ICRC2017

35th International Cosmic Ray Conference
The Astroparticle Physics Conference

Dark Matter

(Rapporteur Talk)

Carsten Rott

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20, 2017

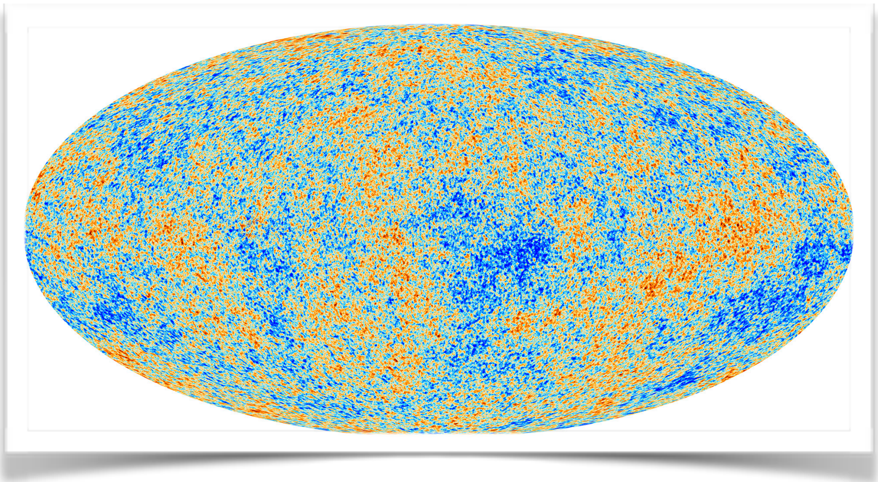
35th International Cosmic Ray Conference 2017(ICRC2017) at the
Busan Exhibition & Convention Center (BEXCO) in Busan, South Korea

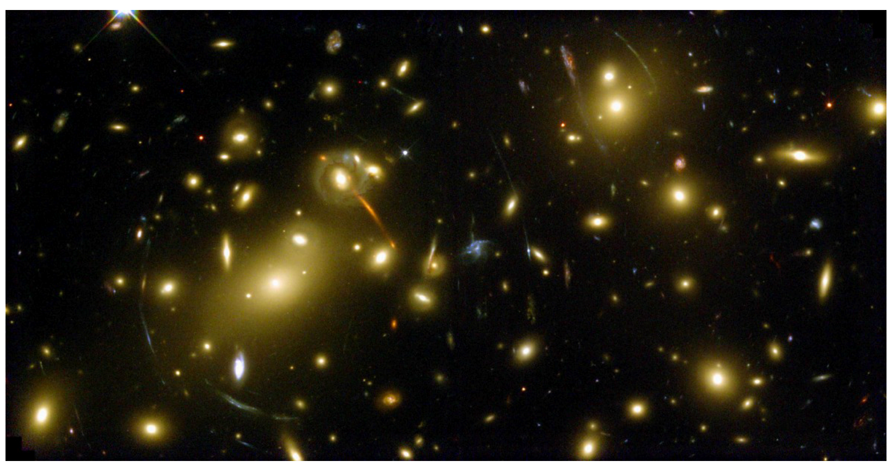
General Statement

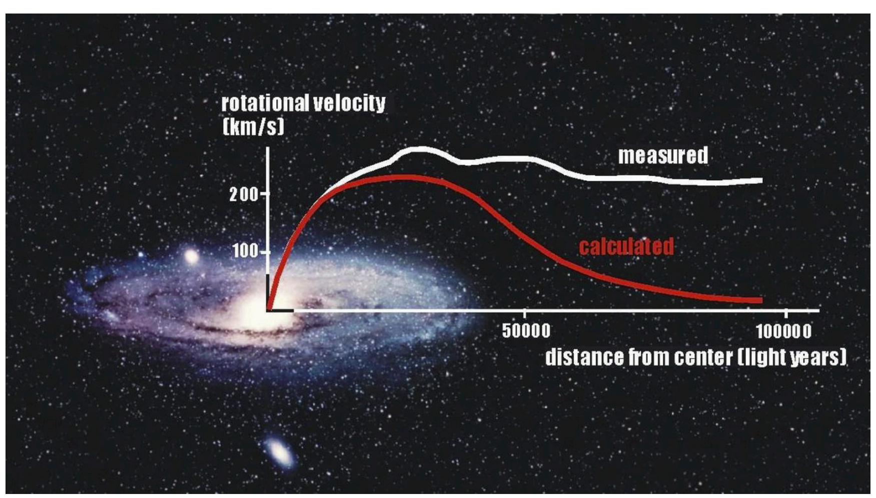
- Will only cover the contributions to the DM session (poster and talks)
  - Many talks in other sessions included beyond SM scenarios. I will reference relevant talks where possible.
- The main focus of this conference is indirect DM searches, direct detection was already covered in two highlight talks.
- Lastly due to the large amount of contributions, I cannot cover everything, apologize for what is not highlighted here.

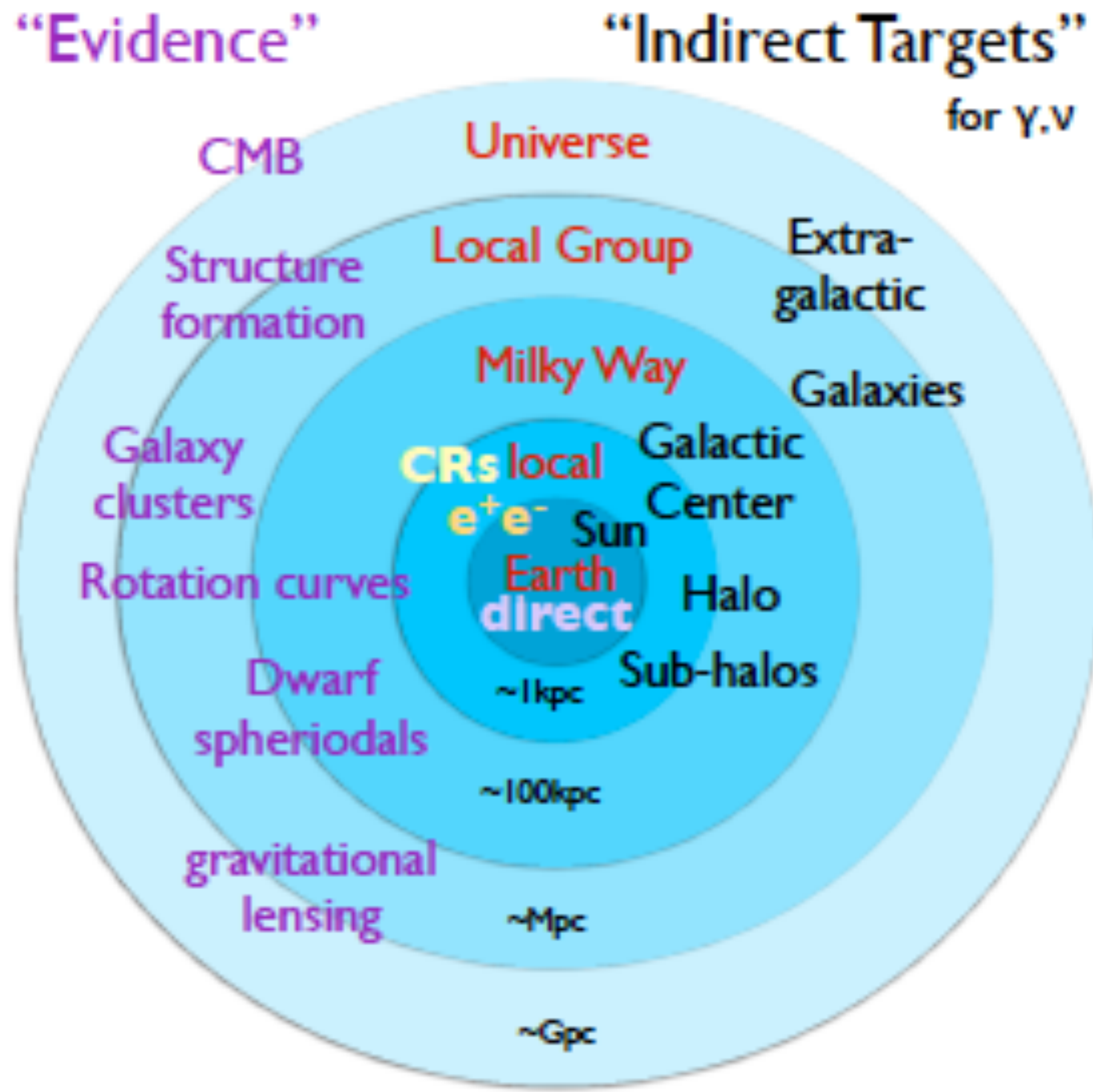
Motivation

Evidence for Dark Matter







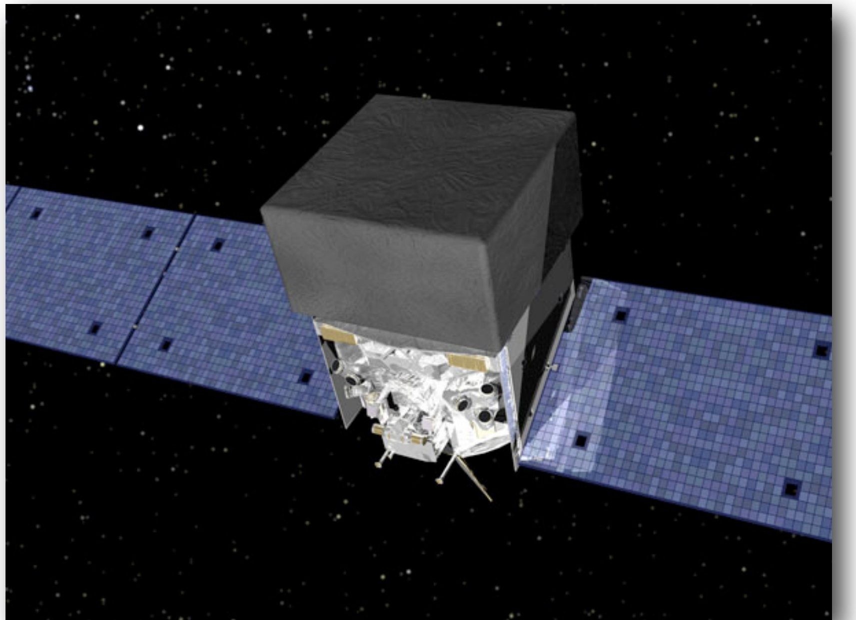


- Dark Matter already gravitationally "observed", but ...
  - What is it ?
  - What are it's properties ?

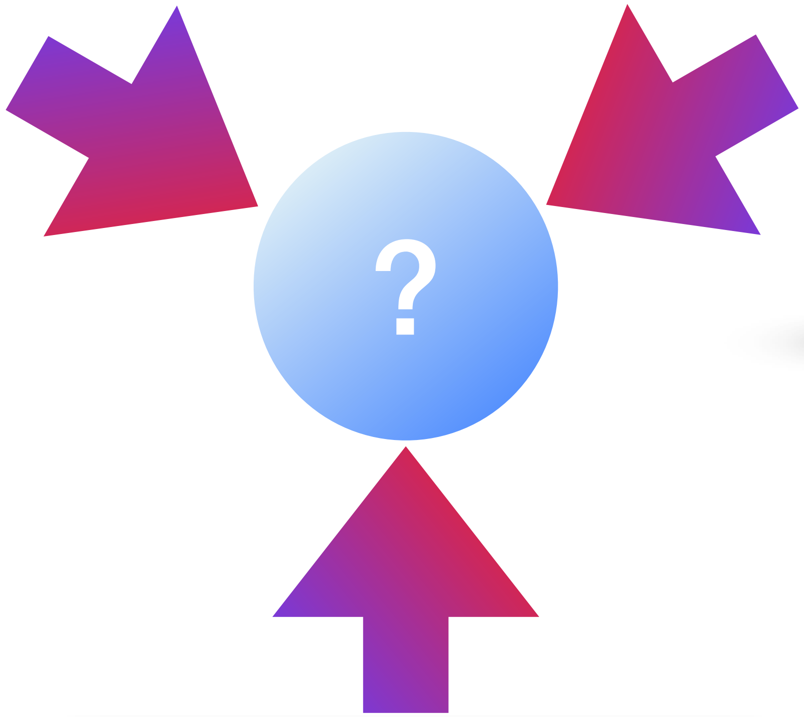
χ

Synergy

Indirect



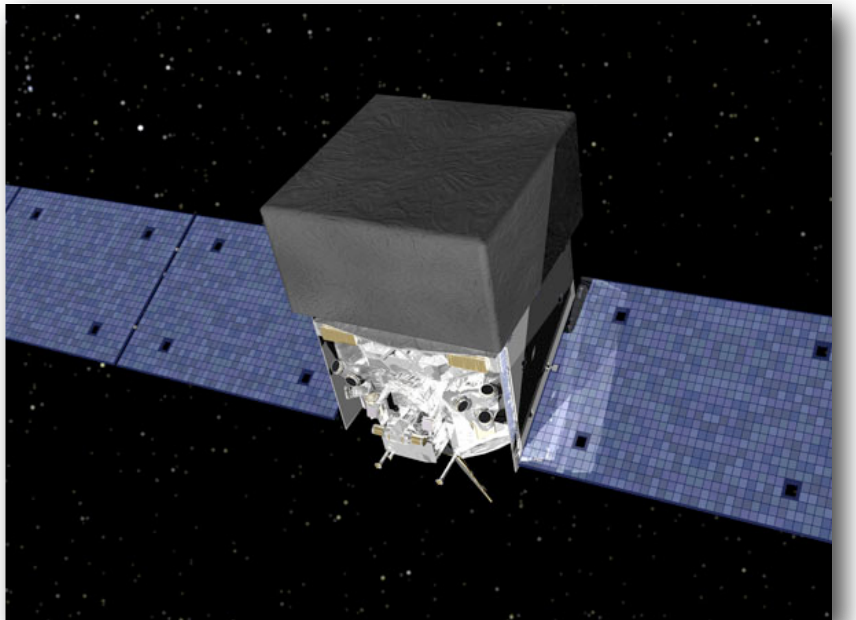
Direct



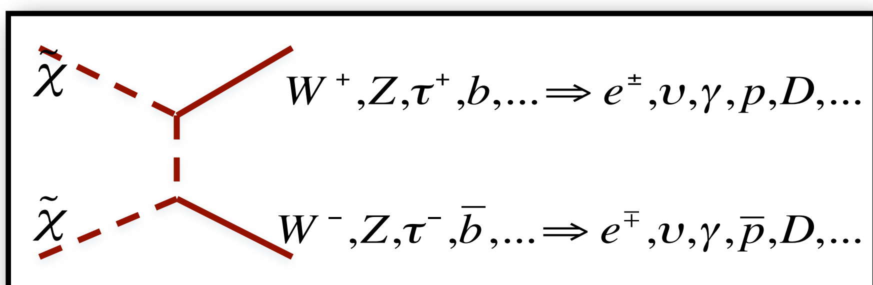
Collider

Synergy

Indirect



Annihilation / Decay



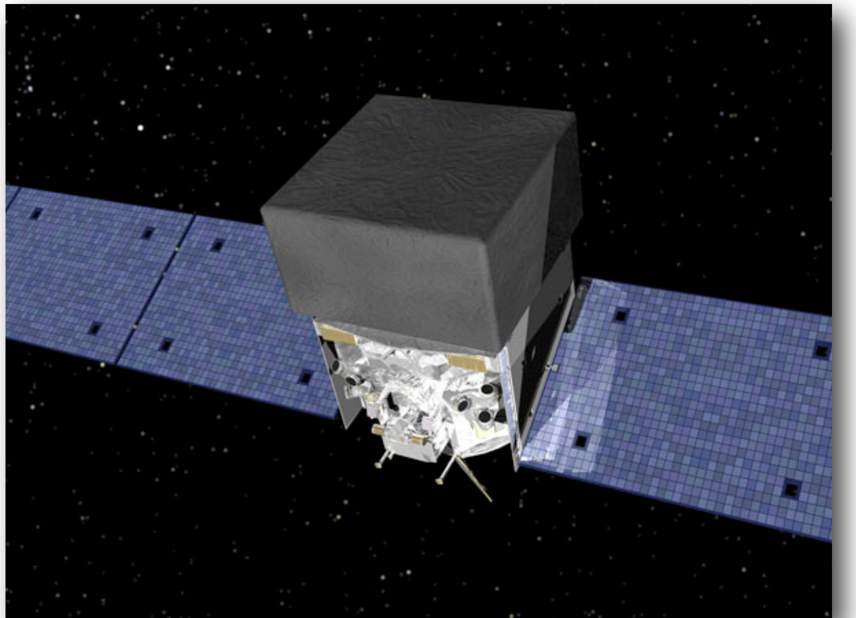
Direct

?

Collider

Synergy

Indirect



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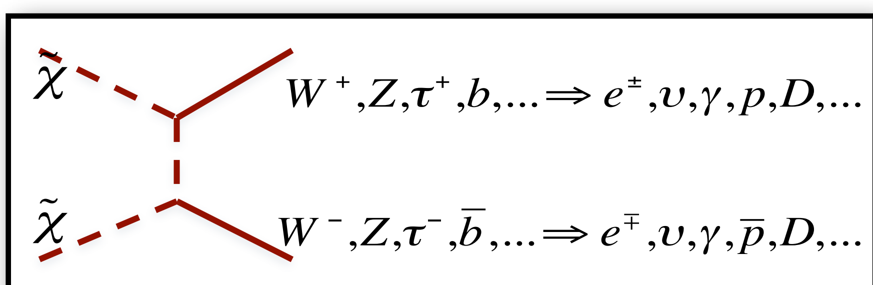
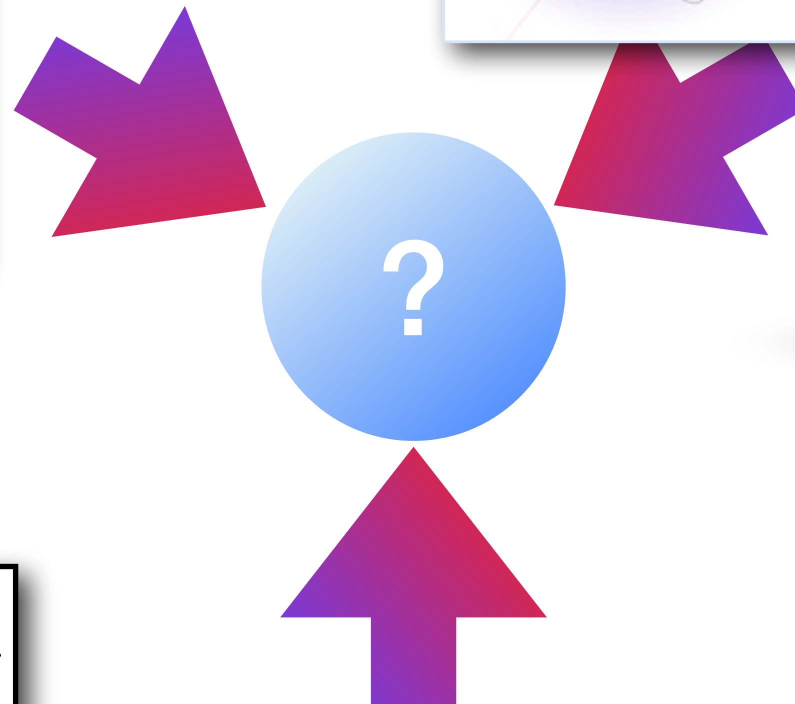
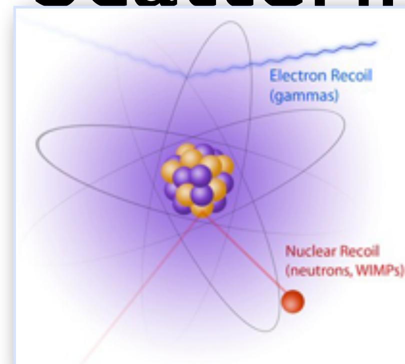




Scattering

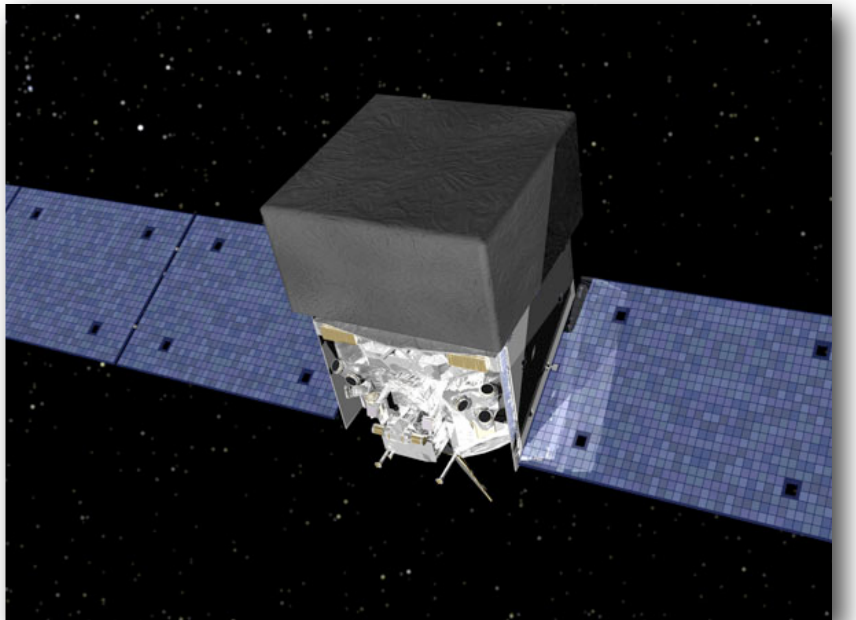


Direct

Collider

Synergy

Indirect



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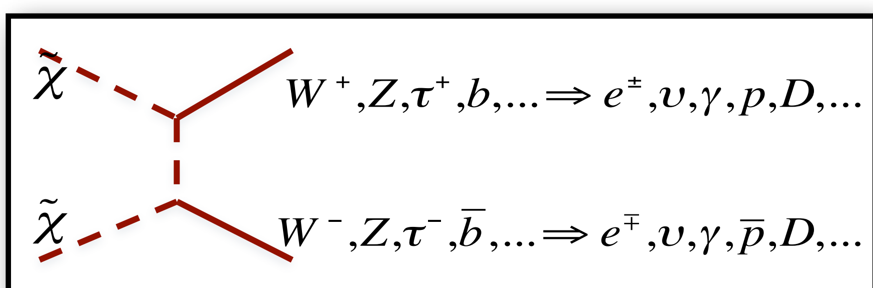
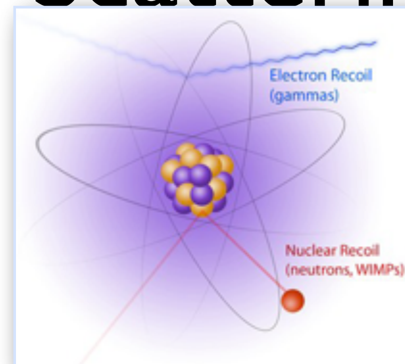


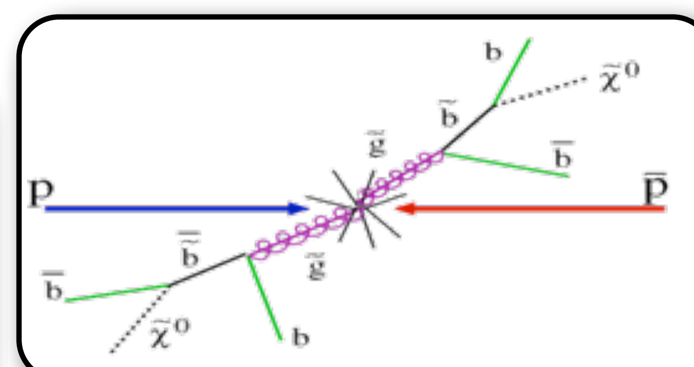
Scattering



Direct

?

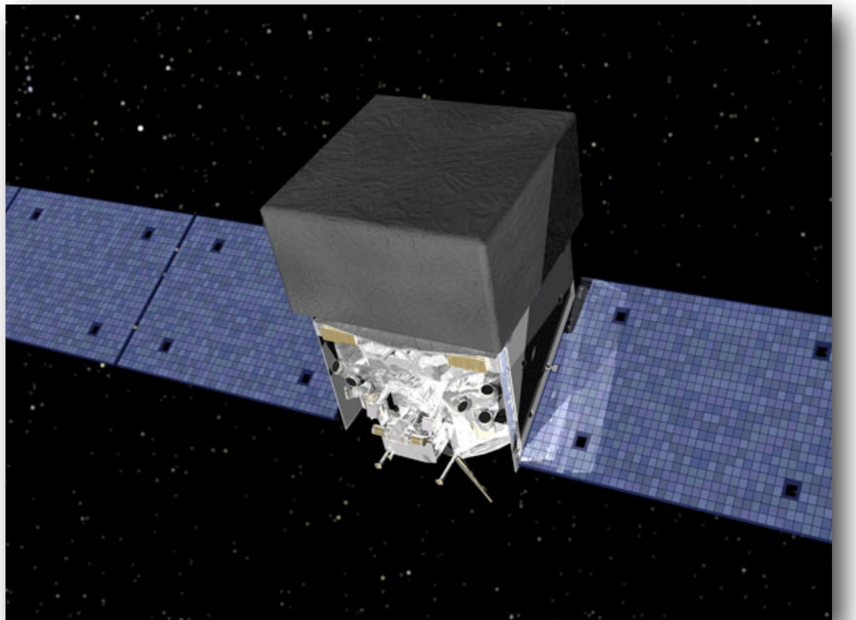
Production



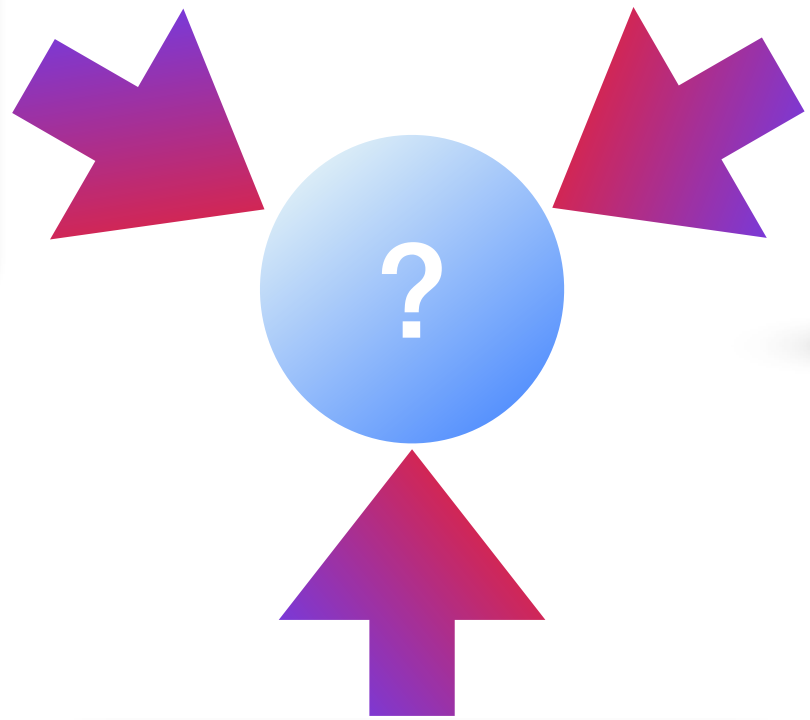
Collider

Synergy

Indirect



Direct



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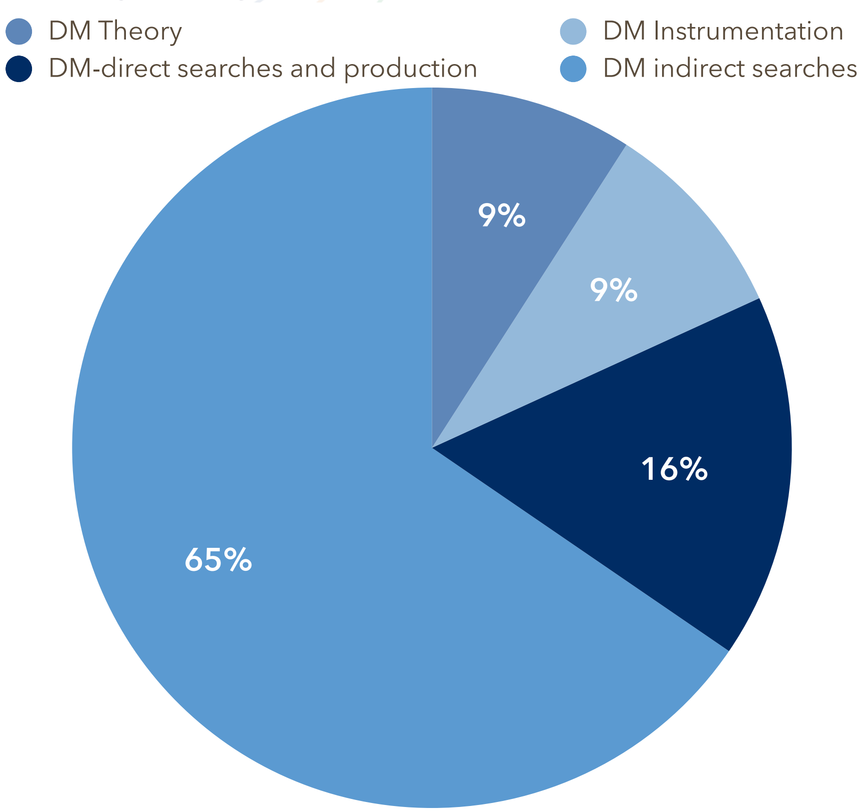
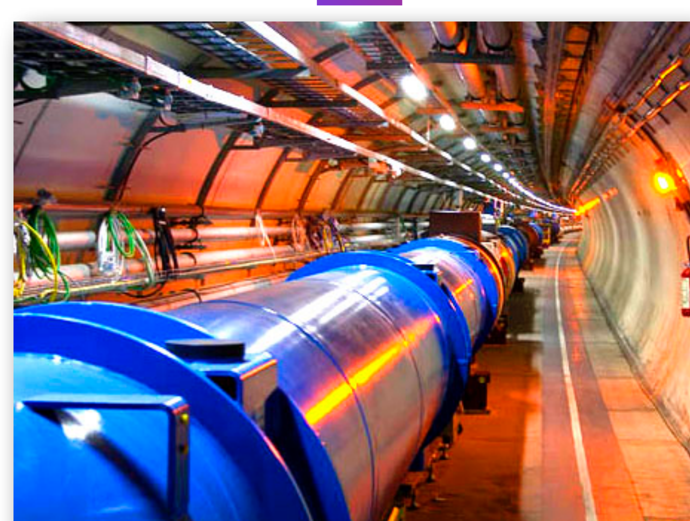
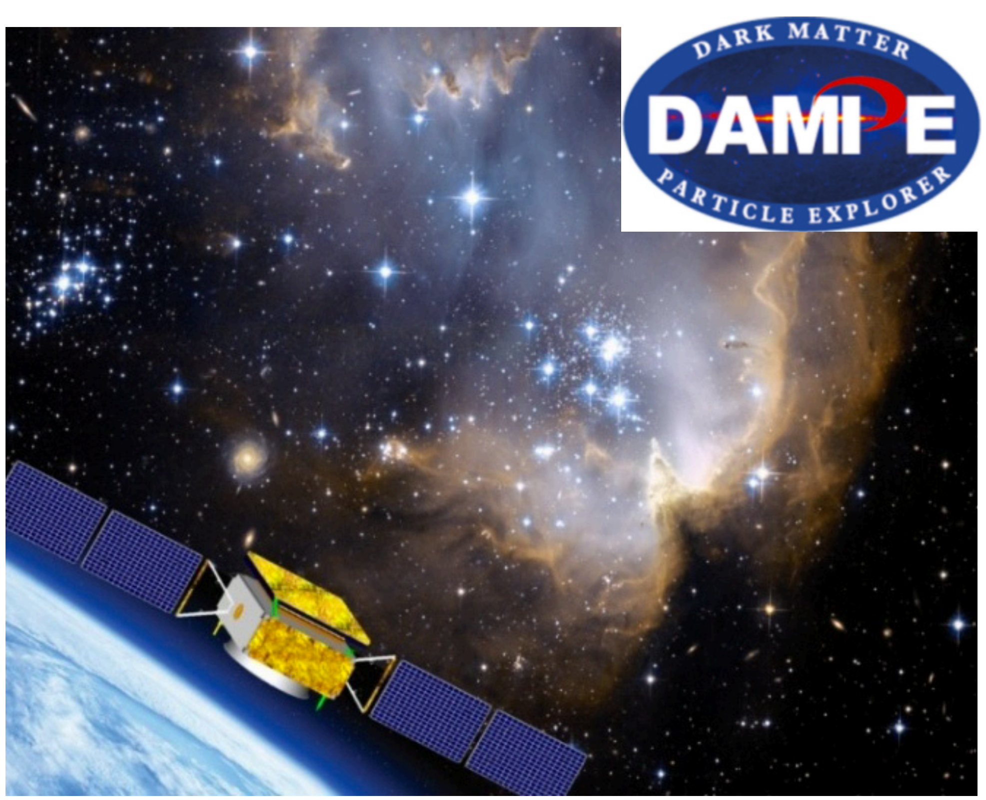


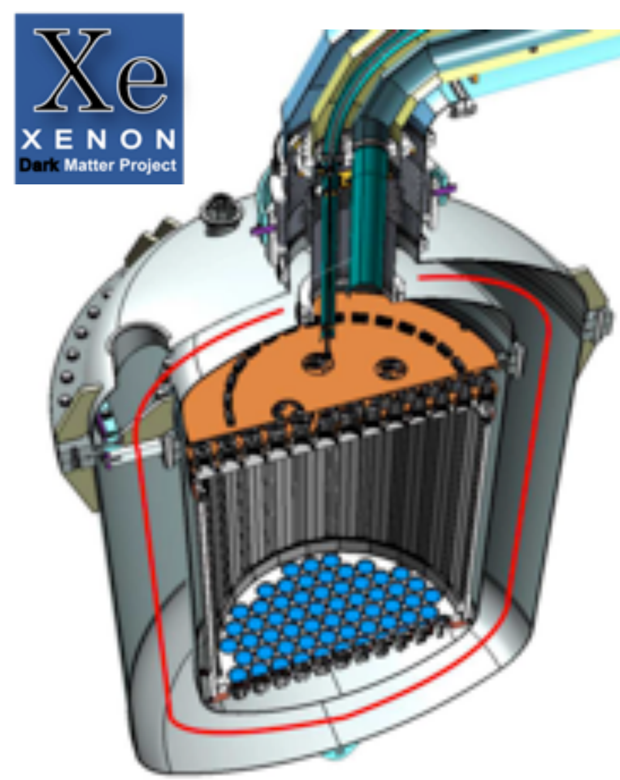


Collider

Dark Matter Talks

- **DM related Review / Highlight talks**
  - Review of Dark Matter Physics (Yeongduk Kim) [Invited Review Talk (Wednesday morning)]
  - First Light from the XENON1T Dark Matter Experiment (Elena Aprile) [High light talk (Wednesday morning)
  - **Dar**k **M**atter **P**article **E**xplorer: The First Chinese Astronomical Satellite (Jin Chang) [High light talk (Monday morning)





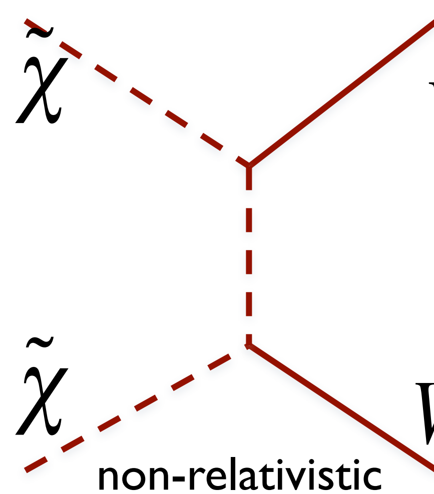
Indirect Dark Matter Searches

Dark Matter Signals

- Identify overdense regions of dark matter

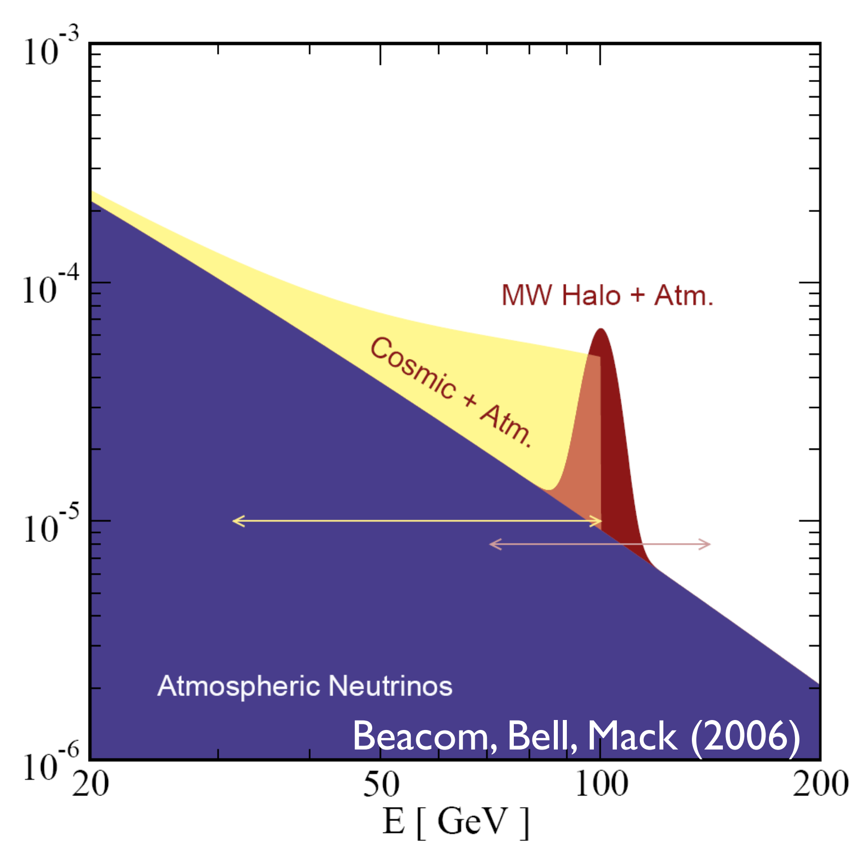
  ⇒self-annihilation can occur at significant rates
- Pick prominent Dark Matter target
- Understand / predict backgrounds
- Exploit features in the signal to better distinguish against backgrounds

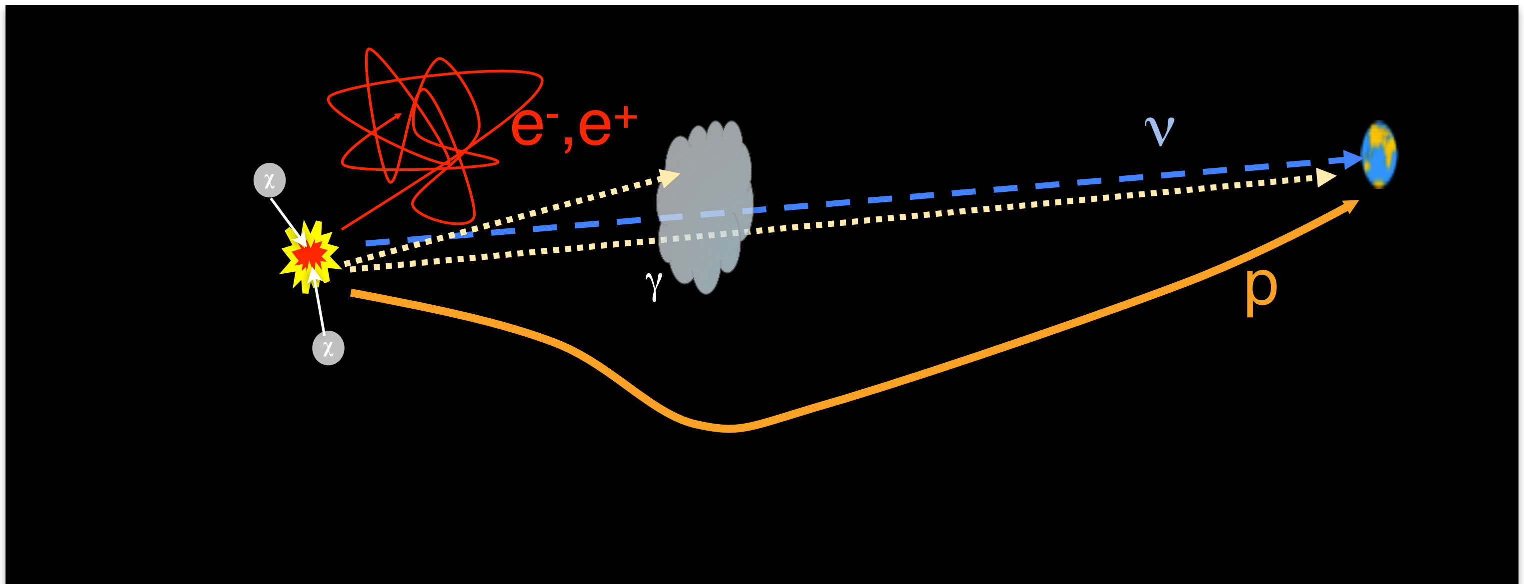
Annihilation Rate ~ρ^2
(Decay Rate ~ρ)



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

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





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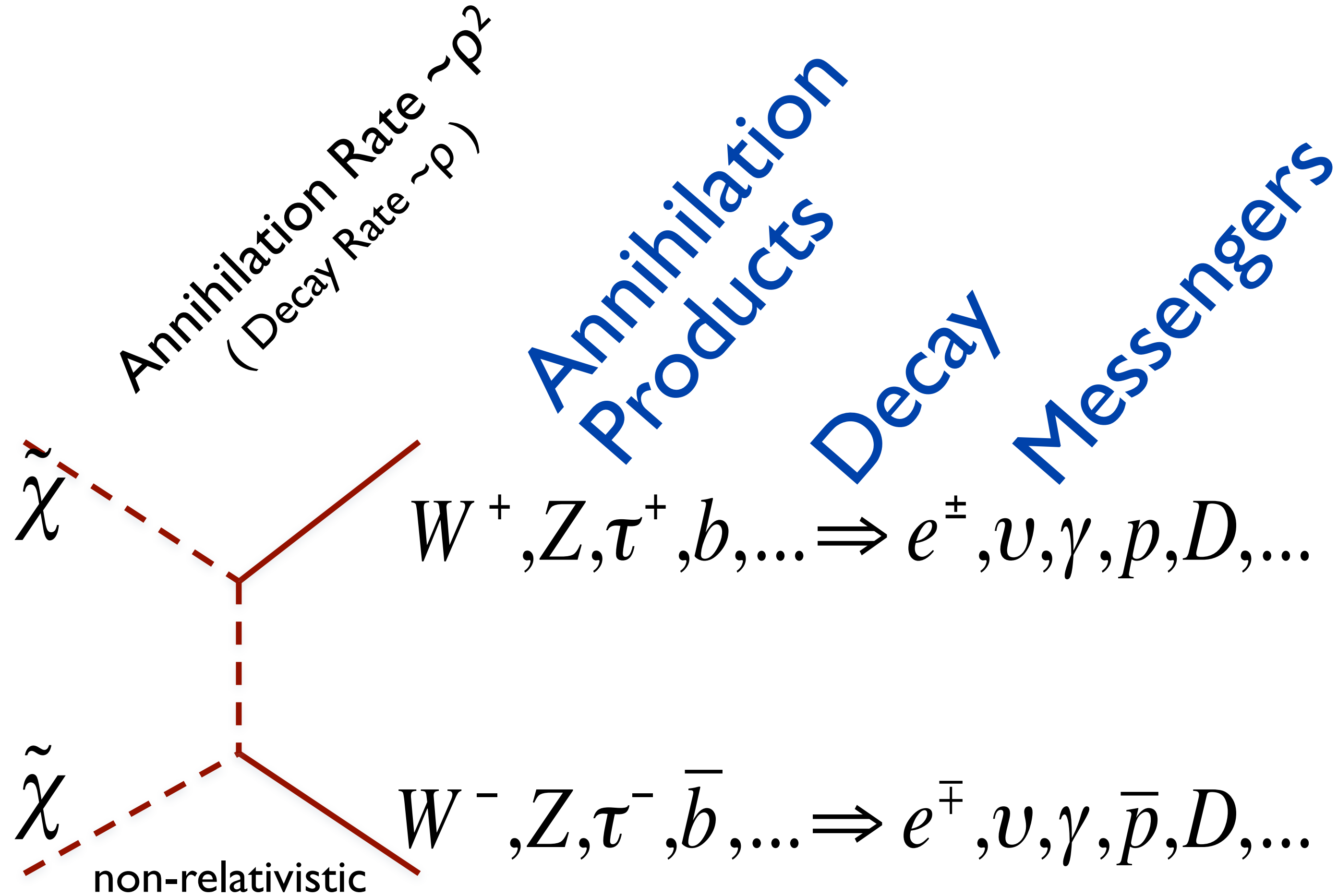
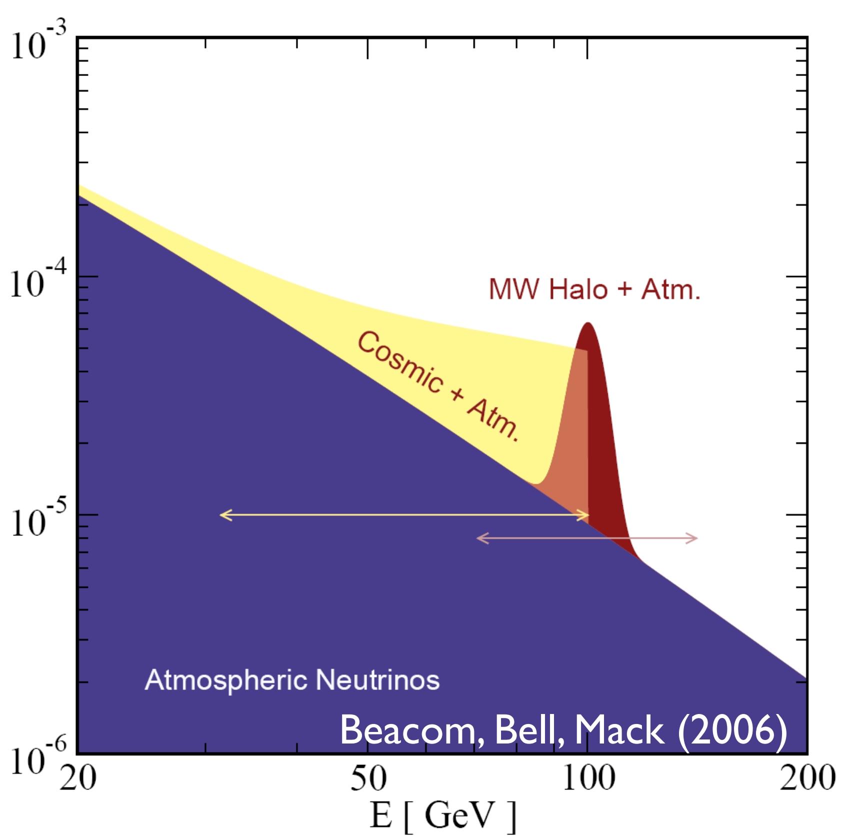
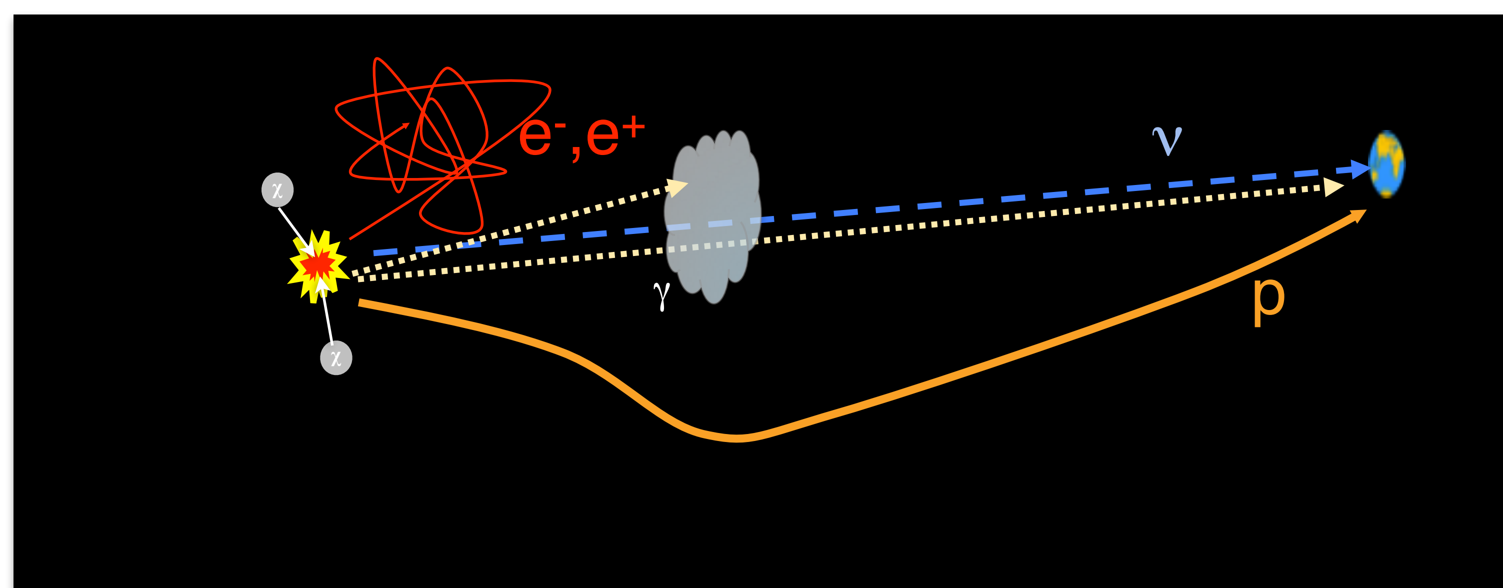
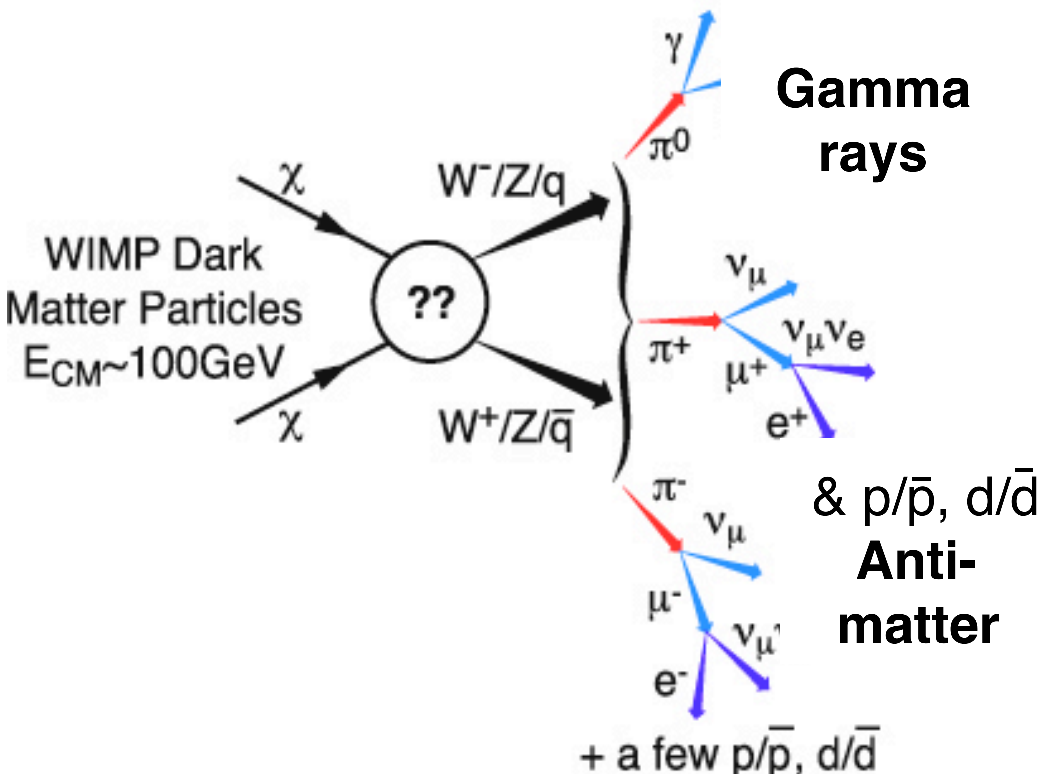


