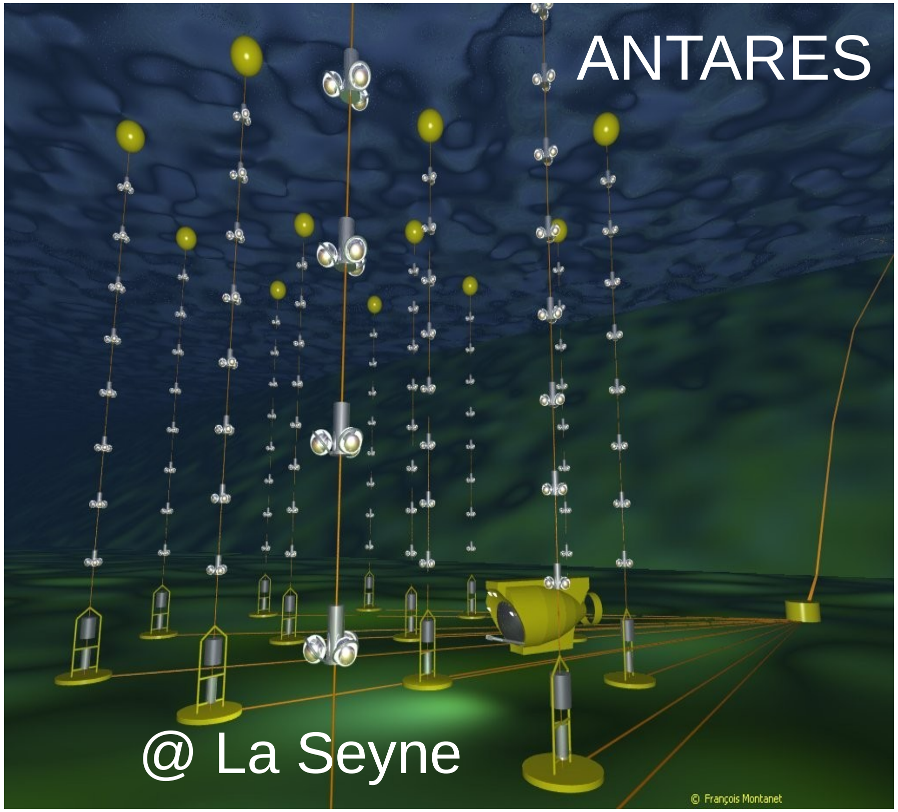
arXiv:2008.04323

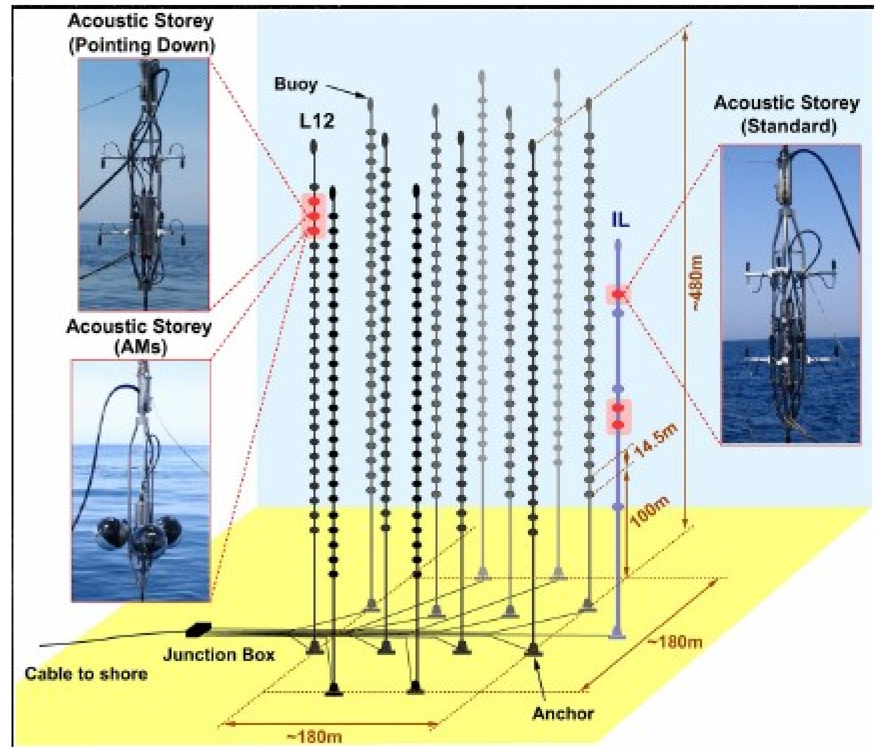


Schedule



ANTARES


ANTARES
@ La Seyne
© François Montanet


Acoustic Storey
(Pointing Down)
Acoustic Storey
(AMs)
Buoy
L12
IL
Acoustic Storey
(Standard)
~480m
14.5m
100m
~180m
~180m
Cable to shore
Junction Box
Anchor

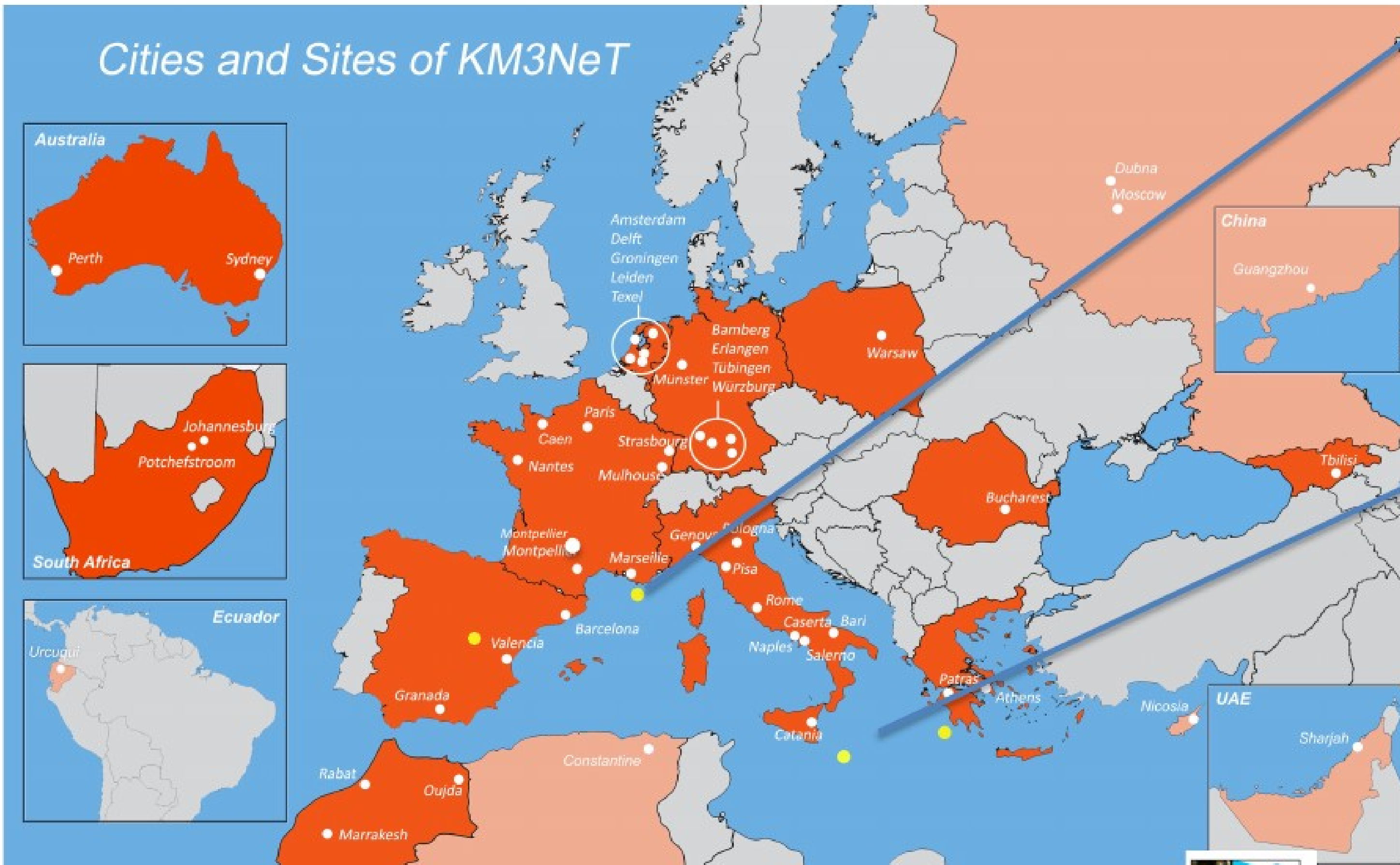

Marseille
Toulon
Nice
Cannes
Hyères
Bastia
Calvi
Ajaccio
Antares site
40 km off the coast Toulon - La Seyne
2480m depth

KM3NeT

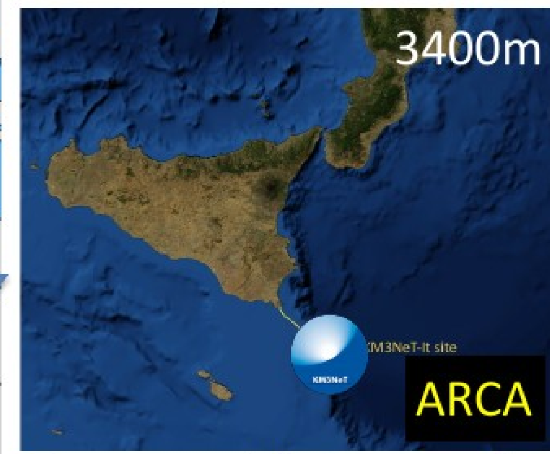
Multi-site, deep-sea infrastructure

Selected for ESFRI roadmap

Single collaboration, Single technology



Oscillation **R**esearch with **C**osmics In the **A**byss



Astroparticle **R**esearch with **C**osmics In the **A**byss

Connection nodes of

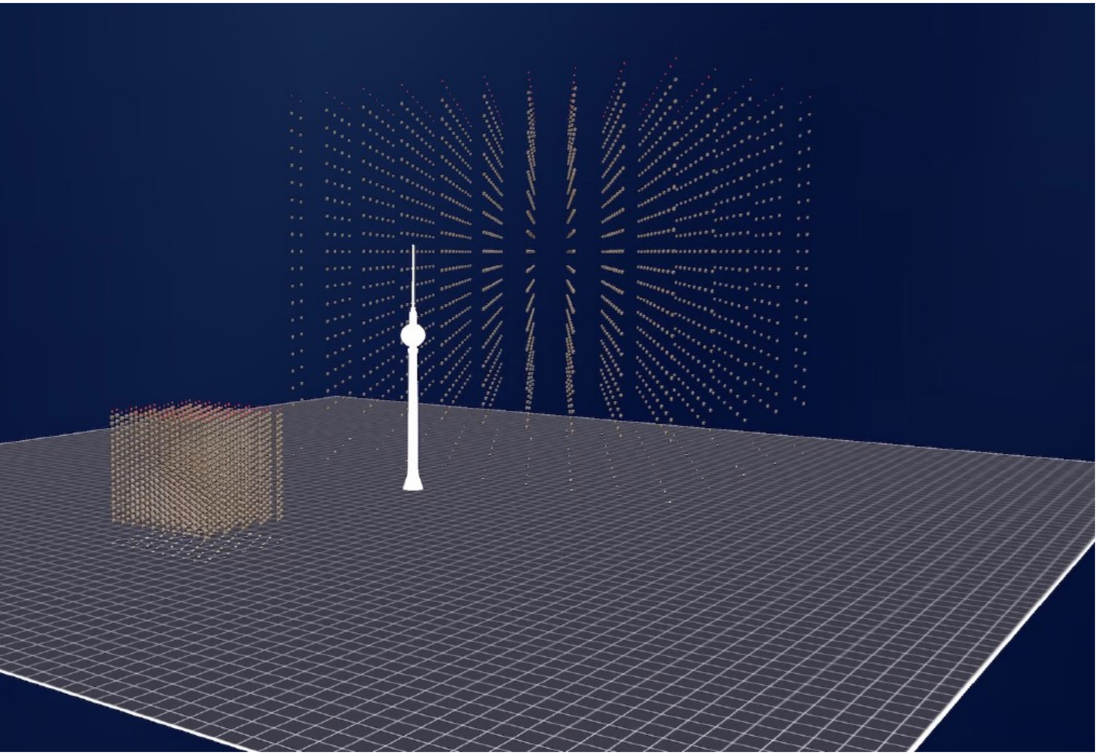
european multidisciplinary seafloor & water column observatory emso

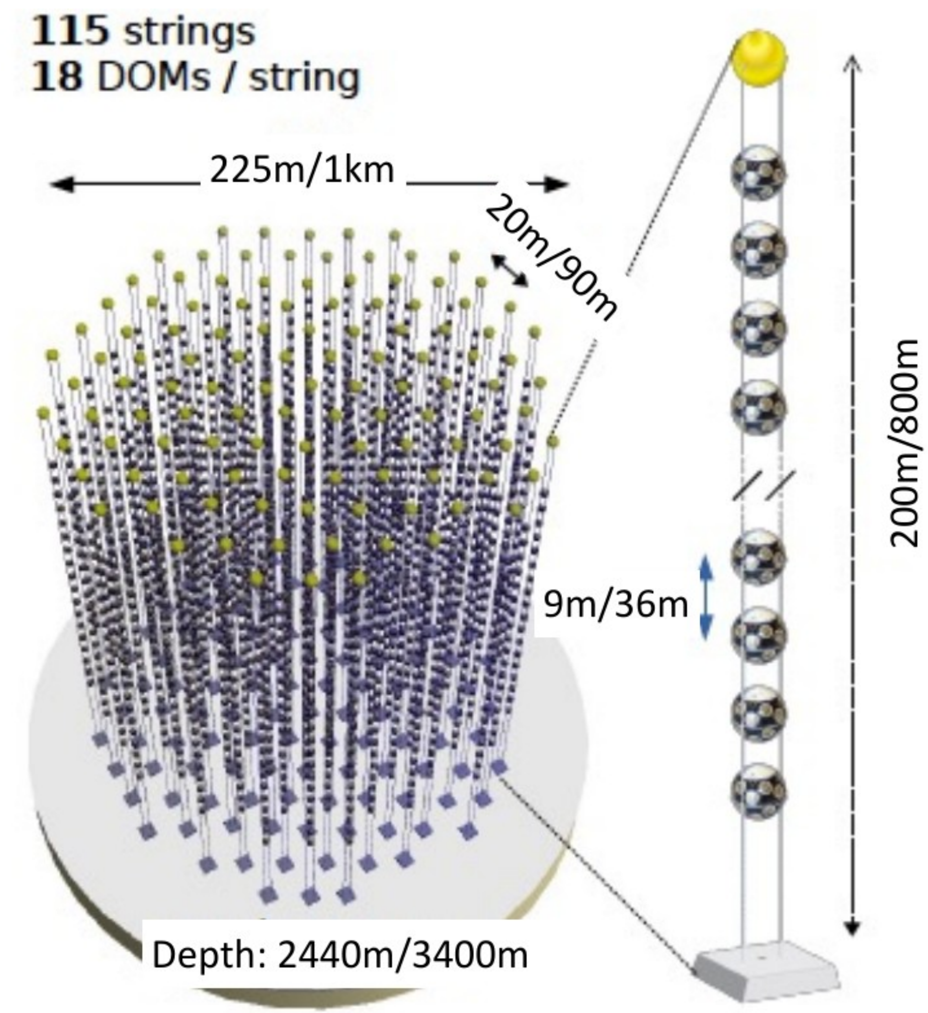
[KM3NeT 2.0: Letter of Intent](http://dx.doi.org/10.1088/0954-3899/43/8/084001)

http://dx.doi.org/10.1088/0954-3899/43/8/084001

J. Phys. G: Nucl. Part. Phys. 43 (2016) 084001

KM3NeT





Instrumented mass	7 Mton	500*2 Mton

Baikal

1980: Start of experiments at "106 km" site

1993: NT36 - 3 strings, 36 optical modules (OM)

1996: NT96 - 4 strings, 96 OM

1998: NT200 - 8 strings, 196 OM

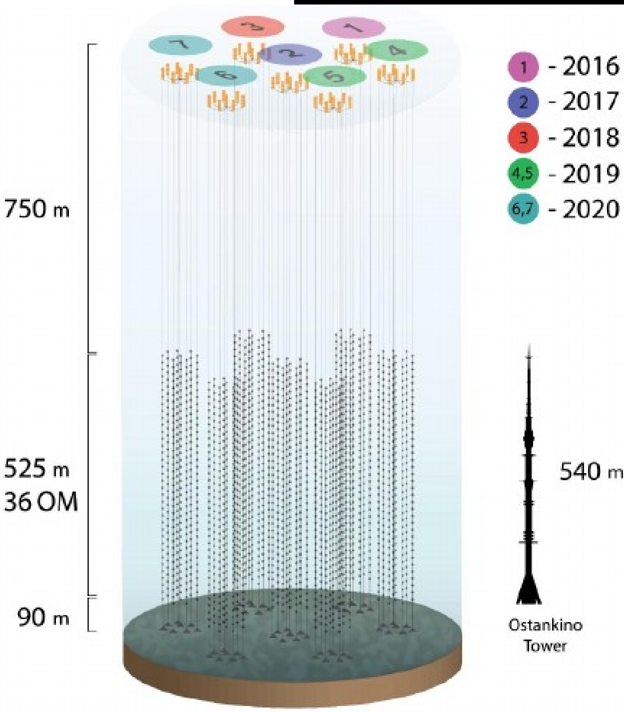
2004-2005: NT200+ - three additional strings, 12 OM each

2015: Start of Baikal-GVD construction. Demonstration clus
"Dubna", 8 strings, 192 OM

2016: First full-scale cluster of Baikal-GVD deployed

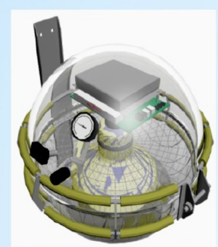
2020: Baikal-GVD operates 7 clusters, 2016 OM

PoS (ICRC2021) 002

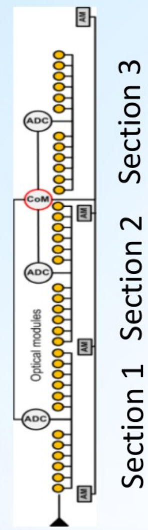


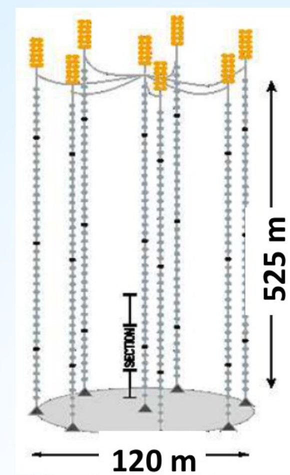
Olga Suvorova @ PPNT2019

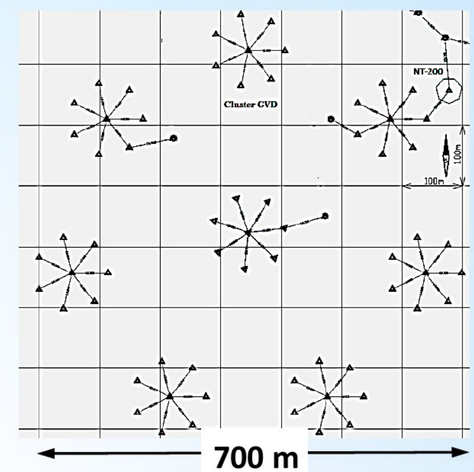
Baikal-GVD: phase I (2020-2021)



