

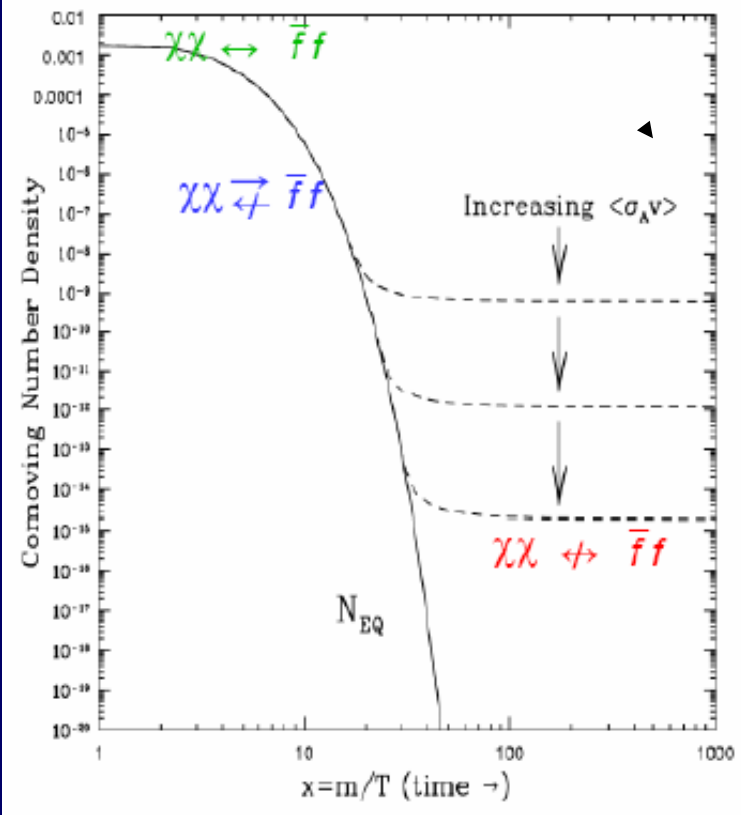
# Indirect detection of WIMP dark matter

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**Progress on Old and New  
Themes in Cosmology  
(PONT), Avignon, 2014**

# Weakly Interacting Massive Particles (WIMPs)

The weak interaction mass scale and ordinary gauge couplings give right relic DM density without fine-tuning. Mass scale O(GeV)-O(TeV), makes them Cold Dark Matter



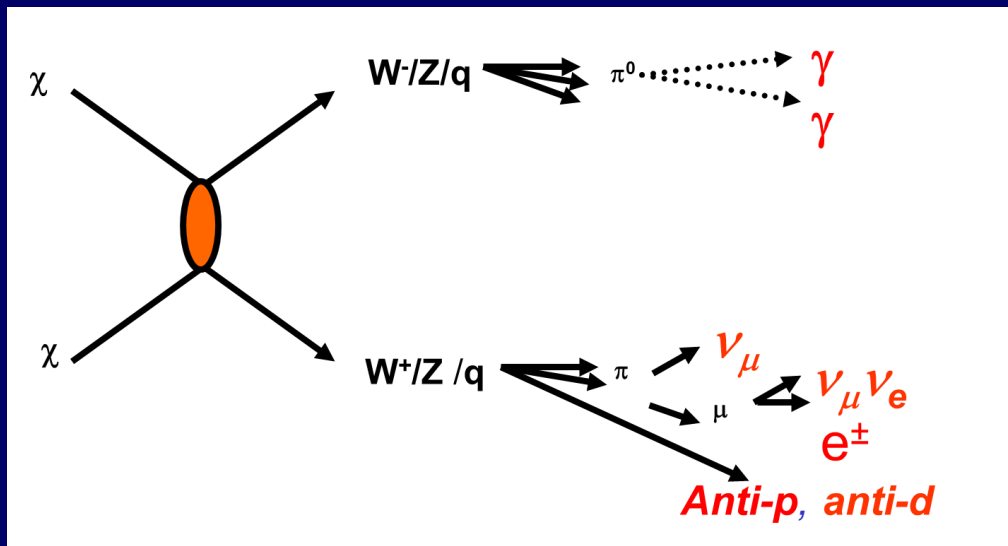
Jungman+, Phys. Rept. (1996)

$$\Omega_{Wimp} \approx \frac{10^{-26} \text{ cm}^{-3} \text{ s}^{-1}}{\langle \sigma v \rangle}$$

$$\langle \sigma v \rangle_{\sim weak} \sim \frac{\alpha^2}{m_{WIMP}^2} \sim 10^{-25} \text{ cm}^{-3} \text{ s}^{-1}$$

Provides benchmark for indirect detection: thermally produced WIMPs

# Indirect detection of Dark Matter



Particle Physics

$$\frac{1}{4\pi} \frac{\langle \sigma_A v \rangle}{2m_\chi^2} \sum_f \frac{dN}{dE} B_f$$

**v, γ: rate = PPP □ Astrophysical part (APP)**

$$APP = \text{"J - factor"} = \iint d\Omega dl \rho^2(l)$$

**cosmic rays PPP = q(r,p,t)**

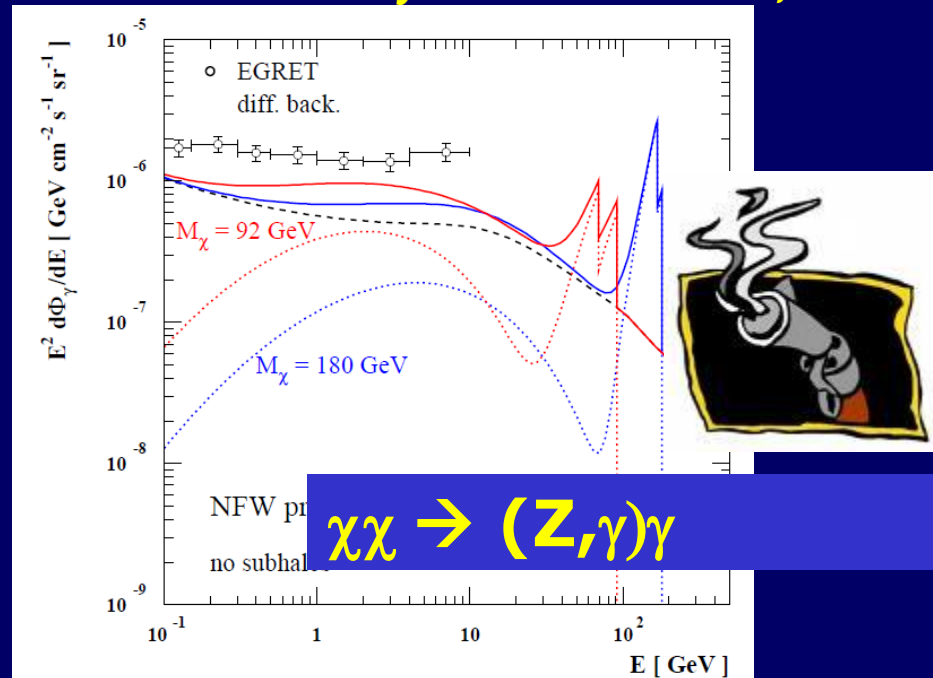
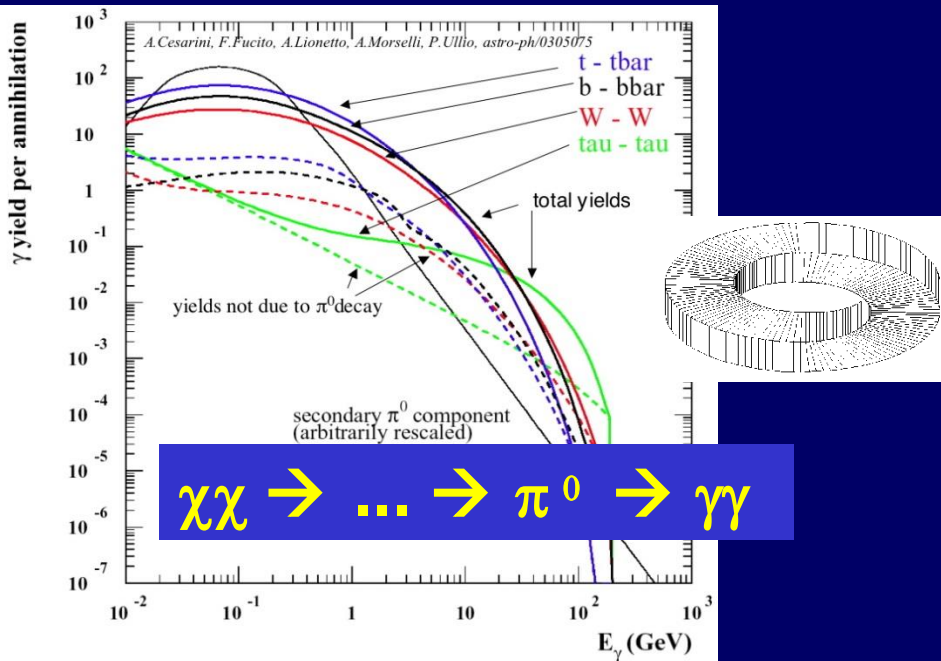
$$\frac{\partial F(\mathbf{r}, p, t)}{\partial t} - \nabla \cdot (\mathbf{D}_{xx} \nabla F) + \nabla \cdot (\mathbf{u}F) - \frac{\partial}{\partial p} \left( p^2 D_{pp} \frac{\partial F}{\partial p} \frac{\partial F}{p^2} \right) + \frac{\partial}{\partial p} \left[ \dot{p}F - \frac{p}{3} (\nabla \cdot \mathbf{u}) F \right] + \frac{F}{\tau_f} + \frac{F}{\tau_d} = q(\mathbf{r}, p, t),$$

- B-field, radiation field, gas, E-field:
- Diffusion
- reacceleration
- convection
- energy loss
- Spallation, decay

**gamma rays: the golden channel**

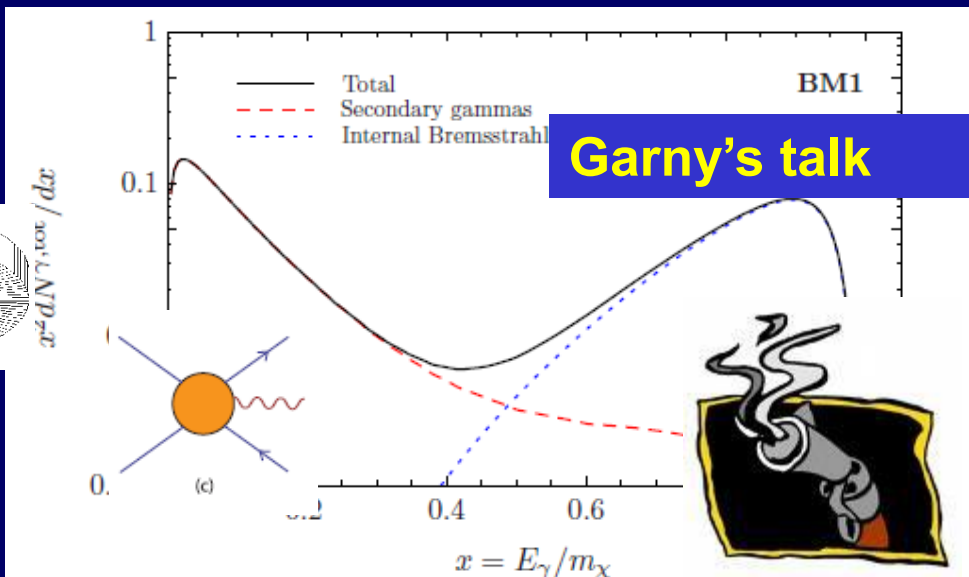
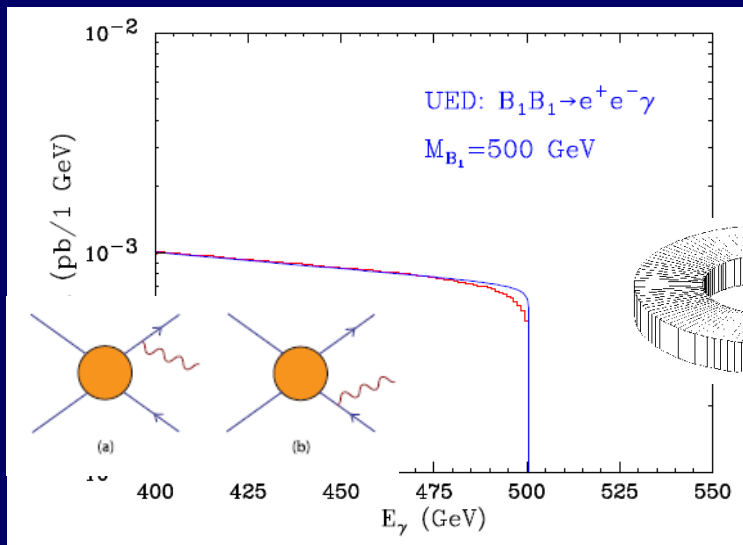
# Universal spectral signatures