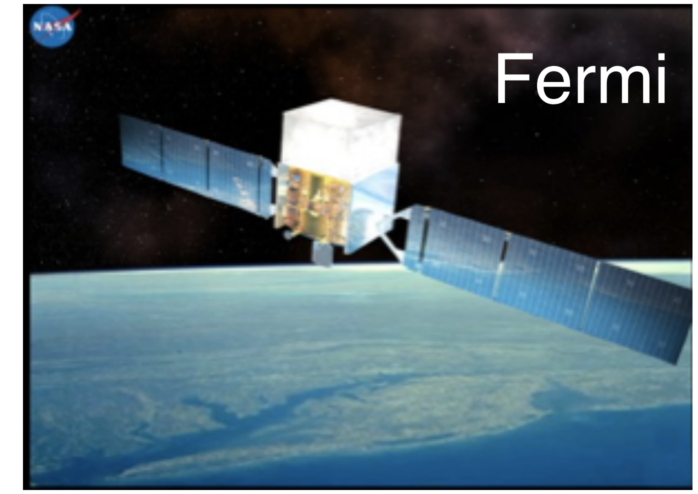


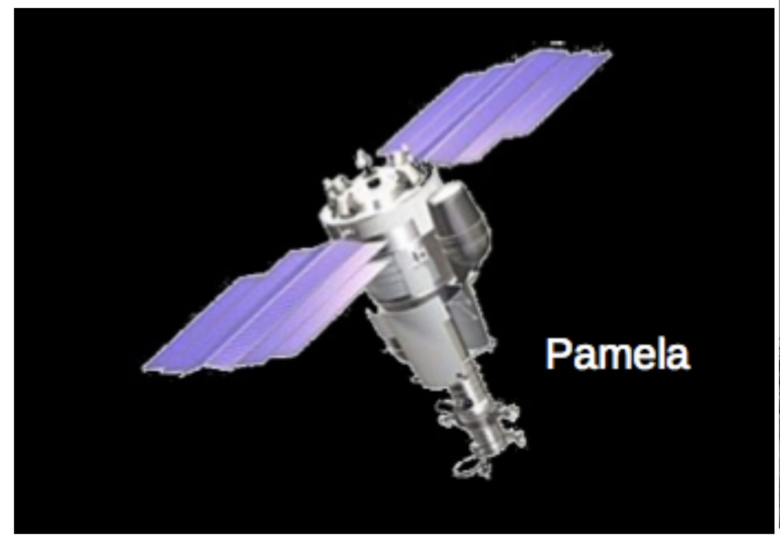


Indirect Detection of Dark Matter

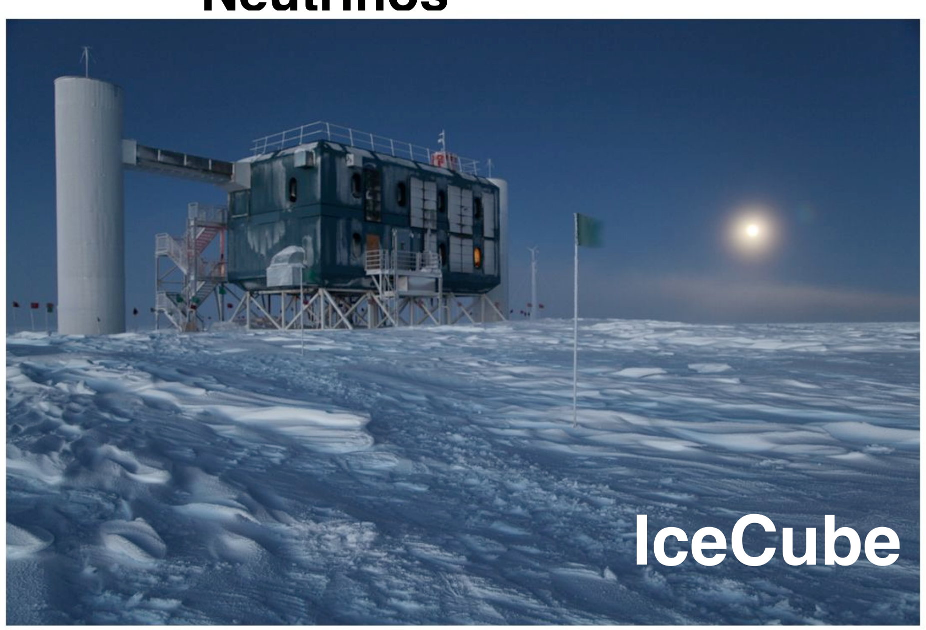
Annihilation signals







Neutrinos



Dark Matter Distributions / Halo Profiles

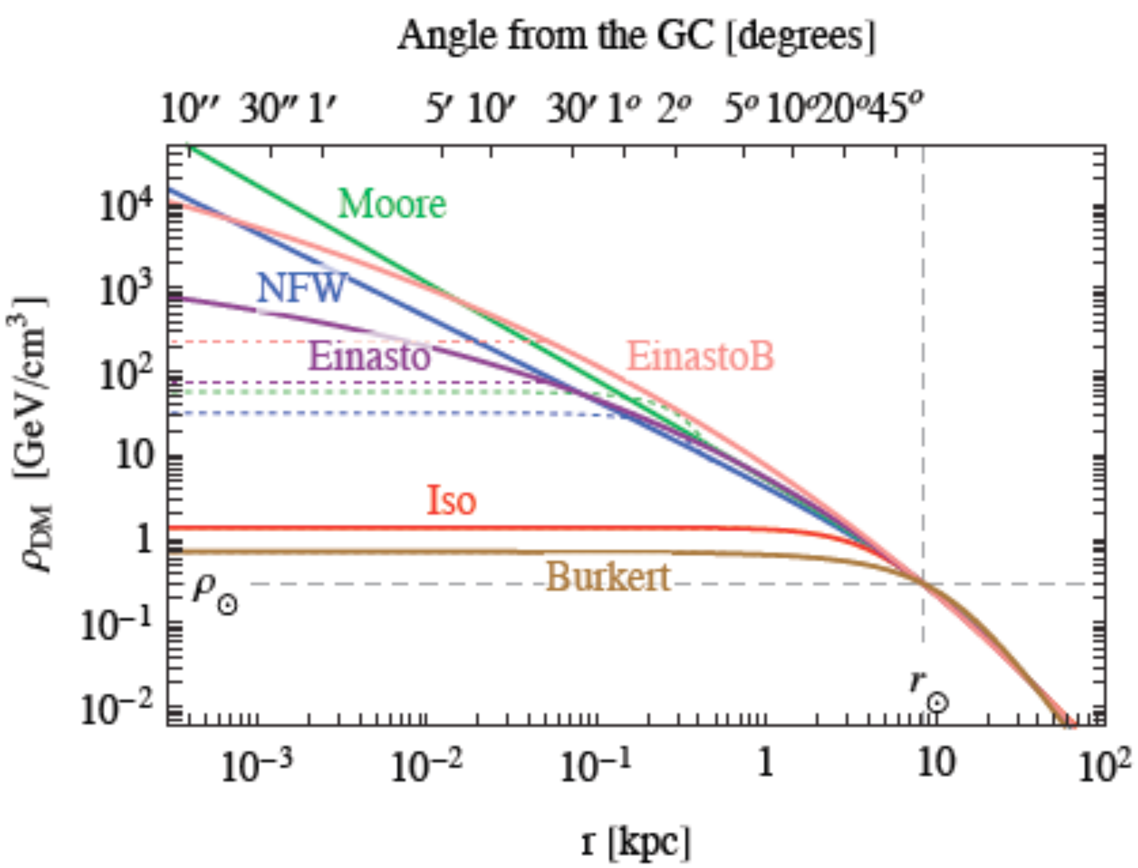
$$\text{NFW}: \quad \rho_{\text{NFW}}(r) = \rho_s \frac{r_s}{r}\left(1+\frac{r}{r_s}\right)^{-2}$$

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

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

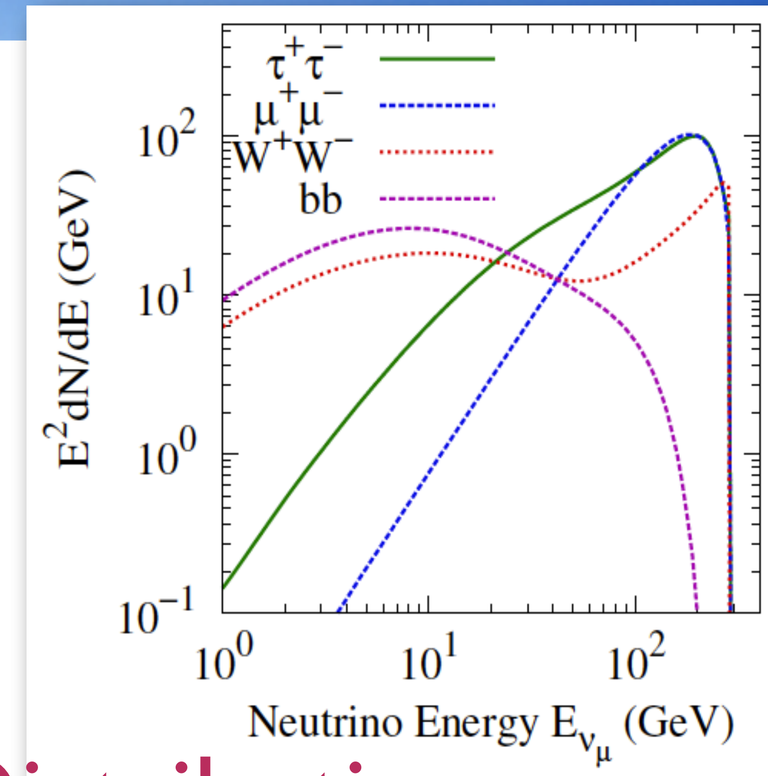
$$\text{Burkert}: \quad \rho_{\text{Bur}}(r) = \frac{\rho_s}{(1+r/r_s)(1+(r/r_s)^2)}$$

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



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

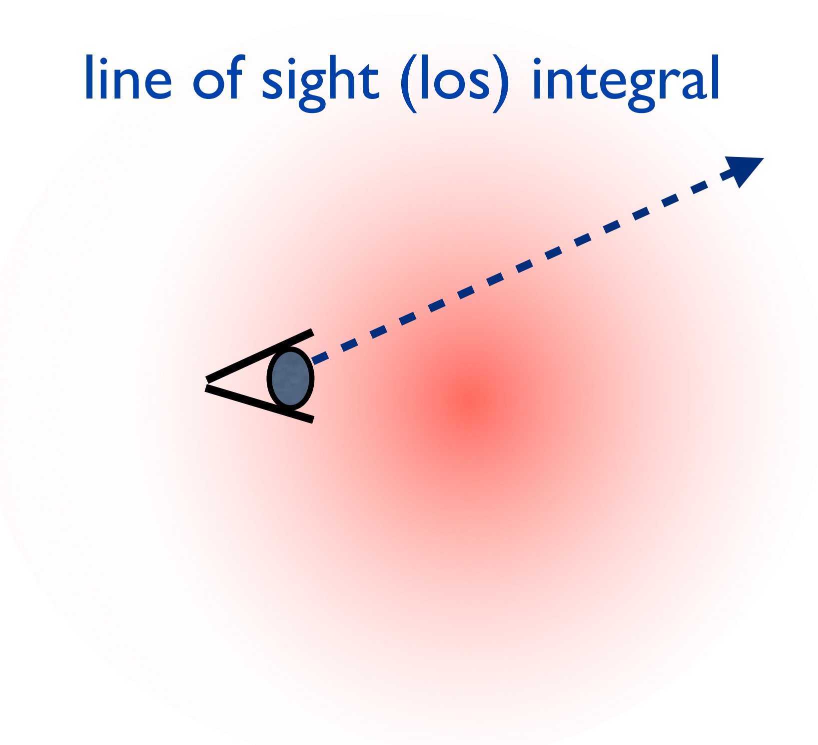
$$\frac{d\Phi}{dE}(E,\phi,\theta) = \frac{1}{4\pi}\frac{\langle\sigma_A v\rangle}{2m_\chi^2}\Sigma_f \frac{dN}{dE}B_f$$

Particle Physics

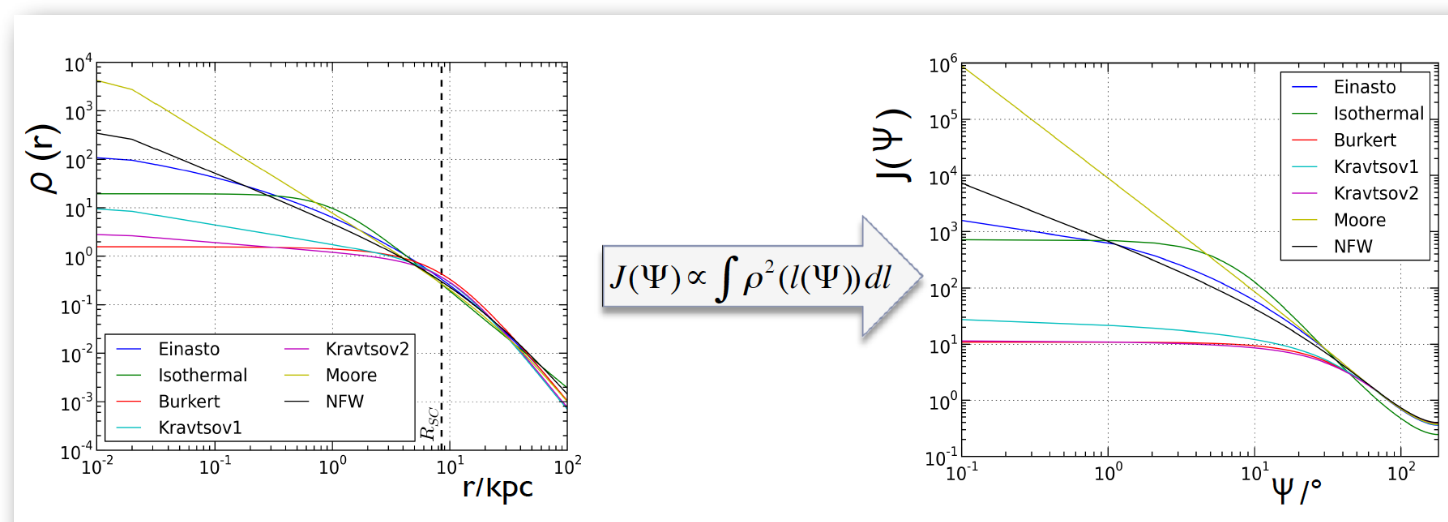
x

Dark Matter Distribution

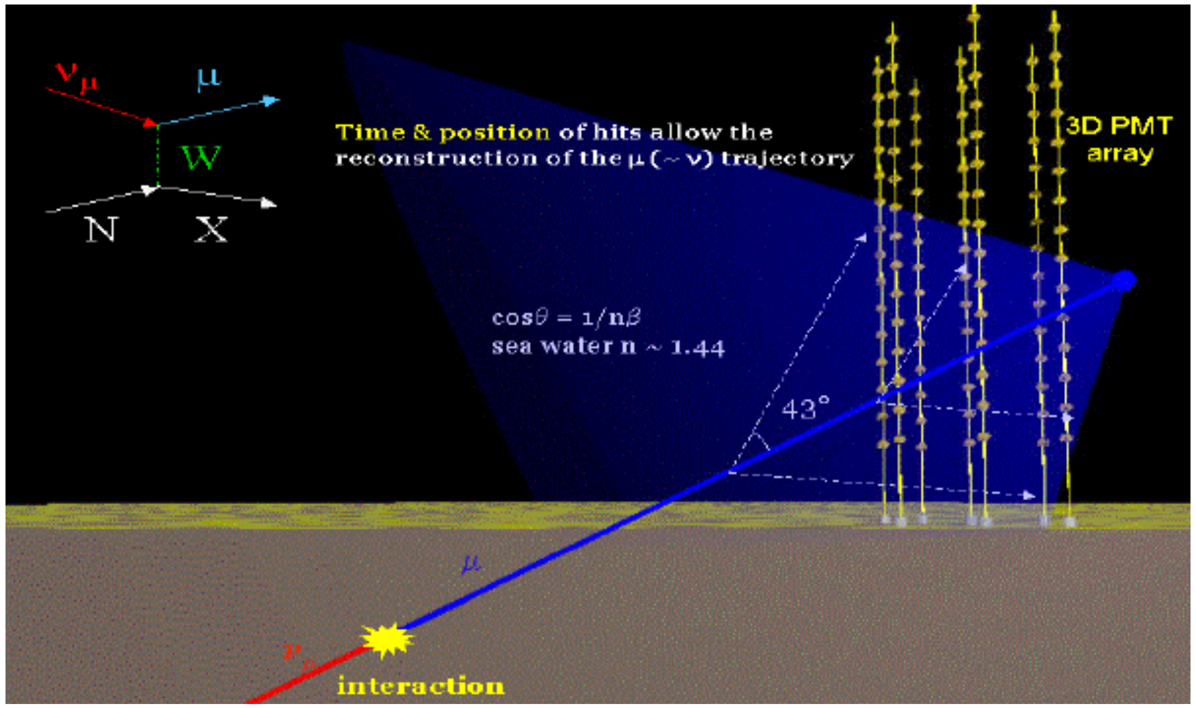
line of sight (los) integral

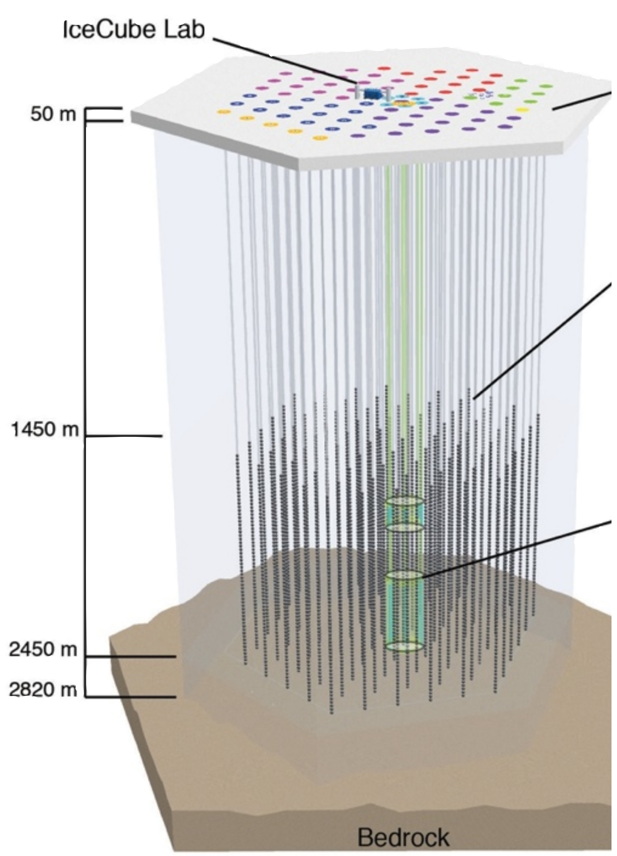


$$\int_{\Delta\Omega(\phi,\theta)} d\Omega' \int_{\text{los}} \rho^2(r(l,\phi'))dl(r,\phi')$$



INDIRECT DARK MATTER SEARCHES IN ICECUBE / ANTARES

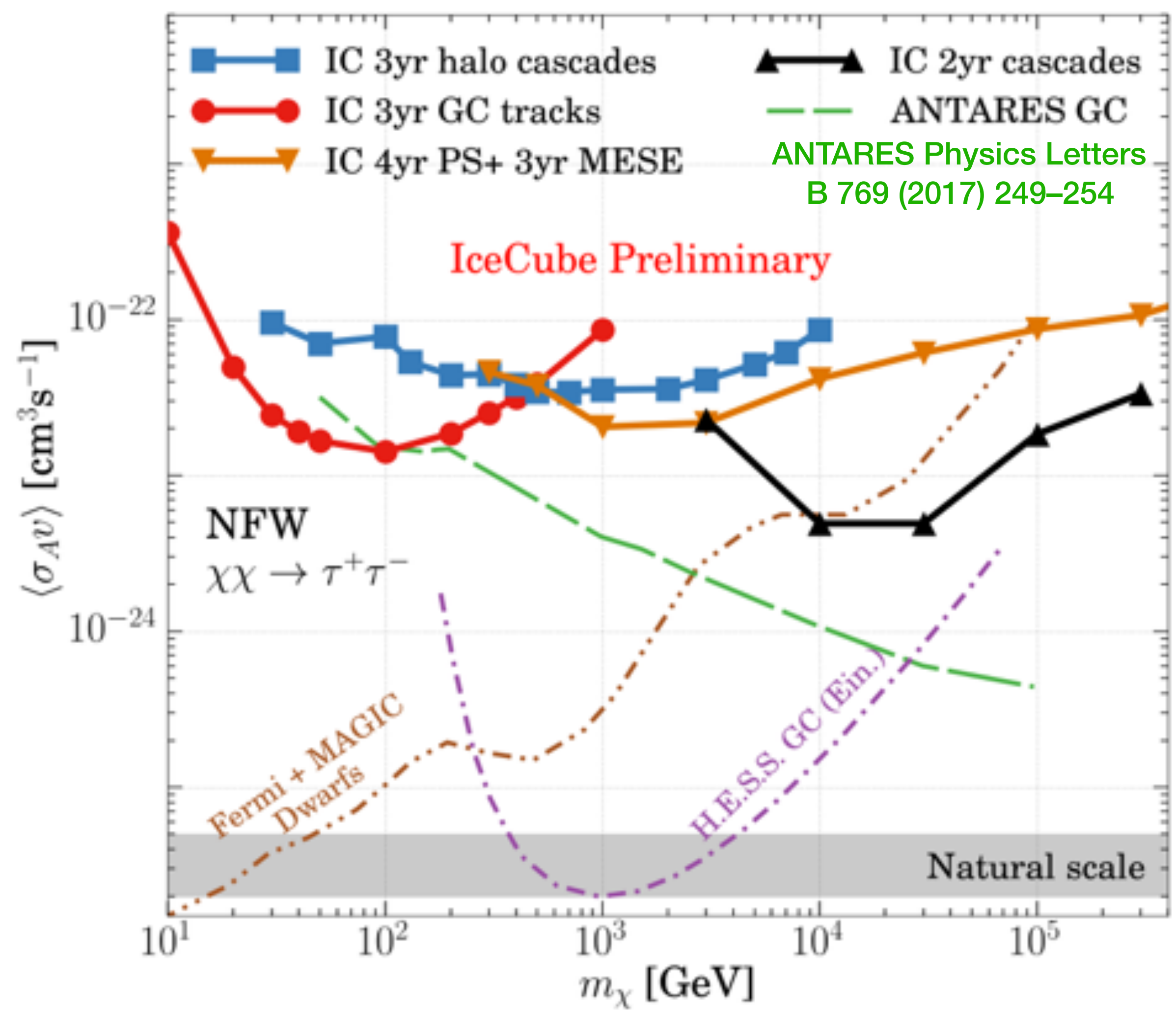




- ANTARES and IceCube complementary positioned on Northern and Southern Hemisphere
- Galactic Center only accessible in down-going events for IceCube
- Weak halo model dependence for observation of extended DM halo

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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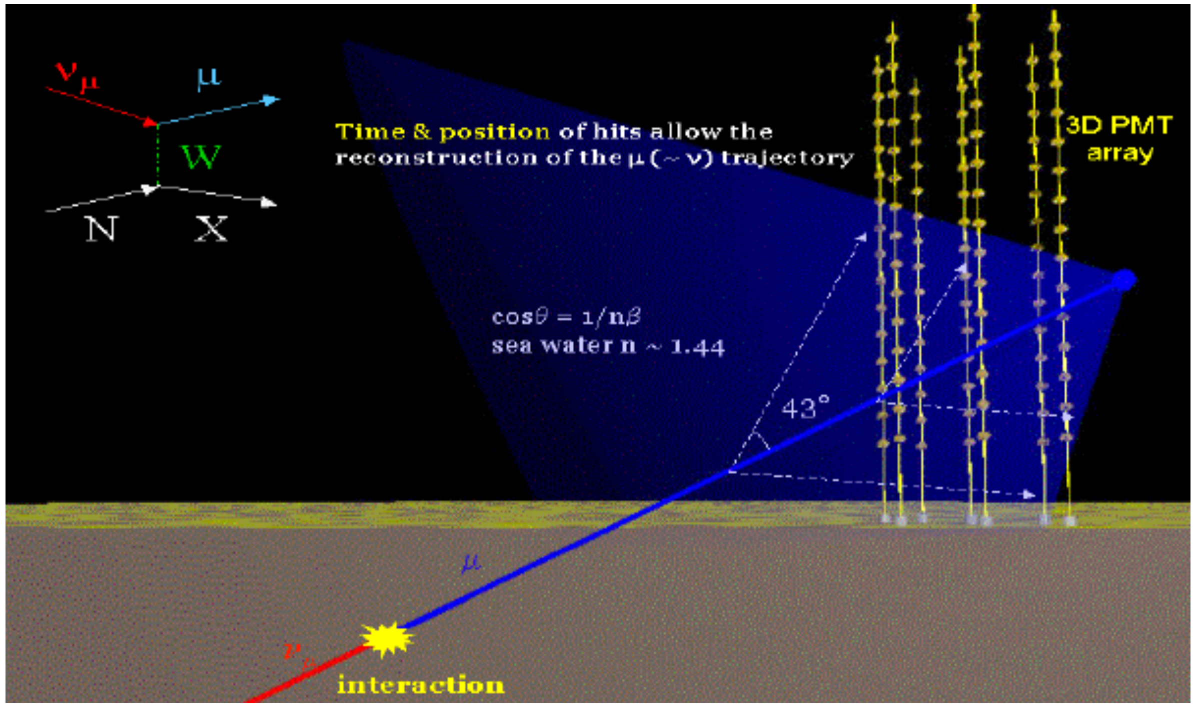

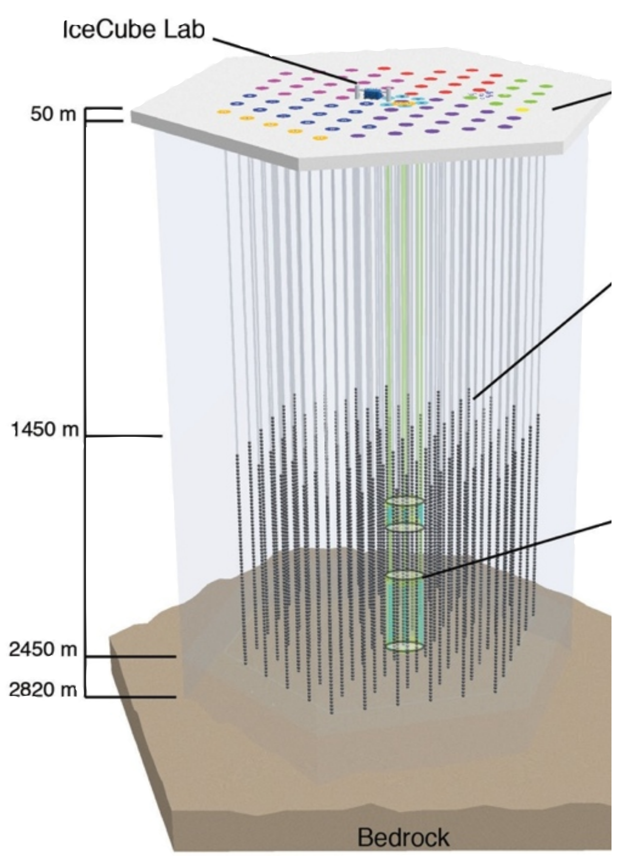

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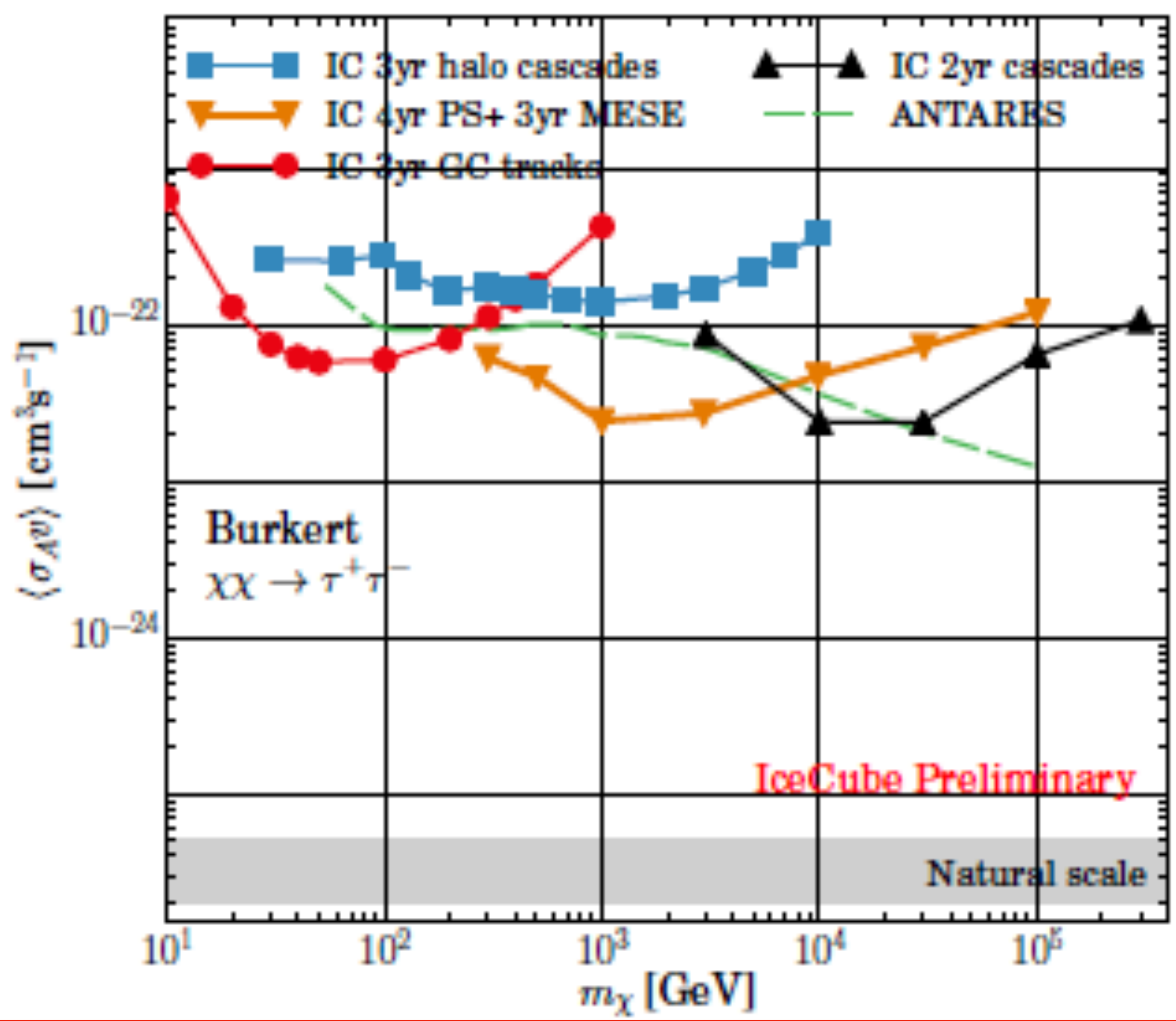
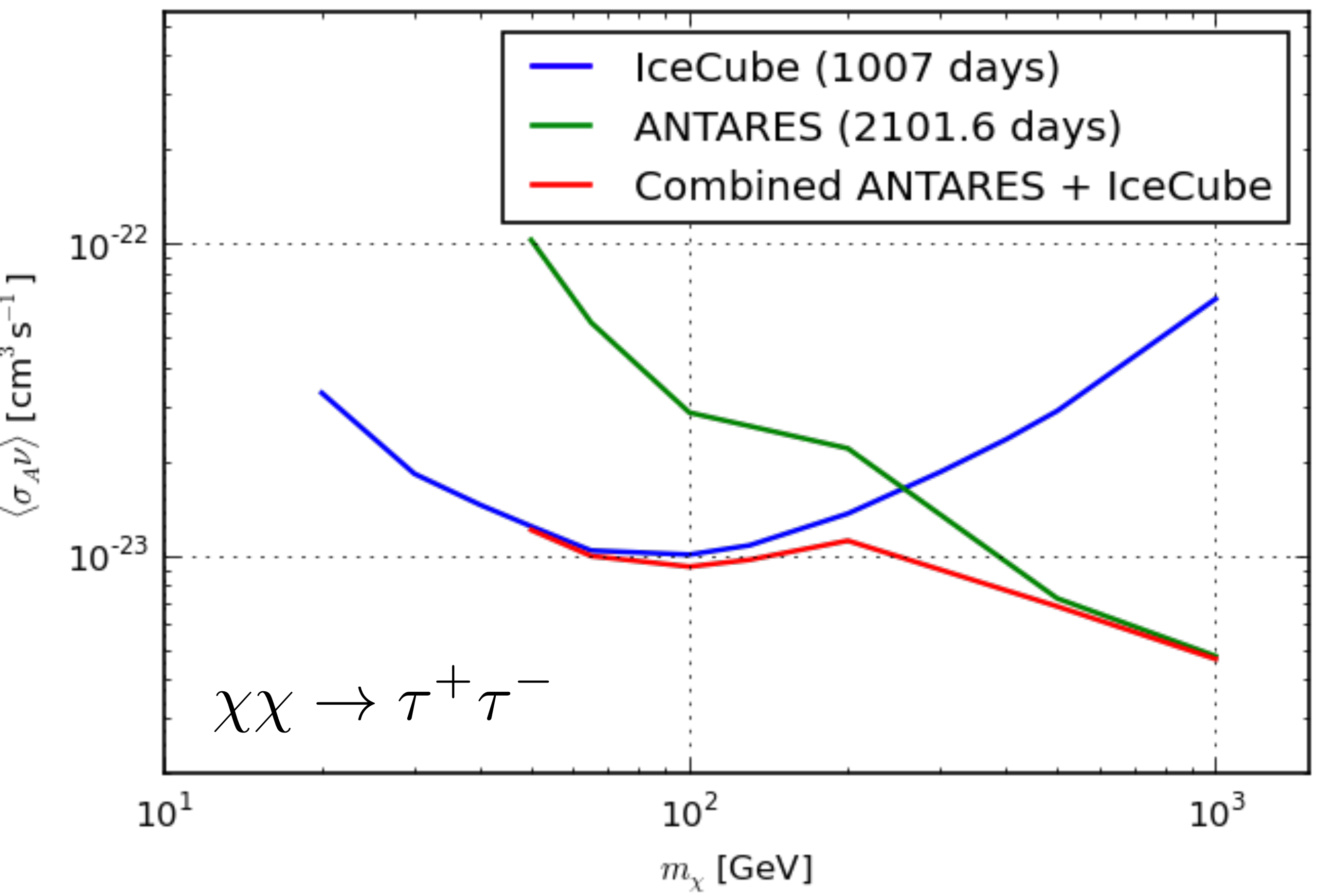
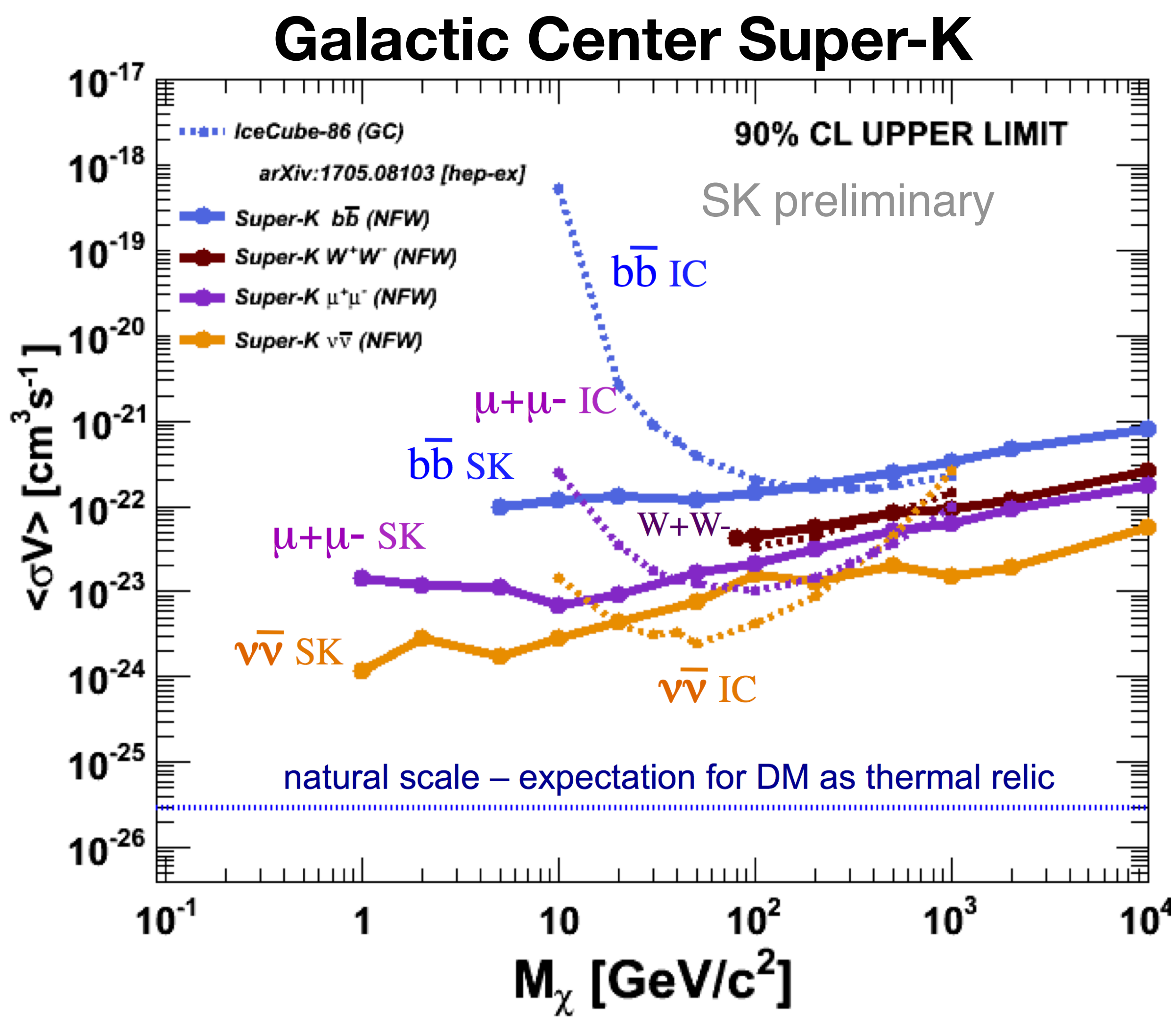


Galactic Center / Galactic Halo - IceCube/ ANTARES/Super-K

J.A. Aguilar Sánchez [ANTARES & IceCube] ICRC2017 (911)

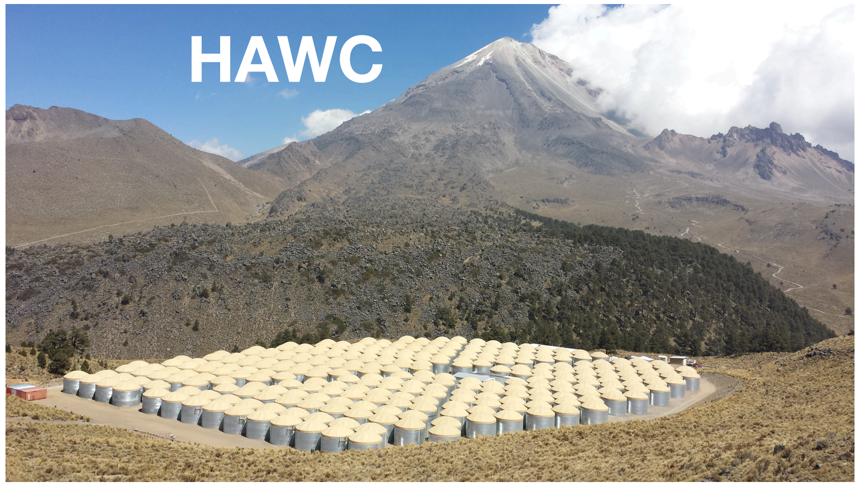


Combined Search for Neutrinos from Dark Matter Annihilation in the Galactic Center using IceCube and ANTARES



- Combined analysis enhances sensitivity in overlap region and helps to make analyses more comparable
- Very competitive result from Super-K for dark matter masses below a 100GeV

More Dark Matter Annihilations



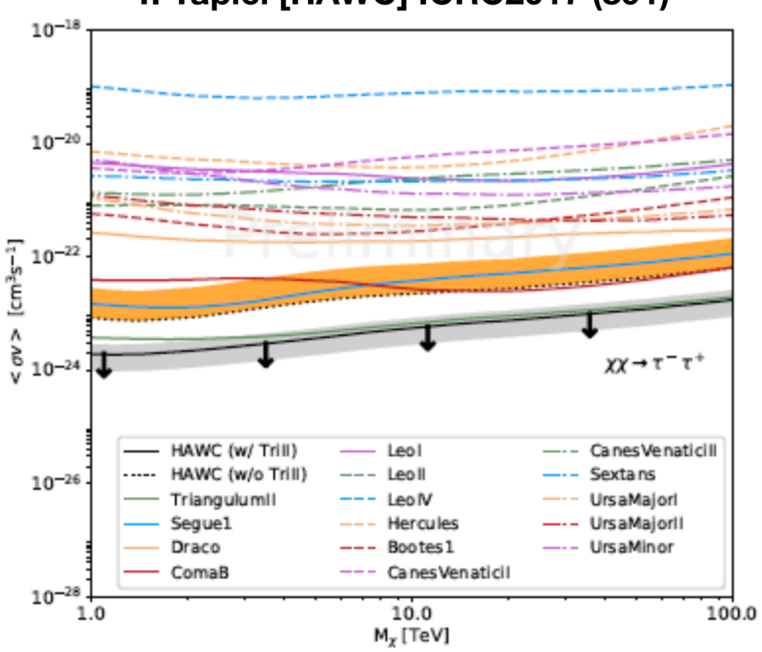
507 days of HAWC data

Combined results were computed for 14 dSph

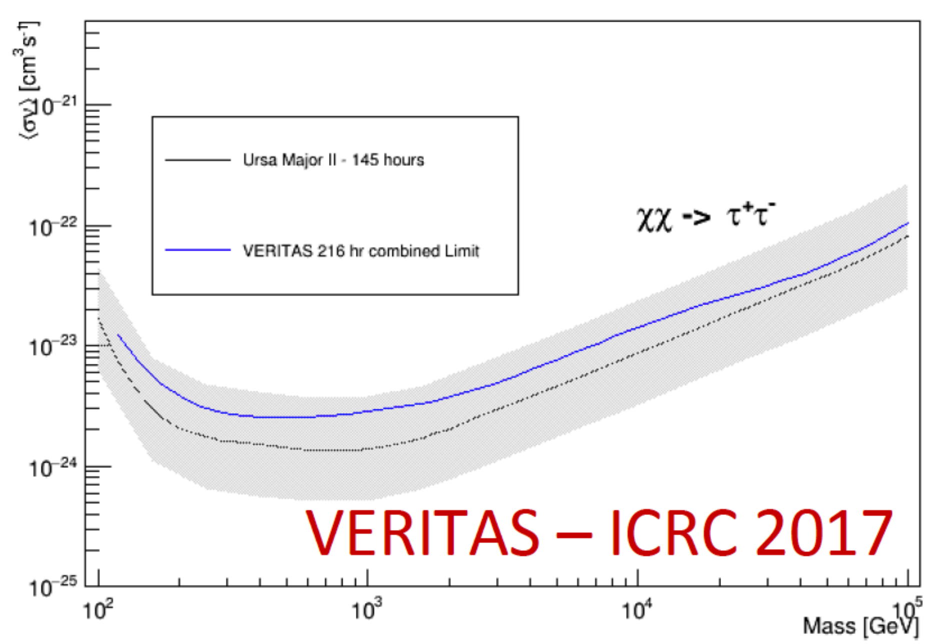
Five **dSphs** observed by VERITAS between 2007 and 2013

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

T. Yapici [HAWC] ICRC2017 (891)



Beniamin Zitzer [VERITAS], ICRC2017 (904)

