TAUP Topics in Astroparticle and Underground Physics

TAUP 2017

Indirect Searches for Dark Matter

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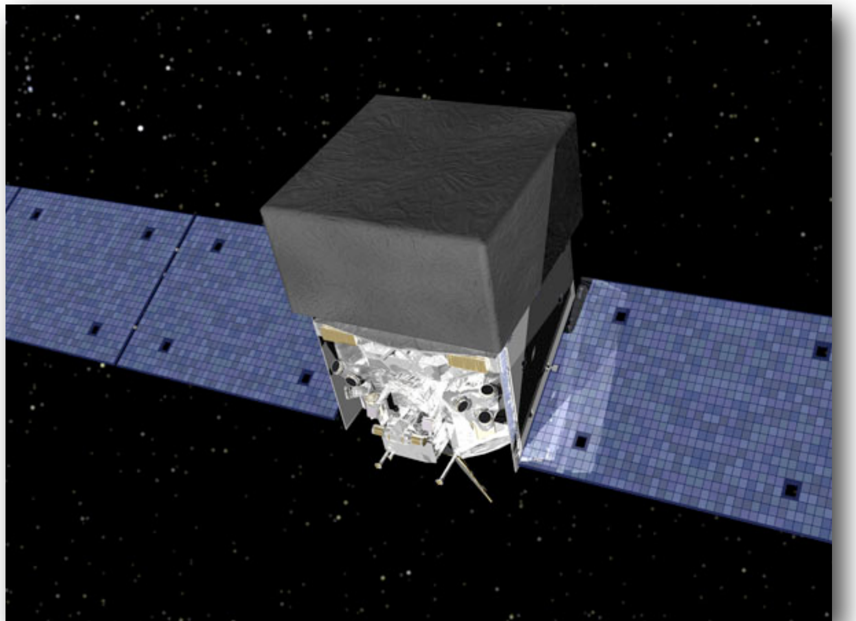
- Motivation
- Search for self-annihilating dark matter
- Search for dark matter decay
- Dark matter captured in the Sun and Earth
- Anomalies
- Outlook & Conclusions

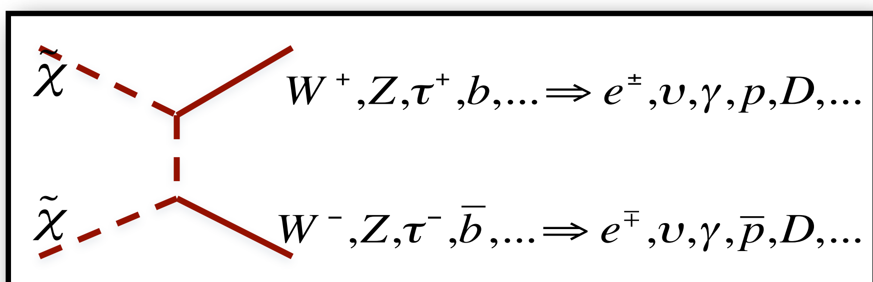
Motivation

Synergy

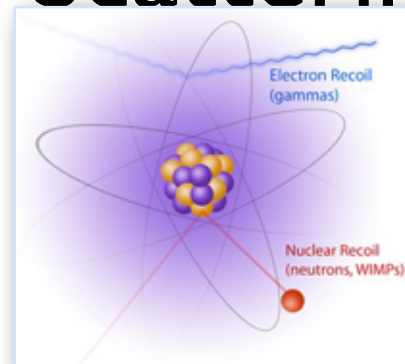
Indirect



Annihilation / Decay



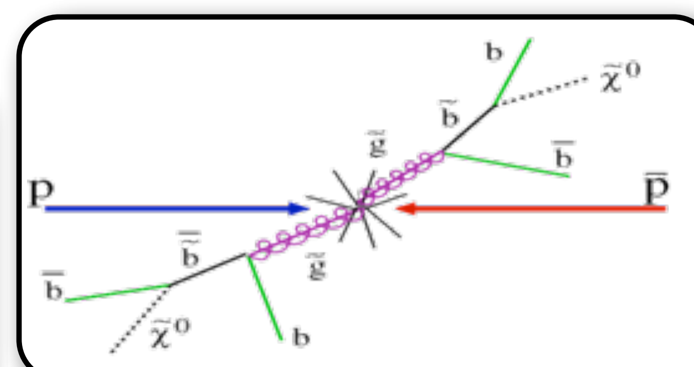
Scattering



Direct

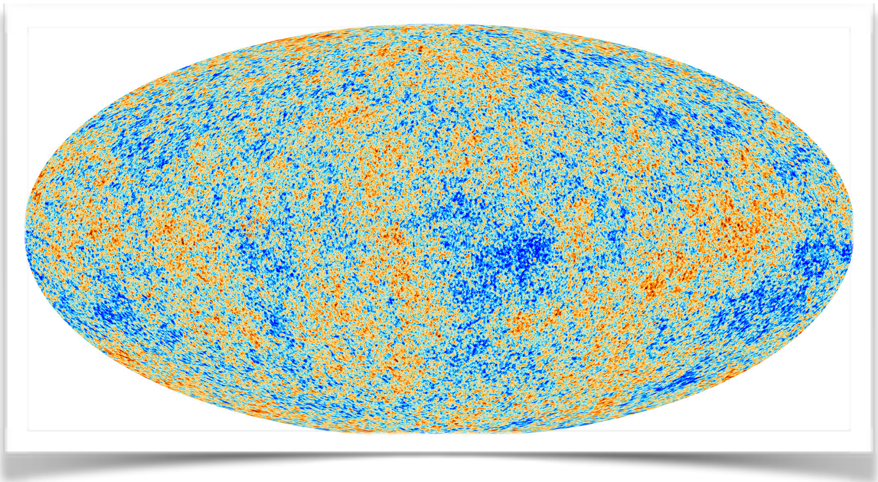
?

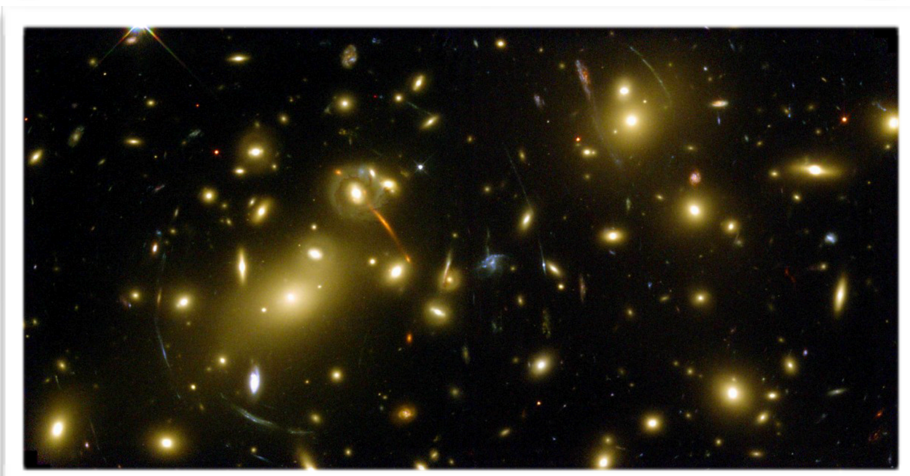
Production

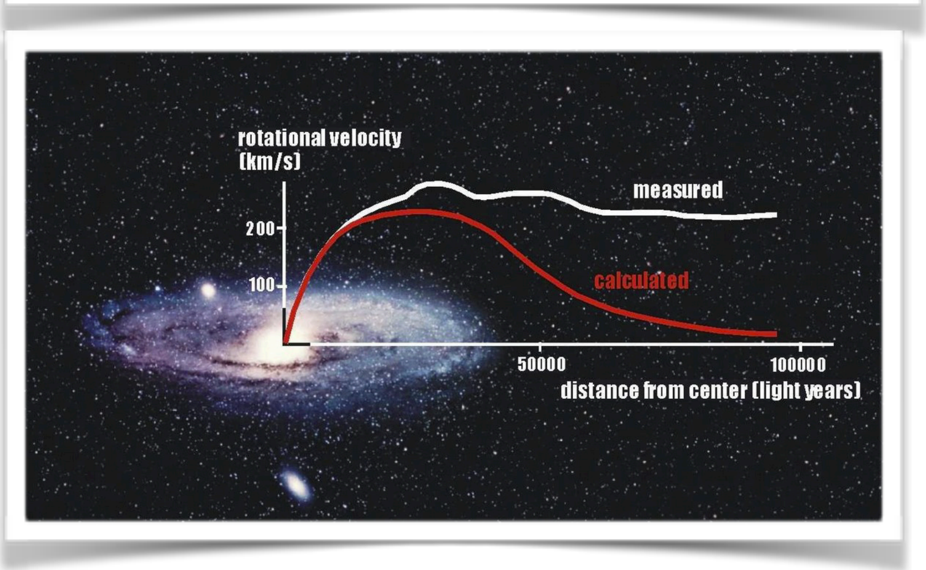


Collider

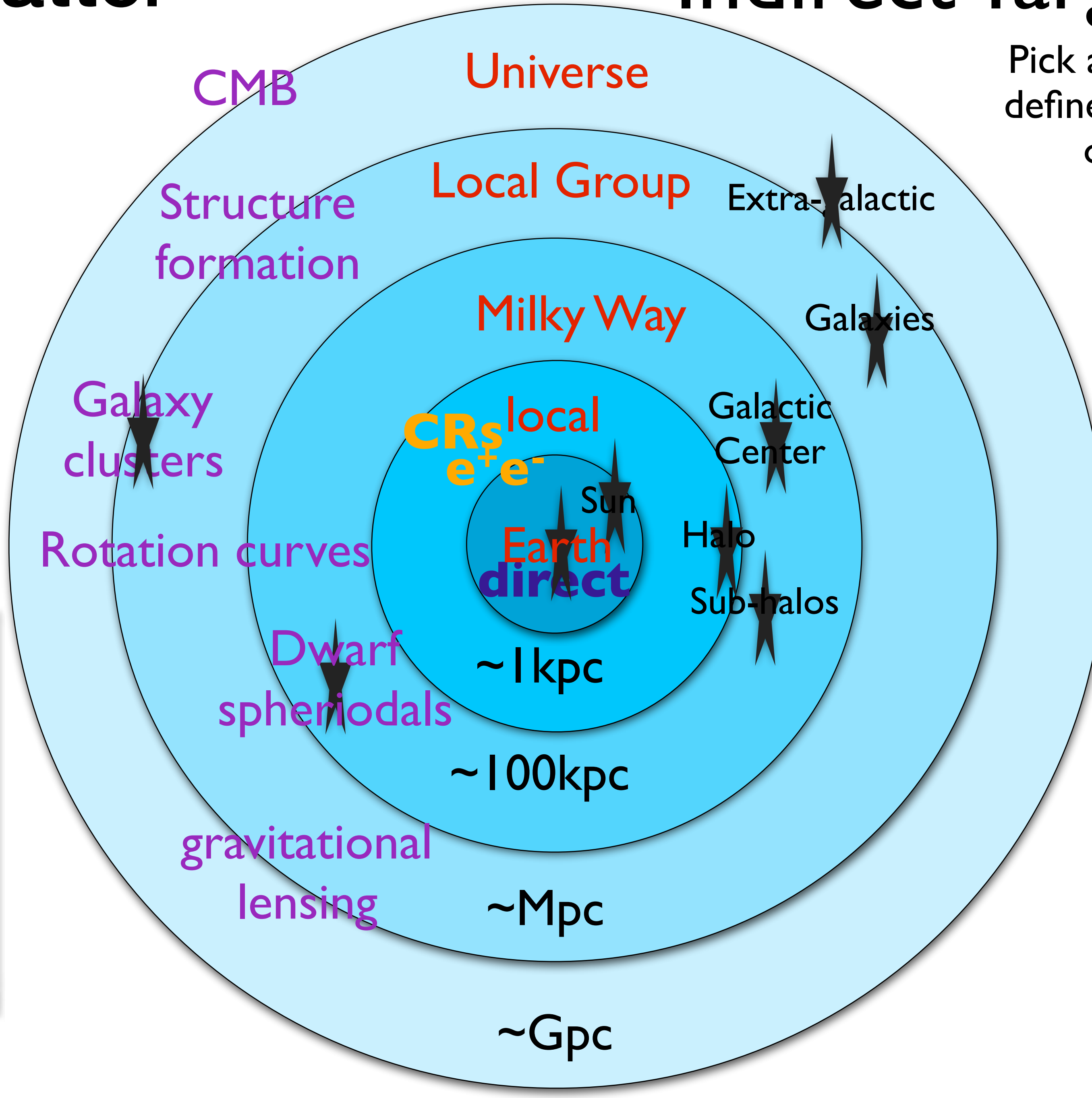
Evidence for Dark Matter







"Indirect Targets"



Pick a target that is well defined and that has low or understood astrophysical backgrounds

- Dark Matter already gravitationally "observed", but …
  - What is it ?
  - What are it's properties ?

Some of us like WIMPs <σv>~3x10^{-26}cm^{3}s^{-1}

Indirect Dark Matter Searches

Dark Matter Signals

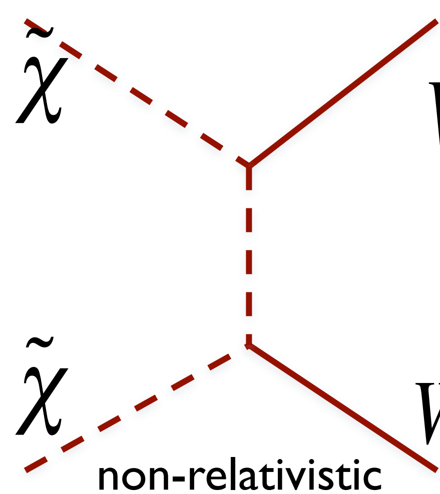
- Identify overdense regions of dark matter
  ⇒self-annihilation can occur at significant rates
- Pick prominent Dark Matter target
- Understand / predict backgrounds
- Exploit features in the signal to better distinguish against backgrounds

Annihilation Rate ~ρ^2
(Decay Rate ~ρ)

Annihilation Products

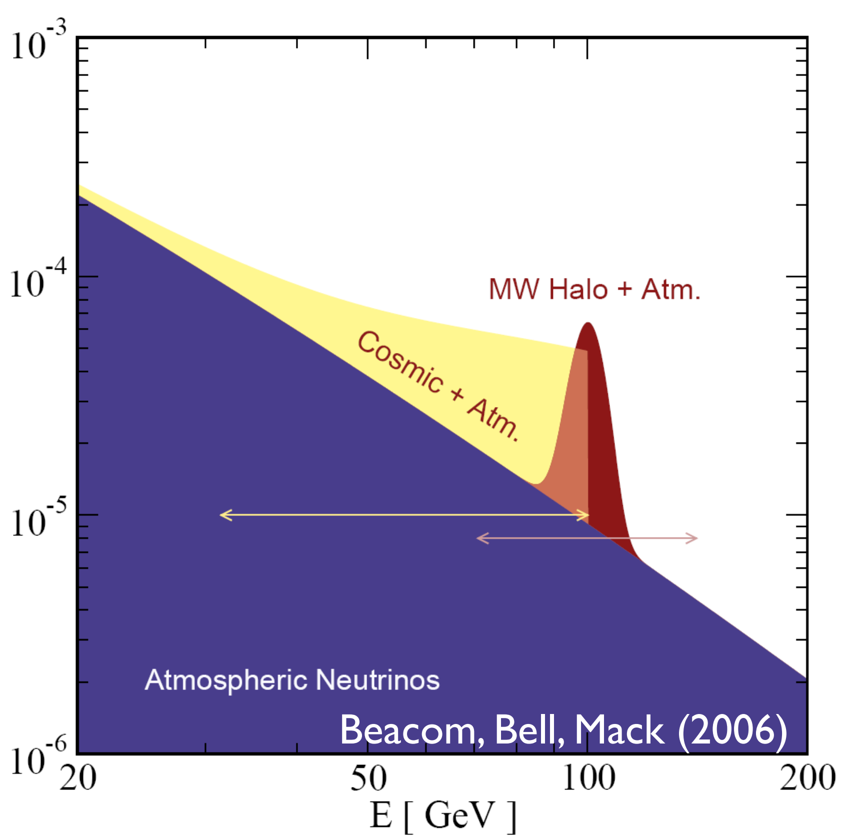
Decay

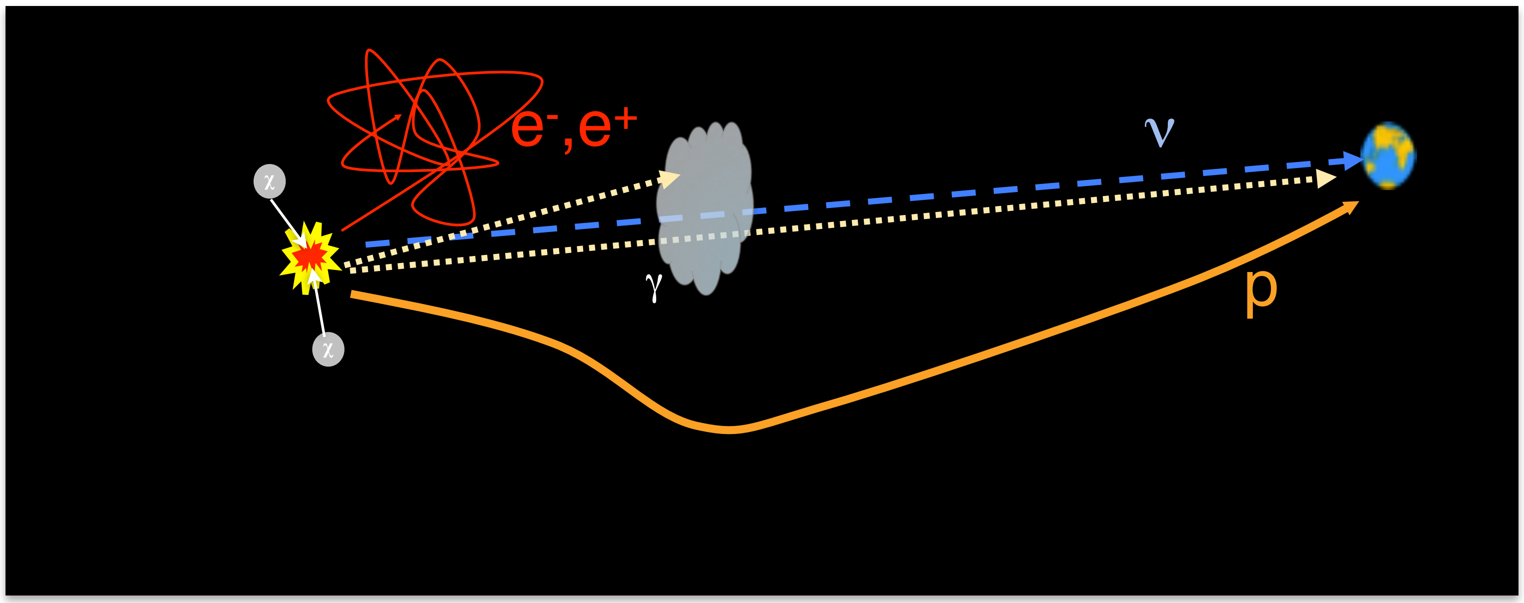
Messengers



$$W^+, Z, \tau^+, b, \ldots \Rightarrow e^\pm, \upsilon, \gamma, p, D, \ldots$$

$$W^-, Z, \tau^-, \bar{b}, \ldots \Rightarrow e^\mp, \upsilon, \gamma, \bar{p}, D, \ldots$$



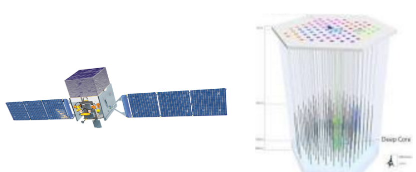


Targets - Dark Matter Annihilations

Small halo model dependence, boost factors

Diffuse flux, spectral feature

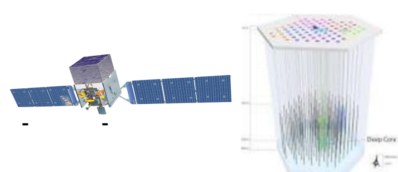
Signal weak compared to Galactic signal



Large DM content, nearby source, O(10) larger flux than extra-galactic

Anisotropy

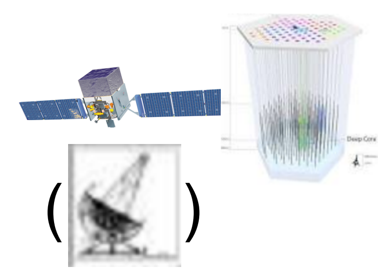
Relatively independent from DM halo profile



Very dense DM accumulation, nearby source

Extended Source

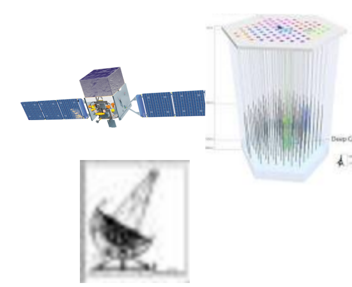
Very strong dependence on DM density profile

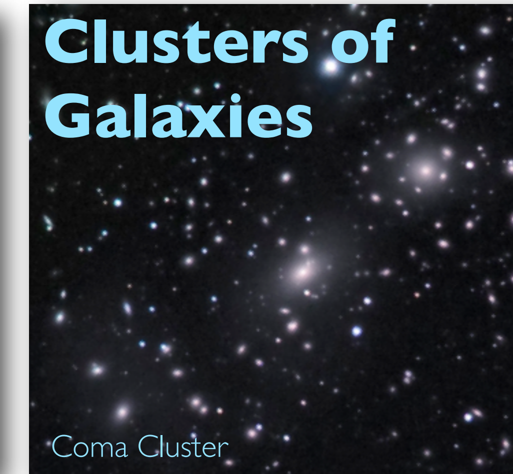


No astrophysical backgrounds

Point source

Cored profiles favored, less flux

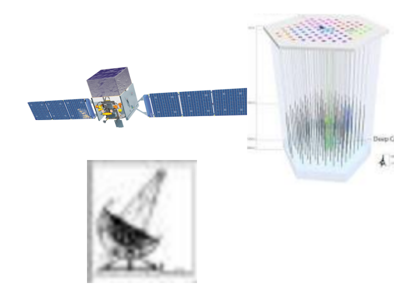




Large DM content, high boost factors from sub structure

Extended source

Understanding of boost factors



For discovery observations at multiple sources with different observatories (Multiwavelength !) that yield a consistent picture

Dark Matter Distributions / Halo Profiles

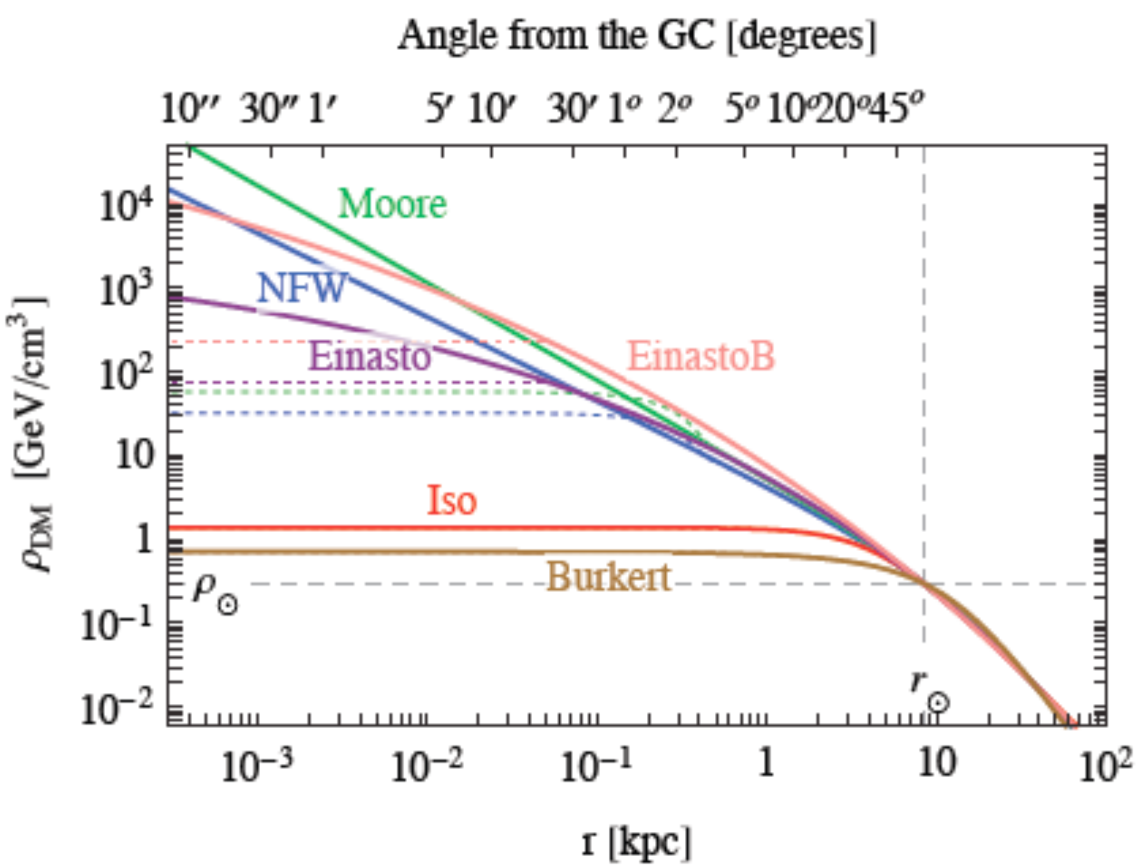
$$\text{NFW}: \quad \rho_{\text{NFW}}(r) = \rho_s \frac{r_s}{r}\left(1+\frac{r}{r_s}\right)^{-2}$$

$$\text{Einasto}: \quad \rho_{\text{Ein}}(r) = \rho_s \exp\left\{-\frac{2}{\alpha}\left[\left(\frac{r}{r_s}\right)^{\alpha}-1\right]\right\}$$

$$\text{Isothermal}: \quad \rho_{\text{Iso}}(r) = \frac{\rho_s}{1+(r/r_s)^2}$$

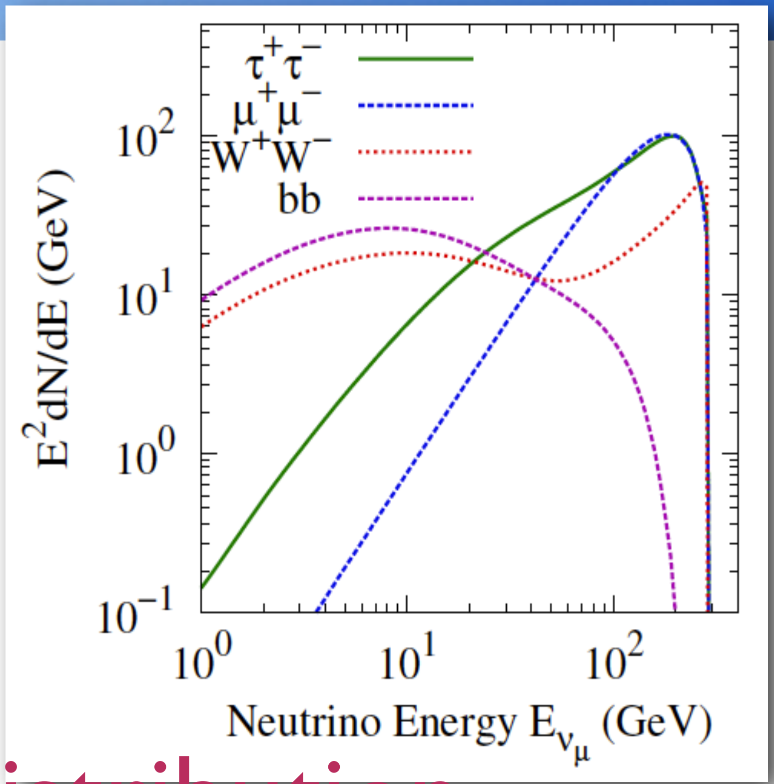
$$\text{Burkert}: \quad \rho_{\text{Bur}}(r) = \frac{\rho_s}{(1+r/r_s)(1+(r/r_s)^2)}$$

$$\text{Moore}: \quad \rho_{\text{Moo}}(r) = \rho_s \left(\frac{r_s}{r}\right)^{1.16}\left(1+\frac{r}{r_s}\right)^{-1.84}$$



DM halo	α	r_s [kpc]	ρ_s [GeV/cm^3]
NFW	–	24.42	0.184
Einasto	0.17	28.44	0.033
EinastoB	0.11	35.24	0.021
Isothermal	–	4.38	1.387
Burkert	–	12.67	0.712
Moore	–	30.28	0.105

Dark Matter Annihilation



Measure Flux

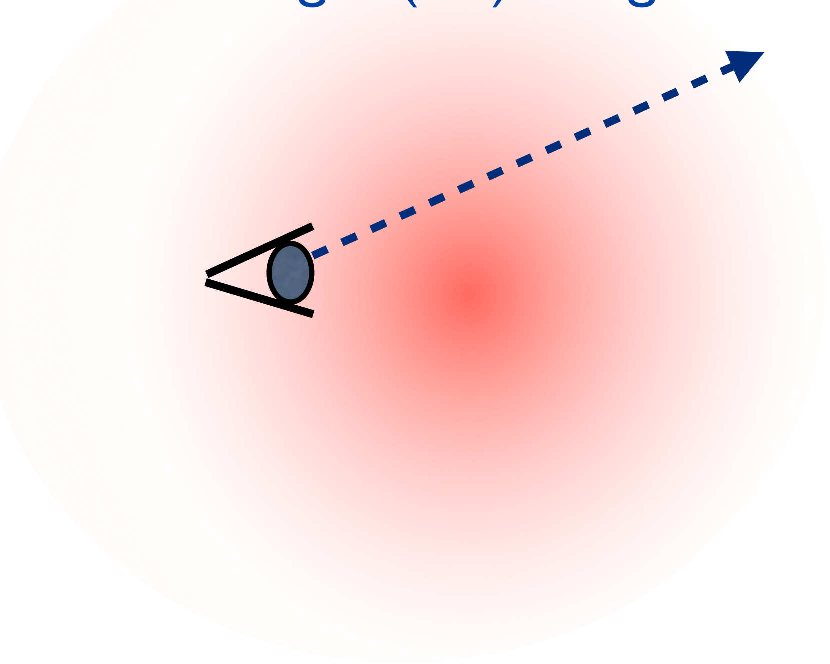
Particle Physics

$$\frac{d\Phi}{dE}(E,\phi,\theta) = \frac{1}{4\pi}\frac{\langle\sigma_A v\rangle}{2m_\chi^2}\Sigma_f \frac{dN}{dE}B_f$$

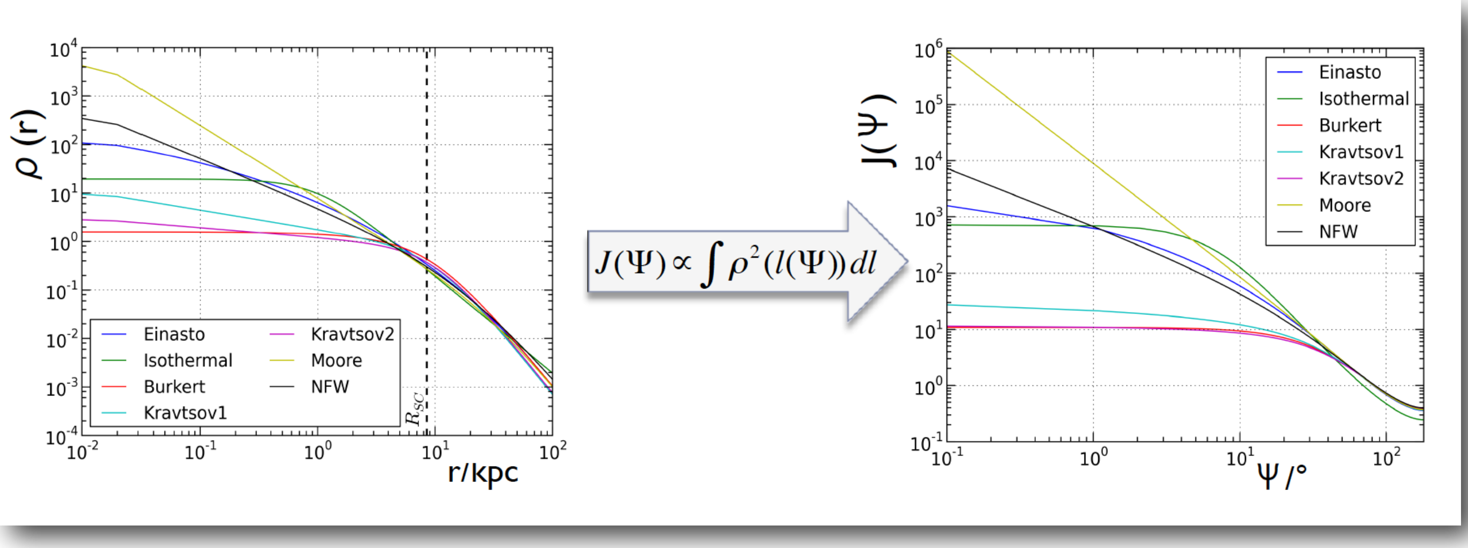
x

Dark Matter Distribution

line of sight (los) integral

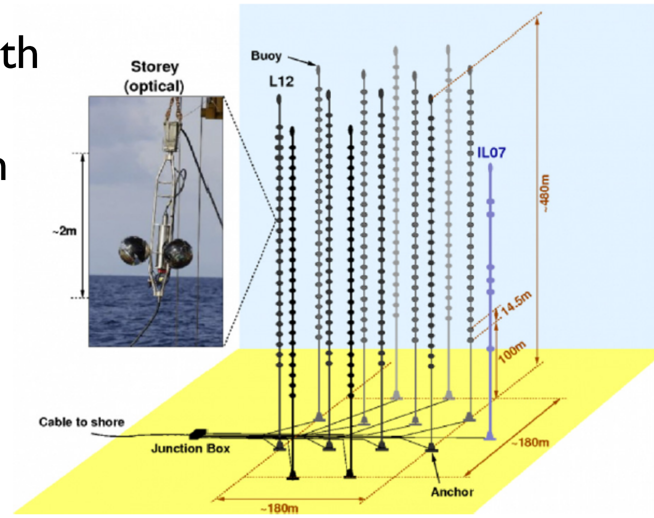


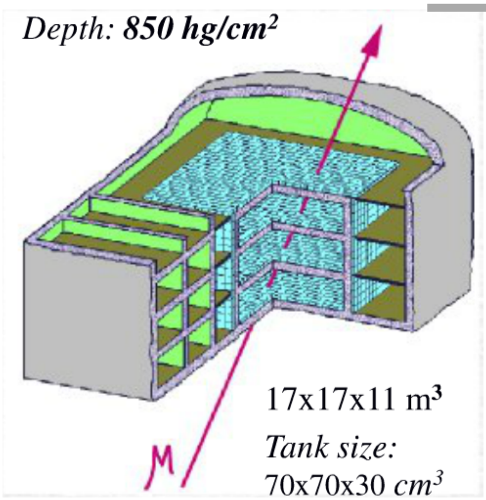
$$\int_{\Delta\Omega(\phi,\theta)} d\Omega' \int_{\text{los}} \rho^2(r(l,\phi'))dl(r,\phi')$$



Neutrino Telescopes / Detectors

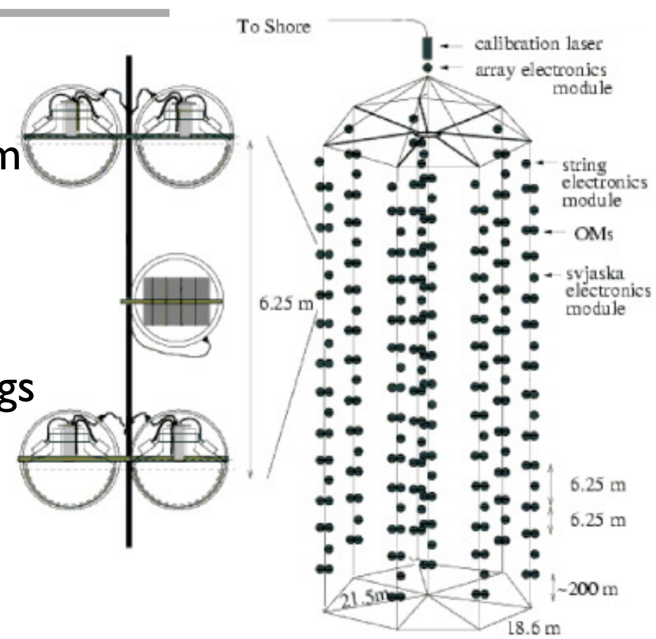
- **ANTARES** is located at a depth of 2475 m in the Mediterranean Sea, 40 km offshore from Toulon
- Consists 885 10”PMTs on 12 lines with 25 storeys each.
- Detector was competed in May 2008



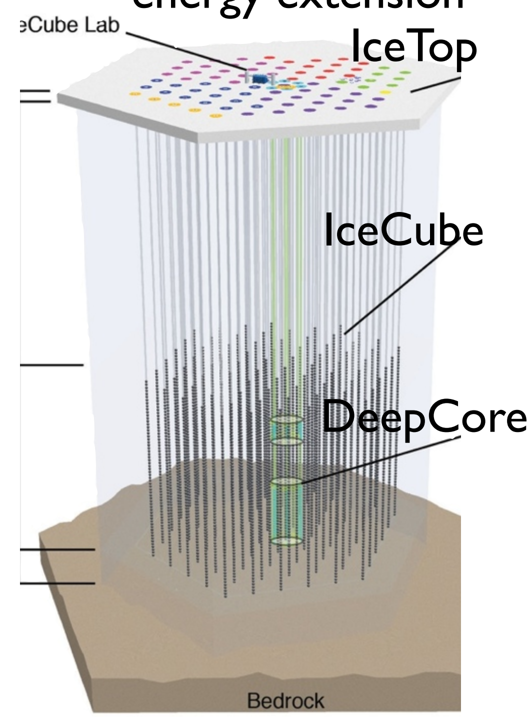


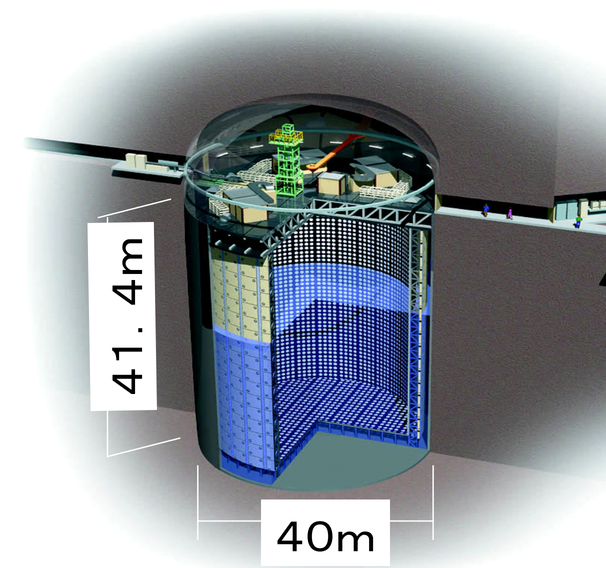
- **Baksan** Underground Scintillator Telescope with muon energy threshold about 1 GeV using 3,150 liquid scintillation counters
- Operating since Dec 1978 ; More than 34 years of continuous operation

- Lake **Baikal**, Siberia, at a depth 1.1 km NT36 in 1993
- NT200 (since Apr 1998) consists of one central and seven peripheral strings of 70m length



- **IceCube** at the Geographic South Pole
- 5160 10”PMTs in Digital optical modules distributed over 86 strings instrumenting ~1km³
- Physics data taking since 2007 ; Completed in December 2010, including **DeepCore** low-energy extension