Ullio et al. Phys.Rev.D66:123502,2002

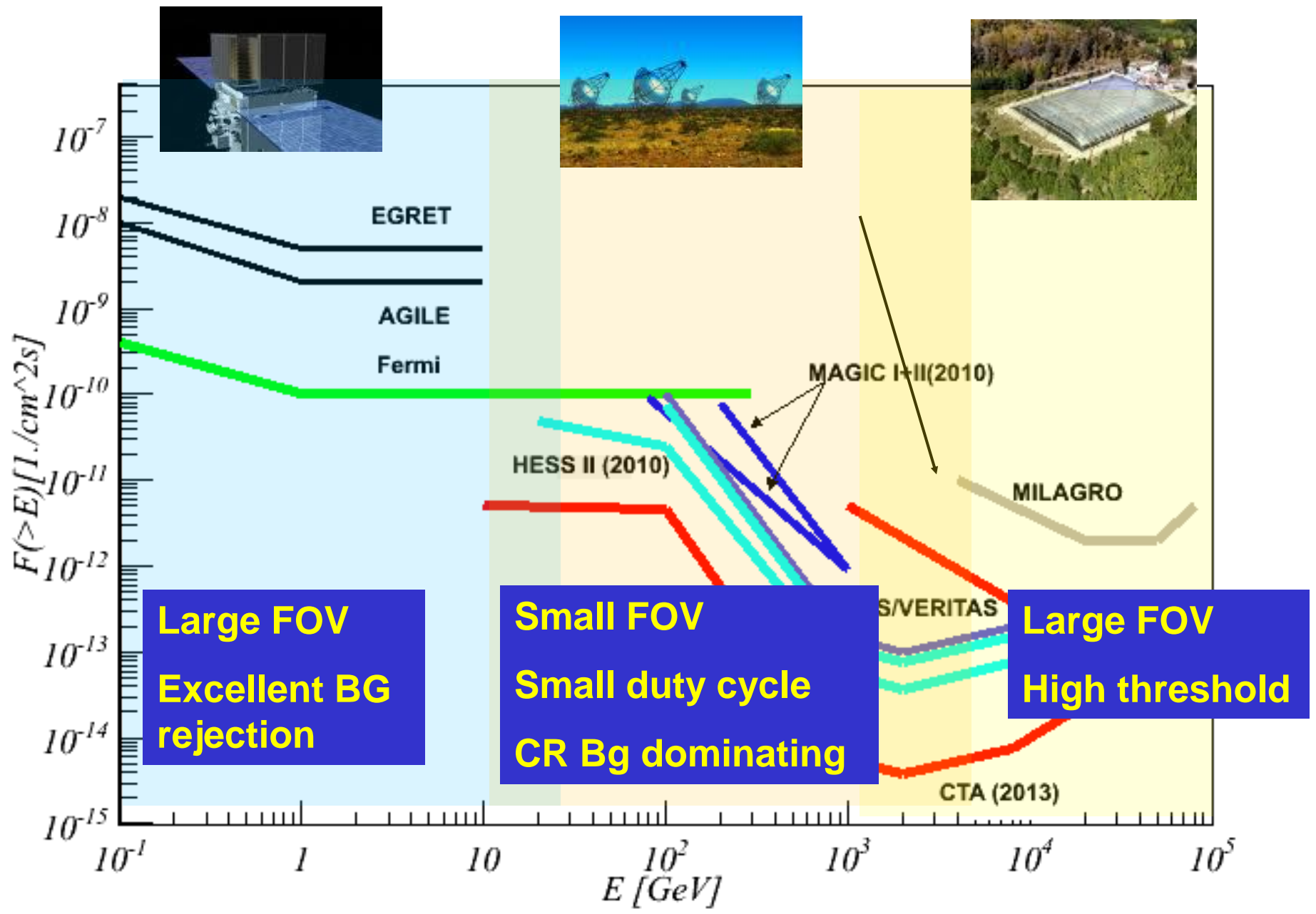


Birkedal et al.,

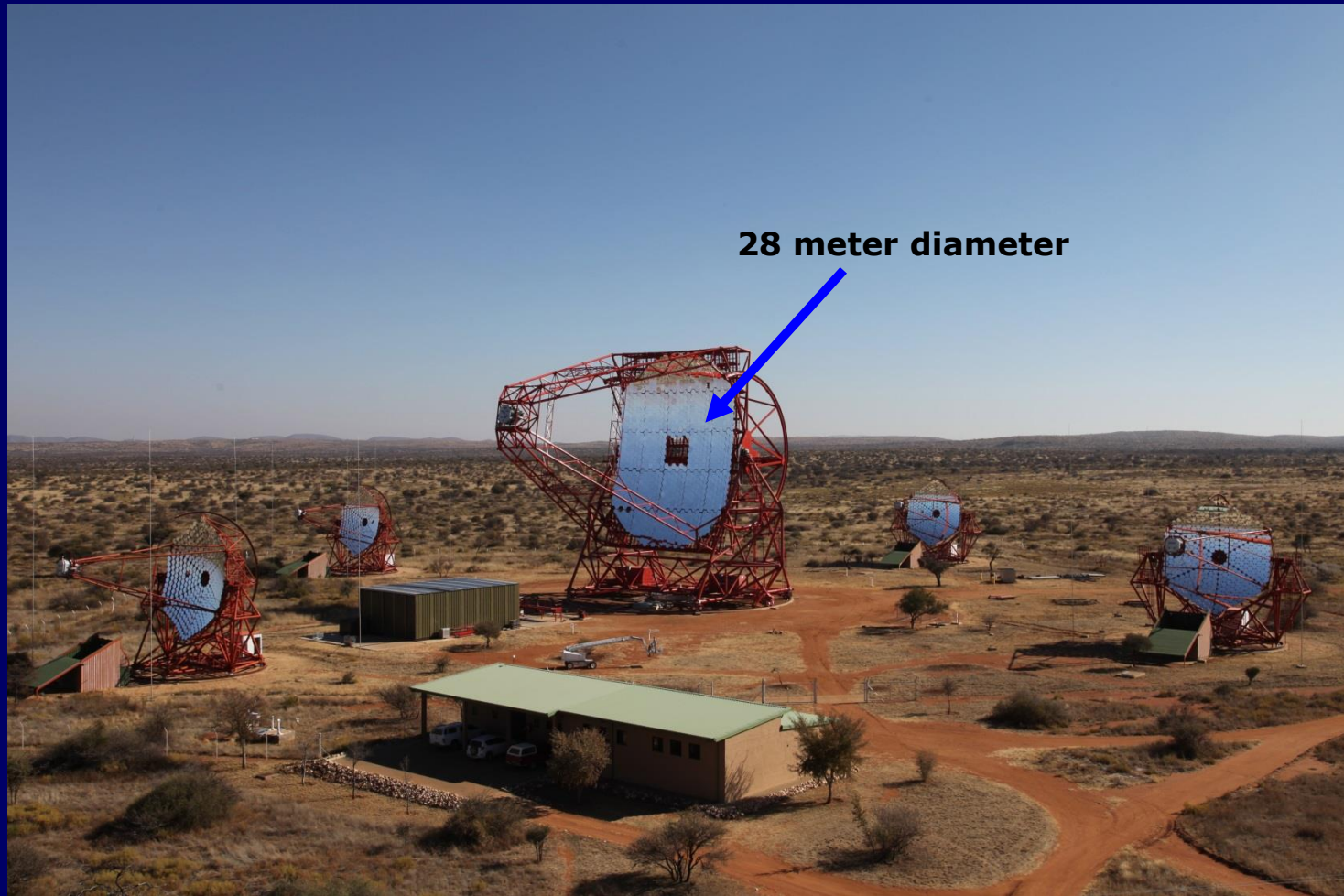
Bringmann et al. JHEP 0801:049,2008



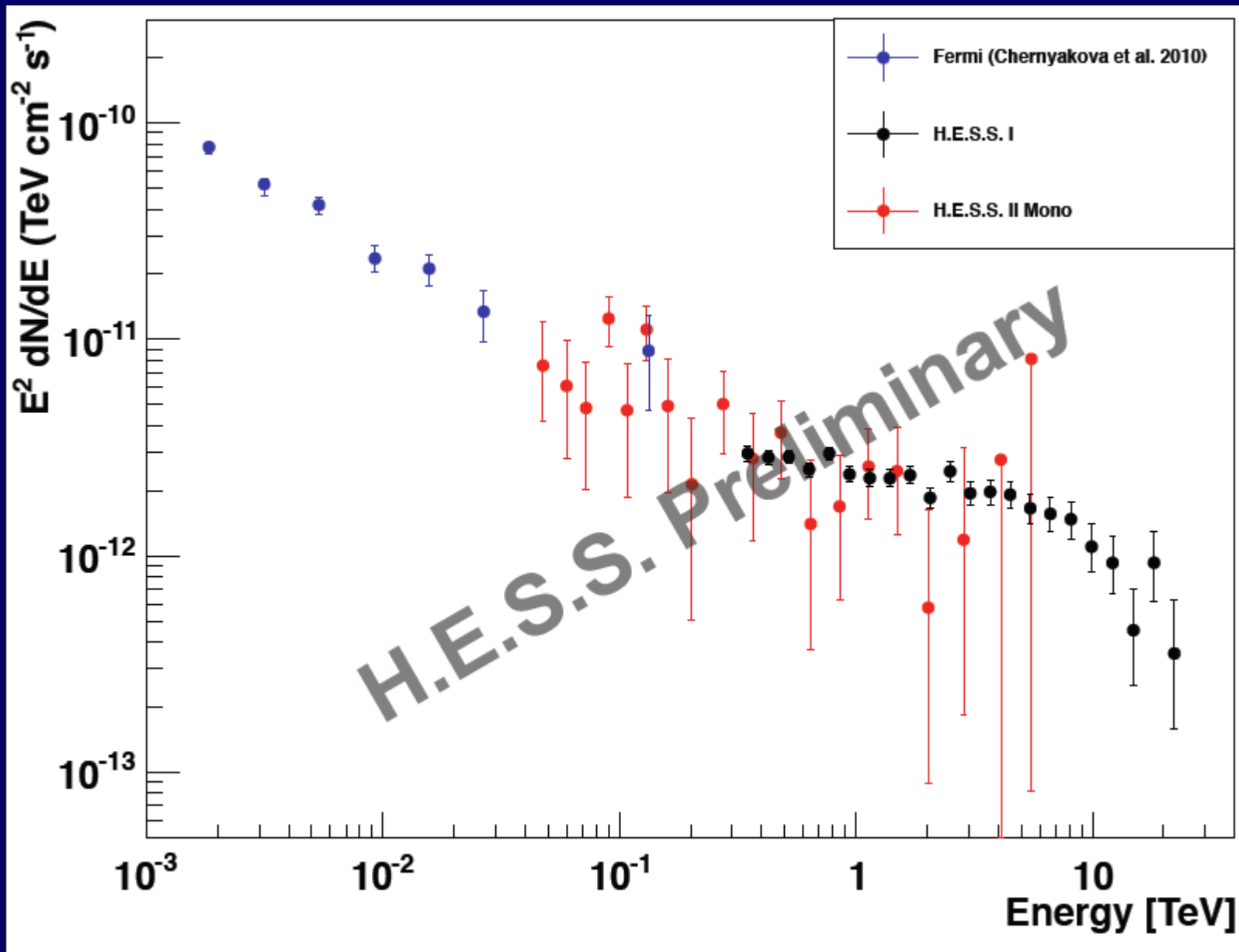
# Gamma-rays: sensitivity illustration



# First light for worlds largest Cherenkov Telescope: HESS II, Summer 2012

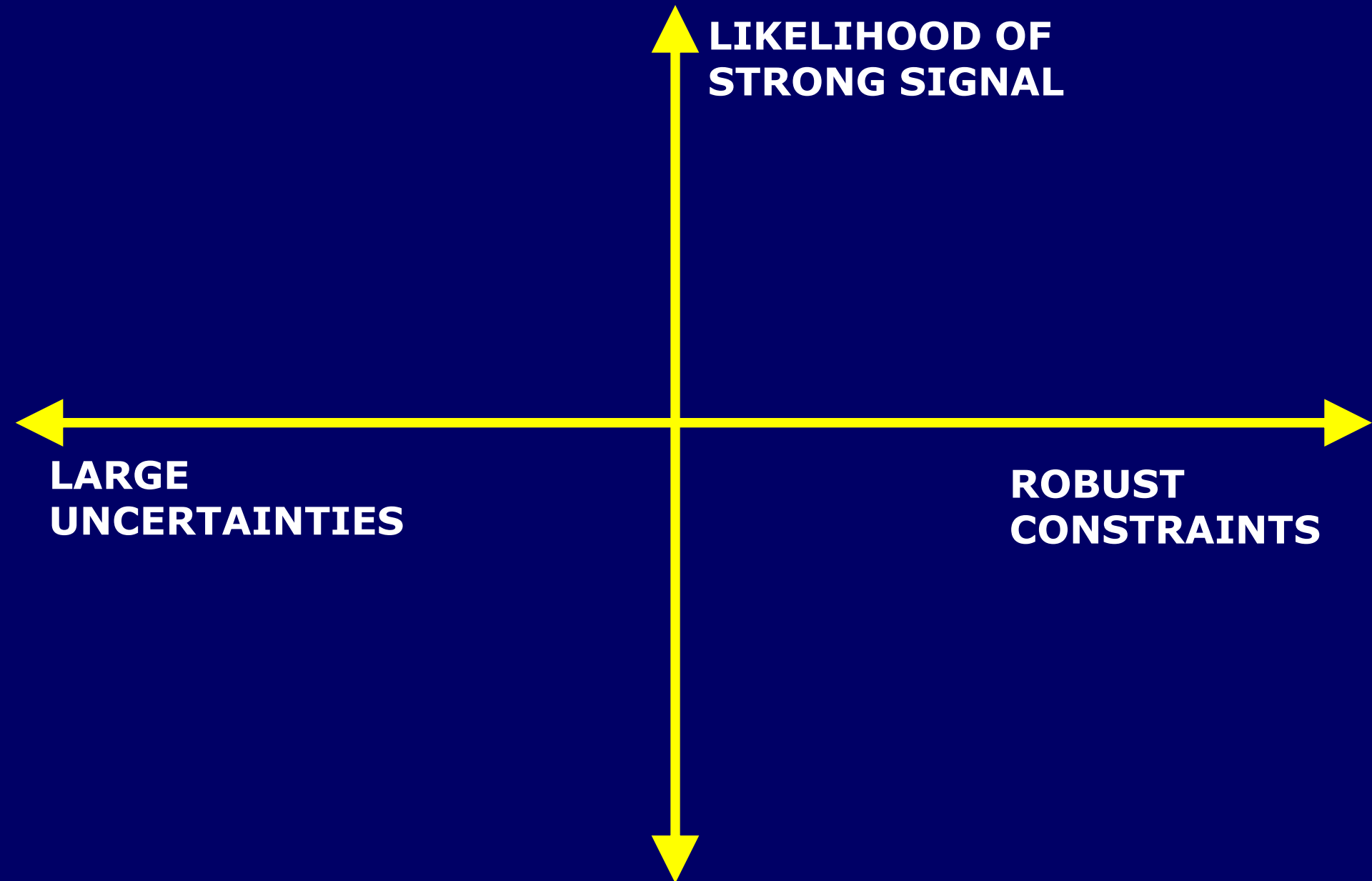


# Spectrum for Galactic Centre source Sag A\*

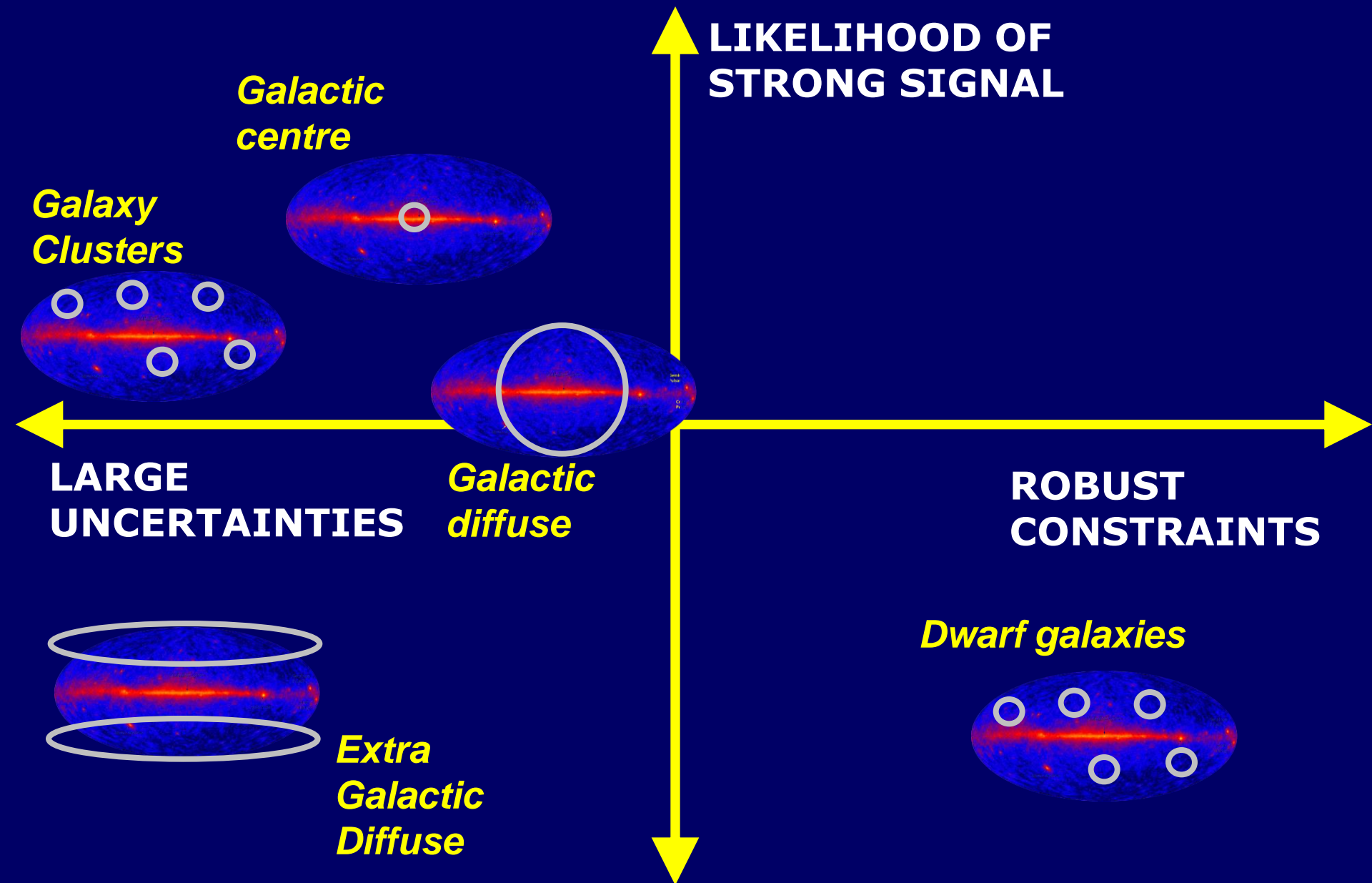




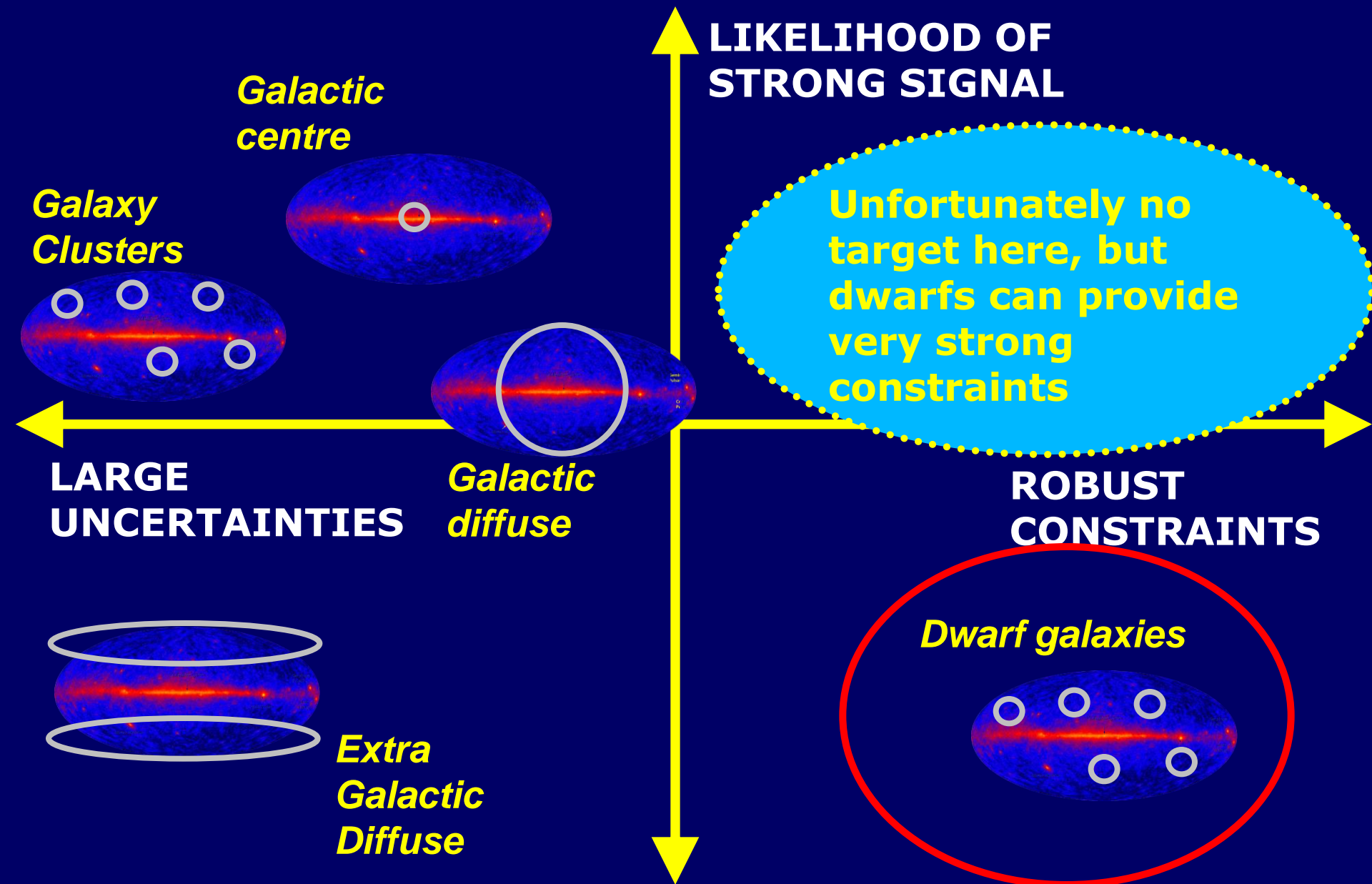
# Targets and Challenges - Satellites



# Targets and Challenges - Satellites

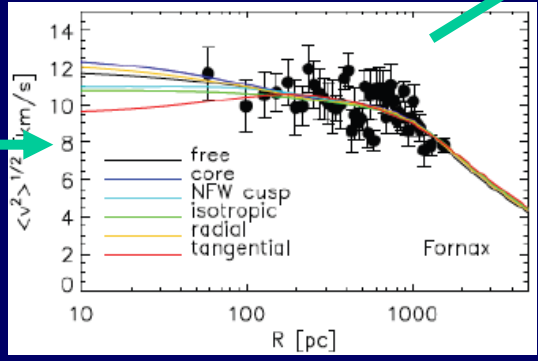
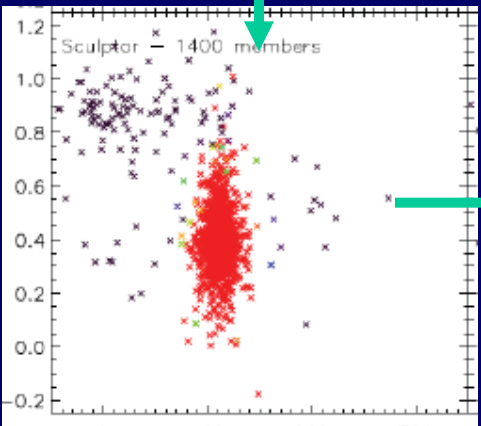
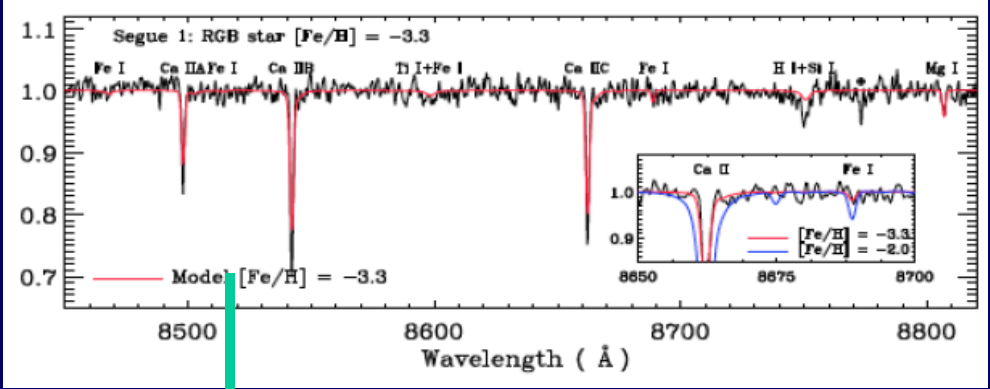