Optical module
PMT: R7081-100





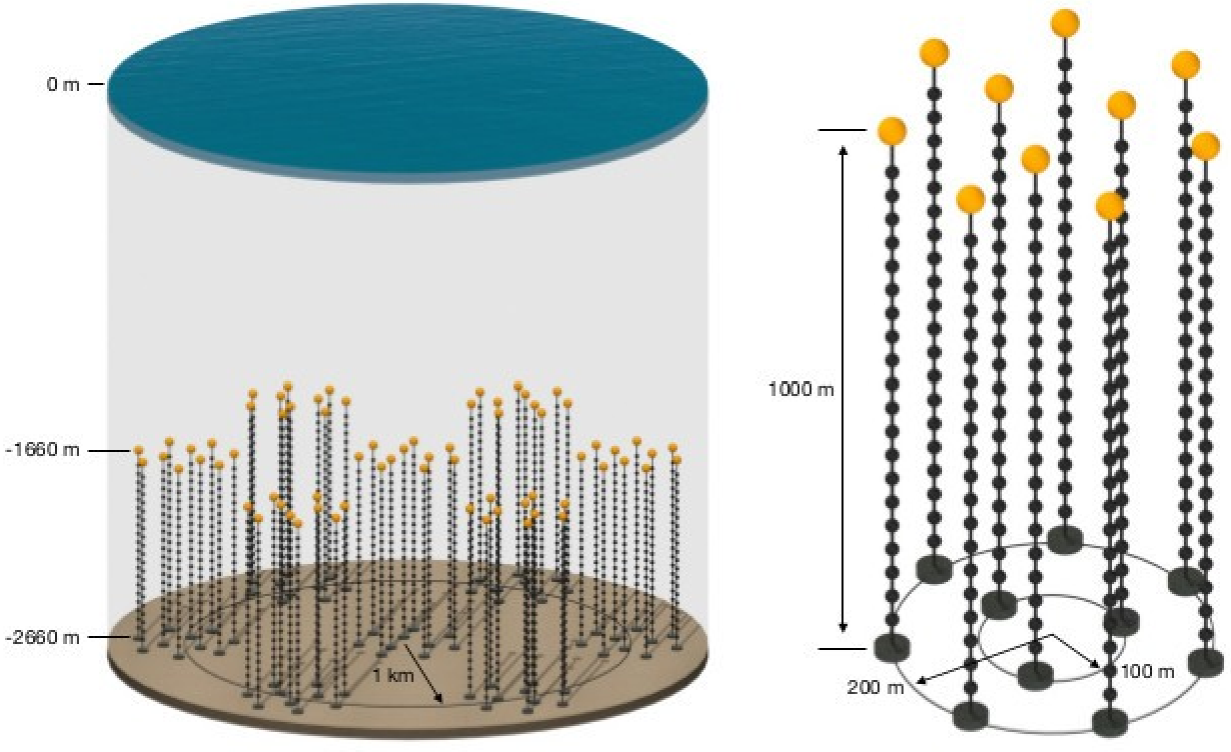


GVD-1	
OMs	2304
Clusters (8 Strings)	8
Depths, m	750 – 1275
Eff. Volume	0.4 km³

Directional resolution	Energy resolution
Cascades: 3.5° – 5.5°	δ(E/Esh) ~ 0.15
Muons: 0.25° - 0.5°	δ(lgE) ~ 0.4

P-ONE
Pacific Ocean Neutrino Experiment

arXiv:2005.09493

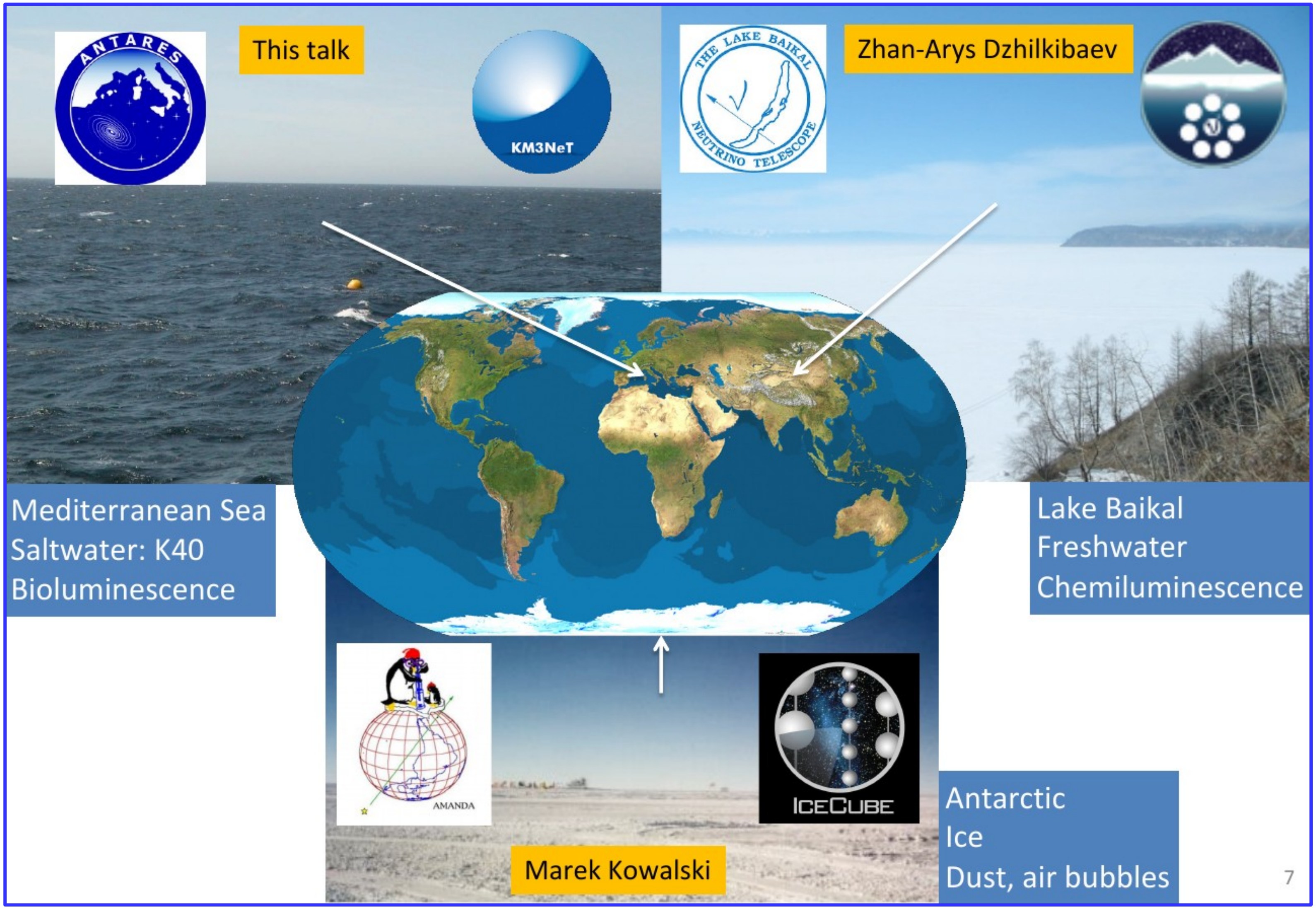


A KM3 size telescope installed whithin the deep Pacific Ocean underwater infrastructure of Ocean Networks Canada

10 first lines 2023-2024

+ 70 lines 2028-2030

From Paschal Coyle @ ICRC2021



Water:

less diffusion, angular resolution

salt water: K40, Bioluminescence

freshwater: chemiluminescence

moving detector (waves and sea current)

need boat + ROV (remotely operated underwater vehicle)

Ice:

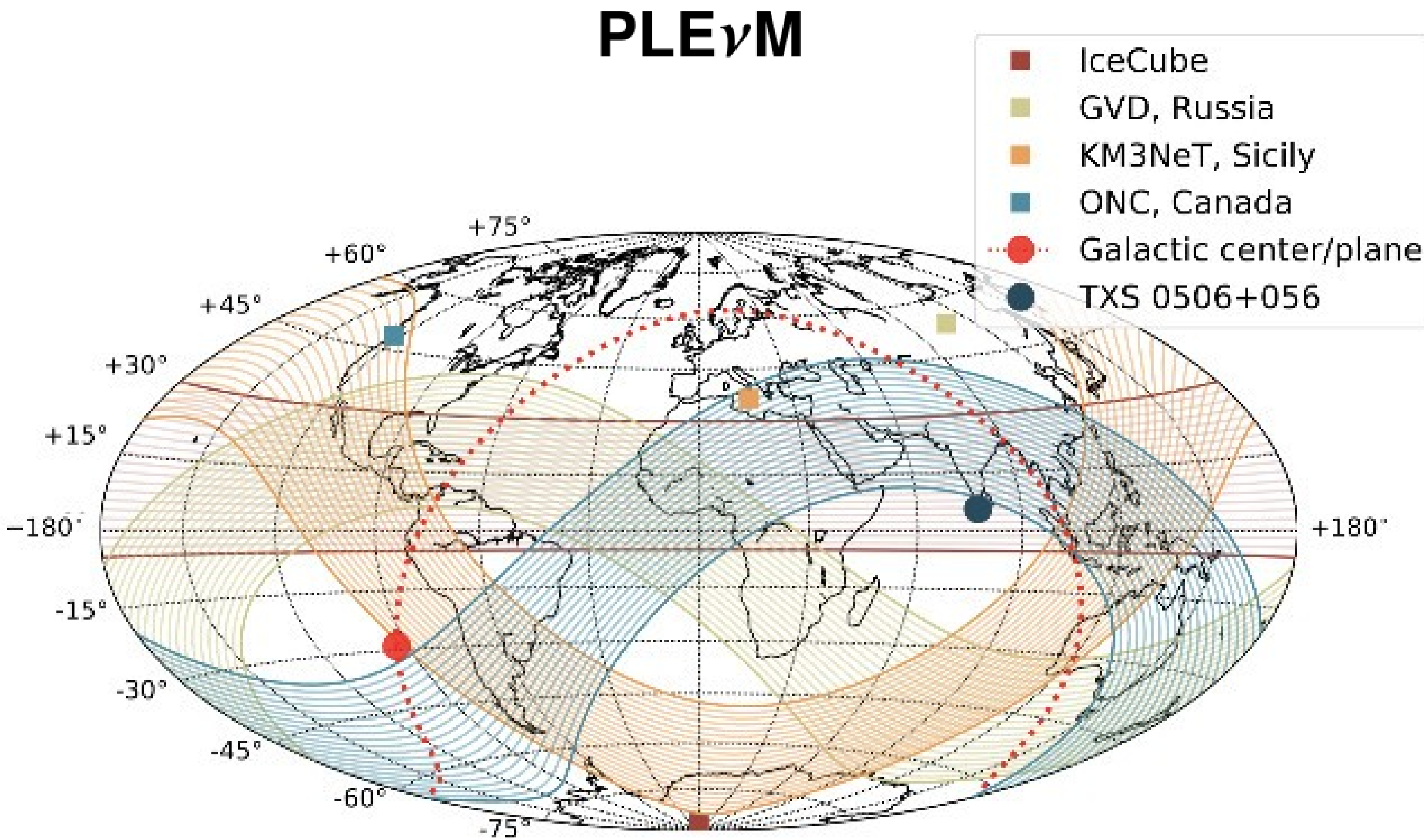
easier to install (but south pole)

less constraints once installed,

more diffusion/angular resolution

Dust, air bubbles

Sky coverage



Planetary Neutrino Monitoring System (**PLEνM** *)*

A global and distributed monitoring system of high-energy astrophysical neutrinos

Lisa Schumacher@ICRC2021 and arXiv:2107.13534

Science scope

Neutrino and multimessenger astronomy

Neutrino oscillations

New physics, exotic searches

Indirect dark matter searches

Dark matter detection with neutrinos

Dark matter annihilation :

$$\chi\chi \to t\bar{t},\ b\bar{b},\ c\bar{c},\ \tau^+\tau^-,\ W^+W^-,\ ZZ,\ \mu^+\mu^-,\ \nu\bar{\nu}...$$

Decay of annihilation products → Neutrino spectrum = $\sum_i \frac{dN_\nu^i}{dE_\nu} BR_i$

$$\chi\chi \to X\bar{X} \to \nu Y$$

Typical spectra:

Pythia / WIMPSIM / PPPC4DM

Typically use extremal cases:

Hard spectrum $\tau^+\tau^-$ W^+W^- $\mu^+\mu^-$

Soft spectrum $b\bar{b}$

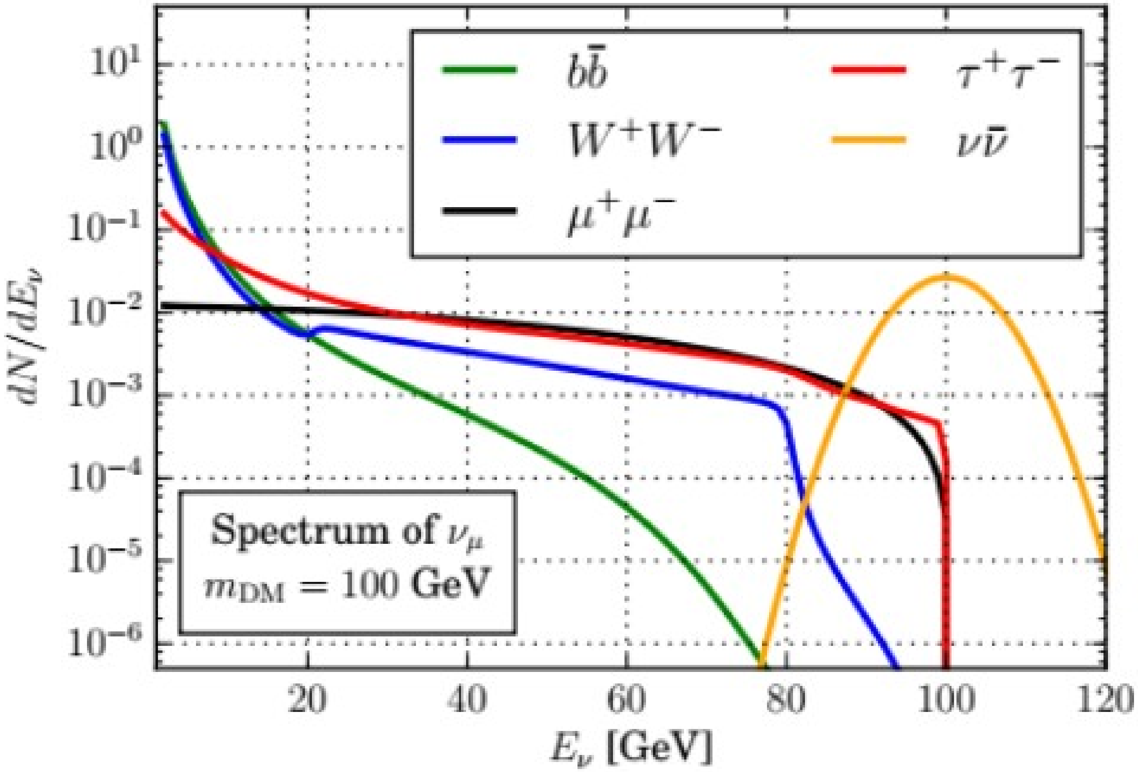
(recent update see HDMspectra

Bauer,Rodd,Webber arXiv:2007.15001)

Dark Matter Spectra from the Electroweak to the Planck Scale

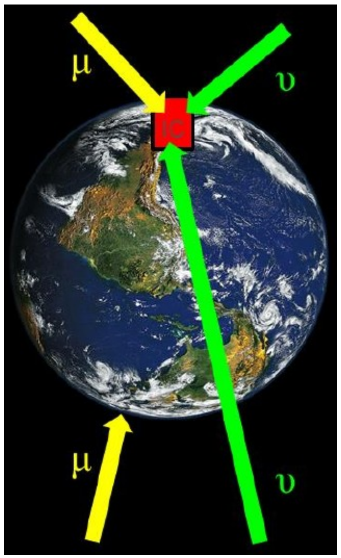
Christian W. Bauer,[1,2] Nicholas L. Rodd,[1,2] Bryan R. Webber[3]

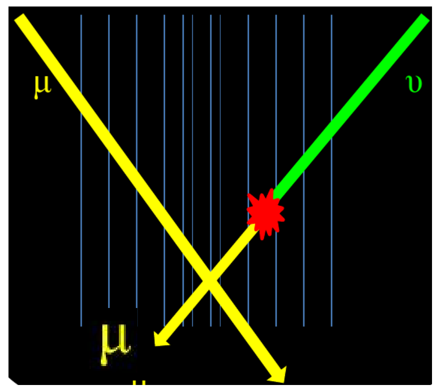
[1] Berkeley Center for Theoretical Physics, University of California, Berkeley, CA 94720, USA
[2] Theoretical Physics Group, Lawrence Berkeley National Laboratory, Berkeley, CA 94720, USA
[3] University of Cambridge, Cavendish Laboratory, J.J. Thomson Avenue, Cambridge, UK

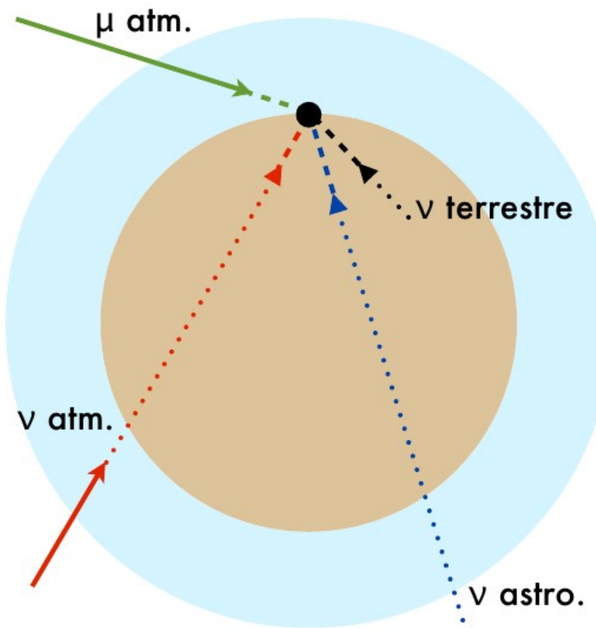


Background

Atmospheric neutrinos/muons:







Select upgoing events to reduce atmospheric muons

Flux

Annihilation case

$$\frac{d\phi_\nu^{ann}}{dE_\nu} = \frac{\delta}{4\pi}\frac{\langle\sigma v\rangle}{m_{DM}^2}\sum_f b_f \frac{dN_\nu^f}{dE_\nu}\int_{res.} d\Omega \int_{l.o.s} \rho_{DM}^2(r)dl$$

Dark matter distribution ?