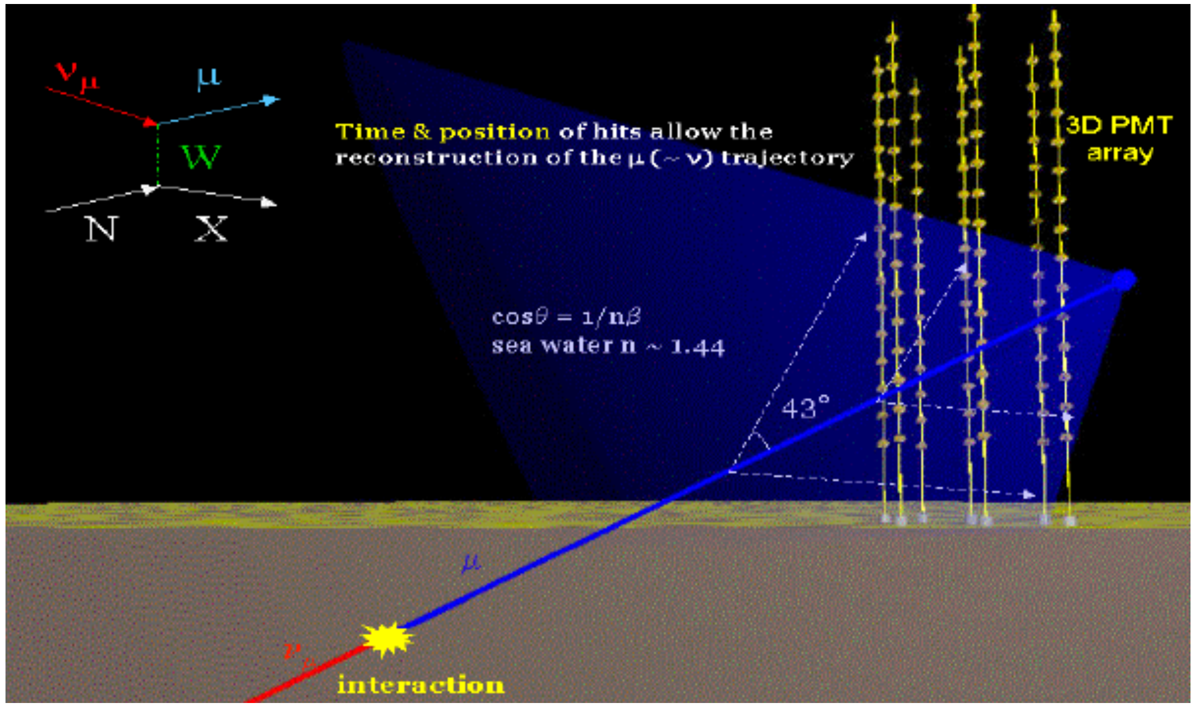


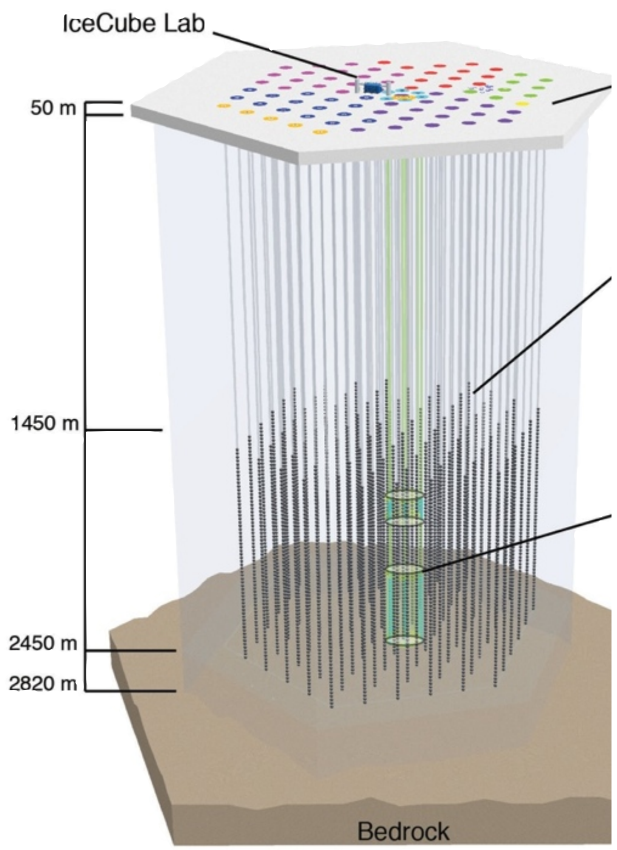


- **Super-Kamiokande** at Kamioka uses 11K 20” PMTs
- 50kt pure water (22.5kt fiducial) water-cherenkov detector
- Operating since 1996

see talks from Vincent Bertine and Morten Medici

INDIRECT DARK MATTER SEARCHES IN ICECUBE / ANTARES

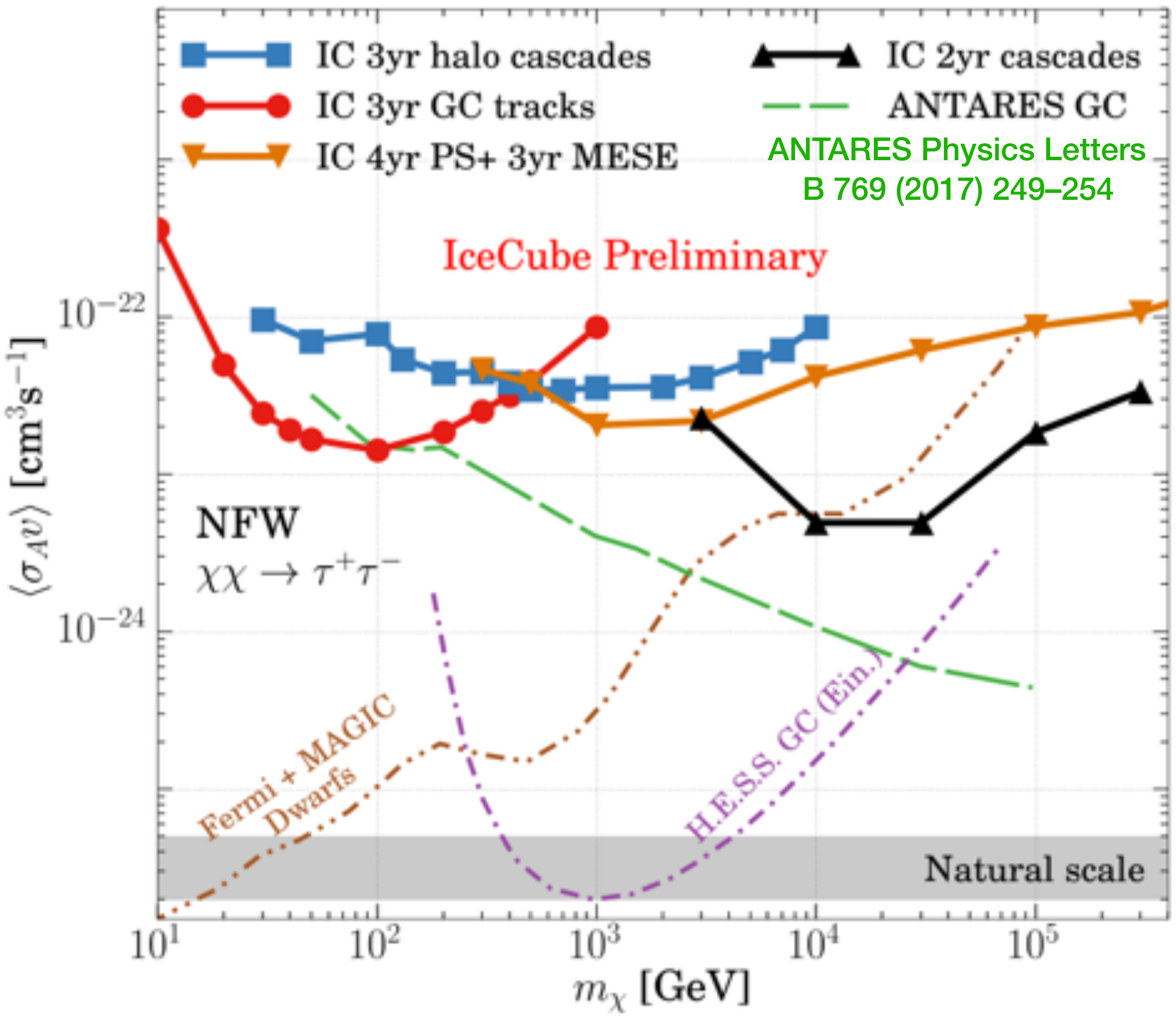




- ANTARES and IceCube complementary positioned on Northern and Southern Hemisphere
- Galactic Center only accessible in down-going events for IceCube
- Weak halo model dependence for observation of extended DM halo

Galactic Halo DM annihilation searches cover 10 GeV - 300 TeV Dark Matter masses with 4 analyses:

- ANTARES GC 2007 to 2015
- IceCube Galactic Halo Cascades 2yrs
- IceCube Galactic Center Tracks 4yrs (incl. 3yr MESE)
- IceCube Galactic Center Track 3yrs (low-energy)
  - IceCube [arXiv:1705.08103]



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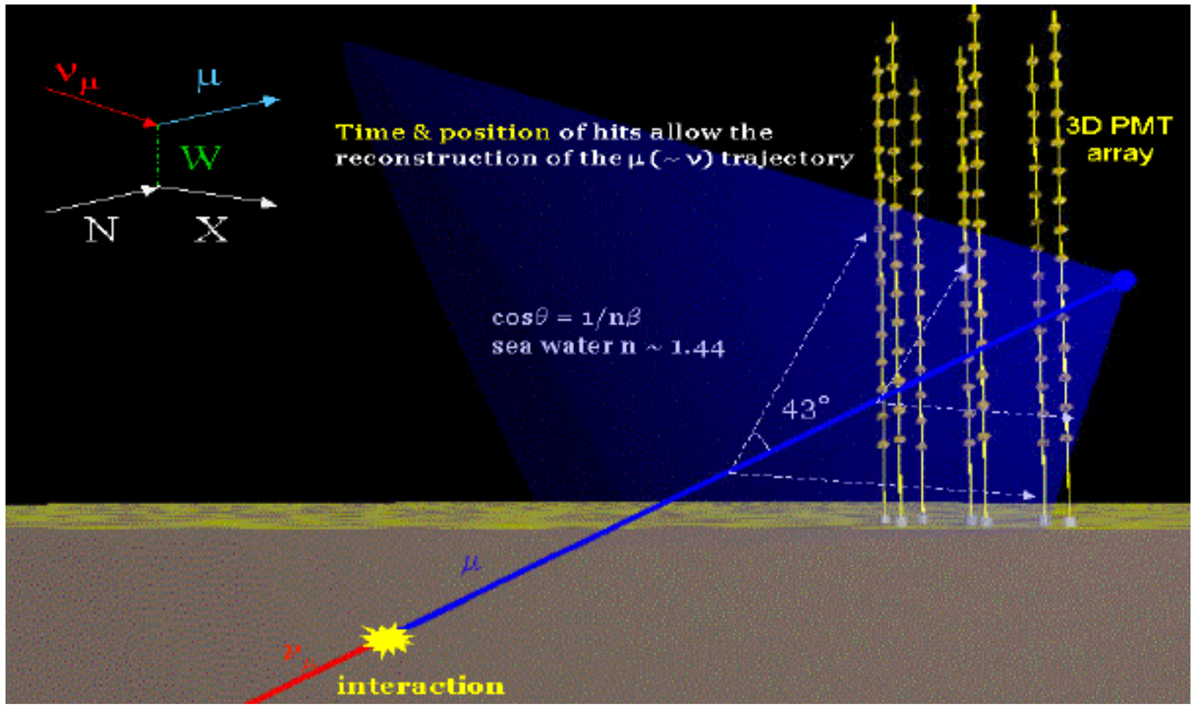

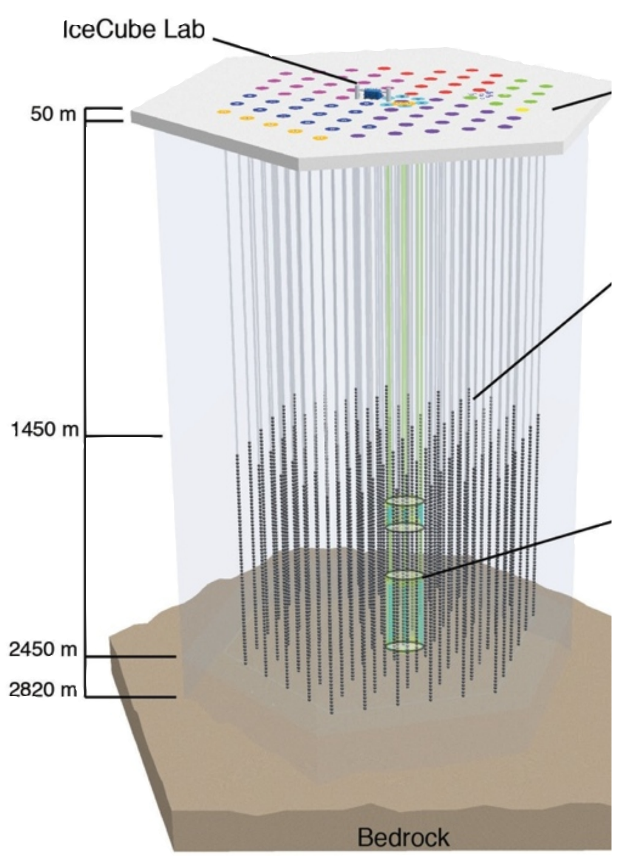

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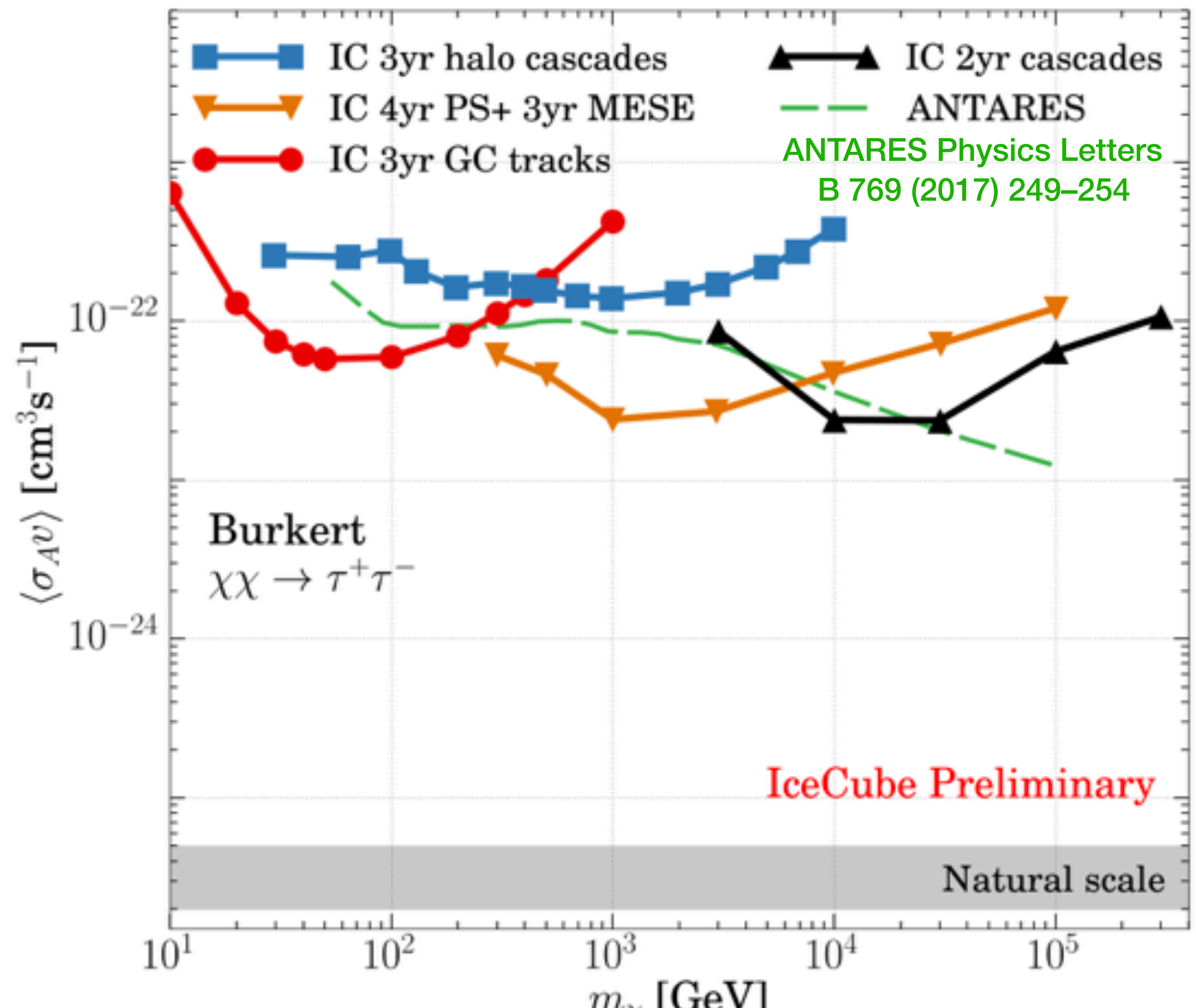
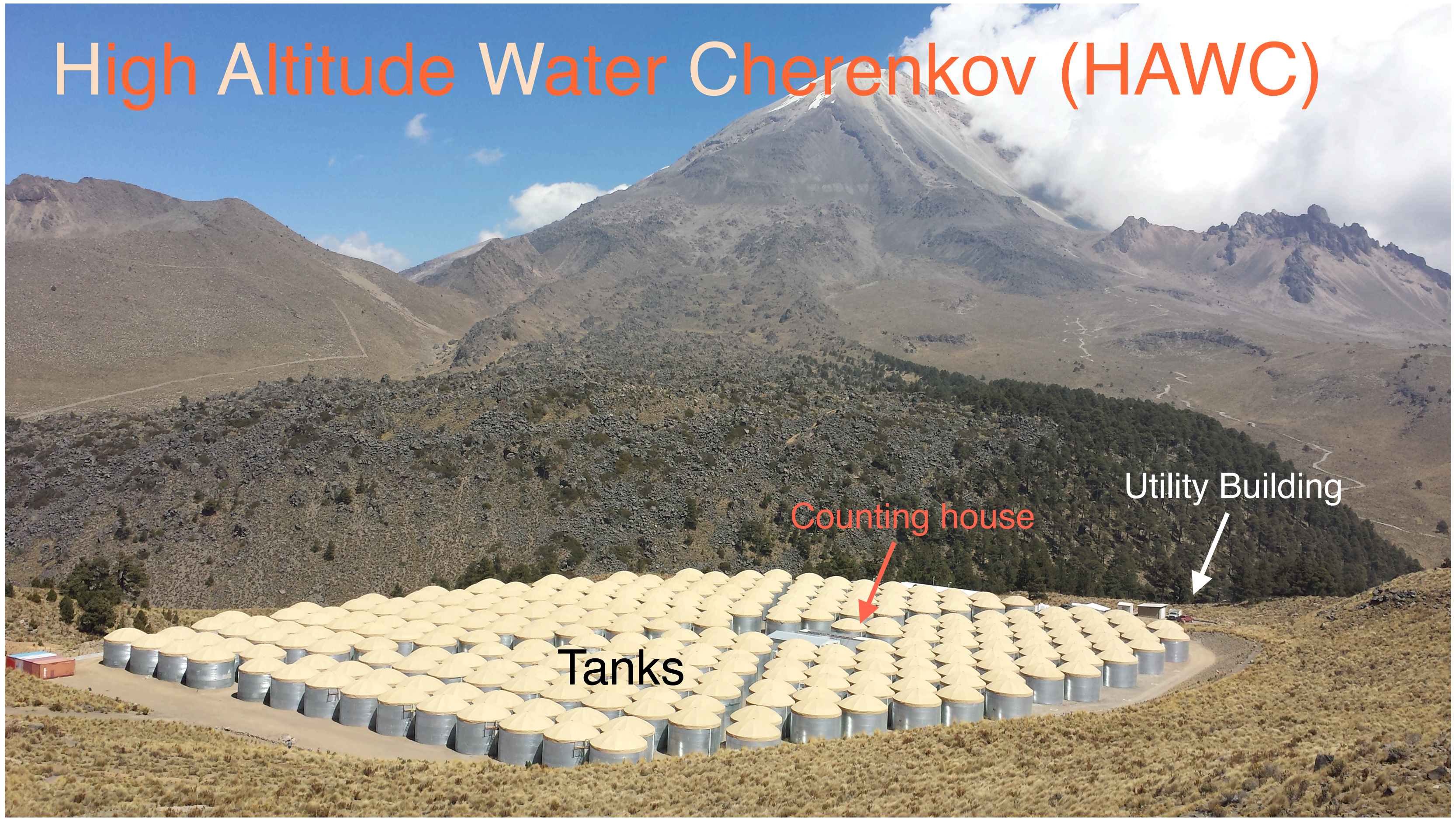


Jim Linnemann

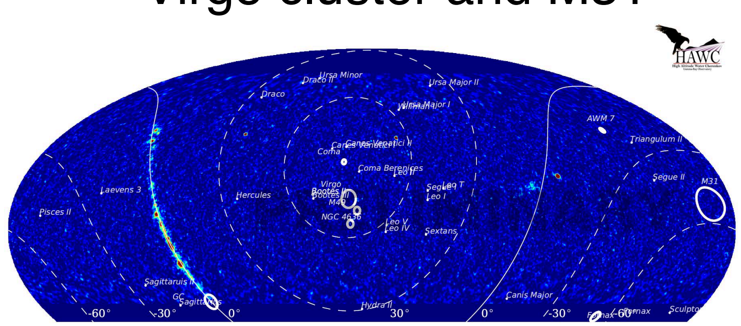
High Altitude Water Cherenkov (HAWC)



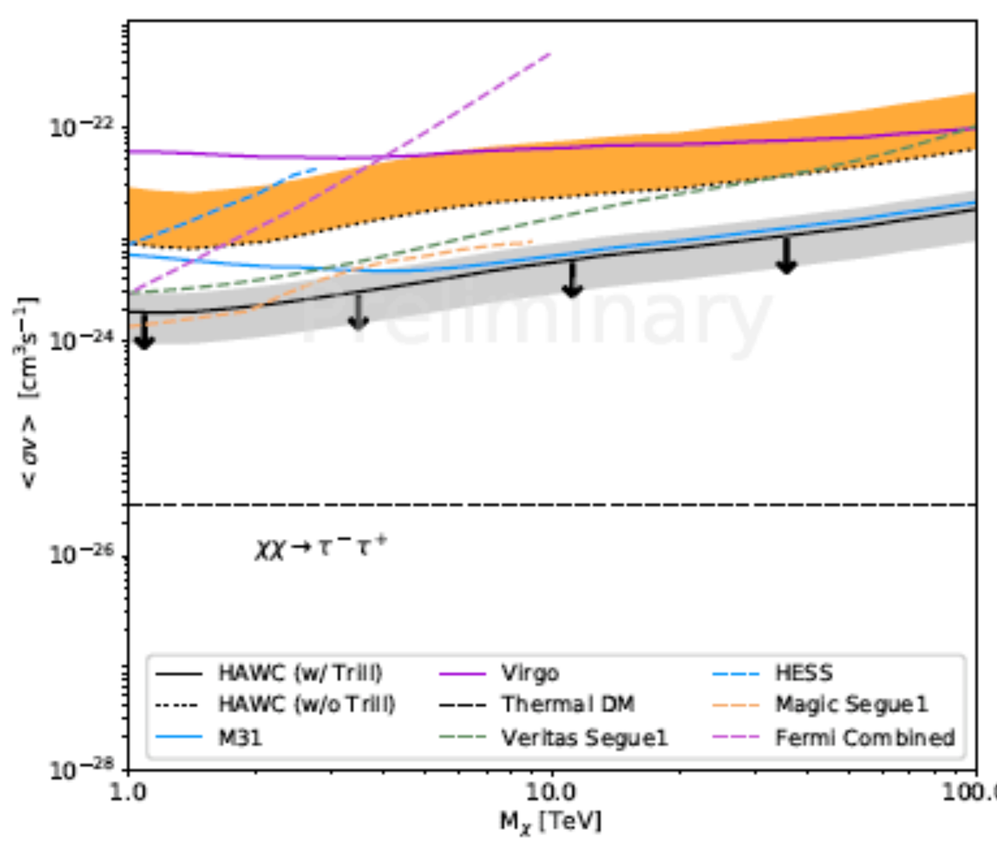
- Located at 97.5° W, 18.9° N (Parque Nacional Pico de Orizaba) at 4100m
- 300x 7.3 m diameter, 5 m height tanks,
  - 3x 8" R5912 PMTs and 1x 10" R7081-HQE PMT
- In total: 55kT of water
- Covers 22000 m^2
- Completed in 2016
- Trigger rate: 24kHz
- Data rate: 2TB of data per day, 95% livetime

507 days of HAWC data analyzed

Targets:
- Dwarf spheroidal (dSph)galaxies
  - Combined results were computed for 15 dSph
- Galaxies / Galaxy clusters
  - Virgo cluster and M31



Potential sources to look for dark matter signature



Future improvements:
- include more dSph
- extended source analysis
- more data …

Also measurements on:
- TeV γ emission from pulsars
- Dark Matter Decay

Michael Daniel Tuesday afternoon

Dark Matter Annihilation Search with VERITAS

Array of four IACTs in Southern AZ, USA

- Energy Range: 85 GeV to > 30 TeV
- Energy Resolution: 15-25%
- Pointed observation (FOV~3.5°)

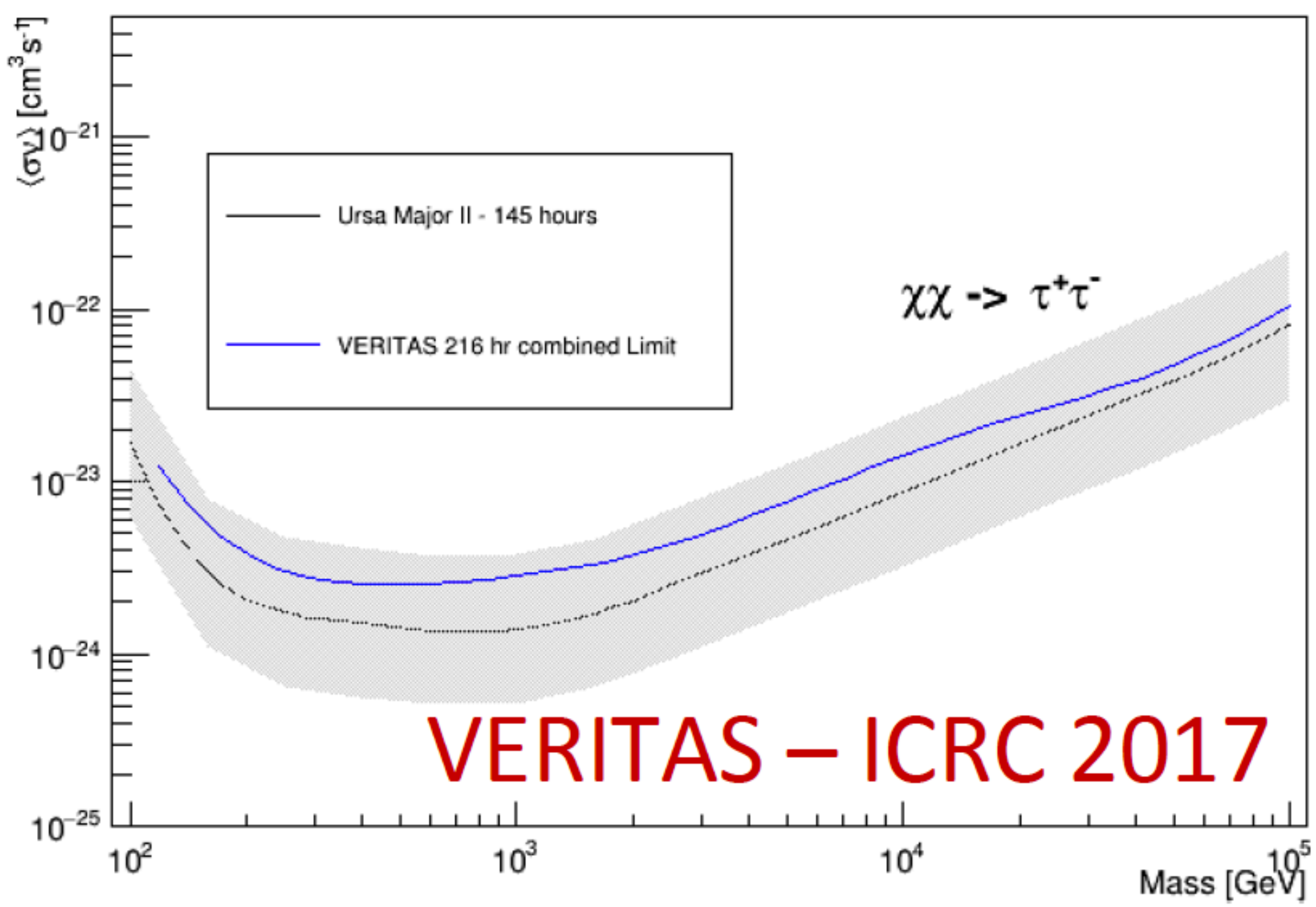
Targets

- Dwarf Spheriodal Galaxies
- Fermi-LAT unidentified sources
- Galactic Center (soon)
    - Galactic Center region does not transit above 30°elevation at VERITAS site

Five **dSphs** observed by VERITAS between 2007 and 2013

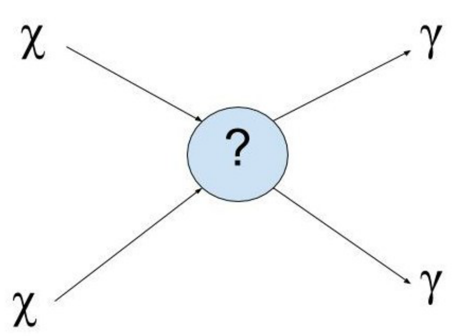
- Total of 230 hours after data quality selection
- 92 hours for Segue 1

Benjamin Zitzer [VERITAS]. ICRC2017 (904)



see also Archambaultet al. [VERITAS] Phys. Rev. D 95, 082001

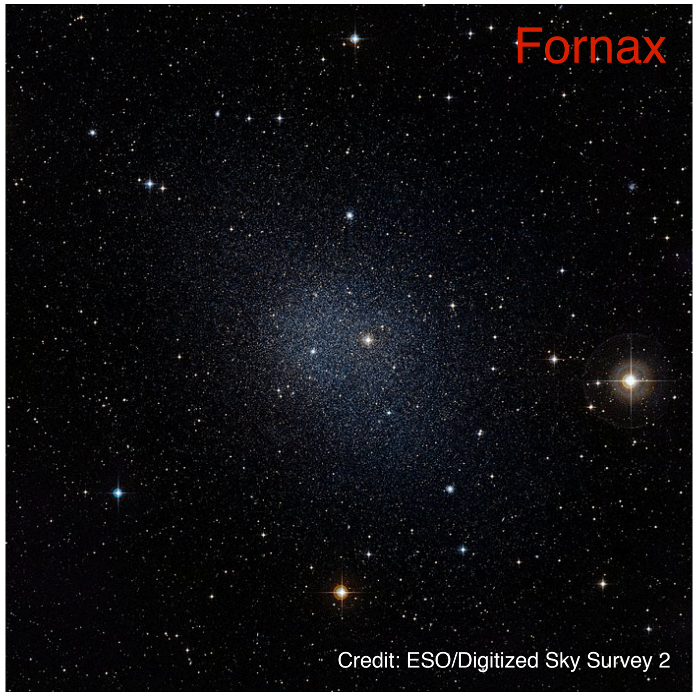
Line Searches

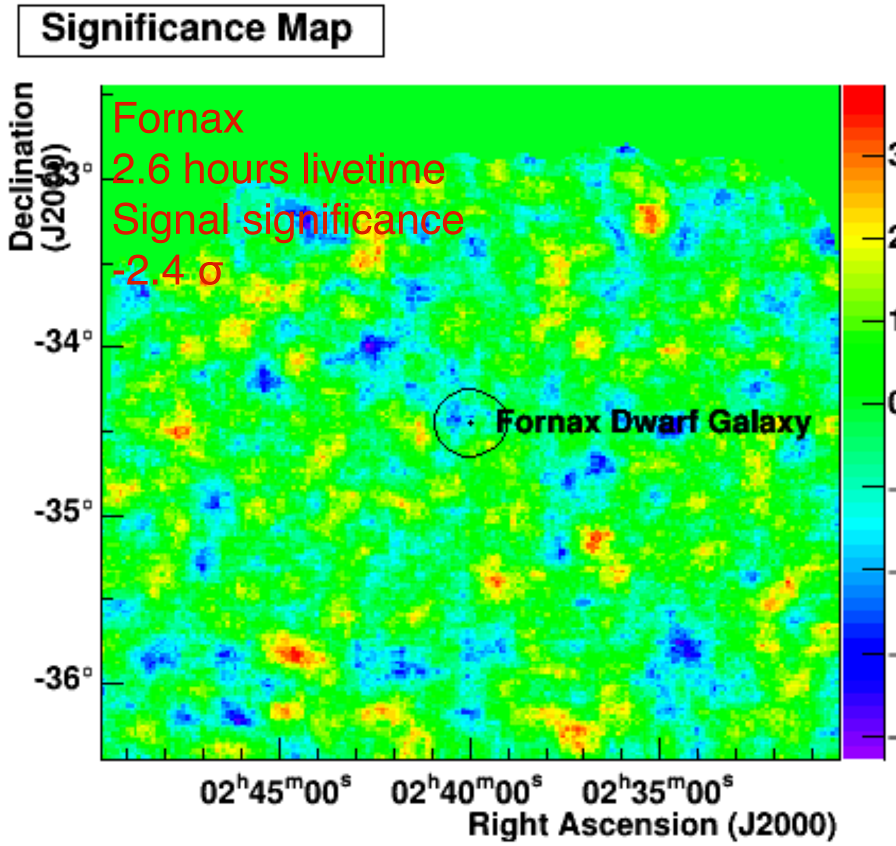


Peak in the γ energy distribution at the WIMP mass ("γ-ray line") would be clear signal for DM annihilations.

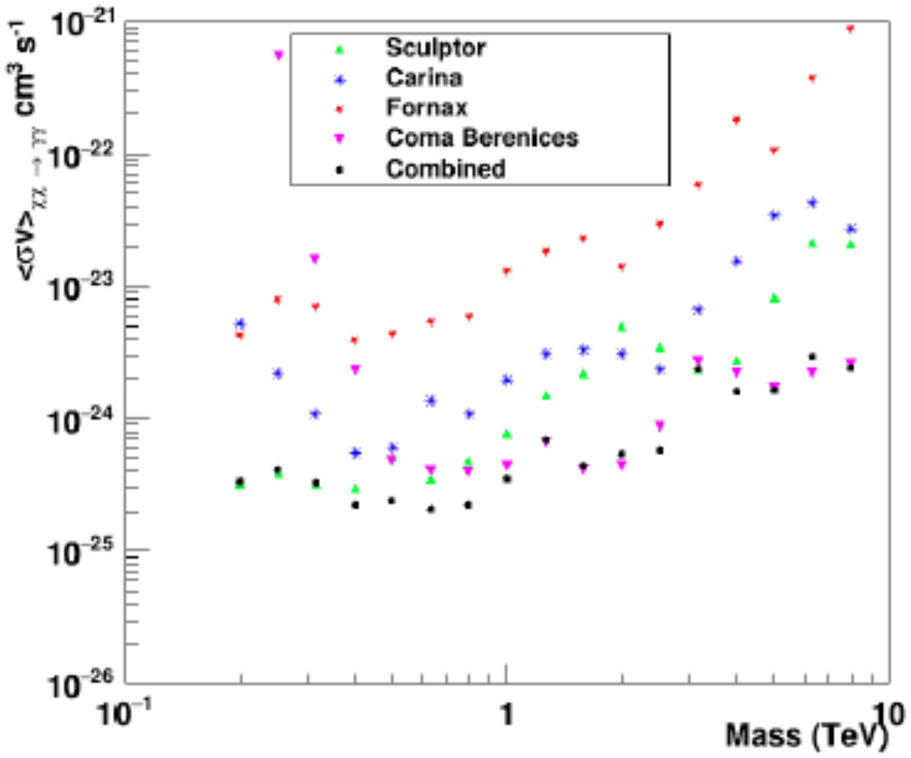
Dwarf Spheroidal Galaxies (dSphs)

- Low/no gas, dust or recent star formation
- DM dominated
- Several large datasets already recorded



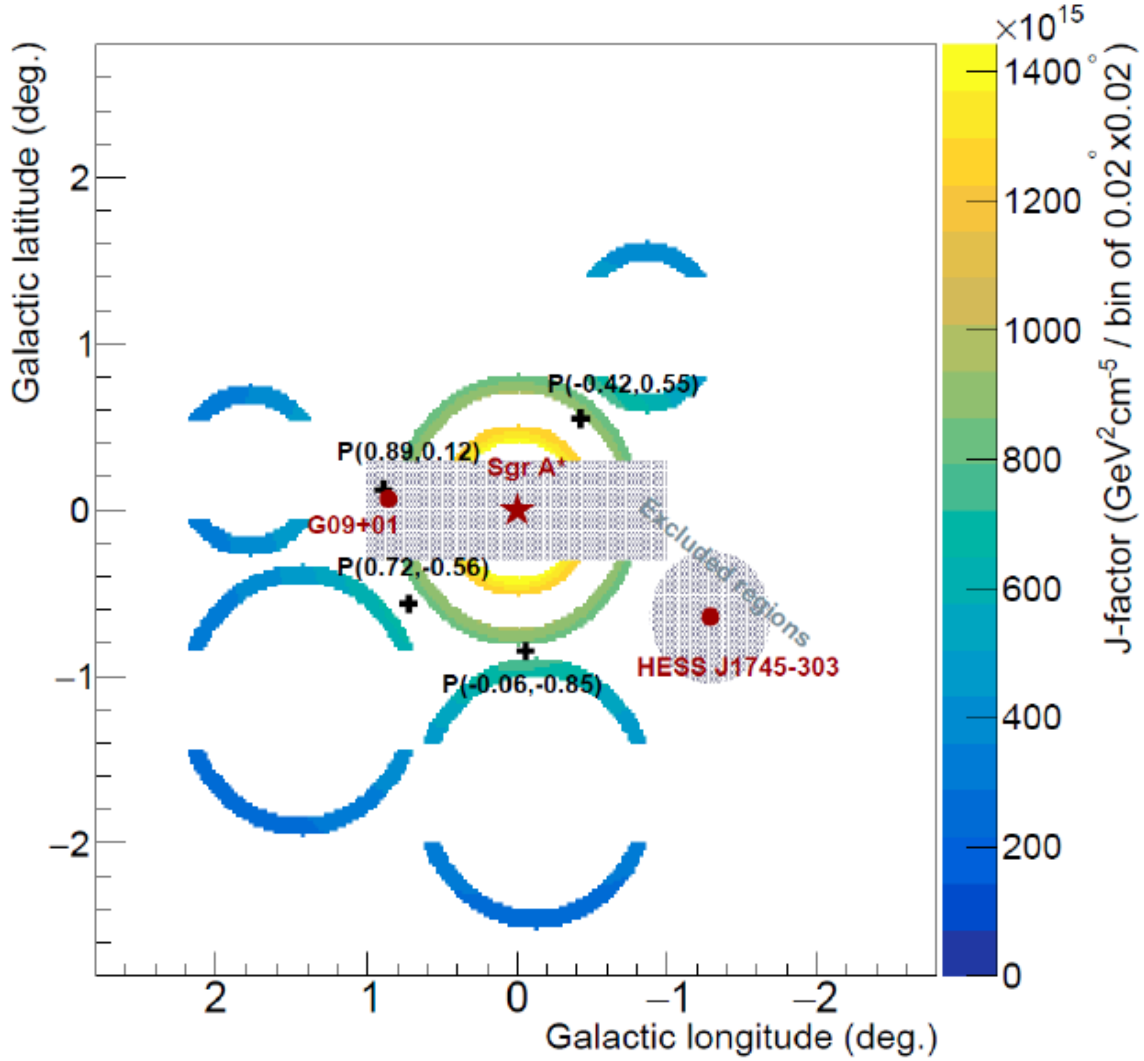


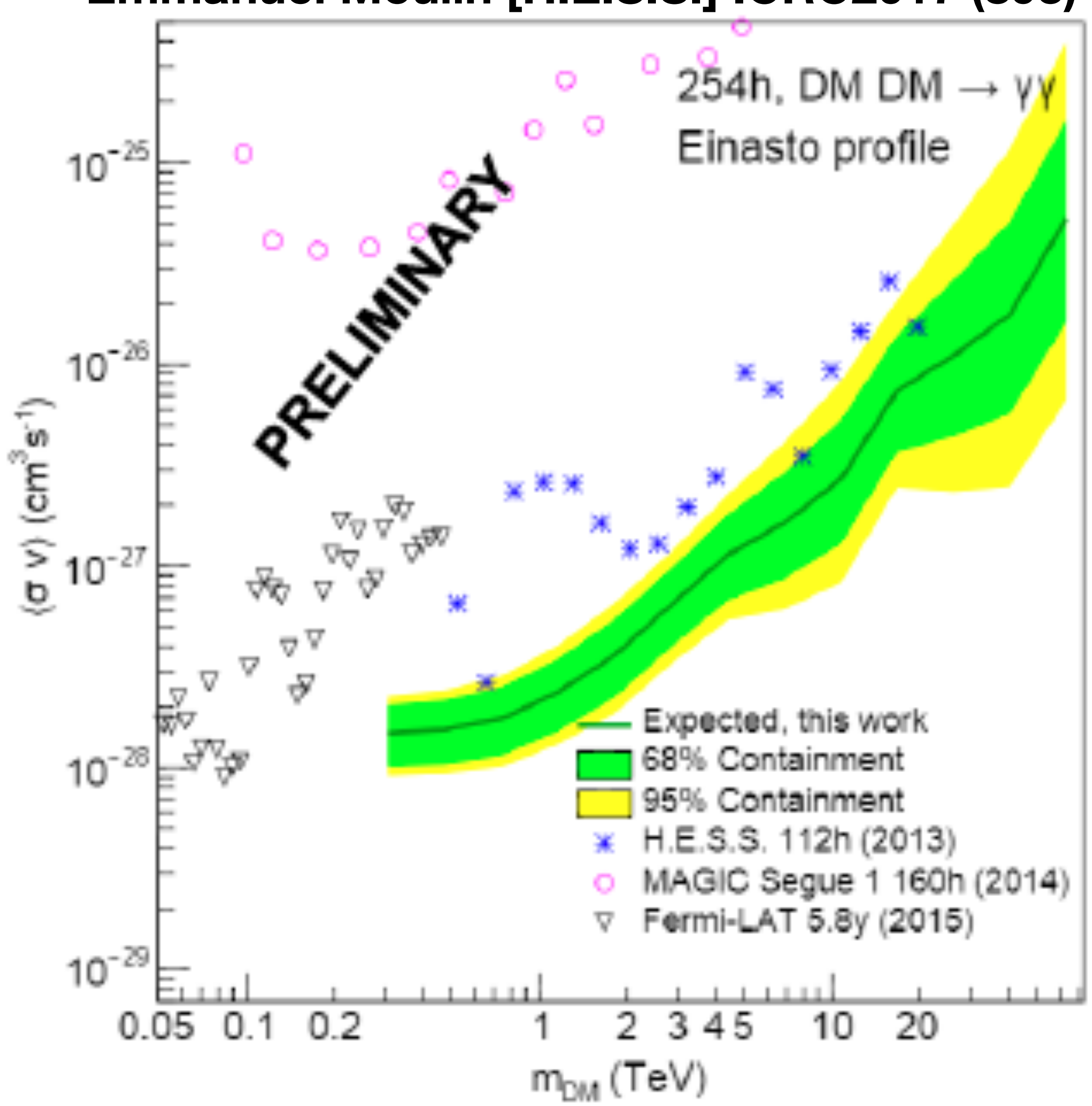
L. Oakes [H.E.S.S.] ICRC2017 (905)



- Limit on <σv> of 3×10^{-25} cm^3s^{-1} reached for M_χ range 0.4-1.0 TeV
- First H.E.S.S. DM line search from dwarf galaxies and first combined DM line search
- More complex line-like models to be included for upcoming paper

Line Searches





- Sensitivity only (2x10^{-28} cm^{3} s^{-1} @1TeV) , unblinding in progress … expect results soon
- lower energy threshold thanks to the improved raw data analysis: best limit shifted down to lower masses
- Fermi-LAT limits surpassed of a factor about 6 @300 GeV

Dark Matter Decay

Heavy Decaying Dark Matter

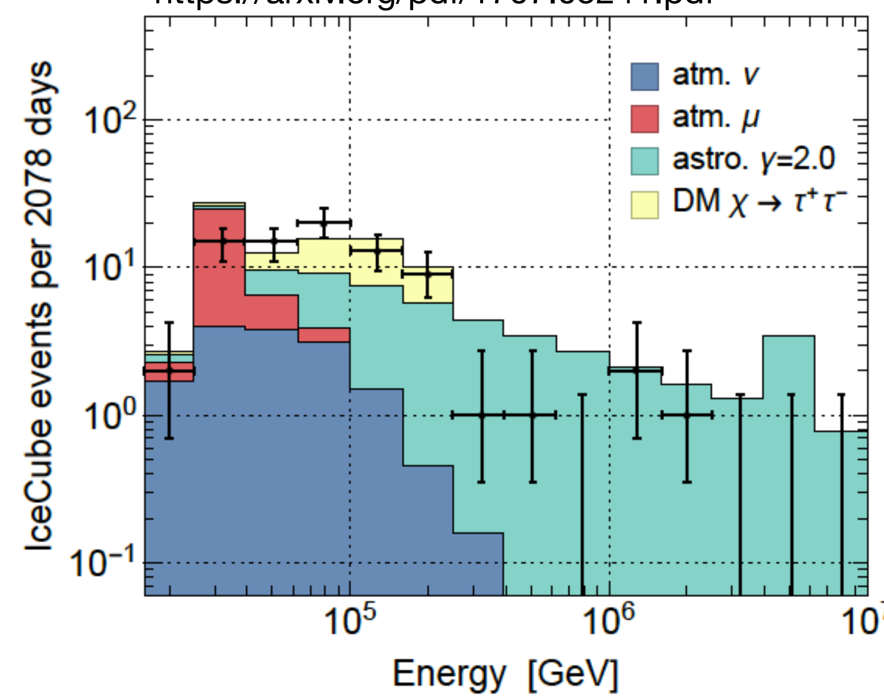
see Claudio Kopper (HESE 6yrs)

Could the observed neutrino flux be due to only dark matter decaying into multiple channels?