# Targets and Challenges - Satellites



# Dwarfs galaxies – cleanest target

- DM dominated (M/L ~10--1000).
- Nearby (~ 100 kpc)
- Stellar velocities can be used to measure DM density (error can be propagated to particle constraints) → propagated to constraints



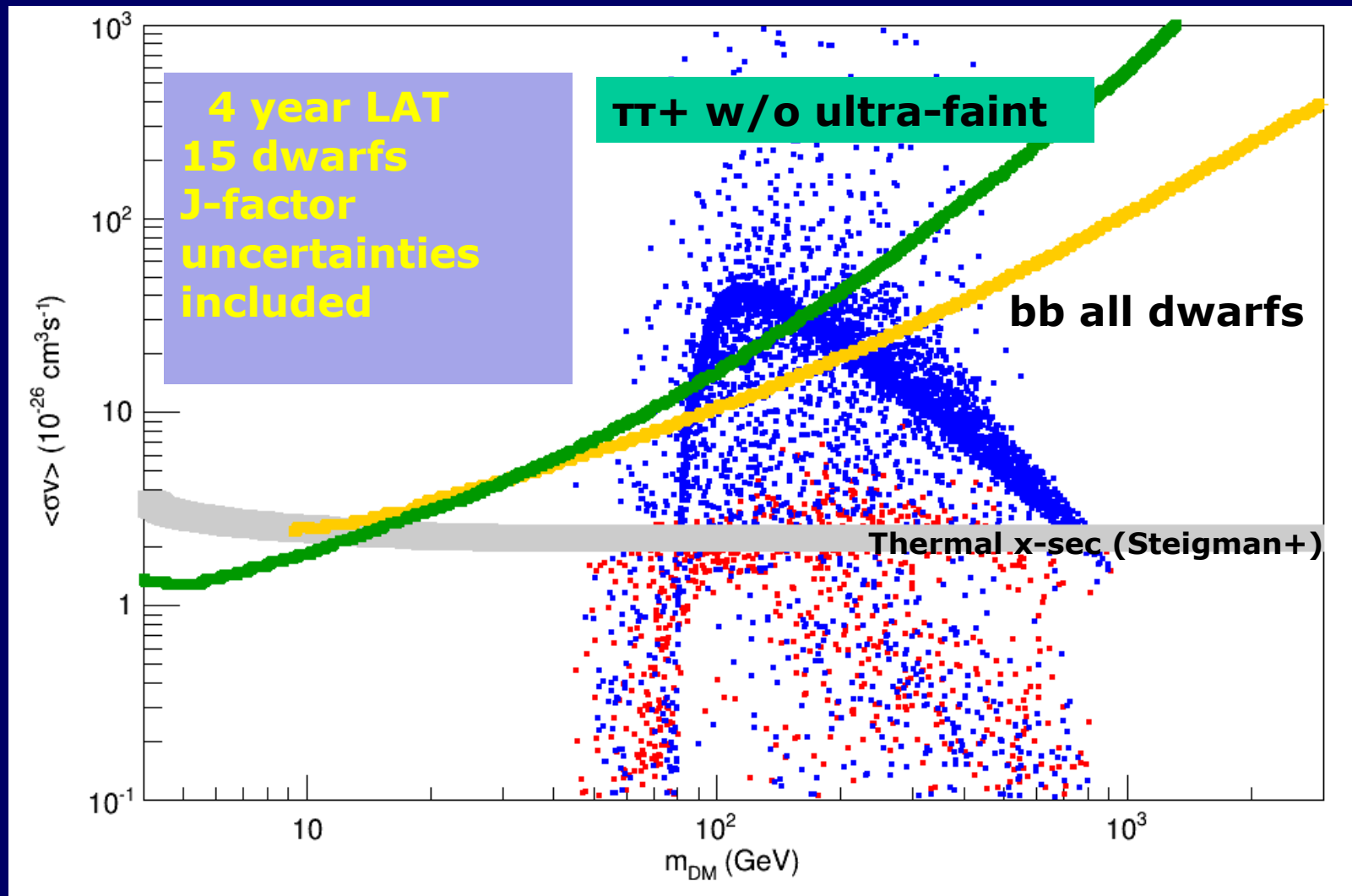
Name	l deg.	b deg.	d kpc	$\log_{10}(J)$ $\log_{10}[\text{GeV}^2\text{cm}^{-5}]$	$\sigma$	ref.
Bootes I	358.08	69.62	60	17.7	0.34	[15]
Carina	260.11	-22.22	101	18.0	0.13	[16]
Coma Berenices	241.9	83.6	44	19.0	0.37	[17]
Draco	86.37	34.72	80	18.8	0.13	[16]
Fornax	237.1	-65.7	138	17.7	0.23	[16]
Sculptor	287.15	-83.16	80	18.4	0.13	[16]
Segue 1	220.48	50.42	23	19.6	0.53	[18]
Sextans	243.4	42.2	86	17.8	0.23	[16]
Ursa Major II	152.46	37.44	32	19.6	0.40	[17]
Ursa Minor	104.95	44.80	66	18.5	0.18	[16]

e.g:  
**Charbonnier+, MNRAS 418 (2011) 1526**  
**Strigari+, Phys. Rev. D, 75, 083526**  
**Evans+, Phys. Rev., D69, 123501, (2004)**

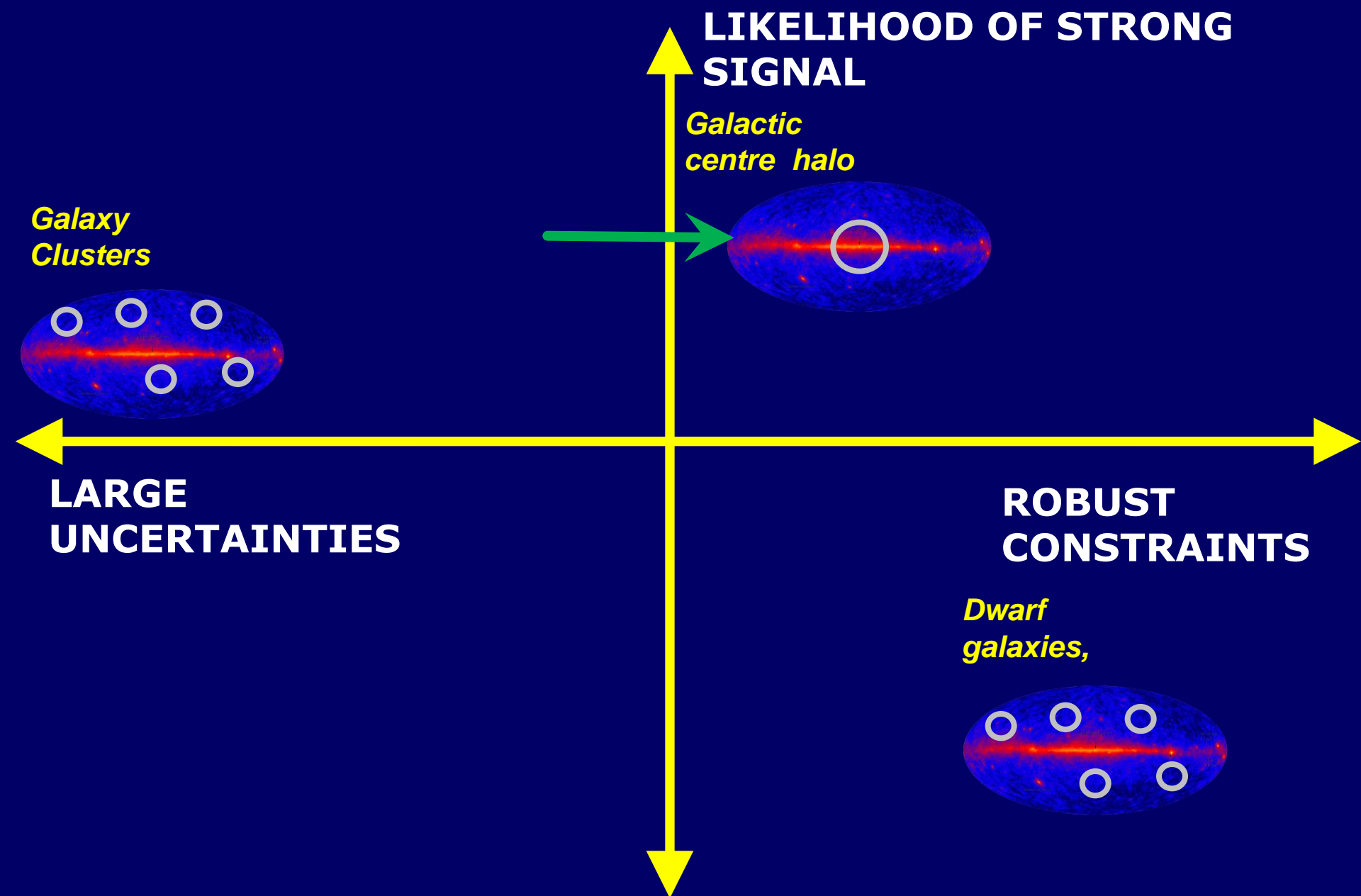
# Constraints from likelihood combination of dwarf galaxies

Fermi-LAT: Phys. Rev. Lett. 107, 241302 (2011)

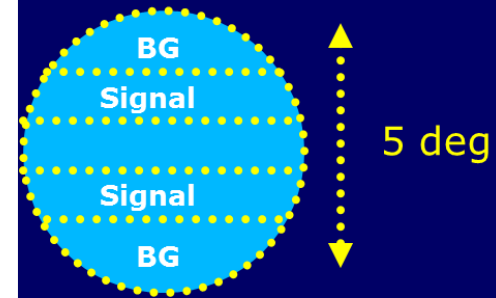
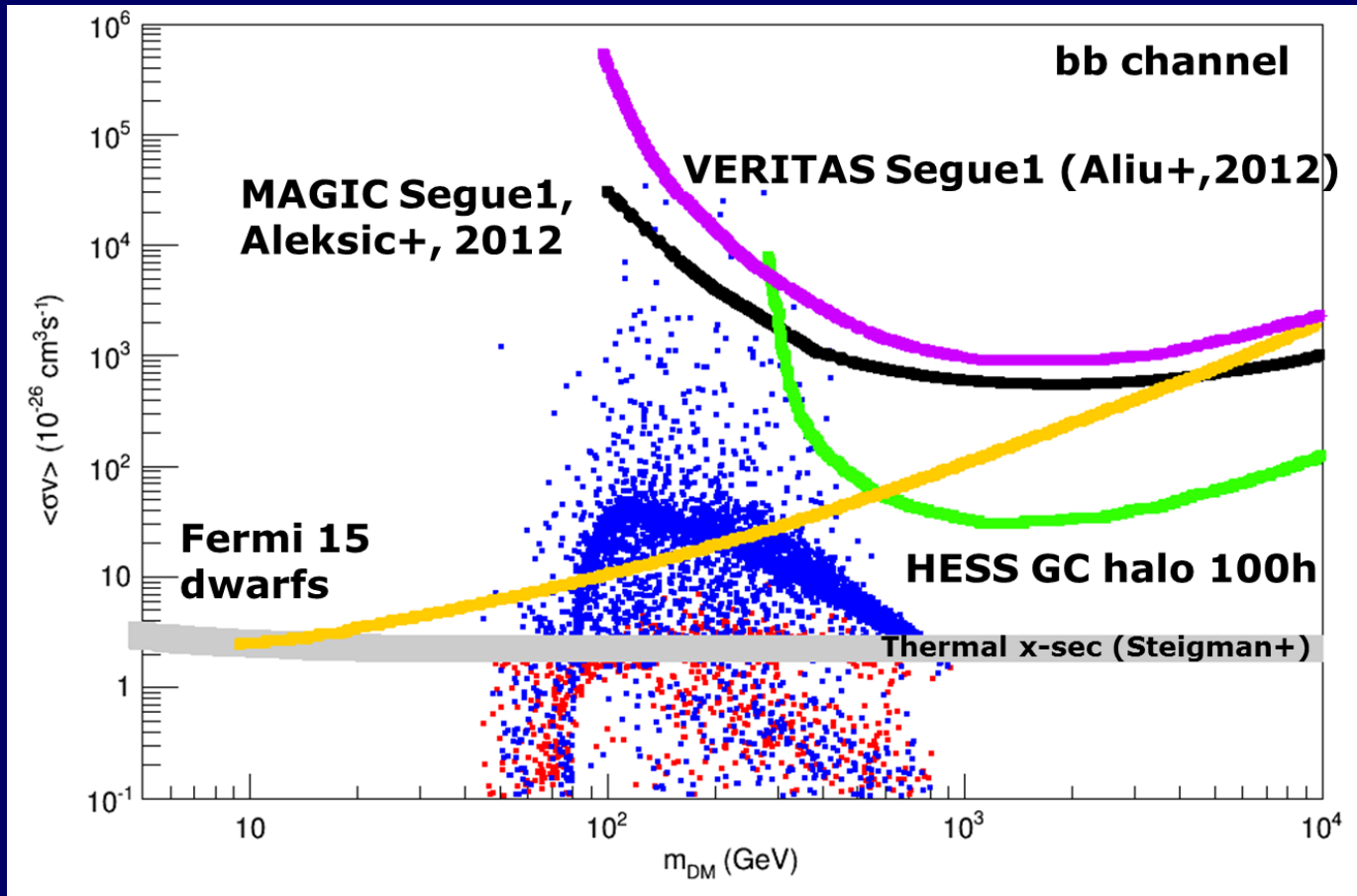
Fermi-LAT: Phys. Rev. D . 89 , 042001, (2014)



# Targets and Challenges – IACT



# Most important gamma-ray constraints - summary



**What about discovery?**

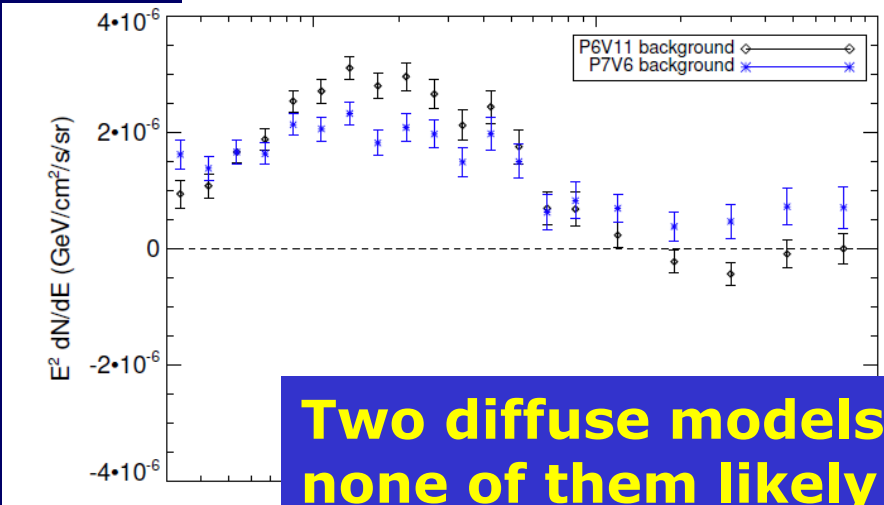
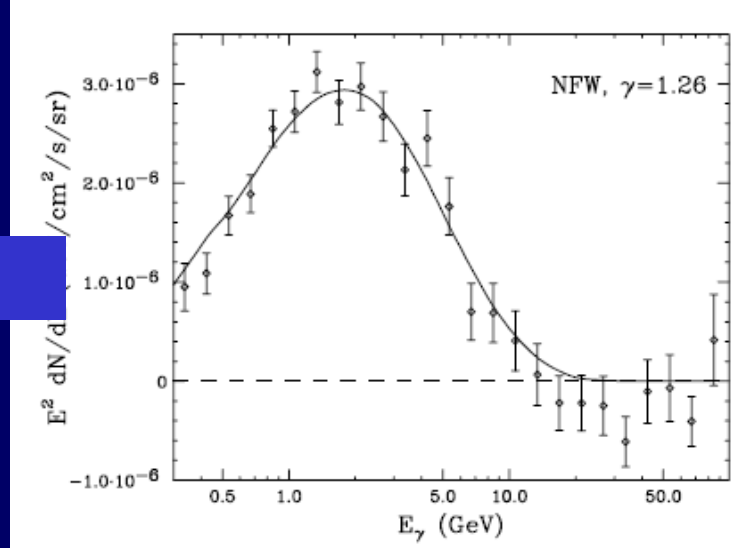
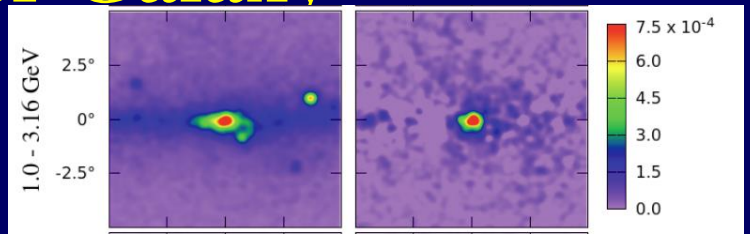


# Extended emission in the Inner Galaxy consistent with dark matter?

T. Daylan+ (2014)

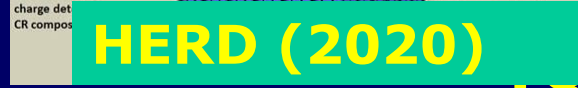
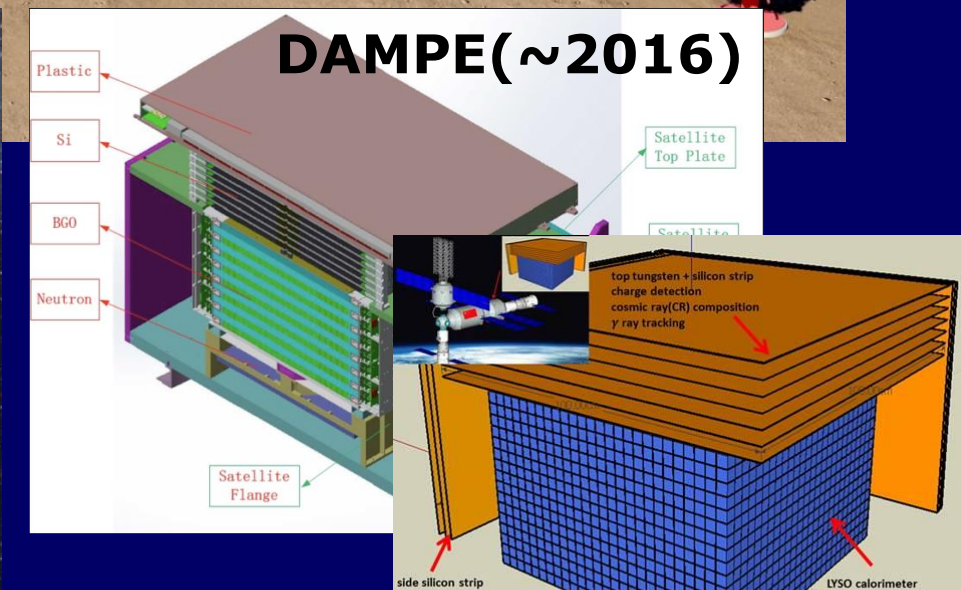
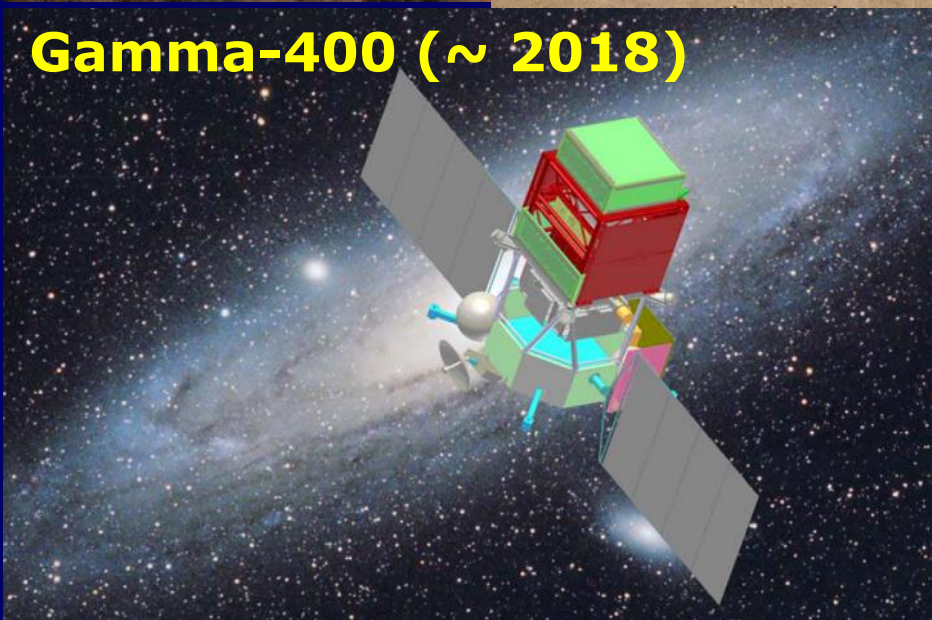
- Excess exhibits spatial and spectral features consistent with dark matter (quark annihilation, 30-40 GeV, thermal cross-section)
- Potential problems arise from the custom made event selection and corresponding diffuse modelling. Whether these aspects invalidate the conclusion, I don't know.
- Can this be resolved in the Galactic Centre? I doubt it ....