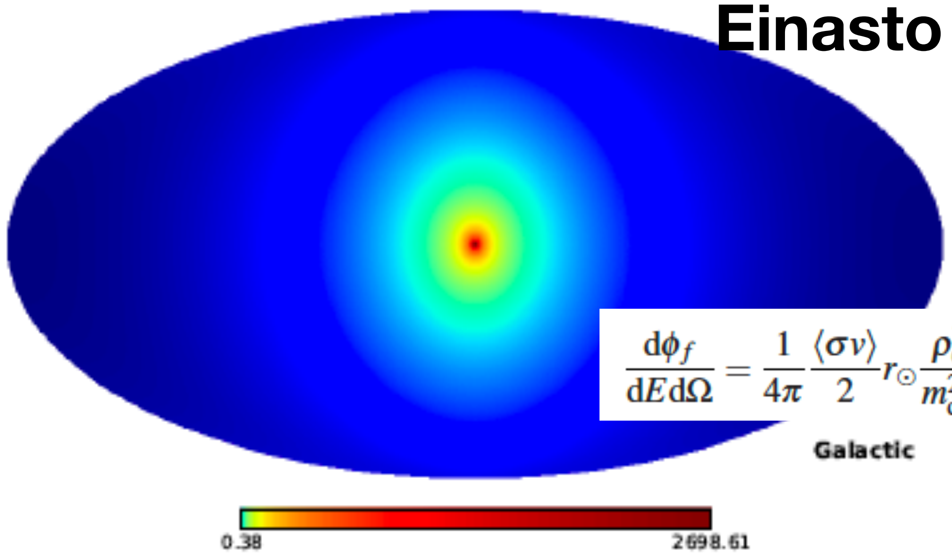


see also Archambaultet al. [VERITAS] Phys. Rev. D 95, 082001

Spotting imprints of dark matter in the extragalactic gamma-ray sky with photon counts statistics

- Using 1-point photon counts statistics for decomposing the EGB detected with Fermi-LAT
- Generalize the analysis to incorporate a potential contribution from annihilating dark matter

Einasto

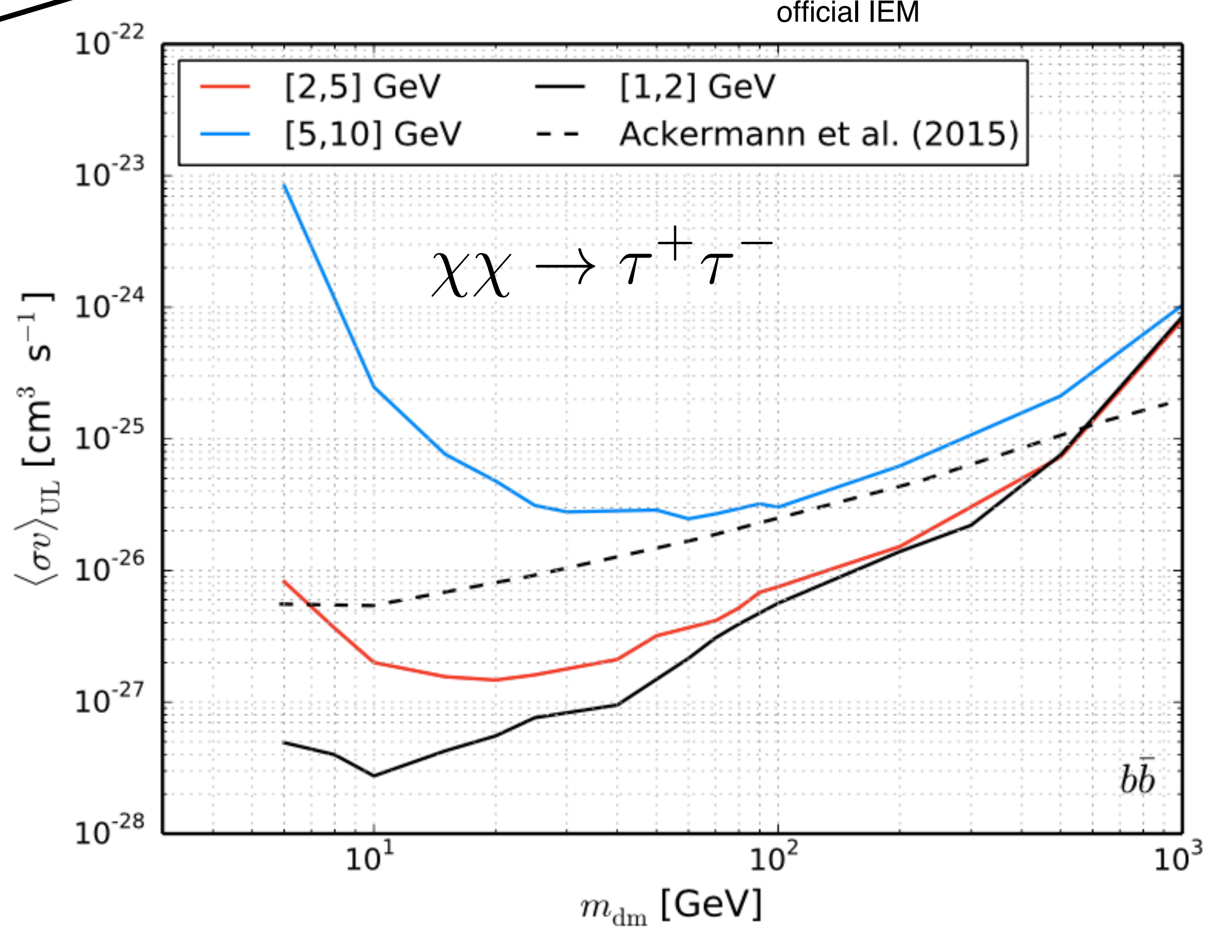


$$\frac{d\phi_f}{dE\,d\Omega} = \frac{1}{4\pi}\frac{\langle\sigma v\rangle}{2} r_\odot \frac{\rho_\odot^2}{m_{dm}^2}\frac{dN_f}{dE}\mathcal{J}$$

diffuse isotropic background emission was assumed to follow a power law spectrum (photon index Γ = 2:3)

$$x^{(p)}_{\rm diff} = A_{\rm gal} x^{(p)}_{\rm gal} + A_{\rm dm} x^{(p)}_{\rm dm} + \frac{x^{(p)}_{\rm iso}}{F_{\rm iso}} F_{\rm iso}$$

Use systematic model uncertainties of the official IEM

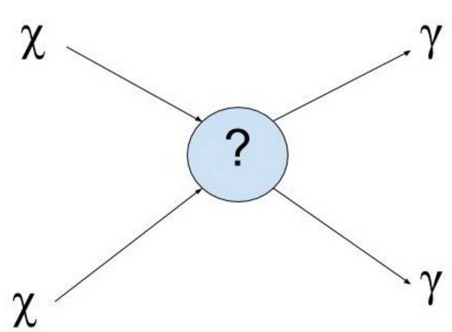


- Sensitivity reach of the 1pPDF method for detecting an additional component of annihilating DM
- The upper limits have been obtained from the analysis of the 1-2, 2-5, 5-10 GeV energy bands, employing the official (IEM - interstellar emission model)

Hannes-S. Zechlin ICRC2017 (922)
Zechlin et al. (2016), ApJS, 225, 2, 18
Zechlin et al. (2016), ApJL, 826, 2, L31

Line Searches

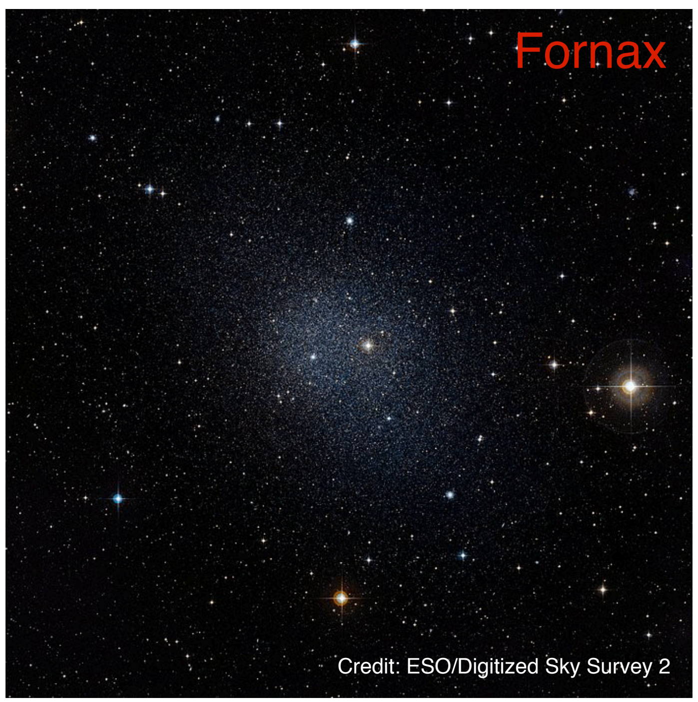
H.E.S.S.

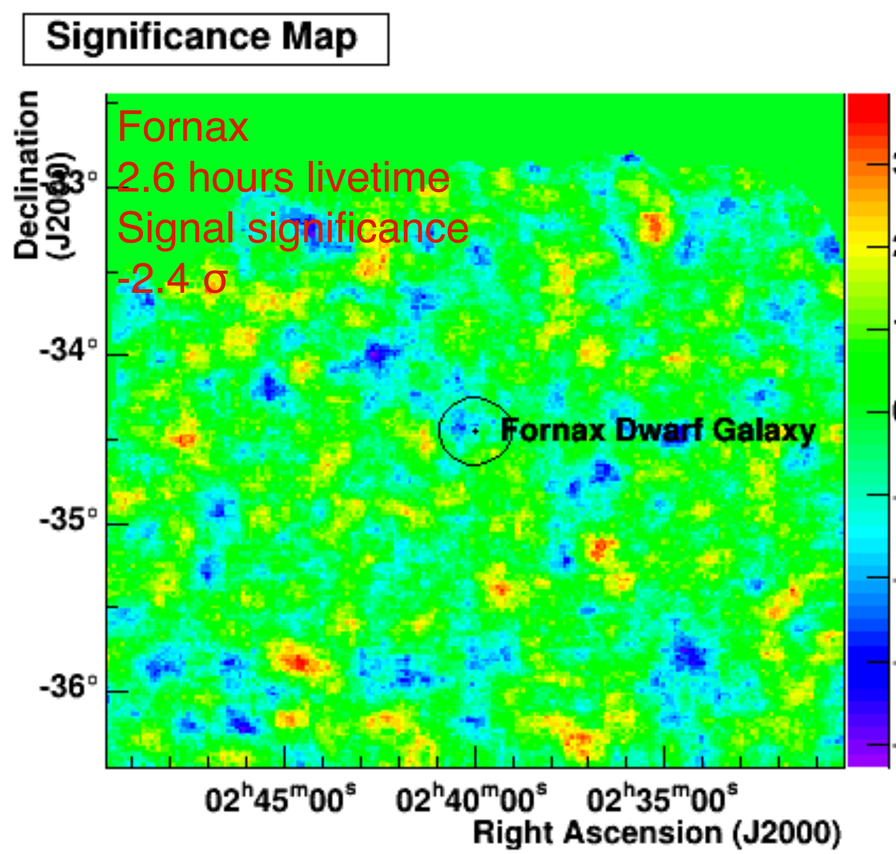


Peak in the γ energy distribution at the WIMP mass ("γ-ray line") would be clear signal for DM annihilations.

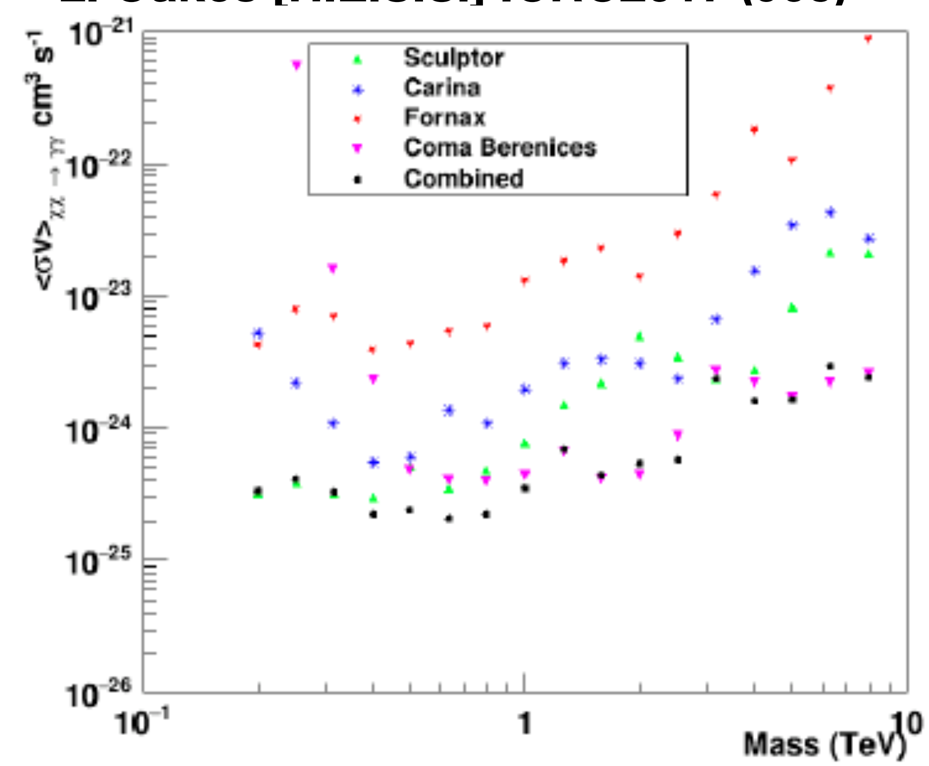
Dwarf Spheroidal Galaxies (dSphs)

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



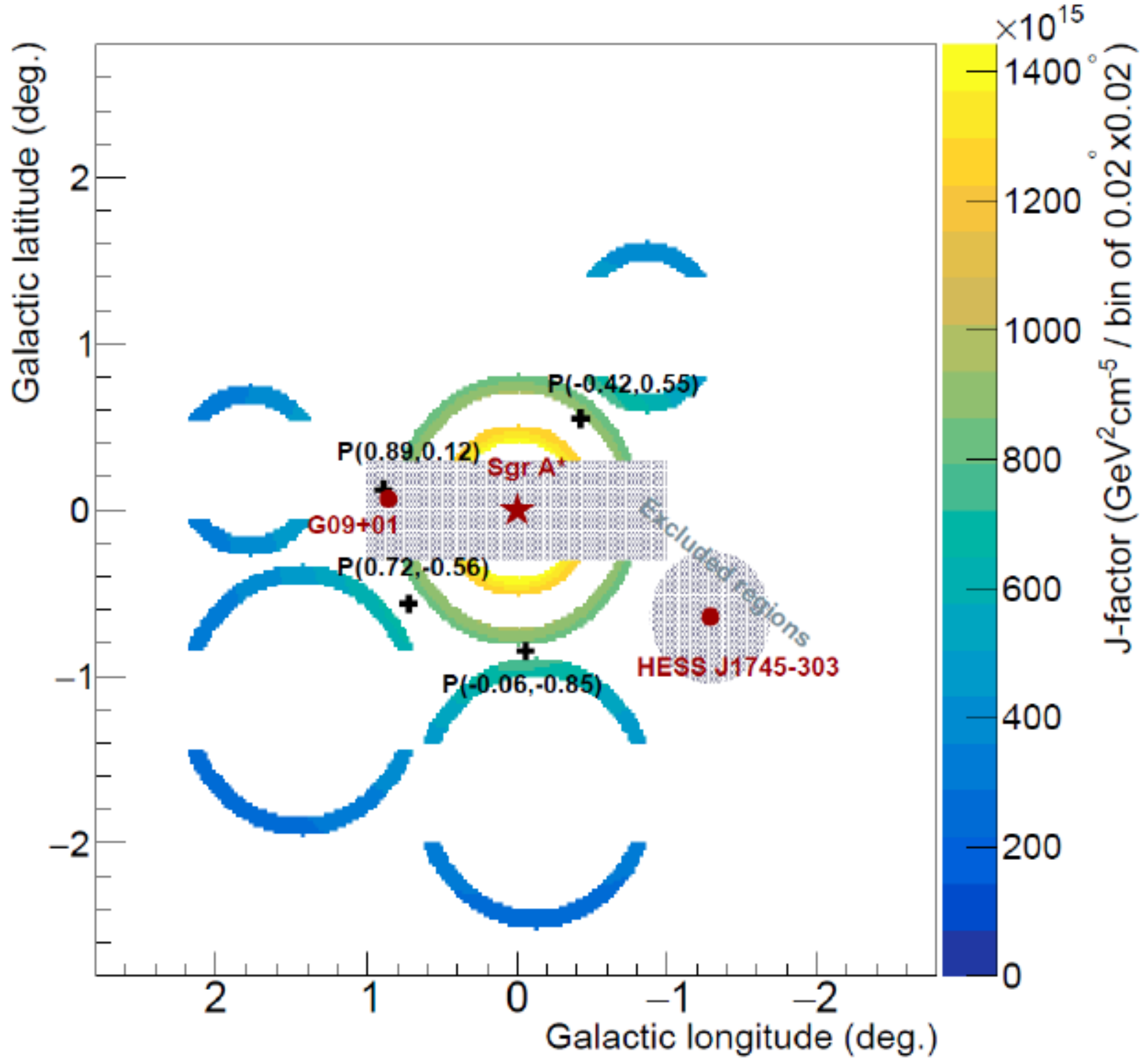


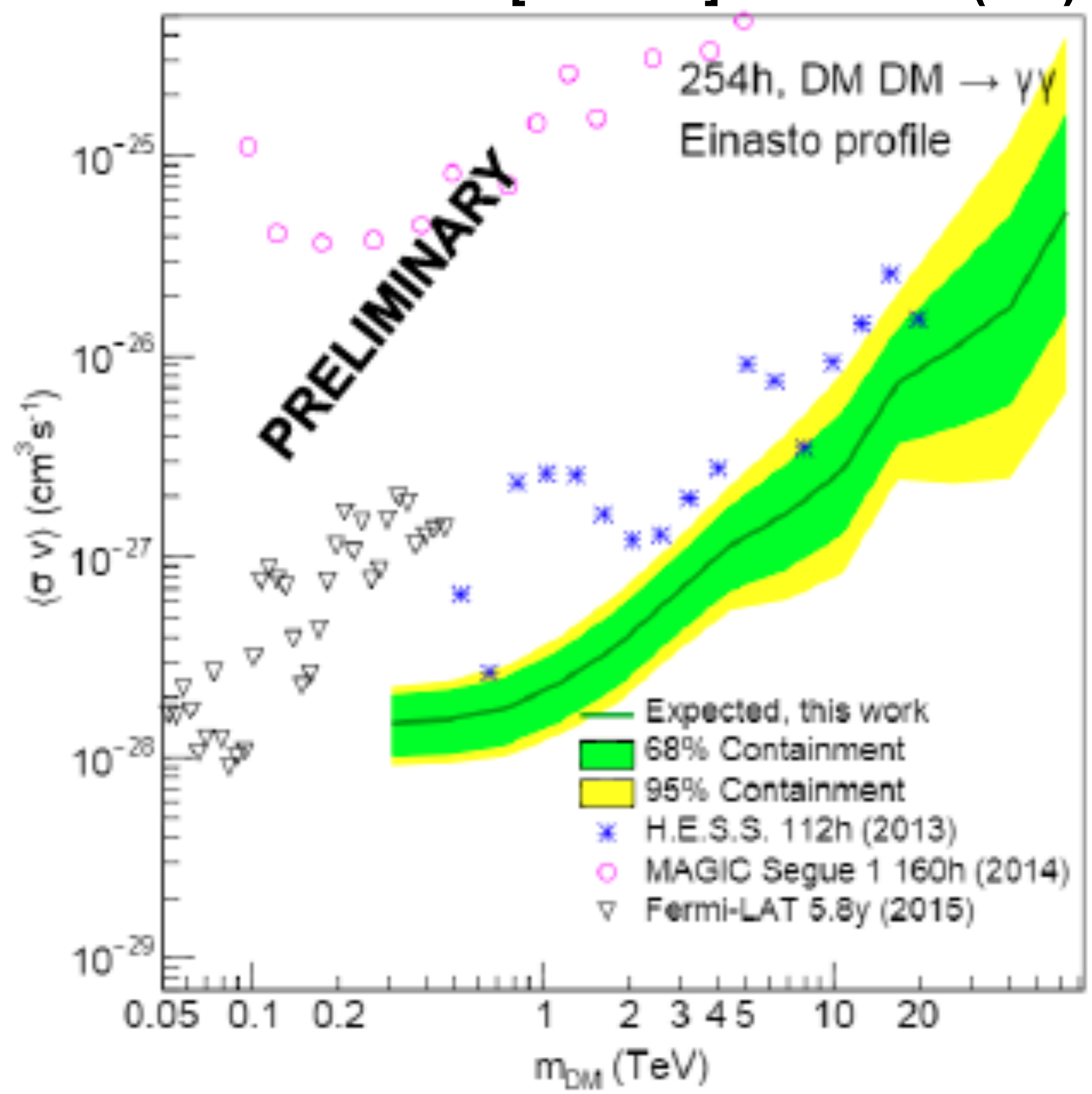
L. Oakes [H.E.S.S.] ICRC2017 (905)



- Limit on <σv> of 3×10^{-25} cm^{3}s^{-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

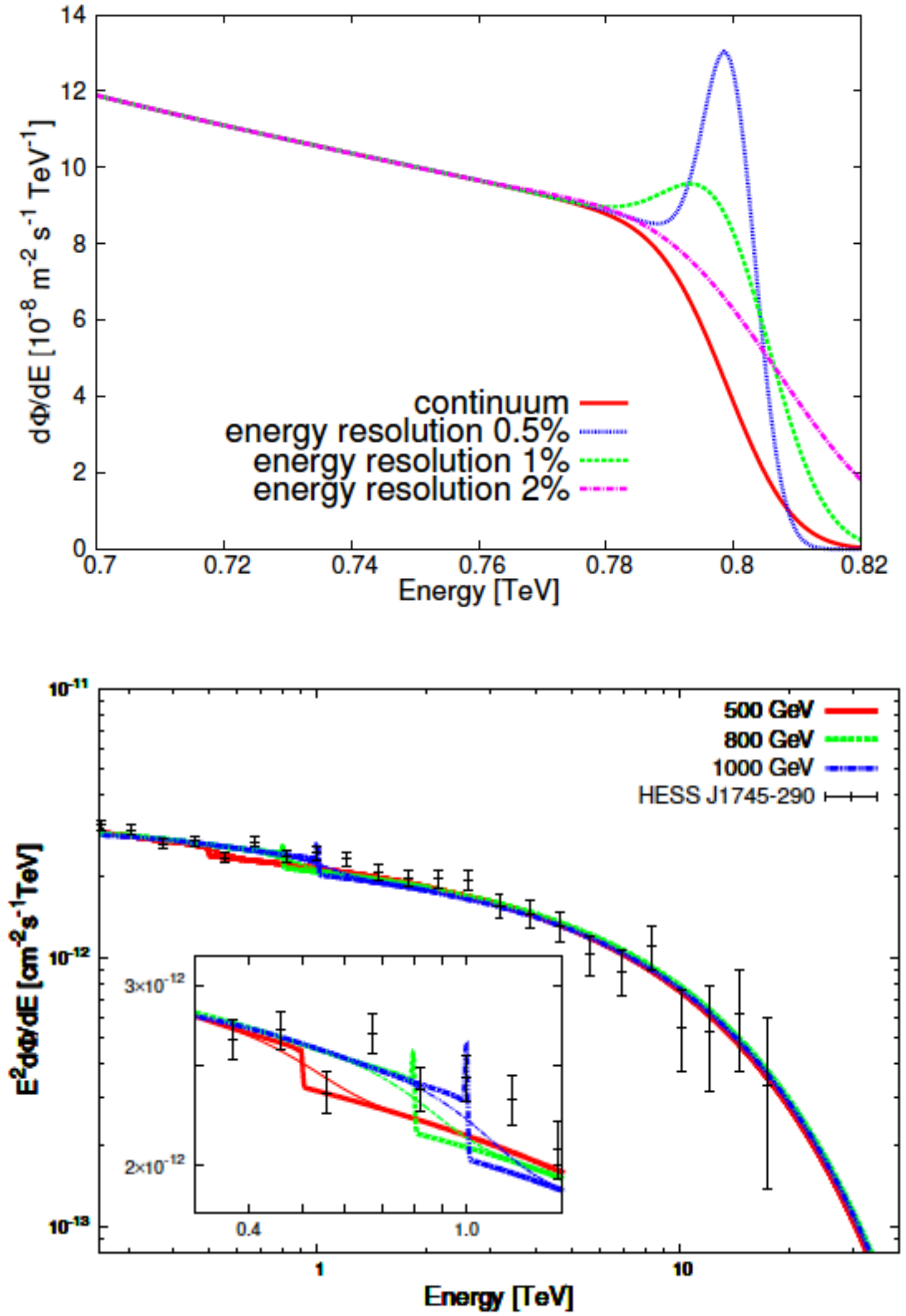
Line Searches





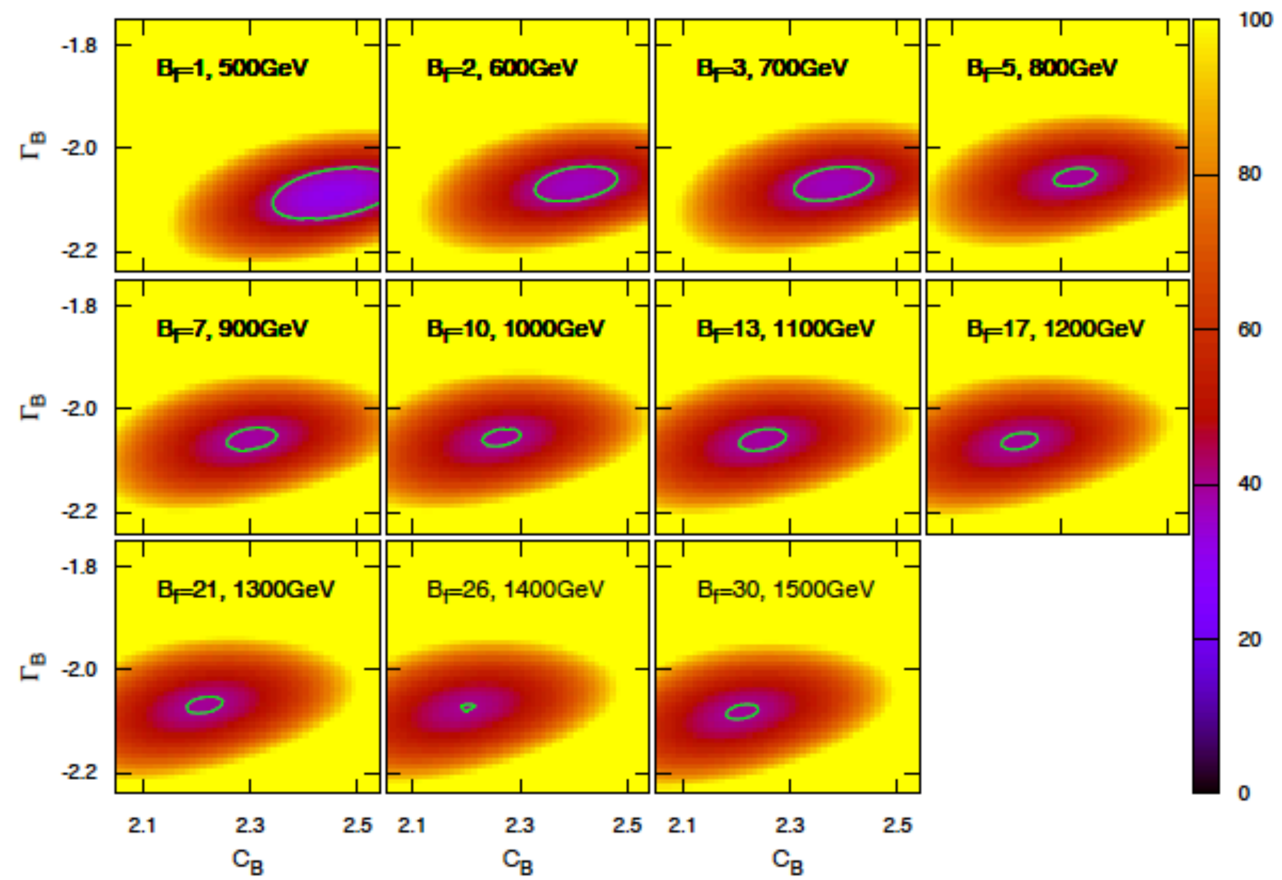
- Sensitivity only (2x10^{-28} cm^{3} s^{-1} @1TeV) , unblinding in progress … expect results soon
- lower energy threshold thanks to the improved raw data analysis: best limit shifted down to lower masses
- Fermi-LAT limits surpassed of a factor about 6 @300 GeV

Concentration of Kaluza–Klein dark matter in the Galactic center: constraints from gamma–ray signals



$$\frac{d\Phi_\gamma}{dE_\gamma} = \frac{d\Phi_\gamma^{\rm Bkgd}}{dE_\gamma} + B_f \frac{d\Phi_\gamma^{\rm LKP}}{dE_\gamma}$$

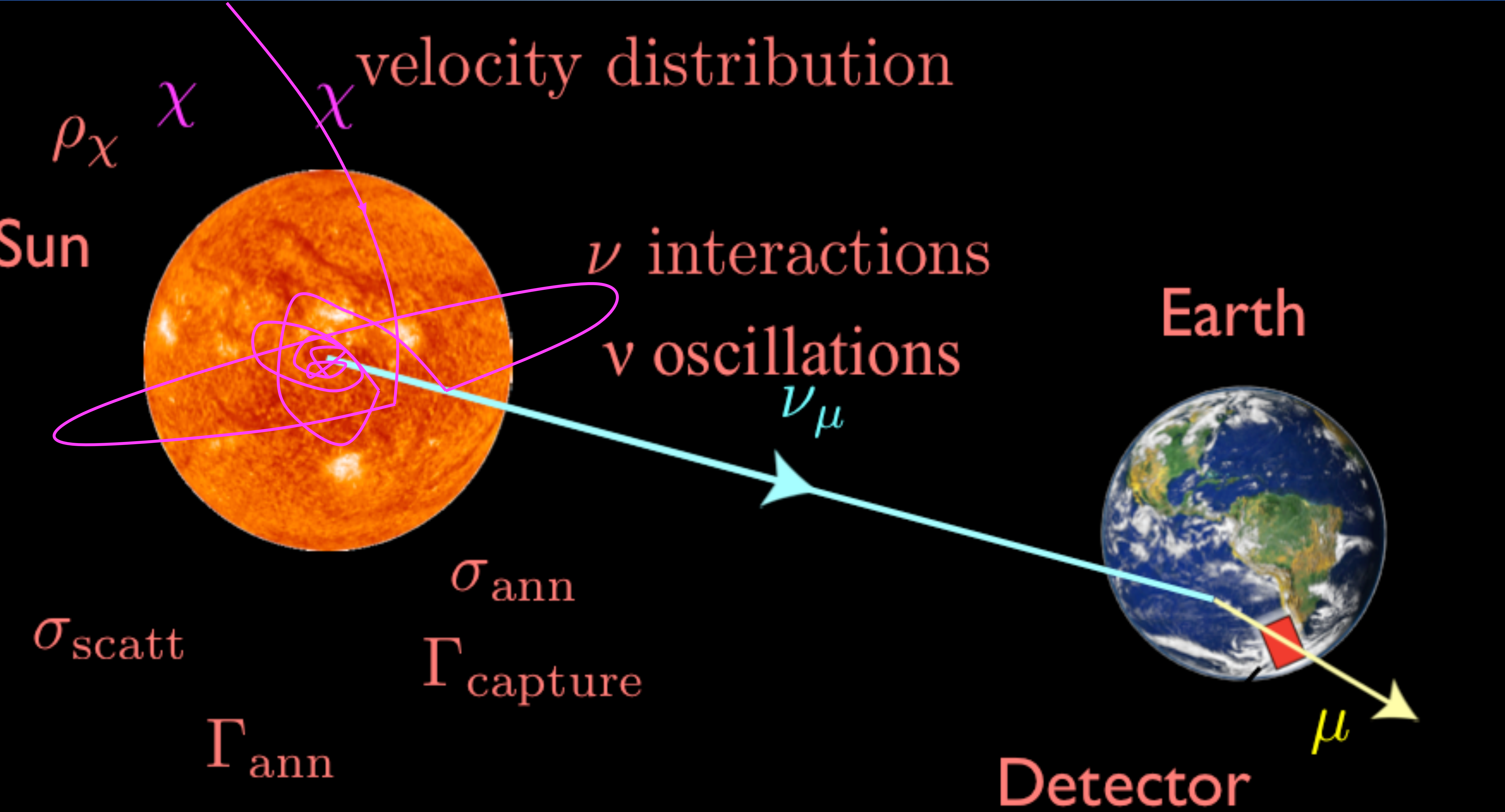
$$\frac{d\Phi_\gamma^{\rm Bkgd}}{dE_\gamma} = C_B \left(\frac{E}{\rm TeV}\right)^{\Gamma_B} \exp\left[-\frac{E}{10.7\ {\rm TeV}}\right] \times 10^{-8}\ {\rm m^{-2}\ s^{-1}\ TeV^{-1}}$$



Obtained upper limits on boost factor B_f assuming the coefficient C_B and index Γ_B for the powerlaw background spectrum based on the HESS observation

Solar Dark Matter Searches

Solar WIMPs



Freese '86

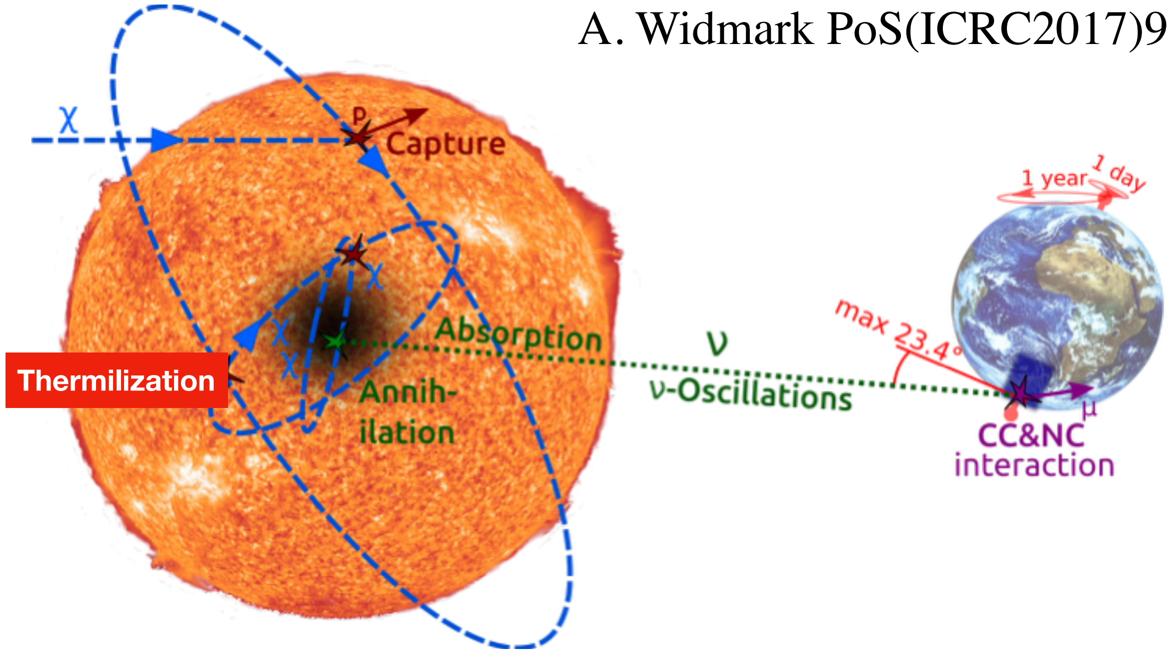
Krauss, Srednicki & Wilczek '86

Gaisser, Steigman & Tilav '86

Silk, Olive and Srednicki '85

Gaisser, Steigman & Tilav '86

A. Widmark PoS(ICRC2017)916

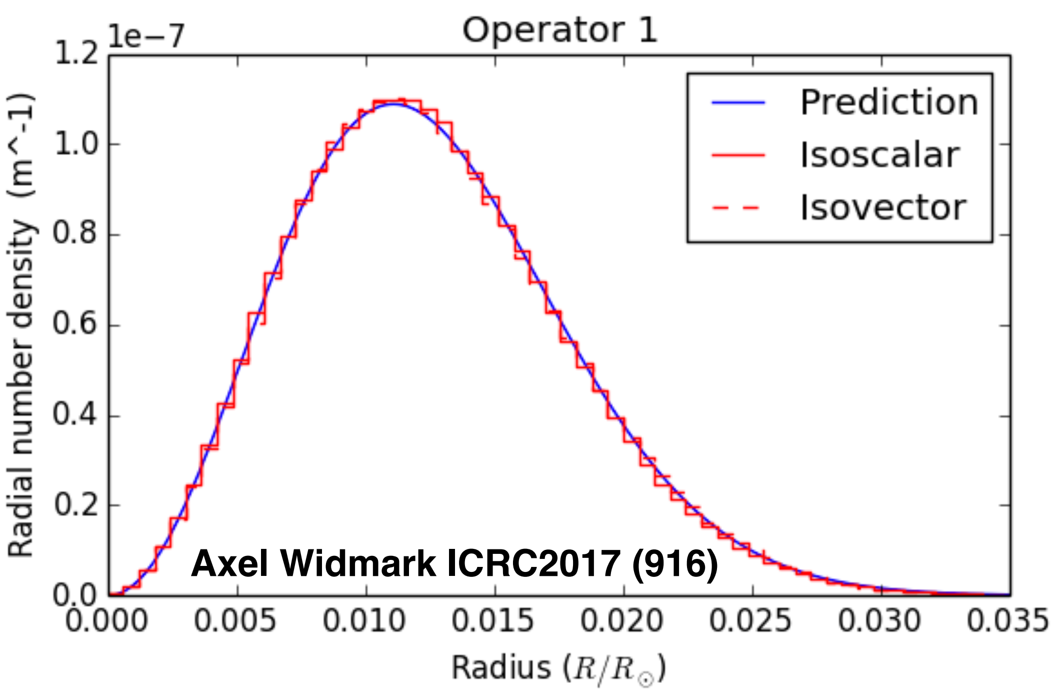


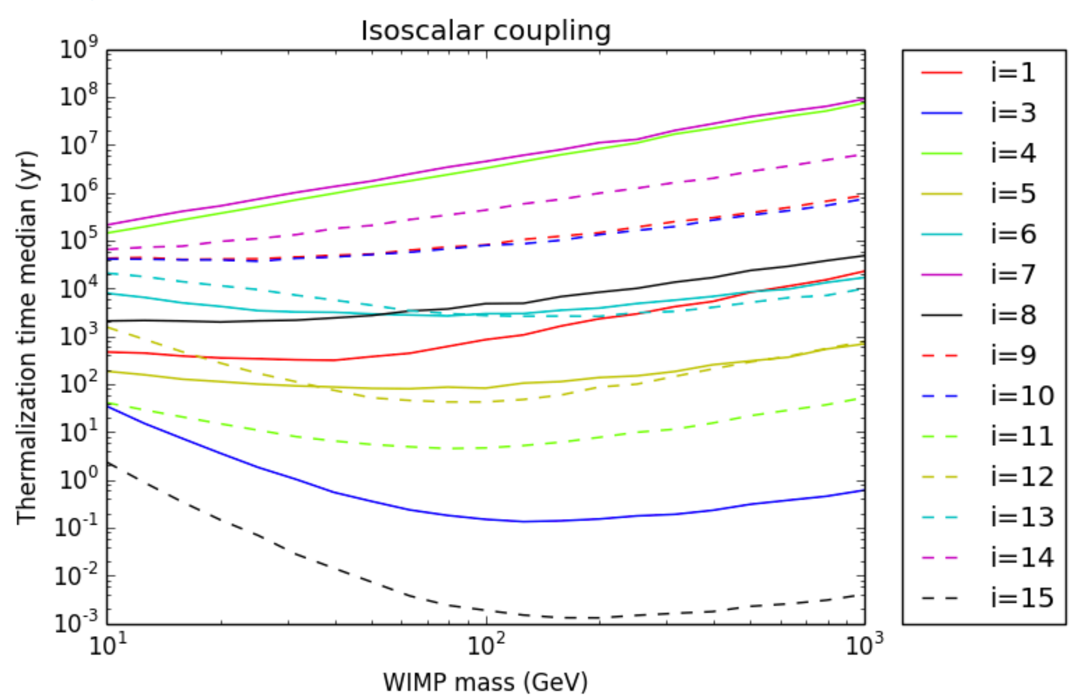
Dark Matter capture in the Sun

- Galactic halo WIMPs can collide with atomic nuclei in the solar interior.
- If they lose enough kinetic energy in such a collision, they will be bound in orbit.
- With further collisions, they will settle to thermal equilibrium in the Sun's core

[DM022] Thermalization time scales for WIMP capture by the Sun in effective theories

- Compute thermal profiles and thermalization time scales for WIMP capture in the Sun
- Monte-Carlo integration of WIMP trajectories
- Use WIMP-nucleon interaction operators of a non-relativistic effective field theory
- Isoscalar (isoscalar coupling WIMPs interact the same with protons and neutrons)
- isovector (proton and neutron interactions have opposite signs)



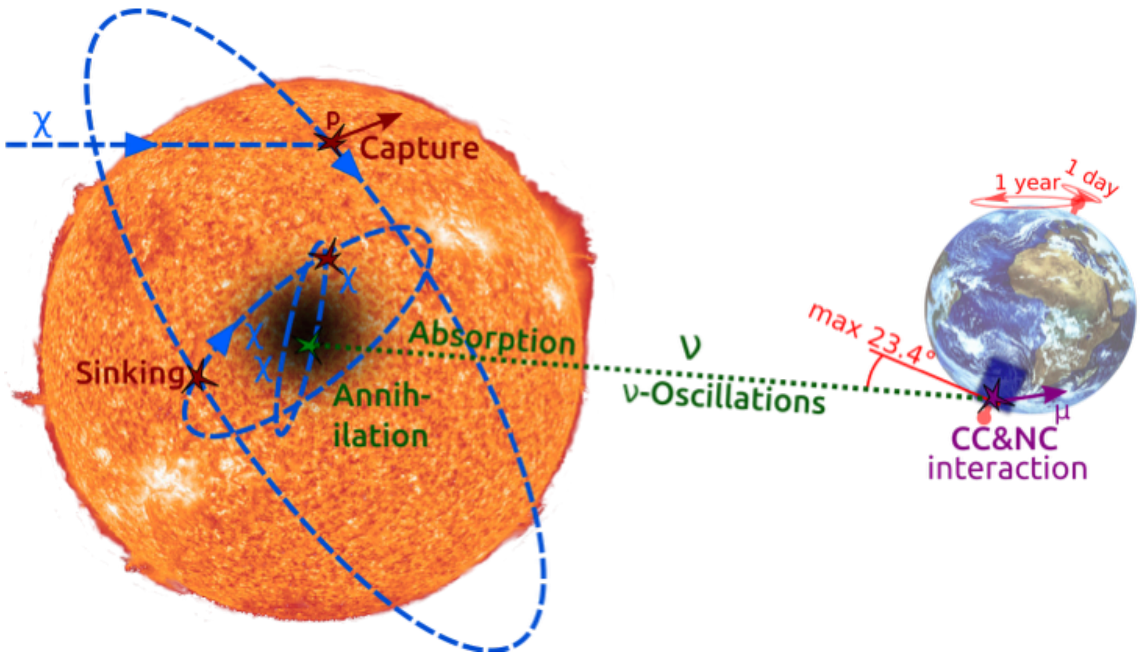


leading order WIMP-nucleon interaction operators

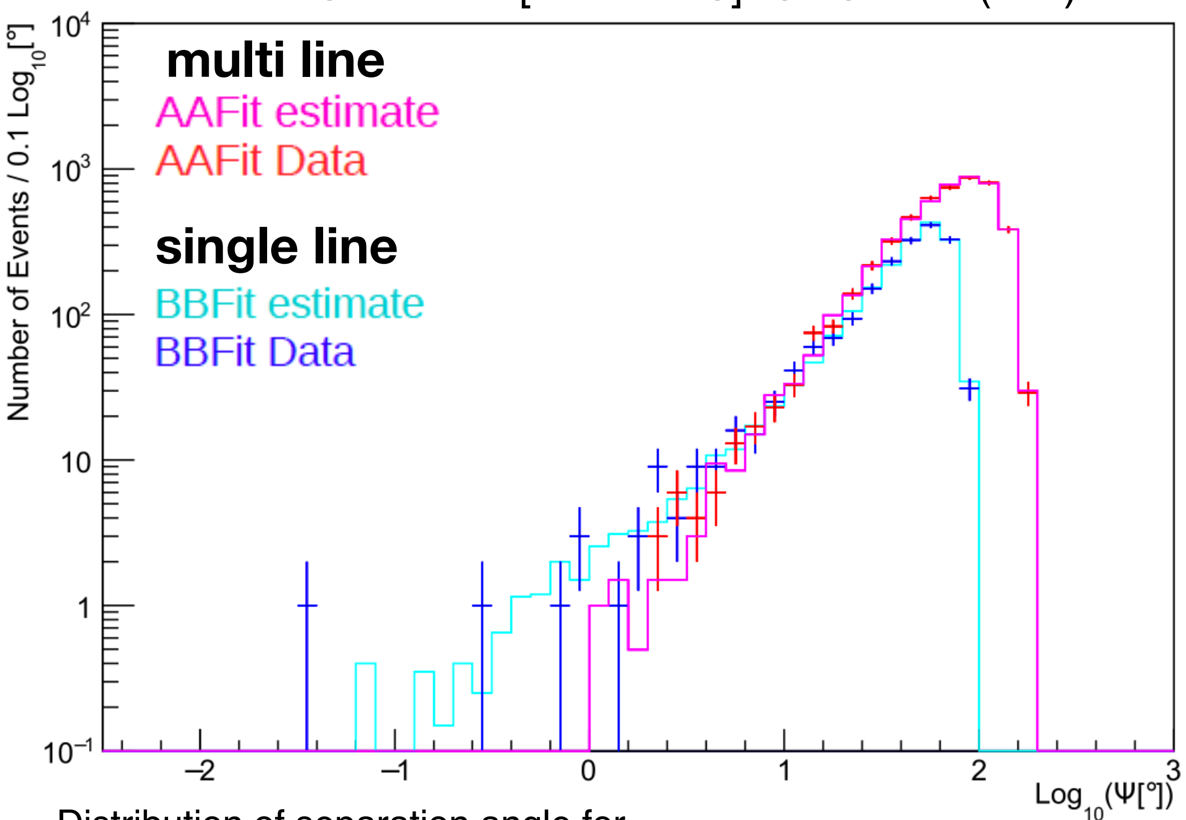
$$\hat{\mathcal{O}}_1 = \mathbb{1}_{\chi N}$$
$$\hat{\mathcal{O}}_3 = i\hat{\mathbf{S}}_N \cdot \left(\frac{\hat{\mathbf{q}}}{m_N} \times \hat{\mathbf{v}}^\perp\right)$$
$$\hat{\mathcal{O}}_4 = \hat{\mathbf{S}}_\chi \cdot \hat{\mathbf{S}}_N$$
$$\hat{\mathcal{O}}_5 = i\hat{\mathbf{S}}_\chi \cdot \left(\frac{\hat{\mathbf{q}}}{m_N} \times \hat{\mathbf{v}}^\perp\right)$$
$$\hat{\mathcal{O}}_6 = \left(\hat{\mathbf{S}}_\chi \cdot \frac{\hat{\mathbf{q}}}{m_N}\right)\left(\hat{\mathbf{S}}_N \cdot \frac{\hat{\mathbf{q}}}{m_N}\right)$$
$$\hat{\mathcal{O}}_7 = \hat{\mathbf{S}}_N \cdot \hat{\mathbf{v}}^\perp$$
$$\hat{\mathcal{O}}_8 = \hat{\mathbf{S}}_\chi \cdot \hat{\mathbf{v}}^\perp$$
$$\hat{\mathcal{O}}_9 = i\hat{\mathbf{S}}_\chi \cdot \left(\hat{\mathbf{S}}_N \times \frac{\hat{\mathbf{q}}}{m_N}\right)$$
$$\hat{\mathcal{O}}_{10} = i\hat{\mathbf{S}}_N \cdot \frac{\hat{\mathbf{q}}}{m_N}$$
$$\hat{\mathcal{O}}_{11} = i\hat{\mathbf{S}}_\chi \cdot \frac{\hat{\mathbf{q}}}{m_N}$$
$$\hat{\mathcal{O}}_{12} = \hat{\mathbf{S}}_\chi \cdot \left(\hat{\mathbf{S}}_N \times \hat{\mathbf{v}}^\perp\right)$$
$$\hat{\mathcal{O}}_{13} = i\left(\hat{\mathbf{S}}_\chi \cdot \hat{\mathbf{v}}^\perp\right)\left(\hat{\mathbf{S}}_N \cdot \frac{\hat{\mathbf{q}}}{m_N}\right)$$
$$\hat{\mathcal{O}}_{14} = i\left(\hat{\mathbf{S}}_\chi \cdot \frac{\hat{\mathbf{q}}}{m_N}\right)\left(\hat{\mathbf{S}}_N \cdot \hat{\mathbf{v}}^\perp\right)$$
$$\hat{\mathcal{O}}_{15} = -\left(\hat{\mathbf{S}}_\chi \cdot \frac{\hat{\mathbf{q}}}{m_N}\right)\left[\left(\hat{\mathbf{S}}_N \times \hat{\mathbf{v}}^\perp\right) \cdot \frac{\hat{\mathbf{q}}}{m_N}\right]$$

