Dark Matter

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Summer School
on Particle Physics
ICTP, Trieste
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Production of gamma-rays

The gamma ray flux from dark matter annihilations/decays has two components:

- Inverse Compton Scattering radiation of electrons/positrons produced in the annihilation/decay.
- Always smooth spectrum.

- Prompt radiation of gamma rays produced in the annihilation/decay (final state radiation, pion decay...)
- May contain spectral features.

Inverse Compton Scattering radiation

The inverse Compton scattering of electrons/positrons from dark matter annihilation/decay with the interstellar and extragalactic radiation fields produces gamma rays.

$$e^{\pm} + \gamma \rightarrow e^{\pm} + \gamma^{*}$$

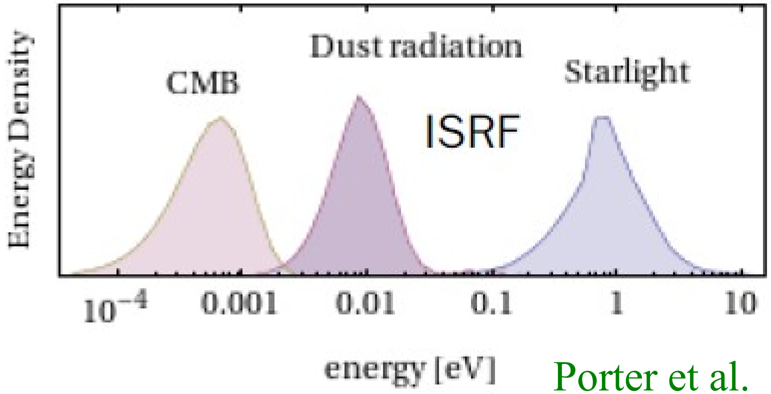
$e^{\pm}$ from dark matter annihilation/decay
$E_e \lesssim 1$ TeV

Upscattered photon

$$E_{\gamma^*} \leq 4 \left(\frac{E_e}{m_e} \right)^2 E_\gamma$$

This produces
$E_{\gamma*} \lesssim 100$ GeV

Interstellar radiation field (starlight, thermal radiation of dust, CMB)



Porter et al.

Prompt radiation

Annihilation

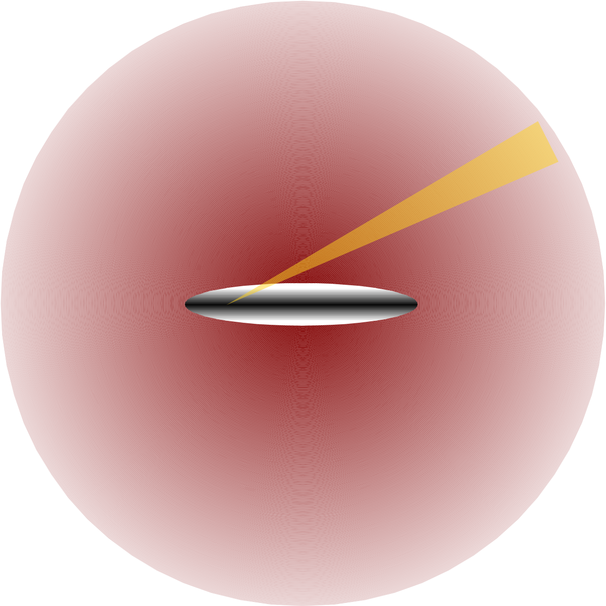
$$\frac{dJ}{dE_\gamma} = \frac{1}{4\pi}\underbrace{\left[\frac{\langle\sigma_{\rm ann}v\rangle}{2m_{\rm DM}^2}\sum_f \frac{dN_\gamma^f}{dE_\gamma}B_f\right]} \times \underbrace{\int_{\rm l.o.s.}\rho^2(\vec{l})\,d\vec{l}}$$

Source term
(particle physics)

Line-of-sight integral
(astrophysics)

Decay

$$\frac{dJ}{dE_\gamma} = \frac{1}{4\pi}\overbrace{\left[\frac{1}{\tau_{\rm DM}\,m_{\rm DM}}\sum_f \frac{dN_\gamma^f}{dE_\gamma}B_f\right]} \times \overbrace{\int_{\rm l.o.s.}\rho(\vec{l})\,d\vec{l}}$$



Prompt radiation

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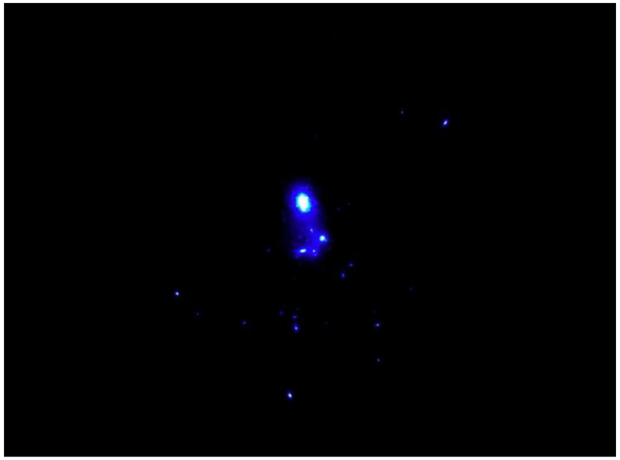

Source term
(particle physics)

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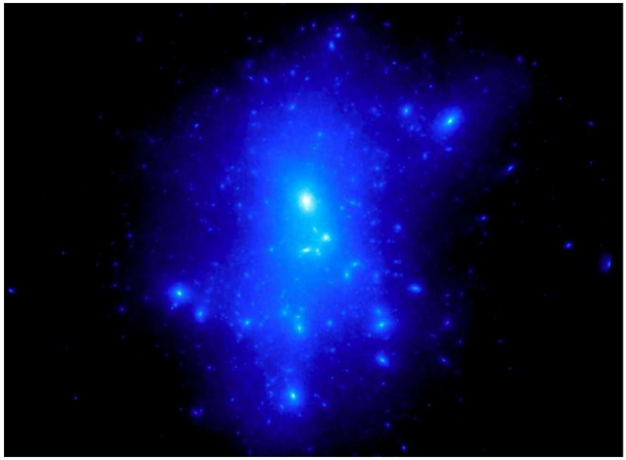
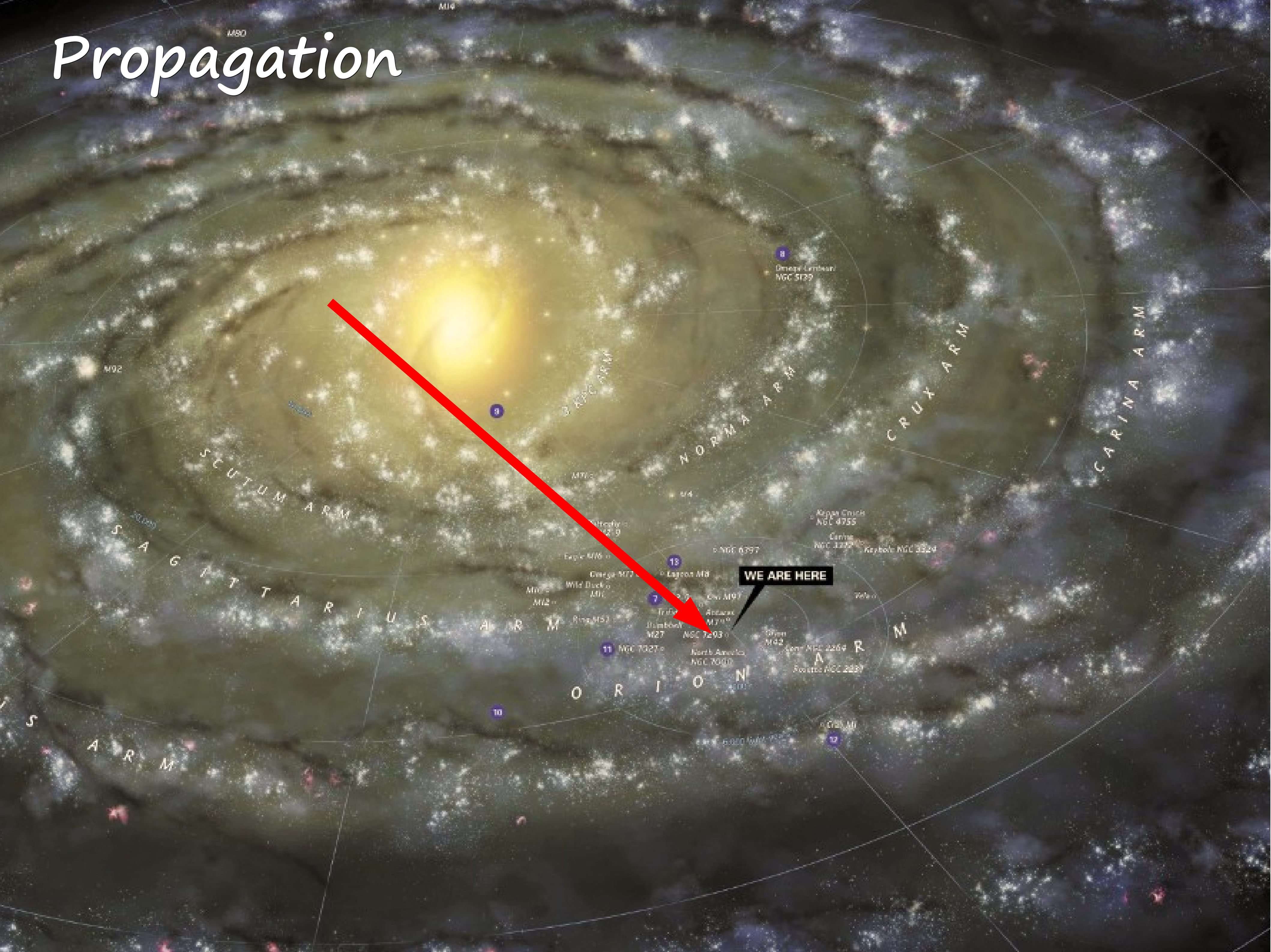
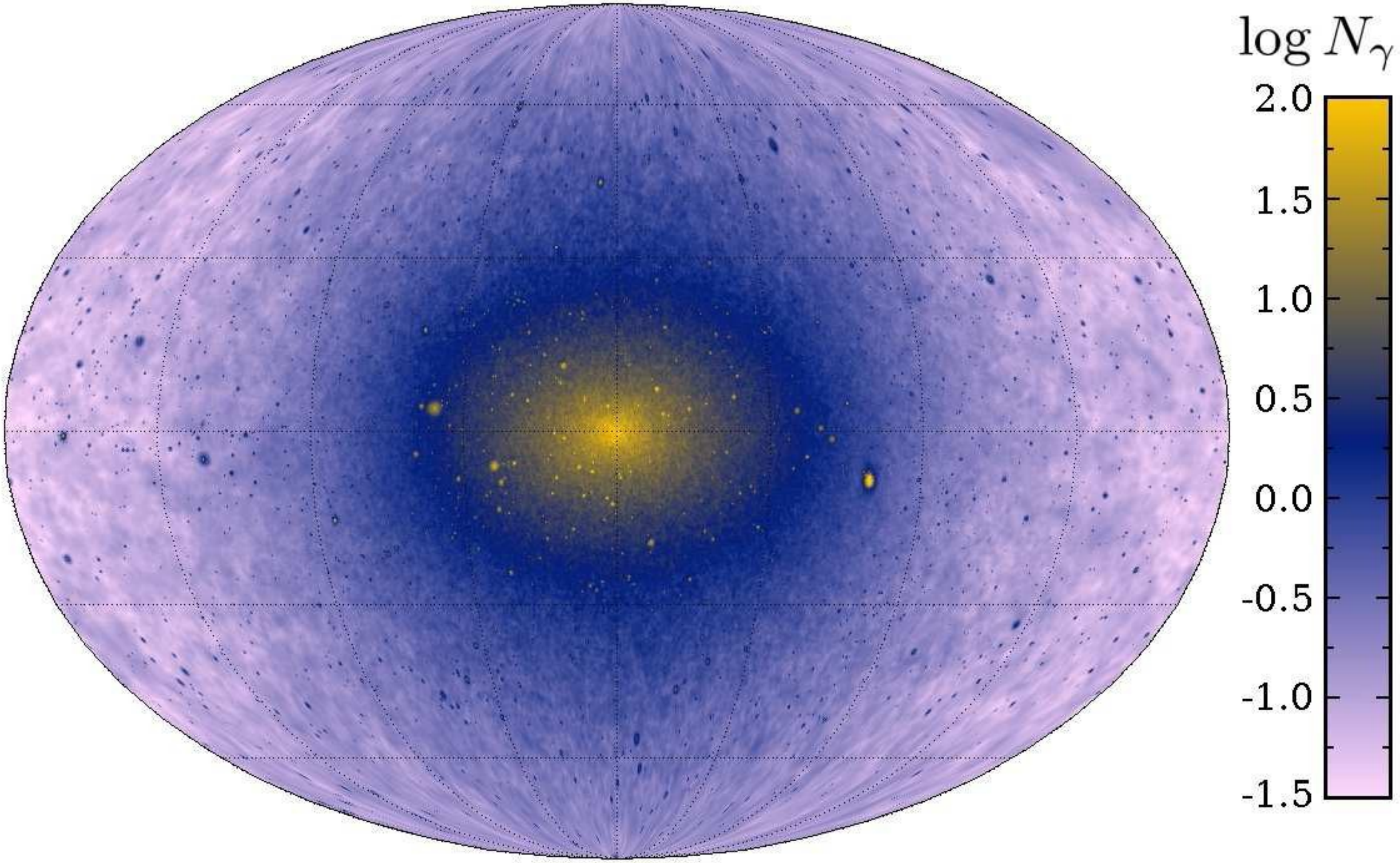


Propagation



Where to look for annihilating dark matter

Baltz et al.
arXiv:0806.2911



Kuhlen, Diemand, Madau

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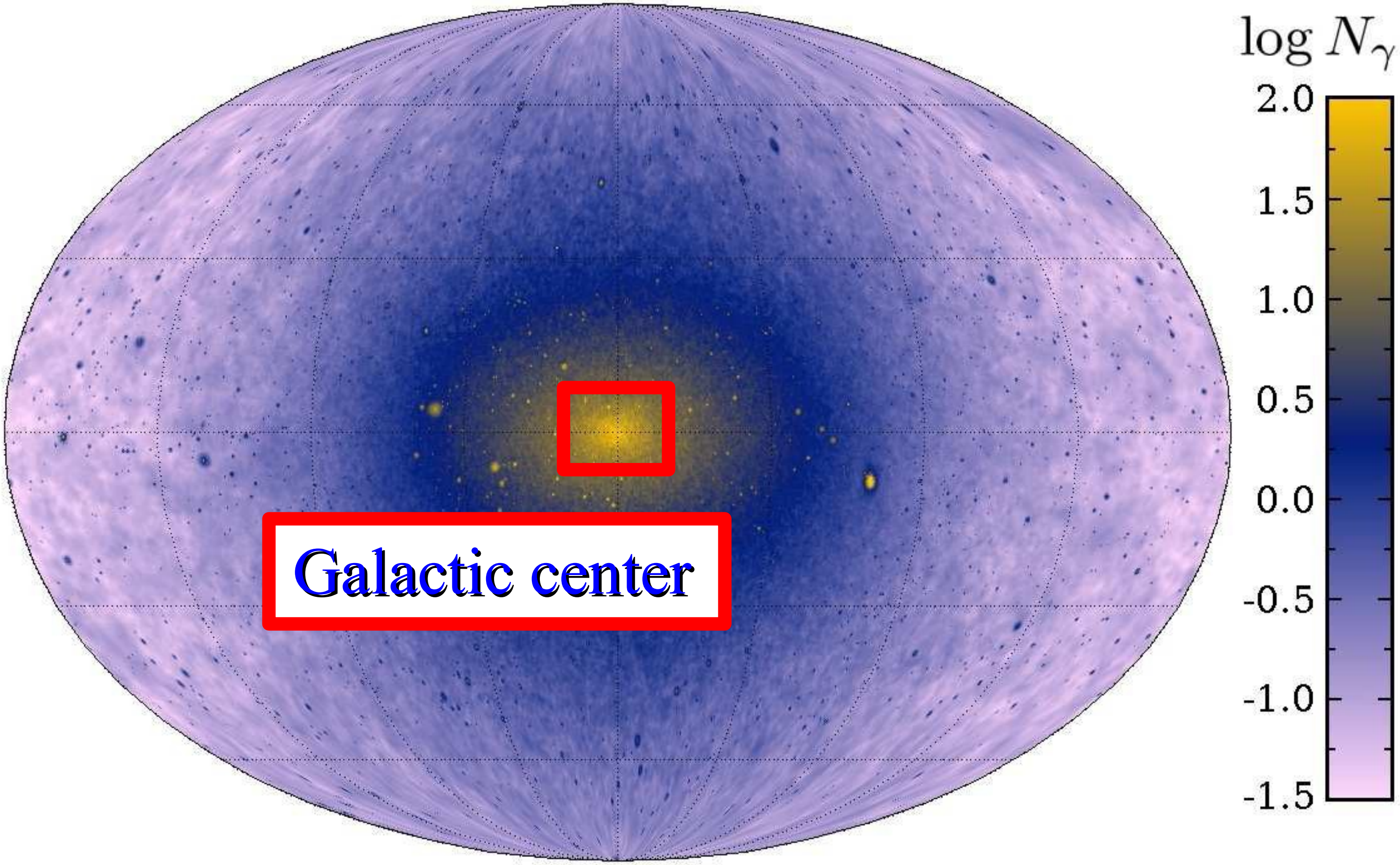

Galactic center

Kuhlen, Diemand, Madau

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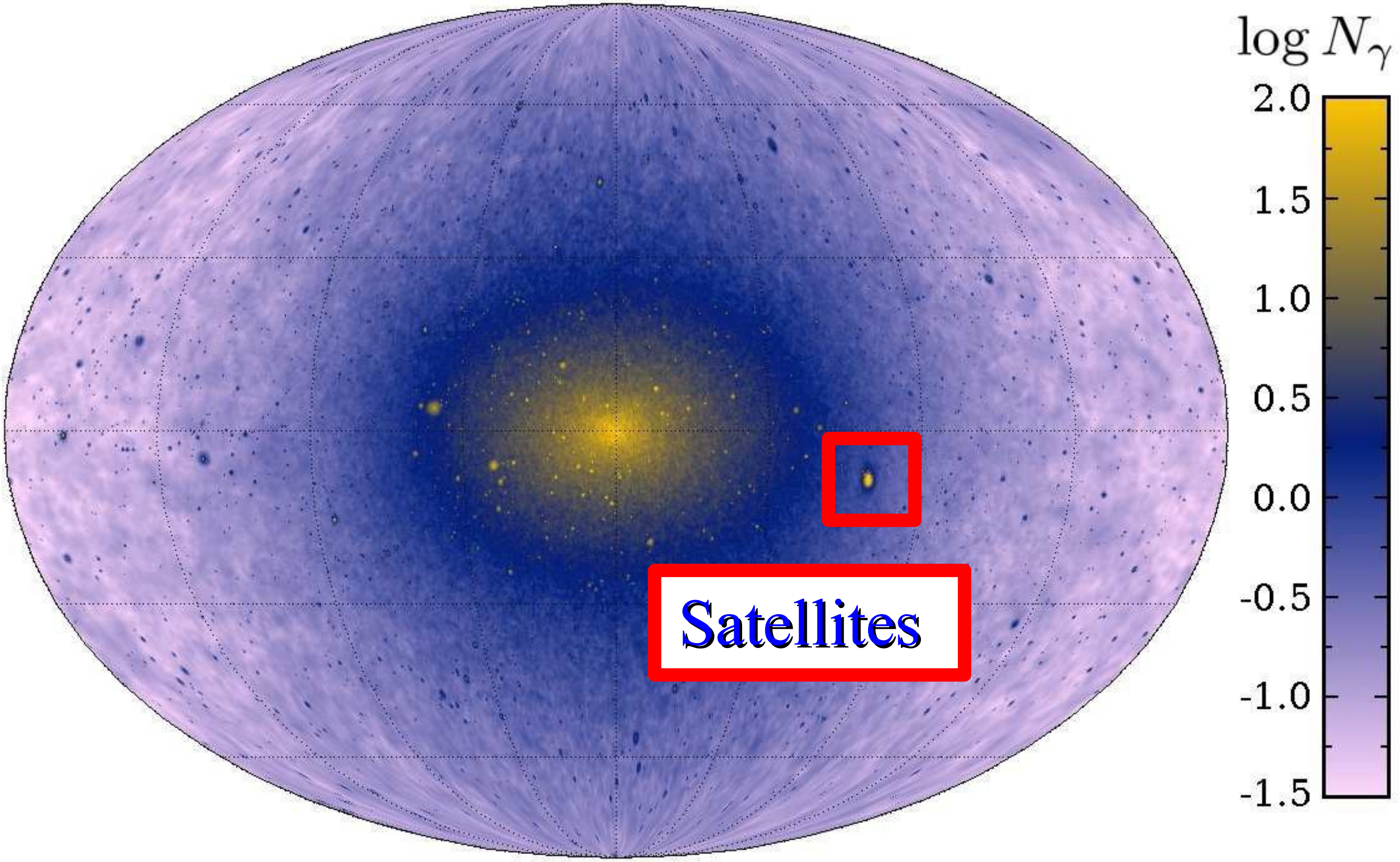