Horiuchi talk

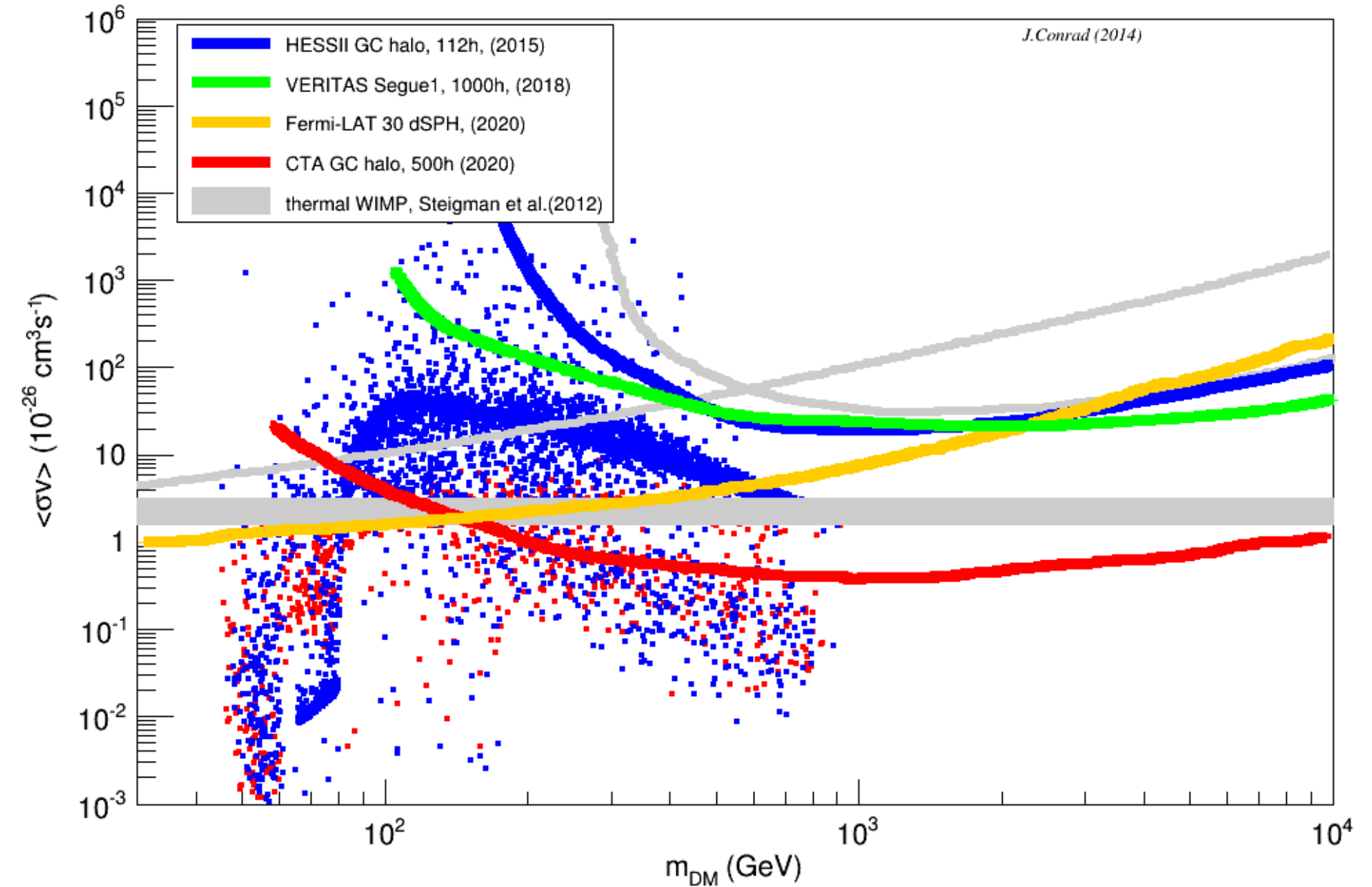


Two diffuse models, none of them likely appropriate

# Future experiments



# Future Gamma-ray constraints – from now to 2020



# Summary (gamma rays):

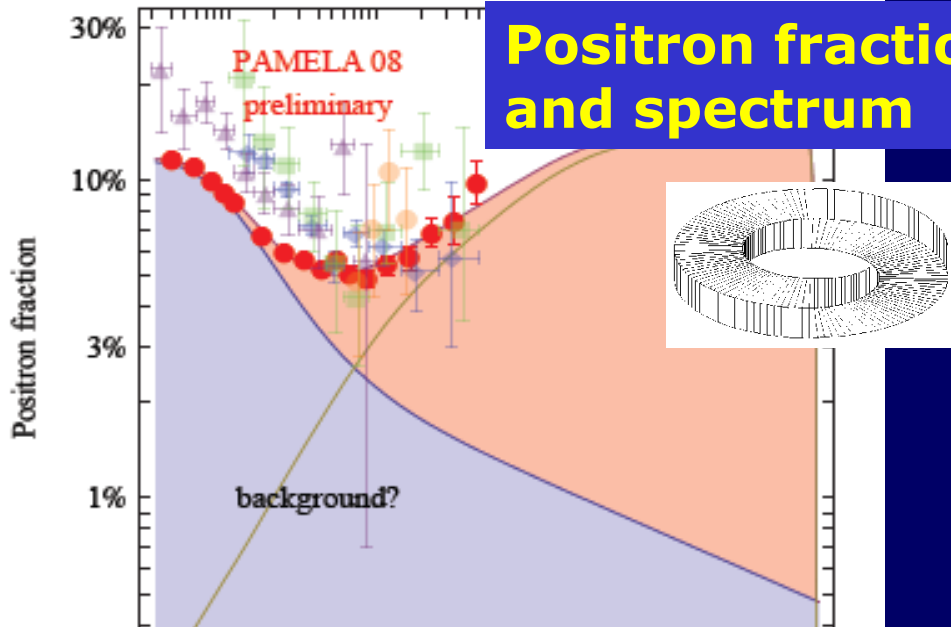
- General:
  - Gamma rays are the golden channel for indirect detection of dark matter, due to the wealth of information they carry and simple propagation
- Status:
  - The most robust constraints (and stringent) are obtained from dwarf galaxies (Fermi-LAT) and the vicinity of the galactic center (HESS)
  - Gamma ray searches provide the most stringent, robust constraints to WIMP dark matter, excluding thermal WIMPS below masses of about 20-30 GeV.
  - An excess at the Galactic Center with respect to simple diffuse emission models can be interpreted as dark matter → solution in the next iteration of the combined dwarf analysis?
- Outlook:
  - Fermi-LAT/CTA will be able to exclude thermal WIMPS from a few GeV upto several TeV within the next decade → we are entering the endgame for the WIMP paradigm

**Cosmic rays: a clear signal – but of what?**

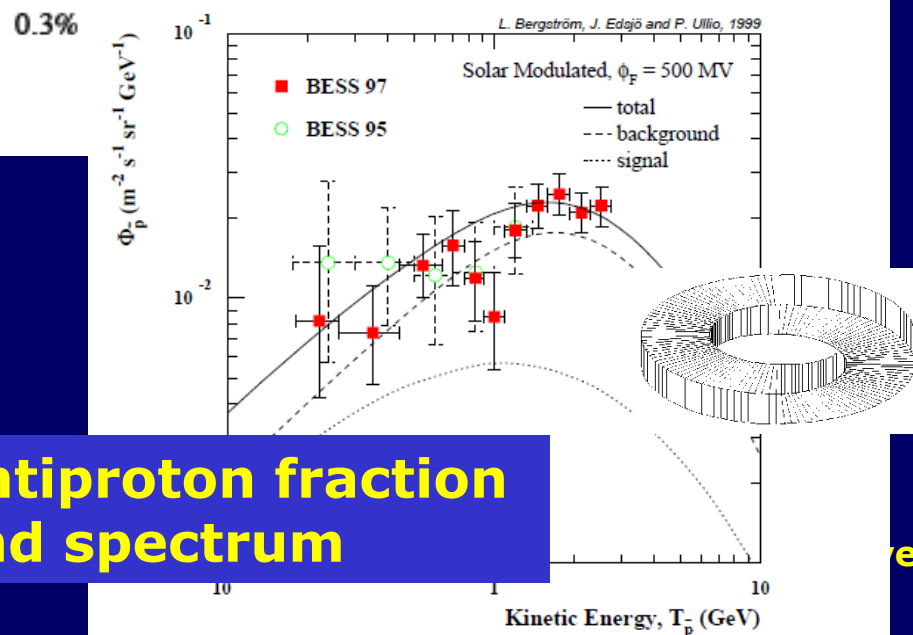
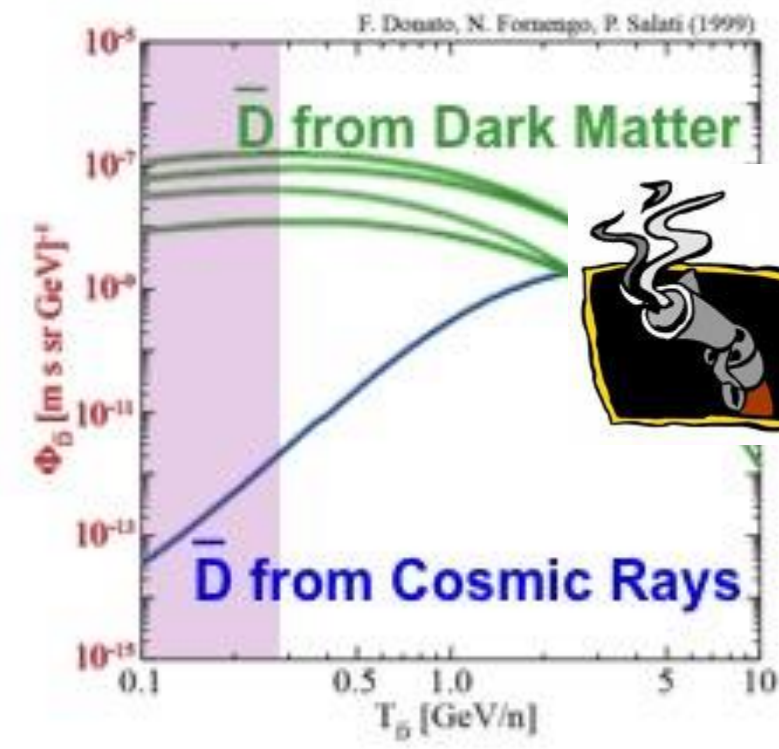


# Cosmic rays: signatures

## Positron fraction and spectrum



Antideuteron flux at the earth (w/propagation and solar modulation)

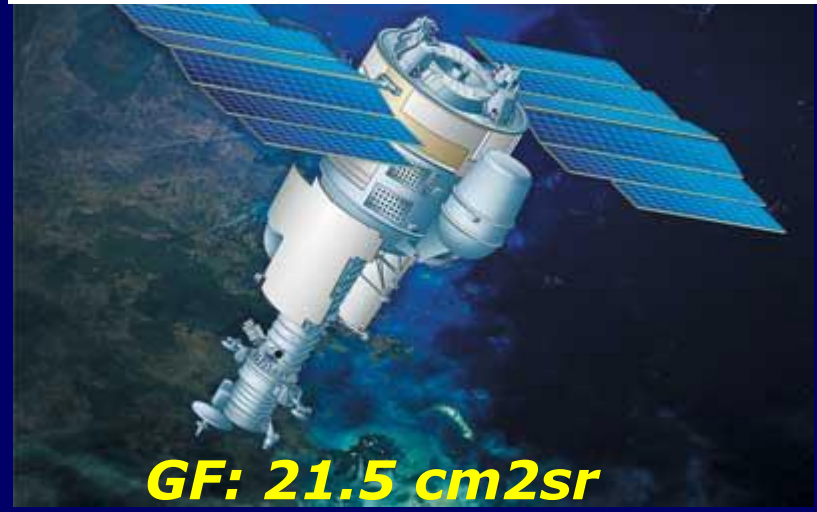
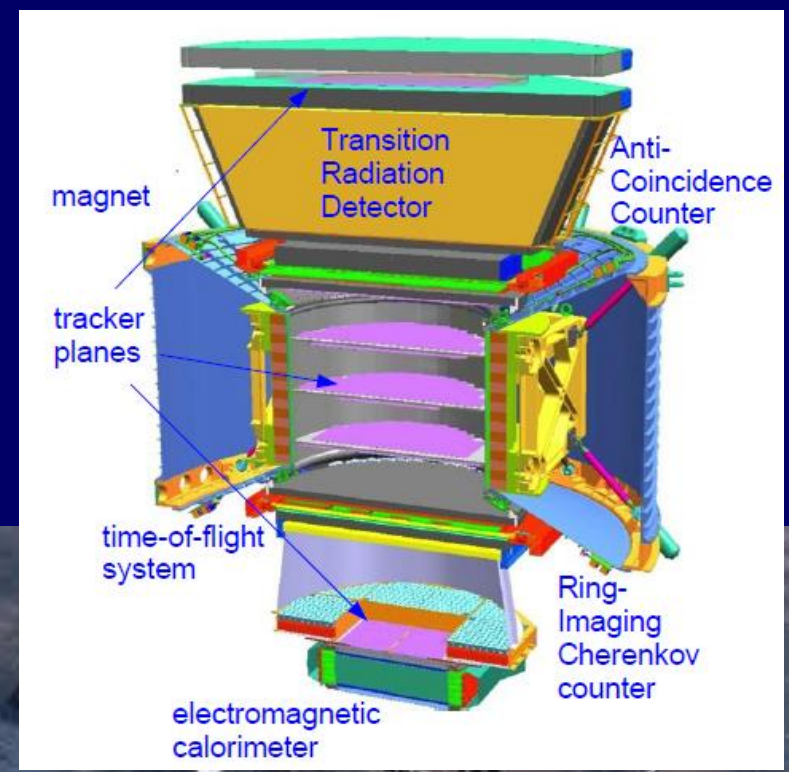
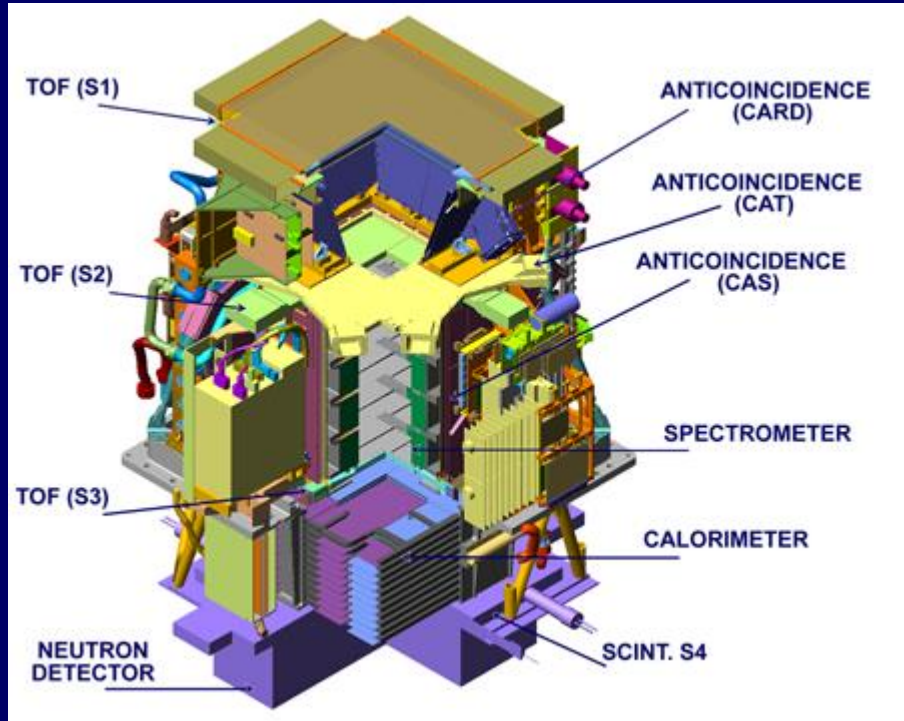


