The Ohio State University's Center for Cosmology and AstroParticle Physics

A review of indirect Weakly Interacting Massive Particle search experiments

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Summary

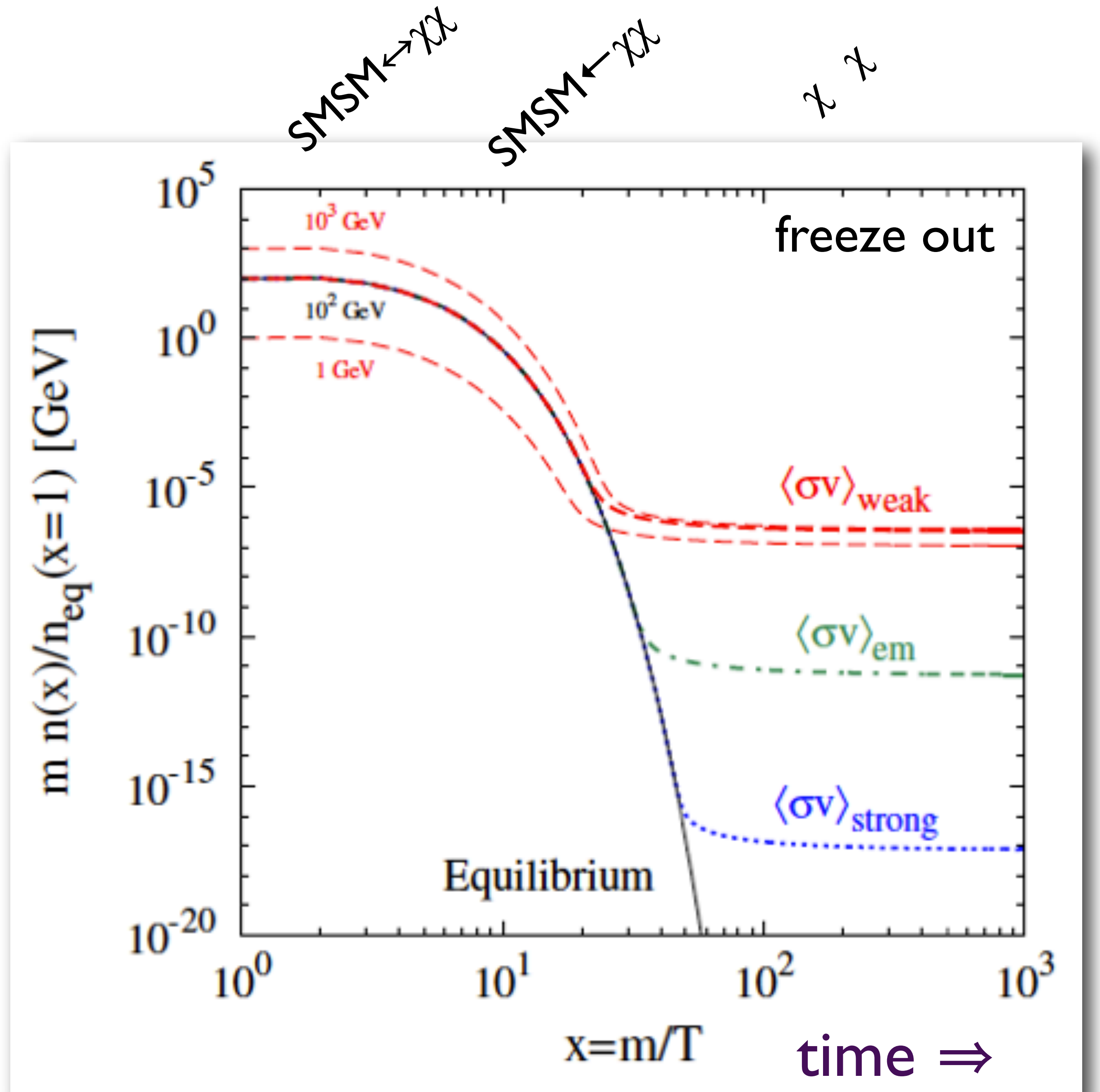
- Motivation
  - WIMPs Signals
  - Strategies and Targets
- Instruments
- Indirect Searches
  - Current Status and Results
  - Future Prospects
- Conclusions

Thermal Relic

- If dark matter is a WIMP (χ) that is a thermal relic of the early Universe, then its total self-annihilation cross section $<\sigma_A v>$ is revealed by its present-day mass density
- Evolution is determined by the competition between production and annihilation
- Common temperature T ($\equiv T_\gamma$)

$$\frac{dn}{dt} + 3Hn = \frac{d(na^3)}{a^3 dt} = \langle\sigma_A v\rangle \left(n_{eq}^2 - n^2\right)$$

$$n_{eq} = g_\chi (mT/(2\pi))^{3/2} \exp(-m/T)$$



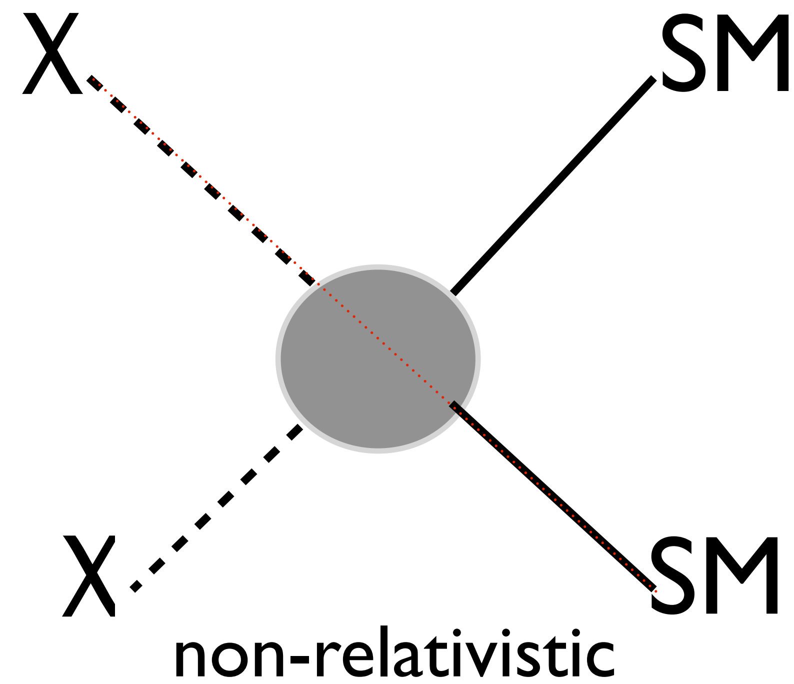
$m_\chi \approx 1\text{GeV} \Rightarrow <\sigma_A v> \sim 4.5 \cdot 10^{-26}\ \text{cm}^3\text{s}^{-1}$

$m_\chi > 5\text{GeV} \Rightarrow <\sigma_A v> \sim 2 \cdot 10^{-26}\ \text{cm}^3\text{s}^{-1}$

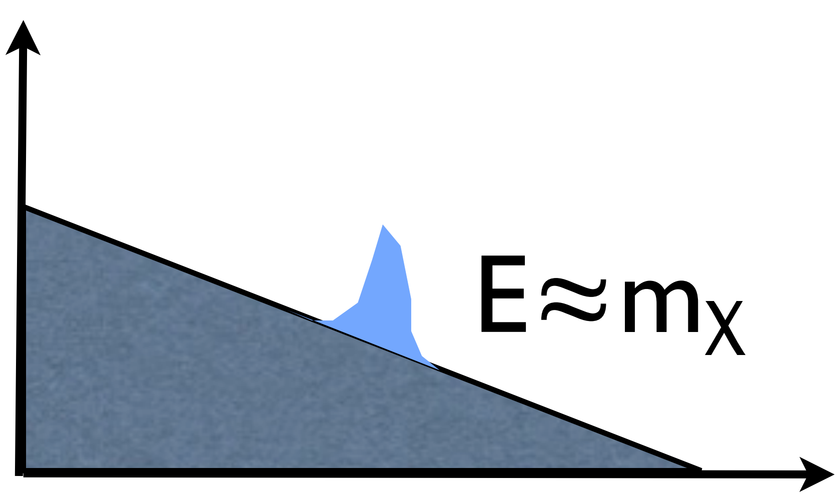
G. Steigman, B. Dasgupta, J.F. Beacom 1204.3622
G. Jungman, M. Kamionkowski, K. Griest, Phys. Rept., 267 (1996) 195.

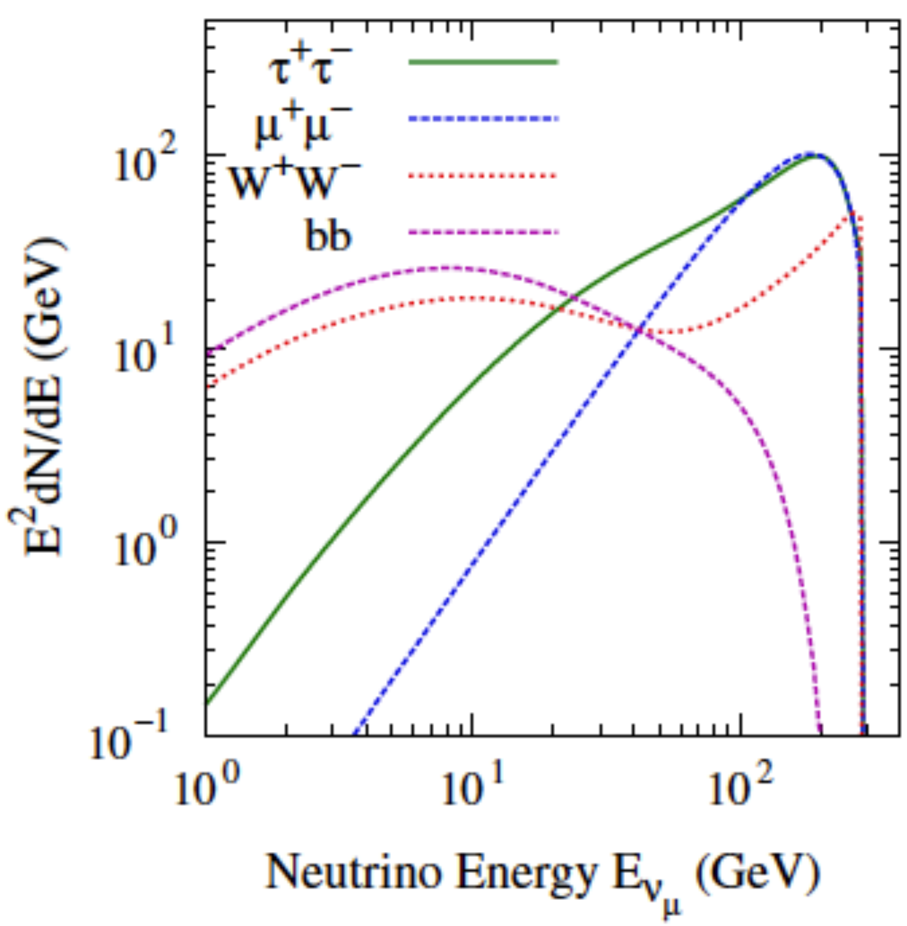
Signals

Dark Matter Annihilation



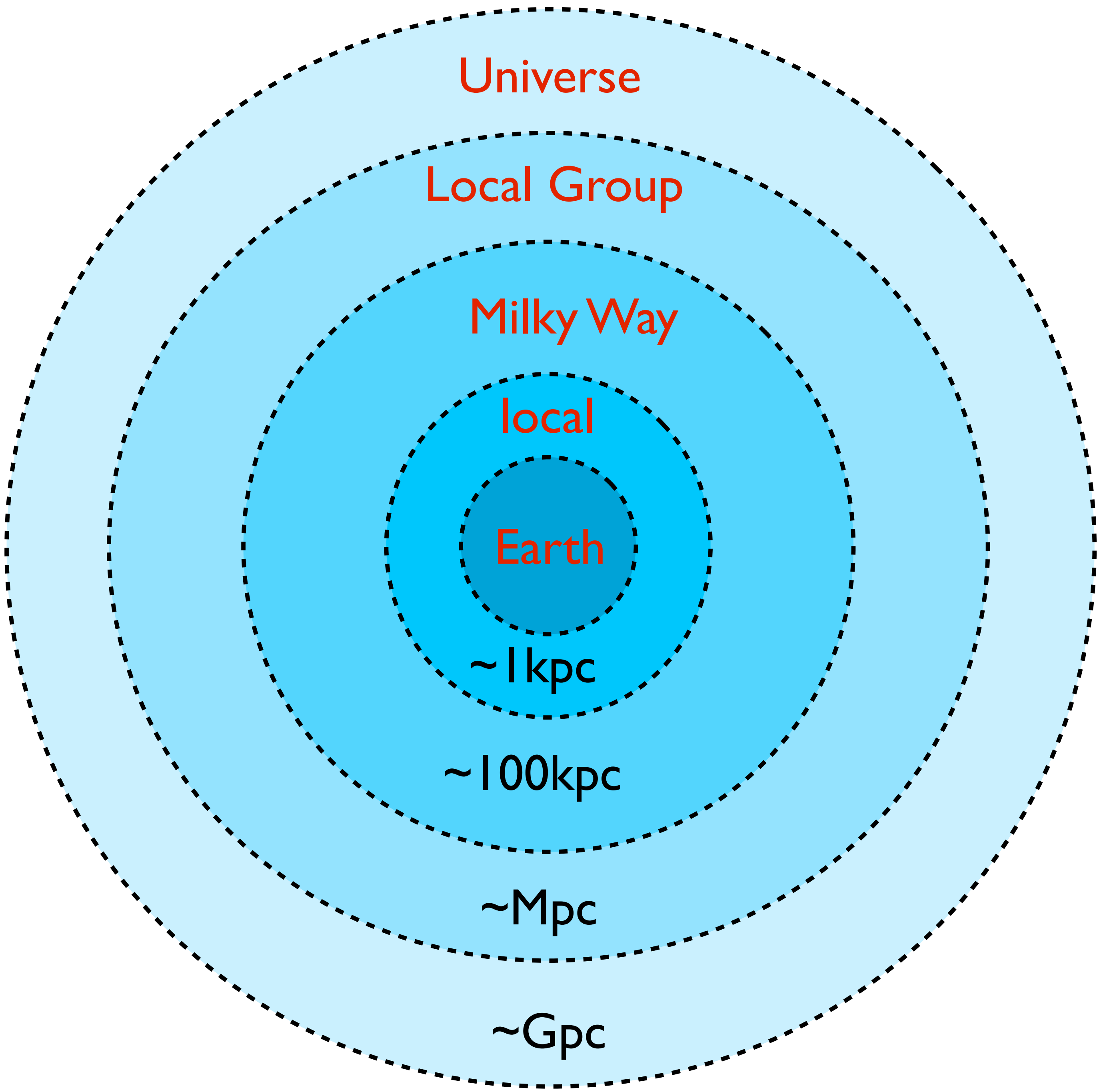
- Interactions that determine the WIMP relic abundance also lead to self-annihilations in the present epoch
  - Identify overdense region of Dark Matter where self-annihilation can occur at significant rates
- Pick Prominent DM Target
- Understand Backgrounds
- Features in the signal enhance to chance distinguish backgrounds
  - Line / End-point





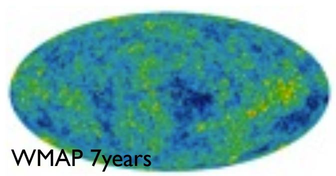
Strategies and Targets

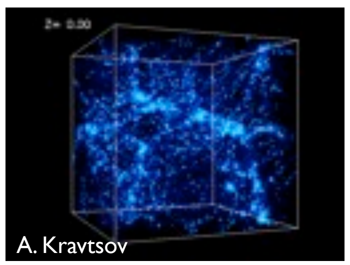
Dark Matter at all scales

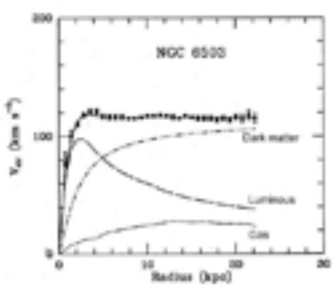


Dark Matter at all scales

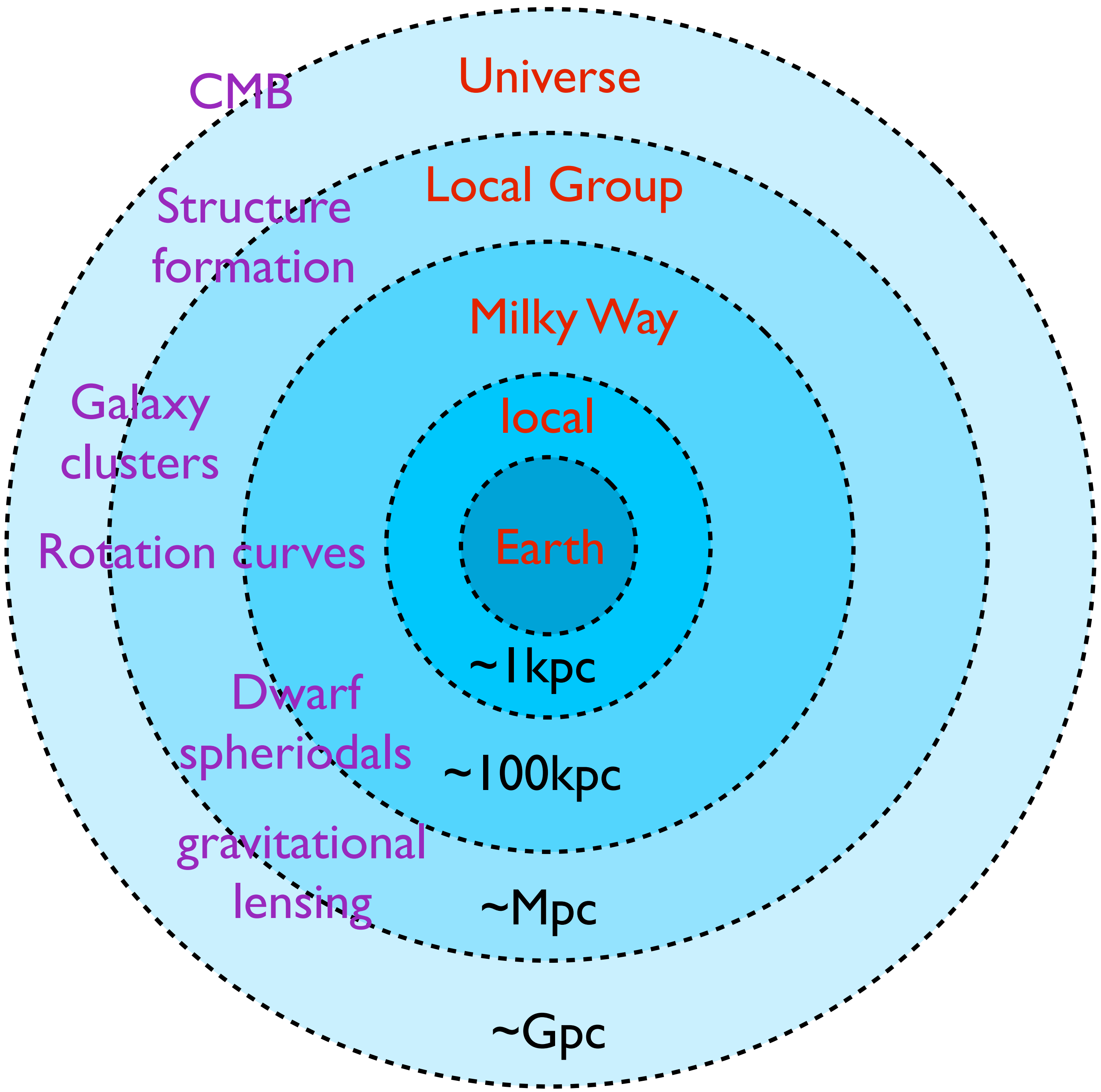
“Evidence”







Begeman, Broels & Sanders (1991)



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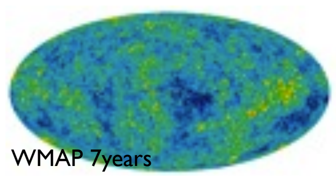
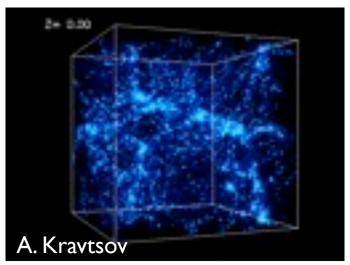
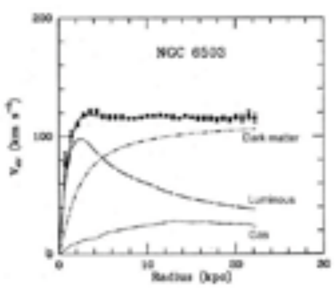
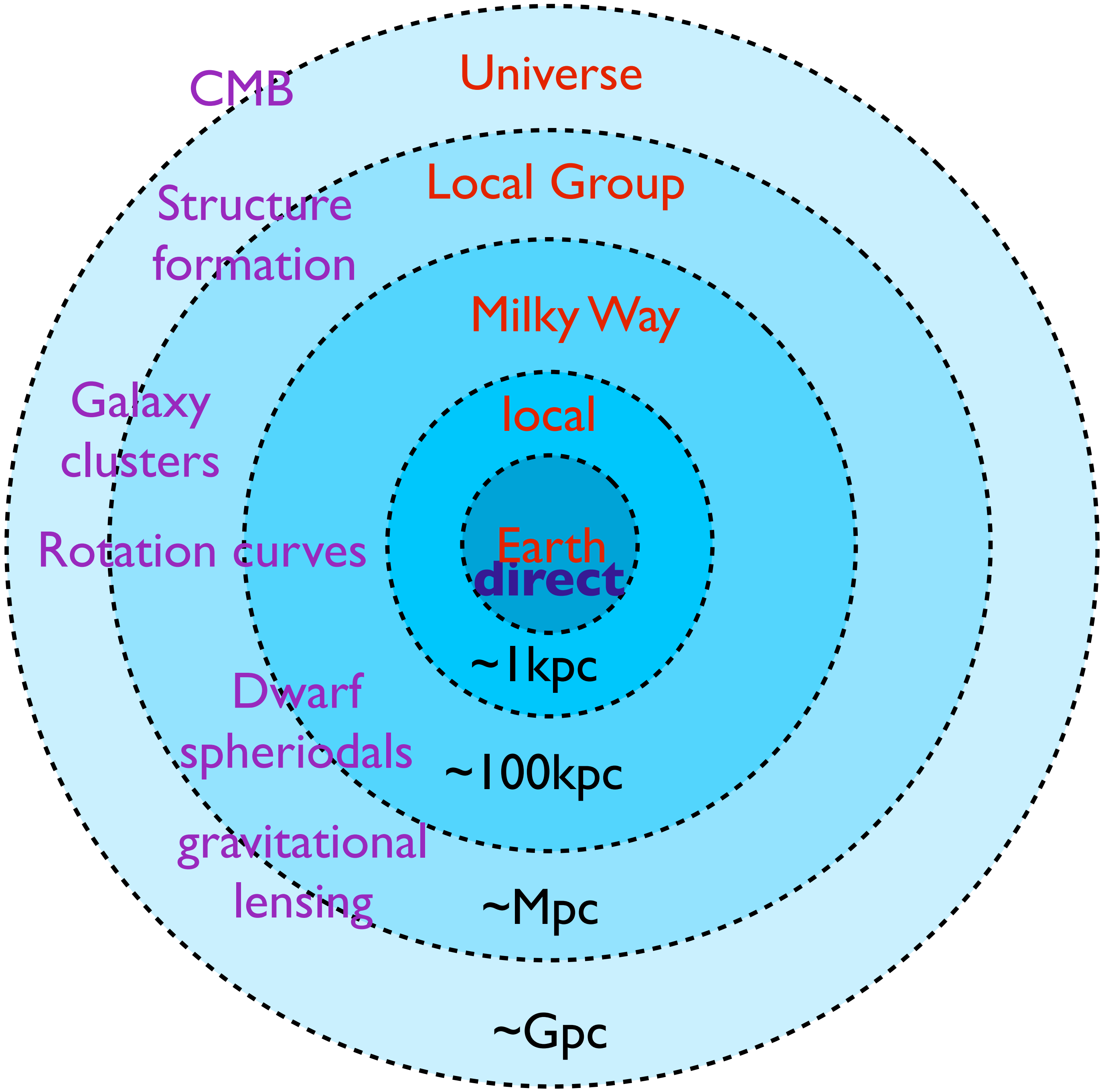

WMAP 7years


A. Kravtsov



Begeman, Broels & Sanders (1991)


Gravitational Lensing in the Galaxy Cluster Abell 2218 NASA / A. Fruchter / STScI



Dark Matter at all scales

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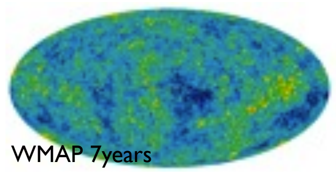
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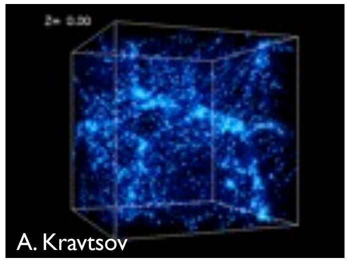
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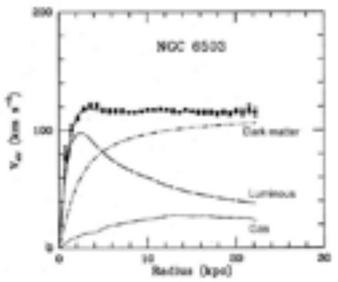

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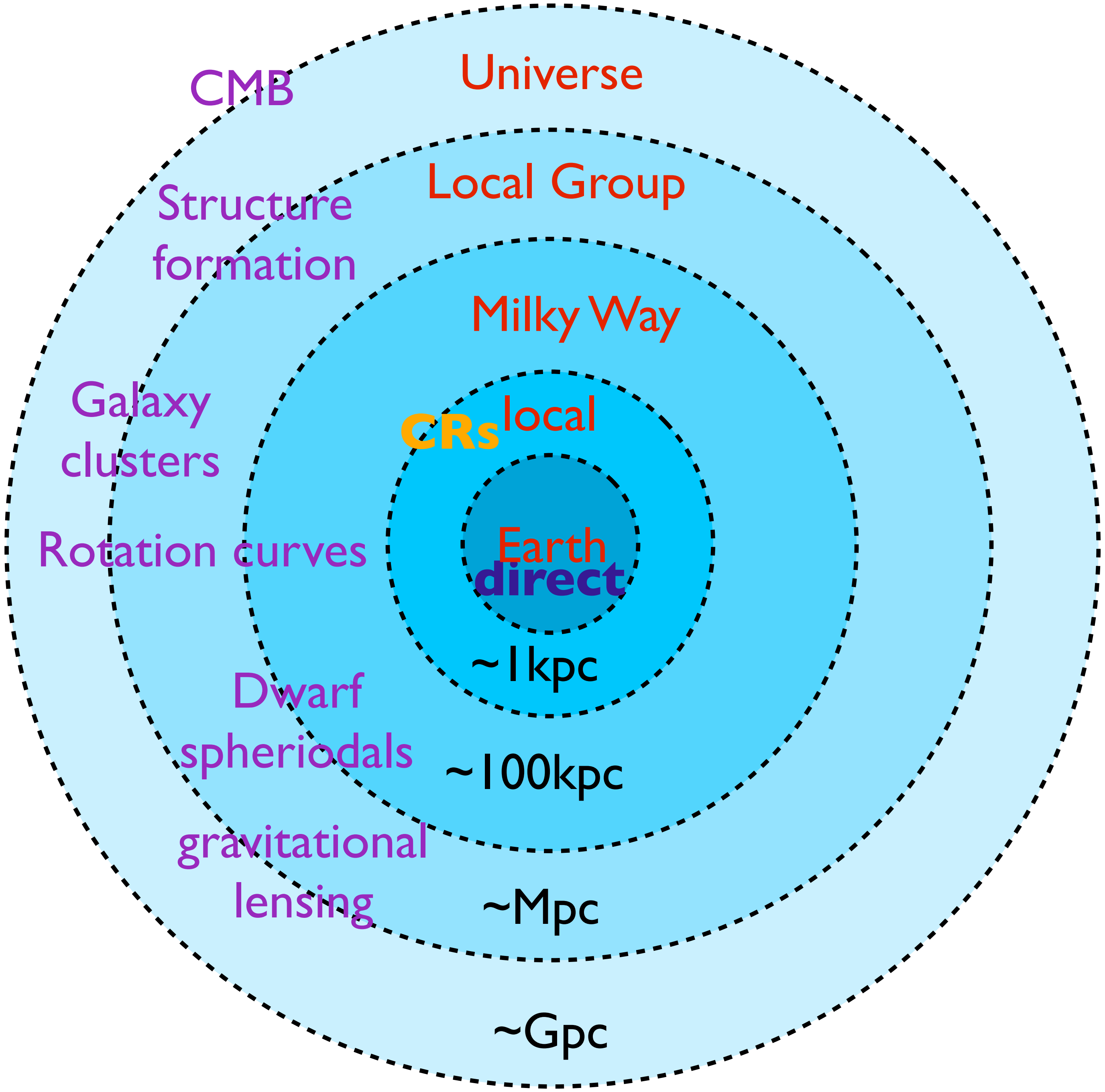

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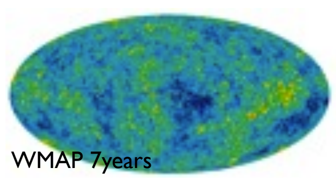

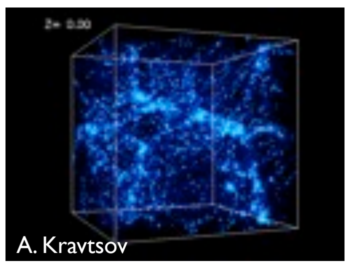

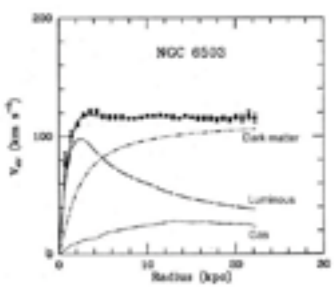

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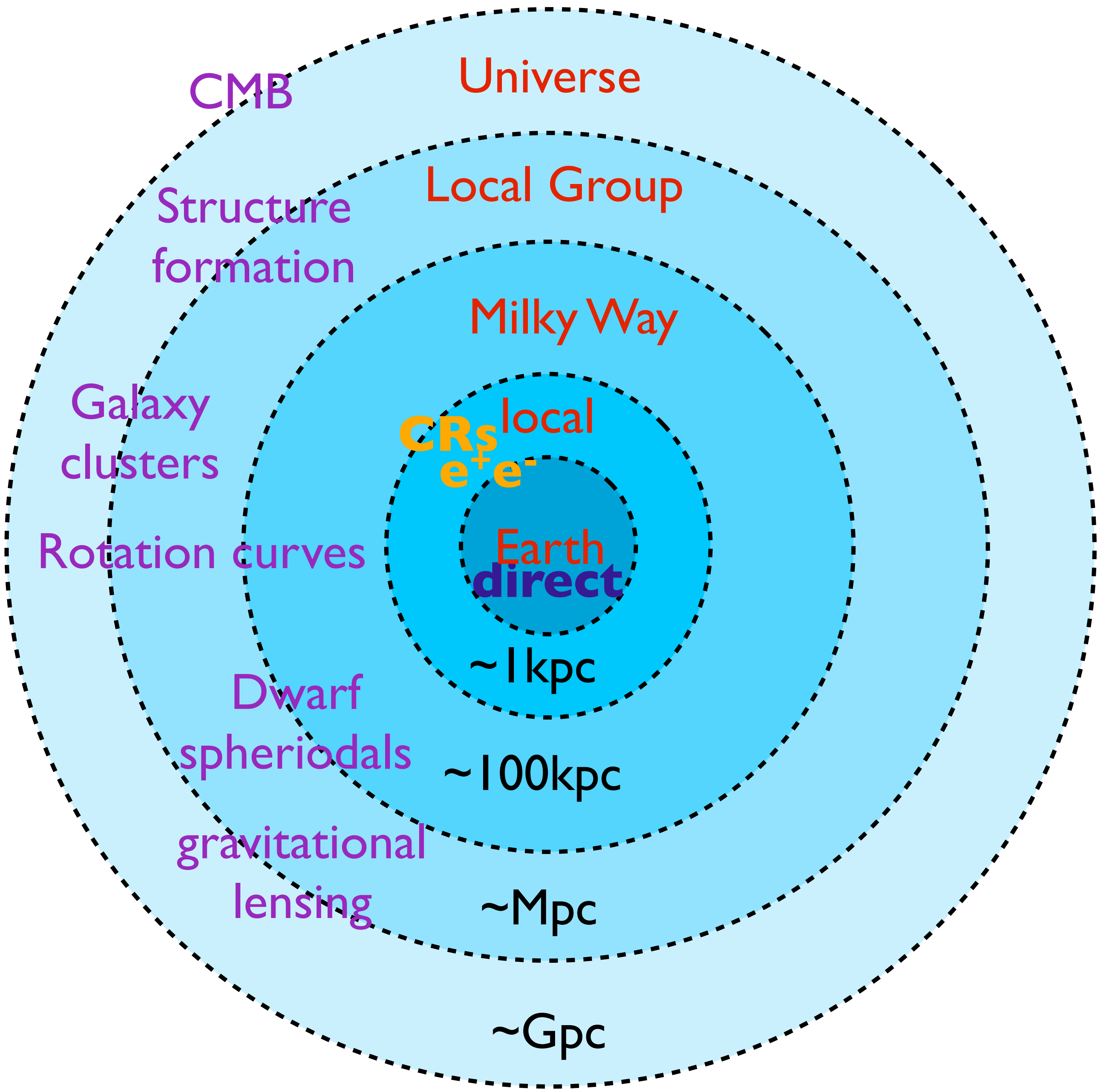

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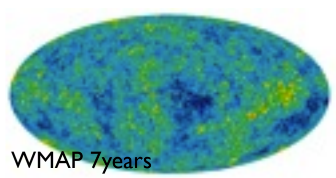
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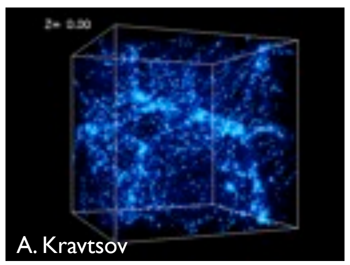
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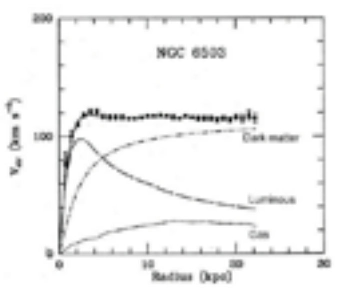

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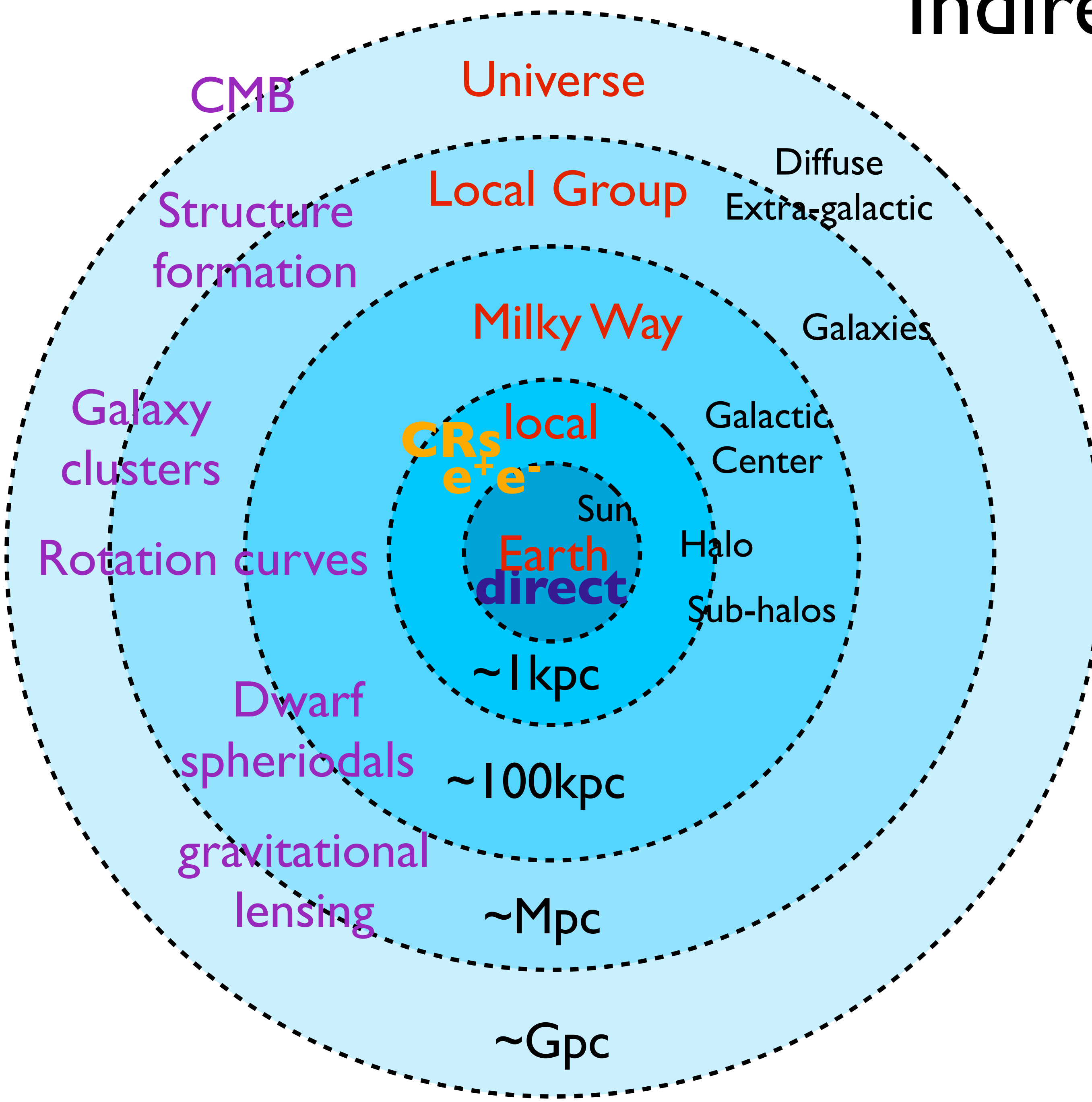
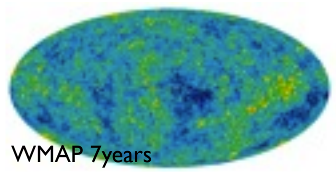
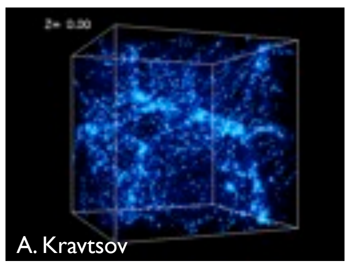
“Indirect Targets” for γ,ν

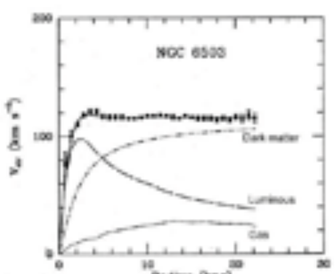


Dark Matter at all scales

"Evidence"







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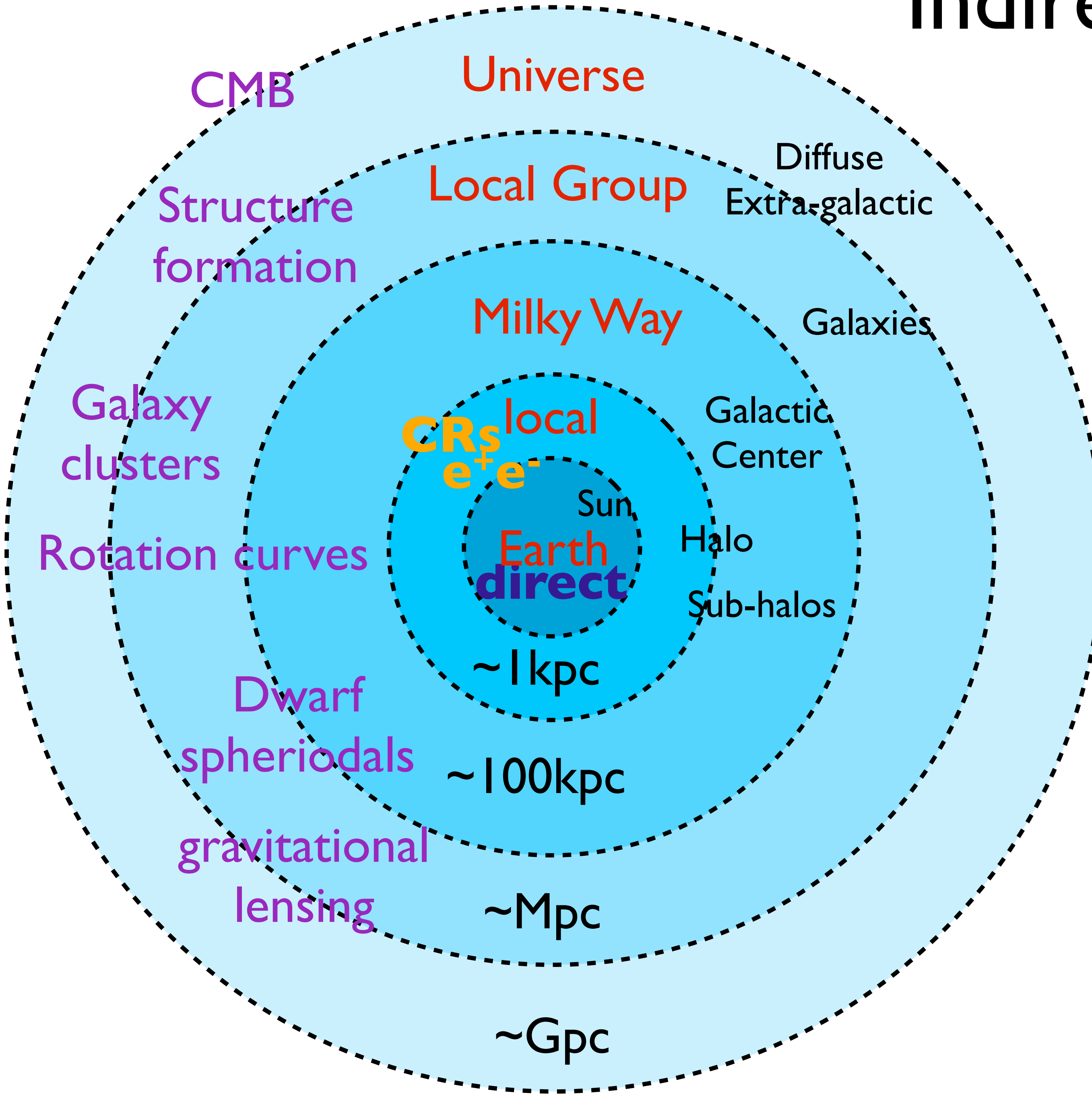

