INDIRECT DETECTION and SIMULATIONS, and DATA too

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Dark matter in the Milky Way

Mainz, May 2-13 2016

Talk main drivers

TWO QUESTIONS:

1. WHAT ARE THE MAIN OPEN ISSUES IN (GALACTIC) INDIRECT DARK MATTER SEARCHES AT PRESENT?

2. HOW COULD SIMULATIONS AND NEW DATA CAN HELP TO SHED LIGHT ON THEM?

Outline

- **Astrophysical (Galactic) fore/backgrounds**

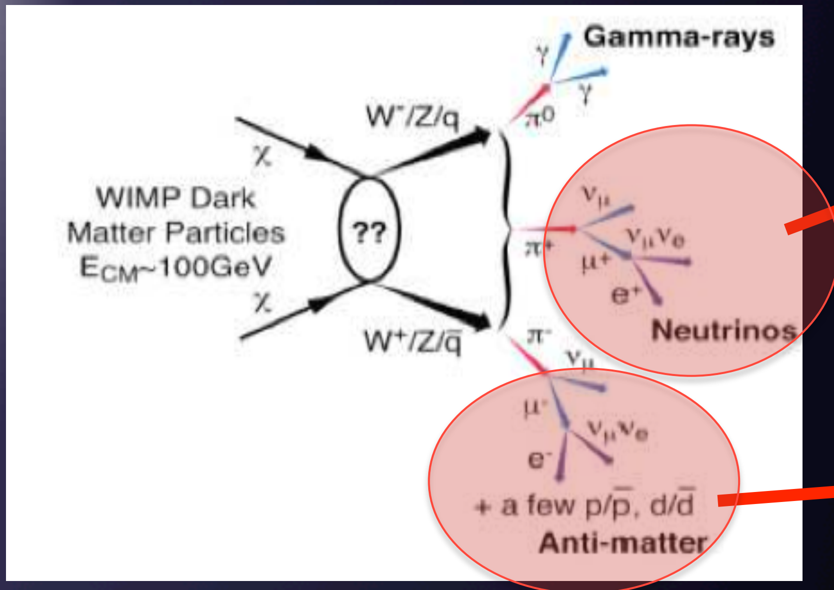
- **Galactic targets:**
  - **Galactic center**
  - **Dwarfs**
  - **Dark satellites**

- **Subhalo boosts to the annihilation signal**

For each of the items above:

i) Current status
ii) Open issues
iii) Possible ways to address them (simulations, data).

The ‘golden channel’: GAMMAS



Neutrinos
- ✓ No deflection
- ✓ No absorption
- ✓ BUT difficult to detect

Antimatter
- ✓ Low background in some cases
- ✓ BUT deflected by B fields
- ✓ BUT energy loses

Why gammas?

✓Energy scale of annihilation products set by DM particle mass

→ favored models ~GeV-TeV

✓Gamma-rays travel following straight lines

→ source can be known

✓[In the local Universe] Gamma-rays do not suffer from attenuation

→ spectral information retained.

Present gamma-ray observatories

E. range: 20 MeV → 1 TeV

E. resolution: ~10% @ GeV

FoV: ≈ 2.4 sr

Angular res.: ~0.2º@10 GeV

Aeff ~ m^2

Fermi LAT

[>2008]

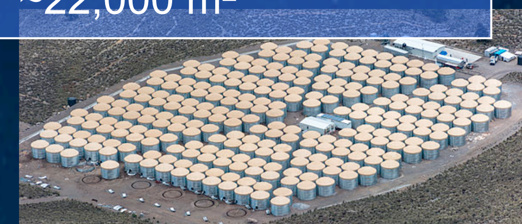
E. range: 0.1 → 100 TeV

E. resolution: ~20% @ 10 TeV

FoV: ≈ 2 sr

Angular res.: ~0.2º@10 TeV

Aeff ~22,000 m^2



HAWC

[>2015]

MAGIC

[>2003]

HESS

[>2002]

VERITAS

[>2006]

E. range: 50 GeV → 10TeV

E. resolution: ~20%

FoV: ≈ 4 deg.

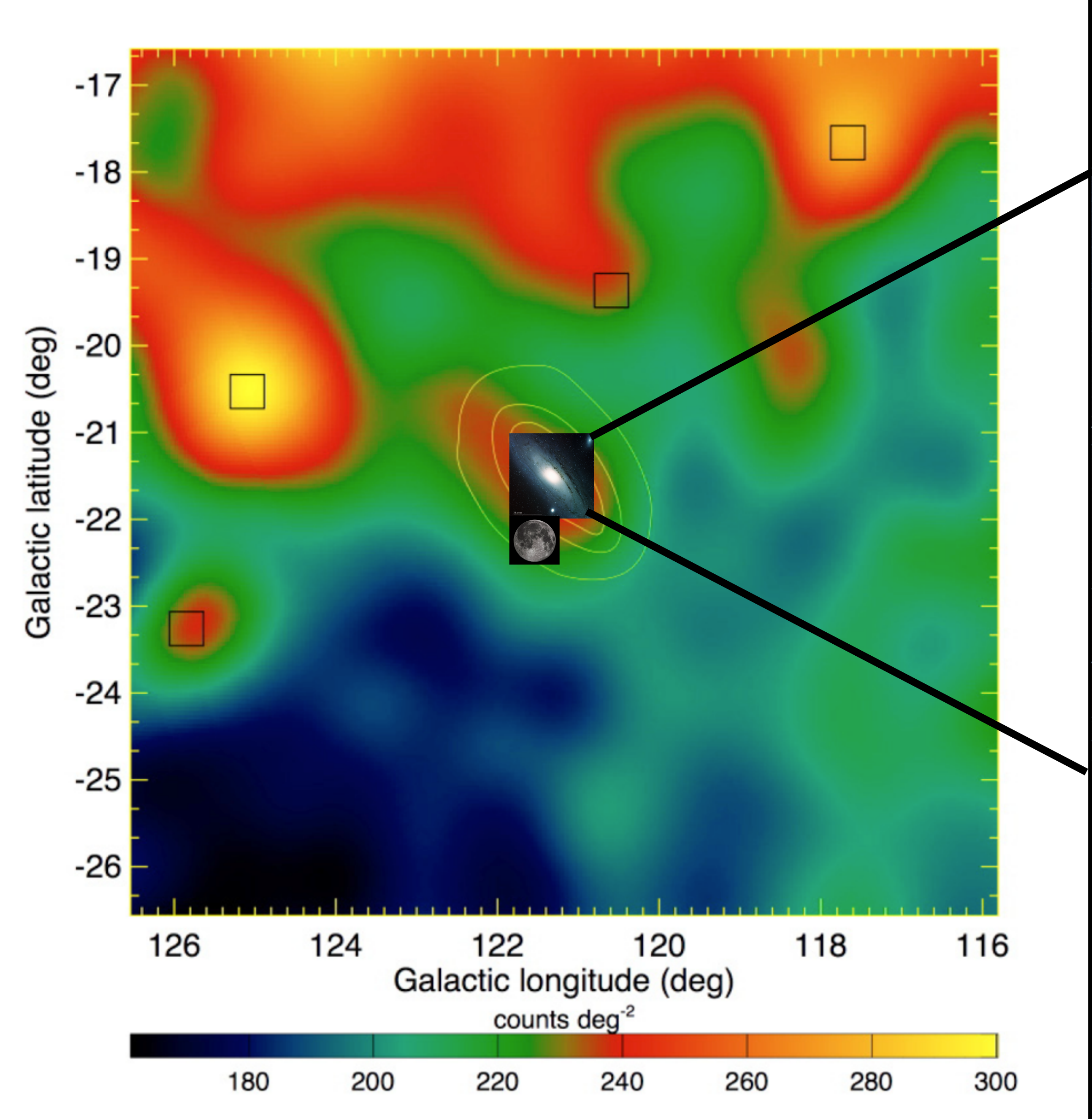
Angular res.: ≈ 0.1º

Aeff ~ 10^5 m^2

DESY/Milde Science Comm./Exozet

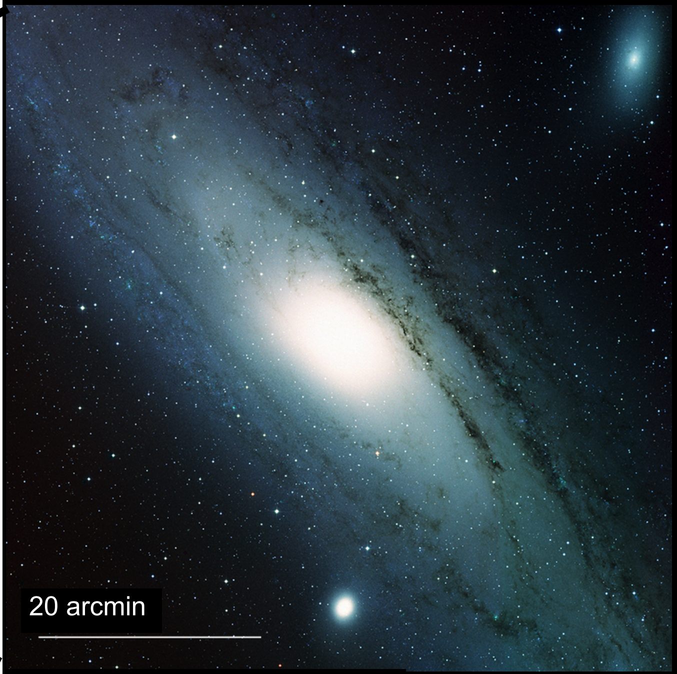
The sky through the Fermi-LAT eyes

[Abdo+10]



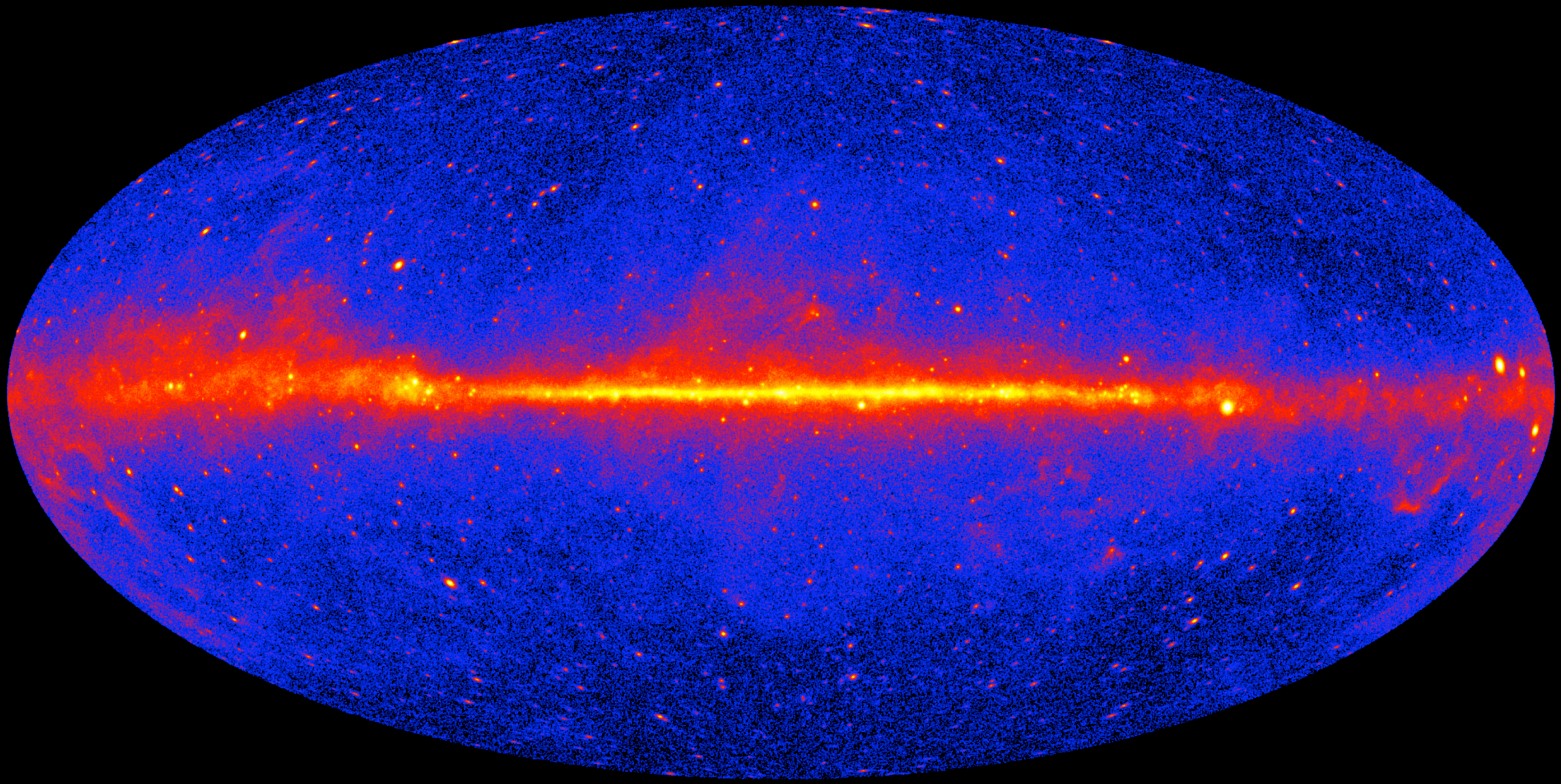
Andromeda (M31)

Optical DSS Image

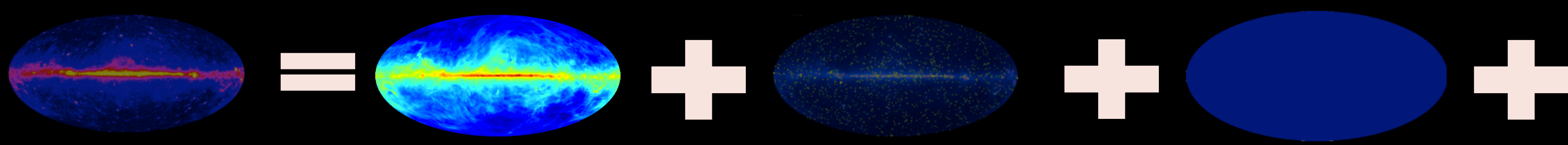


THE GAMMA-RAY SKY above 1 GeV

5 years of Fermi LAT data



The complexity of the gamma-ray sky

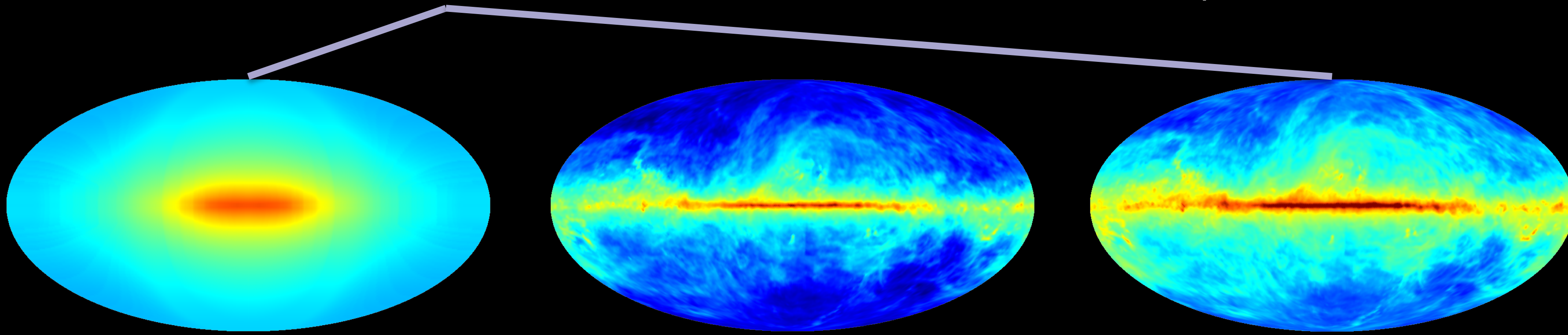


???