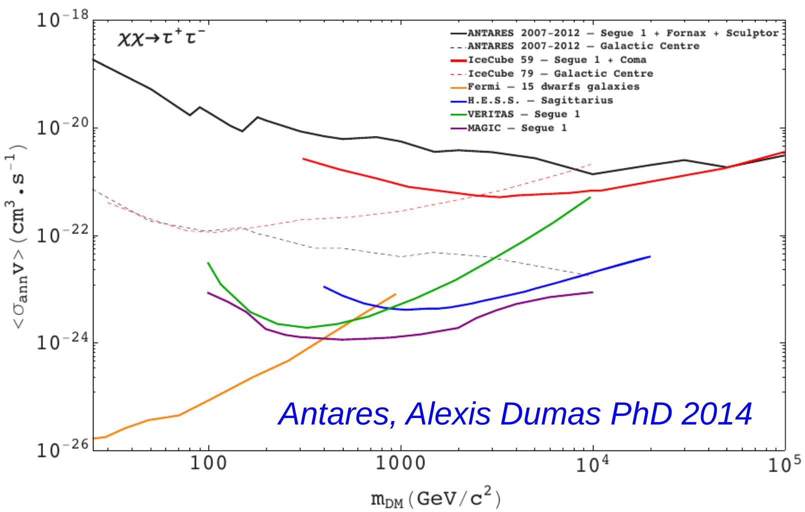
Clumps
Mas spectrum
Concentration
Spatial distribution
Streams

Density profile
Cusp/core
Baryons ?
...

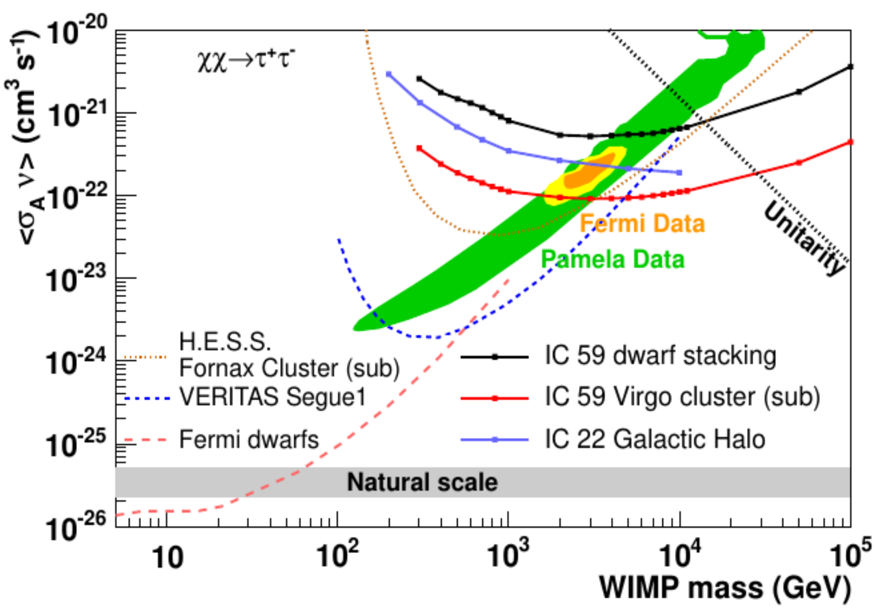
Dsphs

- Jeans equation to constrain the DM profile parameters

$$\sigma_p^2(R) = \frac{2}{I(R)} \int_R^\infty \left(1 - \beta_a \frac{R^2}{r^2}\right) \frac{\nu \sigma_r^2 r}{\sqrt{r^2 - R^2}} dr$$



[Results from Baikal see O.Suvorova PPNT2019]



arXiv:1307.3473

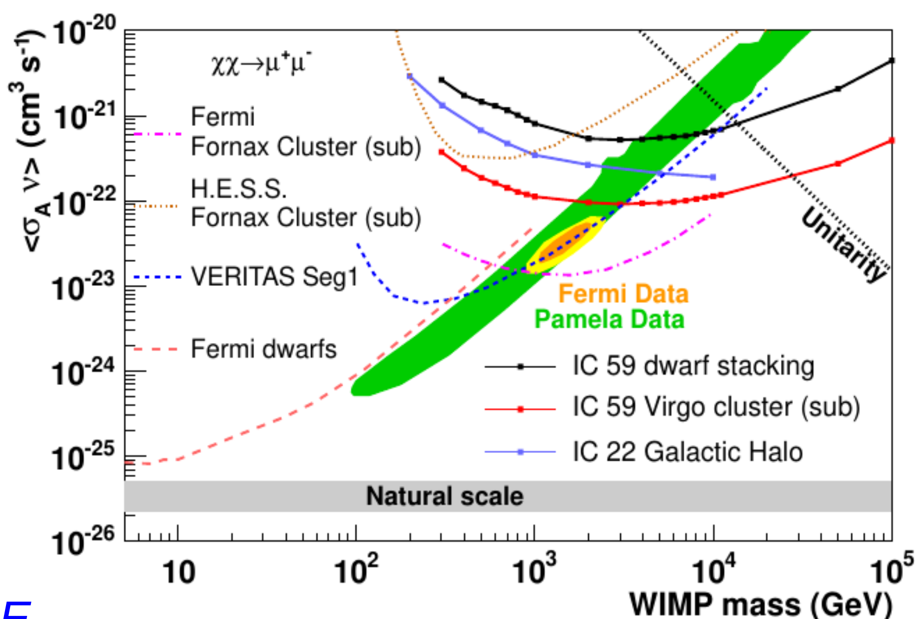
Clusters

- Derive profile parameters from X-ray data

Use J factor from Fermi for comparison and effective boost factor from Gao et al 2012 (Phoenix DMO simulation)

$$b(M_V) = \frac{J_{\text{sub-cluster}}}{J_{\text{NFW}}} = 1.6 \times 10^{-3} \left(\frac{M_V}{M_\odot}\right)^{0.39}$$

Discuss here angular size of objects vs resolution



ICECUBE

Galactic center and MW halo

- Flux:

Annihilation case

$$\frac{d\phi_\nu^{ann}}{dE_\nu} = \frac{\delta}{4\pi}\frac{\langle\sigma v\rangle}{m_{DM}^2}\sum_f b_f \frac{dN_\nu^f}{dE_\nu}\int_{res.} d\Omega \int_{l.o.s} \rho_{DM}^2(r)dl$$

Dark matter density in the Milky Way ?

Clumps
Mas spectrum
Concentration
Spatial distribution
Streams

Density profile
Cusp/core
Baryons ?
Compression ?
Stellar formation/SN feedback ?
DM halo driven by the history of assembly of baryons. Steepening-Flattening ?

Galactic center and MW halo

- Flux:

Annihilation case

$$\frac{d\phi_\nu^{ann}}{dE_\nu} = \frac{\delta}{4\pi}\frac{\langle\sigma v\rangle}{m_{DM}^2}\sum_f b_f \frac{dN_\nu^f}{dE_\nu}\int_{res.} d\Omega \int_{l.o.s} \rho_{DM}^2(r)dl$$

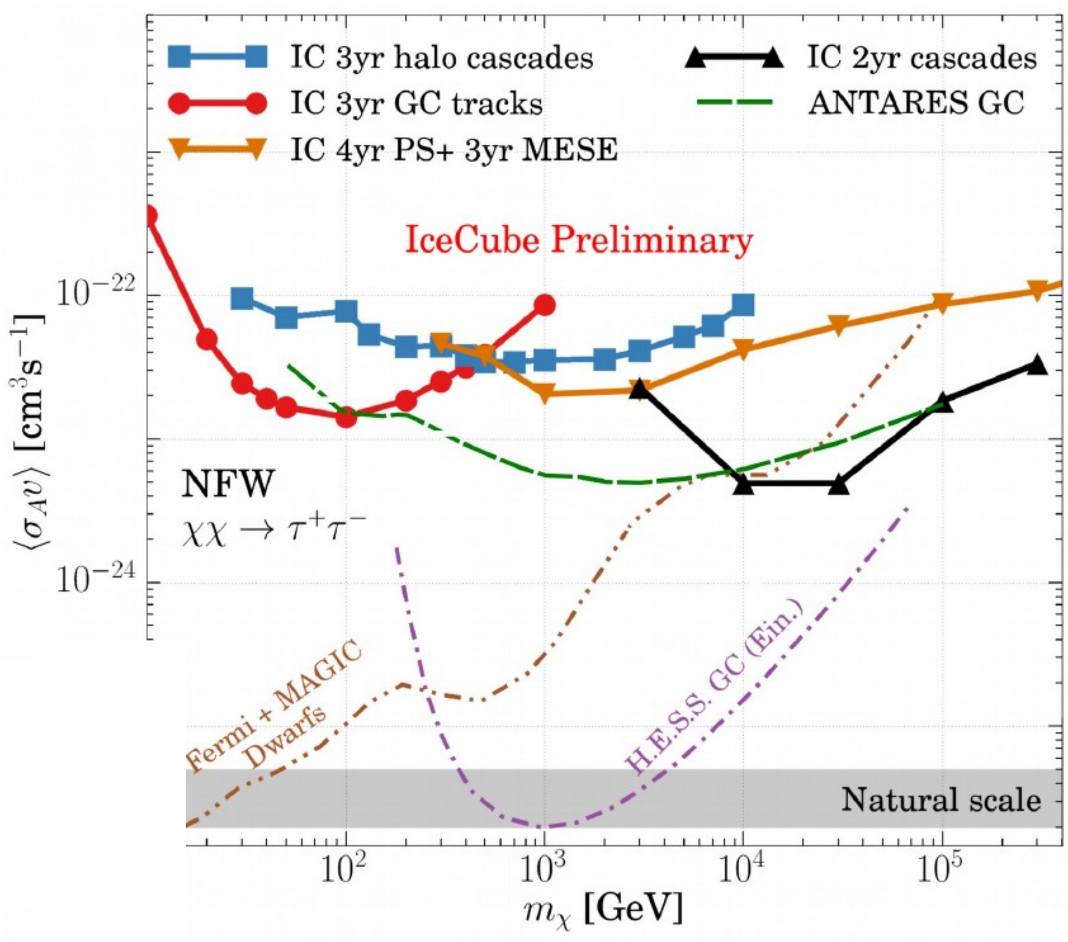
Dark matter density in the Milky Way ?

- Popular profile from (irrelevant) DMO simulations ? NFW, Einasto, Via Lactea, Aquarius ...
- (unrealistic but consistent) cosmo hydro simulations ? With strong cusps induced by stellar potential ? With cores induced by feedback ? Evaluate the diffuse emission ? (not only the DM emission)
- or (unrealistic) semi-analytic models ? (faster) Stref, Lavalle 2017, CLUMPY Hutten, Combet, Maurin 2019, Hiroshima, Ando,Ishiyama 2018 ...
- Cored profiles suggested by data ? (simple only smooth component)

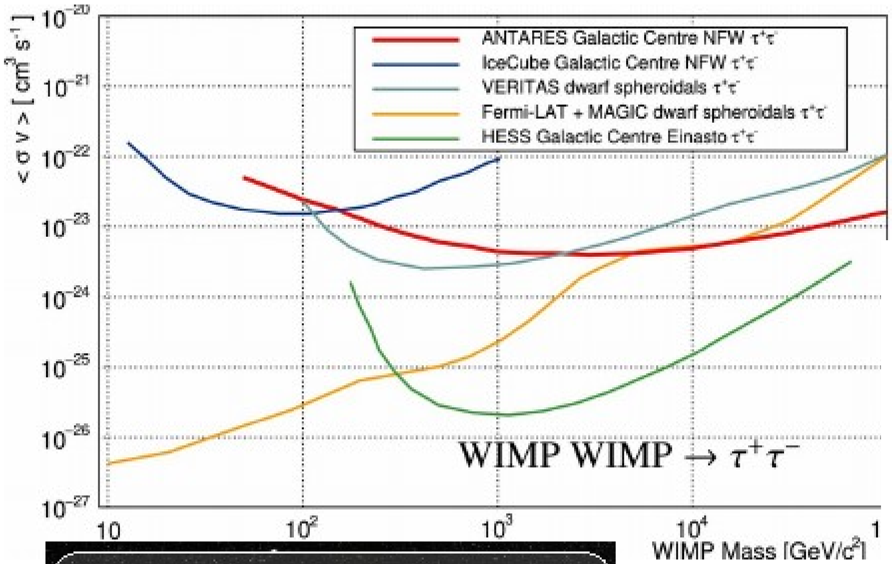
MacMillan 2016, Portail 2016.

Galactic center

[EPJC 77 (2017) 627]

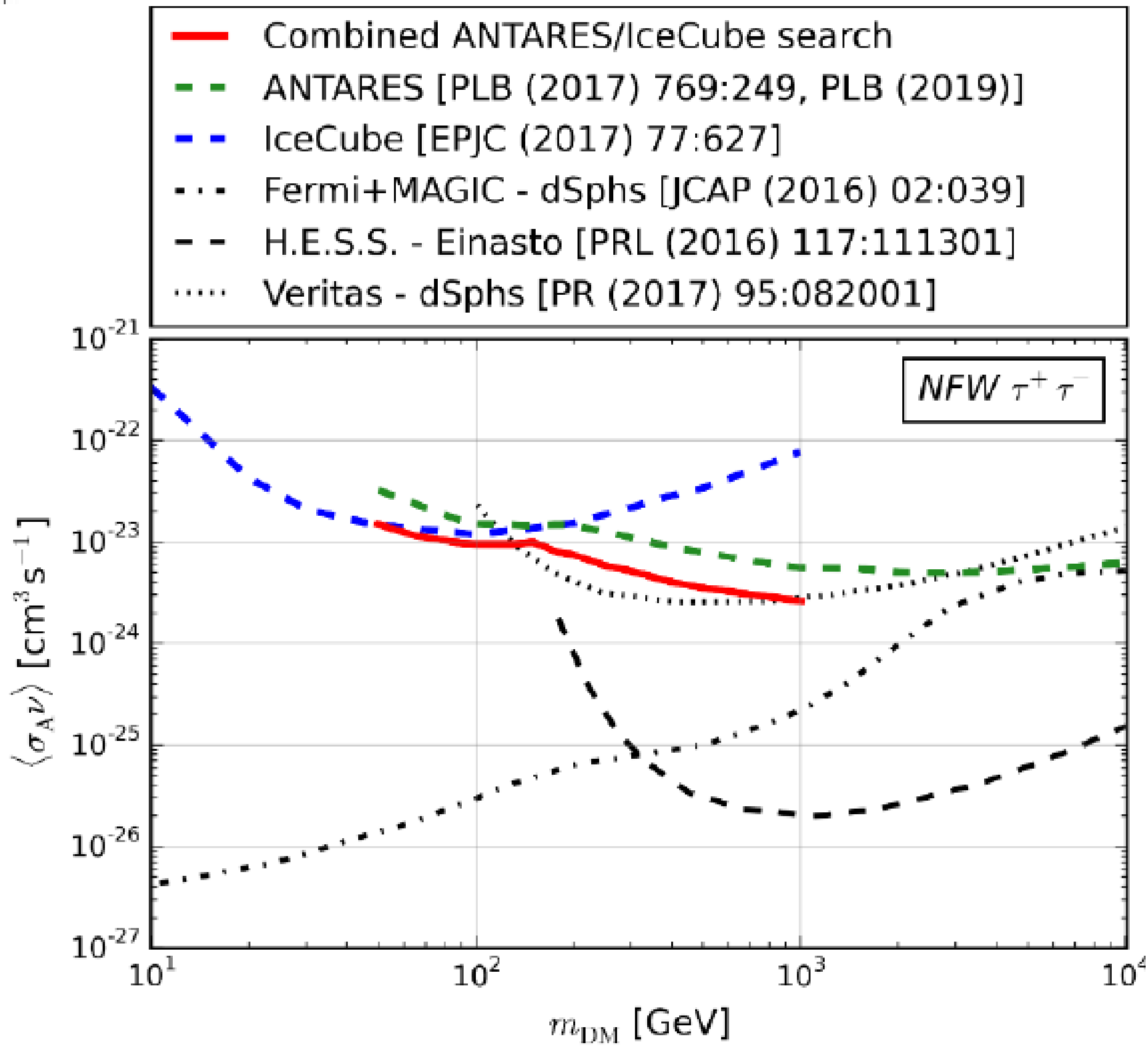


Galactic center

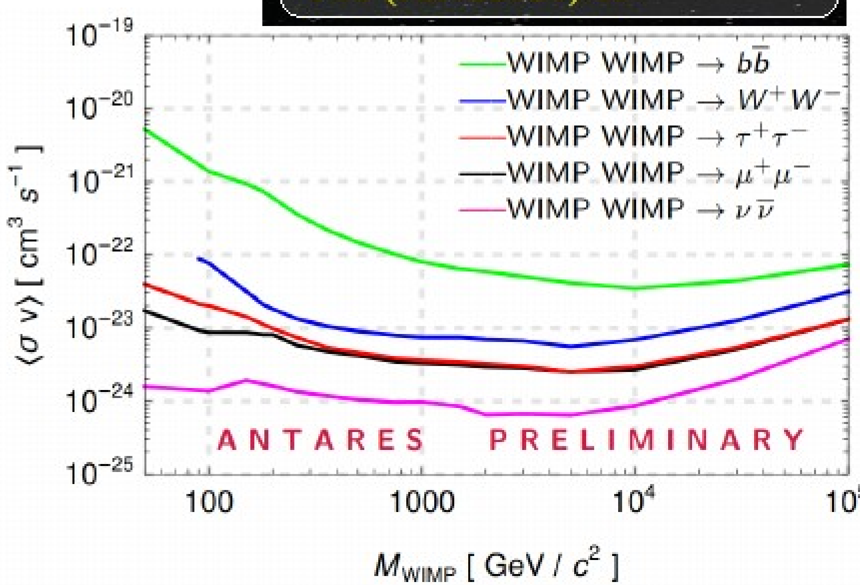


ANTARES GC,
11 years of Data (2007-2017)
Physics Letters B, Vol 805,2020

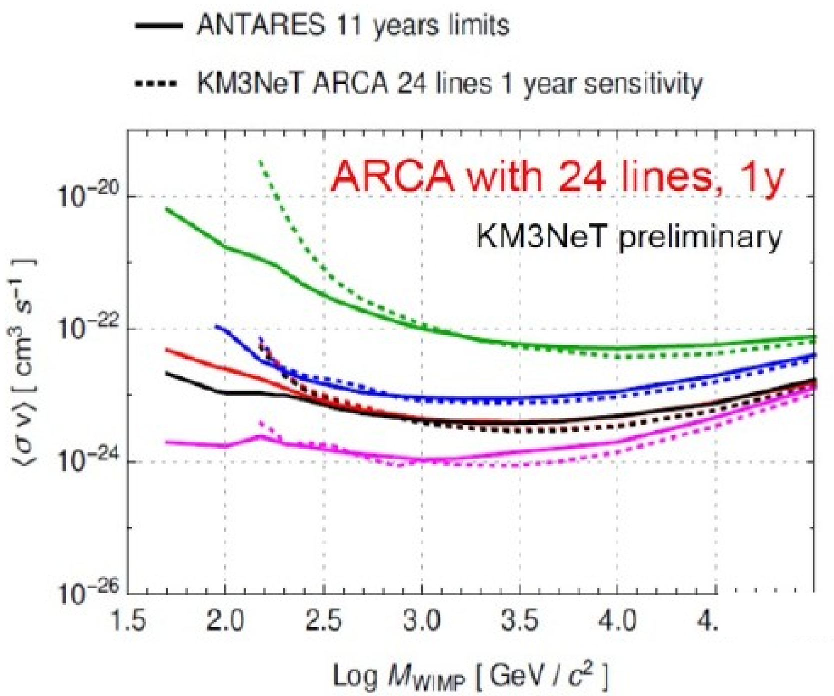
ANTARES + IC combined GC,
11 years of Data (2007-2017)
PRD 102 (2020) 082002