- The density of thermalized WIMPs are found to adhere to a thermal profile.
- With the exceptions of some fine-tuned cases, the thermalization time is significantly shorter than the age of the solar system

Solar WIMP - IceCube/ANTARES

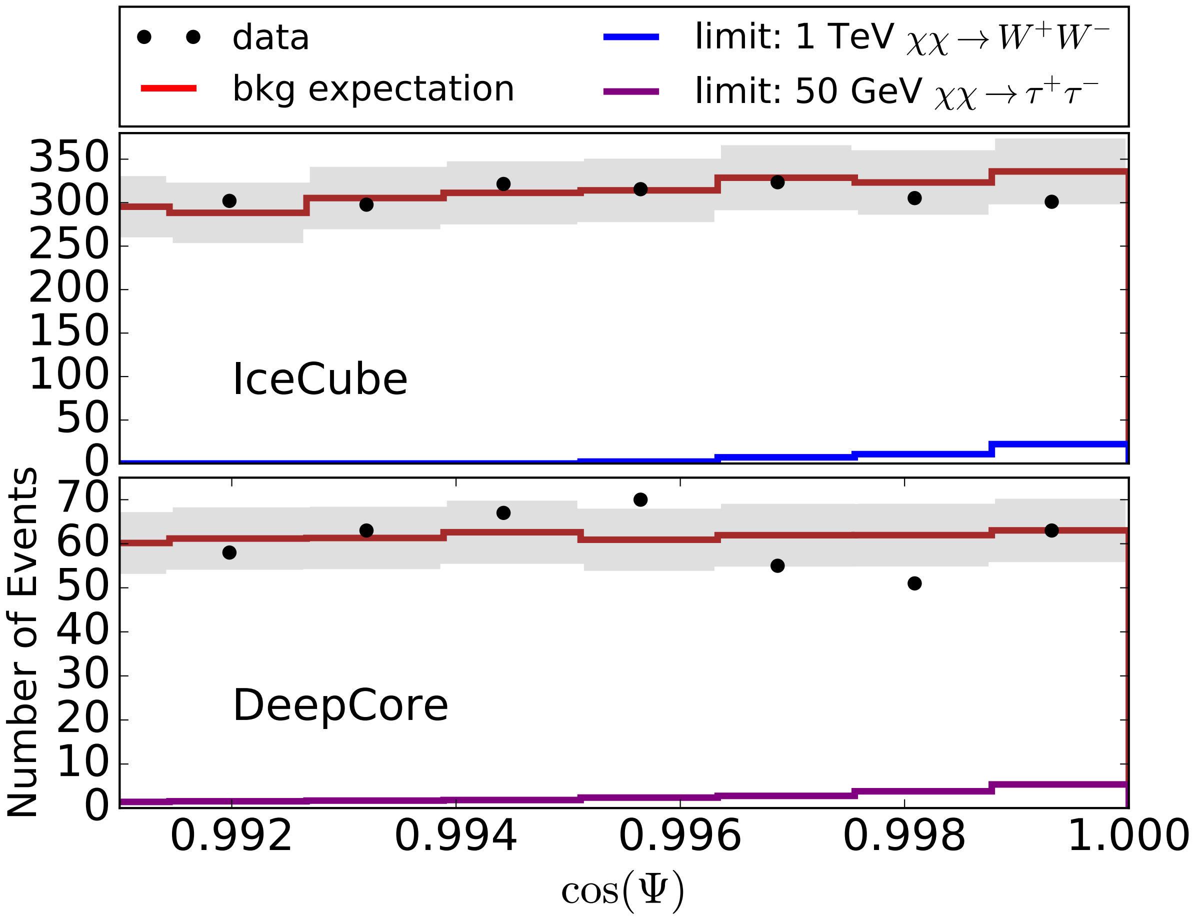


C. Tönnis [ANTARES] ICRC2017 (913)



Distribution of separation angle for 2007-2012 ANTARES data

S. In [IceCube] ICRC2017 (912)

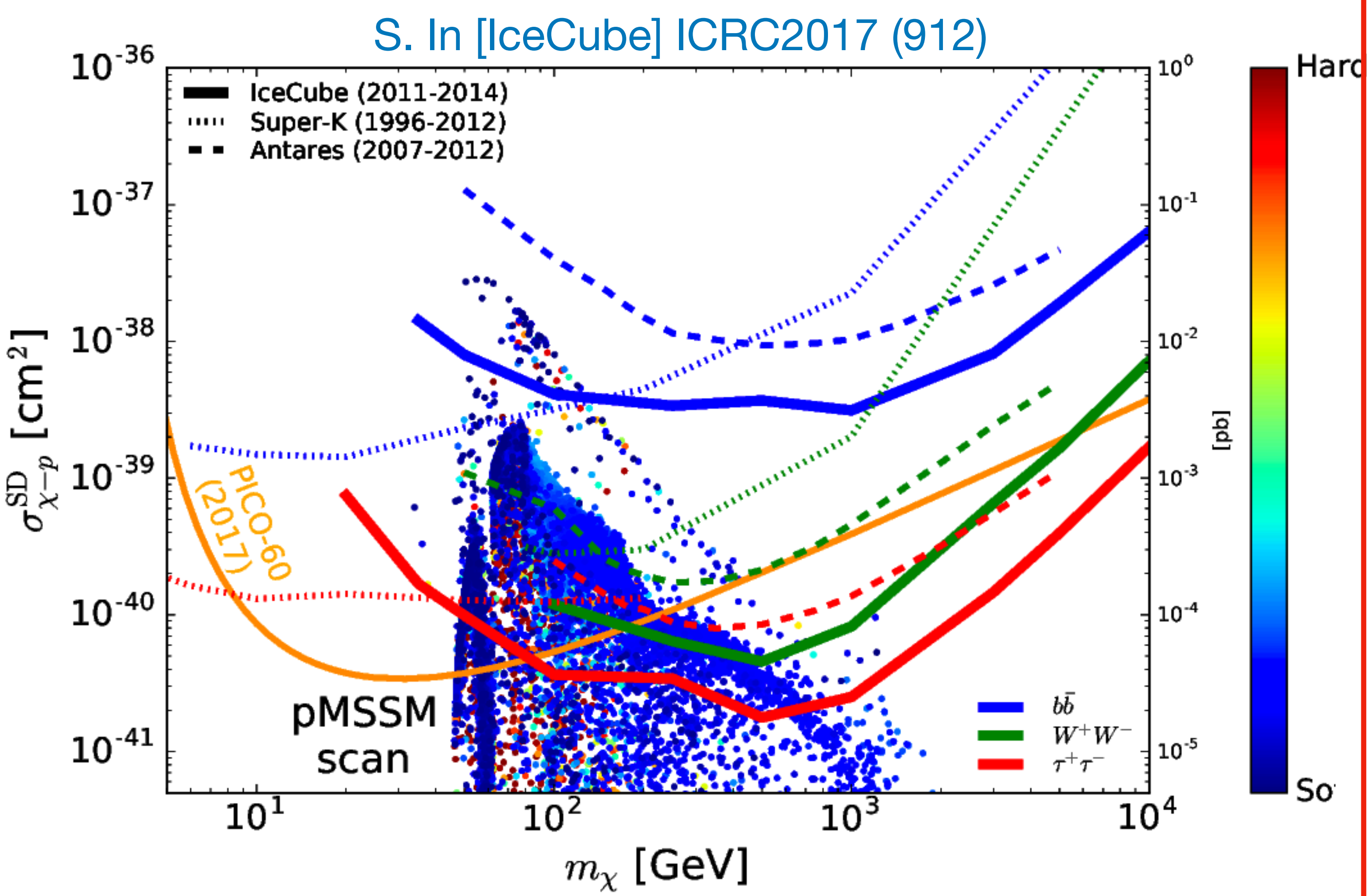


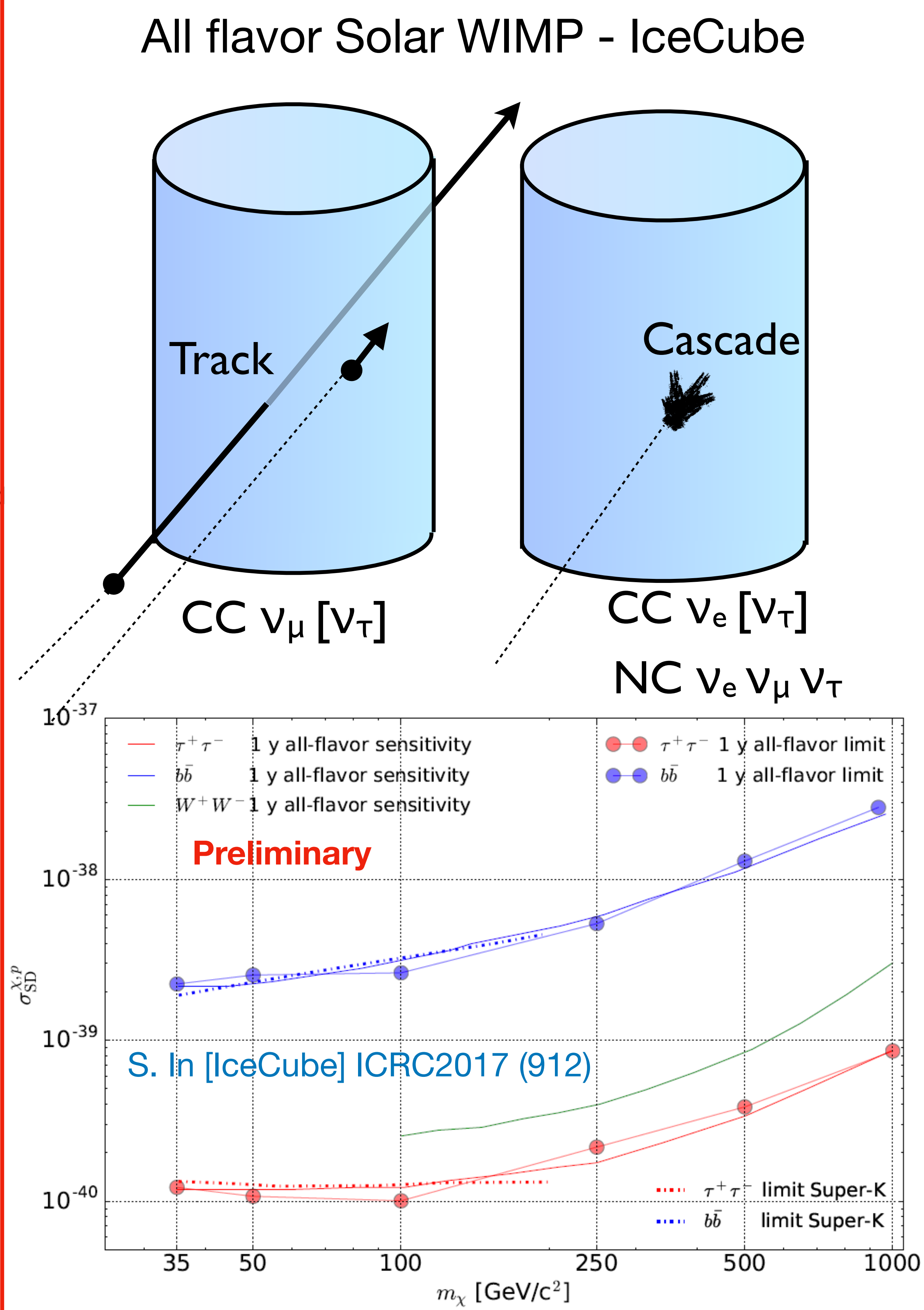
- Search for an excess in direction of the Sun
- Off source region can be used to reliable predict backgrounds from data

Solar WIMPs
- S. In [IceCube] ICRC2017 (912)
- C. Tönnis [ANTARES] ICRC2017 (913)

Solar WIMP - IceCube/ ANTARES

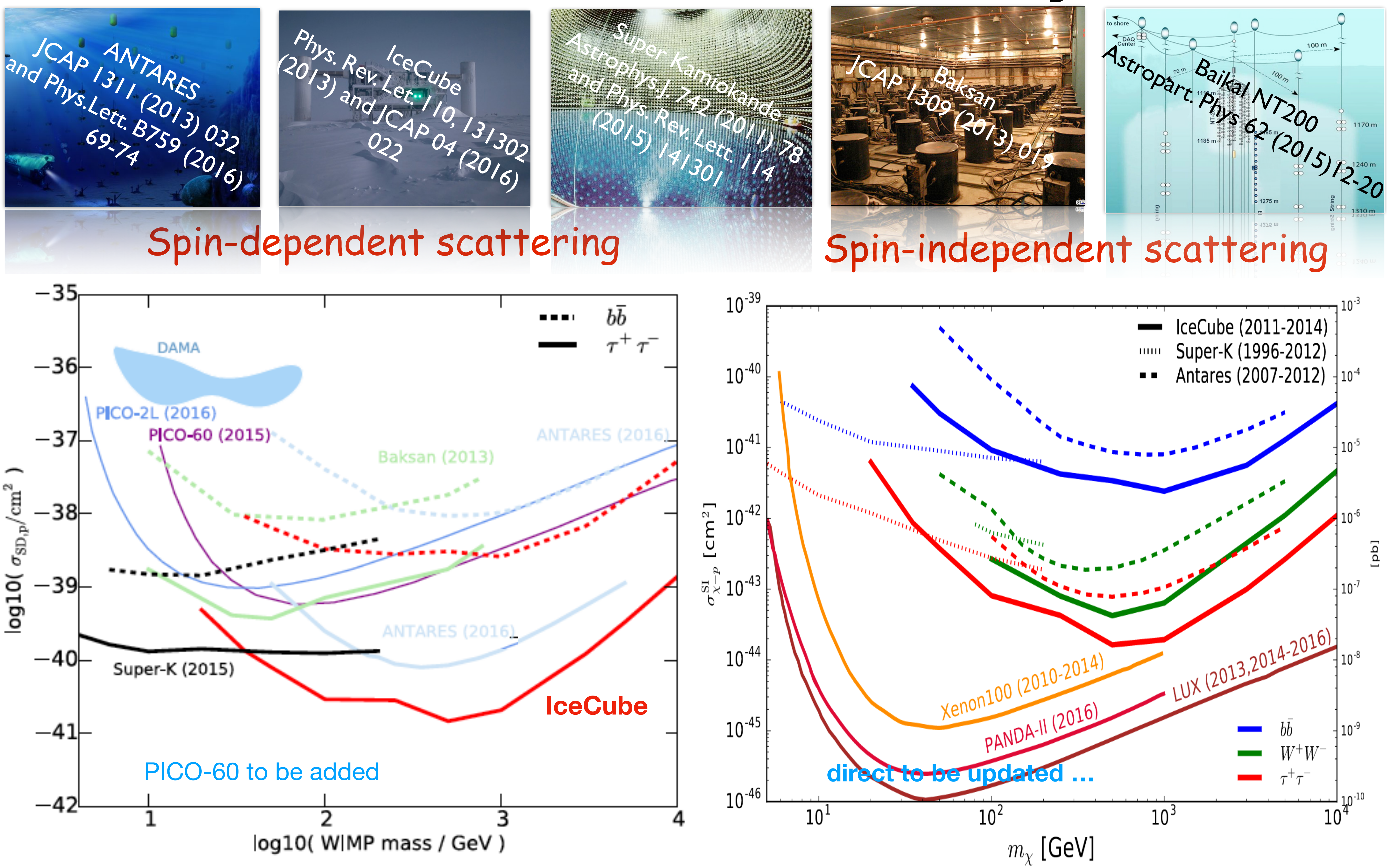
- Convert neutrino flux limit into limit on WIMP-nucleon scattering cross section



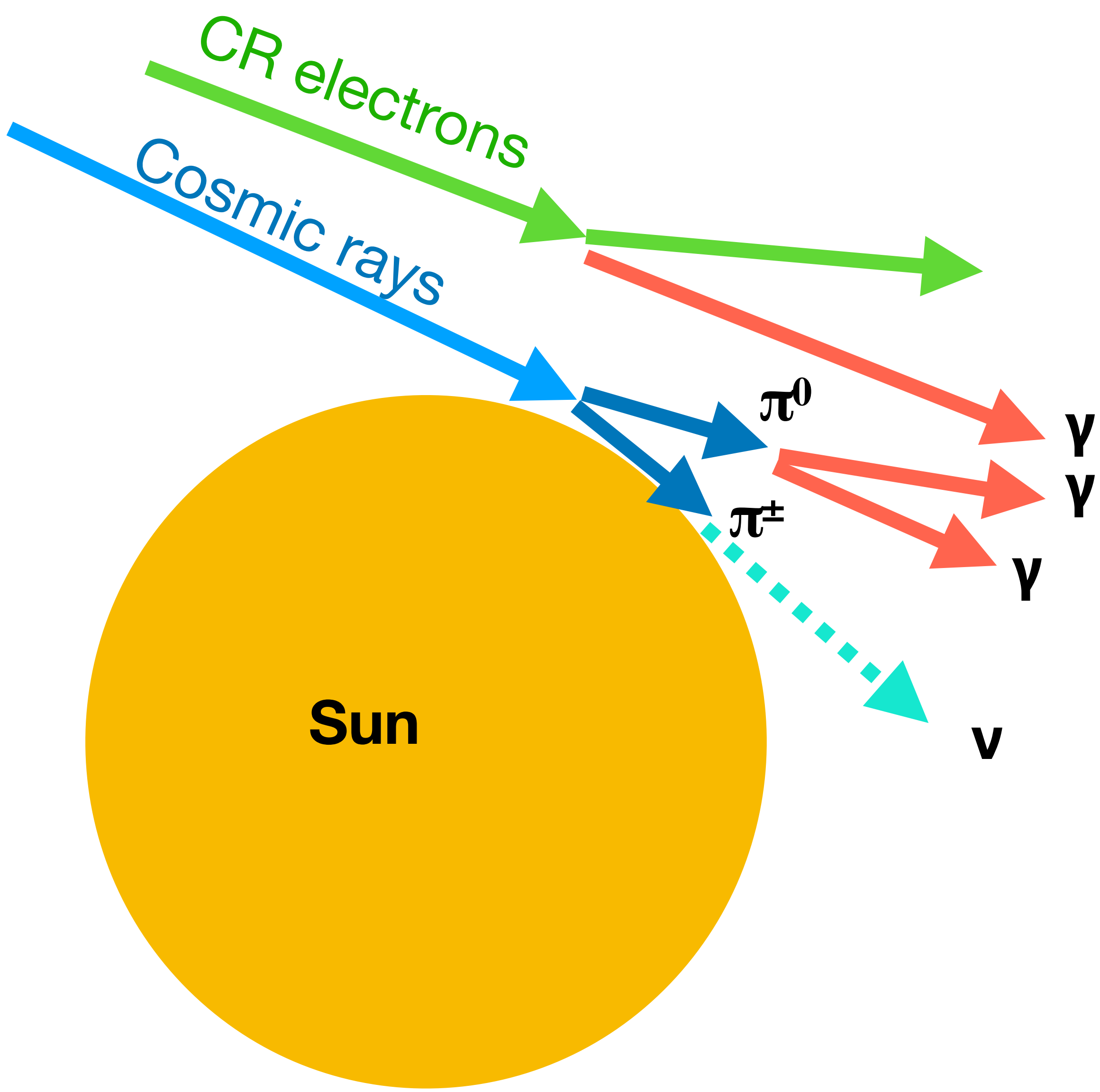


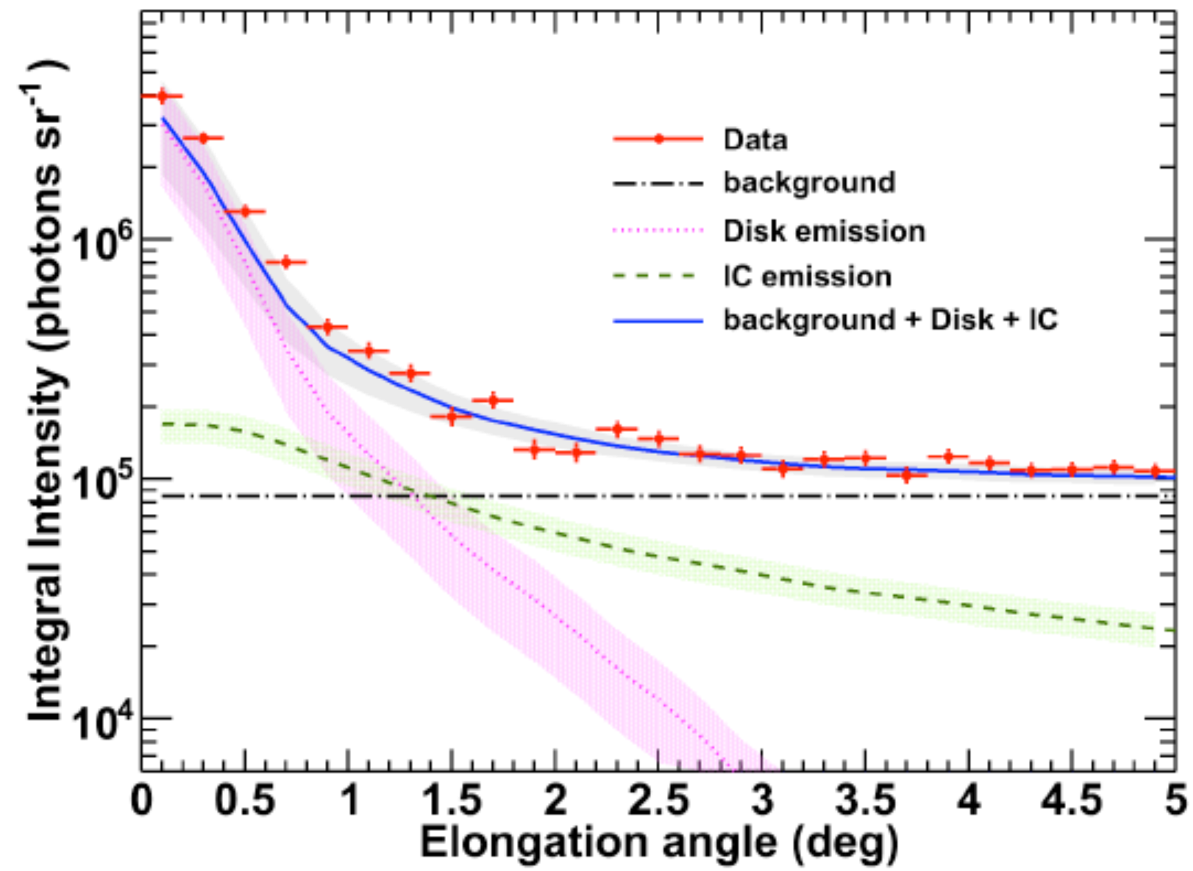
Solar WIMPs
- S. In [IceCube] ICRC2017 (912)
- C. Tönnis [ANTARES] ICRC2017 (913)

Solar WIMPs Summary



Cosmic ray interactions with the Sun





Leptonic

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

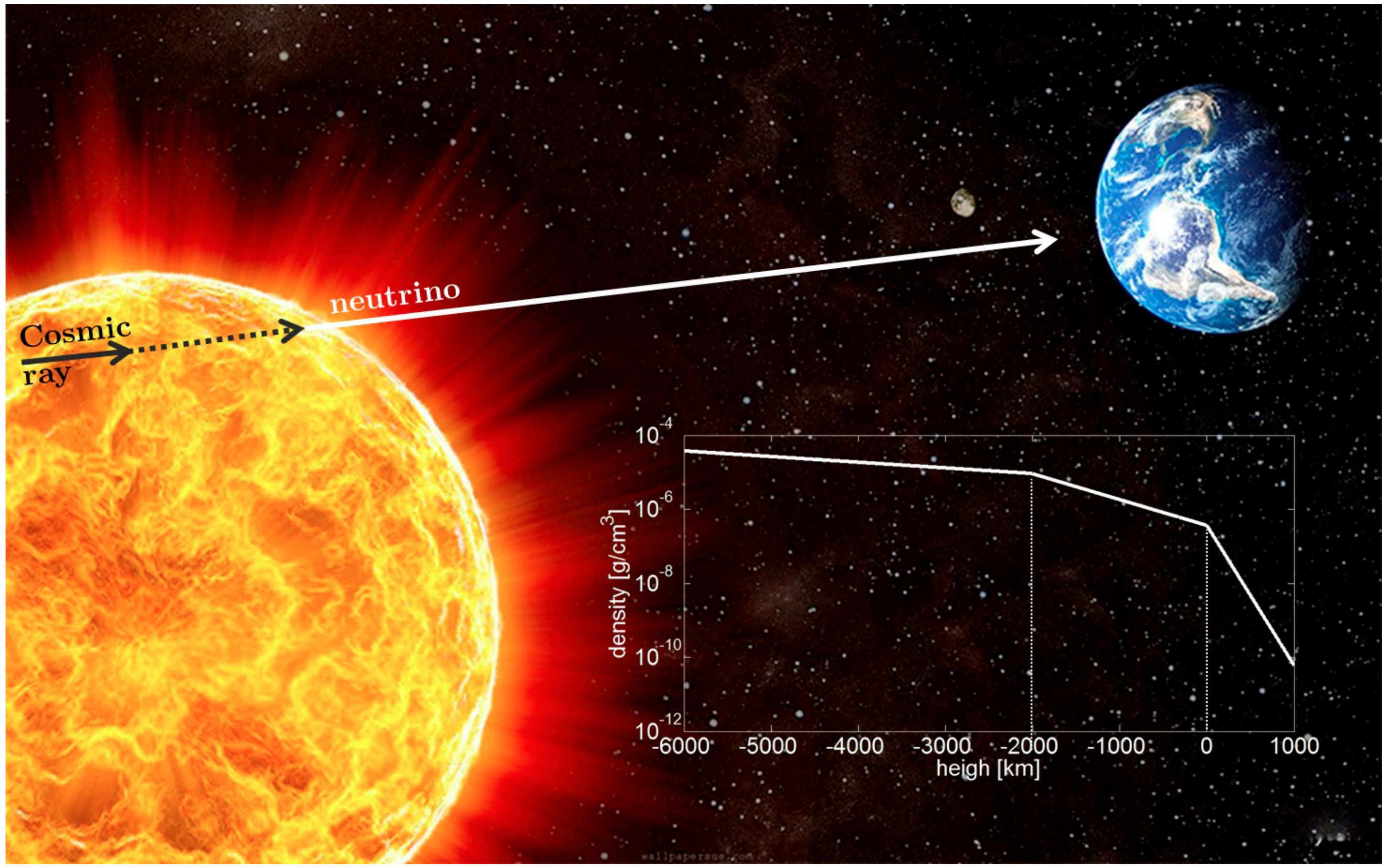
Hadronic

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

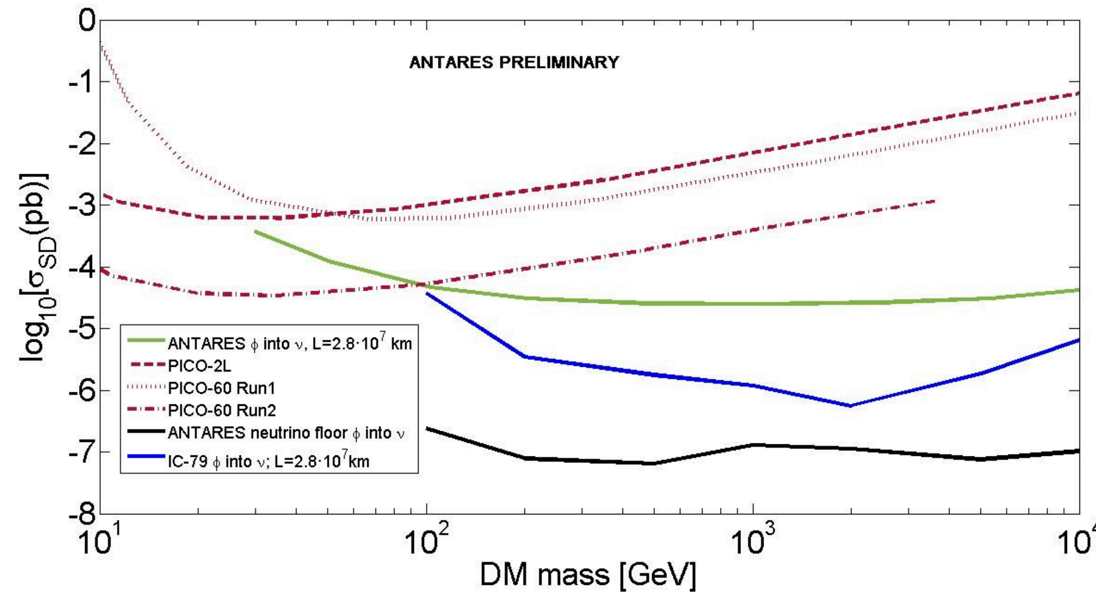
- Natural background to Solar Dark Matter Searches !
- However, energy spectrum expected to be different
- DM annihilation neutrinos significantly attenuated above a few 100GeV

Cosmic background from the Sun

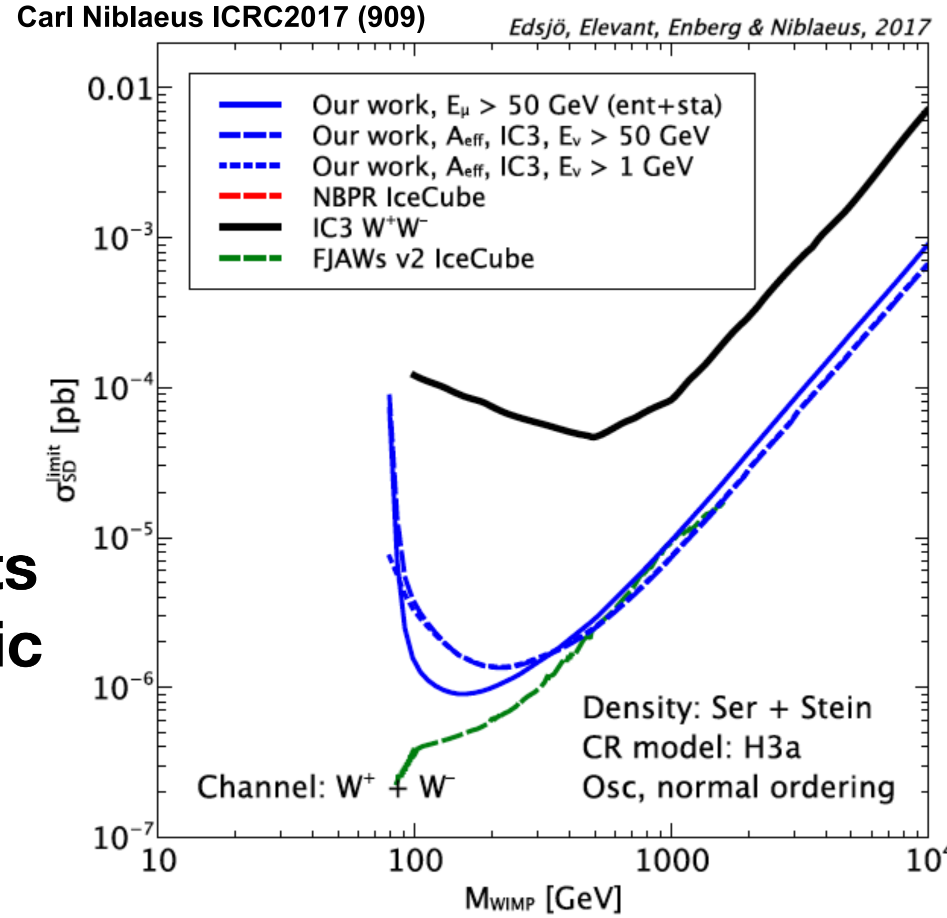
C. Tönnis ANTARES ICRC2017 (907)



C. Tönnis ANTARES ICRC2017 (907)



Carl Niblaeus ICRC2017 (909)



Solar Atmospheric Neutrino Floor

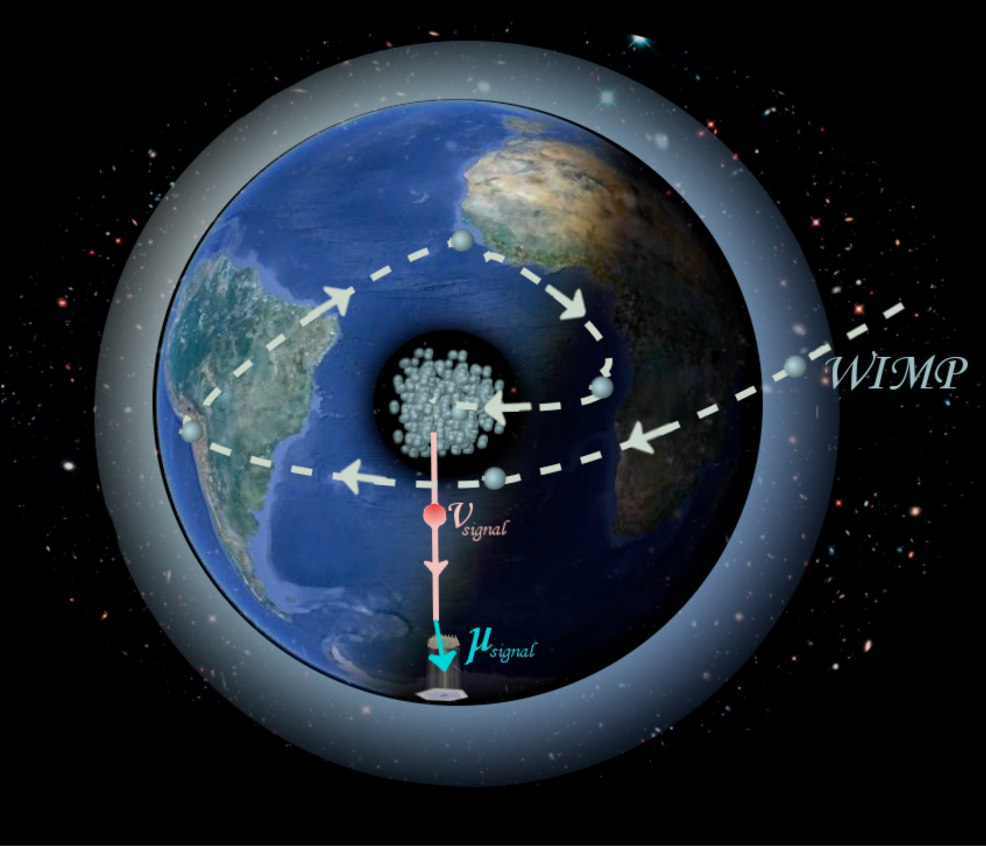
- Carl Niblaeus ICRC2017 (909)
- C. Tönnis [ANTARES] ICRC2017 (907)
- S. In [IceCube] ICRC2017 (965)

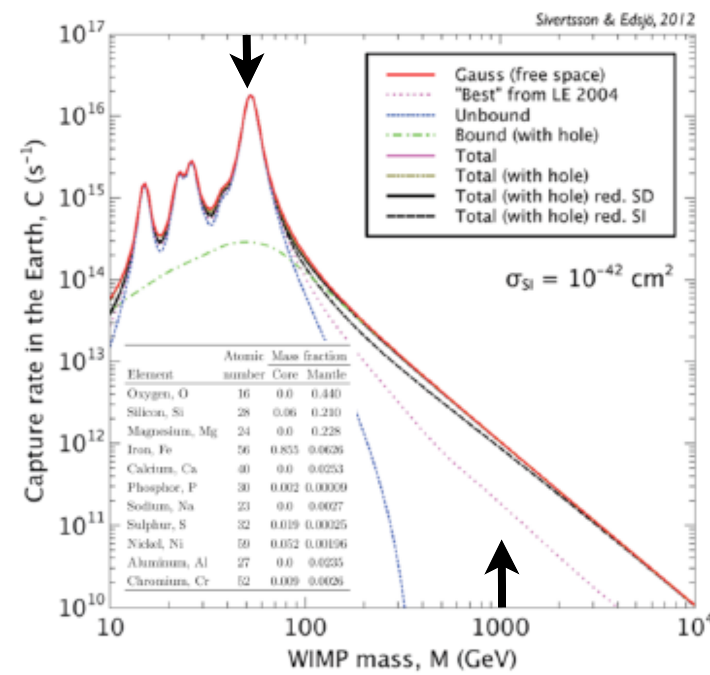
see also

- 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, arXiv: 1704.02892 [astro-ph.HE]
- M. Masip (2017), arXiv: 1706.01290 [hep-ph]

Expect ~2events per year at cubic kilometer detector

Earth WIMPs

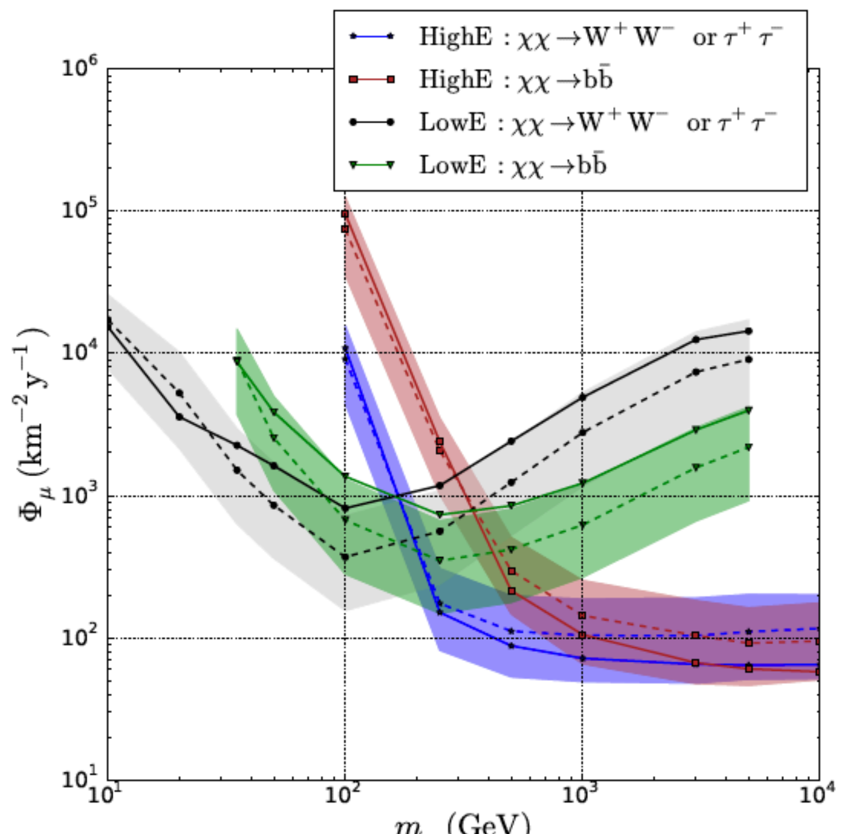


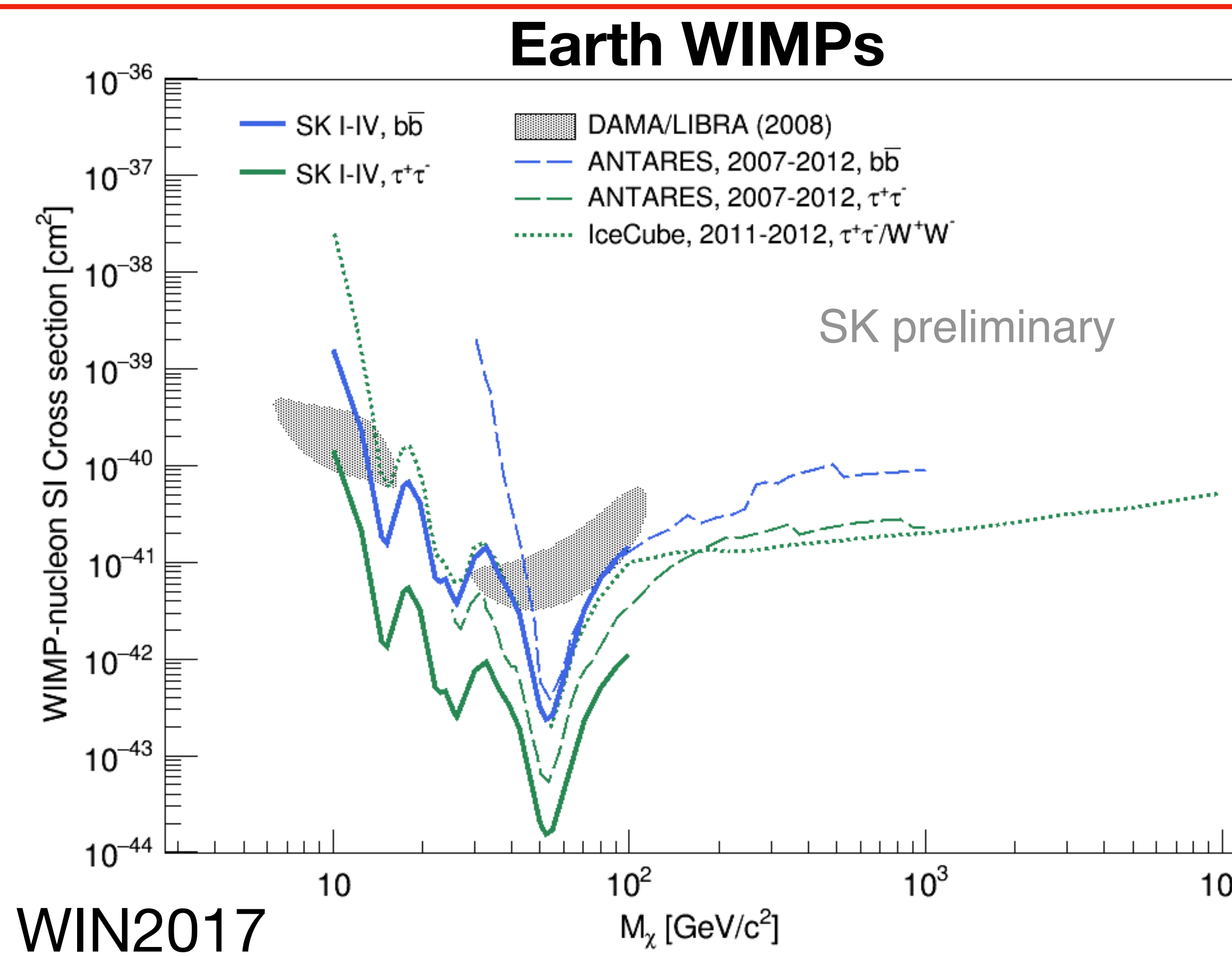


Element	Atomic number	Mass fraction Core	Mass fraction Mantle
Oxygen, O	16	0.0	0.440
Silicon, Si	28	0.06	0.210
Magnesium, Mg	24	0.0	0.228
Iron, Fe	56	0.855	0.0626
Calcium, Ca	40	0.0	0.0253
Phosphor, P	30	0.002	0.00009
Sodium, Na	23	0.0	0.0027
Sulphur, S	32	0.019	0.00025
Nickel, Ni	59	0.052	0.00196
Aluminum, Al	27	0.0	0.0235
Chromium, Cr	52	0.009	0.0026

- Dark Matter could be captured in the Earth and produce a vertically up-going excess neutrino flux

Jan Luenemann PoS(ICRC2017)896





Earth WIMPs

- J. Luenemann ICRC2017 (896)
- C. Tönnis [ANTARES] ICRC2017 (913)

Dark Matter Decay

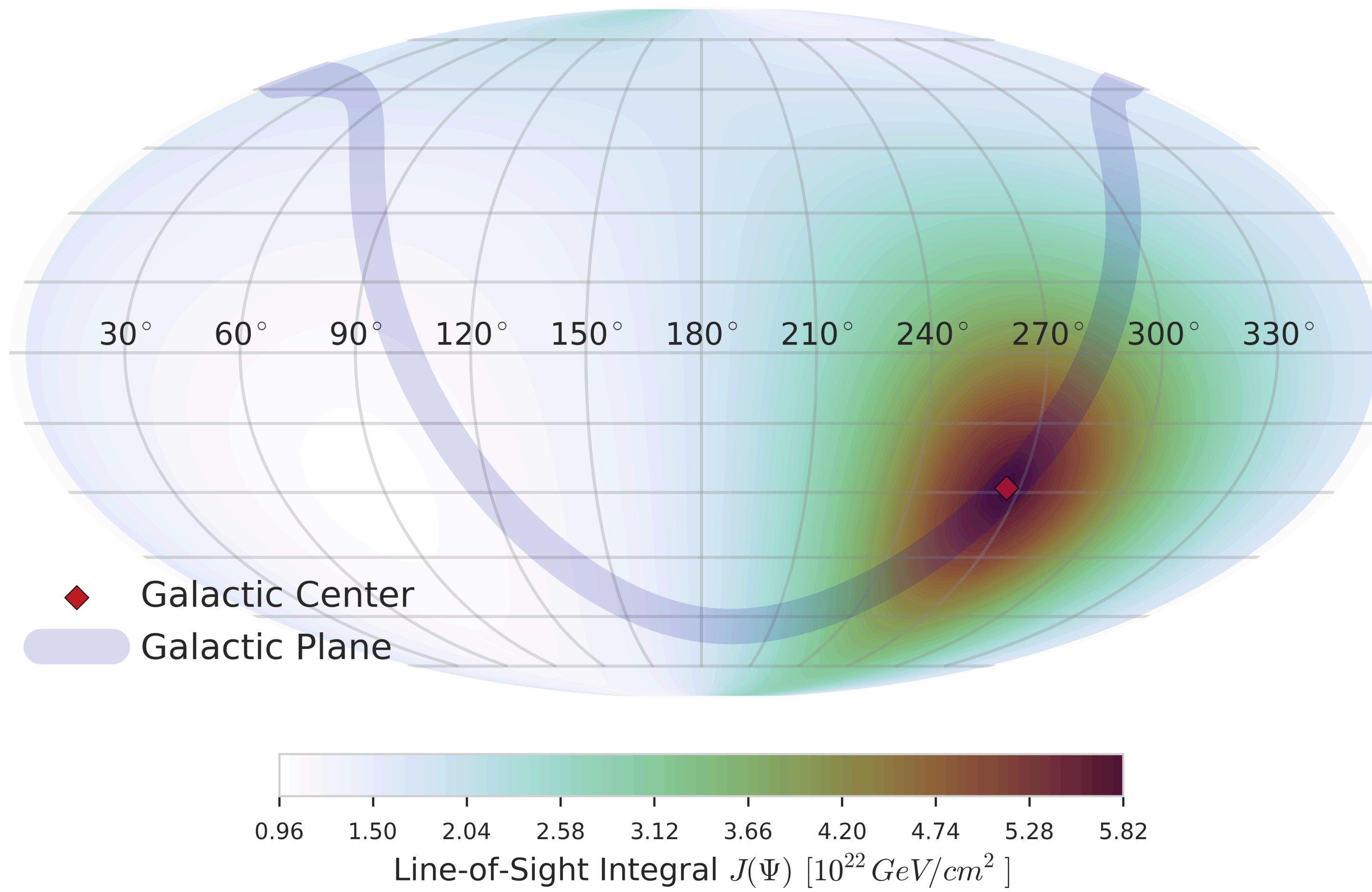
Dark Matter Decay with IceCube

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

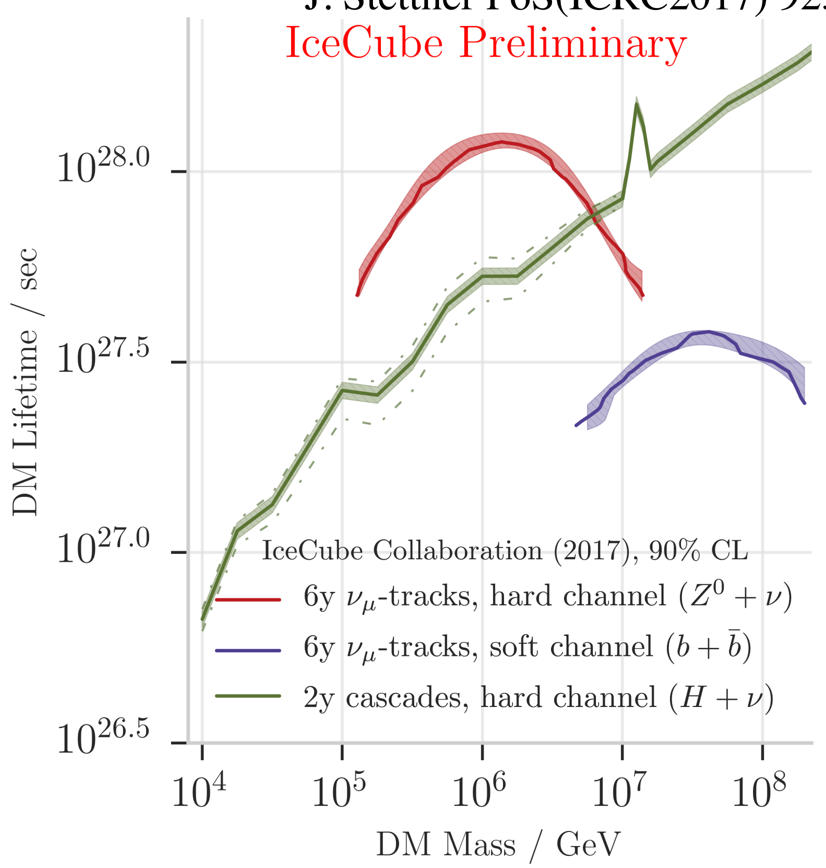
$$\frac{d\Phi^{G}}{dE_\nu} = \frac{1}{4\pi\, m_{DM}\, \tau_{DM}} \frac{dN_\nu}{dE_\nu} \int_0^\infty \rho(r(s,l,b))\, ds$$