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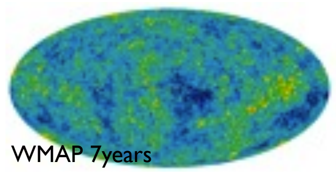
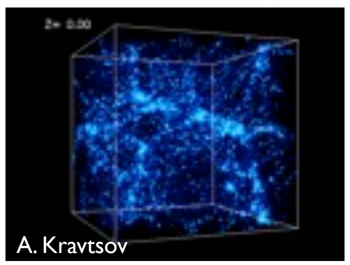
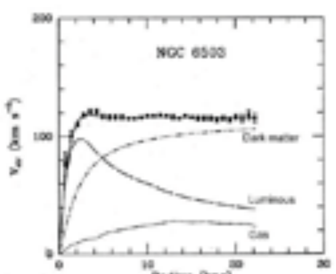
"Evidence"







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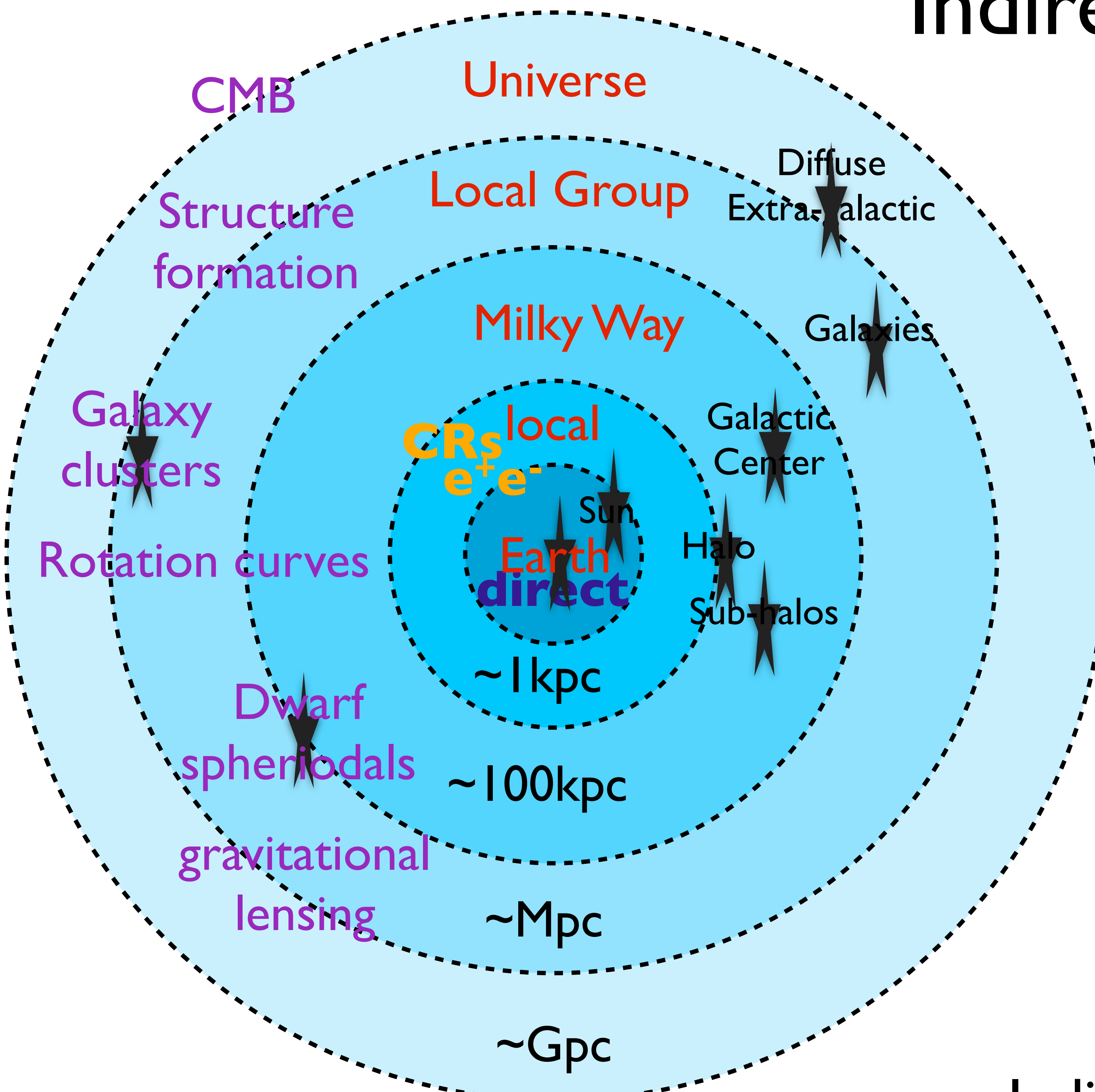
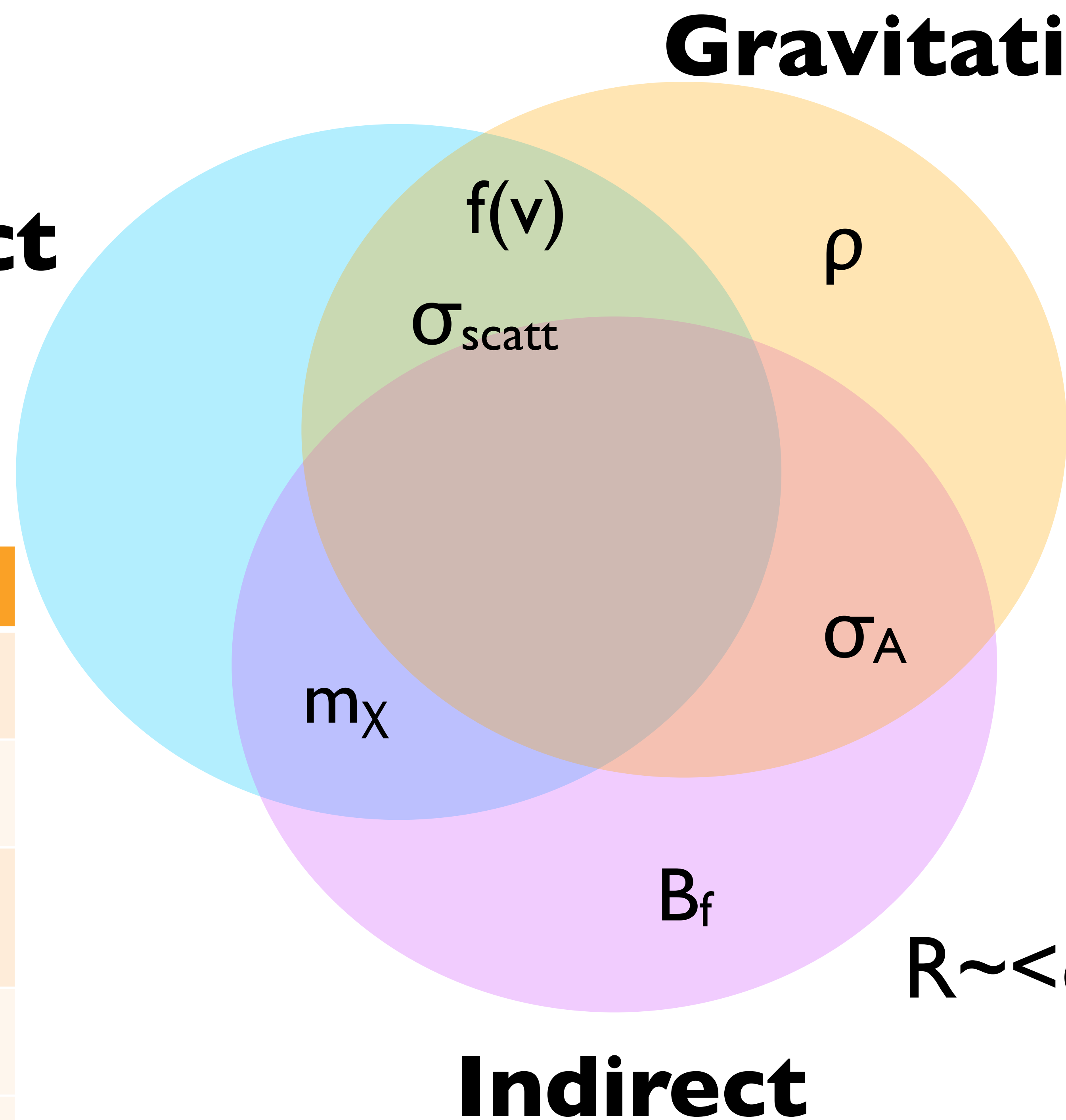


"Indirect Targets" for γ,ν

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

Individual sources and diffuse

What Can Indirect Detection Answer ?



$R \sim \sigma_{scatt} n N$

$n \sim \rho / m_\chi$

$R \sim \langle \sigma_A v \rangle n^2$

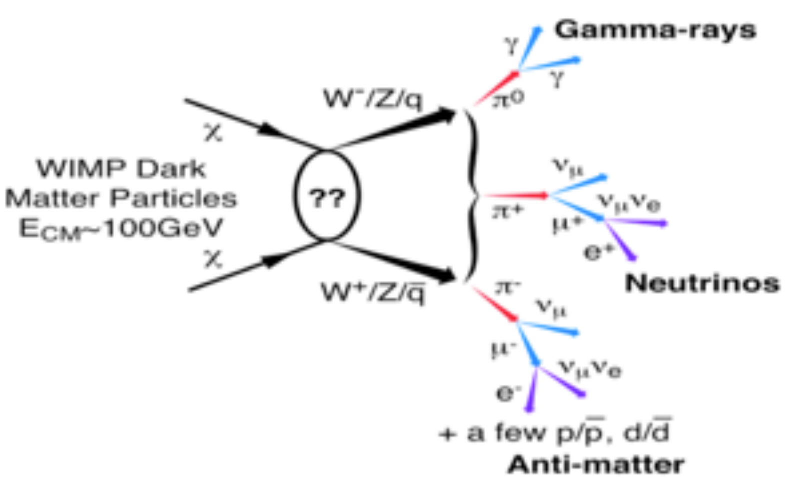
	Description
ρ	Dark Matter Density
σ_{scatt}	Scattering cross section
f(v)	local WIMP velocity distribution
m_χ	WIMP Mass
σ_A	Self-annihilation cross section
B_f	Branching fraction

What do we test ? Example: 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

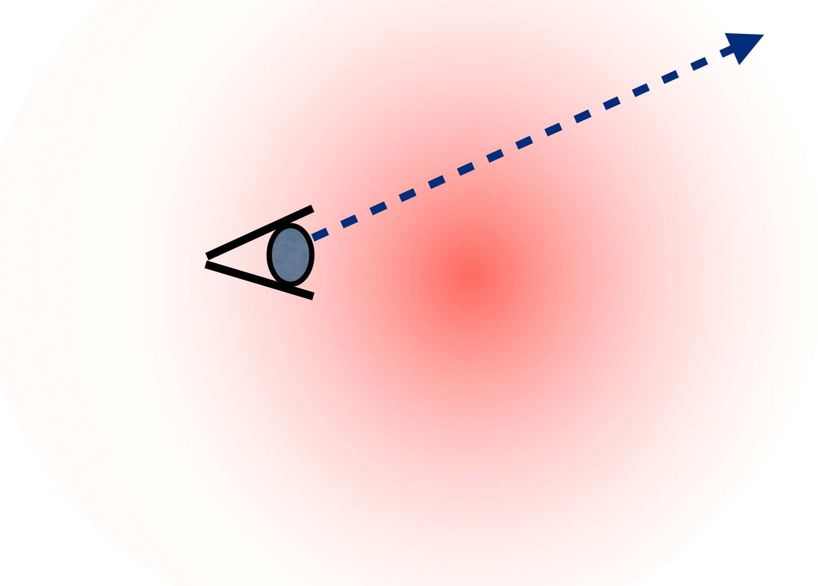


x

Dark Matter Distribution

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

line of sight (los) integral



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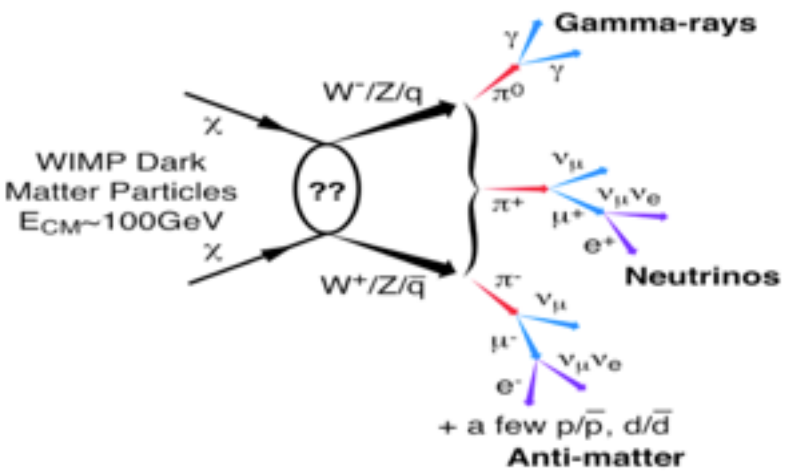

x

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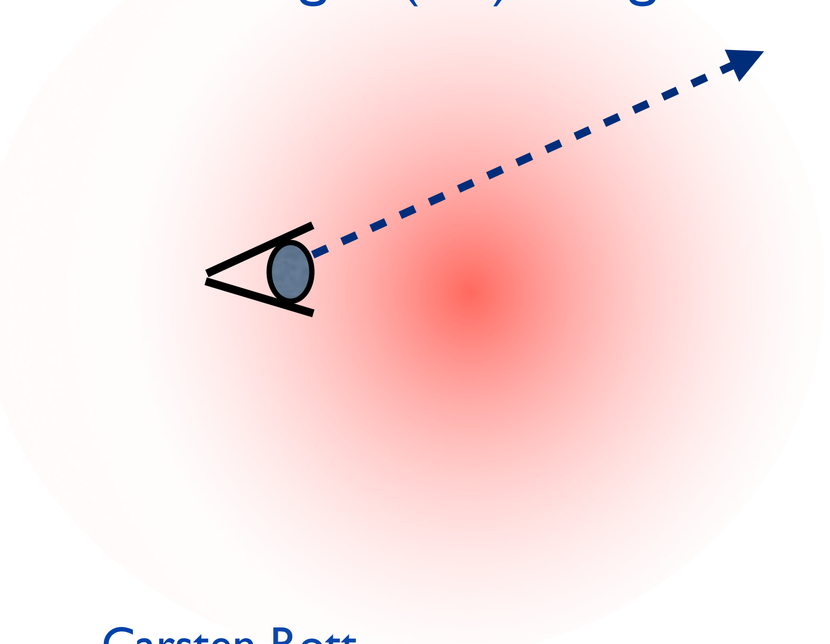
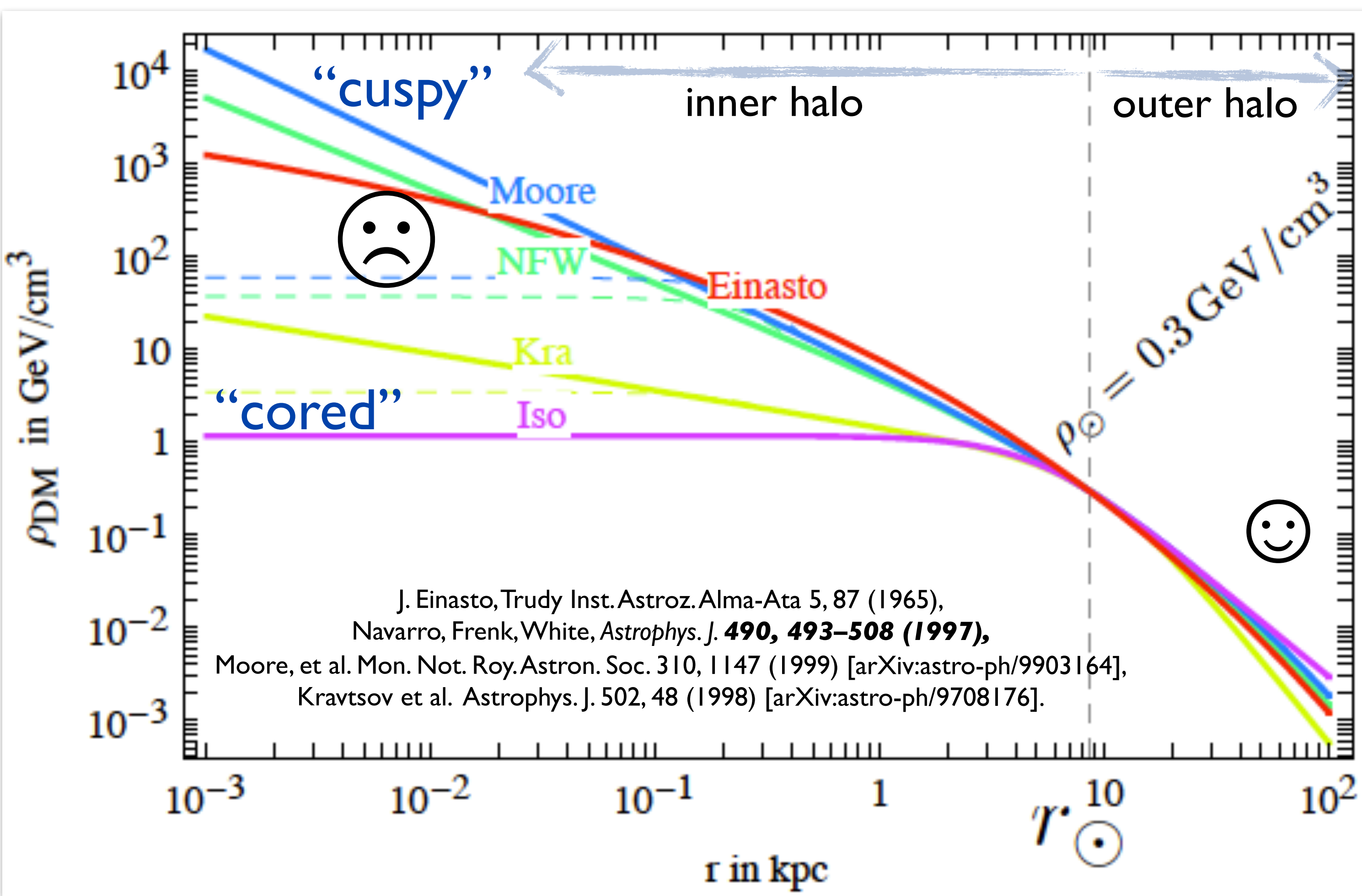


How Dark Matter is distributed

- N-body simulations of Milky Way like galaxies yield halo profiles ρ(r). Halo profiles described the average dark matter density (smooth)
- Two major difficulties
  - Inner halo shape (cuspy or cored ?)
  - Sub-structure in outer halo



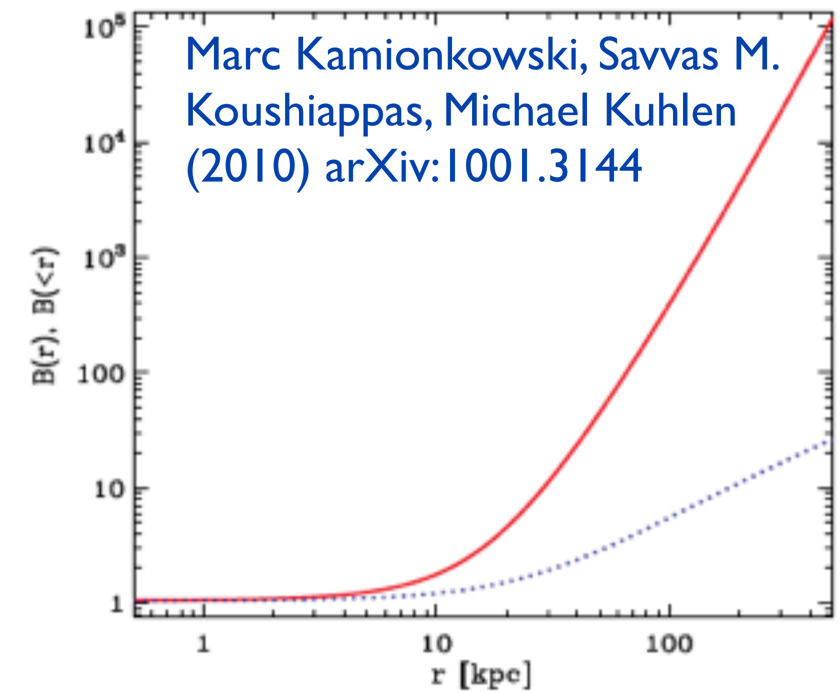


FIG. 4. The local substructure boost $B(r)$ (*solid*) and the cumulative luminosity boost $B(<r)$ (*dotted*), as a function of radius.

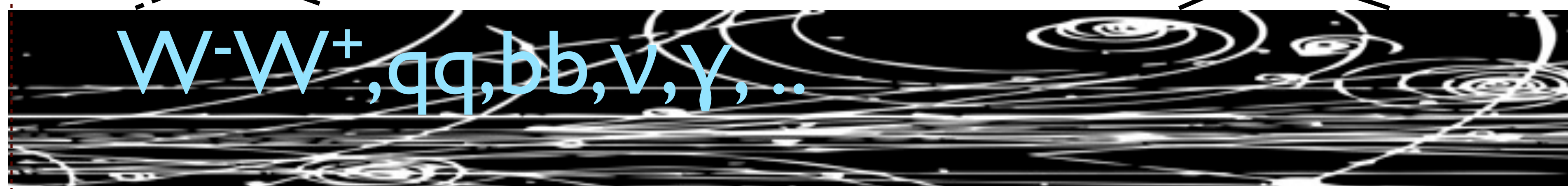
- Sub-structure in halos can significantly enhance annihilation rates (~ρ^2) over those expected from a smooth halo. It is convenient to define a boost factor B to describe this enhancement
- Boost factor ~ 1 (for central halo region <10kpc) tidal stripping
- Typical boost factors are B~ 1-20 (simulations)

Indirect Searches in one Slide

Distributions

DM Interaction

Primary Products



Propagation

Detection

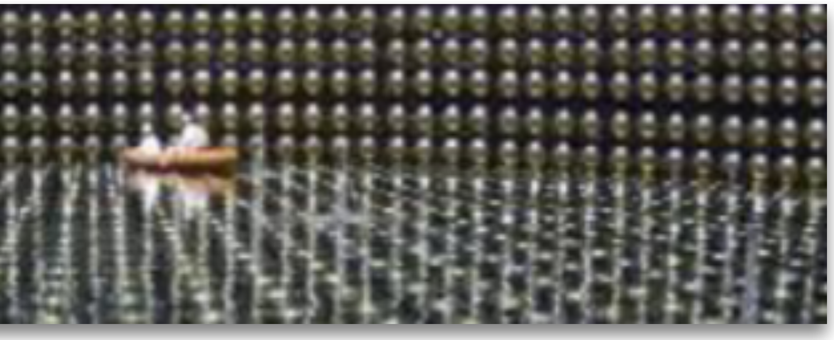
Interpretation

■ 噴水のあるエリアの展示作品

The Thinker
Auguste Rodin (1840-1917)
1880
Kyoto National Museum

The Instruments

The Instruments



Neutrino Detectors

- ANTARES, NESTOR, NEMO, KM3Net...
- Baikal, ...
- IceCube, PINGU, ...
- Super-K, KamLAND, Hyper-K, LBNE, Laguna, ...

Gamma Ray Telescopes

- MAGIC, H.E.S.S., VERITAS, ...
- Fermi
- CTA

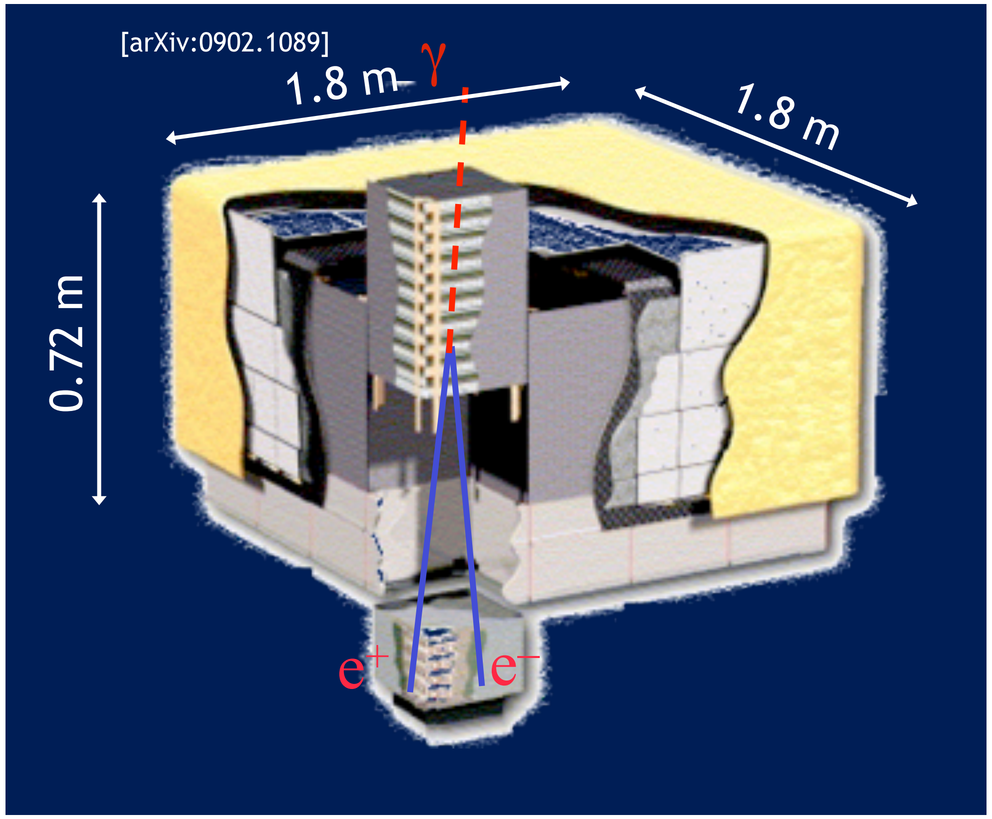
Anti-Matter Satellites

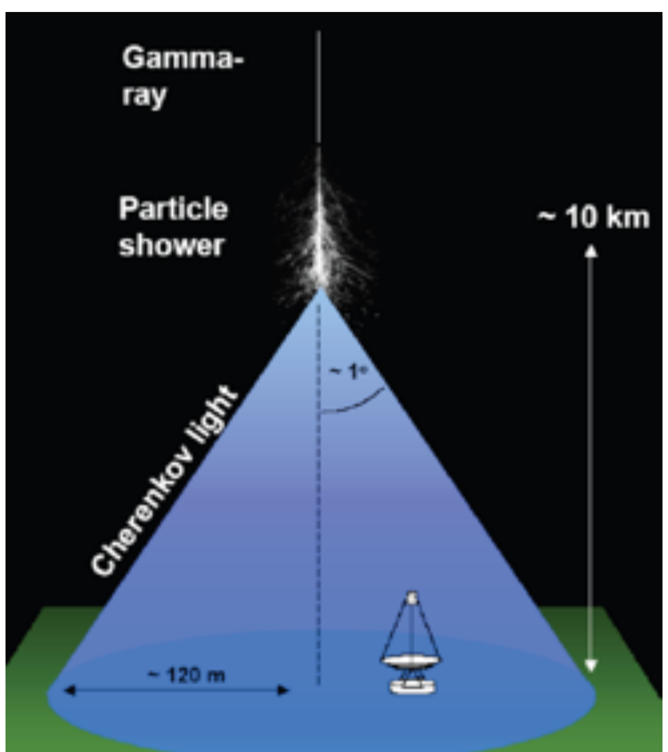
- PAMELA, ATIC, PPB-Bets, ...
- AMS-02

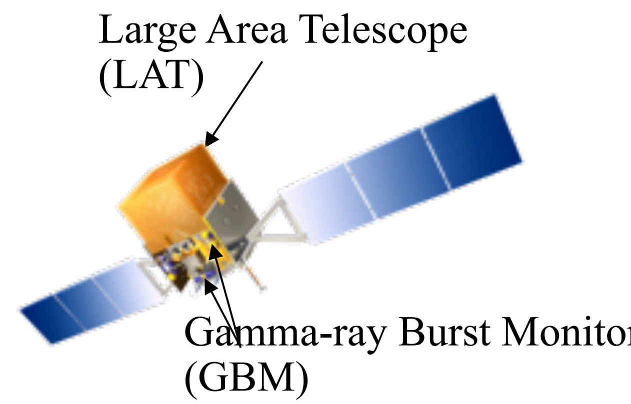
Others

- x-ray, radio, ...

gamma-rays



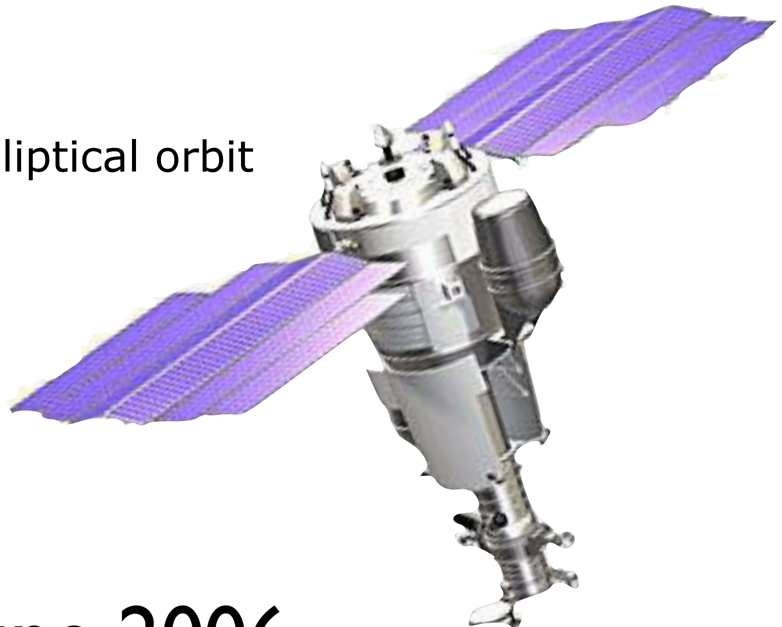




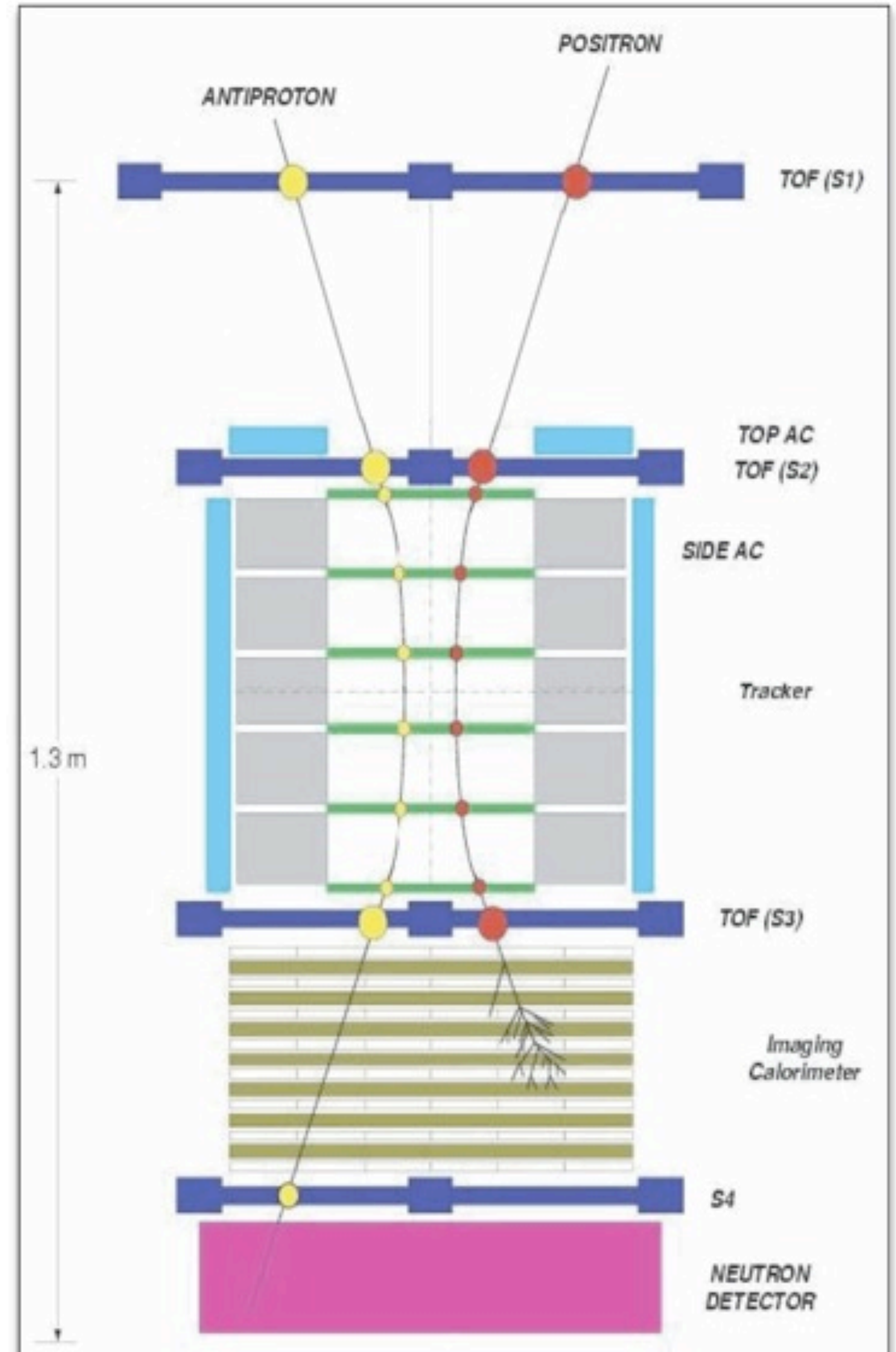
	Fermi-LAT	Imaging Air Cherenkov Telescopes
Detection Method	Pair conversion	Cherenkov light from particle shower
Effective Area	1m^2	~400-500m^2
Field of View (FOV)	2.5sr	3.5° - 5.0°
Duty cycle	~100% ?	~15%
Energy range	20MeV - 300GeV	>100GeV
Energy resolution	4% (@5GeV) 2% (@200GeV)	10% - 20%
Angular resolution	~0.1° (@10GeV) ~3.5°(@100MeV)	0.1° at 100 GeV

PAMELA – Payload for Anti-Matter Exploration and Light-nuclei Astrophysics

Low-earth elliptical orbit



- Launched: June 2006
- Satellite-born Magnetic spectrometer
- Size 70x70x130cm^3
- $e^+(e^-)$ - 50 MeV –300GeV (600GeV)
- Protons up to ~1TeV

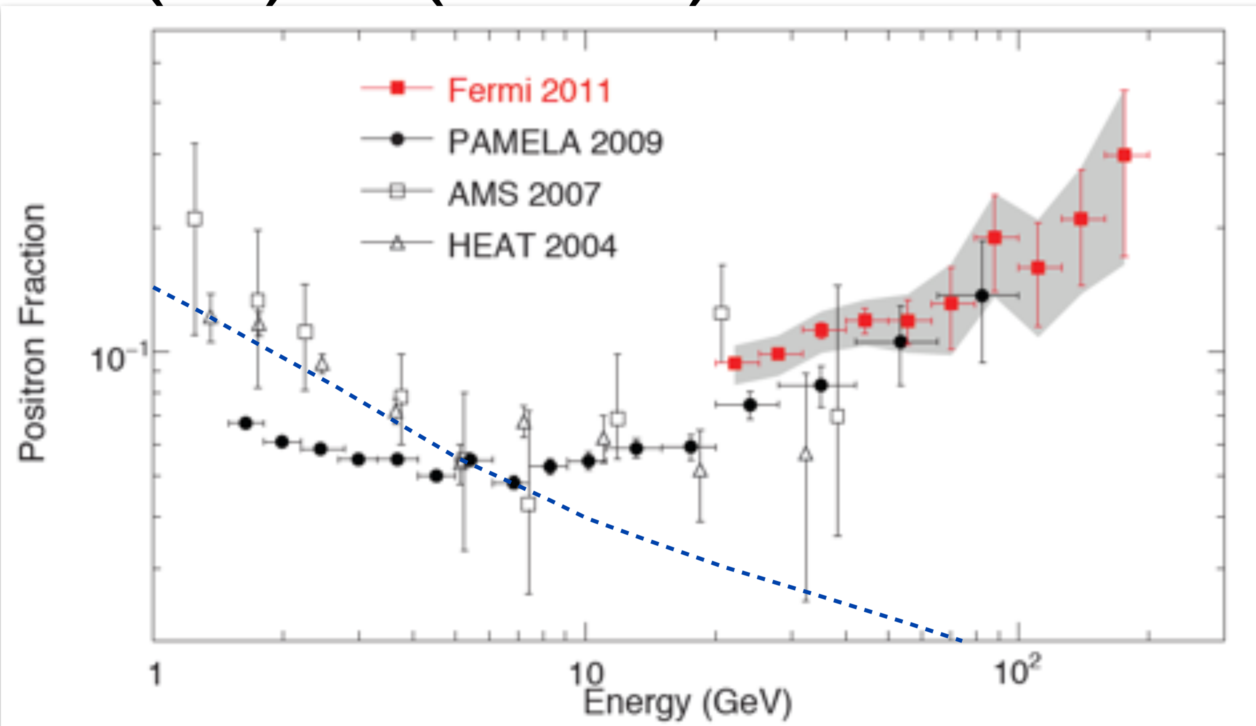


Astropart.Phys. 27 (2007) 296-315

Status and Results

Cosmic e^+e^-

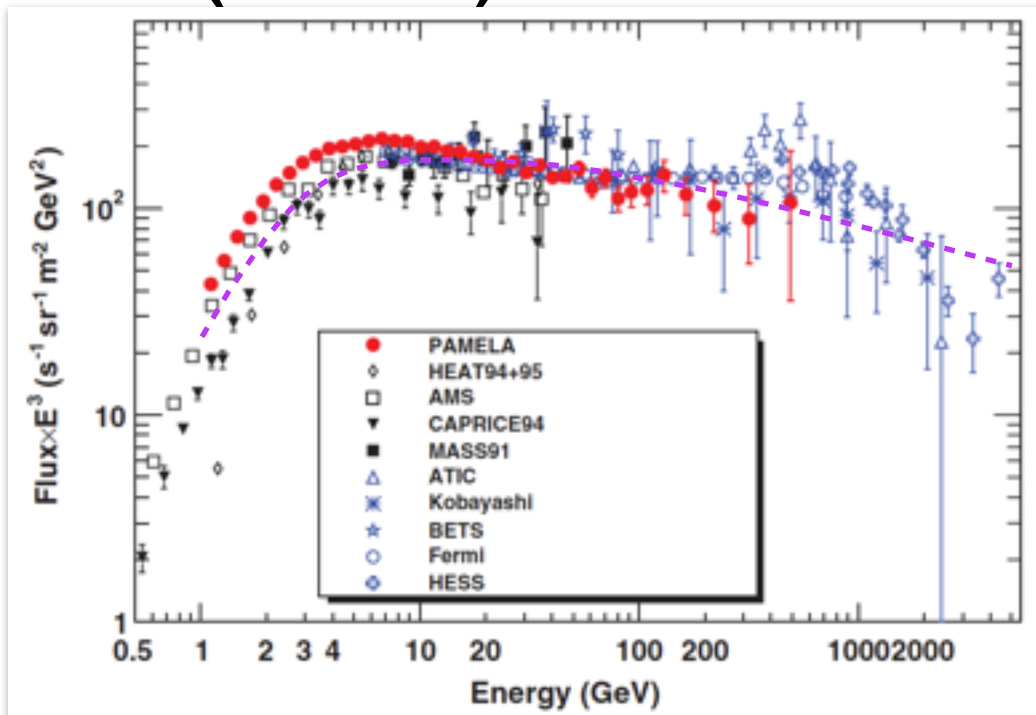
$\Phi(e^+)/\Phi(e^++e^-)$



Ackermann et al. [Fermi LAT Collaboration] 2011

Adriani et al. [PAMELA] 2009

$\Phi(e^++e^-)$



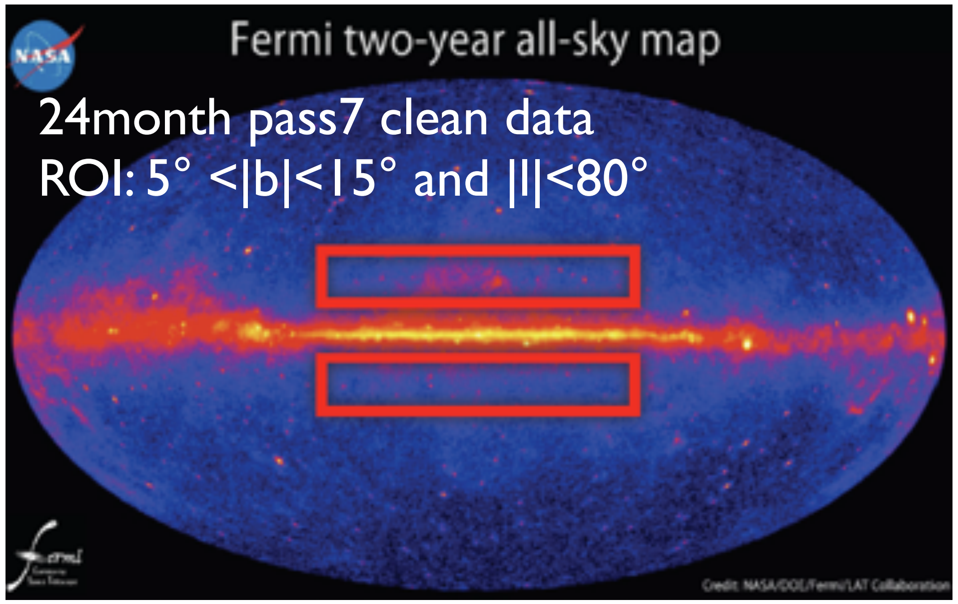
Phys. Rev. Lett. 106, 201101 (2011)