Satellites

Kuhlen, Diemand, Madau

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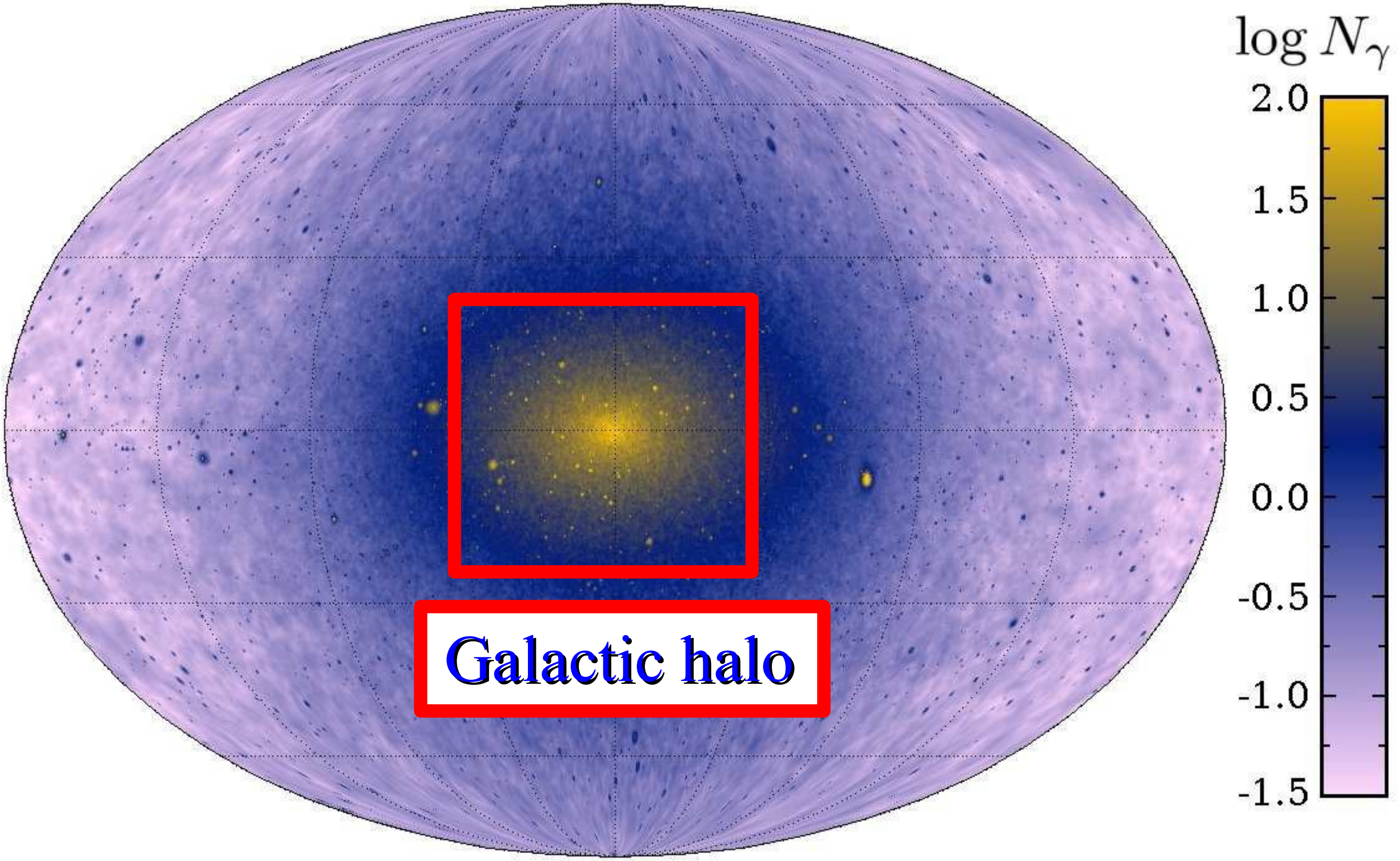

Galactic halo

Kuhlen, Diemand, Madau

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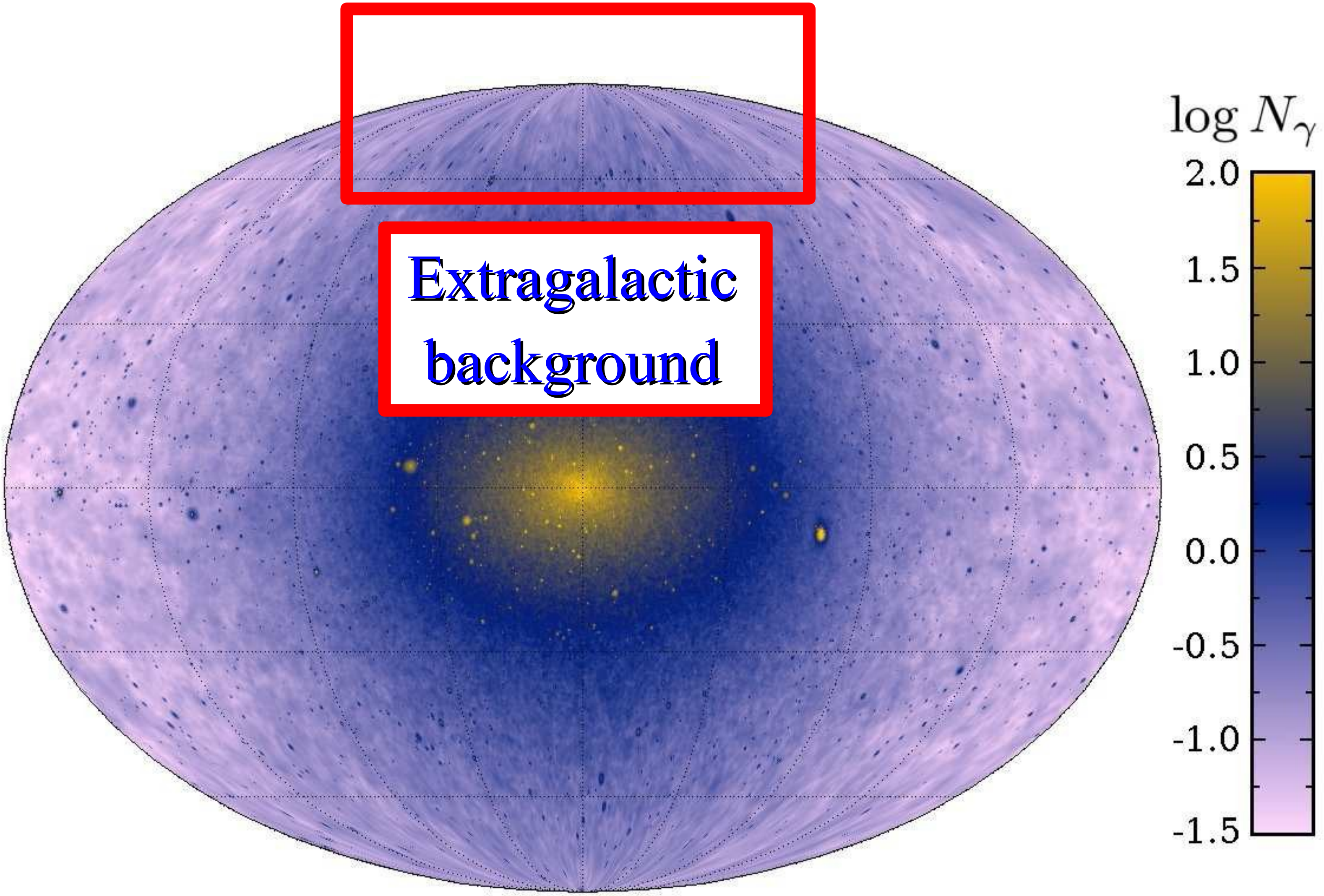
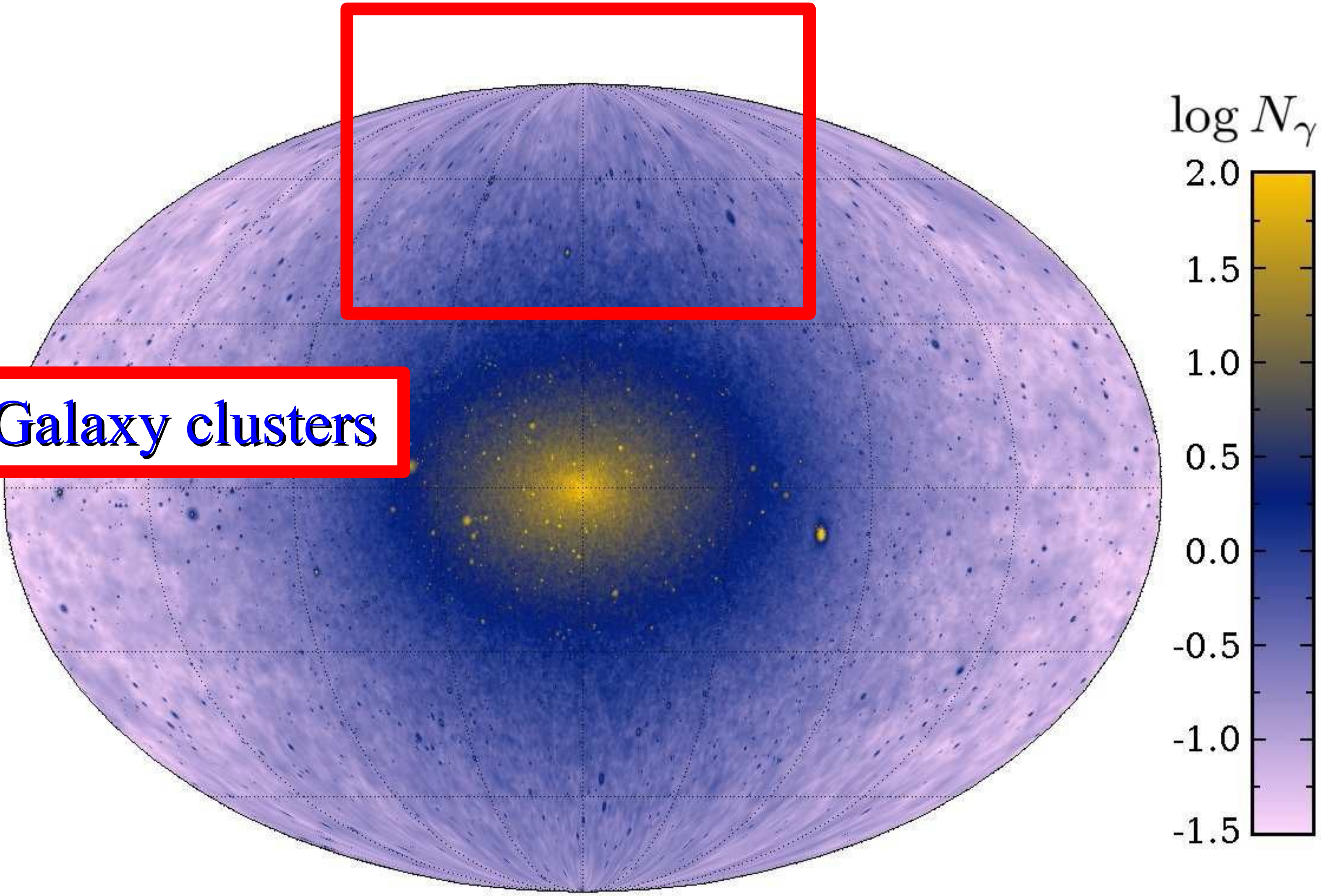


Extragalactic background

Kuhlen, Diemand, Madau

Where to look for annihilating dark matter

Baltz et al.
arXiv:0806.2911

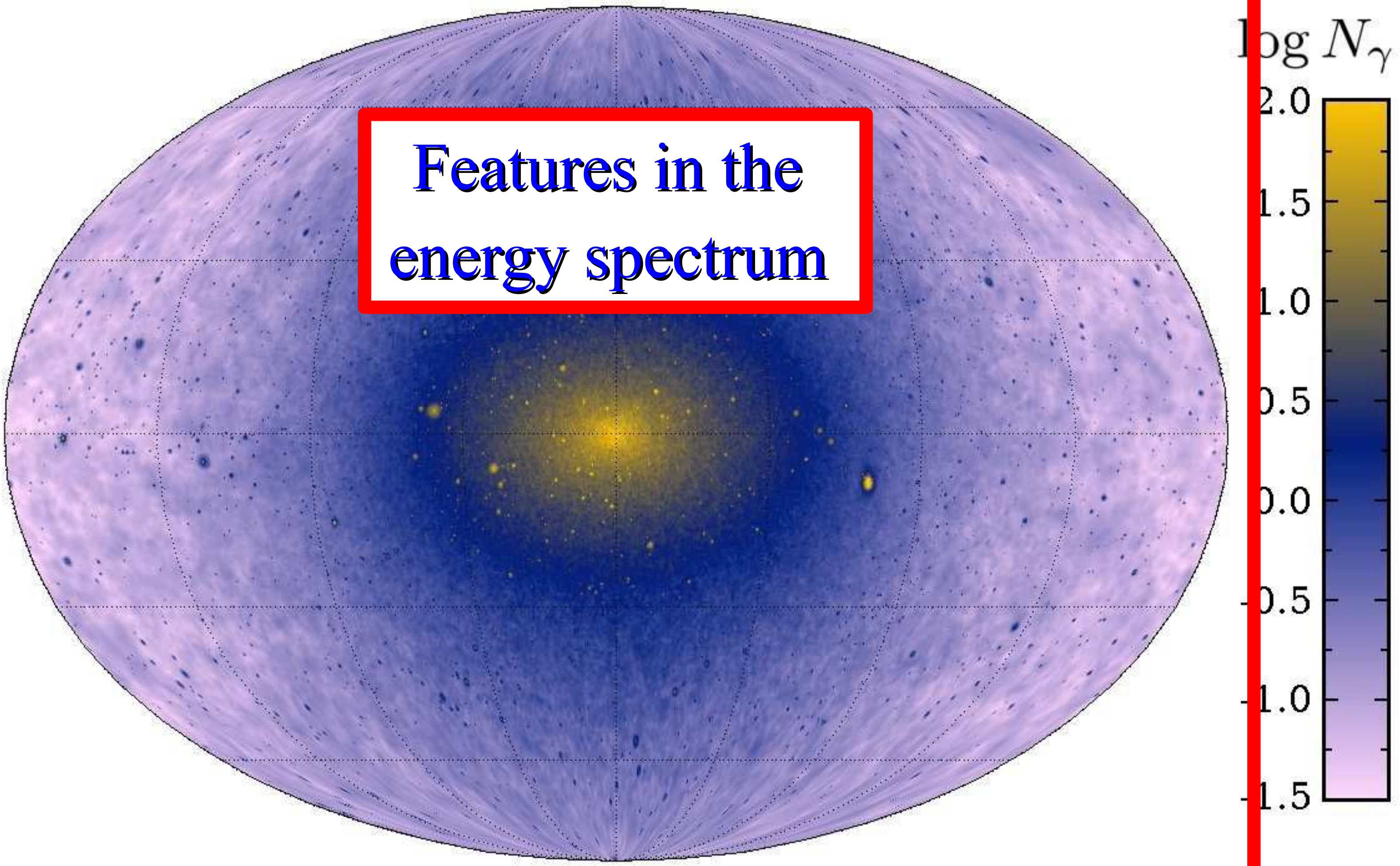


Galaxy clusters

Kuhlen, Diemand, Madau

Where to look for annihilating dark matter

Baltz et al.
arXiv:0806.2911

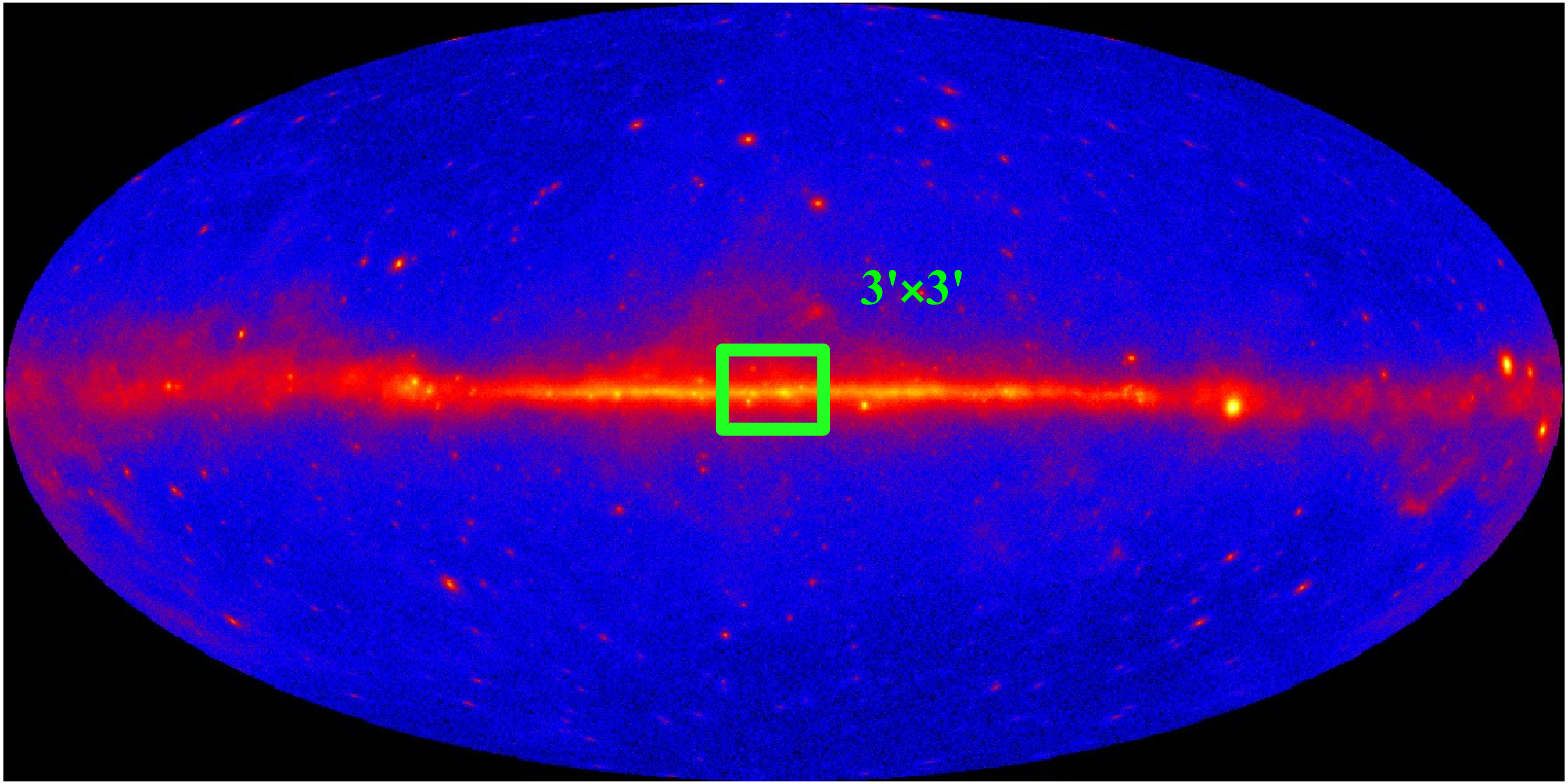


Features in the energy spectrum

Kuhlen, Diema d, Madau

Diffuse Galactic emission

Divide the sky in different regions:



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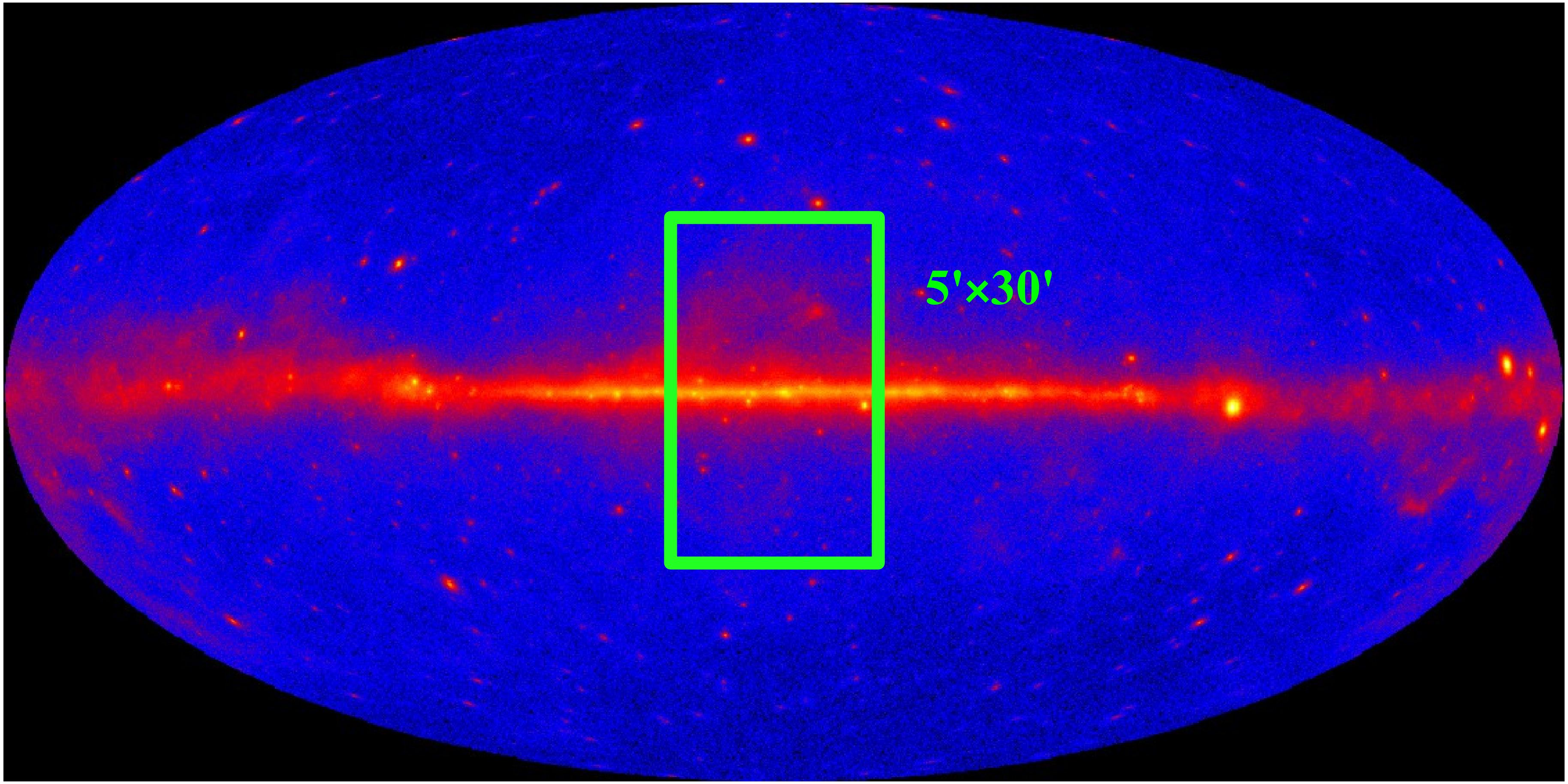

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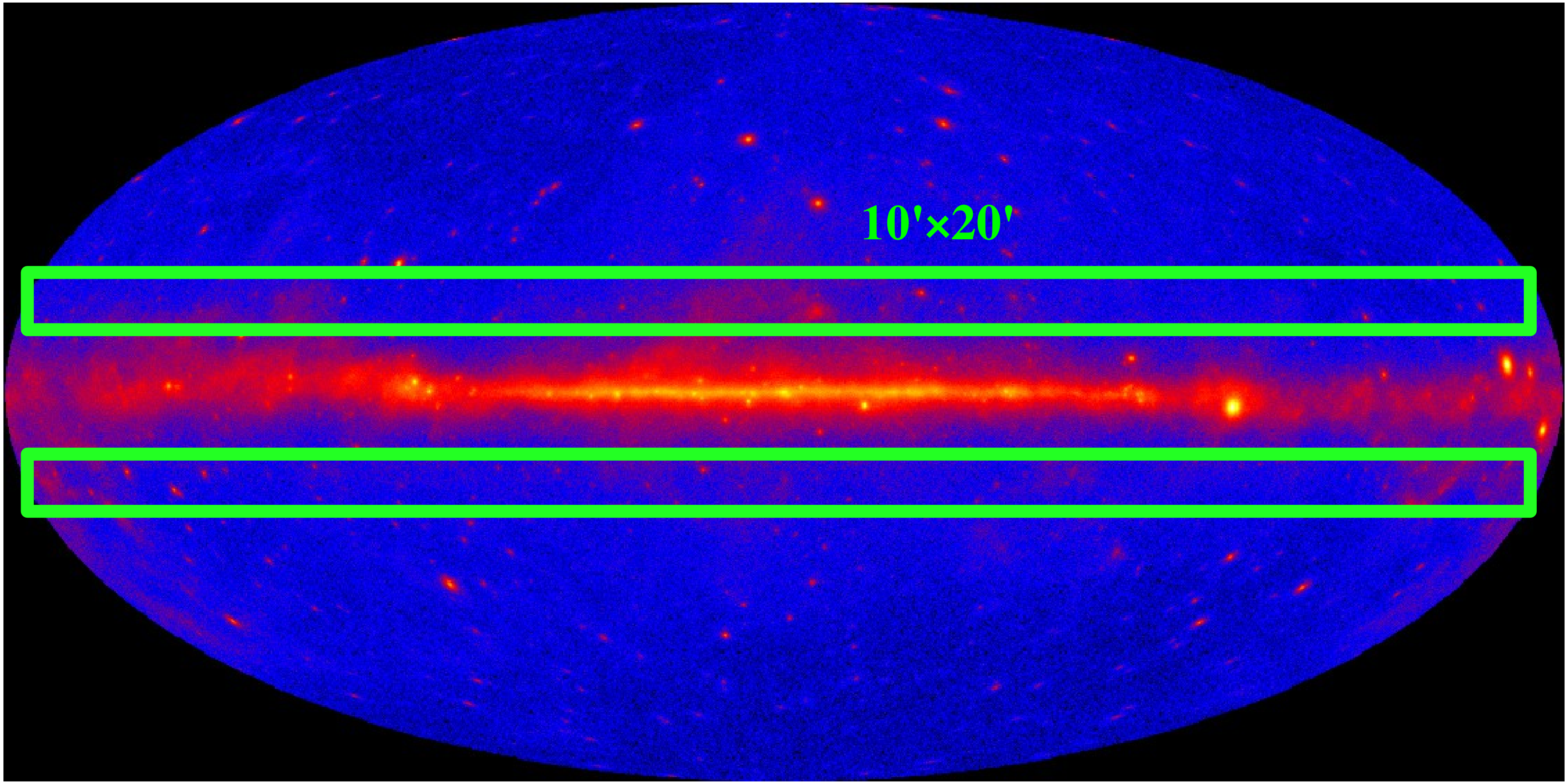

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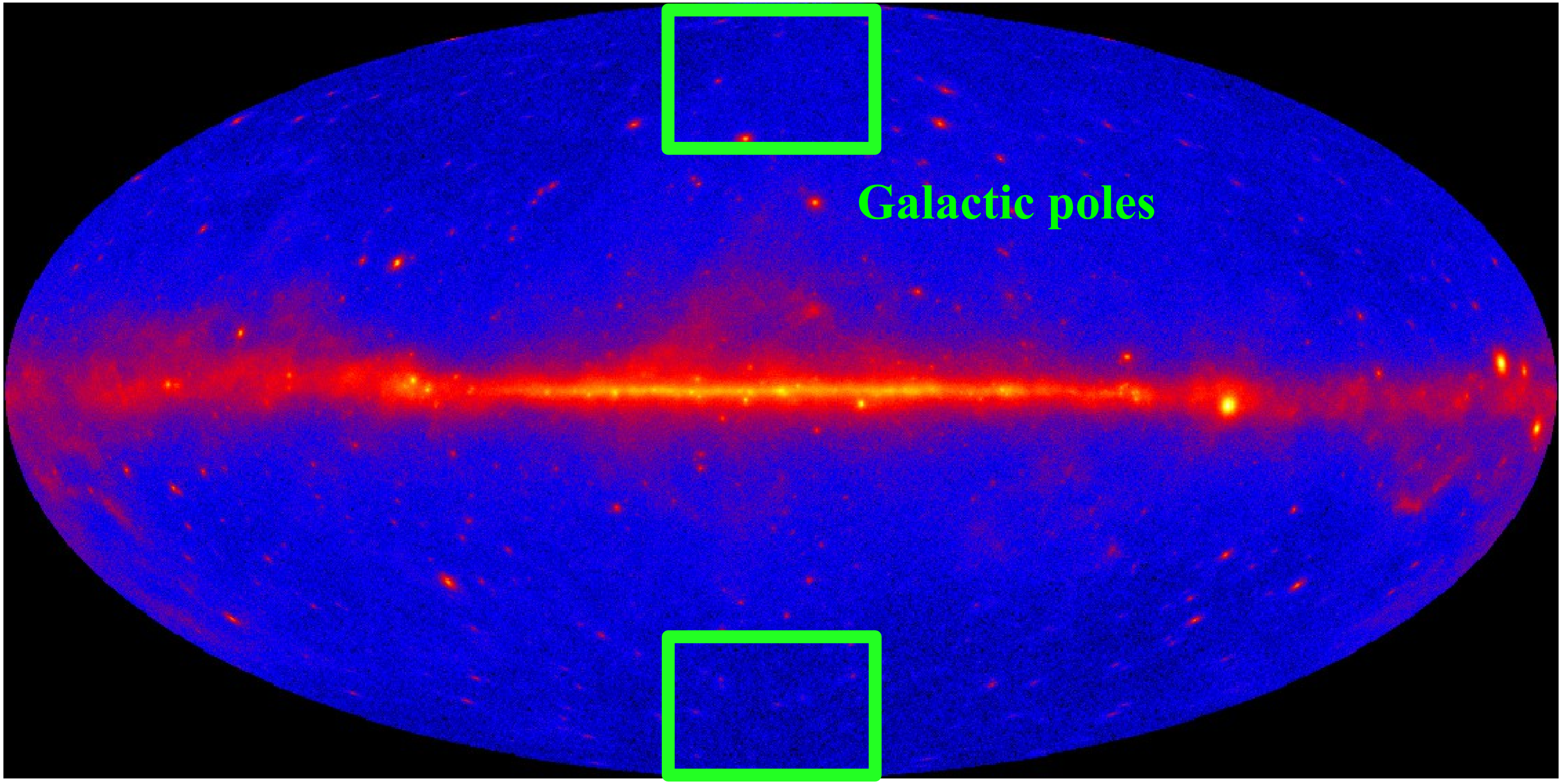
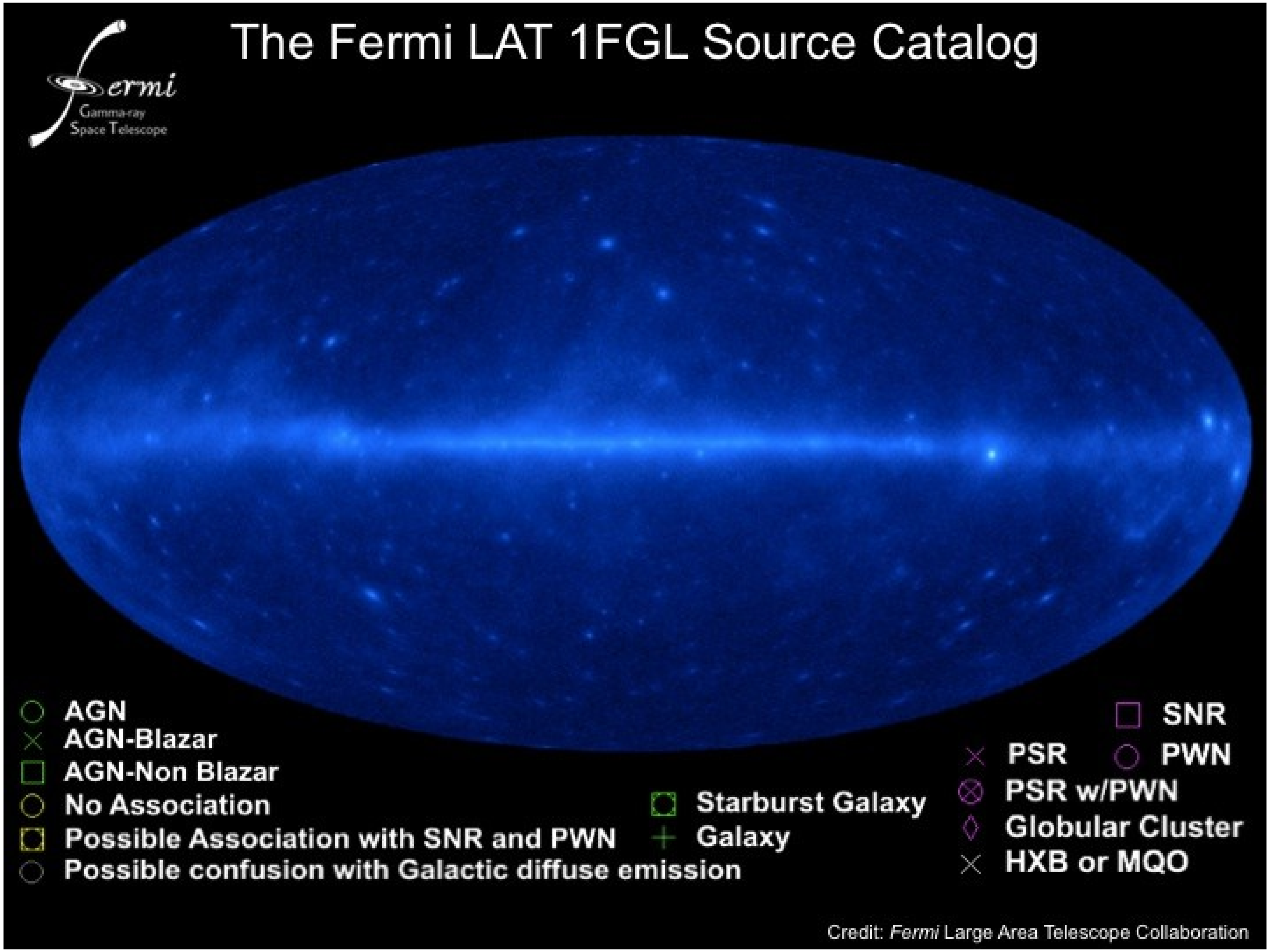


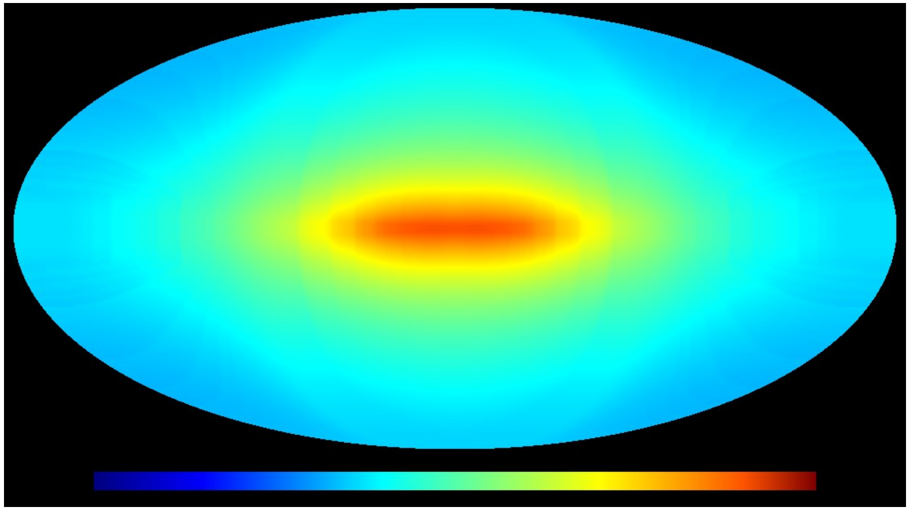
But beware of backgrounds when searching for dark matter...