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

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



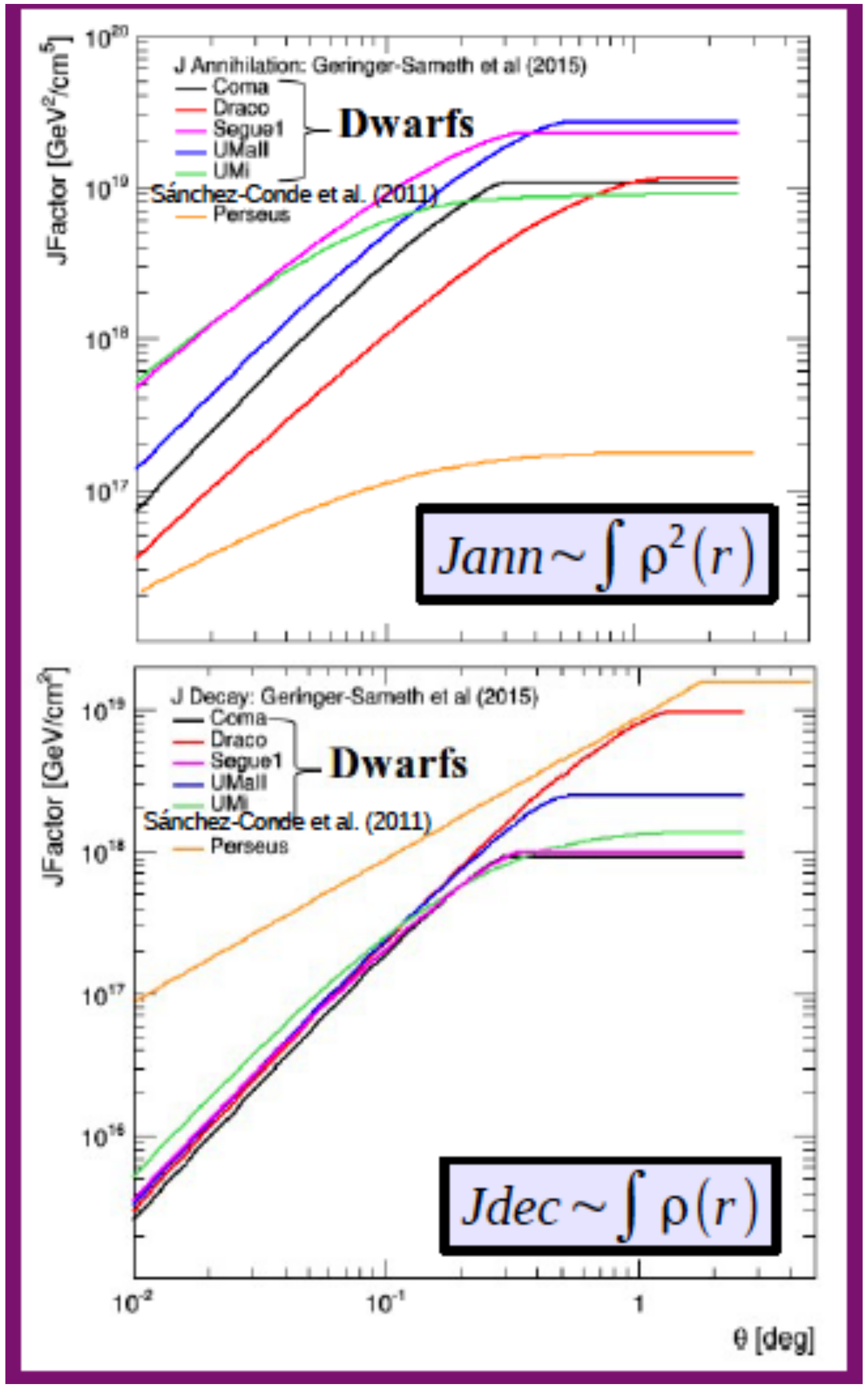
J. Stettner PoS(ICRC2017) 923



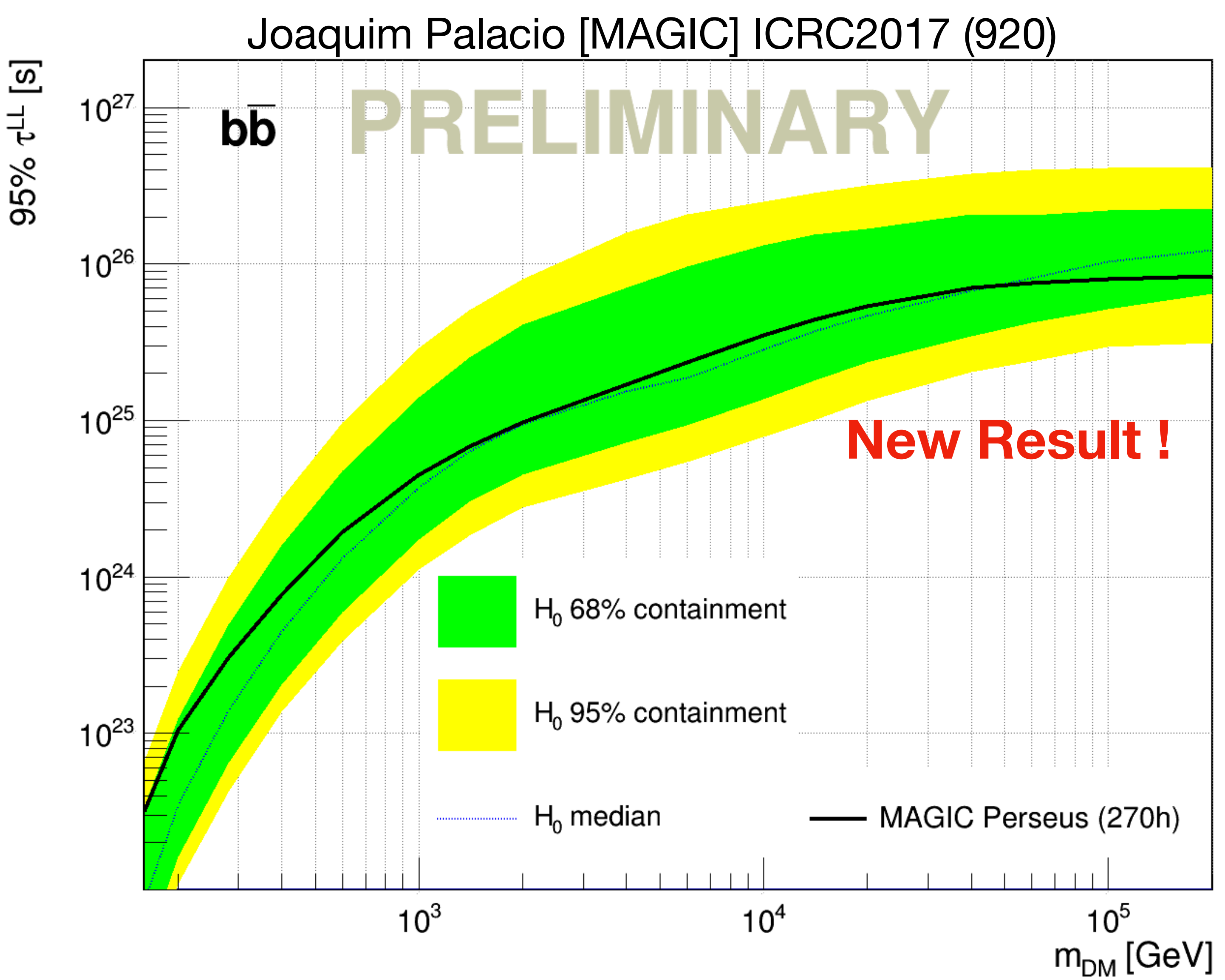
Test-Statistic: $TS = 2 \times \log \frac{\mathcal{L}(X|\tau^{DM}, M^{DM}, \Phi^{Astro}, \gamma^{astro})}{\mathcal{L}(X|\tau^{DM}=\infty, \hat{\Phi}^{Astro}, \hat{\gamma}^{astro})}$

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

MAGIC - Perseus Cluster



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

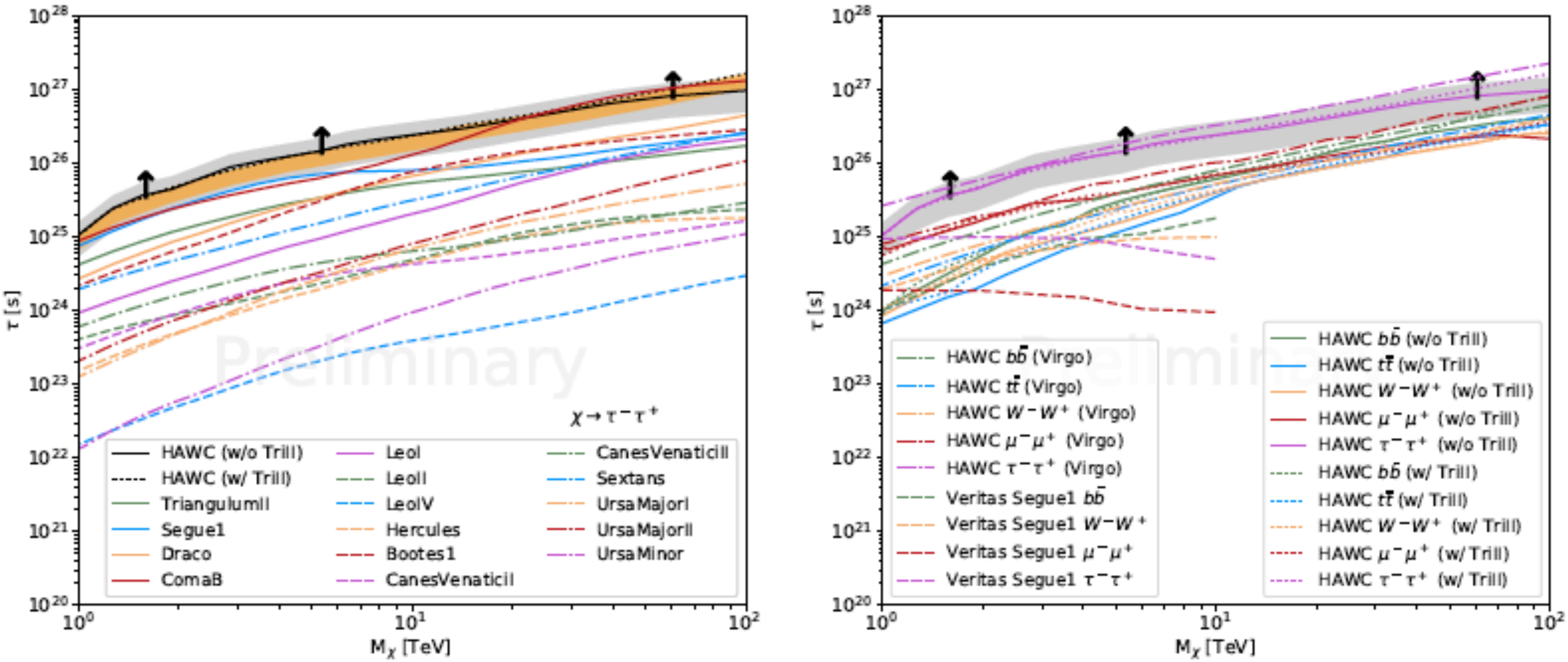


No evidence of dark matter decay observed

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

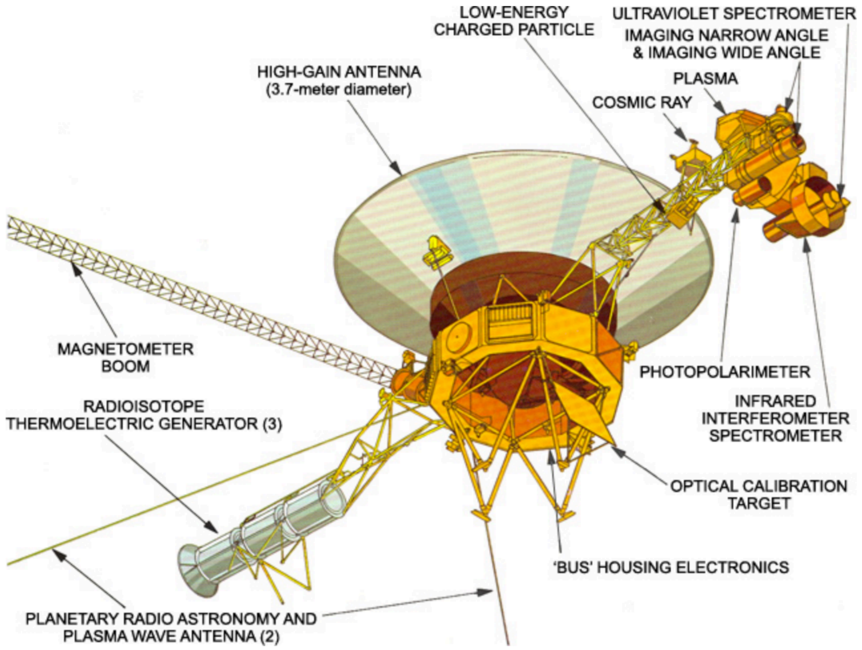
Dark Matter Decay with HAWC

T. Yapici [HAWC] ICRC2017 (891)



Results for 15 dSph, Virgo Cluster and M31

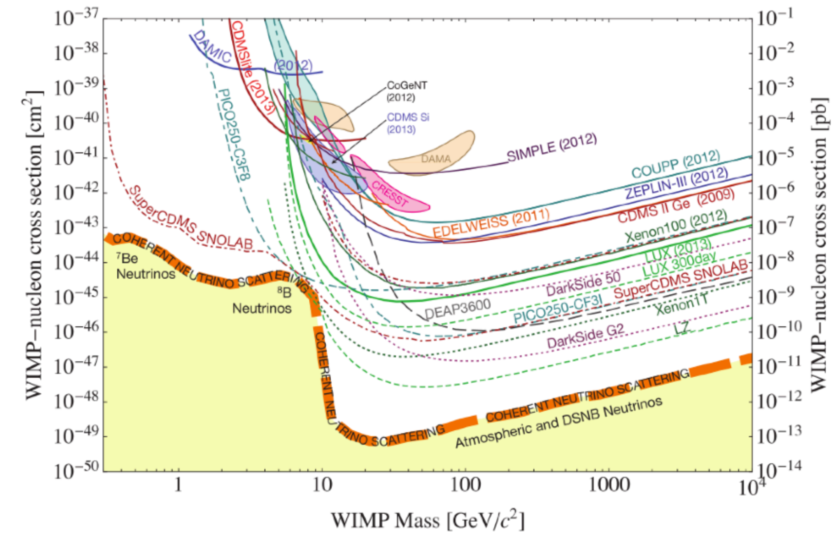
What do Galactic electrons and positrons tell us about Dark Matter?



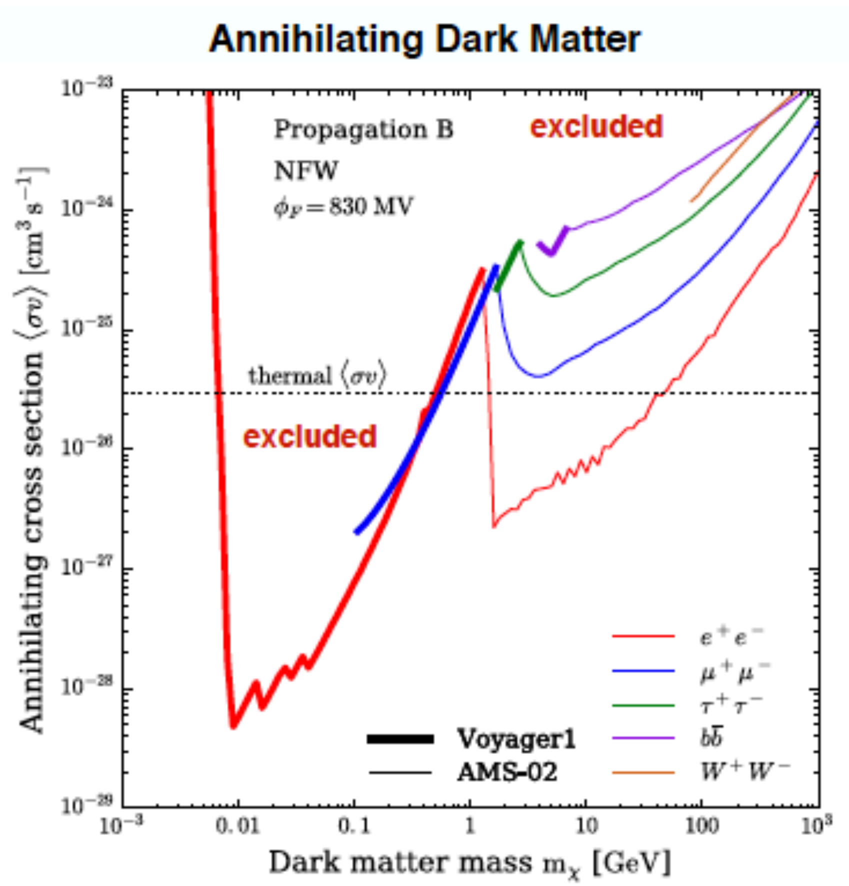
https://voyager.jpl.nasa.gov/spacecraft/instruments.html

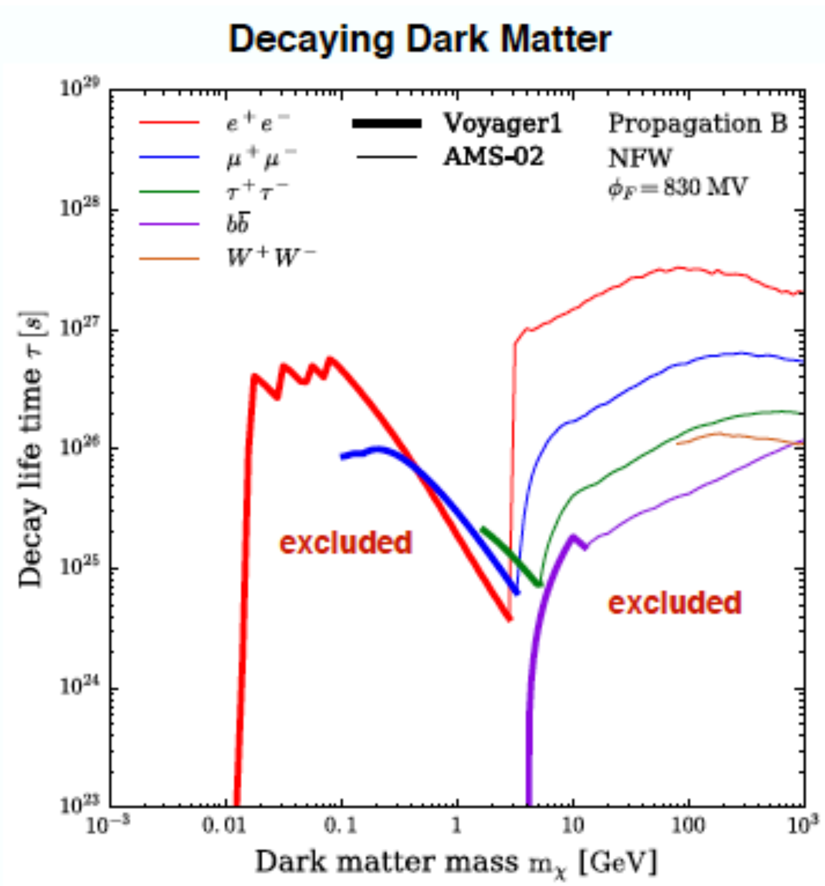
Voyager-I spacecraft has crossed the heliopause during summer 2012.

- New semi-analytical method to deal with the propagation of Galactic electrons and positrons from MeV to TeV energies: ***the pinching method***
- Derive novel constraints on MeV DM particle using the Voyager I data



MeV dark matter ?
- Not well constraint
- Not many channels kinematically available
  - e,ν,γ,μ (>105MeV), π (140MeV)





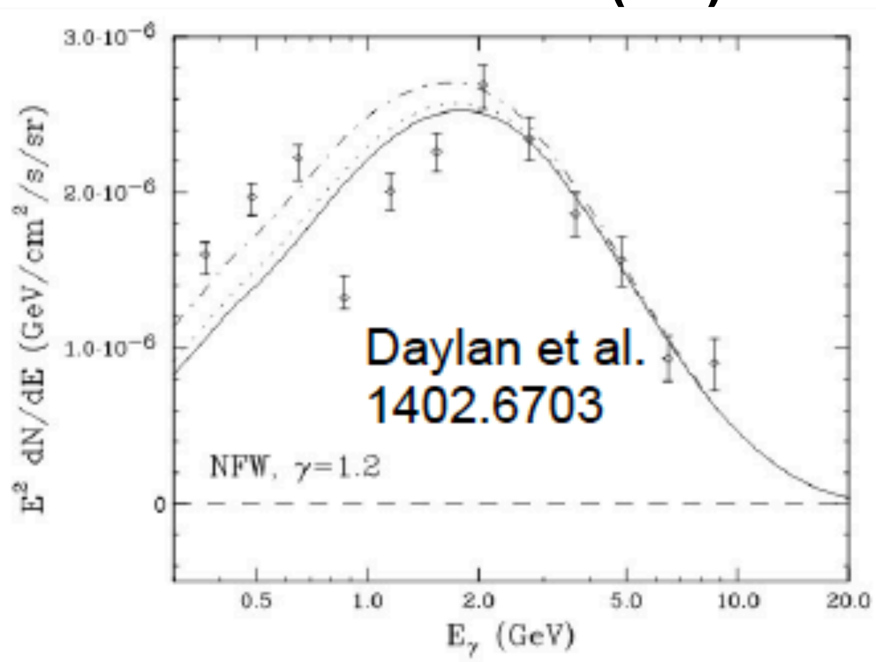
Mathieu Boudaud ICRC2017 (915)
see also
Mathieu Boudaud et al arXiv:1612.03924
Mathieu Boudaud et al arXiv:1612.07698

Anomalies ?

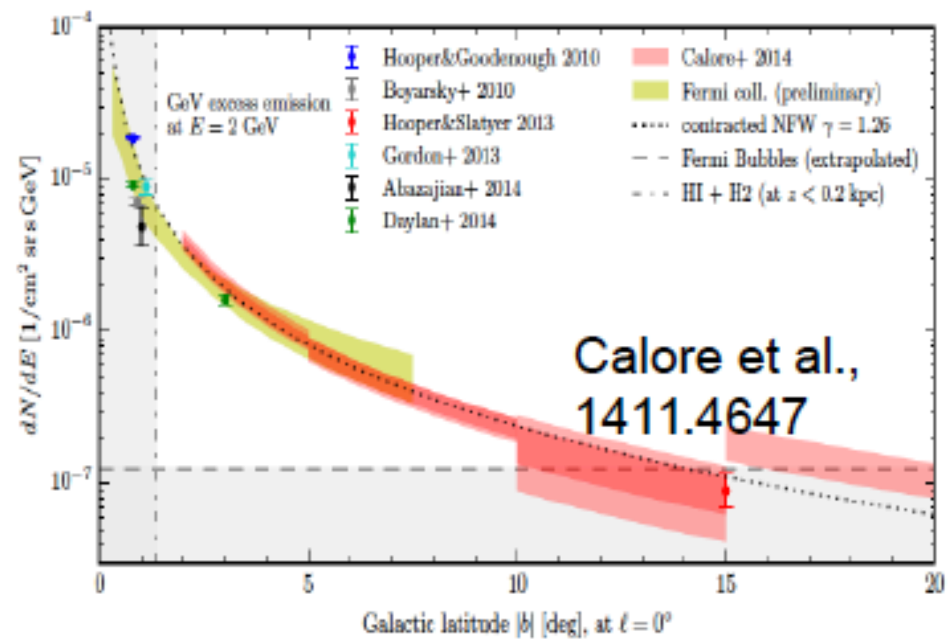
Fermi-LAT GeV excess @ Galactic Center

What's going on in the Galactic Center?

Iris Gebauer ICRC2017 (908)



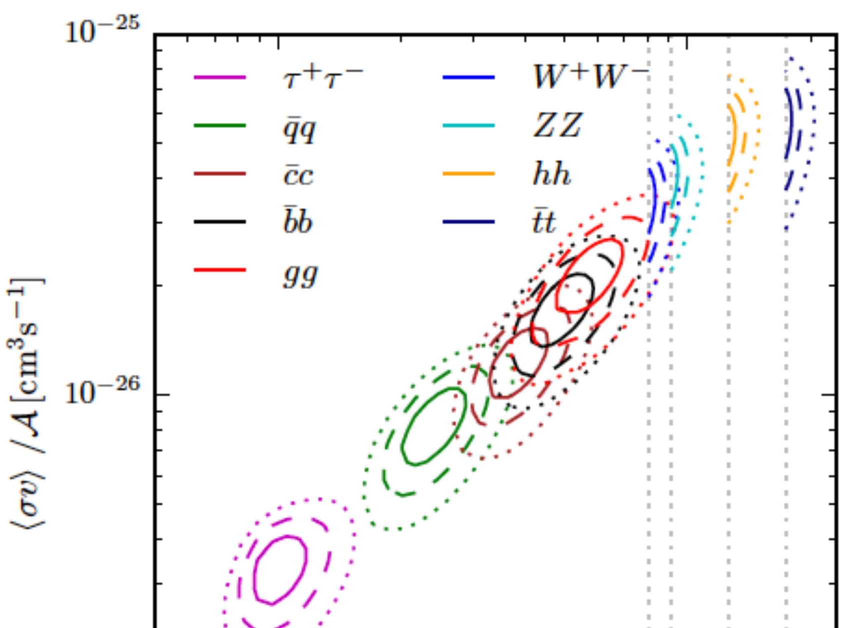
Spectral shape of excess compatible with 35 GeV DM particle annihilating into $b\bar{b}$.



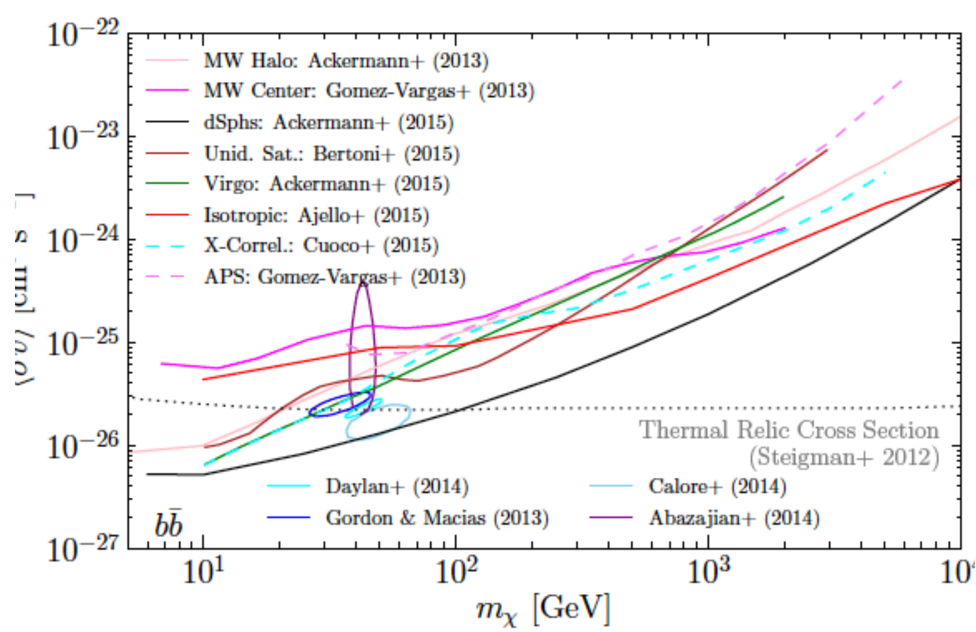
Spatial distribution in latitude compatible with generalized NFW profile

The GeV excess @ Galactic Center

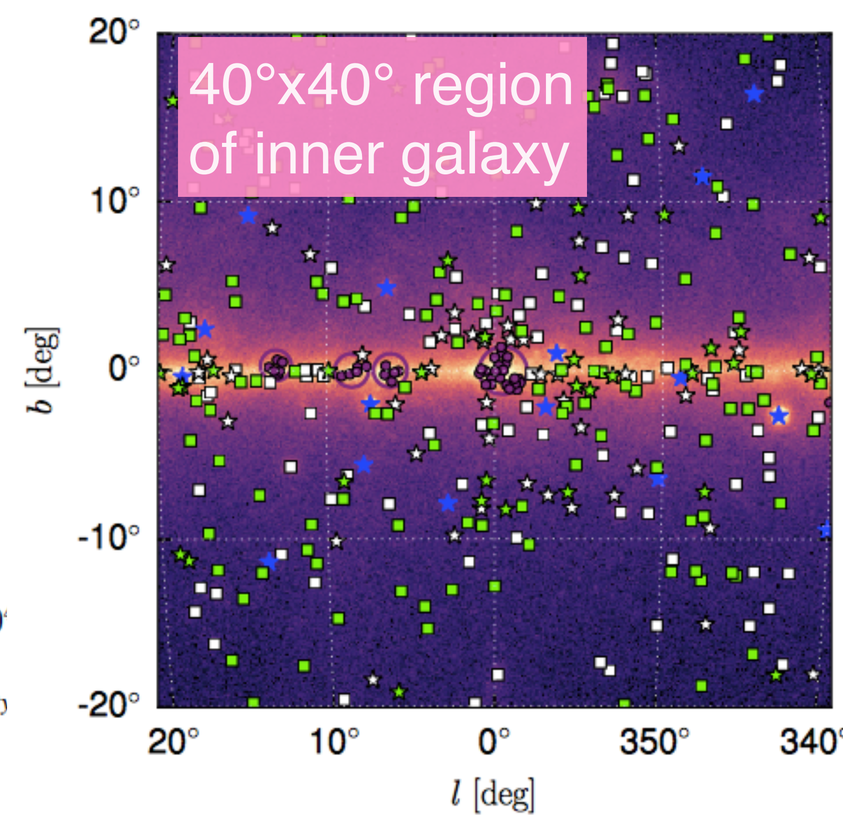
- First claimed in 2009 with Fermi data (arXiv:0910.2998)
  - If interpreted as dark matter, it points to O(10-100) GeV DM
  - DM claim is in tension with bounds from dwarf spheroidal galaxies
- Fermi-LAT collaboration finds that
  - The spectrum and morphology is sensitive to the assumed diffuse emission 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)



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

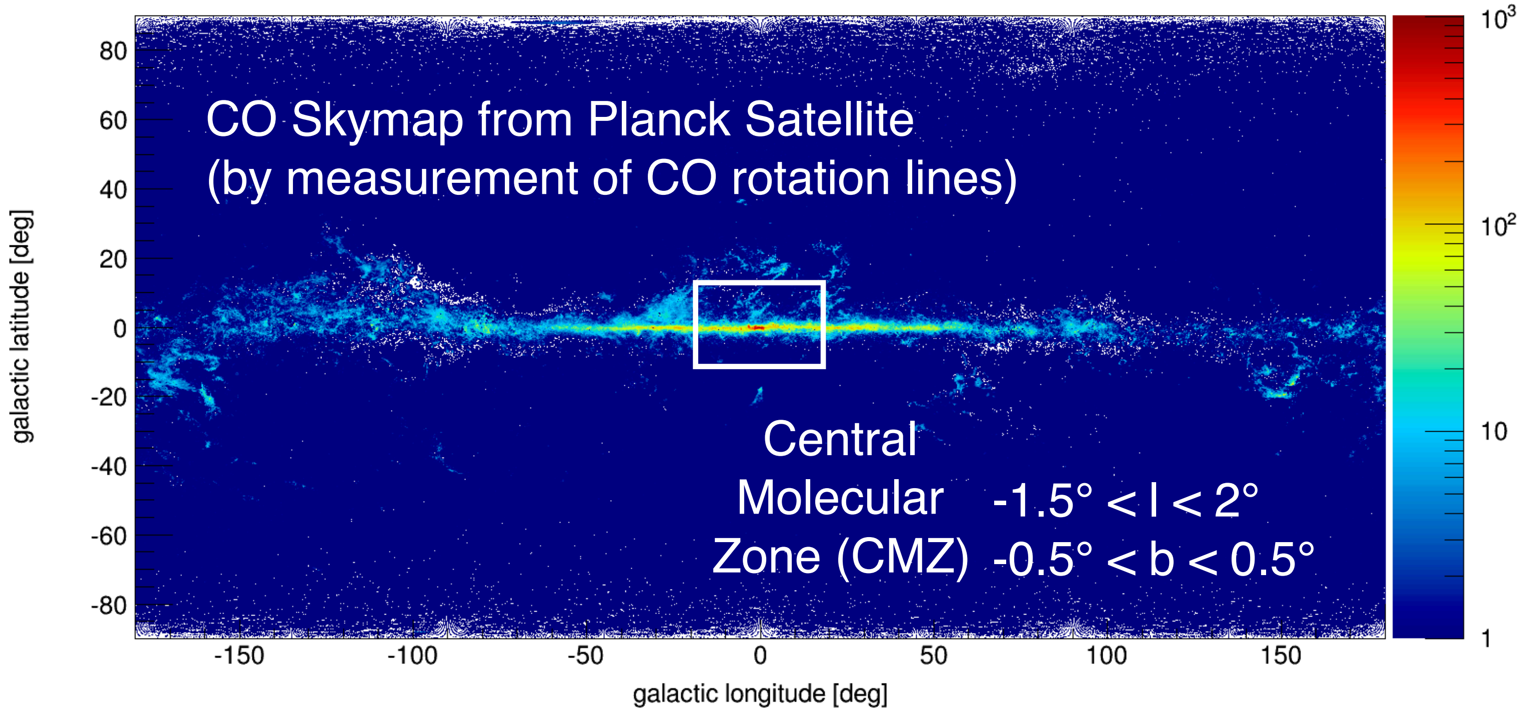


E. Charles, M. Sánchez-Conde, B. Anderson, R. Caputo, A. Cuoco, M. Di Mauro et al., *Sensitivity projections for dark matter searches with the Fermi large area telescope*, Phys.~Rep. 636 (June, 2016) 1–46, [1605.02016].

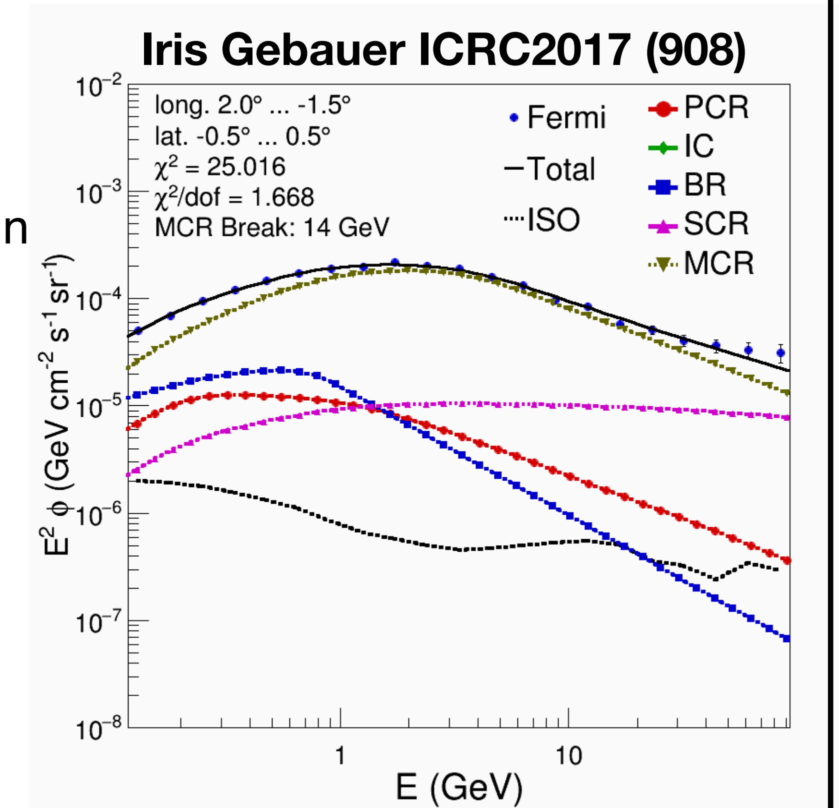


Could molecular clouds explain the explain GC excess ?

Use **spectral templates** instead of **spacial templates**, which is usually done



CO molecules abundant in molecular clouds

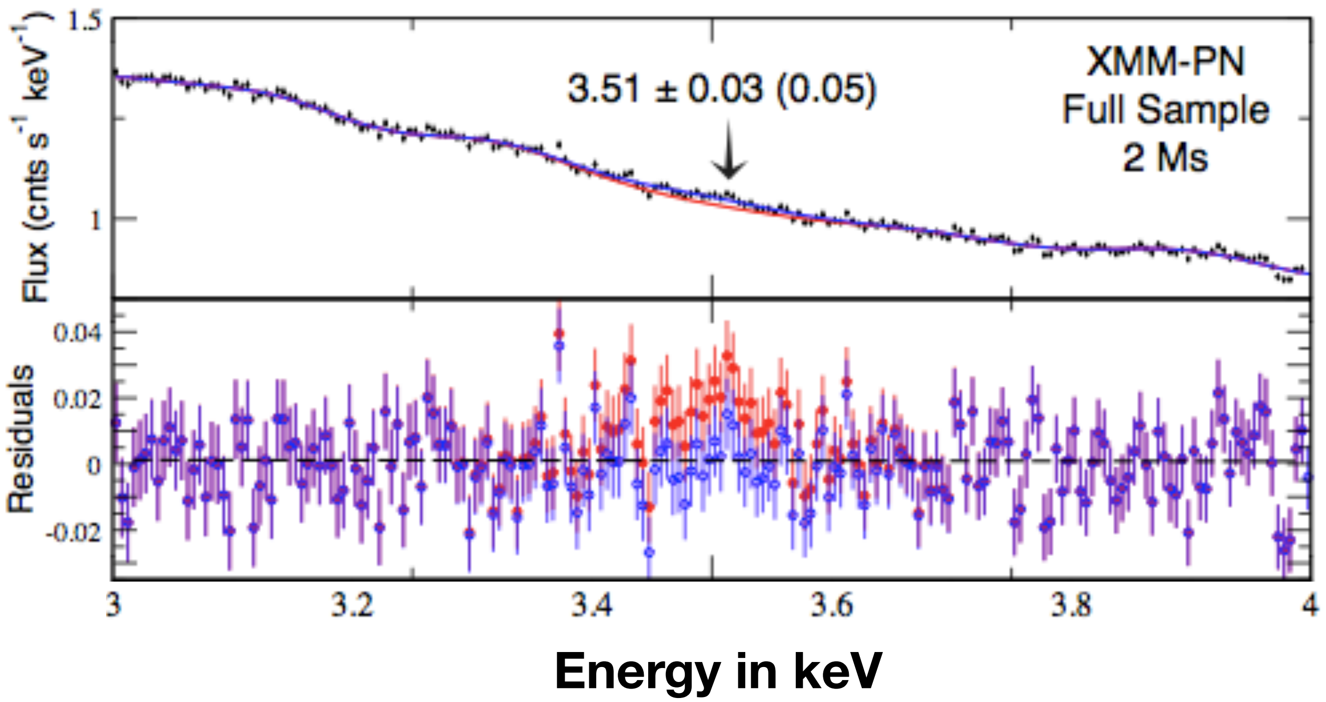


Find that the GeV excess is compatible with the emission of π^0 decay from molecular clouds.
The molecular cloud hypothesis is preferred over dark matter for the following reasons:

- It provides better fits if the whole sky and all energies are considered
- Both hypotheses follow the CO profile instead of a NFW profile
- The CMZ shows a strong excess in the Galactic Center in a longitudinal extended rectangular profile of l x b=4° x 1° instead of a spherical DM profile

Note: Ackermann 2017 (1704.03910) showed that the excess is robust to the inclusion of a CMZ template …

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)

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 …

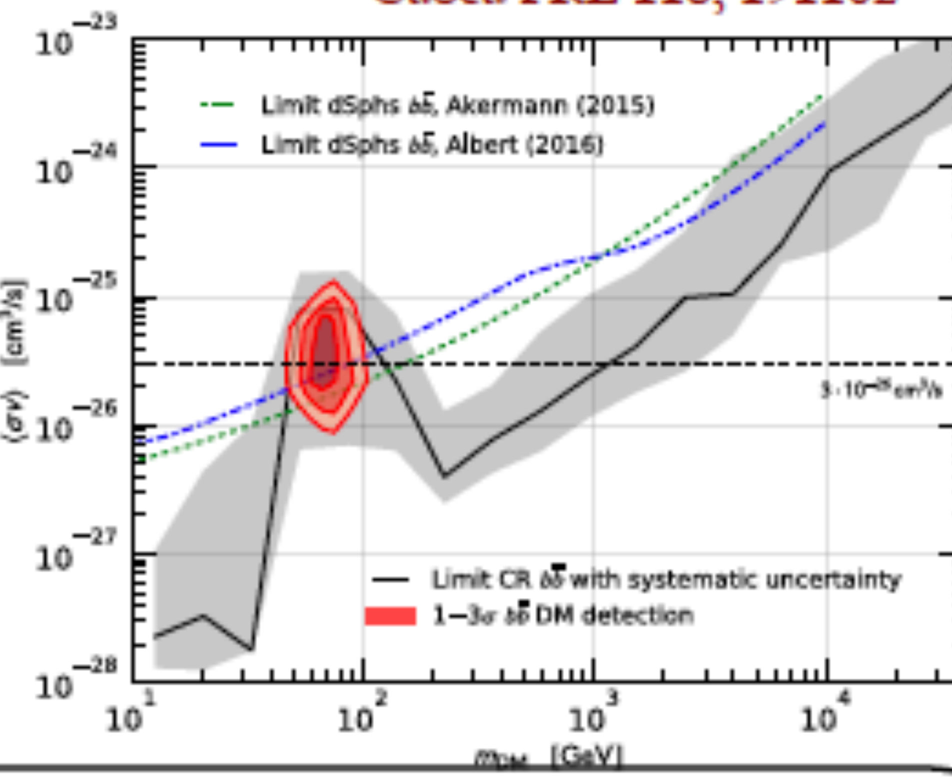
- **Future observations ATHENA, HERD, Micro-X, …**
- **Dark matter velocity spectroscopy (Speckhard, Ng, Beacom, Laha Phys. Rev. Lett. 116 (2016) 031301)**
- **Look where no background is expected …**

AMS-02

- AMS Antiprotons

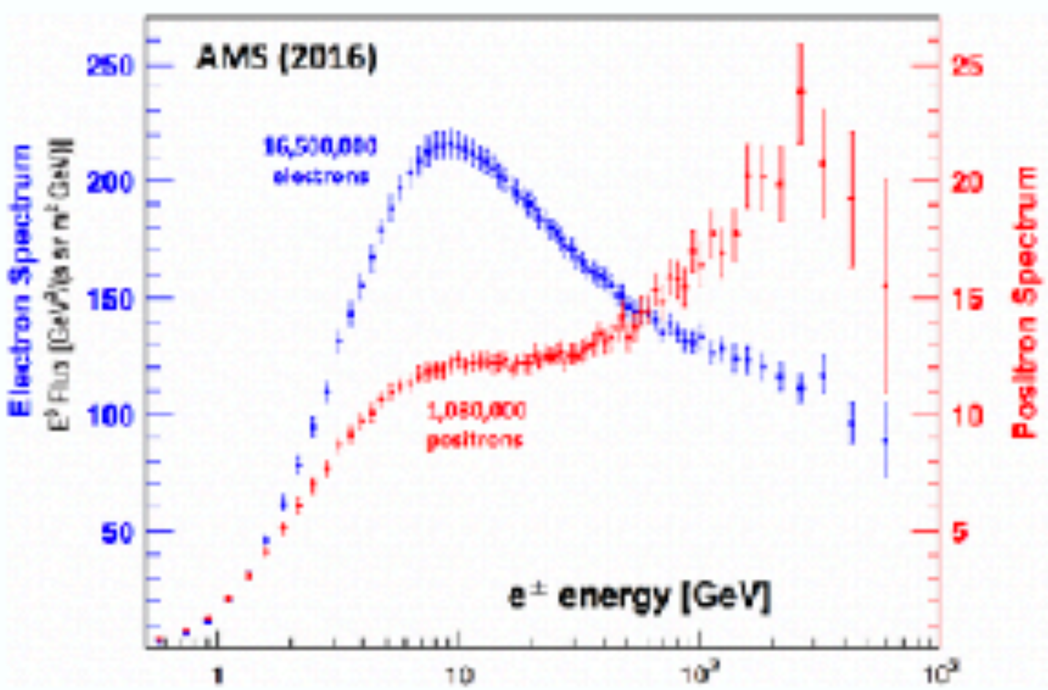
- Excess ~4.5σ possibly attributed to DM *(PRL 118, 191102; PRL 118, 191101)*
- Significant uncertainties: modeling of antiproton production cross section, cosmic-ray propagation, solar modulation.