ANTARES GC,
13 years of Data (2007-2020)
PoS (ICRC2021) 537



Galactic center : Next



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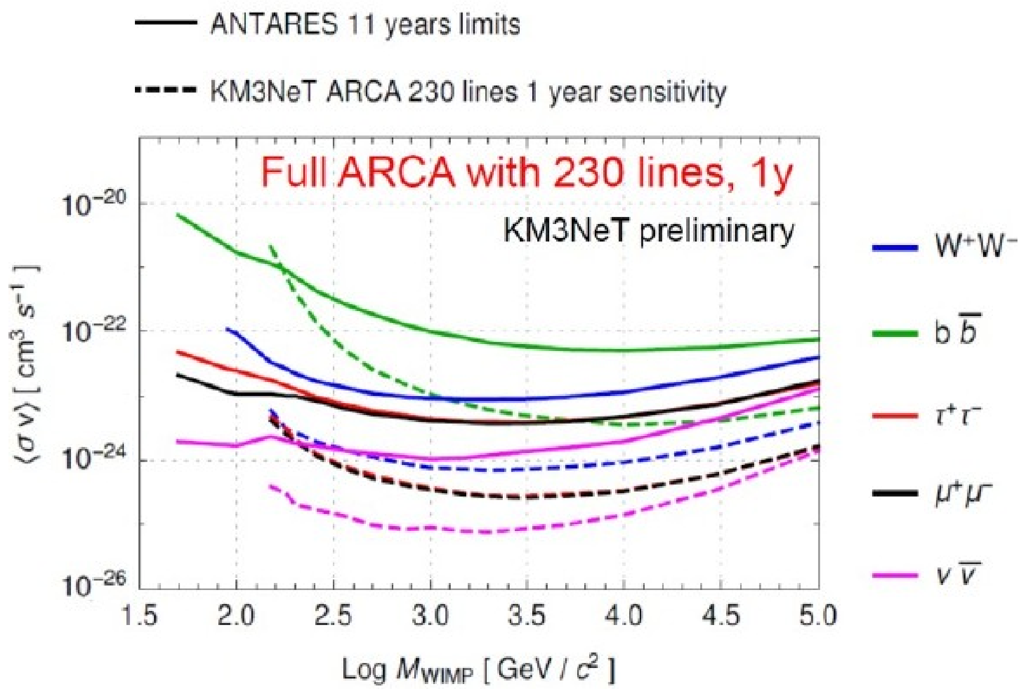
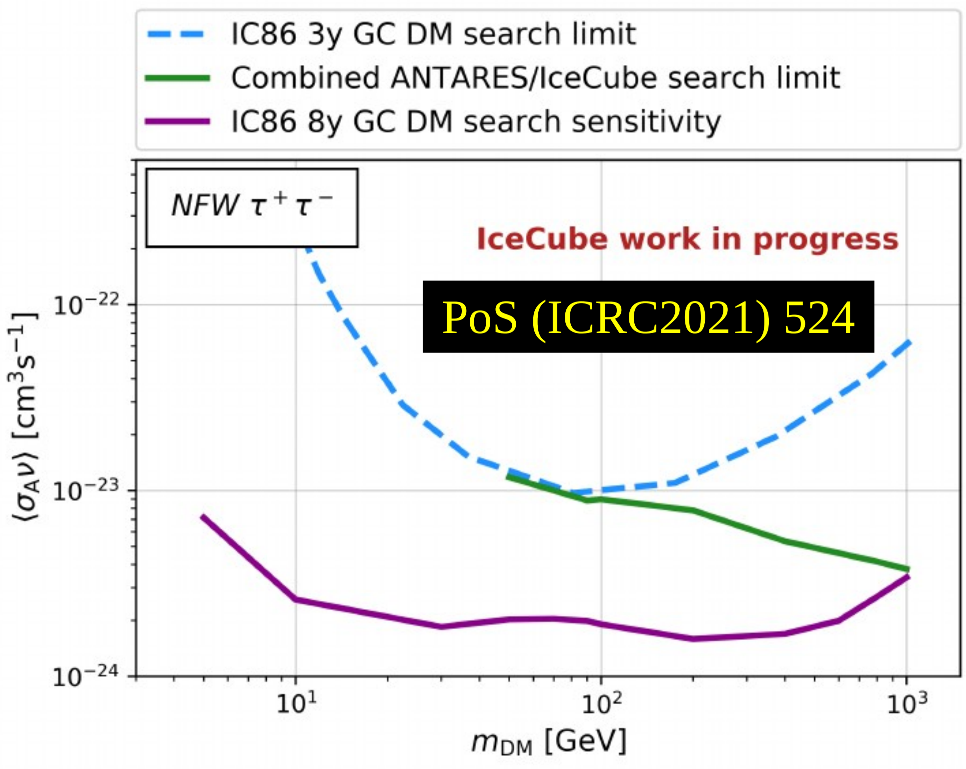
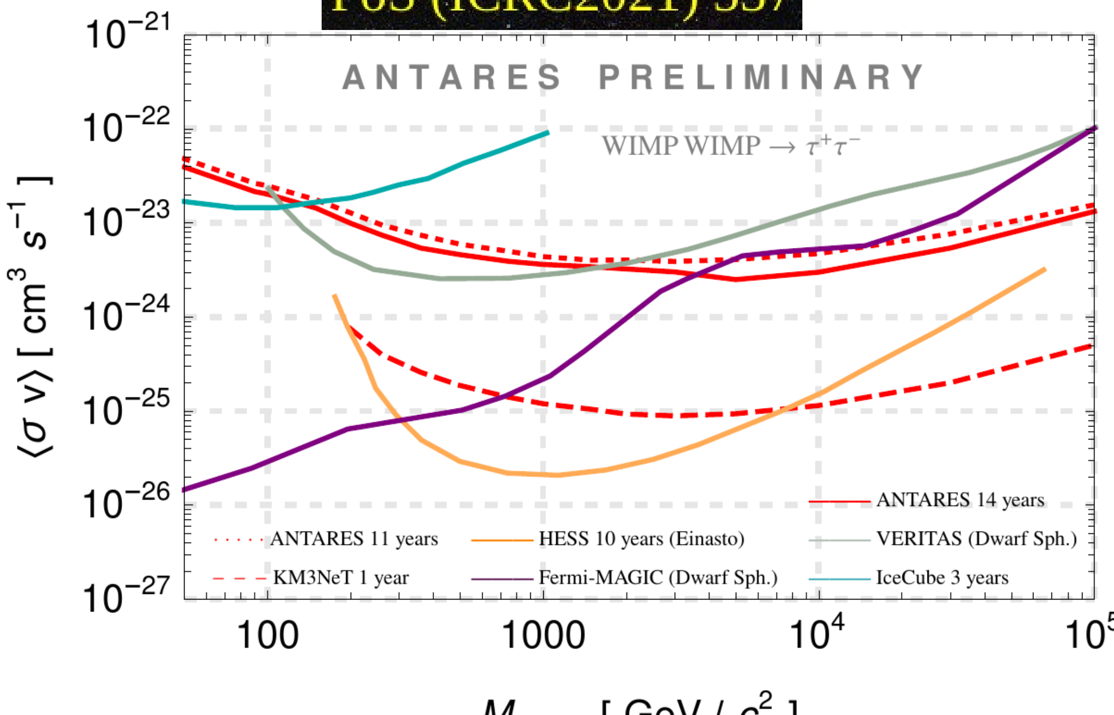


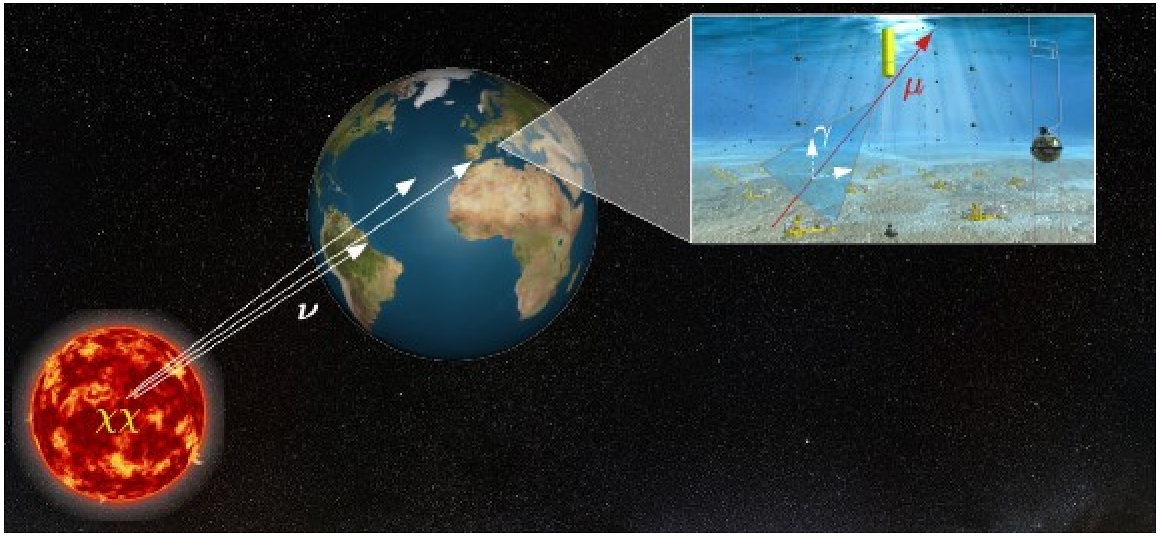


PoS (ICRC2021) 537



The Sun

A. Gould, Astrophys. J. 321 (1987) 571
A. Gould, Astrophys. J. 388 (1991) 338
G. Jungman et al./Physics Reports 267 (1996)



Captured population

$$\dot{N}_\chi = C - C_A N_\chi^2$$

$$N_\chi = \left(\frac{C}{C_A}\right)^{1/2} \tanh(t\sqrt{CC_A})$$

Annihilation rate : $\Gamma_A = \frac{1}{2} C_A N_\chi^2$

Capture rate : $$\frac{dC_i}{dV} = \frac{\rho_\odot}{m_\chi} \int_0^{u_{esc}^\odot} du \frac{f(u)}{u} \Omega_i(Q)$$

local DM density and velocity distribution

$$C = \int_0^{R_\odot} 4\pi r^2 dr \sum_i \frac{dC_i}{dV}$$

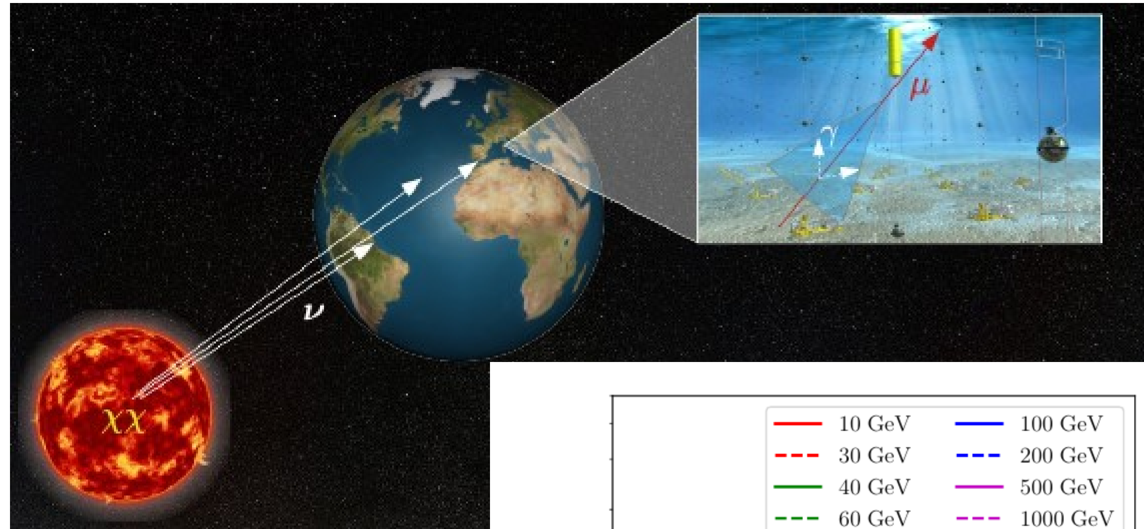
$$\Omega_i = \sigma_i n_i \frac{M_i}{2\mu_i^2} \int_{Q_{min}}^{Q_{max}} F_i^2(Q) dQ$$

$$\frac{t_\odot}{\tau_\odot} = 330 \left(\frac{C}{s^{-1}}\right)^{1/2} \left(\frac{\langle\sigma_A v\rangle}{\mathrm{cm^3\ s^{-1}}}\right)^{1/2} \left(\frac{m_\chi}{10\ \mathrm{GeV}}\right)^{3/4}$$

Annihilation rate at equilibrium driven by capture only

$$\sqrt{CC_A}t > 1,\ \Gamma_A \sim \frac{C}{2} = cste$$

The Sun



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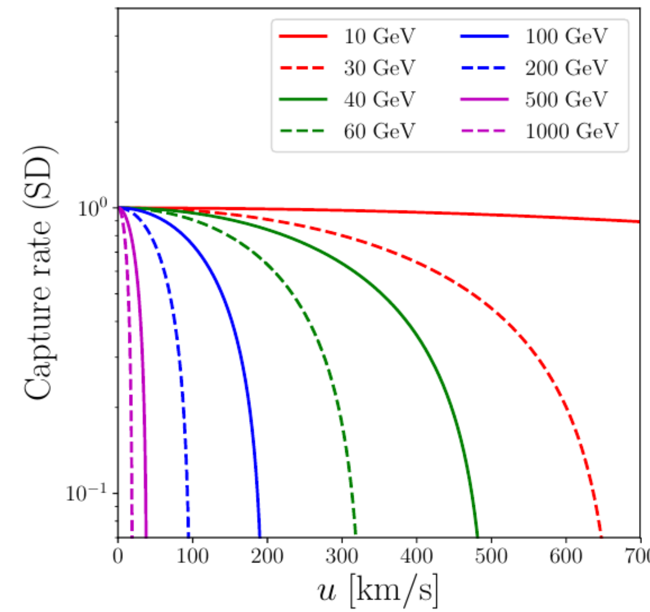
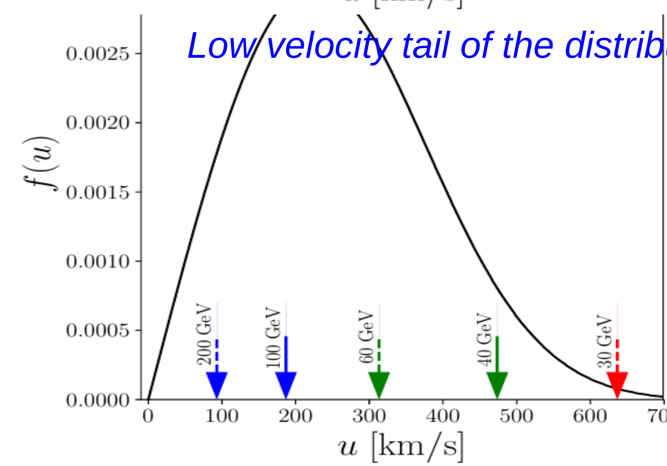




Annihilation rate at equilibrium driven by capture only

$$\sqrt{CC_A}t > 1,\ \Gamma_A \sim \frac{C}{2} = cste$$

The Sun

Capture rate :

$$\frac{dC_i}{dV} = \frac{\rho_\odot}{m_\chi} \int_0^{u_{esc}^\odot} du \frac{f(u)}{u} \Omega_i(Q)$$

Usual assumptions : Standard Halo Model (SHM)
Maxwellian velocity distribution
(self-grav isothermal sphere)

$$f_{\vec{v}}(\vec{v}) = \frac{1}{v_0^3 \pi^{3/2}} \exp\left(-\frac{|\vec{v}|^2}{v_0^2}\right)$$

$$v_c = 220 \text{ km/s}, \quad v_0 = v_c$$

$$\rho_\odot = 0.3 \text{ GeV/cm}^3 \qquad v_{esc} = 544 \text{ km/s}$$

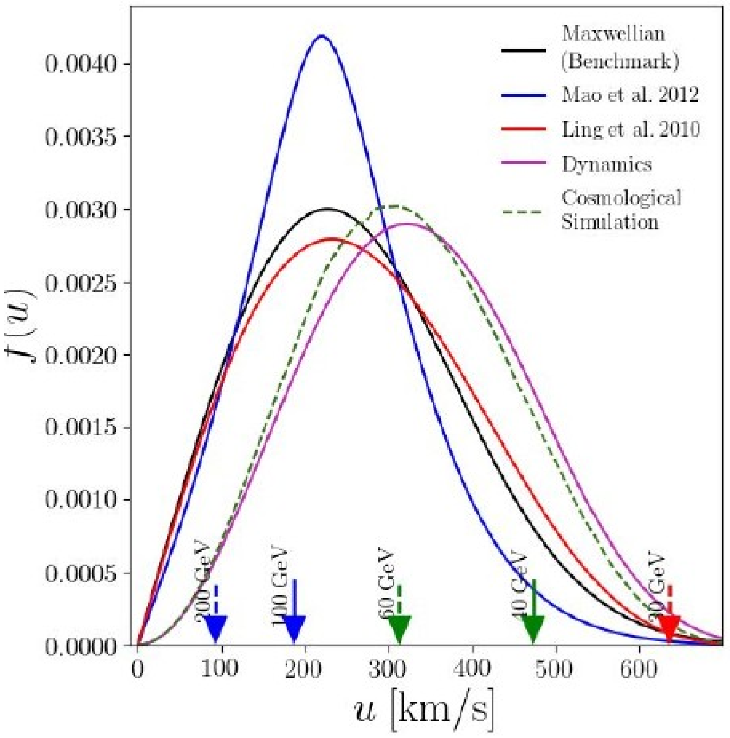
Beyond SHM :

- Cosmological simulations of spiral galaxies

- Other functions
Generalized Maxwellian, Tsallis. Mao+2013 ...