Galactic

Point Sources

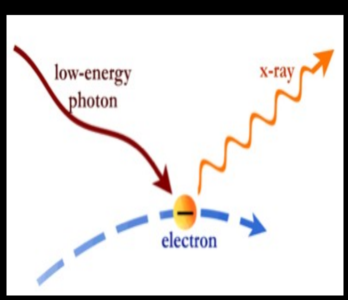
Isotropic

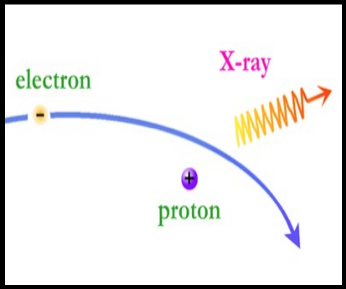


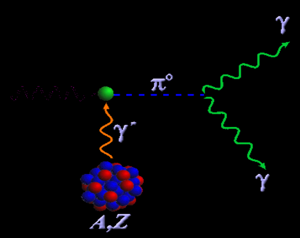
Inverse Compton

Bremsstrahlung

π^o decay

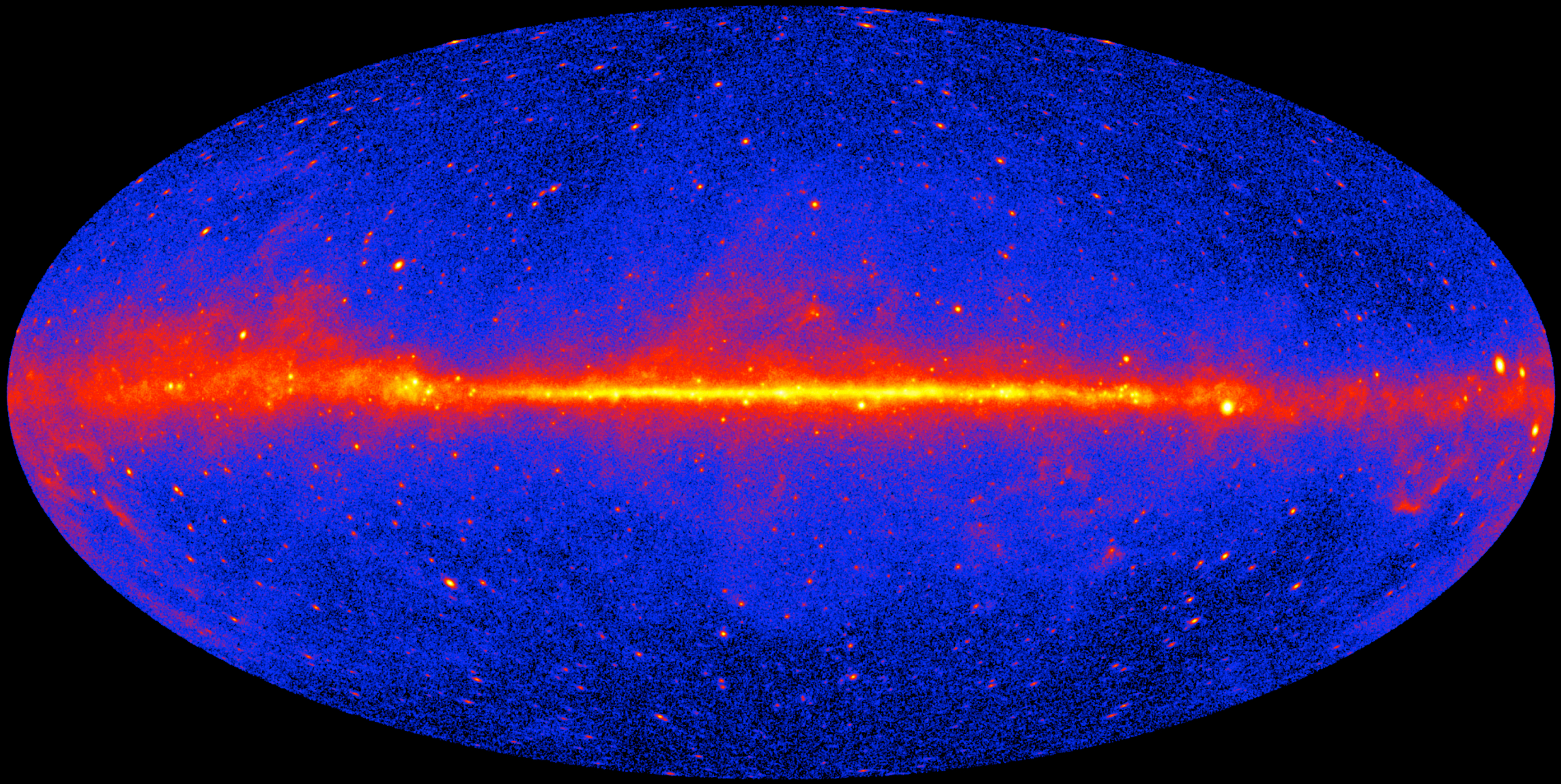




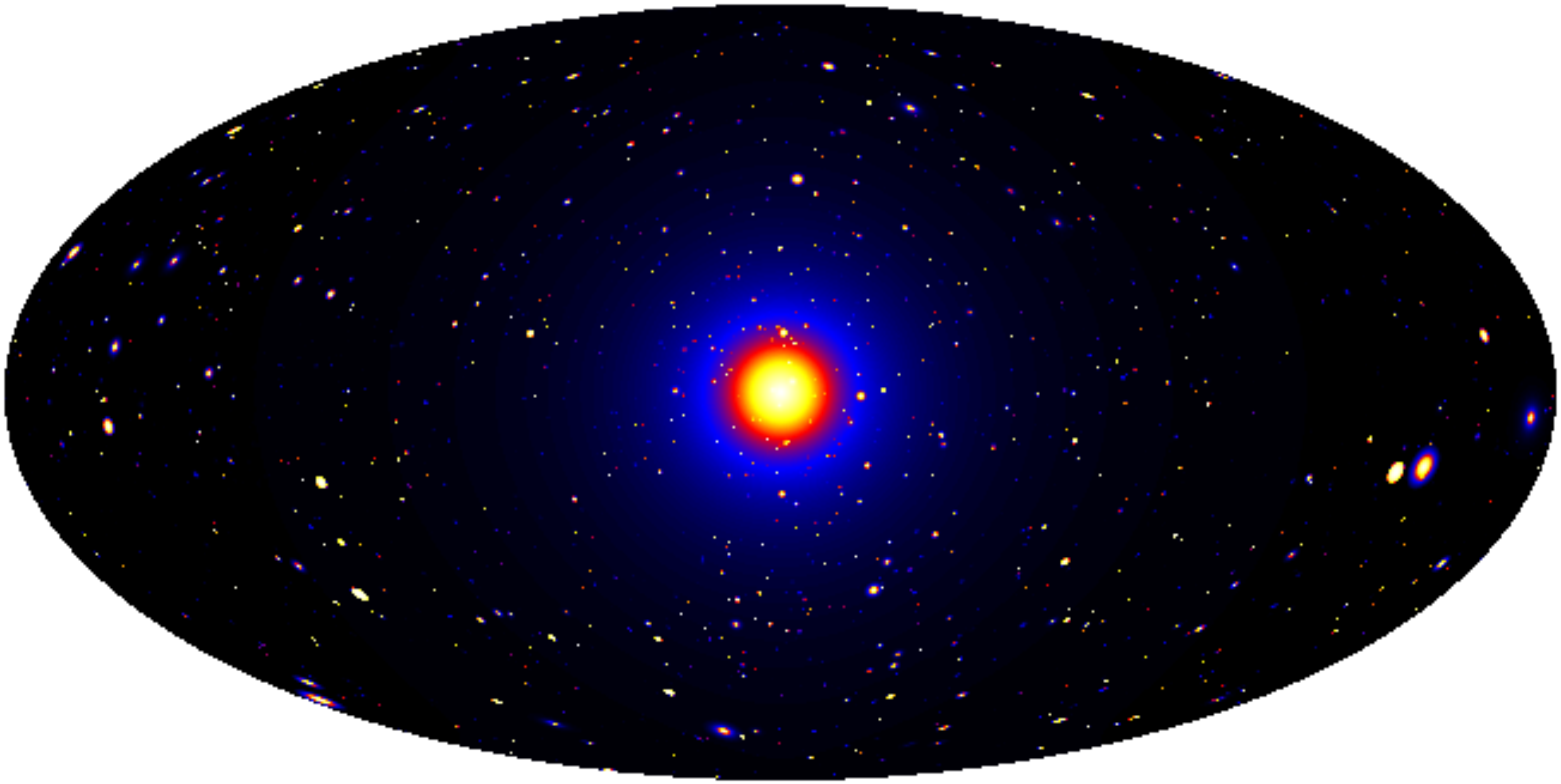


THE GAMMA-RAY SKY above 1 GeV

5 years of Fermi LAT data



The dark matter-induced gamma-ray sky

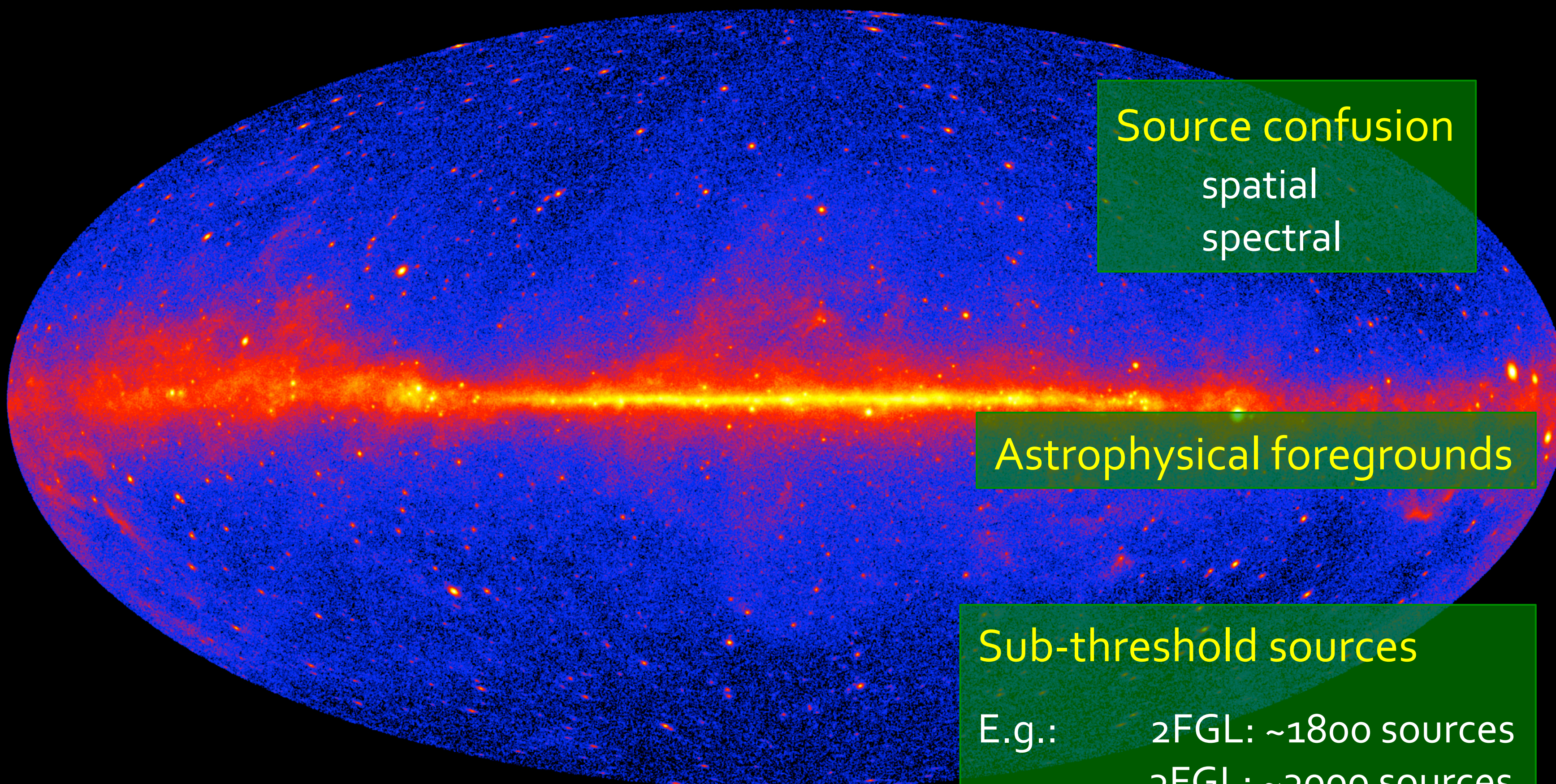


Dark Matter simulation:
Pieri+09, arXiv:0908.0195

Need to disentangle dark matter annihilations from 'conventional' astrophysics.

Crucial to understand the astrophysical processes in great detail.

Challenges



Source confusion

spatial

spectral

Astrophysical foregrounds

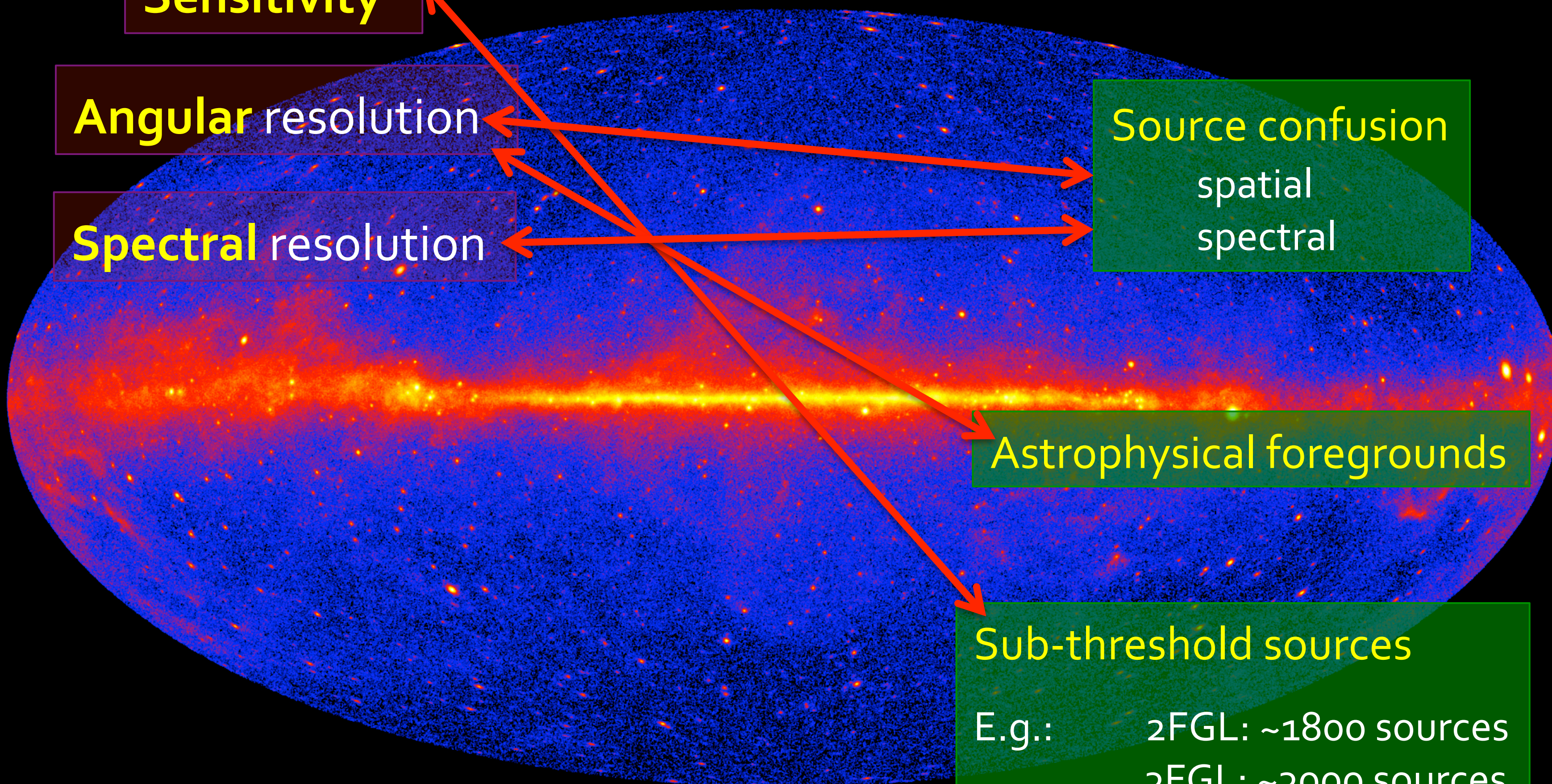
Sub-threshold sources

E.g.: 2FGL: ~1800 sources

3FGL: ~3000 sources

Needs

Challenges



Sensitivity

Angular resolution

Spectral resolution

Source confusion
- spatial
- spectral

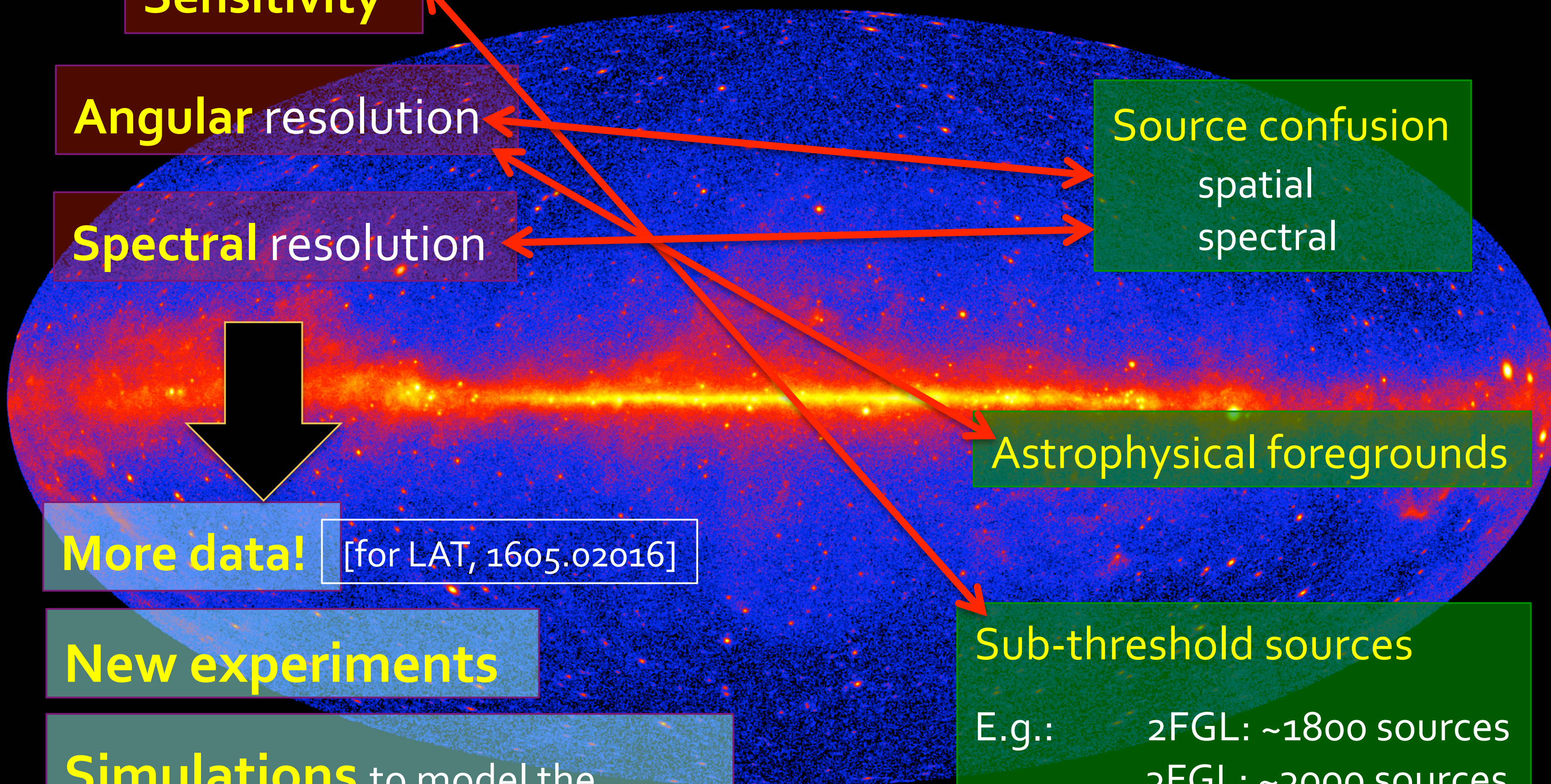
Astrophysical foregrounds

Sub-threshold sources

E.g.: 2FGL: ~1800 sources
3FGL: ~3000 sources

Needs

Challenges



Sensitivity

Angular resolution

Spectral resolution

More data! [for LAT, 1605.02016]

New experiments

Simulations to model the diffuse emission? → Marinacci's talk!

Source confusion
spatial
spectral

Astrophysical foregrounds

Sub-threshold sources

E.g.: 2FGL: ~1800 sources
3FGL: ~3000 sources

Fermi LAT: the future ahead

- Formally approved till the end of the year.
  - Very likely 2018. Probably beyond?
- With more LAT data:
  - A better knowledge of foregrounds possible.
  - More sub-threshold sources detected.
  - General improvement on DM limits:
    - linearly with time at high energies (better statistics)
    - sqrt(time) at low energies.
- **Pass 8** (>mid 2015): improved performance

The inminent future for current generation IACTs

HESS-II

- first light in 2012
- push the threshold to lower energies ~50 GeV
- Expected to lead the IACT limits using the GC.

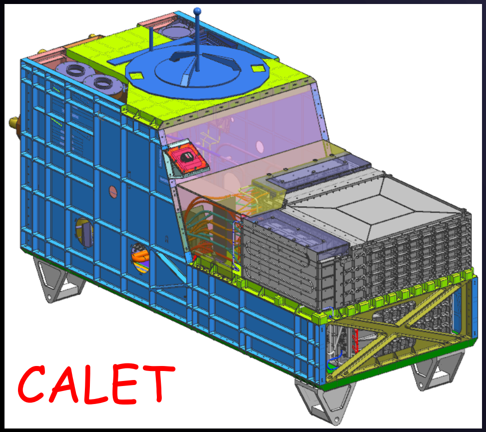
VERITAS

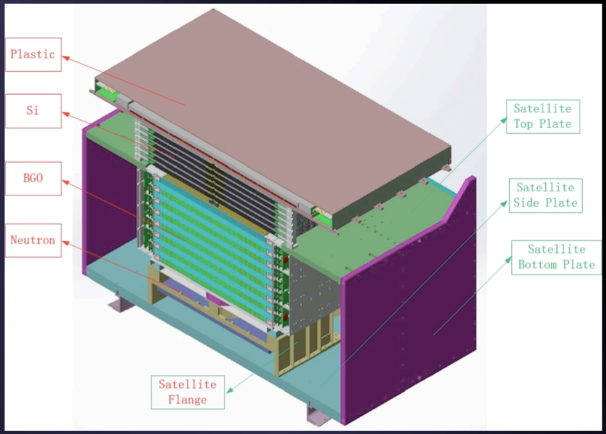
- 1000h observation of Segue 1 by 2018 (Smith +13)

MAGIC

- Expected to produce new DM limits from dwarfs

The inminent future for satellite-based experiments





CALET

- Japanese-led.
- Launched in Aug 15
- Placed at the ISS

DAMPE

- Chinese
- Launched in Dec 2015

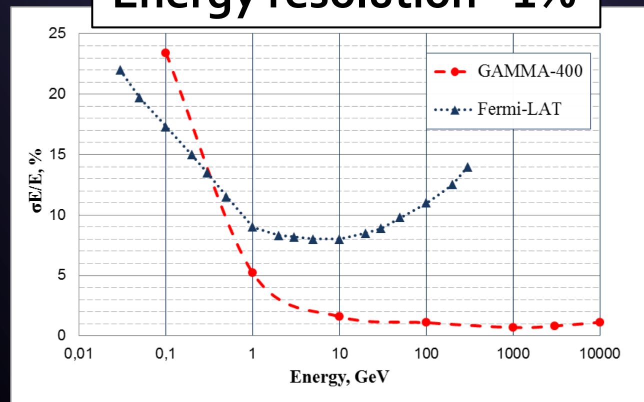
Both:
✓ deep calorimeter, 1 GeV – 10 TeV
✓ superb energy resolution ~2% @ 100 GeV
✓ 0.3º angular resolution @ 100 GeV
✓ Very good background rejection power
✓ Small collecting area of ~0.15 and ~0.5 m²

The future beyond

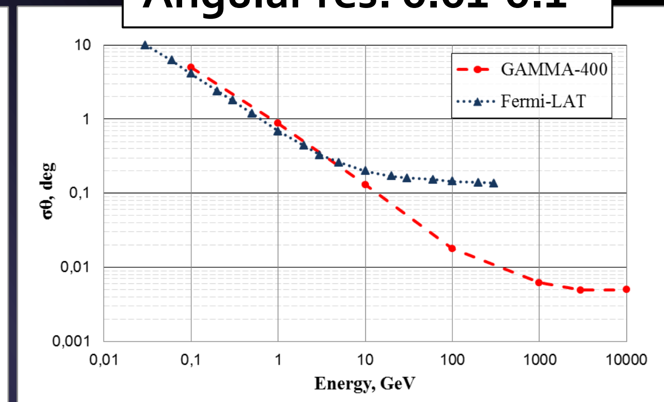
GAMMA-400

- Russian-led.
- Launch by 2018/19.
- 100 MeV – 3TeV
- Efective area ~0.4 m²
- FoV: ~1.2 sr

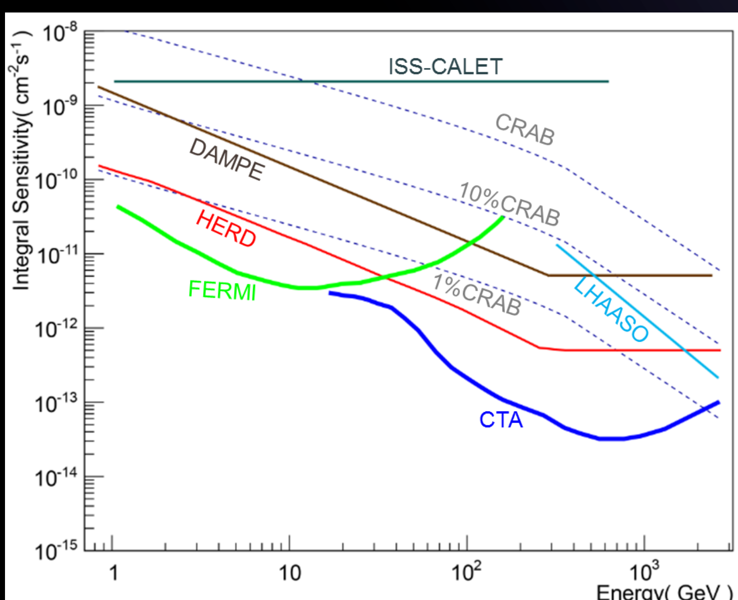
Energy resolution ~1%



Angular res. 0.01-0.1°



Big improvement w.r.t. Fermi, but smaller collection area.



HERD

- Chinese
- Launch by 2018/19.
- 100 MeV – 10 TeV
- Efective area ~3.7 m²sr
- ΔE/E ~1% > 100 GeV
- 0.1° @ 200 GeV angular resolution.

The future beyond?

PANGU (Wu+14)

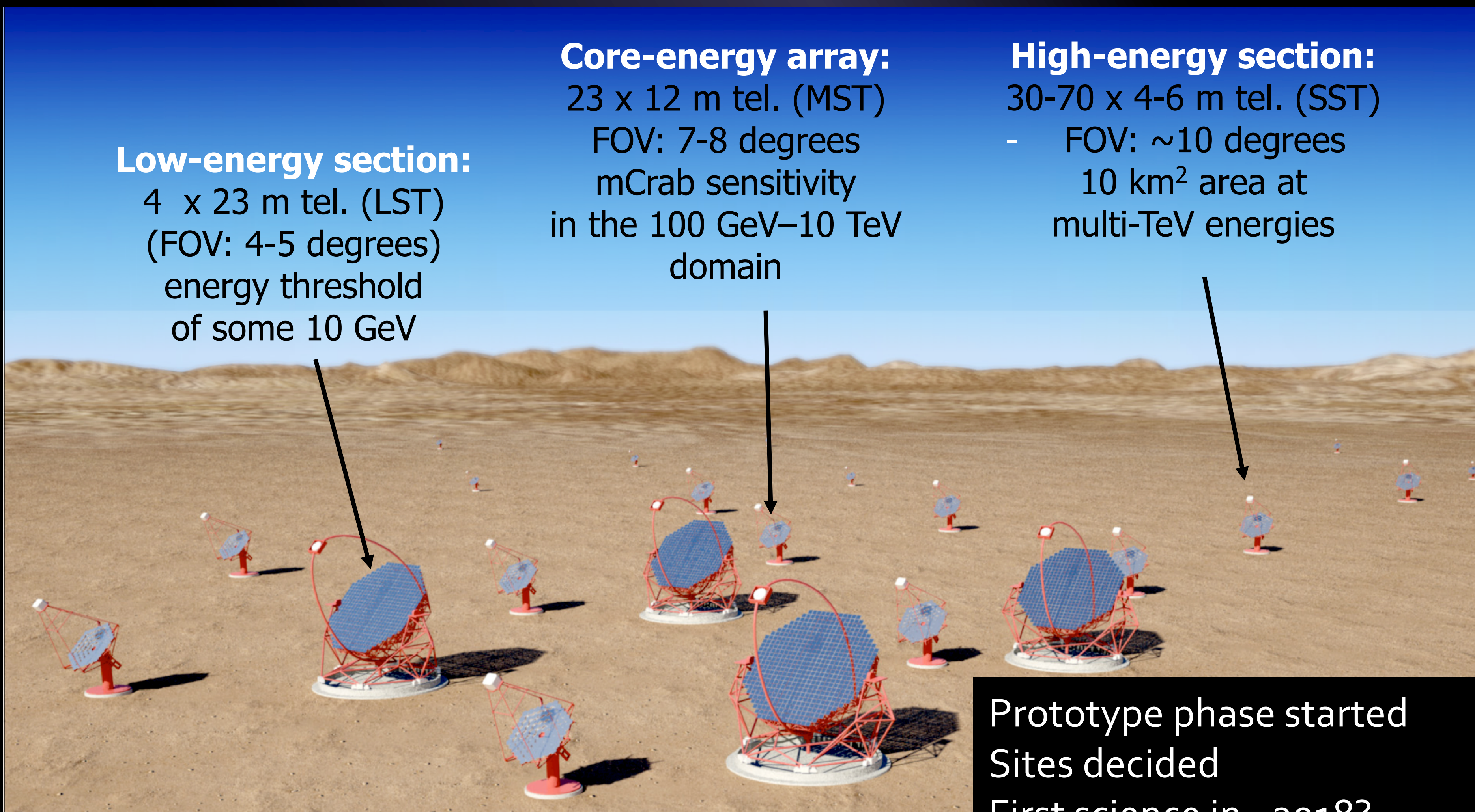
- ESA/CAS joint small mission.
- Spectro-imaging, timing and polarization.
- 10 MeV – few GeV
- $\Delta E/E \sim 1\% > 100$ GeV
- 0.1° @ 1 GeV angular res.