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)

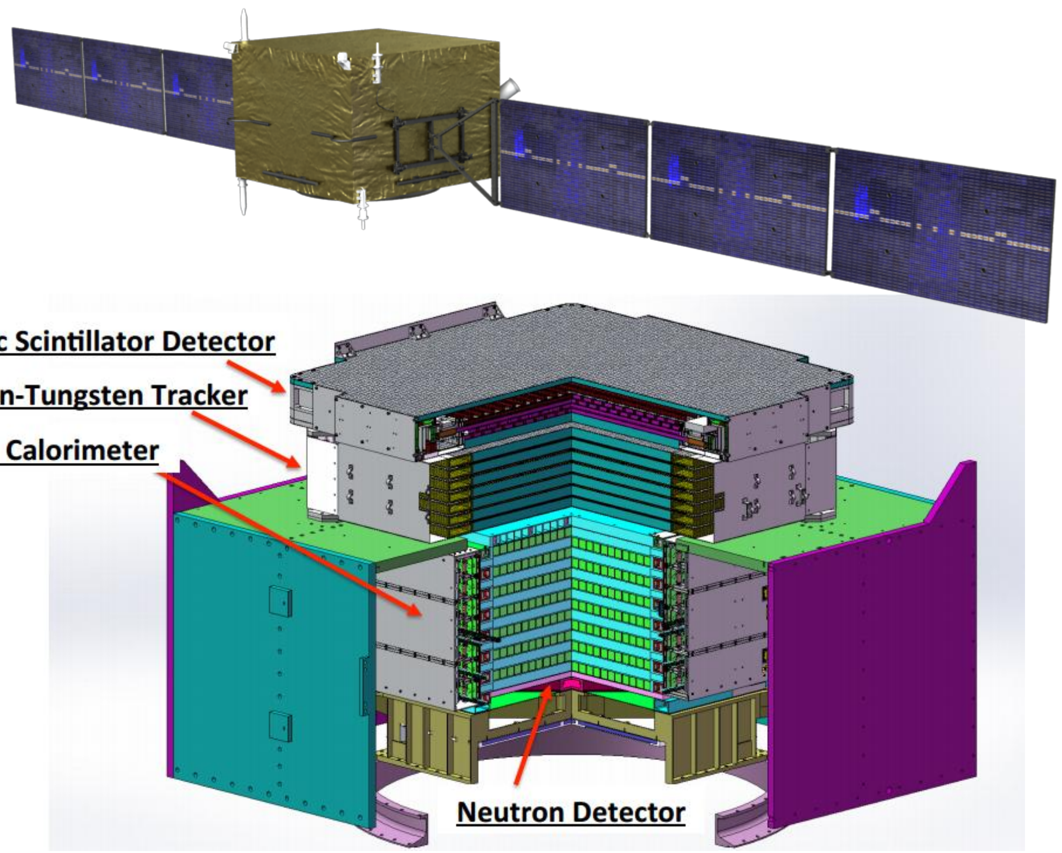
What to expect in the future with Indirect Searches

see also highlight talk

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

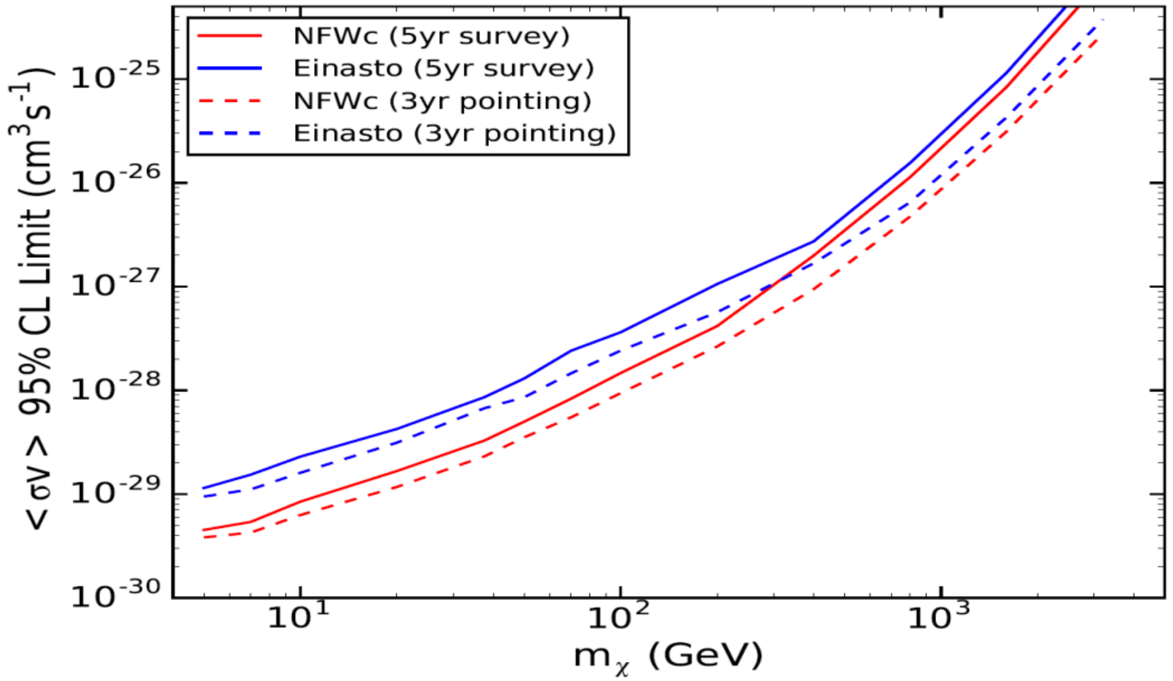
DAMPE
- Shubin LIU [DAMPE] ICRC2017 (925) [BGO Calorimeter]
- X. Wu [DAMPE] ICRC2017 (926) [Tracker]
- Y. Zhang [DAMPE] ICRC2017 (898) [Performance]
- S. Wen [DAMPE] ICRC2017 (899) [Energy Calibration]
- Y. Wei [DAMPE] ICRC2017 (900) [Acceptance e-/e+]

DAMPE

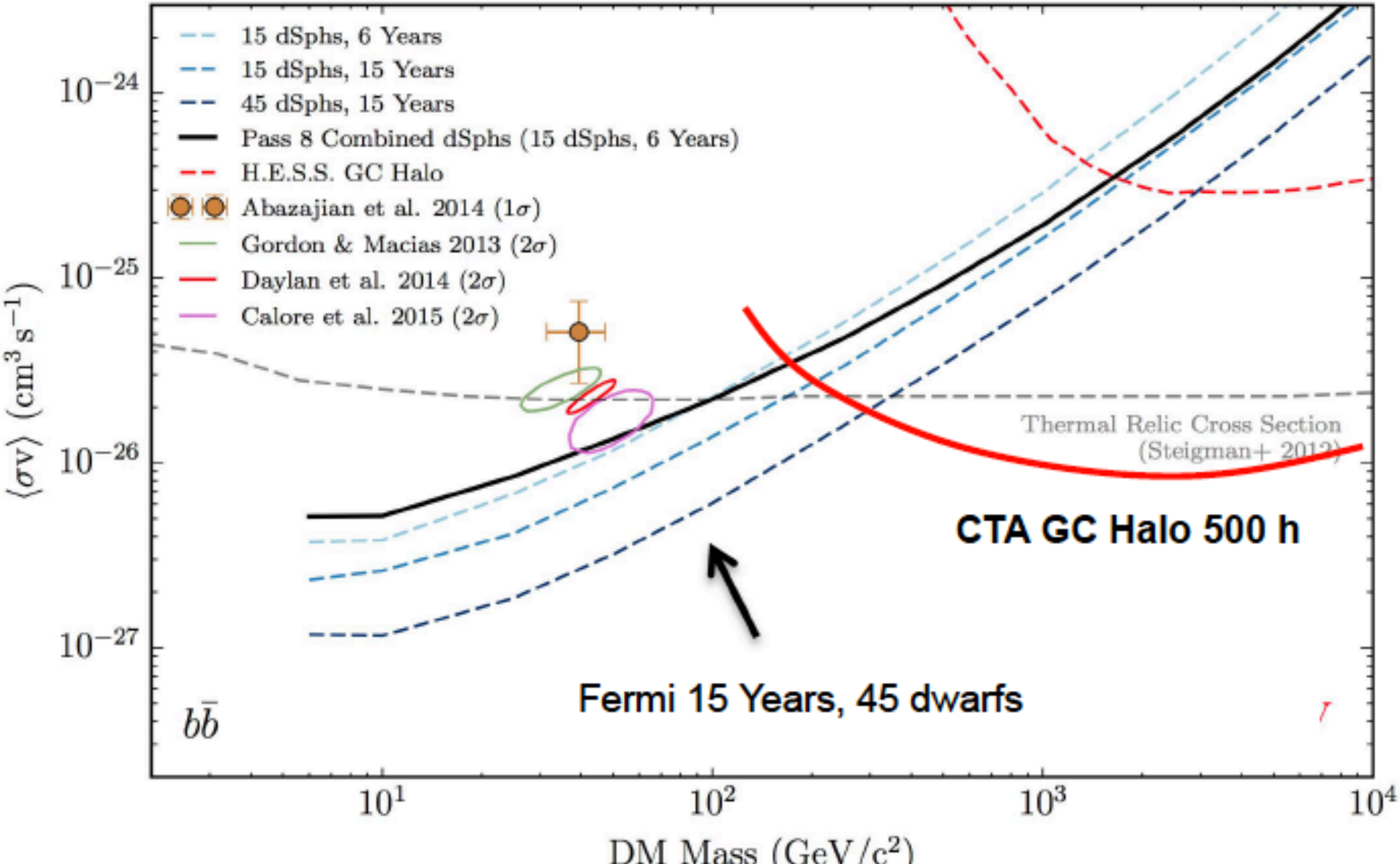


- DAMPE detector, consists of 4 subsystems:
  - the plastic scintillator strips detector (PSD),
  - the silicon-tungsten tracker-converter (STK),
  - the BGO imaging calorimeter (BGO), and
  - the neutron detector (NUD).

Sensitivity with 3 yrs of data DAMPE



Dark Matter improvement estimate by 2023

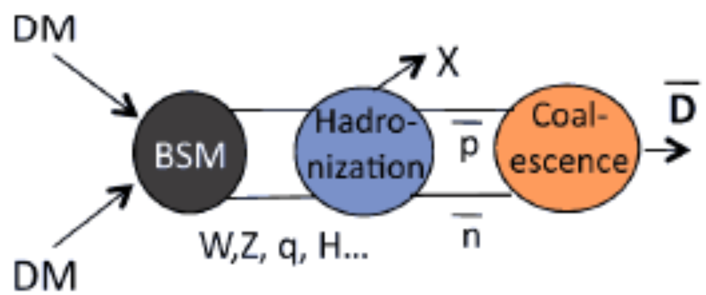


CTA sensitivity curve from Carr et al. 2015 500 hr, statistical only, NFW, 30 GeV threshold arXiv:1508.06128

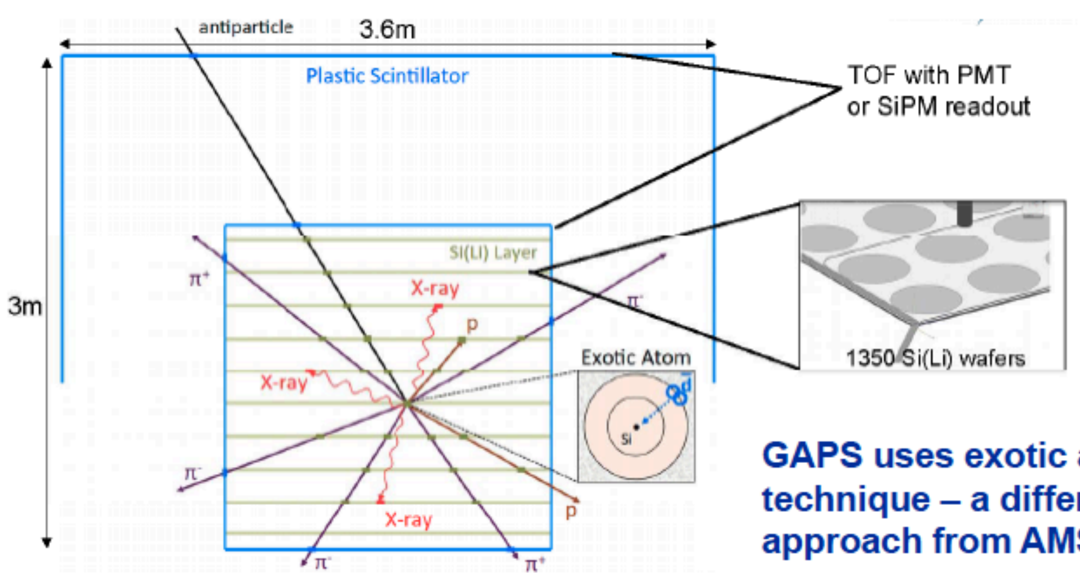
Together Fermi and CTA will probe most of the space of WIMP models with thermal relic annihilation cross section

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

Anti-D's production

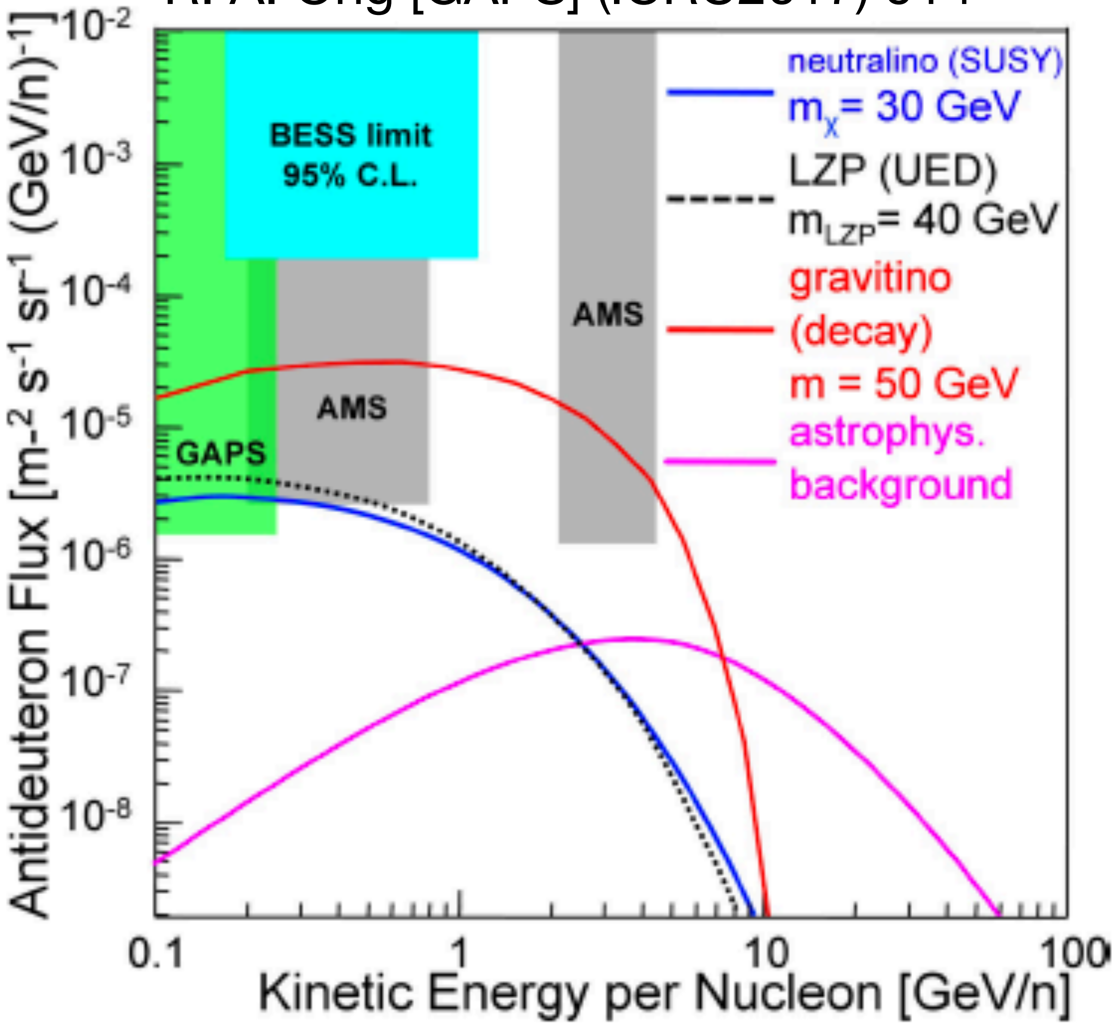


essentially background free
(secondary production)



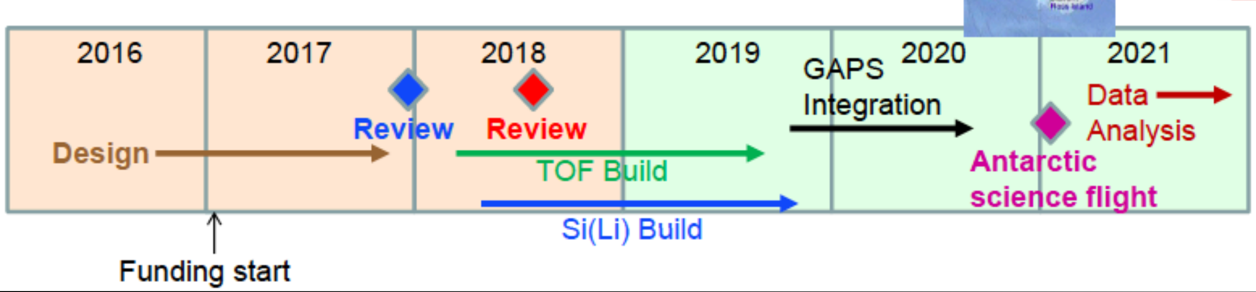
GAPS uses exotic atom technique – a different approach from AMS, BESS…

R. A. Ong [GAPS] (ICRC2017) 914



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



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

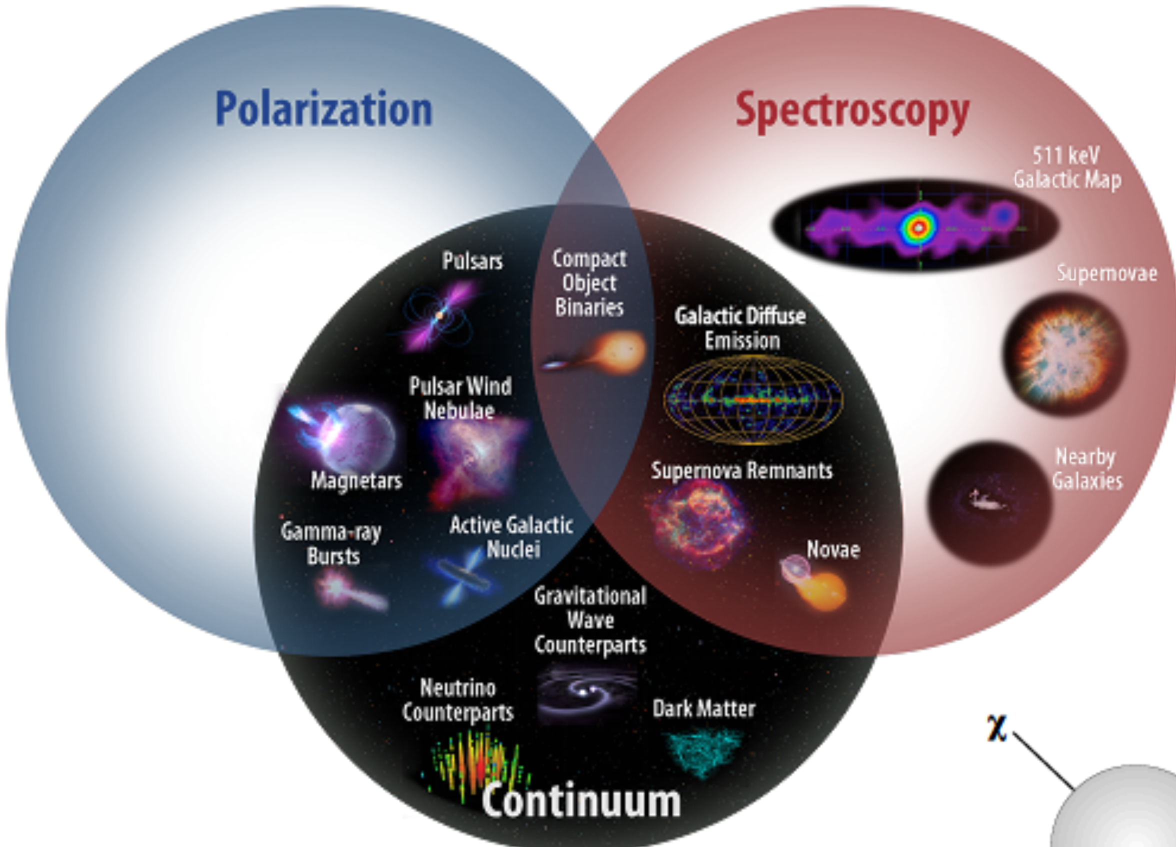
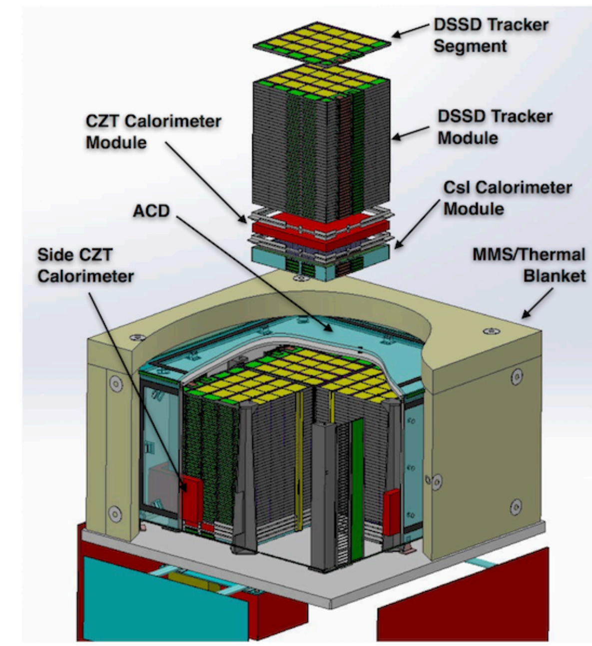
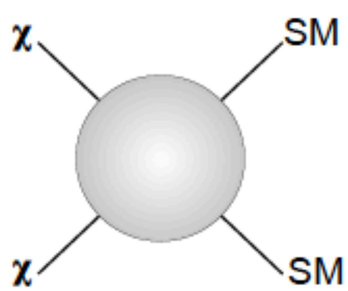


Image - https://asd.gsfc.nasa.gov/amego/

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



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



WIMPs	WISPs
• Interact via gravity and "weak" force • Thermal: <σv> ~$3x10^{26}cm^3s^{-1}$ • 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

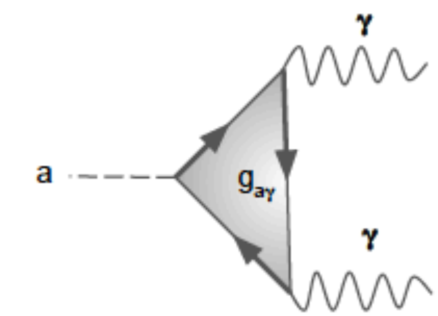
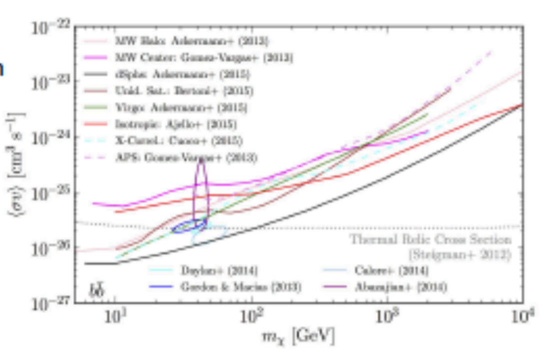


Figure 1: (top) Feynman cartoon of WIMP annihilation (χ) to Standard Model Particles (SM). (right) Summary of WIMP dark matter results obtained with *Fermi*-LAT. Lines are upper limits while closed contours are the Galactic Center Excess from dark matter annihilations [7, 10].



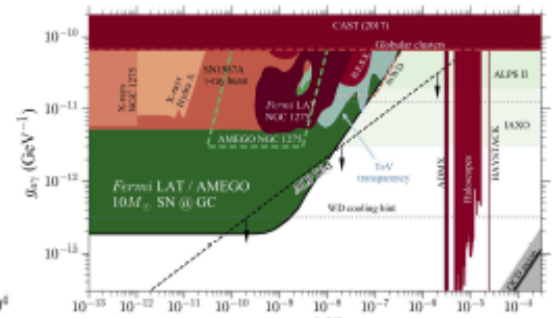


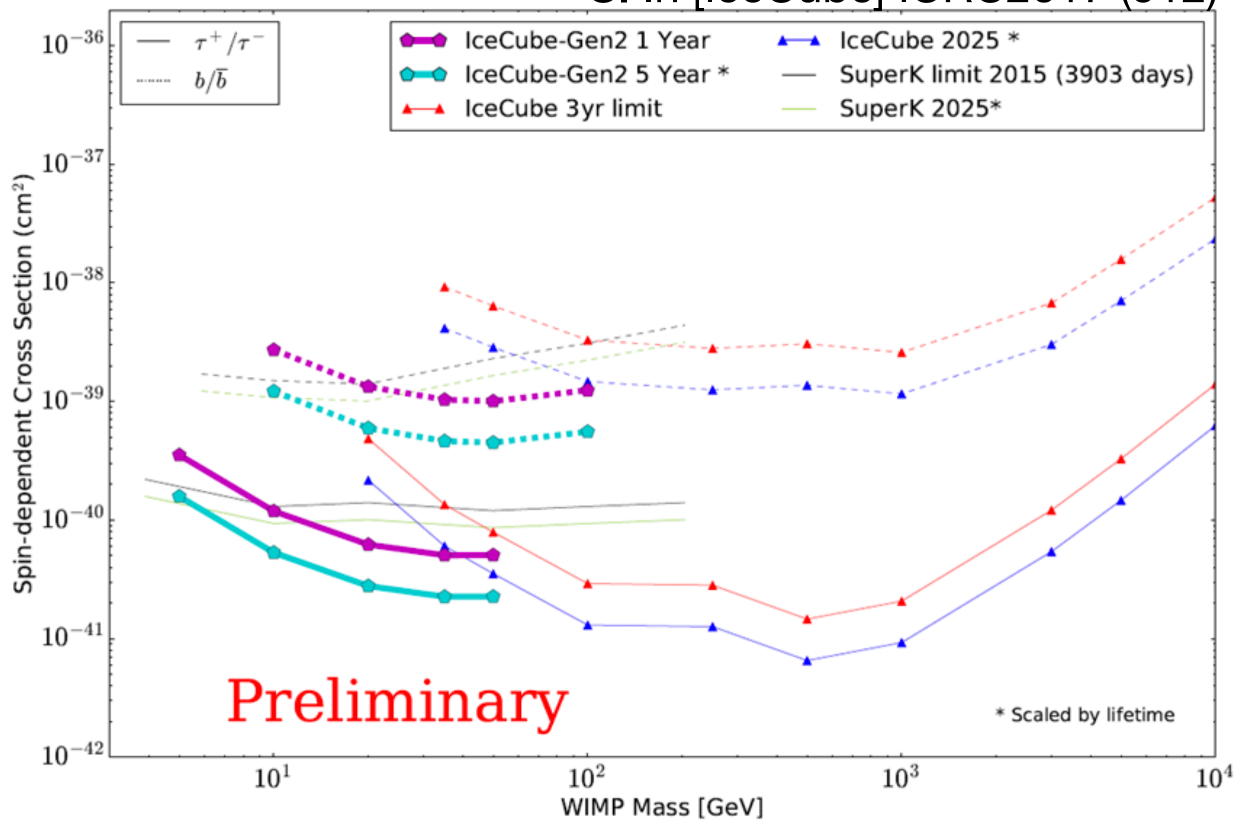
Figure 2: (top) Feynman cartoon of WISP oscillation (a) to γ-rays. (left) Summary of ALP results obtained with *Fermi*-LAT and regions of sensitivity for AMEGO. Shaded regions are excluded [11].

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

Next generation neutrino detectors

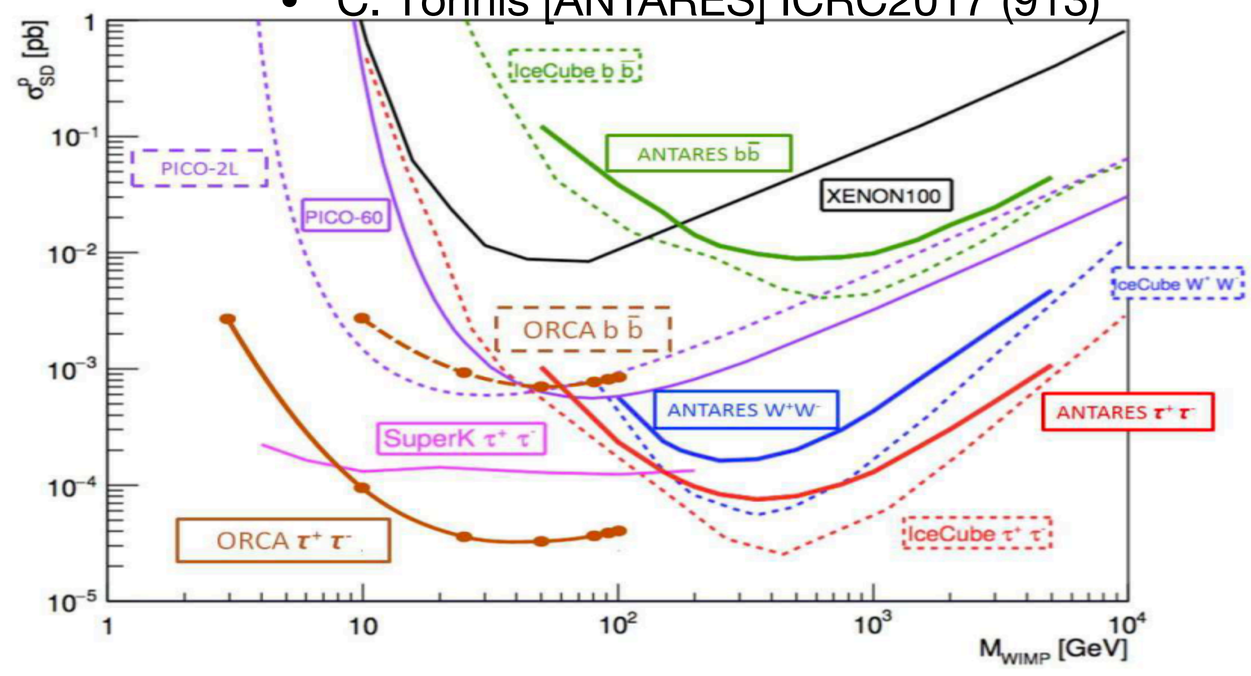
IceCube-Gen2 (PINGU fill in)

S. In [IceCube] ICRC2017 (912)



ORCA

- C. Tönnis [ANTARES] ICRC2017 (913)



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

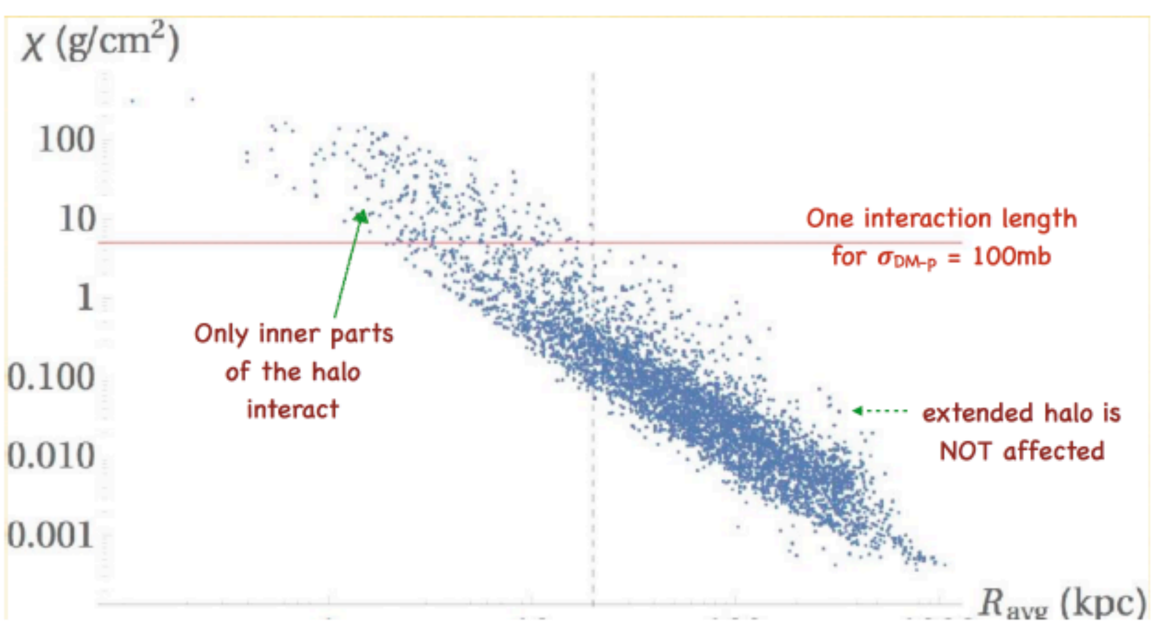
Beyond WIMP Dark Matter

Non-WIMP DM

Glennys R. Farrar ICRC2017 (929)

Sexaquark - scalar 6-quark state (uuddss)

- m~1.5-1.8GeV
- evades accelerator detection (looks like n)
- yields correct relic abundance
- freezes out before primordial nucleosynthesis
- Interacts with Galactic gas to form co-rotating disc



explains small scale structure of rotation curves

Jae-Kwang Hwang ICRC2017 (933)

Cosmic rays and new fermionic dark matters

Table 1. Elementary fermions in the three-dimensional quantized space model. The bastons (Dark matters) interact gravitationally but not electromagnetically with the electrons and protons because the bastons do not have the lepton (LC) and color (CC) charges.

	Bastons (EC)				Leptons(EC,LC)				Quarks(EC,LC,CC)			
	EC				EC				EC			
X1	-2/3	B1			0	ν_e	ν_μ	ν_τ	2/3	u	c	t
X2	-5/3	B2			-1	e	μ	τ	-1/3	d	s	b
X3	-8/3	B3			-2	Le	Lμ	Lτ	-4/3	Q1	Q2	Q3
Total	-5				-3				-1			
	Dark matters				LC				LC			
X4					-2/3	ν_e	e	Le	0	u	d	Q1
X5	Each flavor (charge) corresponds to each dimensional axis.				-5/3	ν_μ	μ	Lμ	-1	c	s	Q2
X6					-8/3	ν_τ	τ	Lτ	-2	t	b	Q3
Total					-5				-3			
									CC			
X7	Baryon: CC = -5 (3 quarks)								-2/3(r)			
X8	Meson: CC = 0 (quark - anti quark)								-5/3(g)			
X9	Paryon: LC = -5 (3 leptons)								-8/3(b)			
Total	Koron: LC = 0 (lepton - anti lepton)								-5			

Study of Fast Moving Nuclearites and Meteoroids using High Sensitivity CMOS Camera with EUSO-TA

F. Kajino [JEM-EUSO] ICRC2017 (924)

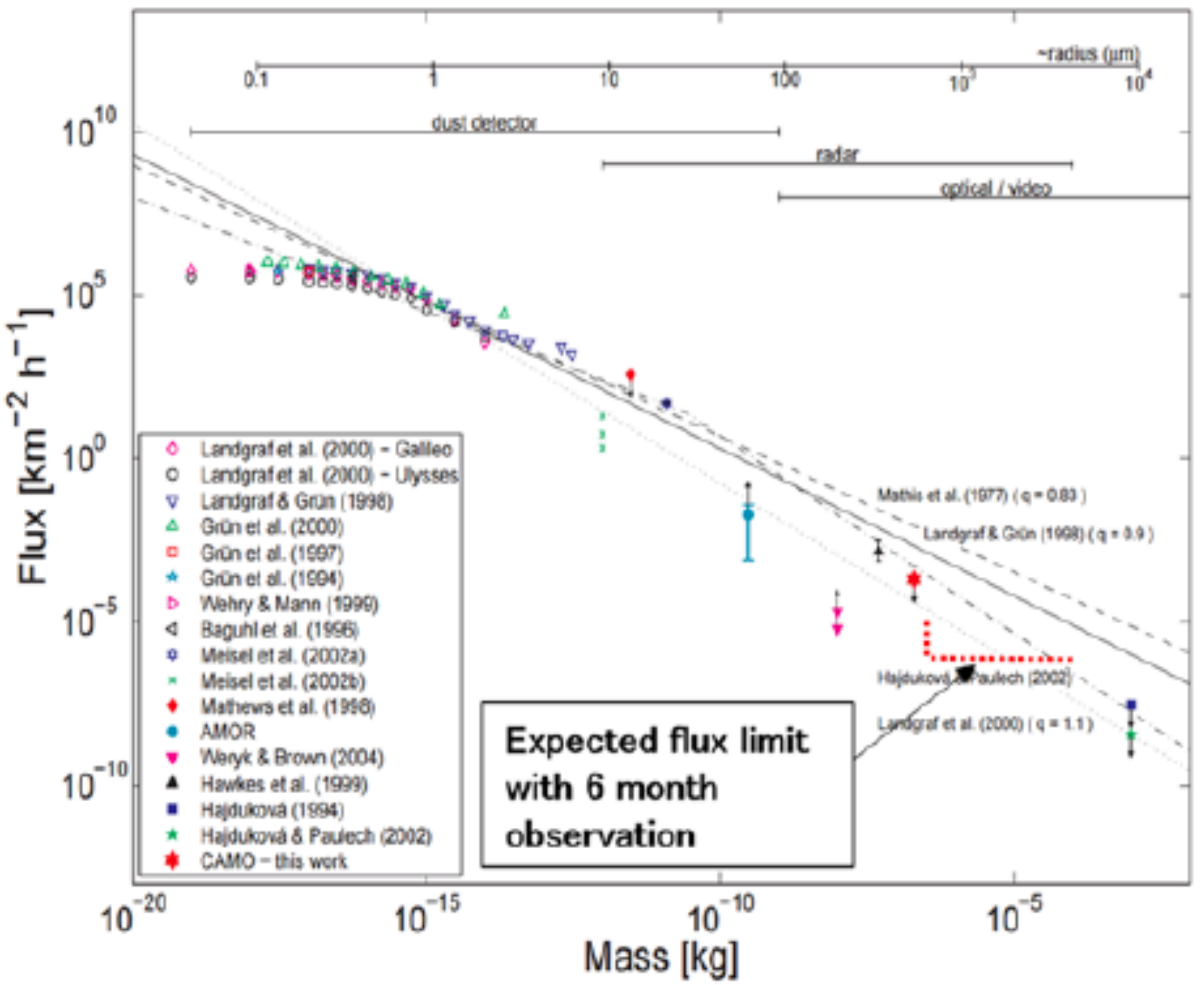
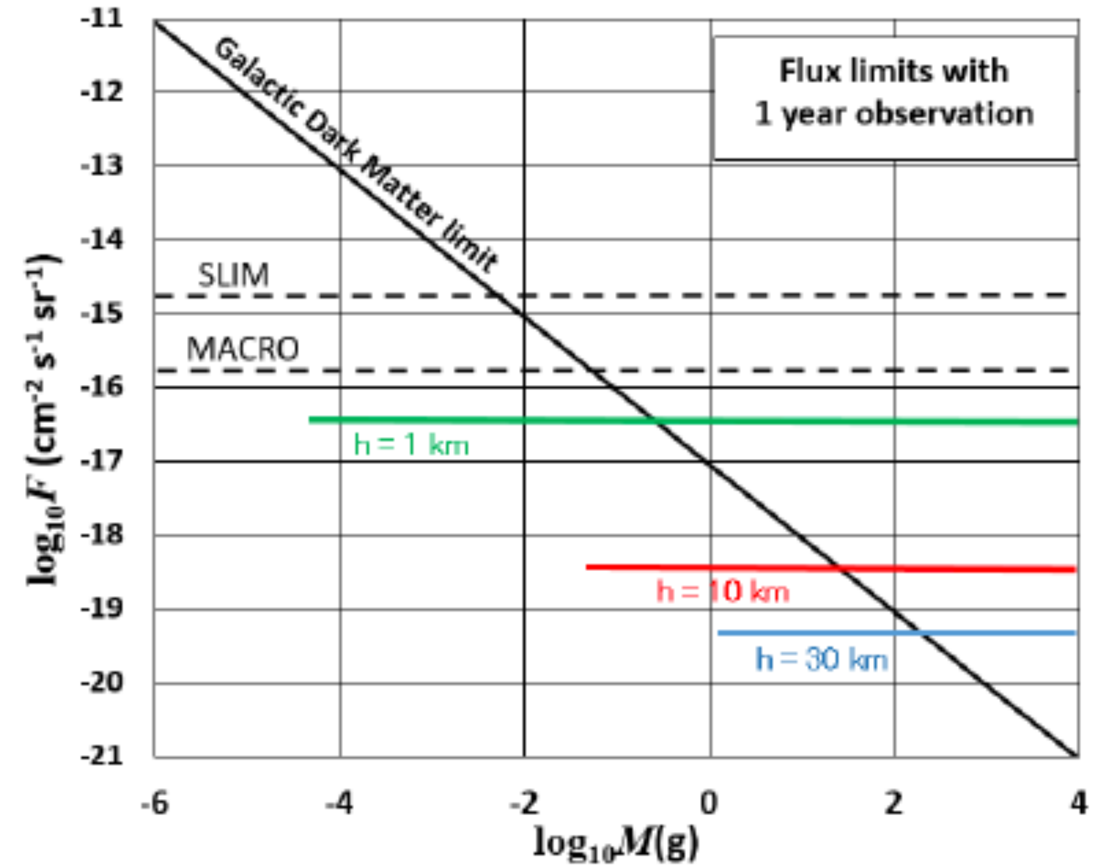


Fig. 6 Expected flux limit for the observation of interstellar meteoroids.

F. Kajino [JEM-EUSO] ICRC2017 (924)



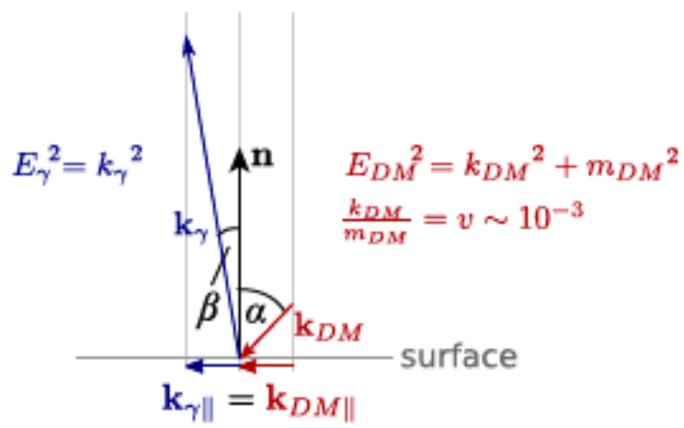
Expected upper limit on nucleorites

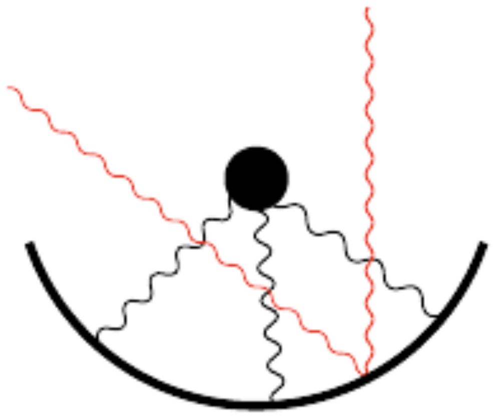
Search for Hidden Photon Dark Matter with FUNK

Dark matter could predominantly consist of hidden photons

- Additional U(1) symmetry and corresponding photons predicted by many extensions to the Standard Model
- Kinetic mixing between photons and hidden photons possible

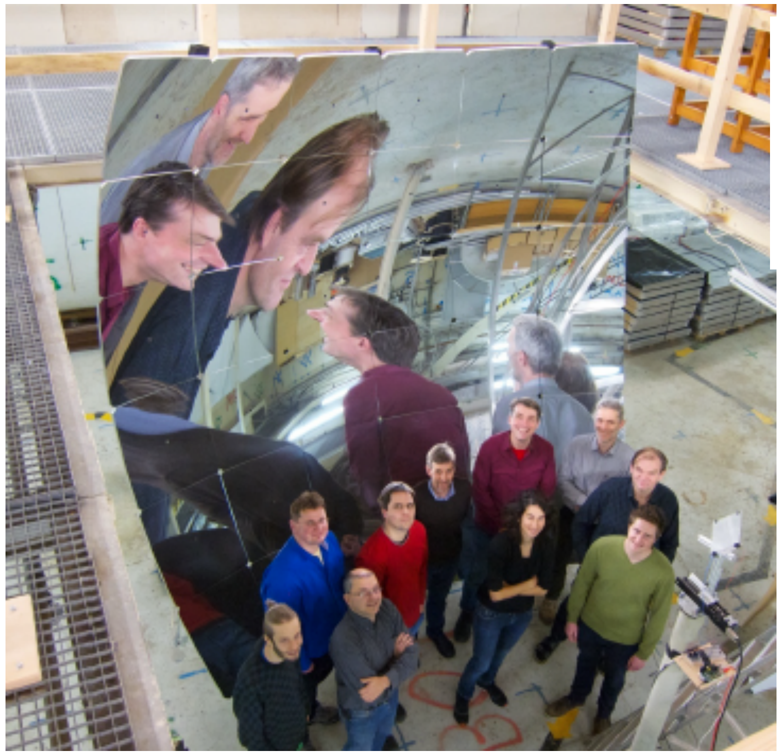
$$\mathcal{L} = -\frac{1}{4}(F_{\mu\nu}F^{\mu\nu} + X_{\mu\nu}X^{\mu\nu}) + J^{\mu}A_{\mu} + \frac{m^2}{2}X_{\mu}X^{\mu} - \frac{\chi}{2}F_{\mu\nu}X^{\mu\nu}$$

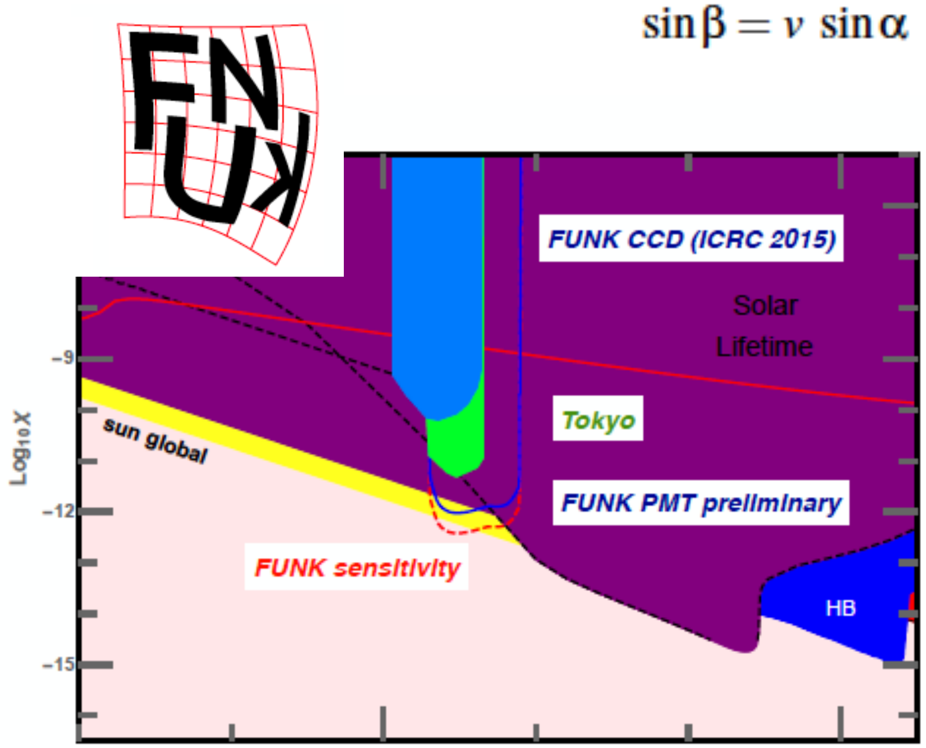




$$\sin\beta = v \sin\alpha \approx 10^{-3}$$

$$P_{center} \approx \chi^2 \rho_{CDM} A_{mirror}$$

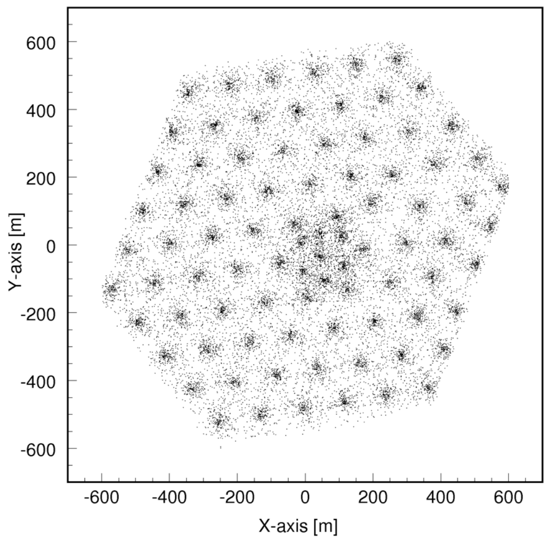


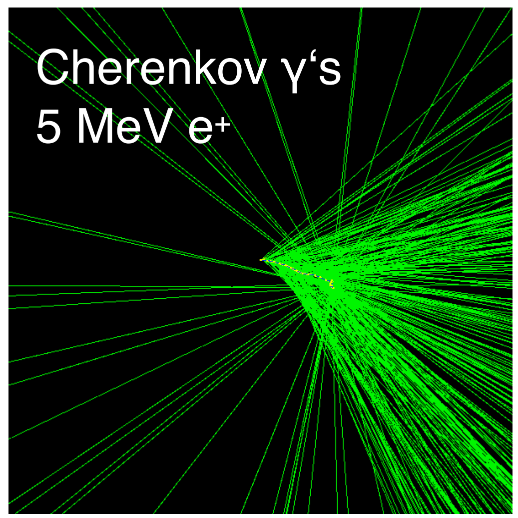


- Use of Fluorescence telescope of Auger Observatory (for a new purpose)
- Next move beyond visual range to cover other phase space regions