- Semi analytic methods:
Eddington inversion …

Lacroix et al arXiv:1805.02403, arXiv:2005.03955
Petac et al arXiv:2106.01314



The Sun

Capture rate :

$$\frac{dC_i}{dV} = \frac{\rho_\odot}{m_\chi}\int_0^{u_{esc}^{\odot}} du \frac{f(u)}{u}\Omega_i(Q)$$

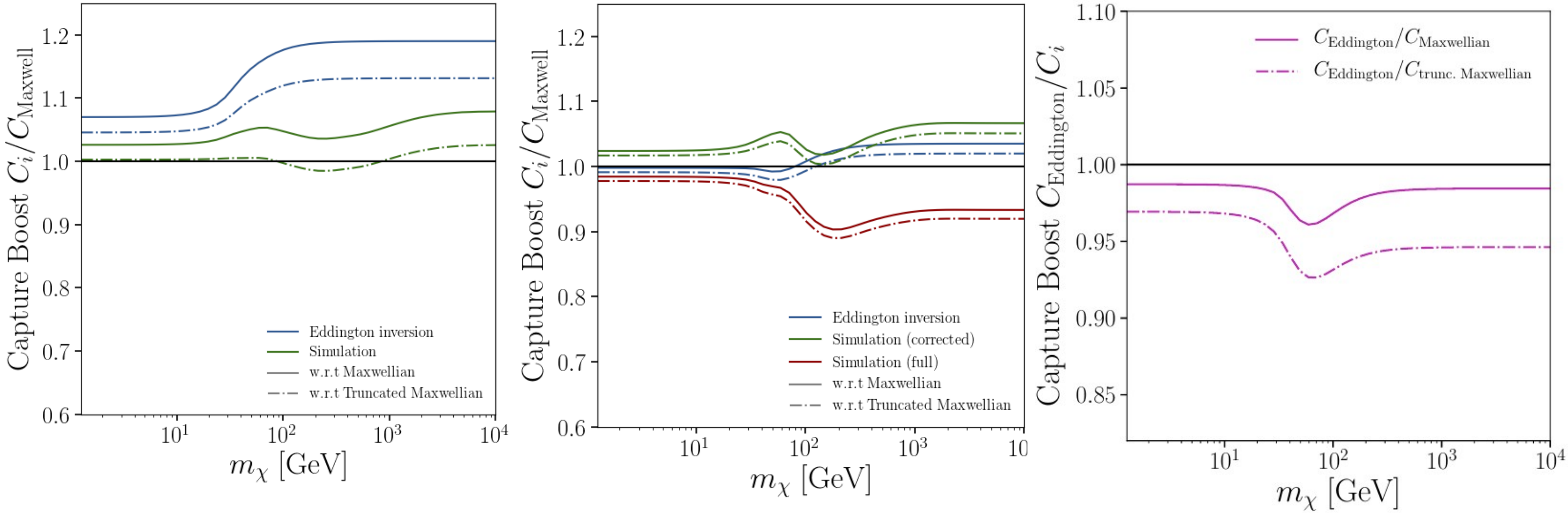
Usual assumptions : Standard Halo Model (SHM)
Maxwellian velocity distribution
(self-grav isothermal sphere)

$$f_{\vec{v}}(\vec{v}) = \frac{1}{v_0^3 \pi^{3/2}} \exp\left(-\frac{|\vec{v}|^2}{v_0^2}\right)$$

$$v_c = 220 \text{ km/s}, \quad v_0 = v_c$$

$$\rho_\odot = 0.3 \text{ GeV/cm}^3 \qquad v_{esc} = 544 \text{ km/s}$$

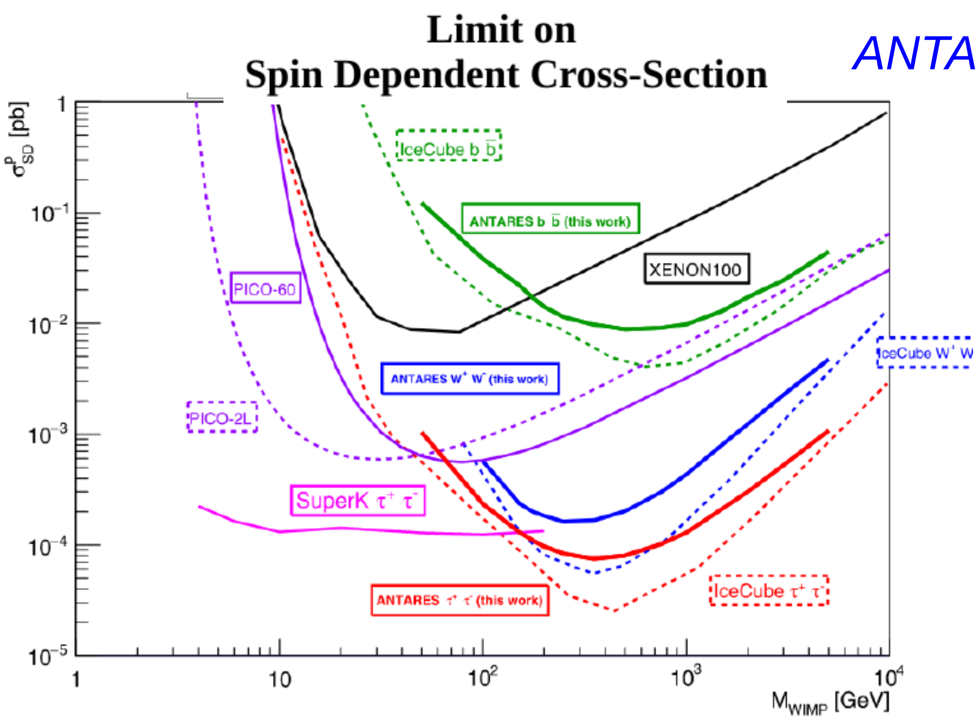
Beyond SHM :



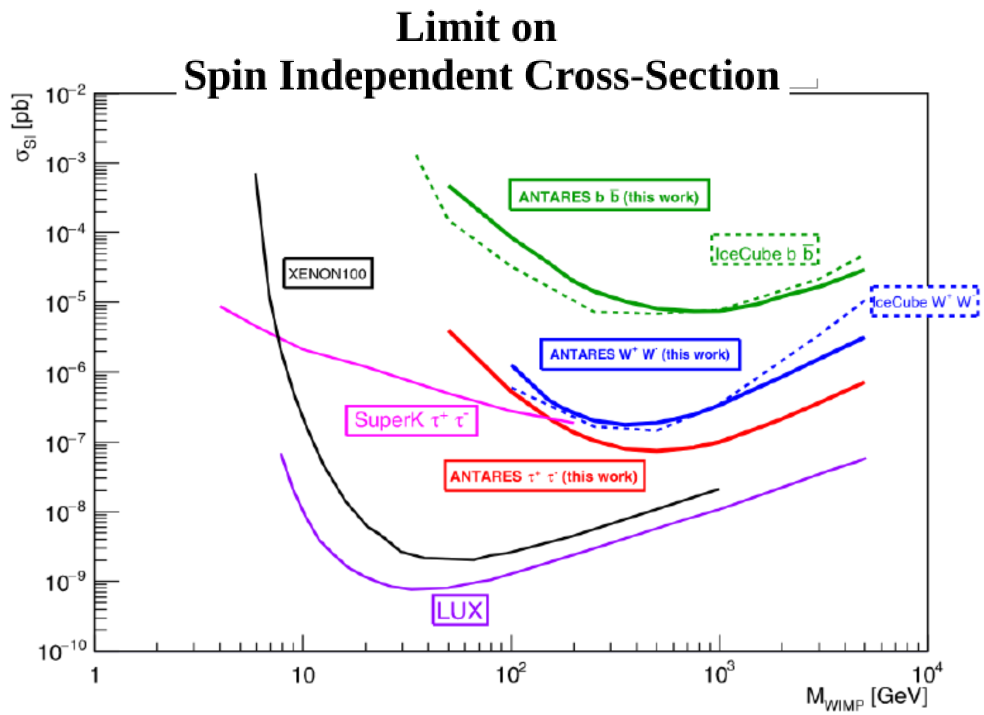
Nunez-Castineyra et al 2019, 20%uncertainties on capture
Choi et al 2014

The Sun

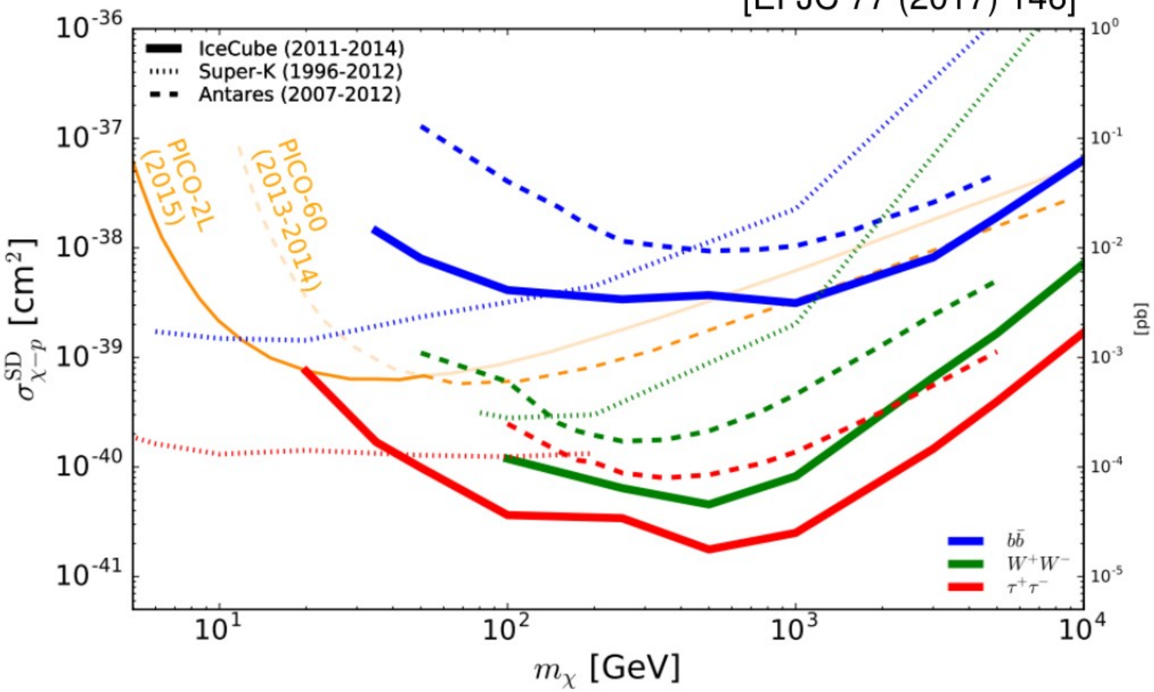
ANTARES



Phys. Lett. B 759 (2016) 69



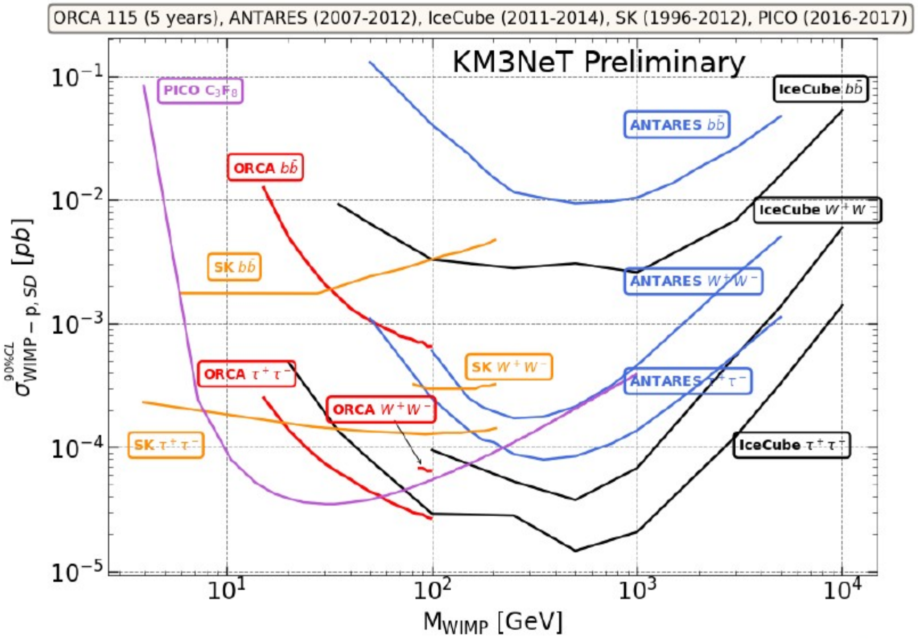
[EPJC 77 (2017) 146]

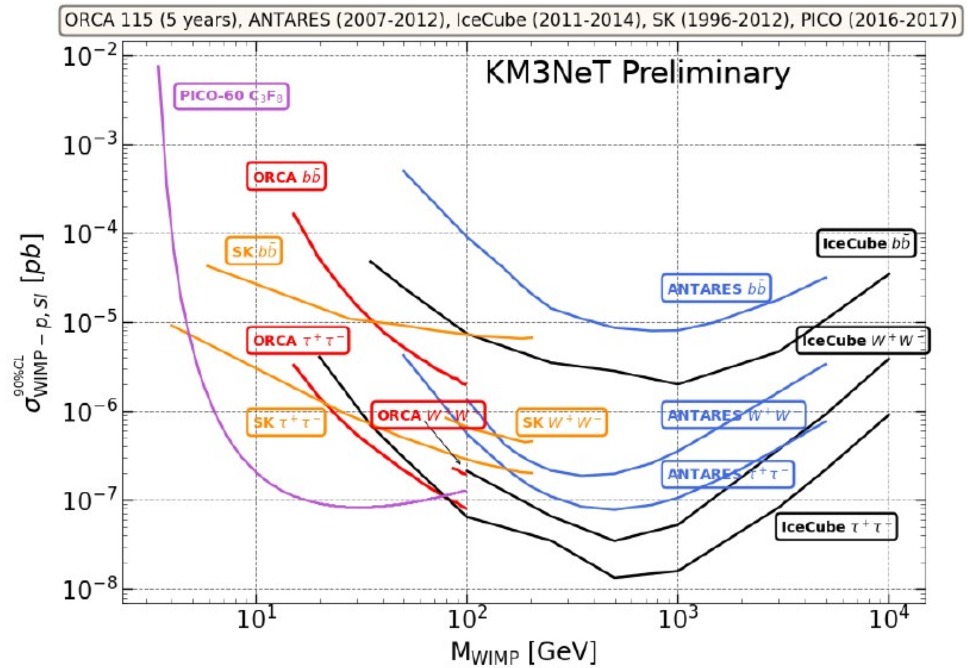


ICECUBE

The Sun

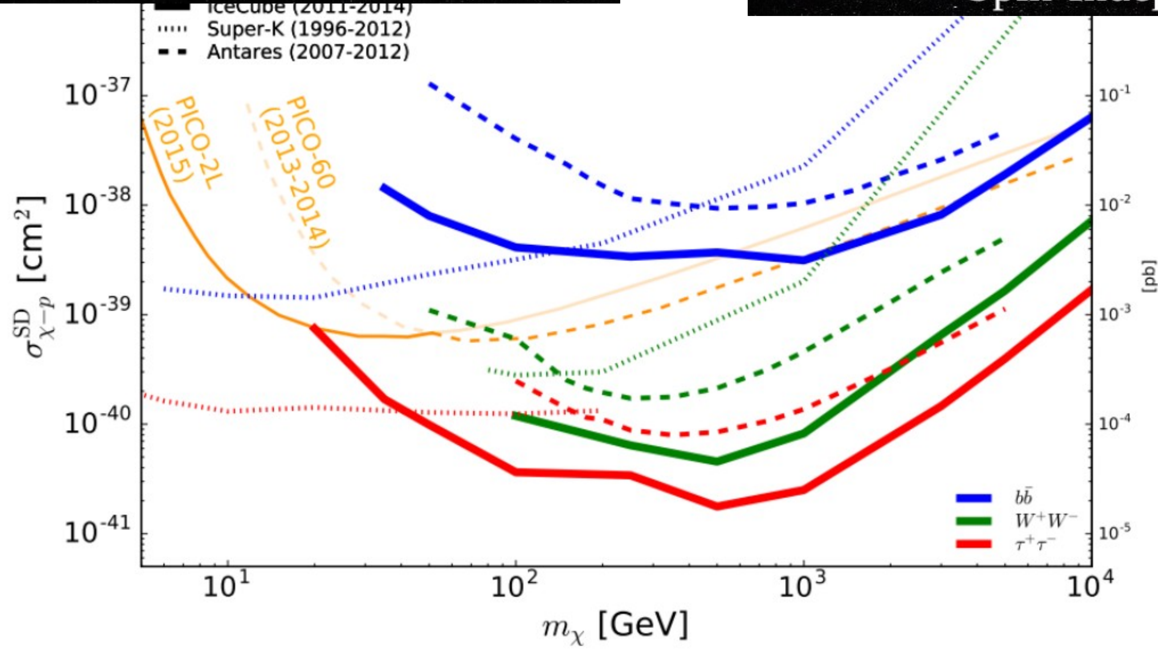
KM3NeT





Spin-Dependent Cross section

Spin-Independent Cross section



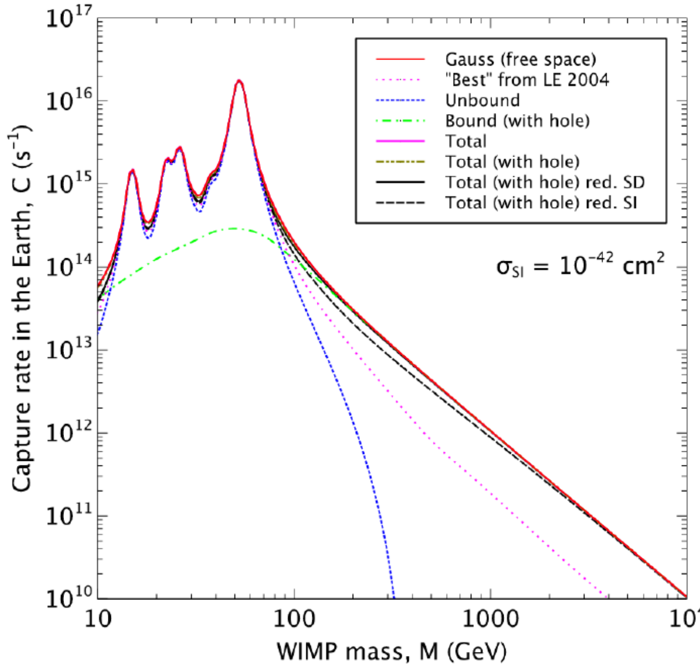
ICECUBE

The Earth

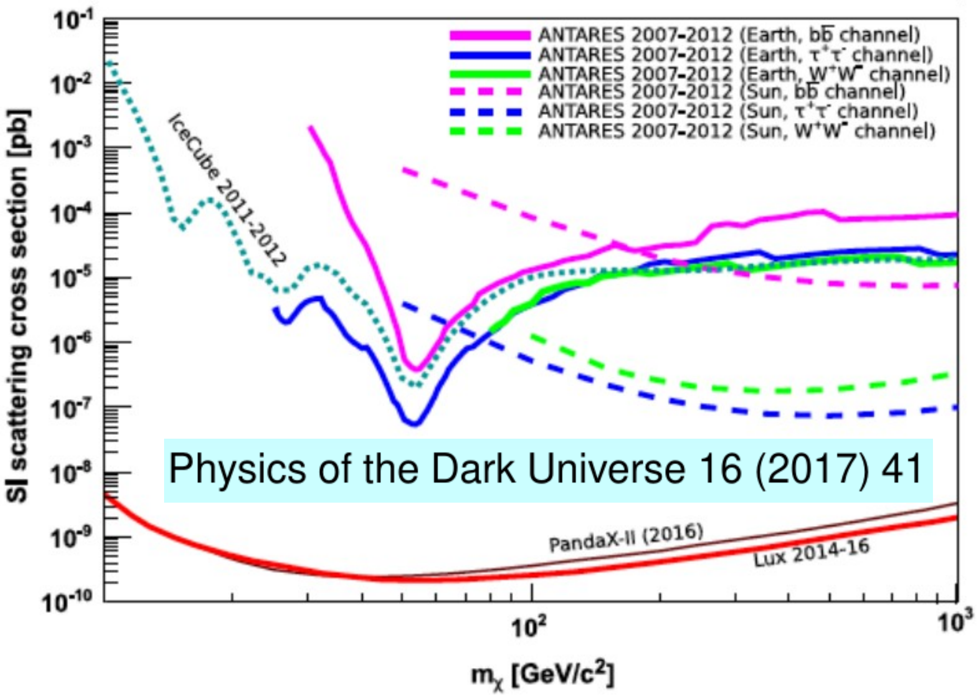
- Scalar coupling, Resonant capture with nuclei masses.