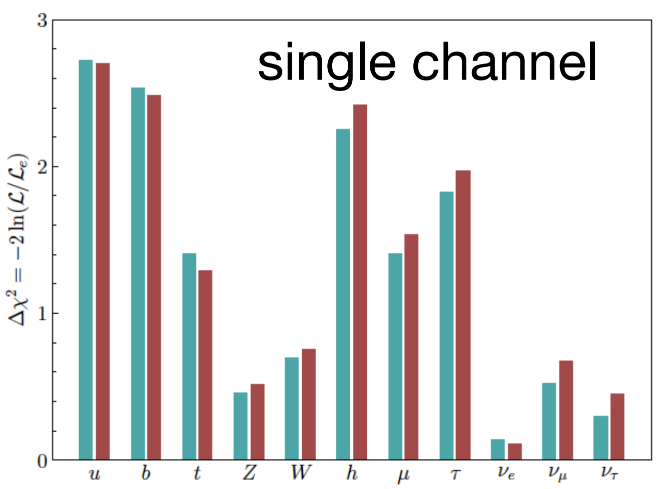
$$\frac{d\Phi_{\mathrm{DM},\nu_\alpha}}{dE_\nu} = \frac{d\Phi_{\mathrm{G},\nu_\alpha}}{dE_\nu} + \frac{d\Phi_{\mathrm{EG},\nu_\alpha}}{dE_\nu}$$

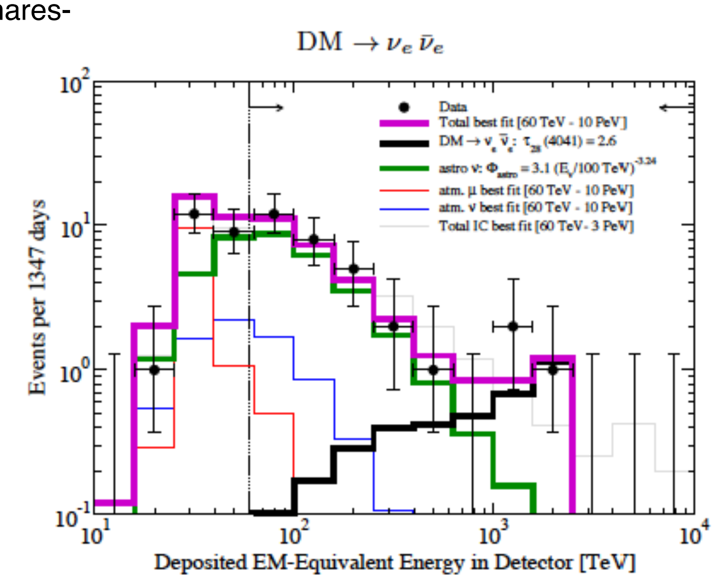
Take Galactic and Extra galactic contributions into account

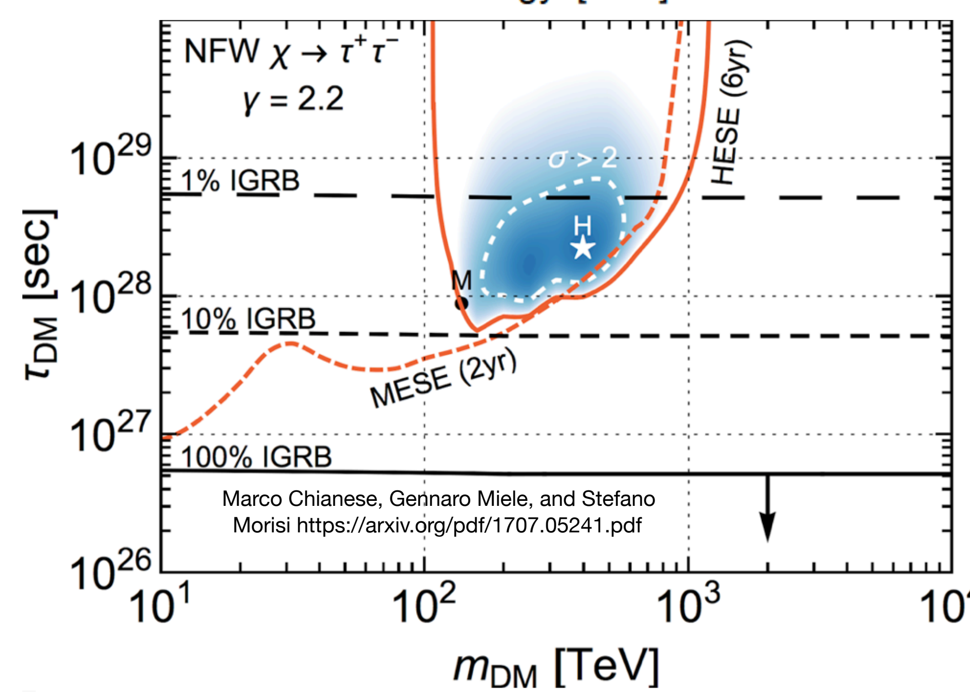
Marco Chianese, Gennaro Miele, and Stefano Morisi
https://arxiv.org/pdf/1707.05241.pdf



Atri Bhattacharya, Arman Esmaili, Sergio Palomares-Ruiz and Ina Sarcevic, arXiv:1706.05746







Find that HESE data can be best described with the combination of the astrophysical neutrino flux and the dark matter decay

Caution when interpreting HESE events:
- Earth absorption needs to be considered
- Outcome strongly depends on background assumption

Heavy DM bounds with neutrinos, see also
Murase and Beacom JCAP 1210 (2012) 043
Esmaili, Ibarra, and Perez JCAP 1211 (2012) 034
Rott, Kohri, Park PRD92, 023529 (2015)
El Aisati, Gustafsson, Hambye 1506.02657

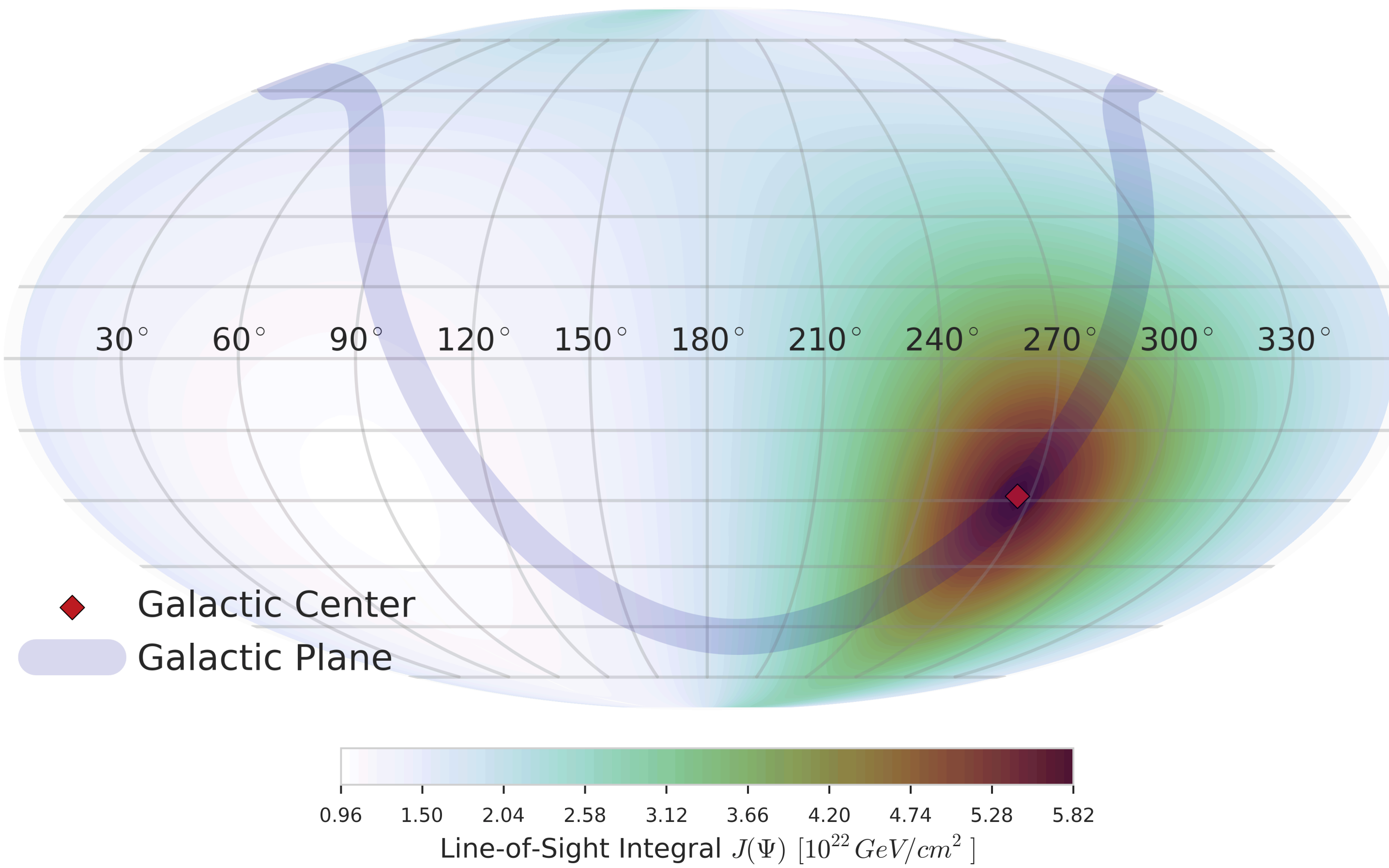
Dark Matter Decay with IceCube

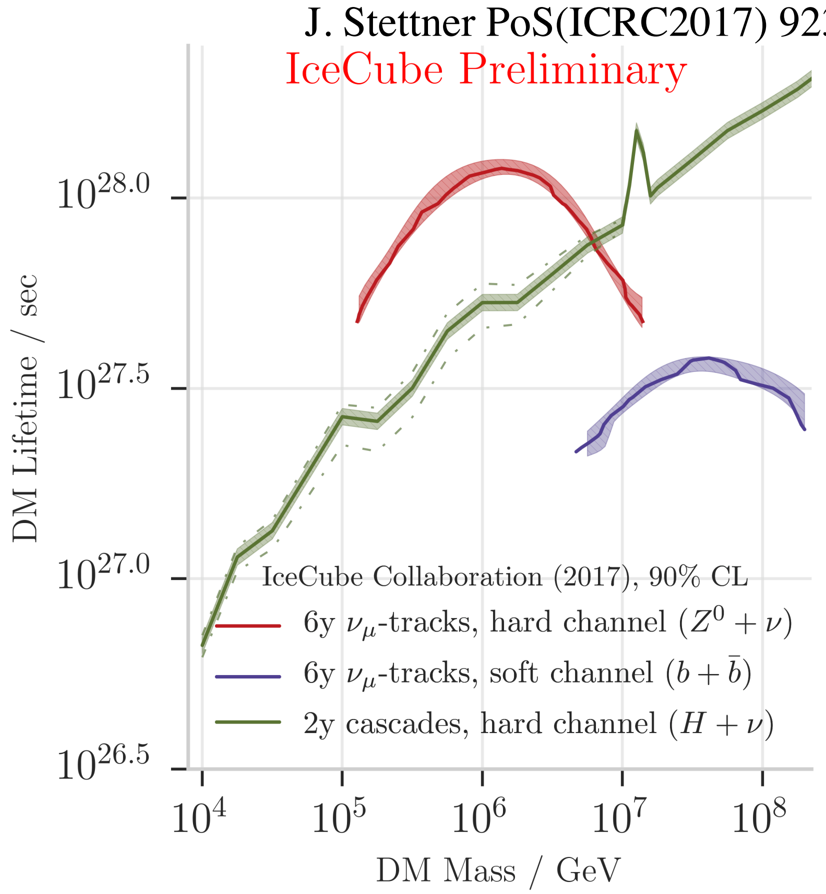
- Two expected flux contributions:
  - Dark Matter decaying in the Galactic Halo (Anisotropic flux + decay spectrum)

$$\frac{d\Phi^G}{dE_\nu} = \frac{1}{4\pi\, m_{DM}\, \tau_{DM}} \frac{dN_\nu}{dE_\nu} \int_0^\infty \rho(r(s,l,b))\, ds$$

  - Dark Matter decaying at cosmological distances (Isotropic flux + red-shifted spectrum)

$$\frac{d\Phi^{EG}}{dE} = \frac{\Omega_{DM}\, \rho_c}{4\pi\, m_{DM}\, \tau_{DM}} \int_0^\infty \frac{1}{H(z)} \frac{dN_\nu}{dE_\nu} [(1+z)E_\nu]\, dz$$



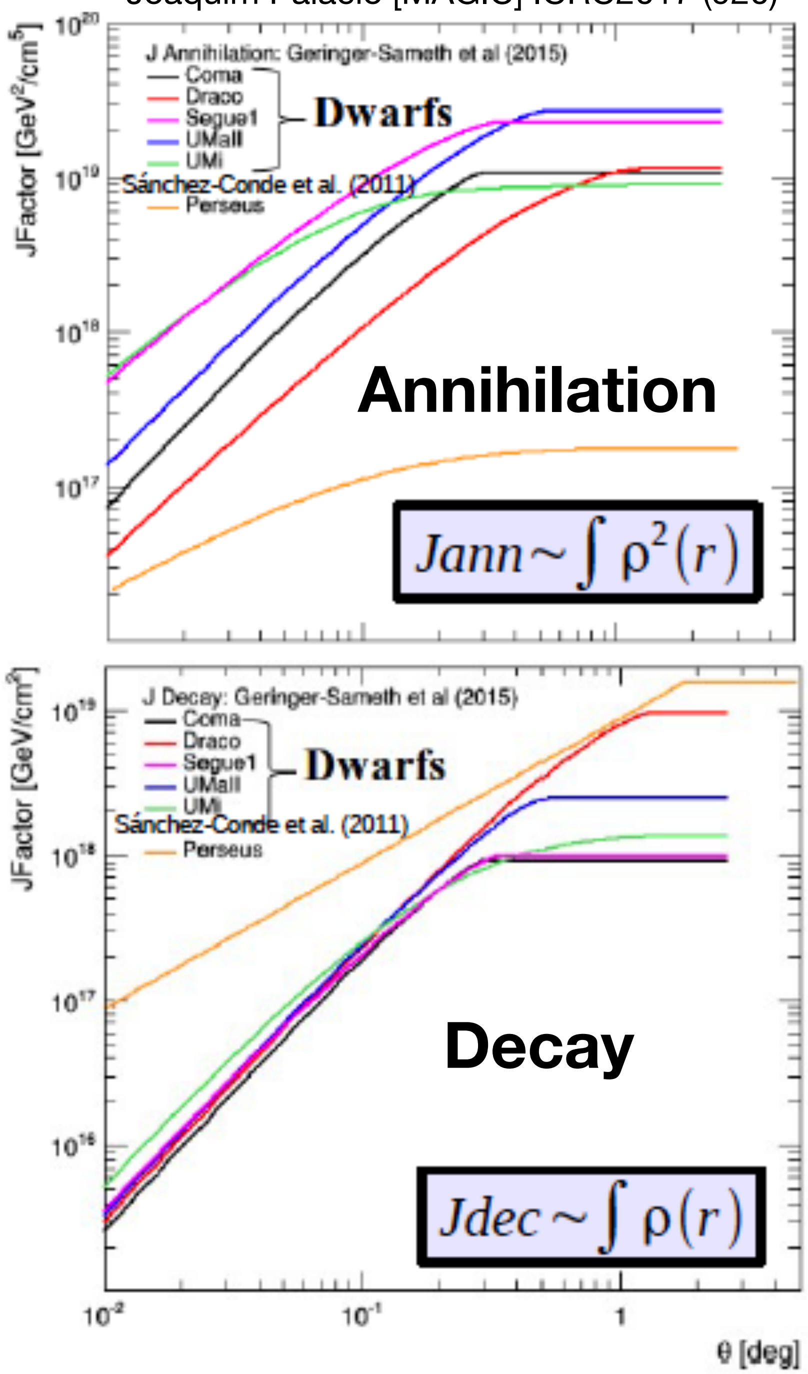


Test-Statistic: $$TS = 2 \times \log \frac{\mathcal{L}(X|\tau^{DM}, M^{DM}, \Phi^{Astro}, \gamma^{astro})}{\mathcal{L}(X|\tau^{DM}=\infty, \hat{\Phi}^{Astro}, \hat{\gamma}^{astro})}$$

Bound on DM lifetime up to $10^{27.5}$s obtained with IceCube data for m_{DM}>100TeV

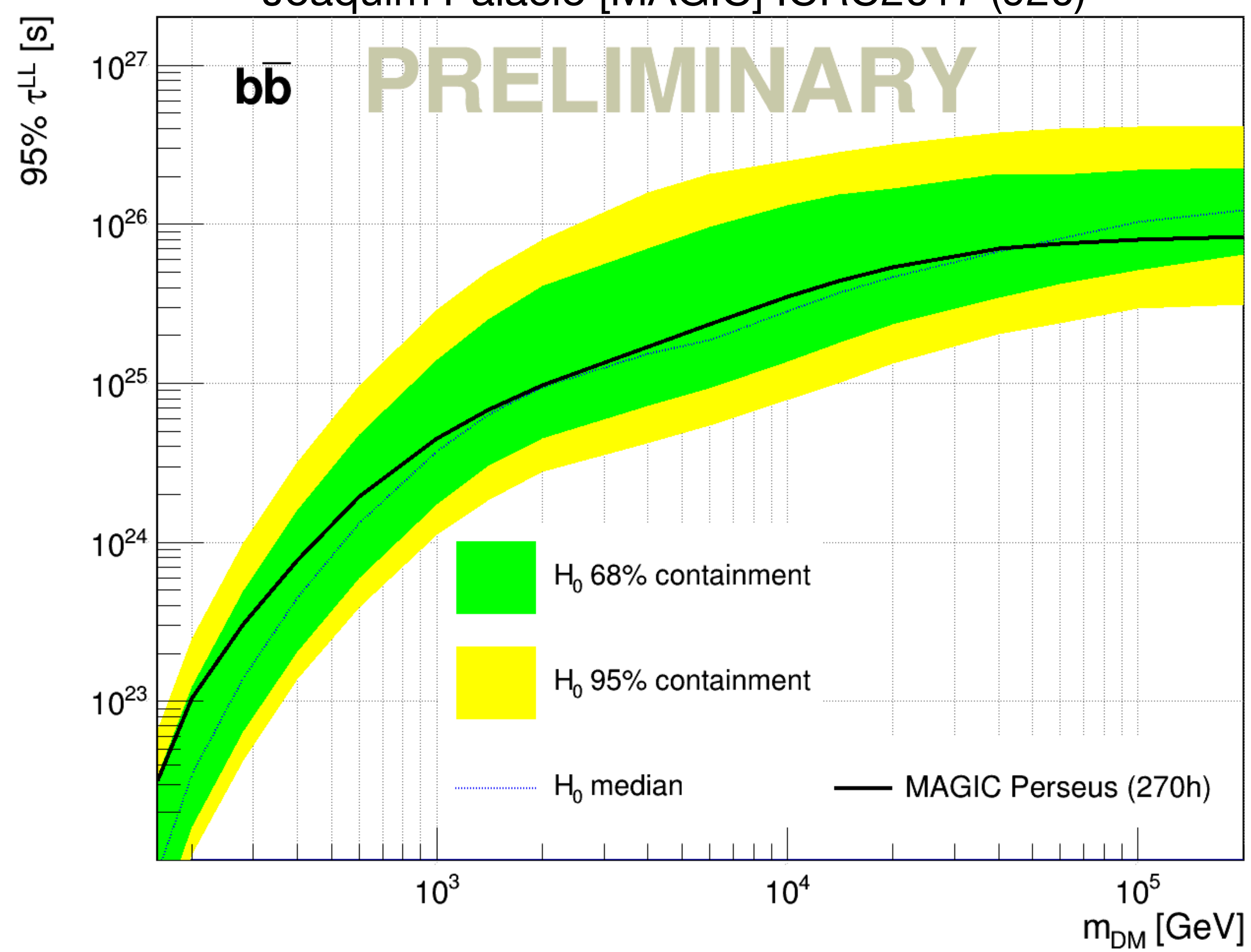
MAGIC - Perseus Cluster

Joaquim Palacio [MAGIC] ICRC2017 (920)



Results from 270h of good quality data (from 2009-2017)

Joaquim Palacio [MAGIC] ICRC2017 (920)



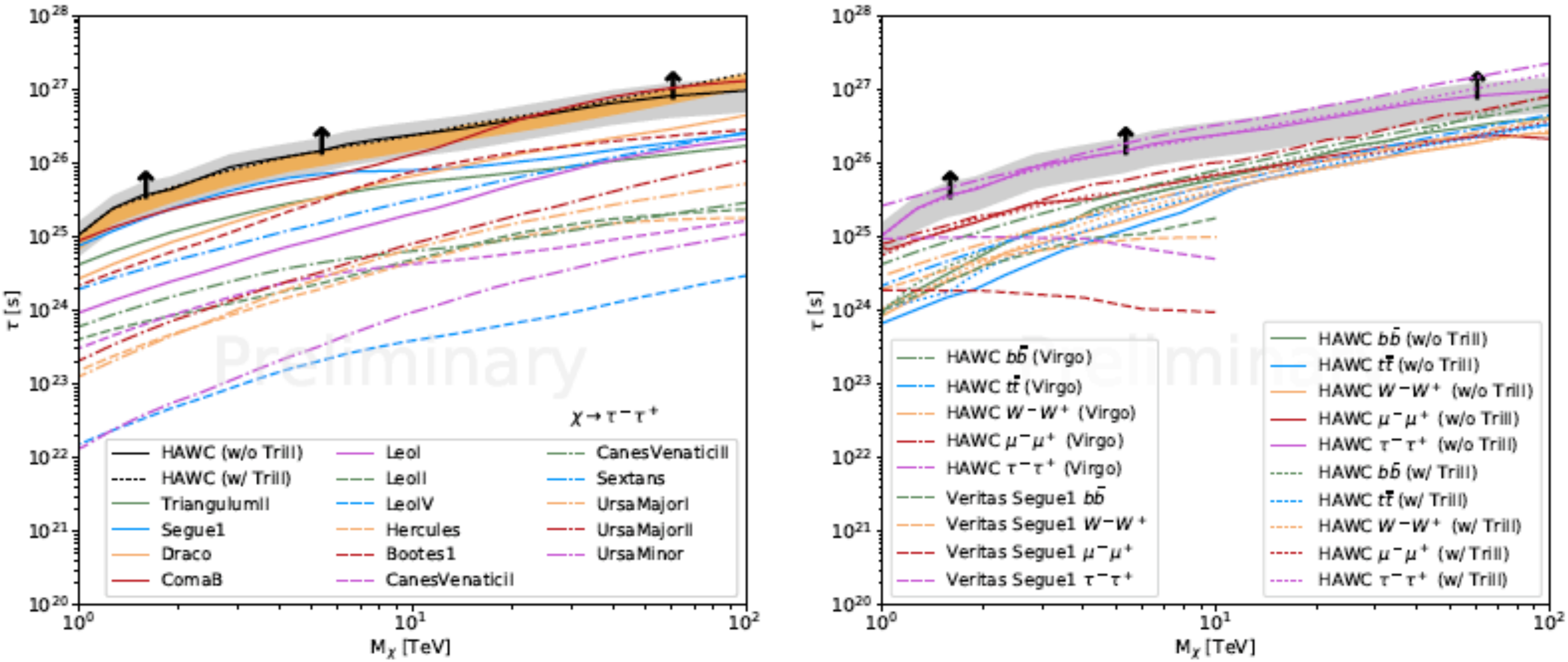
No evidence of dark matter decay observed

Obtain limit on DM life times of ~8 ·10^{25} s for bb and ττ

Jim Linnemann

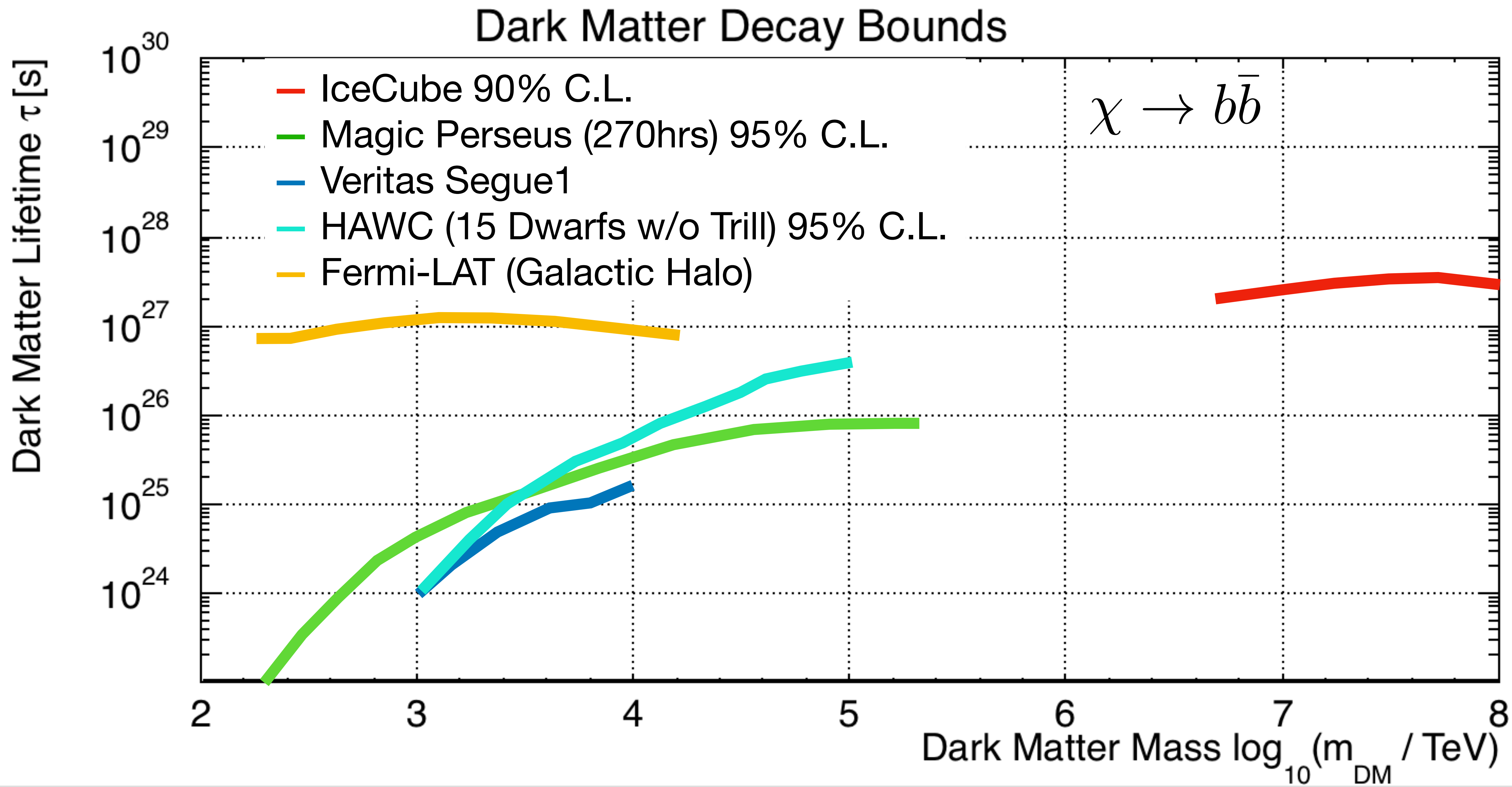
Dark Matter Decay with HAWC

T. Yapici [HAWC] ICRC2017 (891)



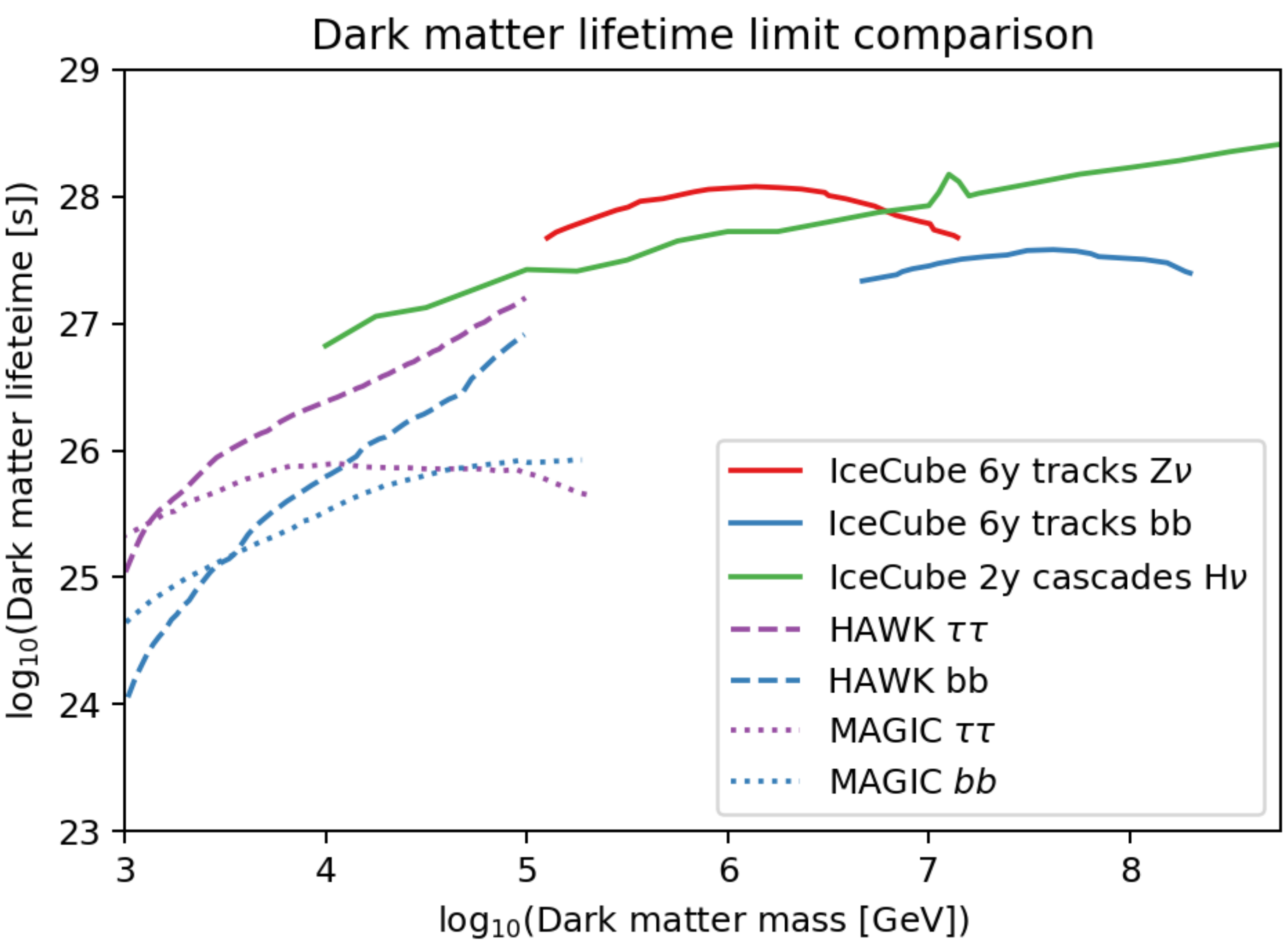
Results for 15 dSph, Virgo Cluster and M31