## Antiproton fraction and spectrum

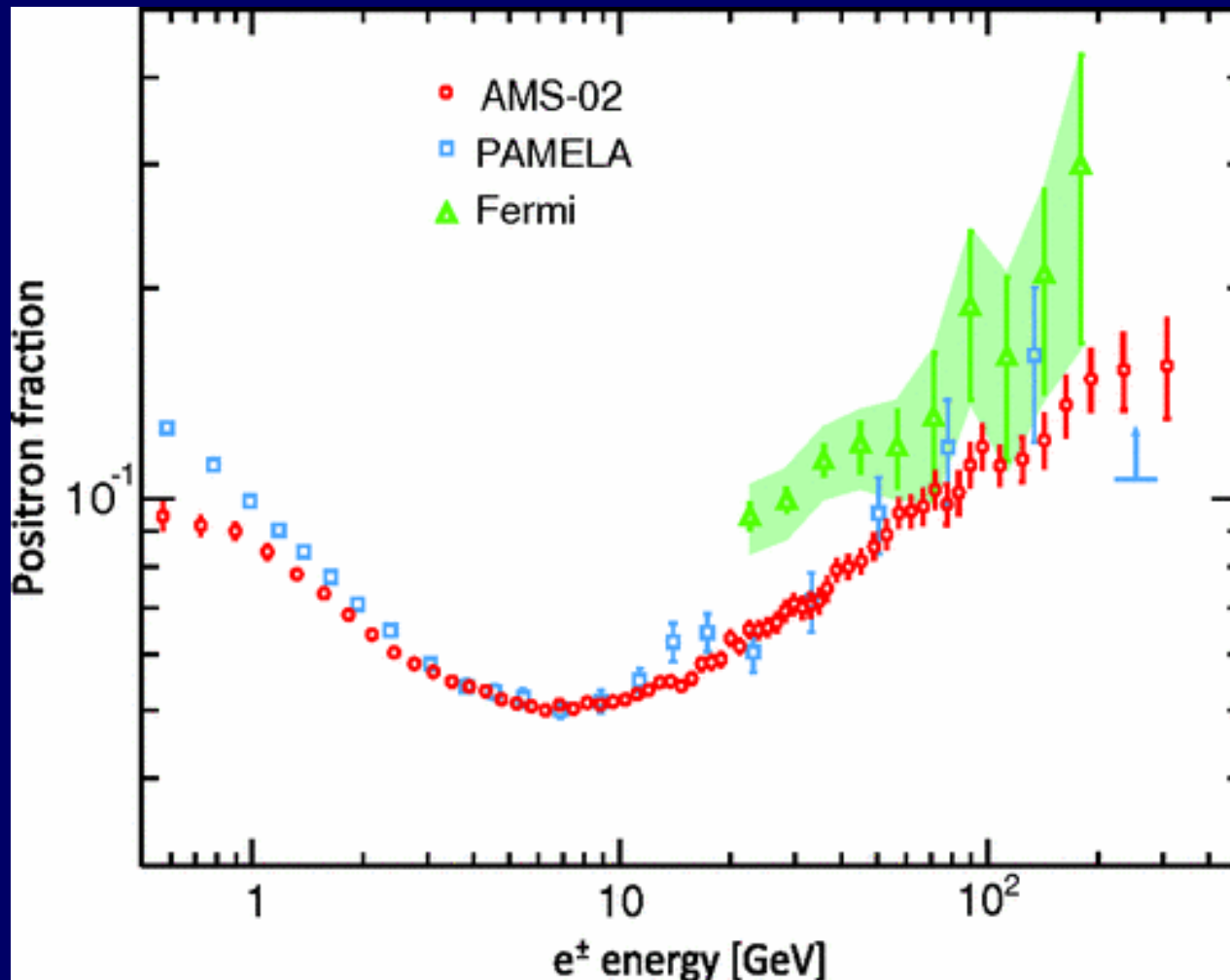
ersitet

## Anti-deuteron spectrum

# PAMELA/AMS



# Positron fraction



Requires non-standard source of positrons but what?

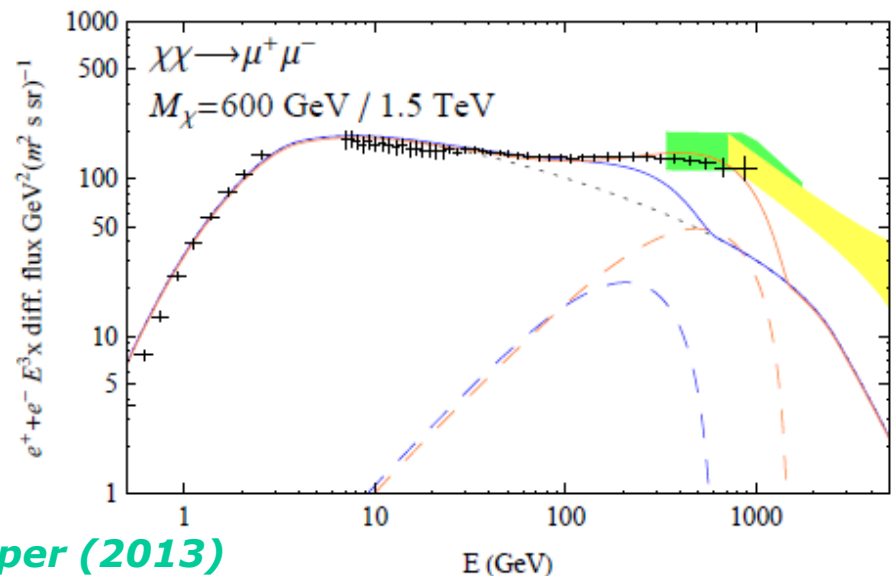
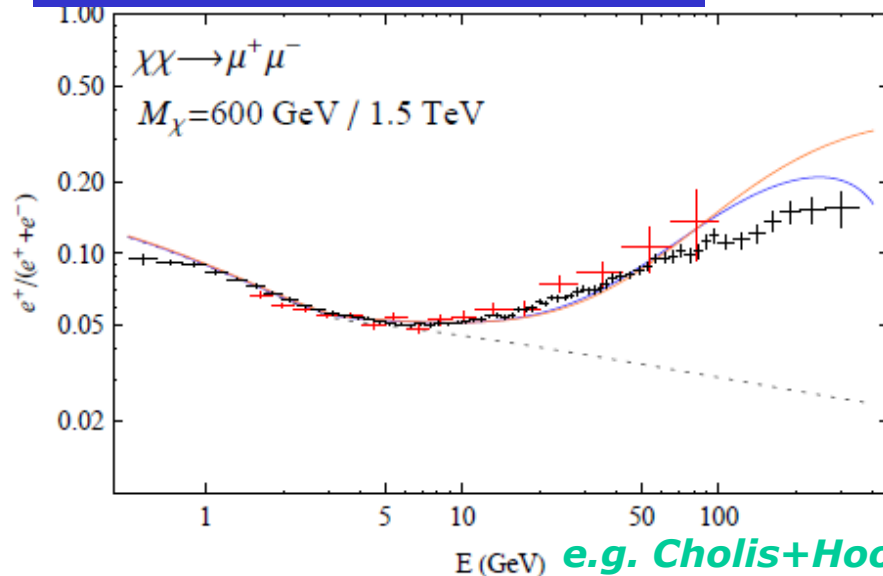
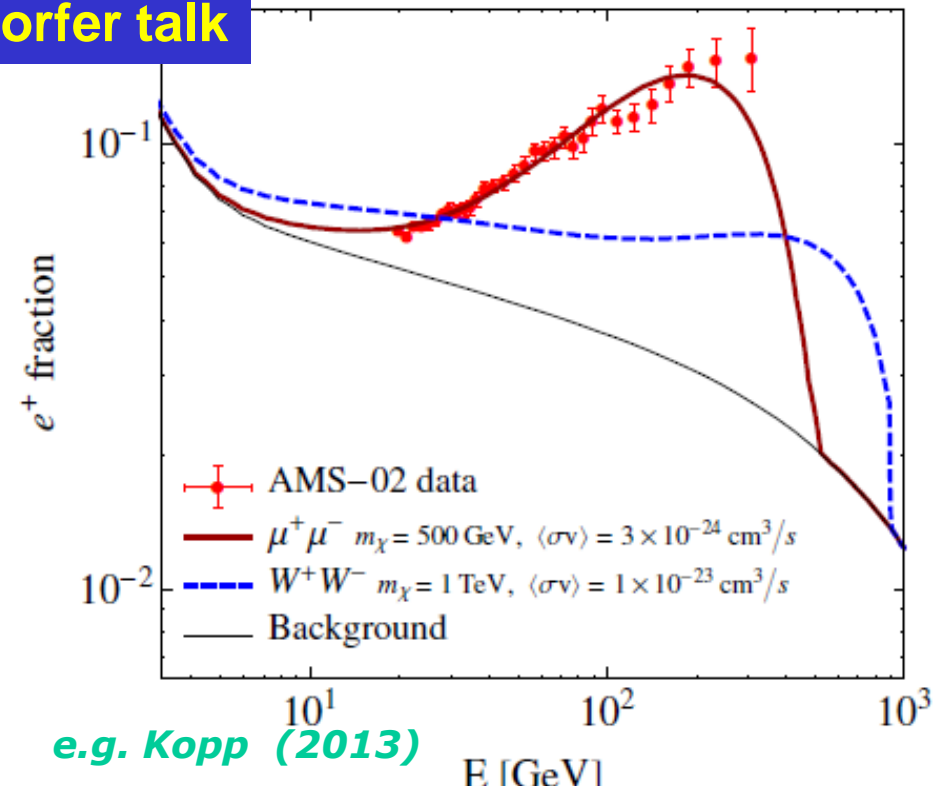


# Dark Matter

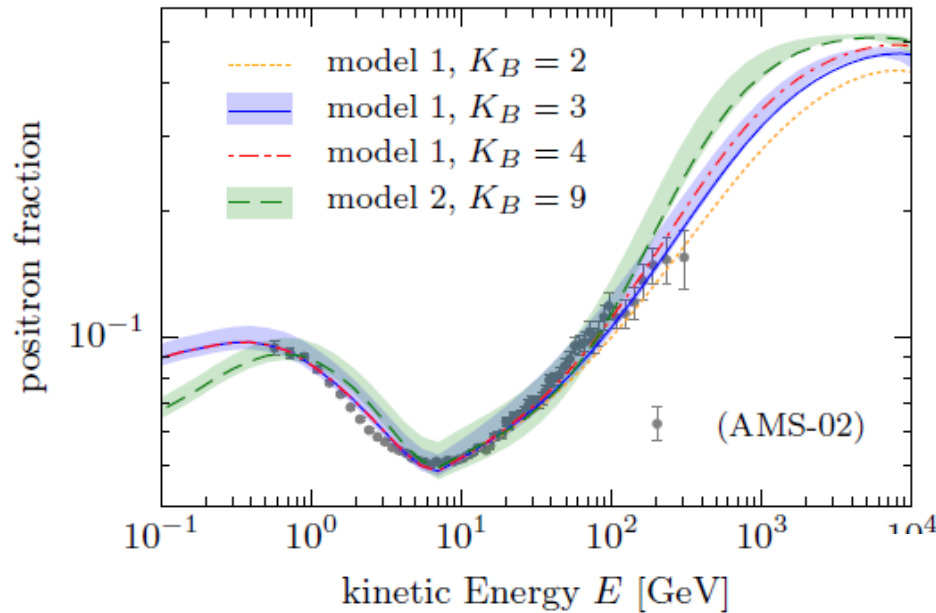
Lamperstorfer talk

- Data prefers models with leptonic annihilation, largish masses ( $\sim$  TeV), large x-sec or boost
- Difficult to accomodate both the positron fraction and the hard Fermi-LAT electron spectrum ( decay via light mediator states )

See also Pospelov talk



# Can it be secondary? E.g by close by SNRs?



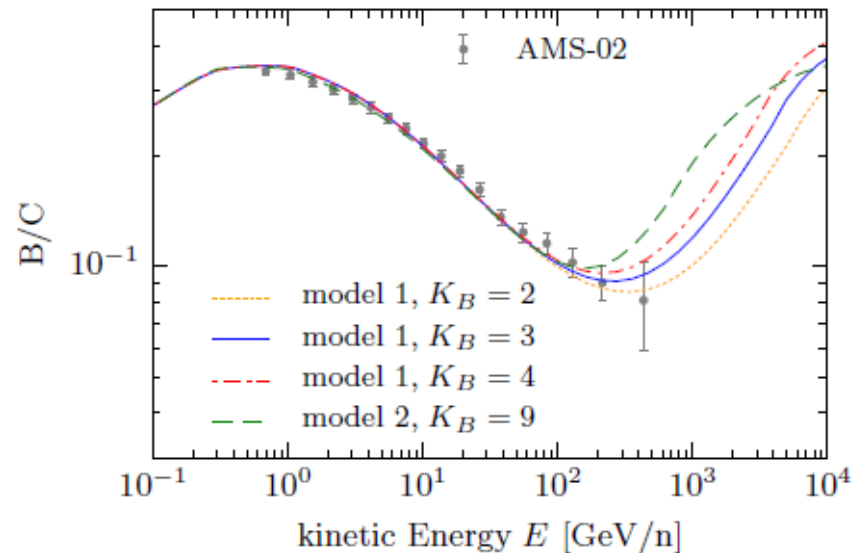
**$e^+$  produced inside SNR  
→ harder positron  
spectrum**

***Blasi+ (2009), Ahlers+ 2009***

***Mertsch+Sarkar (2014)***

**Prediction: rise in  
p/anti-p and B/C ratio**

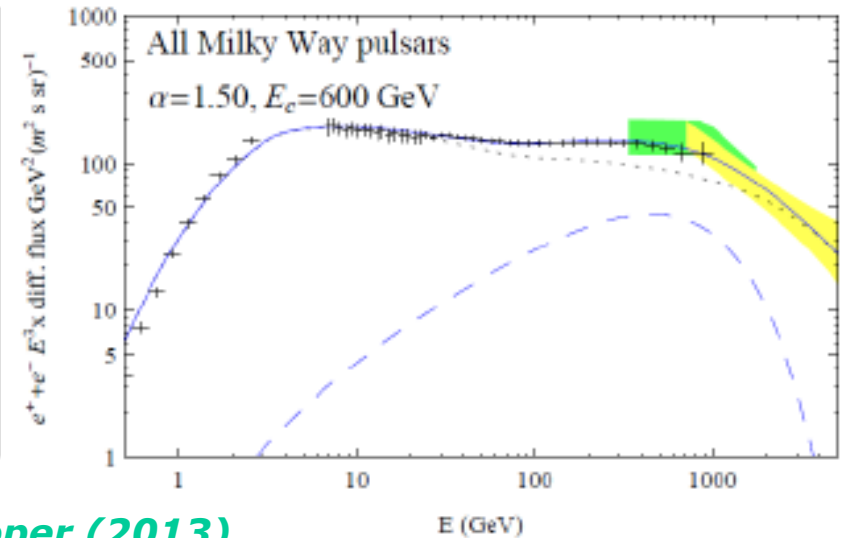
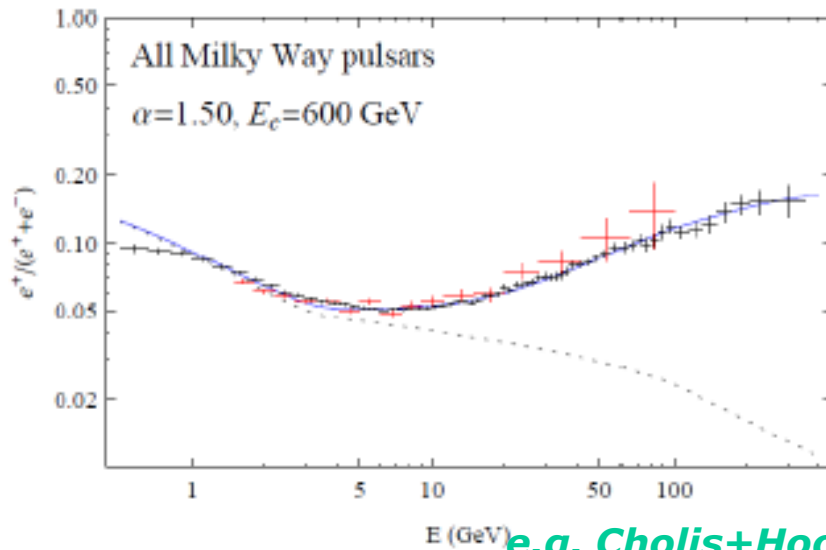
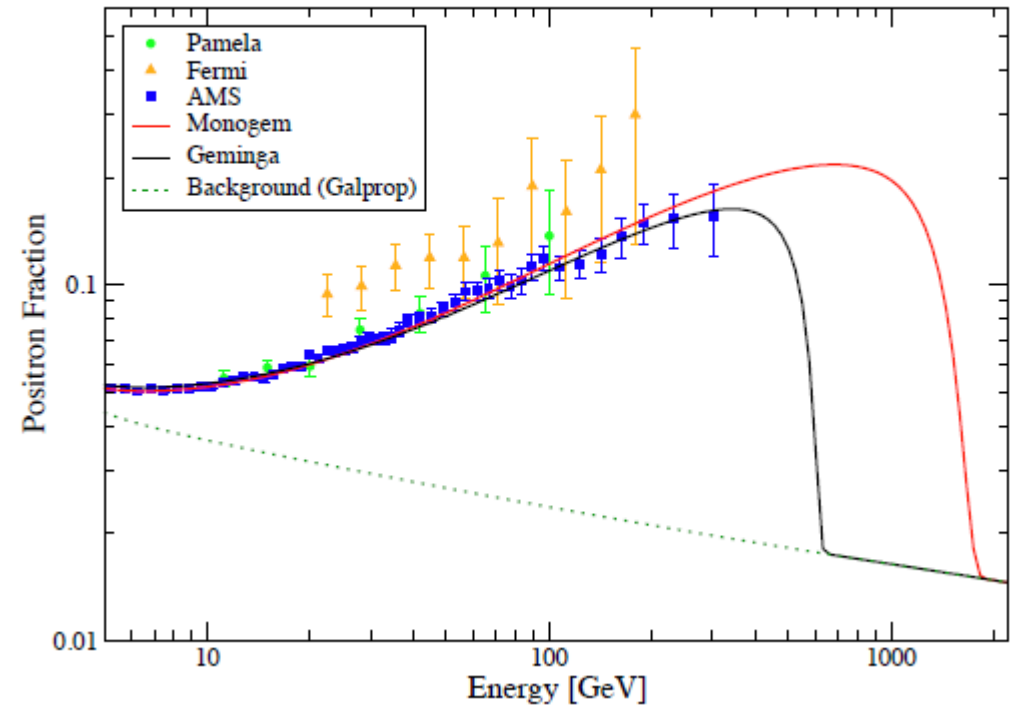
**Marginally consistent  
with current AMS data,  
if you ask me.**



# Pulsars

- Single mature pulsar
  - Monogem
  - Geminga
- ...or sum of all MW pulsars ....