- Out of equilibrium

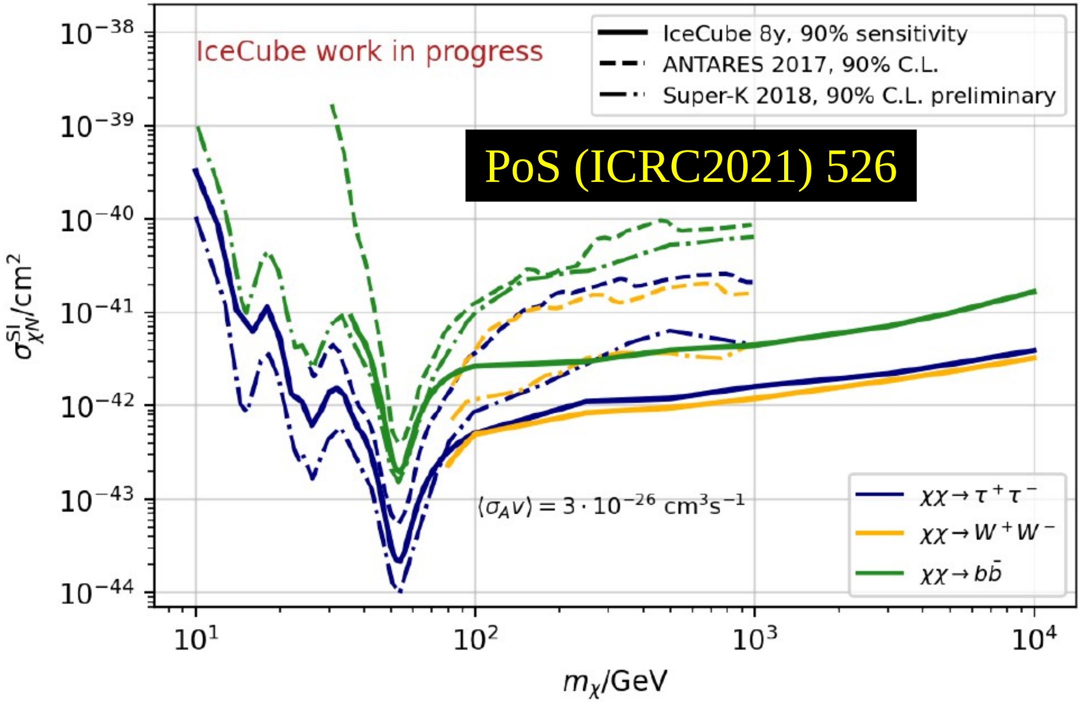
$$\sqrt{CC_A}t << 1,\ \Gamma_A \approx \frac{1}{2}C^2C_At^2$$



Limit on WIMP-nucleon SI cross-section assuming 100% BR of annihilation into benchmark channel



Spin Independent WIMP-nucleon cross section



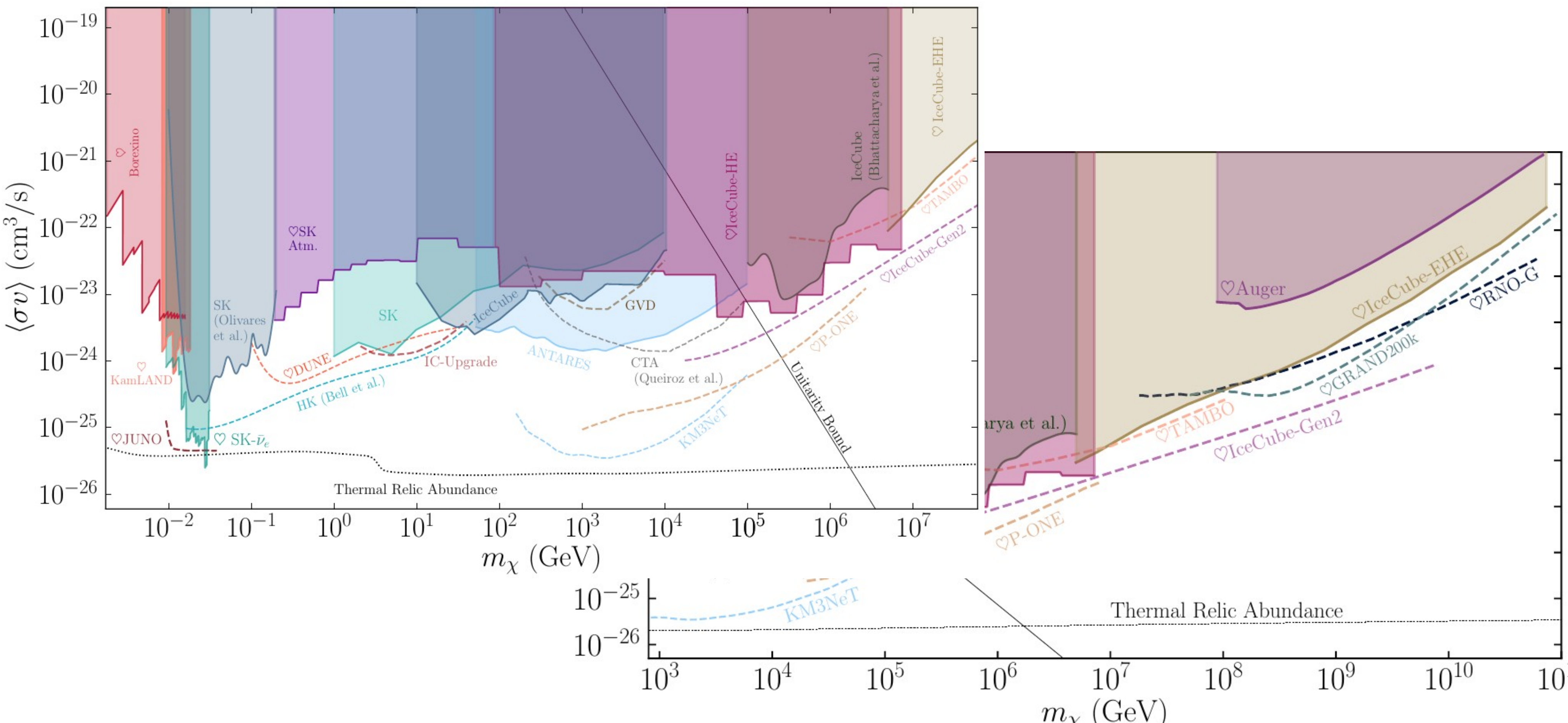
Dark Matter annihilation to Neutrinos

PoS (ICRC2021) 542

$$\chi\chi \rightarrow \nu\bar{\nu}$$

Galactic flux :
$$\frac{d\Phi_{\nu+\bar{\nu}}}{dE_\nu} = \frac{1}{4\pi}\frac{\sigma v}{\kappa m_\chi^2}\frac{1}{3}\frac{dN_\nu}{dE_\nu}\int d\Omega \int_{\text{l.o.s.}} \rho_\chi^2(x)\,dx$$

Extra galactic:
$$\frac{d\Phi_{\nu+\bar{\nu}}}{dE_\nu} = \frac{1}{4\pi}\frac{\Omega_{DM}^2 \rho_c^2 \sigma_\nu}{\kappa m_x^2}\frac{1}{3}\int_0^{z_{up}} dz \frac{(1+G(z))\,(1+z)^3}{H(z)}\frac{dN_{\nu+\bar{\nu}}(E')}{dE'}$$



Angular Power Spectrum analysis

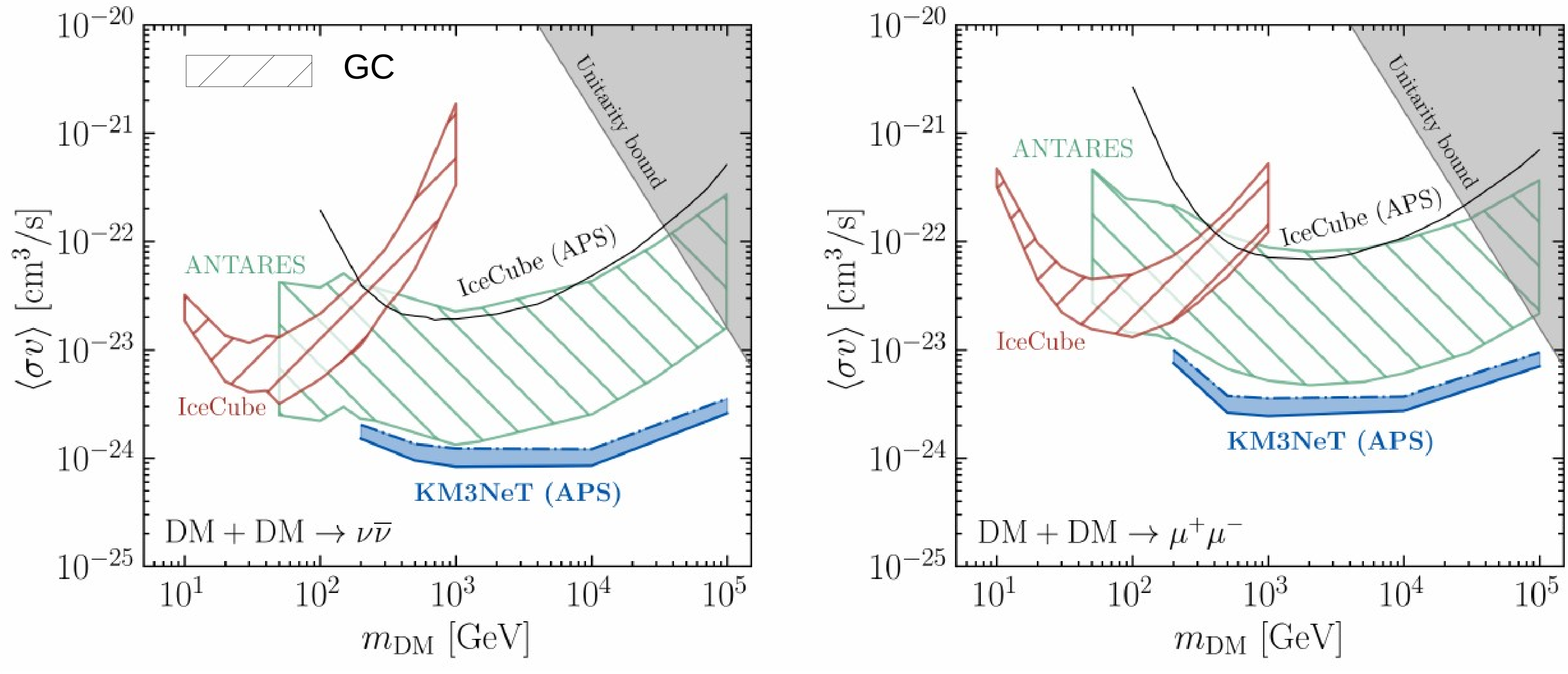
PoS (ICRC2021) 550

arXiv:2103.01237

Flux :

$$\frac{d\Phi^{DM}_{\nu_\alpha+\bar{\nu}_\alpha}}{dE_\nu d\Omega} = \sum_{\alpha\beta} P_{\alpha\beta}\left[\frac{d\Phi^{gal.}_{\nu_\beta+\bar{\nu}_\beta}}{dE_\nu d\Omega} + \frac{d\Phi^{ext.gal.}_{\nu_\beta+\bar{\nu}_\beta}}{dE_\nu d\Omega}\right]$$

$P_{\alpha\beta} = \sum_{i=3}^{3} |U_{\alpha i}|^2 |U_{\beta i}|^2$ are the flavour-transition probabilities

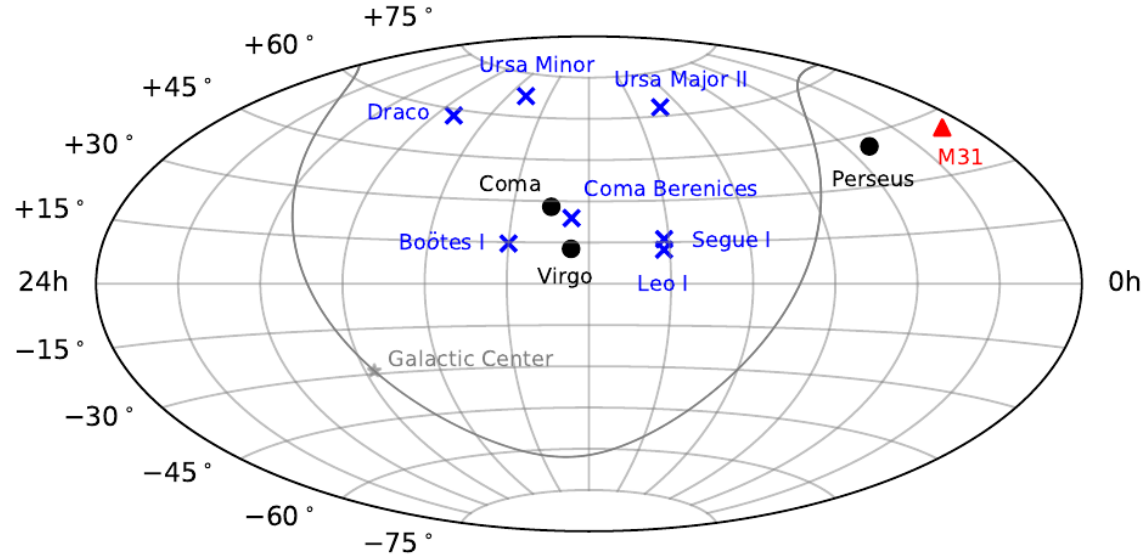


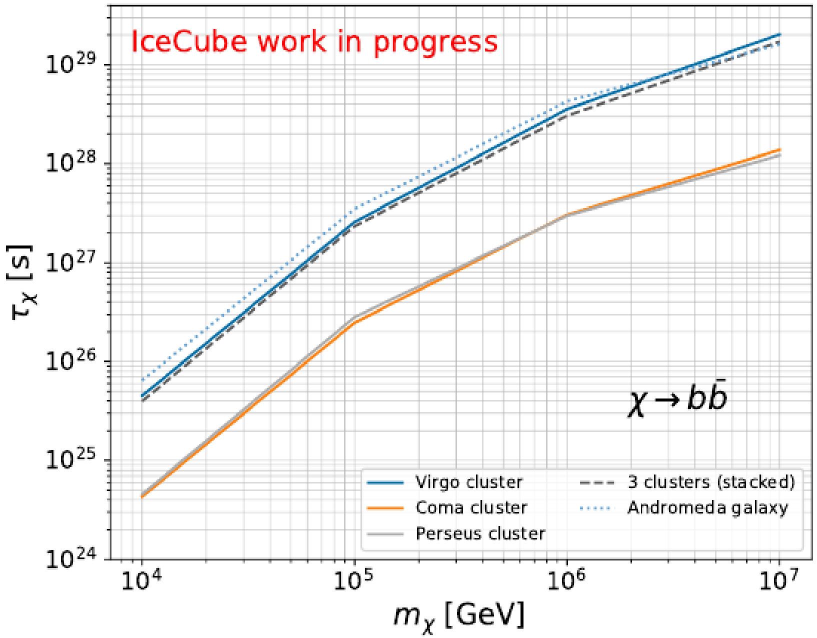
Decaying Dark Matter

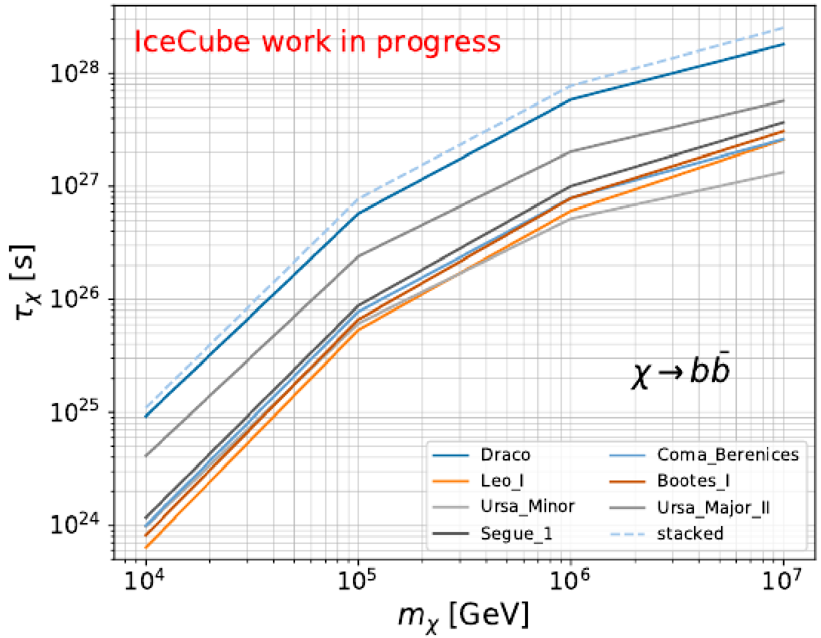
PoS (ICRC2021) 506

Flux :

$$\frac{d\Phi_\nu}{dE_\nu}(E_\nu) = \frac{1}{4\pi m_\chi \tau_\chi} \frac{dN_\nu}{dE_\nu}(E_\nu) \int_0^{\Delta\Omega} d\Omega \int_0^{\infty} \rho_\chi(l\hat{n}) dl,$$





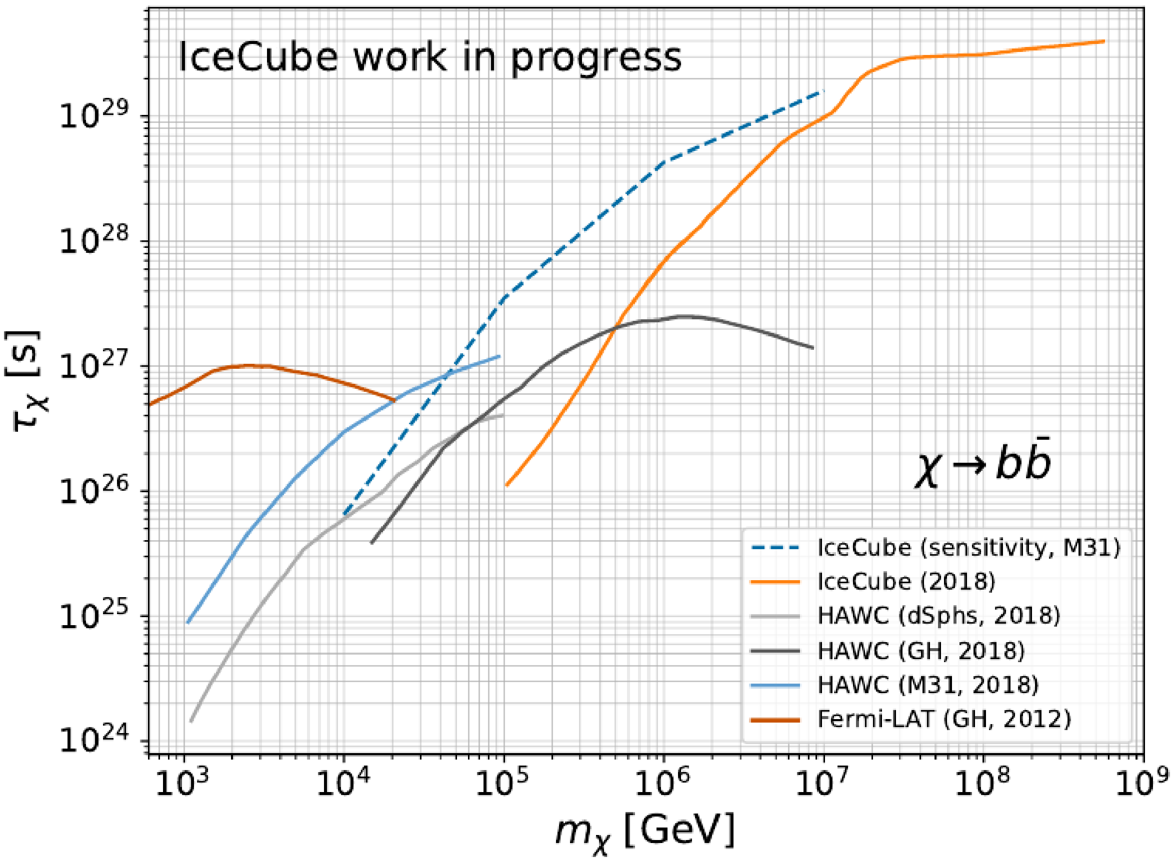


Decaying Dark Matter

PoS (ICRC2021) 506

Flux :

$$\frac{d\Phi_\nu}{dE_\nu}(E_\nu) = \frac{1}{4\pi m_\chi \tau_\chi}\frac{dN_\nu}{dE_\nu}(E_\nu)\int_0^{\Delta\Omega} d\Omega \int_0^{\infty} \rho_\chi(l\hat{n})dl,$$