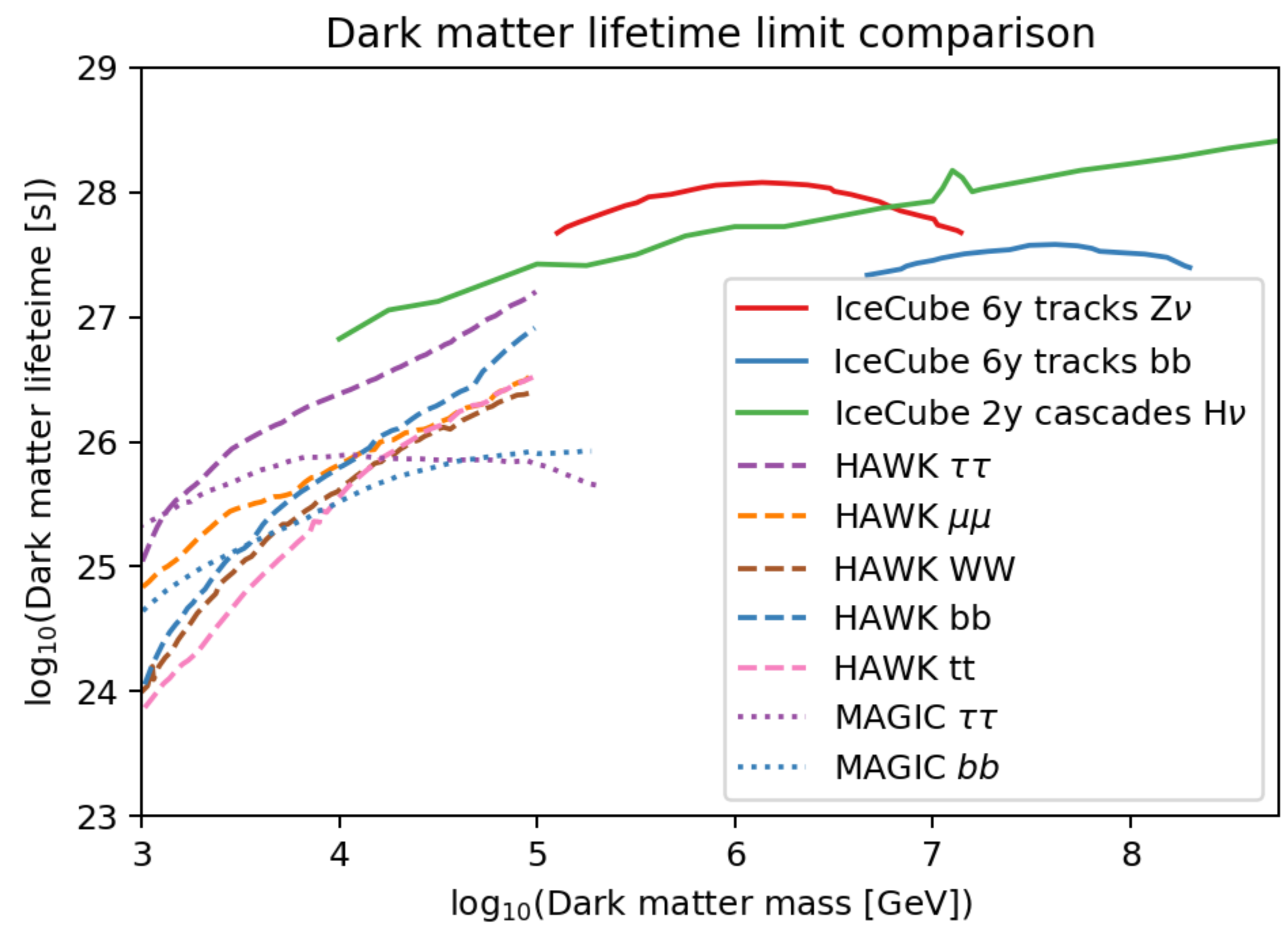
Dark Matter Decay Bounds



see also Fermi-LAT Astrophys.J. 761 (2012) 91

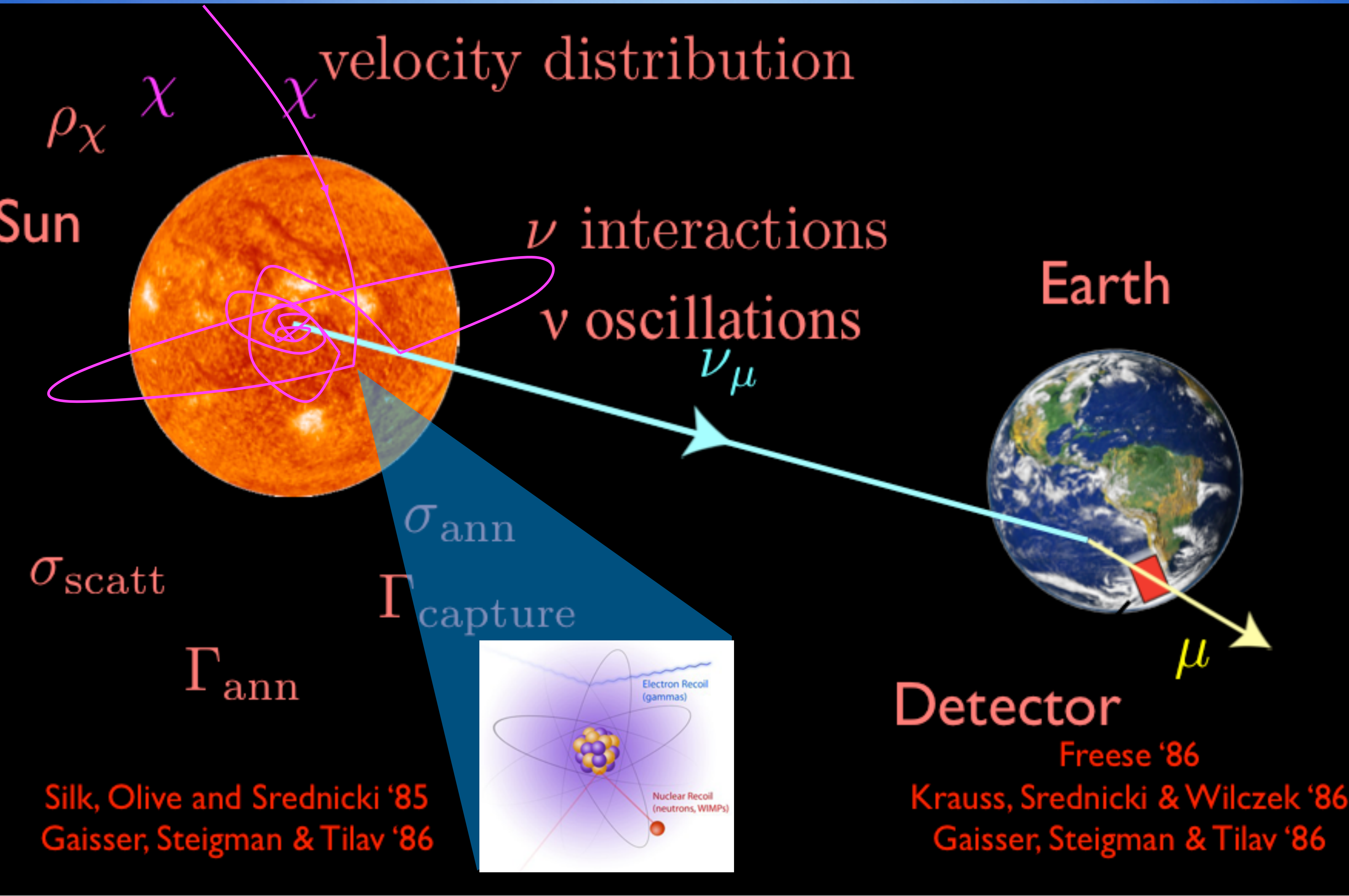
Dark Matter Decay Bounds



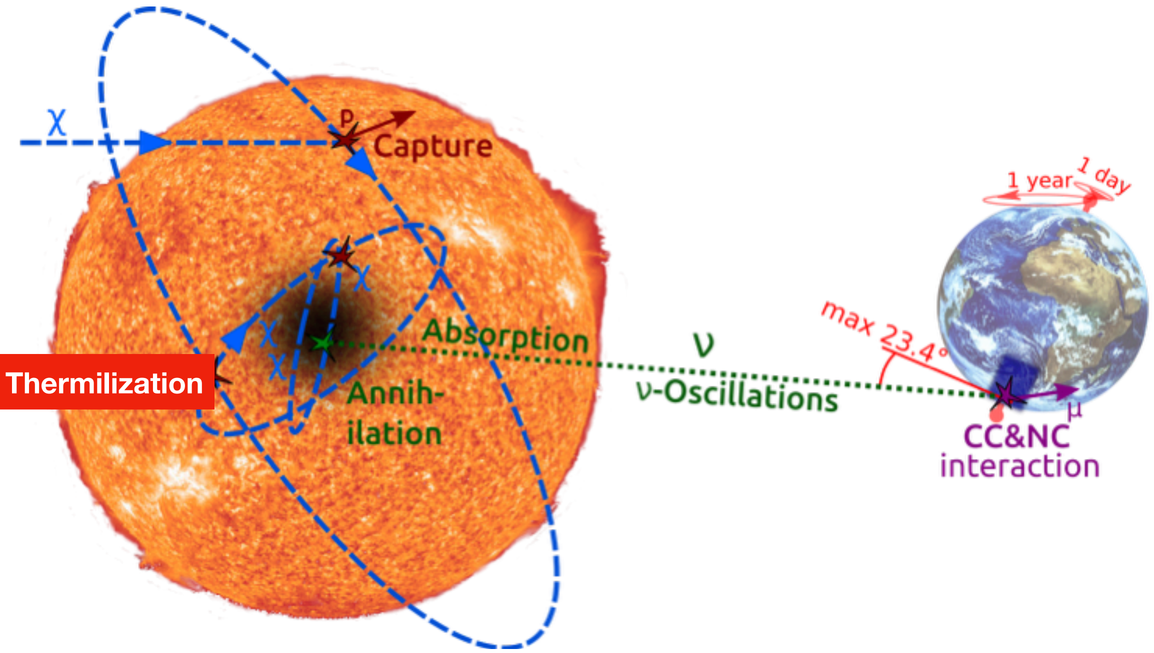


Solar Dark Matter Searches

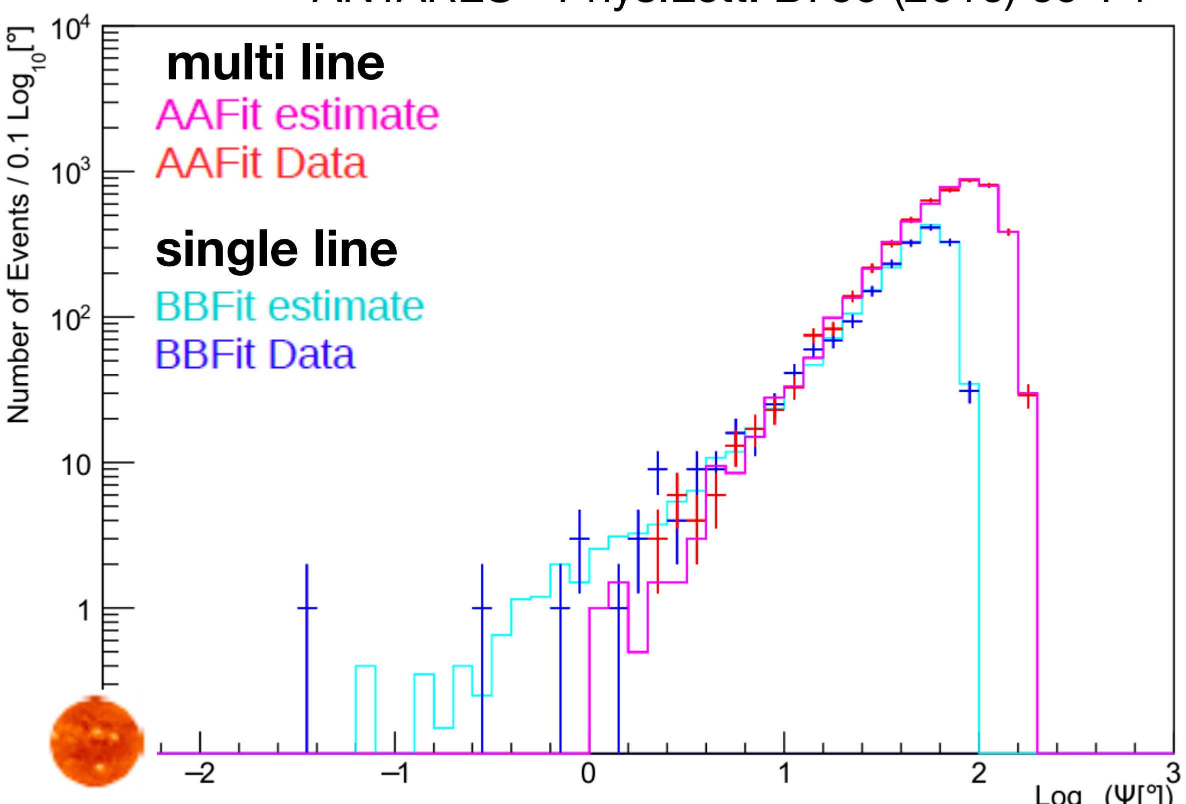
Solar Dark Matter



Solar Dark Matter - IceCube/ANTARES

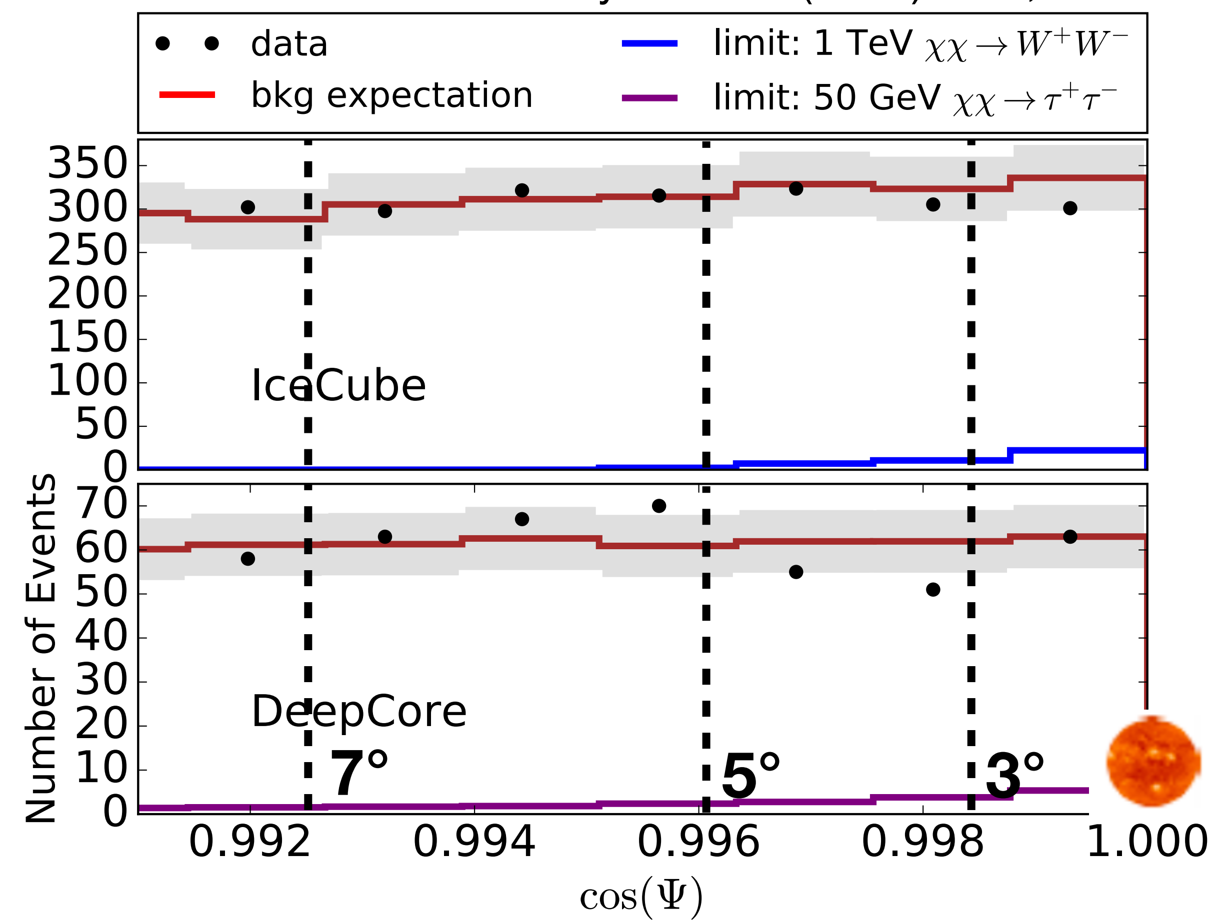


ANTARES - Phys.Lett. B759 (2016) 69-74



Distribution of separation angle for
2007-2012 ANTARES data

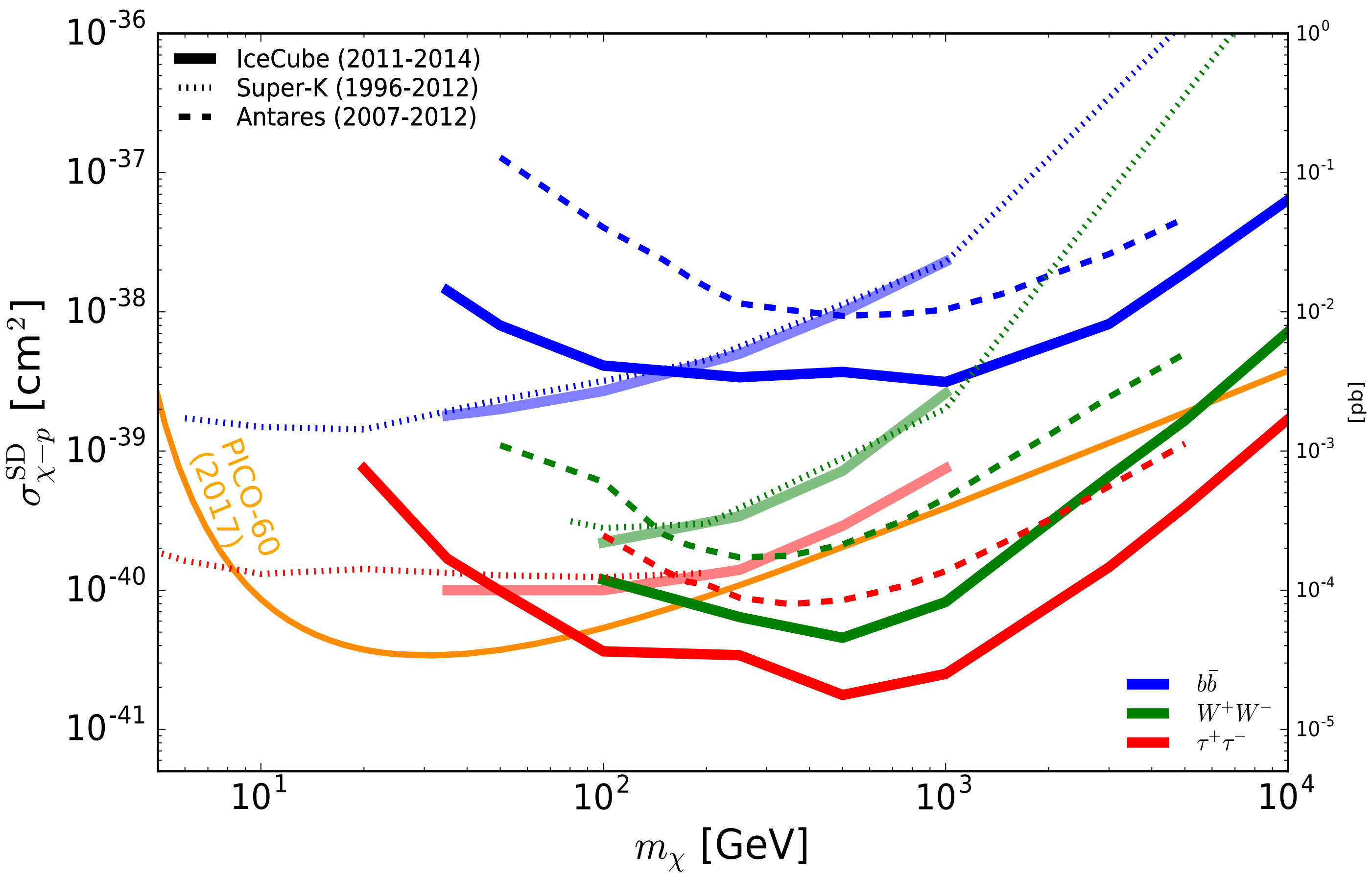
IceCube Eur.Phys.J. C77 (2017) no.3, 146



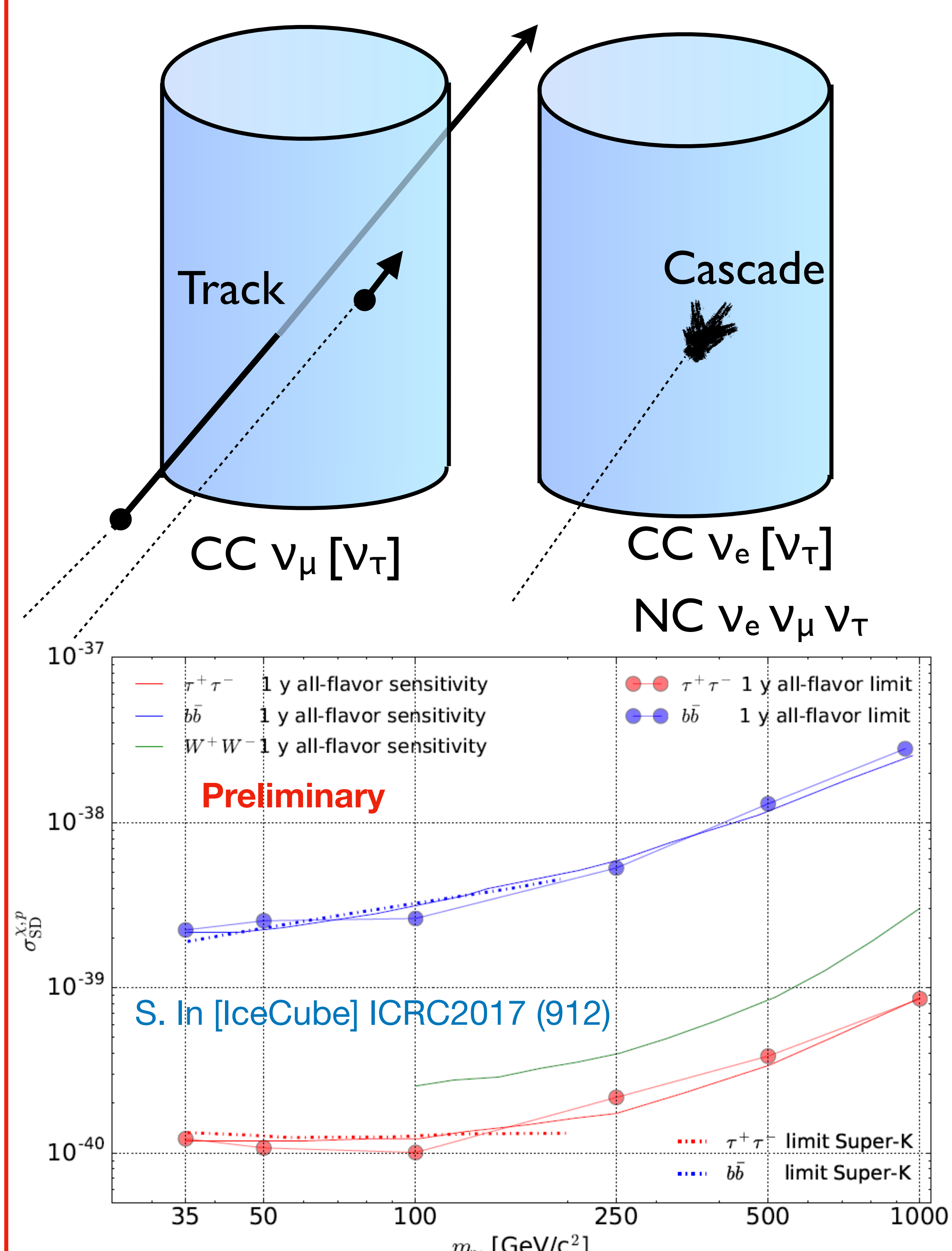
- Search for an excess in direction of the Sun
- Off source region used to reliable predict backgrounds from data

Solar Dark Matter - IceCube/ANTARES

- Convert neutrino flux limit into limit on WIMP-nucleon scattering cross section

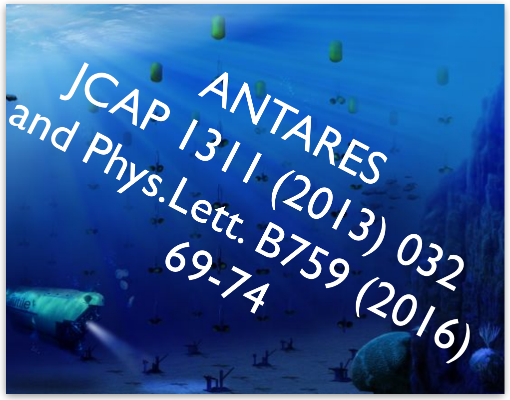


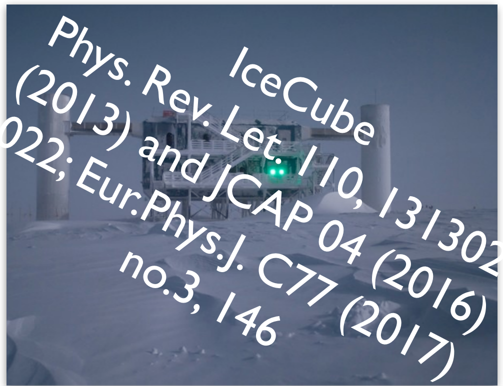
All flavor Solar WIMP - IceCube

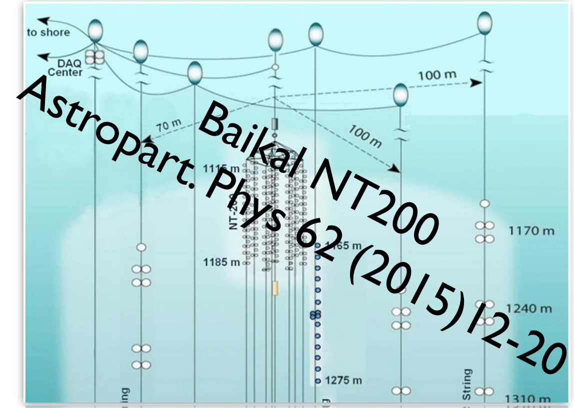


Solar WIMPs
- ANTARES - Phys.Lett. B759 (2016) 69-74
- IceCube Eur.Phys.J. C77 (2017) no.3, 146
- S. In and K. Wiebe [IceCube] ICRC2017 (912)

Solar Dark Matter Summary

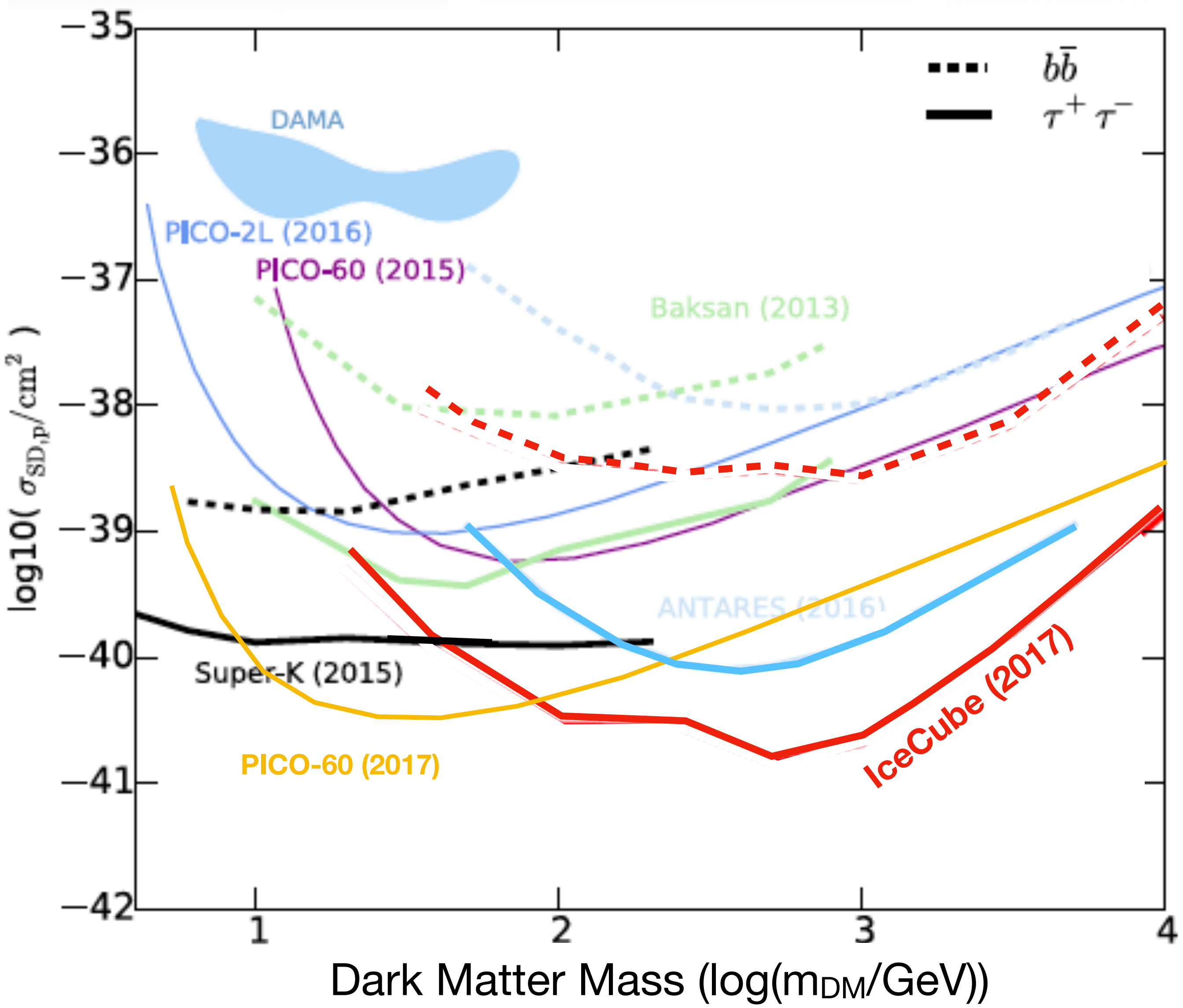


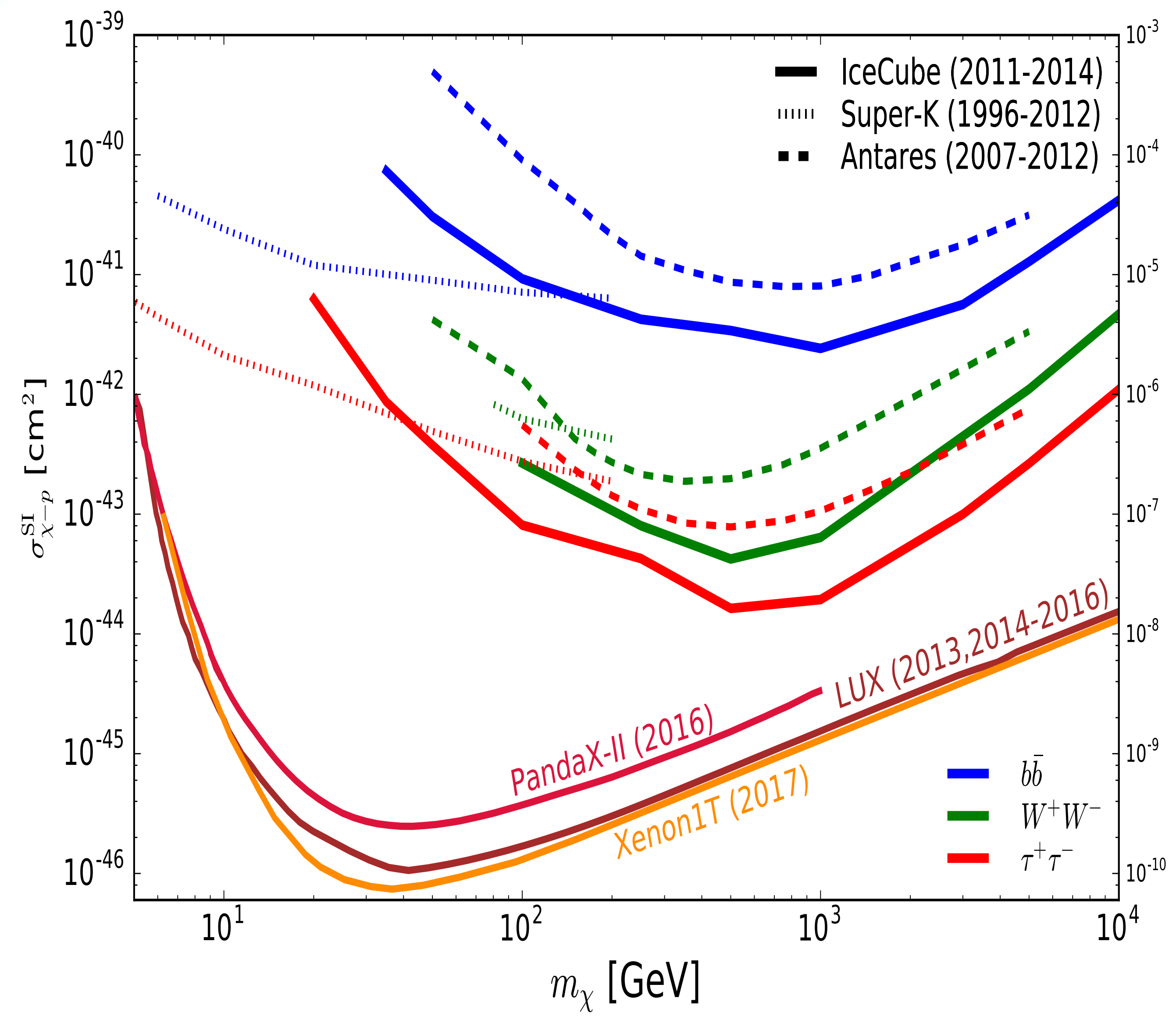




Spin-dependent scattering

Spin-independent scattering



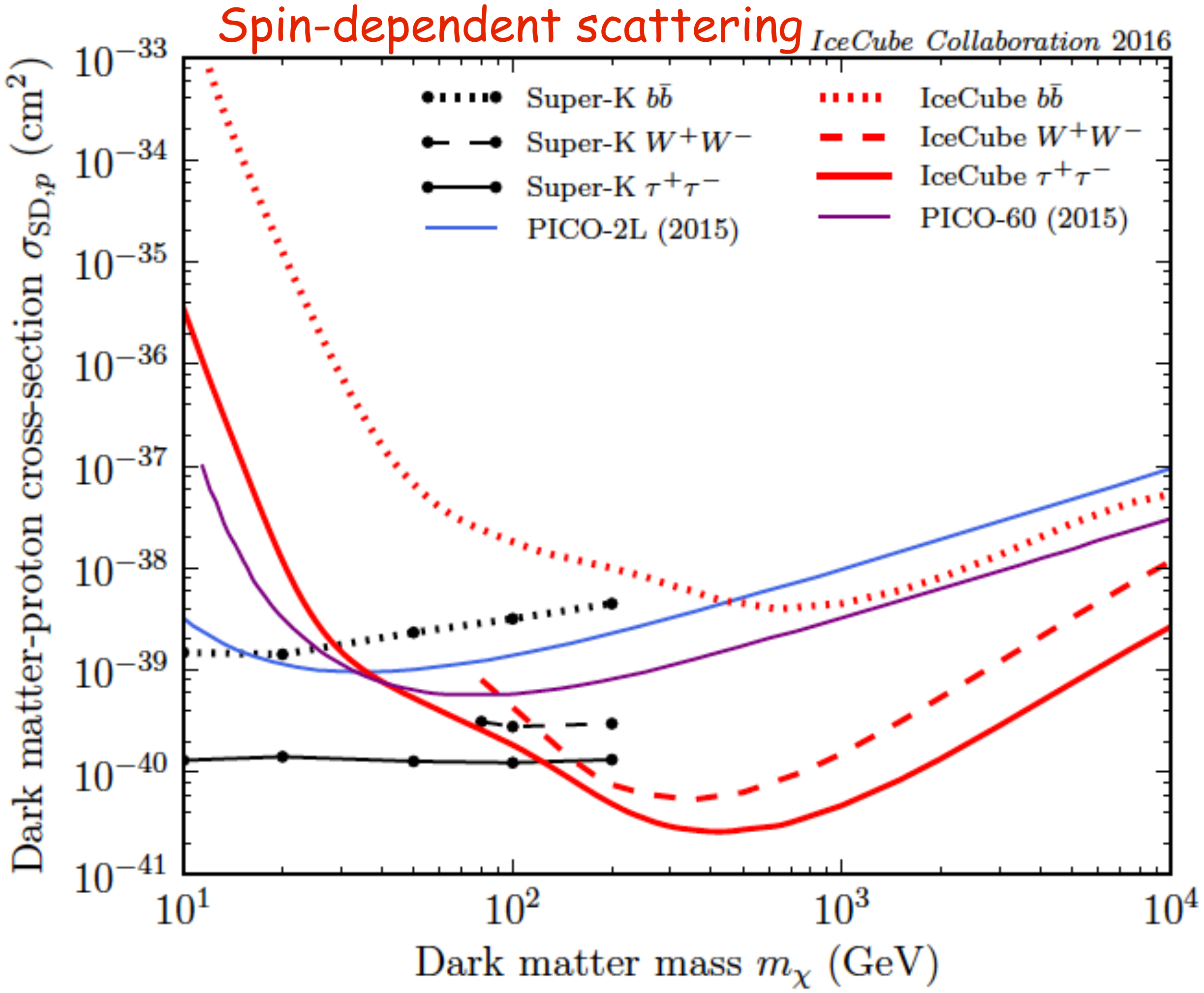


Availability of data

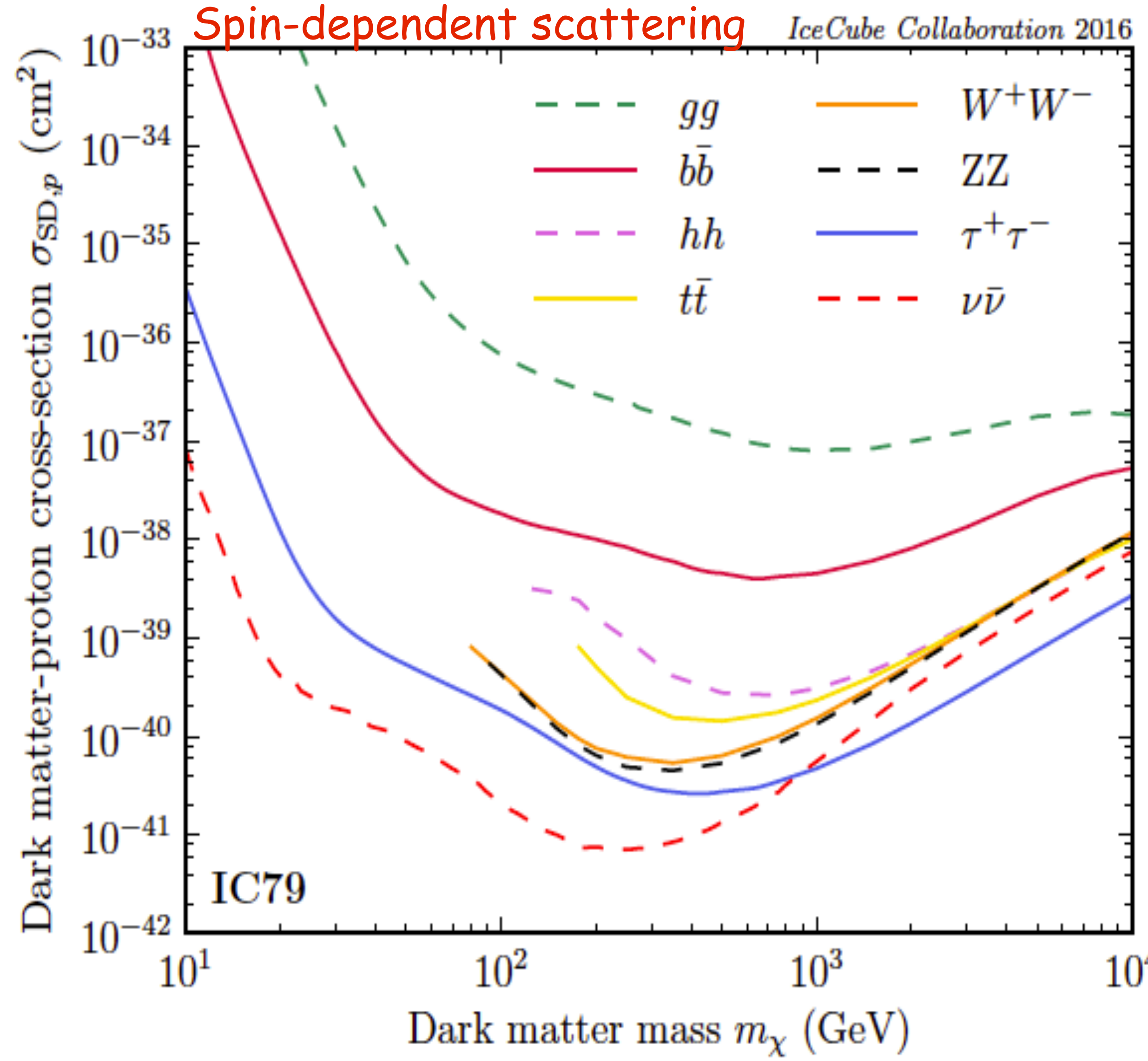
http://nulike.hepforge.org./

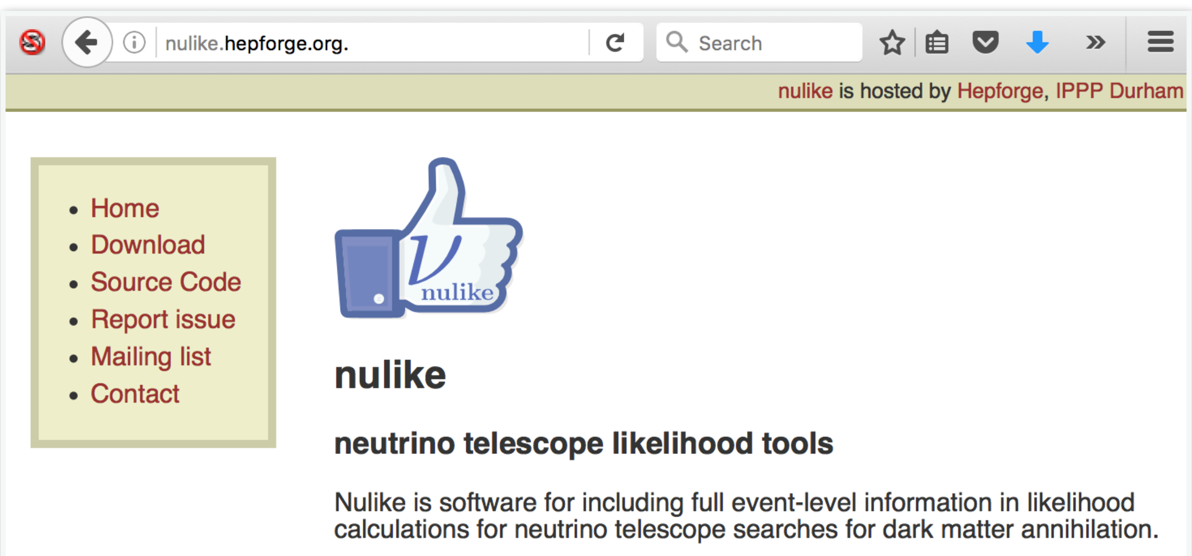
JCAP 04 (2016) 022 / http://arxiv.org/pdf/1601.00653.pdf

Spin-dependent scattering



Spin-dependent scattering

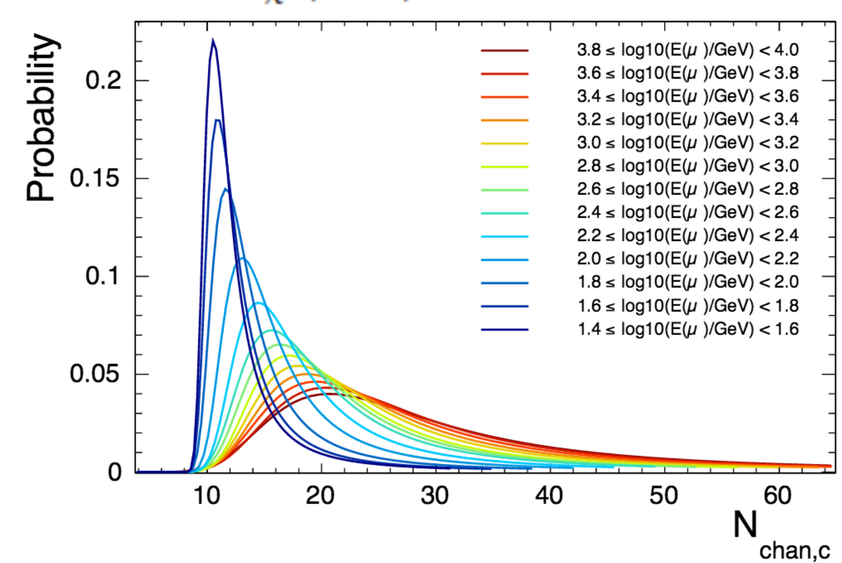




software to test your own model (cross section/ branching ratios)

- IceCube data released

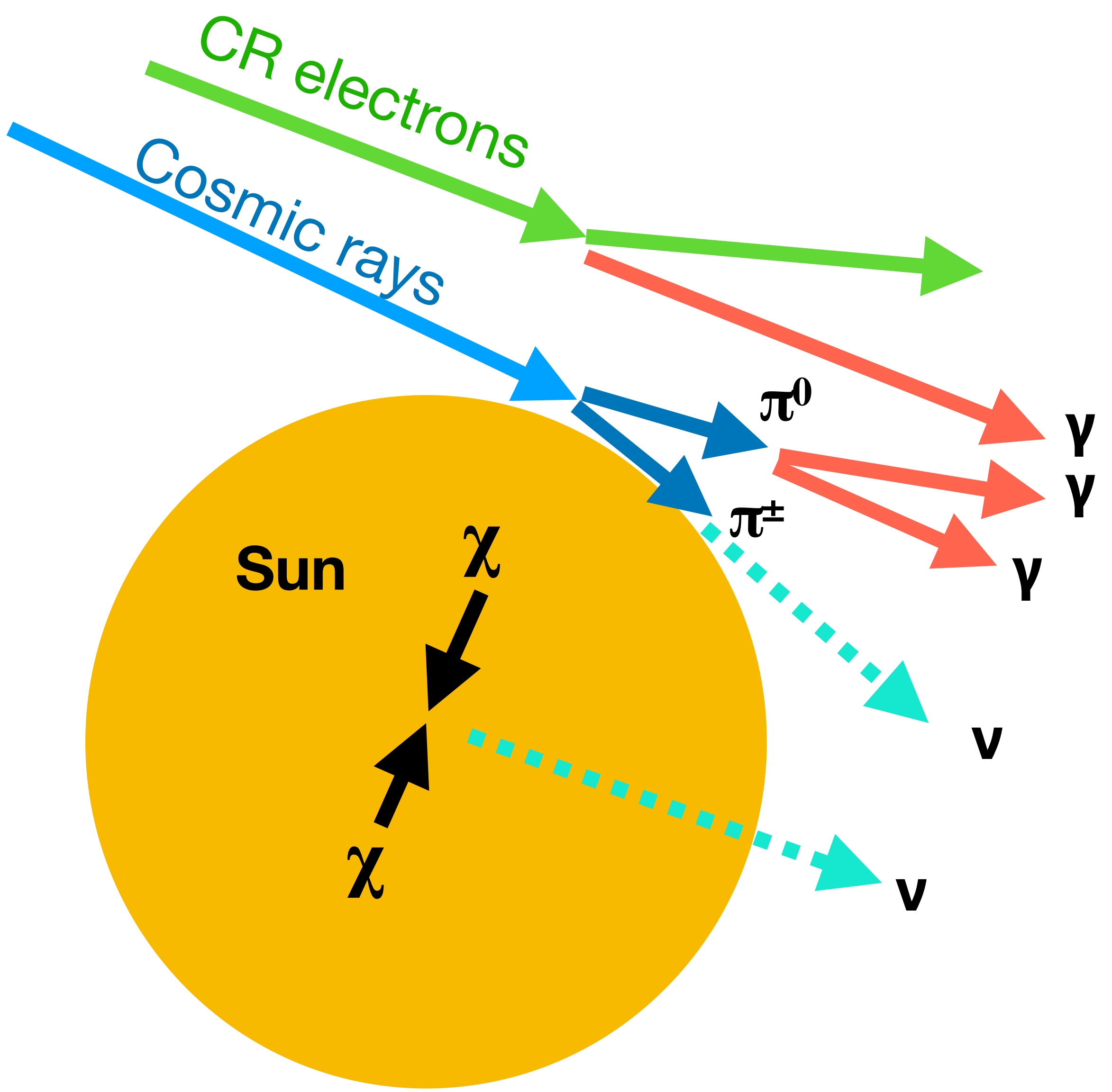
- Likelihood includes:
  - energy and directional information