Background I: sources

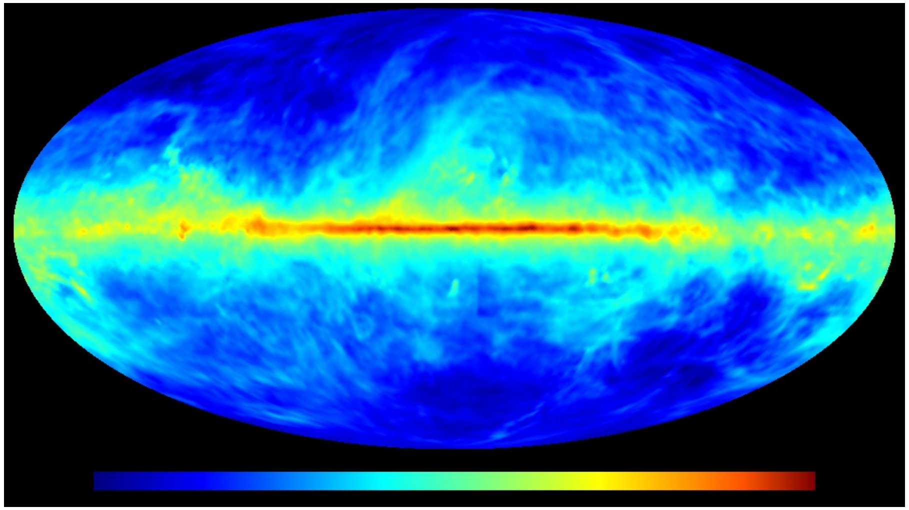


Credit: *Fermi* Large Area Telescope Collaboration

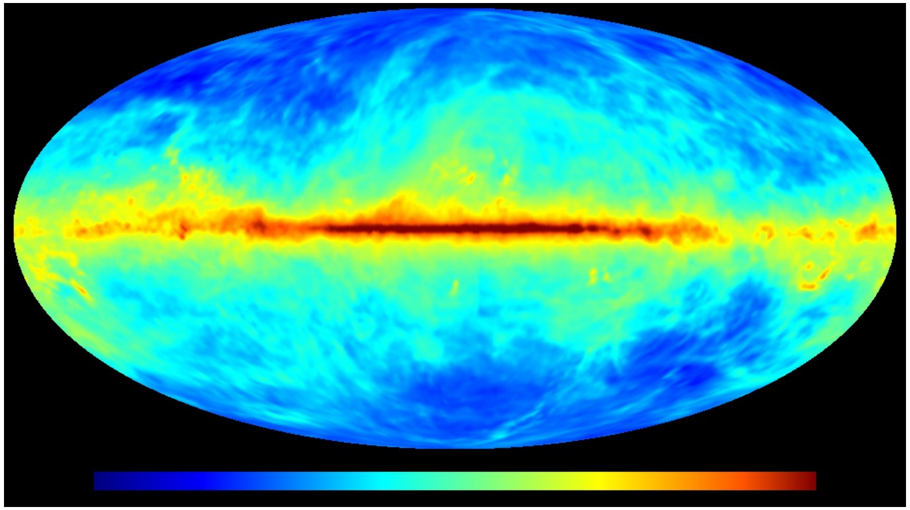
Background II: modelling of the diffuse emission



Inverse compton

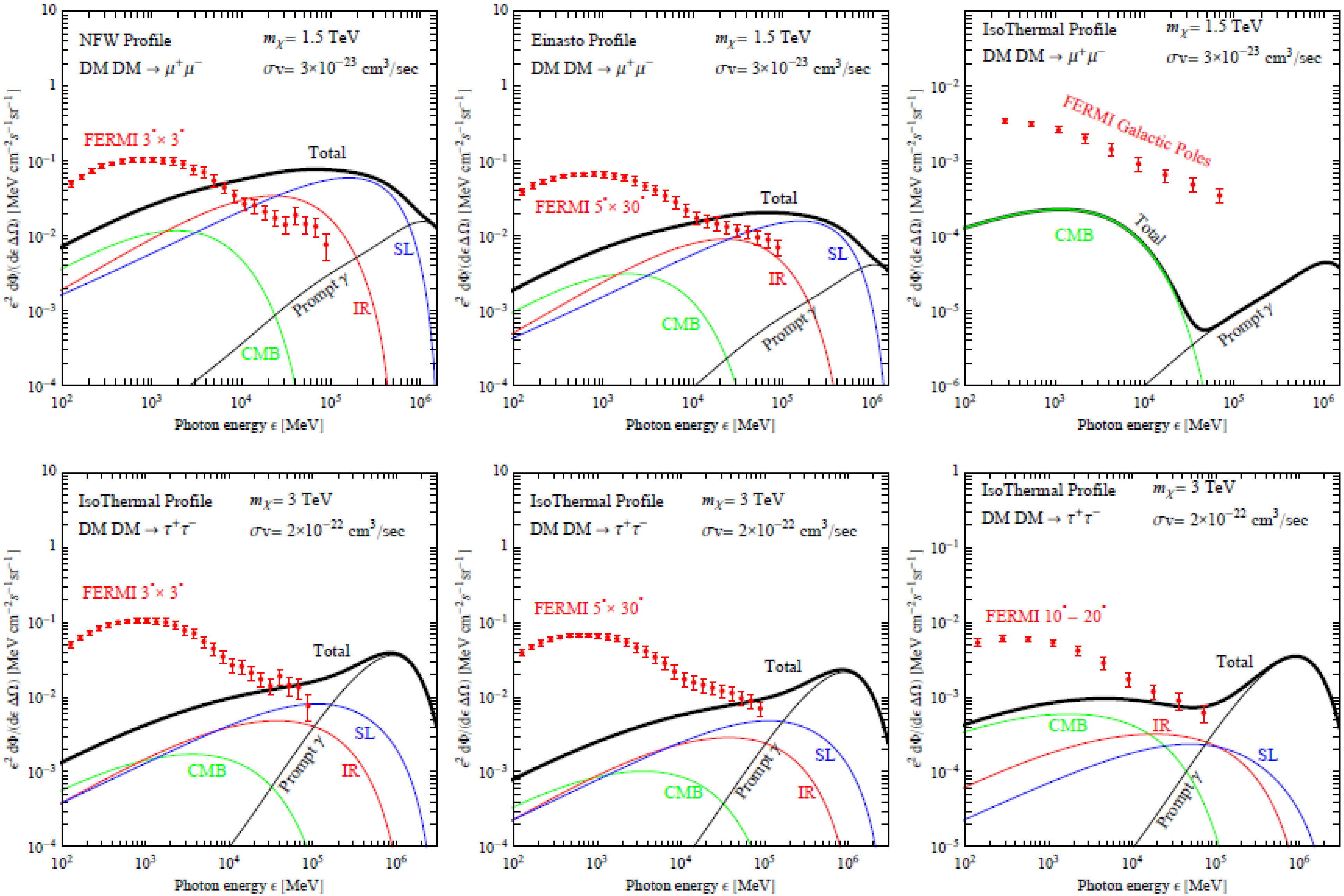


bremmstrahlung

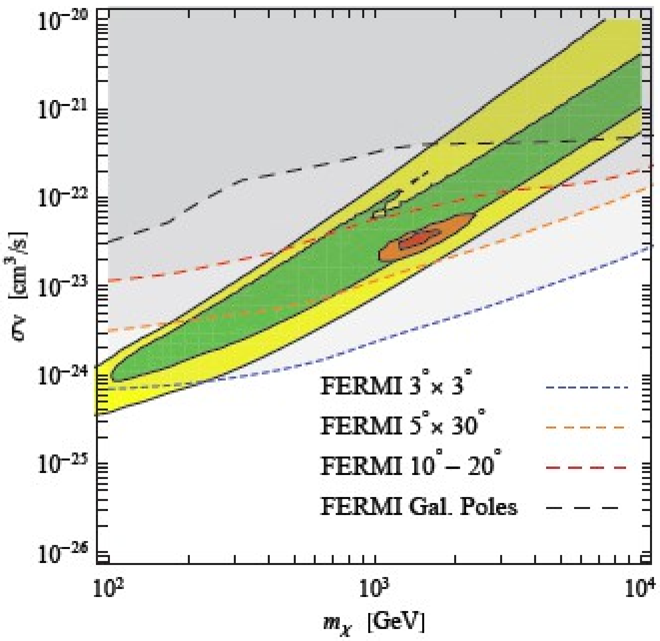


π^0-decay

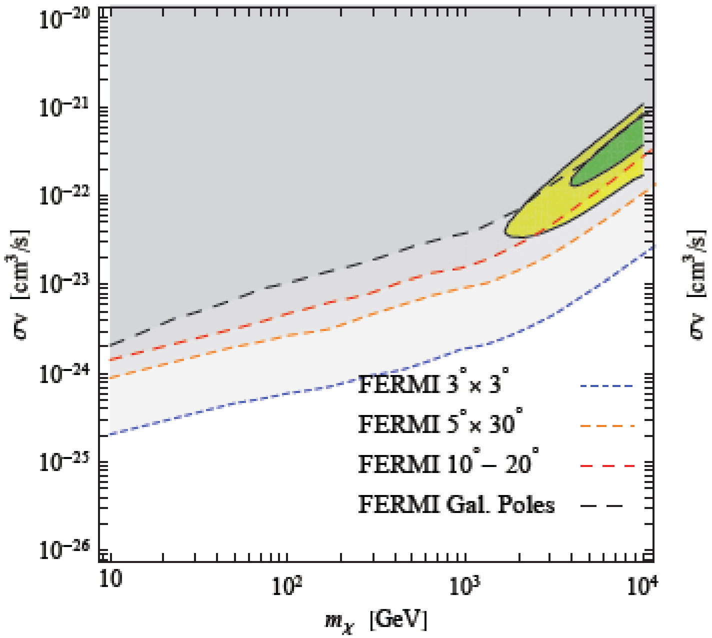
Conservative approach: demand that the flux from dark matter does not exceed the measured flux



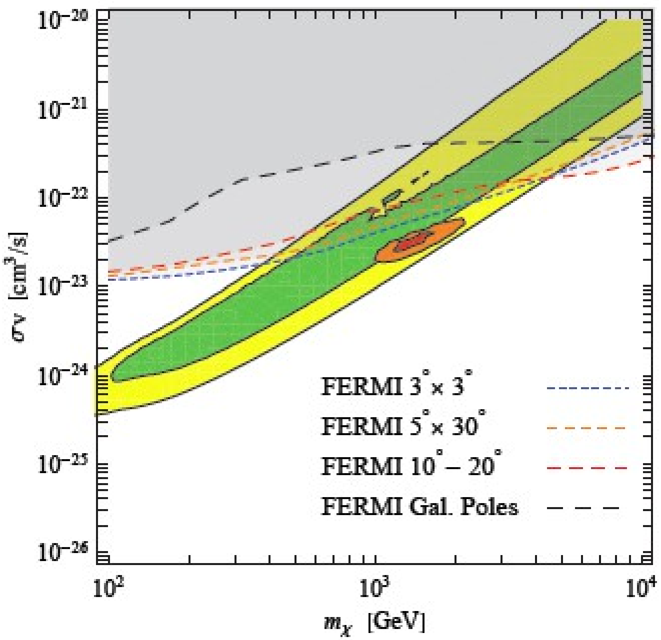
Cirelli, Panci, Serpico



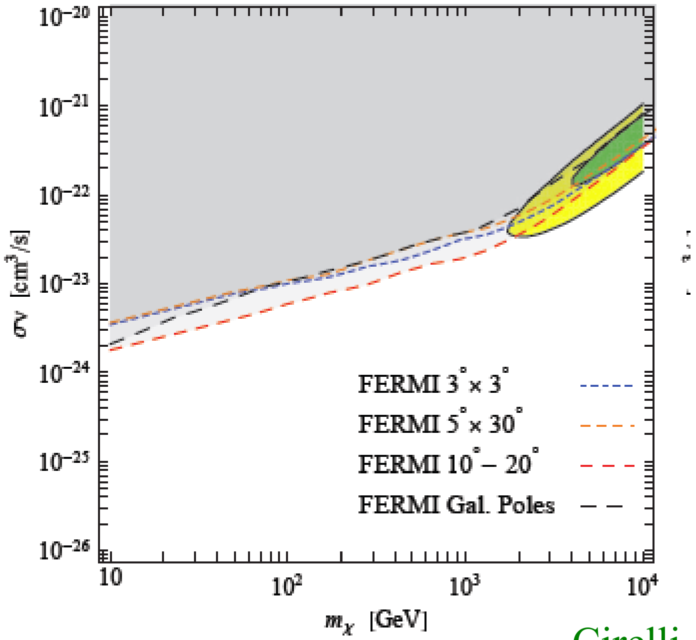
DM DM $\to \mu\mu$, Einasto profile



DM DM $\to$ bb, Einasto profile



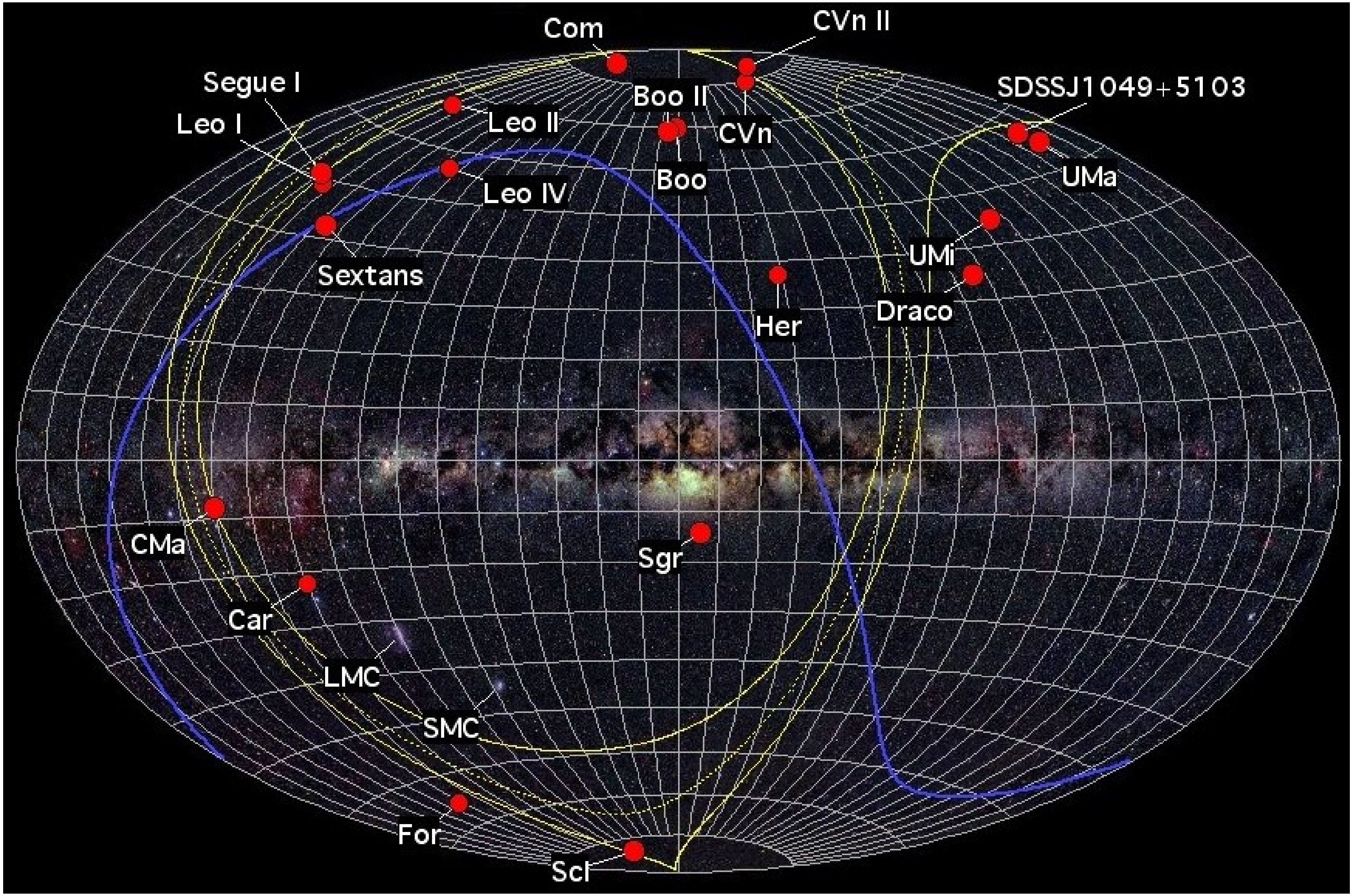
DM DM $\to \mu\mu$, Iso profile

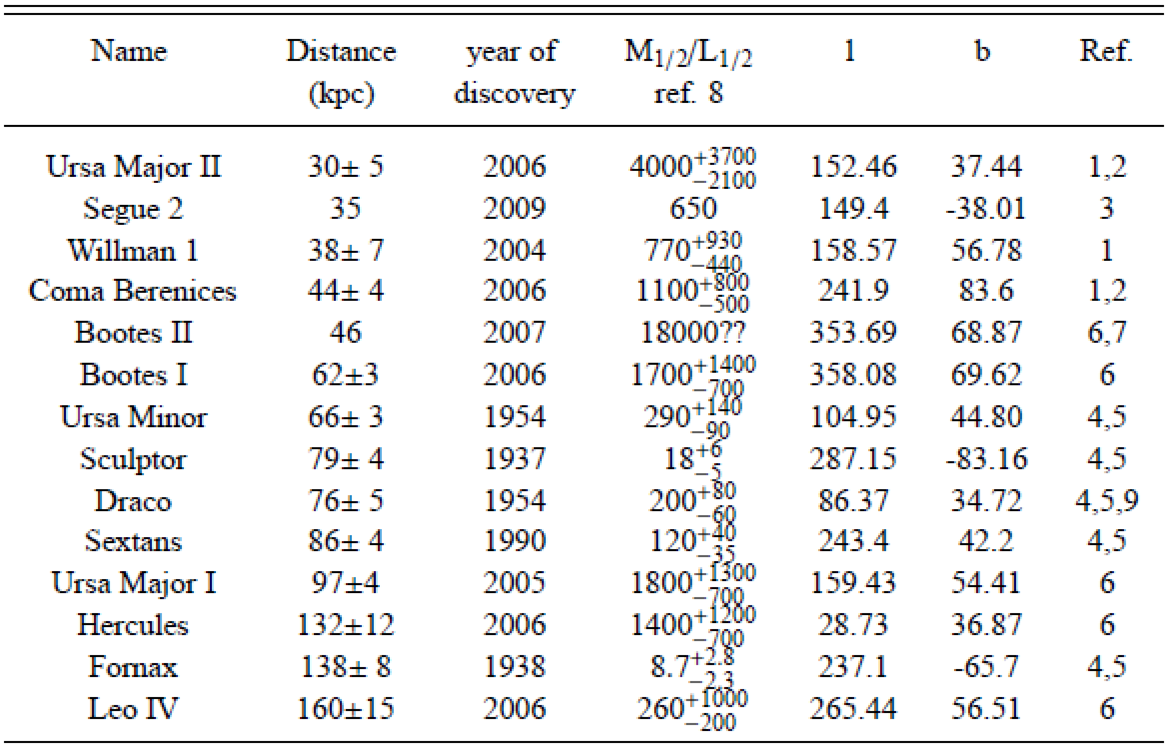


DM DM $\to$ bb, Iso profile

Cirelli, Panci, Serpico

Dwarf spheroidal galaxies





Name	Distance (kpc)	year of discovery	$M_{1/2}/L_{1/2}$ ref. 8	l	b	Ref.
Ursa Major II	30± 5	2006	4000^{+3700}_{-2100}	152.46	37.44	1,2
Segue 2	35	2009	650	149.4	-38.01	3
Willman 1	38± 7	2004	770^{+930}_{-440}	158.57	56.78	1
Coma Berenices	44± 4	2006	1100^{+800}_{-500}	241.9	83.6	1,2
Bootes II	46	2007	18000??	353.69	68.87	6,7
Bootes I	62±3	2006	1700^{+1400}_{-700}	358.08	69.62	6
Ursa Minor	66± 3	1954	290^{+140}_{-90}	104.95	44.80	4,5
Sculptor	79± 4	1937	18^{+6}_{-5}	287.15	-83.16	4,5
Draco	76± 5	1954	200^{+80}_{-60}	86.37	34.72	4,5,9
Sextans	86± 4	1990	120^{+40}_{-35}	243.4	42.2	4,5
Ursa Major I	97±4	2005	1800^{+1300}_{-700}	159.43	54.41	6
Hercules	132±12	2006	1400^{+1200}_{-700}	28.73	36.87	6
Fornax	138± 8	1938	$8.7^{+2.8}_{-2.3}$	237.1	-65.7	4,5
Leo IV	160±15	2006	260^{+1000}_{-200}	265.44	56.51	6