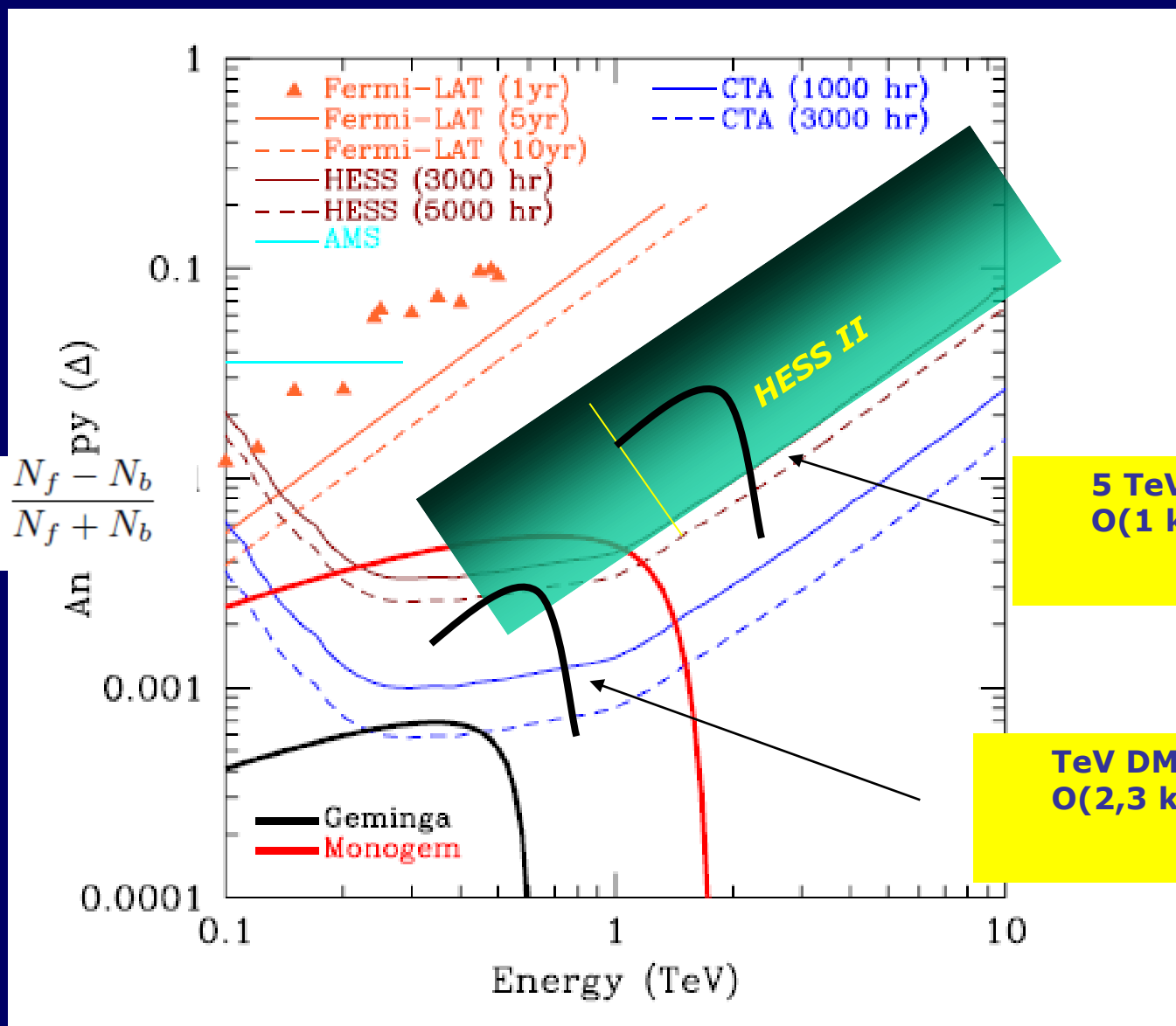
*e.g. Linden+Profumo (2013)*



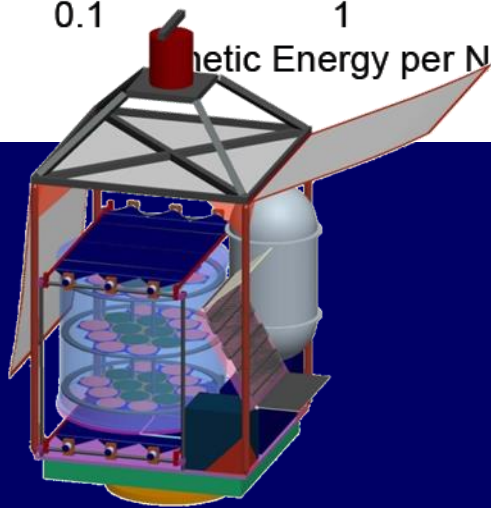
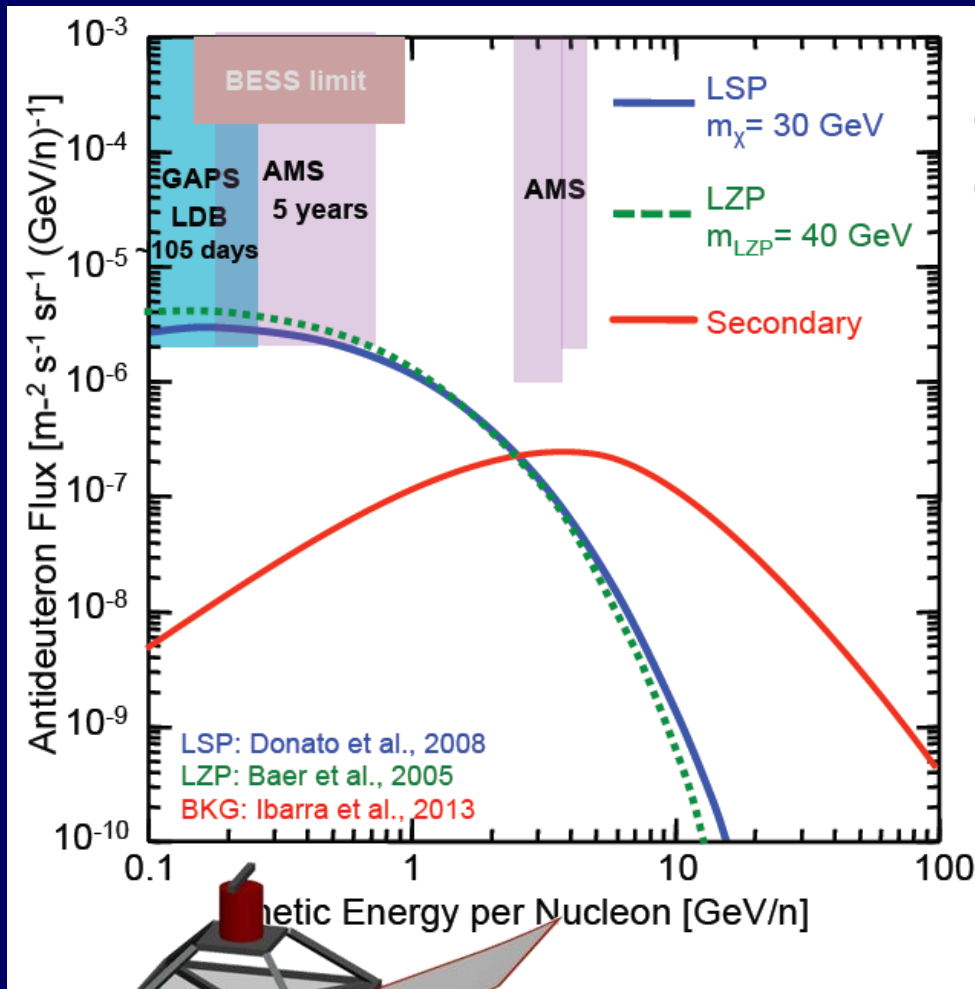
*e.g. Cholis+Hooper (2013)*

# Can air cherenkov telescopes help?

$$\Delta = \frac{N_f - N_b}{N_f + N_b}$$



# Anti-deuteron: GAPS



Vittino talk

- TOF and Si(Li) strip detector, signature: x-rays from deexcitation of exotic atom and tracks of decay products (p, pions)
- Successful prototype flight in 2012
- First flight 2018/2019
- Full sensitivity achieved: 2020/21 (?), (AMS 5 year reached by 2017)

# Summary (cosmic rays):

- **General:**

- Cosmic (anti-) rays can provide convincing signals of Dark Matter
- Competitive constraints for leptonic channels

- **Status:**

*e.g. Bergström+(2013)*

- AMS has spectacularly confirmed the existence of a new source of positrons.
- DM IMHO even less likely than after PAMELA.

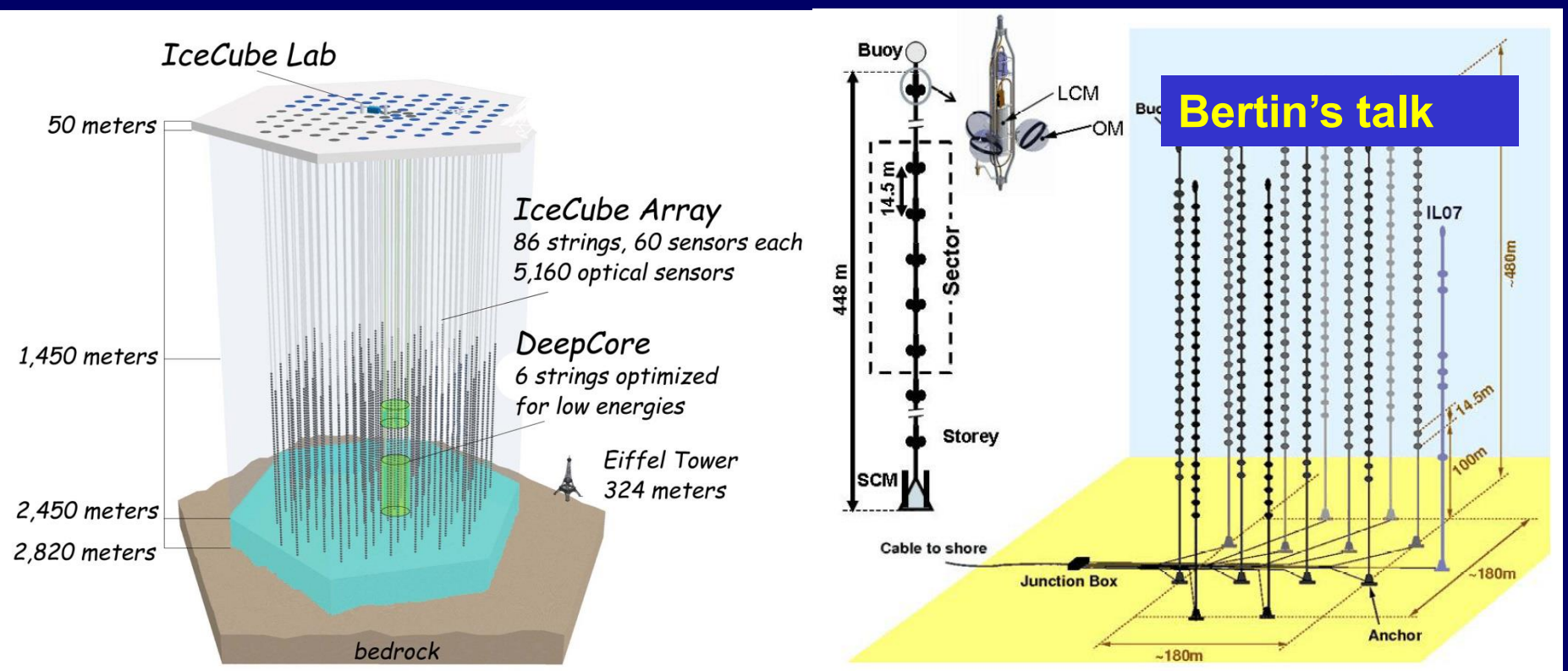
- **Outlook:**

- Anti-proton/spectra and B/C measurements highly anticipated to rule out or confirm proposal of SN production
- Can IACTs provide sensitive anisotropy measurement?

# Neutrinos: direct detection in disguise

Bertin's talk

# IceCube and ANTARES



~ 5000 channels

Mainly northern hemisphere

~ 900 channels

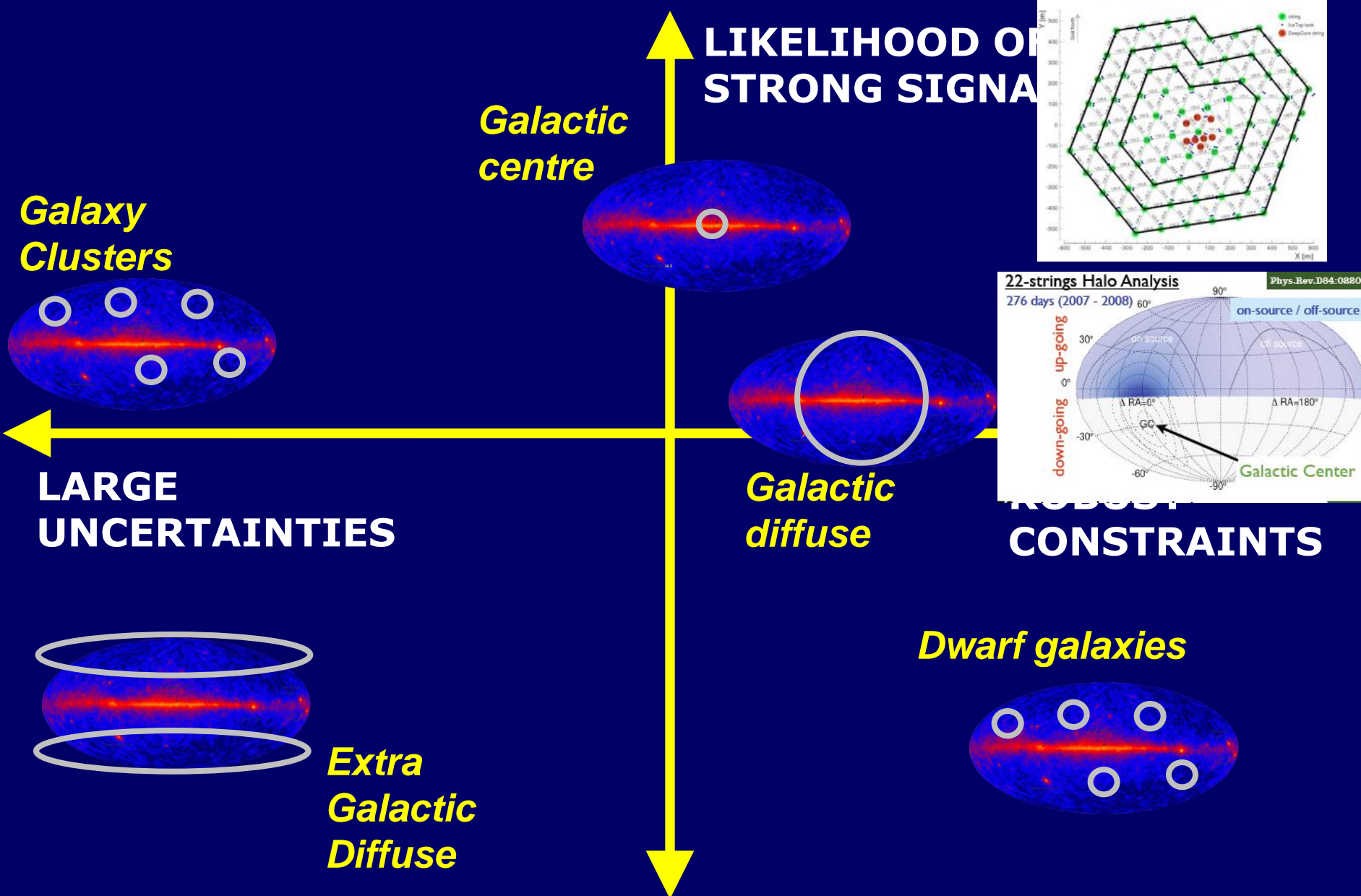
Mainly southern hemisphere



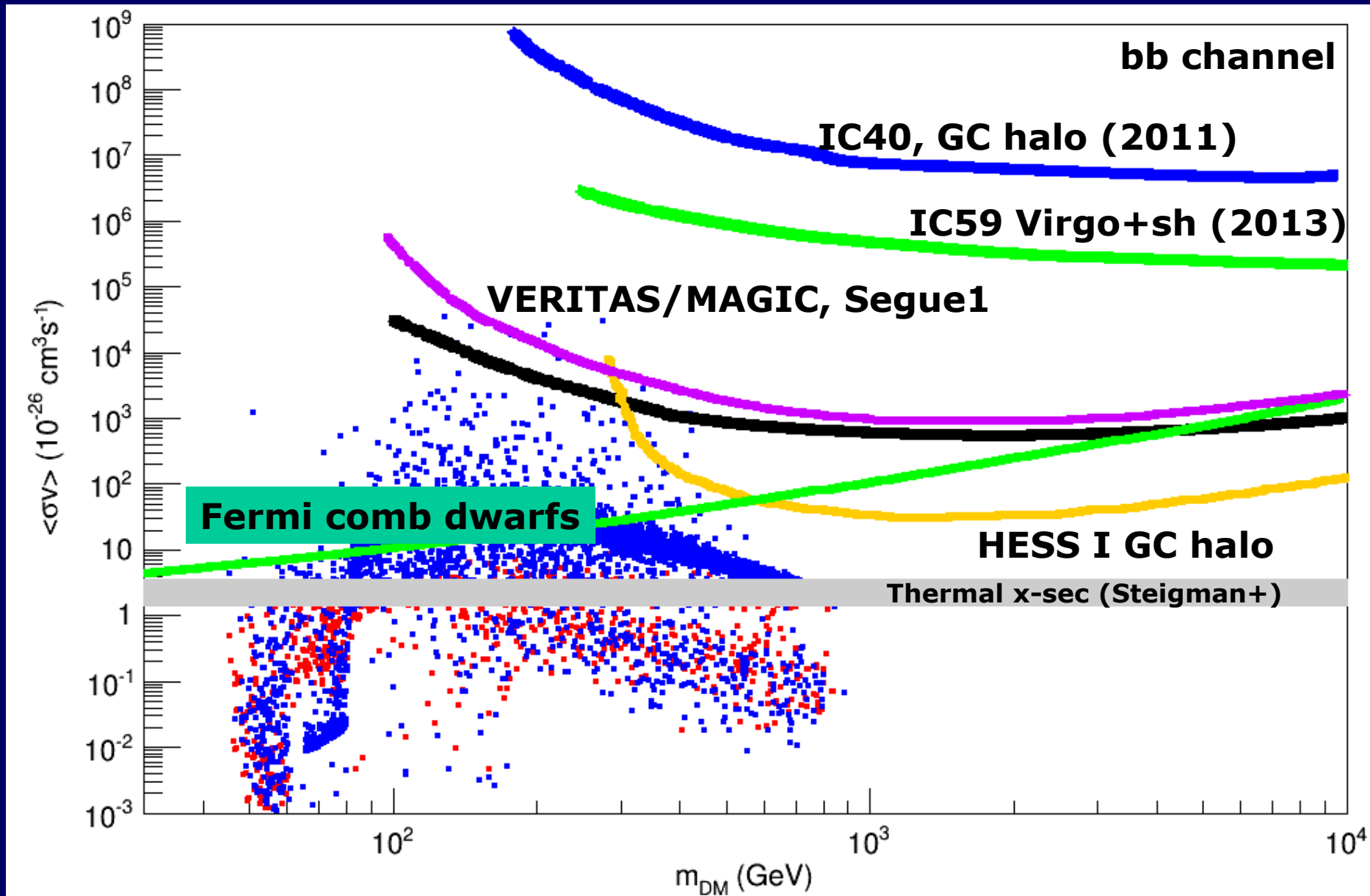
**First, constraints on annihilation cross-sections**

