Indirect dark matter detection with dwarf spheroidals

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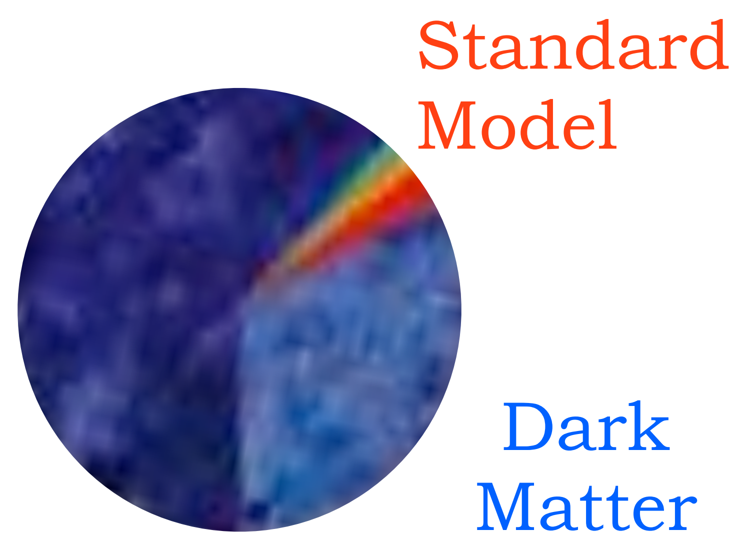
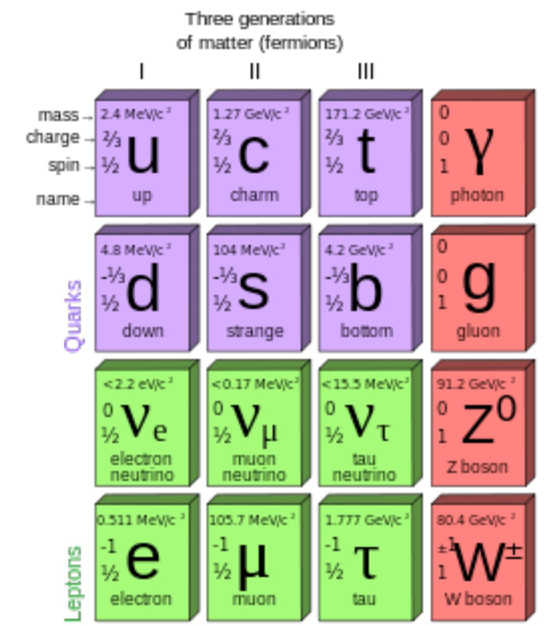
Dark matter/Cosmology

✦ Dark matter not contained within Standard Model of particle physics





✦ A particle's annihilation cross section and abundance are related:

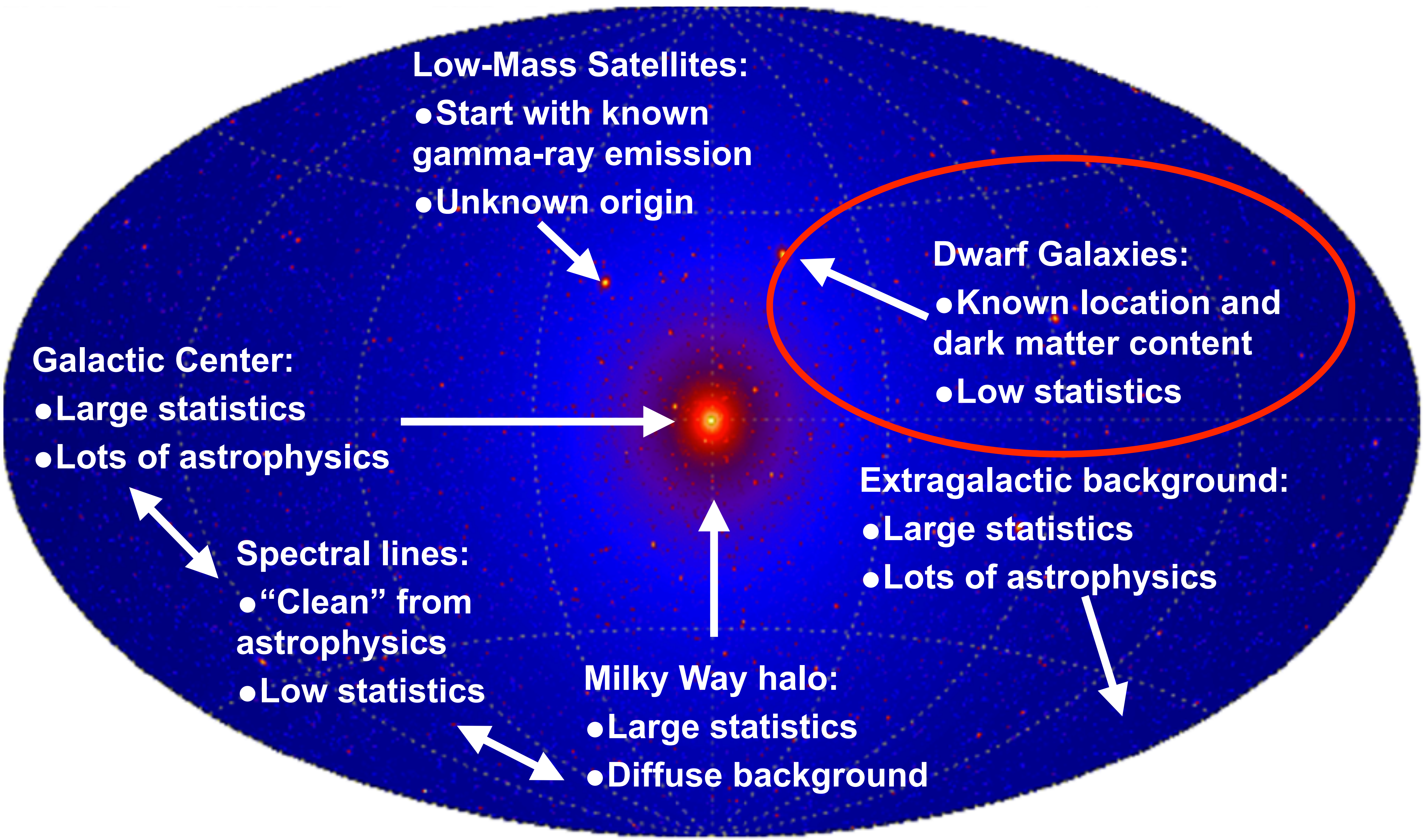
$$\langle \sigma_{\rm ann} v \rangle \approx \frac{3 \times 10^{-27}\,{\rm cm^3 s^{-1}}}{\Omega_{\rm DM} h^2} \longrightarrow \langle \sigma_{\rm ann} v \rangle \simeq 3 \times 10^{-26}\,{\rm cm^3\,s^{-1}}$$

"Thermal relic scale"

✦ Weakly-interacting particles (WIMPs) a leading candidate for dark matter

✦ Annihilation cross section characteristic of a weakly-interacting particle

(Theoretical) Gamma-ray view of Galaxy and beyond



Space and ground-based gamma-ray astronomy

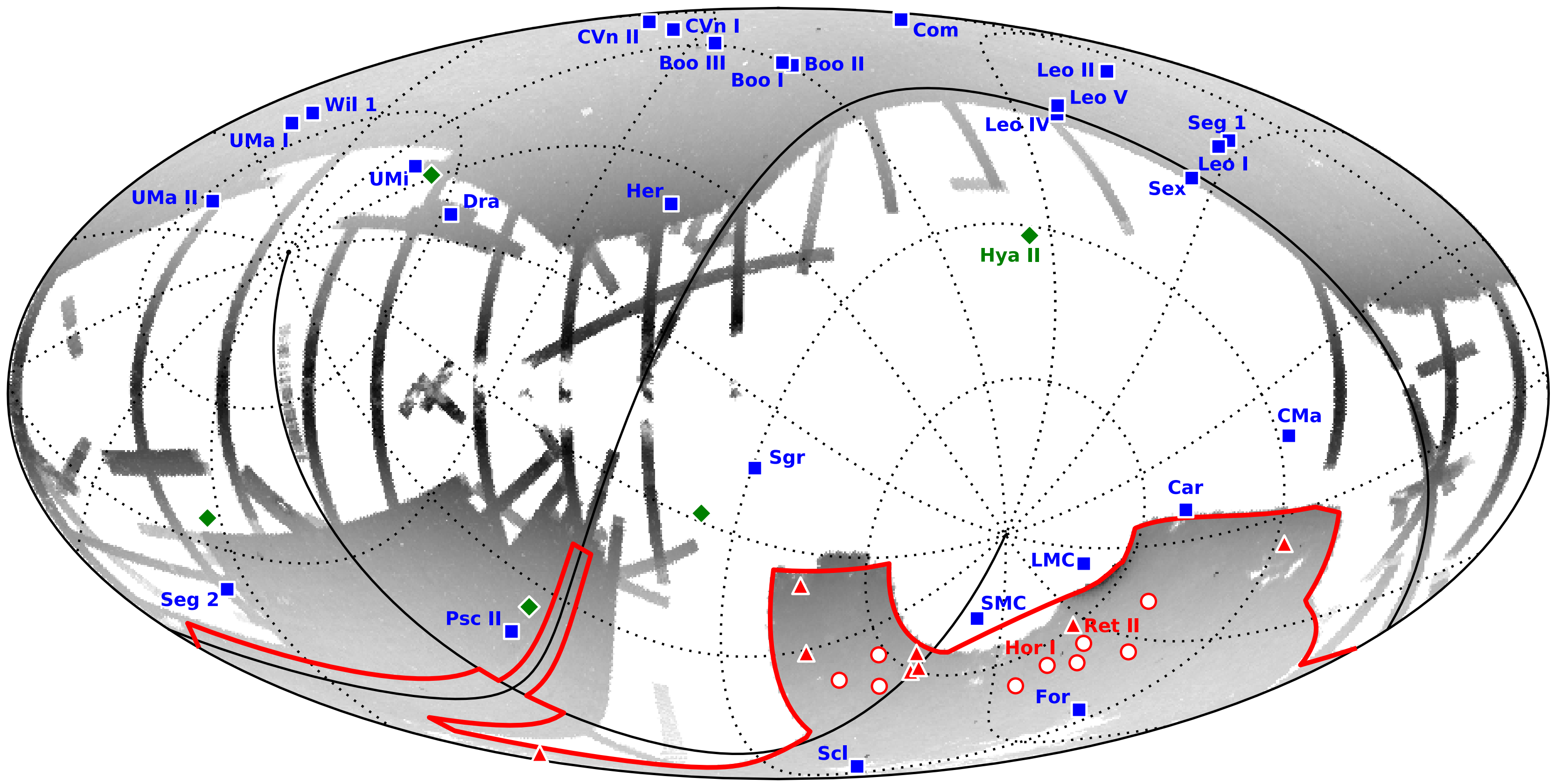
Fermi gamma-ray
space telescope
20 MeV-300 GeV