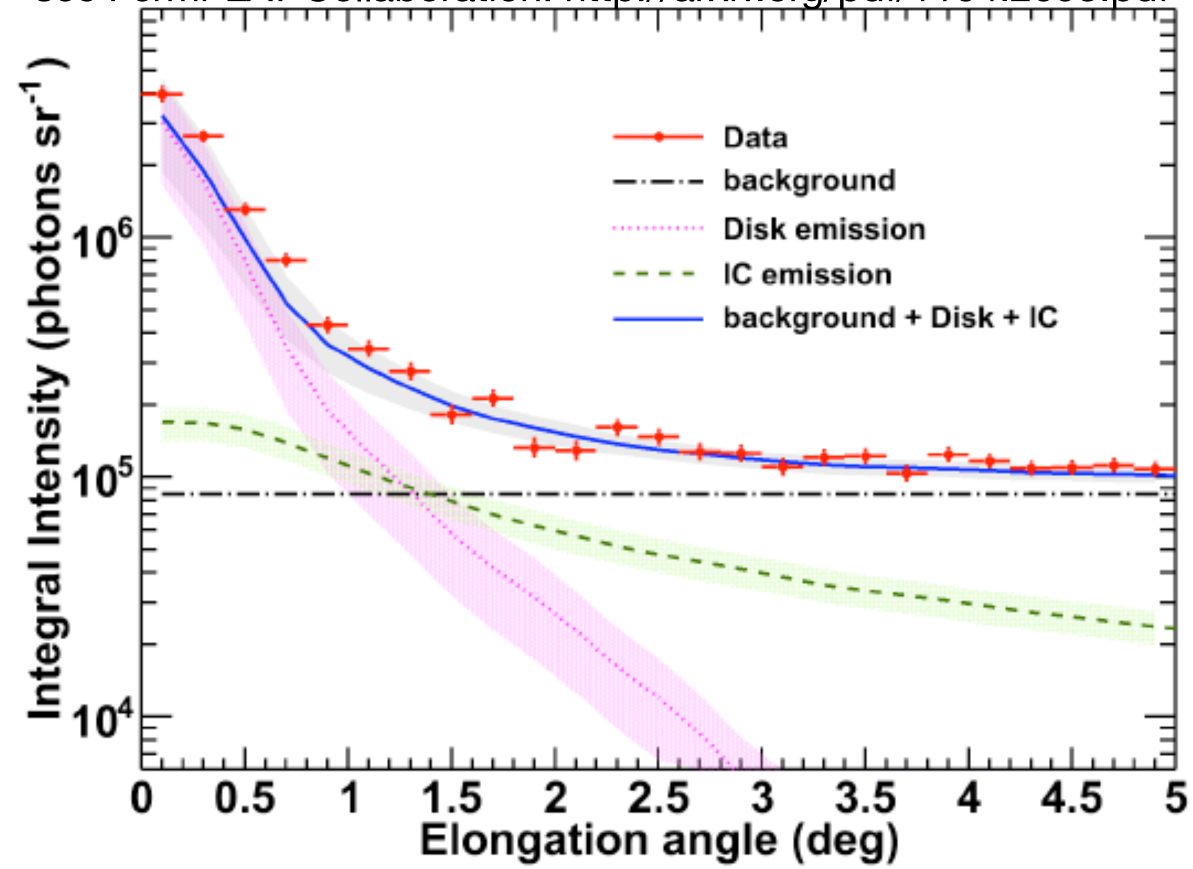
Nulike part of GAMBIT (see Talk Thursday afternoon Jonathan Cornell)

Solar Atmospheric Neutrino Floor

Cosmic ray interactions with the Sun



see Fermi-LAT Collaboration: http://arxiv.org/pdf/1104.2093.pdf



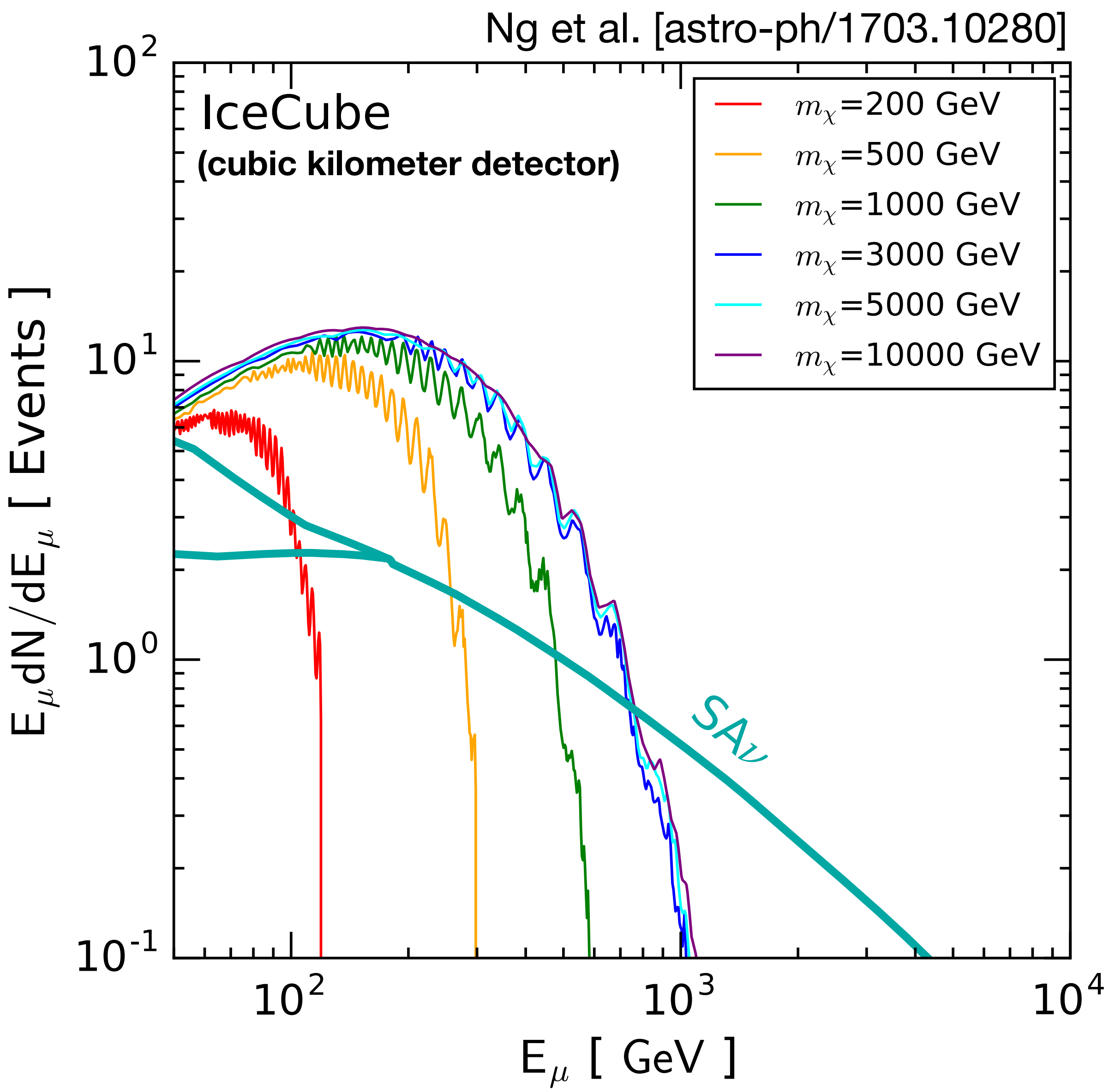
- CR interaction in the Solar atmosphere result produce gamma-rays and neutrinos
- Background to dark matter search from the Sun, that soon will be relevant (and first high-energy neutrino point source ??)

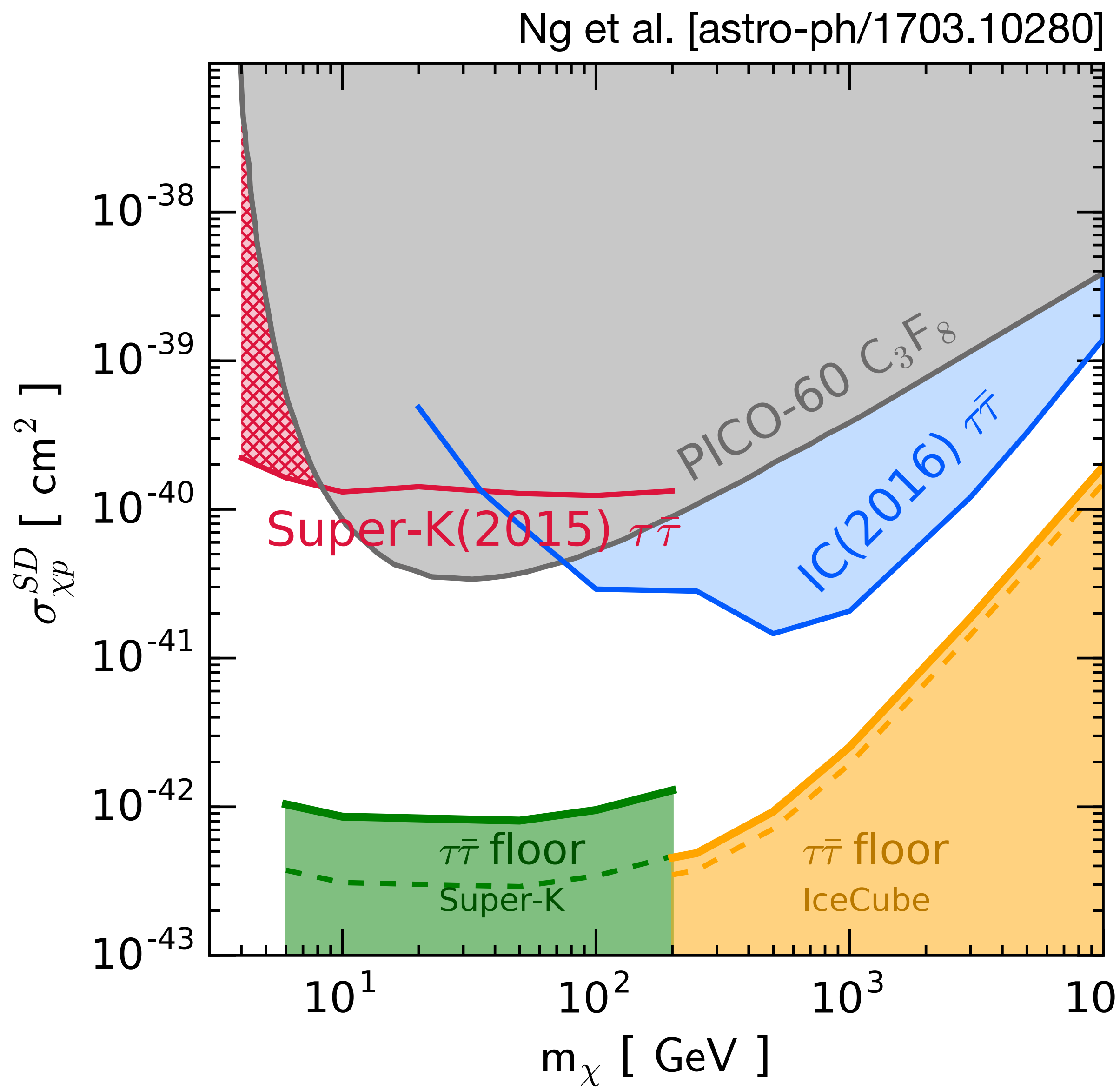
Leptonic
- Moskalenko, Porter, Digel (2006)
- Orlando, Strong (2007)

Hadronic
- Seckel, Stanev, Gaisser (1991)
- Moskalenko, Karakula (1993)
- Ingelman & Thunman (1996)

see talk by Kenny Ng

Cosmic background from the Sun





- Natural background to Solar Dark Matter Searches !
- However, energy spectrum expected to be different
- DM annihilation neutrinos significantly attenuated above a few 100GeV

Expect ~2events per year at cubic kilometer detector

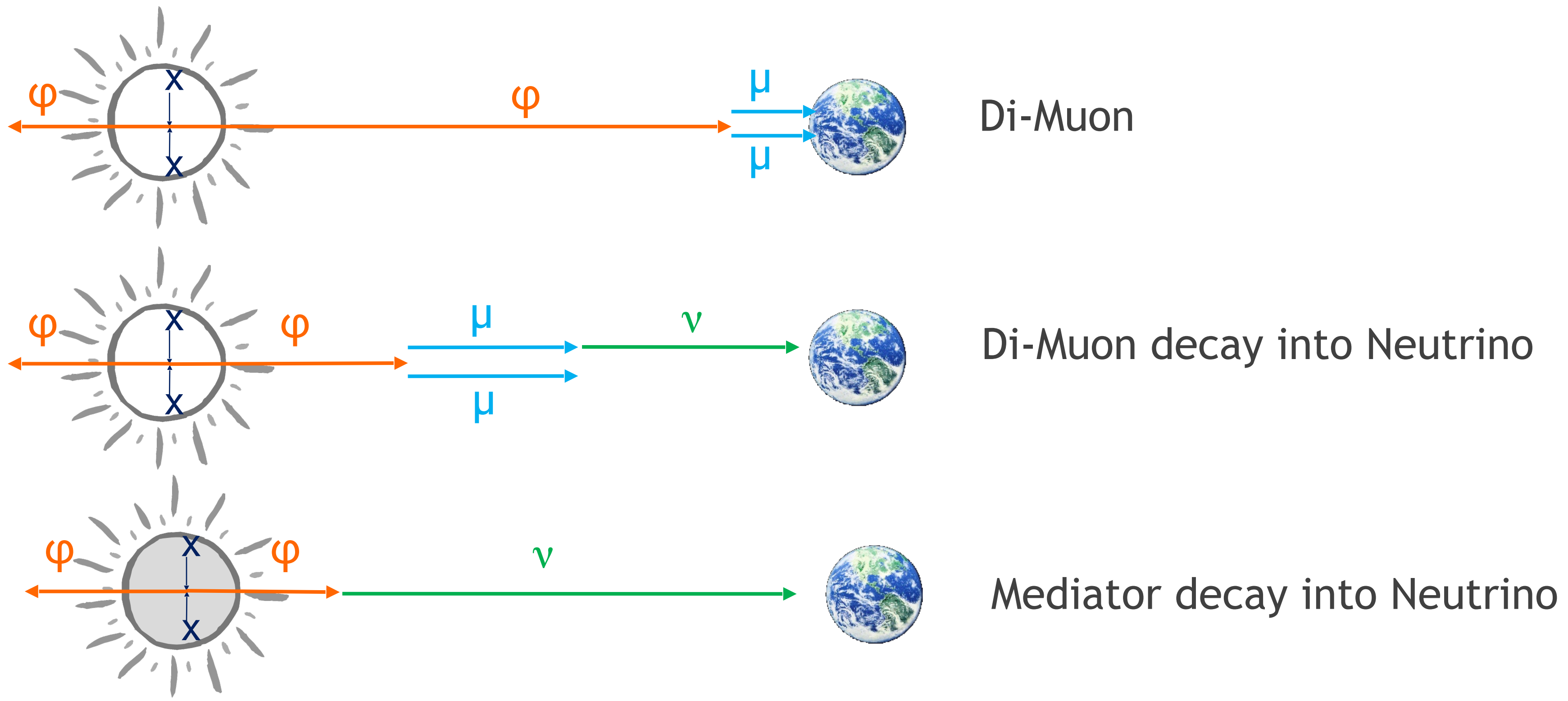
Recent works on the Solar Atmospheric Neutrino Floor

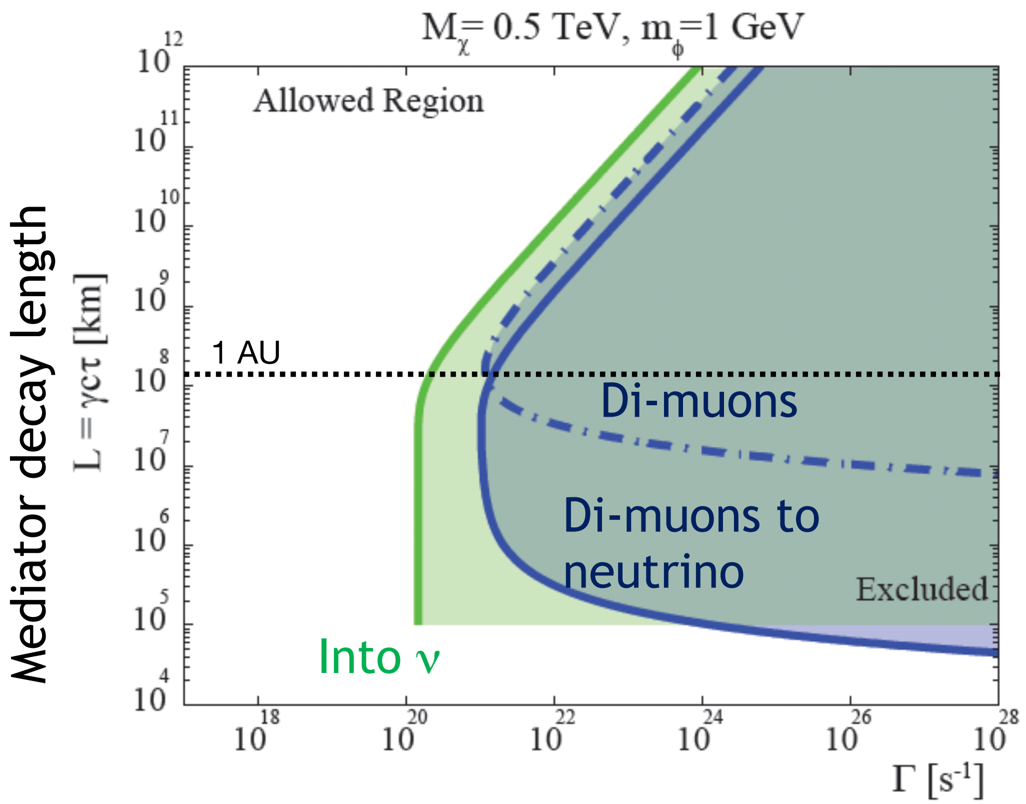
- Argüelles et al. [astro-ph/1703.07798]
- Ng et al. [astro-ph/1703.10280]
- J. Edsjö, J. Elevant, R. Enberg, and C. Niblaeus, JCAP 2017 .06 (2017), p. 033, [astro-ph/1704.02892]
- M. Masip (2017), [hep-ph/1706.01290]

ANTARES Coll. JCAP 1605 (2016) no.05, 016

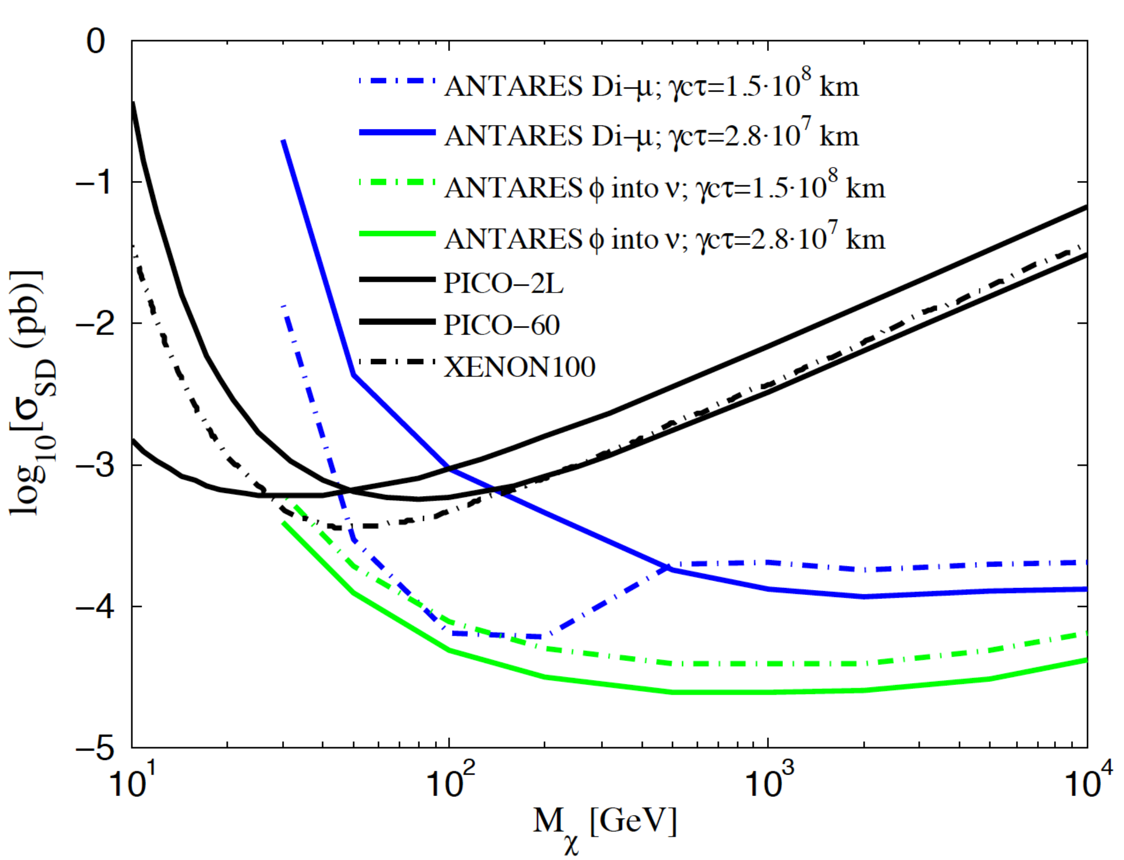
ANTARES Secluded Dark Matter

- Dark matter annihilates into meta-stable particle
  - χχ annihilates into mediator ϕ
    - ϕ → νν or μμ
- Livetime of 1321 days (Jan 2007 to Oct 2012)



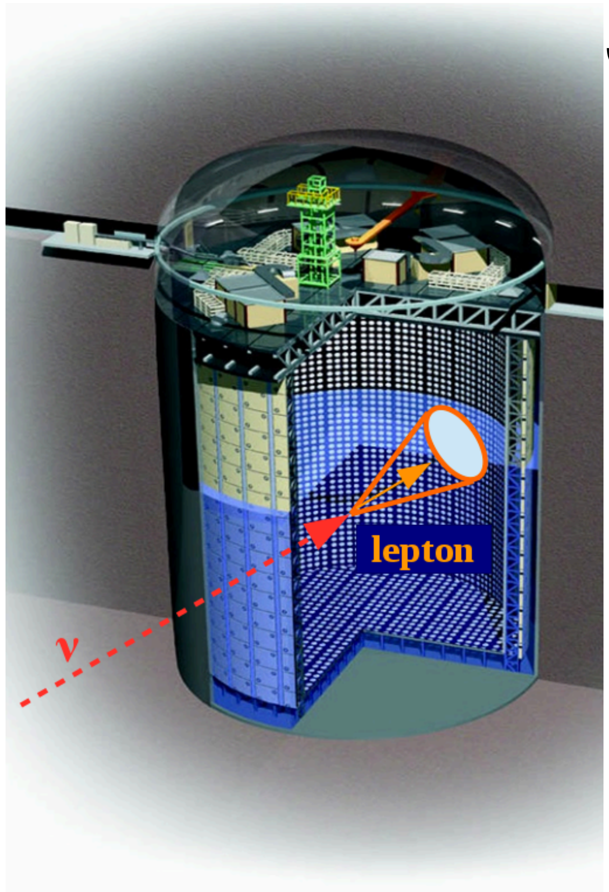


Annihilation of DM in the Sun x Branching ratio

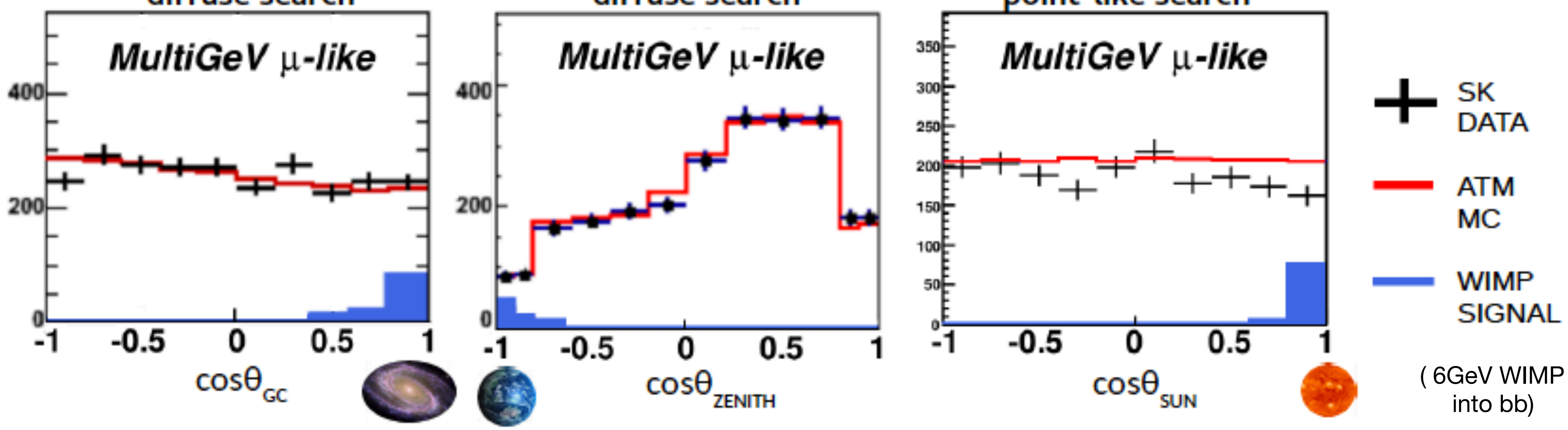


Piotr Mijakowski

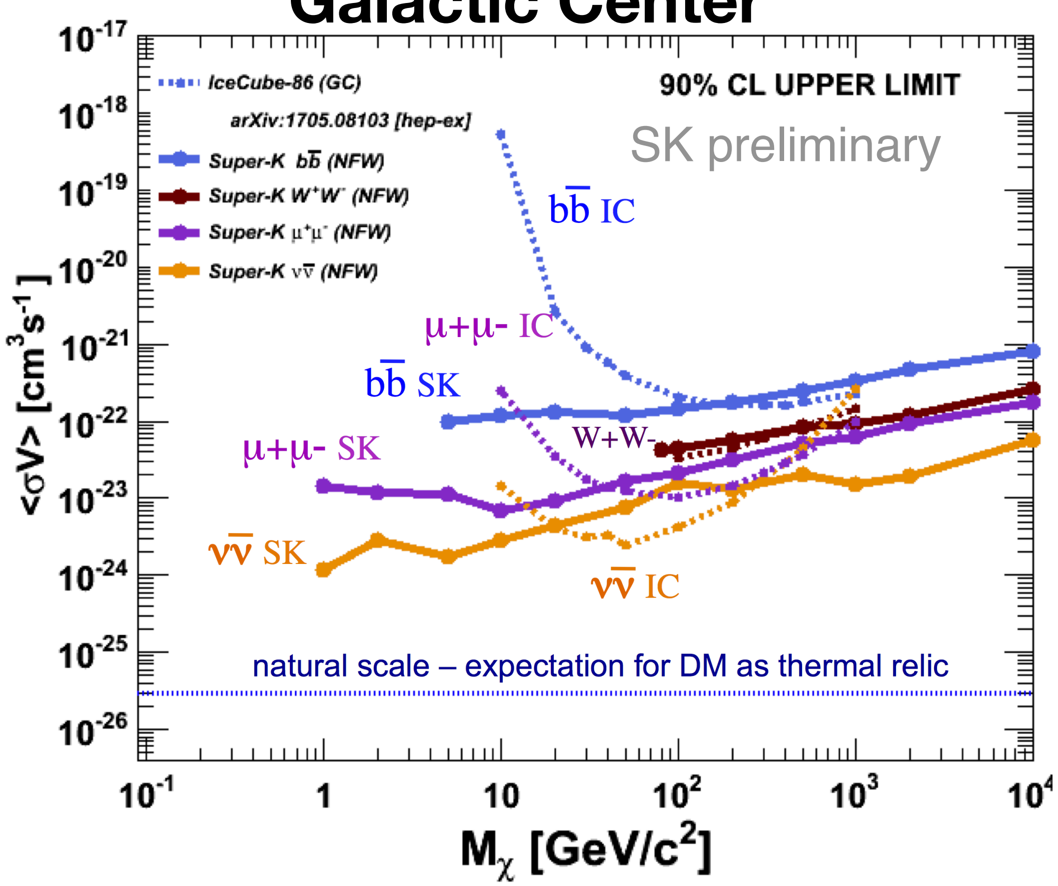
Super-K Dark Matter Searches



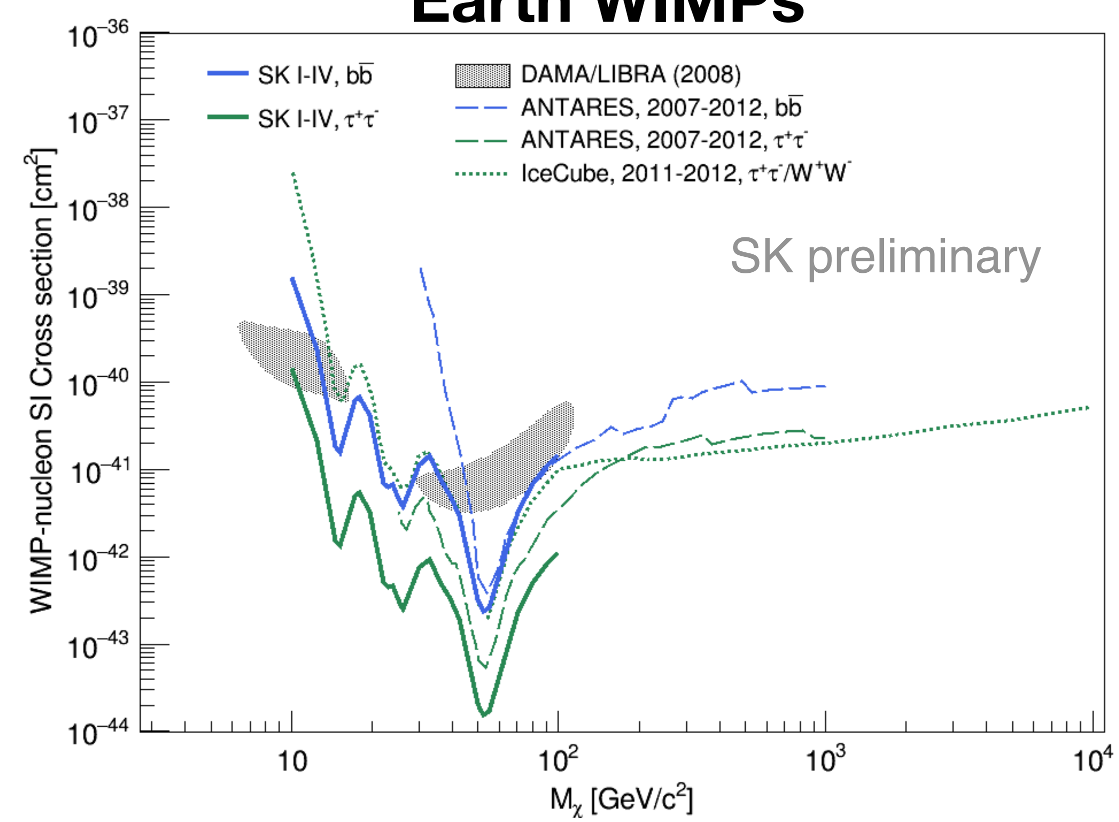
Galactic WIMP search - diffuse search | Earth WIMP search - diffuse search | Solar WIMP search - point-like search



Galactic Center



Earth WIMPs

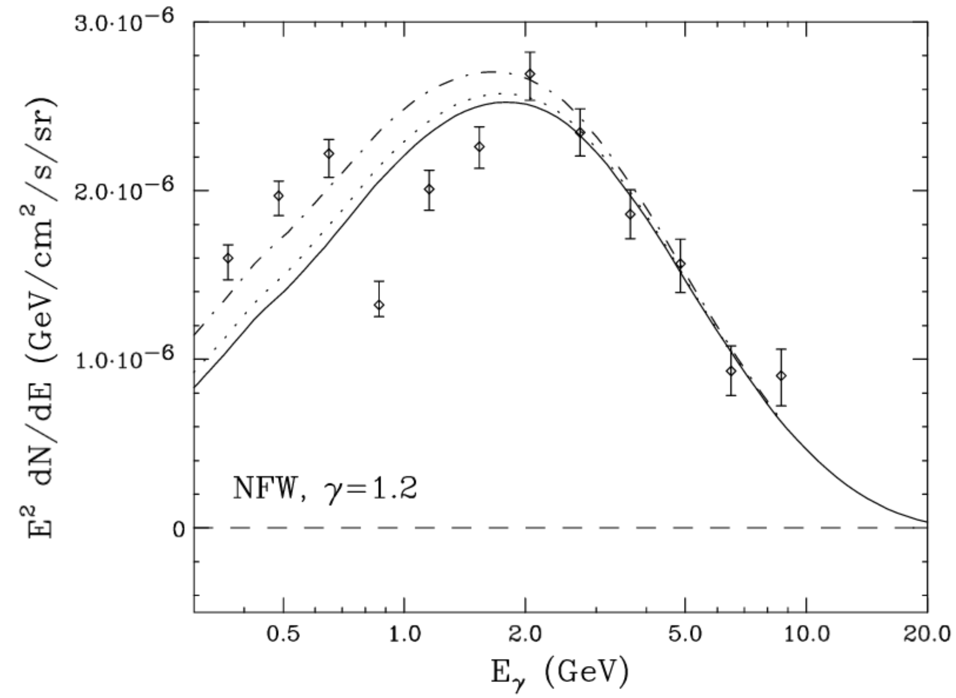


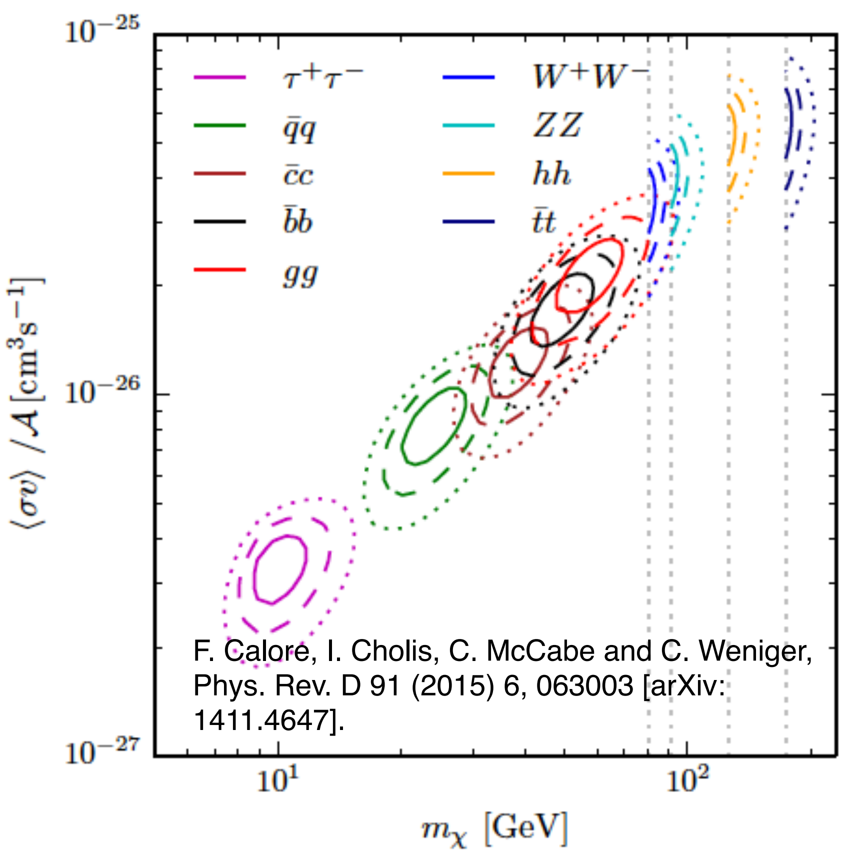
Anomalies ?

The GeV excess @ Galactic Center

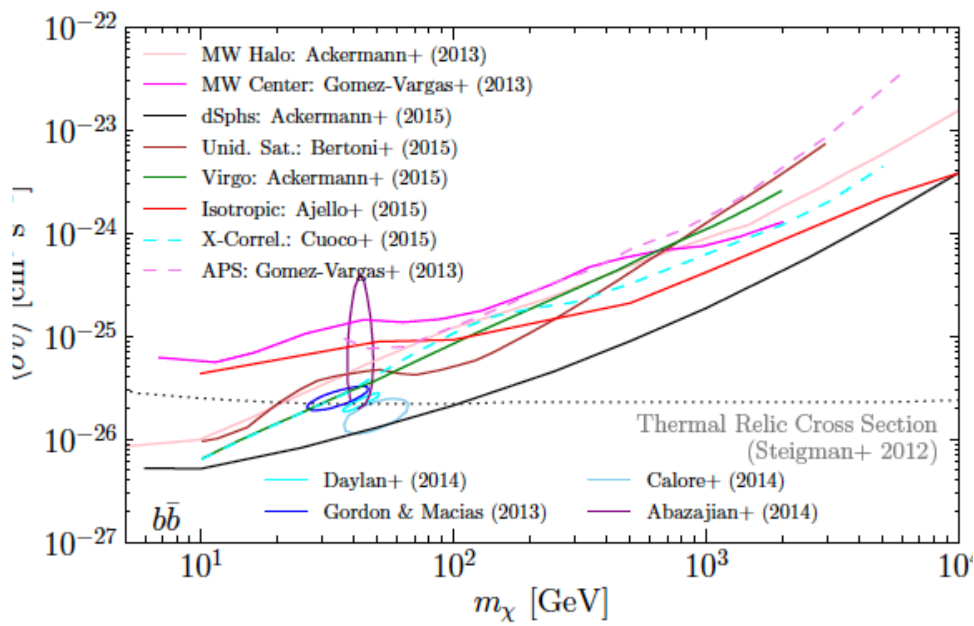
- First claimed in 2009 with Fermi data (arXiv:0910.2998)
  - If interpreted as dark matter, it points to O(10-100) GeV DM
  - DM claim is in tension with bounds from dwarf spheroidal galaxies
- Fermi-LAT collaboration finds that
  - The spectrum and morphology is sensitive to the assumed diffuse emission model. However the excess is still statistically significant under all models tested. (Astrophys.J. 819 (2016) no.1, 44 & arXiv:1704.03910)
- More recently, mounting evidence for large contribution from pulsars (arXiv 1706.01199, PRL 116, 051102, arXiv:1412.6099, Fermi-LAT arXiv:1705.00009)

Tansu Daylan, Douglas P. Finkbeiner, Dan Hooper, Tim Linden, Stephen K. N. Portillo, Nicholas L. Rodd, Tracy R. Slatyer arXiv:1402.6703

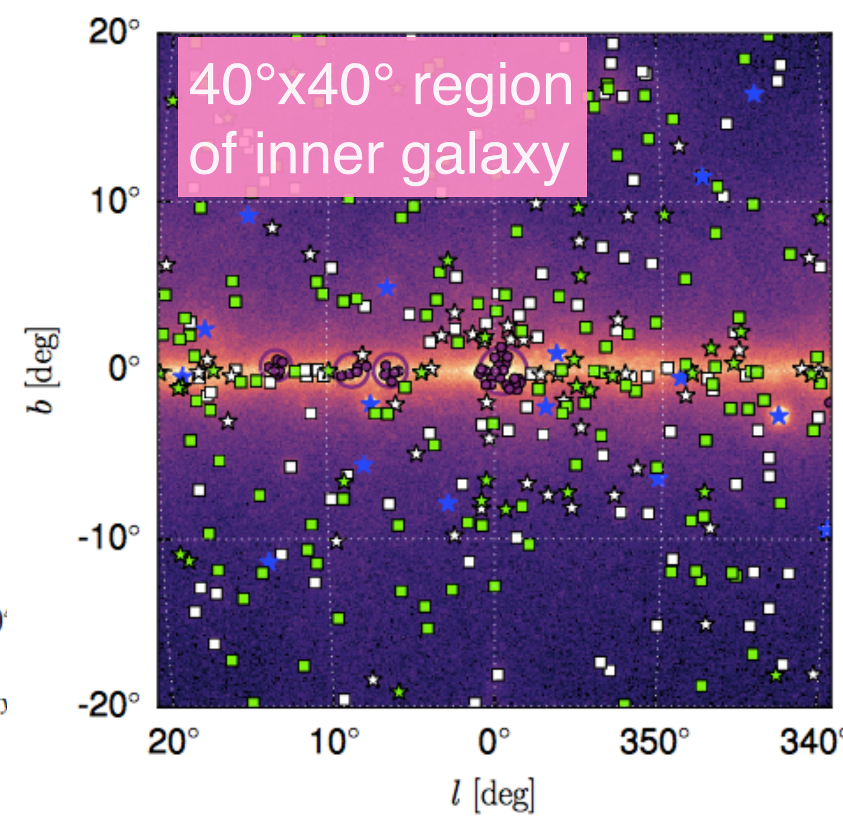




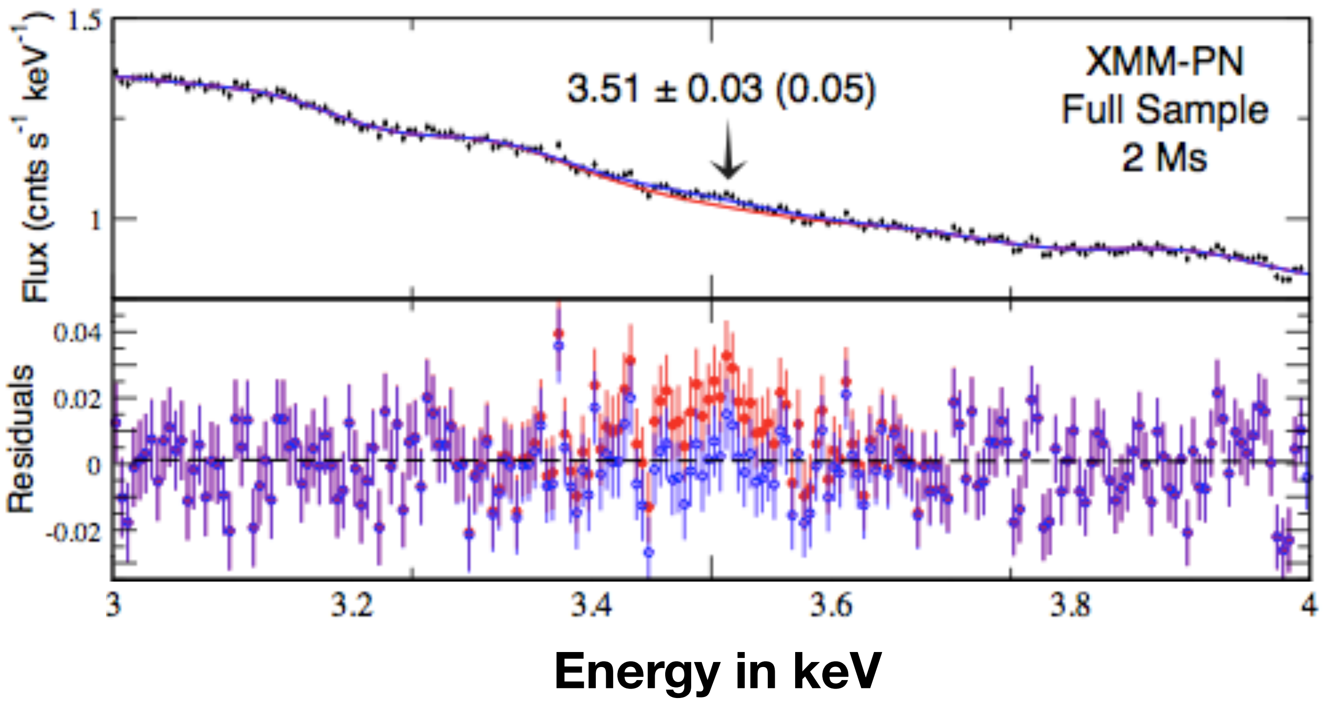
F. Calore, I. Cholis, C. McCabe and C. Weniger, Phys. Rev. D 91 (2015) 6, 063003 [arXiv:1411.4647].