Relatively close

High mass-to-light ratio: dwarf galaxies contain large amounts of dark matter

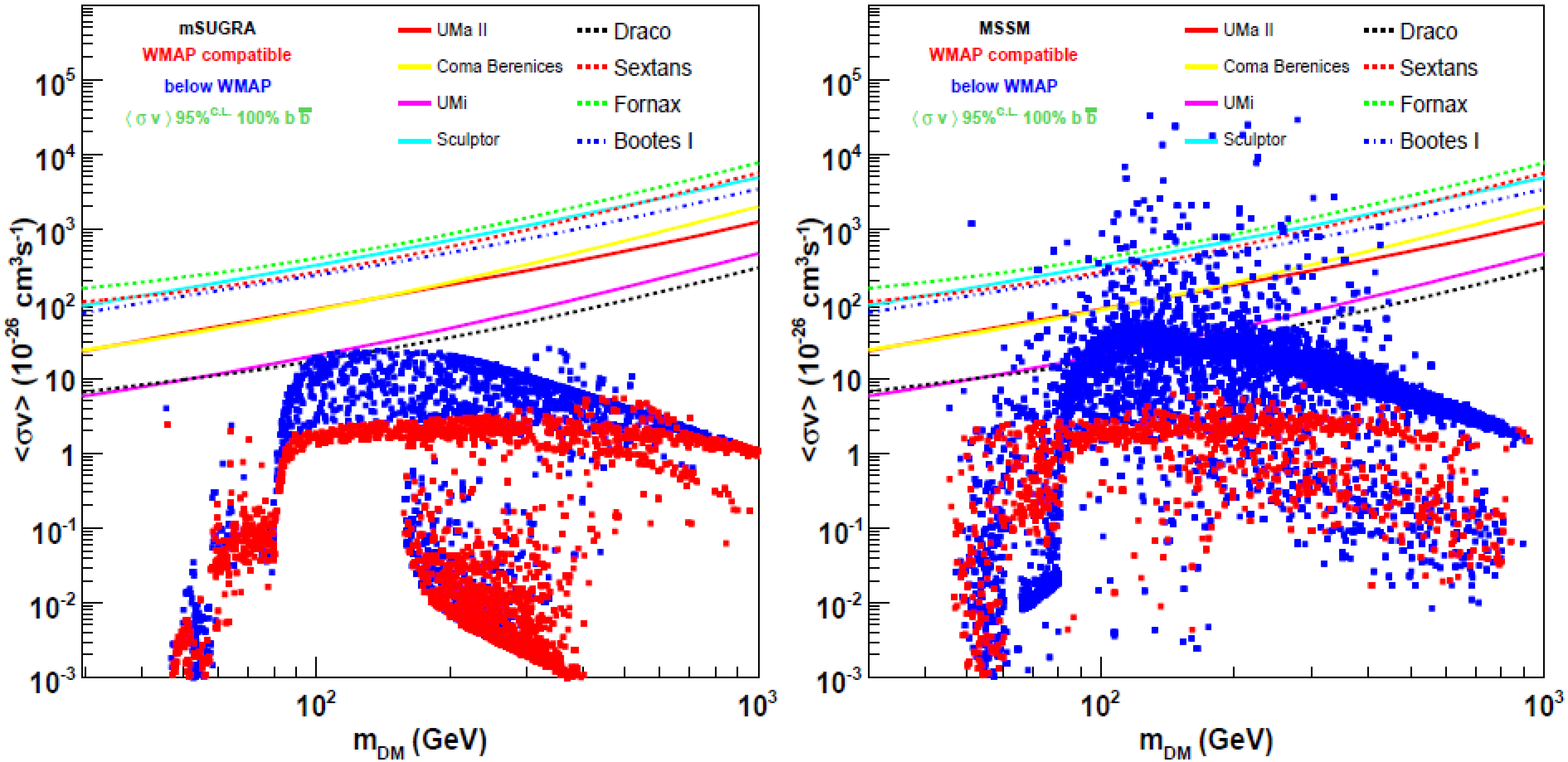
Assume a Navarro-Frenk-White dark matter halo profile inside the tidal radius:

$$\rho(r) = \begin{cases} \frac{\rho_s r_s^3}{r(r_s+r)^2} & \text{for} \quad r < r_t \\ 0 & \text{for} \quad r \geq r_t \end{cases}$$

Name	ρ_s $(M_\odot\ pc^{-3})$	r_s (kpc)	J^{NFW} $(10^{19} GeV^2 cm^{-5})$
Segue 1	1.65	0.05	0.97
Ursa Major II	0.17	0.25	0.57
Segue 2	0.61	0.06	0.1
Willman 1	0.417	0.17	0.84
Coma Berenices	0.232	0.22	0.42
Usra Minor	0.04	0.97	0.35
Sculptor	0.063	0.52	0.12
Draco	0.13	0.50	0.43
Sextans	0.079	0.36	0.05
Fornax	0.04	1.00	0.11

$$J(\psi) = \int_{\text{l.o.s}} dl(\psi)\rho^2(l(\psi))$$

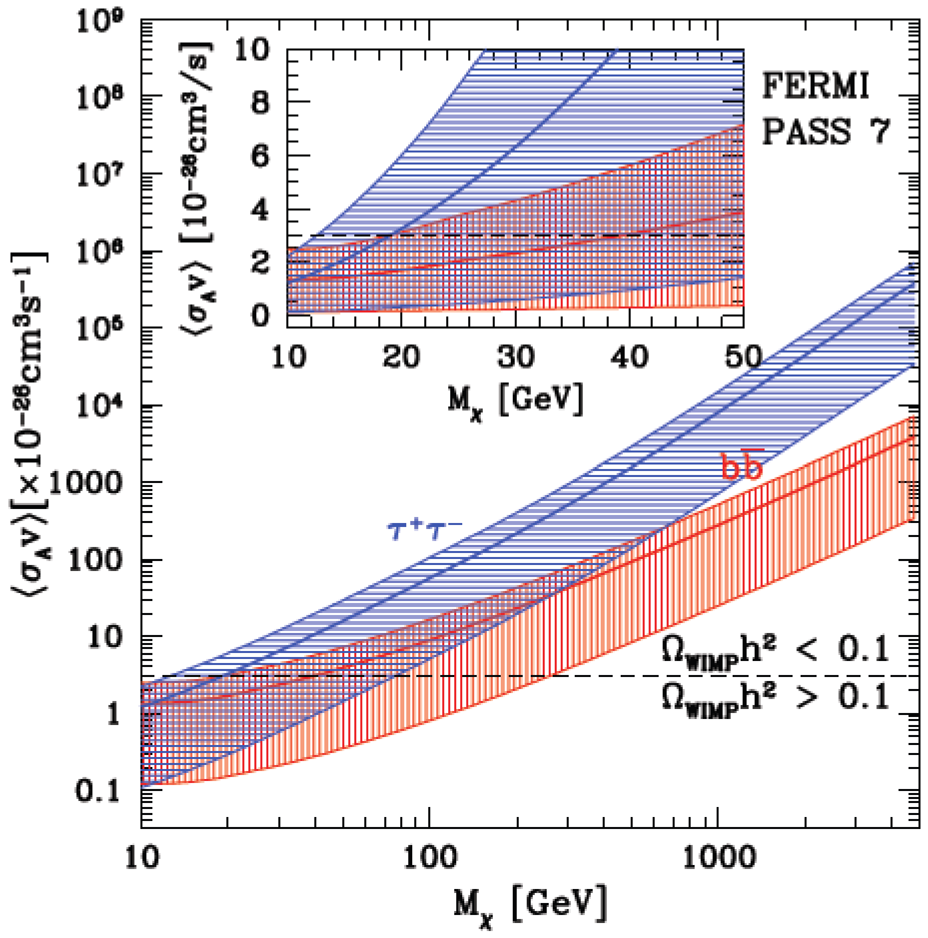
Constraints on WIMP dark matter models

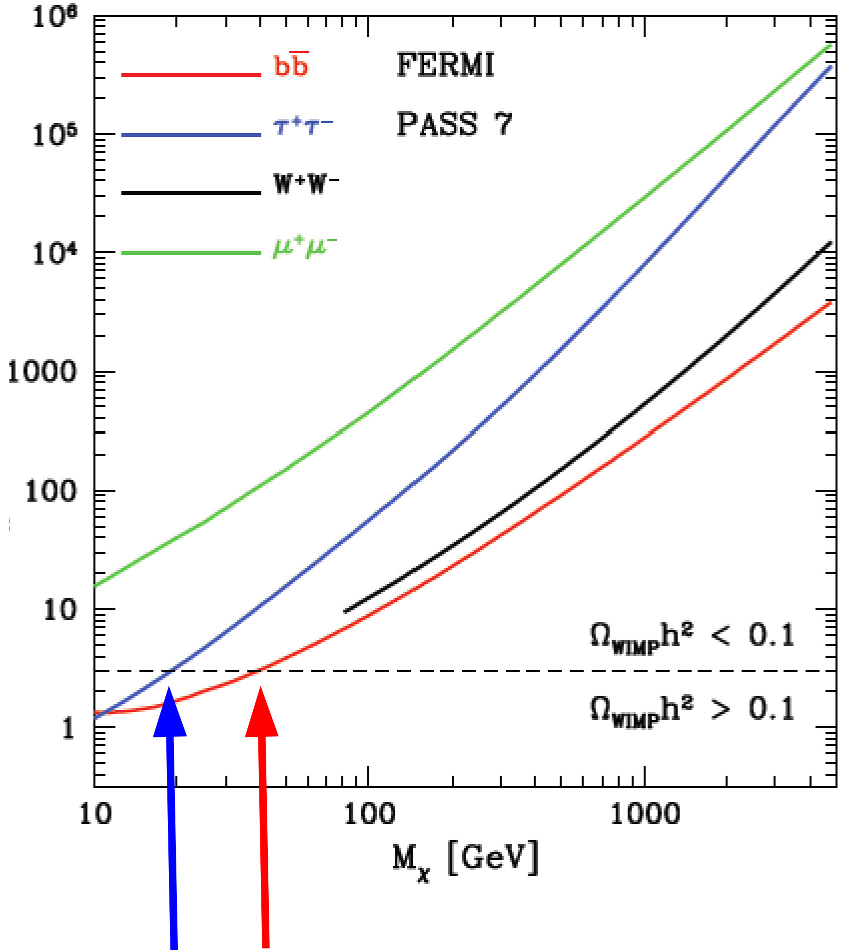


Fermi coll.
arXiv:1001.4531

Closing in on light WIMP scenarios from dwarf galaxy observations

Geringer-Sameth, Koushiappas '11





M_{DM}> 40 GeV for DM DM → $b\,\bar{b}$

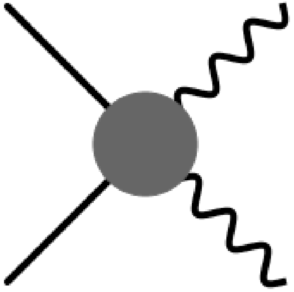
M_{DM}> 19 GeV for DM DM → $\tau^+\,\tau^-$

Gamma-ray features

"Smoking gun" for dark matter: no (known) astrophysical process can produce a sharp feature in the gamma-ray energy spectrum

Three gamma-ray spectral features have been identified:

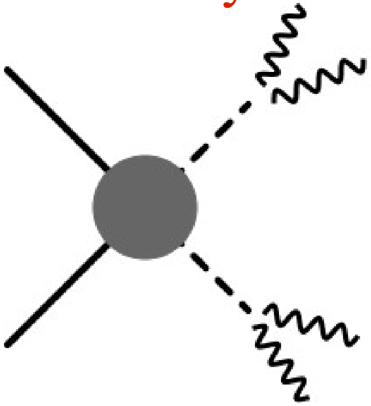
Gamma ray line



Srednicki, Theisen, Silk '86
Rudaz '86
Bergstrom, Snellman '88

$$\boxed{\langle \sigma v \rangle^{\text{expected}} \lesssim 10^{-29}\,\text{cm}^3\,\text{s}^{-1}}$$

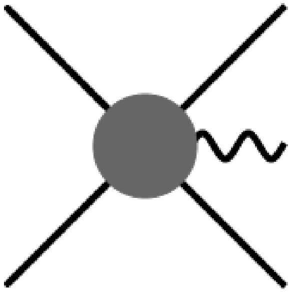
Gamma ray box



AI, Lopez Gehler, Pato '12

$$\boxed{\langle \sigma v \rangle^{\text{expected}} \lesssim 10^{-26}\,\text{cm}^3\,\text{s}^{-1}}$$

Internal bremsstrahlung



Bergstrom '89
Flores, Olive, Rudaz '89
Bringmann,Bergstrom, Edsjo '08

$$\boxed{\langle \sigma v \rangle^{\text{expected}} \lesssim 10^{-28}\,\text{cm}^3\,\text{s}^{-1}}$$

Gamma-ray features

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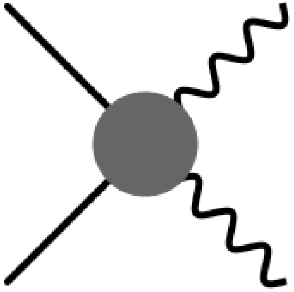

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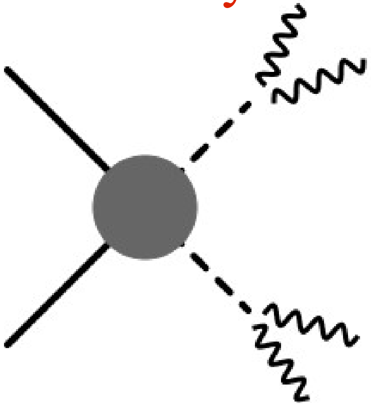

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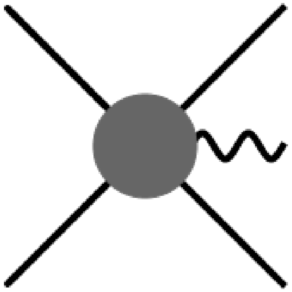
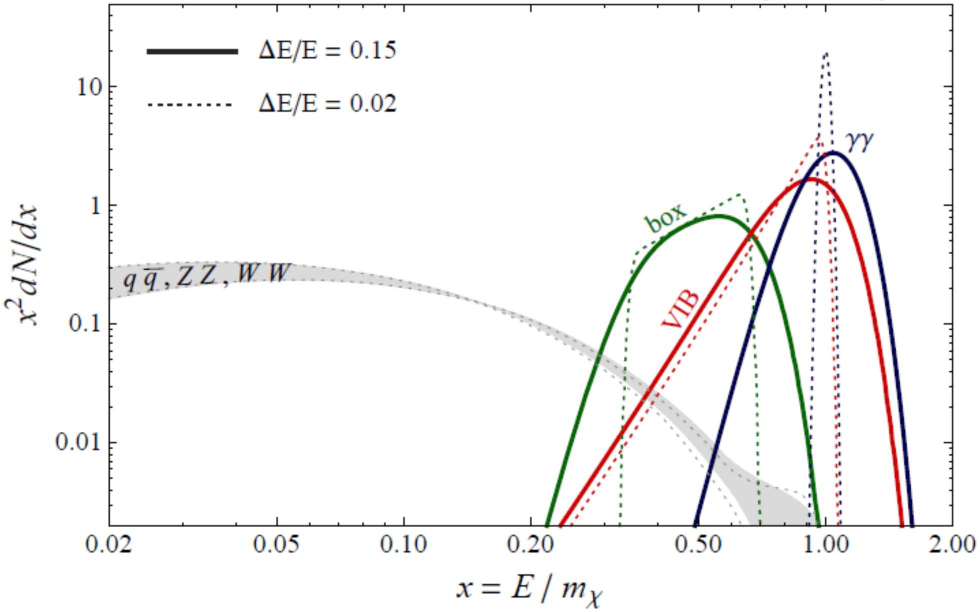
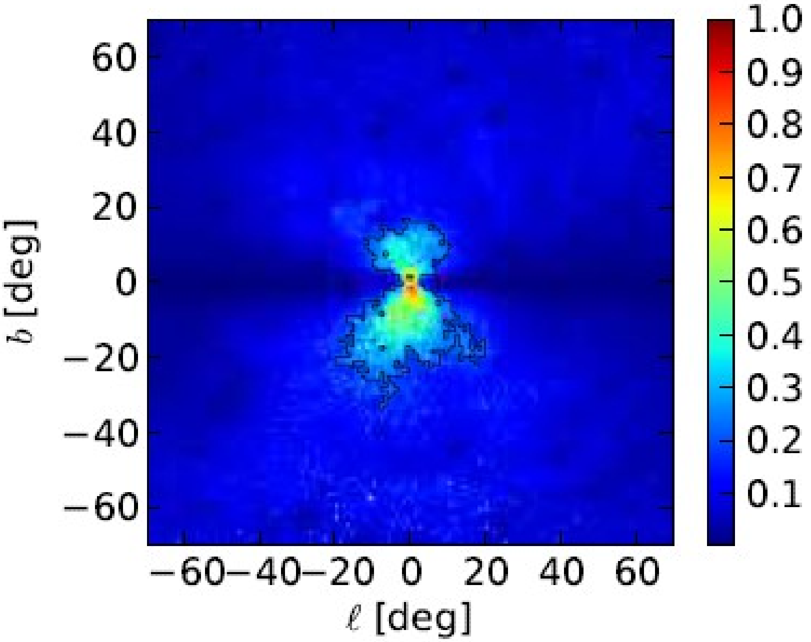
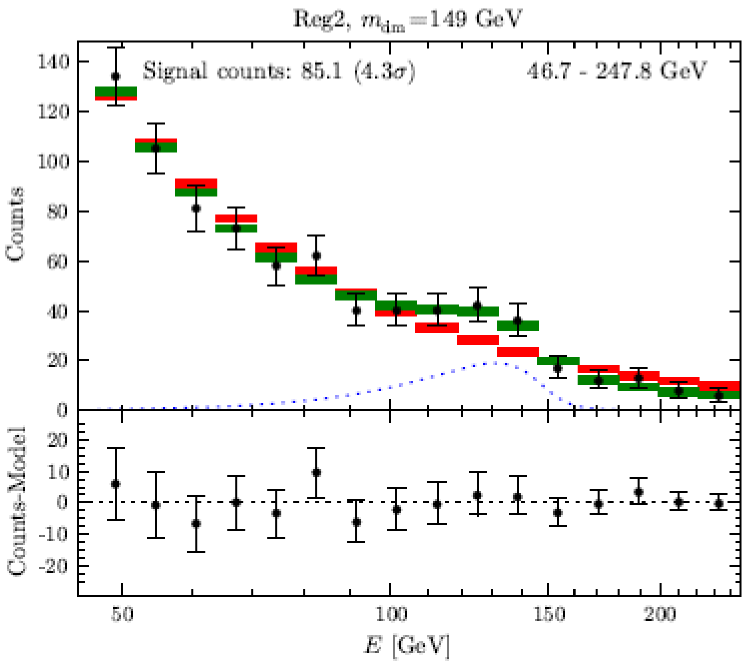




Bringmann & Weniger (2012)

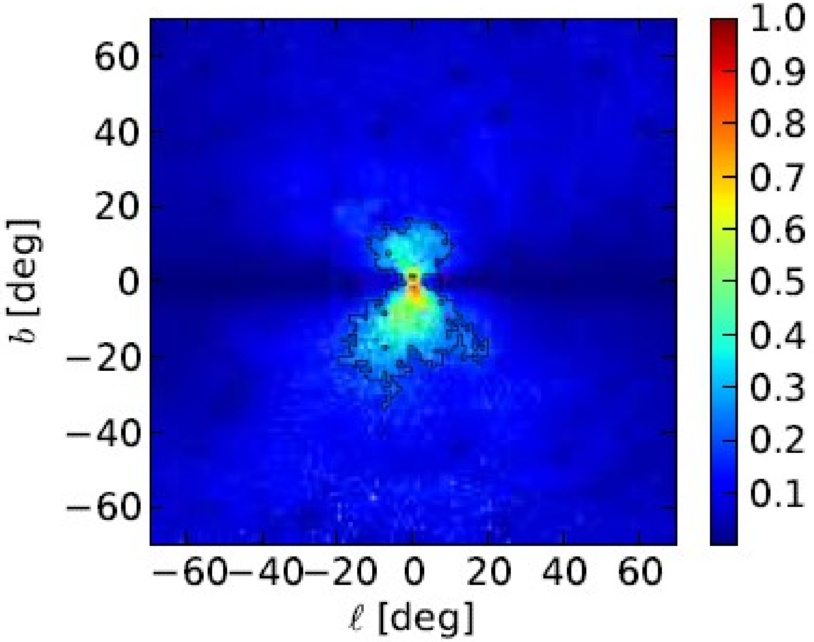
Searching for spectral features with the Fermi-LAT

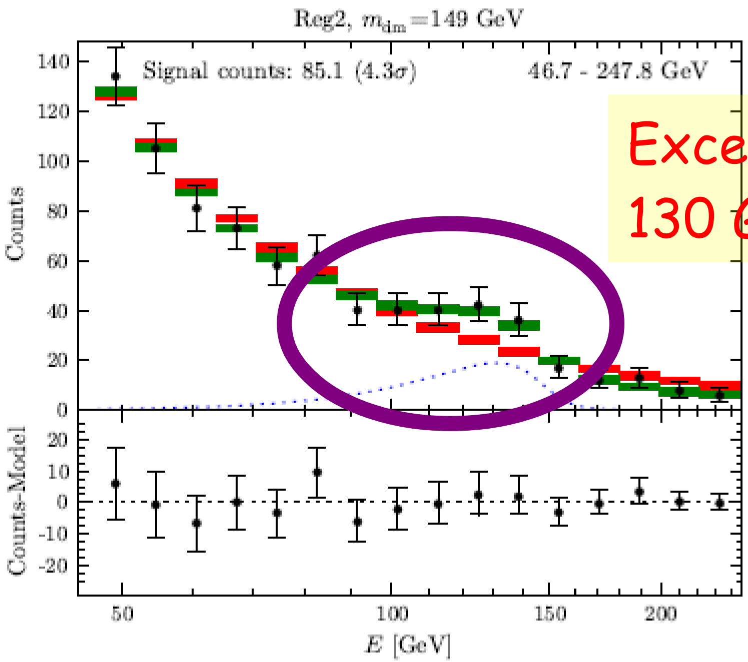




Bringmann, Huang, AI, Vogl, Weniger arXiv:1203.1312

Searching for spectral features with the Fermi-LAT





Excess at 130 GeV !!