AstroMeV

- Space mission by ~2025.
- 0.1 – 100 MeV
- Consortium formed to respond to AO of space agencies.
- http://astromev.in2p3.fr/

Full list of Future High-Energy Astrophysics missions:
https://heasarc.gsfc.nasa.gov/docs/heasarc/missions/concepts.html

IACT future:
Cherenkov Telescope Array (CTA)



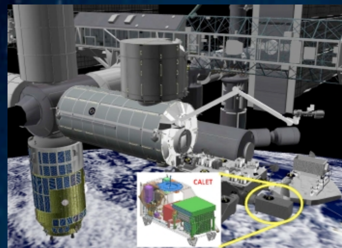
Prototype phase started
Sites decided
First science in ~2018?

Gammas: the future ahead

DESY/Milde Science Comm./Exozet

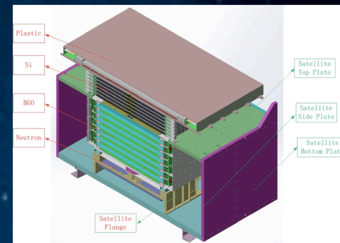
Fermi

[<2018?]



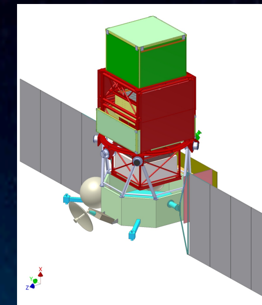
CALET

[>2015]



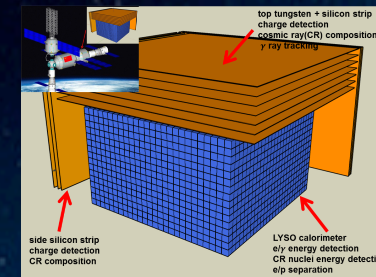
DAMPE

[>2015]



GAMMA-400

[> 2018]



HERD

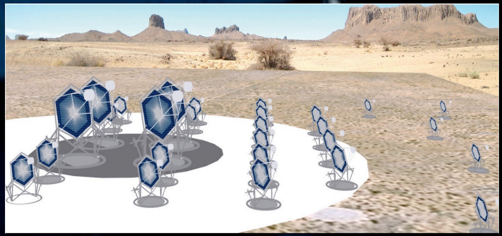
[> 2019]

HESS-II

[>2012]

HAWC

[>2015]



CTA

[>2018?]

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Outline

- Astrophysical (Galactic) fore/backgrounds
- Galactic targets:
  - Galactic center
  - Dwarfs
  - Dark satellites
- Subhalo boosts to the annihilation signal

For each of the items above:

i) Current status
ii) Open issues
iii) Possible ways to address them (simulations, data).

Dark Matter search strategies

Satellites

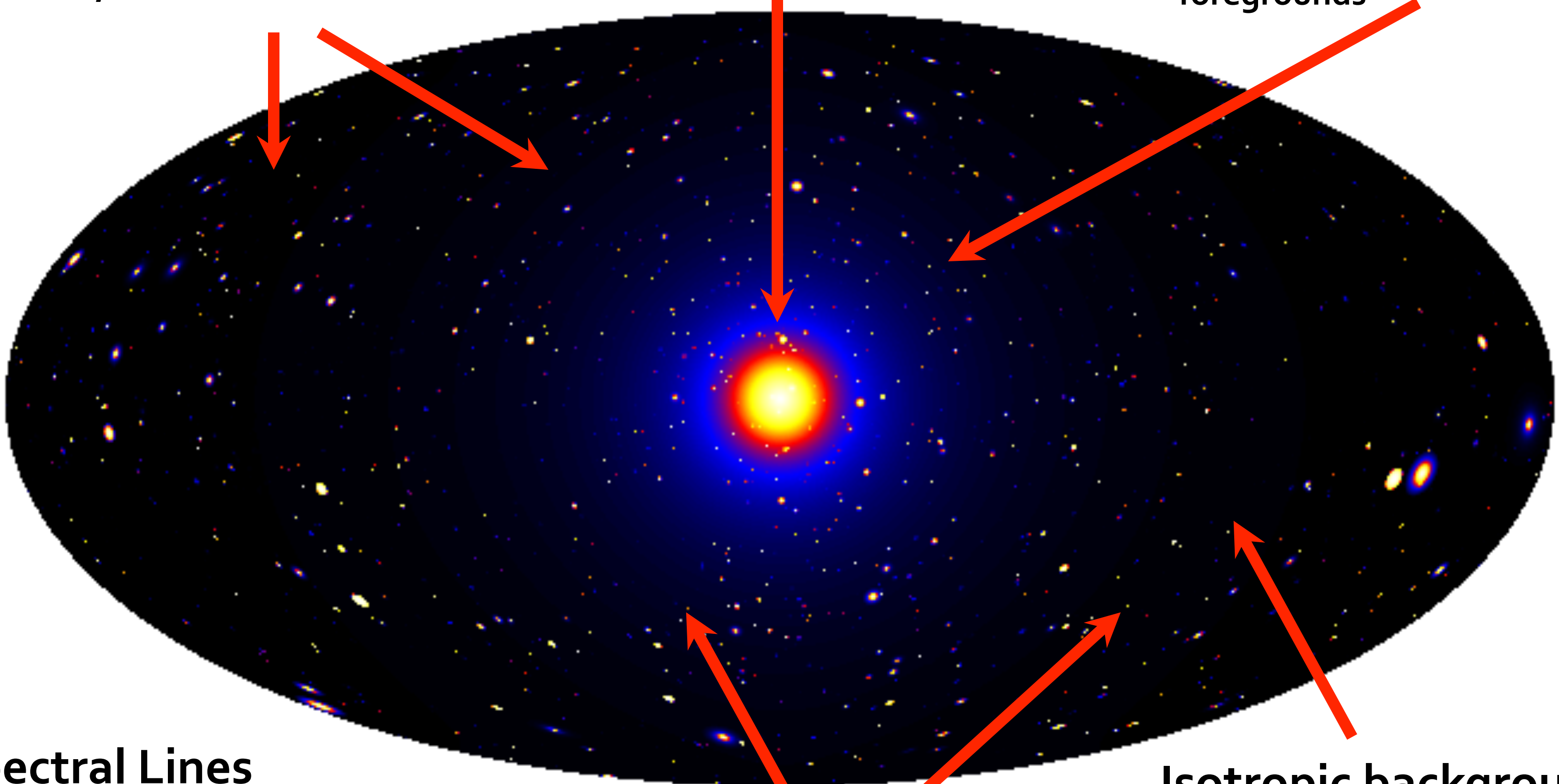
Low background and good source id, but low statistics

Galactic Center

Largest statistics, but source confusion/diffuse foregrounds

Milky Way Halo

Large statistics, but diffuse foregrounds



Spectral Lines

Little or no astrophysical uncertainties, good source id, but low signal expected

Galaxy Clusters

Large, extended signal, but diffuse background and astrophysics

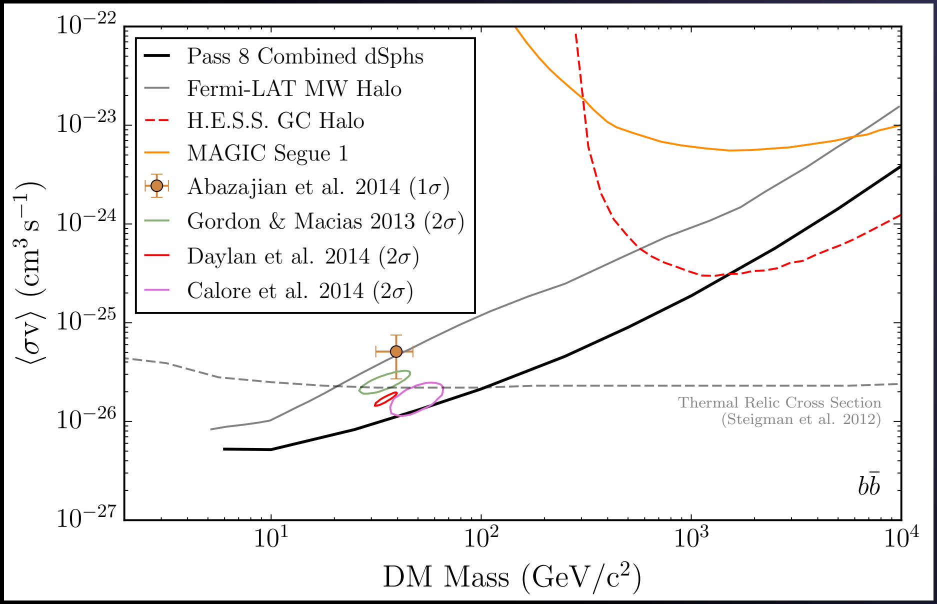
Isotropic background

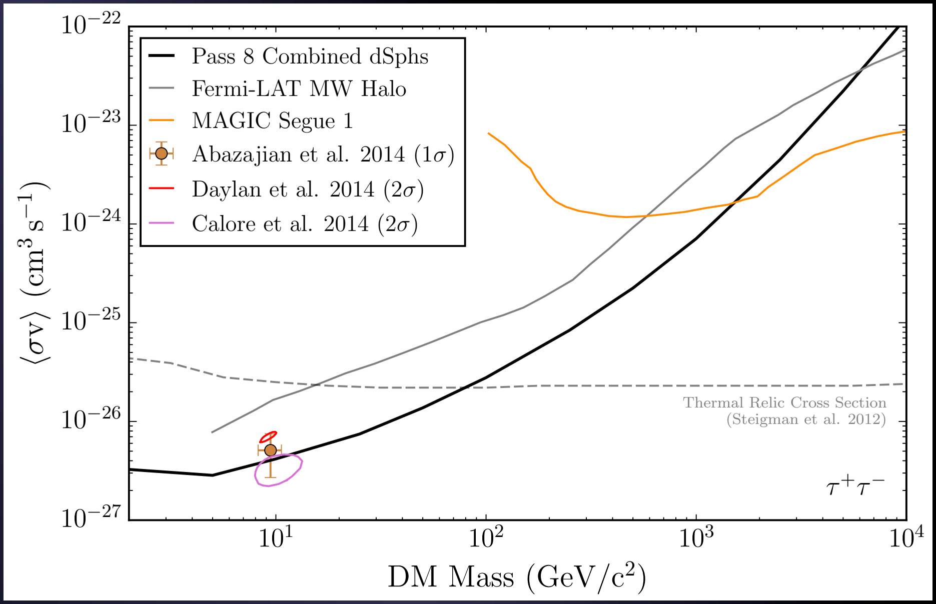
Large statistics, but astrophysics, galactic diffuse foregrounds, signal uncertainties

Dark Matter simulation: Pieri+(2009) arXiv:0908.0195

(γ-ray) DM searches: today

[Ackermann+15, the LAT collab., 1503.02641]

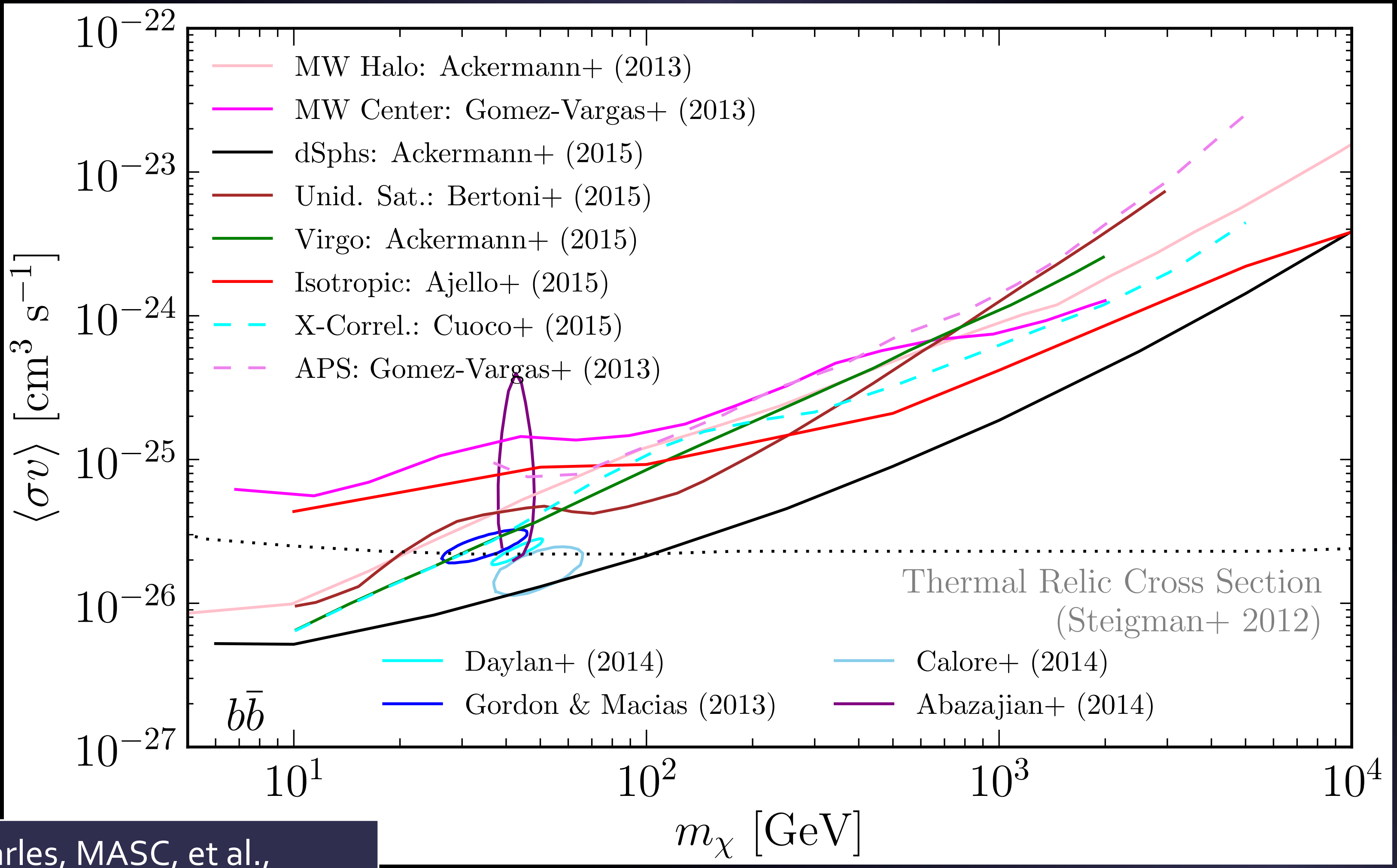




→ GC excess persists. Origin unclear.
→ Dwarfs the most promising independent way to test it.
→ Fermi LAT ruling out thermal WIMPs below ~100 GeV.
→ IACTs and HAWC competitive in the TeV energy range.

How to improve the limits?
What are the actual uncertainties on them?

… and not only GC and dwarfs!



Charles, MASC, et al., Physics Reports, accepted [1605.02016]

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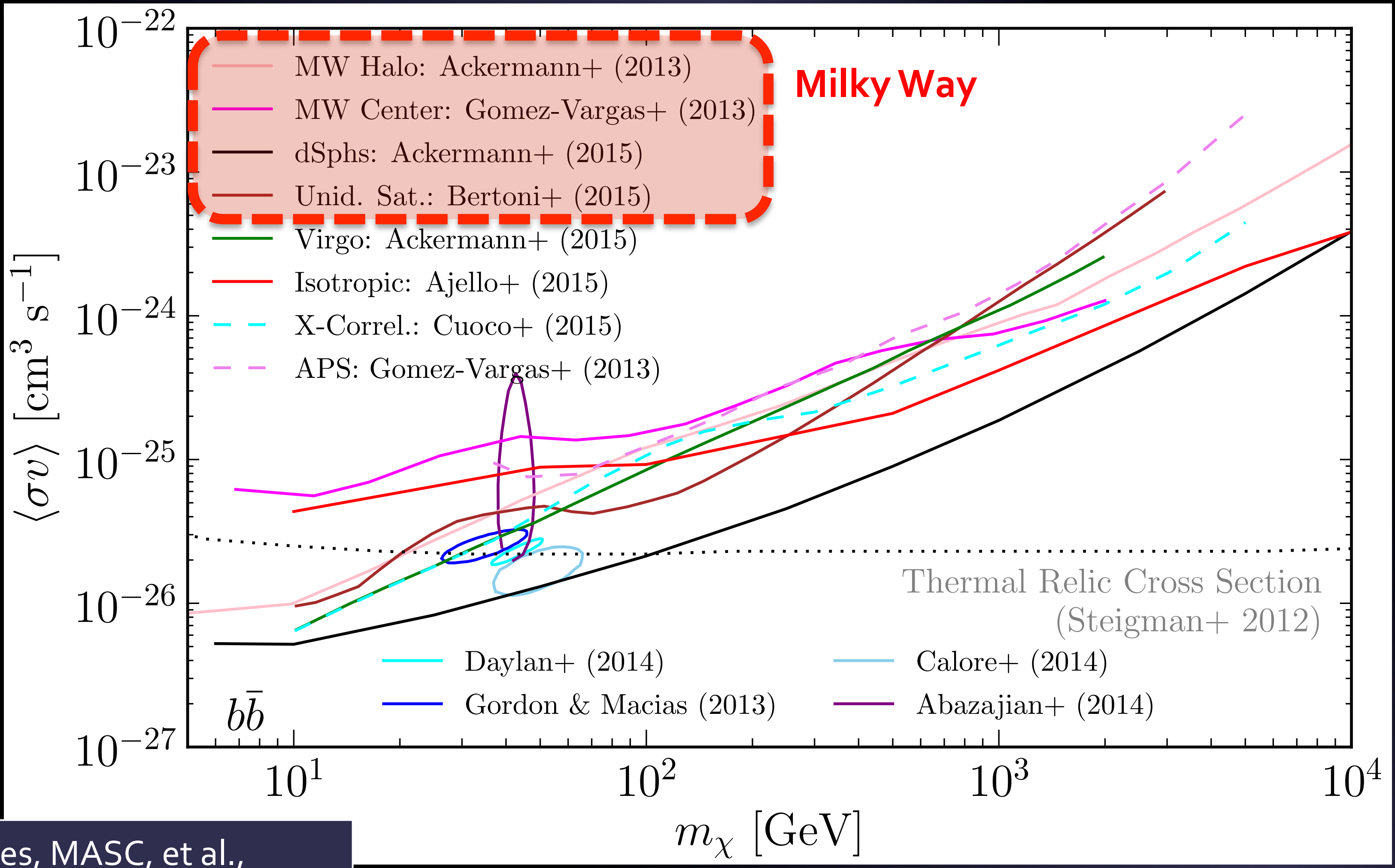

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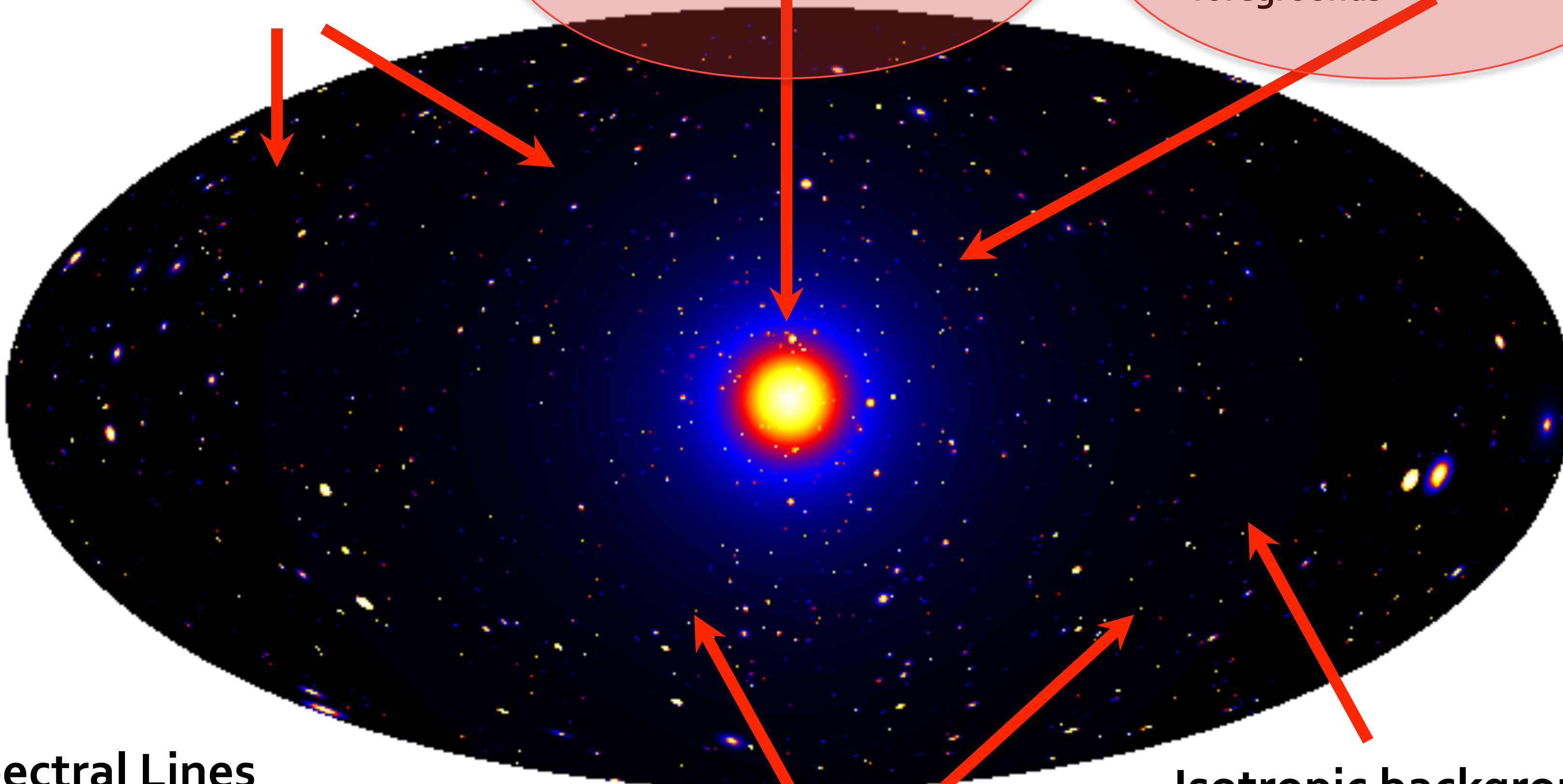

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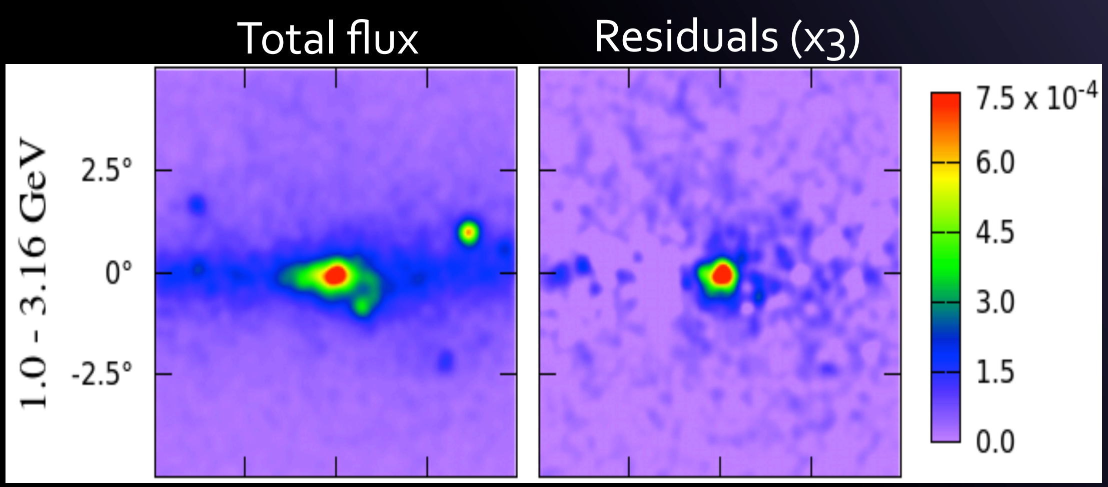
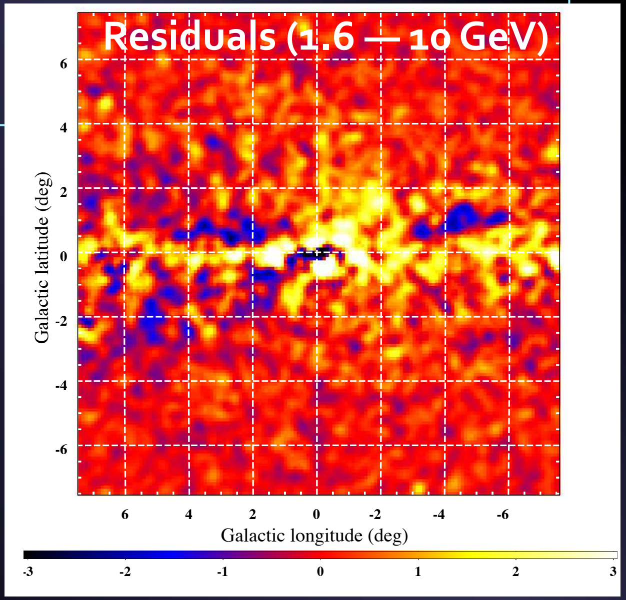
'GeV excess' in the Galactic center