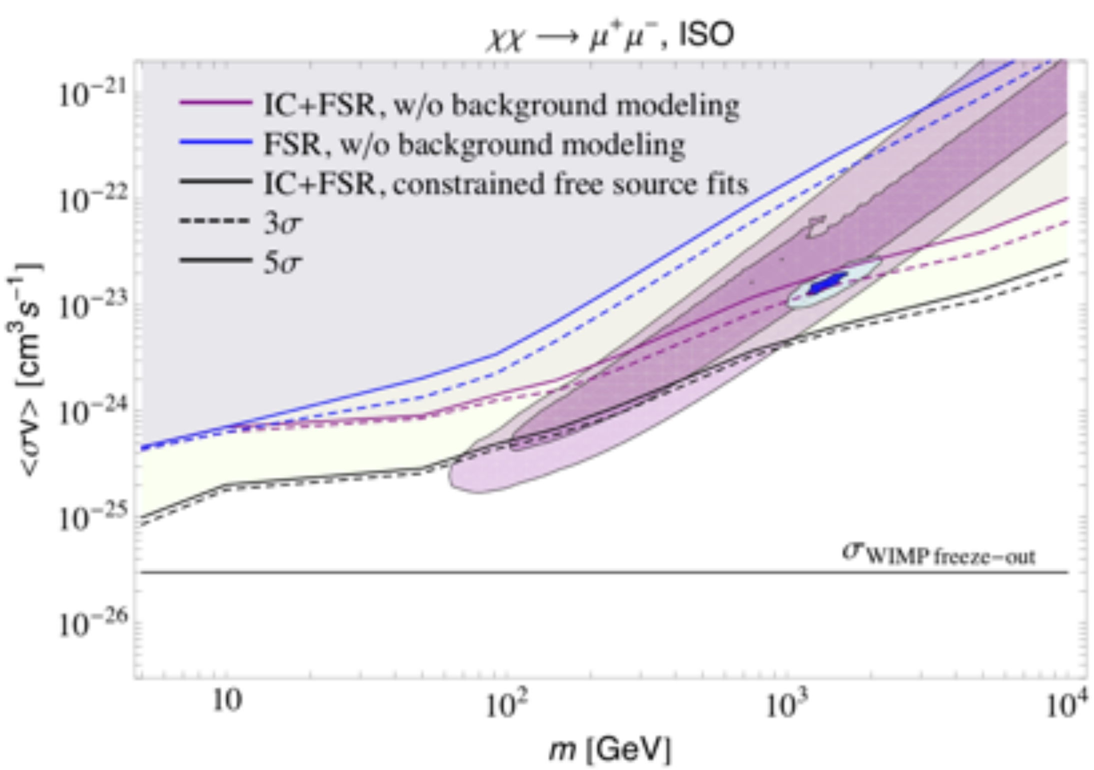
Alternatively one or more near by sources could explain excess

Anomaly could be hint of dark matter
see for example:
P. Meade, M. Papucci, A. Strumia, and T. Volansky, Nucl. Phys. B831, 178 (2010)

Galactic Center / Halo

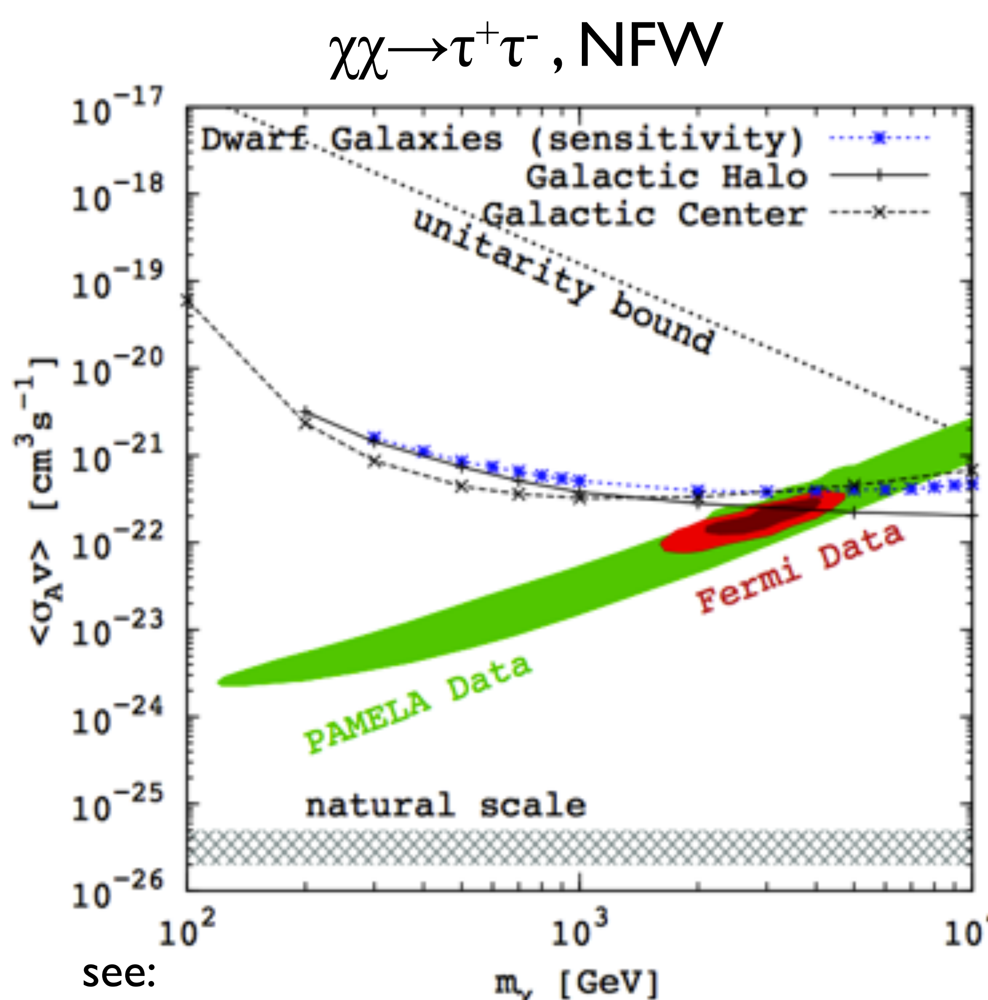
gamma-rays





neutrinos

1yr 22-string IceCube data -- Galactic Halo
1yr 40-string IceCube data -- Galactic Center

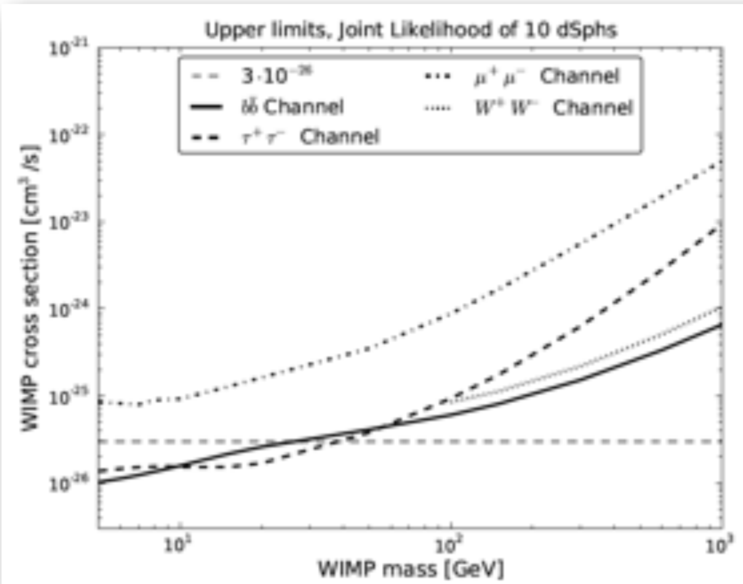


see:
75-3 M. Bissok and J. Luenemann "Search for Dark Matter in Galactic and Extragalactic Halos with the IceCube Neutrino Observatory"

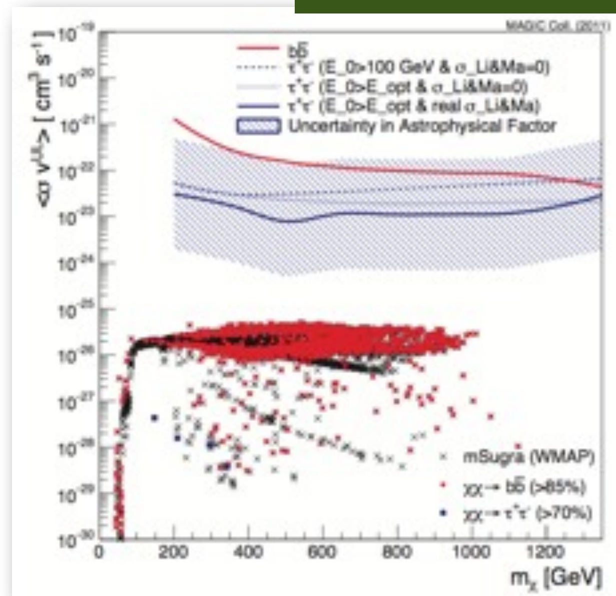
Dark Matter interpretation of PAMELA/Fermi CR anomalies strongly disfavored (for annihilating DM)

Individual Sources: Dwarfs

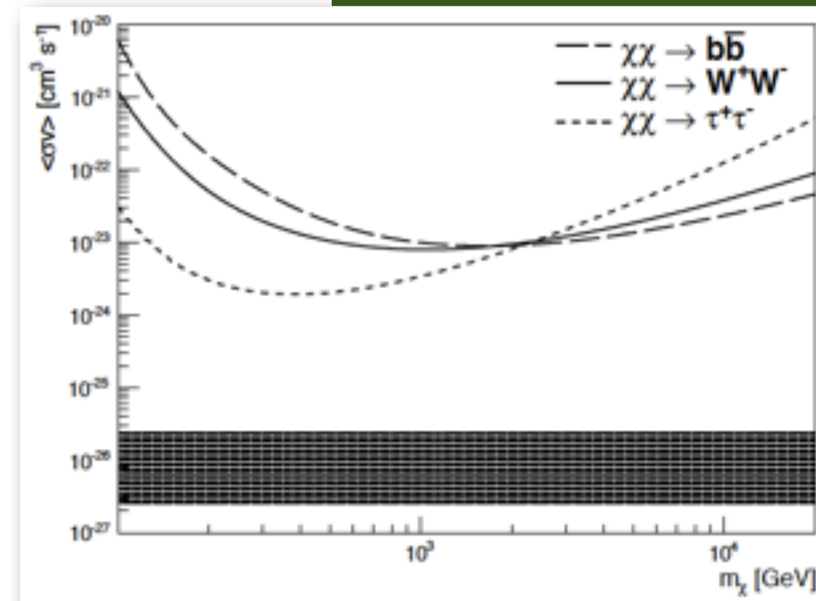
Fermi — Ackermann et al. arXiv:1108.3546



MAGIC — JCAP 1106 (2011) 035 arXiv:1103.0477



Veritas — E. Aliu et al. arXiv 1202.2144



- Some of the most dark matter dominated objects in the Universe
- Roughly two dozen known dwarf spheroidal satellite galaxies in the Milky Way
- No astrophysical gamma-ray production expected
- Boost factor expected to be less than 10 [J.Diemand, et al., Nature 454,735 (2008) / V. Springel et al., Mon. Not. R. Astron. Soc., 391, 1685 (2008), ...]

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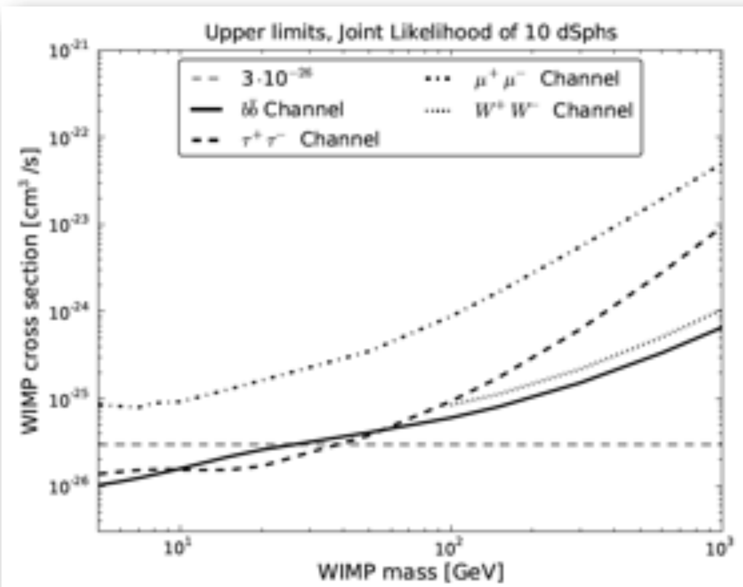
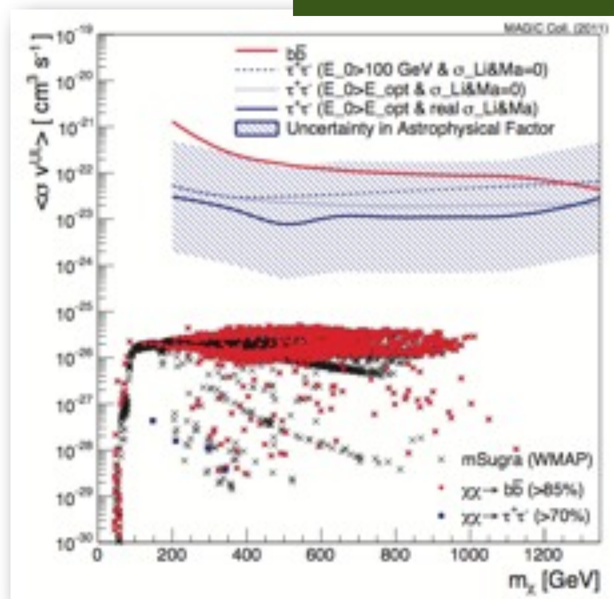
Individual Sources: Dwarfs

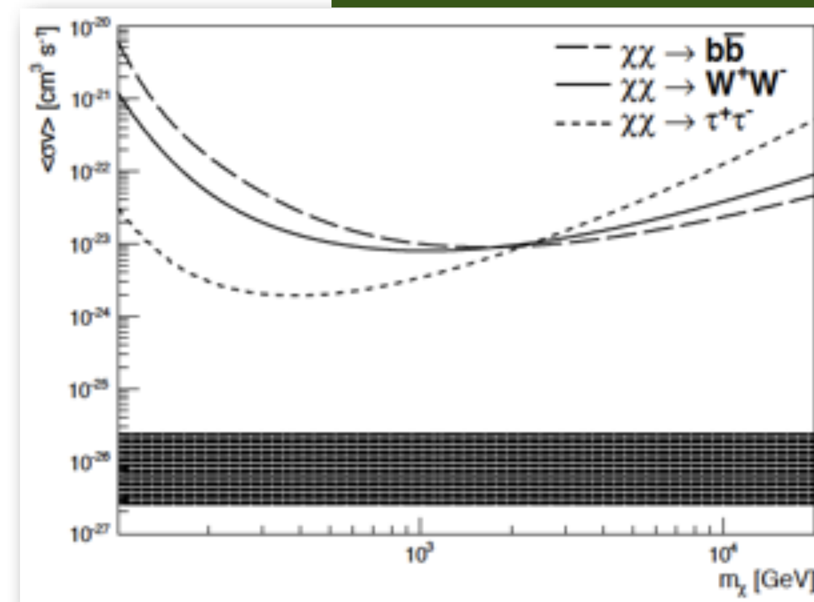
Fermi Ackermann et al. arXiv:1108.3546



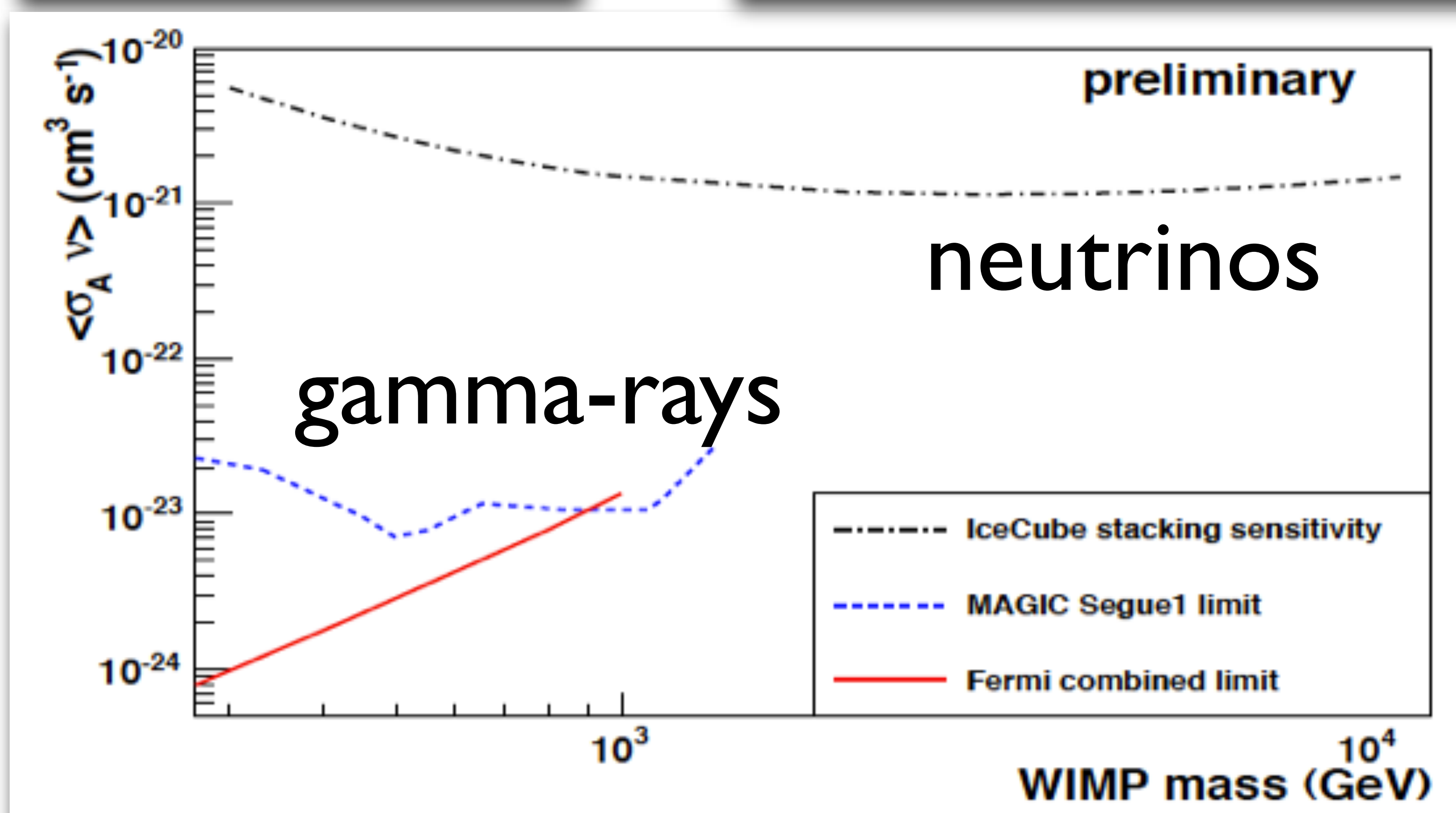
MAGIC JCAP 1106 (2011) 035 arXiv:1103.0477



Veritas E. Aliu et al. arXiv 1202.2144

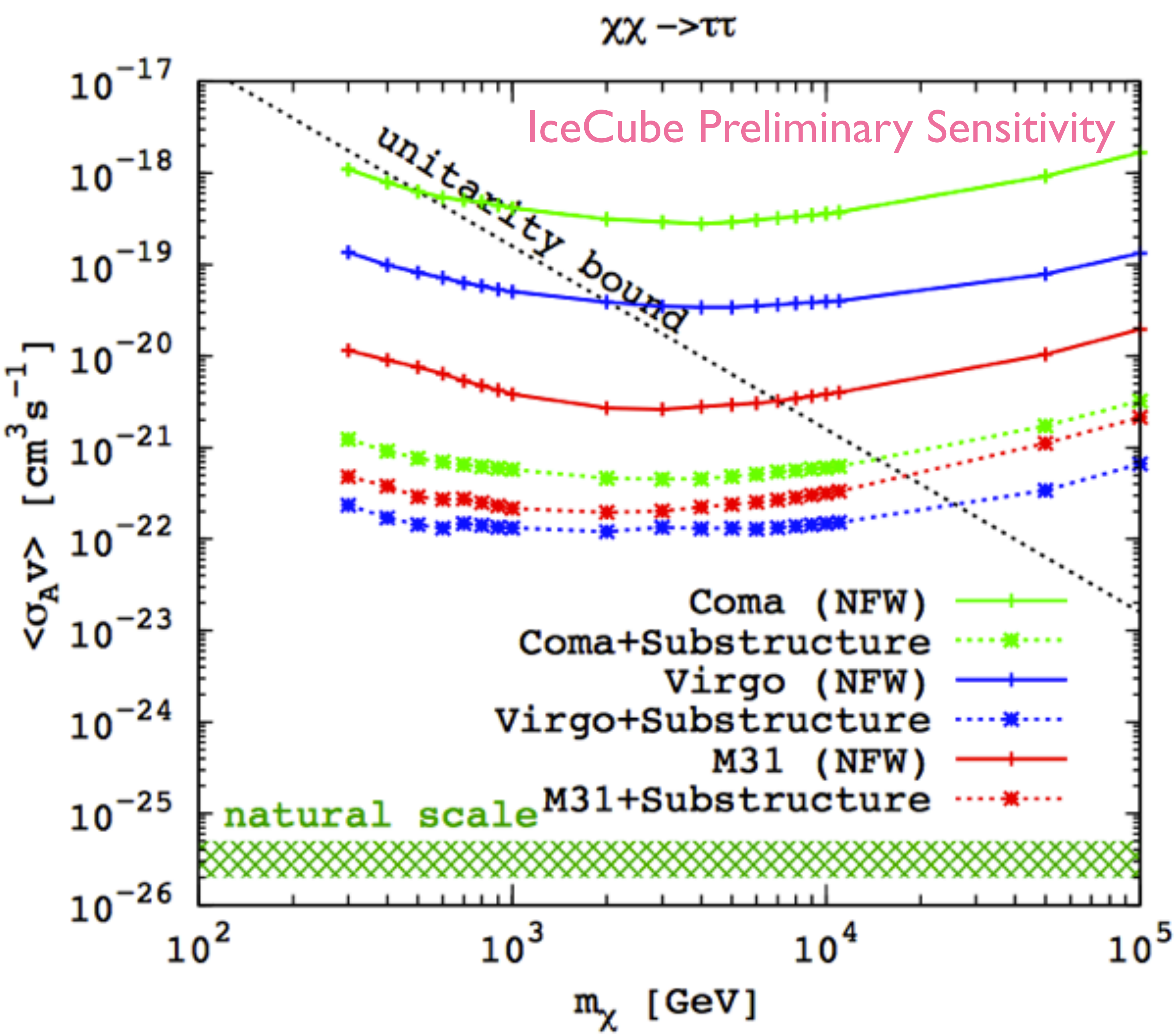


- Some of the most dark matter dominated objects in the Universe
- Roughly two dozen known dwarf spheroidal satellite galaxies in the Milky Way
- No astrophysical gamma-ray production expected
- Boost factor expected to be less than 10 [J.Diemand, et al., Nature 454,735 (2008) / V. Springel et al., Mon. Not. R. Astron. Soc., 391, 1685 (2008), ...]



see:
75-3 M. Bissok and J. Luenemann "Search for Dark Matter in Galactic and Extragalactic Halos with the IceCube Neutrino Observatory"

Individual Sources: Clusters of Galaxies



Clusters of Galaxies have potentially significant substructure in their halos that could boost signals by 10^3

Sensitivity for IceCube 1yr data in 59-string configuration

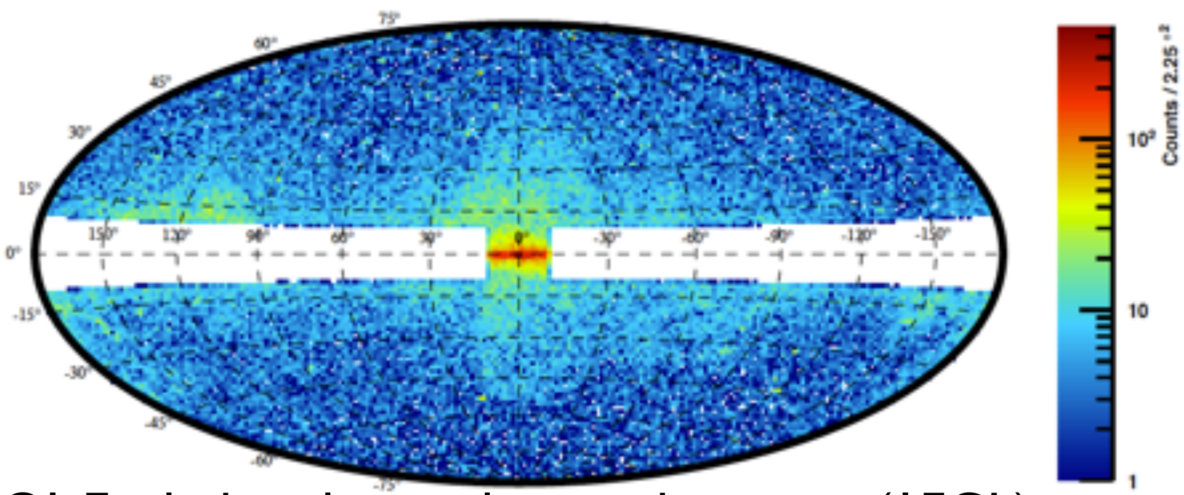
Upgoing events selected via Boosted Decision Tree (BDT)

see:

75-3 M. Bissok and J. Luenemann "Search for Dark Matter in Galactic and Extragalactic Halos with the IceCube Neutrino Observatory"

Diffuse: Line Search

M. Ackermann [Fermi-LAT] arXiv:1205.2739v1



ROI: Exclude galactic plane and sources (1FGL)

Fermi-LAT analysis based on 2yrs of data

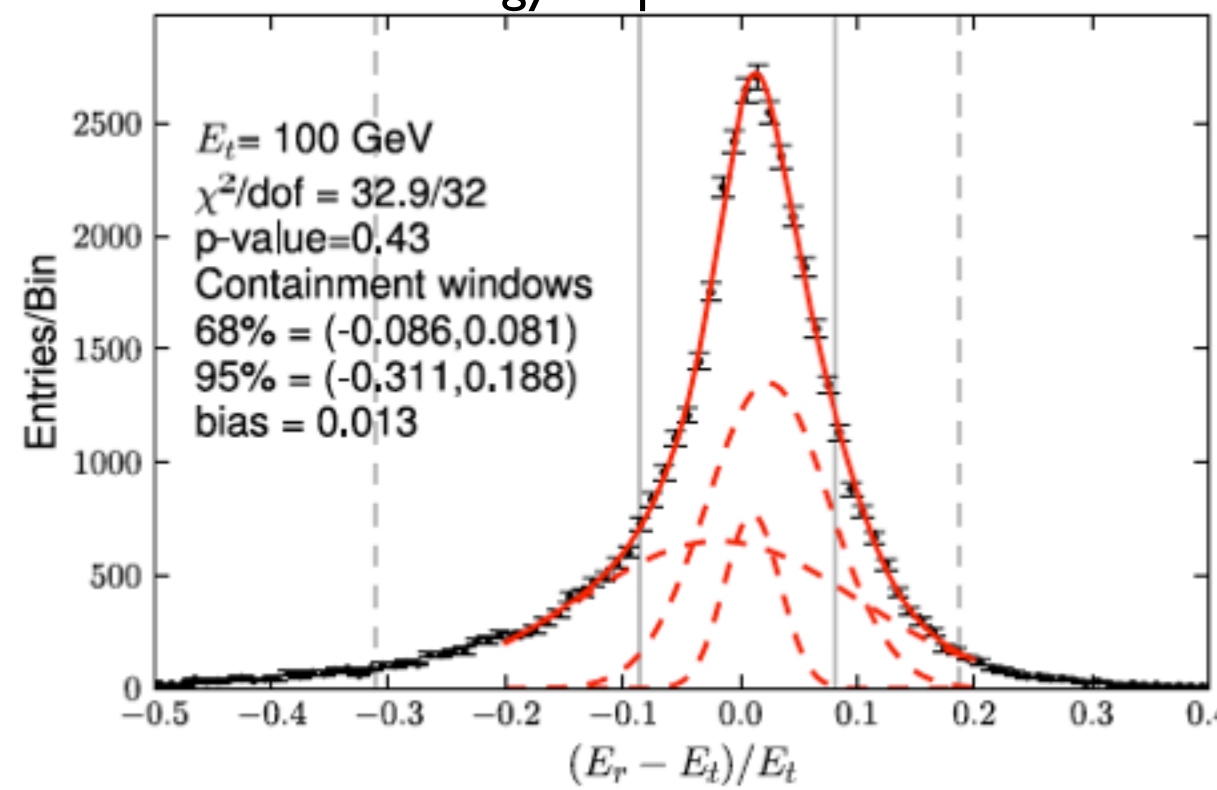
Search for line from dark matter annihilation or decay to γγ or Zγ

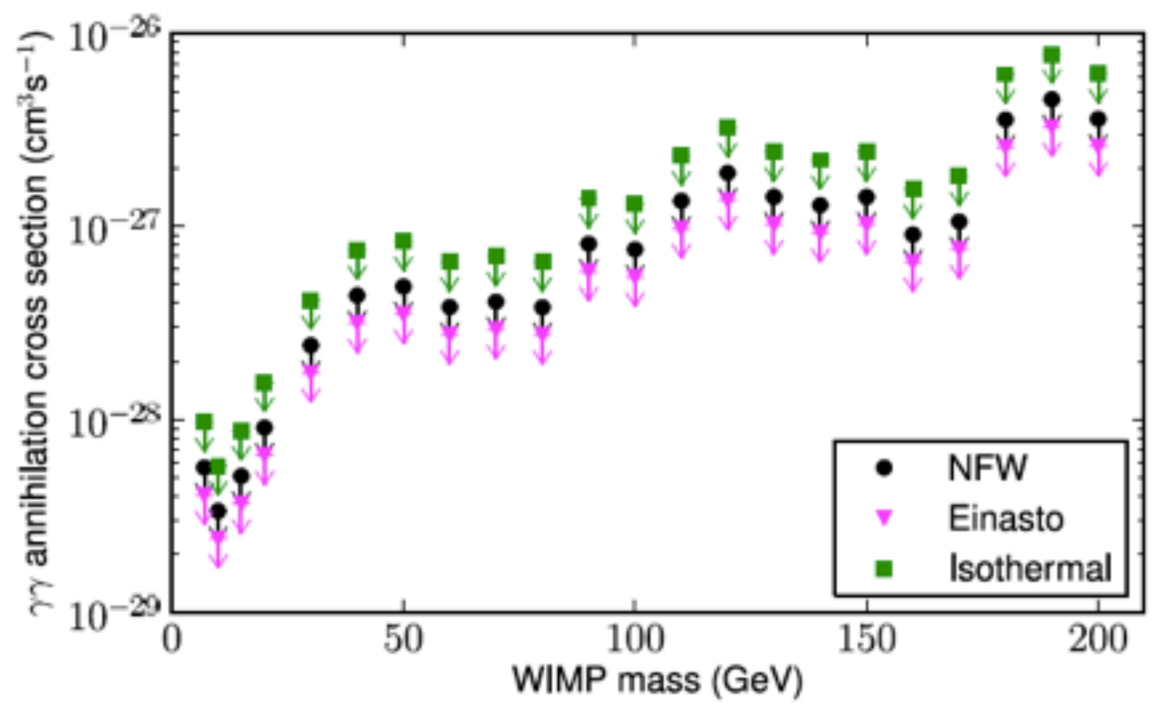
Assume power-law background (spectral index free to vary

Recent papers claim discovery of 130 GeV line ... stay tuned !

see also:
Vertongen & Weniger, JCAP1105(2011)027;
Bringmann et al., arXiv:1203.1312
Weniger, arXiv:1204.2797

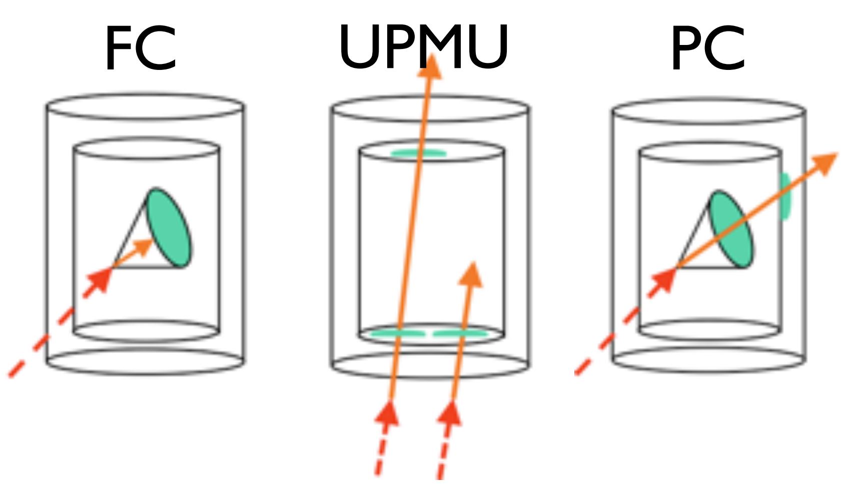
Fermi-LAT energy response to 100 GeV line

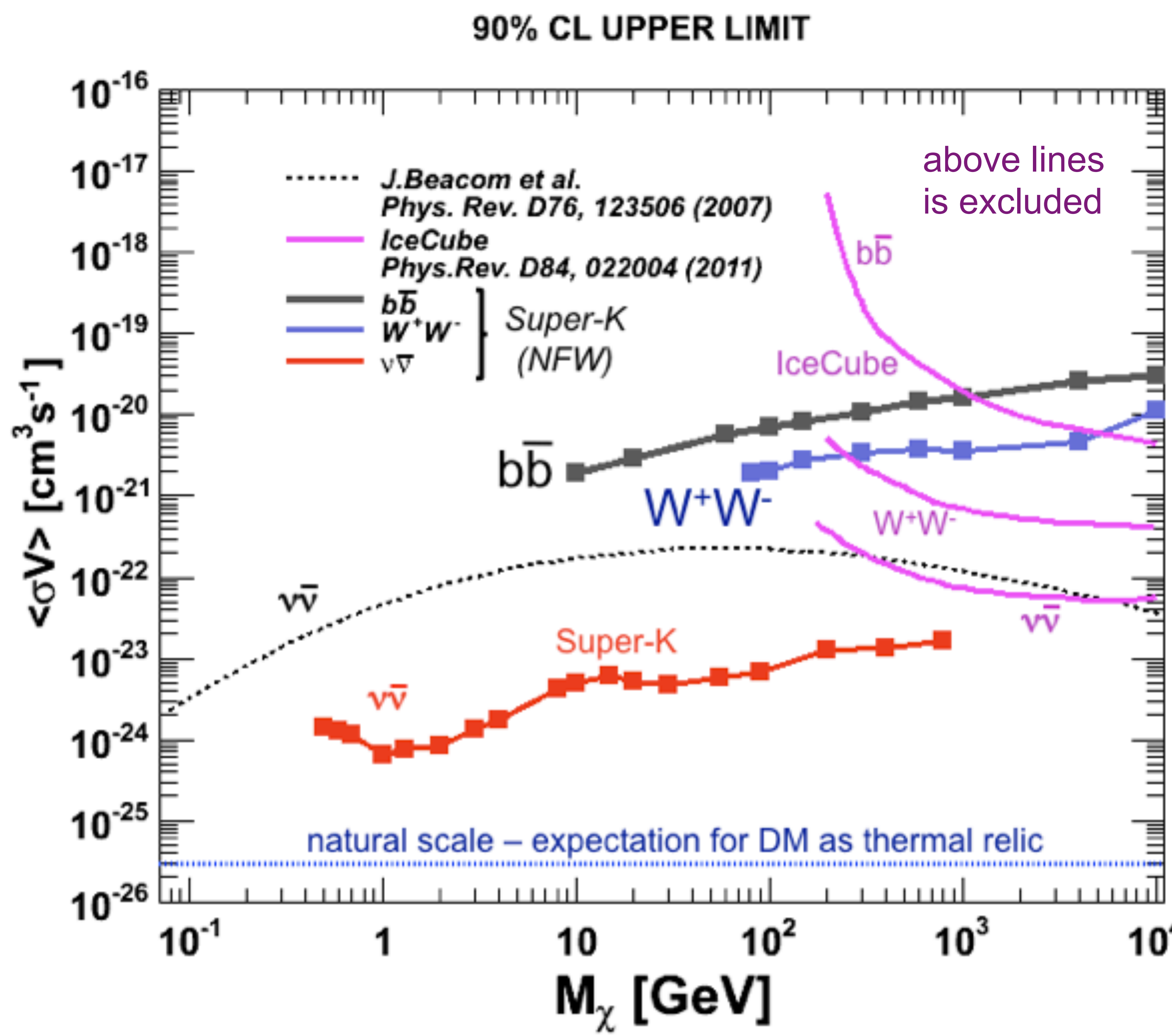




SuperK - Line Search

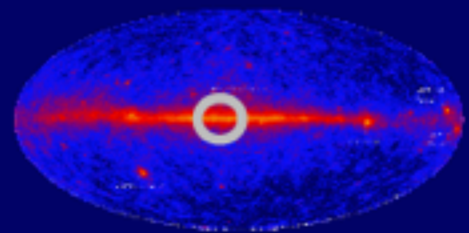
- Search for a diffuse signal from Milky Way halo
  - Assume annihilation into $\nu\nu$ (or bb, WW)
- Use all samples e-like + mu-like FC + PC (2806 days)+UPMU (3109 days)
- Use all neutrino flavors and topologies





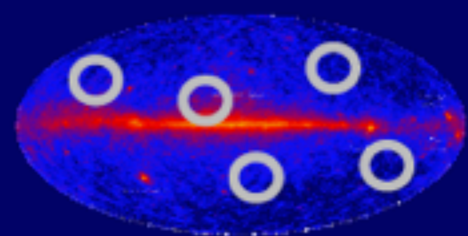
gamma-ray summary

Galactic Centre



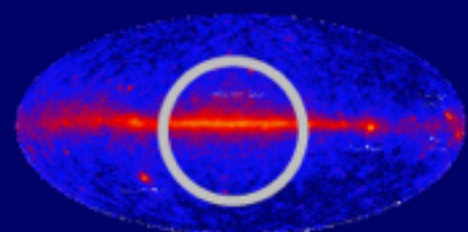
Fermi-LAT: TeVPA 2009, arXiv:0912.3828
Fermi: Goodenough & Hooper, arXiv:0910.2998
Fermi: Dobler et al., arXiv:0910.4583 (Fermi- data)

Dwarf galaxies and Galaxy Clusters



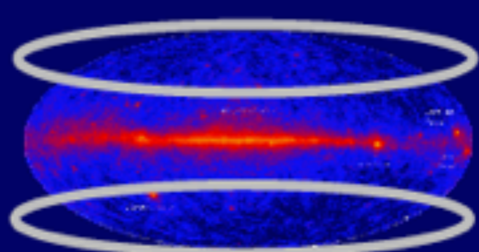
Fermi-LAT: Astrophys.J.712:147-158,2010
Fermi-LAT: JCAP 1005:025,2010
Fermi: Scott, J.C. et al.: JCAP 1001:031,2010
H.E.S.S.: Astropart.Phys. 34 (2011) 608-616
MAGIC: Astrophys.J. 697 (2009) 1299-1304
VERITAS: Astrophys.J. 720 (2010) 1174-1180

Galactic Halo



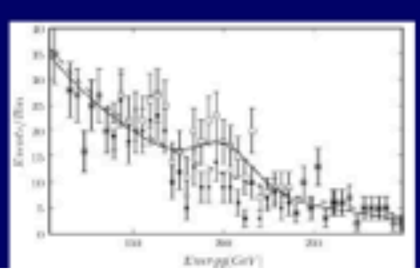
Fermi: Cirelli et. al. arXIv: 0912.0663
H.E.S.S. Phys.Rev.Lett. 106 (2011) 161301

Extra Galactic



Fermi-LAT: JCAP 1004:014,2010
Fermi: Akorvazian et. al. arXiv:1002.3820
Fermi : Huetsi et. al. arXiv:1004.2036

Lines

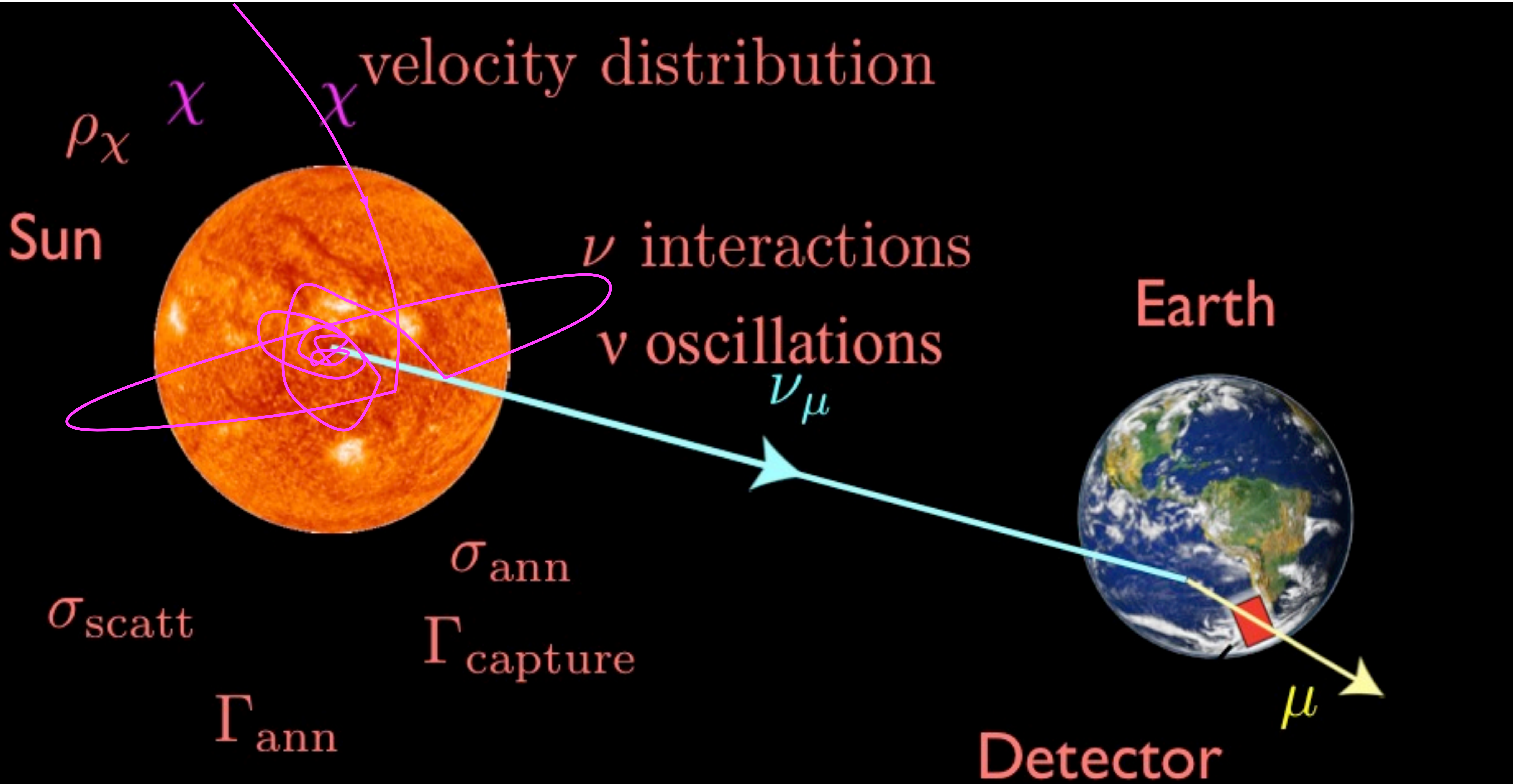


Fermi-LAT: Phys.Rev.Lett.104:091302,2010
Fermi: Vertongen et al. JCAP 1105 (2011) 027
Fermi: Weniger et. al arXiv, Bringmann et al.