E. Charles, M. Sánchez-Conde, B. Anderson, R. Caputo, A. Cuoco, M. Di Mauro et al., *Sensitivity projections for dark matter searches with the Fermi large area telescope*, Phys.~Rep. 636 (June, 2016) 1–46, [1605.02016].



3.5keV line

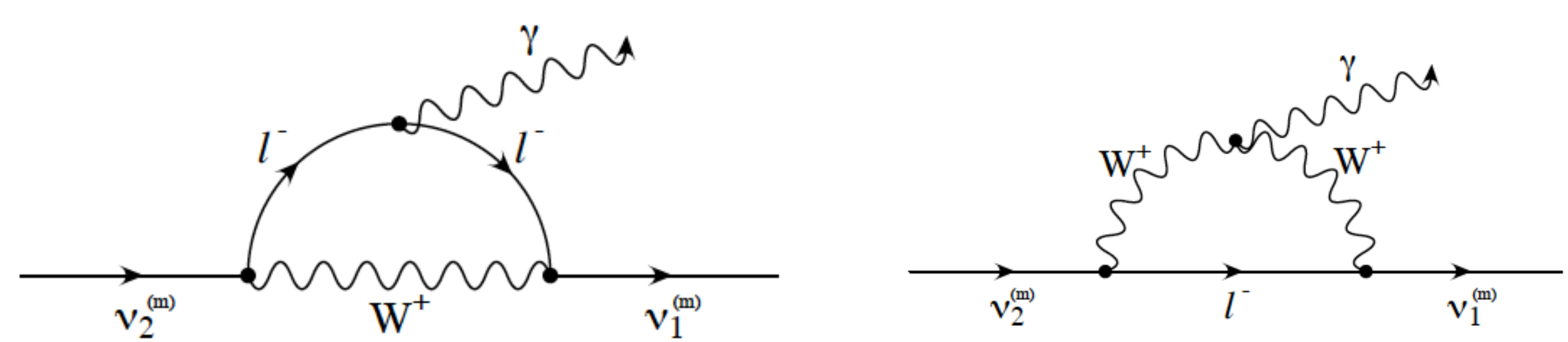


3.5 keV x-ray line may indicate the existence of 7 keV sterile neutrino

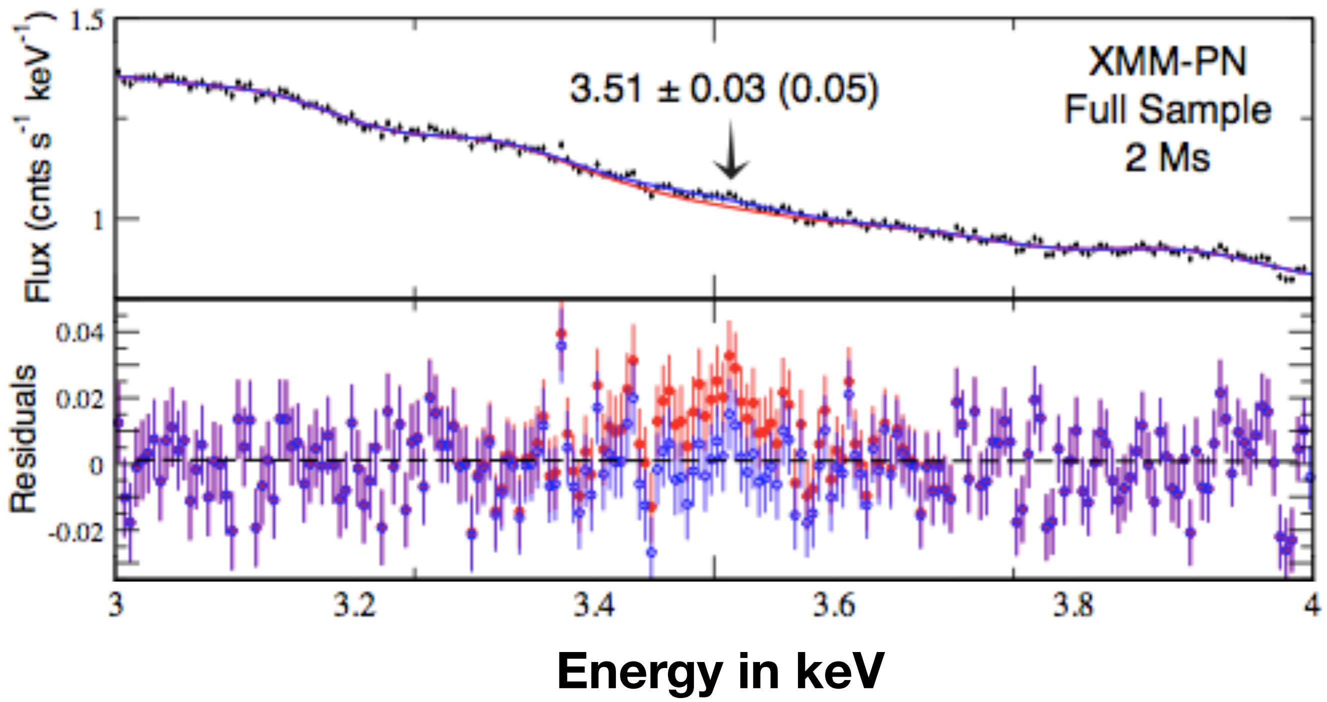
- Bulbil et al., arXiv:1402.2301 (APJ) (Stacked galaxy clusters, Perseus)
- Boyarsky et al. Phys.Rev.Lett. 113 (2014) 251301 (Andromeda, Perseus)

“smooking gun” line signal

Has been proposed as sterile neutrino signal



3.5keV line



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What could it be ?

- **X-ray lines also from atomic transitions of highly-ionized Z ~ 16-20 atoms**
    - **Example K XVIII has lines near 3.5 keV**
        - **To predicted the brightness based on other lines we need the relative elemental abundance and plasma temperature**

Why we should be skeptical:

- **Hitomi collaboration, APJL 837, L15 (2017) "Hitomi Constraints on the 3.5 keV Line in the Perseus Galaxy Cluster "**
- **T. Jeltema, S. Profumo Mon.Not.Roy.Astron.Soc. 458 (2016) no.4, 3592-3596 "Deep XMM Observations of Draco rule out at the 99% Confidence Level a Dark Matter Decay Origin for the 3.5 keV Line"**

Final word …

- **Future observations ATHENA, HERD, Micro-X, …**
- **Dark matter velocity spectroscopy (Speckhard, Ng, Beacom, Laha Phys. Rev. Lett. 116 (2016) 031301)**
- **Look where no background is expected …**

Dark matter velocity spectroscopy

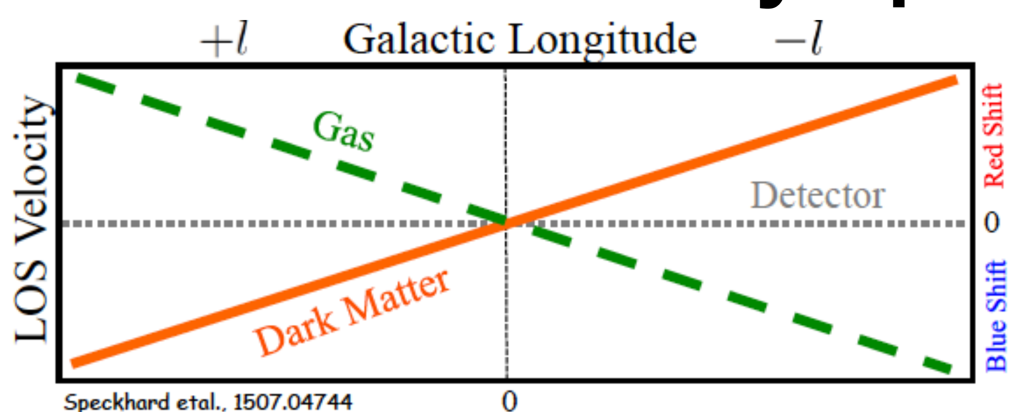
- Dark matter halo has little angular momentum

Bett, Eke, etal., "The angular momentum of cold dark matter haloes with and without baryons"; Kimm etal., "The angular momentum of baryons and dark matter revisited"

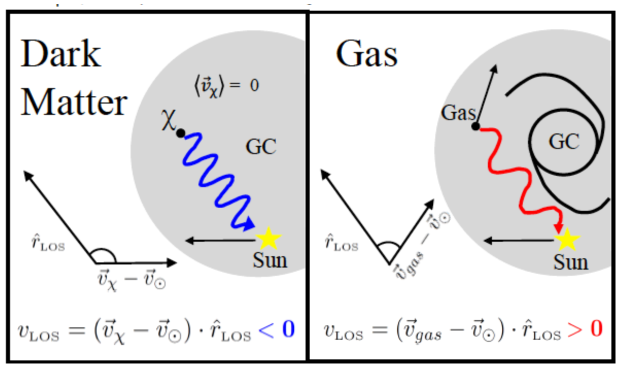
- Sun moves at ~220 km/s

- Distinct longitudinal dependence of signal

- Doppler effect



Speckhard etal., 1507.04744



Instruments with $\sim \mathcal{O}(0.1)\%$ energy resolution

Past

Hitomi/ Astro-H

$$\frac{\sigma_E}{E} \approx \frac{1.7\,\text{eV}}{3.5\,\text{keV}}$$

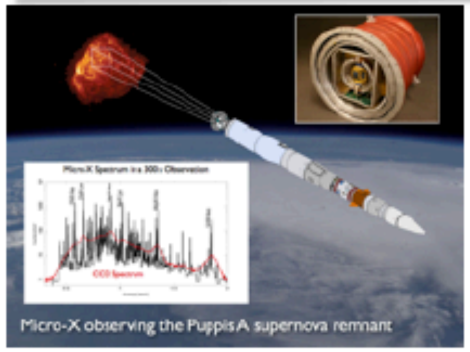
Present

INTEGRAL/ SPI

2.2 keV (FWHM) at 1.33 MeV

http://www.cosmos.esa.int/web/integral/instruments-spi

Future



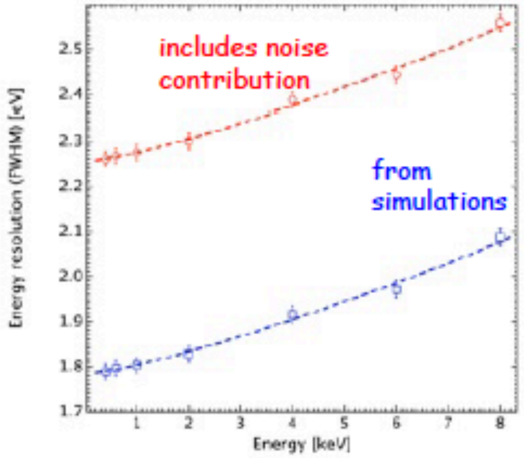
Micro-X

FWHM of 3 eV at 3.5 keV

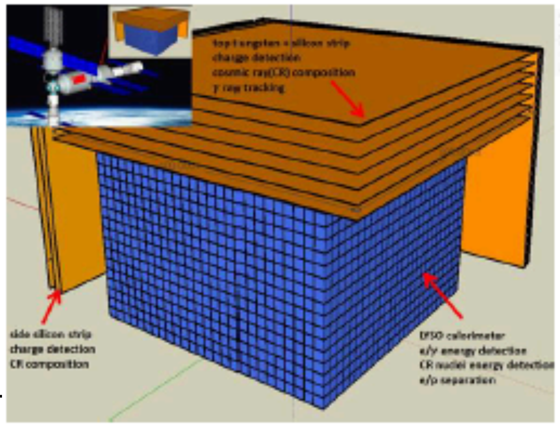
Figueroa-Feliciano etal. 2015

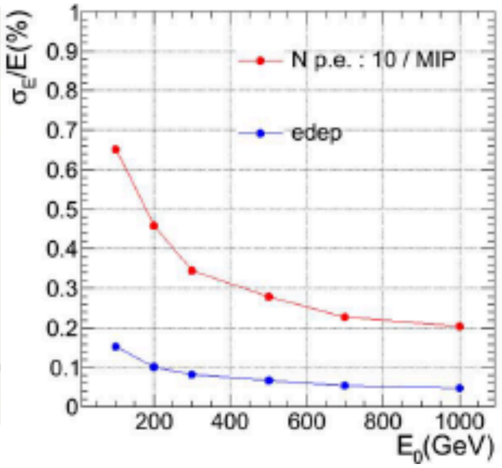
ATHENA

ATHENA X-IFU 1608.08105



HERD: High Energy Cosmic Radiation Detection





Energy resolution for electrons and gamma will be < 1% at 200 GeV

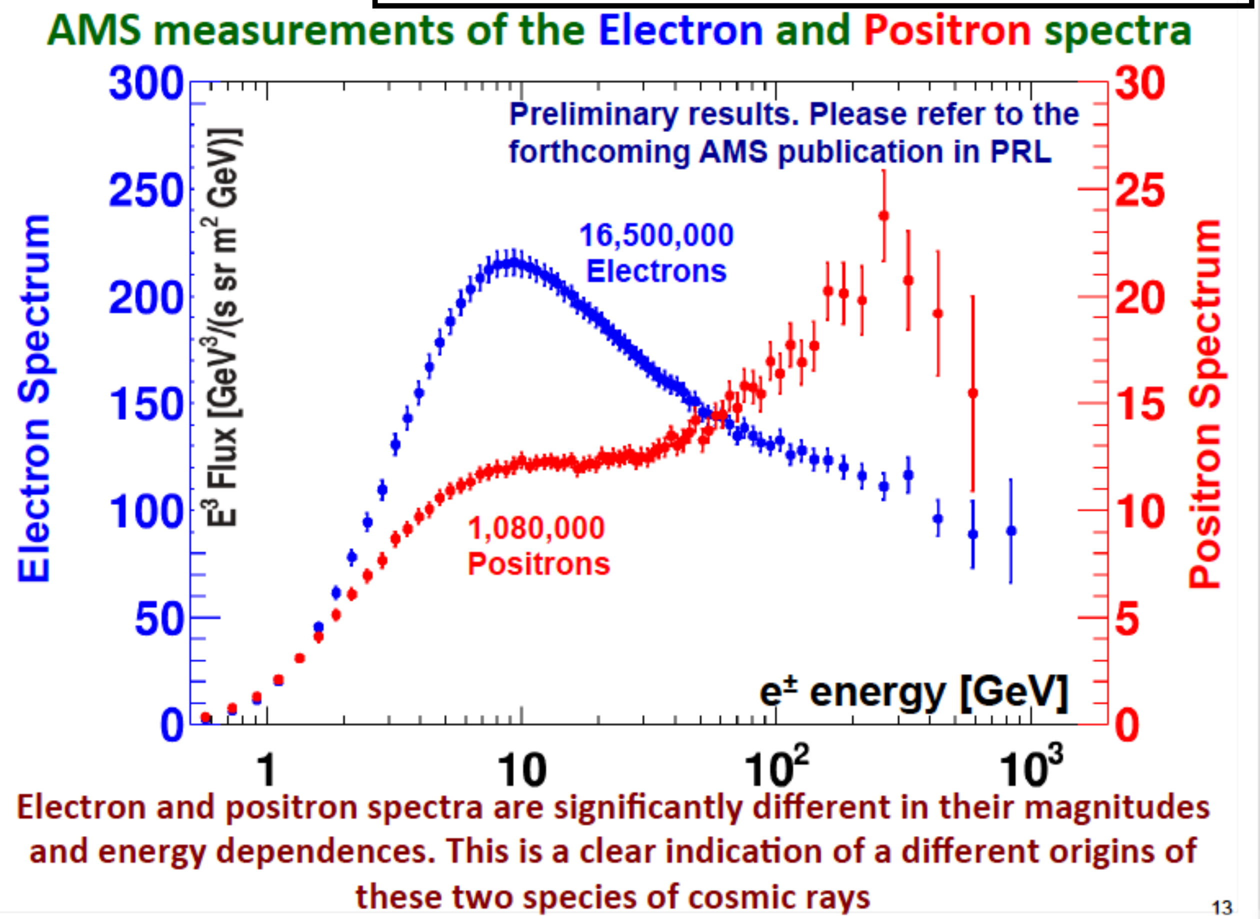
Wang & Xu Progress of the HERD detector

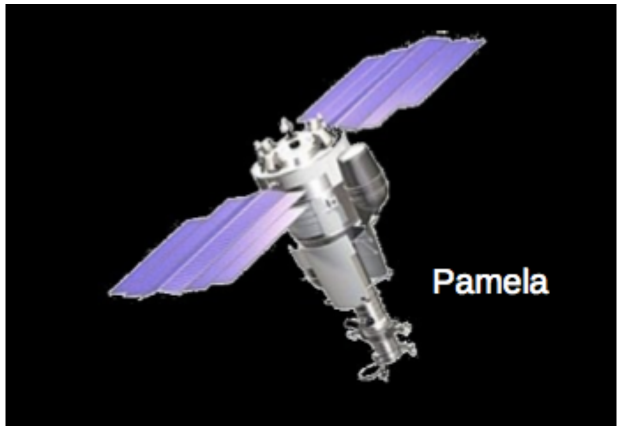
Dark matter velocity spectroscopy is a promising tool to distinguish signal and background in dark matter indirect detection

- We see a smoking gun in motion
- Immediate application to the 3.5 keV line
- Future improvements in the energy resolution of telescopes at various energies will result in this technique being widely adopted

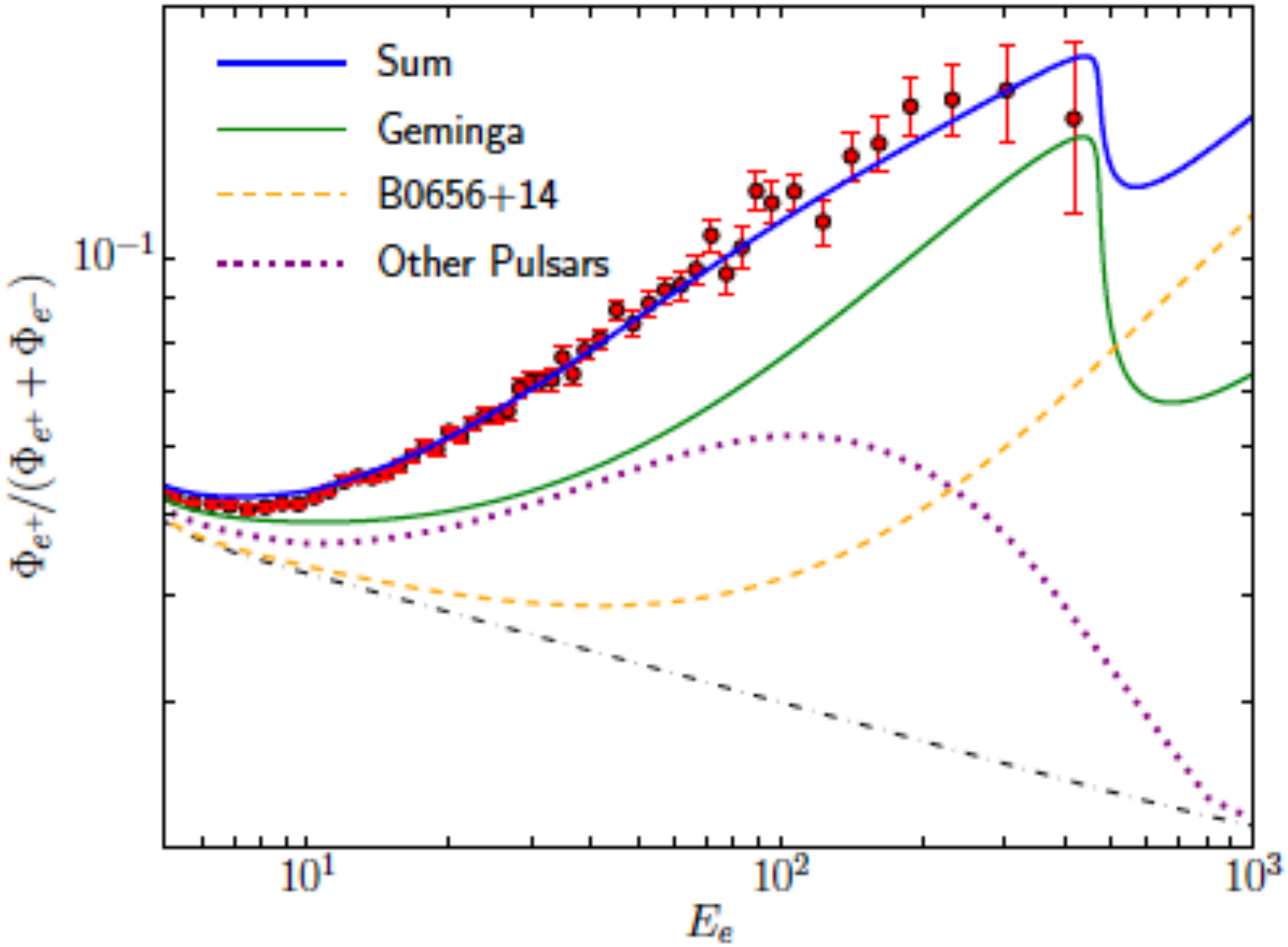
Positron Excess

Andrei KOUNINE @ ICRC2017





Dan Hooper, Ilias Cholis,, Tim Linden, and Ke Fang arXiv:1702.08436



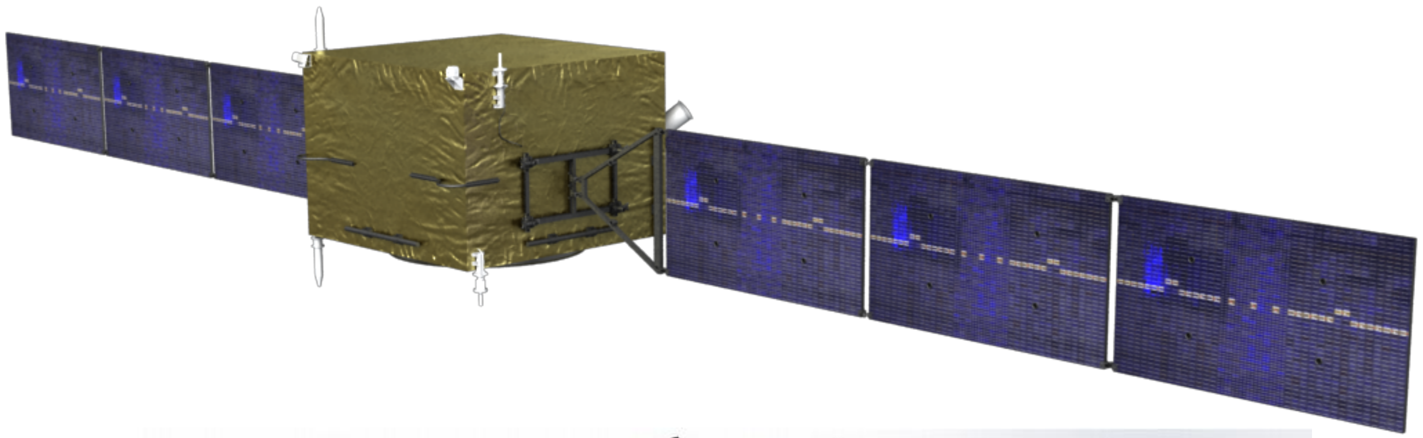
- Large excess of positrons above 10GeV inconsistent with secondary production expectations (PAMELA / Fermi-LAT / AMS-02)
- Dark matter interpretation for decay or annihilation in tension with other indirected bounds
- Astrophysical sources (pulsars) potentially provide large signal contributions

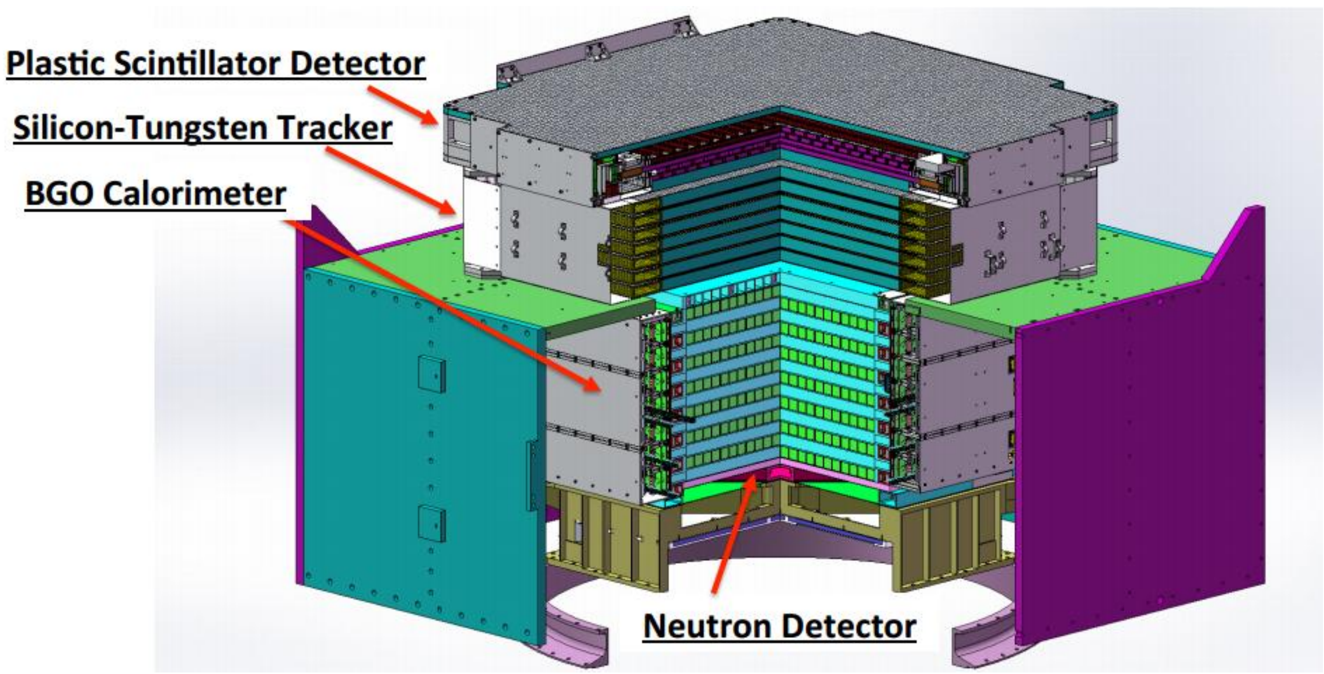
… not every bump in the data is from DM

What to expect in the future with Indirect Searches

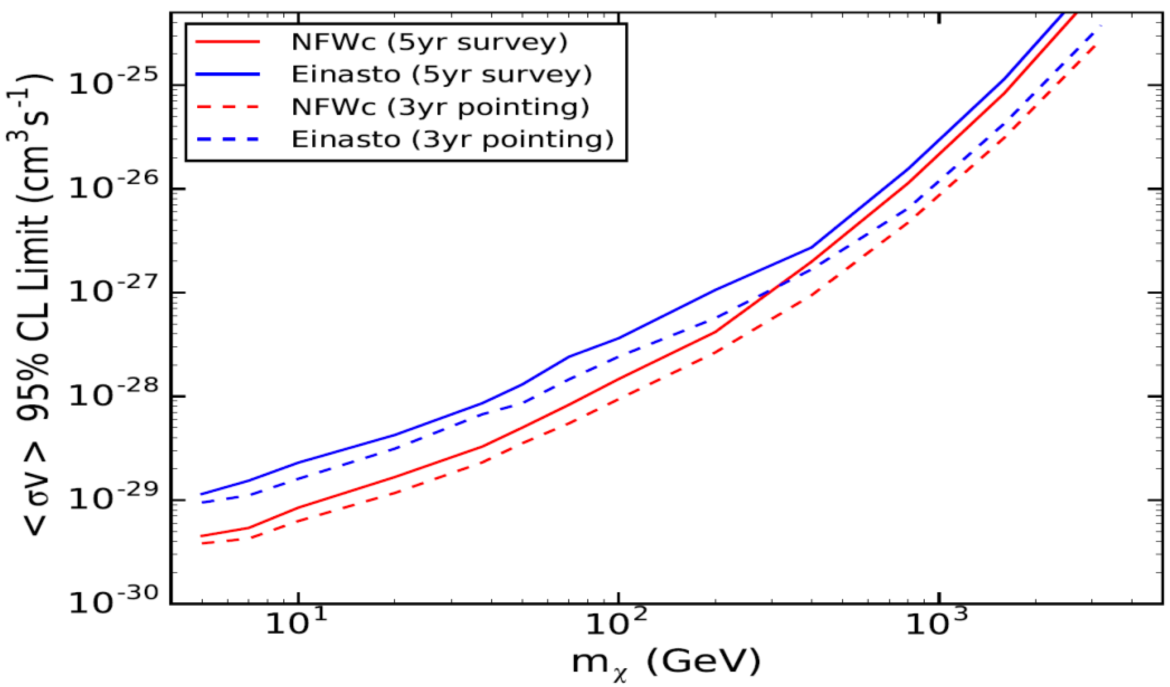
https://arxiv.org/pdf/1706.08453.pdf

DAMPE





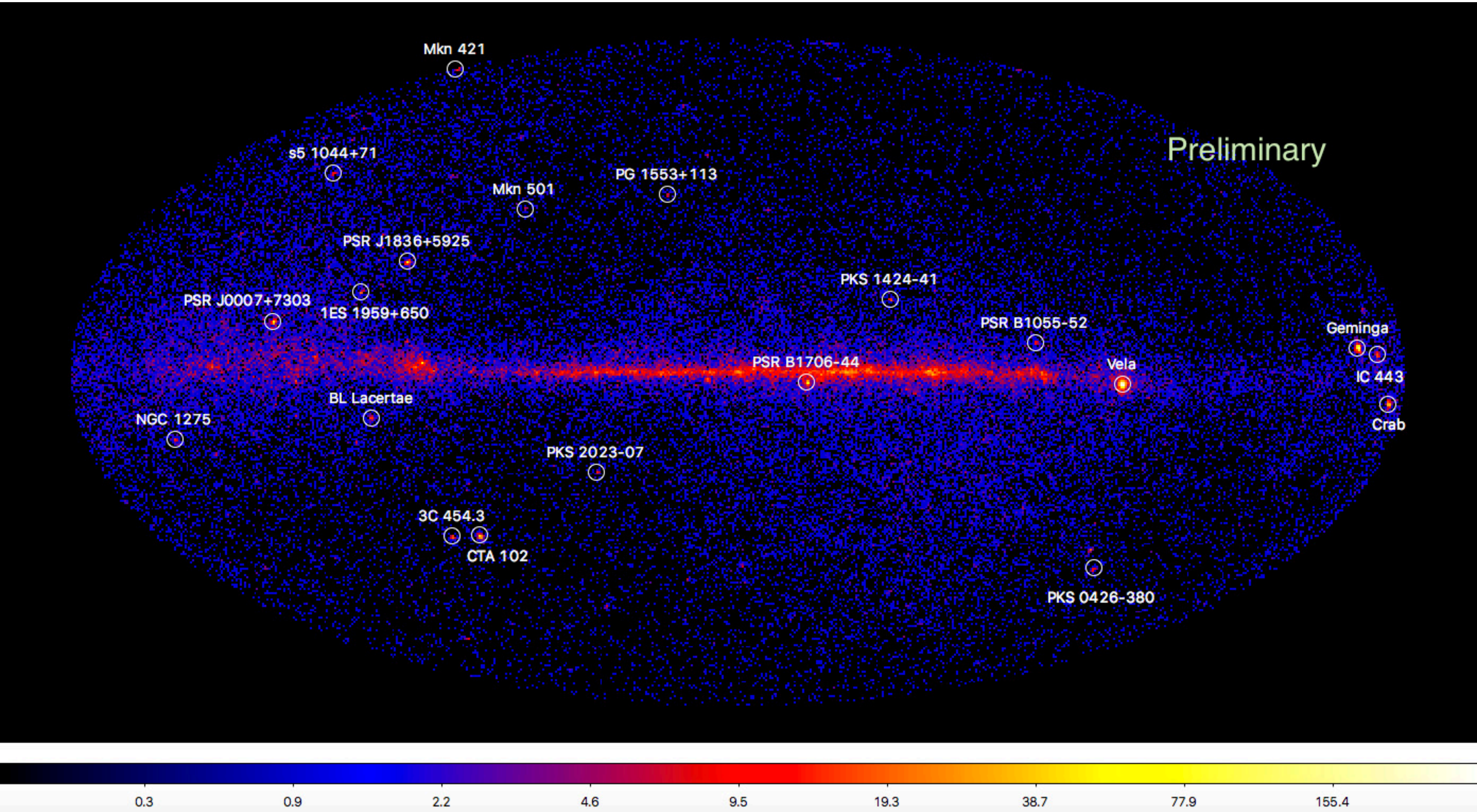
Sensitivity with 3 yrs of data DAMPE



- DAMPE detector, consists of 4 subsystems:
  - the plastic scintillator strips detector (PSD),
  - the silicon-tungsten tracker-converter (STK),
  - the BGO imaging calorimeter (BGO), and
  - the neutron detector (NUD).