- **Several groups** have reported an excess of GeV photons from the GC region (e.g., Goodenough & Hooper 09, 11; Daylan+14, Abazajian+14, Calore+14; Gordon & Macías 14, Ajello+16)
- General agreement on the excess **peaking at a few GeV** above the ***standard*** diffuse emission models.
- **Interpretation difficult** due to complicated foreground/background modeling.
- **DM annihilation** a plausible and exciting possibility!
  - Spatially consistent with gNFW
  - Approx. half the thermal cross section
  - Around 50 GeV DM particle mass (bb)



[Daylan+14]



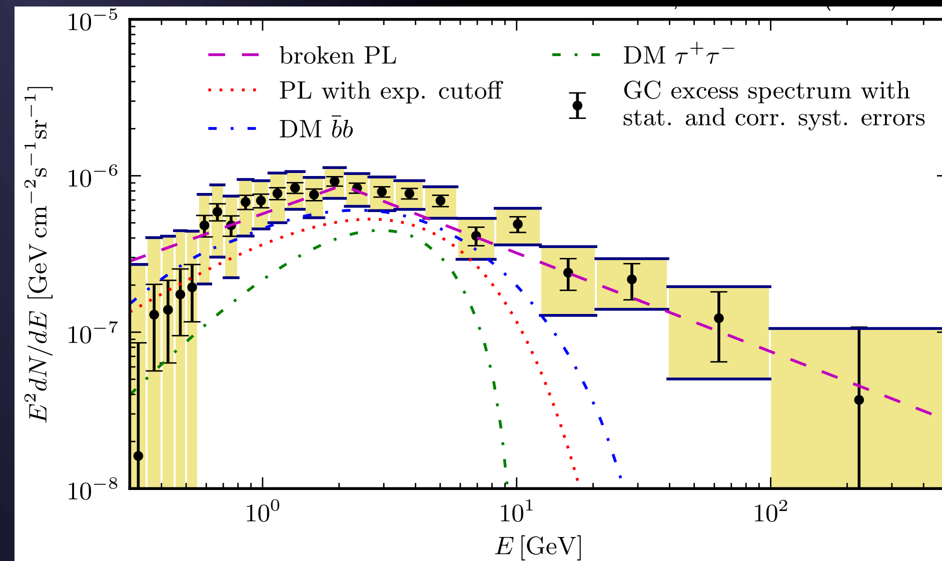
[Ajello+16, Fermi-LAT collab.]

Properties of the GC excess

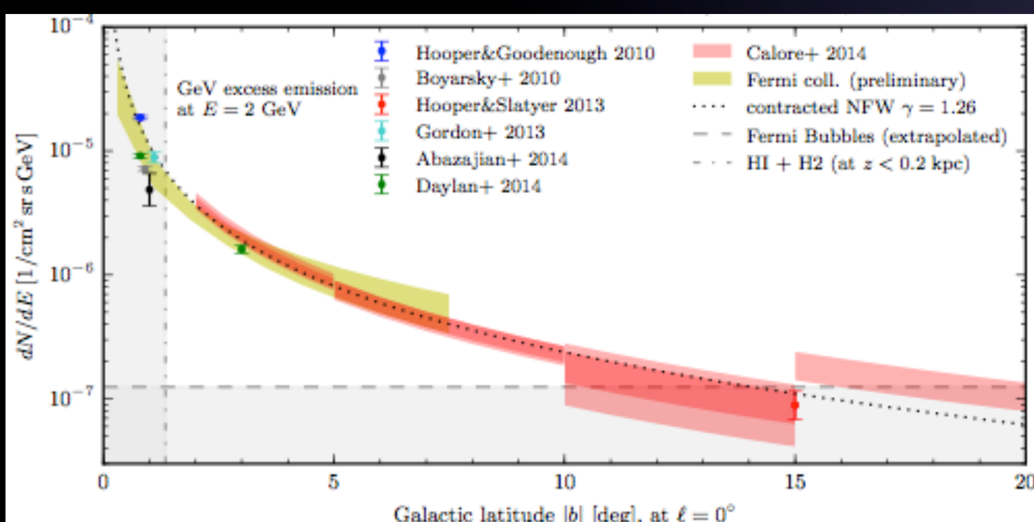
Spectrum

peaks at 2-3 GeV
high-energy tail up to >100 GeV

Robust to changes in the diffuse modeling
Yet, substantial *spectral variations* possible
→ large systematics



[Calore+14]



[Calore+14]

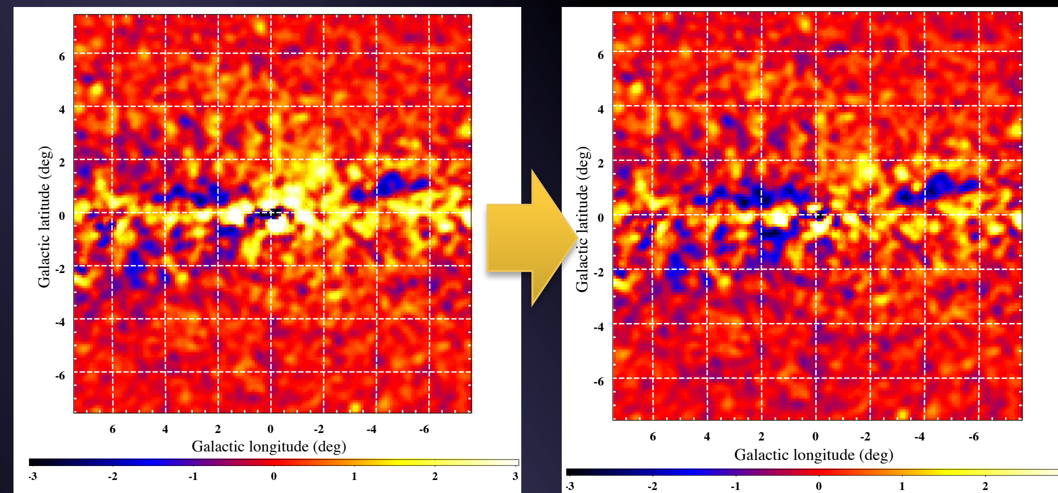
Morphology

spatially extended
spherically symmetric

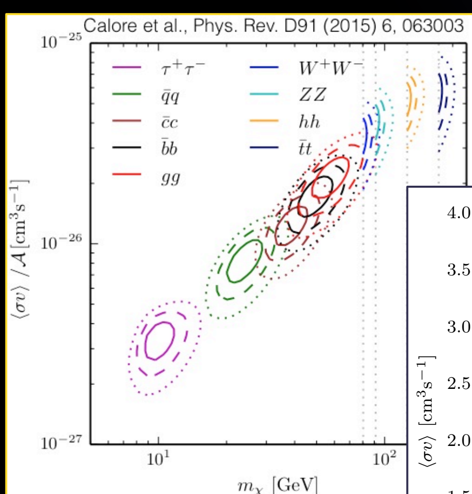
GeV excess: a DM origin?

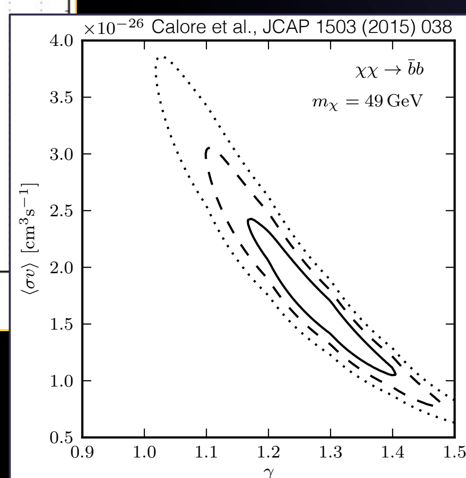
- Residuals improve by adding a DM template (but don't disappear!)
- Spectral fit to DM models equally preferred against e.g. broken power law.

Residuals (1.6 — 10 GeV)



[The Fermi-LAT collab., 1511.02938]



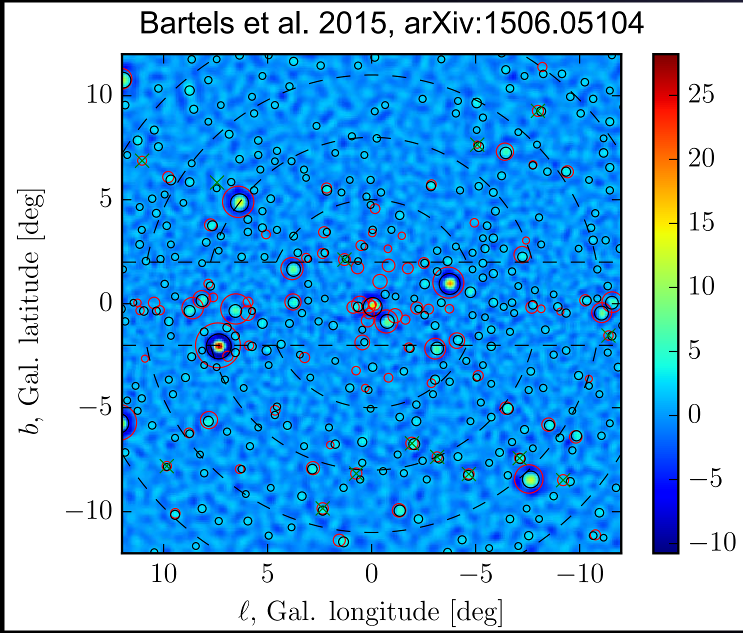


[Calore+14]

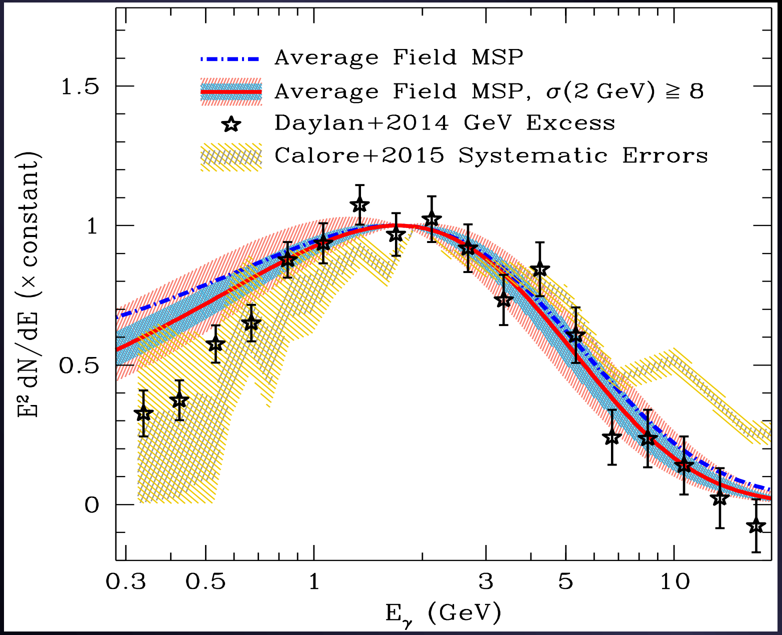
- ✓ Consistent with gNFW
- ✓ Approx. half $\langle\sigma v\rangle_{thermal}$
- ✓ DM mass:
  - ~49 GeV (b quarks)
  - ~38 GeV (c quarks)

Interpretation (II): Unresolved sources?

- O(1000) Millisecond pulsars (MSPs) within ~1kpc of the GC [Abazajian+14]
- Young MSPs [O'Leary+15]
- MSPs from globular clusters' disruption [Brandt+15]
- Non-poissonian photon statistics template analysis [Lee+15]
- Wavelet decomposition of the gamma-ray sky [Bartels+15]



[Bartels+15]



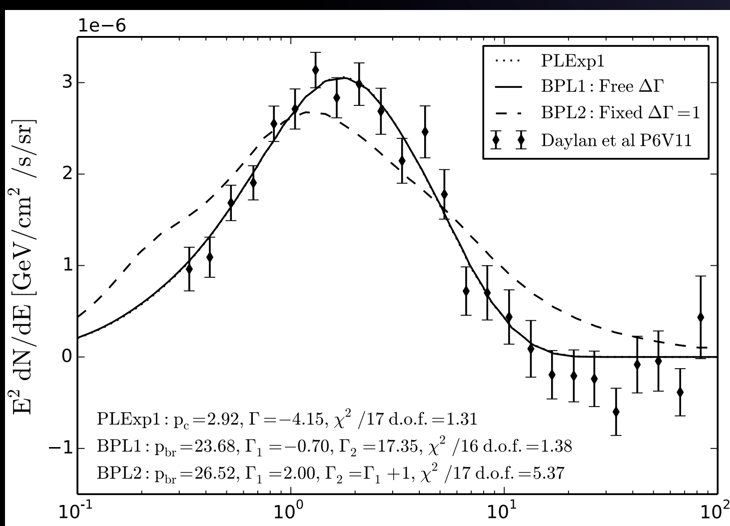
[Brandt+15]

Interpretation (III): Cosmic-ray outbursts?

CR-induced emission may vary with time due to outburst events (black hole, starbursts)

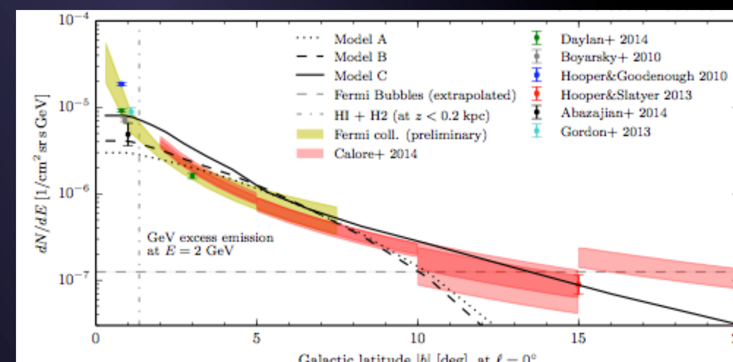
1) HADRONIC

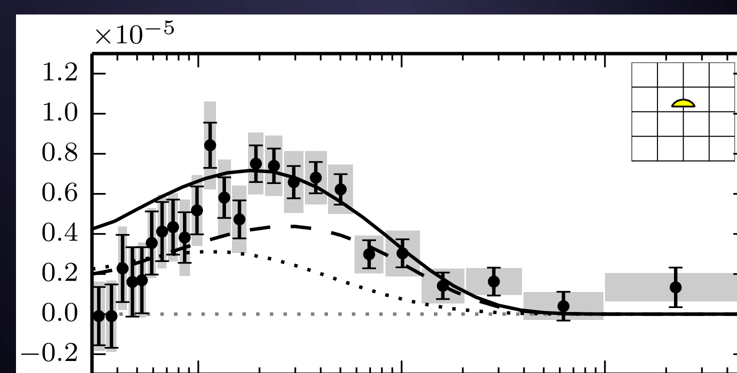
E.g., protons from supernova remnants [Carlson&Profumo 14]



2) LEPTONIC

E.g., multiple burst events injecting electrons [Petrovic+14, Cholis+15]





[Cholis+15]

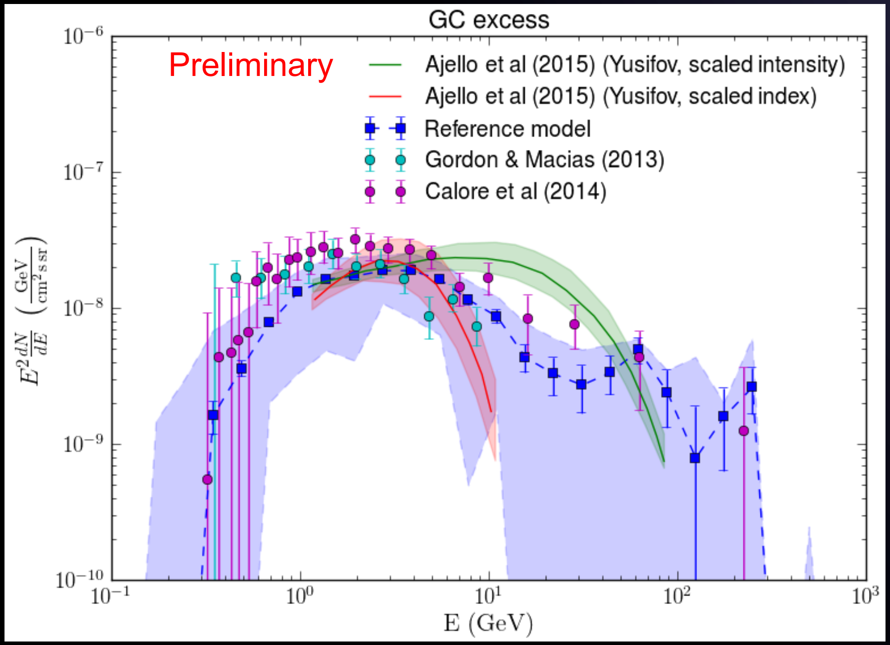
To be addressed

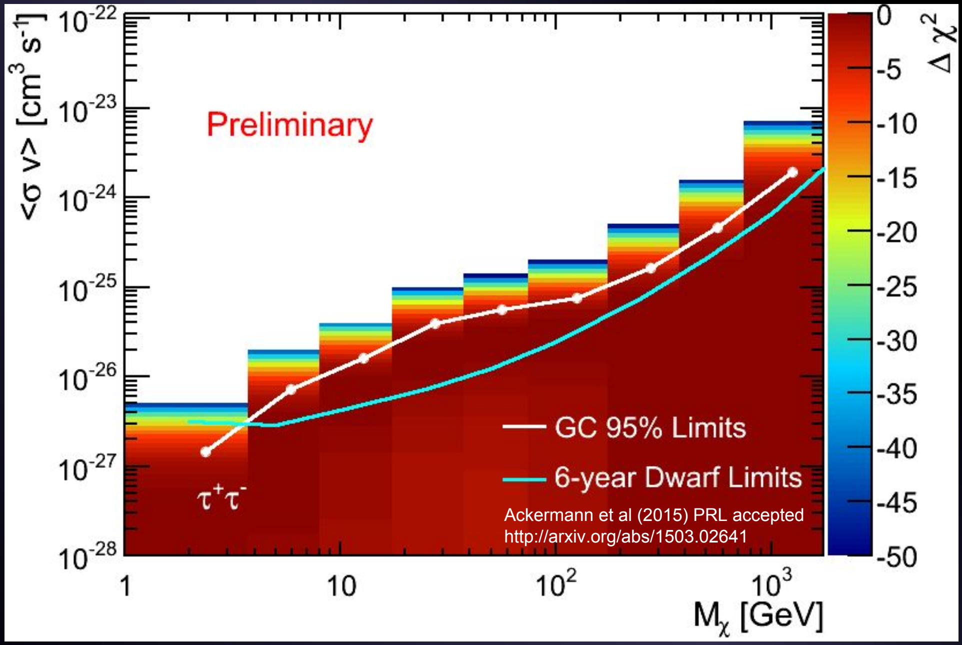
- **Diffuse emission uncertainties**
  - New satellite missions coming with improved angular resolution
  - CTA from the ground (though probably too high energy threshold for this…)
  - Improved models of CR propagation in the Galaxy.
- **Sub-threshold sources** in the inner Galaxy
  - Targeted radio and X-ray MSP searches. Future radio surveys.
  - Sophisticated gamma-ray analysis techniques (e.g. Bartels+15; Lee+15)
- Exact **DM density profile** in the Inner (<1-2 kpc) Galaxy?
  - Can *observations* help? Probably not for a while. MOONS in the near future?
  - *Simulations* and the cusp/core issue for MW-like galaxies. C'mon guys! ☺

    → But will they provide a reliable answer for THIS specific case??