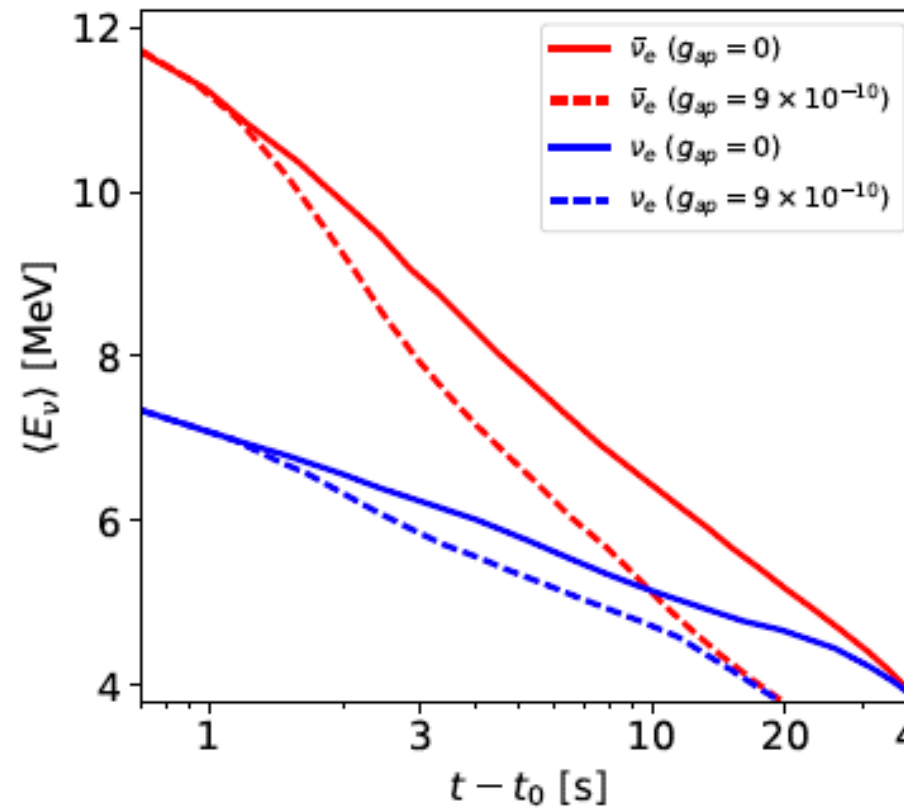
ALPs from Galactic Supernovae

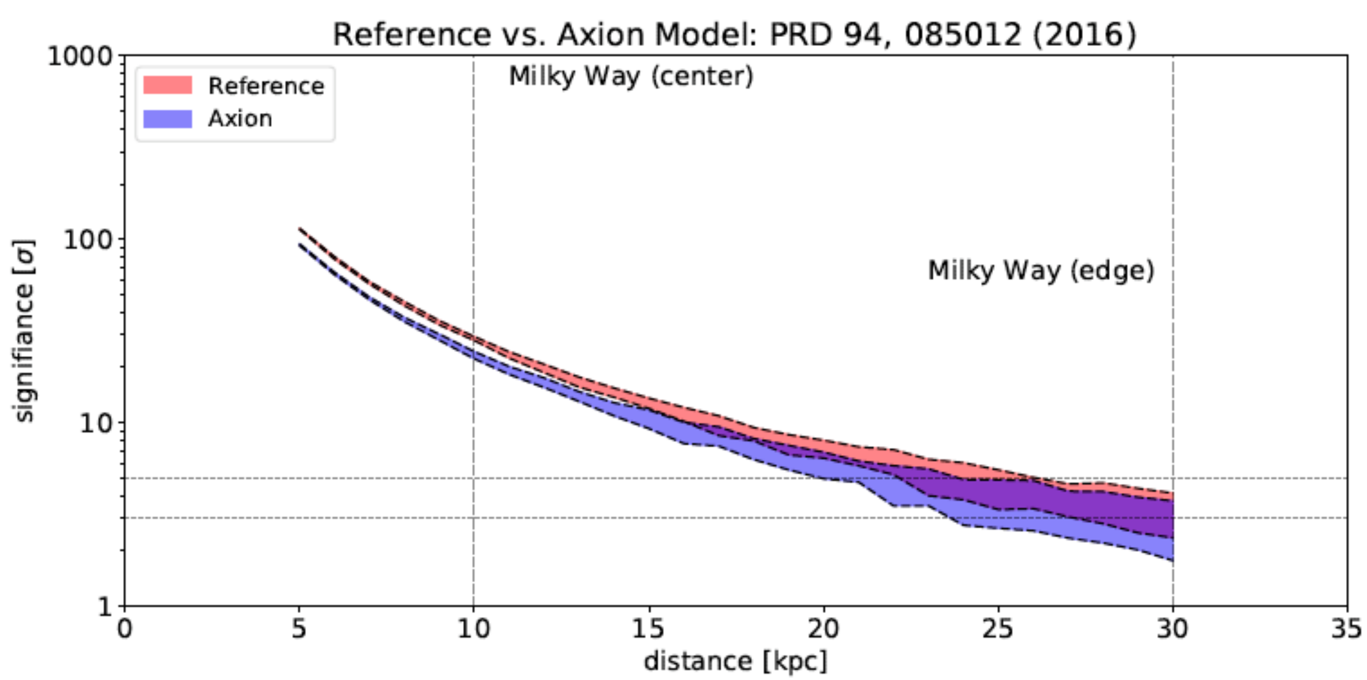
Axions generated in Supernovae burst

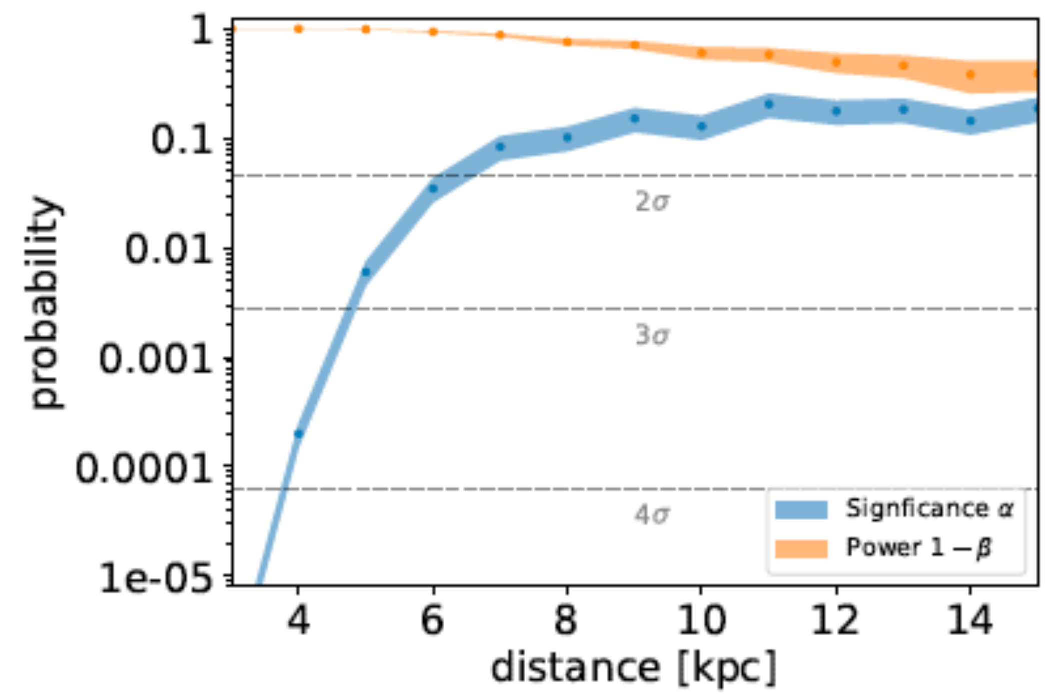




IceCube R. Cross ICRC2017 (892)





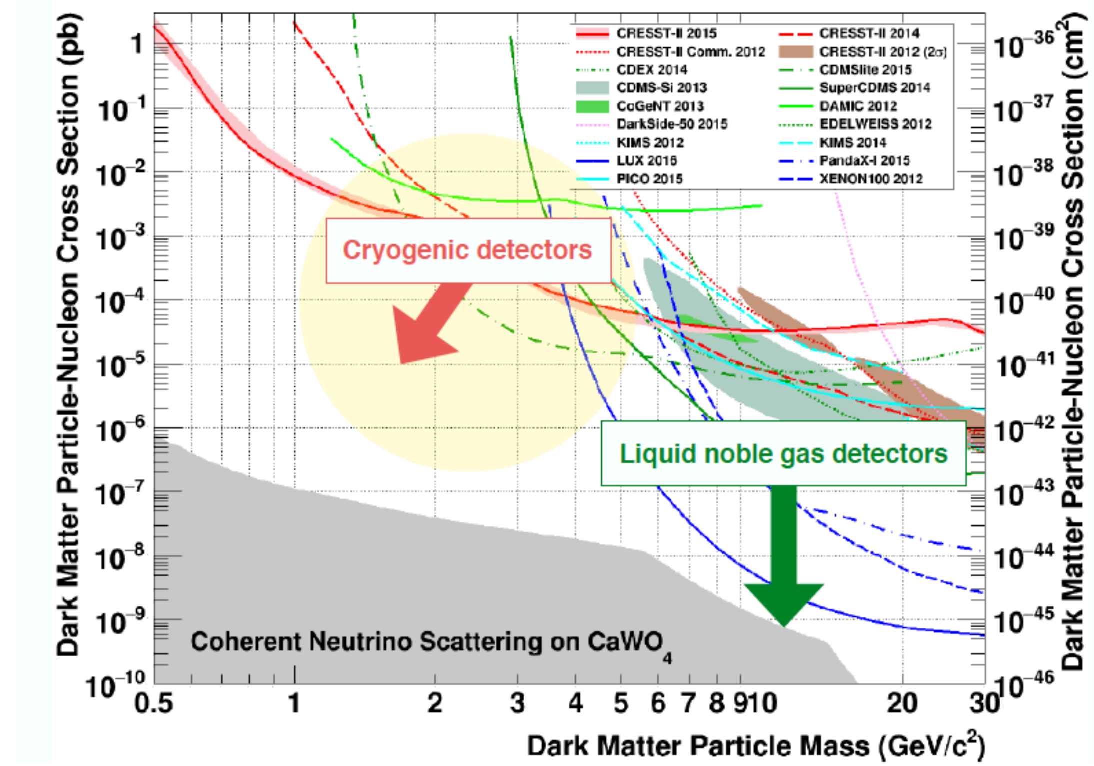


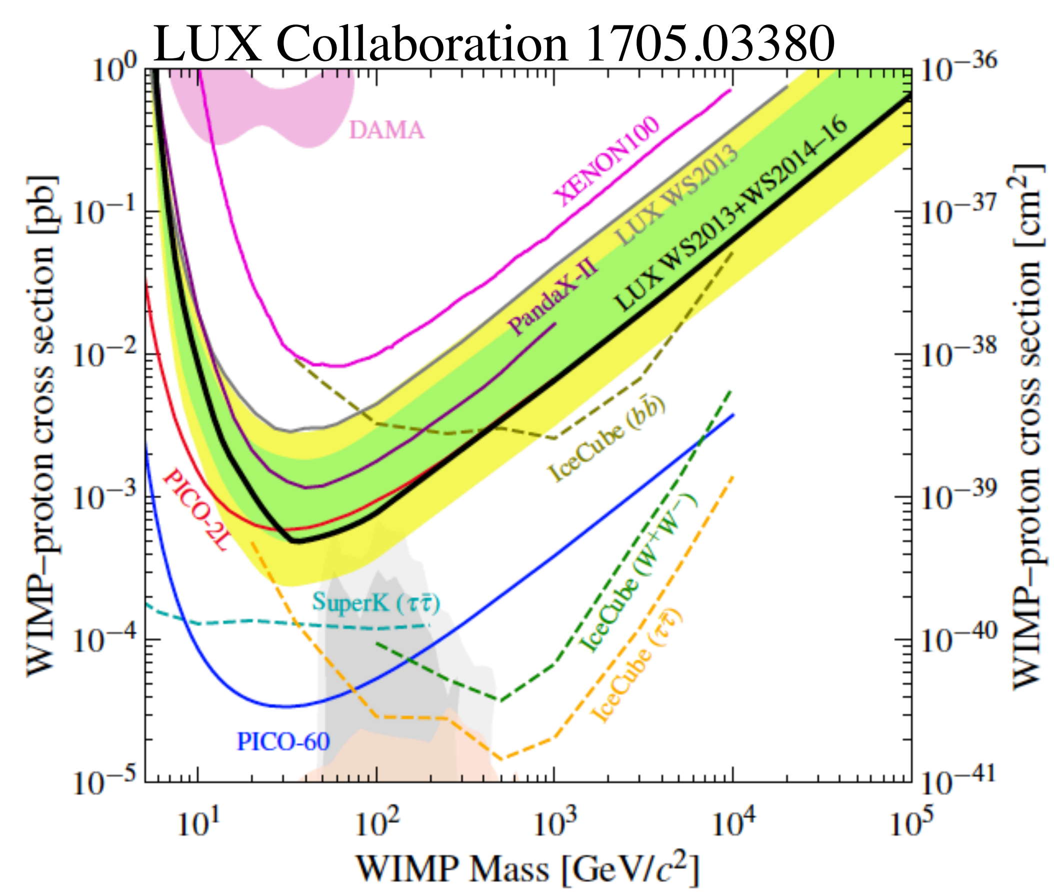
Dark Matter Direct Detection

many details in talks by Elena Aprile and Youngduk Kim

Dark Matter Direct Detection

- Liquid Nobel Gases making rapid progress
  - Moving towards multi ton scales
  - Neutrino Floor in reach
- Bubble Chambers proves to be extremely competitive for SD searches (PICO, …)
- Impressive progress in exploring light DM region with cryogenic detectors (CRESST-III, CDMSLite, …)
- DAMA Anomaly to be resolved in the near future
- Directional DM to go below the neutrino floor
- Next generation experiments are going beyond single purpose



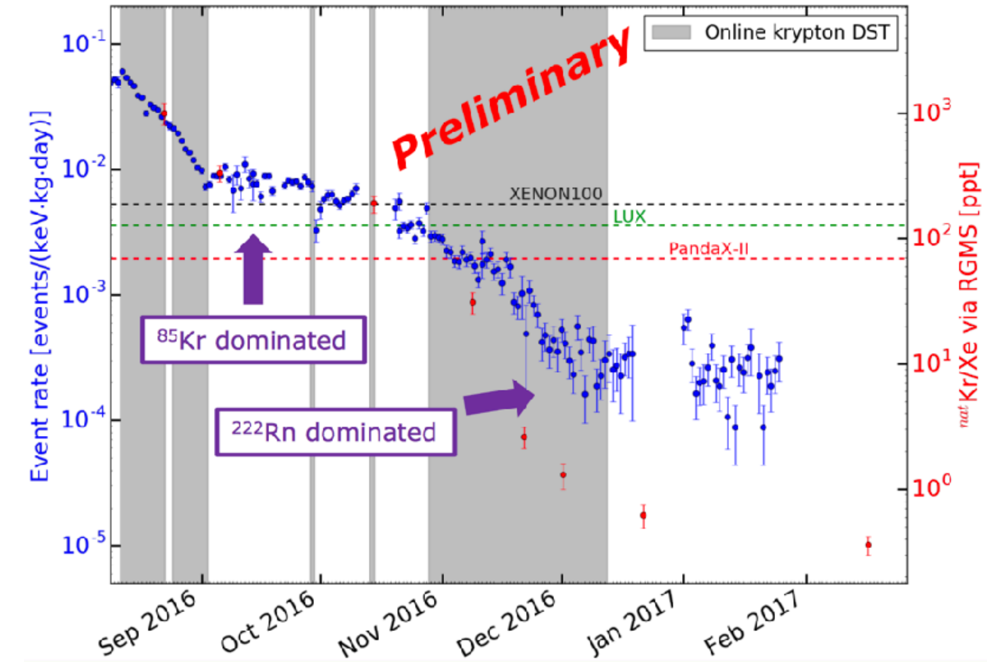


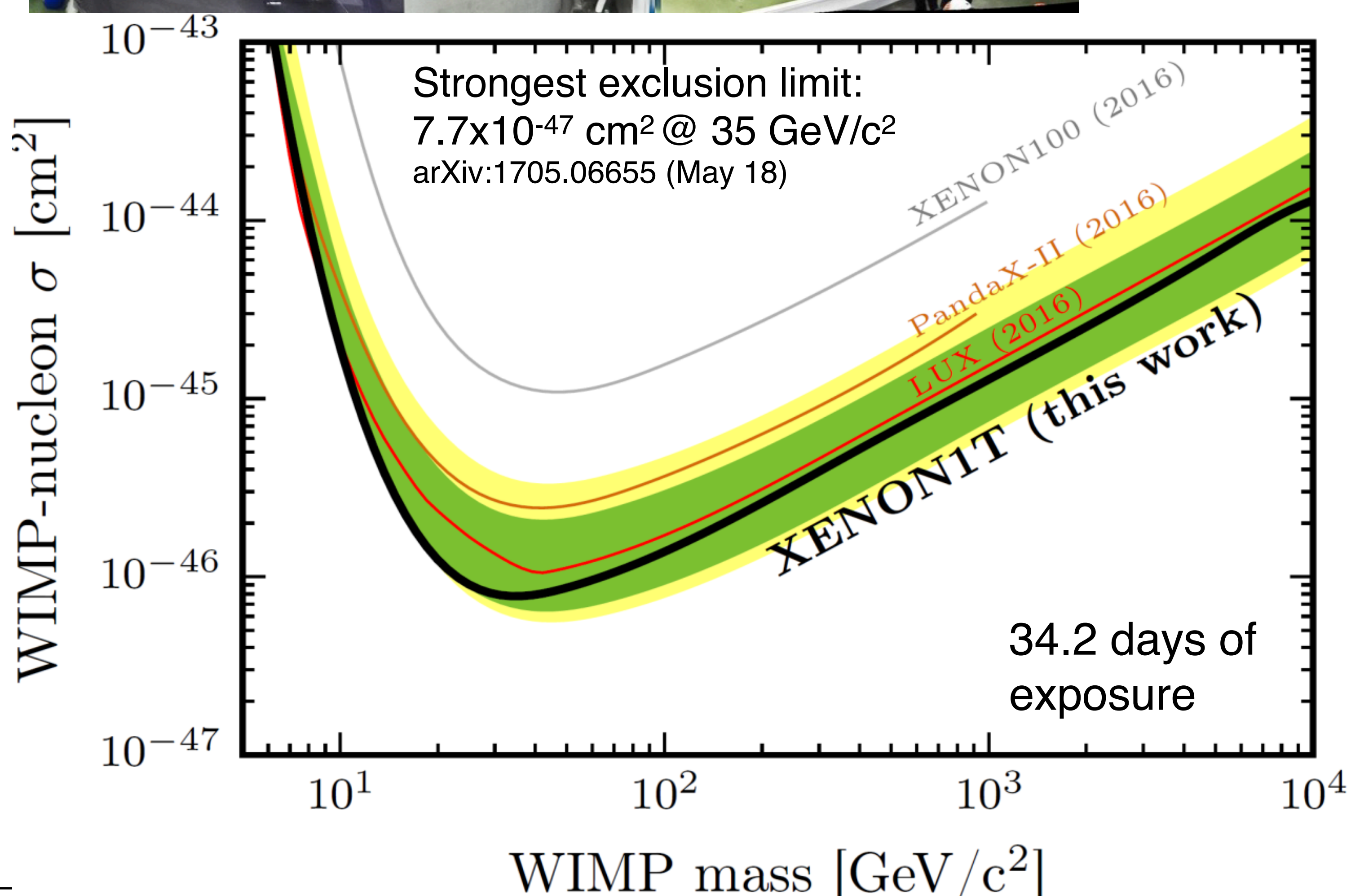
FIRST RESULTS FROM THE XENON1T EXPERIMENT

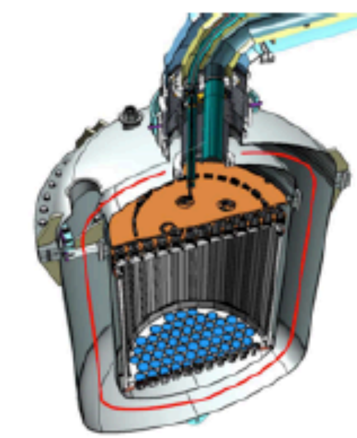
Patrick de Perio ICRC2017 (881)

Active removal of Kr contamination in Xe

arXiv:1702.06942 Eur. Phys. J. C77 (2017) no.5, 275

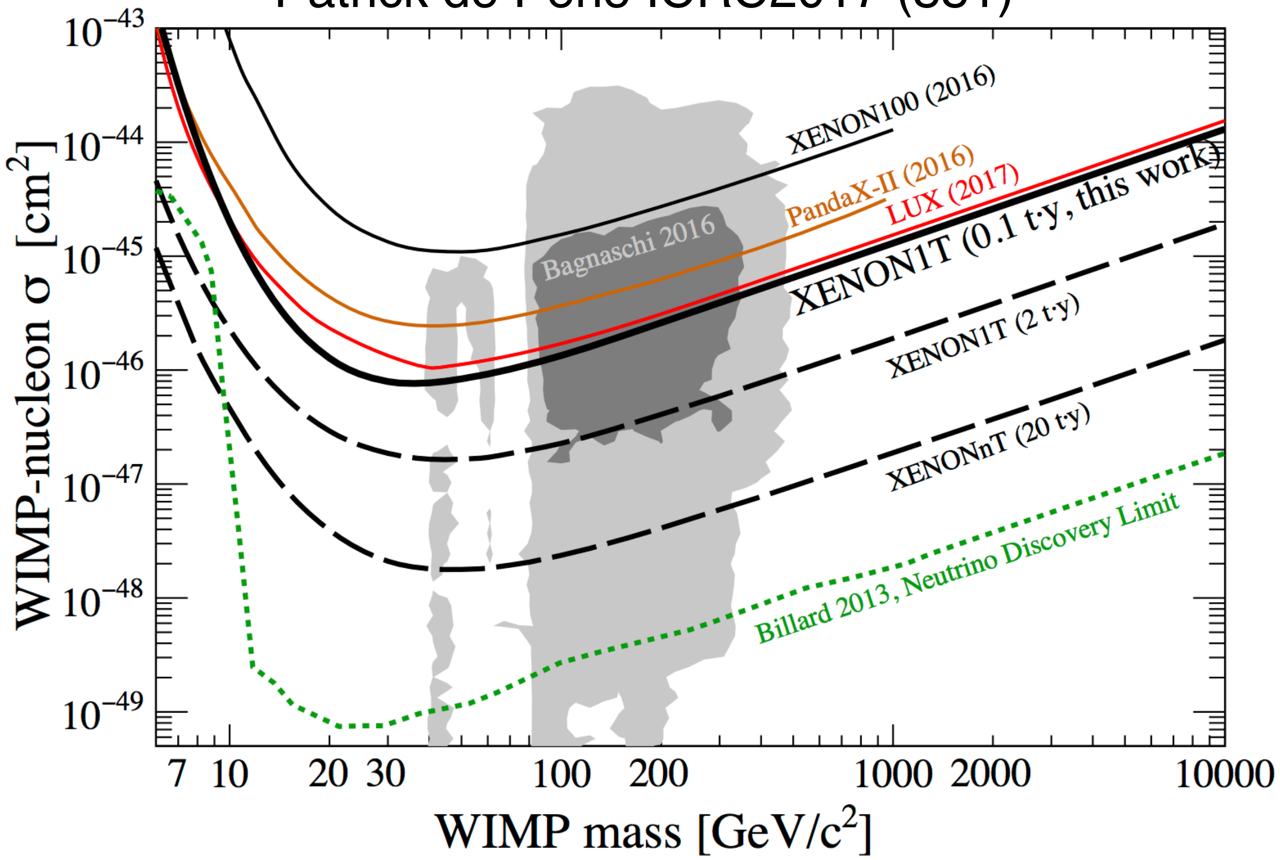




XENON1T	XENONnT	DARWIN
2012 – 2019	2017 – 2023	~2023 –
		
Total mass : 3.2 t	Total mass : ~8 t	Total mass : ~50 t
Target mass: 2 t	Target mass: ~6 t	Target mass: ~40 t
Drift TPC: 96 cm	Drift TPC: 144 cm	Drift TPC: 260 cm
Sensitivity ~ 10^{-47}cm^2	Sensitivity ~ 10^{-48}cm^2	Sensitivity ~ 10^{-49}cm^2

Outlook

Patrick de Perio ICRC2017 (881)



- Cover a large of the region of theoretical interest
- Close in on neutrino discovery limit

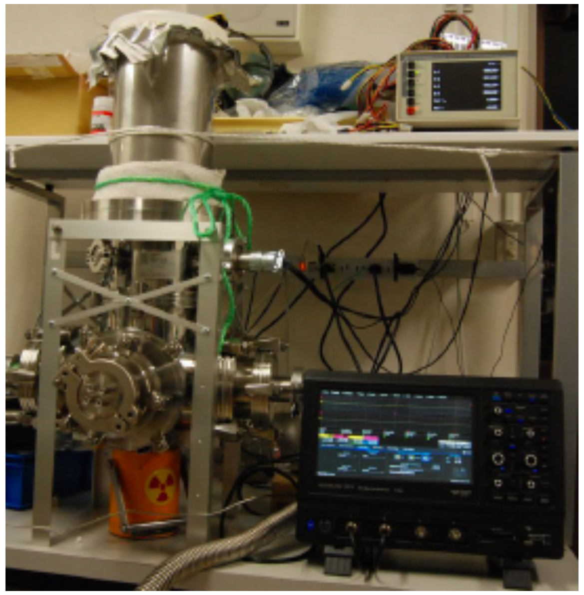
Kai Martens ICRC2017 (927)

Overcoming the scattering length limitation in liquid xenon scintillation?

Rayleigh scattering only (no absorption, etc.):
50 cm **scattering length**, from center of sphere:

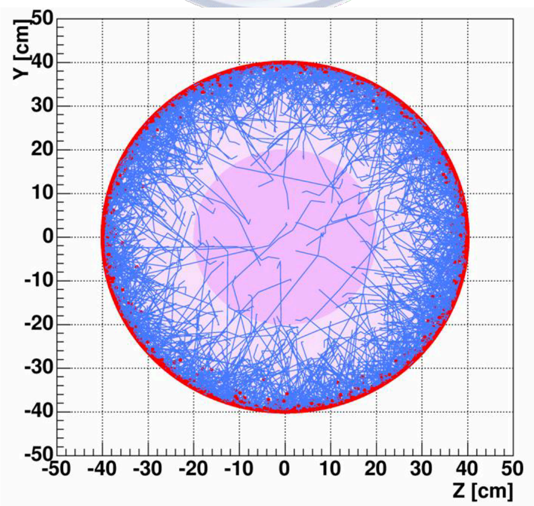
target mass:		light propagation to surface:	
∅ sphere [cm]	LXe [kg]*	mean number of scatters	mean total path length [cm]
80	780	1.07	54
250	23807	5.25	260

*density: 2.91 g/cm^3

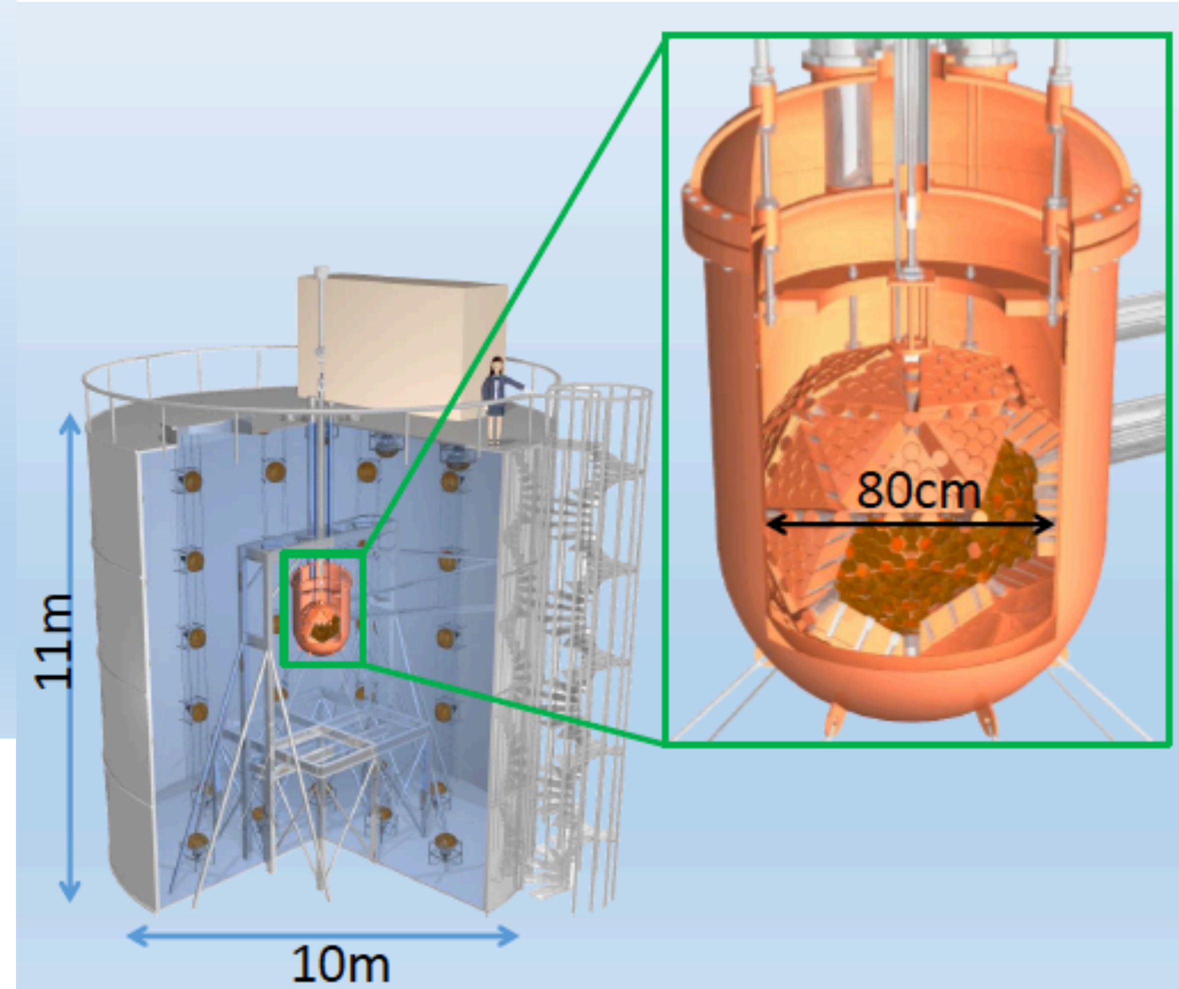


Hiroshi Ogawa [XMASS] ICRC2017 (888)

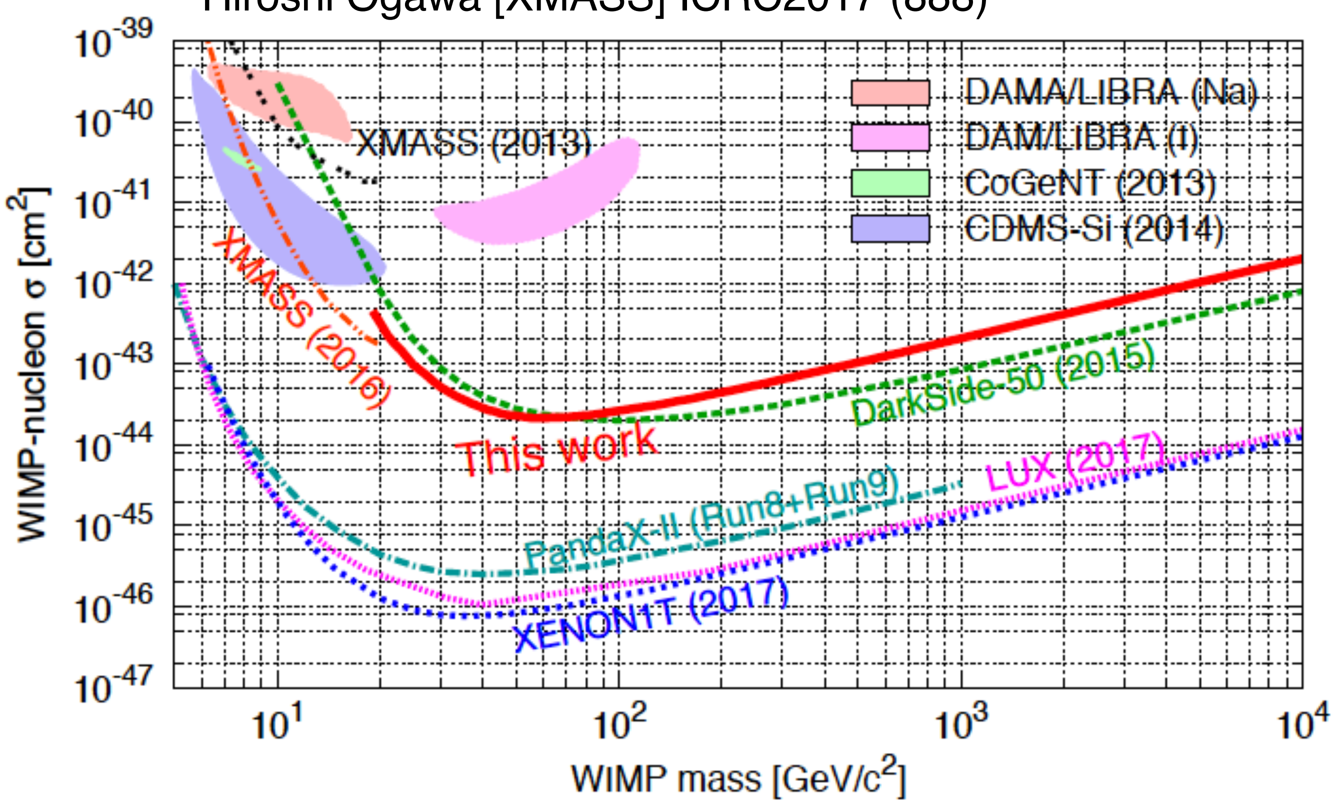
Recent results from XMASS



- Liquid xenon detector
  - 832 kg of liquid xenon (-100 ºC)
  - 642 2-inch PMTs (Photocathode coverage >62%)
  - Each PMT signal is recorded by 10-bit 1GS/s waveform digitizers
- Water Cherenkov detector
  - 10m diameter, 11m high
  - 72 20-inch PMTs
  - Active shield for cosmic-ray muons
  - Passive shield for n/γ



Hiroshi Ogawa [XMASS] ICRC2017 (888)

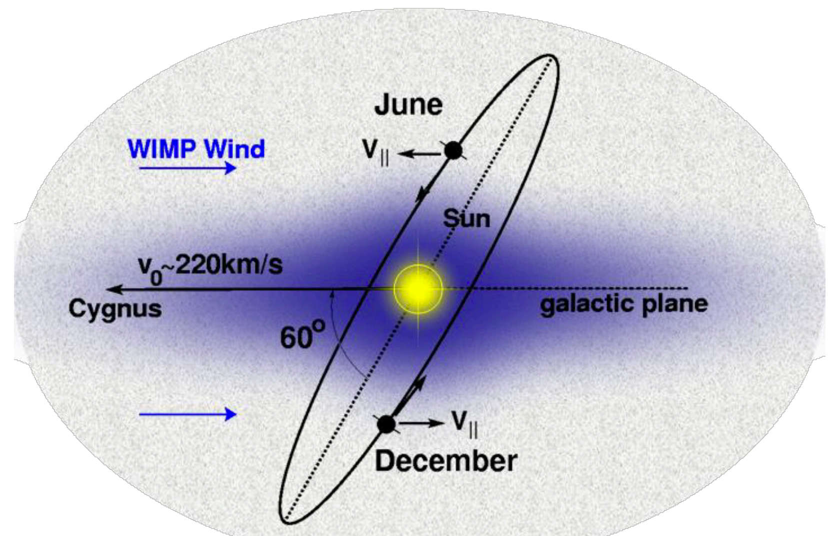


- XMASS is a multi-purpose experiment using liquid xenon.
- Annual modulation search
  - With 1-year of data, no significant modulation was observed.
  - Results from 2.7 years of data will come soon.
- WIMP search by fiducialization
  - 706 live days x 97 kg fiducial mass
  - Limit on SI WIMP-nucleon cross section $\sigma<2.2\times10^{-44}$ cm² for 60 GeV/c²
- XMASS is waiting for neutrinos from galactic supernovae
- More physics results will be presented at coming summer conferences.

[DM008] The recent results from the annual modulation analysis of the XMASS-I dark matter data

Annual modulation

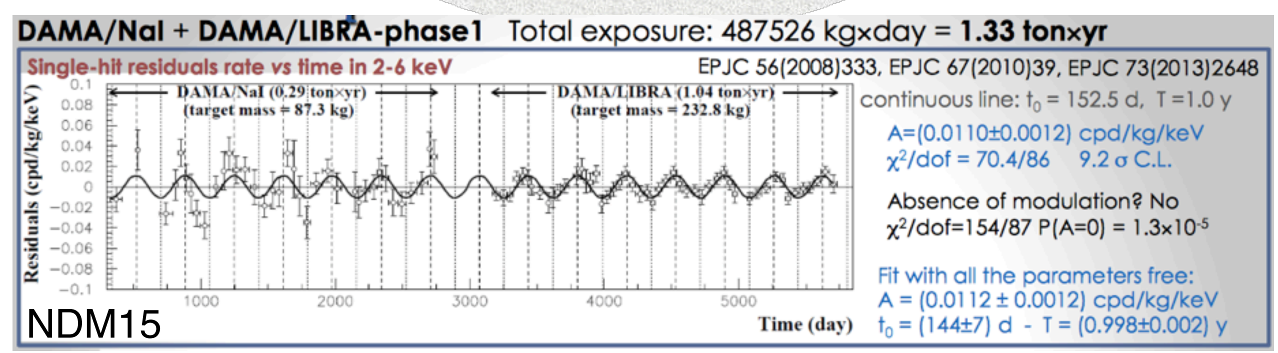
- Event rate of dark matter signal is expected to modulate annually due to relative motion of the Earth around the Sun. It would be a strong signature of dark matter.
- DAMA/LIBRA claims modulation at 9.3σ
  - Total exposure of 1.33 ton*year (14 cycles)
  - Modulation amplitude of (0.0112+/-0.0012) cpd/kg/keV for 2-6 keV



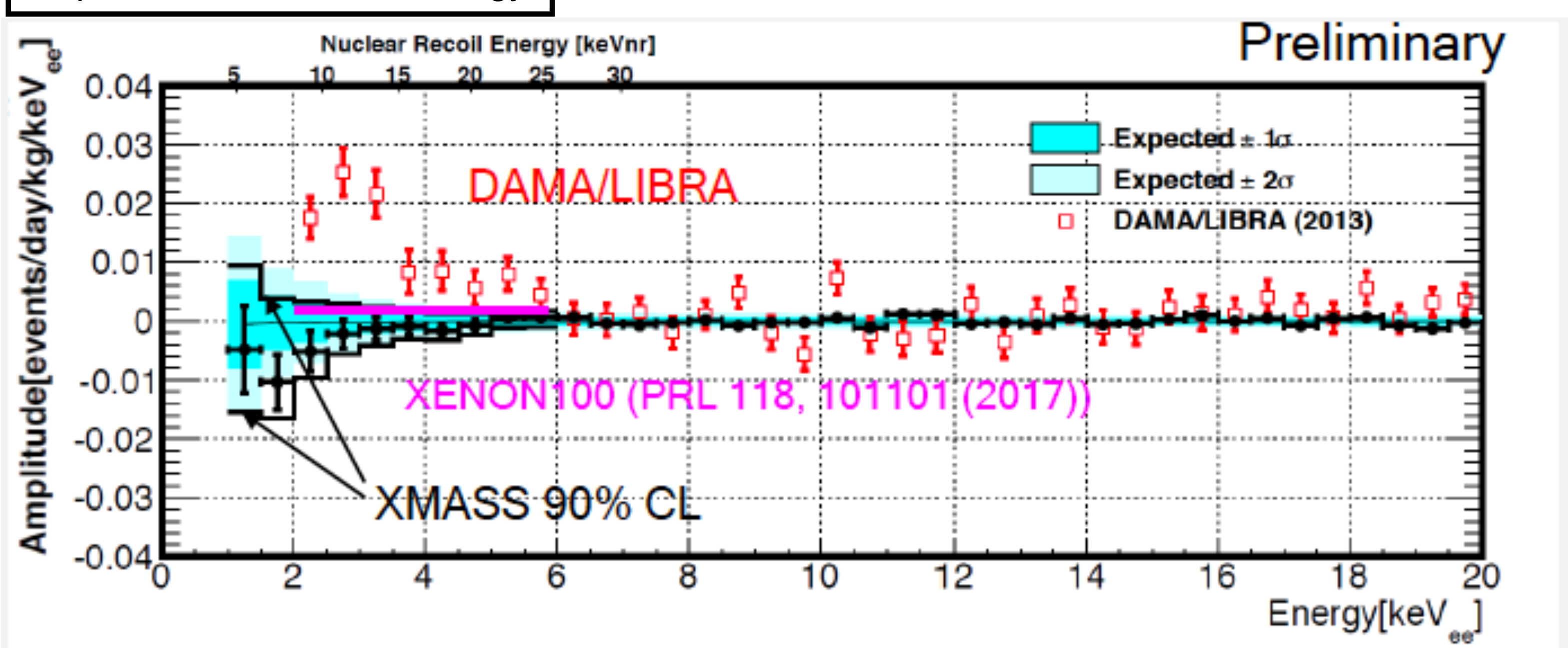
PLB 759 272 (2016))

ICRC2017

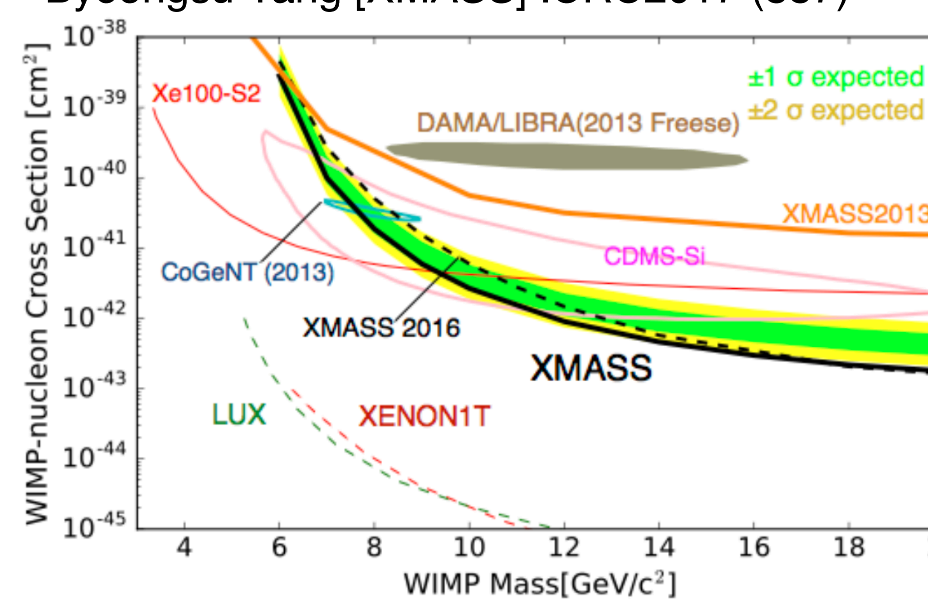
Run	From (dd/mm/yr)	To (dd/mm/yr)	Real (years)	Live (days)	Exposure (ton*year)
Run1	21/11/2013	30/03/2015	1.35	387.8	0.88
Run2	30/03/2015	20/07/2016	1.31	412.2	0.94
Total	21/11/2013	20/07/2016	2.66	800.0	1.82



Amplitude as function of energy



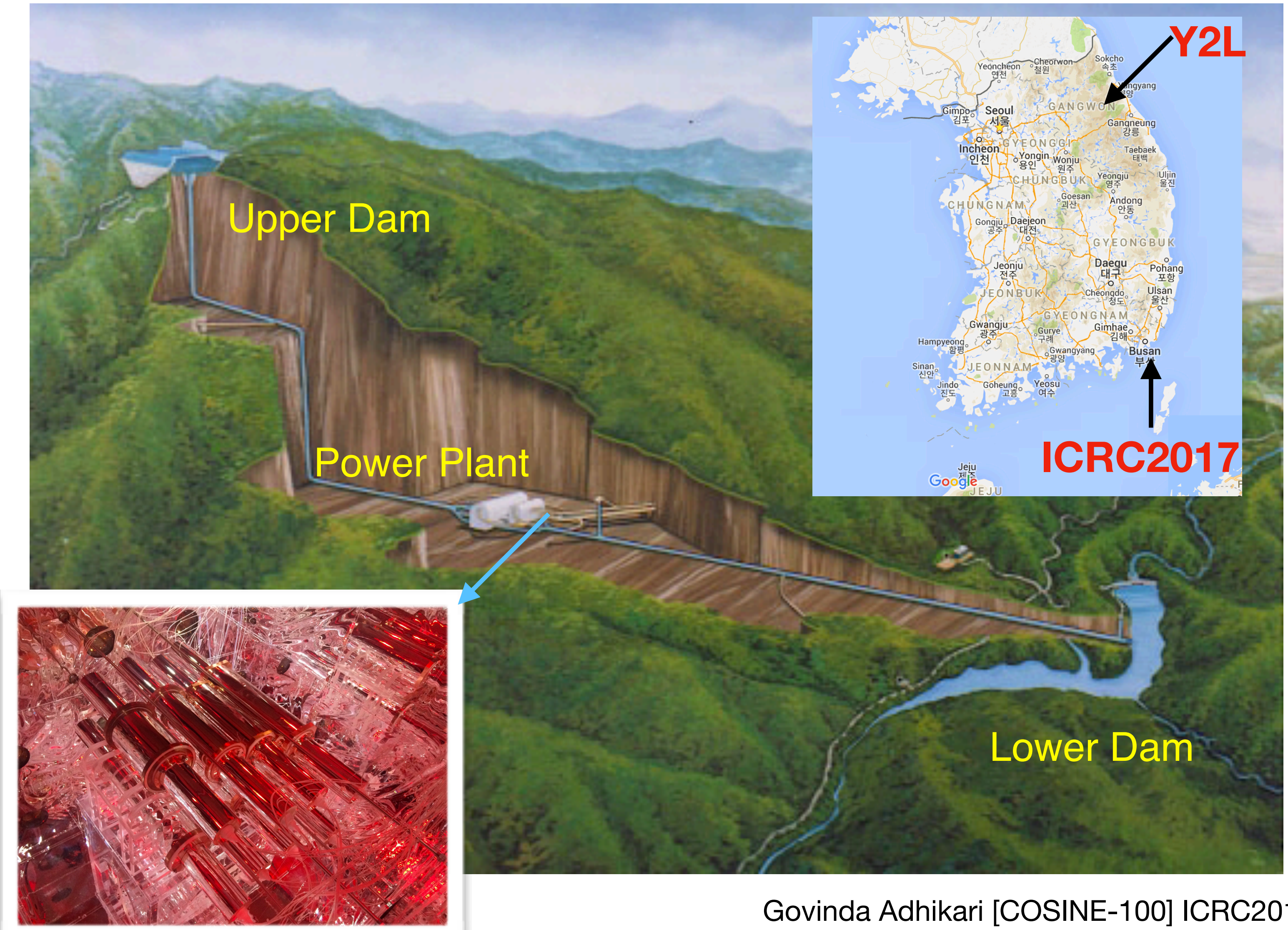
Byeongsu Yang [XMASS] ICRC2017 (887)



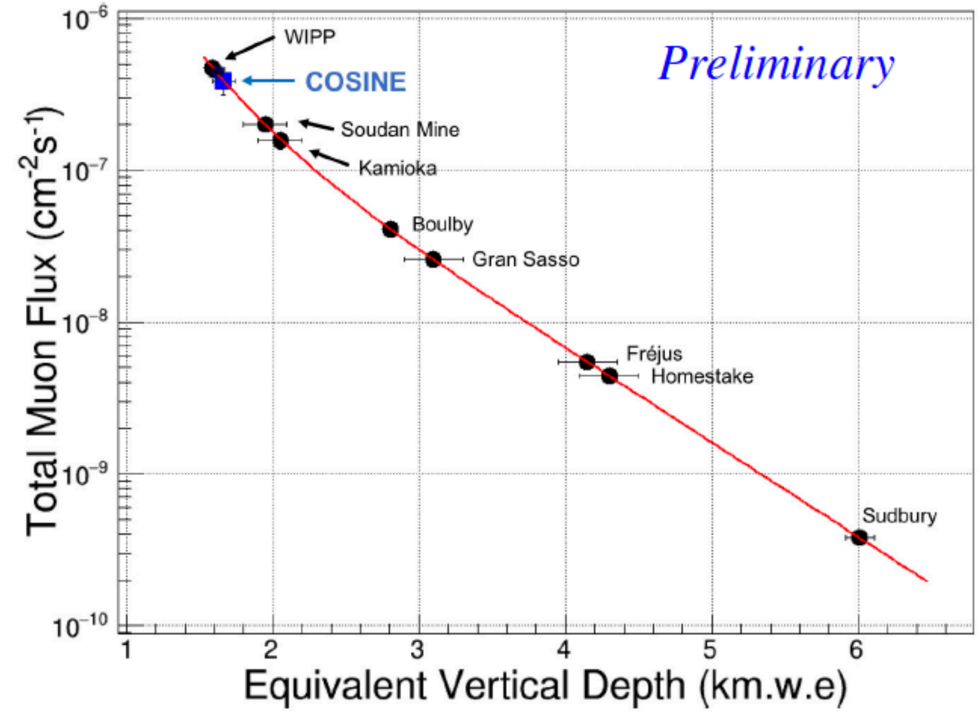
Exclude all the DAMA/LIBRA allowed region by modulation search.