DAMPE - First Light (Skymap)

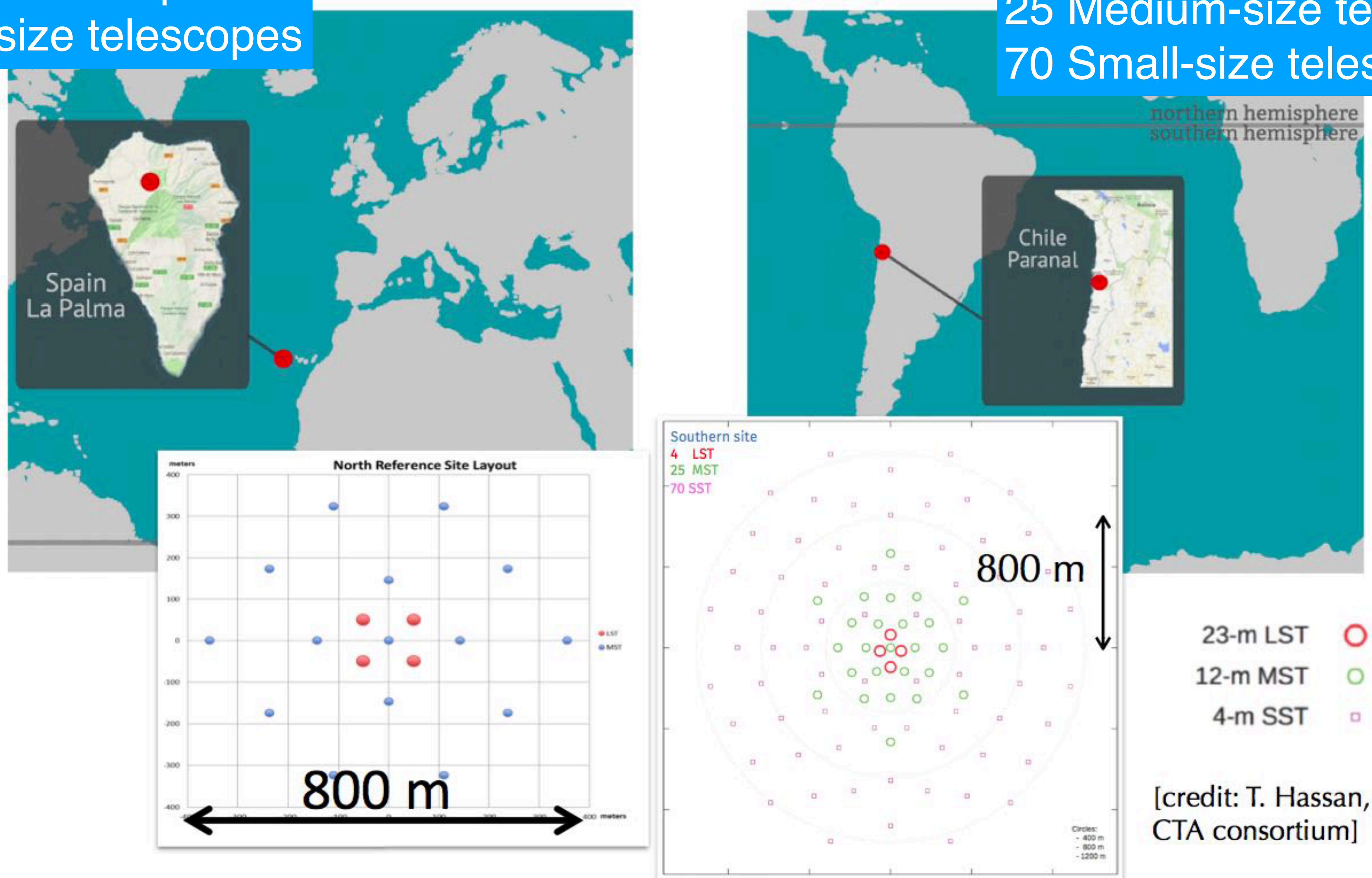
Jin Chang - Highlight Talk ICRC2017



CTA - Cherenko Telescope Array

Northern Site
4 Large-size telescopes
15 Medium-size telescopes

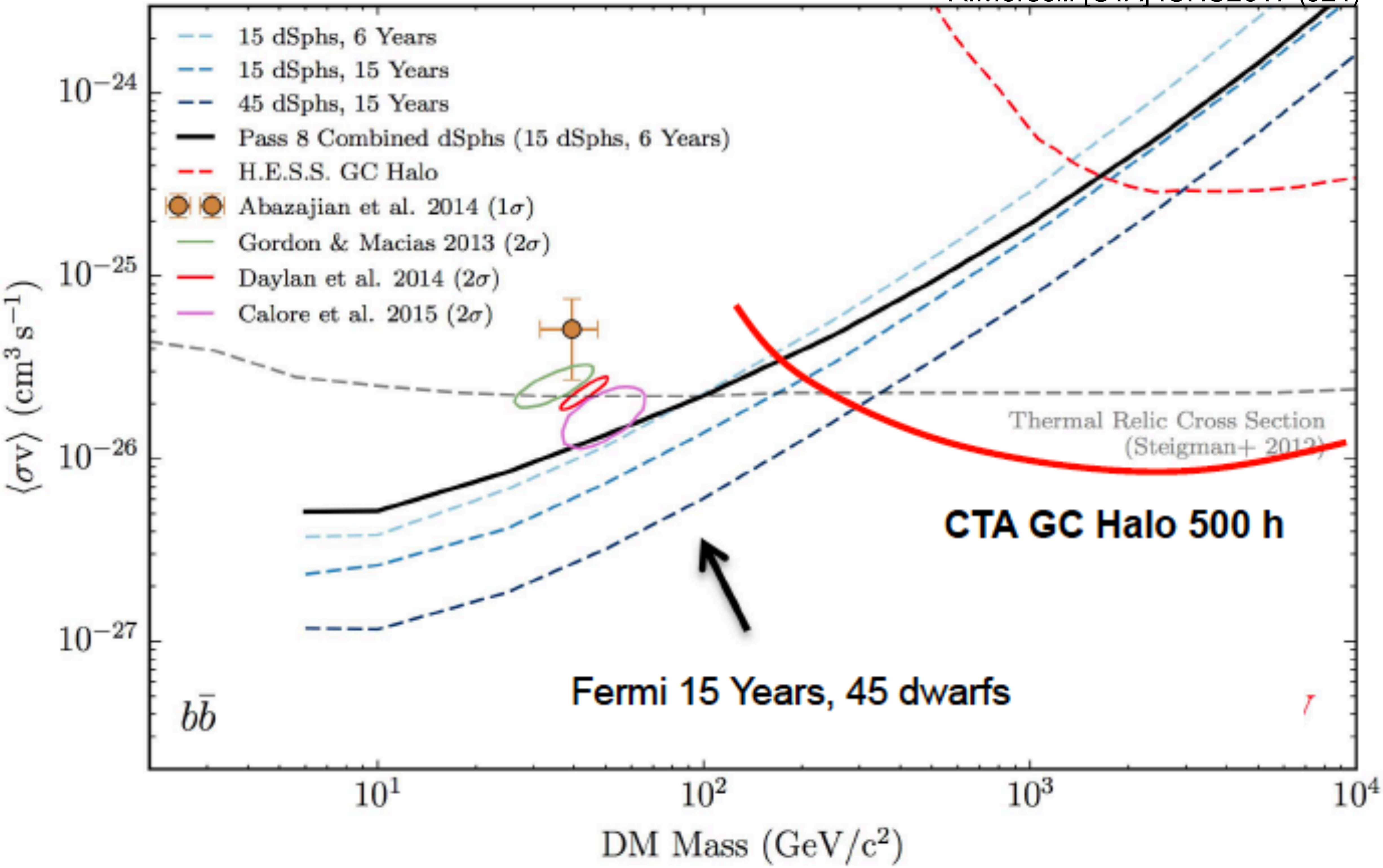
Southern Site
4 Large-size telescopes
25 Medium-size telescopes
70 Small-size telescopes



CTA sites and example telescope layouts different deployment strategies

Dark Matter improvement estimate by 2023

A.Morselli [CTA] ICRC2017 (921)

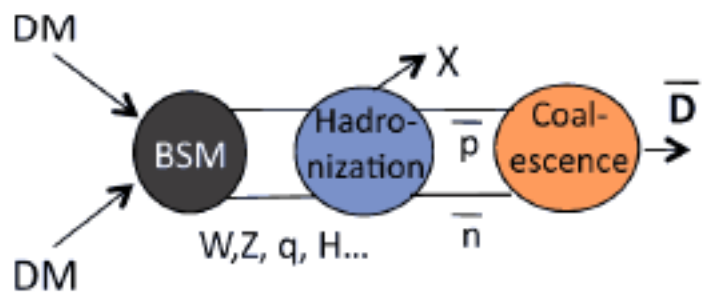


CTA sensitivity curve from Carr et al. 2015 500 hr, statistical only, NFW, 30 GeV threshold arXiv:1508.06128

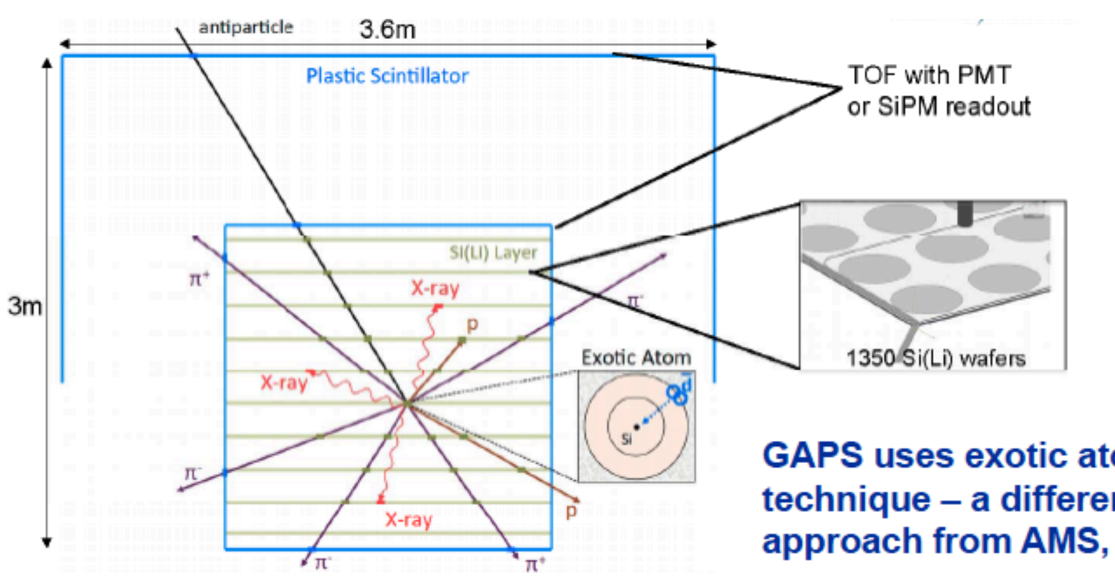
Together Fermi and CTA will probe most of the space of WIMP models with thermal relic annihilation cross section

The GAPS Experiment to Search for Dark Matter using Low-energy Antimatter

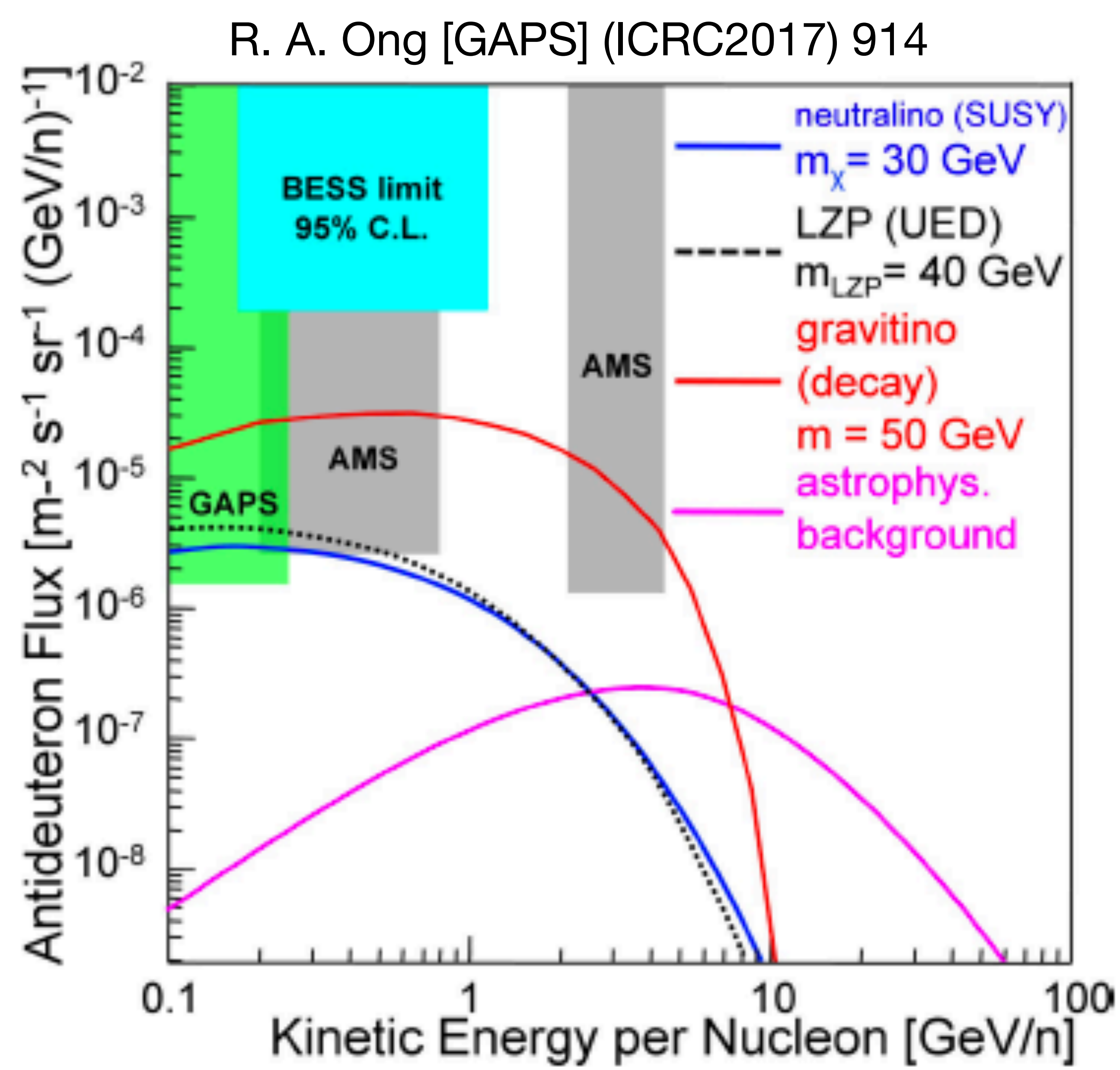
Anti-D's production



essentially background free
(secondary production)

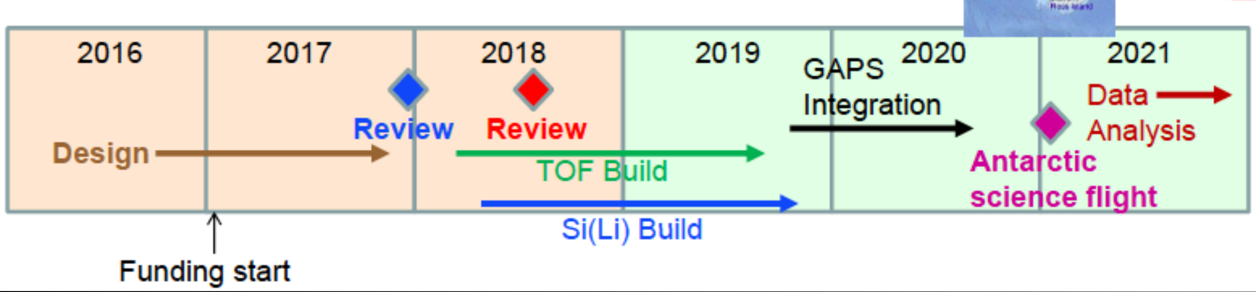


GAPS uses exotic atom technique – a different approach from AMS, BESS…



GAPS Sensitivity (35days) T. Aramaki et al . Astroparticle Phys. 74 , 6 (2016).
AMS Sensitivity estimate (5yrs) T. Aramaki et al ., Phys. Rep. 618 , 1 (2016).
BESS upper limit H. Fuke et al ., Phys. Rev. Lett. 95 , 081101 (2005).

Timeline & Summary

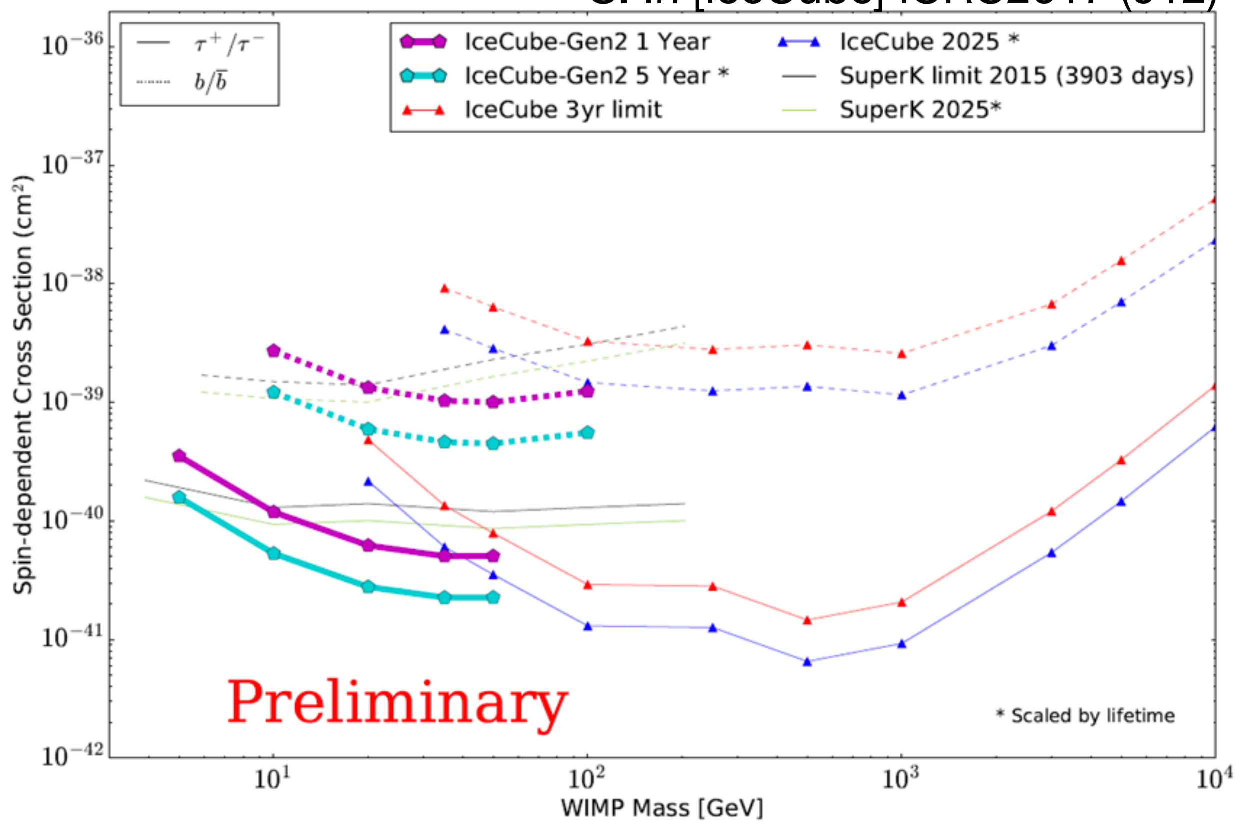


Next generation neutrino detectors

At TAUP2017 see also
- Jason Kumar (Friday morning)
- Claudio Kopper (Tuesday morning)
- Hidekazu Tanaka (Wednesday afternoon)
- Takatomi Yano (Wednesday afternoon)
- Sunny Seo (Wednesday afternoon)

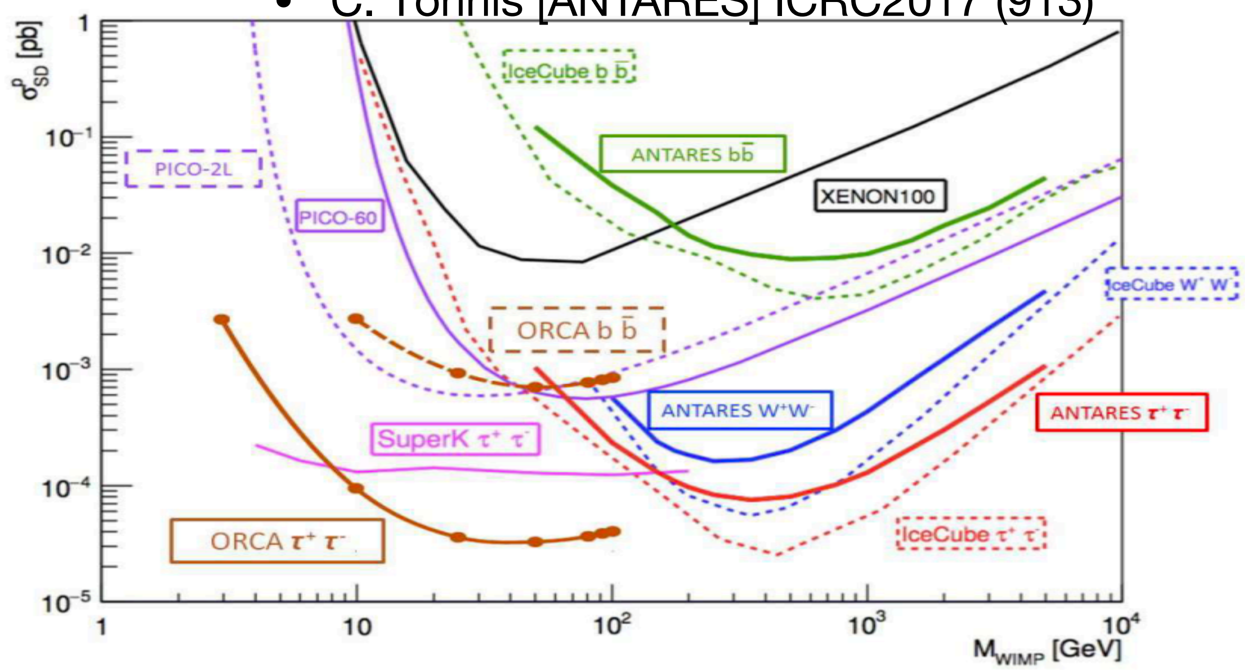
IceCube-Gen2 (PINGU fill in)

S. In [IceCube] ICRC2017 (912)

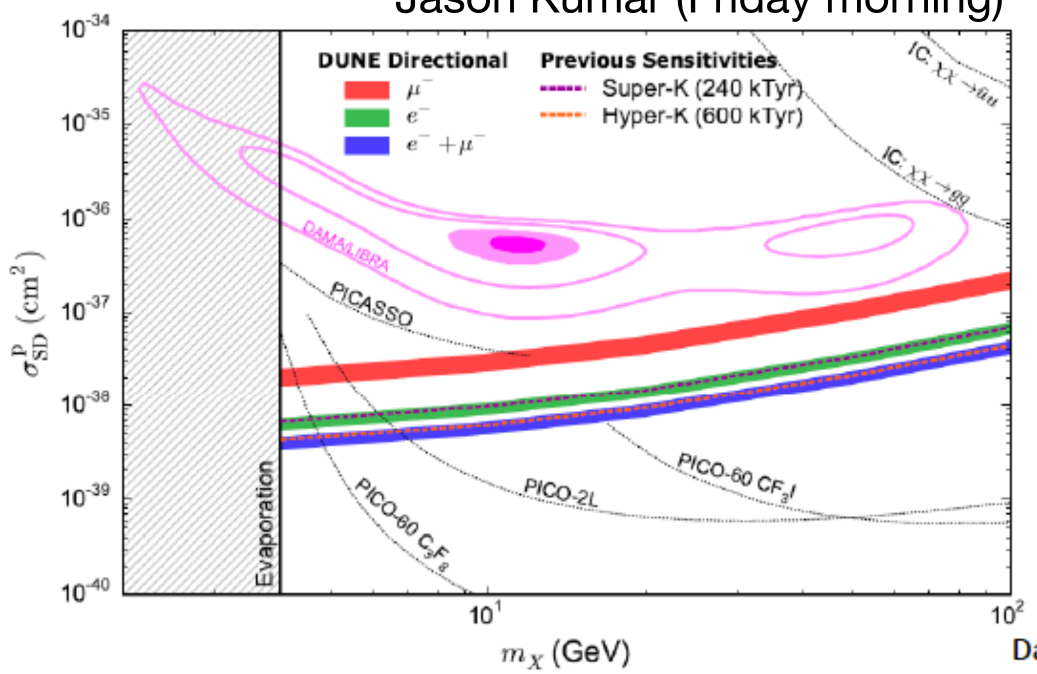


ORCA

- C. Tönnis [ANTARES] ICRC2017 (913)



Jason Kumar (Friday morning)



David Yaylali

- ORCA and IceCube-Gen2 (PINGU infill) have unique capability to explore DM between 4-50GeV in indirect solar wimp searches
  - This will also be an interesting region for Hyper-K / T2HKK / DUNE
- KM3NeT and IceCube-Gen2 extremely competitive for high-mass DM decay

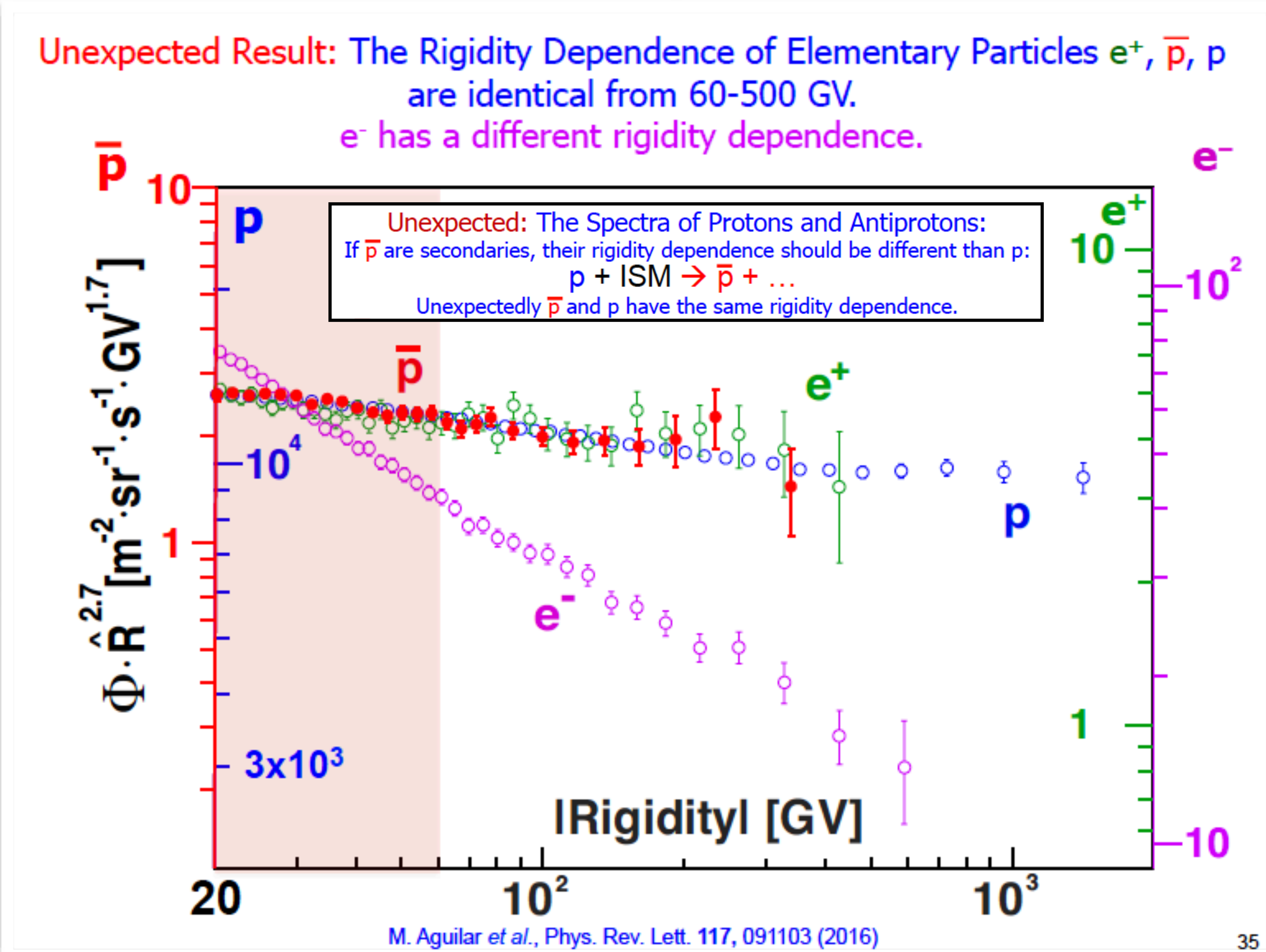
Conclusions

- Dark Matter exists
- Multiwavelength campaigns needed to identify it
- Anomalies remain of high interest, but alternative explanations becoming more compelling
- Vibrant field with many new results
- New strong bounds on dark matter decay and annihilations
- Solar Atmospheric neutrinos new background to solar dark matter searches
- Taking searches beyond the WIMP paradigm - still useful framework for result interpretation

Backup

AMS-02

Andrei KOUNINE @ ICRC2017

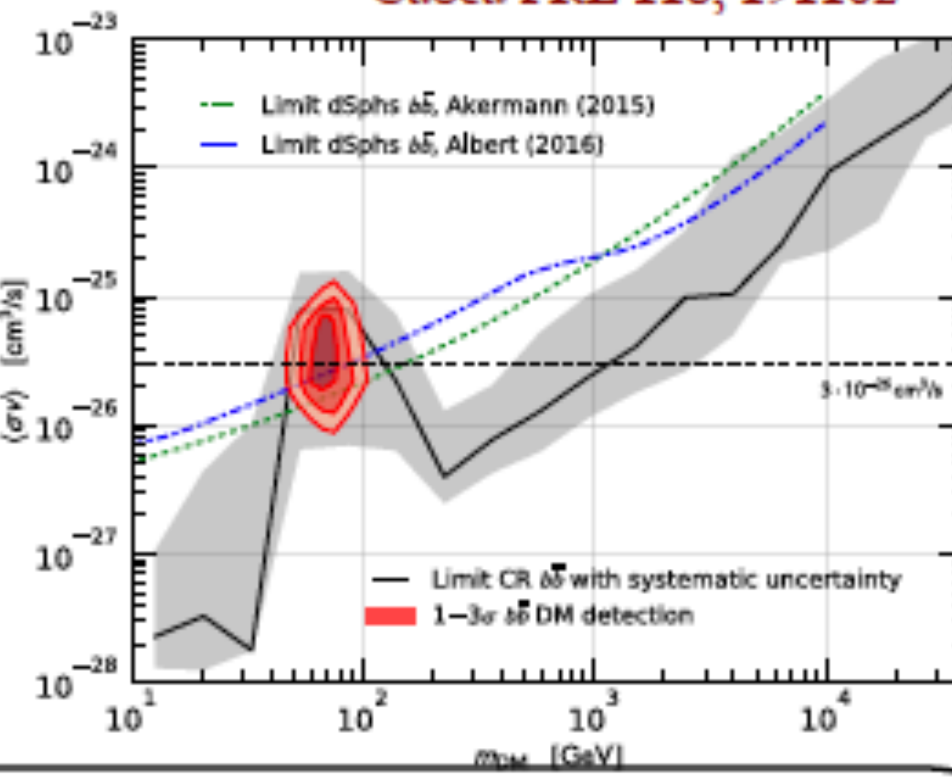


AMS-02

- AMS Antiprotons

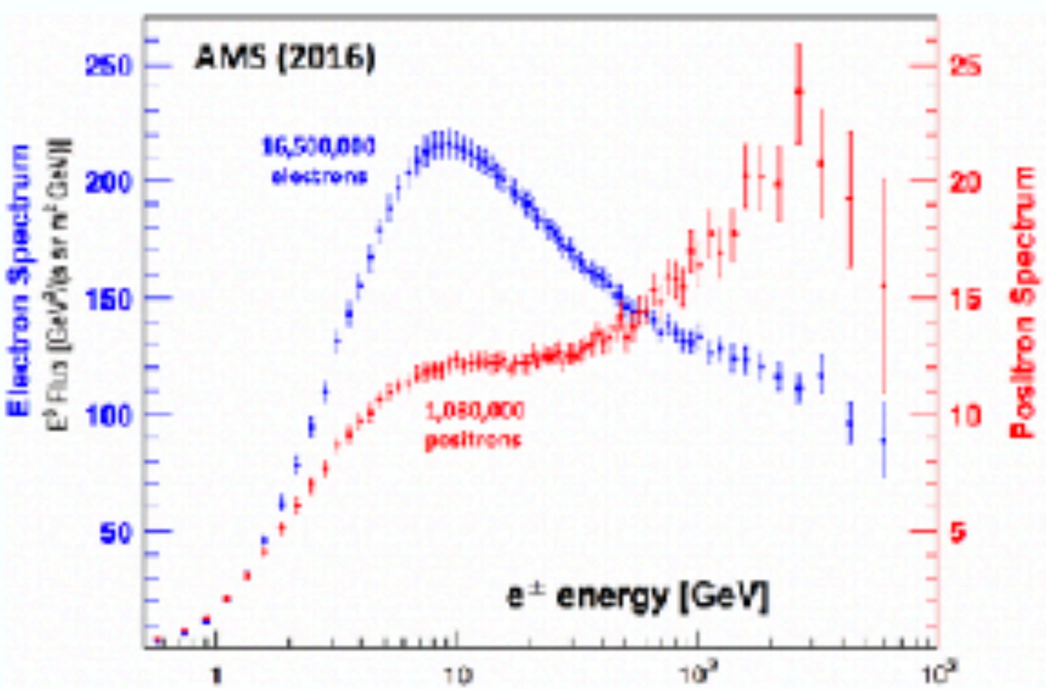
- Excess ~4.5σ possibly attributed to DM *(PRL 118, 191102; PRL 118, 191101)*
- Significant uncertainties: modeling of antiproton production cross section, cosmic-ray propagation, solar modulation.

Cuocu PRL 118, 191102



- AMS Positrons

Ting, 8/12/16 CERN Colloquium

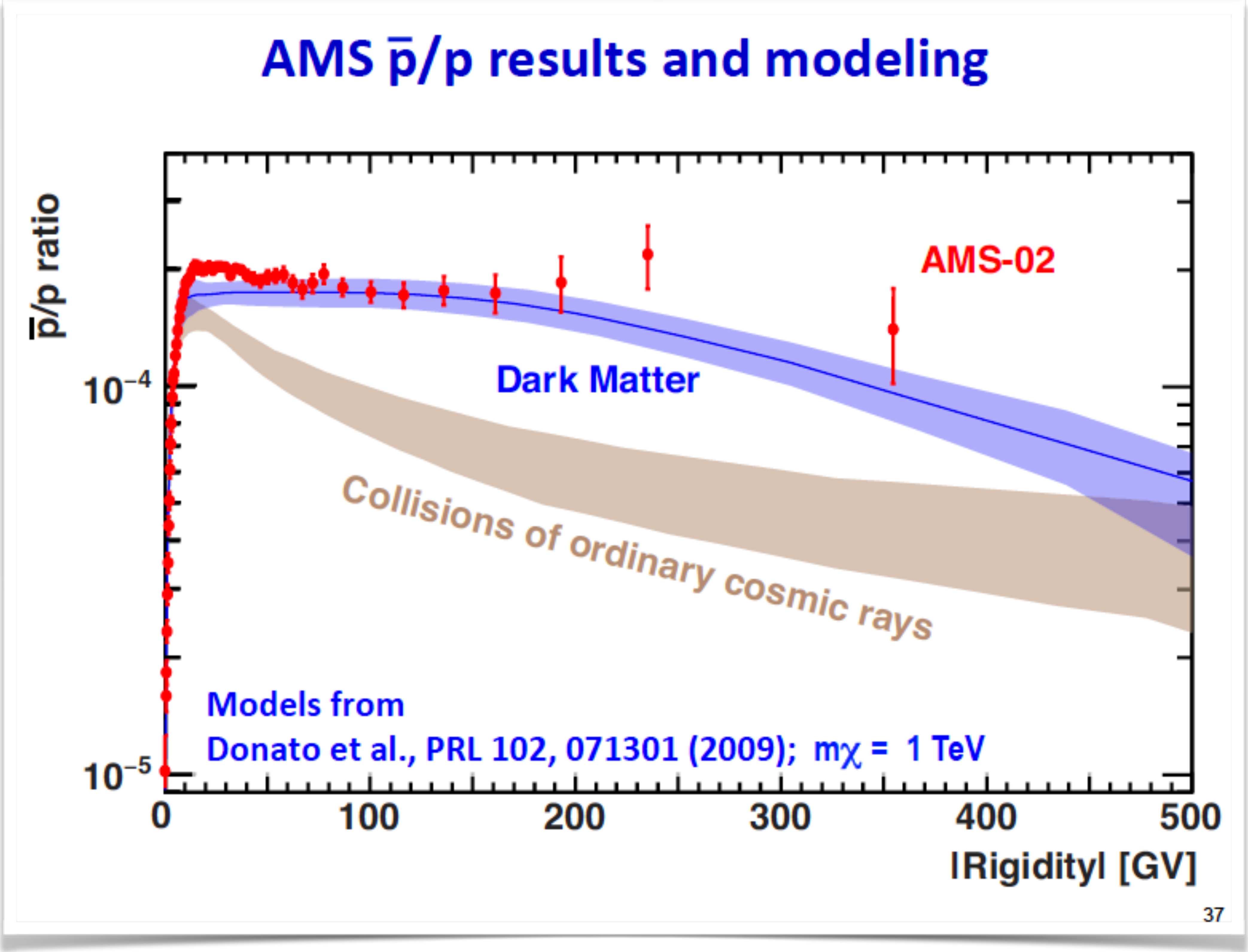


- Large excess of e^+ > 10 GeV inconsistent with exceptions for secondary e^+ from proton collisions with interstellar medium.
- DM interpretation of signature for annihilation or decay in tension with other measurements.
- Potential for large pulsar contribution to signal. (arXiv:1702.08436)

Jodi Cooley (WIN2017)

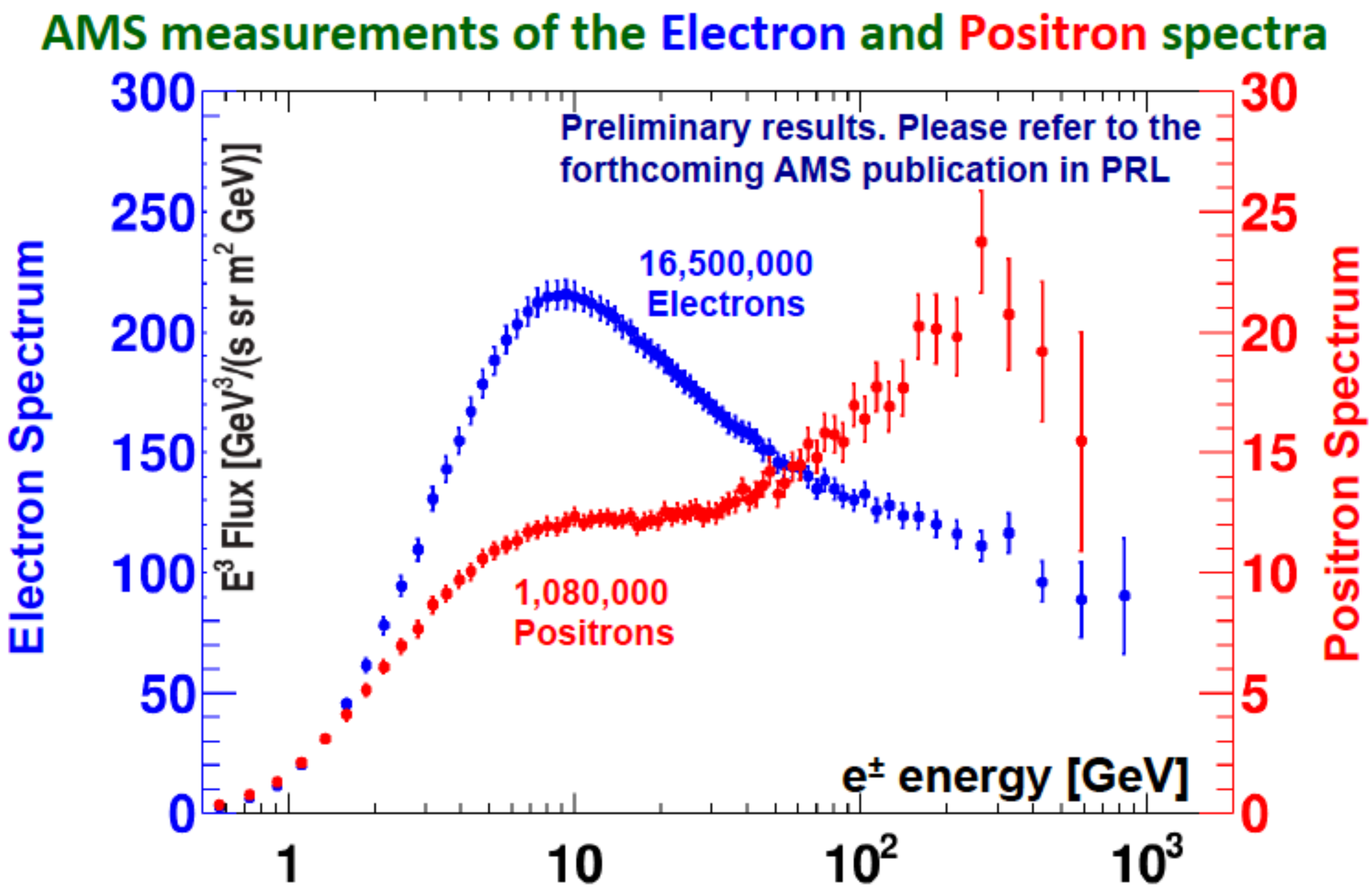
AMS-02

Andrei KOUNINE @ ICRC2017



AMS-02

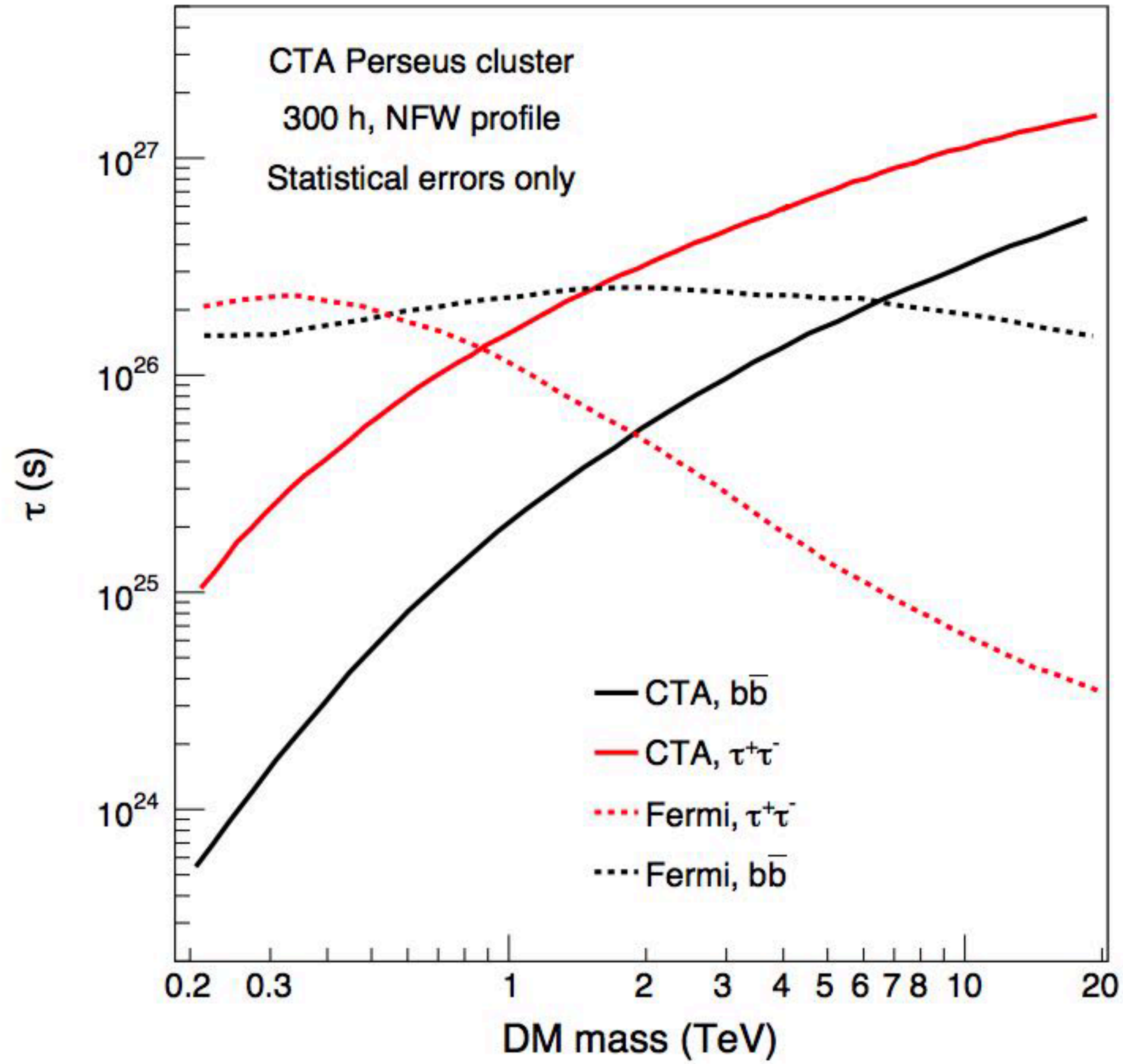
Andrei KOUNINE @ ICRC2017



Electron and positron spectra are significantly different in their magnitudes and energy dependences. This is a clear indication of a different origins of these two species of cosmic rays