The GC excess in Fermi-LAT Pass 8 data

- Excess persists
- Similar excesses at other longitudes along the Galactic Plane
  - → not expected from DM
  - → diffuse emission residuals can mimic a DM signal
- DM limits derived incorporating systematic uncertainties



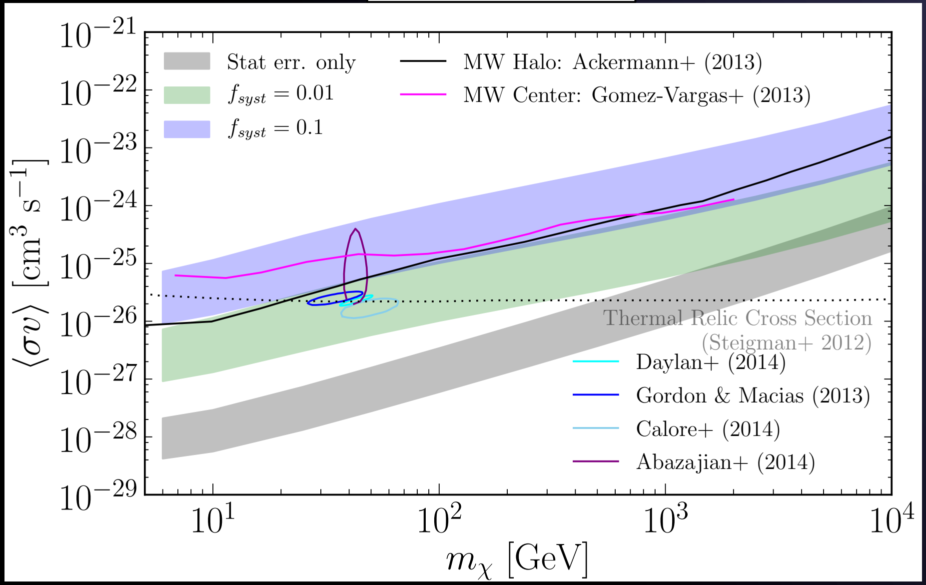


A. Albert, for the LAT collab.,
[APS meeting, Apr 16]

D. Malyshev, for the LAT collab.,
[Gamma-rays and dark matter, Obergurgi, Dic 15]

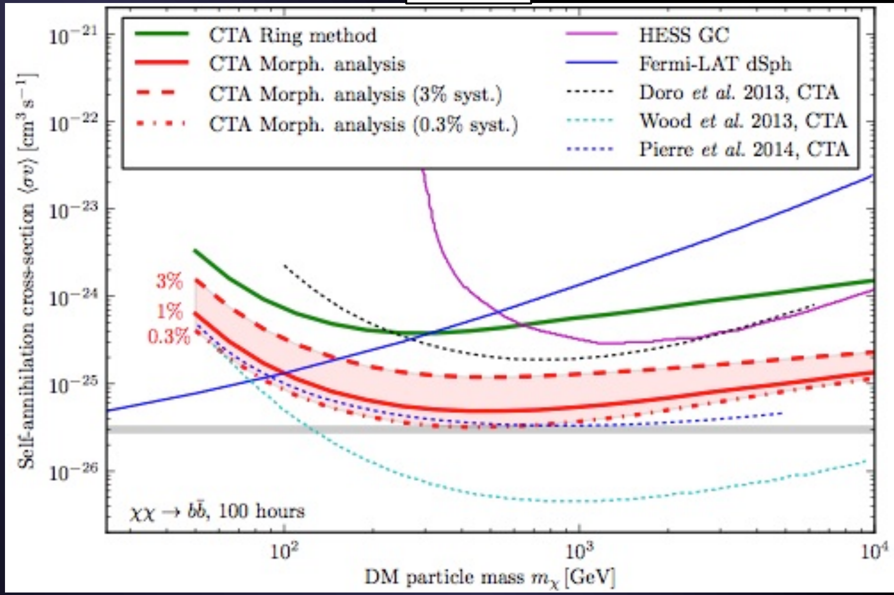
Control of systematics critical

FERMI LAT



Charles, MASC+ [1605.02016]

CTA



Silverwood+14

Dark Matter search strategies

Satellites

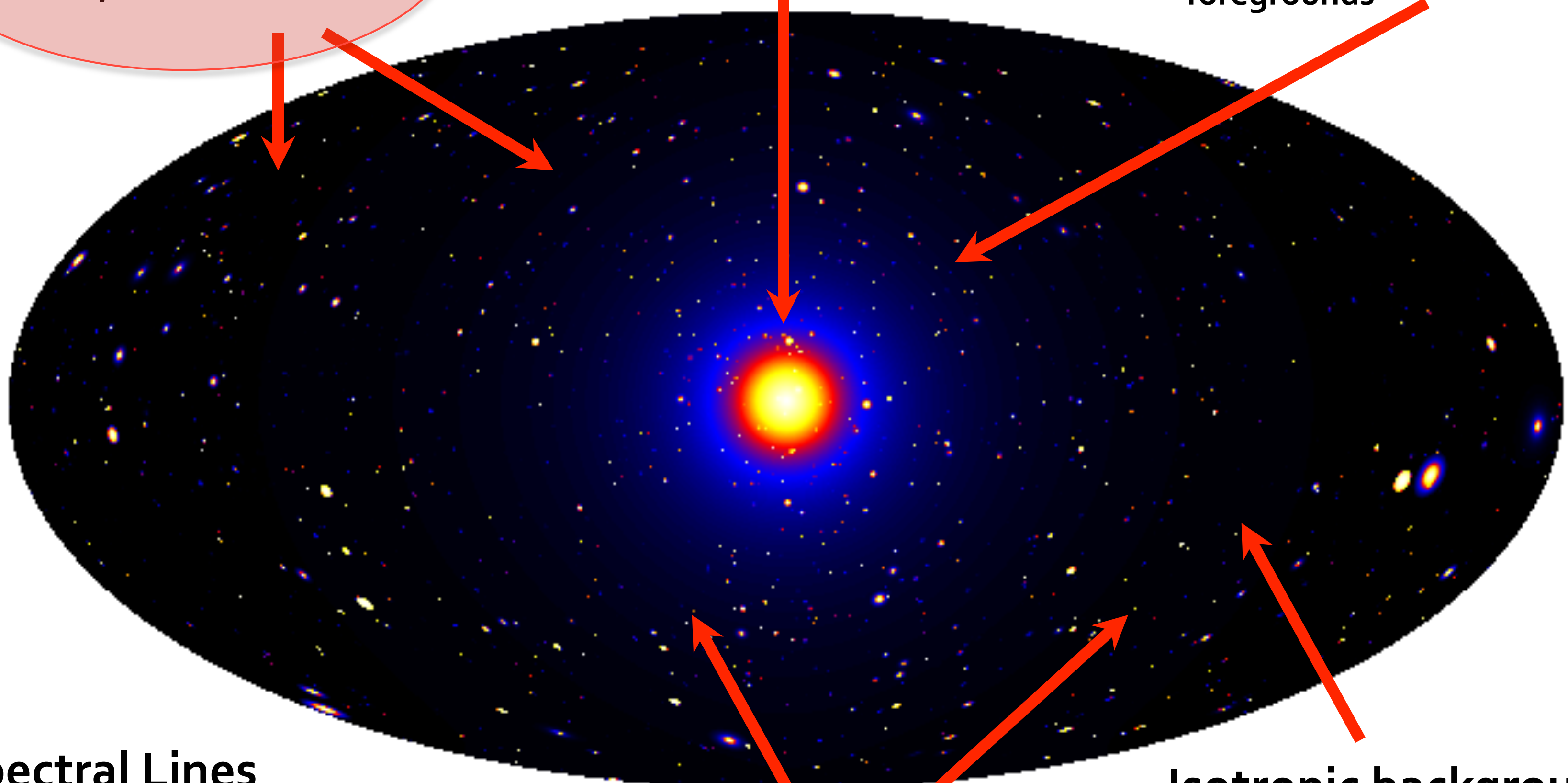
Low background and good source id, but low statistics

Galactic Center

Largest statistics, but source confusion/diffuse foregrounds

Milky Way Halo

Large statistics, but diffuse foregrounds



Spectral Lines

Little or no astrophysical uncertainties, good source id, but low signal expected

Galaxy Clusters

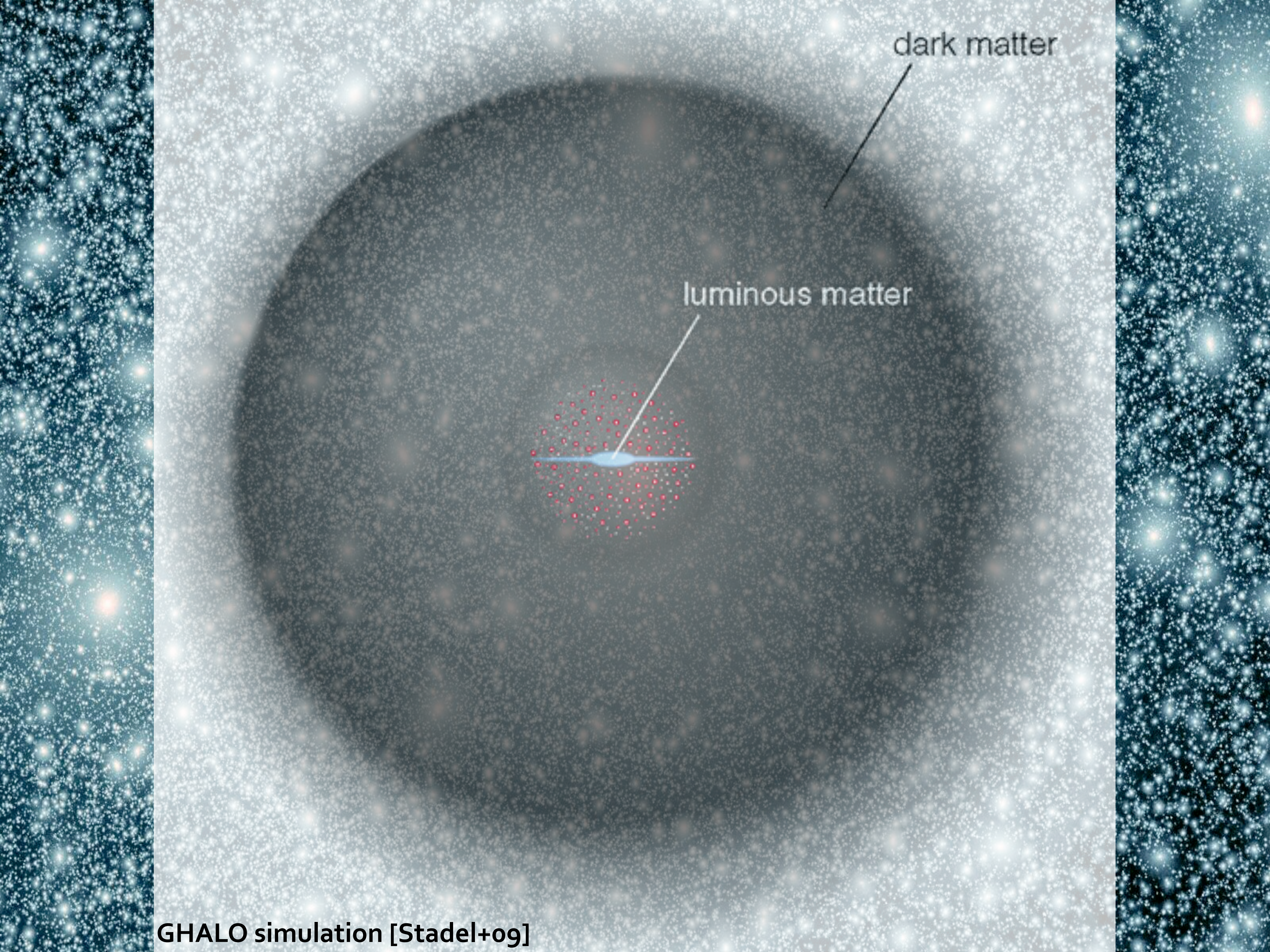
Large, extended signal, but diffuse background and astrophysics

Isotropic background

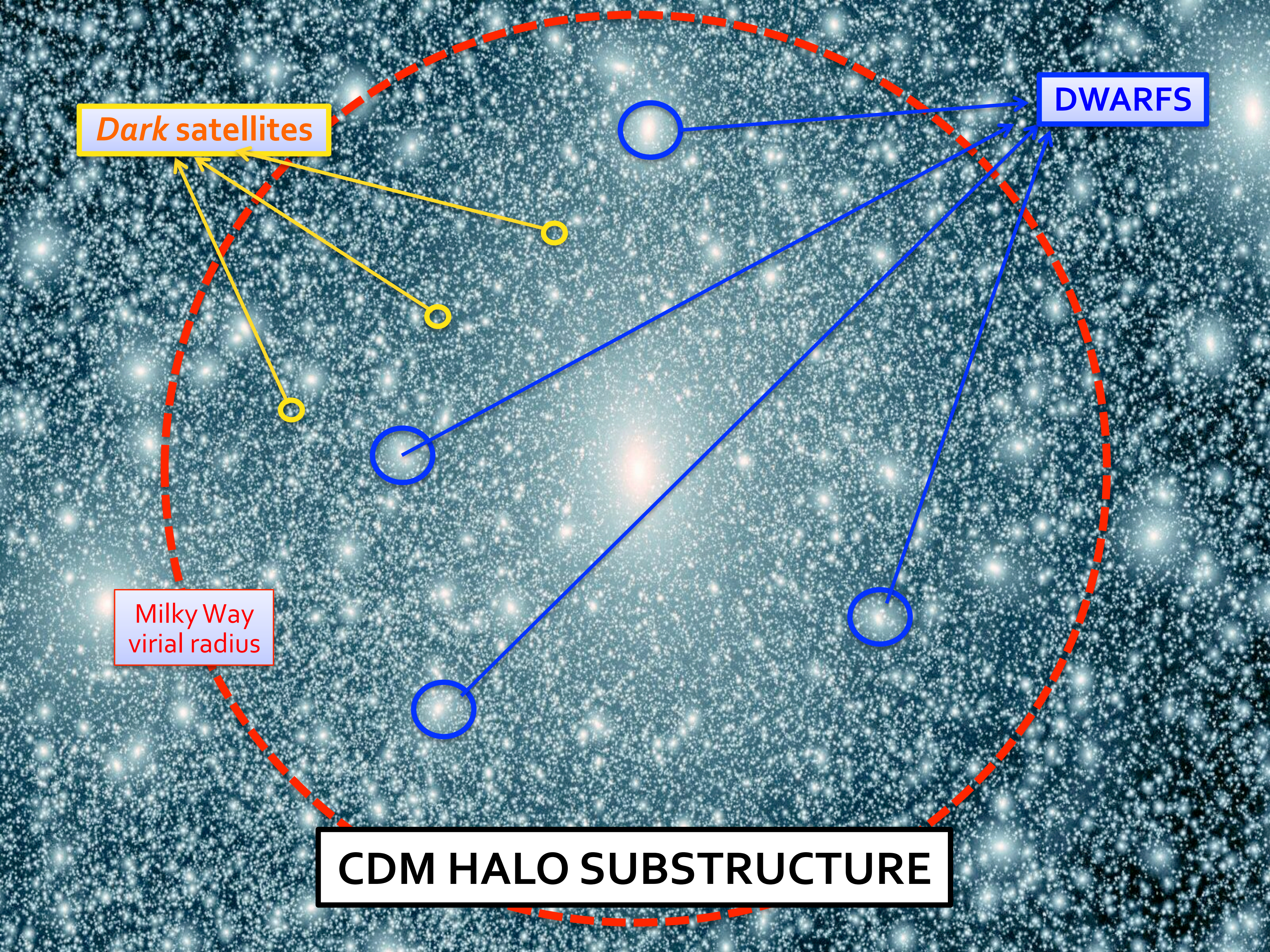
Large statistics, but astrophysics, galactic diffuse foregrounds, signal uncertainties

Dark Matter simulation: Pieri+(2009) arXiv:0908.0195

GHALO simulation [Stadel+09]



GHALO simulation [Stadel+09]


Dark satellites
DWARFS
Milky Way virial radius
CDM HALO SUBSTRUCTURE

The role of DM substructure in γ-ray DM searches

Both *dwarfs* and *dark satellites* are highly DM-dominated systems

→ GOOD TARGETS

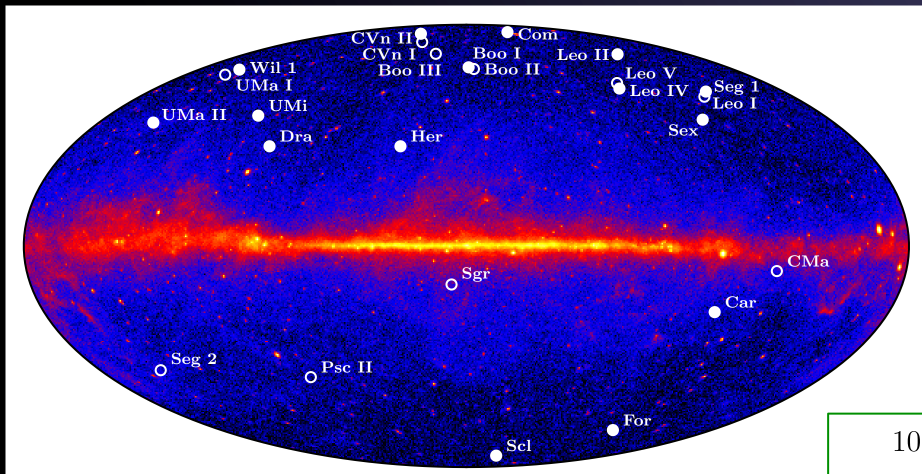
The *clumpy distribution* of subhalos inside larger halos may boost the annihilation signal importantly.

→ SUBSTRUCTURE BOOSTS

Dwarf spheroidal satellite galaxies

- The most DM dominated systems known in the Universe.
- Nearly 30 confirmed dwarfs in the Milky Way. More on the way!
- Close to us. Several of them within 50 kpc.
- Free from bright astrophysical gamma-ray sources

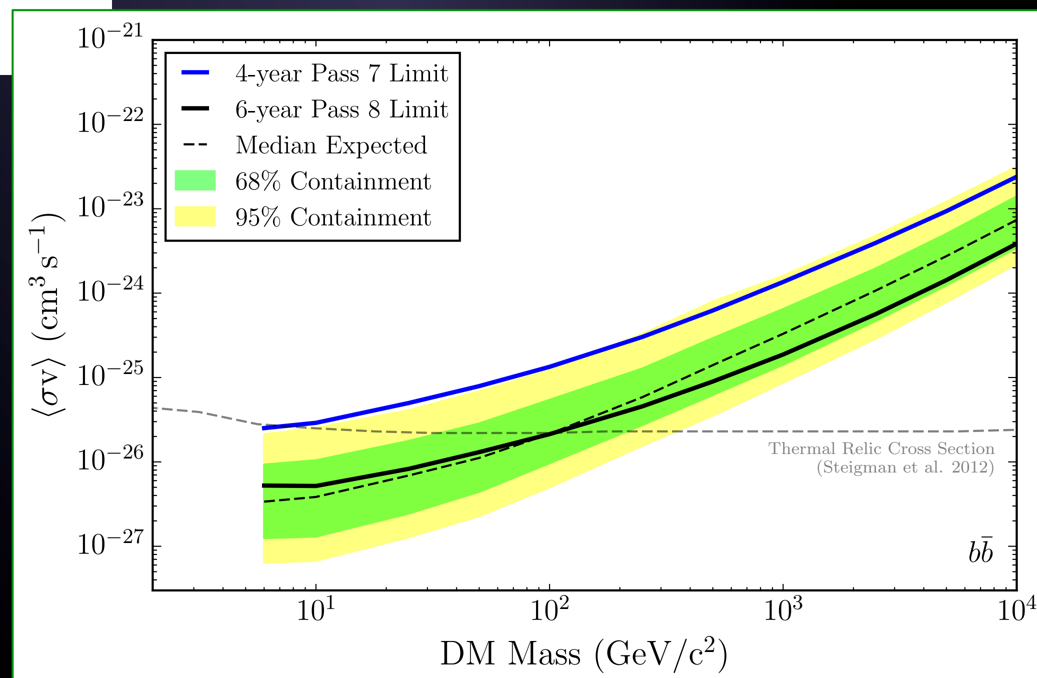
Fermi-LAT DM search in dwarfs



[Ackermann+15, the LAT collab., 1503.02641]

Joint likelihood analysis of **15 dwarfs**

Makes use of Pass 8 data



No gamma signal → DM limits

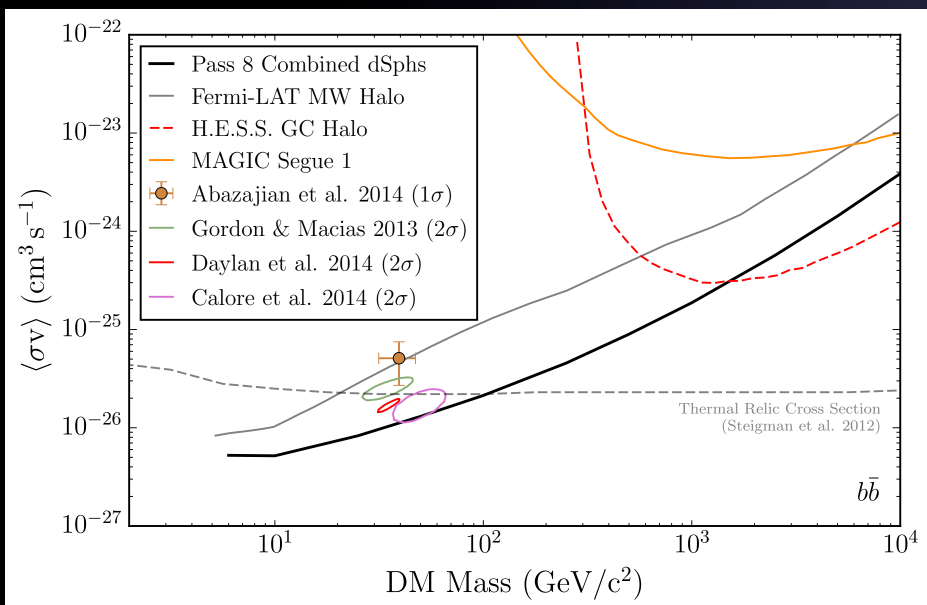
Excludes thermal WIMPs <100 GeV

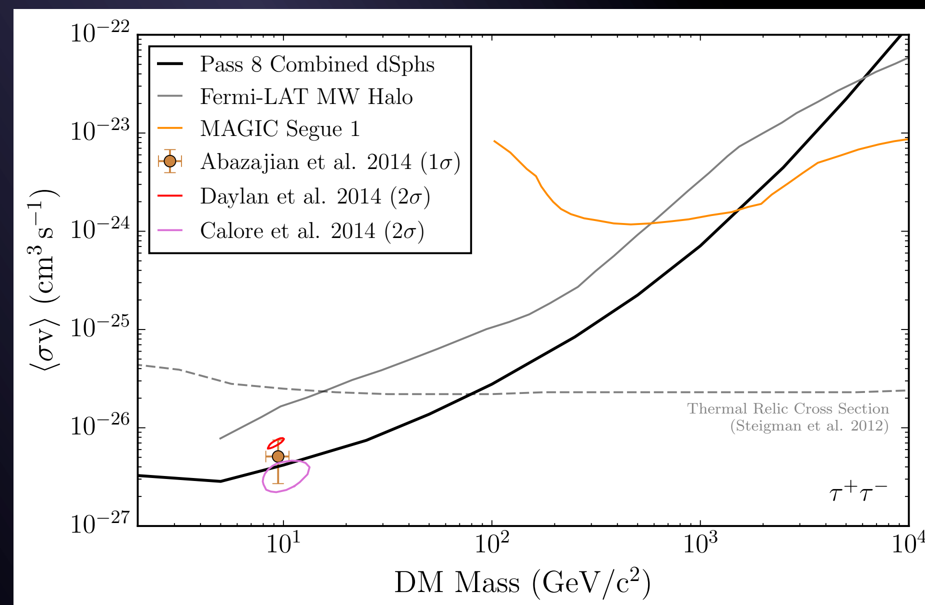
Expectation bands from control regions

Relevance of these limits

Most robust and competitive limits in the <1 TeV WIMP mass regime so far.

Dwarfs as a test of the GeV GC excess.