Hafizh Prihtiadi [COSINE-100] ICRC2017 (883) (Muon flux at Y2L)
Govinda Adhikari [COSINE-100] ICRC2017 (884) (Neutron Monitoring)
Pushparaj Adhikari [COSINE-100] ICRC2017 (885) (NaI(Tl) crystals)
Chang Hyon Ha [COSINE-100] ICRC2017 (886) (Status)

COSINE-100



Hafizh Prihtiadi [COSINE-100] ICRC2017 (883)



Hafizh Prihtiadi [COSINE-100] ICRC2017 (883)

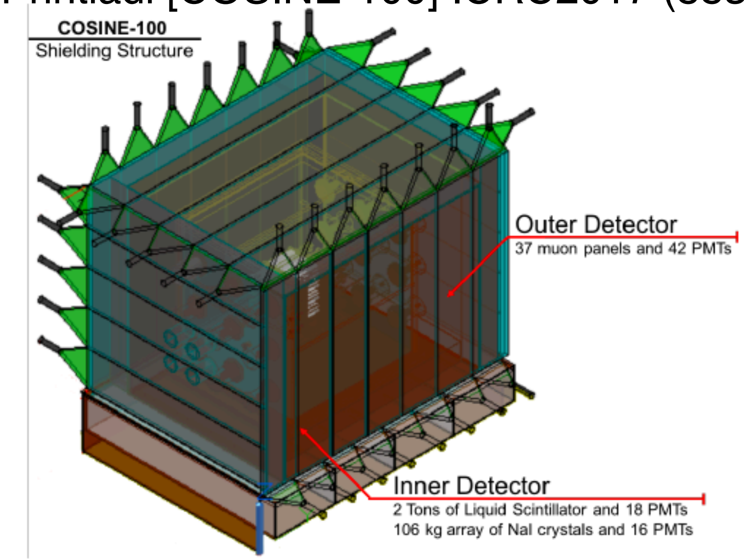


Figure 1: A sketch of the COSINE-100 shielding structure

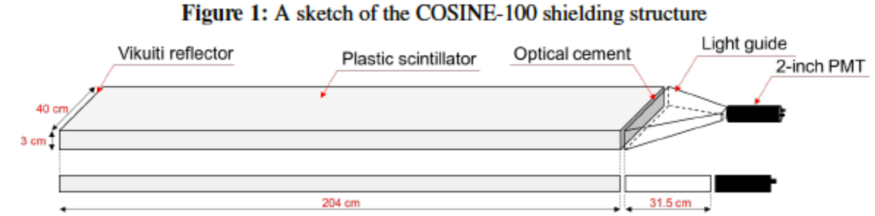
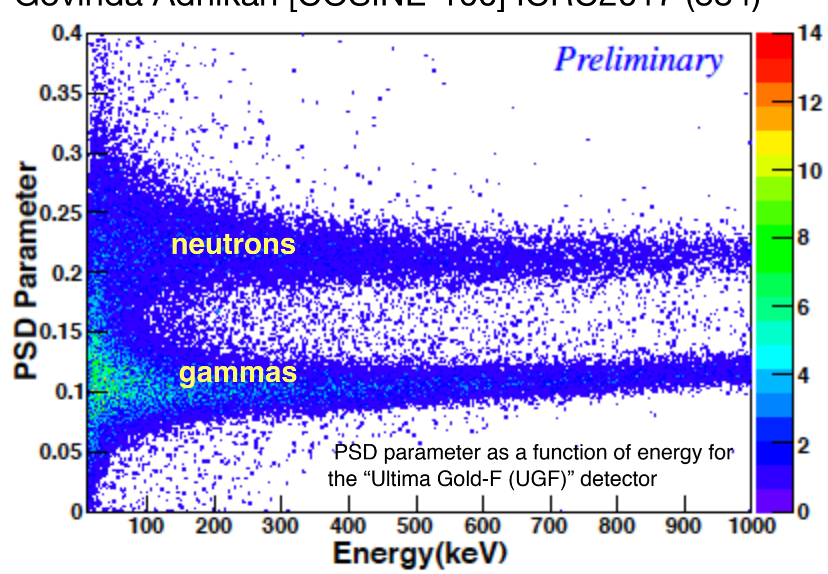


Figure 2: Schematic view of muon detector materials and assembly part

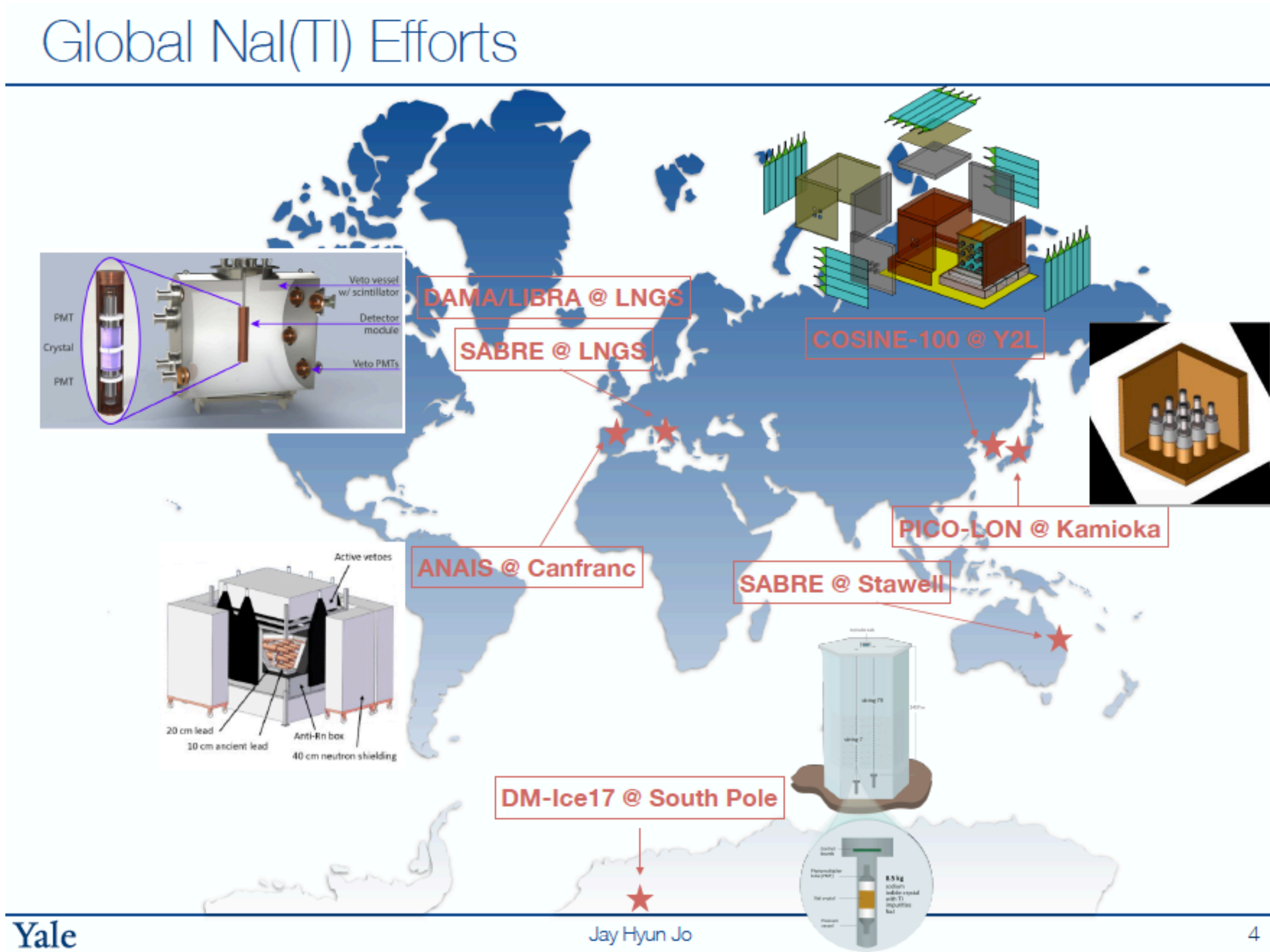
Govinda Adhikari [COSINE-100] ICRC2017 (884)



Pushparaj Adhikari [COSINE-100] ICRC2017 (885)

Crystal-ID	Mass (kg)	Powder	T (Growth)	T (Y2L)
Crystal-1	8.26	AS-B	2011.9	2013.9
Crystal-2	9.15	AS-C	2013.4	2014.1
Crystal-3	9.16	AS-WSII	2014.7	2014.12
Crystal-4	18.01	AS-WSII	2015.10	2016.03
Crystal-5	18.28	AS-C	2013.4	2016.03
Crystal-6	12.5	AS-WSIII	2015.10	2016.02
Crystal-7	12.5	AS-WSIII	2015.10	2016.02
Crystal-8	18.28	AS-C	2013.4	2016.03

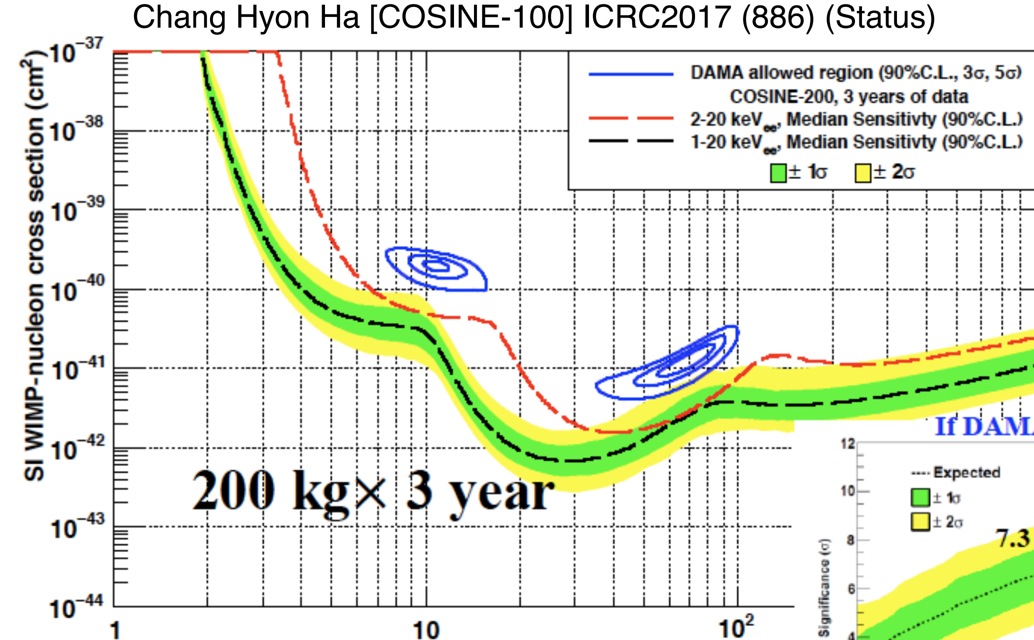
Status of the COSINE-100 Dark Matter Experiment

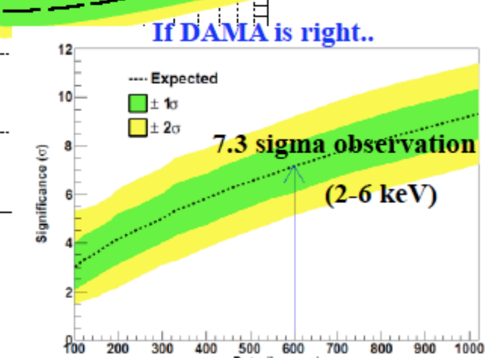


- KIMS and DM-Ice join forces (the COSINE-100 collaboration) to reproduce DAMA annual modulation using the same NaI(Tl) target material.
- COSINE-100 (Phase-I) is running with 106 kg of NaI(Tl) crystals.
- CR muon tagging and liquid scintillator tagging.
- Physics run started on September 2016
- Initial performance of COSINE-100 is promising. 2 keV thres., 2-4 dru at ROI
- Expect to have DAMA-comparable sensitivity in ~2 years
- Continued R&D for higher purity crystals for COSINE-200 (Phase-II)

COSINE-200 (Phase-II)

Chang Hyon Ha [COSINE-100] ICRC2017 (886) (Status)





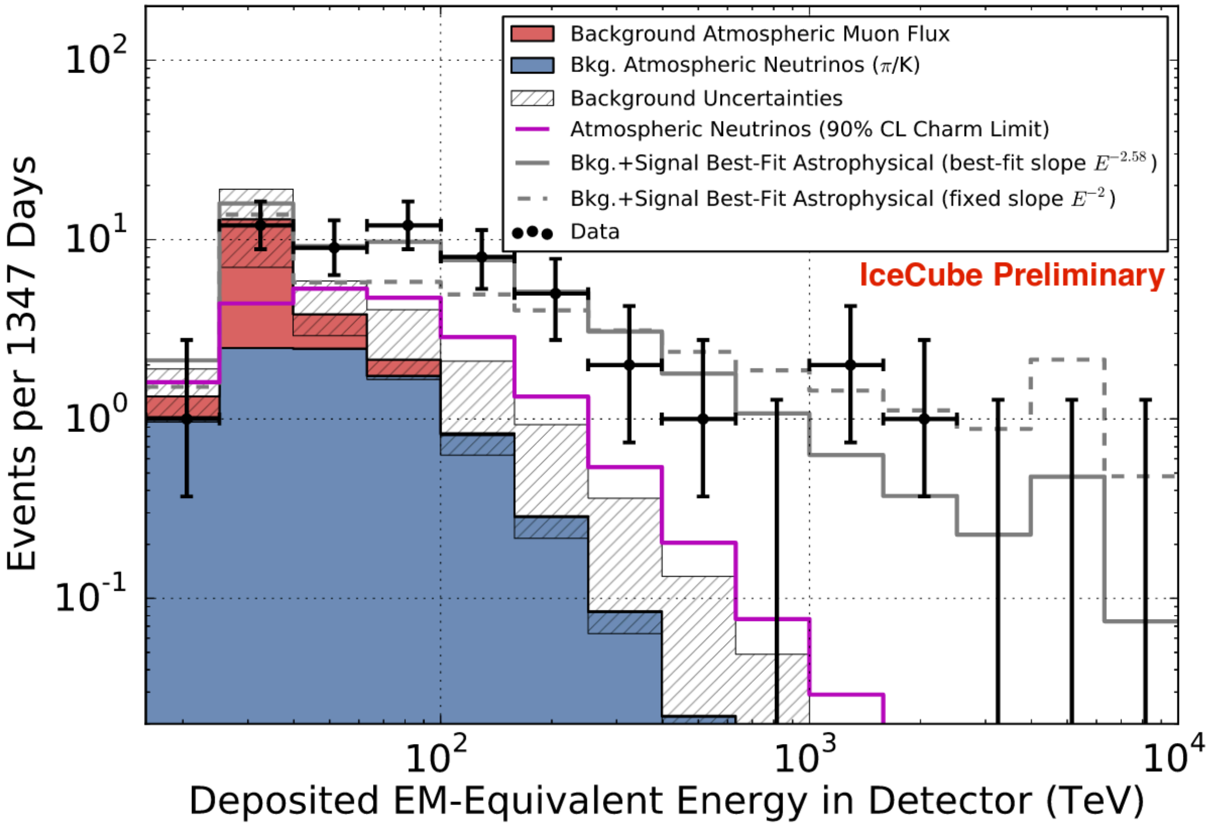
Conclusions

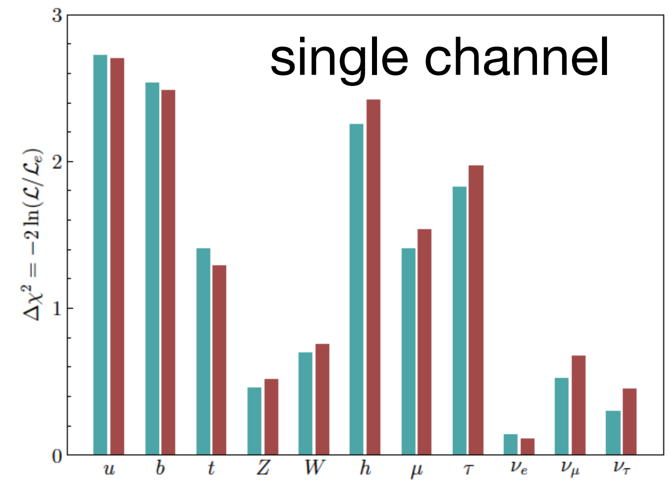
- Dark Matter exists
    - To understand the universe we need to understand dark matter
- Vibrant field with many new results from indirect and direct searches
- Exciting prospects with new instrumentation
- Going beyond WIMP paradigm
    - Often one can reuse existing technologies or data
- No smocking gun at this ICRC2017

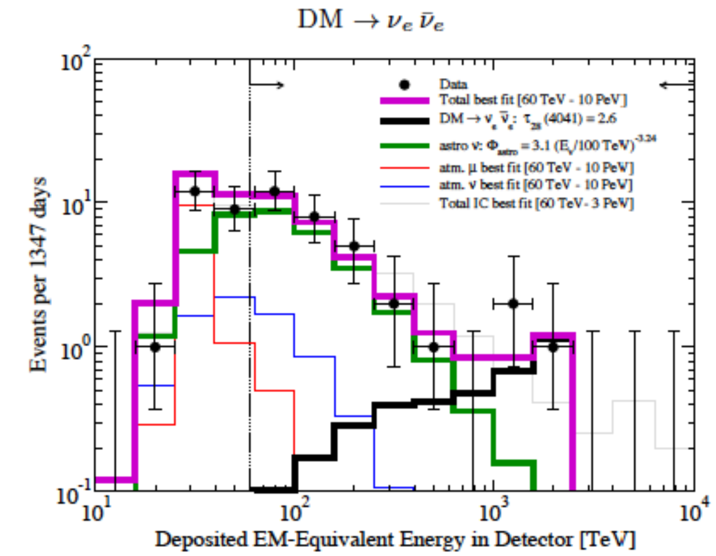
Backup

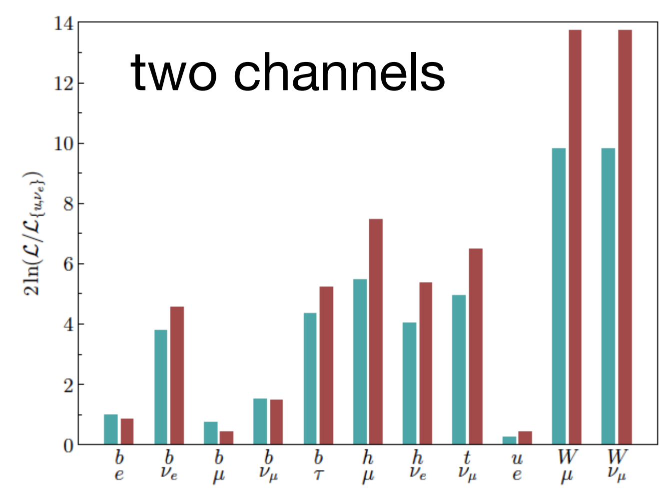
Atri Bhattacharya, Arman Esmaili, Sergio Palomares-Ruiz and Ina Sarcevic, arXiv: 1706.05746

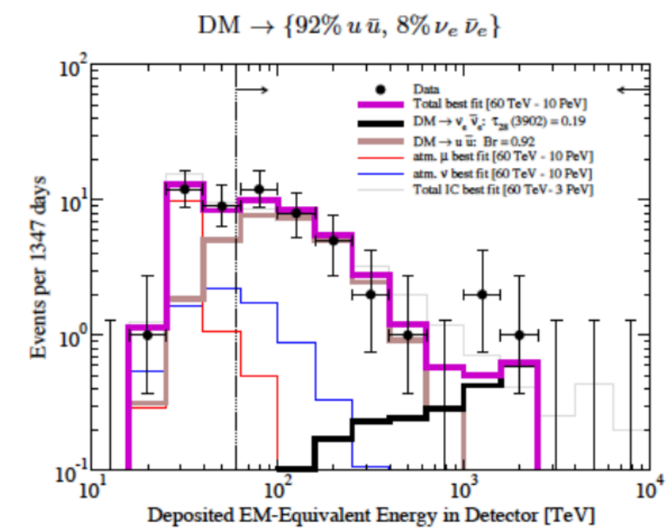
Probing Decaying Heavy Dark Matter with 4-year IceCube HESE data











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

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

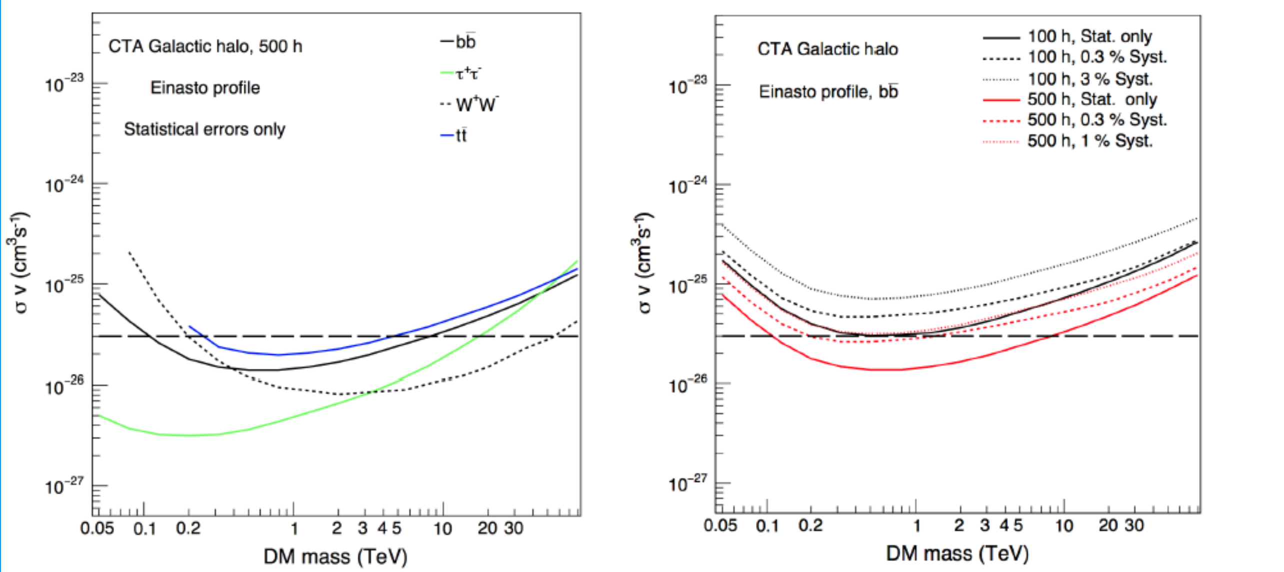
Take Galactic and Extra galactic contributions into account

- Consider DM decay into two channels, one that would describe low energy data and the other high energy (PeV) events
- We find that HESE data can be best described with the combination of the astrophysical neutrino flux and the dark matter decay
- Best fit values for DM mass and lifetime depend on the channel, for DM decay into leptons, DM mass is of the order of several PeV, describing PeV events, while astrophysical flux describes lower energy flux
- DM decay into bb is disfavored

CTA

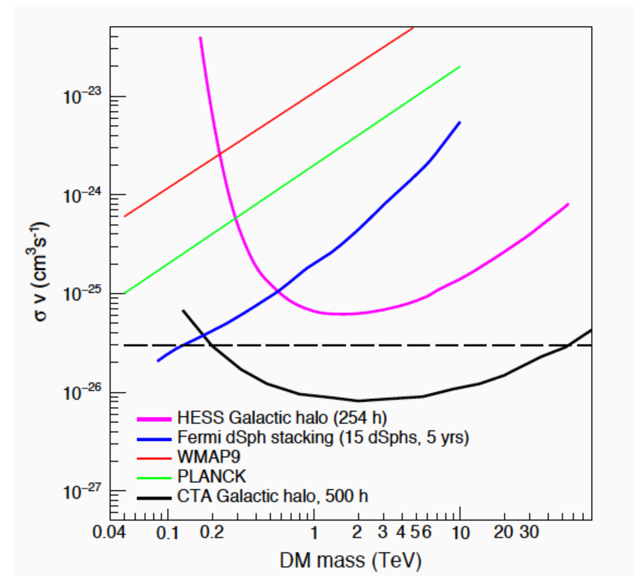
Galactic Halo (Einasto)

A.Morselli [CTA] ICRC2017 (921)



Galactic Halo (comparison)

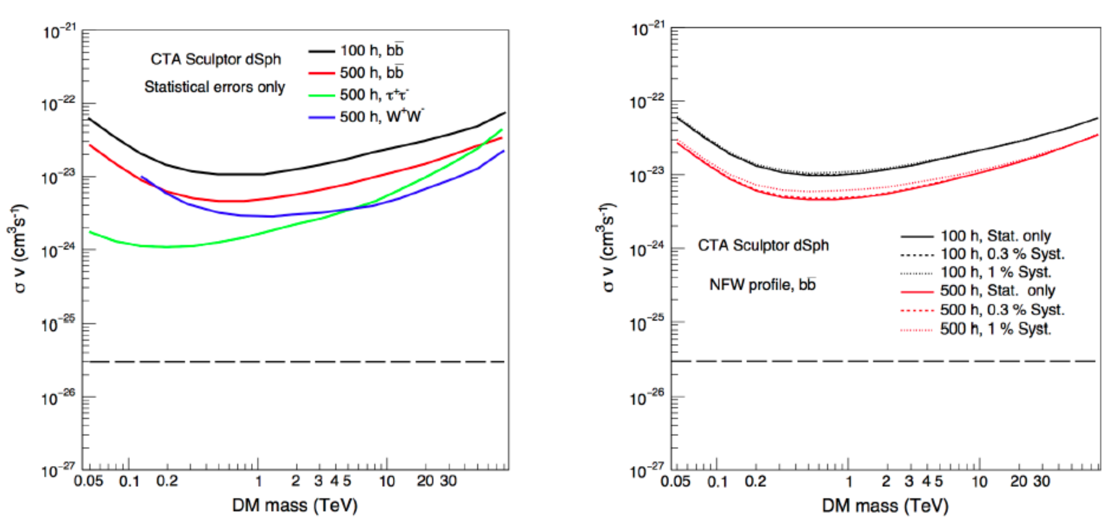
A.Morselli [CTA] ICRC2017 (921)



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

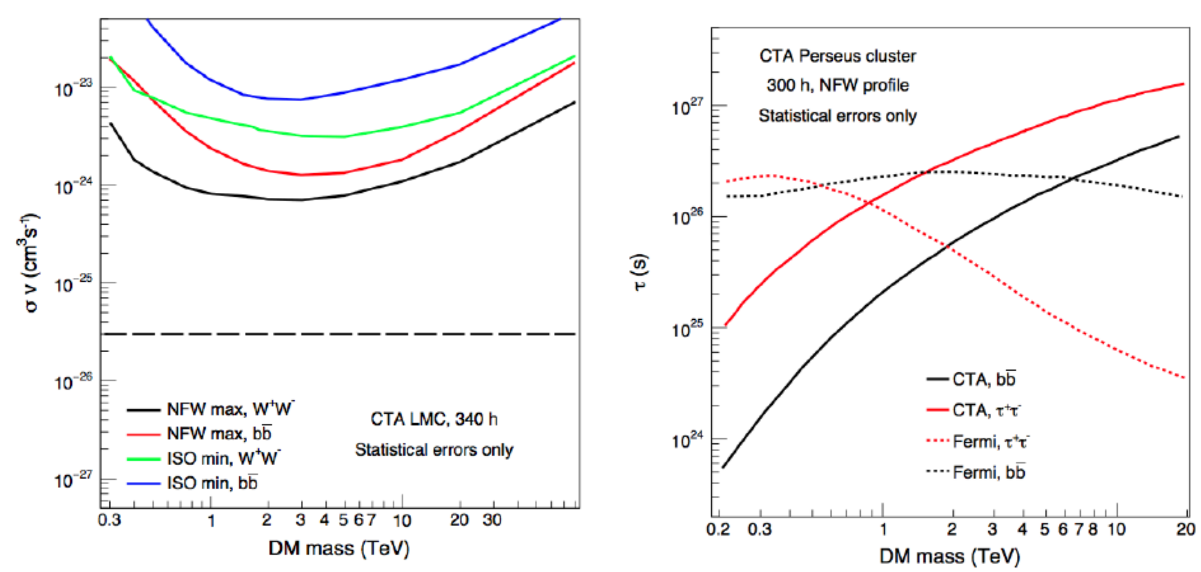
Dwarfs (Sculptor)

A.Morselli [CTA] ICRC2017 (921)

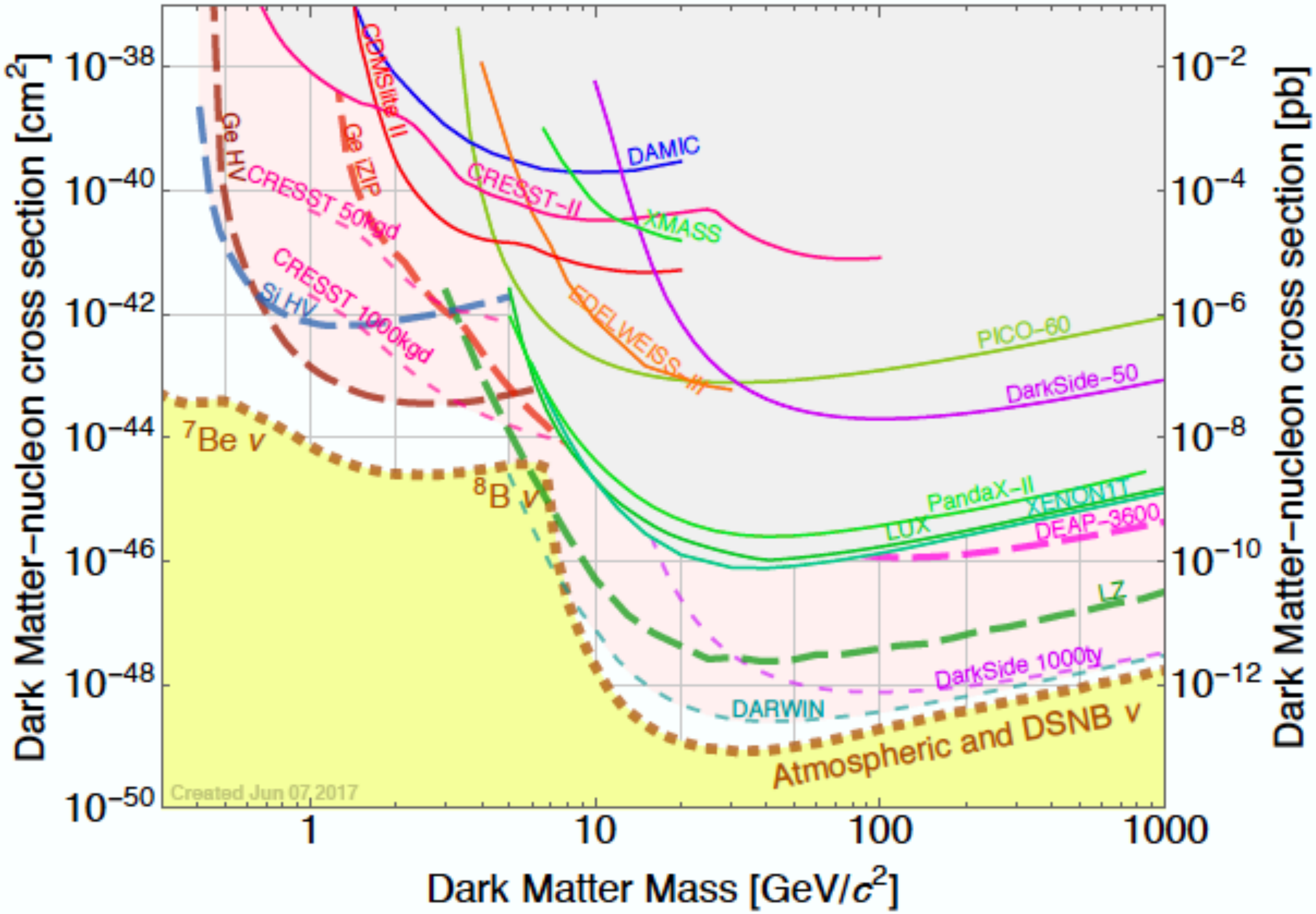


Large Magellanic Cloud

A.Morselli [CTA] ICRC2017 (921)



Dark Matter Direct

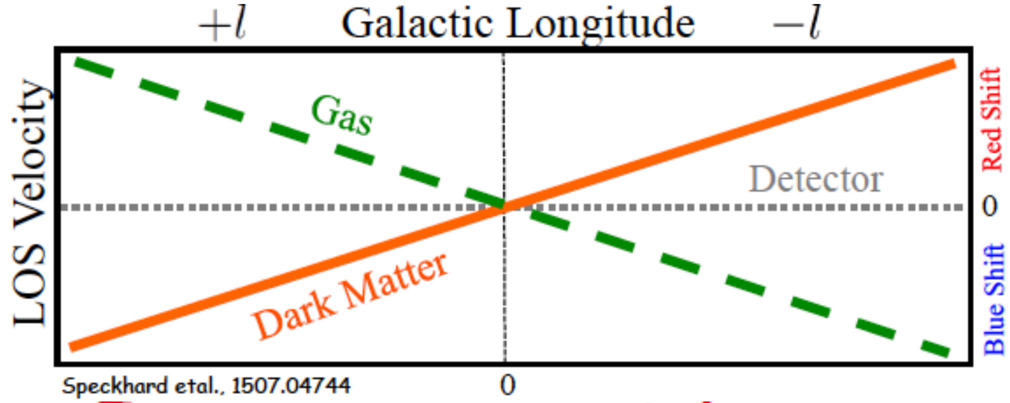


arXiv 1507.04744 Phys. Rev. Lett. 116 (2016) 031301 (Editors' Suggestion)

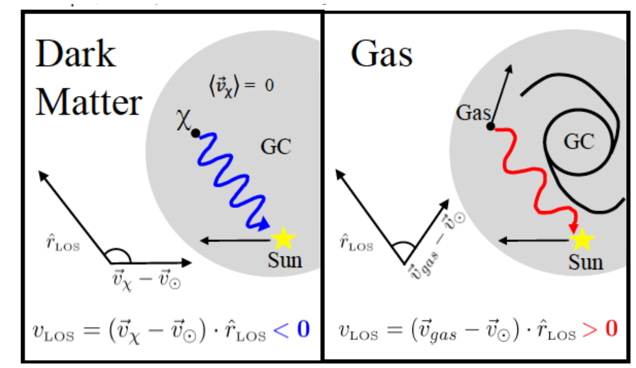
Dark matter velocity spectroscopy

- 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"



Speckhard etal., 1507.04744



- Sun moves at ~220 km/s

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

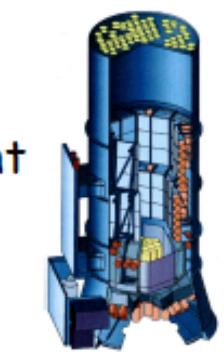
- Distinct longitudinal dependence of signal

Past

Hitomi/ Astro-H

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

Present



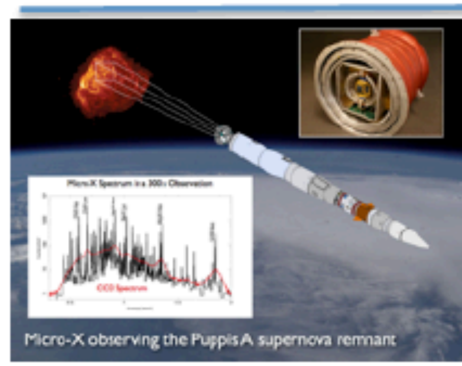
INTEGRAL/ SPI

2.2 keV (FWHM) at 1.33 MeV

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

- Doppler effect

Future



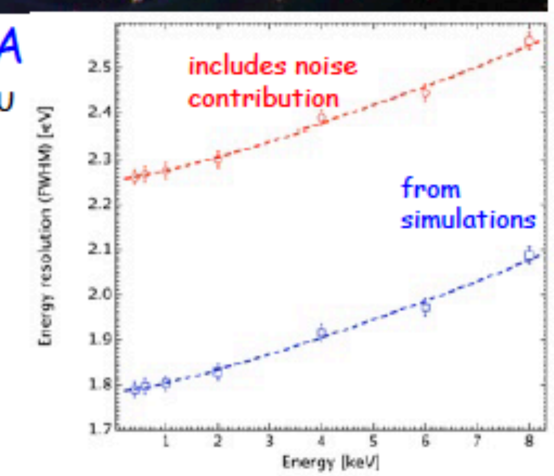
Micro-X

FWHM of 3 eV at 3.5 keV

Figueroa-Feliciano etal. 2015

ATHENA

ATHENA X-IFU 1608.08105

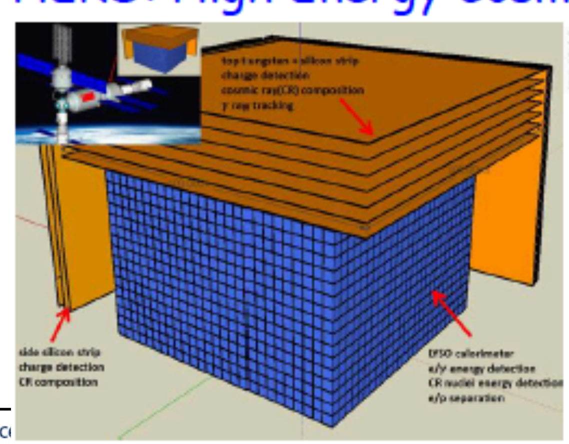


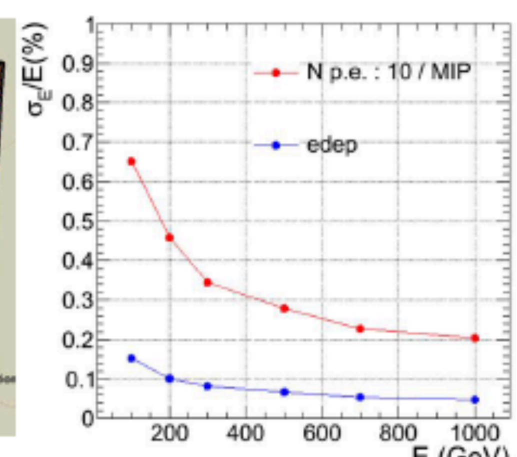
Dark matter velocity spectroscopy is a promising tool to distinguish signal and background in dark matter indirect detection

- 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

HERD: High Energy Cosmic Radiation Detection



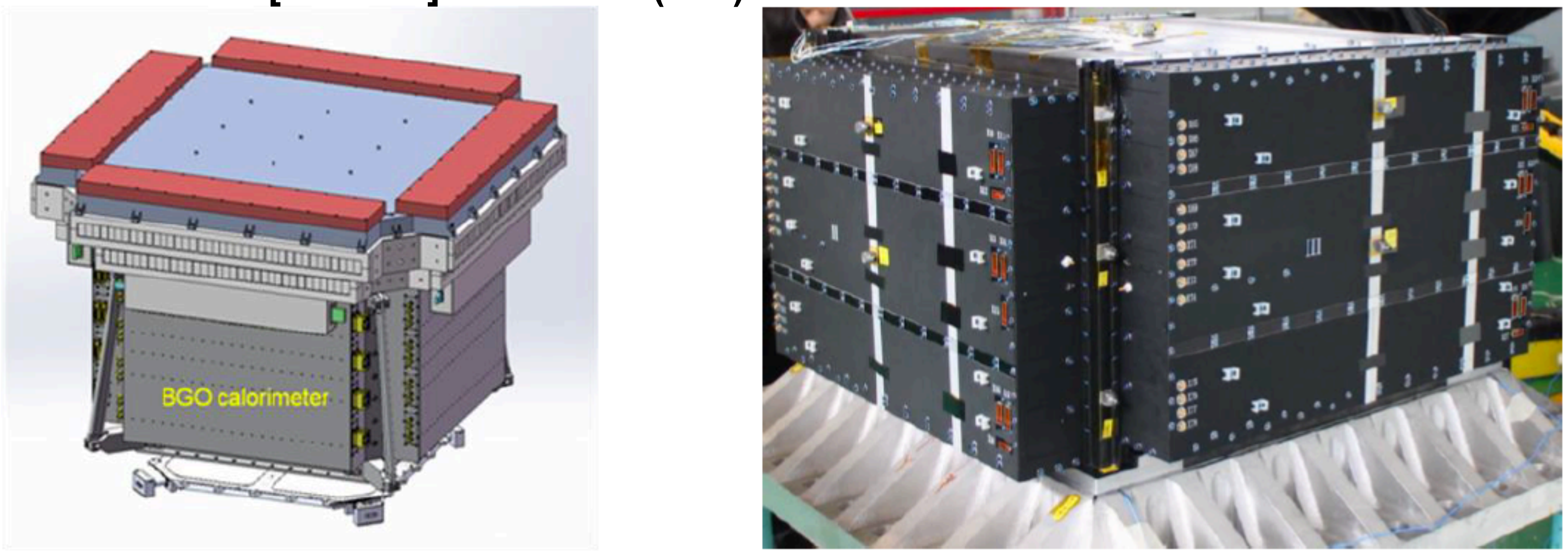


Energy resolution for electrons and gamma will be < 1% at 200 GeV

Wang & Xu Progress of the HERD detector

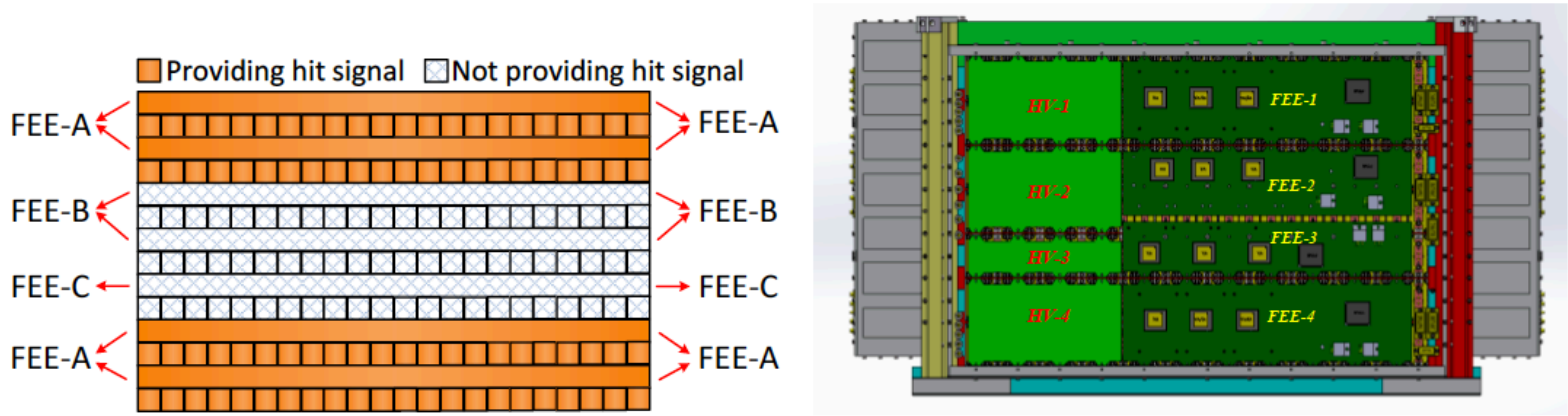
Readout Electronics of DAMPE BGO Calorimeter and the Status in Orbit

Shubin LIU [DAMPE] ICRC2017 (925)



(a) (b)

Fig. 1 (a) 3D structure of the DAMPE payload; (b) photograph of the BGO calorimeter flight model

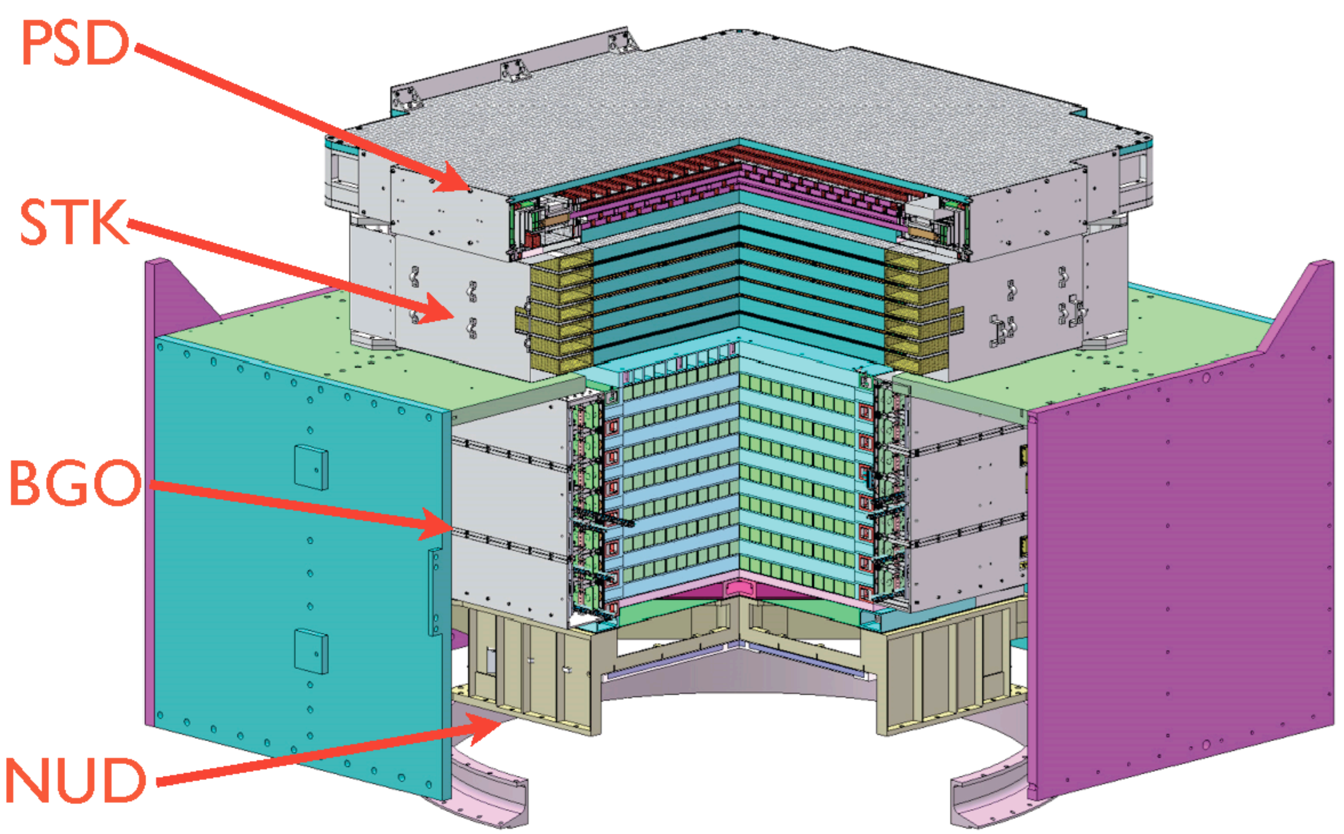


(a) (b)

Fig. 2 (a) Configuration of the BGO FEEs; (b) Circuit boards installed with BGO detector

Si-Tungsten tracker for DAMPE

X. Wu [DAMPE] ICRC2017 (926)



- 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).