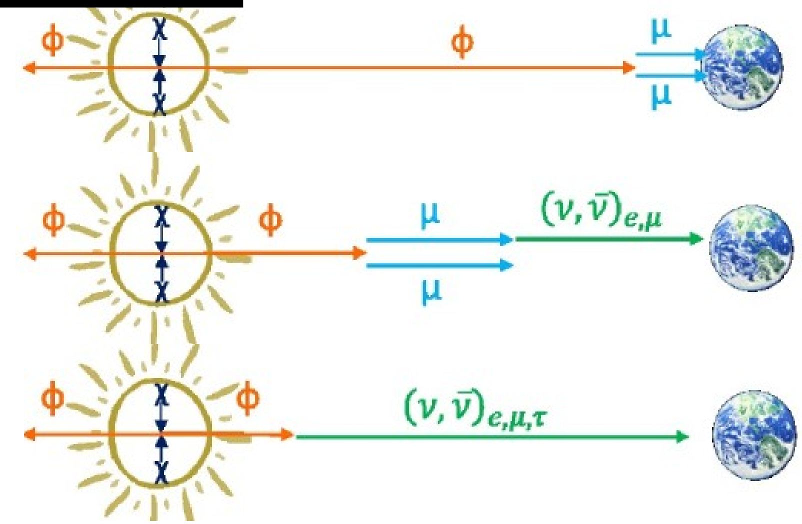
Secluded Dark Matter

JCAP 05 (2016) 016

JCAP04(2017) 010

- DM annihilates into **unstable mediator Φ**.
- Detectable particles: dimuons or neutrinos.
- 3 cases:
  - $\Phi \rightarrow \mu\mu$.
  - $\Phi \rightarrow \mu\mu \rightarrow \nu\nu$.
  - $\Phi \rightarrow \nu\nu$.

Testing models from:
- Meade et al., JHEP06 (2010) 29
- Bell and Petraki, JCAP04 (2011) 003



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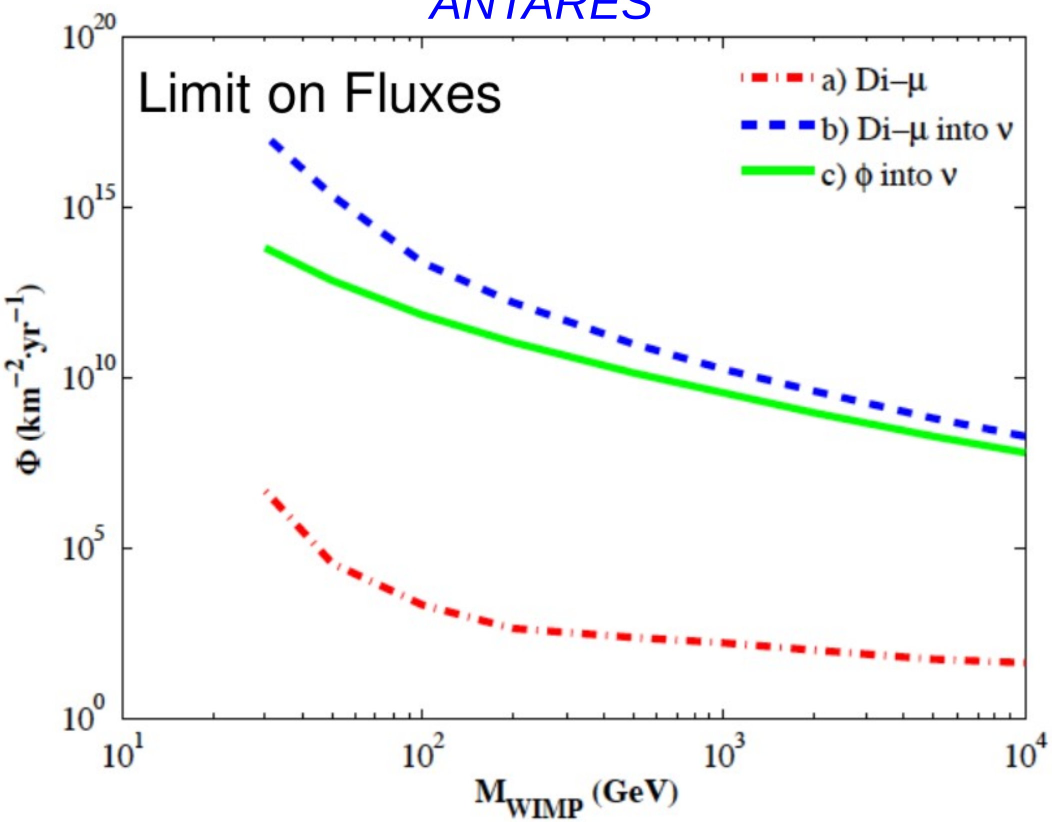

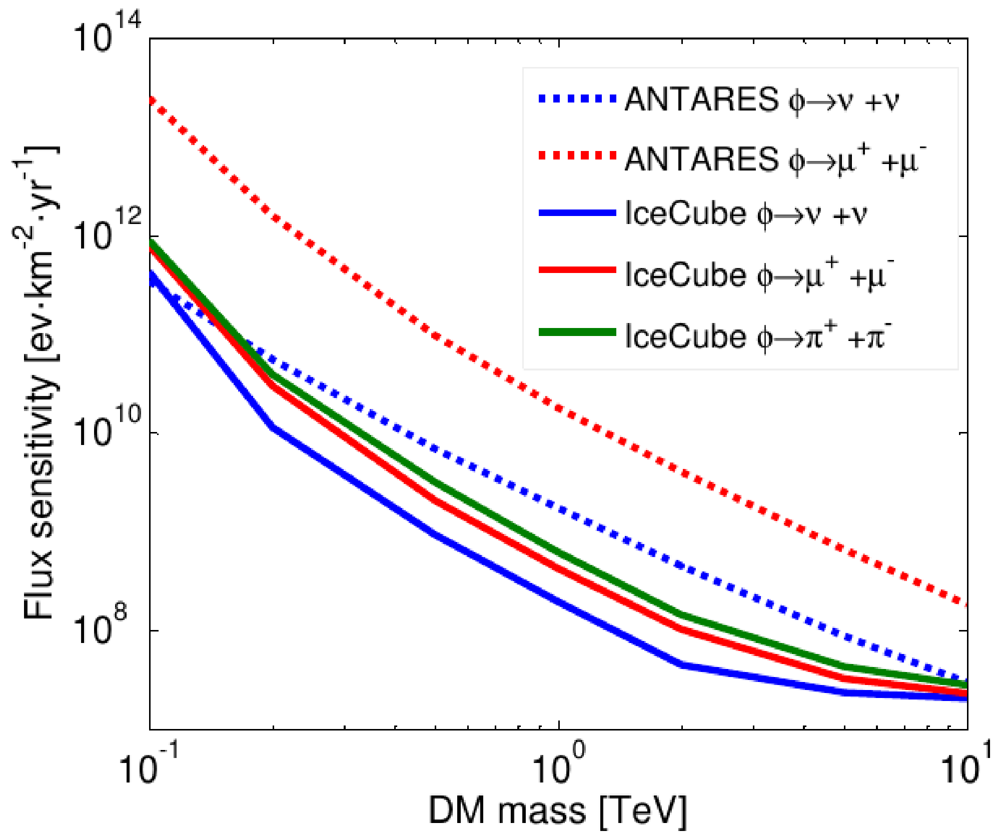

Secluded Dark Matter

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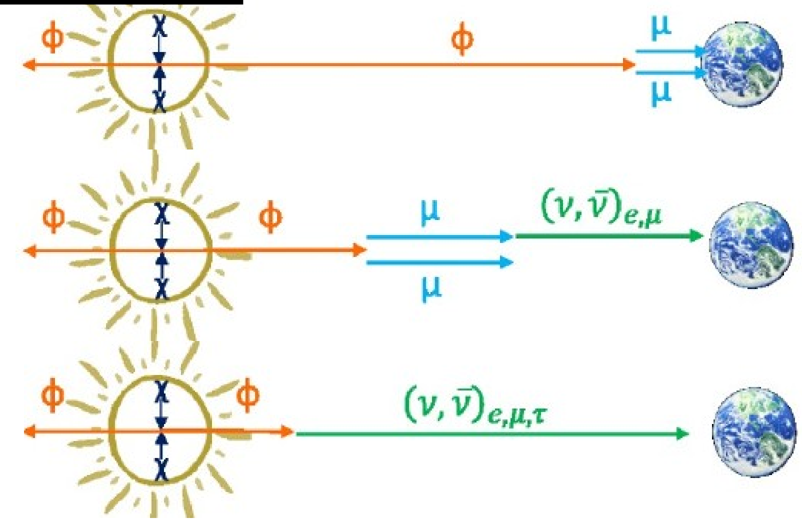
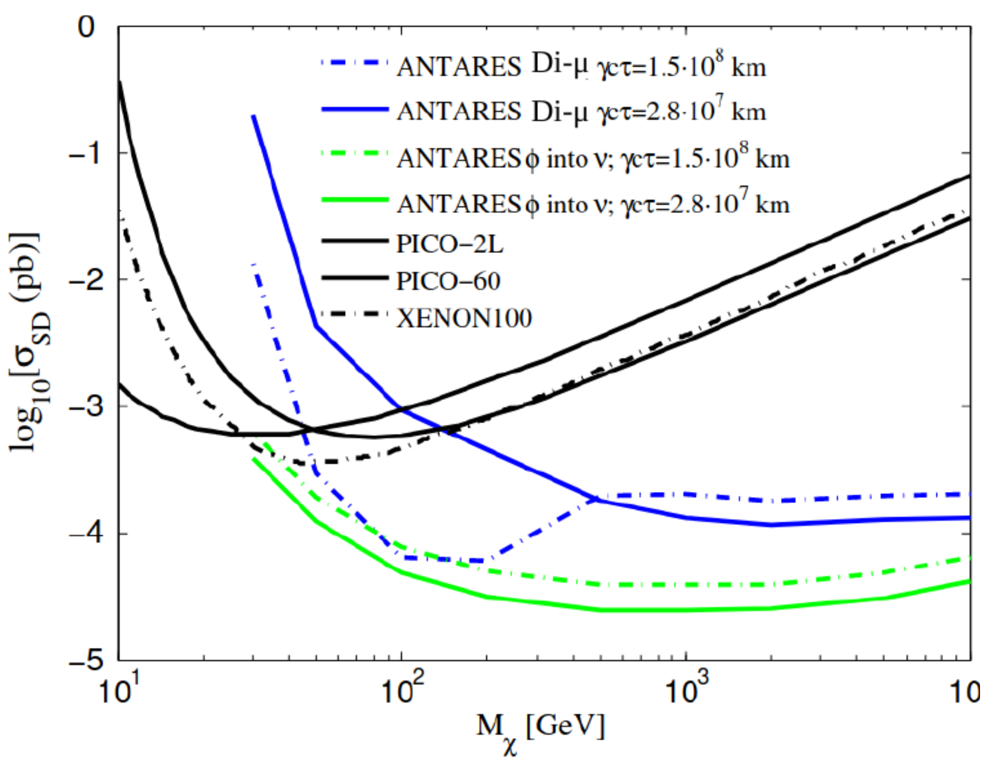
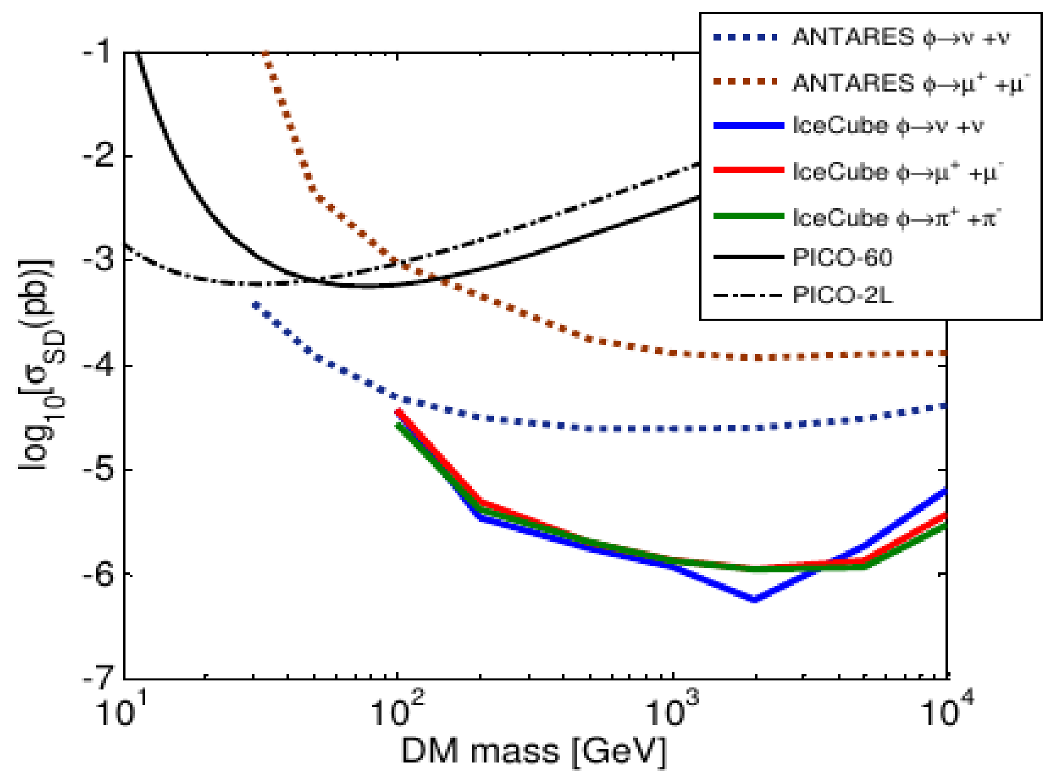






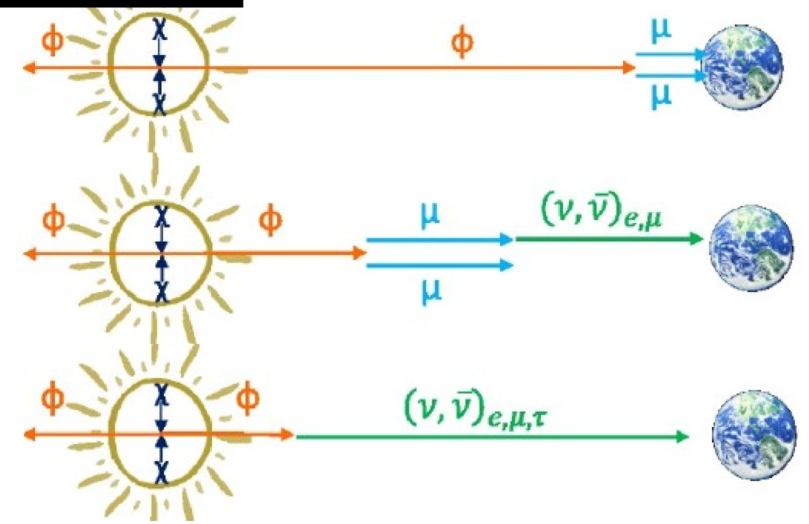
Secluded Dark Matter

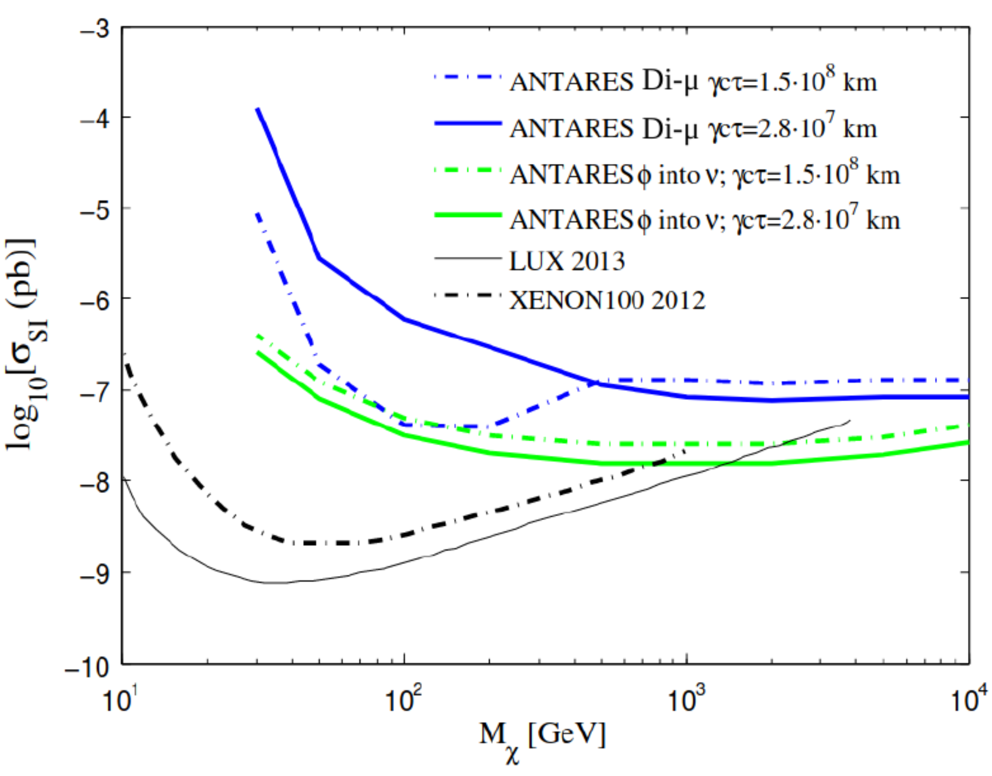
JCAP 05 (2016) 016

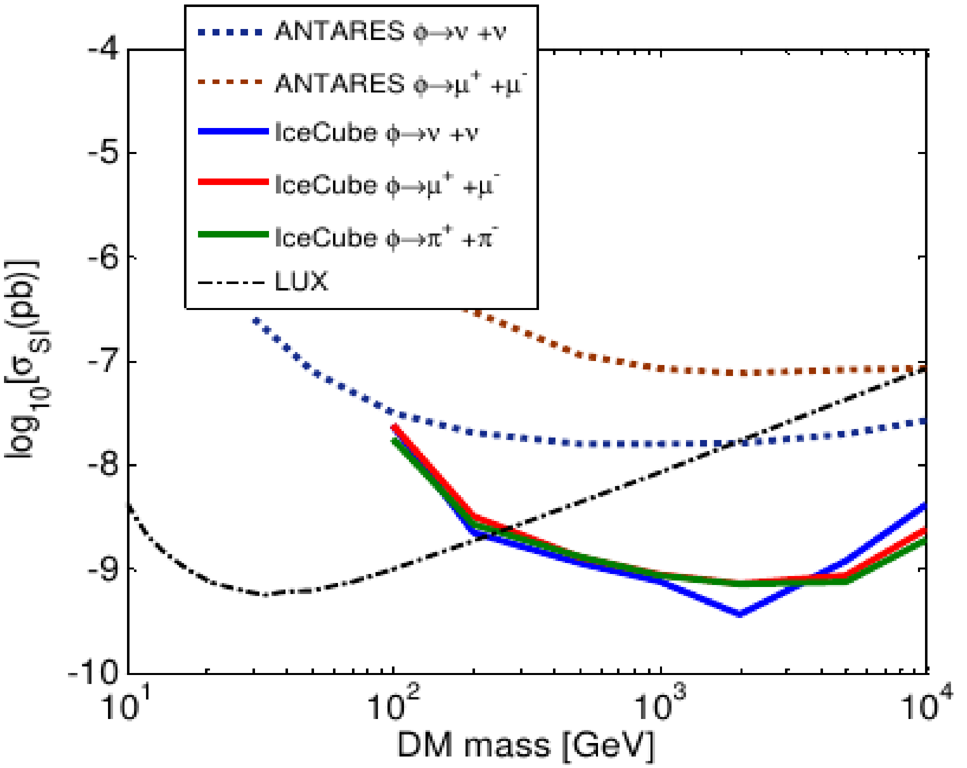
JCAP04(2017) 010

- DM annihilates into **unstable mediator Φ**.
- Detectable particles: dimuons or neutrinos.
- 3 cases:
  - Φ → μμ.
  - Φ → μμ → νν.
  - Φ → νν.