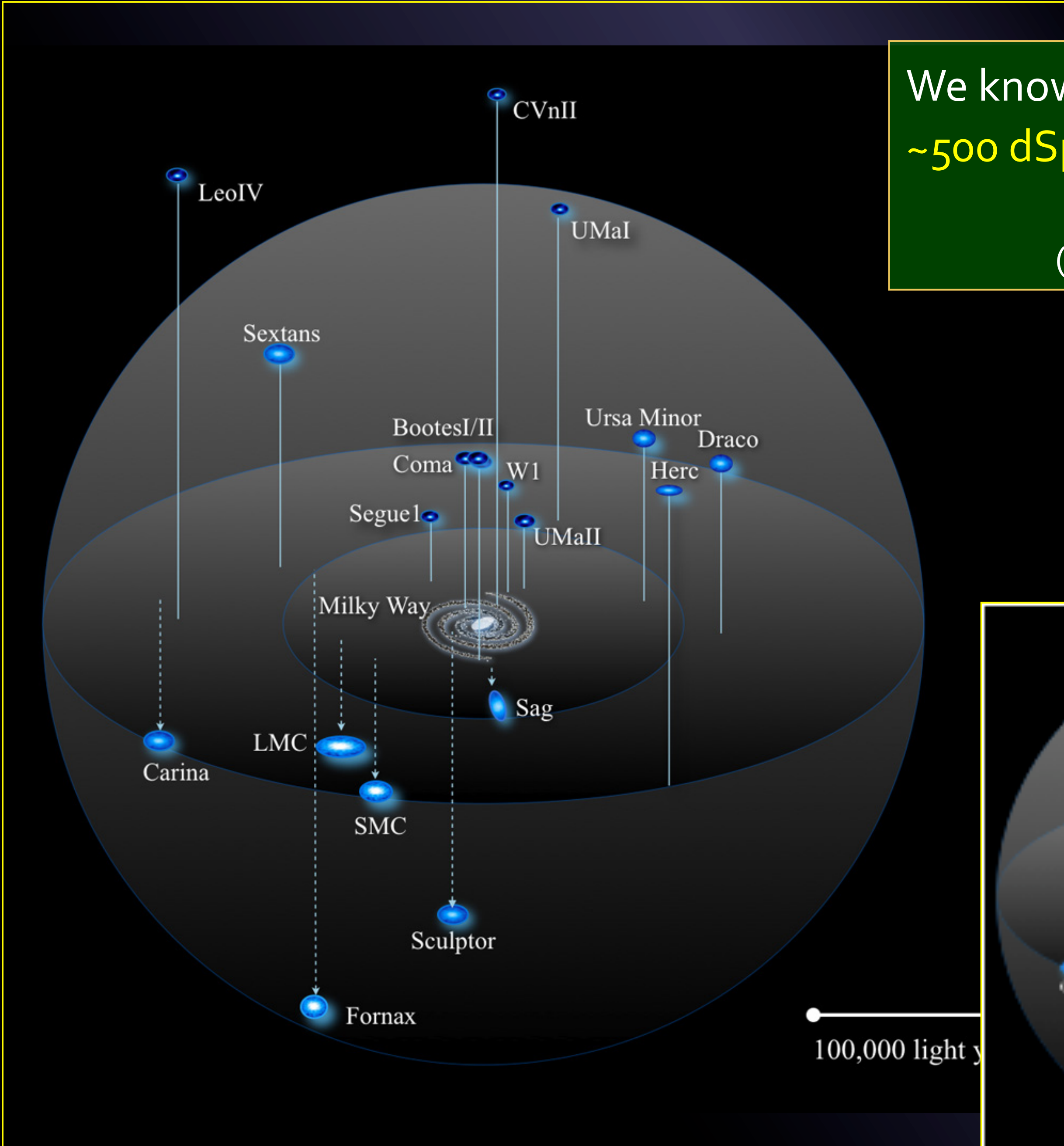


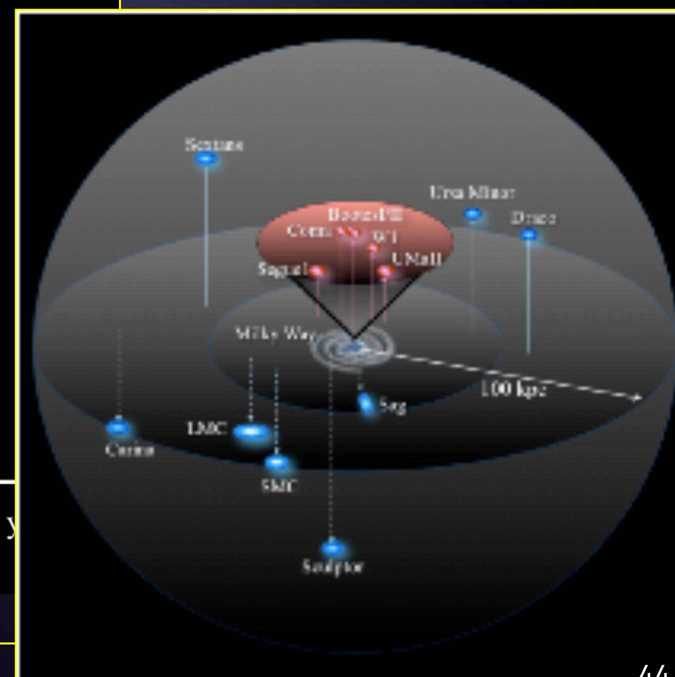
[Ackermann+15, the Fermi-LAT collab., 1503.02641]

We know ~2 dozens of dwarfs, but…

~500 dSphs inside the virial radius?

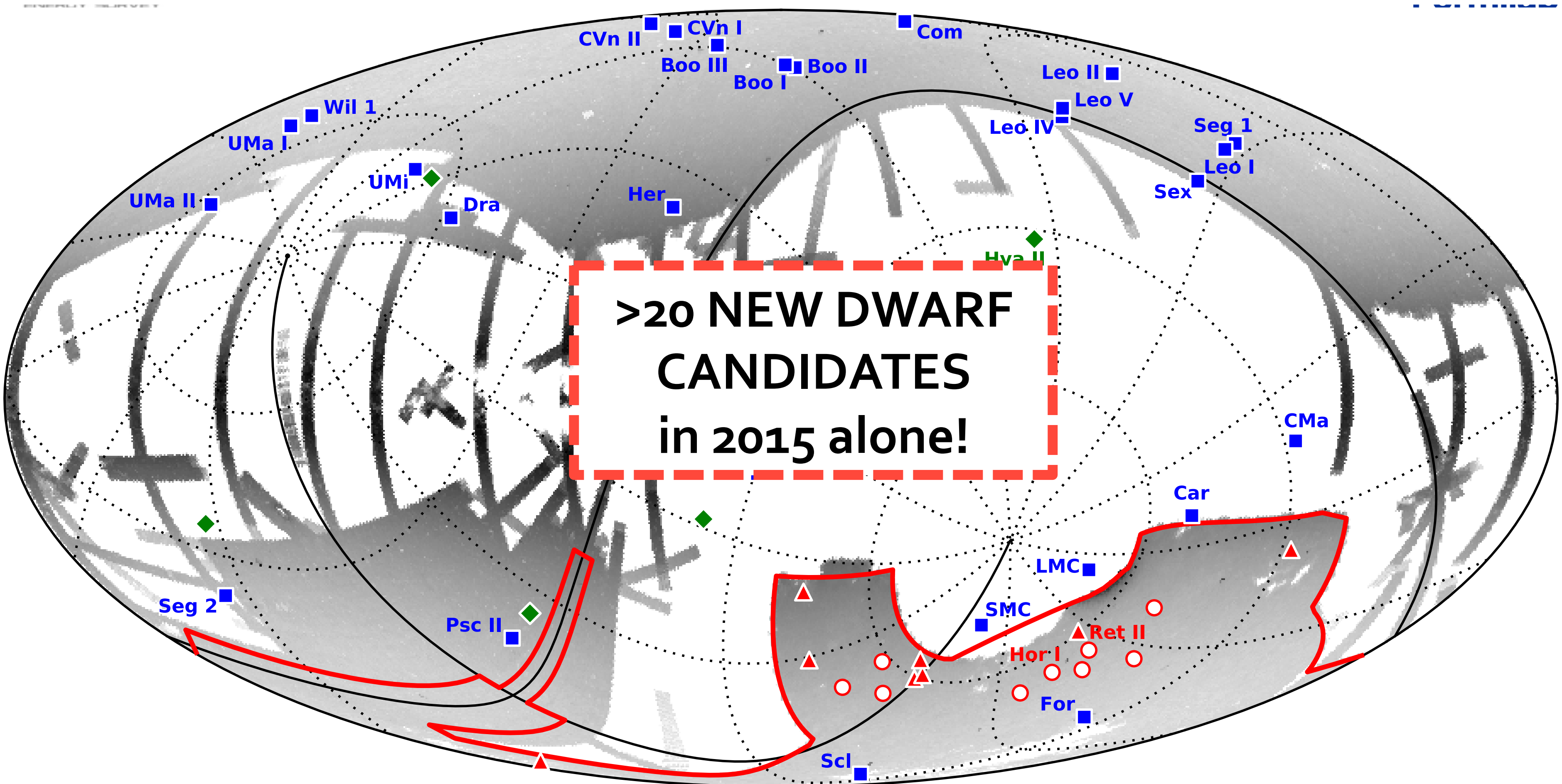
(Tollerud+08; Walsh+09; Hargis+14)





(Bullock et al. 2009)

Recent discovery of new satellites



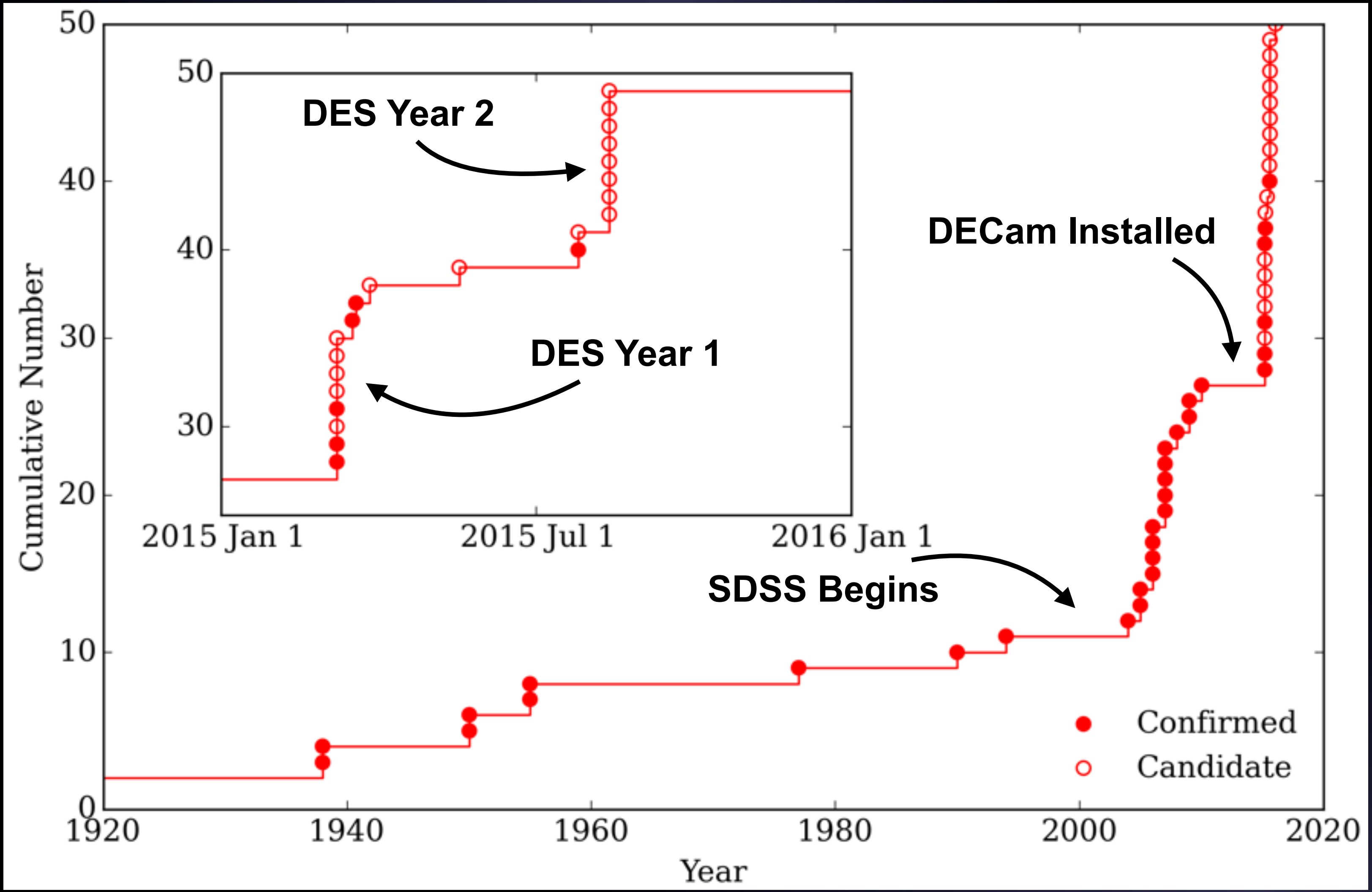
Blue - Previously discovered satellites
Green - Discovered in 2015 with PanSTARRS/SDSS

Red outline - DES footprint
Red circles - DES Y1 satellites
Red triangles - DES Y2 satellites

4 additional DES dwarfs reported from outside the DES collab.
(Koposov+15, Kim&Jerjen15, Kim+15, Martin+15)

DES collab., 1503.02584
DES collab., 1508.03622
Leavens+15

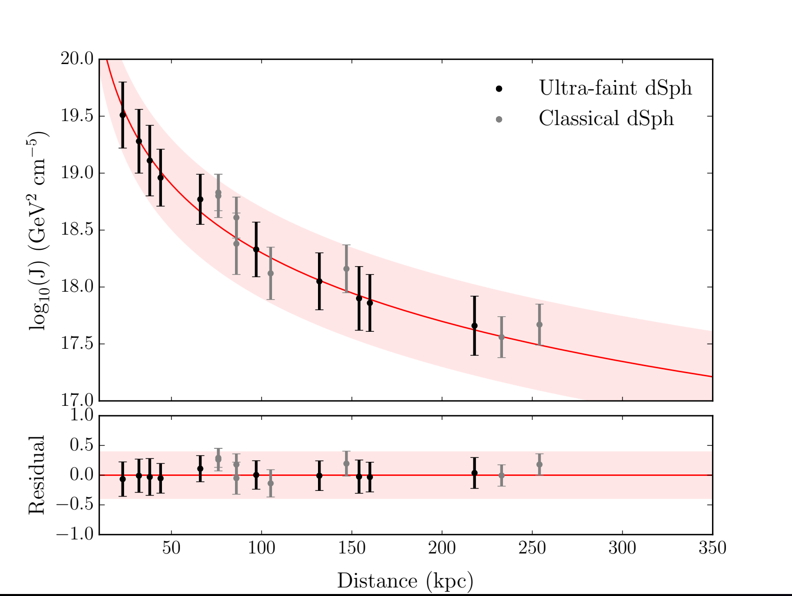
Discovery timeline



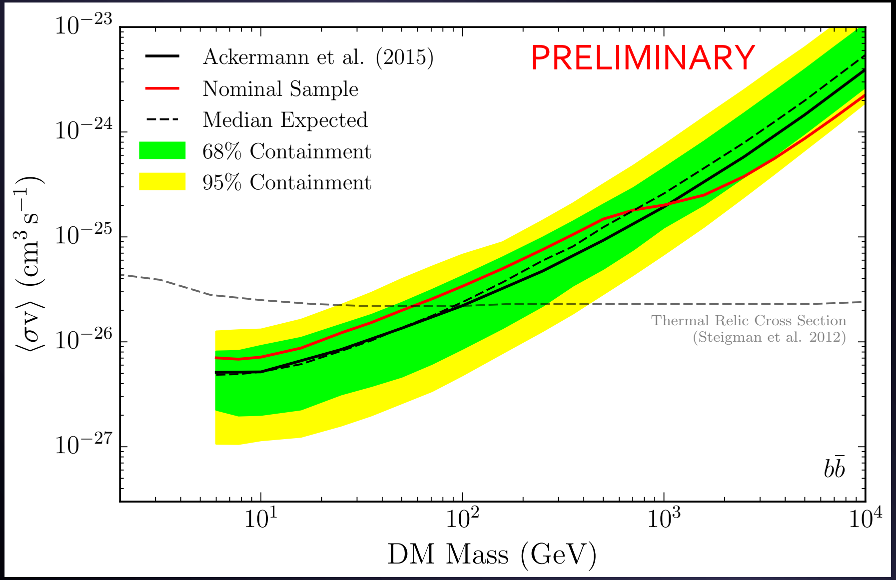
A. Drlica-Wagner for the LAT and DES collaborations
[*UCLA DM 2016*, Feb 2016]

Search for γ-ray emission from the DES dwarf candidates with the Fermi LAT

Drlica-Wagner+15, [astro-ph/1503.02632]



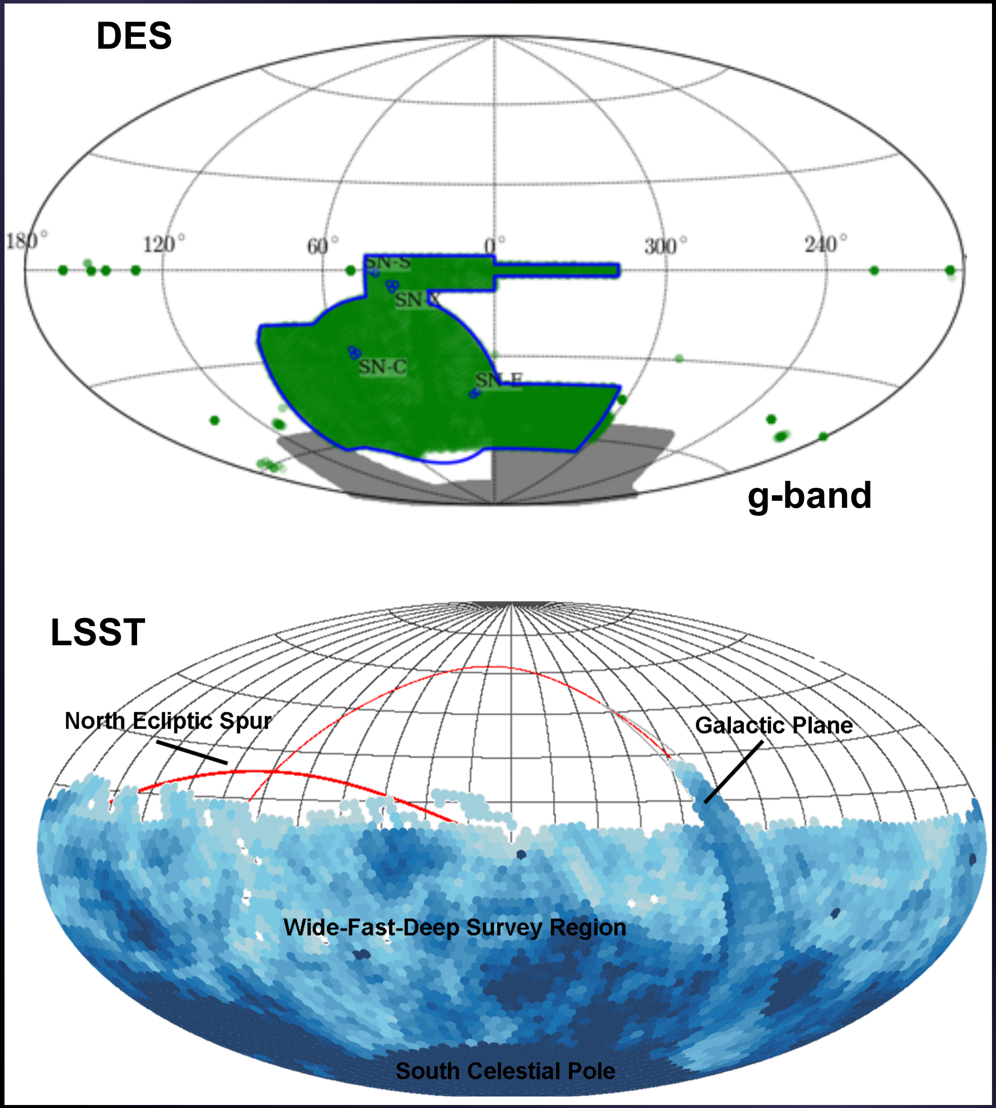
- No gamma-ray signal found
  → Upper limits to the gamma-ray flux.
- Assuming they are dwarfs and share similar properties, we can **combine** individual results
- Most significant excess is < 1σ



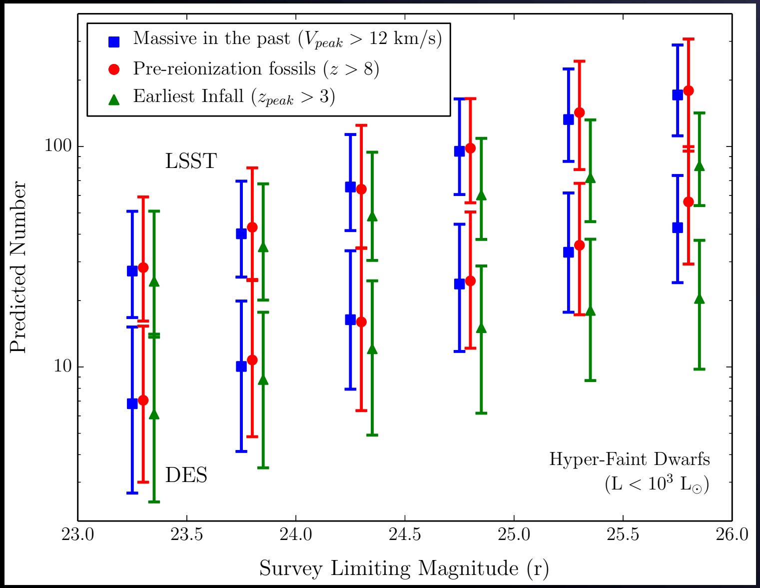
[Drlica-Wagner, on behalf of LAT and DES collab., UCLA DM 2016]

Data: looking forward

- Large **spectroscopic campaign** underway
- More sky coverage:
  - **DES Y3+**: a few hundred more sq.deg at greater sensitivity.
  - **LSST**: 20,000 sq. deg. with much greater sensitivity
- **Increased sensitivity**
  - Are there hyper-faint galaxies out there?
  - Any very nearby?

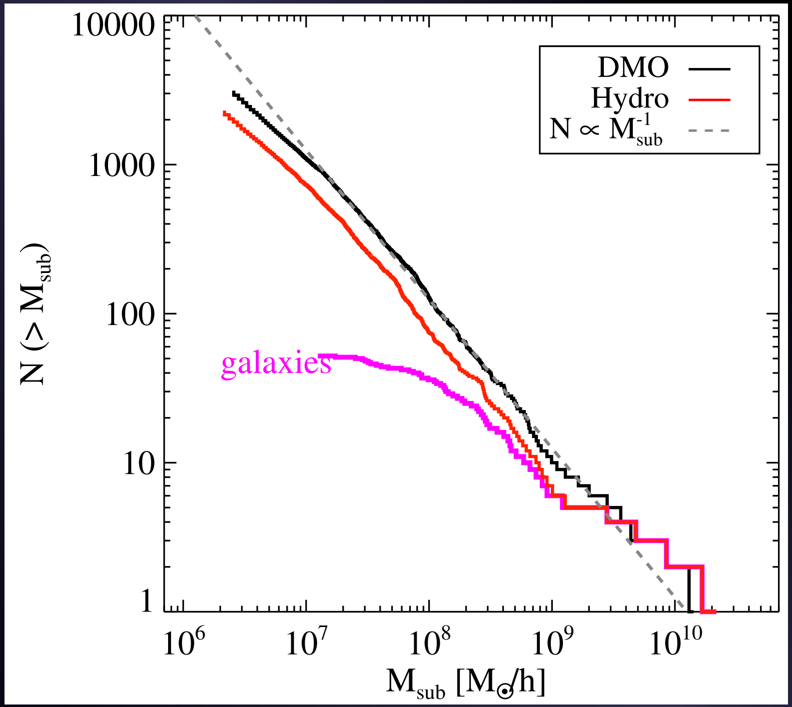


Simulations: looking forward



Hargis+14

How many dwarfs should we expect?

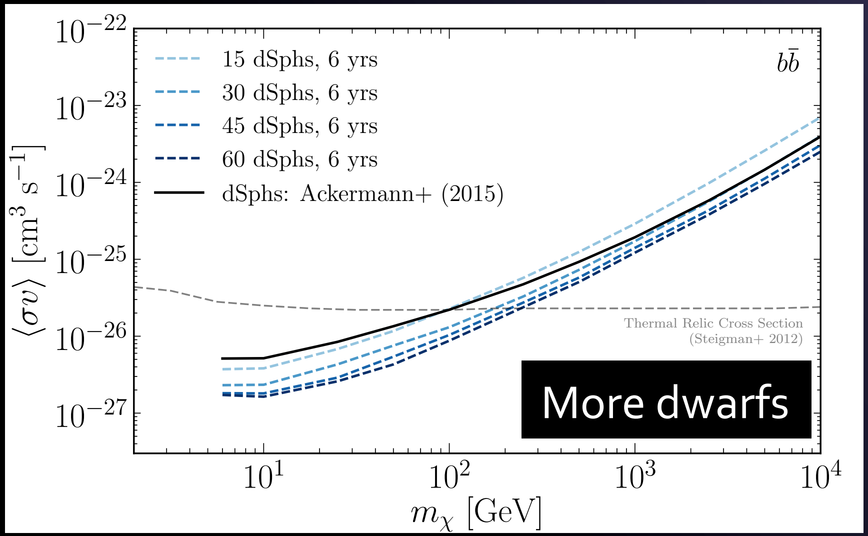


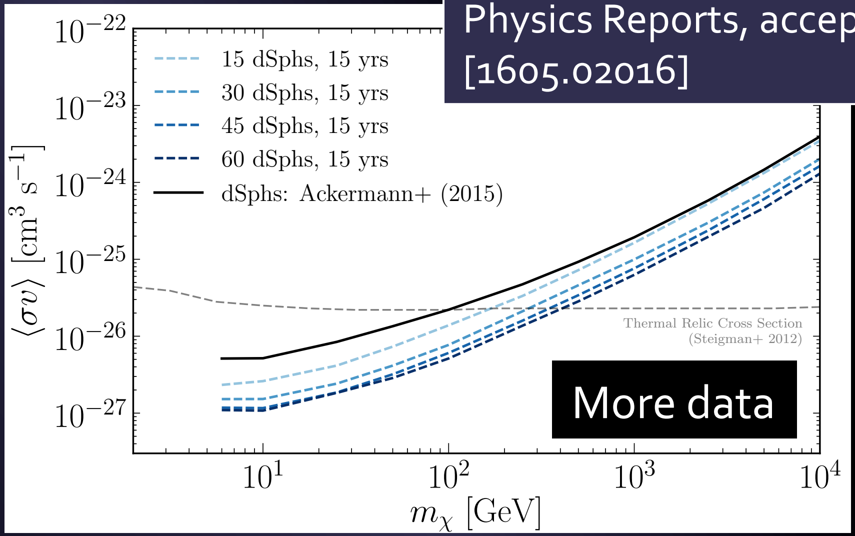
Zhu+15

Impact of baryons on this number?