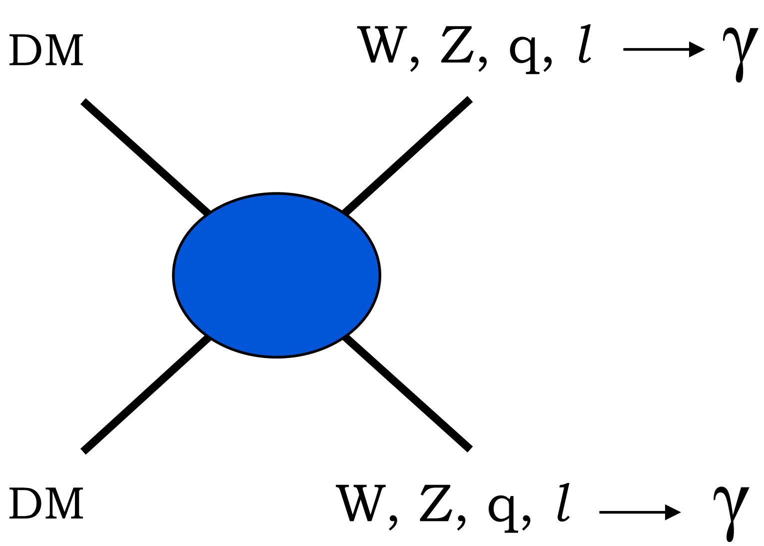
Air Cherenkov
telescopes: H.E.S.S.,
Magic, Veritas
30 GeV-100 TeV

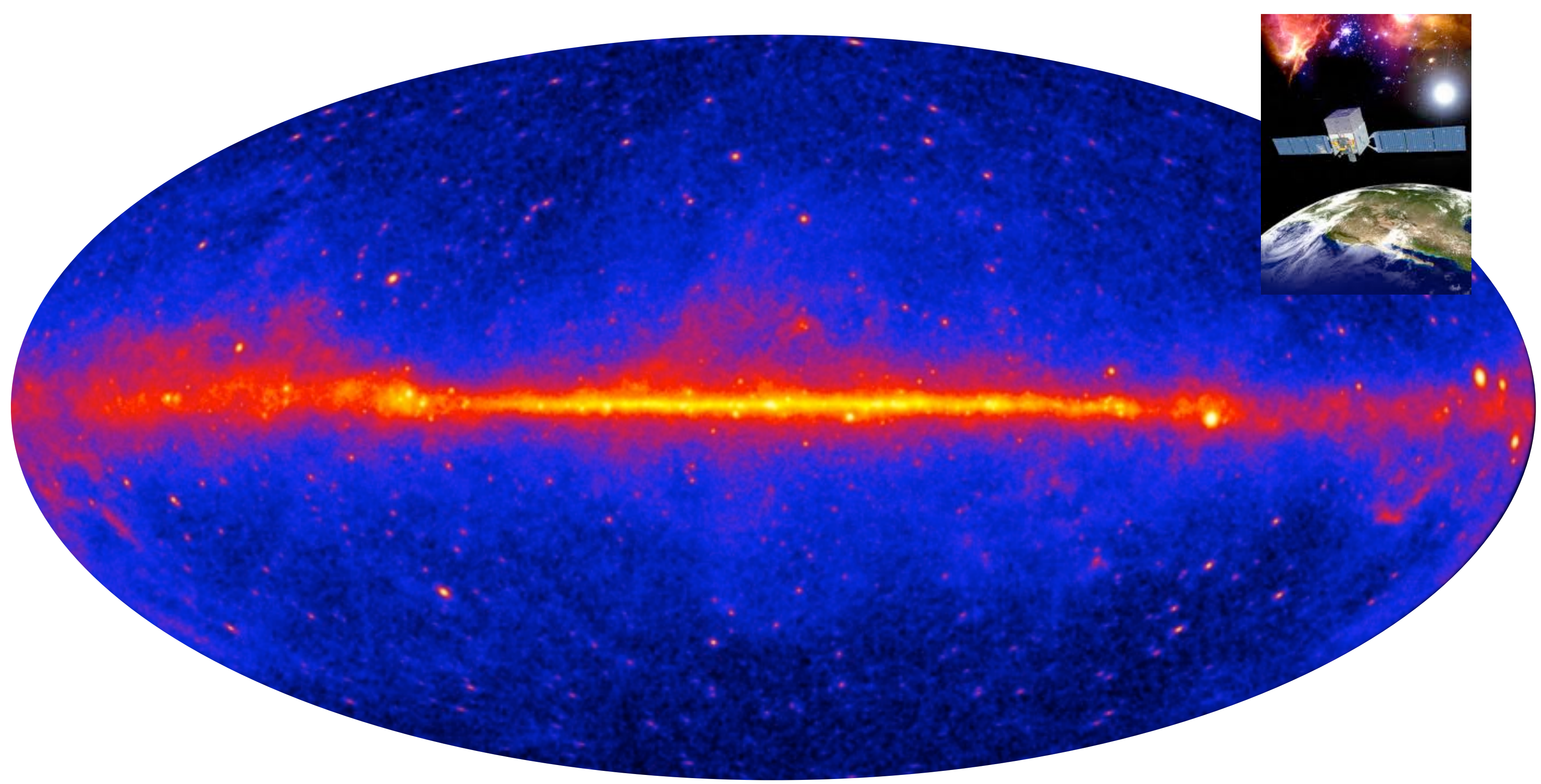
Water Cherenkov
telescopes: HAWC
50 GeV-100 TeV

Milky Way satellites

Dark Energy Survey:
Drlica-Wagner et al. 2016







Dark matter bounds from dSphs with gamma rays

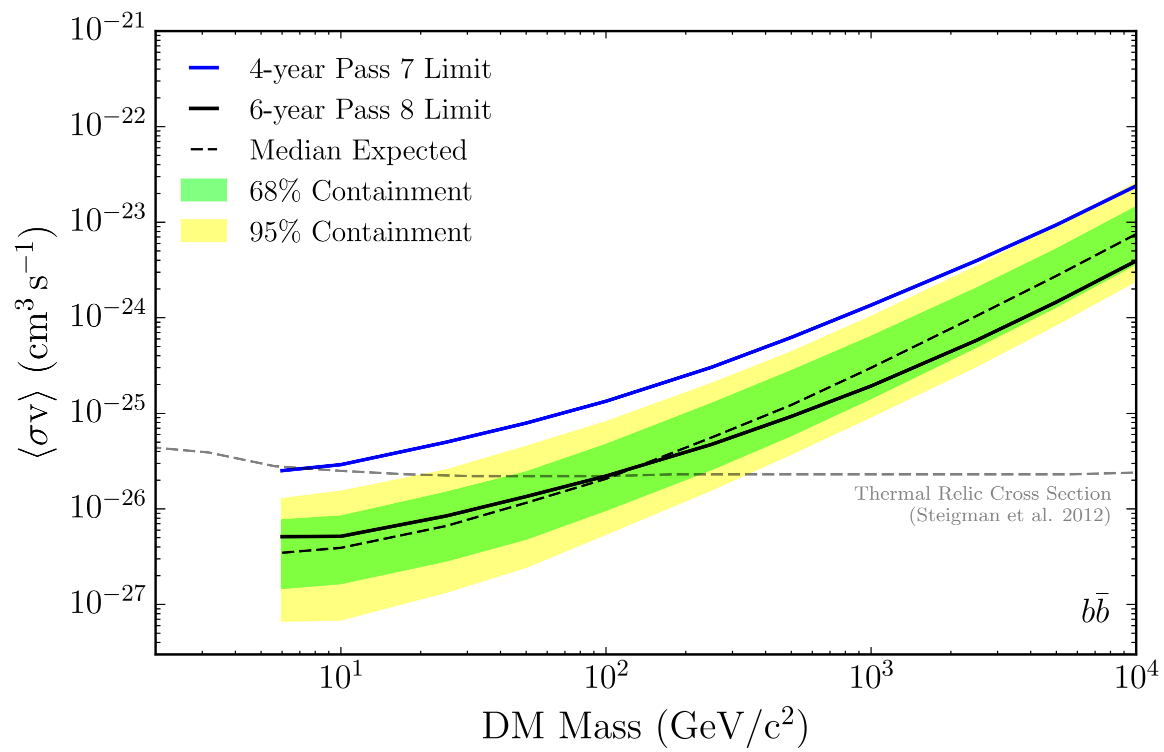
- Integrated DM masses of dSphs well-determined within characteristic Fermi-LAT angular resolution

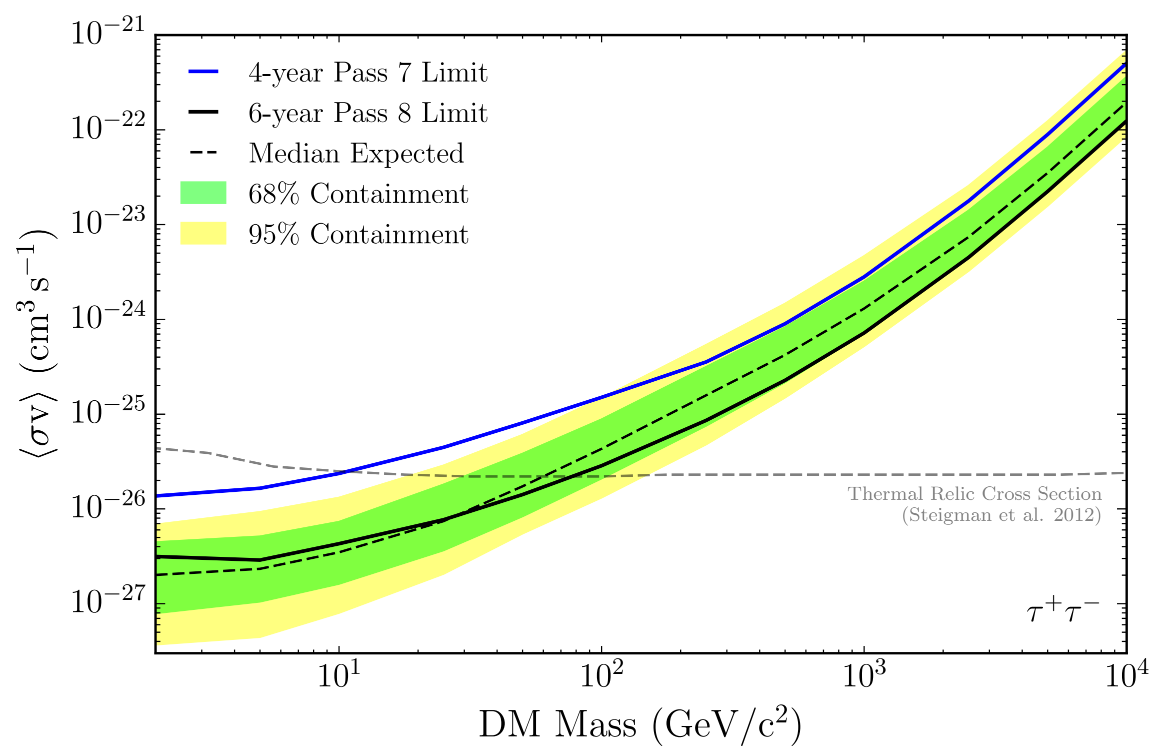
- Combine measured gamma-ray flux upper bound with the total dark matter mass in each satellite to get upper bound on the annihilation cross section

Fermi-LAT collaboration
PRL, 1108.3546
PRD, 1310.0828
PRL, 1503.02641

- Bounds at higher DM mass from ground-based observatories

- Lower mass bounds from CMB (Planck)