J.Conrad

Solar WIMPs

Solar WIMPs

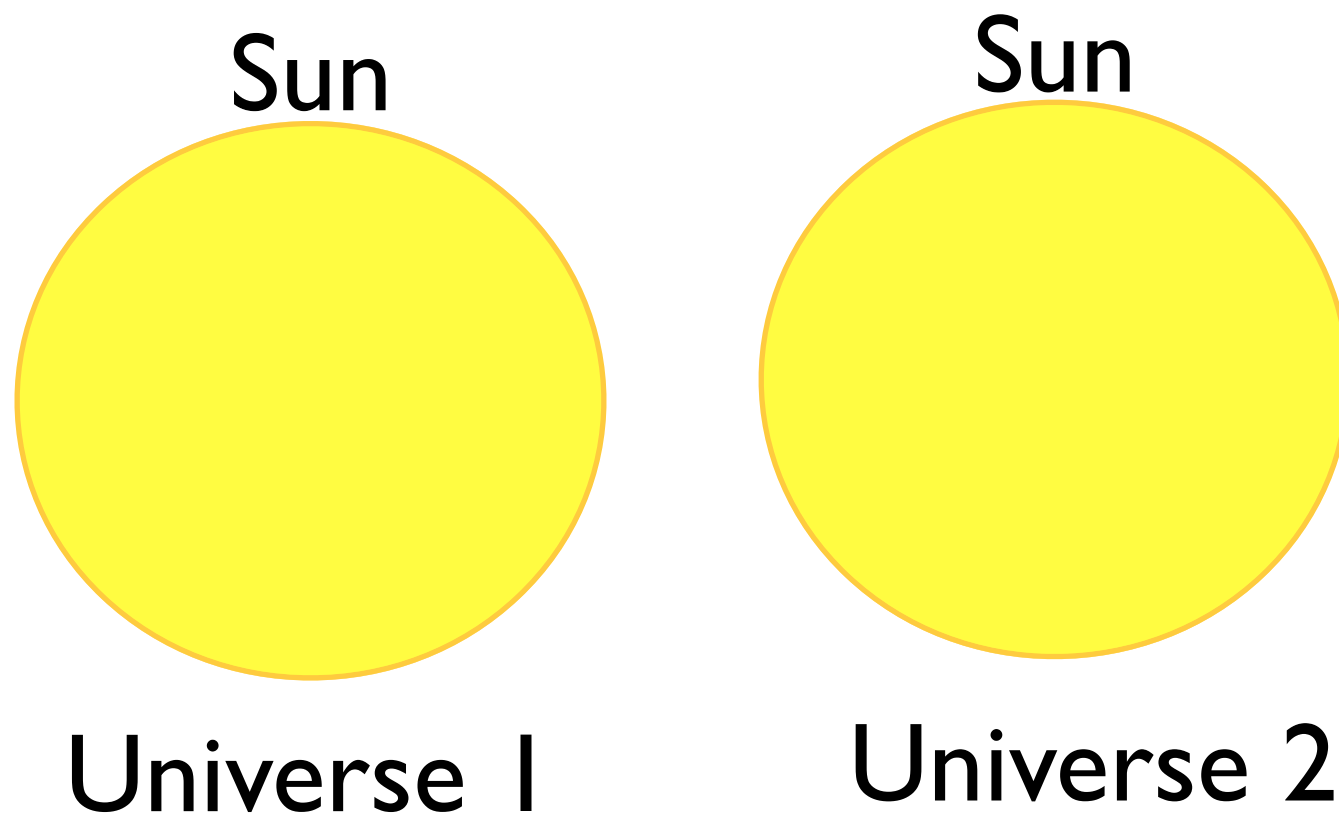


Freese '86
Krauss, Srednicki & Wilczek '86
Gaisser, Steigman & Tilav '86

Silk, Olive and Srednicki '85
Gaisser, Steigman & Tilav '86

Solar WIMP Equilibrium

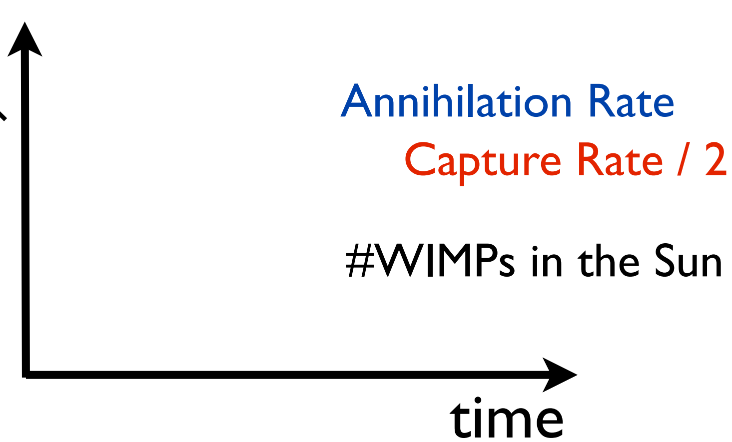
- Dark Matter accumulates and starts annihilating → Neutrinos are the only particles that can make it out
- At equilibrium ($\Gamma_A = 1/2\,\Gamma_C$) the neutrino flux does not depend on the self annihilation cross section !

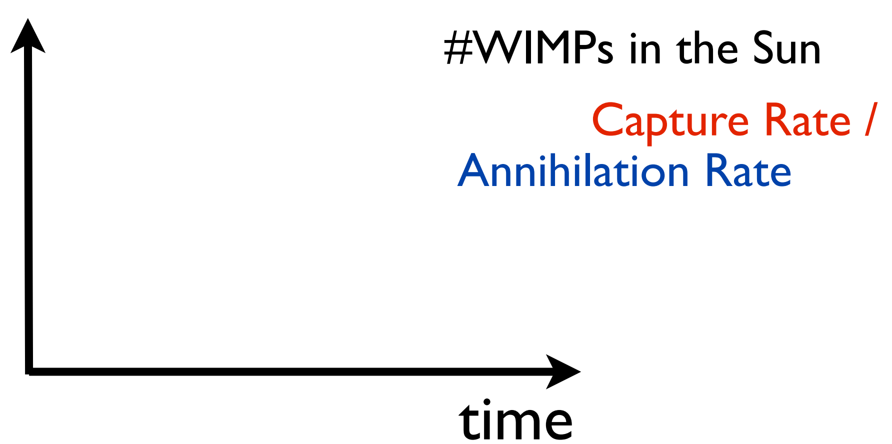


	Universe 1	Universe 2
Self-annihilation cross section:	**large**	**small**
WIMP-Nucleon scattering:	same in both (⇒capture rates are identical)	

N = #WIMPs; Capture Rate (Γ_C); Annihilation Rate (Γ_A); Evaporation

$$\frac{dN}{dt} = C_C - C_A N^2 - C_E N$$



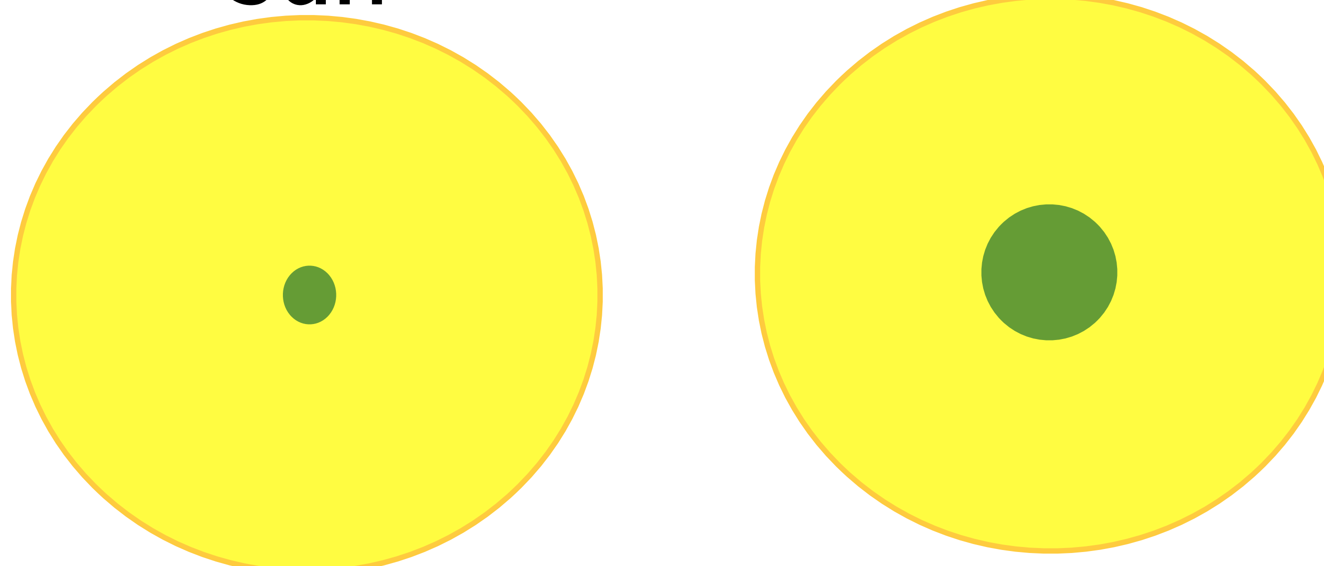


Solar WIMP Equilibrium

- Dark Matter accumulates and starts annihilating → Neutrinos are the only particles that can make it out
- At equilibrium (Γ_A=1/2Γ_C) the neutrino flux does not depend on the self annihilation cross section !

Sun

Sun



Universe 1

Universe 2

	Universe 1	Universe 2
Self-annihilation cross section:	**large**	**small**
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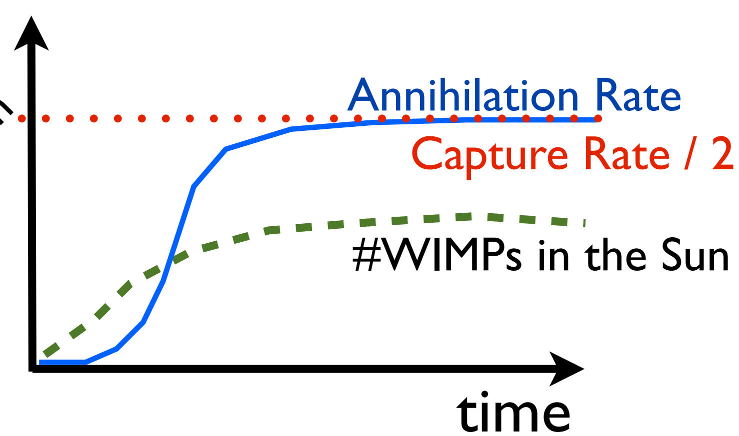
N = #WIMPs

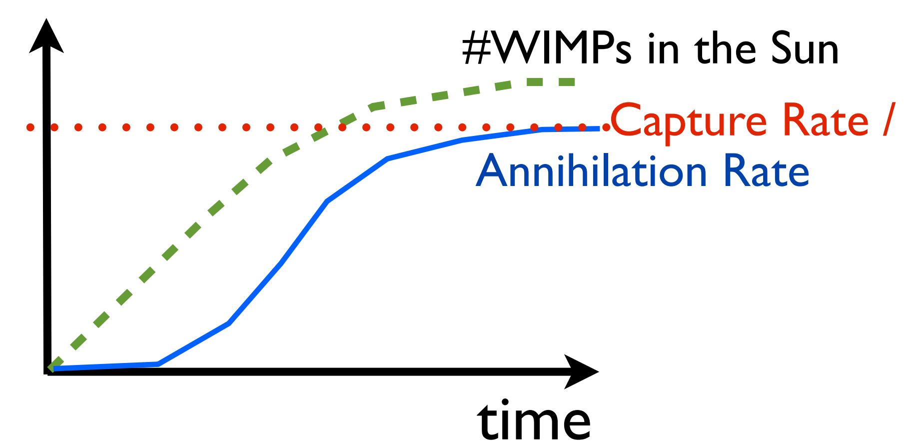
Capture Rate (Γ_C)

Annihilation Rate (Γ_A)

Evaporation

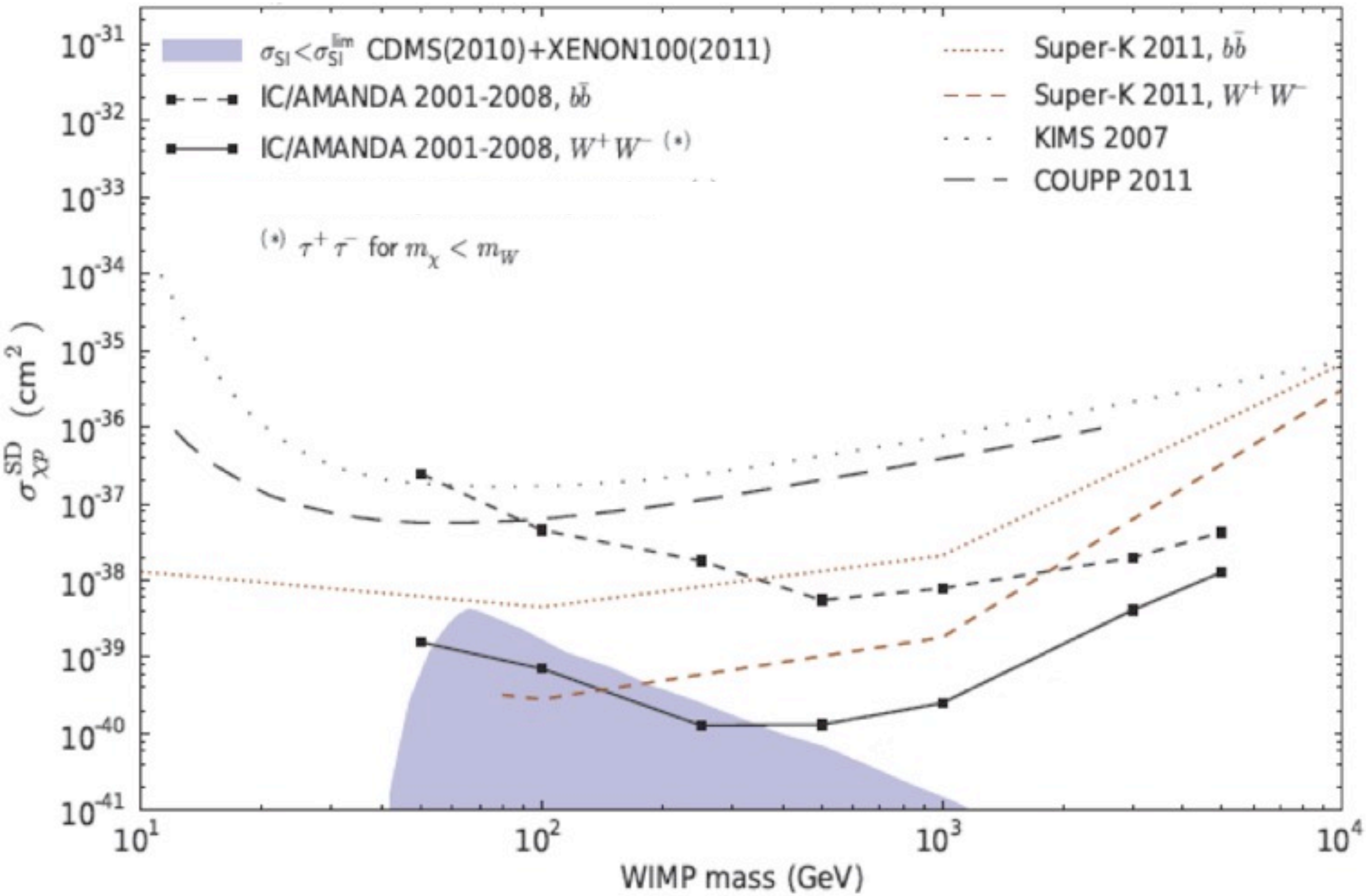
$$\frac{dN}{dt} = C_C - C_A N^2 - C_E N$$





LIMIT on the WIMP-Nucleon scattering cross section

T. Tanaka et al. Astrophys. J. 742, 78 (2011)
R. Abbasi et al. Phys. Rev. D 85, 042002 (2012)



New Preliminary SuperK 2012 Result

T. Tanaka et al. Astrophys. J. 742, 78 (2011)
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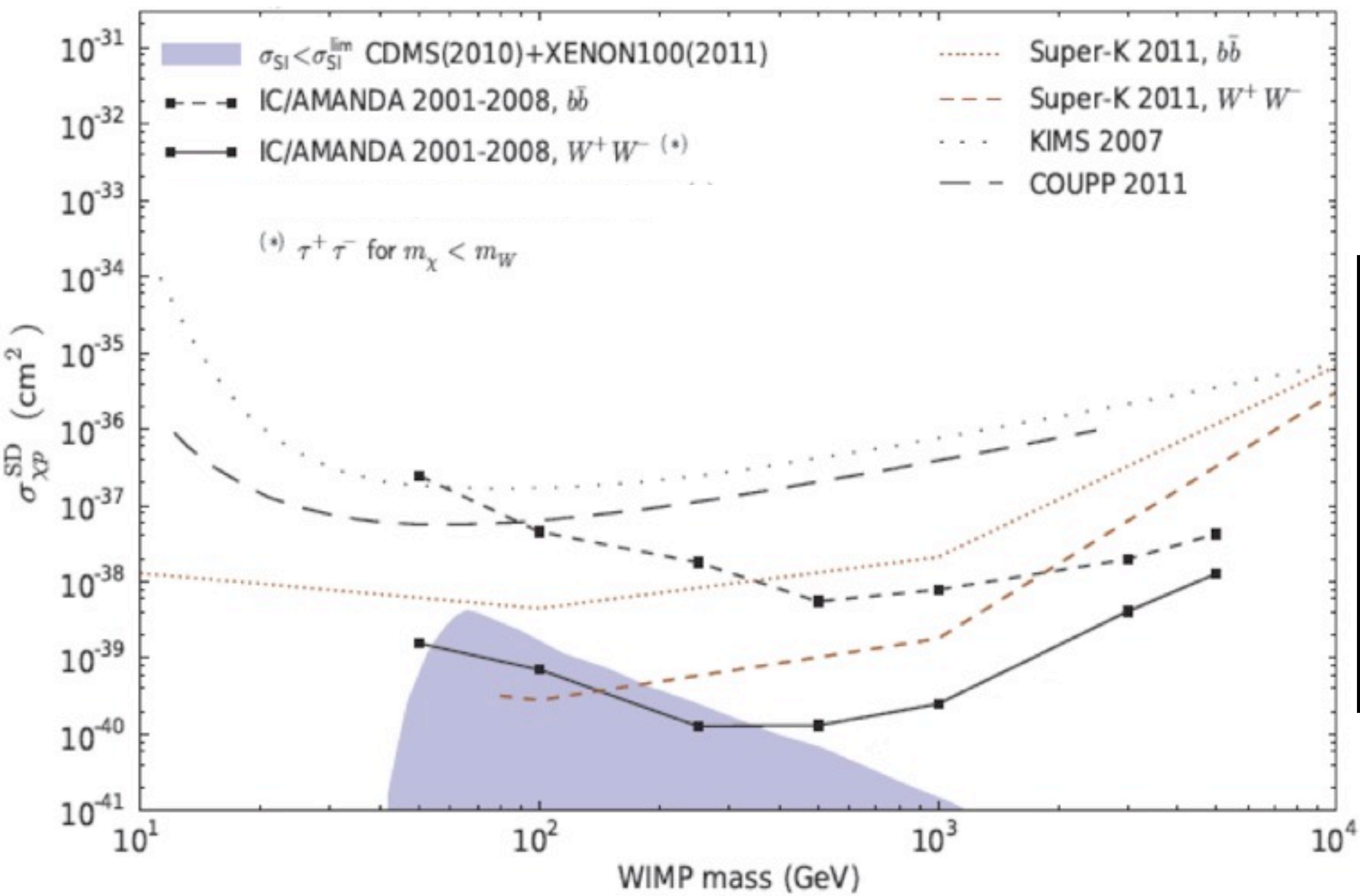
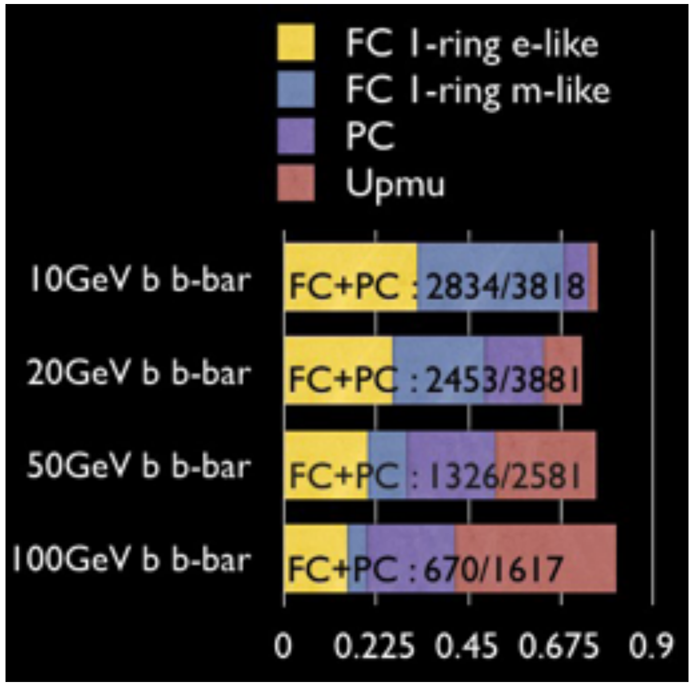


Data from SKI-III (2806days)



Energy / Angular Fit Derive 90% Bayesian upper limit on allowed WIMP induced events

see:
69-3 K.Choi "Search of the WIMP from the Sun in Super-Kamiokande"

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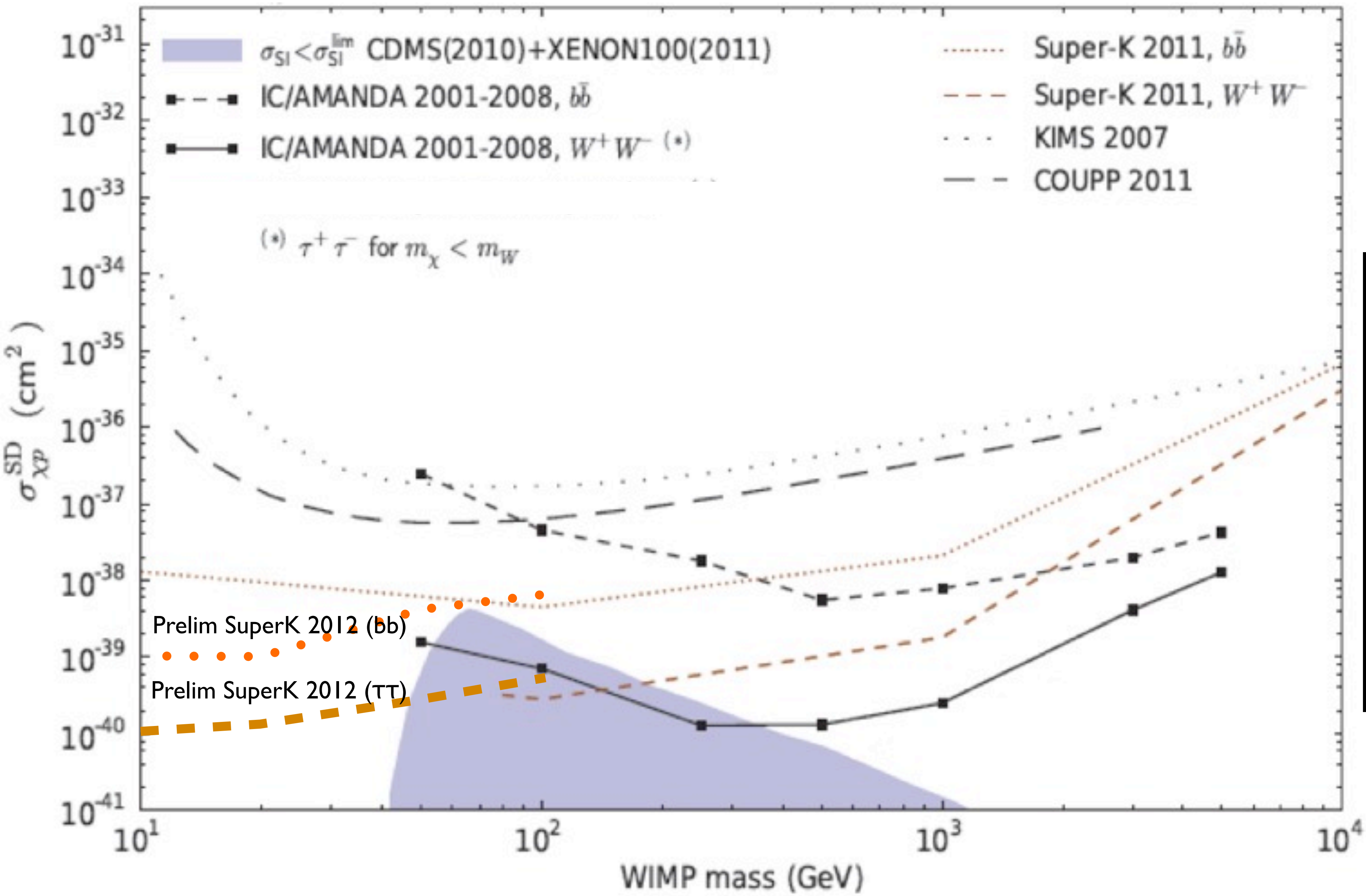

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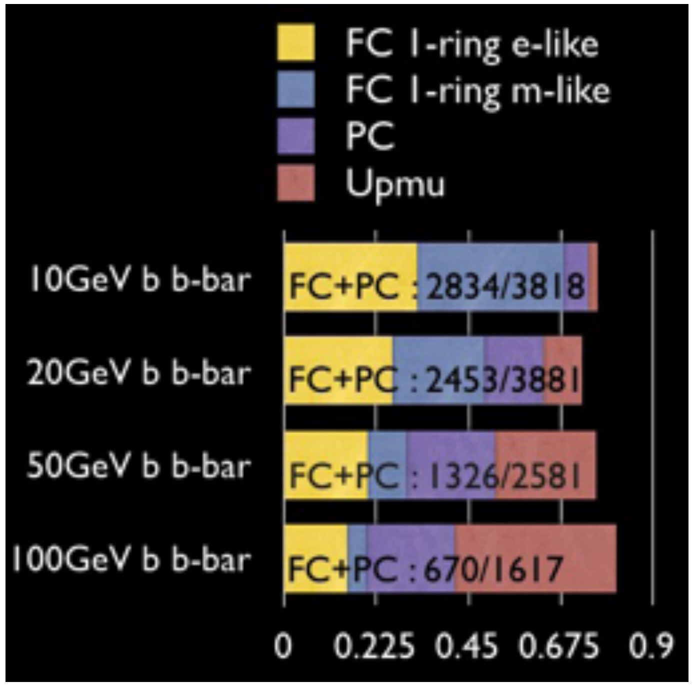

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Derive 90% Bayesian upper limit on allowed WIMP induced events

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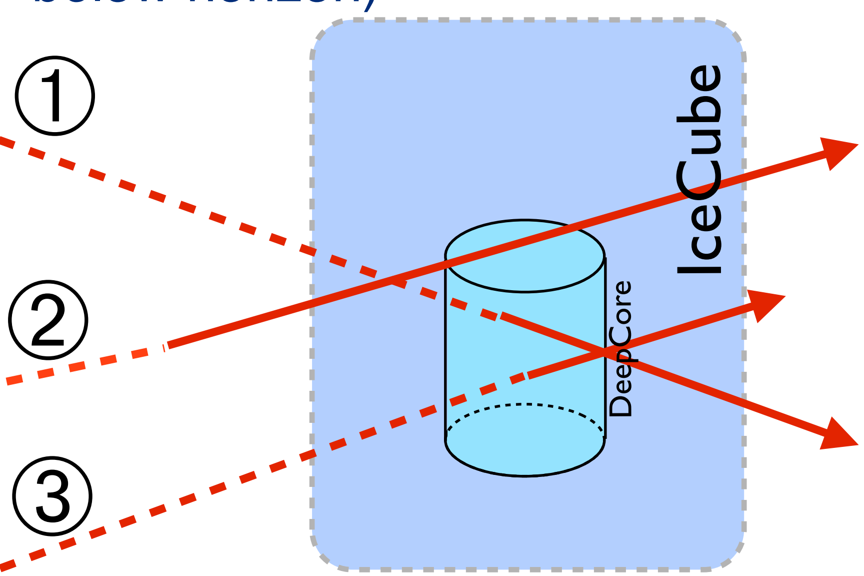
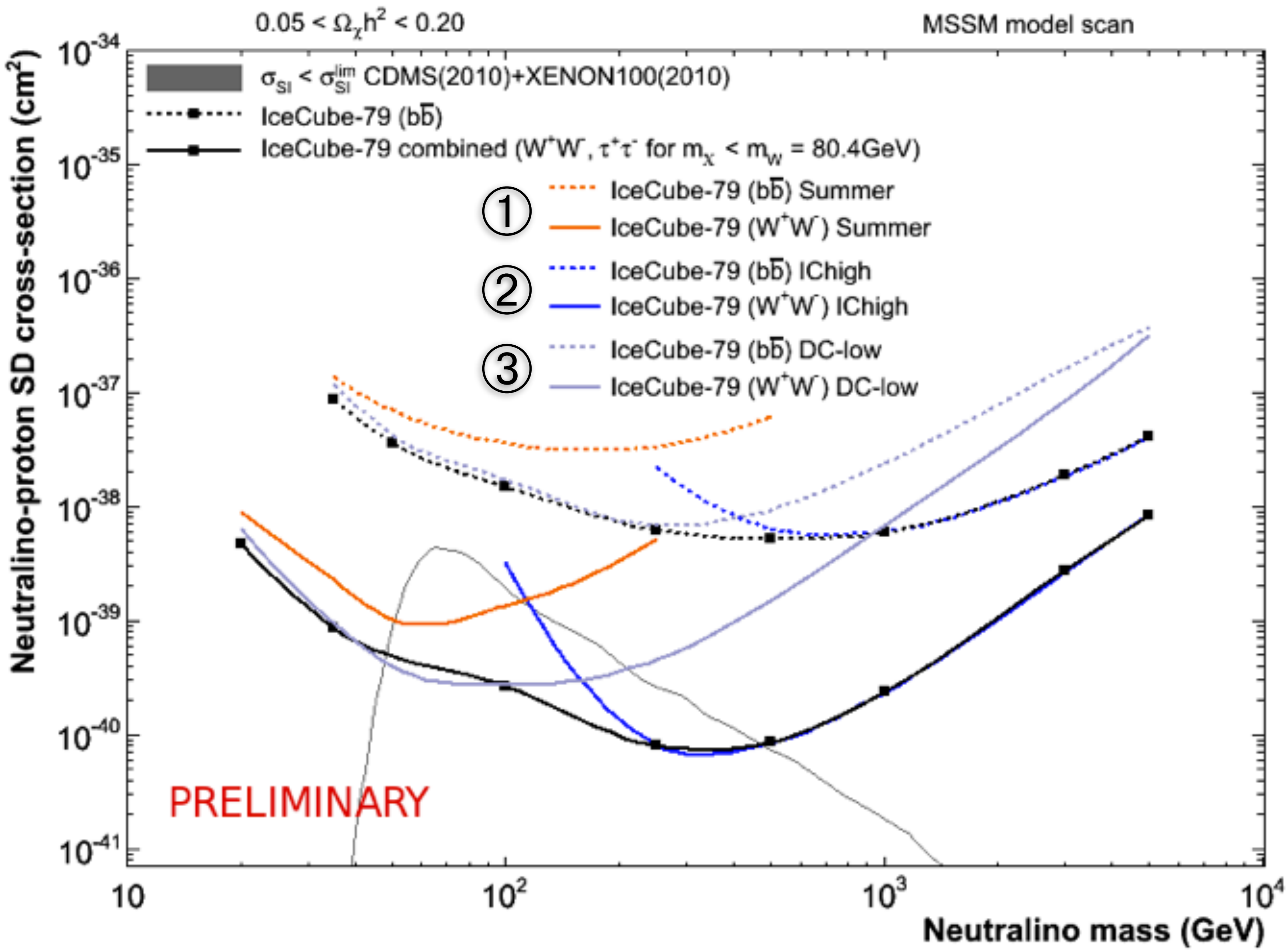
New DeepCore Solar WIMP Sensitivity

IceCube 79-string 318days (May 2010 - May 2011)

Analysis performed separately for austral summer (Sun above horizon) and austral winter (Sun below horizon)



Compare distribution of the final sample to these PDFs of background and signal to determine most likely signal content and combine likelihoods, weighted by relative livetime



$$\mathcal{L}(\mu) = \prod_{i}^{n_{obs}} f(\Psi_i|\mu), \quad \text{where} \quad f(\Psi|\mu) = \frac{\mu}{n_{obs}} f_s(\Psi) + (1 - \frac{\mu}{n_{obs}}) f_{bg}(\Psi)$$

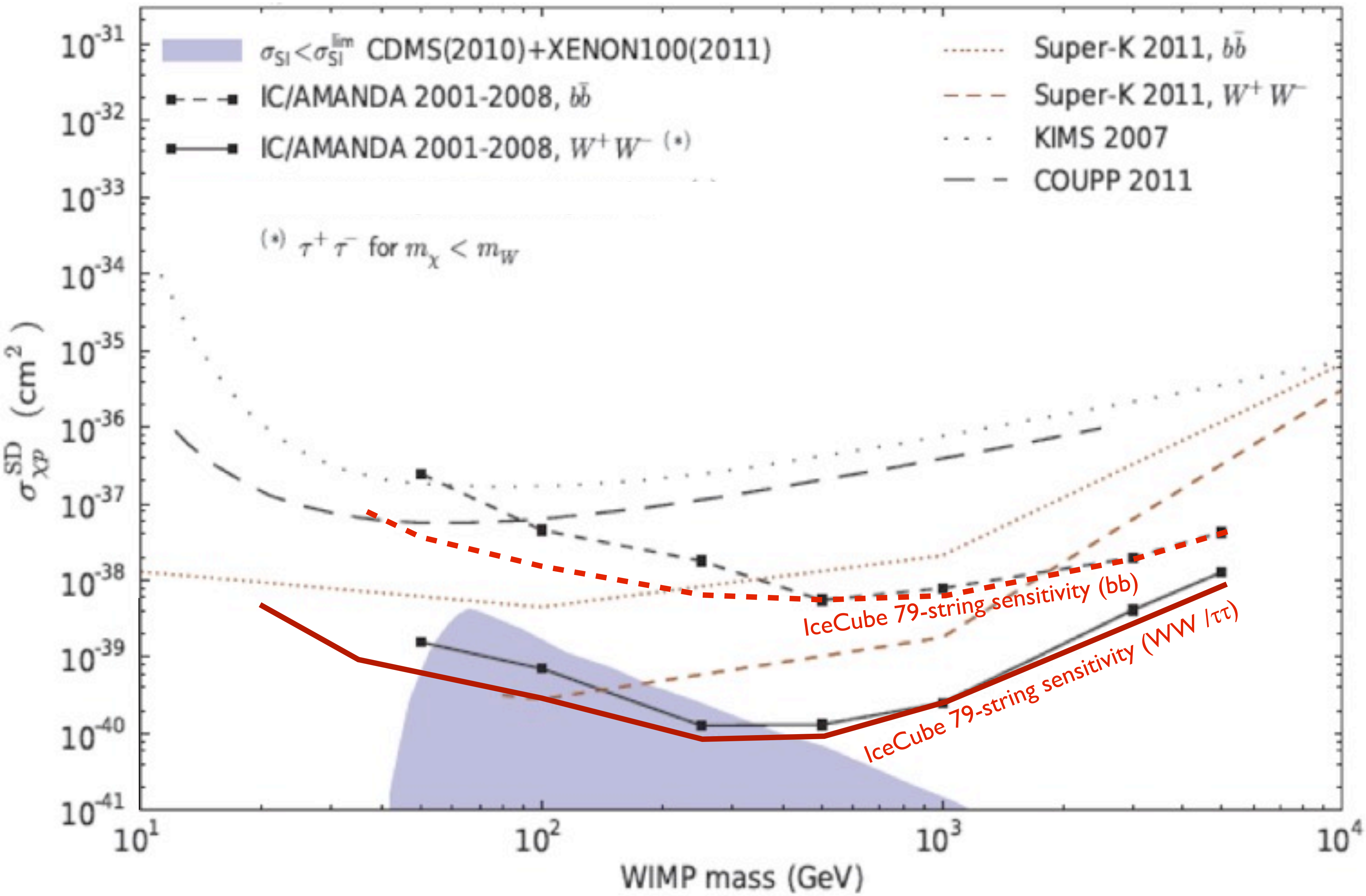
see also:

74-2 M. Danninger, C. Rott and E. Strahler "Search for Dark Matter Captured in the Sun with the IceCube Neutrino Observatory"

76-1 J.Miller "Search for Secluded Dark Matter using the IceCube Neutrino Observatory"

New DeepCore Sensitivity

T. Tanaka et al. Astrophys. J. 742, 78 (2011)
R. Abbasi et al. Phys. Rev. D 85, 042002 (2012)



1 year of IceCube 79-string as sensitive as 7years of AMANDA + partially instrumented IceCube

Sensitivity extends to WIMP masses down to 20GeV

Full analysis results to be released soon ... stay tuned !

see:
74-2 M. Danninger, C. Rott and E. Strahler "Search for Dark Matter Captured in the Sun with the IceCube Neutrino Observatory"

New DeepCore Sensitivity

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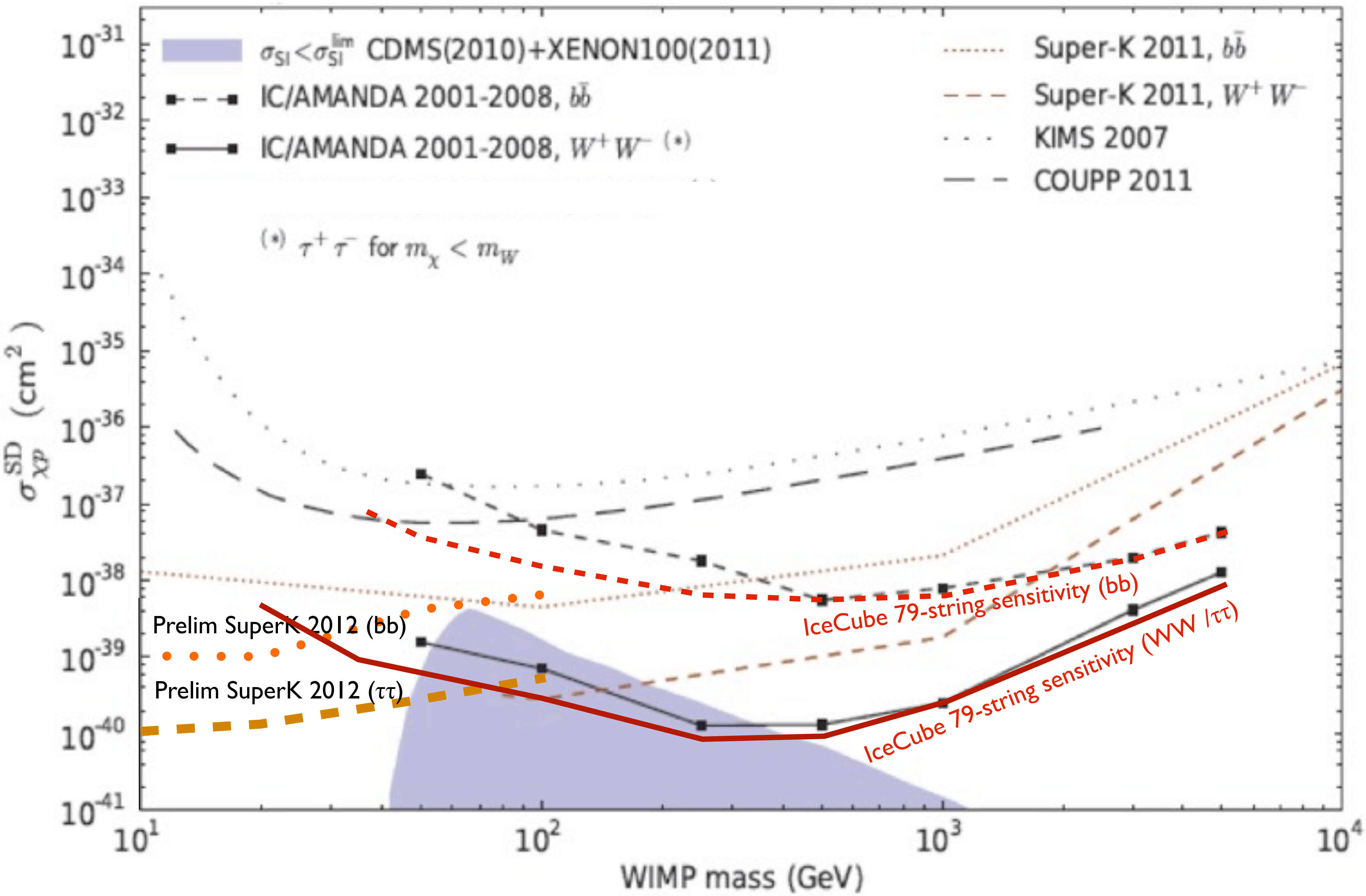