Testing models from:
- Meade et al., JHEP06 (2010) 29
- Bell and Petraki, JCAP04 (2011) 003







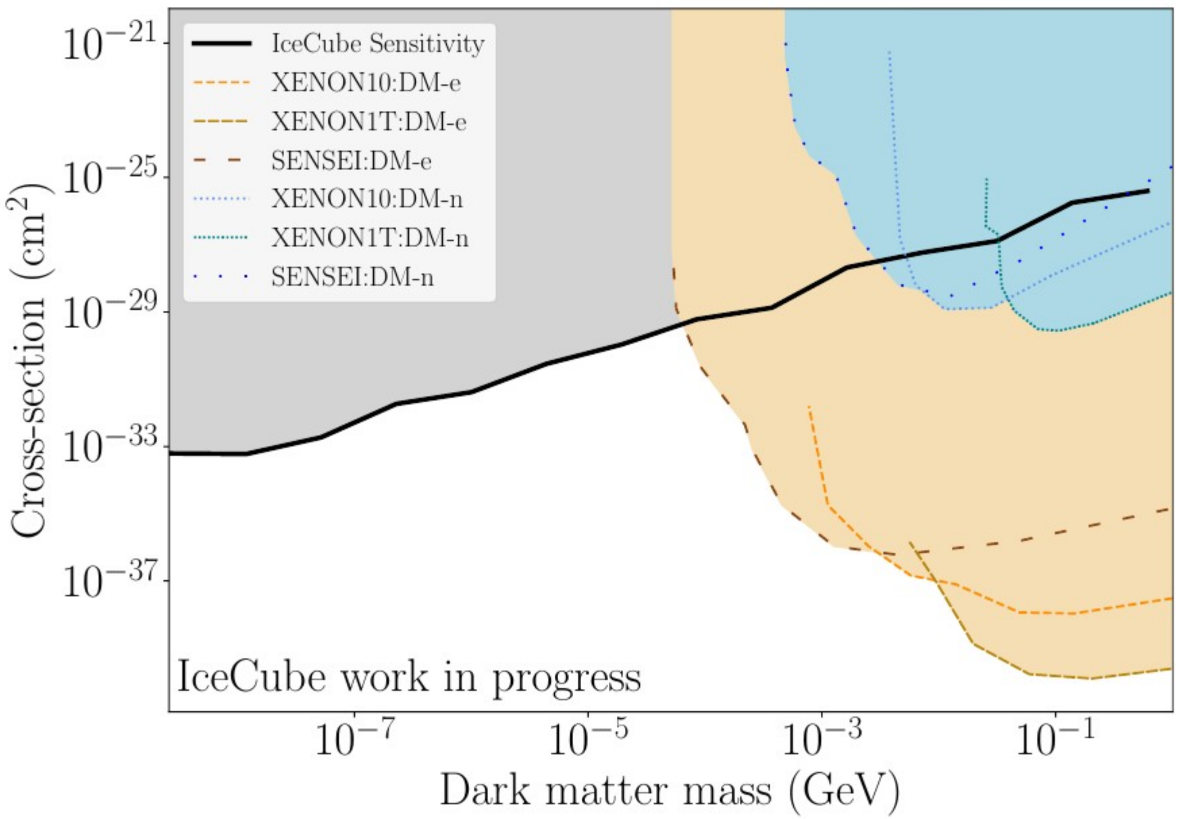
Dark matter neutrino scattering in the Galactic Centre

PoS (ICRC2021) 569

DM-neutrino scattering → Suppression of the high-energy astrophysical neutrino flux in the direction of the Galactic Centre ?

$$\frac{d\Phi(E,\tau)}{d\tau} = -\sigma(E)\Phi(E,\tau) + \int_E^\infty d\tilde{E}\frac{d\sigma(\tilde{E},E)}{dE}\Phi(\tilde{E},\tau)$$

$$\tau(\vec{x}) = \int_{l.o.s} n_\chi(\vec{x})dx \qquad n_\chi = \frac{\rho_\chi}{m_\chi}$$



Summary-Conclusion

- *Specific astronomy, interesting to look for dark matter*

  Dsphs, galaxy clusters, Galactic Center, Sun, Earth

- *Bring info on DM nature, can test specific BSM scenarii/models*

- *(Non)Signal → Complementary researches with*

  direct detection

  gamma, CR indirect detection

- *Sun, golden signal*

- *Km3(s) size detector era already started*

  Stay tuned

P-ONE
Deep water
1 km3
Planned 2023

Baikal/GVD
Deep water
~1 km^3
Construction

ANTARES
Deep water
0.01 km^3
2008 –

KM3NeT
Deep water
1 + 0.006 km^3
Construction

IceCube	IceCube-Gen2
Deep ice	Deep ice
1 km^3	~10 km^3
2011 –	Projected, 1st phase imminent

Thanks

Back-up

Test other assumptions for f(v)

Nunez-Castineyra,EN,Mollitor, Devriendt, Teyssier

In prep

Maxwellian

$$f(\vec{v}) = \frac{N}{2\pi v_0^2} \exp\left(-\frac{3|\vec{v}|^2}{2v_0^2}\right)$$

Generalized Maxwellian

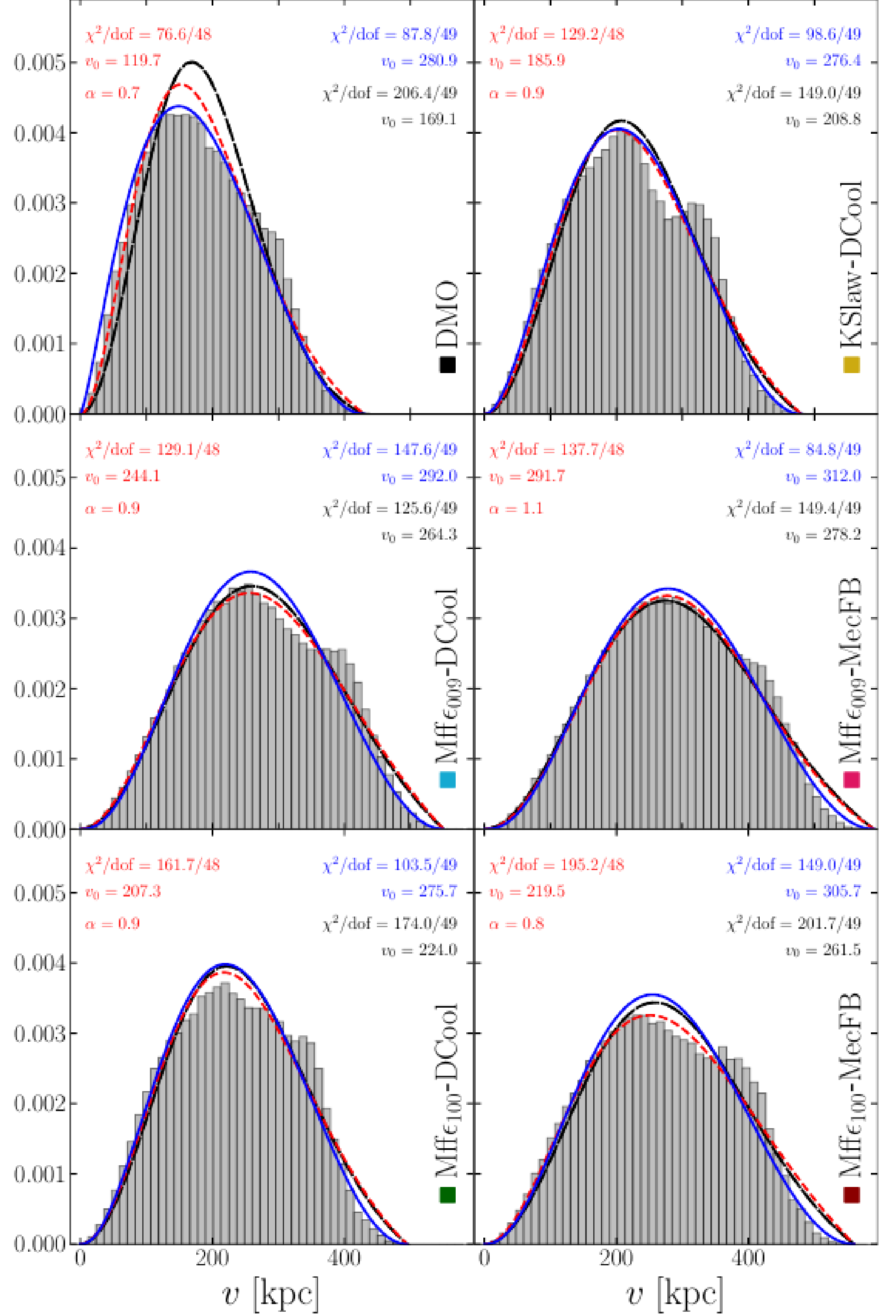
$$f(\vec{v}) = \frac{e^{-(\vec{v}^2/v_0^2)^{\alpha}}}{N(v_0,\alpha)}$$

Tsallis

$$f(\vec{v}) = \frac{1}{N(v_0,q)} \left(1 - (1-q)\frac{\vec{v}^2}{v_0^2}\right)^{q/(1-q)}$$

Mao+ 2013

$$f(v, v_0, v_{\rm esc}, p) = \frac{1}{N} v^2 \exp^{-\frac{v}{v_0}} (v_{\rm esc}^2 - v^2)^p$$



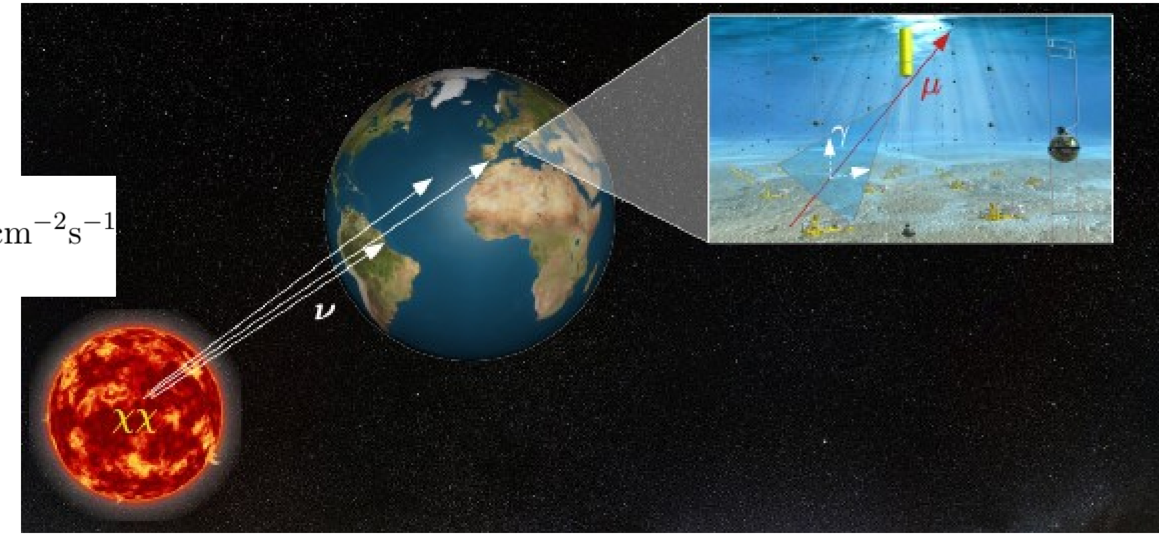
The Sun

Orders of magnitude

$$\rho_\chi^0 \simeq 0.3 - 0.5 \text{ GeV/cm}^3 \; ; \; v_\chi^0 \simeq 220 - 300 \text{ km/sec}$$

$$\phi_\chi = \frac{\rho_\chi^0}{m_\chi} v_\chi^0 \simeq \frac{0.4 \text{ cm}^{-3}}{m_\chi \text{ [GeV]}} \times (3 \times 10^7 \text{ cm/s}) \simeq \frac{1.2 \times 10^7}{m_\chi \text{ [GeV]}} \text{ cm}^{-2}\text{s}^{-1}$$

$$\sigma_{\chi-p} \simeq (G_F m_p^2)^2 \frac{1}{m_W^2} = 6 \times 10^{-42} \text{ cm}^2$$



$$C_\odot = M_\odot N_A \sigma_{\chi-p} = 1.2 \times 10^{57} \sigma_{\chi-p}$$

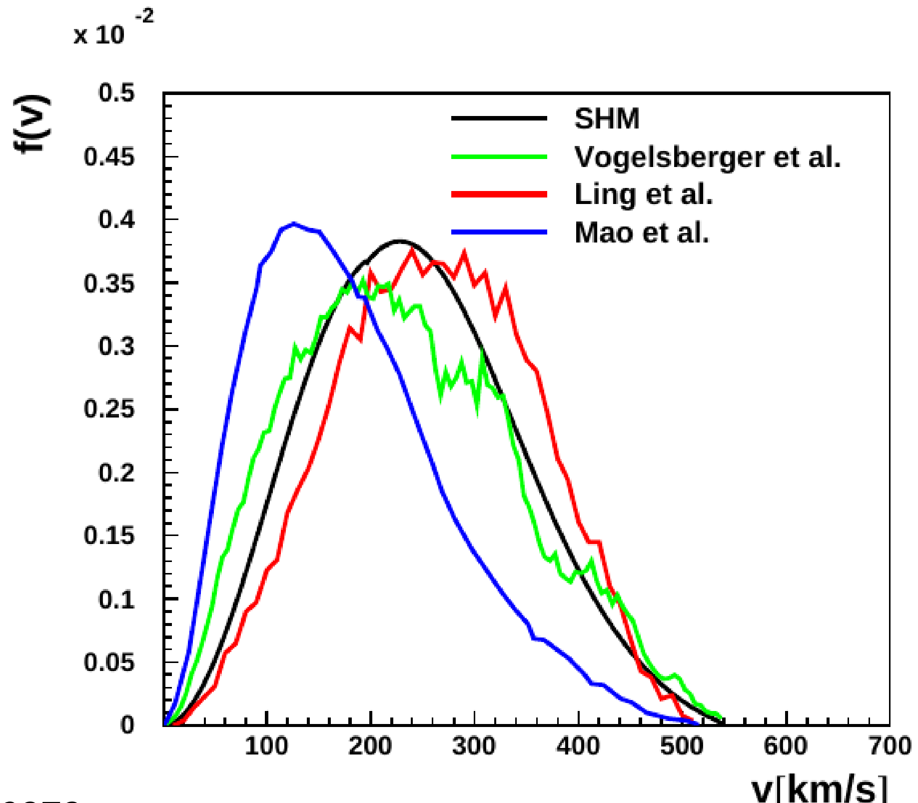
$$\phi_\nu^\odot = \frac{\phi_\chi C_\odot}{4\pi d^2} = \frac{3. \times 10^{-5}}{m_\chi \text{ (GeV)}} \text{cm}^{-2} \text{ s}^{-1} \simeq \frac{1 \times 10^{13}}{\text{m}_\chi \text{[GeV]}} \text{km}^{-2} \text{yr}^{-1}$$

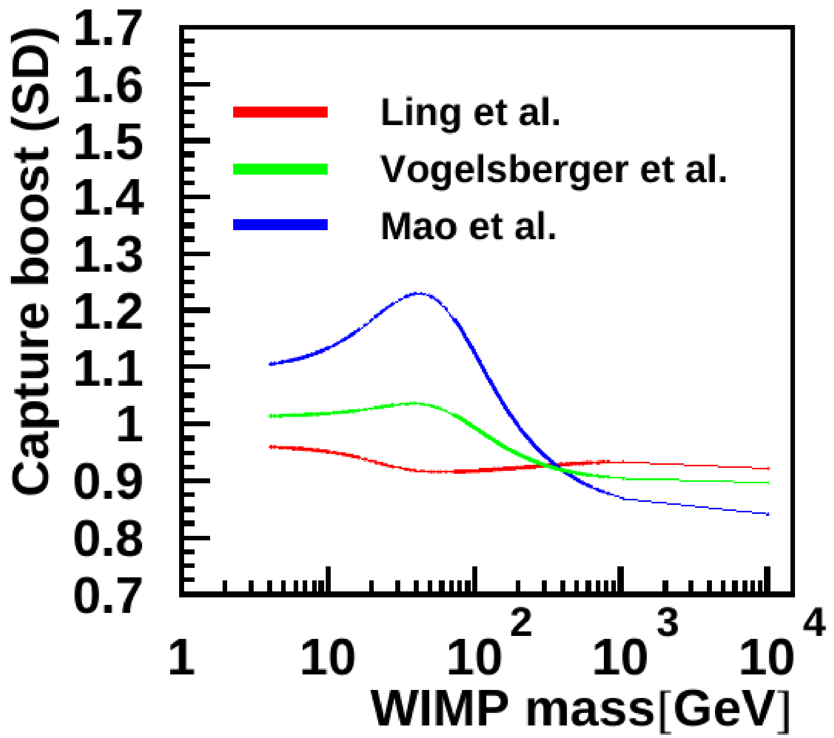
$$P = N_A \sigma_{\nu-N} R_\mu \simeq 1 \; - \; 2 \times 10^{-13} \, (m_\chi \text{ [GeV]})^2$$

$$\phi_\mu^\odot = \phi_\nu^\odot P \simeq 10^2 \; - \; 10^3 \text{ km}^{-2} \text{yr}^{-1}$$

→ *km3 detector*

Capture rate in the Sun





Choi+ 1312.0273

Dark disc :

Read+ 09
Brush+ 09
Ling 2010