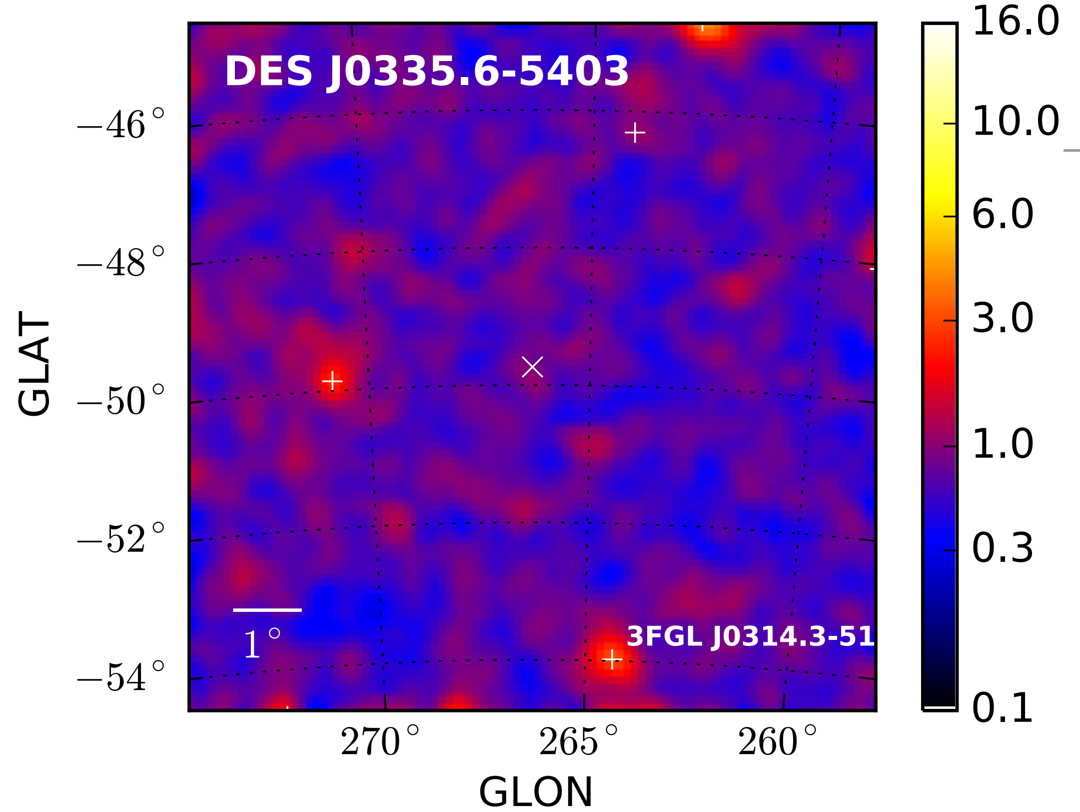




Gamma-ray excesses?

Possible gamma-ray excesses in a few ultra-faint satellites: e.g. Reticulum II

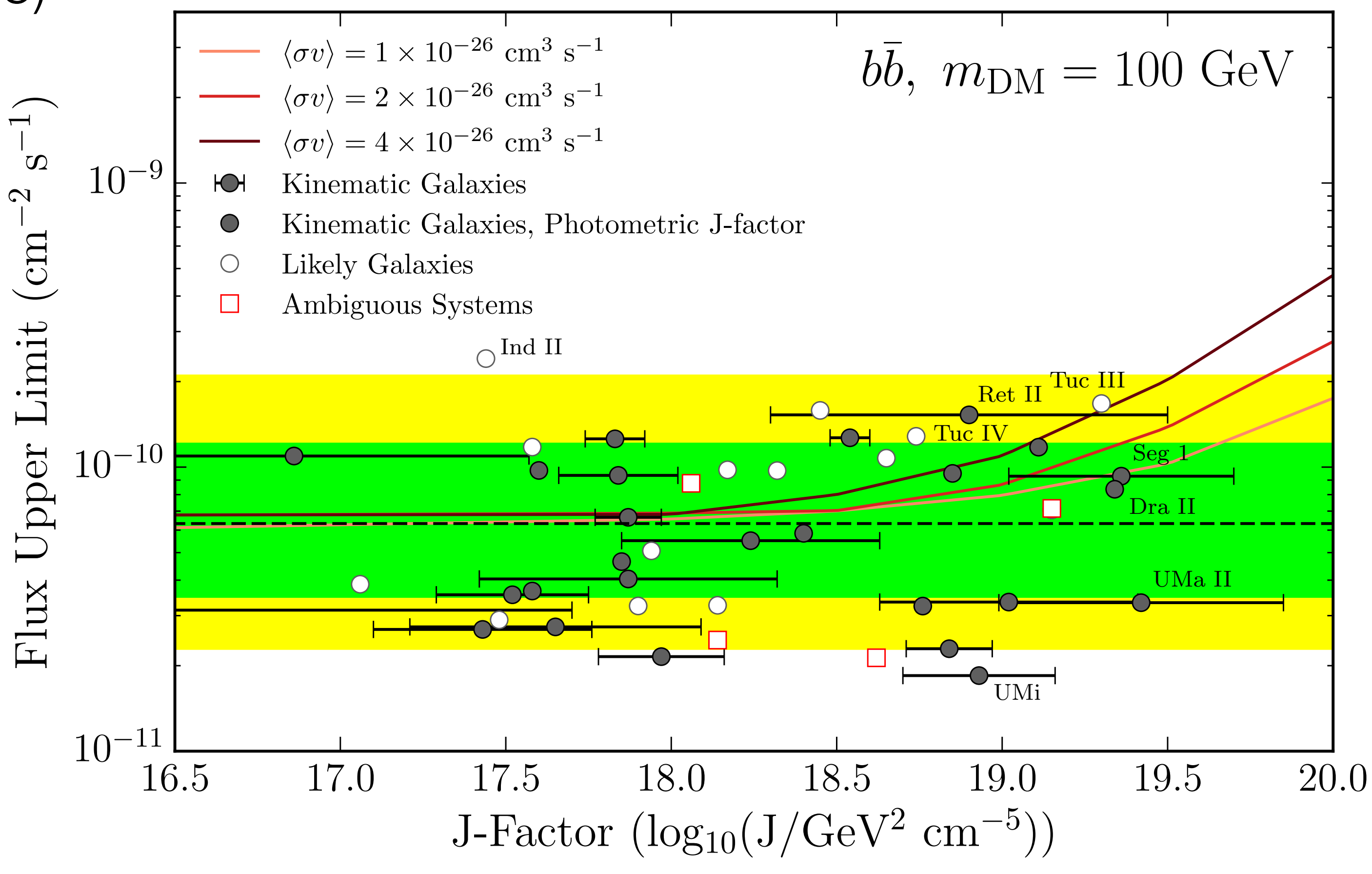
Geringer-Sameth et al. PRL 2015
Hooper & Linden JCAP 2015
Li et al. PRD 1805.06612



Probably not strongest sources from measured DM distribution (Simon et al. 2015)

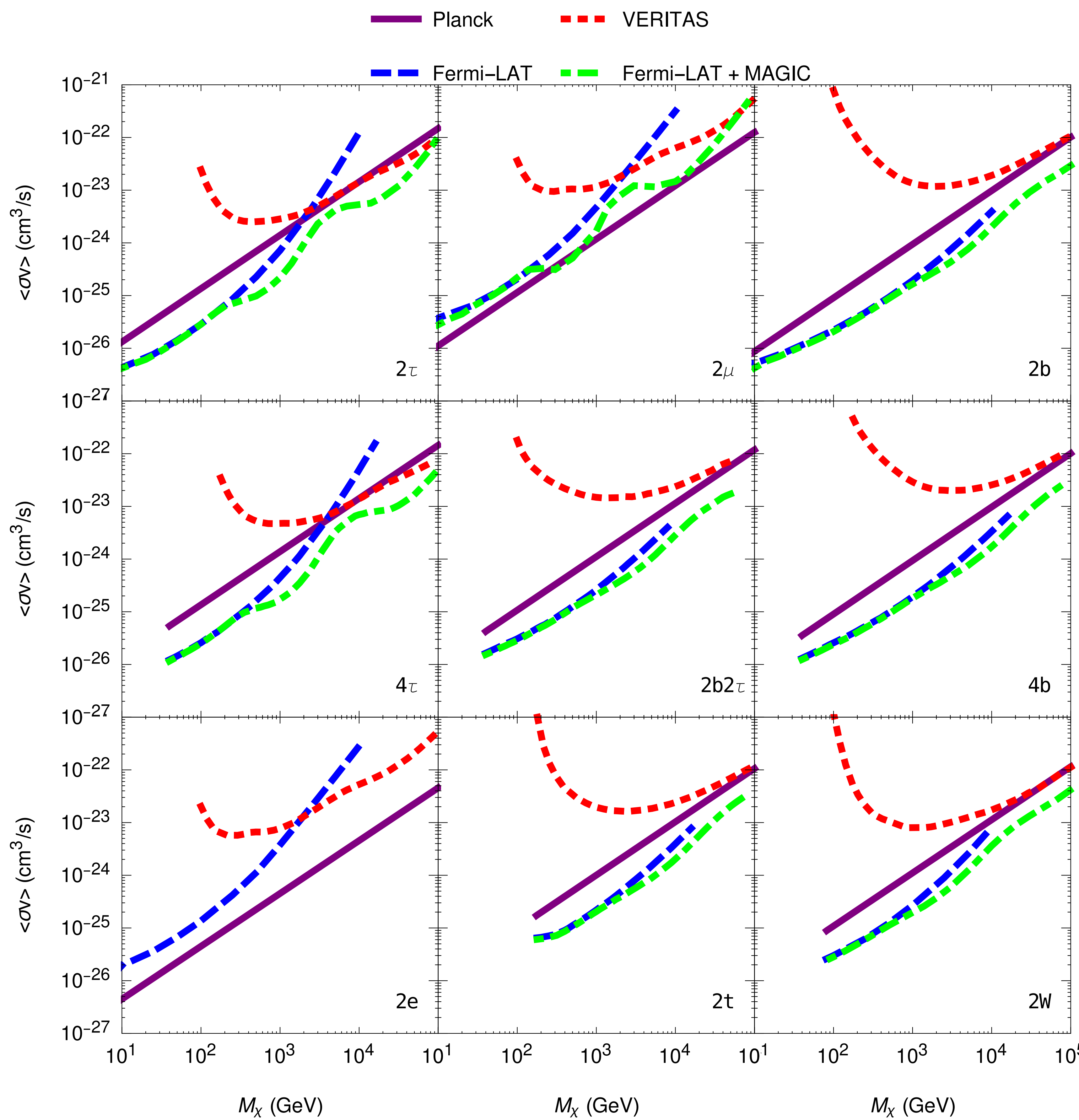
Gamma-ray excesses do not correlate with measured J-factors