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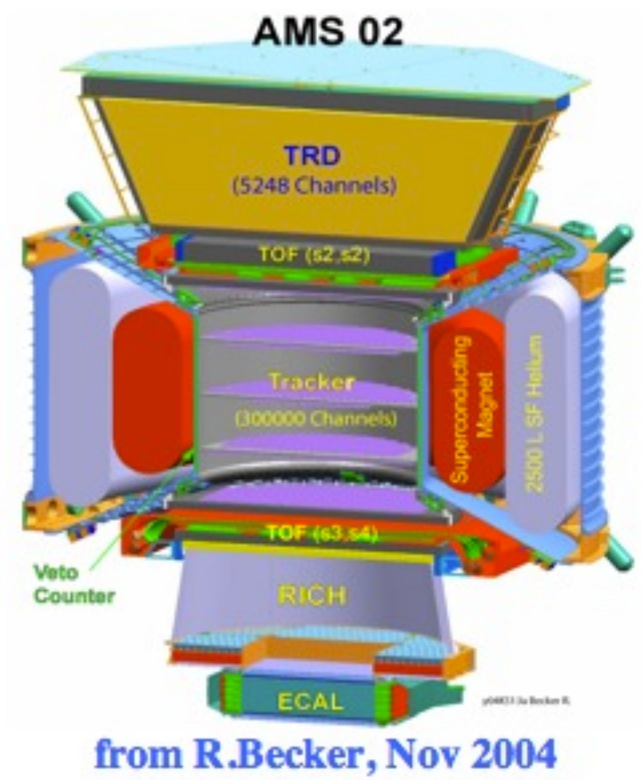
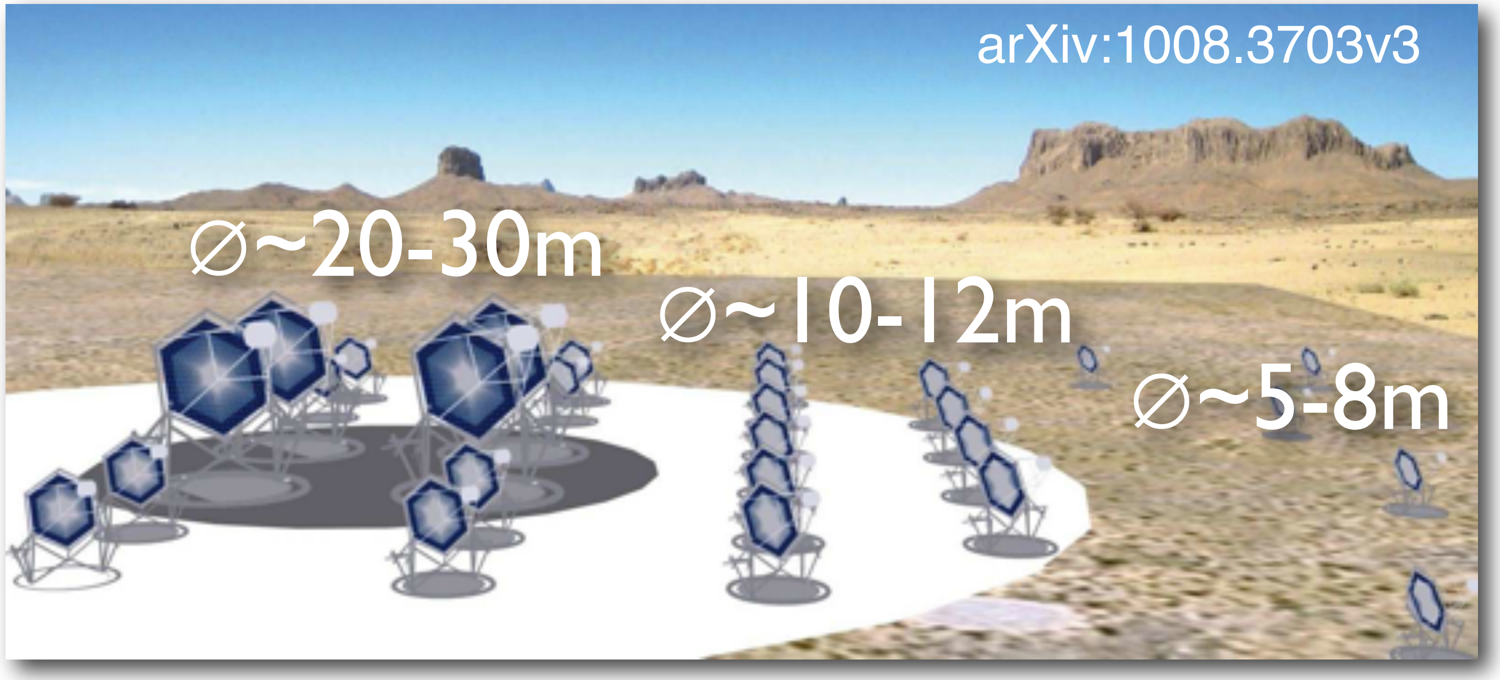
Future Prospects

Cosmic rays and gamma rays



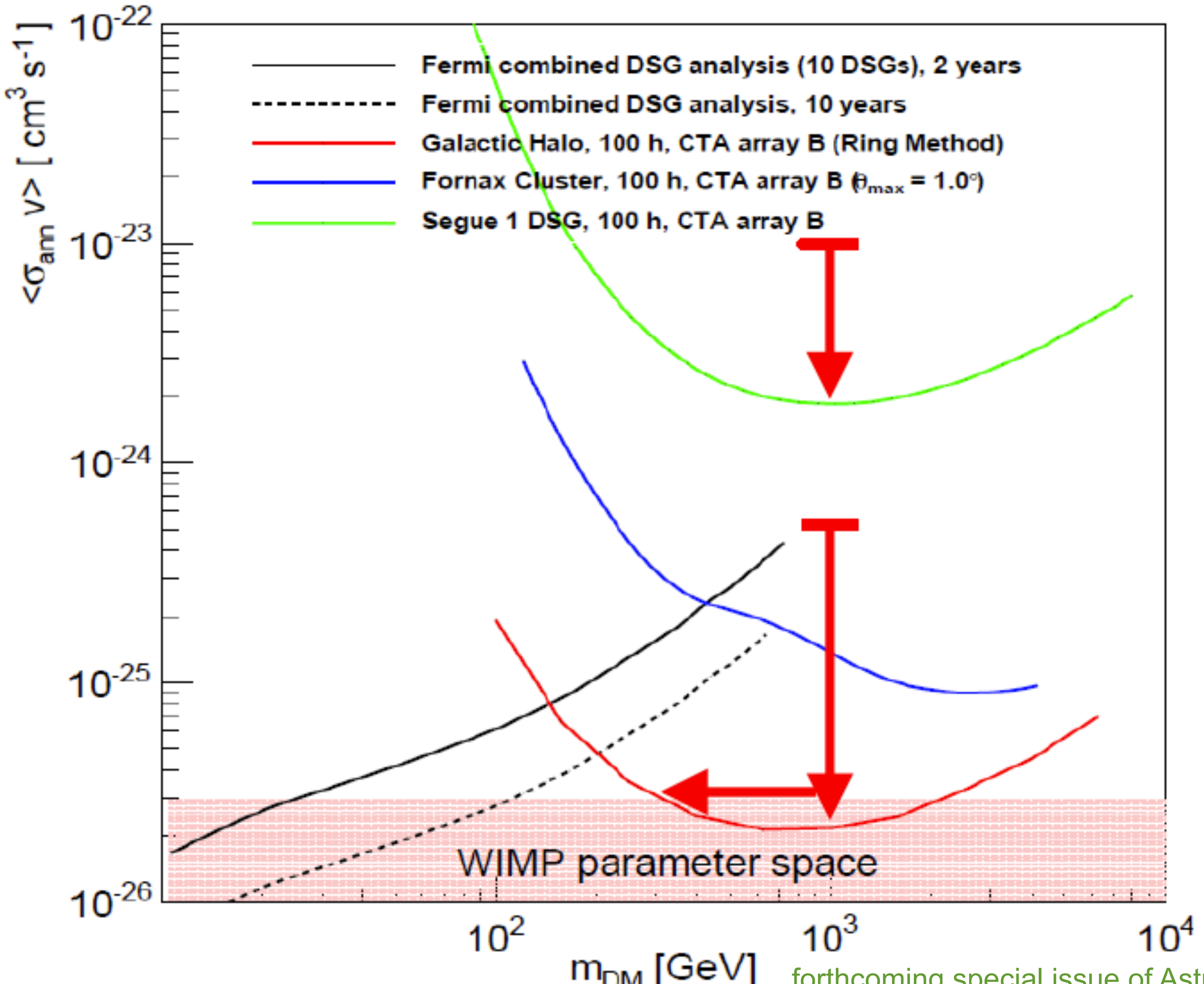
Cherenkov Telescope Array (CTA)



- Alpha Magnetic Spectrometer (AMS-02)
- Launched on May 16, 2011
- Consists of: TRD, TOF, RICH, Tracker, Veto Counters, ECAL, ...
- Resolve positron anomaly ?

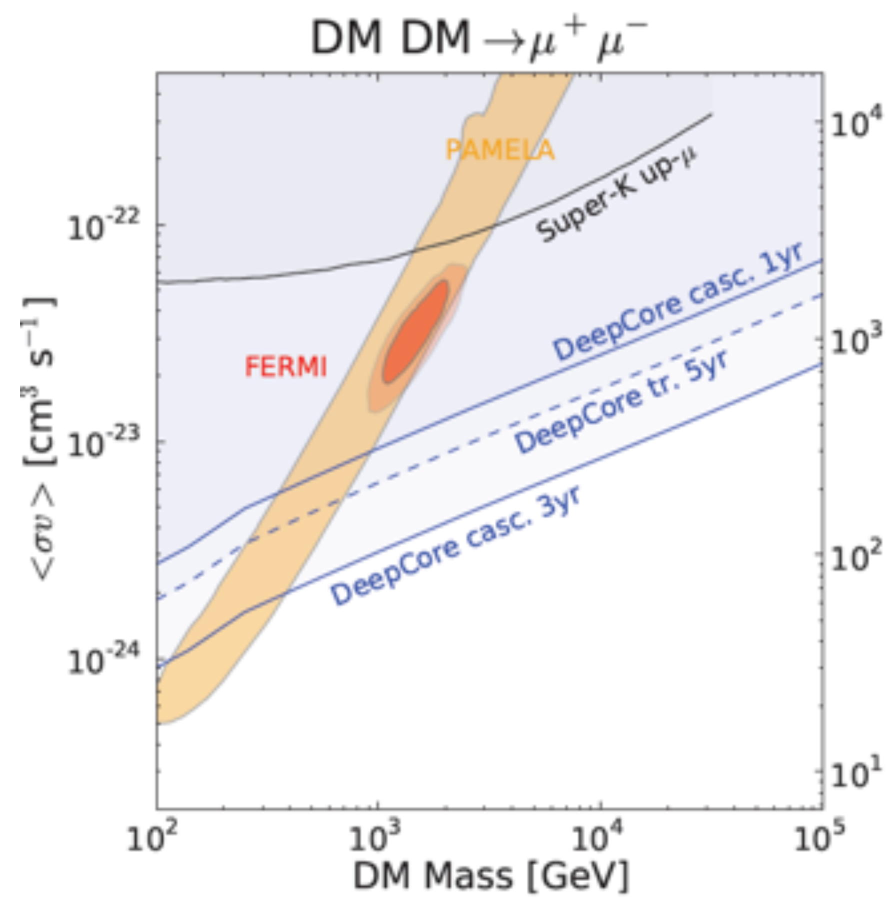
- Energy range: a few tens of GeV to above 100 TeV)
- Baseline design consists of three single-mirror telescopes: Small/Medium/Large size telescopes.
- improvement in flux sensitivity of 1-2 orders of magnitude over current instruments is expected

gamma-rays



forthcoming special issue of Astroparticle Physics

Neutrino Analyses



Mandal et al. PRD 81:043508 (2010)

- Already with existing detectors high mass WIMP scenarios and those motivated by anomalous lepton signals can be tested

Detectors

- Strong interest in the neutrino community to build one or more large neutrino detectors, based on proven or new technology.
- All these detectors have tremendous potential for dark matter detection and should be one of the primary design drivers

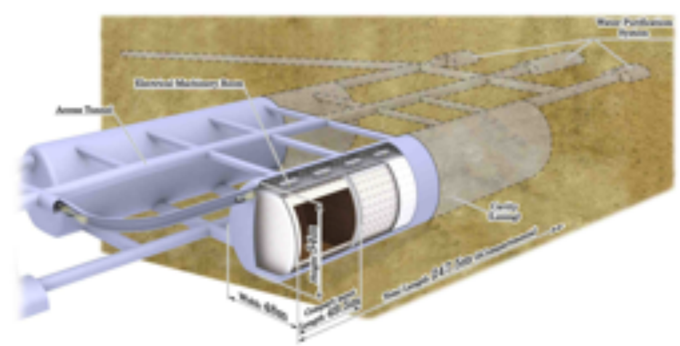
LAr TPC

see talk:
A. Rubbia

Scintillator

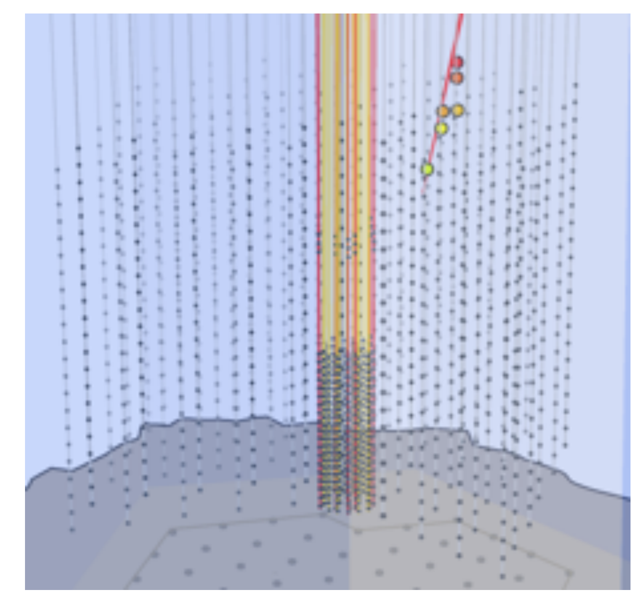
see talk:
L. Oberauer

Water Cherenkov



see talk:
M. Yokoyama

Ice Cherenkov

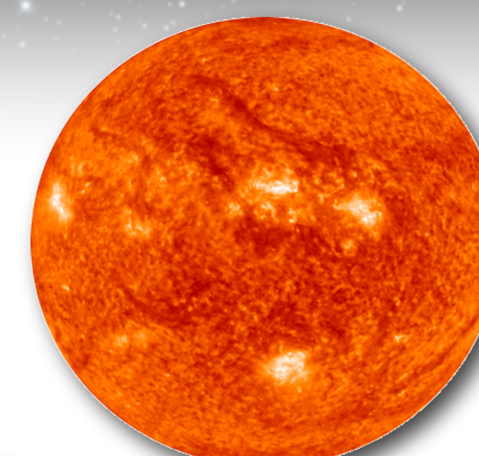


see talk:
A. Karle

see also:
204 - 3 Bair Shaybonov "Status of the BAIKAL-GVD project"
14 - 2 "Extending IceCube-DeepCore with PINGU" Darren R Grant
171 - 3 "Research and Development towards Multi-PMT Optical Module Prototypes for PINGU" Lew Classen, E.de Wolf, O. Kalekin, U. Katz, P. Kooijman

Importance of Neutrinos

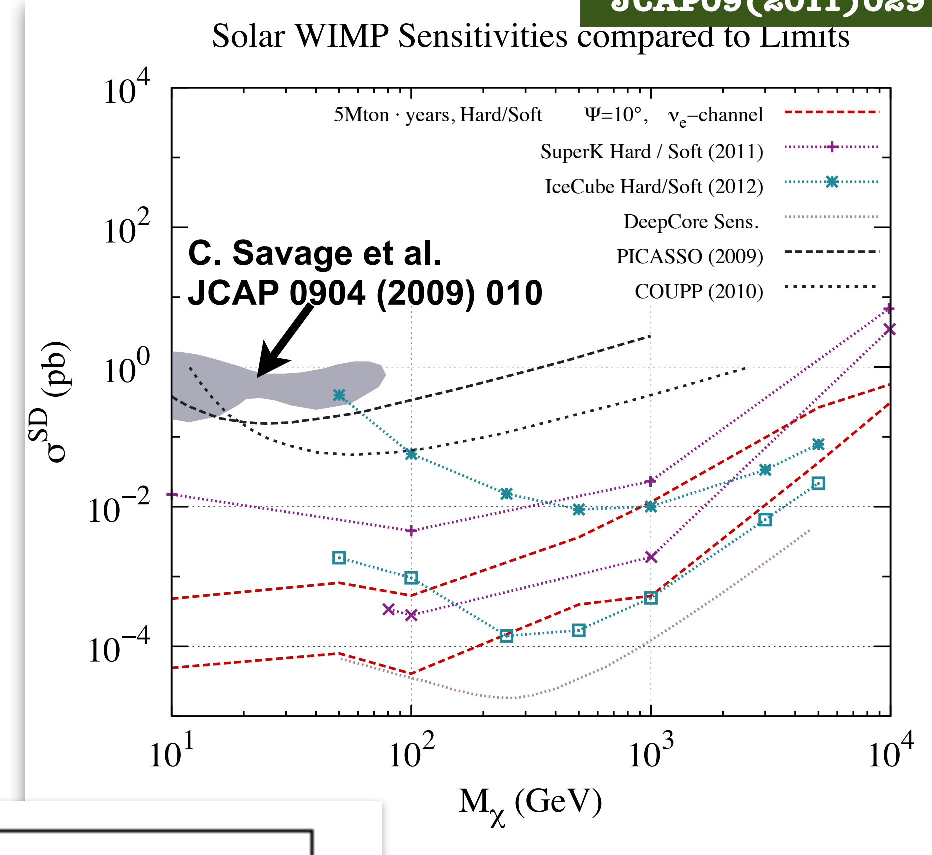
- **Galactic halo, Galactic center, Dwarf spheriodals, Cluster of Galaxies, ...**
  - Gamma-rays much more competitive for low WIMP masses, but any detection would likely require an independent confirmation of neutrino signals
  - high masses(>1TeV) - neutrinos are more competitive than gamma-rays !
  - Tau neutrinos nearly background free (flavor ID)
- **Dark Matter in the Sun**
  - Discovery channel for neutrinos
  - Due to significant neutrino absorption at high energies, Solar WIMP signals are detected in the energy range below 100GeV
- **Dark Matter in the Earth**
  - Capture mechanism highly favors low-mass (<50GeV) WIMPs,
  - Extremely large uncertainties for any flux prediction as for the Earth annihilation and capture rate are not expected to be in equilibrium

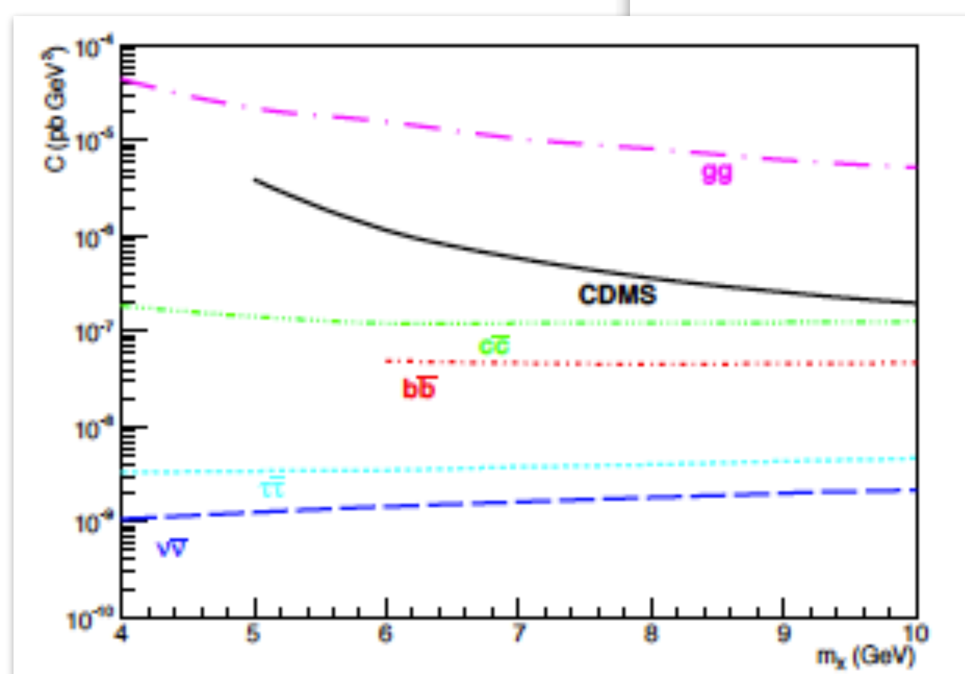


Low mass WIMP sensitivity

- Expanding searches to new neutrino flavors will significantly enhance the sensitivity to WIMPs in 10GeV range
- Benefit from better energy resolution
- Lower atmospheric neutrino background
- Despite limited angular resolution competitive sensitivities can be obtained
- Test of models motivated by anomalous annual modulation signals possible by Megaton scale detector with energy threshold ~1GeV

JCAP09(2011)029





Kumar, Learned, Smith, Richardson arXiv1204:5120

Assume dark matter capture via elastic contact interactions, elastic long-range interactions, or ineleastic contact interactions

Sensitivity shown for 5kton*years liquid scintillator detector (KamLAND) or equivalent to 2.5kton*years Liquid Argon detector

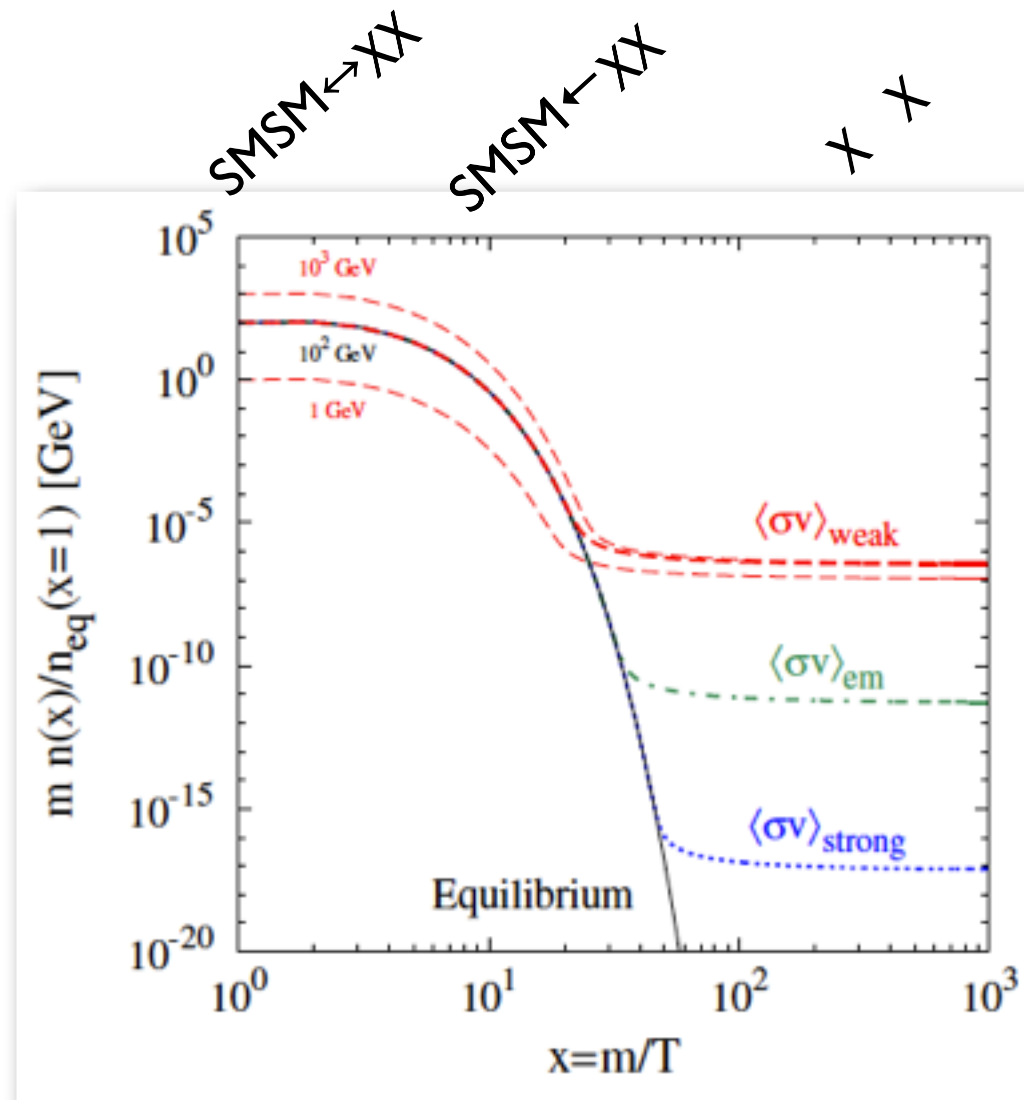
Conclusions

- Striking signatures provide high discovery potential for indirect searches
- Tight constraints from gamma-rays can exclude the WIMP paradigm for some branching fractions and WIMP masses
- SuperK and IceCube provide world best limits on SD WIMP-Proton scattering cross section
- Neutrinos extremely sensitive to test low-mass WIMP scenarios at current and future detectors

Backup

Thermal Relic

- If dark matter is a WIMP that is a thermal relic of the early Universe, then its total self-annihilation cross section is revealed by its present-day mass density
- Cosmological measurements: ~80% of non-relativistic matter are non-luminous particles
- Interactions that determine the WIMP relic abundance also lead to self-annihilations in the present epoch
- Assume WIMPs are sufficiently coupled to other particles in the early Universe so that they are produced by the relativistic plasma. We can establish a common temperature T ($\equiv T_\gamma$)
  - Evolution is determined by the competition between production and annihilation



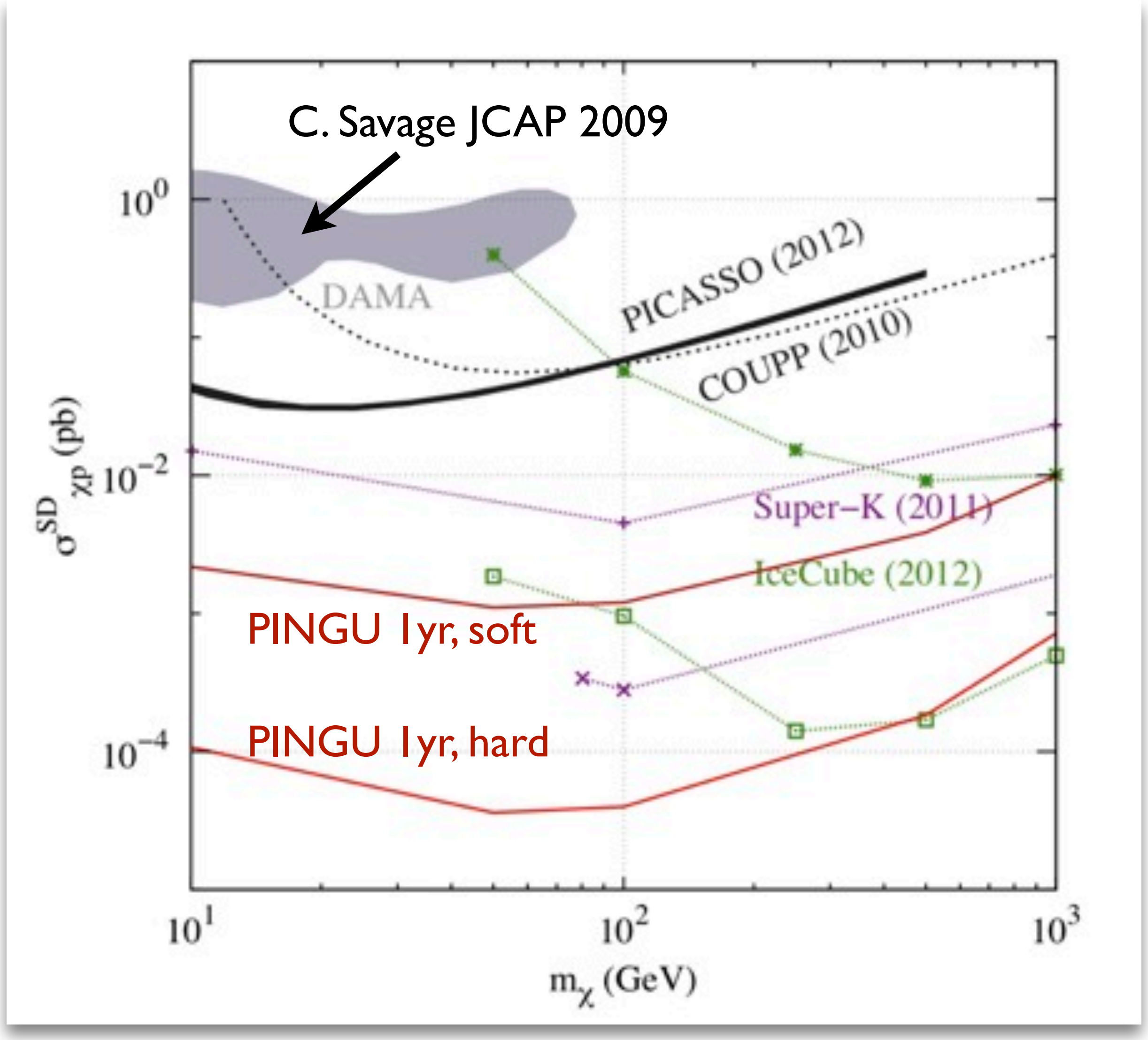
$m_\chi \approx 1\text{GeV} \Rightarrow \sim 4.5 \cdot 10^{-26}\ cm^3 s^{-1}$

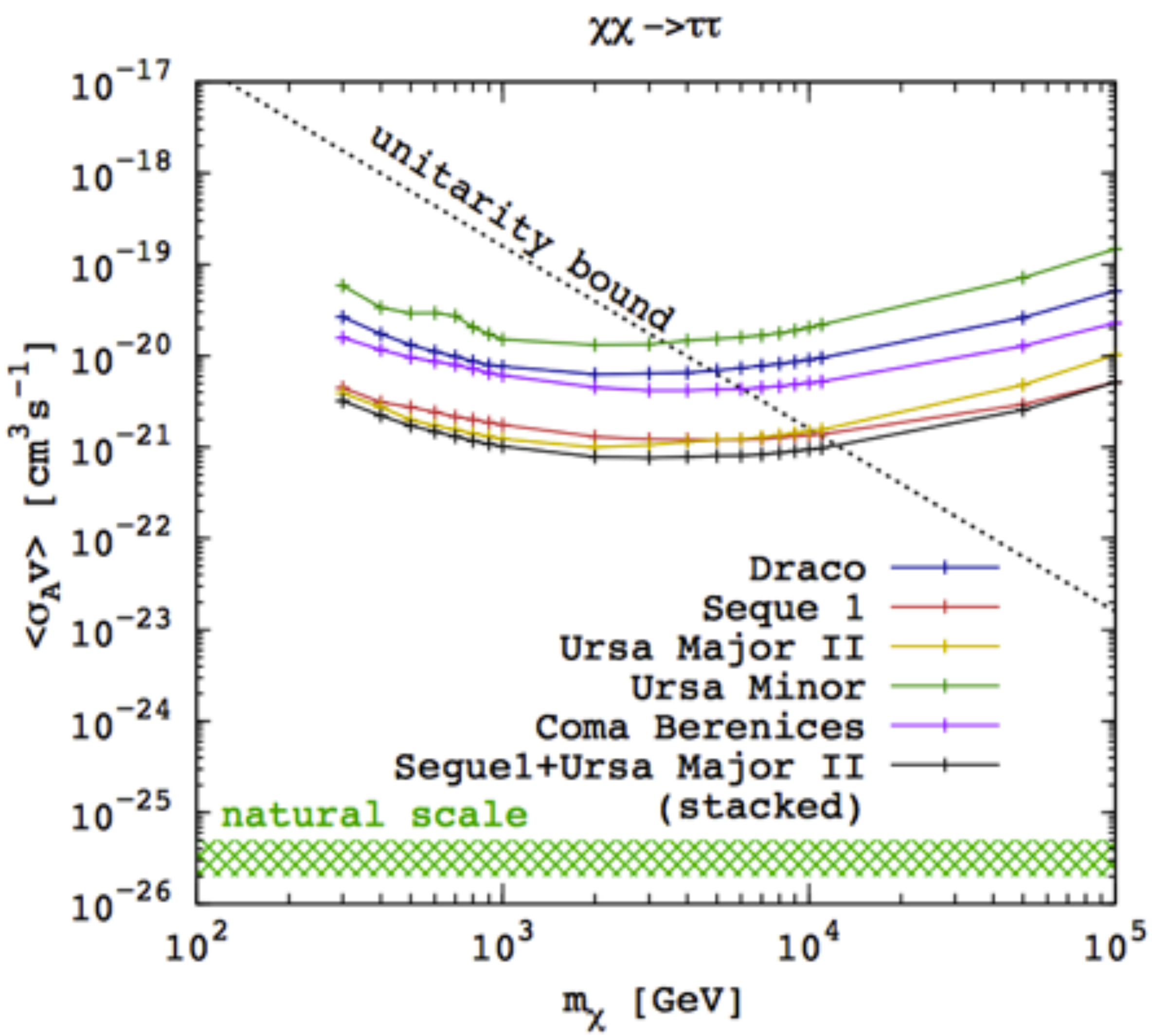
$m_\chi > 5\text{GeV} \Rightarrow \sim 2 \cdot 10^{-26}\ cm^3 s^{-1}$

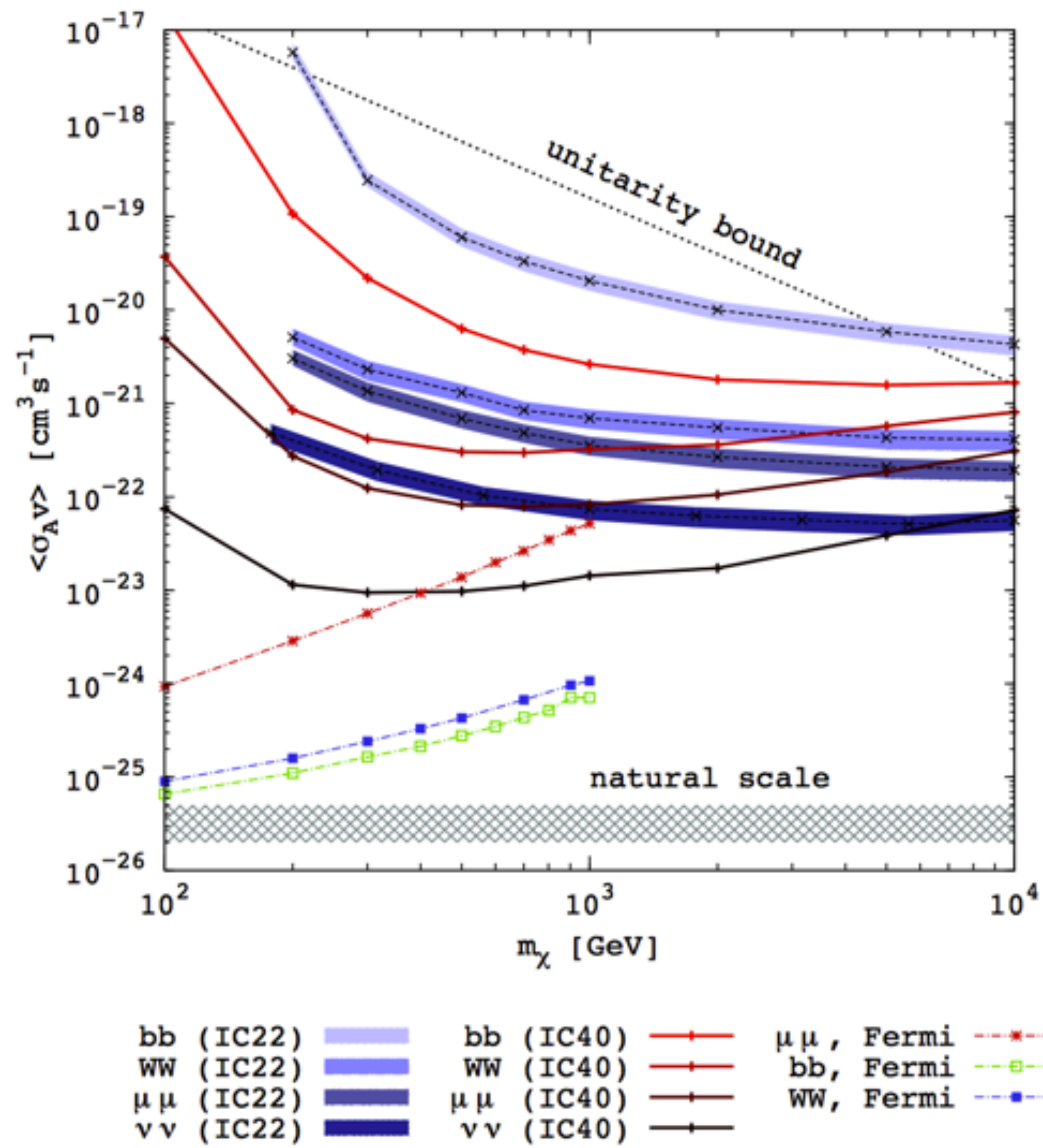
PINGU Solar WIMP Sensitivity

- Preliminary solar WIMP sensitivity based on adapted version of JCAP09 (2011)029 to PINGU.
- Assume that atmospheric muon backgrounds can be effectively rejected (not included in the sensitivity)

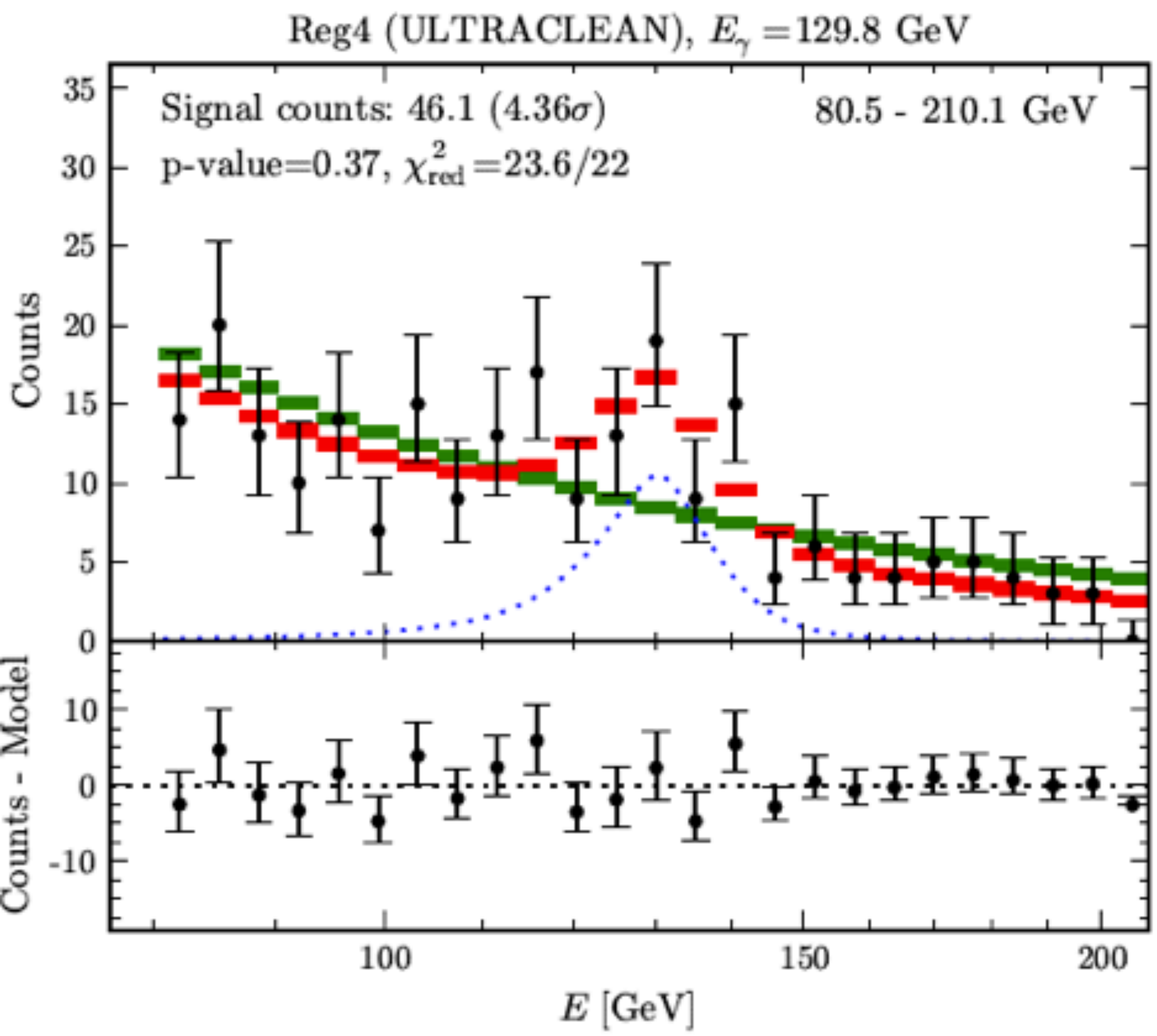
- Low-mass WIMP scenarios well testable
- Next steps:
  - Use new PINGU simulation
  - More sophisticated event reconstruction
  - Check atmospheric muon background




χχ ->ττ
unitarity bound
Draco
Seque 1
Ursa Major II
Ursa Minor
Coma Berenices
Segue1+Ursa Major II
(stacked)
natural scale
<σAv> [cm3s-1]
mχ [GeV]


unitarity bound
natural scale
<σAv> [cm3s-1]
mχ [GeV]
bb (IC22)
WW (IC22)
μμ (IC22)
νν (IC22)
bb (IC40)
WW (IC40)
μμ (IC40)
νν (IC40)
μμ, Fermi
bb, Fermi
WW, Fermi

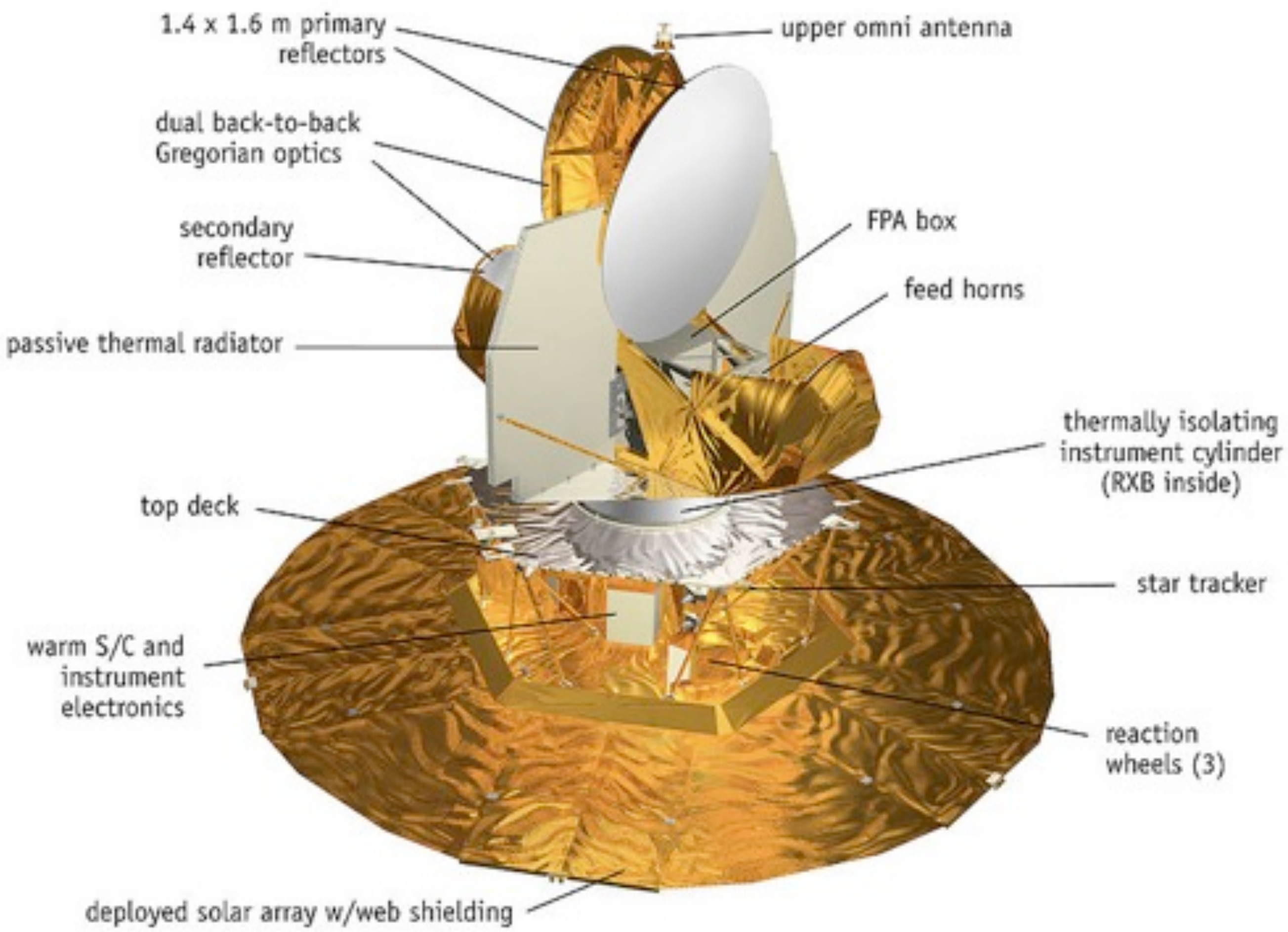
130GeV Line ???