**....**

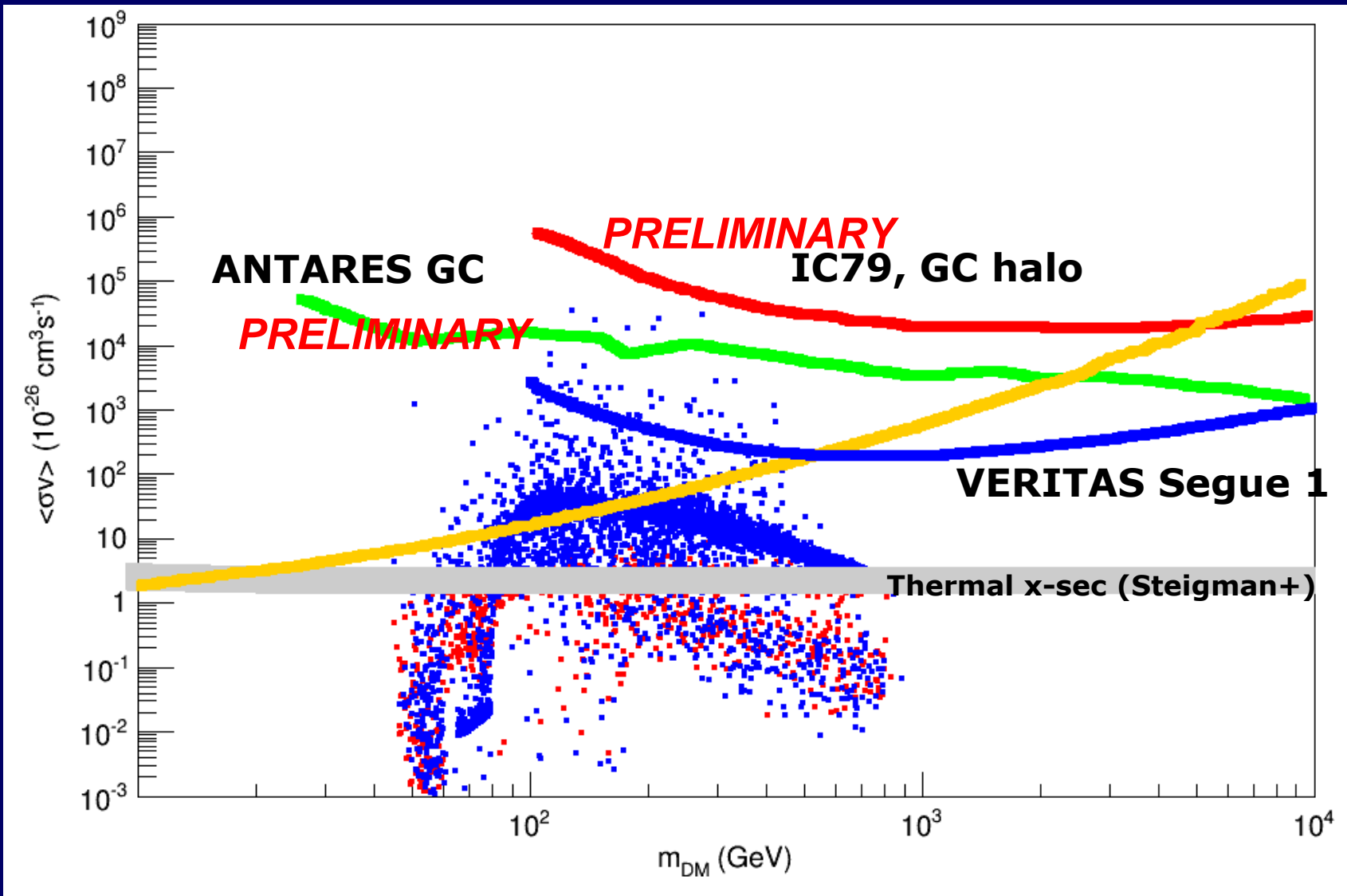
# Targets and Challenges – neutrino telescopes



# Indirect limits ICE3 compared to gamma rays

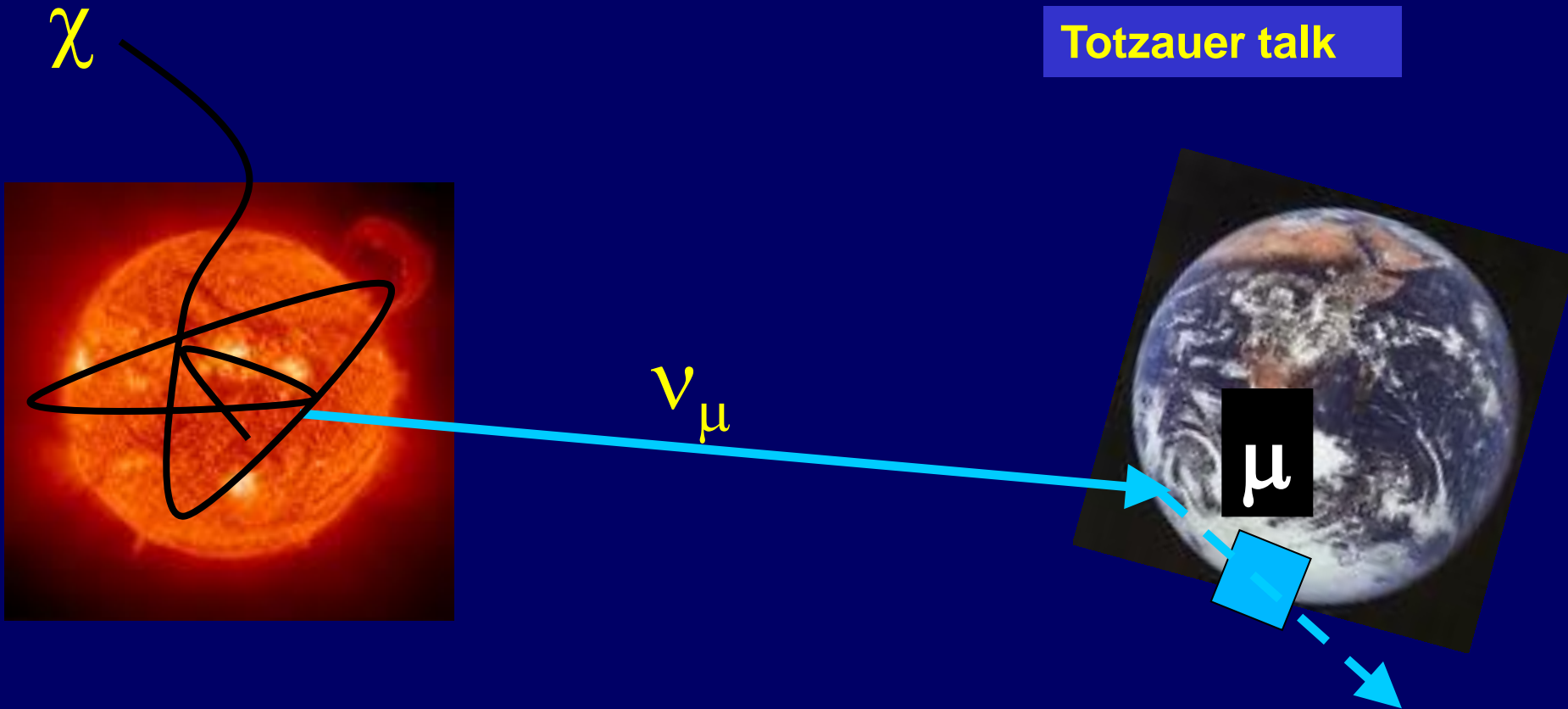


# ◆ channel



# Neutrinos: detection from the Sun

Totzauer talk



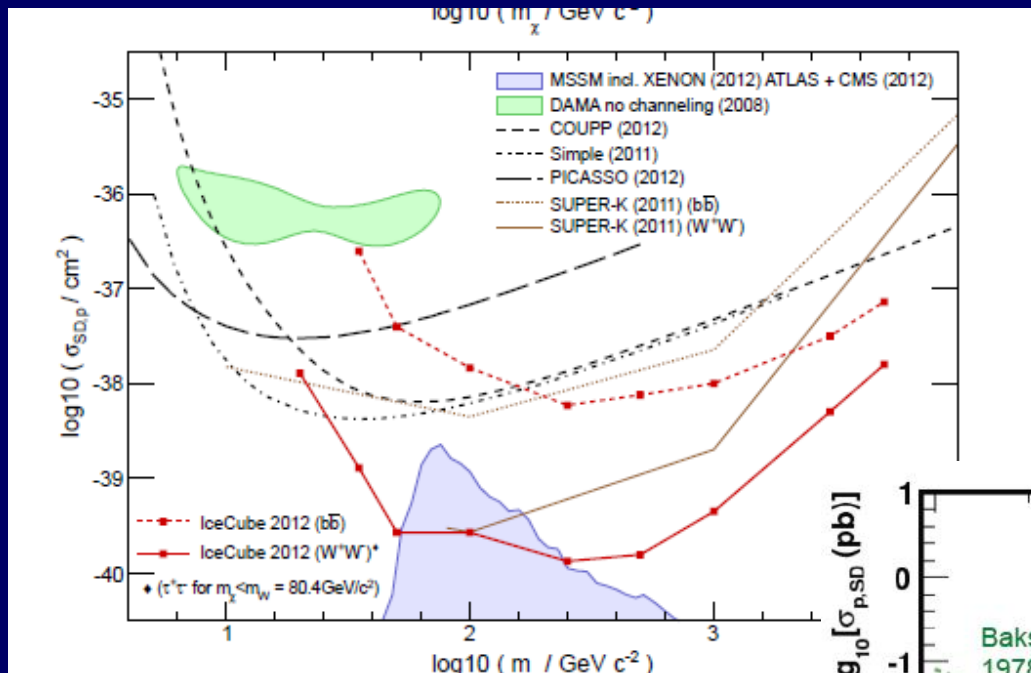
$$\Gamma_{\text{Capture}} (\propto \sigma_{\text{SD}}) = 2 \Gamma_{\text{annihilation}}$$

→ Hydrogen dominated target → excellent sensitivity SD cross section

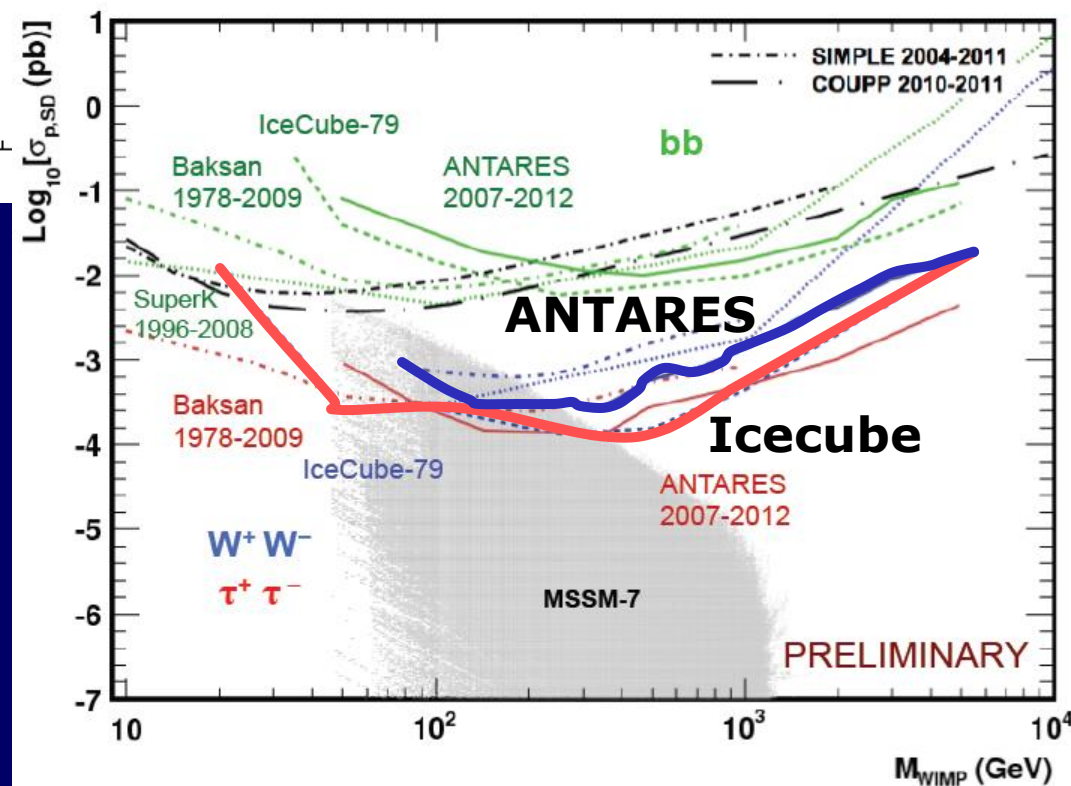
09-08-07

Jan Conrad, Stockholm Universitet

# Icecube 79 and ANTARES



Aartsen+ (IceCube), (2012)



# Summary (neutrinos):

- General:

- The main niche for neutrino telescopes are models with large SD cross section (solar WIMPs)
- Annihilations: hard to compete with IACT, maybe at very high masses ( $\sim 10$ s of TeV ...?), where neutrino x-sec/muon range can compensate  $1/m^{**2}$  scaling of the sensitivity and for leptophilic models

- Status:

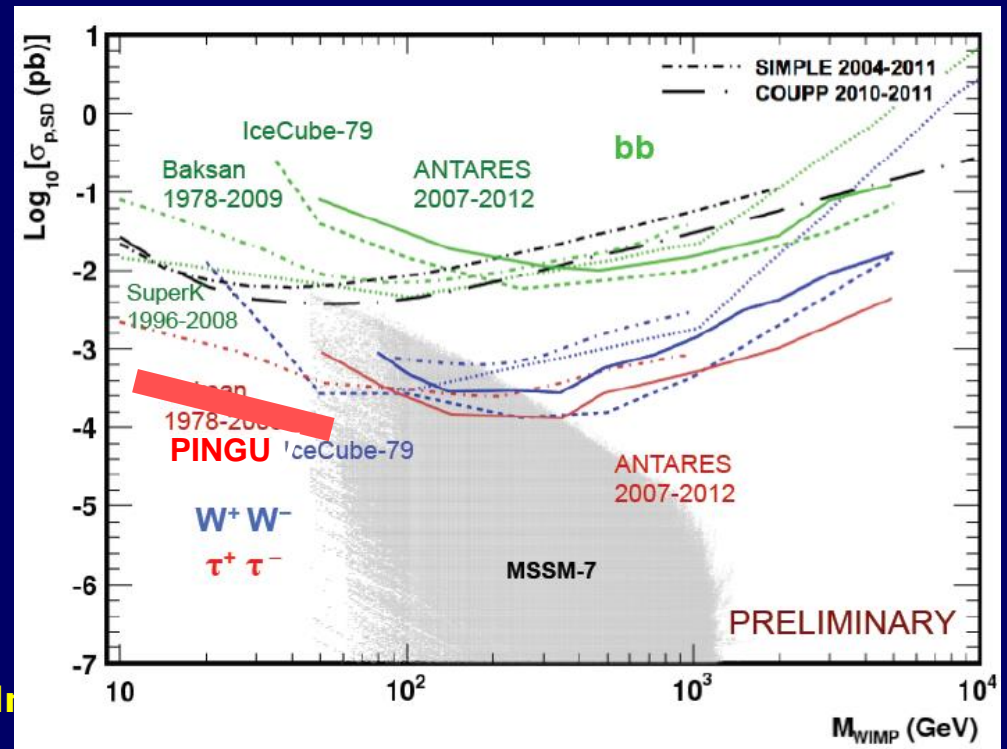
Ice3 and Antares in full swing

- Outlook:

- PINGU: 1-2 dex improvement at low masses (below 100 GeV),  $\sim$ factor 2 at large masses ...