Bringmann, Huang, AI, Vogl, Weniger arXiv:1203.1312

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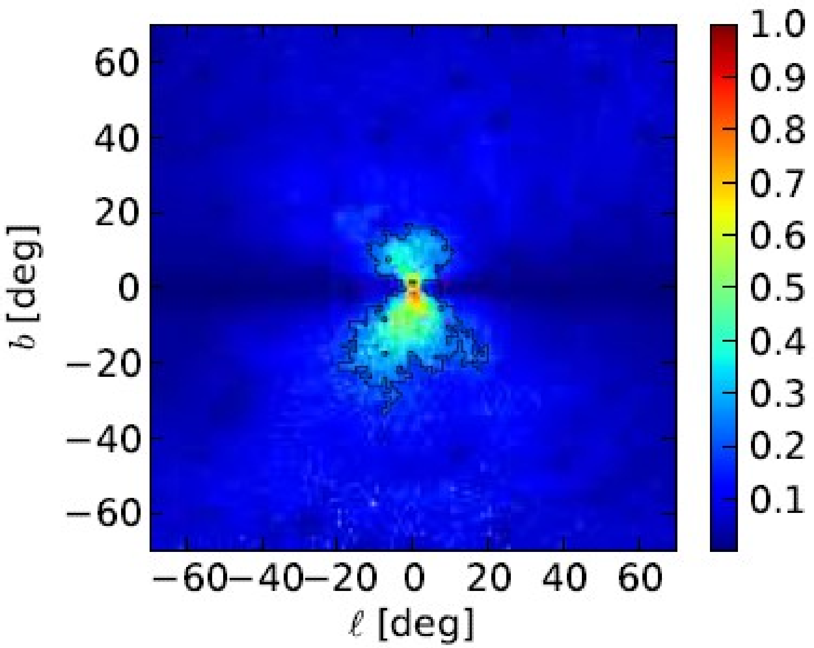

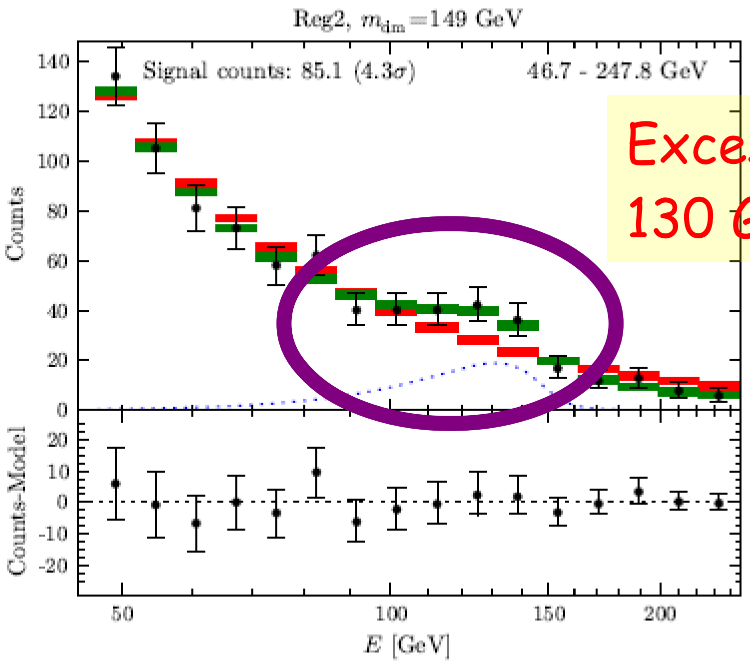

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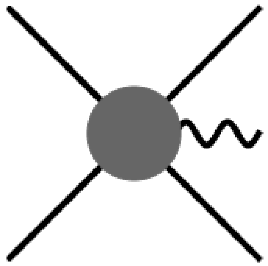
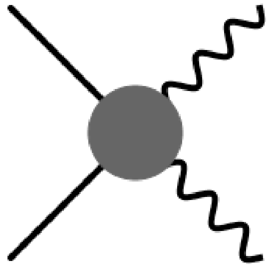


$$m_\chi = (149 \pm 4)\ \text{GeV}$$

$$\langle \sigma v \rangle = (5.7 \pm 1.4) \times 10^{-27}\ \text{cm}^3\ \text{s}^{-1}$$

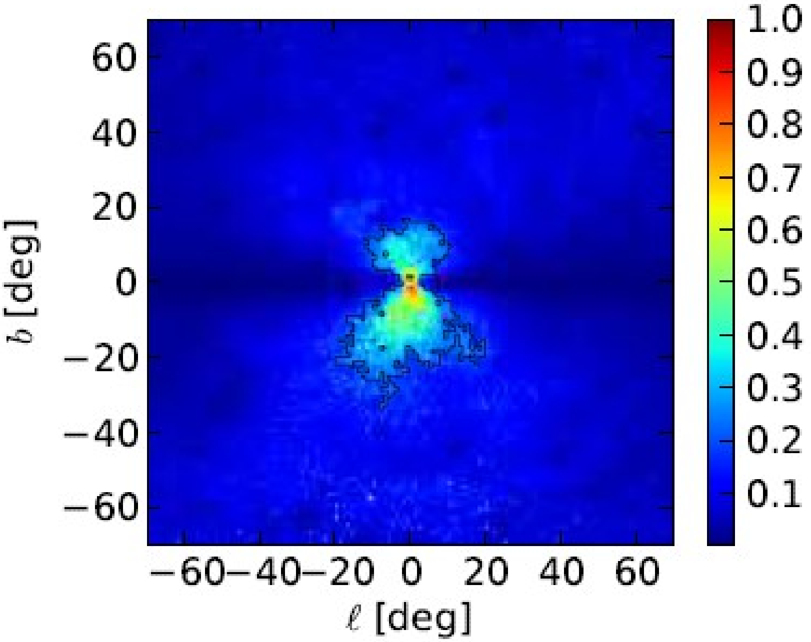
4.3 σ (3.1 σ with LEE)

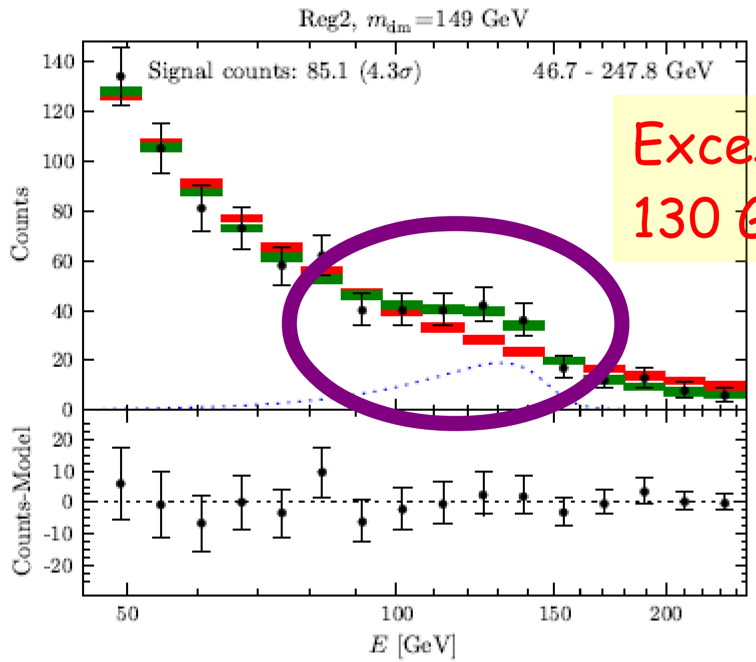


$$m_\chi \sim 130\ \text{GeV}$$

$$\langle \sigma v \rangle_{\chi\chi \to \gamma\gamma} \sim 10^{-27}\ \text{cm}^3\ \text{s}^{-1}$$

Searching for spectral features with the Fermi-LAT





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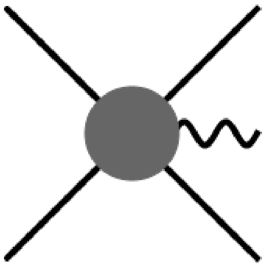

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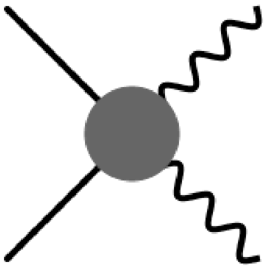


$$m_\chi = 129.8 \pm 2.4\,^{+7}_{-13}\ \text{GeV}$$

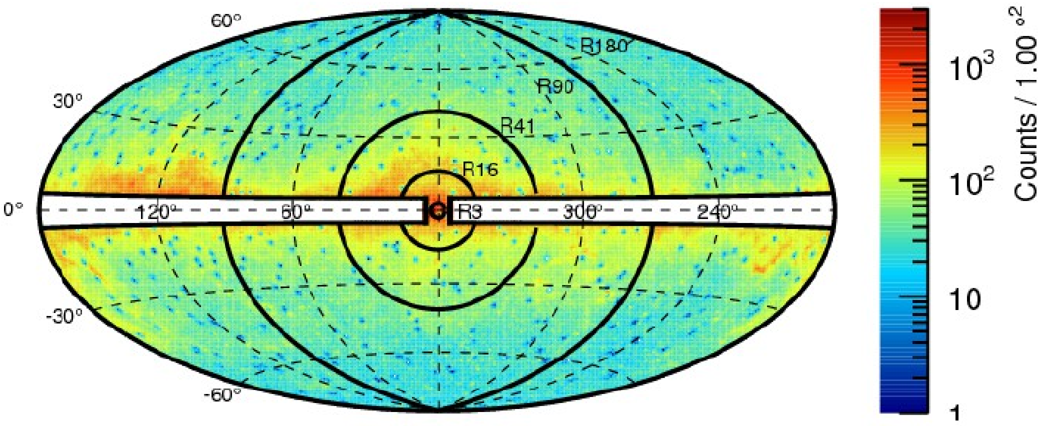
$$\langle \sigma v \rangle = (1.27 \pm 0.32\,^{+0.18}_{-0.28}) \times 10^{-27}\ \text{cm}^3\ \text{s}^{-1}$$

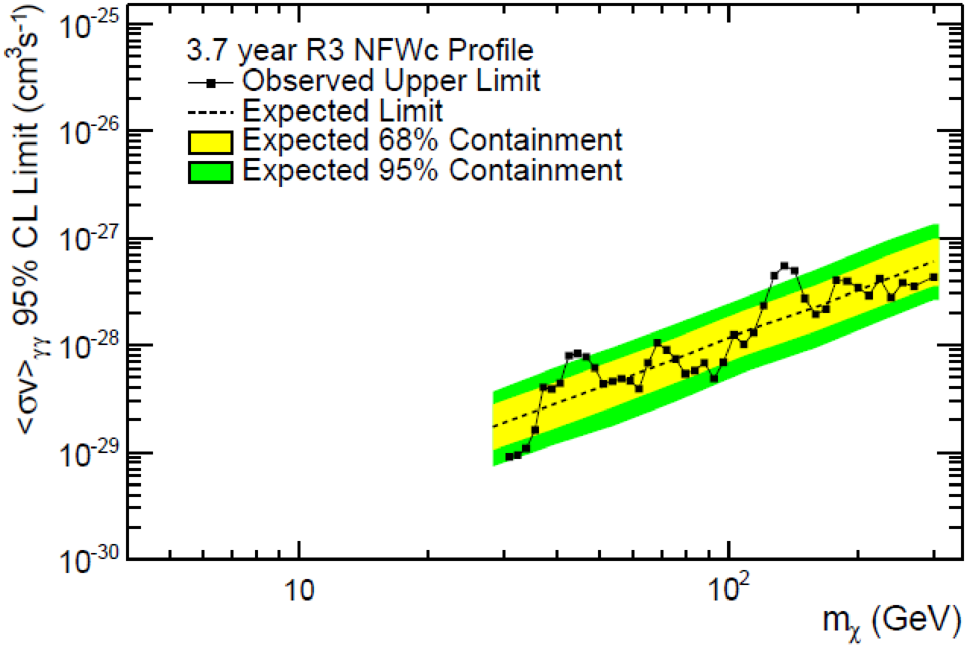
4.6 σ (3.3 σ with LEE)

Weniger, arXiv:1204.2797

Latest news on the 130 GeV excess

Fermi-LAT collaboration
arXiv:1305.5597



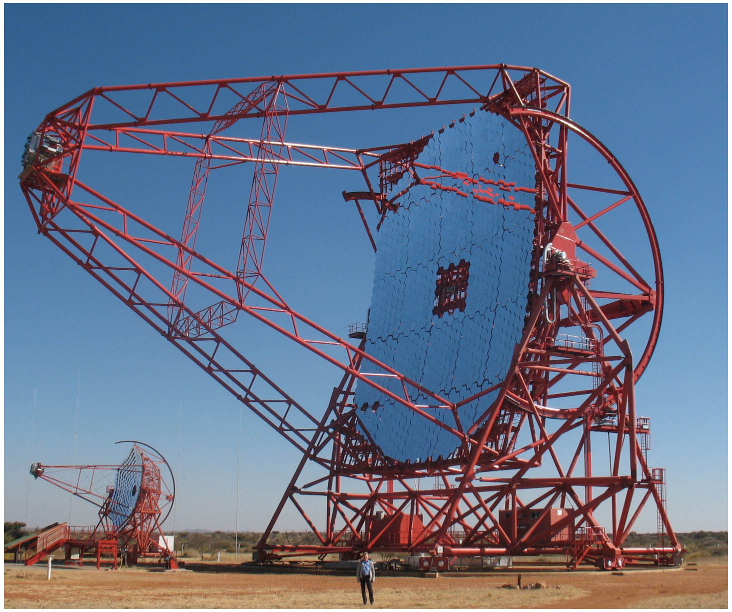


Significance reduced to 3.3σ (1.6σ with LEE)

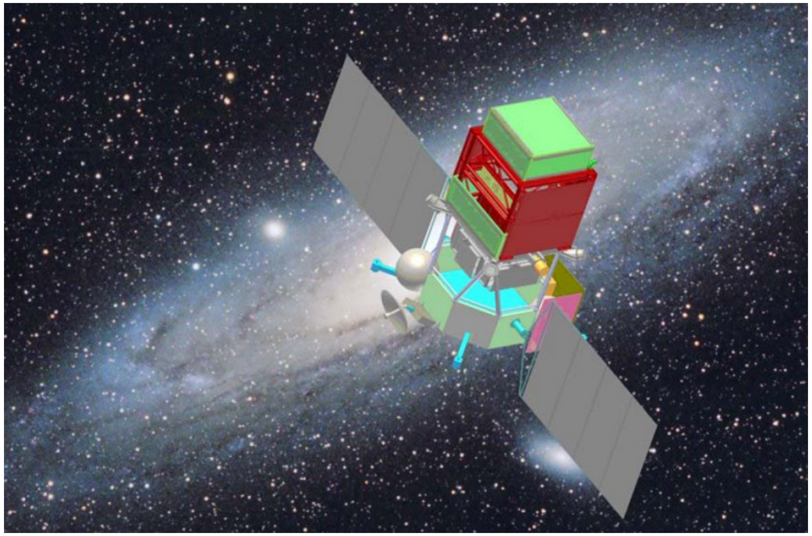
The 130 GeV excess could be just a statistical fluke

Bright future for dark matter searches using gamma-rays!

H.E.S.S. II – in operation

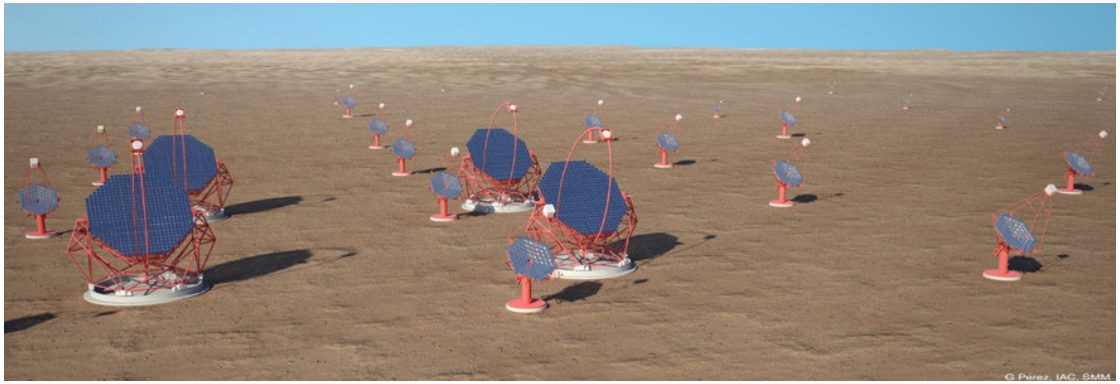


GAMMA 400 – Launch in 2018



DAMPE – Launch in 2015

CTA – Construction starting in 2017



Direct dark matter searches

General idea:

1) The Sun (and the Earth) is moving through a static "gas" of dark matter particles. Or, from our point of view, there is a flux of dark matter particles going through the Earth.