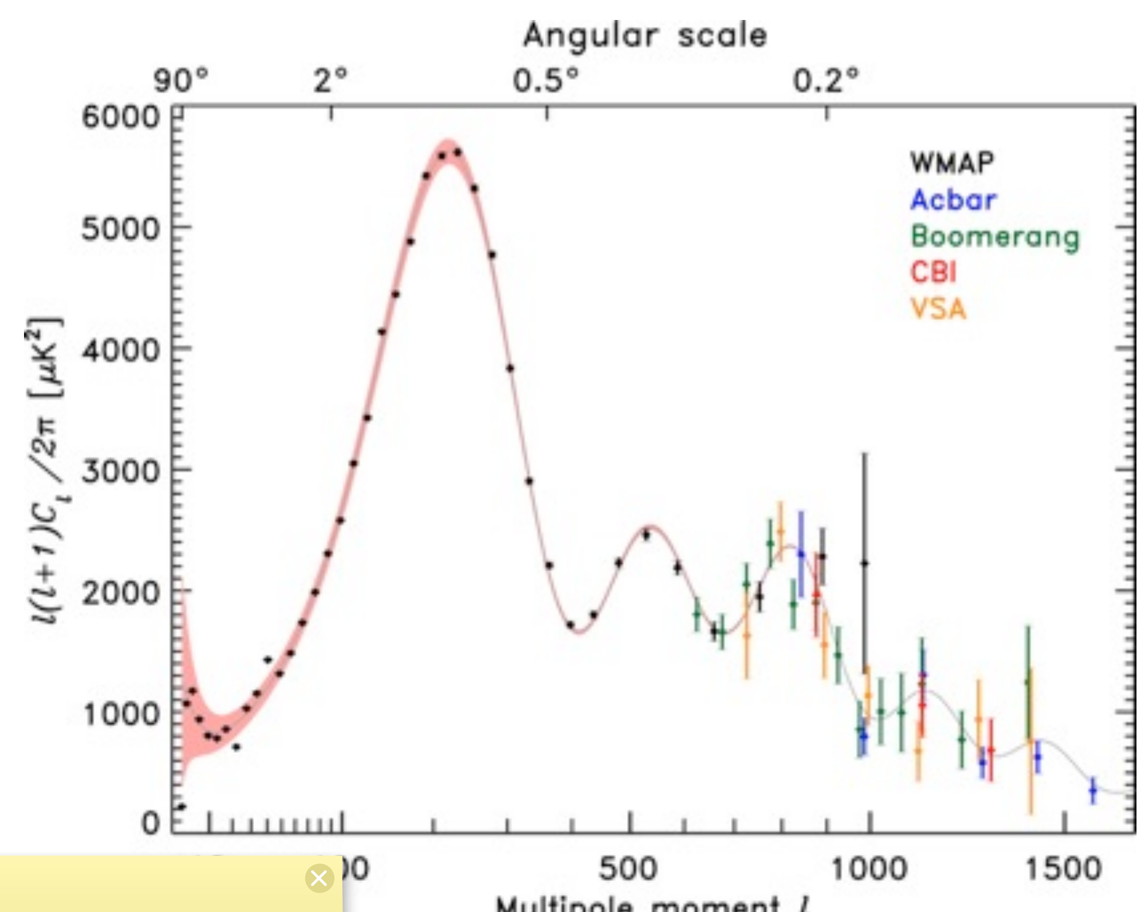


recent excitement ...

Understanding WMAP

Wilkinson Microwave Anisotropy Probe (WMAP) was launched on June 30, 2001





Sachs-Wolfe plateau: l < 100

Acoustic peaks: 100 < l < 1000

Damping tail: l > 1000

http://ned.ipac.caltech.edu/level5/March05/Scott/Scott4.html

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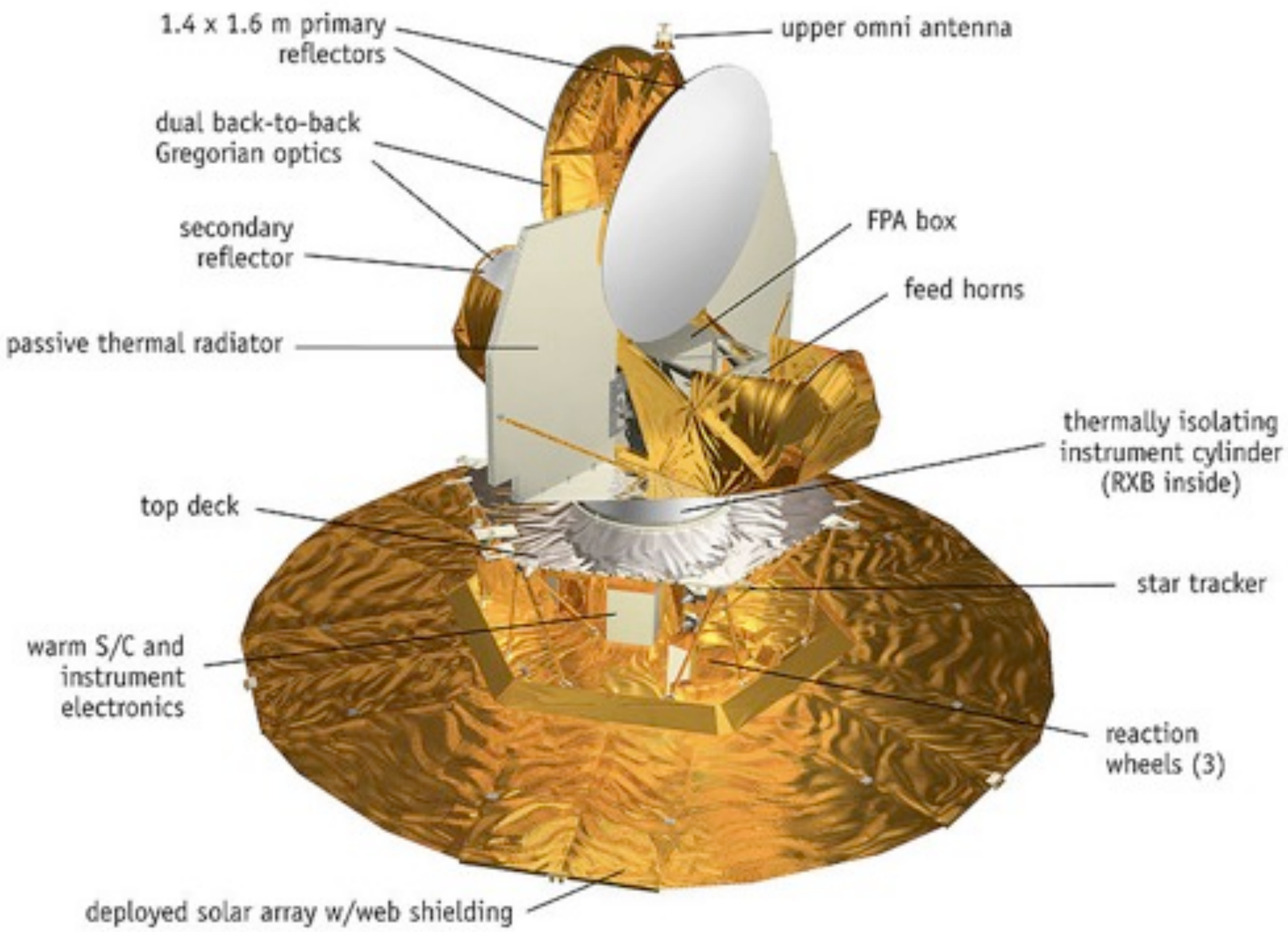
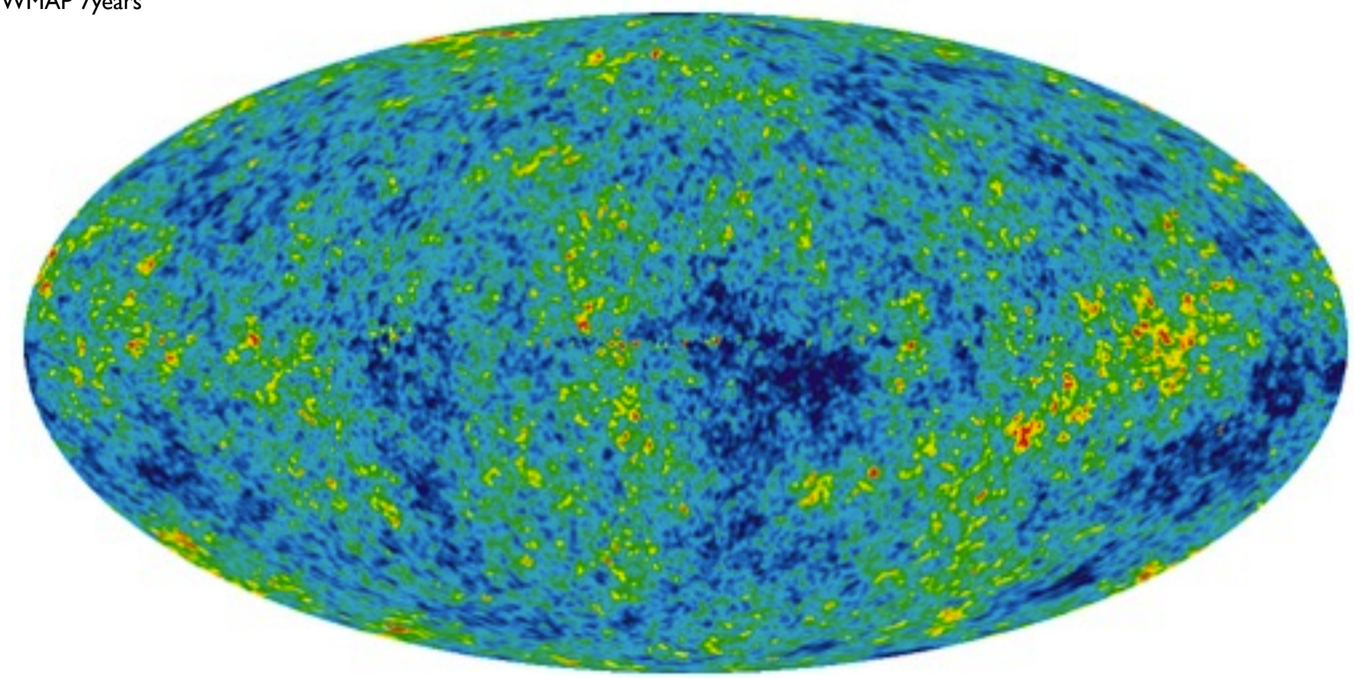
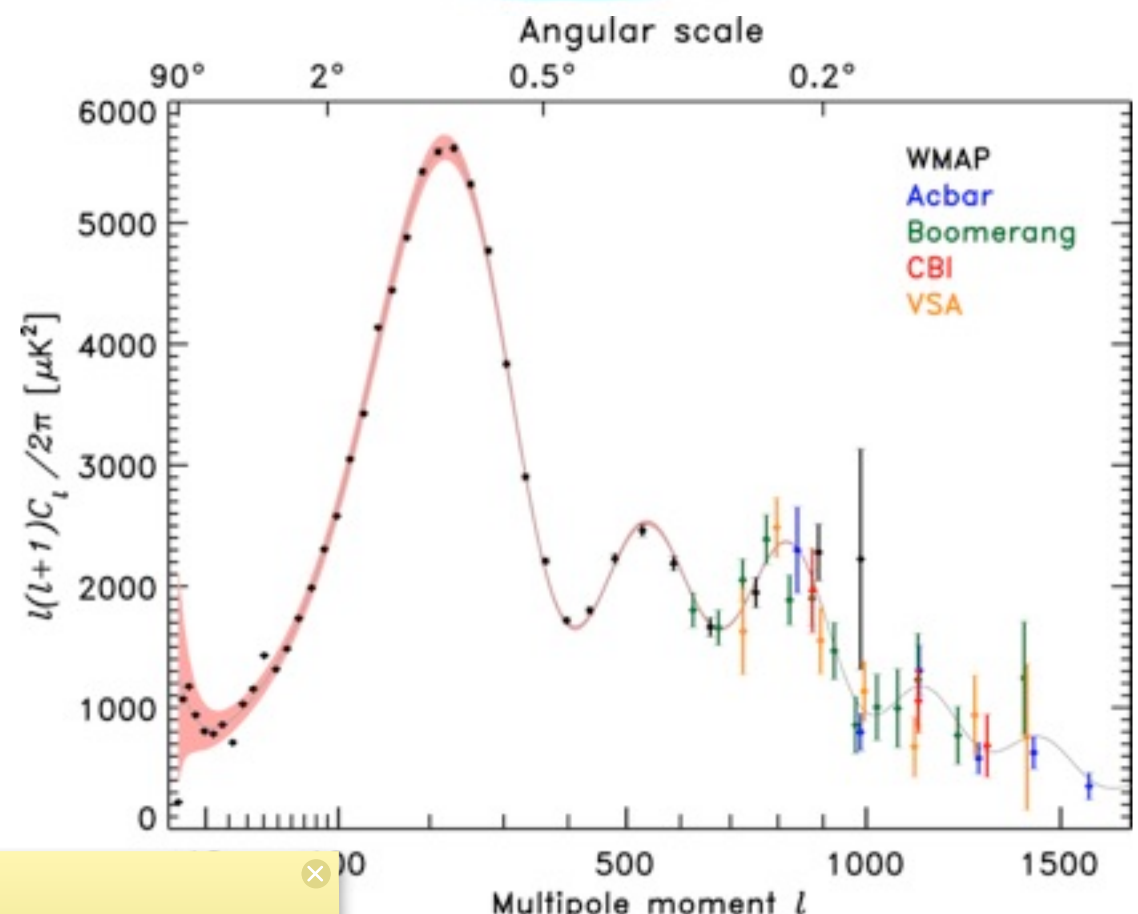


WMAP 7years





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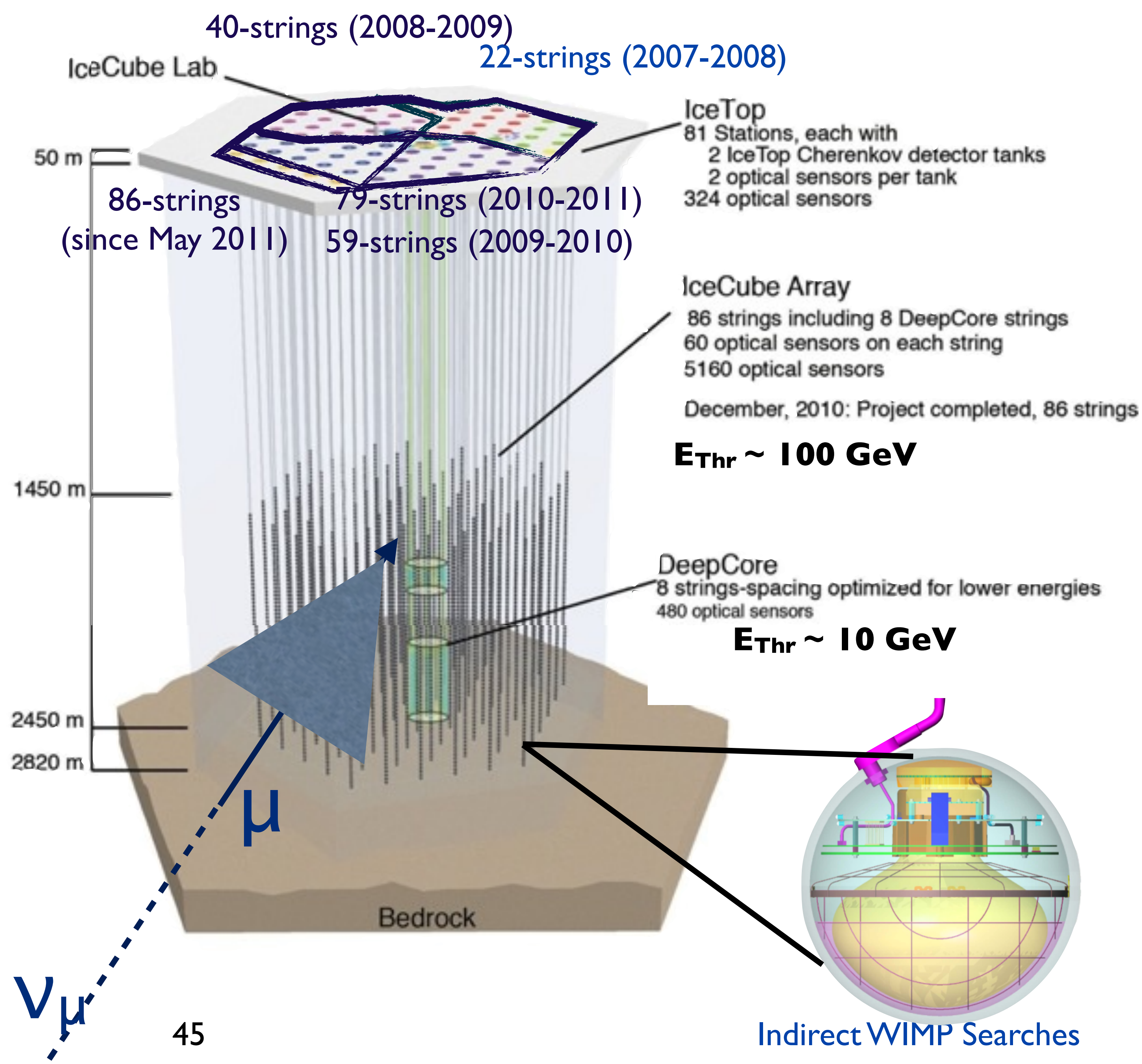
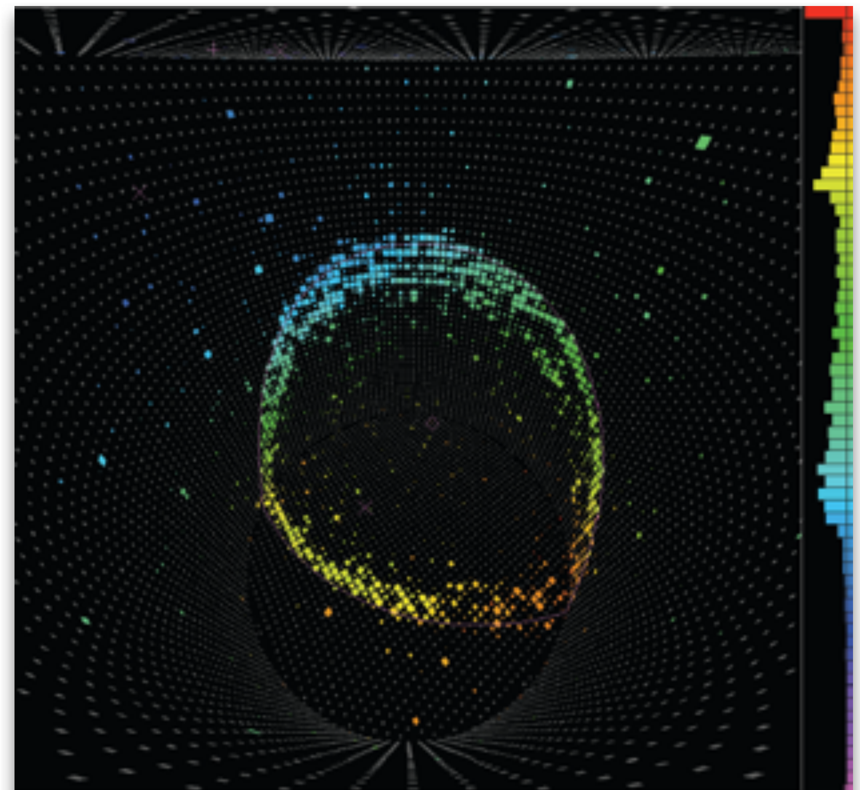
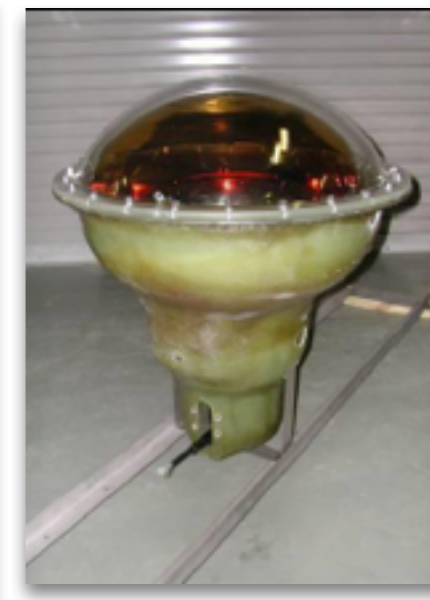
The IceCube Neutrino Telescope

- Gigaton Neutrino Detector at the Geographic South Pole
- 5160 Digital optical modules distributed over 86 strings
- Completed in December 2010, start of data taking with full detector May 2011
- Data acquired during the construction phase has been analyzed
- Neutrinos are identified through Cherenkov light emission from secondary particles produced in the neutrino interaction with the ice

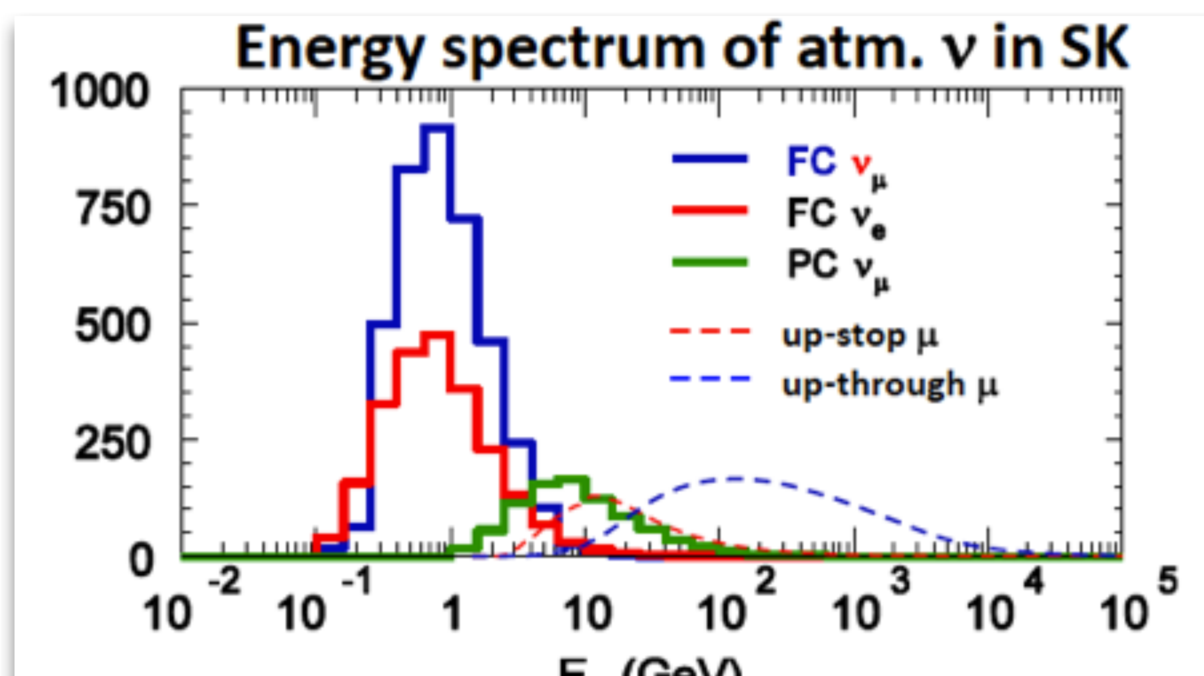


SUper-Kamiokande

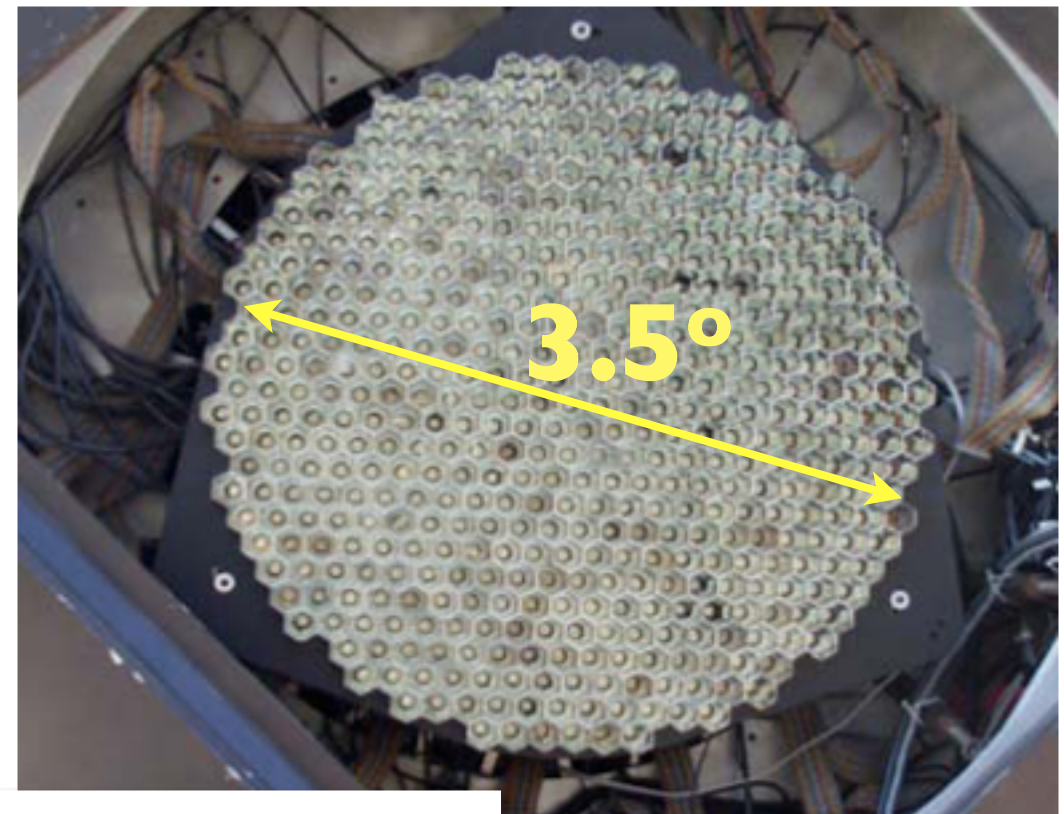




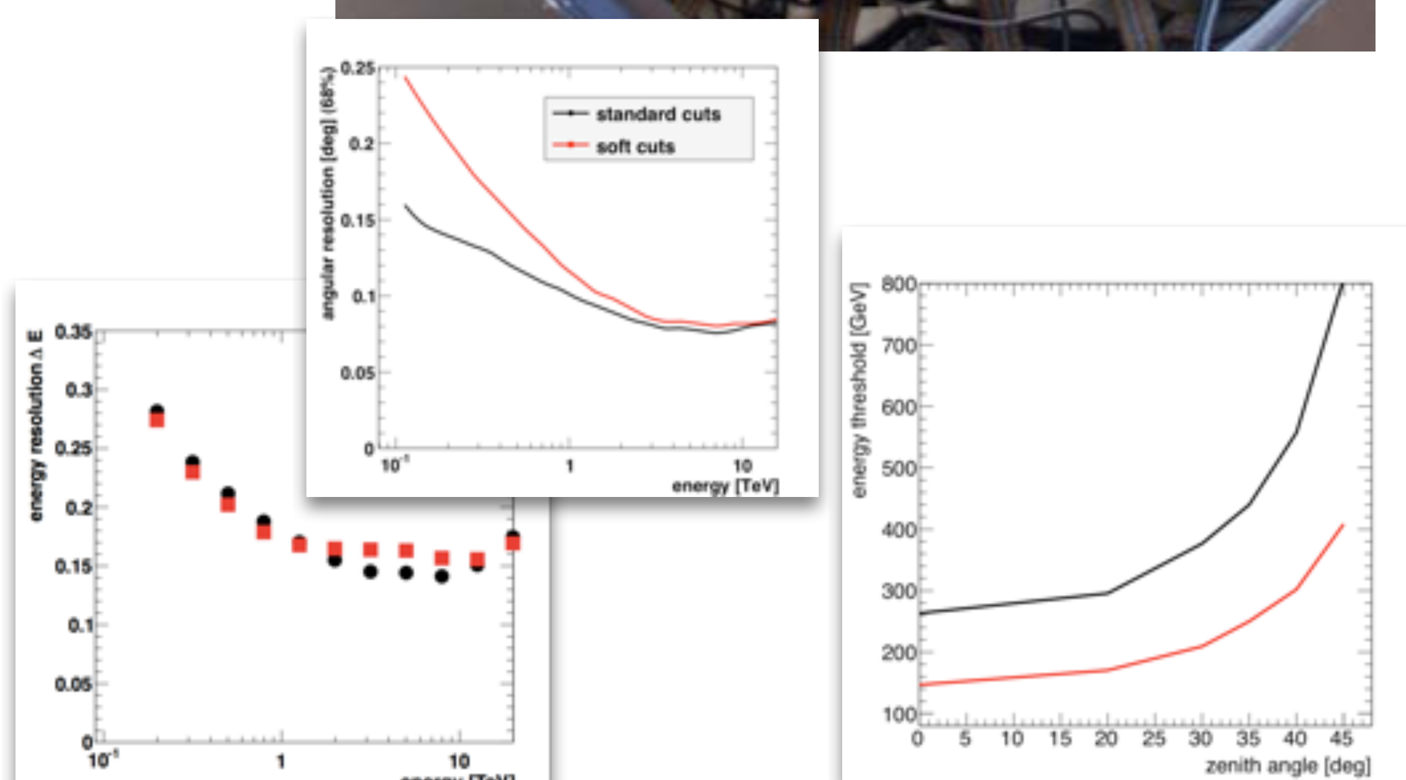
- 50kt pure water (22.5kt fiducial) water-cherenkov detector
- Operating since 1996
- ~11K 20” PMTs
- Photo coverage ~40%



Veritas

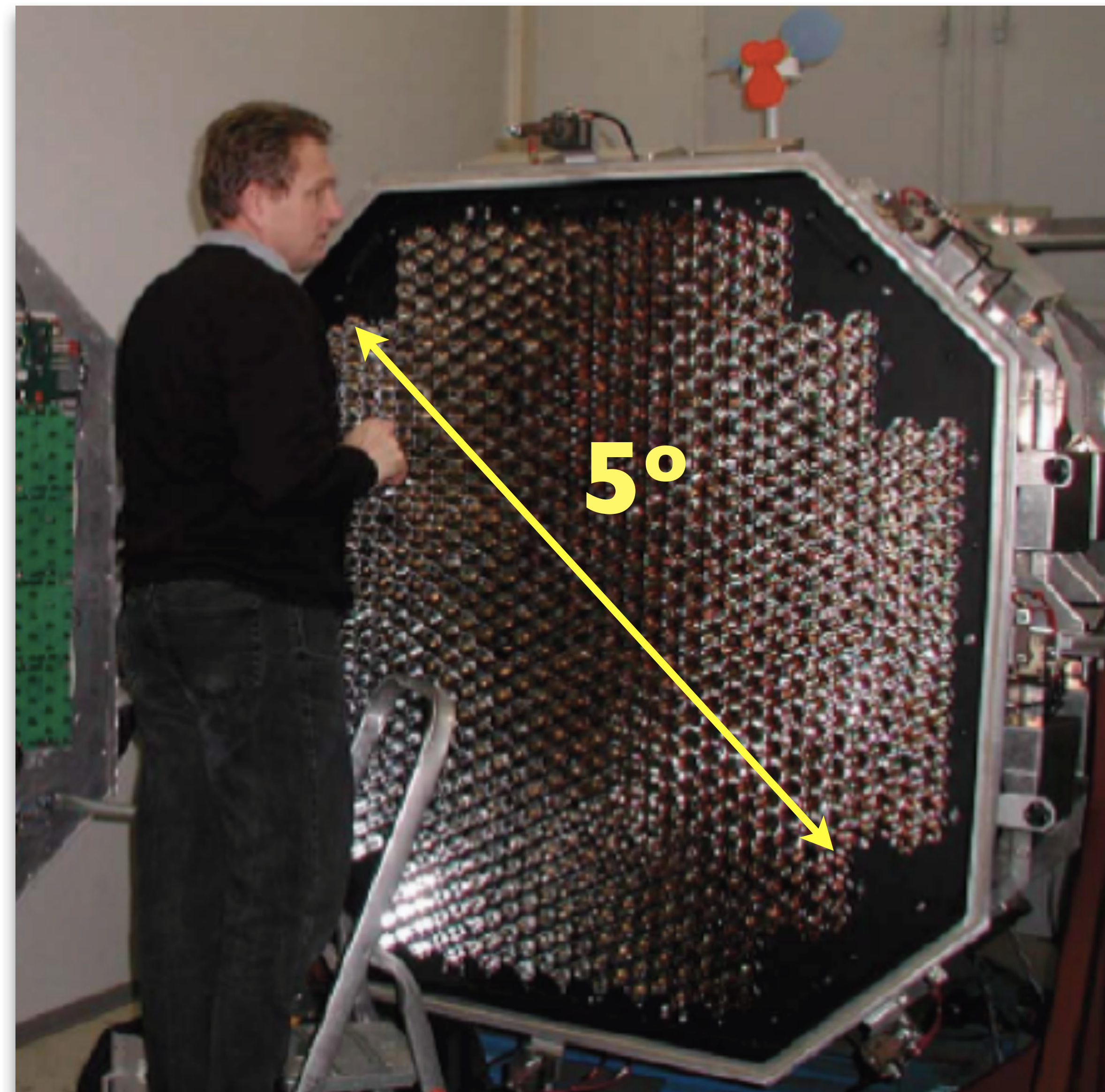


- Array of 4 12-meter IACTs
- Camera: 499 PMTs
- Operational since September 2007
- Sensitivity to a wide range of energies (150GeV - 30TeV) through stereoscopic imaging
- γ-ray reconstruction accuracy ~0.1° and energy resolution ~15%-20%
- Sensitivity 1% Crab at 5σ in 25h

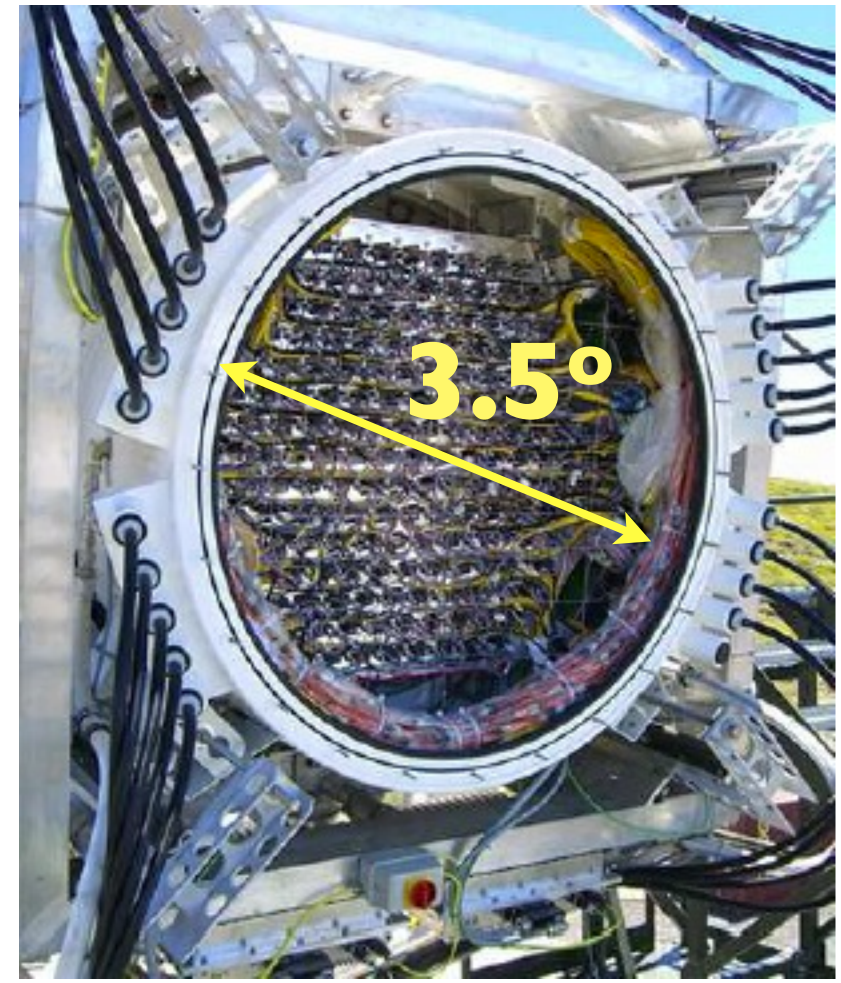


H.E.S.S. - High Energy Stereoscopic System

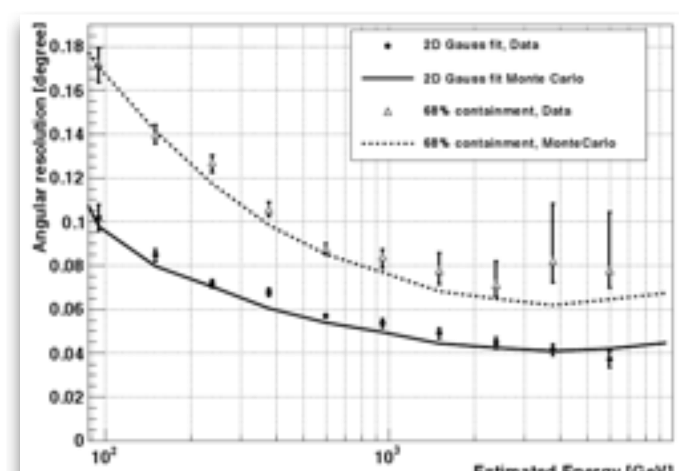
- Array of 4 13-meter IACTs
- Camera: 960 PMTs
- Energy threshold ~200GeV
- γ-ray reconstruction accuracy ~0.1° and energy resolution 10%
- Sensitivity 1% Crab at 5σ in 25h