Fermi-LAT/DES collaborations ApJ arXiv:161103184



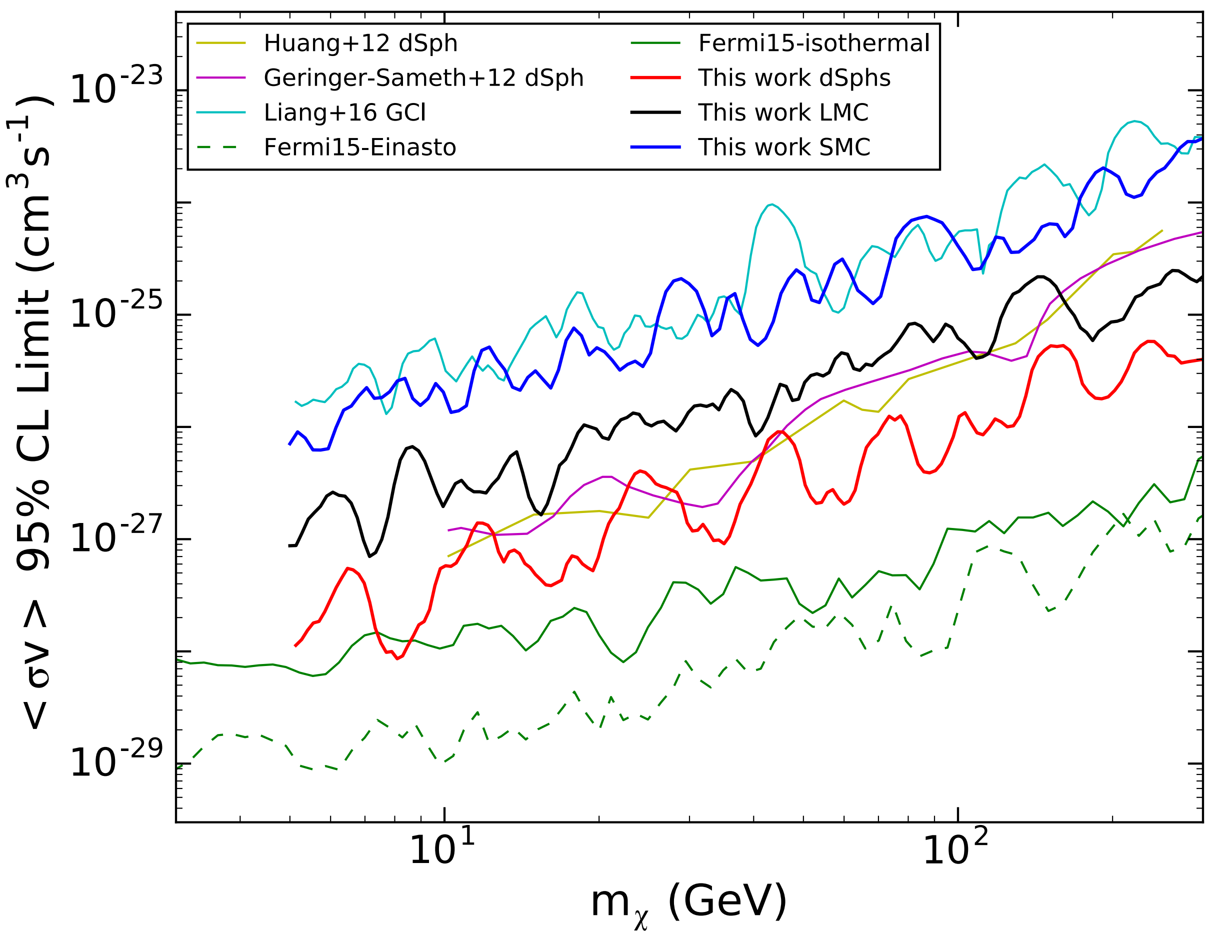
Extending bounds

- More generally, dark matter may annihilate to multi-body final states
- Combining with CMB provides strong limits on these models
- Also limits from 21 cm cosmology