13

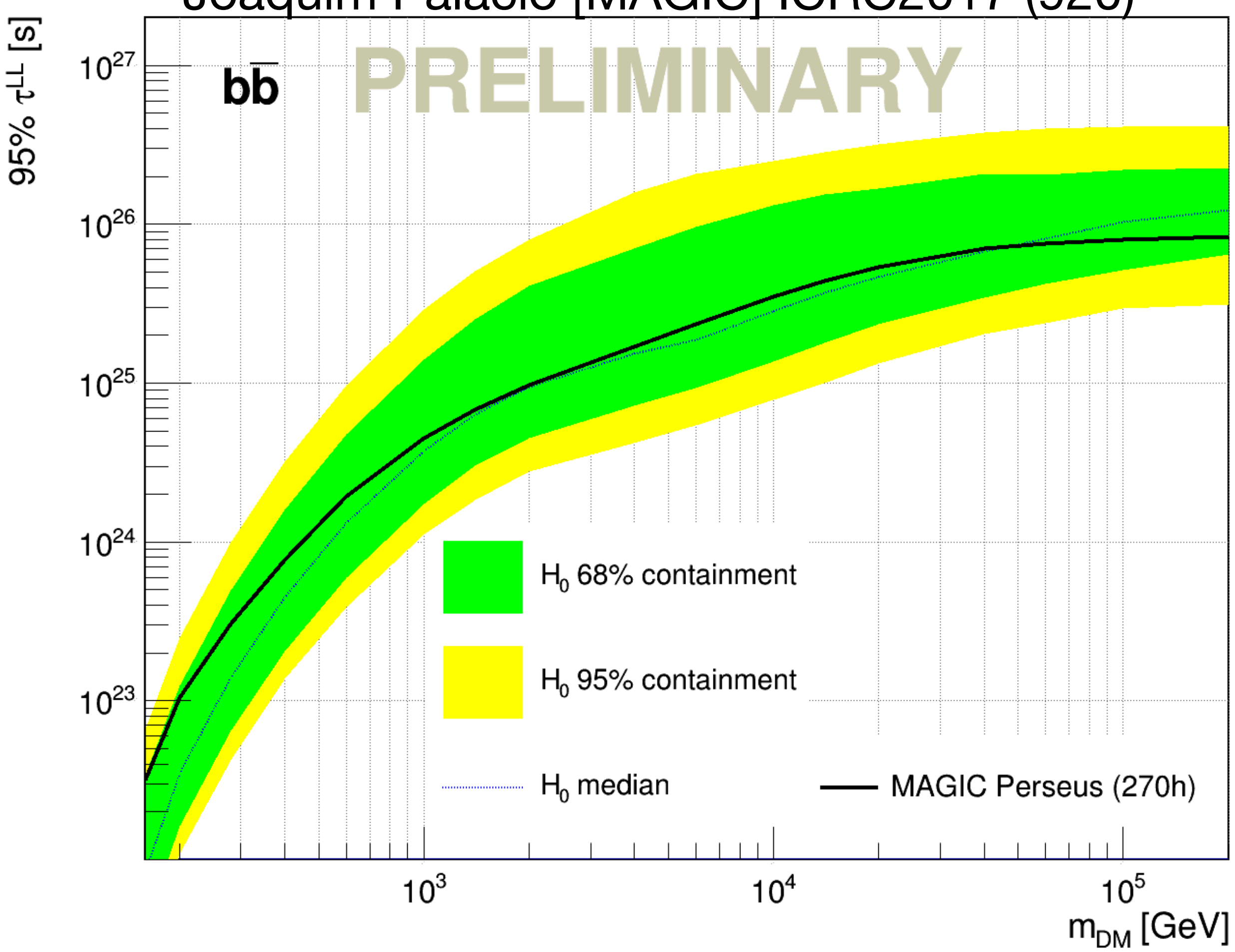
Sensitivity CTA

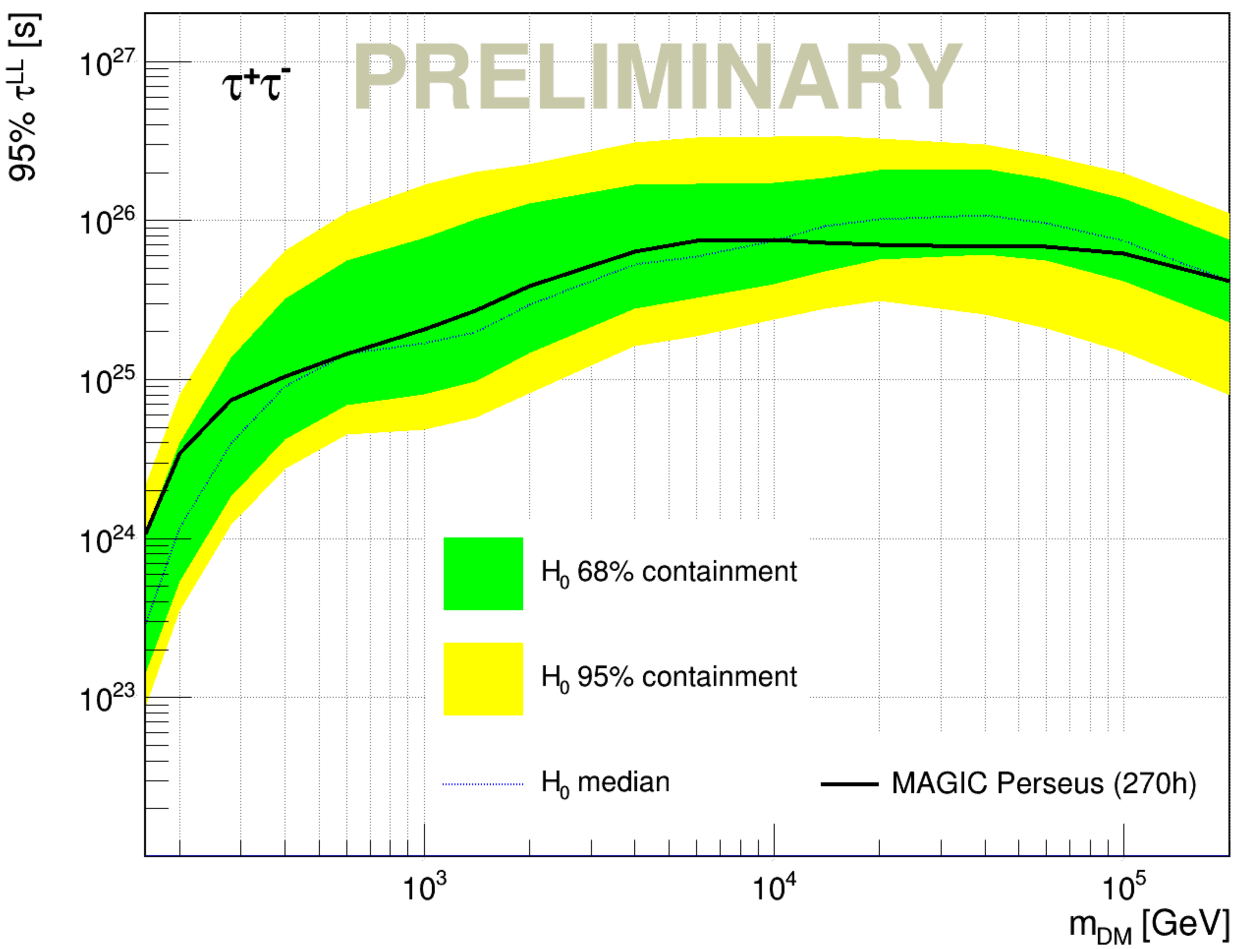


MAGIC DM Decay

Results from 270h of good quality data (from 2009-2017)

Joaquim Palacio [MAGIC] ICRC2017 (920)

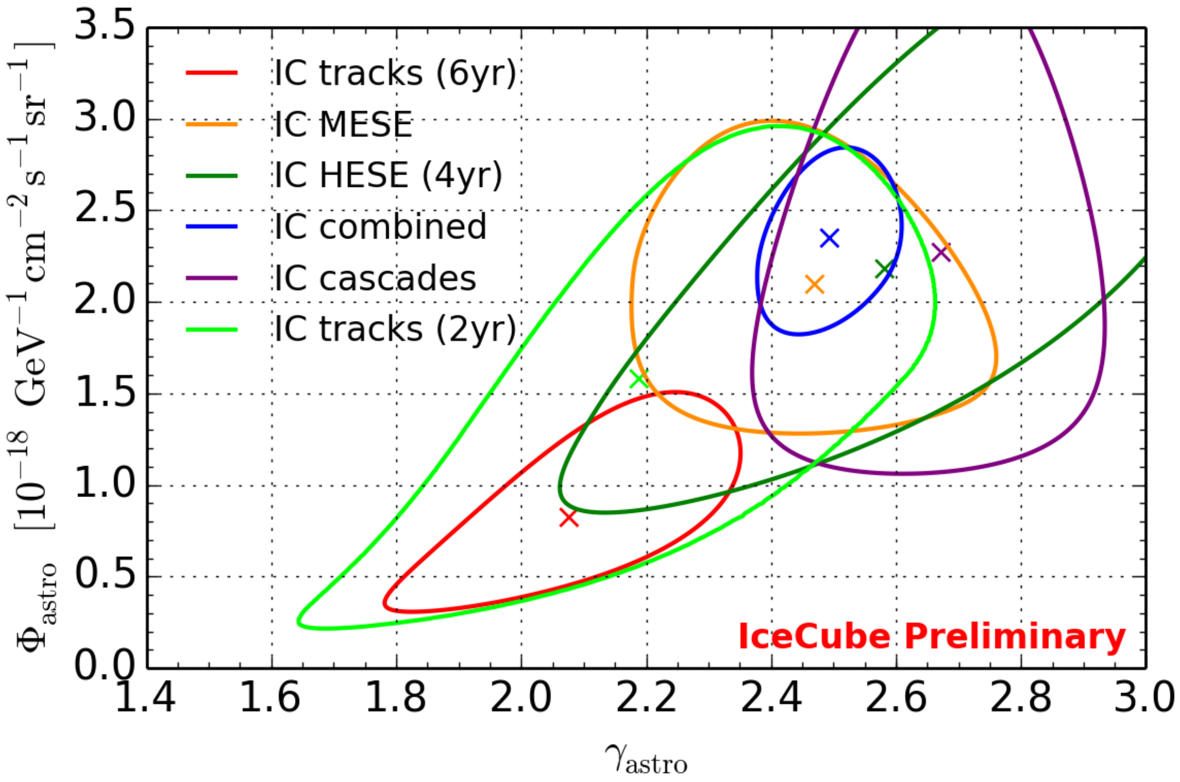




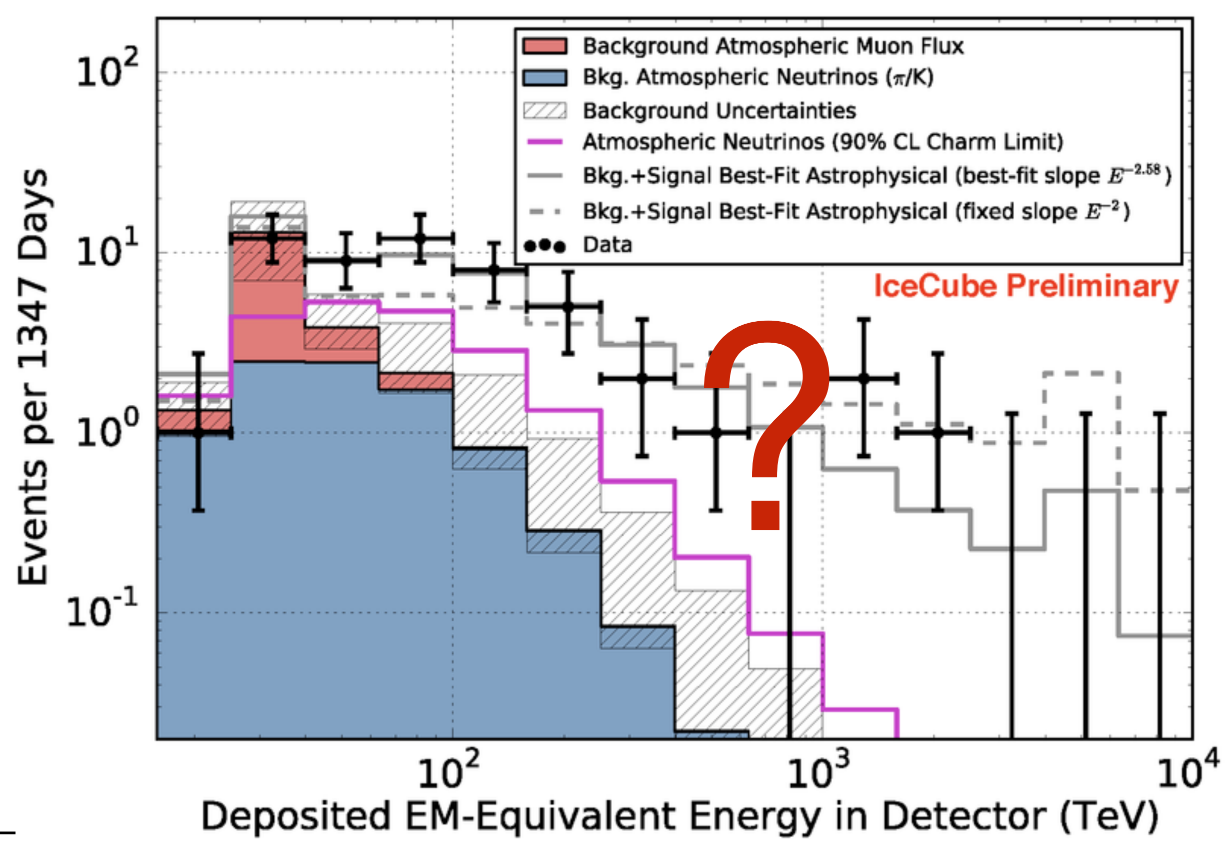
No evidence of dark matter decay observed

Reach sensitivities on decay life times of ~$8 \cdot 10^{25}$ s

Beyond Standard Model Physics at the PeV scale



- Intense interest in high-energy neutrino region
  - Observations defy any simple explanation from a single generic source class
    - Multiple sources classes ?
    - Hints of new physics ?

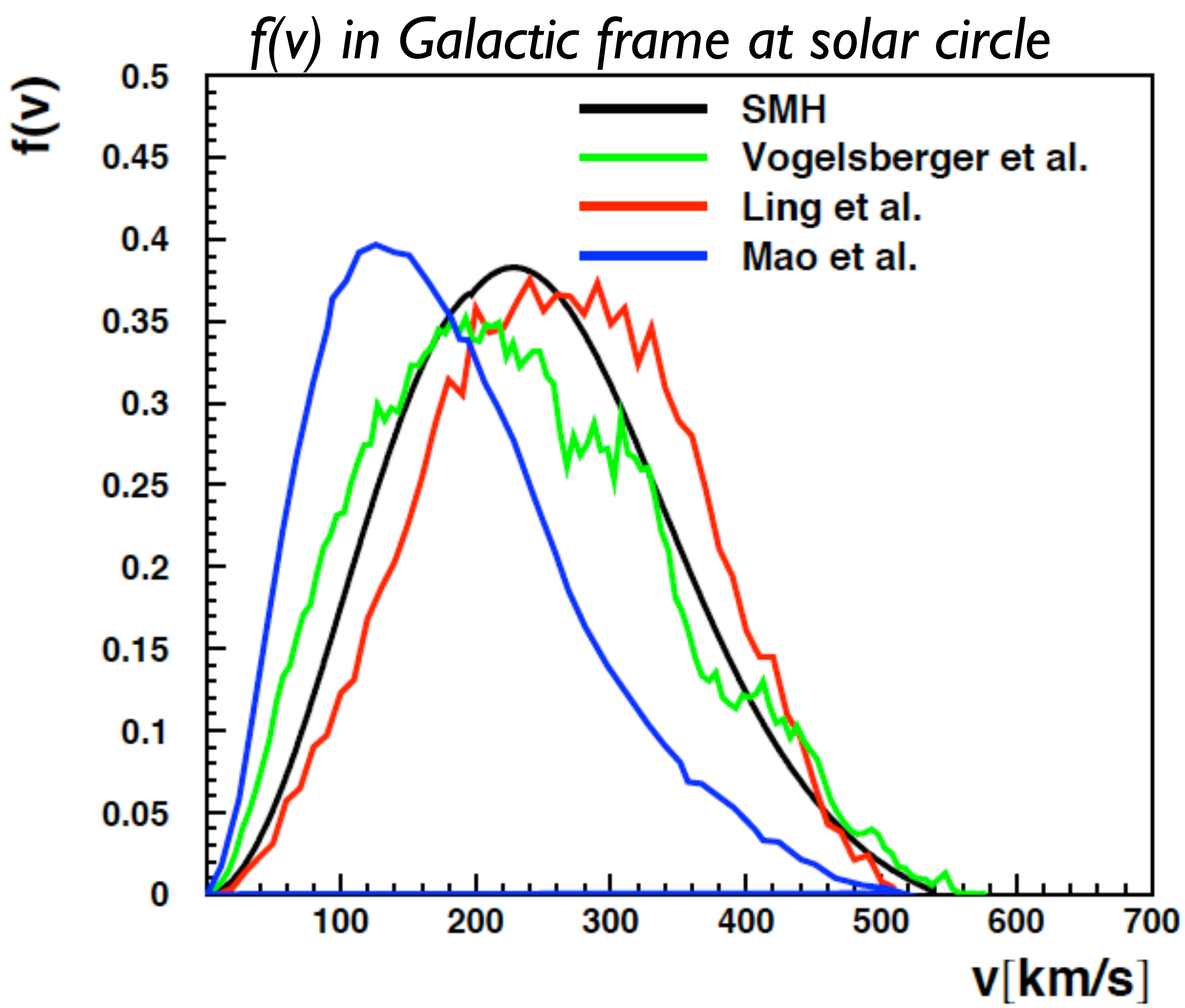


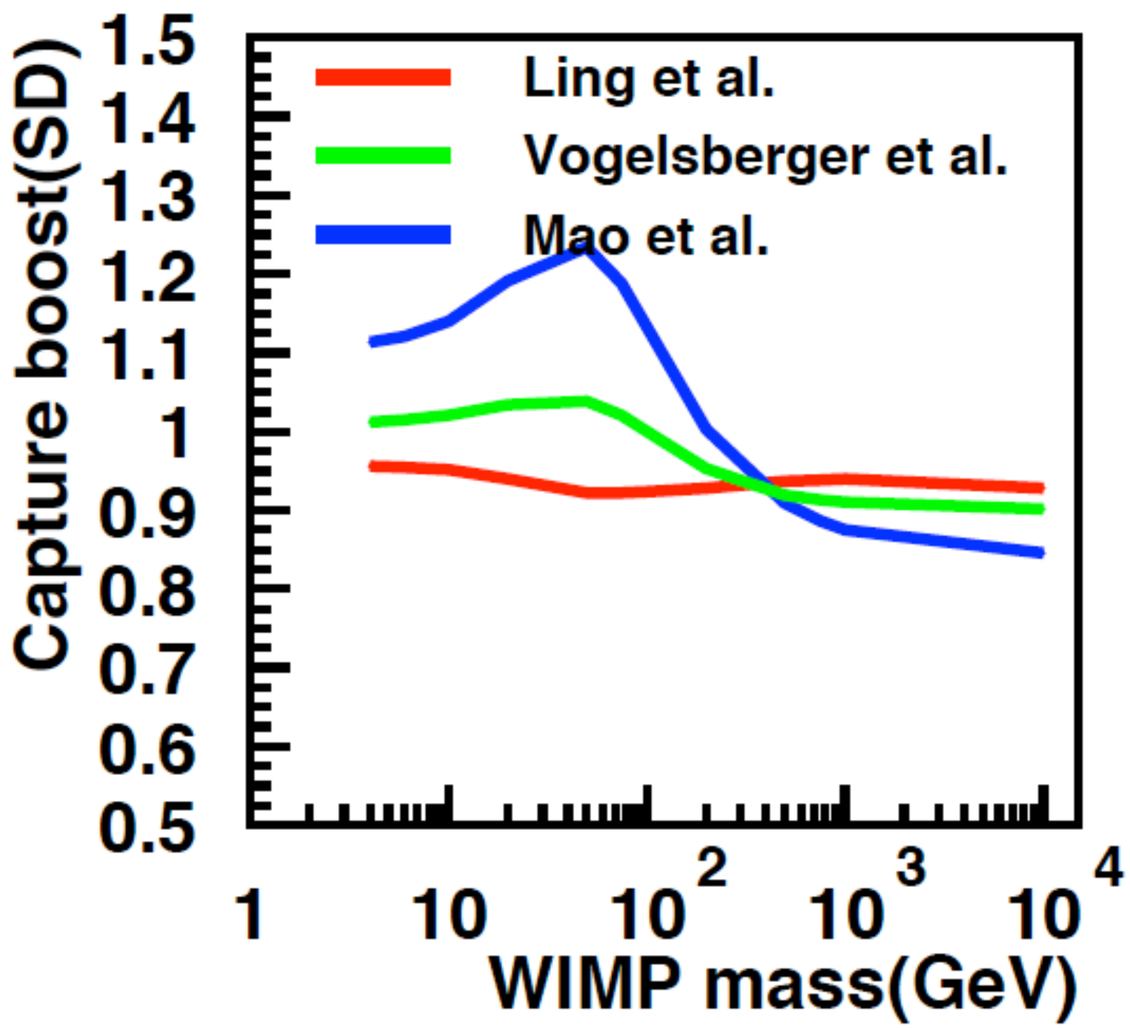
- PeV Scale Right Handed Neutrino Dark Matter
- Super Heavy Dark Matter
- Neutrino Portal Dark Matter
- Right-handed neutrino mixing via Higgs portal
- Heavy right-handed neutrino dark matter
- Leptophilic Dark Matter
- PeV Scale Supersymmetric Neutrino Sector Dark Matter
- Dark matter with two- and many-body decays
- Shadow dark matter
- Boosted Dark Matter
- …

Impact of velocity distribution

- Explore the change in capture rate using different velocity distributions obtained from dark matter simulations

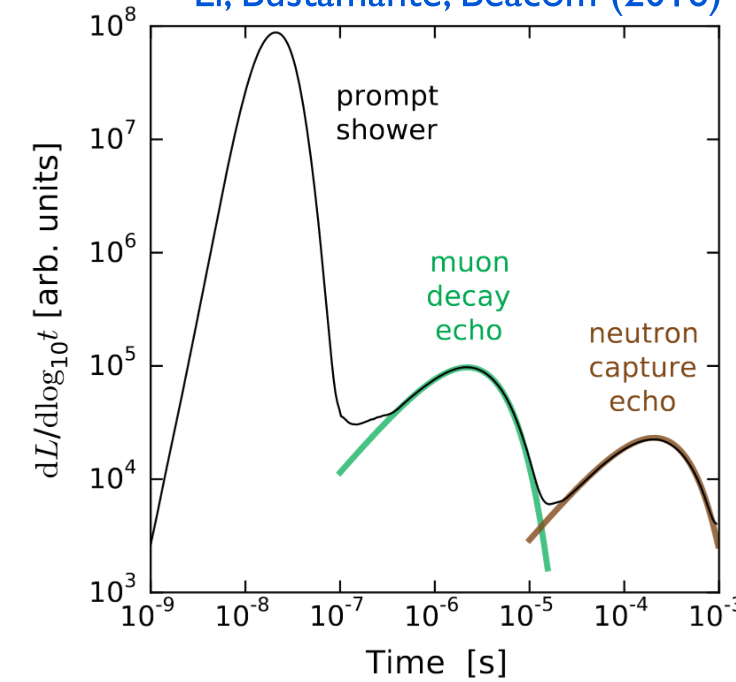
Choi, Rott, Itow JCAP 1405 (2014) 049



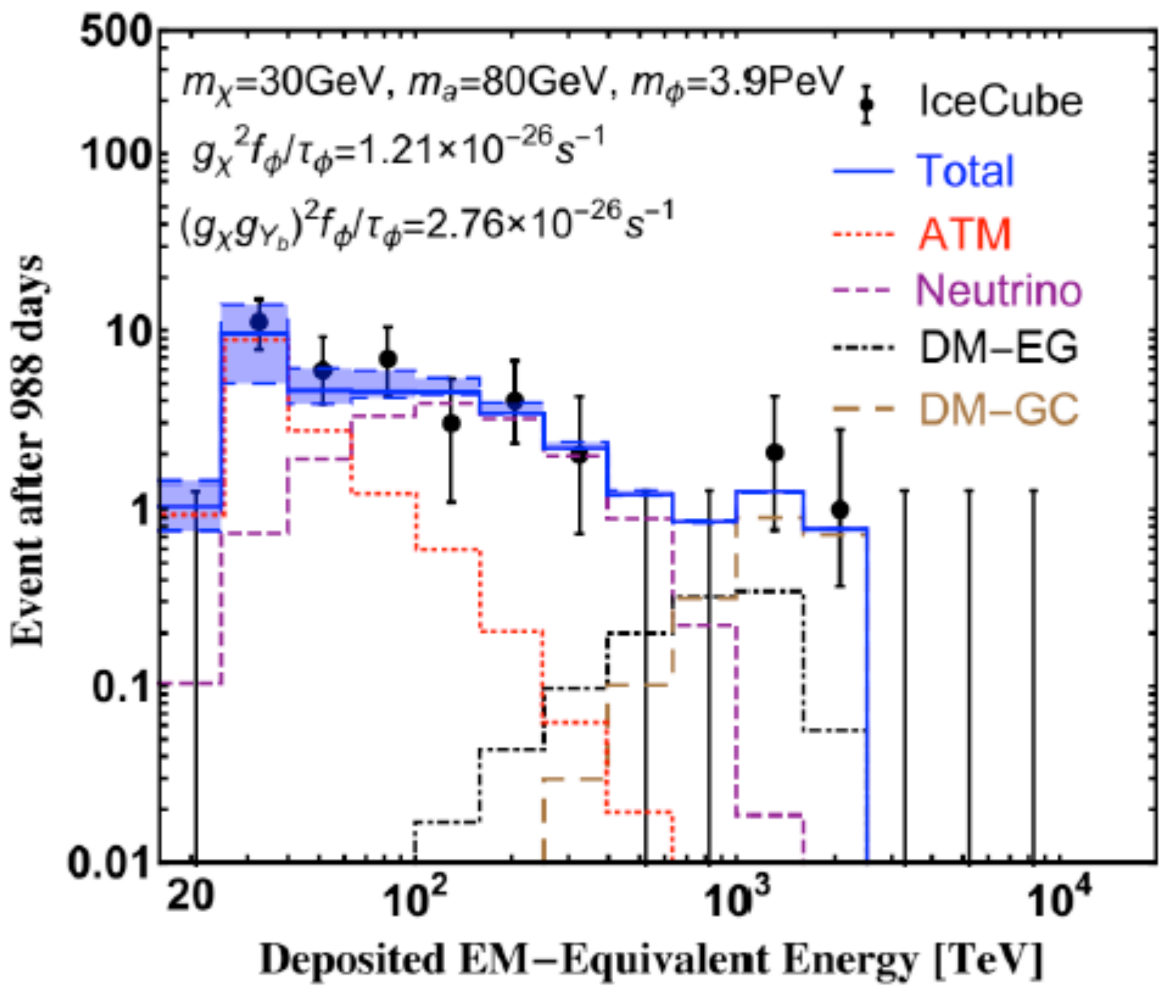


- A comparison of captures rates for different WIMP velocity distributions show that overall changes in the capture rate are smaller than 20%

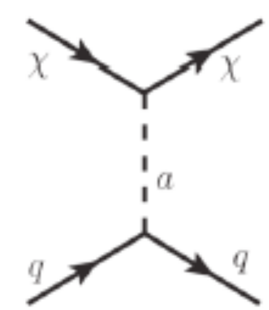
Boosted Dark Matter

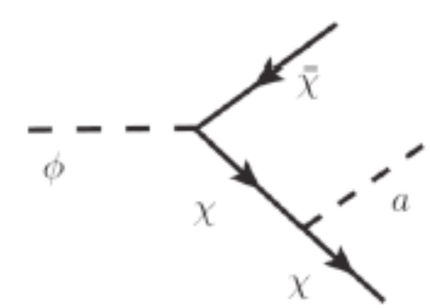


- "Boosted Dark Matter Search"
  - Following search proposed by Kopp, Liu, Wan (2015)
  - using "Echo Technique" Li, Bustamante, Beacom (2016)



Very heavy dark matter particle ϕ decays to lighter stable dark matter χ →boost!





Recoil (only hadronic cascades)

$\phi \to \chi\,\bar{\chi}\,a,\ a \to b\,\bar{b}$
→ν's

May sound crazy, but is just an example for exotic interactions in IceCube detectable via recoil

R. Caputo PoS(ICRC2017) 910 (DM)
J. Perkins PoS(ICRC2017) 761 (Instrument)
R. Caputo PoS(ICRC2017) 783 (Performance)

AMEGO - All-sky Medium Energy Gamma-ray Observatory

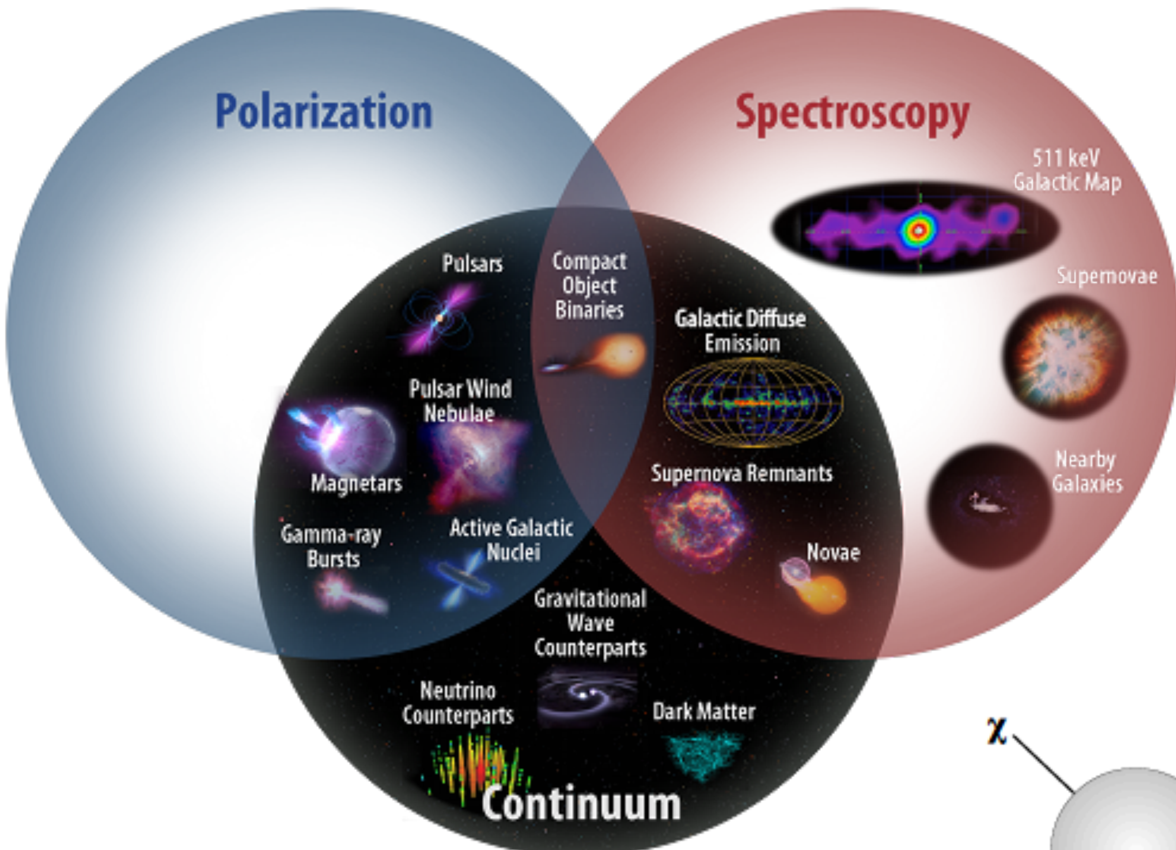
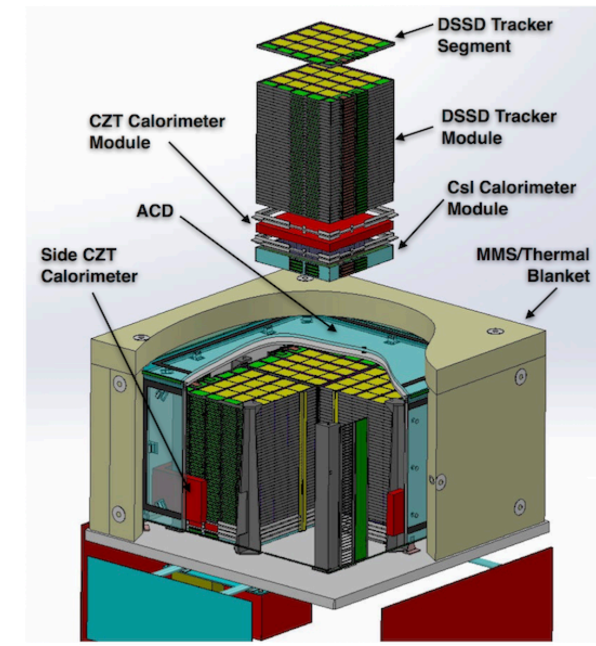
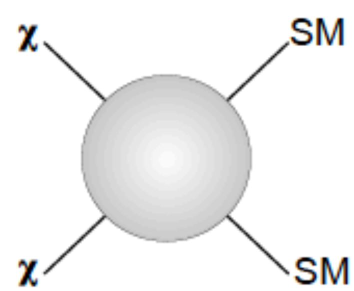


Image - https://asd.gsfc.nasa.gov/amego/

- **Weakly Interacting Massive Particles (WIMPs)**
  - Targets: dwarf spheroidal galaxies, Galactic Center (GC)
  - LAT: m_χ~500 MeV to 100 GeV, ACT: >1 TeV
- **Weakly Interacting Sub-eV Particles (WISPs)**
  - Targets: pulsars, galaxy clusters, SN
  - X-rays, LAT: $m_{neV} \lesssim 10^{-2}$, $0.5 \lesssim m_{neV} \lesssim 100$





WIMPs	WISPs

• Interact via gravity and "weak" force
• Thermal: <σv> ~3x10^{26}cm^{3}s^{-1}
• Dark matter (χ) and dark mediators (A')
• m_χ: ~10 MeV to >TeV
	• Not thermally produced
	• Oscillate to γ in B fields
	  ○ QCD axion ($m_a \propto g_{a\gamma}$)
	  ○ ALPs, etc.
	• WISP-induced spectral features
	• Polarization

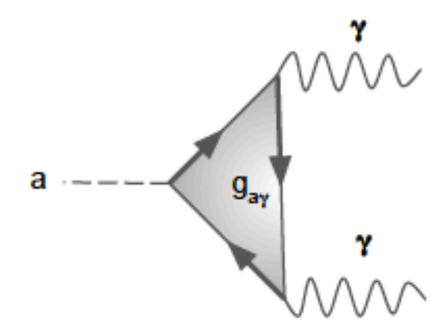
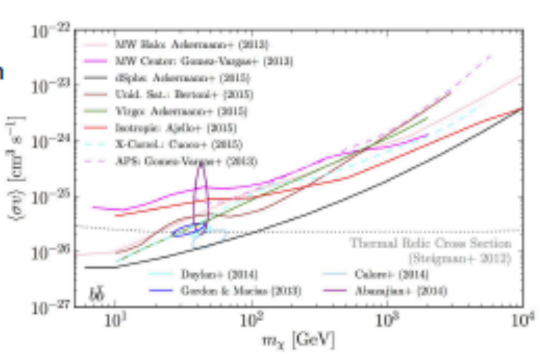


Figure 1: (top) Feynman cartoon of WIMP annihilation (χ) to Standard Model Particles (SM). (right) Summary of WIMP dark matter results obtained with *Fermi*-LAT. Lines are upper limits while closed contours are the Galactic Center Excess from dark matter annihilations [7, 10].



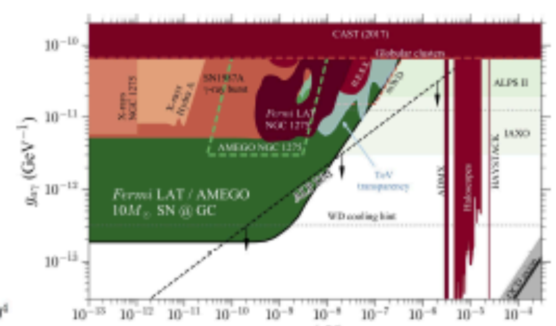


Figure 2: (top) Feynman cartoon of WISP oscillation (a) to γ-rays. (left) Summary of ALP results obtained with *Fermi*-LAT and regions of sensitivity for AMEGO. Shaded regions are excluded [11].

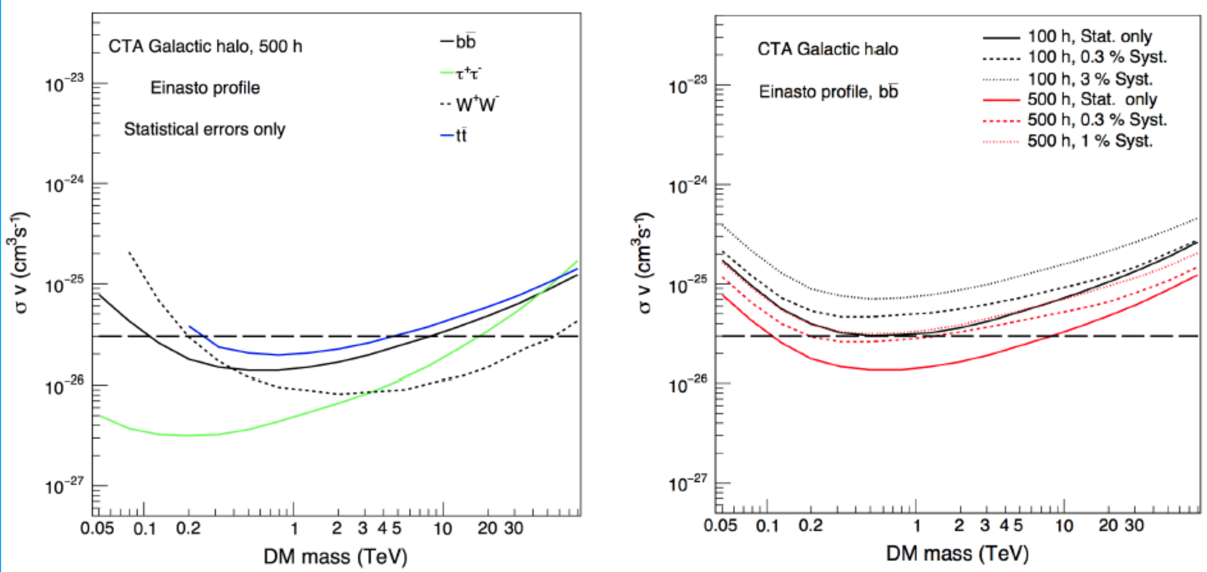
- Probe Concept: 2020 NASA Astrophysics Decadal Review
- Energy Range: 200 keV to 10 GeV
- Observing strategy: survey (80% sky/orbit, ~2.5 sr FoV)

https://asd.gsfc.nasa.gov/amego/

CTA

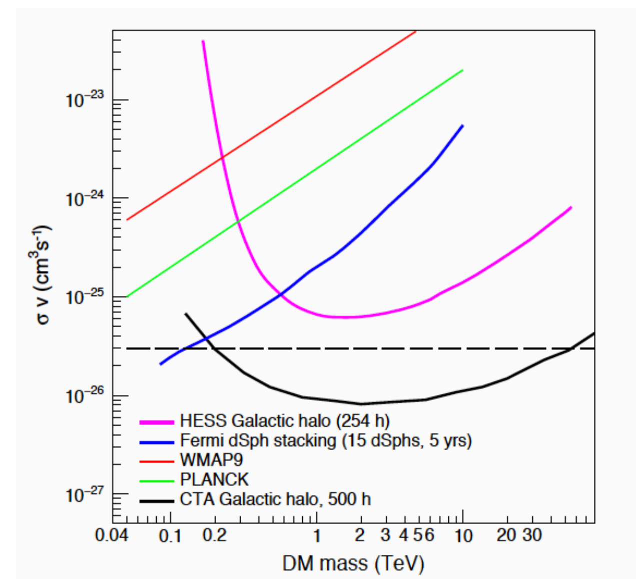
Galactic Halo (Einasto)

A.Morselli [CTA] ICRC2017 (921)



Galactic Halo (comparison)

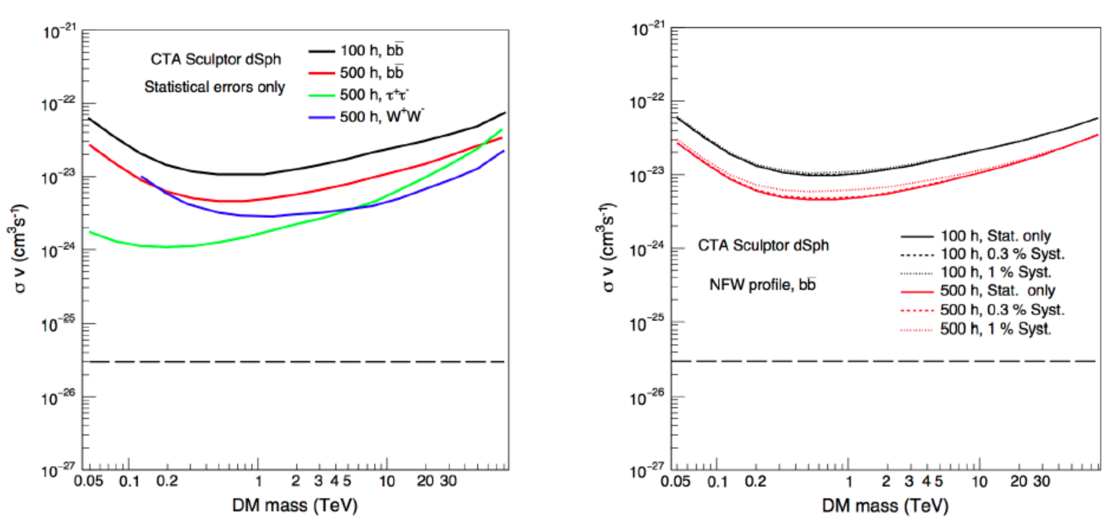
A.Morselli [CTA] ICRC2017 (921)



- Fermi-LAT, H.E.S.S., CTA WW
- PLANCK bb

Dwarfs (Sculptor)

A.Morselli [CTA] ICRC2017 (921)



Large Magellanic Cloud

A.Morselli [CTA] ICRC2017 (921)