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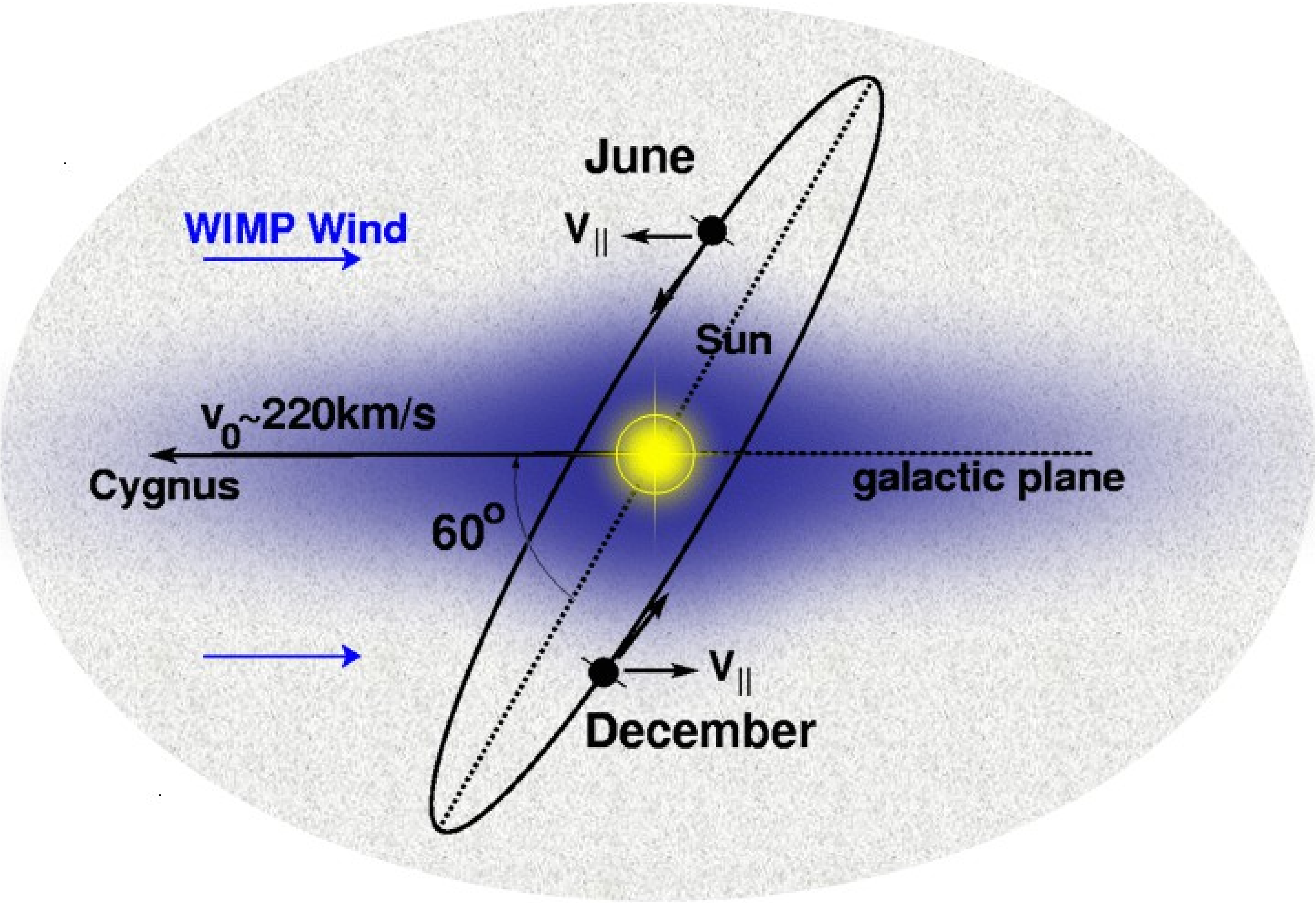
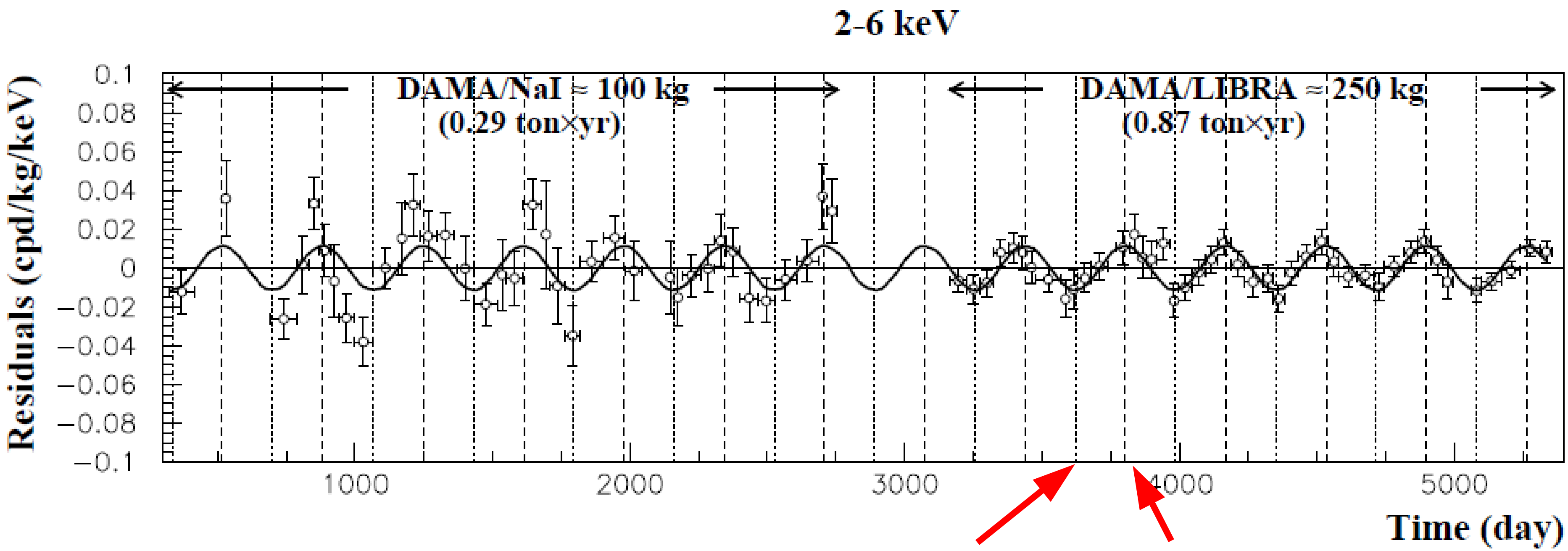
Simple idea…

…but very challenging in practice!

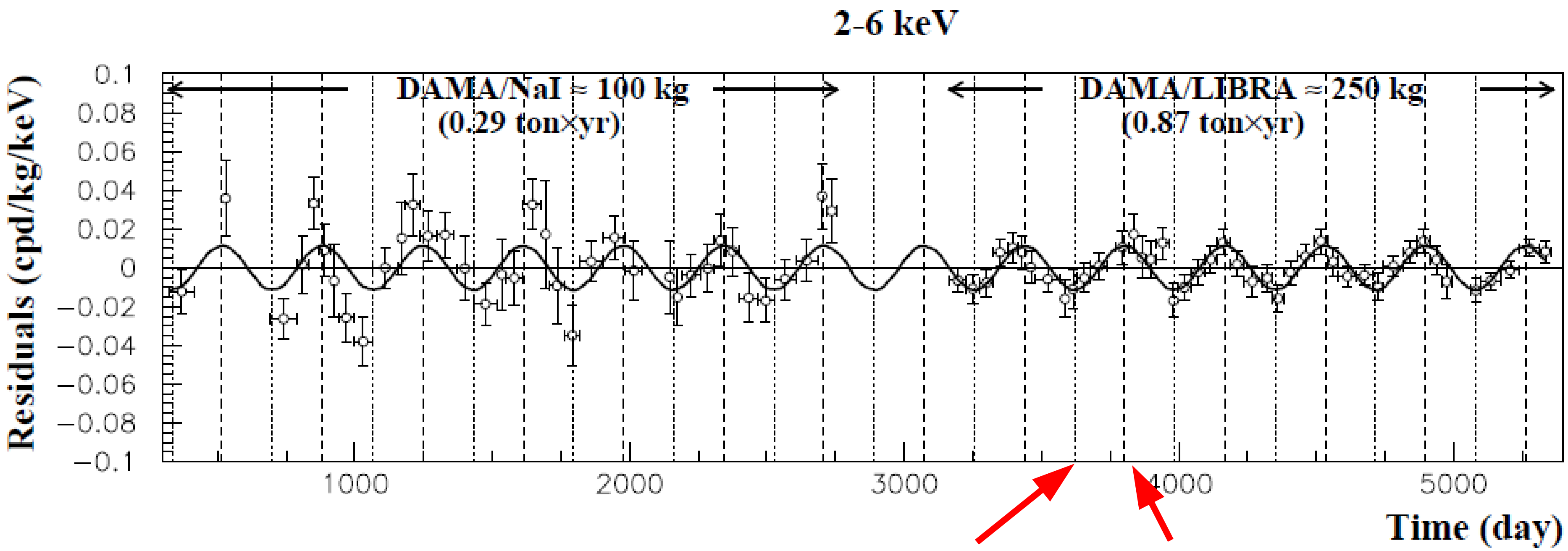
Annual modulation





December 2nd

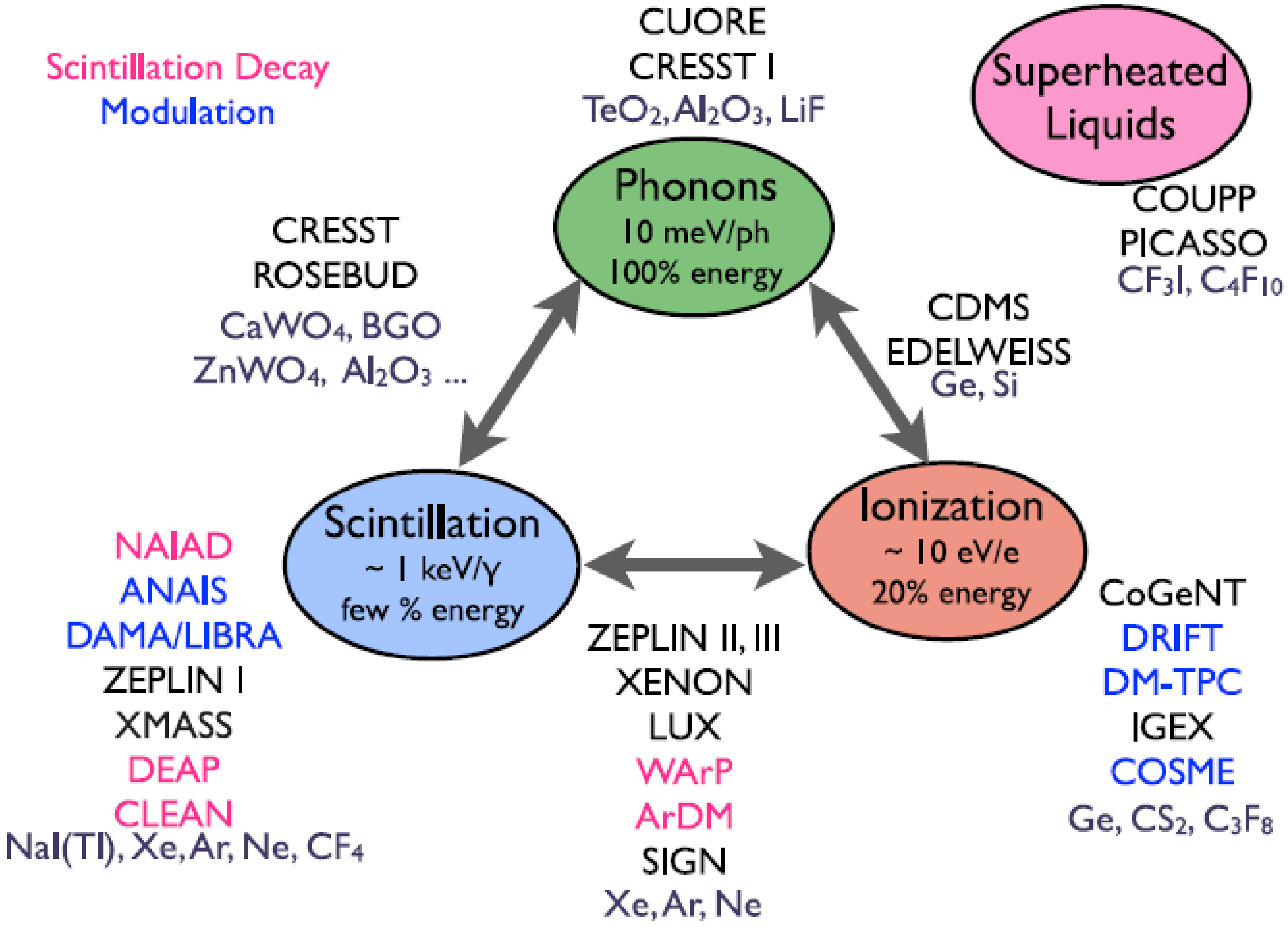
June 2nd



December 2nd

June 2nd

Very controversial result, though! More later...



Scintillation Decay

Modulation

CUORE

CRESST I

TeO_2, Al_2O_3, LiF

Superheated Liquids

COUPP

PICASSO

CF_3I, C_4F_{10}

Phonons

10 meV/ph

100% energy

CRESST

ROSEBUD

$CaWO_4$, BGO

$ZnWO_4$, Al_2O_3 ...