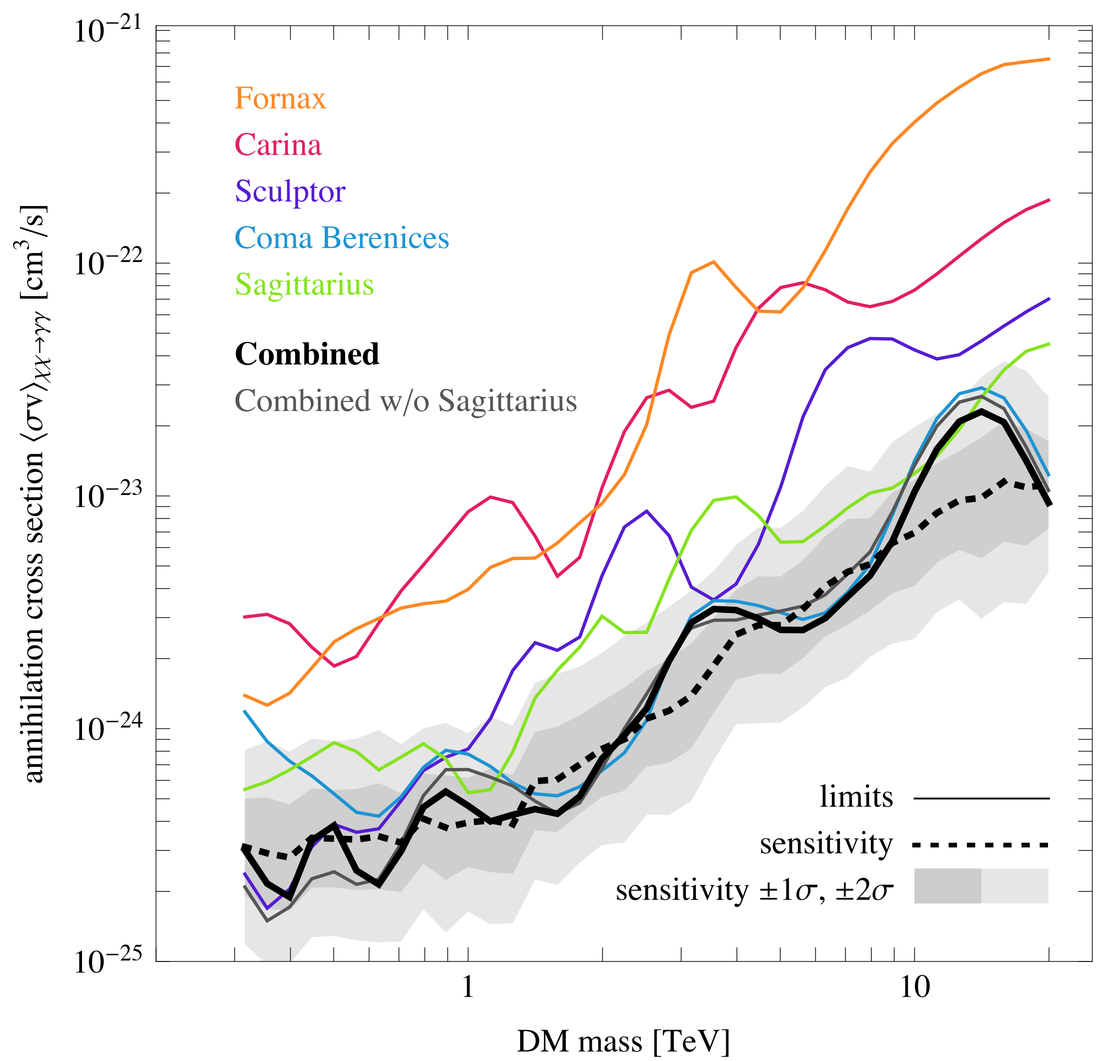


Steven Clark et al. PRD 2017

Gamma-ray lines from dark matter

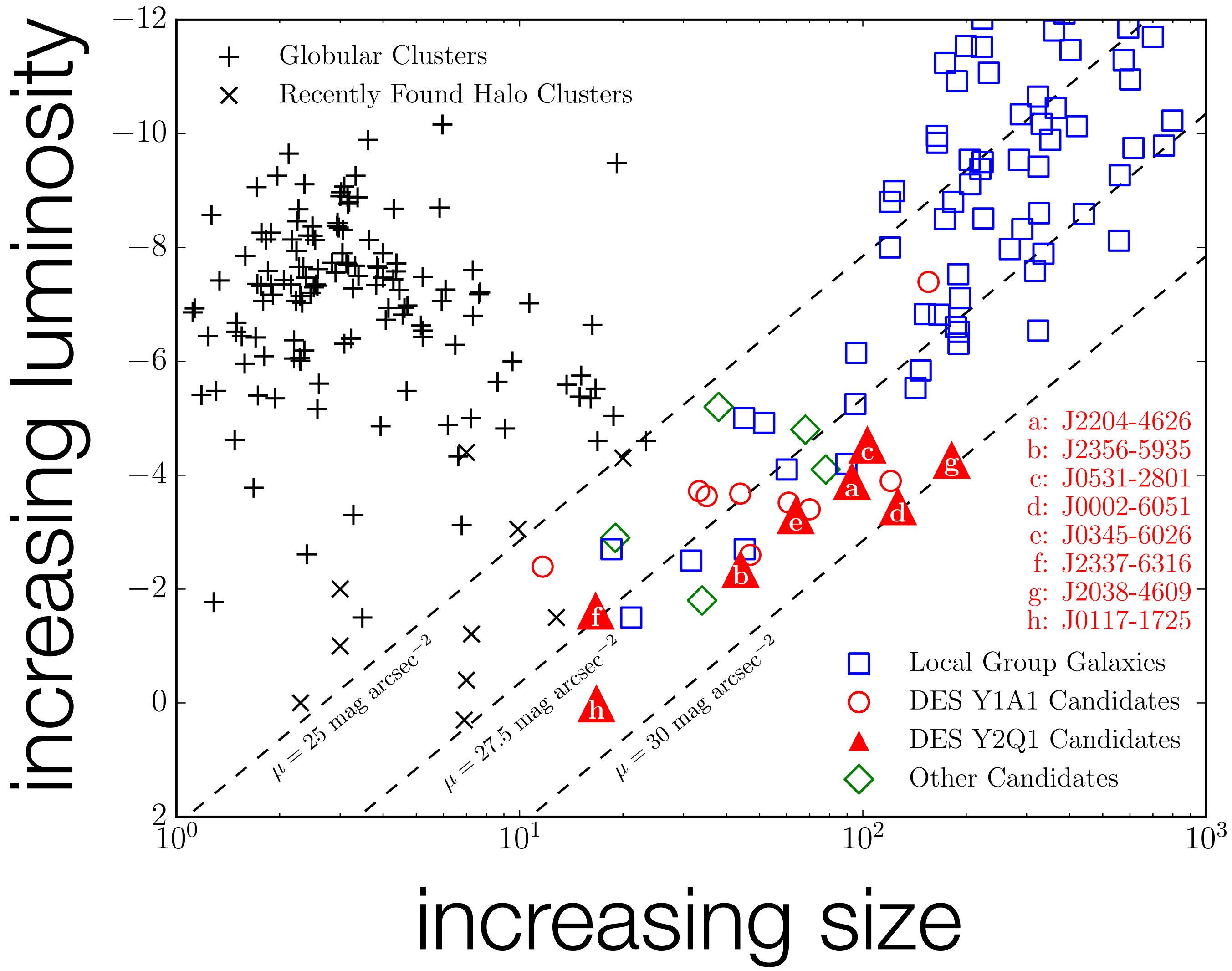


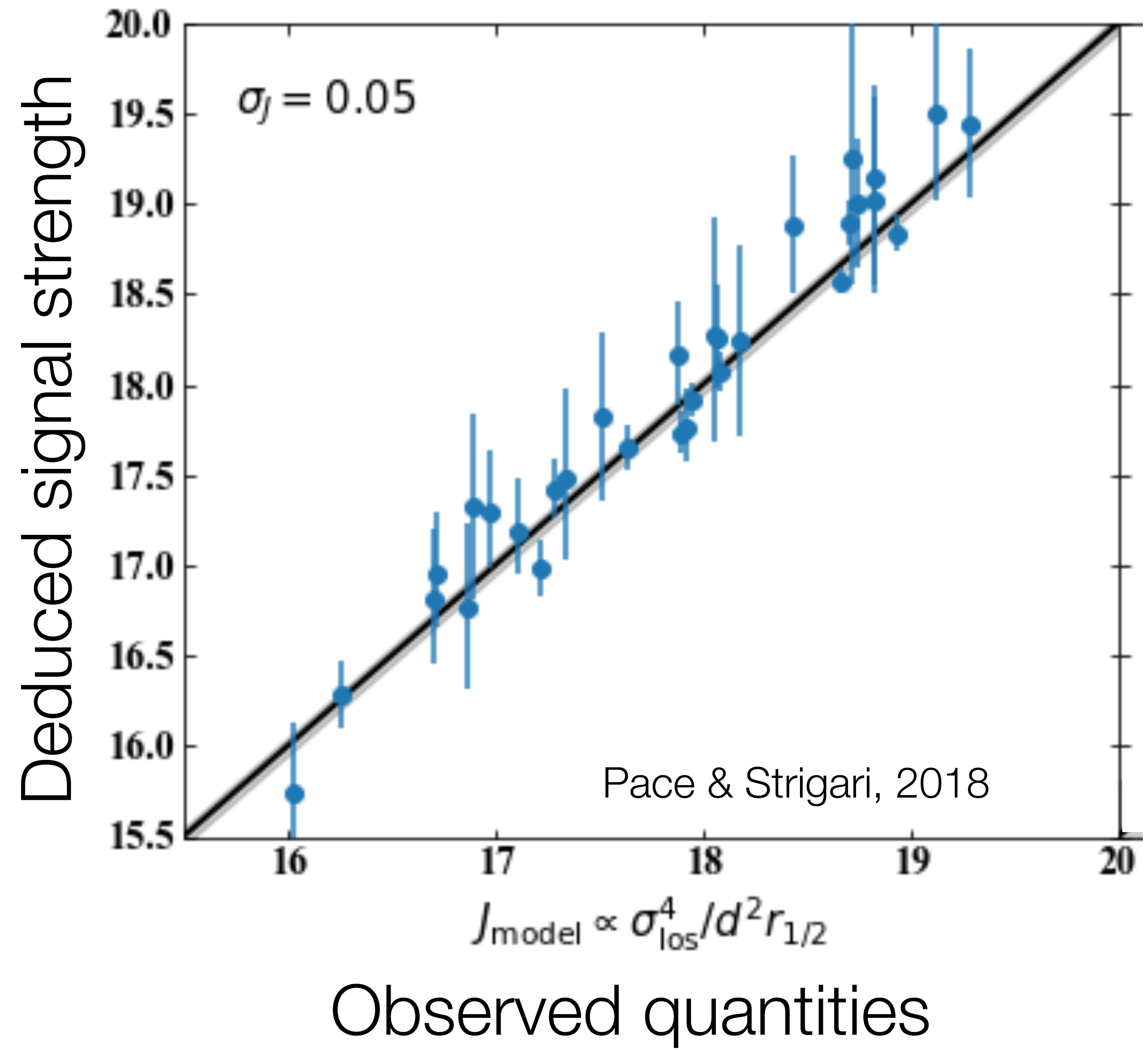
Liang et al. PRD 2016



H.E.S.S Collaboration 2018

Can DM signal be found with Fermi?

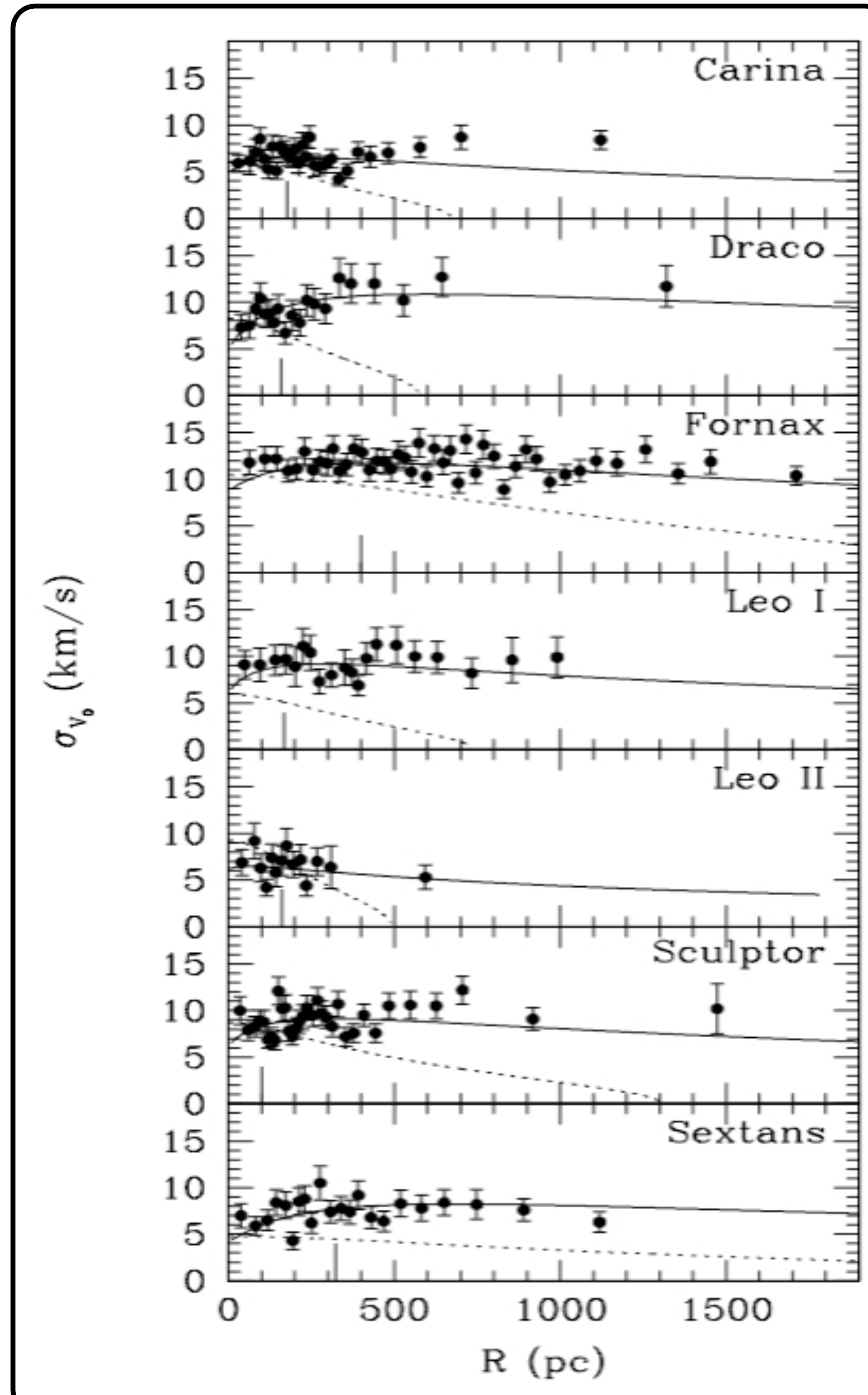




- Not yet done finding faint Milky Way satellites
- But spectroscopic follow up will be more difficult
- Possibly completely ``dark” galaxies

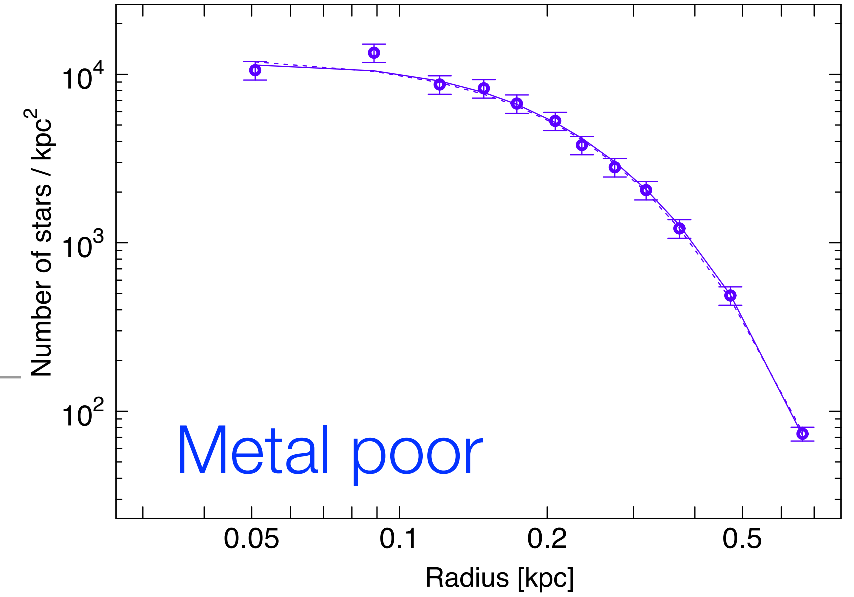
Are dSphs simple single population stellar systems?

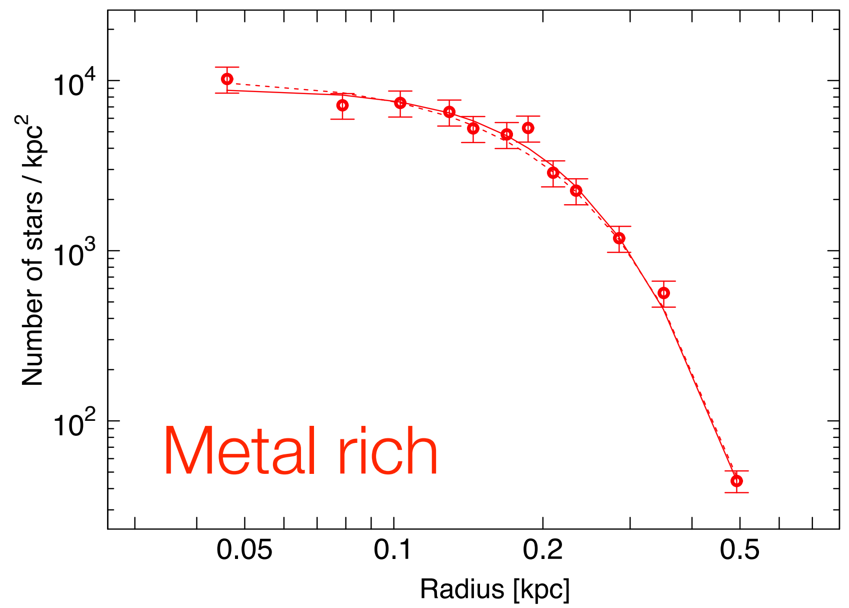
- Many DM density profiles explored
- Standard assumptions: equilibrium, spherical symmetry, isotropy (LS et al. 2008, Lokas 2009, Walker et al. 2009, Read et al. 2018)
- Corrections from non-spherical potentials (Hayashi & Chiba 2012; Kowalczok et al. 2013)
- Stellar distribution function-based models (Strigari, Frenk, White 2010, 2015, 2018)
- Orbit-based models (Breddels et al. 2012; Jardel & Gebhardt 2012, 2013)