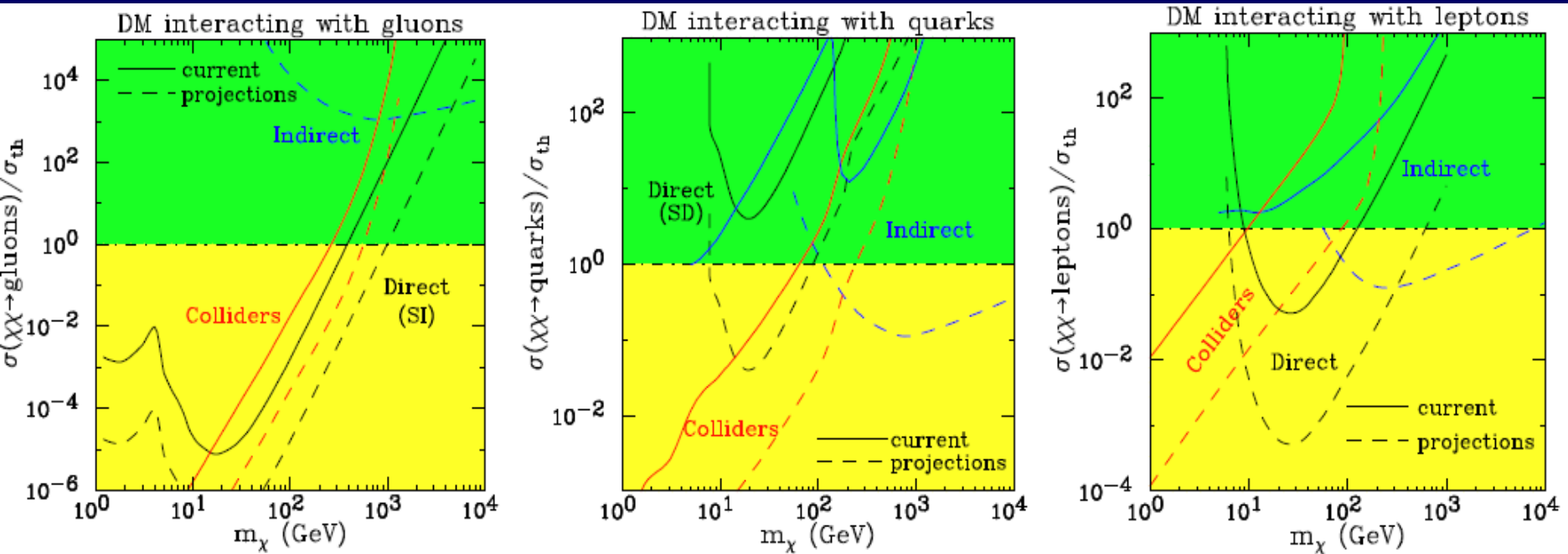
09-08-07

Jan Conrad, Stockholm





# Last slide: complementarity in effective theory approach

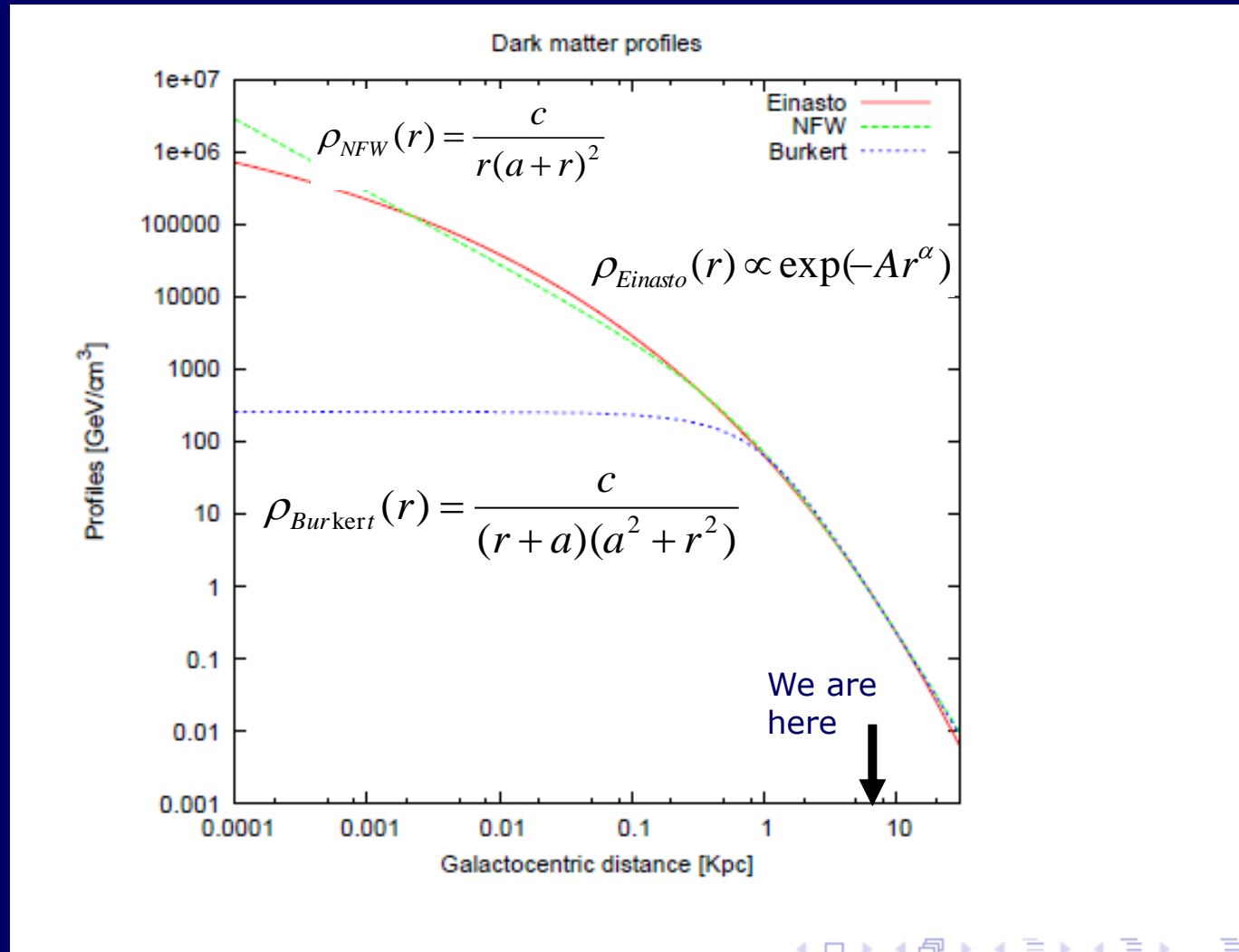


Arrenberg+. Snowmass  
(2013)



# APP- smooth Dark matter halo density profile

Cosmological  
N-body  
simulations:  
Navarro-  
Frenk-White  
Einasto  
→ "Cuspy"  
Stellar  
dynamics:  
e.g. Burkert.  
→ "Cored"



R. Catena

Strongest signal from the Galactic Center !

# Excess continued:

- The spectrum is consistent with a DM particle of mass (30 - 40 GeV) annihilating to quarks and thermal annihilation x-sec  
→ Smack on the current paradigm
- Excess is spherically symmetric
- The emission profile is consistent with what a Dark Matter distribution predicts, and less so with the prime candidate for source confusion (pulsars).
- Potential problems arise from the custom made event selection and corresponding diffuse modelling. Whether these aspects invalidate the conclusion can not be concluded from the paper

# A line in Fermi-LAT data?

- 3.3 $\sigma$  LEE corrected ( $\sim 50$  events)

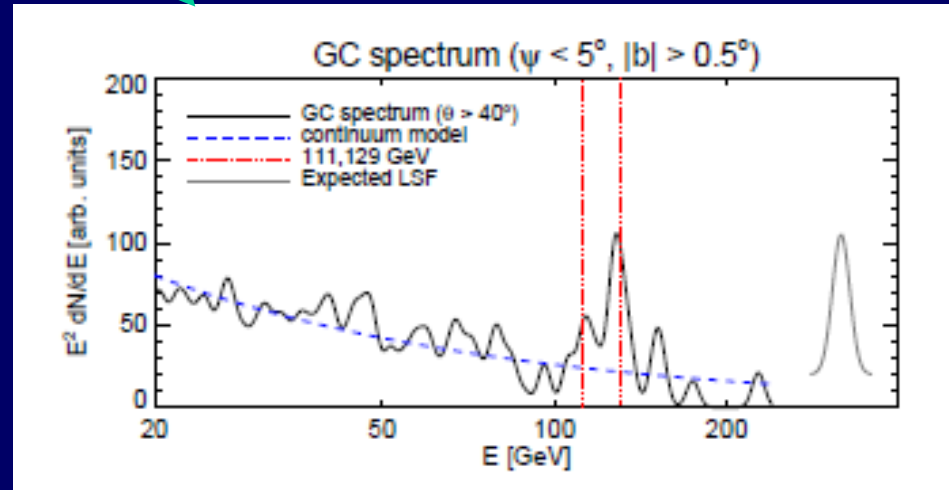
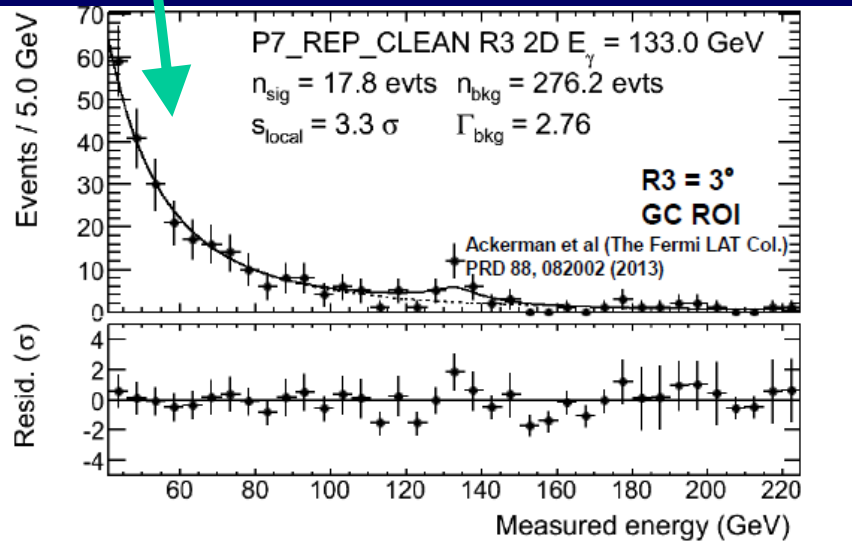
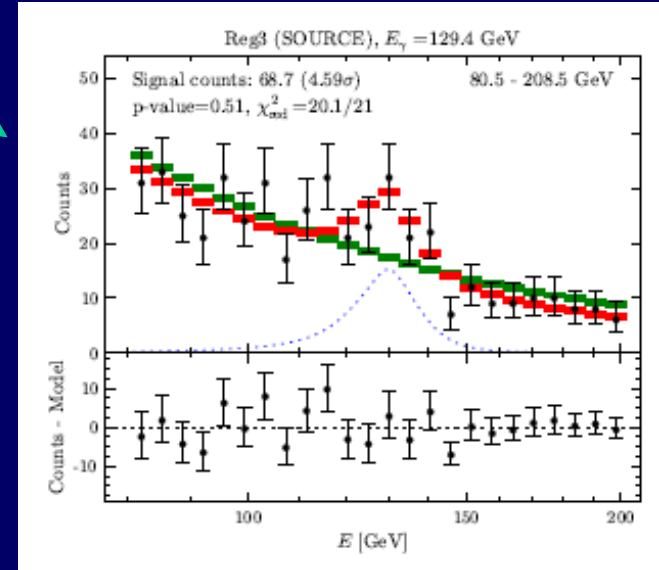
*Bringmann+ (2012)*  
*Weniger (2012)*

- 5 $\sigma$  LEE corrected, and two lines?

*Su&Finkbeiner (2012)*  
*Tempel+ (2012) (4.5 $\sigma$ )*

- 2 $\sigma$  LEE corrected and signal in Earth Limb

*Ackermann+ (Fermi-LAT) (2013)*



Signal 1.5 deg offset

# Significance until September 2013

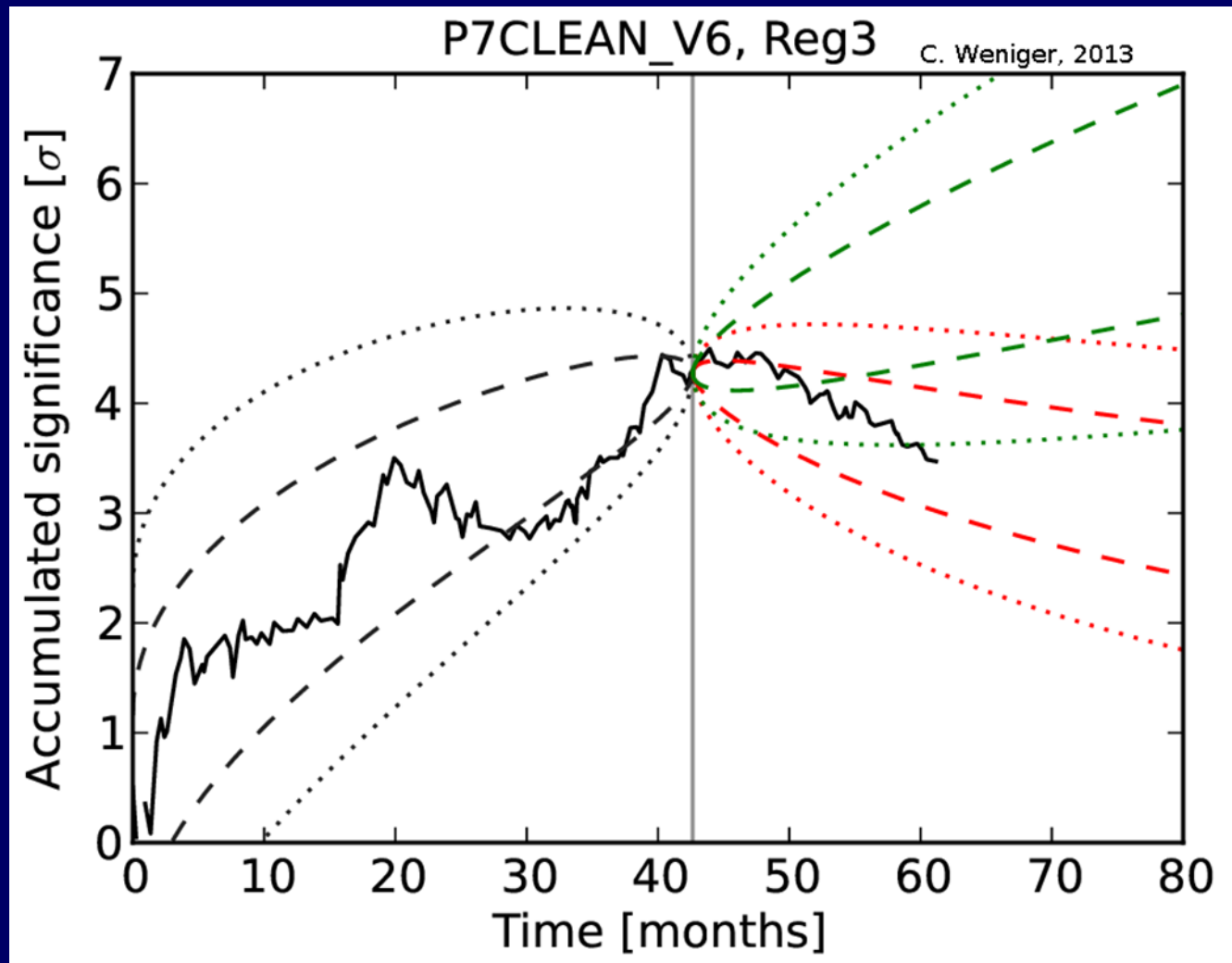
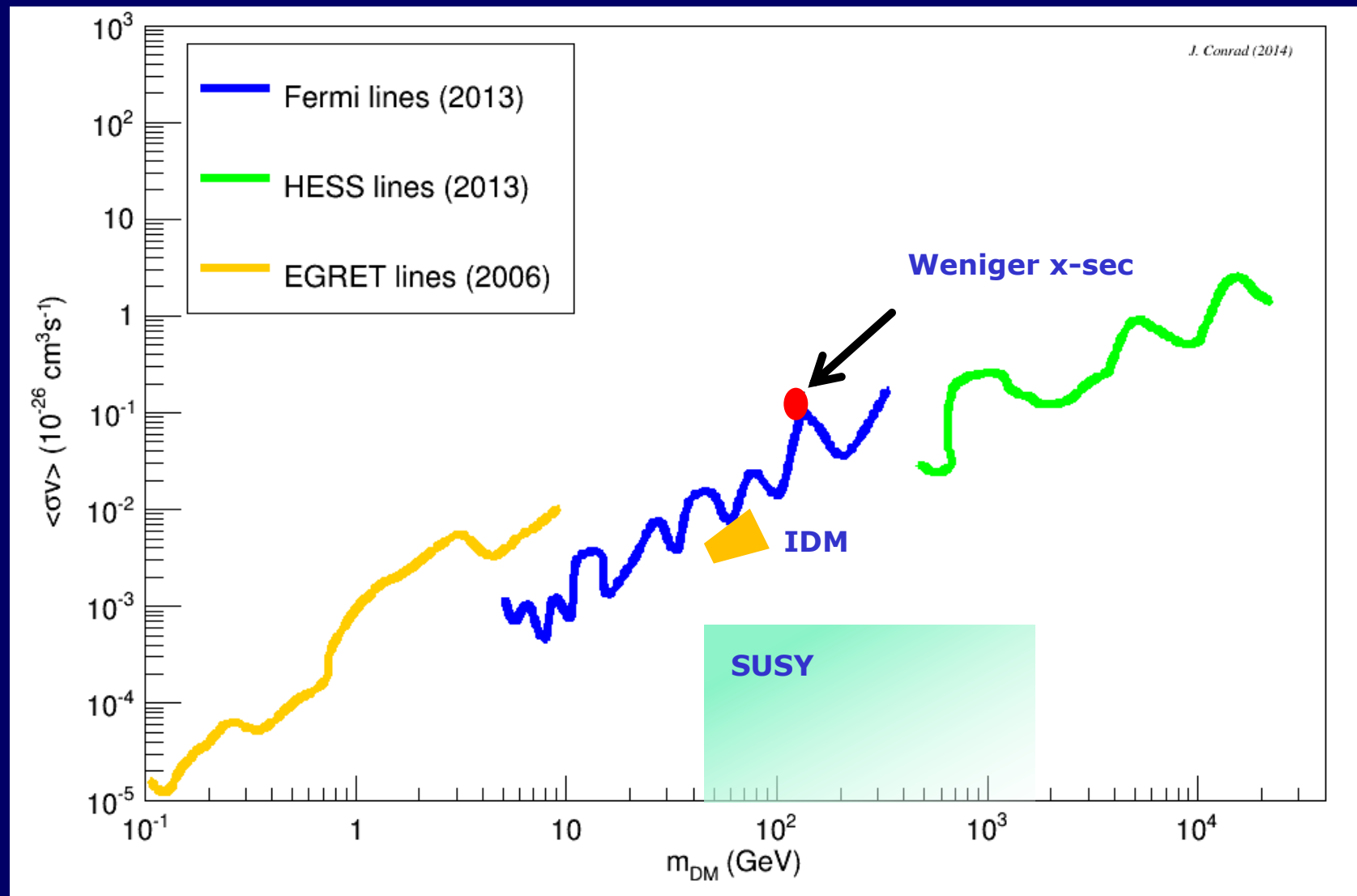
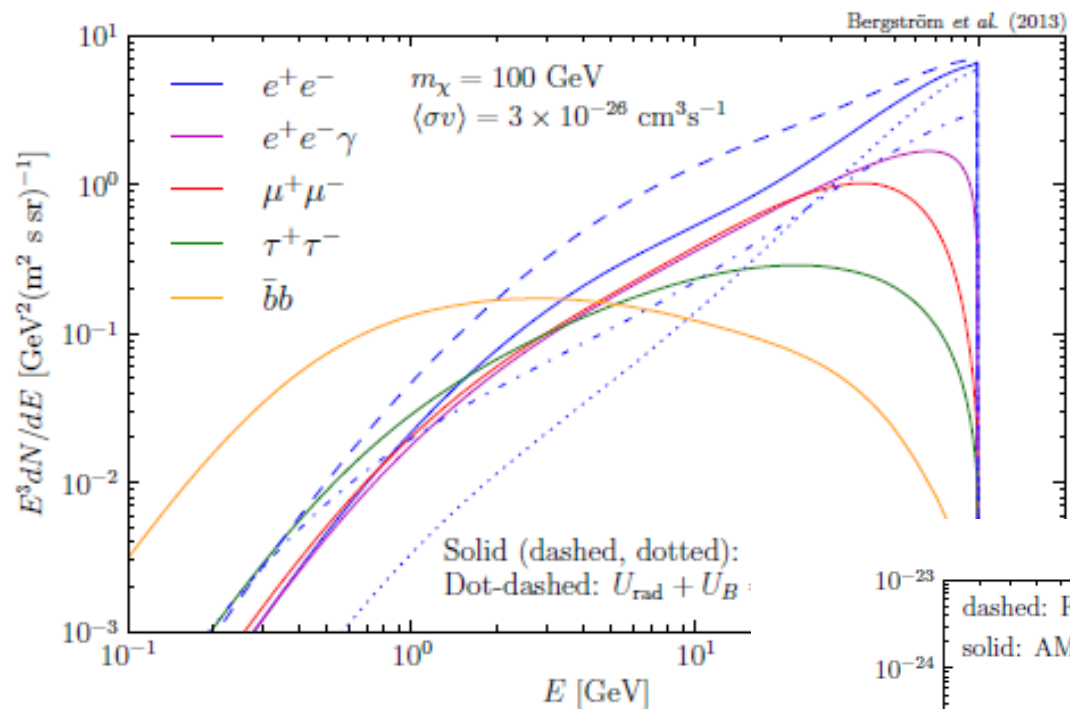


Figure courtesy of C. Weniger

# Line results summary:



# Constraints on leptonic channels



e.g. Bergström+ (2013)