E.g, what Fermi LAT can still do

Charles, MASC, et al., Physics Reports, accepted [1605.02016]

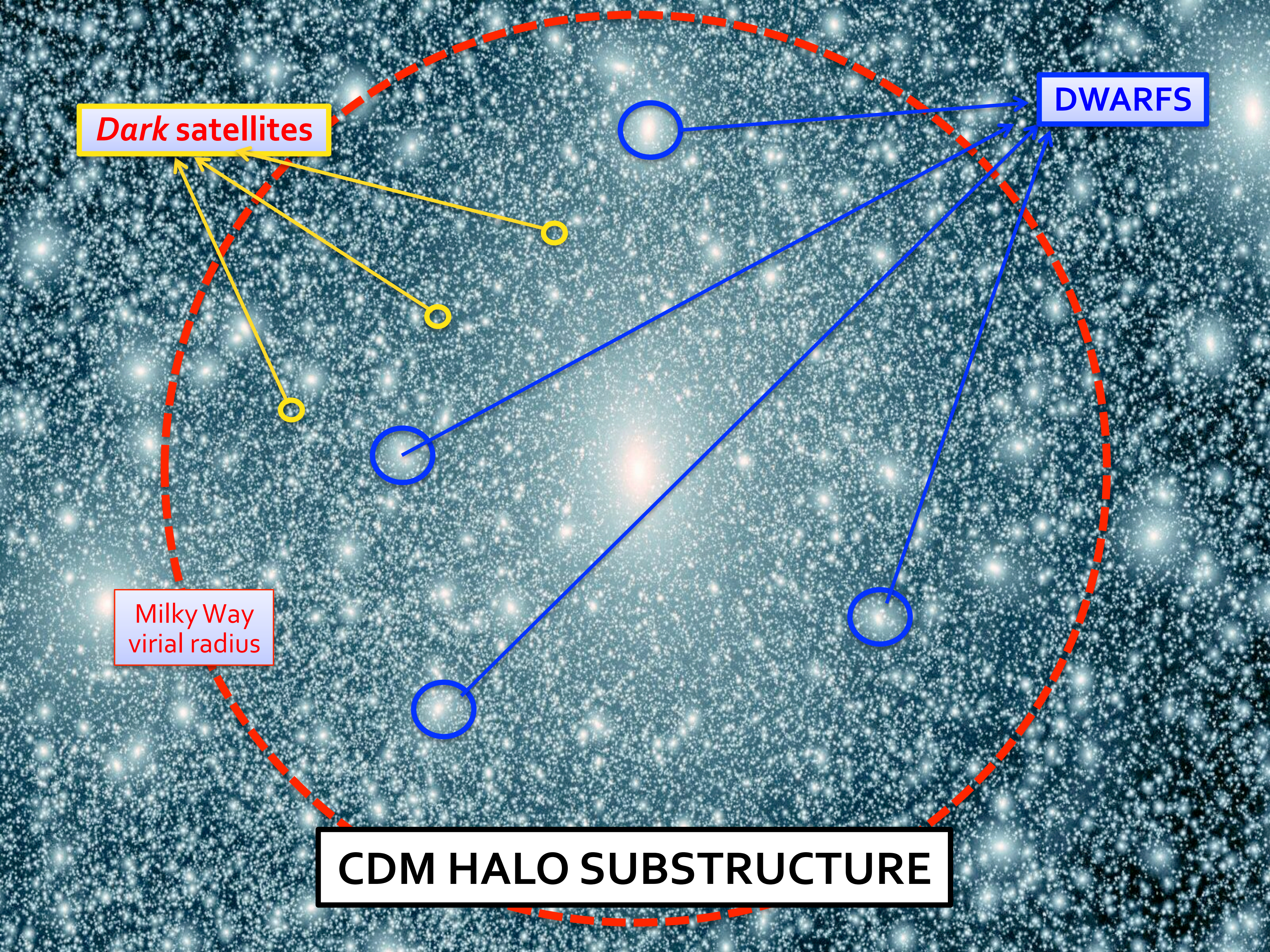




More **data** + dwarf discoveries will provide:

→best tool to improve upon the current DM limits significantly.

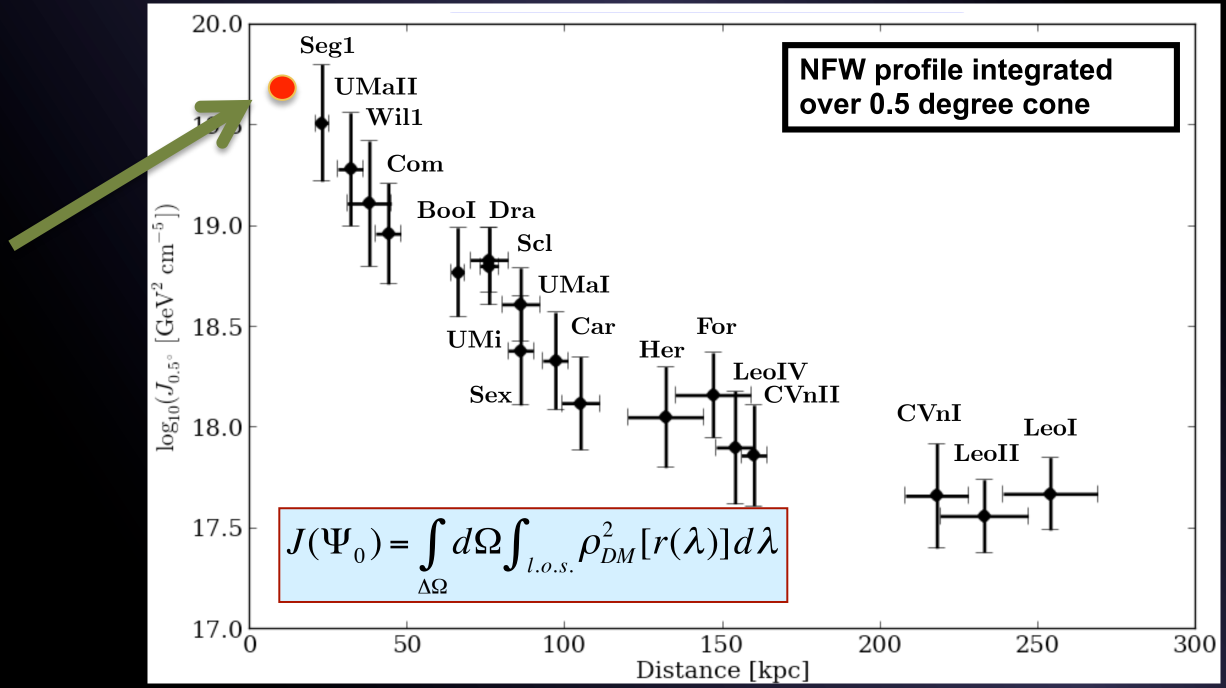
→An independent test of the GC excess as due to DM.


Dark satellites
DWARFS
Milky Way
virial radius
CDM HALO SUBSTRUCTURE

Low-mass subhalos might host few or no stars → no optical counterpart.
Gamma-rays from DM annihilations may be the only way to find them!

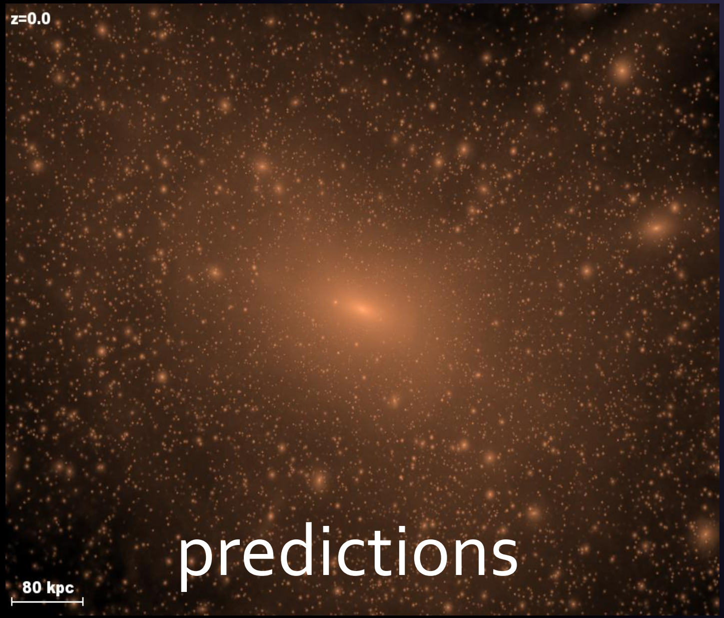
Could some of them be better candidates than dwarfs?
How many of these low-mass subhalos are potentially detectable?

Should we expect any DM satellite e.g. here?

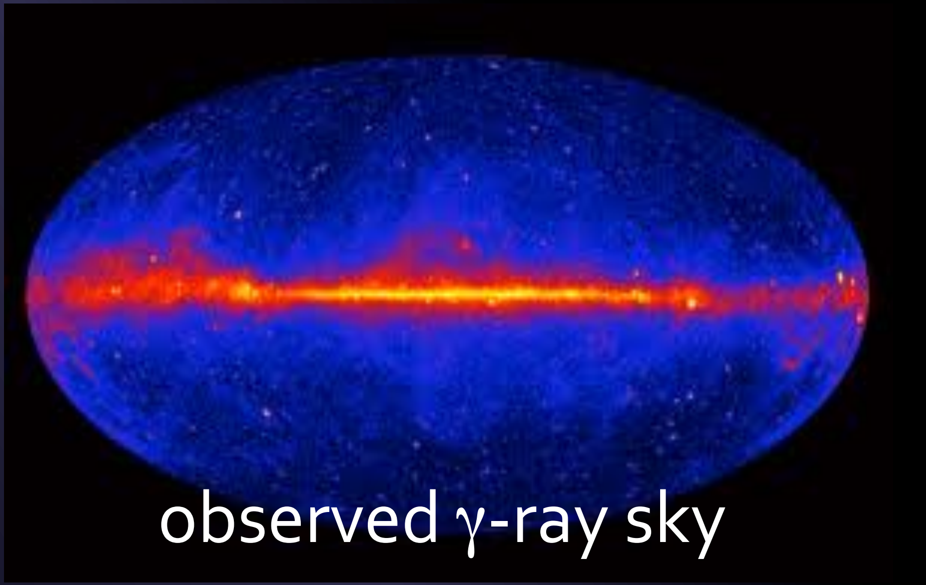


A.Drlica-Wagner DPF 2013

DM constraints from DM satellites



VS



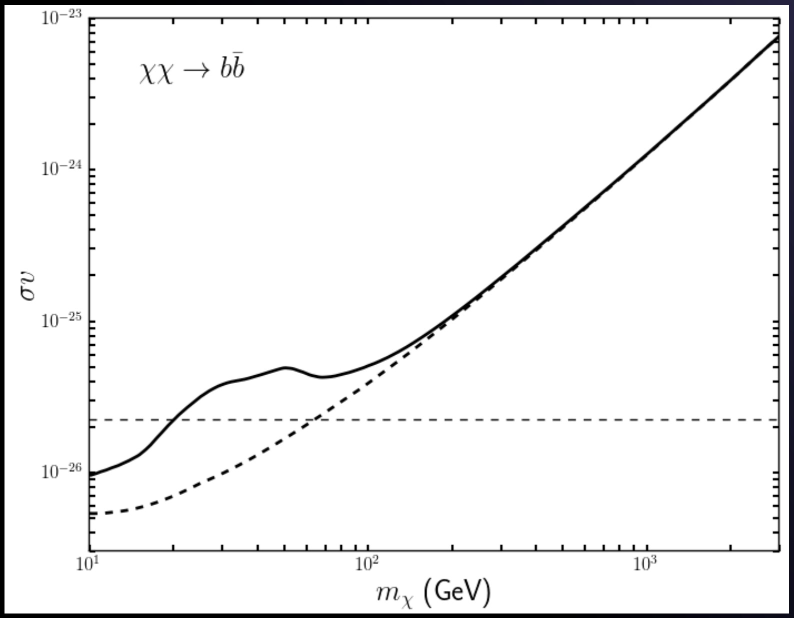
I. J-factors + Particle physics model → annihilation luminosities

II. Fermi sensitivity maps to DM anniihilations → number of detectable DM satellites

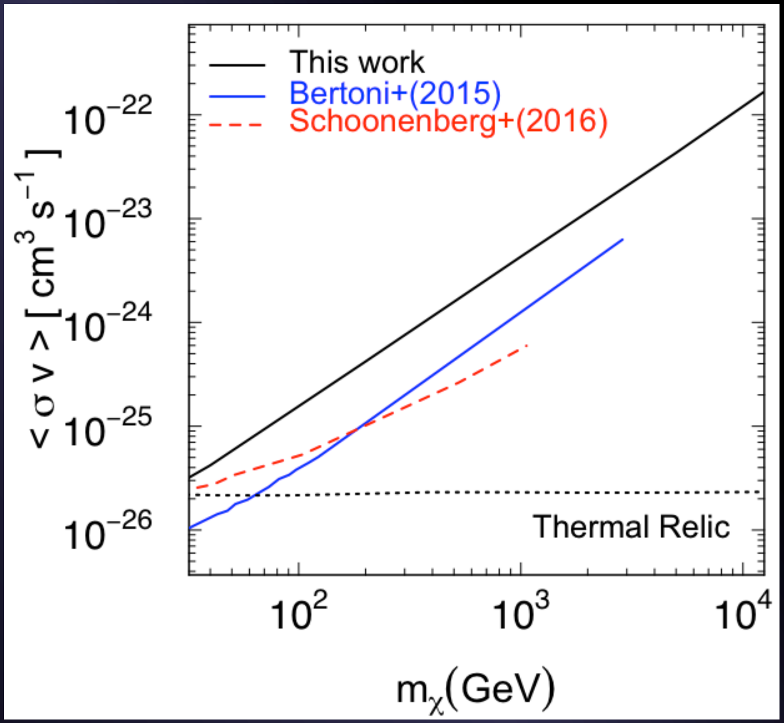
III. Predictions versus data → DM constraints

- 1/3 of the sources 3FGL catalog remains unidentified (~1000 unIDs)
- The more astrophysical associations the better for the limits!

Example of constraints from dark satellites



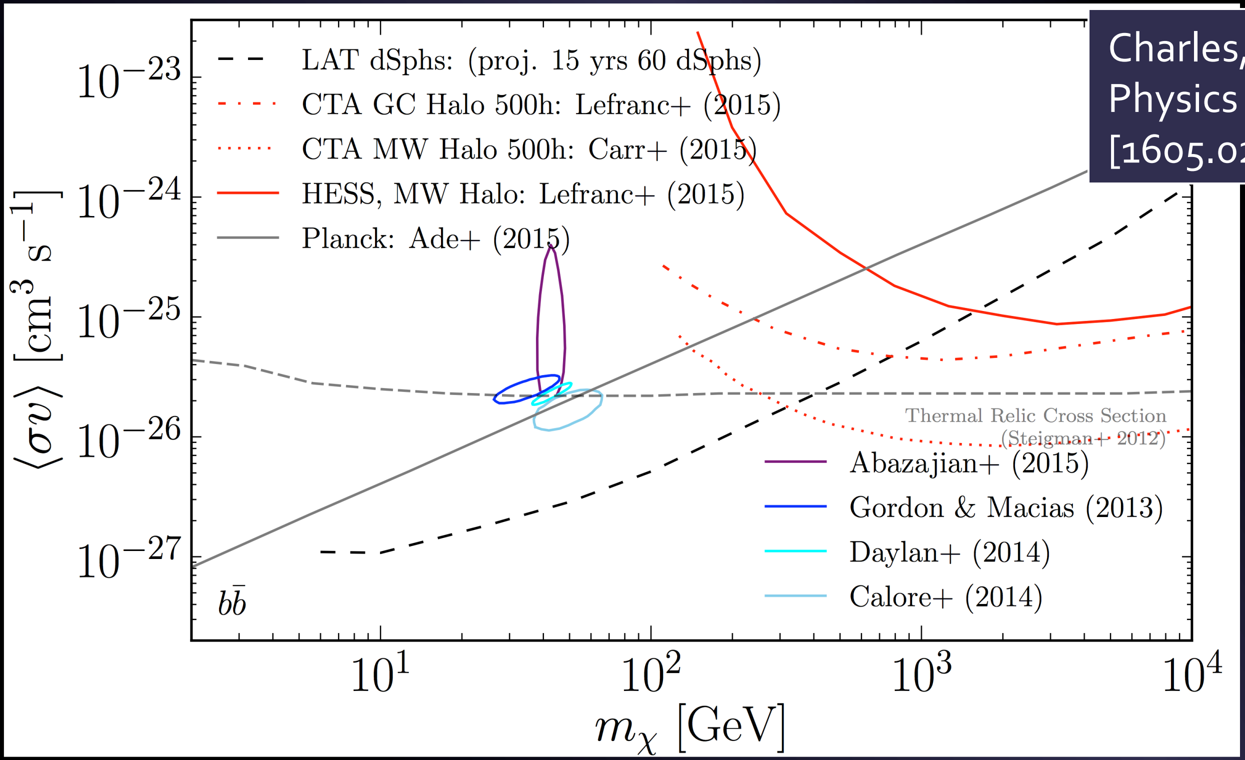
Bertoni+15



Mirabal+16

Data: The more uniD associations the better!
Simulations: How would this picture change by including baryons in the game?

(γ-ray) DM searches: tomorrow



Charles, MASC, et al., Physics Reports, accepted [1605.02016]

→ **Fermi + CTA** will (fully?) test the thermal cross-section value (by ~2020?)

→ **New instruments** from the ground and on space (CTA, GAMMA-400, HERD)

→ These limits only possible if:

  → reliable J-factor estimates from dwarfs are available in the future

  → Understand and control the systematics

→ As usual, **simulations** can guide us in the search!

Outline

- **Astrophysical (Galactic) fore/backgrounds**

- **Galactic targets:**
  - **Galactic center**
  - **Dwarfs**
  - **Dark satellites**

- **Subhalo boosts to the annihilation signal**

For each of the items above:

i) Current status
ii) Open issues
iii) Possible ways to address them (simulations, data).

The role of DM substructure in γ-ray DM searches

Both *dwarfs* and *dark satellites* are highly DM-dominated systems

→ GOOD TARGETS

The *clumpy distribution* of subhalos inside larger halos may boost the annihilation signal importantly.

→ SUBSTRUCTURE BOOSTS

DM annihilation boost factor from substructure

Since DM annihilation signal is proportional to the DM density squared
→ *Enhancement of the DM annihilation signal expected due to subhalos.*

Substructure **BOOST FACTOR**: $L = L_{host} * [1+B]$, so $B=0$ → no boost
$B=1$ → $L_{host} \times 2$ due to subhalos

$$B(M) = \frac{1}{L(M)} \int_{M_{min}}^{M} (dN/dm)\ [1 + B(m)]\ L(m)\ dm$$

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Subhalo mass function

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Subhalo luminosity

Subhalo mass function

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Minimum halo mass

Subhalo mass function

Subhalo luminosity

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Minimum halo mass

Subhalo mass function

Other levels of sub-substructure

Subhalo luminosity

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$B=1$ → L_{host} x 2 due to subhalos

$$B(M) = \frac{1}{L(M)} \int_{M_{min}}^{M} (dN/dm)\, [1 + B(m)]\, L(m)\, dm$$

Host halo luminosity

Minimum halo mass

Subhalo mass function

Other levels of sub-substructure

Subhalo luminosity

B(M) depends on the internal structure of the subhalos and their abundance

→ N-body cosmological simulations

- Integration down to the minimum predicted halo mass $\sim 10^{-6}$ Msun.
- Current Milky Way-size simulations "only" resolve subhalos down to $\sim 10^{5}$ Msun.