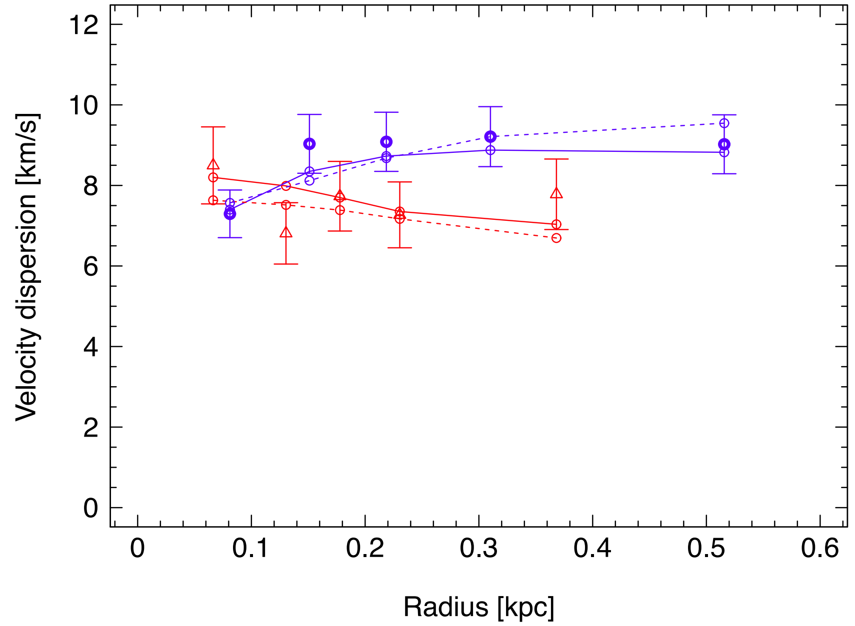


Multiple stellar populations

- Some dSphs (Sculptor, ANDII) show evidence for multiple stellar populations
- Some kinematic studies disfavor NFW for Sculptor (Walker & Penarrubia 2011; Amorisco & Evans: Agnelle & Evans 2012)
- Some studies show NFW cannot be ruled out for Sculptor (Breddels & Helmi 2014; Strigari, Frenk, White 2014)
- No apparent addition information from ANDII multiple populations (Ho et al. 2013)







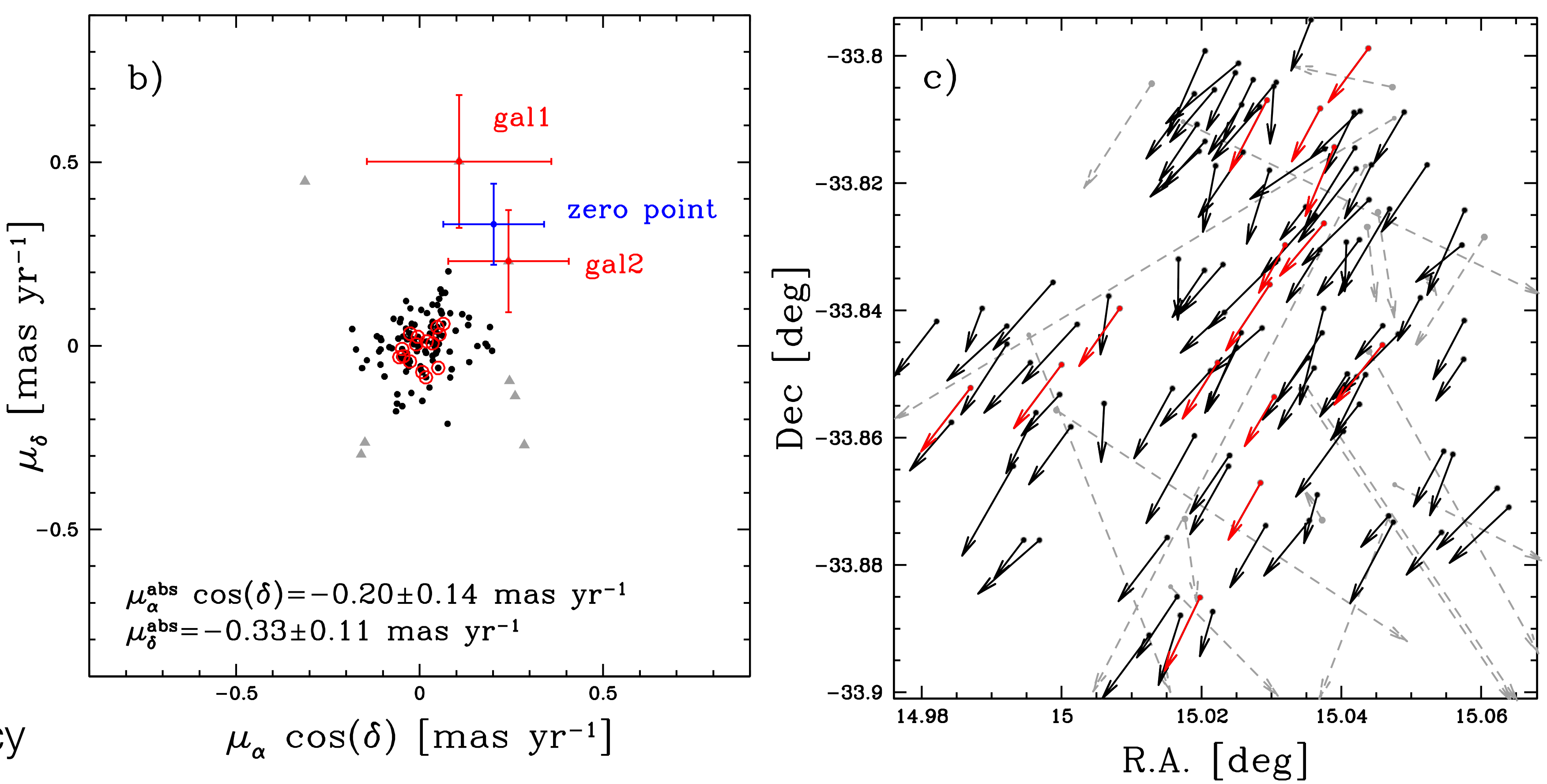
Internal stellar proper motions

3D motions in the Sculptor dwarf galaxy as a glimpse of a new era

D. Massari[1,2,*], M. A. Breddels[1], A. Helmi[1], L. Posti[1], A. G. A. Brown[2], E. Tolstoy[1]

- Internal stellar proper motions provide missing phase space measurements (Wilkinson et al. 2001; LS, Bullock, Kaplinghat 2007)
- Potential to distinguish between DM cores/cusps
- HST Requirements:
  - Sculptor requires PMs ~ 22 micro-arcsec/year
  - Positional accuracy of 0.003 ACS/WFC per epoch
  - For N exposures, the positional accuracy per exposure is 0.003 sqrt(N)
  - For N ~5-19, positional accuracy per exposure is ~ 0.01 pixel
- <u>Not easy!</u>

$$\sigma_R = 11.5 \pm 4.3 \ \mathrm{km\,s^{-1}} \quad \sigma_T = 8.5 \pm 3.2 \ \mathrm{km\,s^{-1}}$$



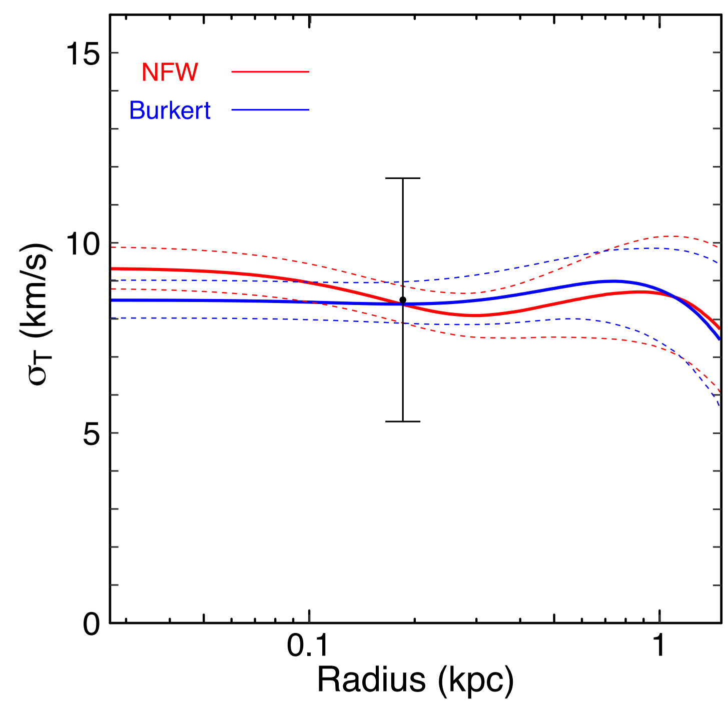
Sculptor stellar populations & proper motions

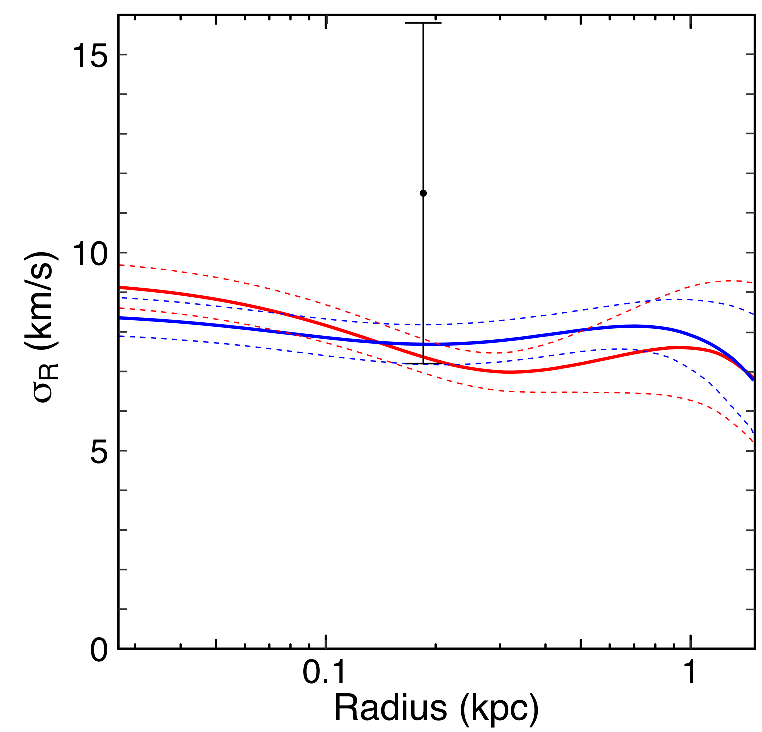
- Self-consistent stellar DF model + LOS velocities predict the PM velocity dispersion profiles

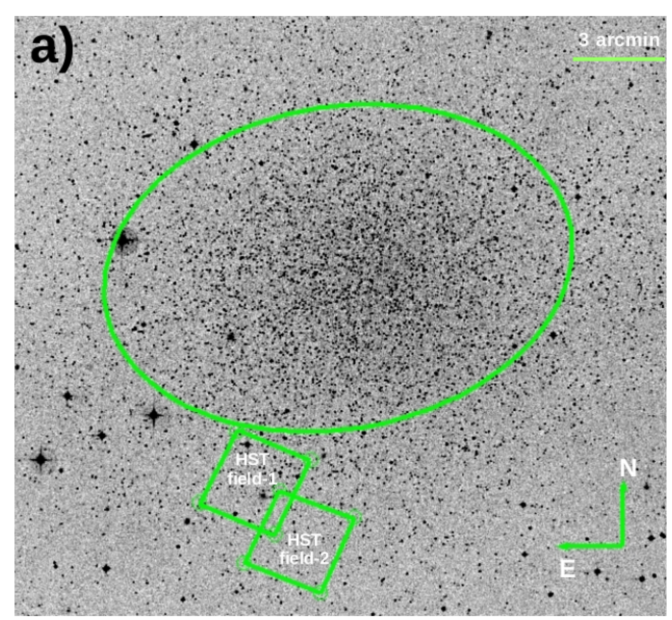
- Multiple populations + PMs provide most significant test of NFW vs cored Burkert model in dSphs