CDMS

EDELWEISS

Ge, Si

Scintillation

~ 1 keV/γ

few % energy

Ionization

~ 10 eV/e

20% energy

NAIAD

ANAIS

DAMA/LIBRA

ZEPLIN I

XMASS

DEAP

CLEAN

NaI(Tl), Xe, Ar, Ne, CF_4

ZEPLIN II, III

XENON

LUX

WArP

ArDM

SIGN

Xe, Ar, Ne

CoGeNT

DRIFT

DM-TPC

IGEX

COSME

Ge, CS_2, C_3F_8

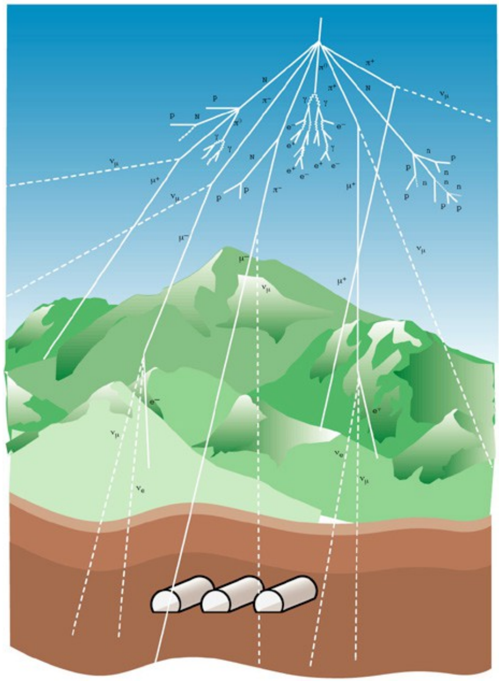
An example: CRESST II

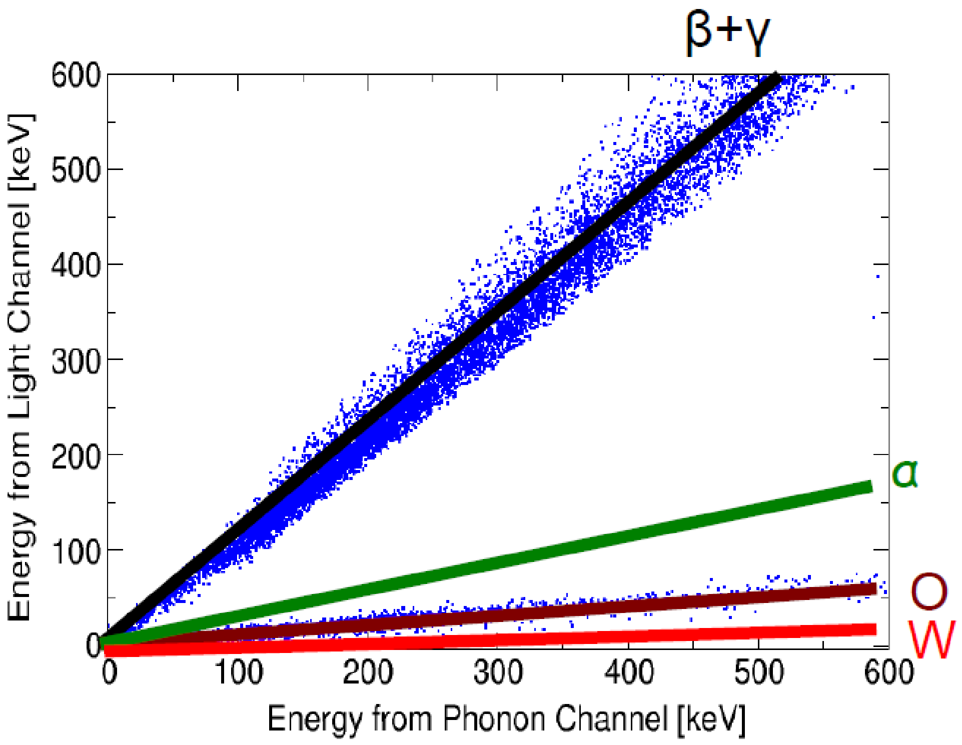
Underground detector

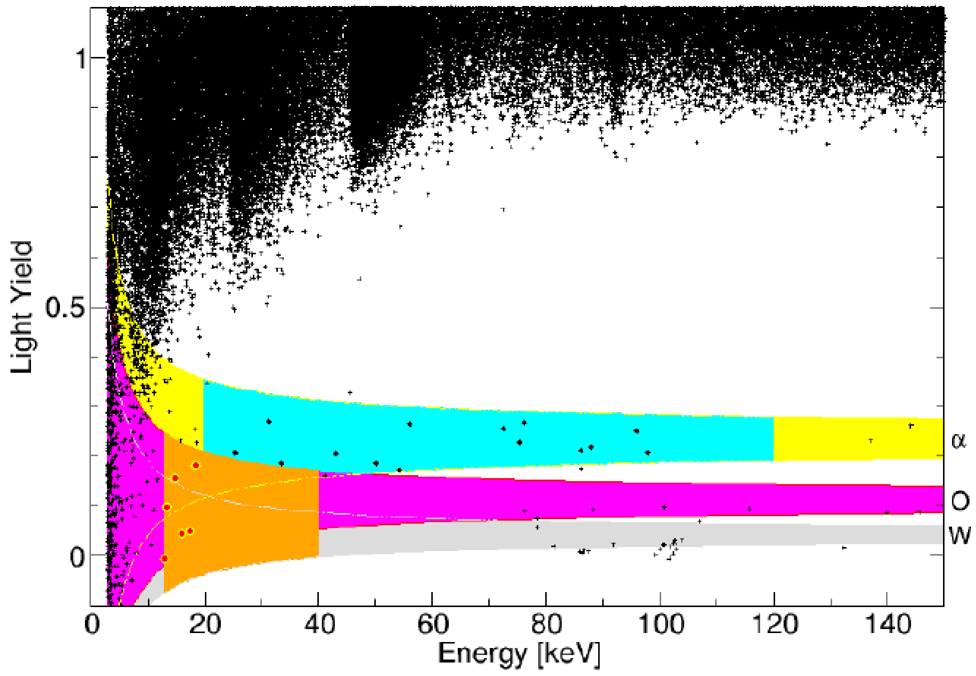
Target: $CaWO_4$

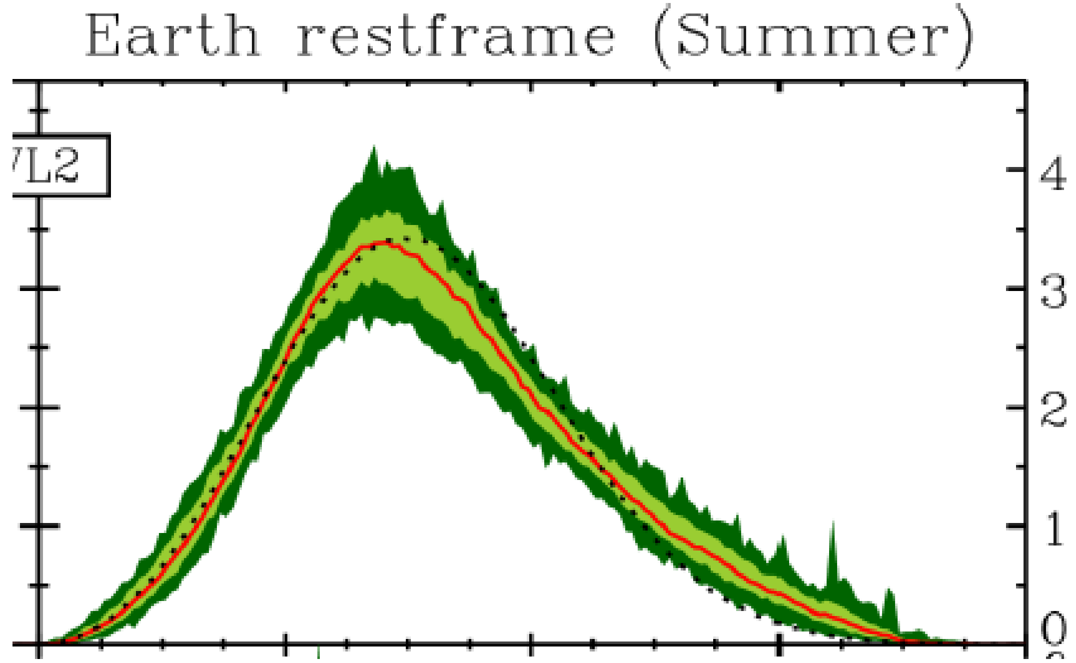
phonon signal + scintillation light

Criogenic: 10 mK

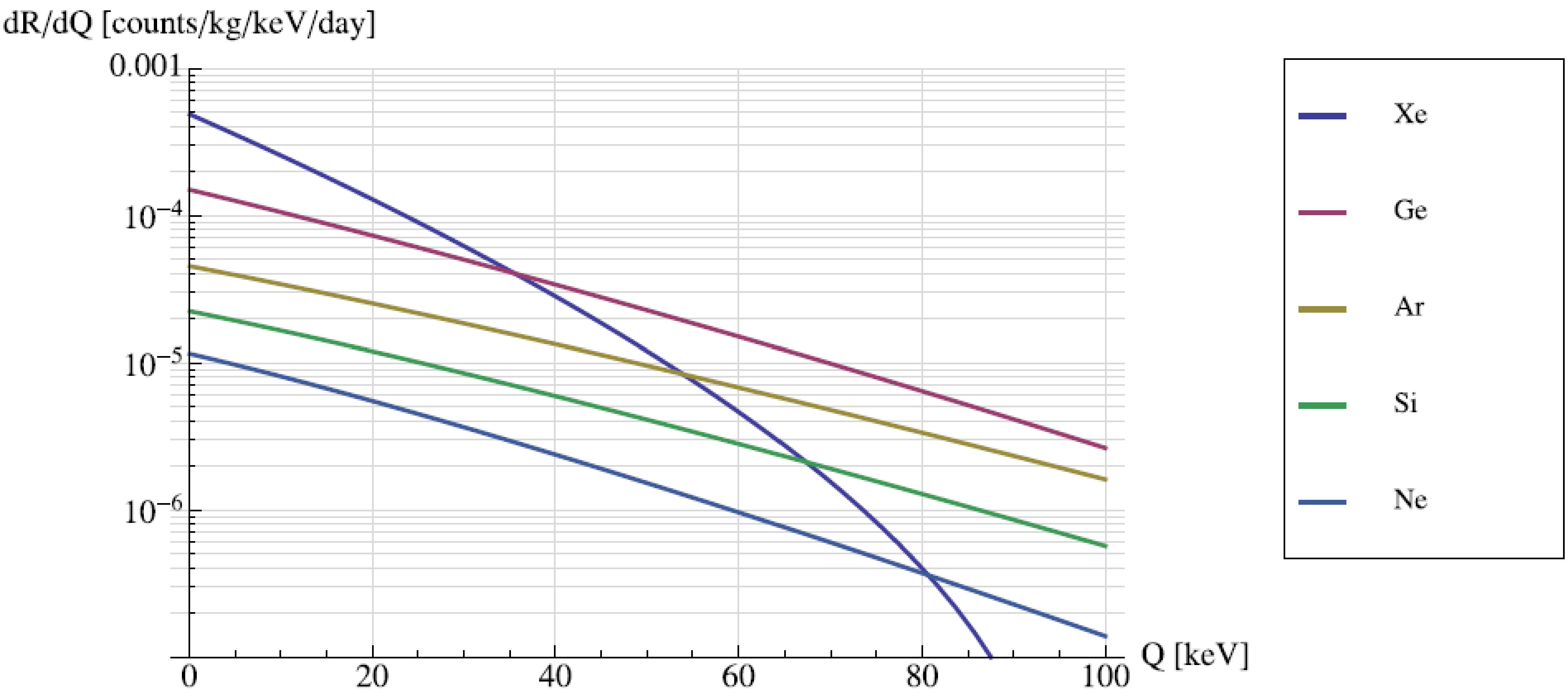


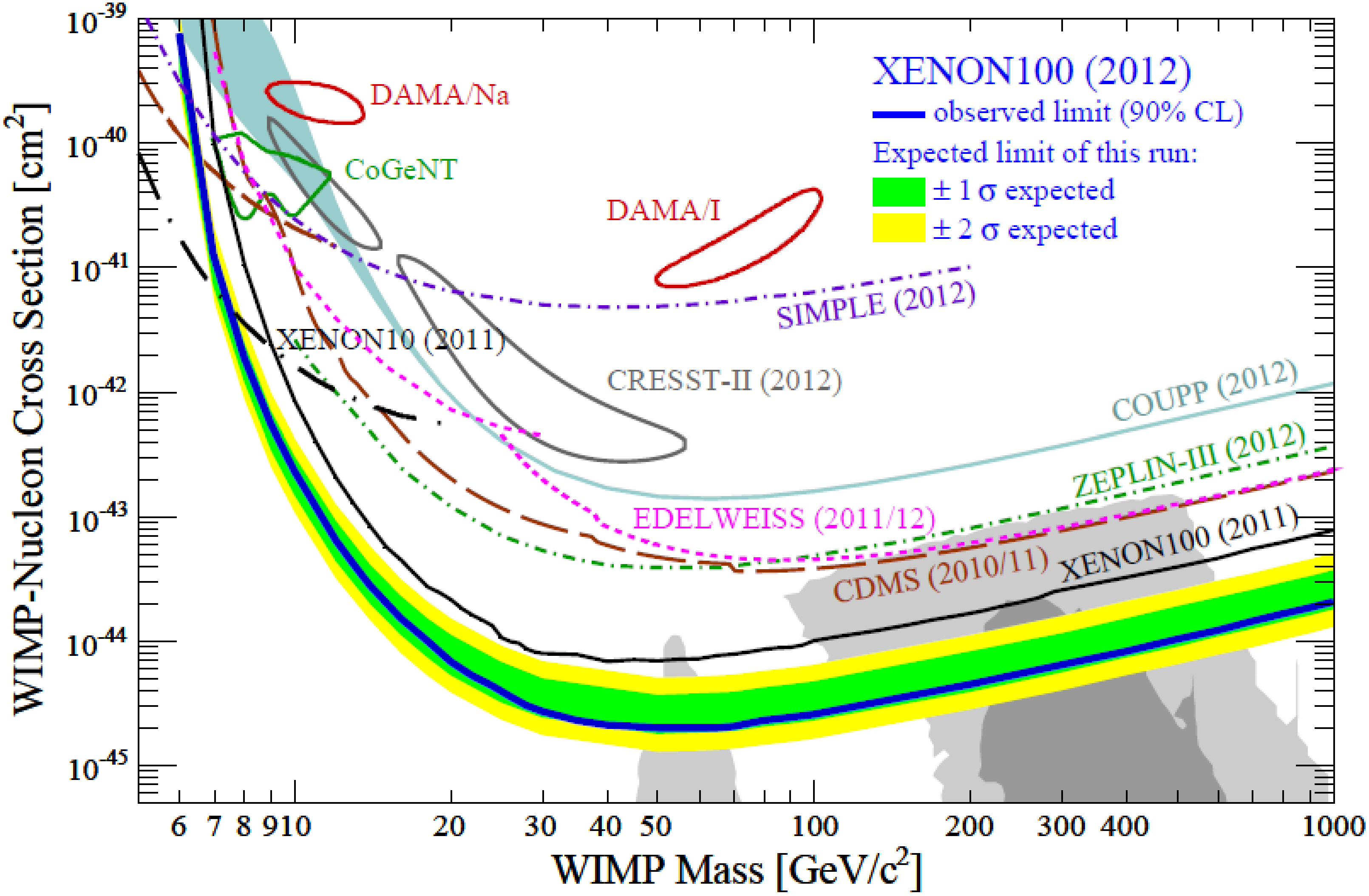





Earth restframe (Summer)

Kuhlen'09

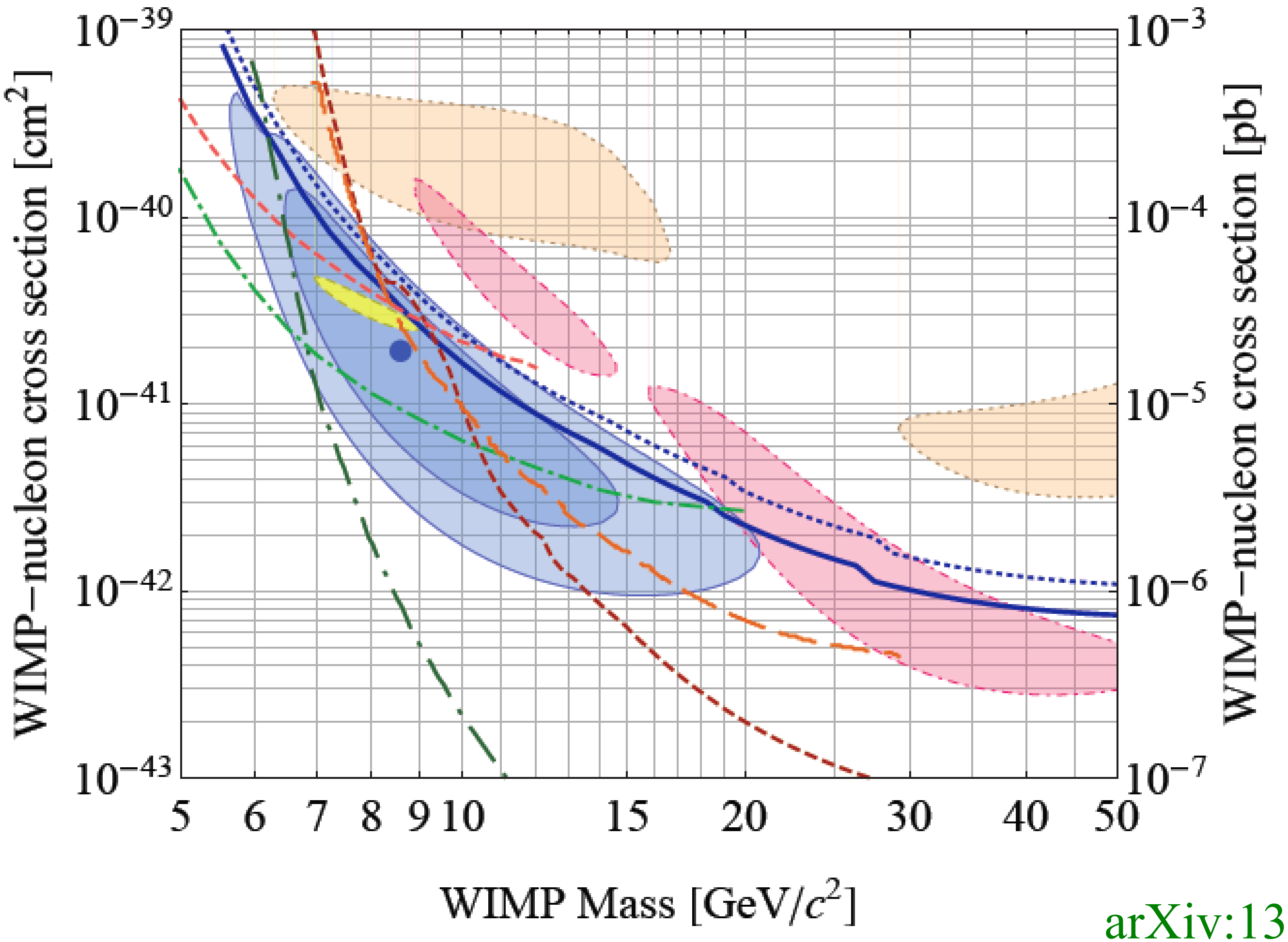

dR/dQ [counts/kg/keV/day]
0.001
10^{-4}
10^{-5}
10^{-6}
0
20
40
60
80
100
Q [keV]
Xe
Ge
Ar
Si
Ne



XENON collaboration
arXiv:1207.5988

Dark Matter Search Results Using the Silicon Detectors of CDMS II

We report results of a search for Weakly Interacting Massive Particles (WIMPs) with the silicon detectors of the CDMS II experiment. A blind analysis of 140.2 kg-days of data revealed three WIMP-candidate events with an expected total background of 0.7 events. The probability that the known backgrounds would produce three or more events in the signal region is 5.4%. A profile likelihood ratio test of the three events that includes the measured recoil energies gives a 0.19% probability for the known-background-only hypothesis when tested against the alternative WIMP+background hypothesis. The highest likelihood occurs for a WIMP mass of 8.6 GeV/c^2 and WIMP-nucleon cross section of 1.9×10^{-41} cm^2.



arXiv:1304.4279

List of conclusions

End of list

Concluding remarks

1- Zwicky's observations of 1933

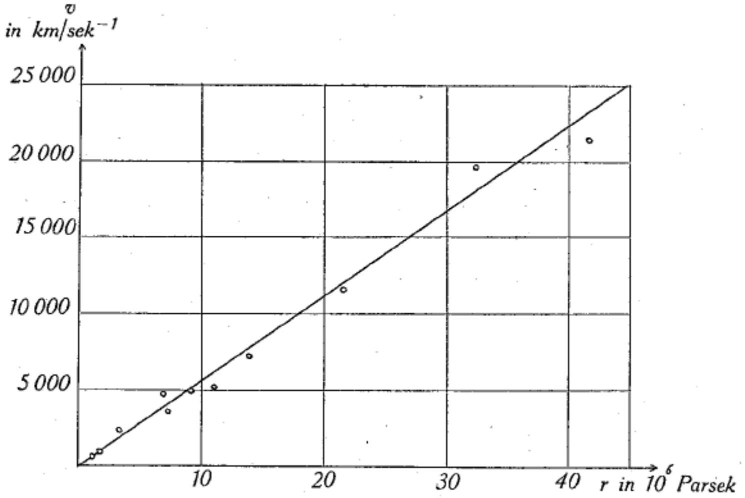


Fig. 2.

Concluding remarks

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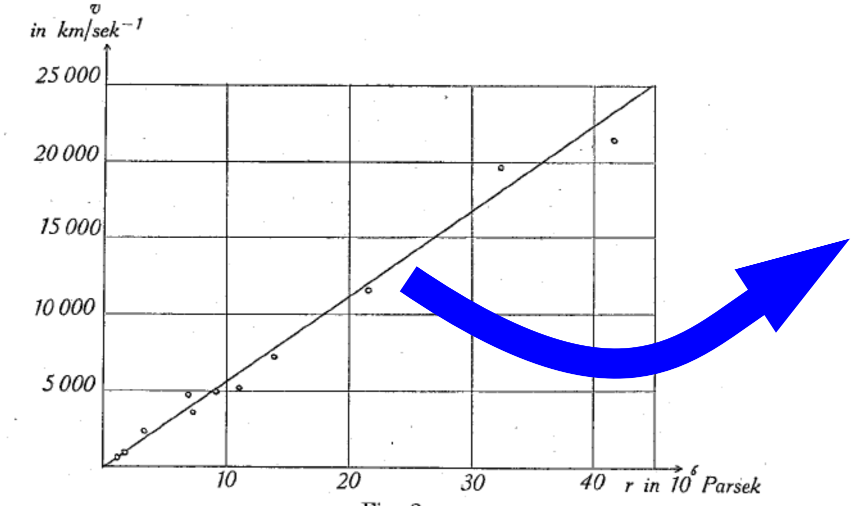

Fig. 2.

80 years later, we still don't know what is producing this.

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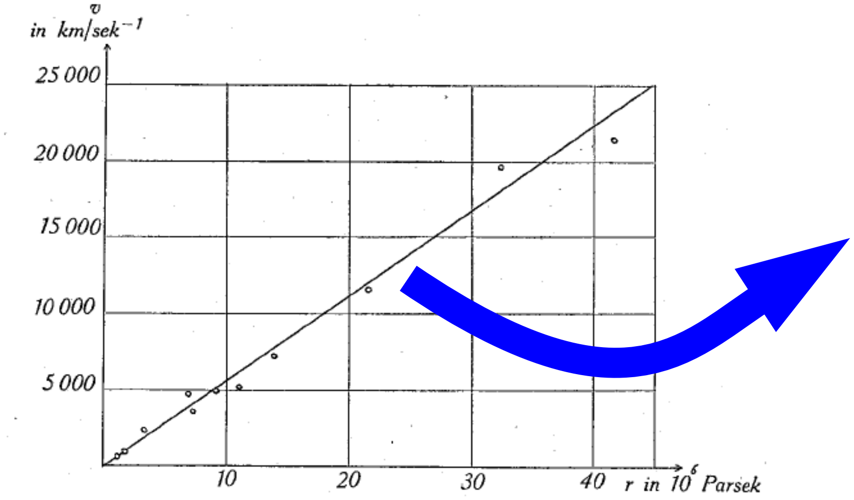

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2- It was a very enjoyable school

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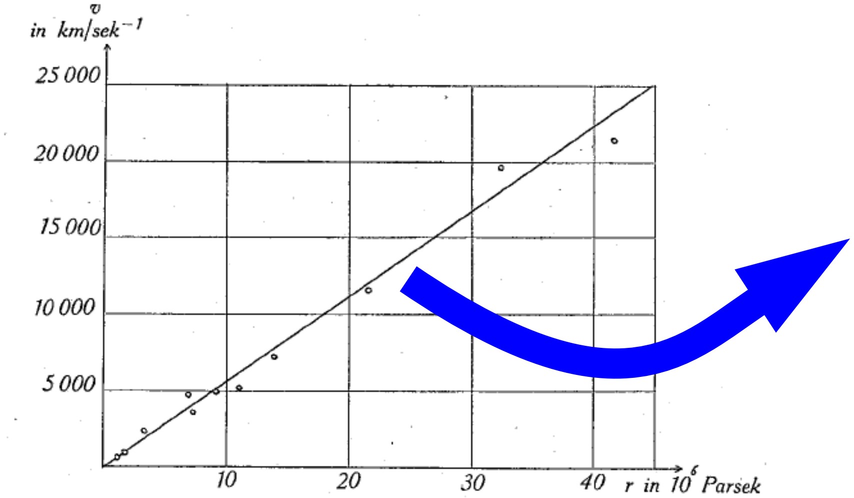

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2- It was a very enjoyable school

lots of success
in your research!