Magic

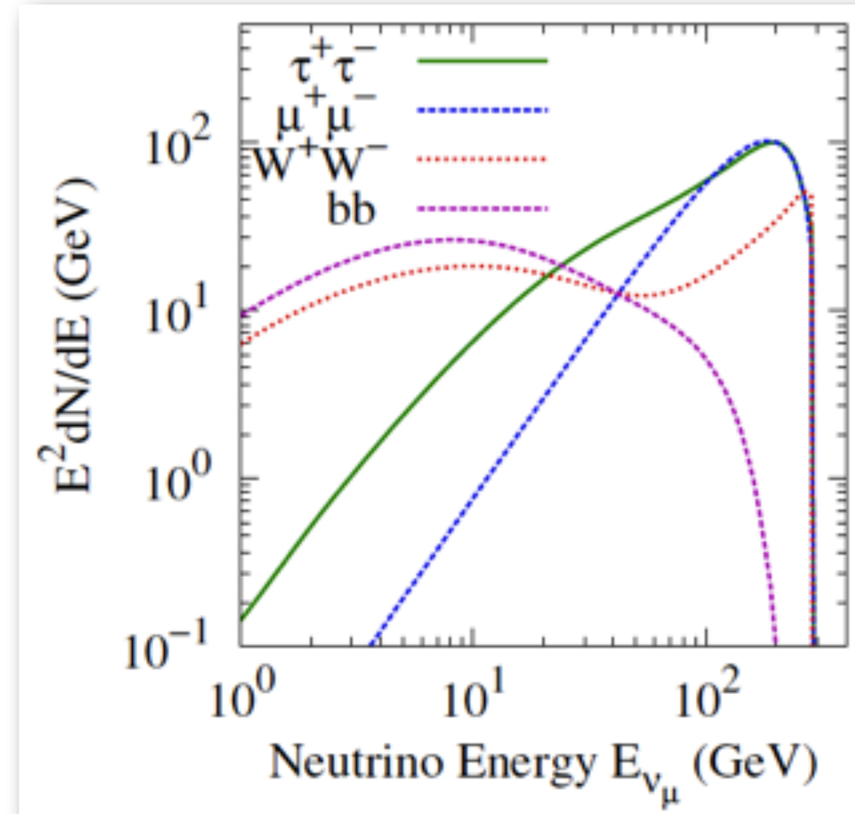


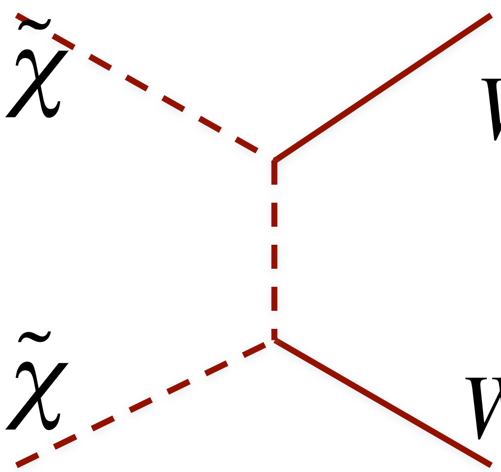
- Stereo IACT with 2 x 17mØ
- Camera: 577pixels (upgrading to 1039)
- Regular stereo observations since Fall 2009
- Energy threshold ~ 50GeV
- Angular resolution: 0.1° at 100 GeV, down to 0.04° at >1 TeV.
- Energy resolution: 20% at 100 GeV, down to 15% around 1 TeV.
- Sensitivity <0.8% Crab at 5σ in 50h above 300GeV



Dark Matter Annihilation Signals

- Annihilation Rate ~ρ^2

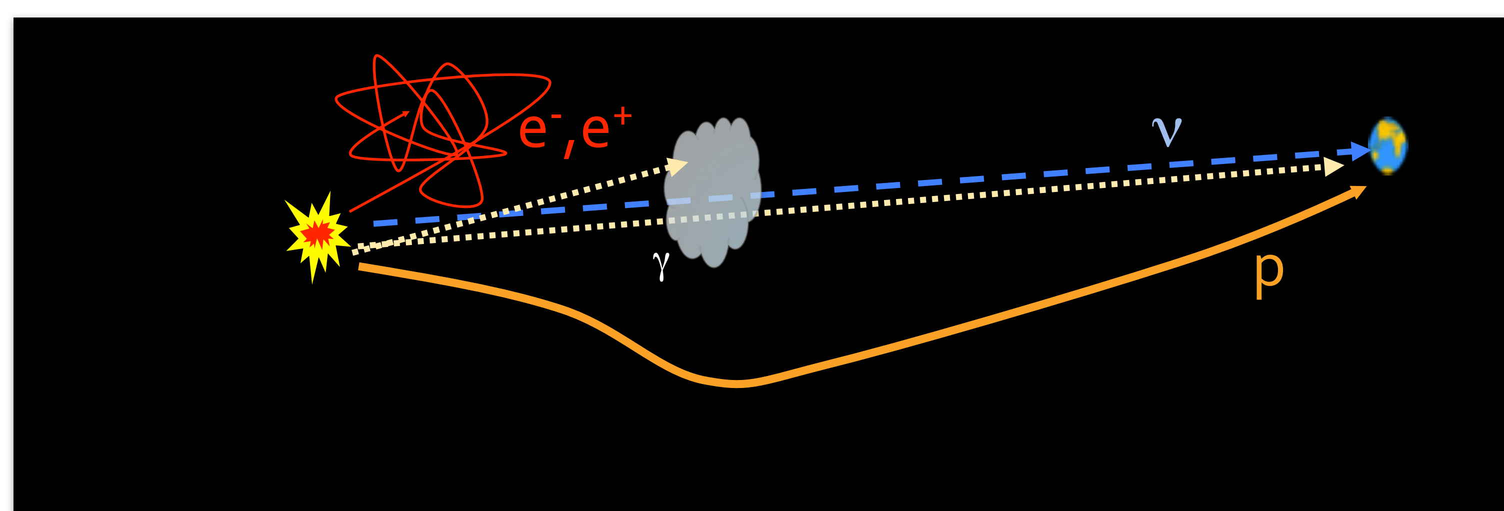




$$W^+, Z, \tau^+, b, \ldots \Rightarrow e^{\pm}, \upsilon, \gamma, p, D, \ldots$$

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

- Propagation of signal:
  - diffusion, energy loss, spallation
  - absorption, scattering
  - neutrino oscillations, ...



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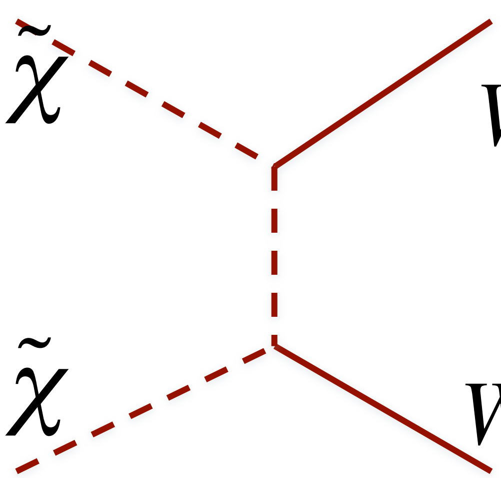

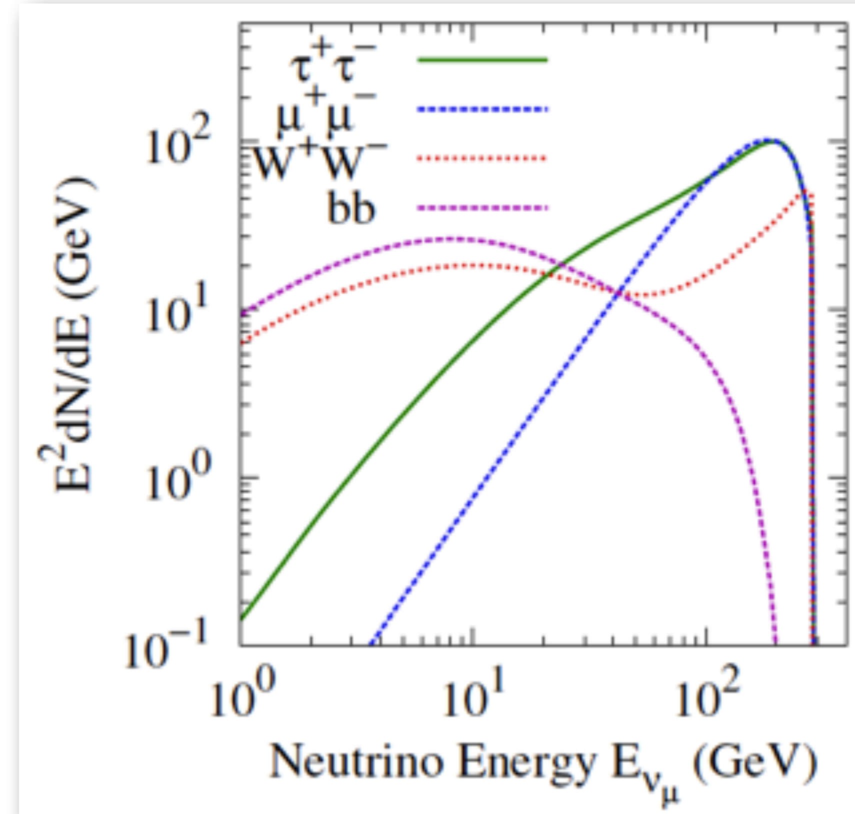

Annihilation Products

$\tilde{\chi}$ $\quad W^+, Z, \tau^+, b, \ldots \Rightarrow e^\pm, \upsilon, \gamma, p, D, \ldots$

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

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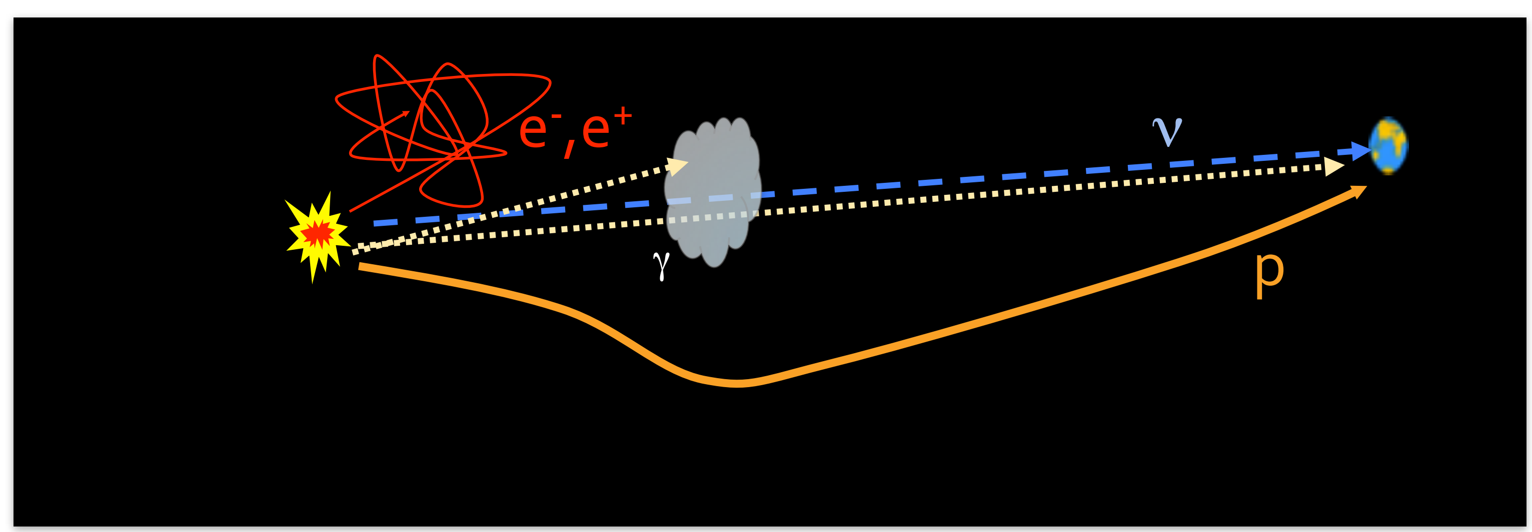
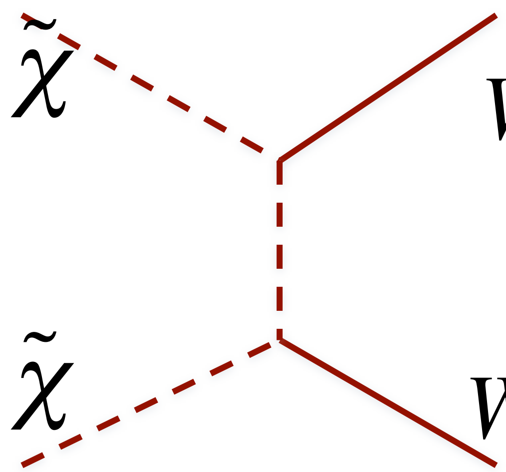


Dark Matter Annihilation Signals

- Annihilation Rate $\sim\rho^2$

Annihilation Products

Decay



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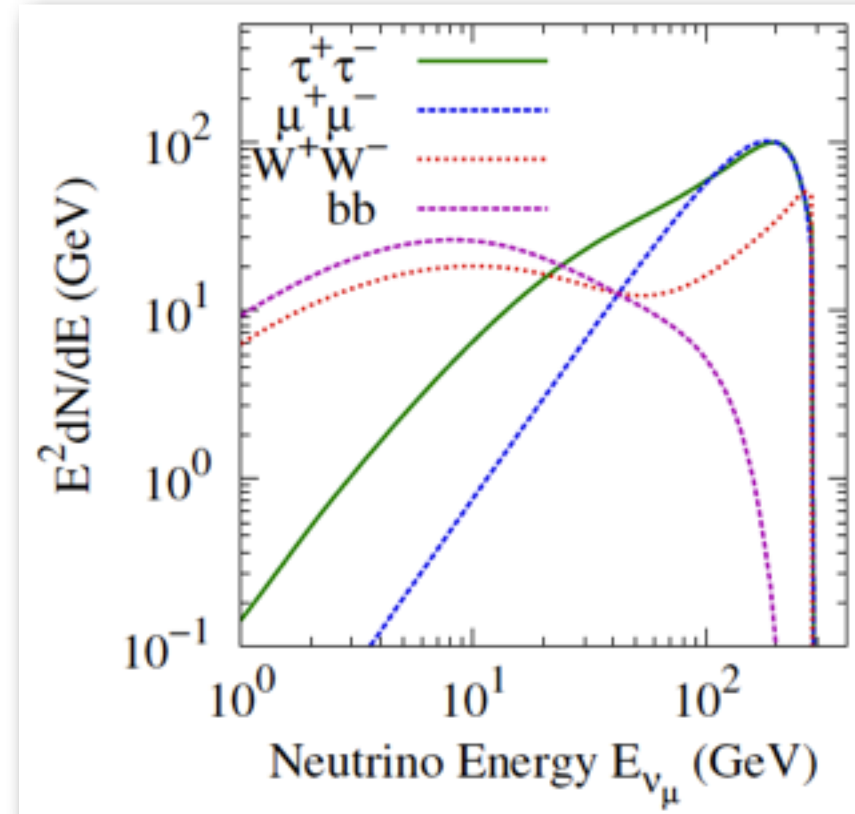

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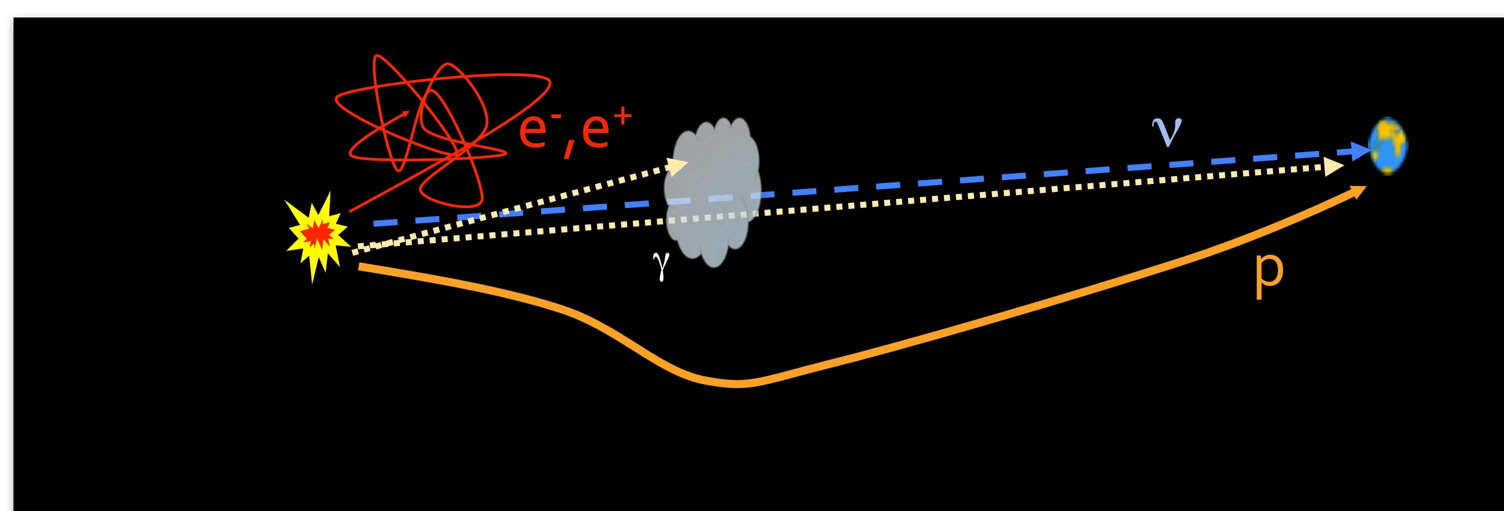
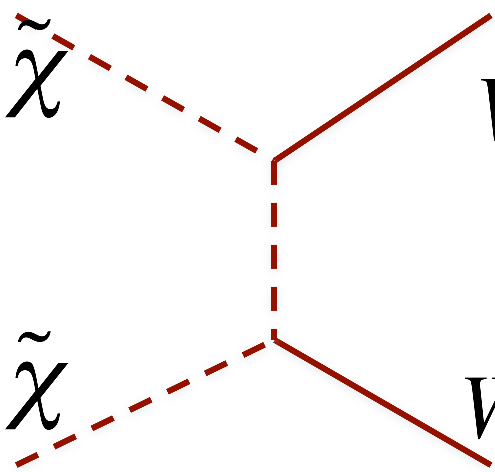


Dark Matter Annihilation Signals

- Annihilation Rate ~ρ^2

Annihilation Products | Decay | Messengers



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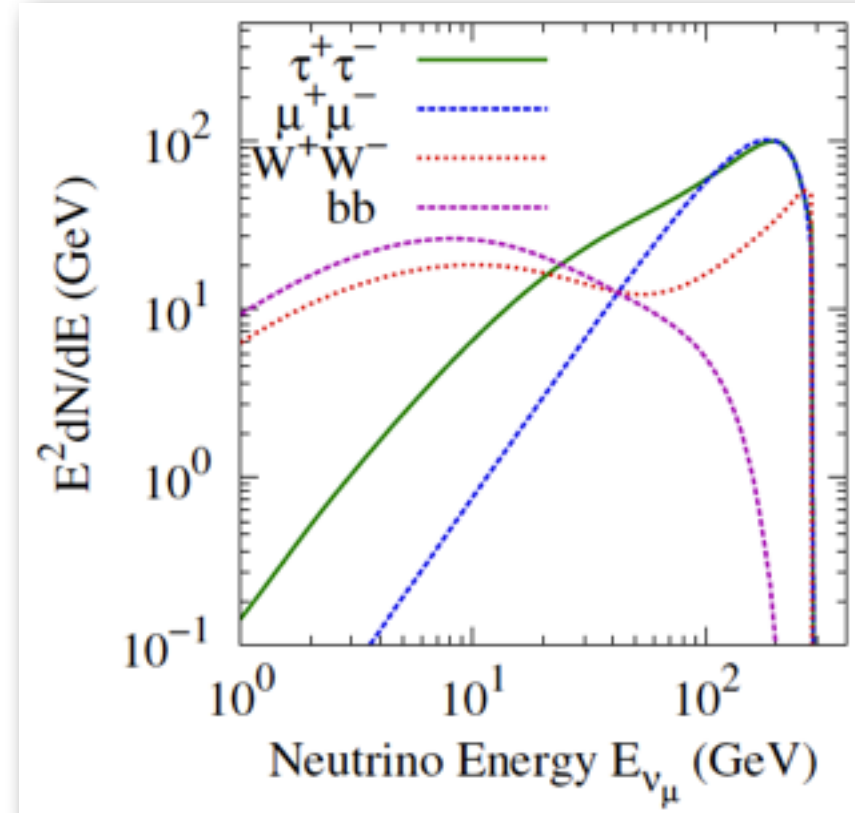

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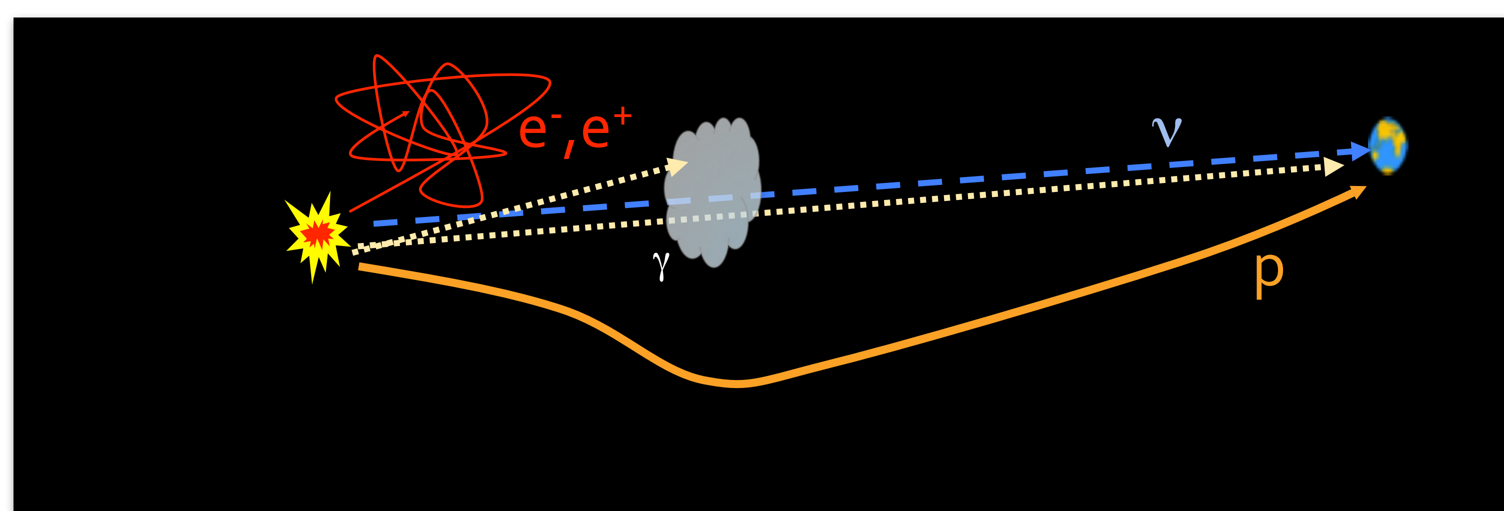
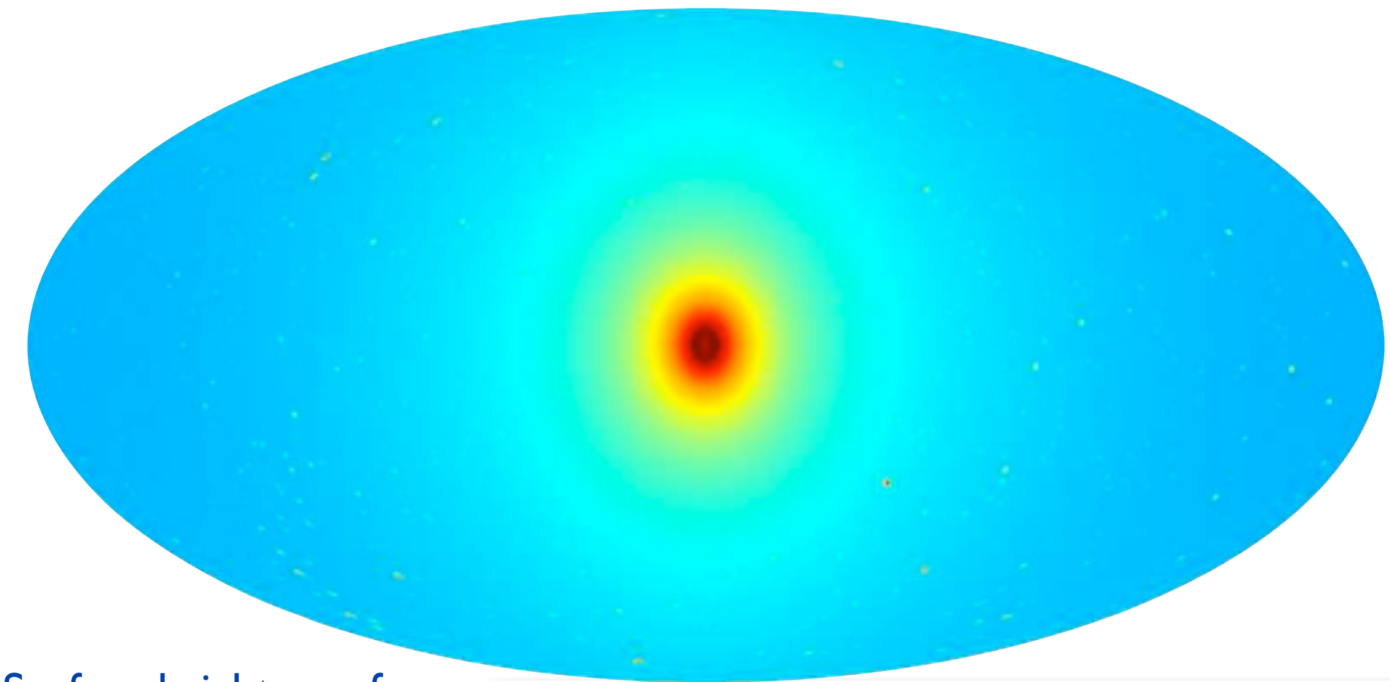


Boost factor

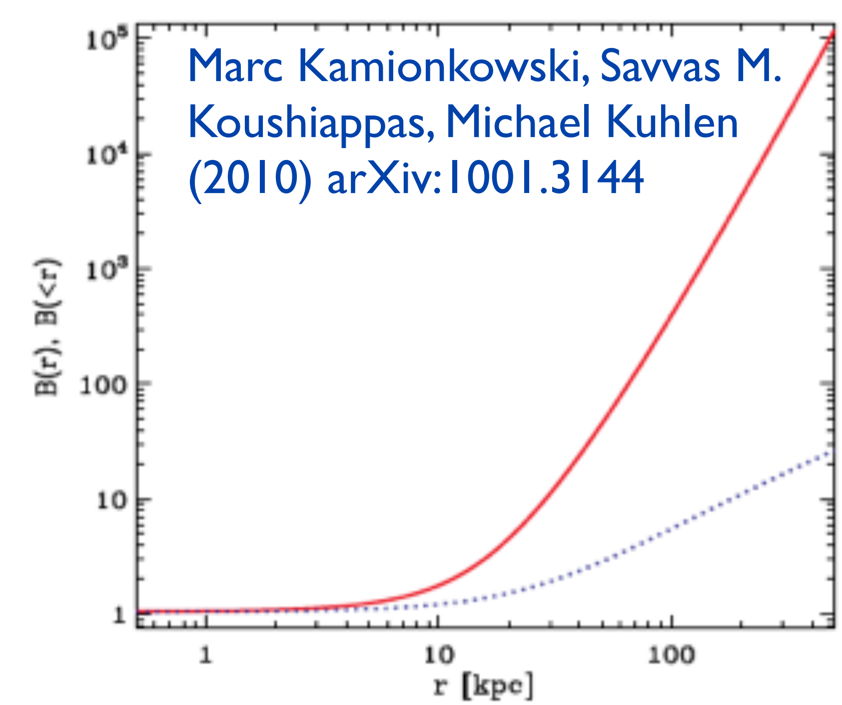
- Local clumps in the DM halo enhance the density and boost the flux from annihilations:

$$boost = \frac{\phi^{actual}(\vec{r})}{\phi^{smooth}(\vec{r})}$$

- Typical boost factors are B~ 1-20 (simulations)
- Boost factor ~ 1 (for central halo region <10kpc) tidal stripping



Surface brightness from dark matter annihilation at the position of the Sun, calculated directly from the Aq-A-1 simulation.



Marc Kamionkowski, Savvas M. Koushiappas, Michael Kuhlen (2010) arXiv:1001.3144

FIG. 4. The local substructure boost $B(r)$ (*solid*) and the cumulative luminosity boost $B(<r)$ (*dotted*), as a function of radius.

- Boost factor important for:
  - Galaxy clusters, Diffuse extra galactic, ...
- Not important for:
  - Galactic Center, Solar circle, ...

Dark Matter Halo Profiles

- N-body simulations of Milky Way like galaxies yield halo profiles
- Outer halo relatively well understood
- Inner halo still subject of debates (cusp-core problem)

$$\rho(r) = \rho_0 \left(\frac{r}{r_s}\right)^{-\gamma} \left[1 + \left(\frac{r}{r_s}\right)^{\alpha}\right]^{(\gamma-\beta)/\alpha}$$

For small r: $\rho(r) \sim 1/r^{\gamma}$

Profile	α	β	γ	r_s
Moore	1.5	3	1.5	28
NFW	1	3	1	20
Kravtsov	2	3	0.4	10
isothermal	2	2	0.4	5

Einasto Profile:
$\alpha=0.17$ $r_s=20\text{kpc}$ $\rho_s=0.06\text{GeV/cm}^3$

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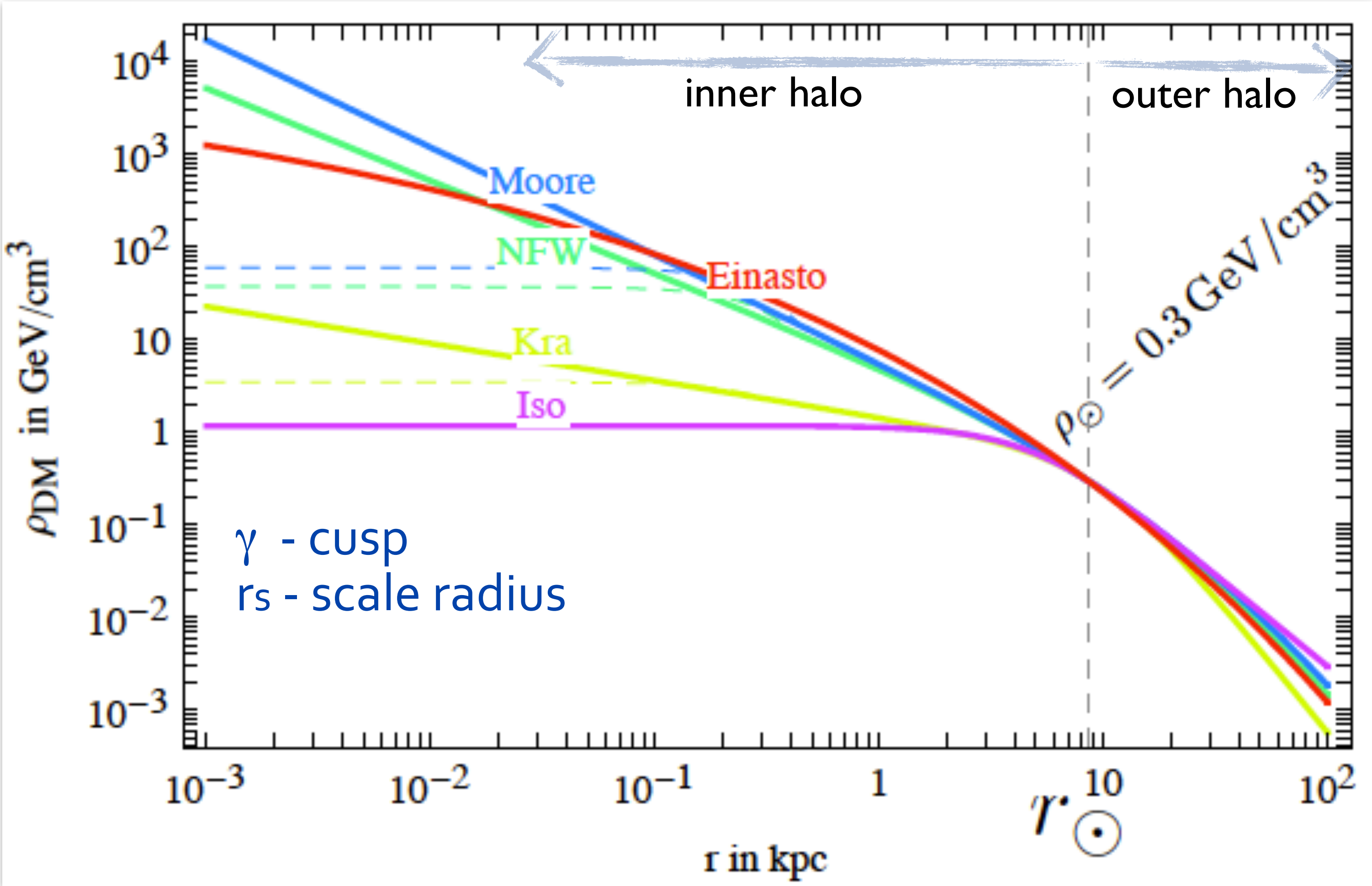

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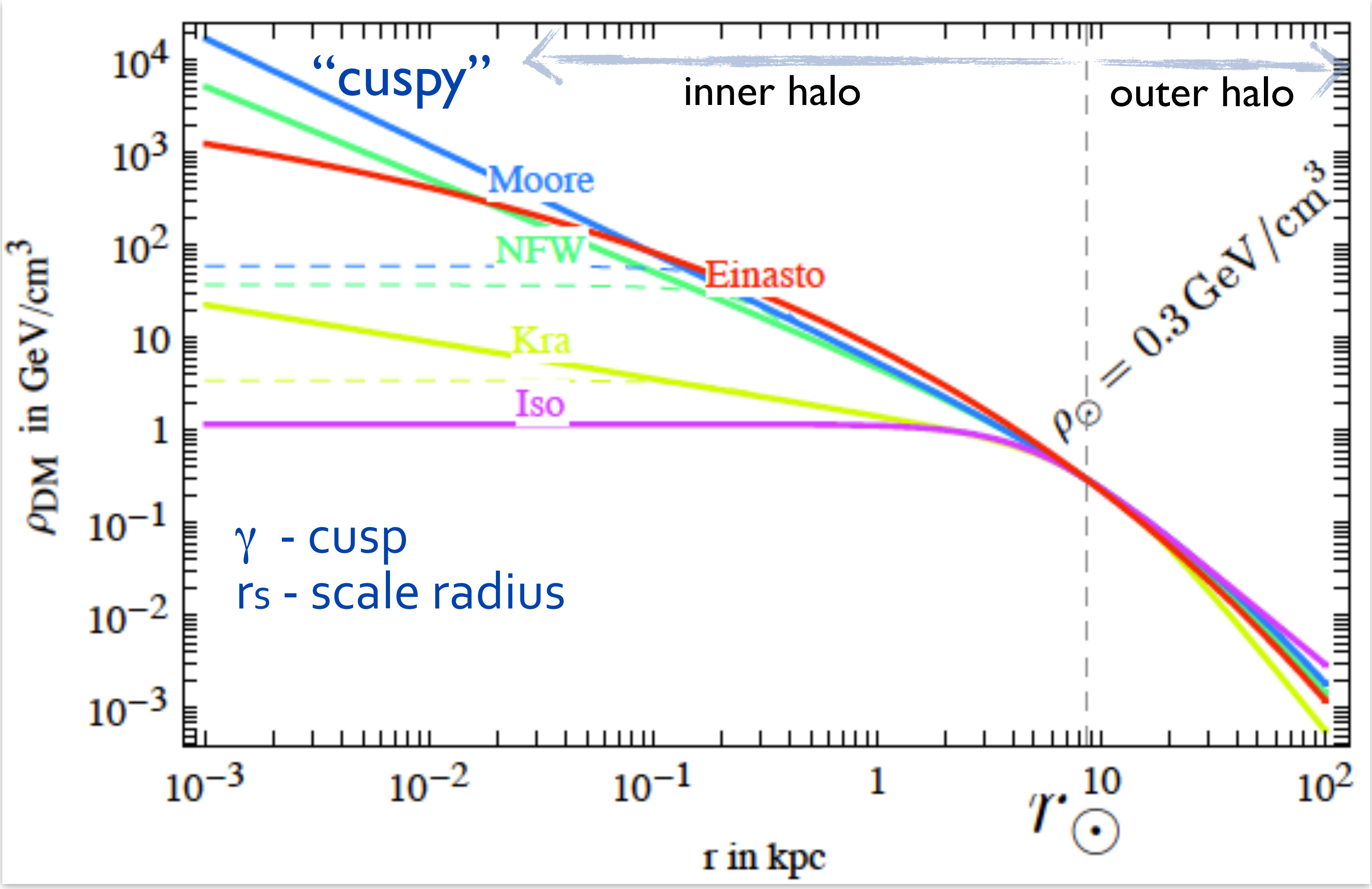

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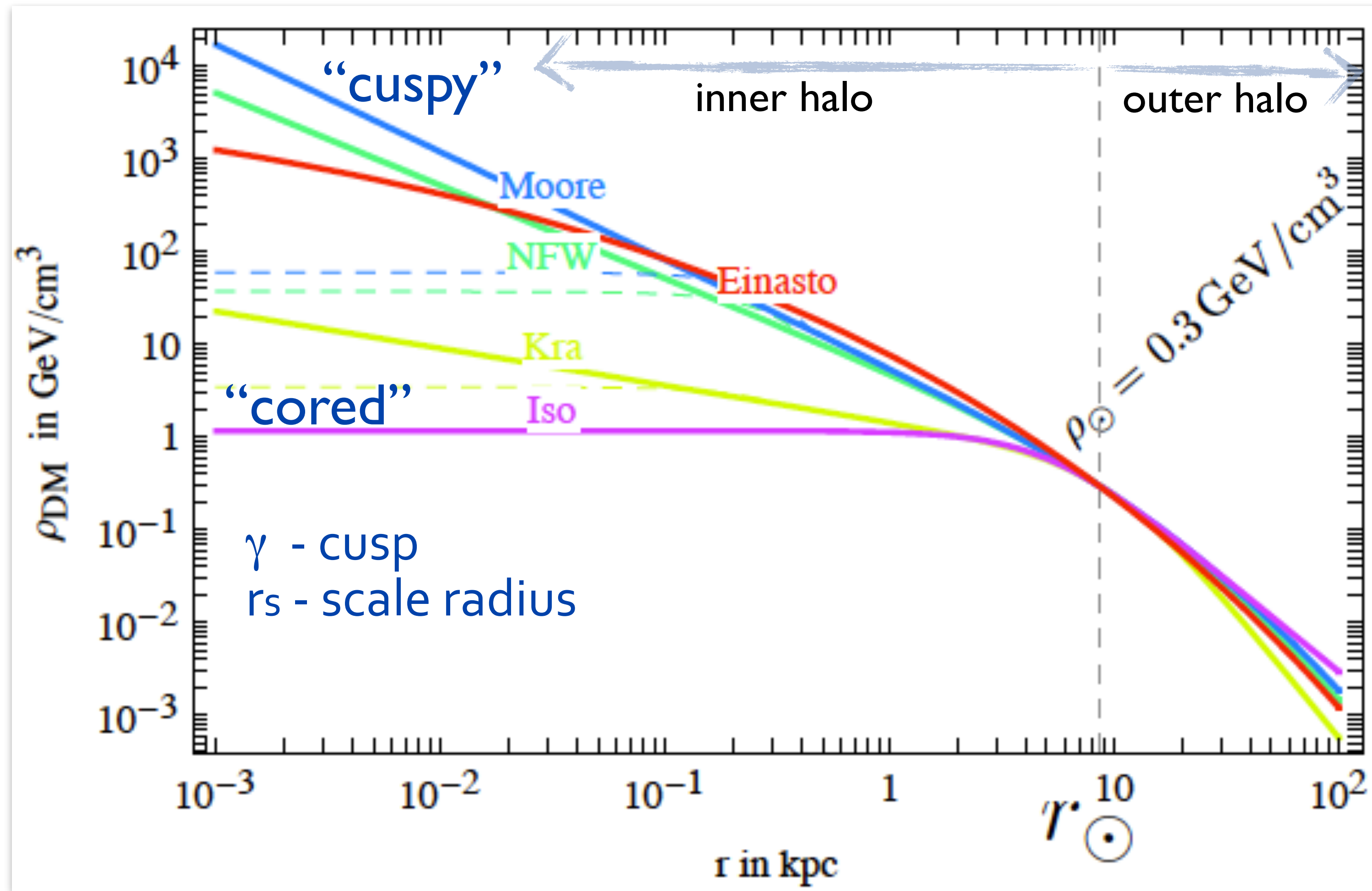