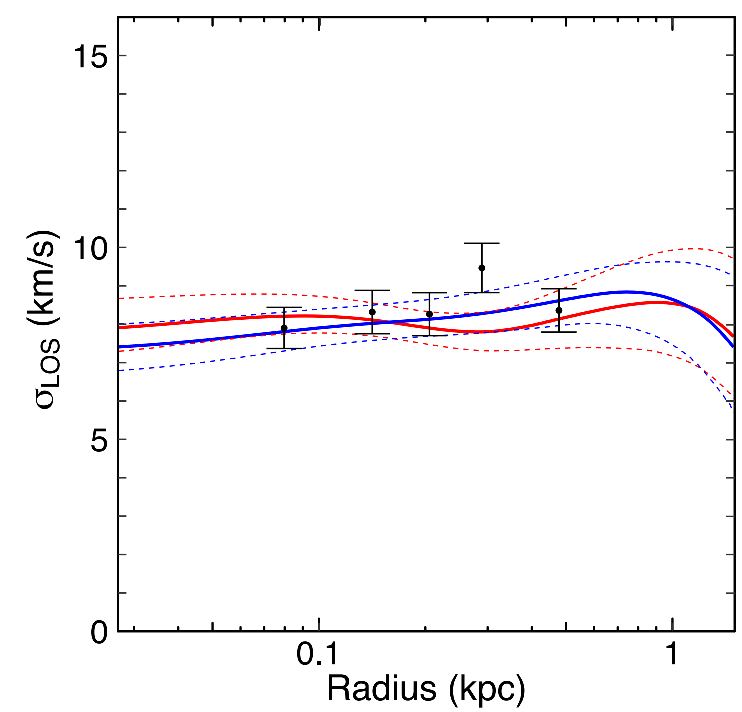
- Gaia + data unable to discriminate cores vs. cusps

- Require PM velocity dispersions to ~ 1 km/s (LS, Frenk, White 2018)

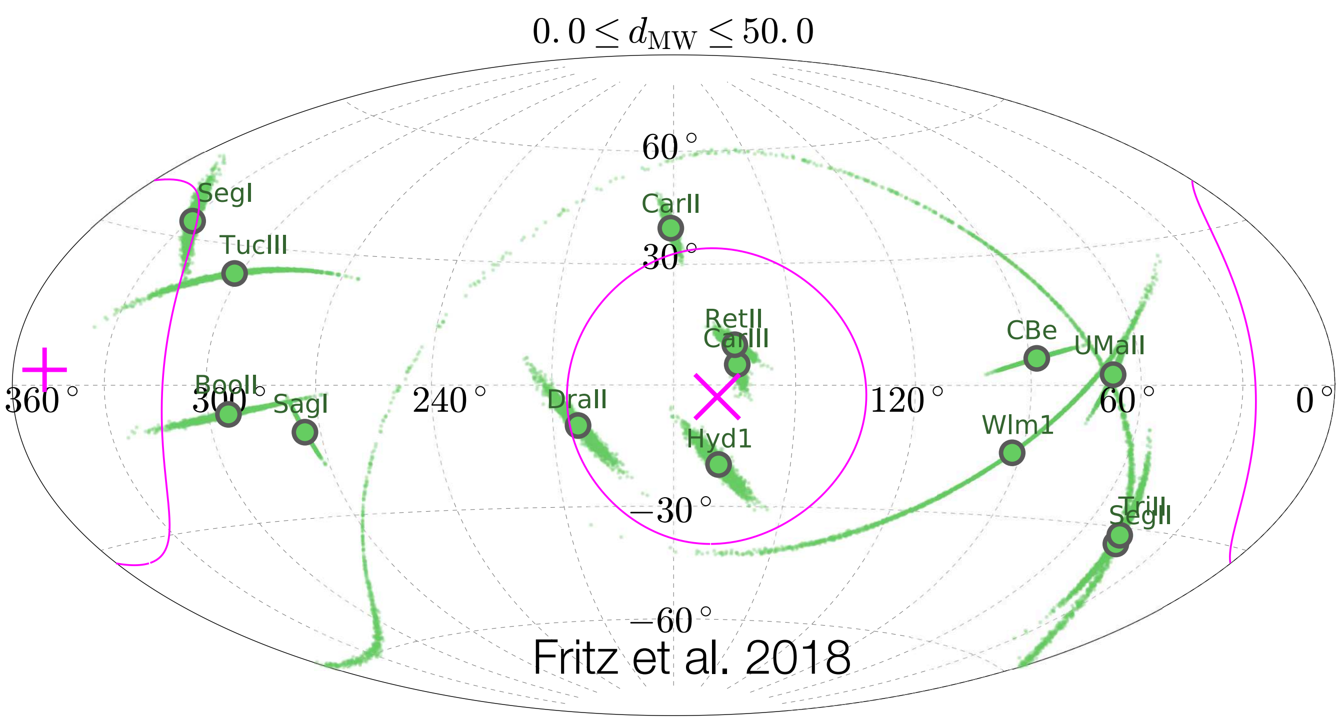




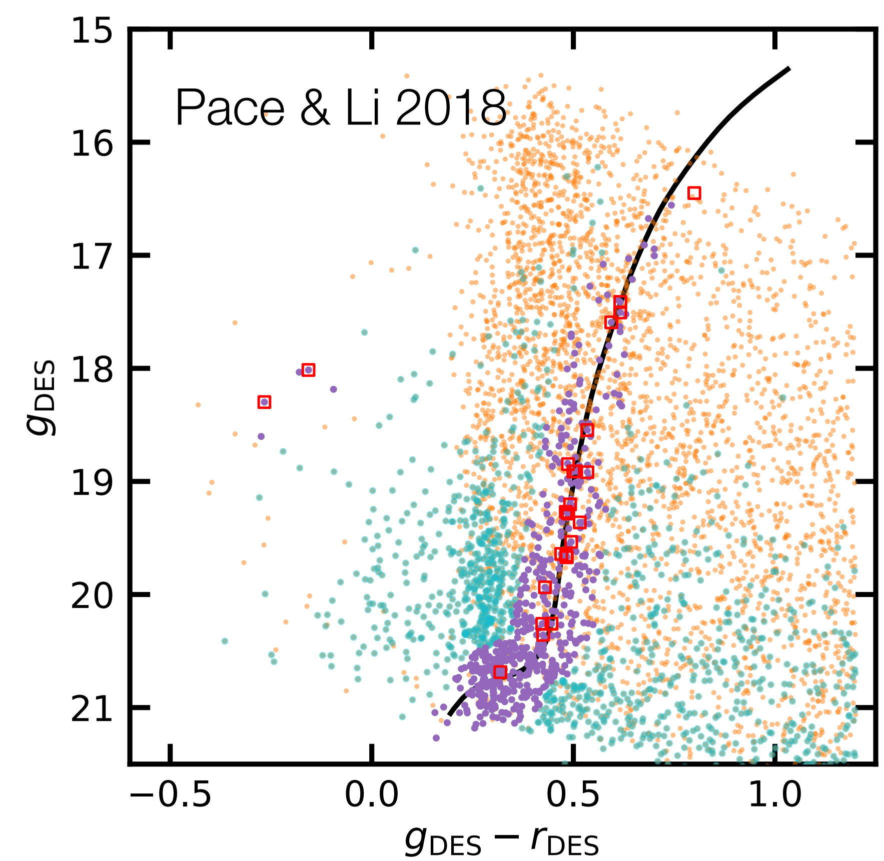




Orbits of dSphs

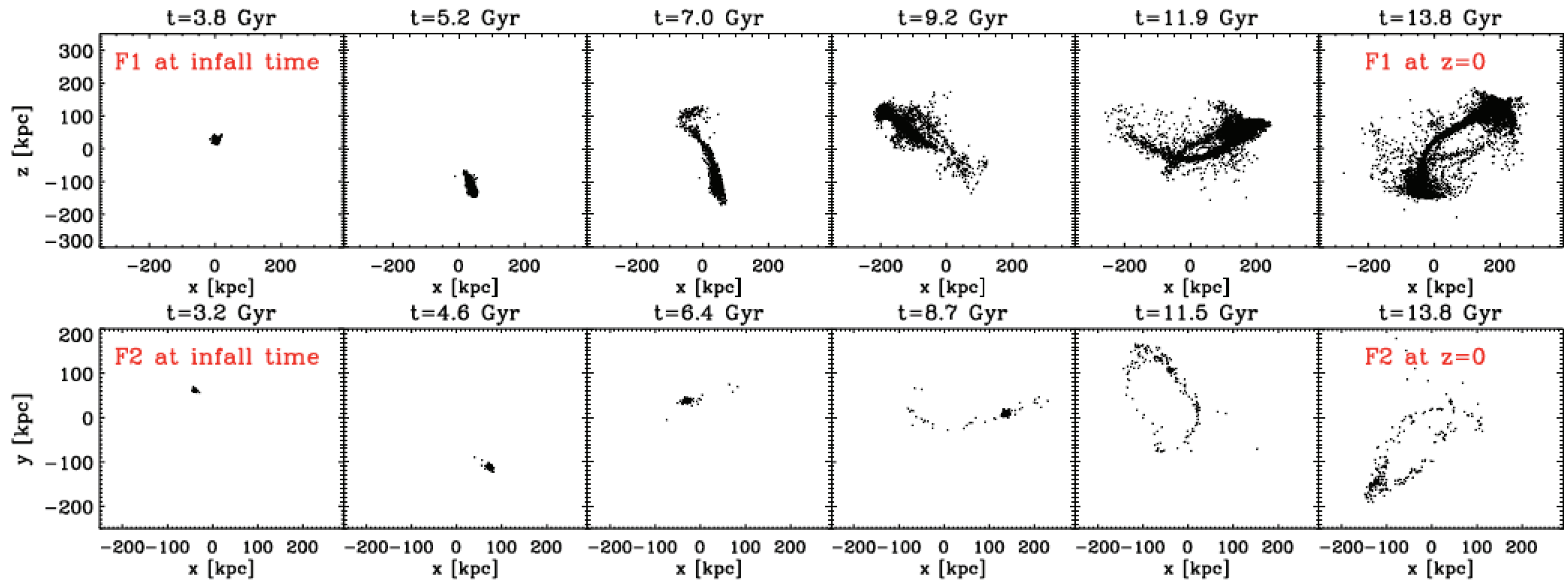


- Members identified from DES photometry & Gaia (Pace & Li 2018)



- 3D orbital dynamics of dSphs from Gaia
- Members from stellar spectra (Gaia collaboration/Helmi et al., Fritz et al., Simon 2018)
- Members from Gaia photometry (Masseri & Helmi 2018)