→ ***Extrapolations below the mass resolution*** *needed.*

Subhalo mass function

$$\boxed{dN/dm = A/M(m/M)^{-\alpha}}$$

α = -1.9 in Aquarius
α = -2 in VL-II

Subhalo annihilation luminosity

J-factor $\boxed{\propto \rho_s^2 r_s^3 \propto M \frac{c^3}{f(c)^2}}$ with

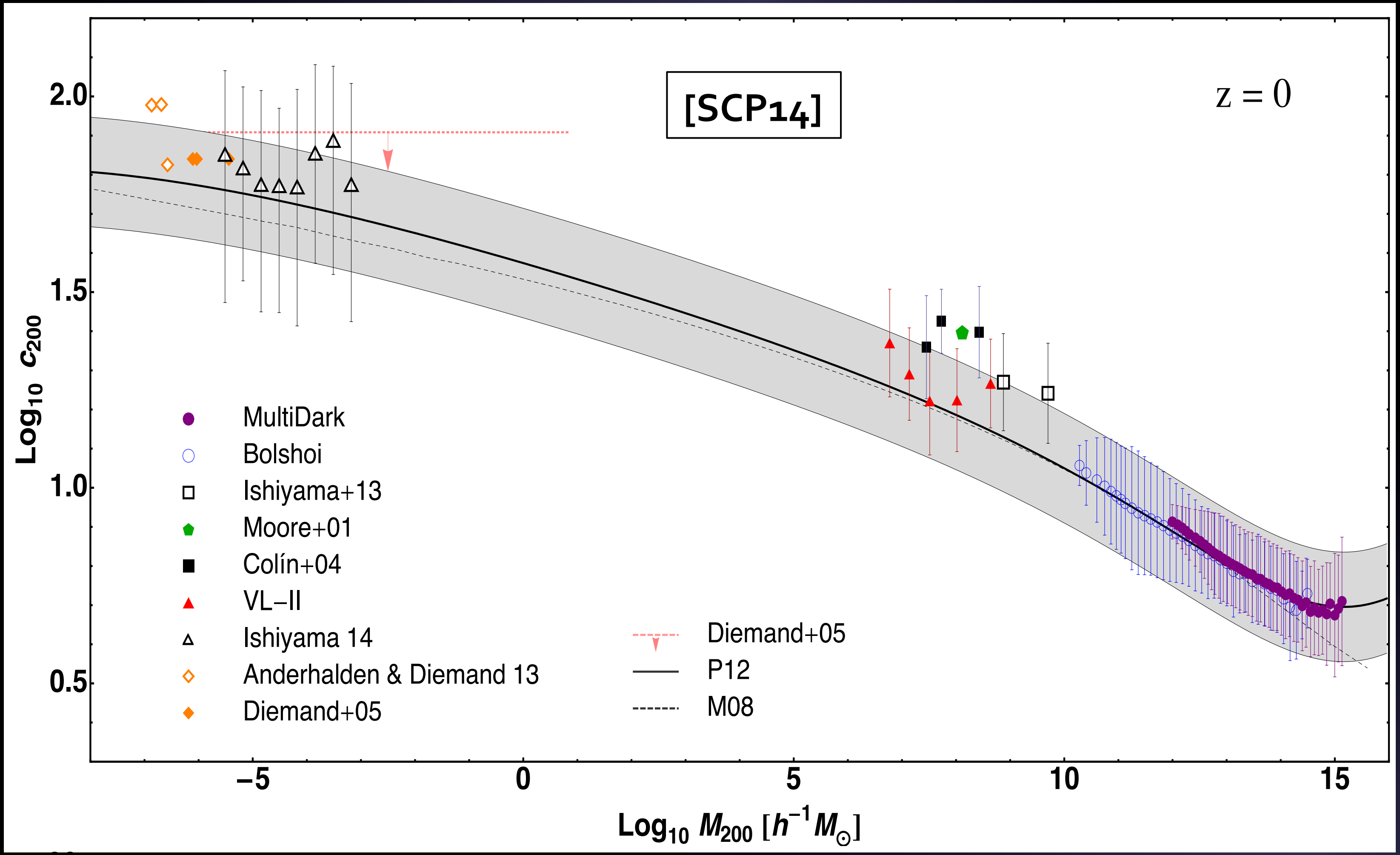
Concentration c = R_{vir} / r_s

$$f(c) = ln(1+c) - c/(1+c)$$

→ Results very sensitive to the c(M) extrapolations down to M_{min}

Current knowledge of the c(M) relation at z=0

Concentration $c = R_{vir} / r_s$



MASC & Prada, MNRAS, 442, 2271 (2014) [astro-ph/1312.1729]

Current knowledge of the c(M) relation at z=0

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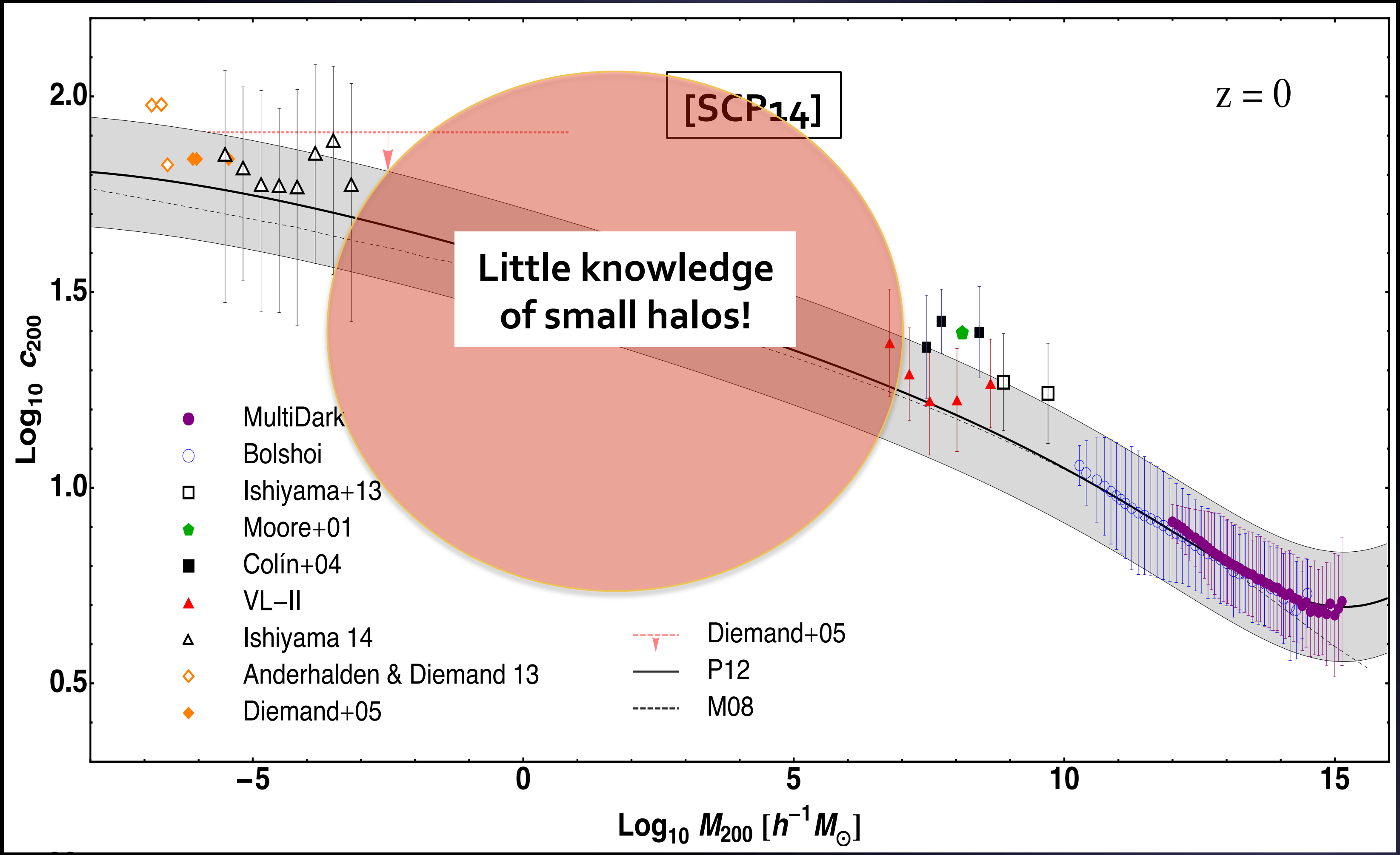
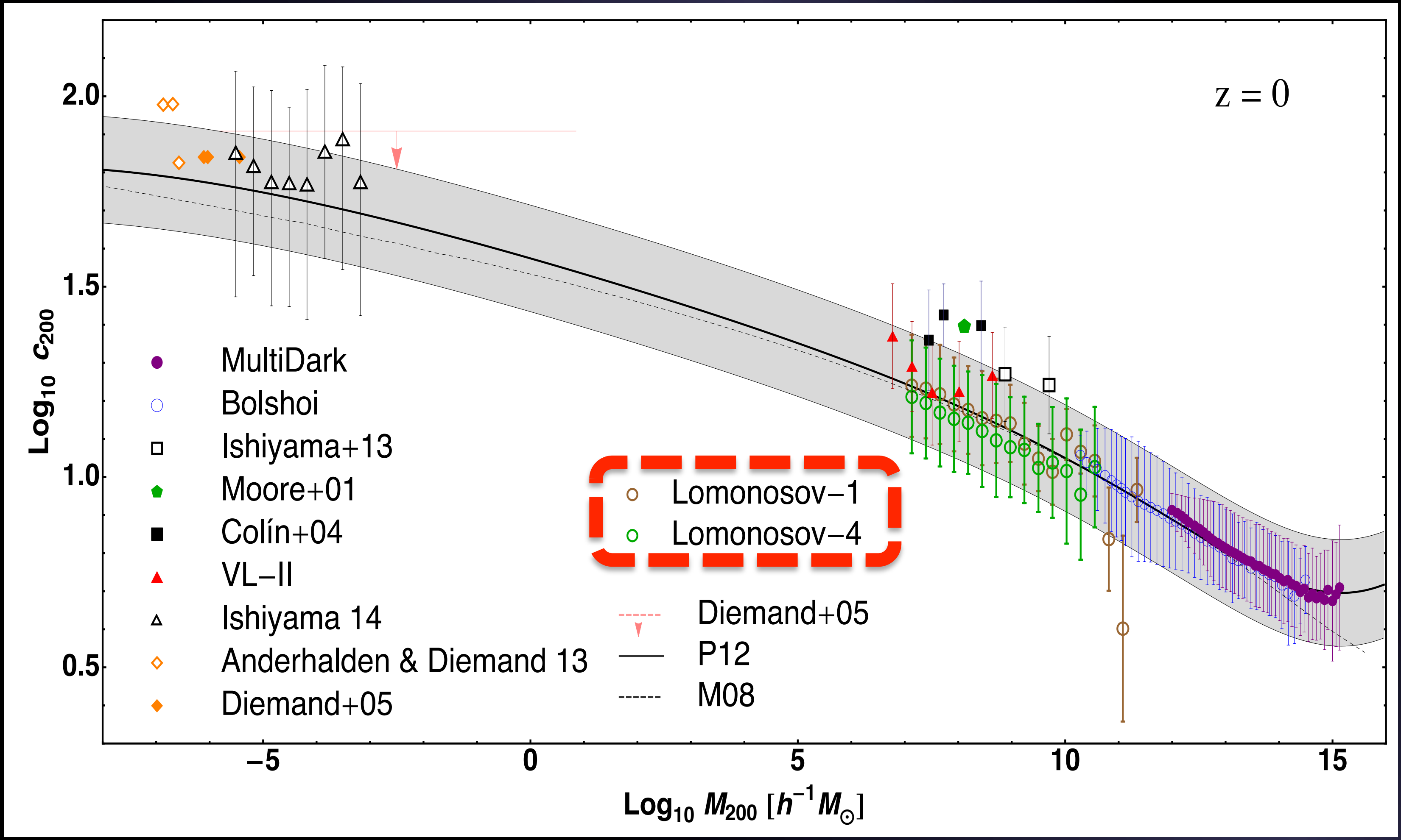


MASC & Prada, MNRAS, 442, 2271 (2014) [astro-ph/1312.1729]

Work ongoing to cover the gap

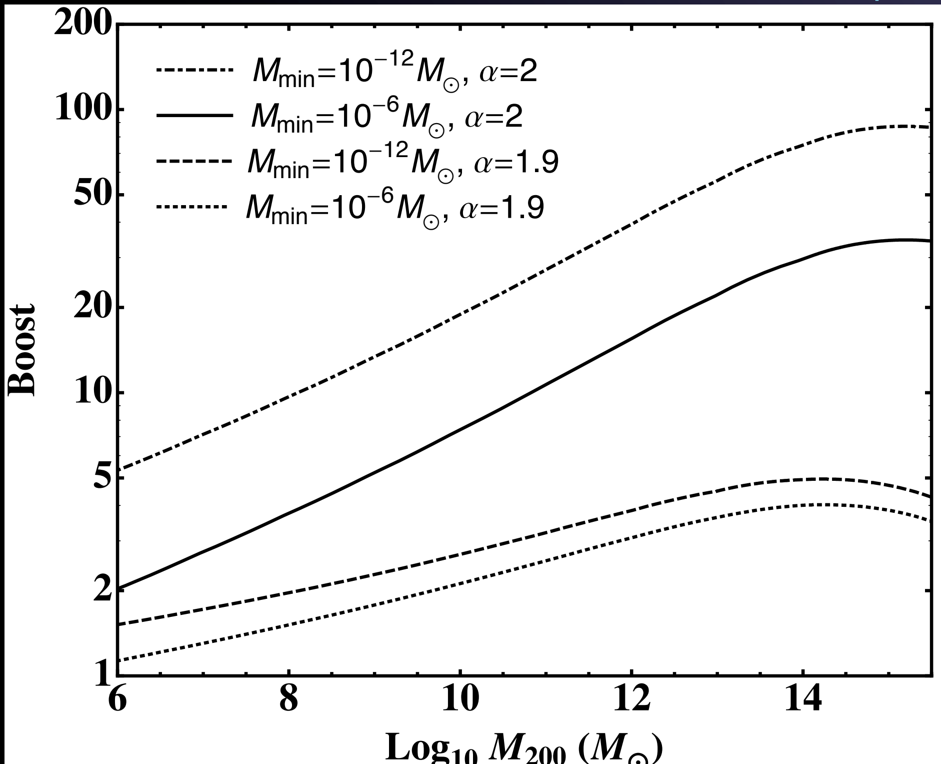
Concentration $c = R_{vir} / r_s$

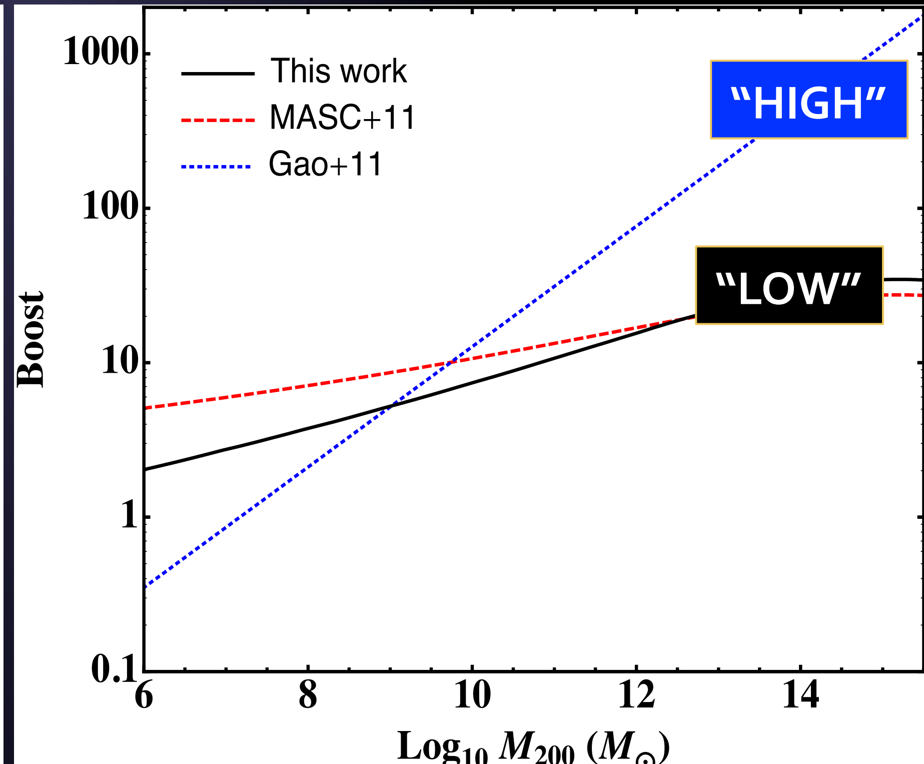


Pilipenko, MASC, Prada, Klypin, Yepes et al. In prep.

SCP14 substructure boosts

MASC & Prada, MNRAS, 442, 2271 (2014) [astro-ph/1312.1729]





Variation with M_{min} and α
[only first two substructure levels included]

Comparison with previous boost models

Reminder: they all assume that both main halos and subhalos possess similar structural properties!

Subhalo concentrations? Yes.

- Difficulty in defining them:
  - More complex evolution compared to field halos.
  - Tidal forces modify the DM density profile
  - Reduced R_{max}, i.e. the radius at which V_{max} is reached

- Solution: choose a definition independent of the profile

$$\boxed{c_{\mathrm{V}} = \frac{\bar{\rho}(R_{\mathrm{max}})}{\rho_c} = 2\left(\frac{V_{\mathrm{max}}}{H_0\, R_{\mathrm{max}}}\right)^2}$$

See also Diemand+08

- Still useful to compare to the standard c_{200}:

For NFW:

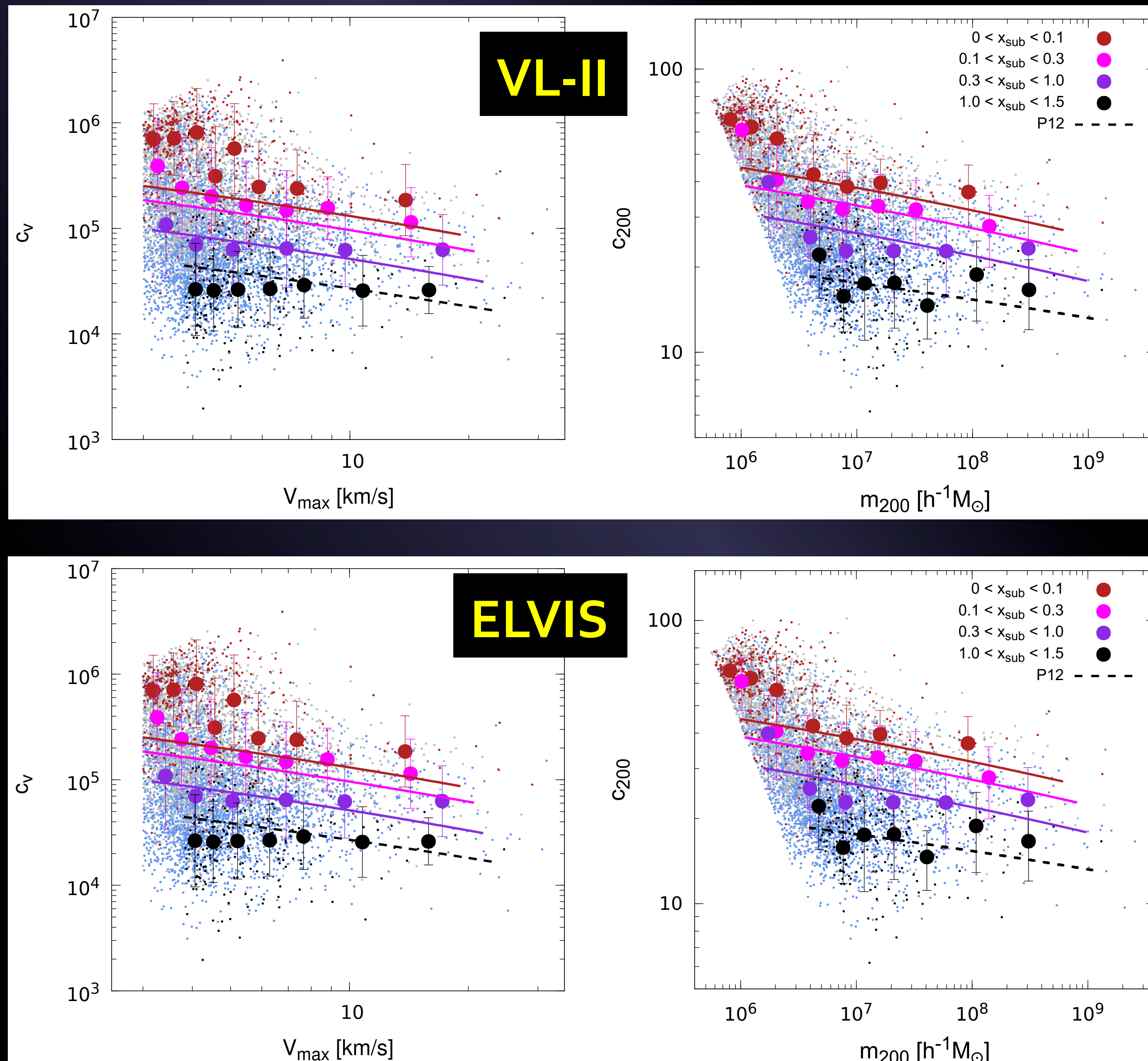
$$\boxed{c_{\mathrm{V}} = \left(\frac{c_\Delta}{2.163}\right)^3 \frac{f(R_{\mathrm{max}}/r_s)}{f(c_\Delta)}\,\Delta}$$

c_v results from VL-II and ELVIS

Median values

Four radial bins:

Clear **increase** of subhalo concentration as we approach the host halo center

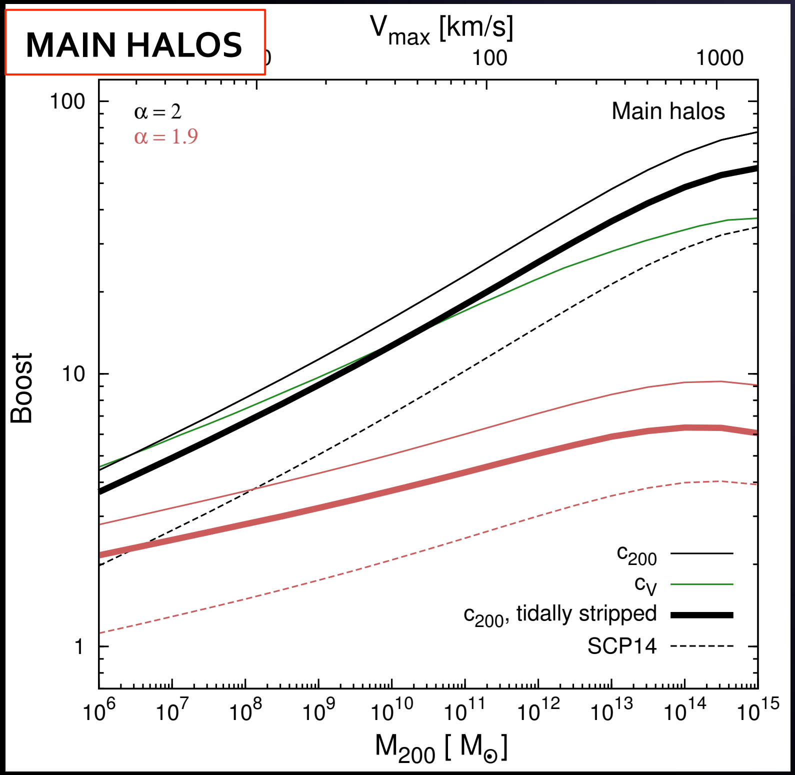


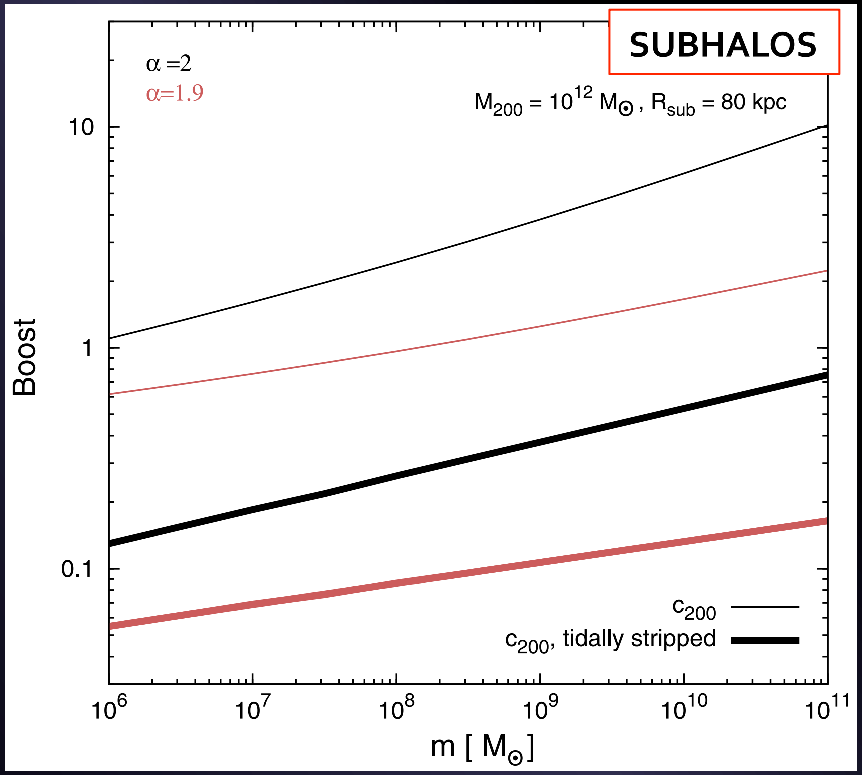
Moliné, MASC+ [1603.04057]

Improved subhalo boost model

1. Make use of our best knowledge on subhalo concentrations.
2. Tidal stripping included (Roche criterium).

Moliné, MASC+ [1603.04057]





Factor 2-3 larger boosts

Very small boost for subhalos, e.g. **dwarfs**

Agrees also with Bartels & Ando (2015) and Zavala & Afshordi (2015)

(Some) OPEN ISSUES

→ Precise structural properties of DM subhalos, including low-mass ones?

→ Exact radial distribution?

→ How many? Mass function, survival probability…

→ How do baryons affect them?

→ Observational evidences? (lensing, Galactic disk 'gaps', etc)

→ Should we already see some dark satellites with current γ-ray experiments?

→ Could they affect DM direct experiments in some way?

THANKS!

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Oskar Klein centre

Stockholm University