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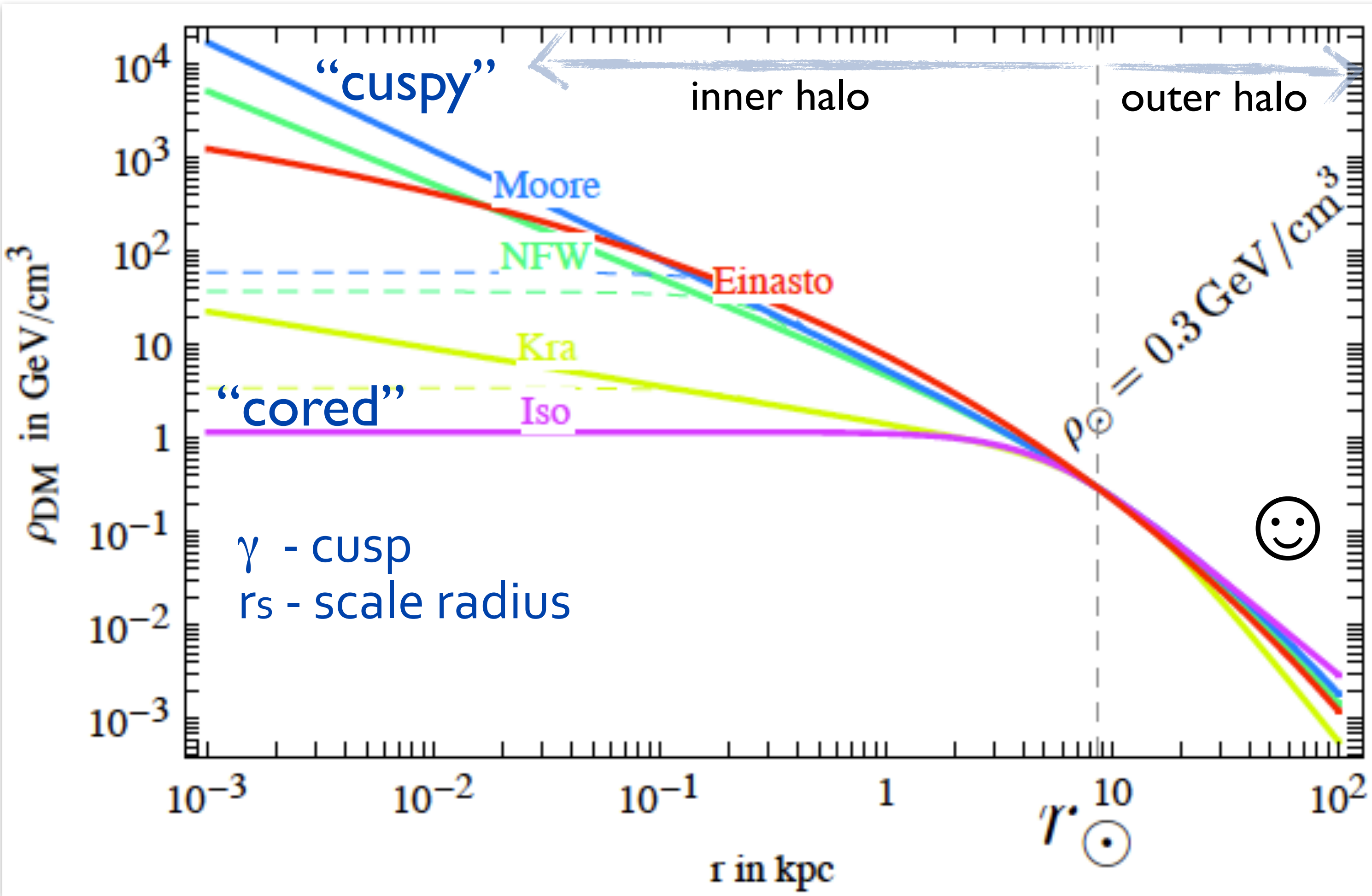

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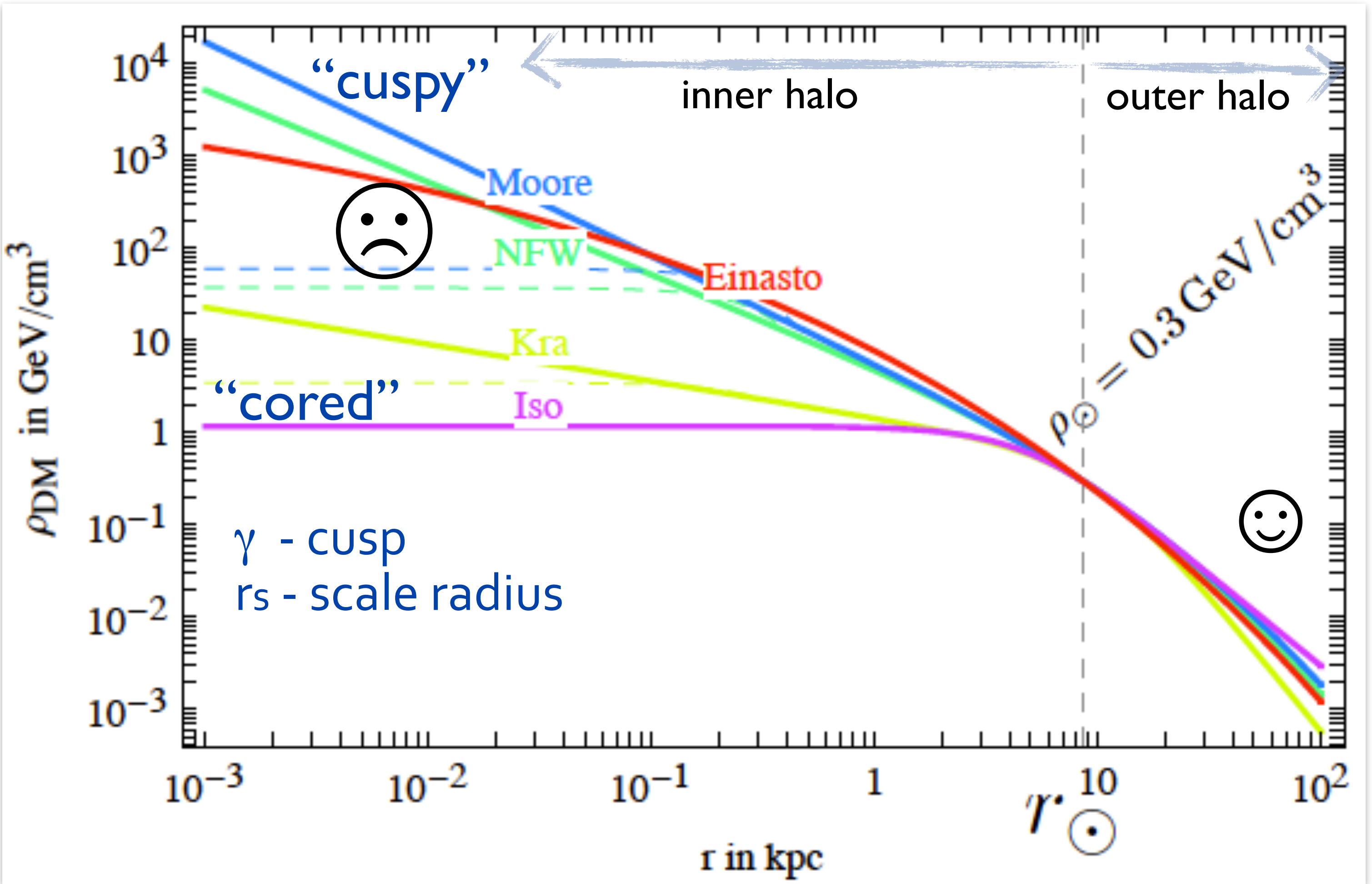

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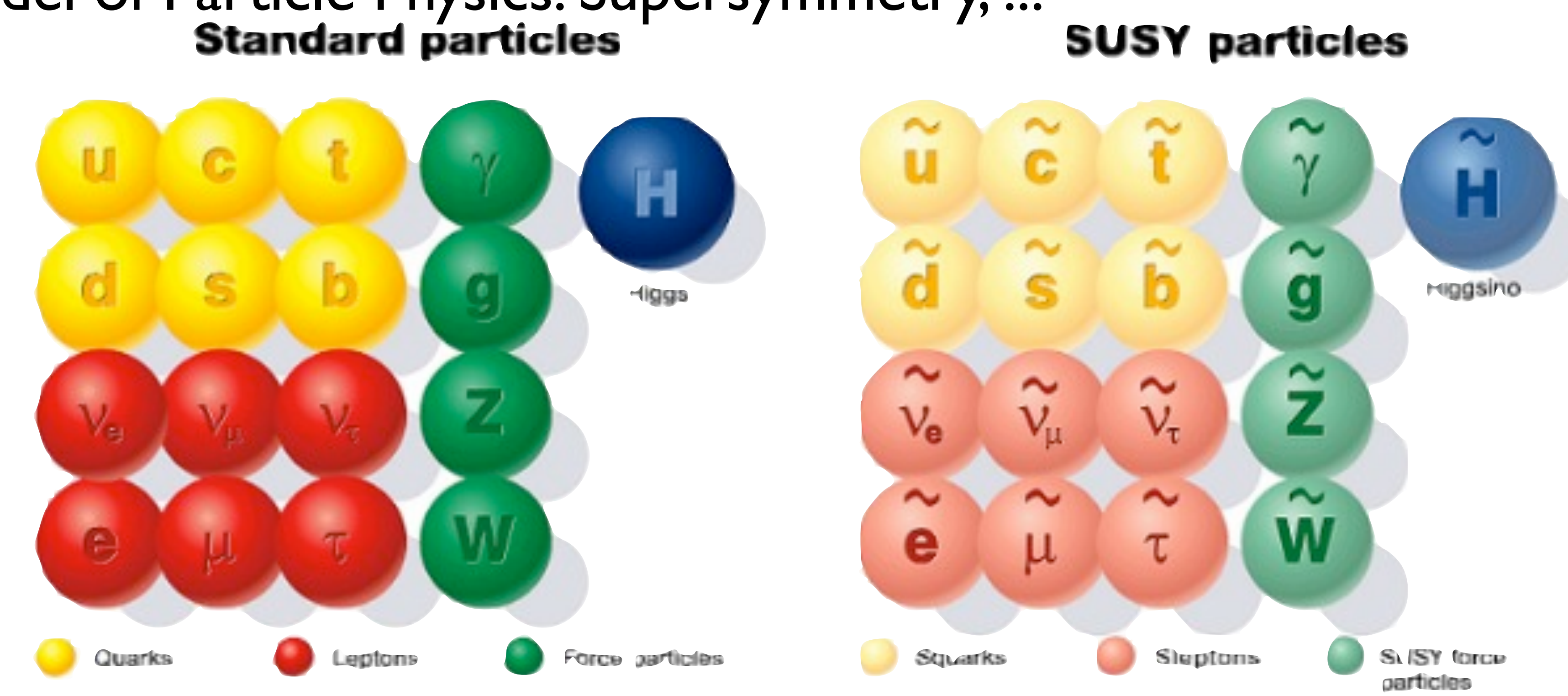
Weakly Interacting Massive Particle

- Observational Evidence for Dark Matter points to
  - Non-baryonic
  - Cold massive
  - Not strongly interacting
  - Stable (long lived)

WIMP

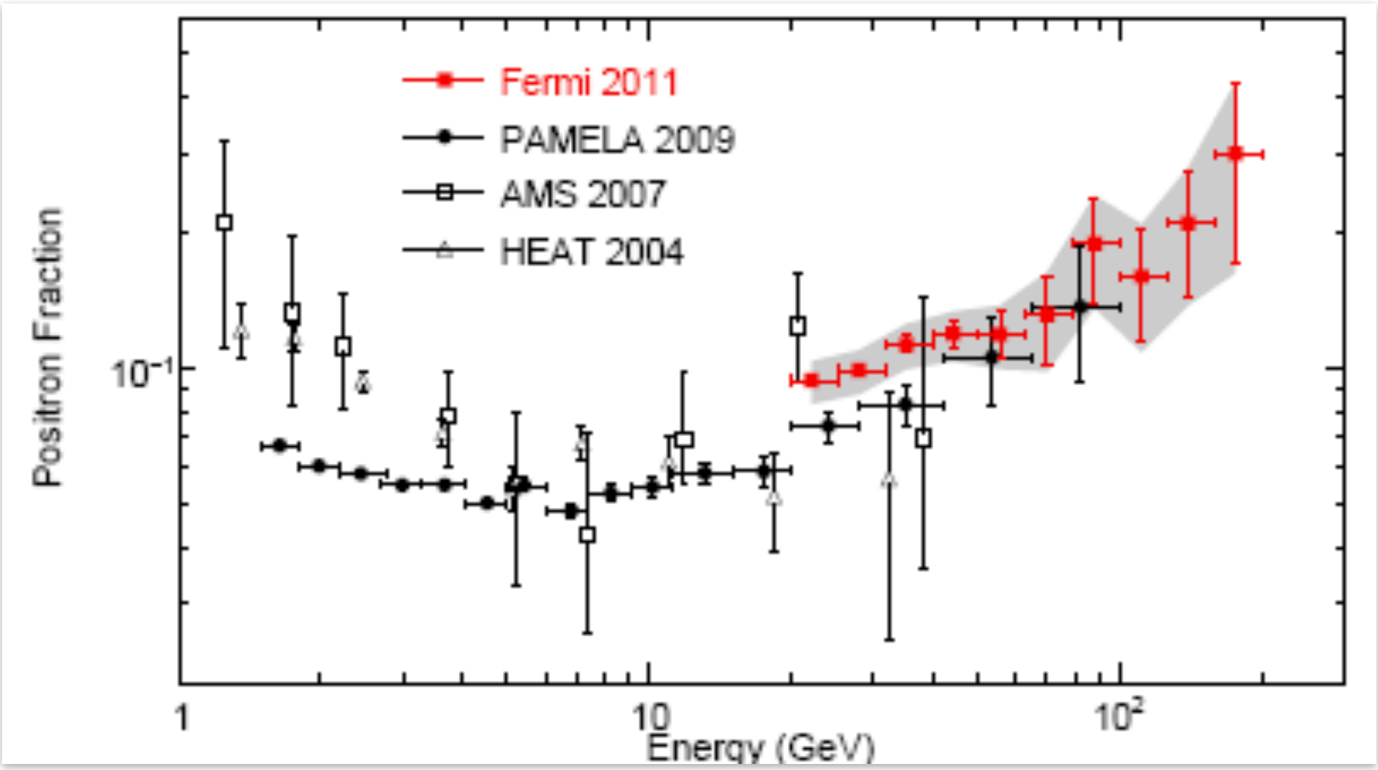
- WIMPs often arise naturally in extensions to the Standard Model of Particle Physics: Supersymmetry, ...

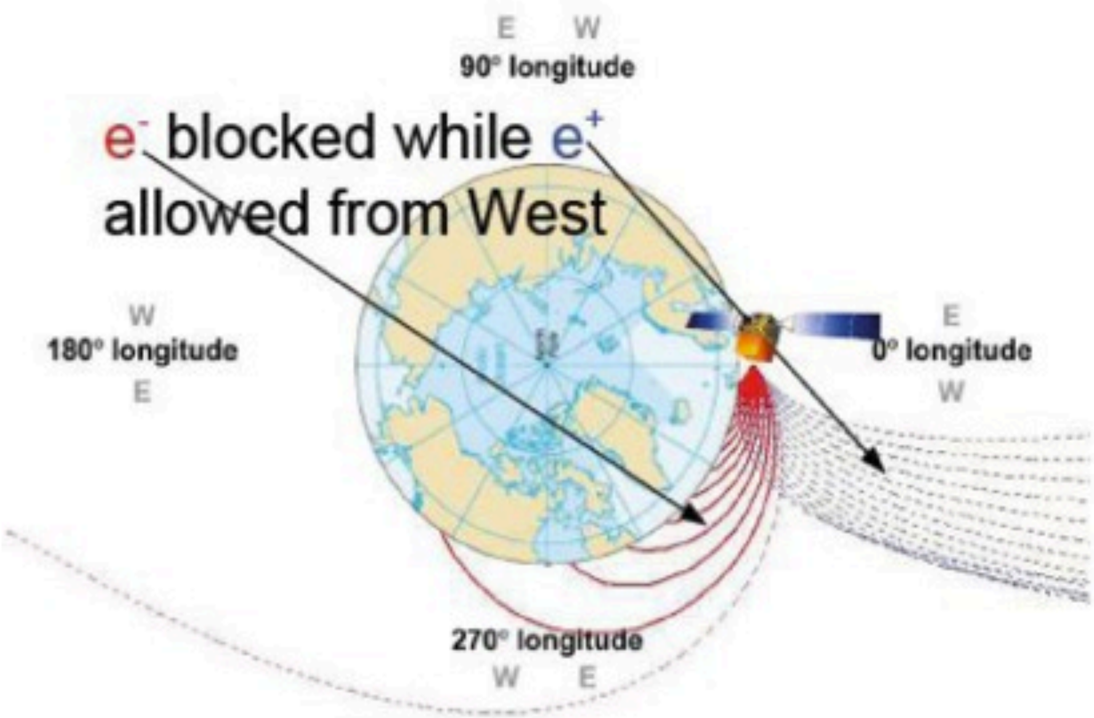


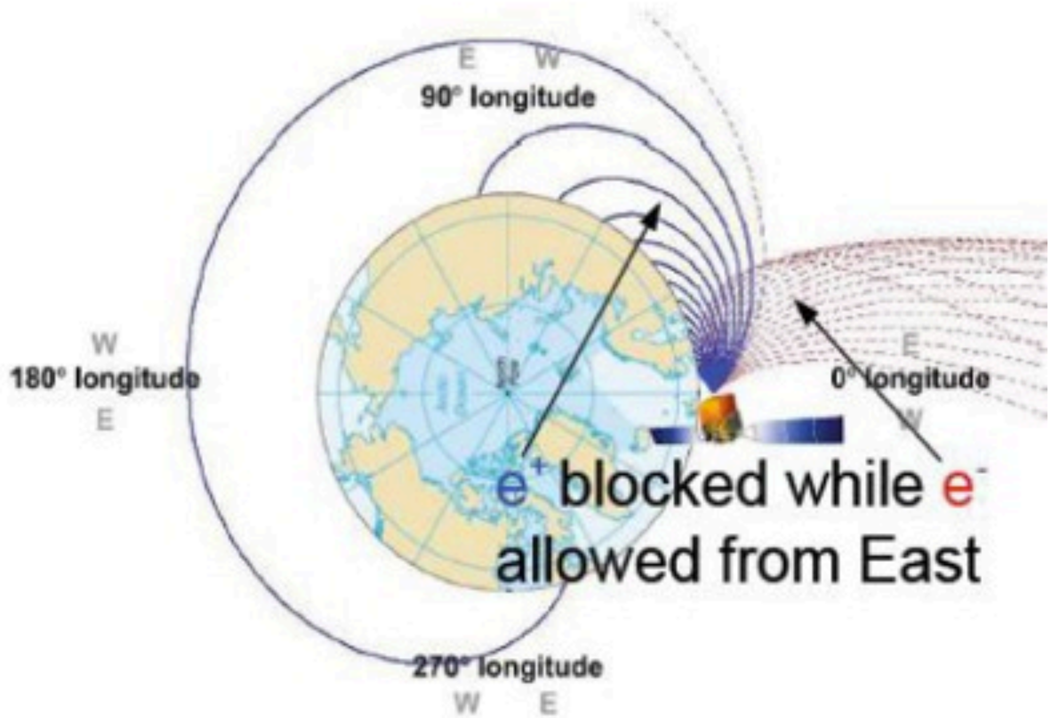
Fermi Positron Fraction

Fermi LAT Collaboration, PRL 108, 011103 (2012)

- Fermi observes increase in positron fraction from 20 to 200GeV consistent with PAMELA
- Positron fraction measurement Uses the Earth's Magnetic Field







Sommerfeld Enhancement

- DM annihilation cross section in the low velocity regime can be enhanced through the "Sommerfeld effect"
  - when non-relativistic particles interact through some kind of force, their wave function is distorted by the presence of a potential
    - In QFT this corresponds to contributions of "ladder" Feynman diagrams
      - gives rise to (non-perturbative) corrections to cross section

$\sigma v = S\ (\sigma v)_0$

"Sommerfeld boost"

tree level cross section times velocity

http://arxiv.org/pdf/0812.0360

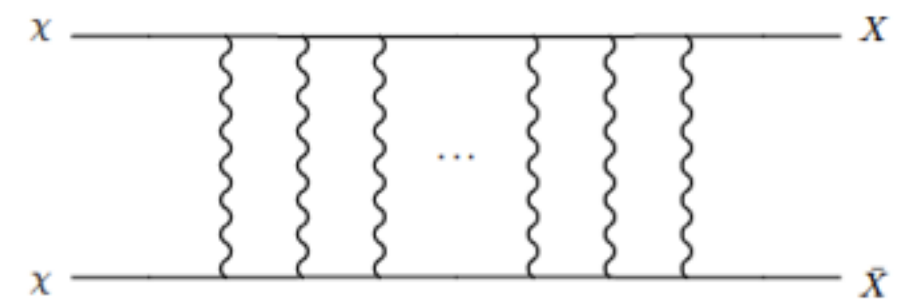


FIG. 1: Ladder diagram giving rise to the Sommerfeld enhancement for $\chi\chi \rightarrow X\overline{X}$ annihilation, via the exchange of gauge bosons.

- Simple case: a particle interacting through Yukawa potential:

Schroedinger Equation

$$\frac{1}{m}\frac{d^2\psi(r)}{dr^2} - V(r)\psi(r) = -m\beta^2\psi(r)$$

Ψ(r) is reduced two-body wave function for s-wave annihilation

V(r)= $-\frac{\alpha}{r}e^{-m_V r}$ attractive Yukawa potential mediated by a boson of mass m_V

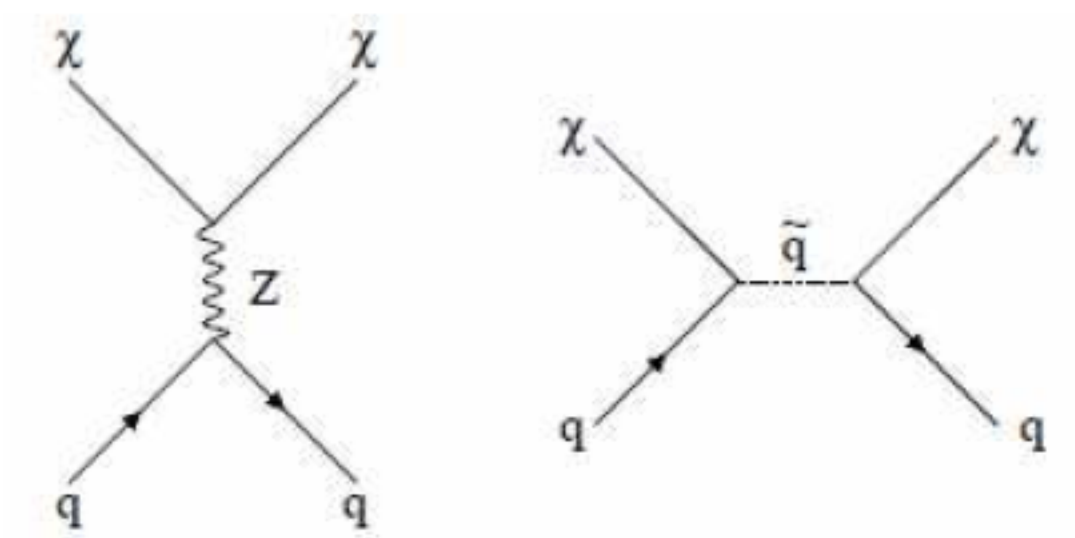
for m_V small the potential becomes Coulomb-like and Schrödinger equation can be solved analytically

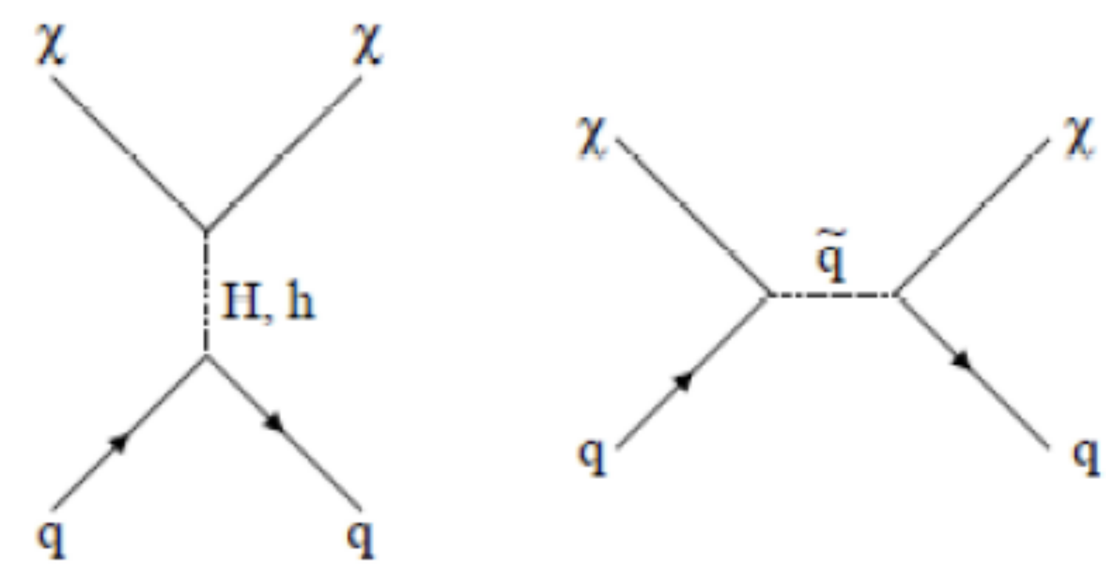
$$S = \frac{\pi\alpha}{\beta}(1 - e^{-\pi\alpha/\beta})^{-1}$$

~1/v

WIMP Nucleon Interaction

- The nucleon coupling of a slow-moving Majorana neutralino (or of any WIMP in the extreme non-relativistic limit) is characterized by two terms: spin-dependent (axial vector) and spin-independent (scalar).





$$\sigma_{SD} = 32\frac{G_F^2\mu^2}{\pi}(a_p\{S_{p(N)}\} + a_n\{S_{n(N)}\})^2\frac{J+1}{J}$$

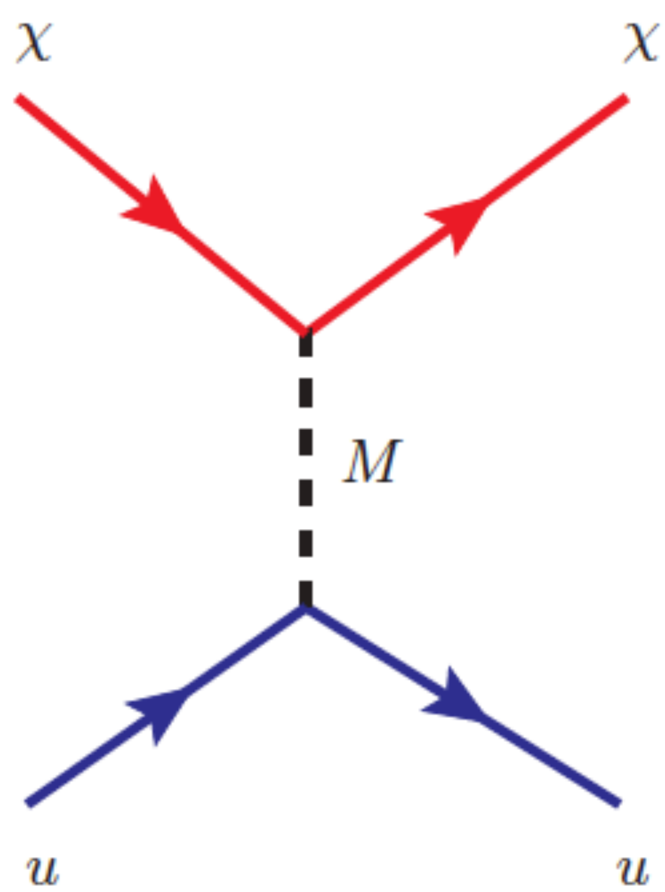
$$\mu = M_\chi M_N \;/\; M_\chi + M_N$$

- J - coupled angular momentum of the nucleus
- $\{S_{n(N)}\}$ spin of neutron in nucleus
- a_n, a_p - coupling constants / G_F - Fermi constant

$$\sigma_{SI} = \frac{4\mu^2}{\pi}(Zf_p + (A-Z)f_n)^2F^2(q)$$

- f_p , f_n - coupling constants to proton and neutron
- $F(q)$ form factor

Accelerator Bounds



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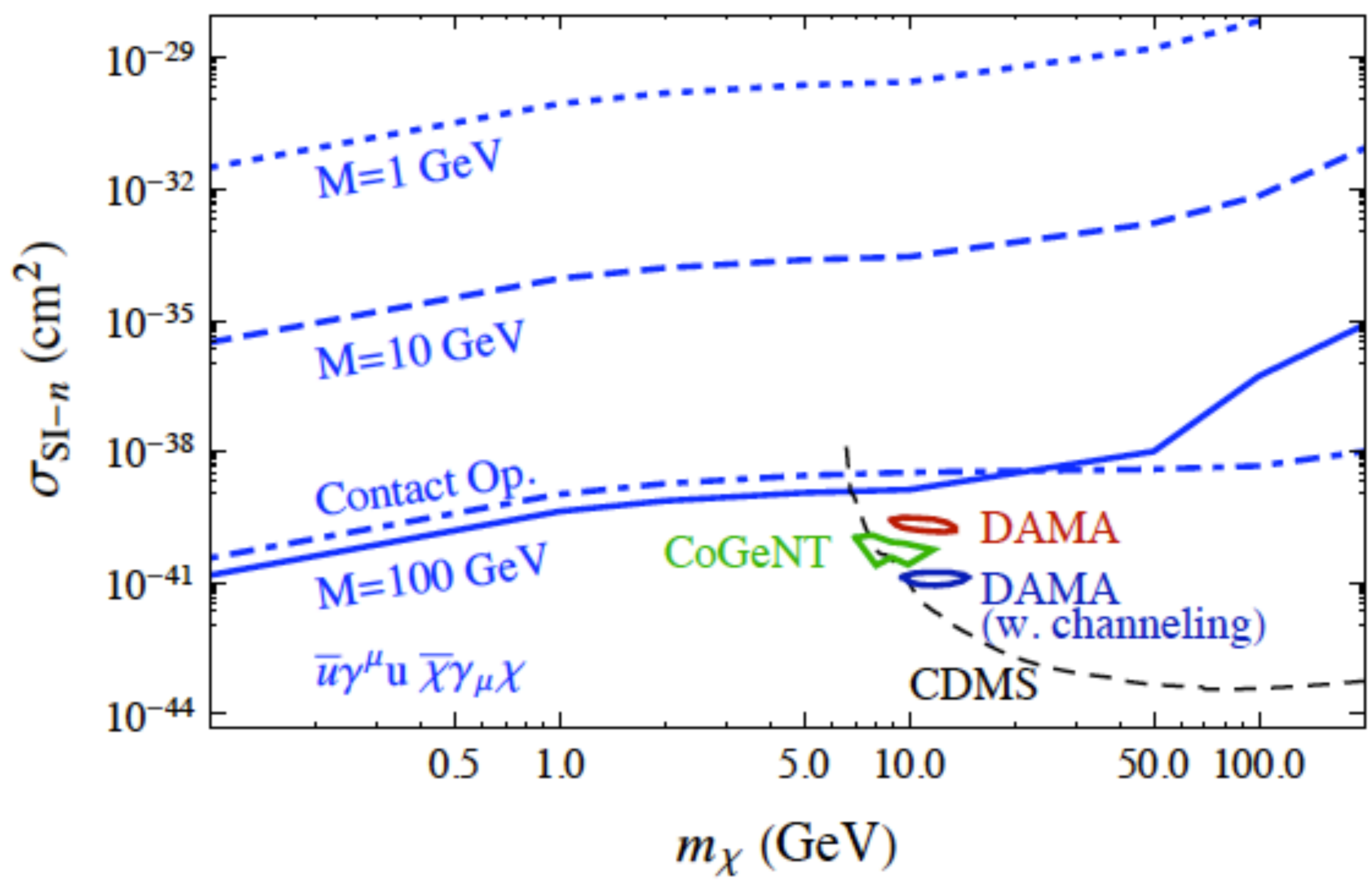


Direct detection enhanced over collider production if exchange has light mediator

$M < p_T(1\,\text{jet})$

velocity dependence

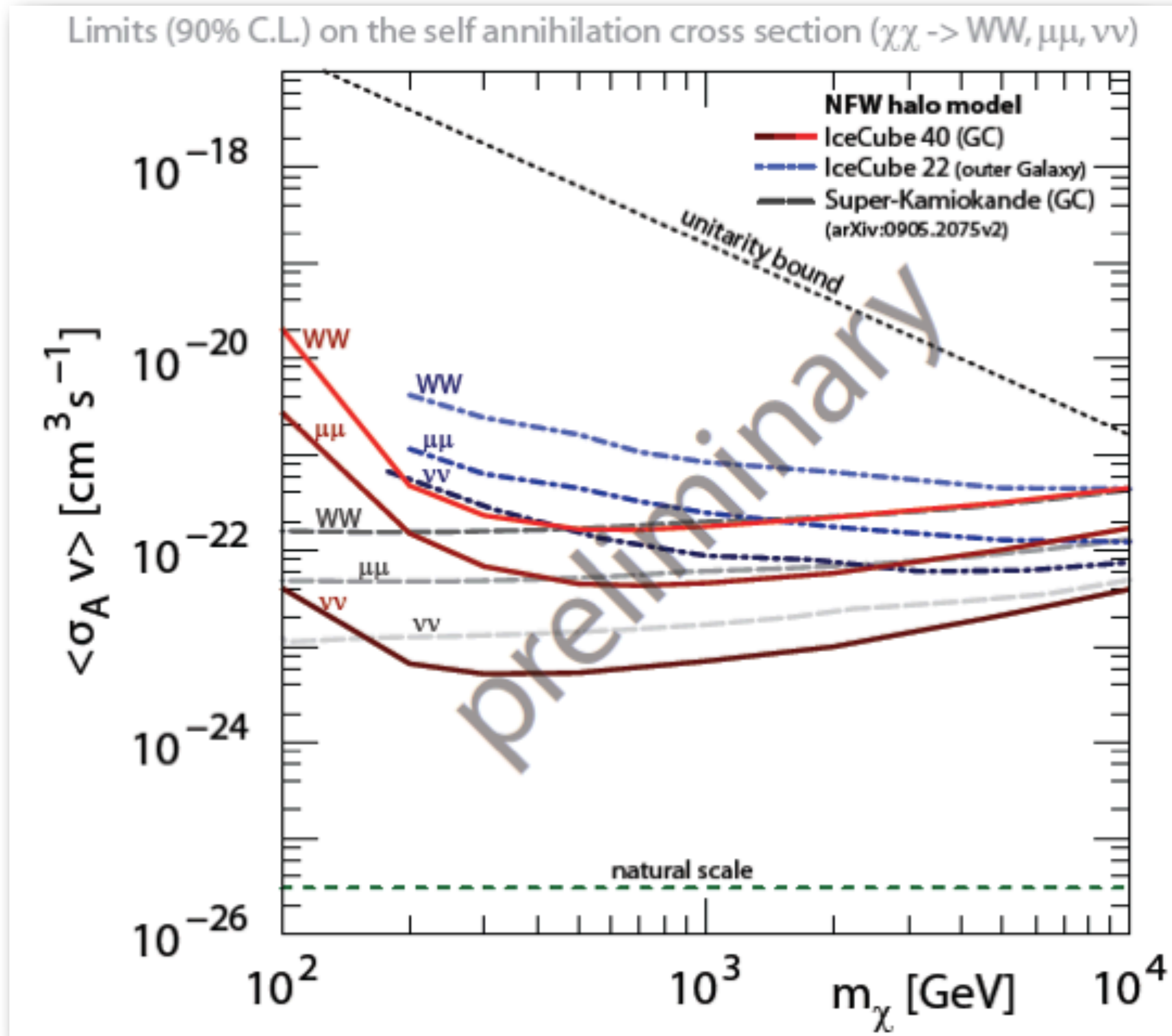
- What is actually being constrained ?

$$\langle \sigma_A v \rangle \approx a + \frac{b}{x}; x = m_\chi / T$$

s-wave p-wave

$$x \sim \frac{1}{v^2}$$

- Relic density is set by full annihilation cross section $\langle \sigma_A v \rangle \approx 3 \times 10^{-26} \frac{cm^3}{s}$
- Indirect detection mostly sensitive to S-wave $\langle \sigma_A v \rangle \approx \langle \sigma_A v \rangle_{v \to 0} \approx a$



Accelerator Bounds - Monojets

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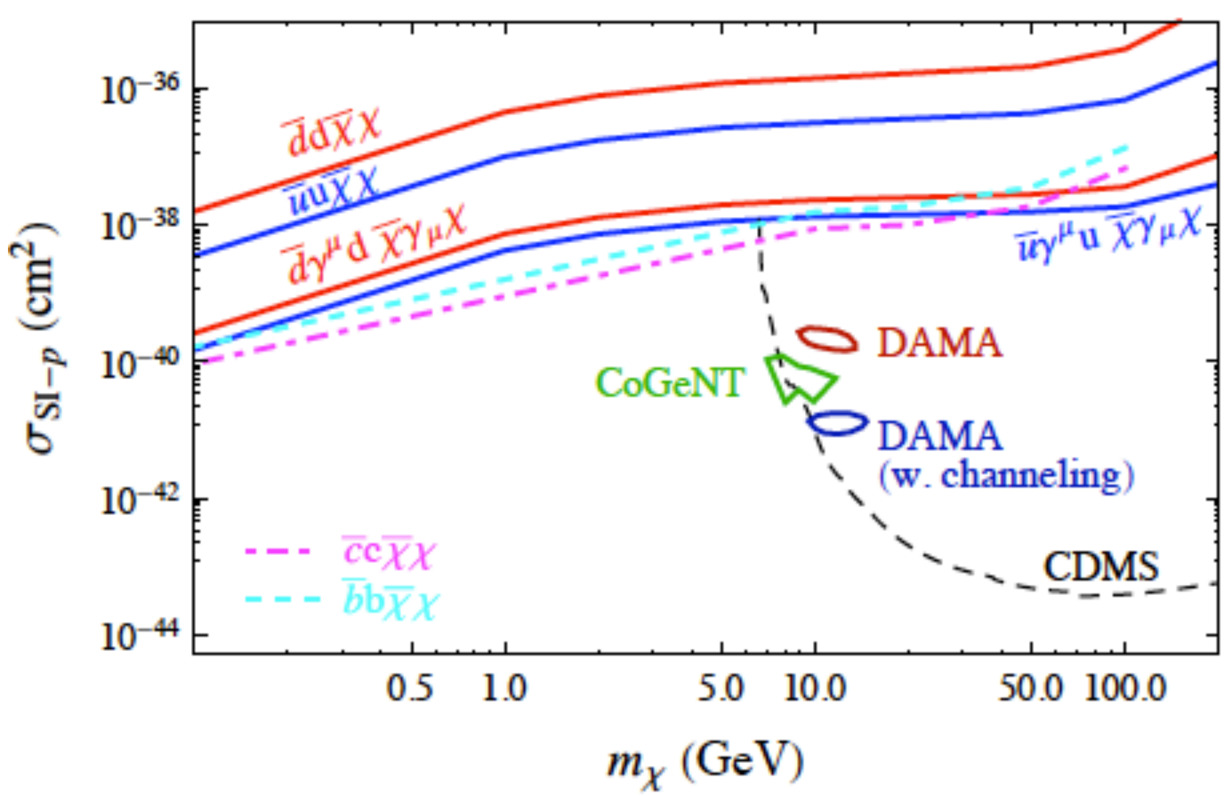

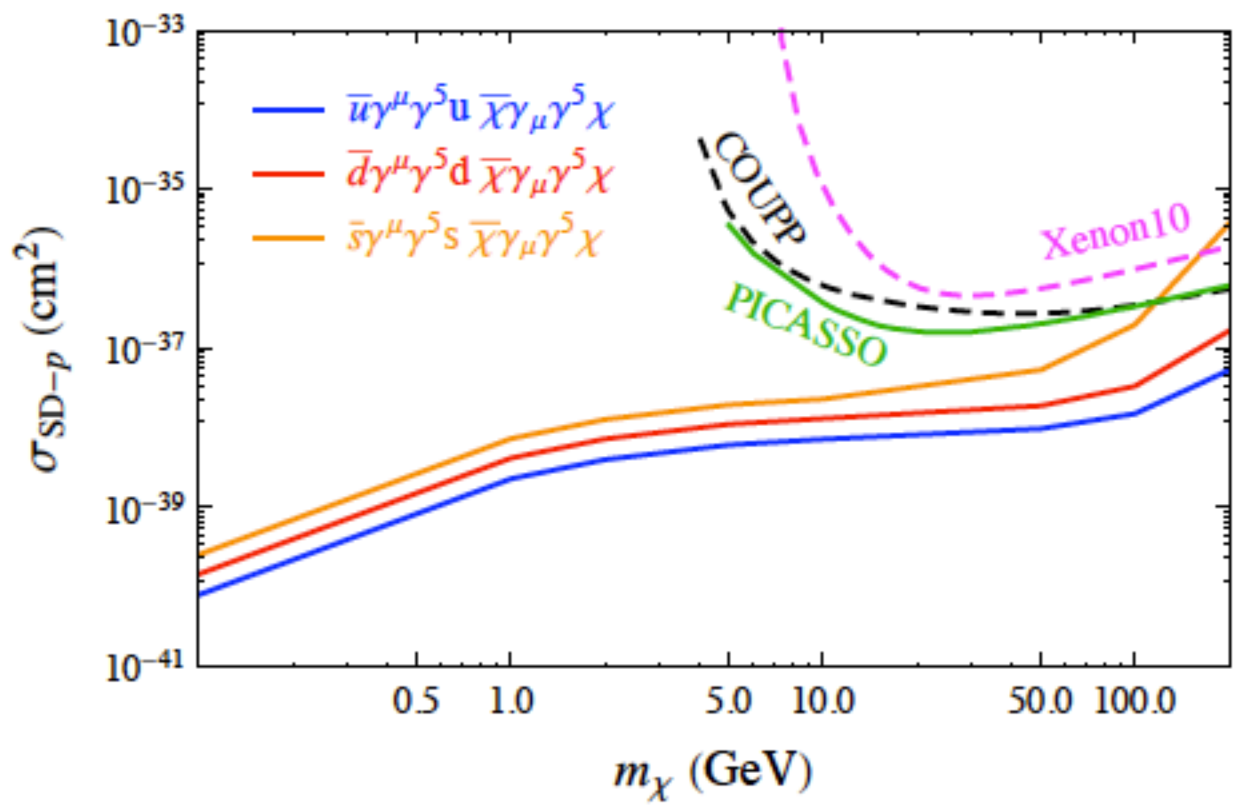

Paper analyzed implications of CDF monojet search in "direct detection" plane