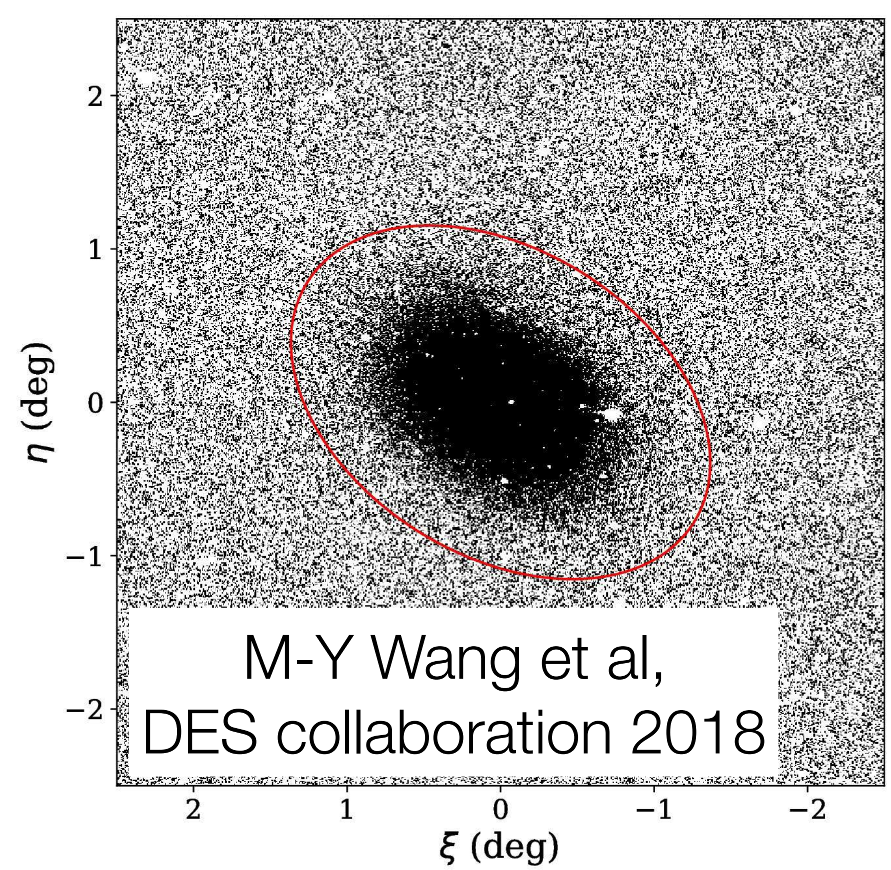
Orbits of dSphs



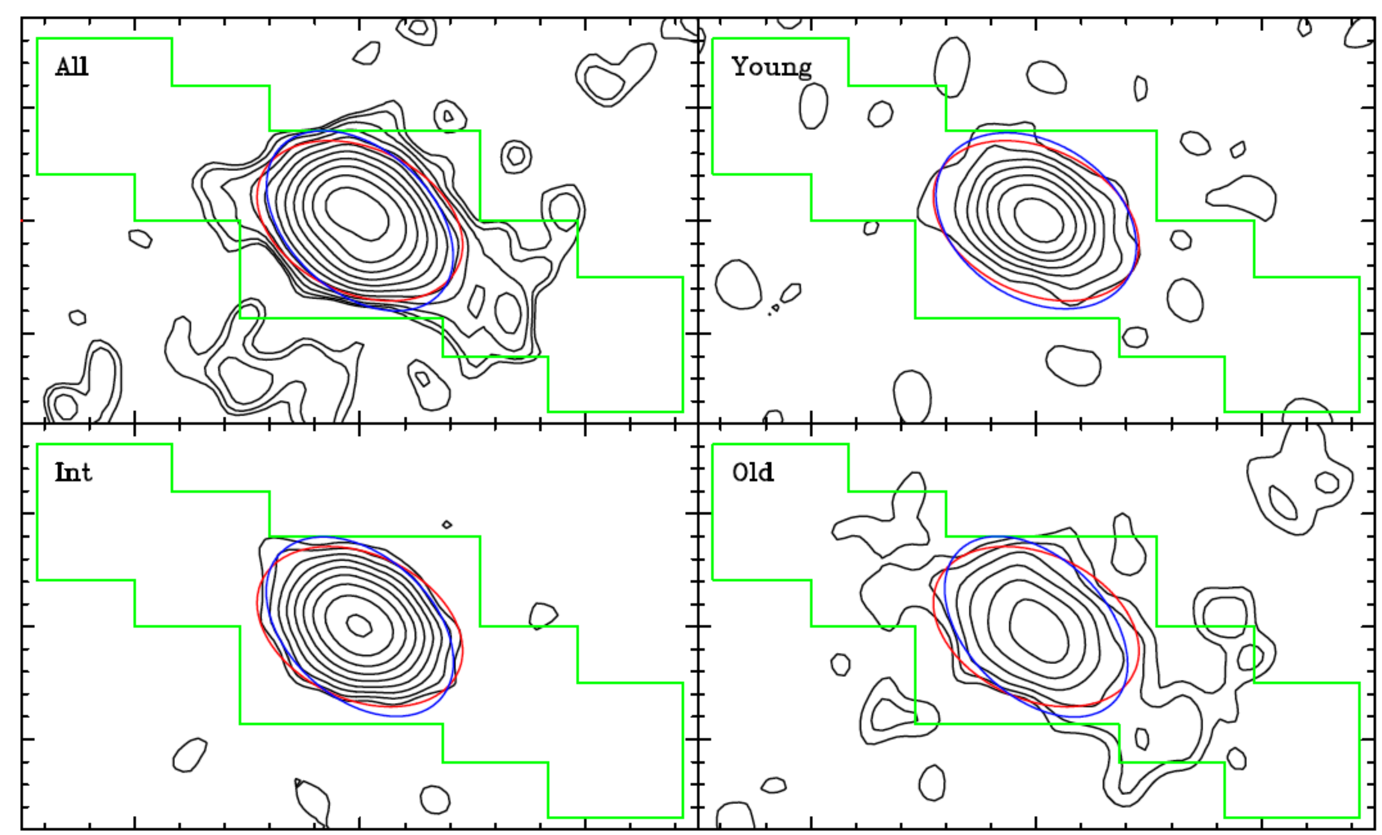
- Fornax analogues in APSOTLE show a range tidal disruption possibilities (Mei-Yu Wang, Azi Fattahi et al. 2017)
- Difficult to match the kinematics & the orbital dynamics simultaneously
- Best model: Stream with surface brightness ~ 32 mag/arcsec^2 (DES, LSST?)

dSphs with deep photometry

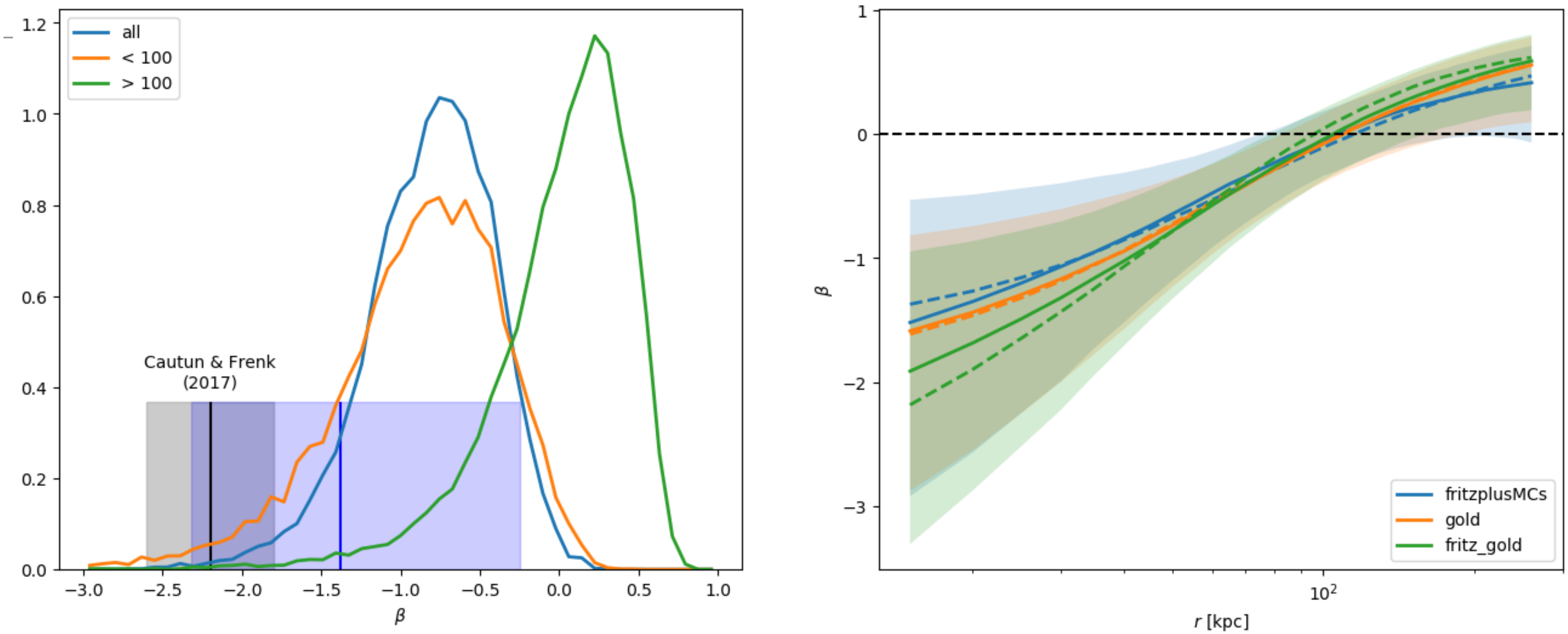
- Fornax
  - Enhanced SF ~3-4 Gyr ago (Coleman & de Jong 2008)
  - CDM infall times ~9 Gyr ago (Rocha et al. 2012, Wang et al. 2015)
  - Heavily stripped halo
  - No apparent tidal signature



- Carina
  - Tidal disruption
  - Multiple episodes of star formation
  - Kinematic models include tidal effects (Ural et al 2015)
  - DECam observations indication minimal tidal disruption (McMonigal et al. 2015)



Statistical properties of satellites orbits



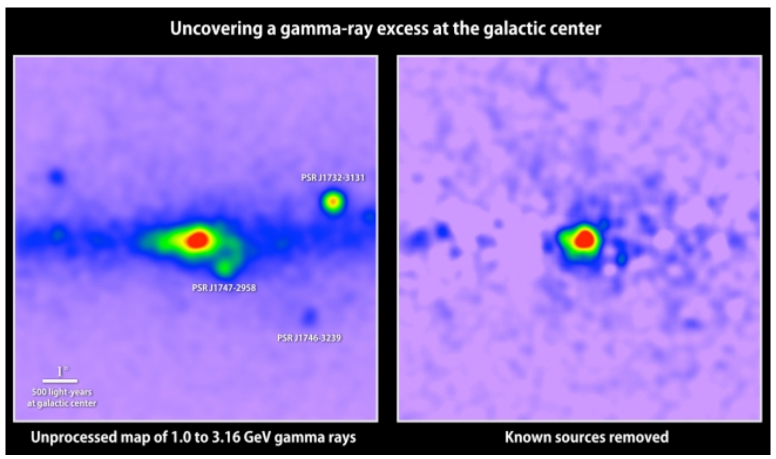
$$\beta = 1 - \frac{\sigma_\theta^2 + \sigma_\phi^2}{\sigma_r^2}$$

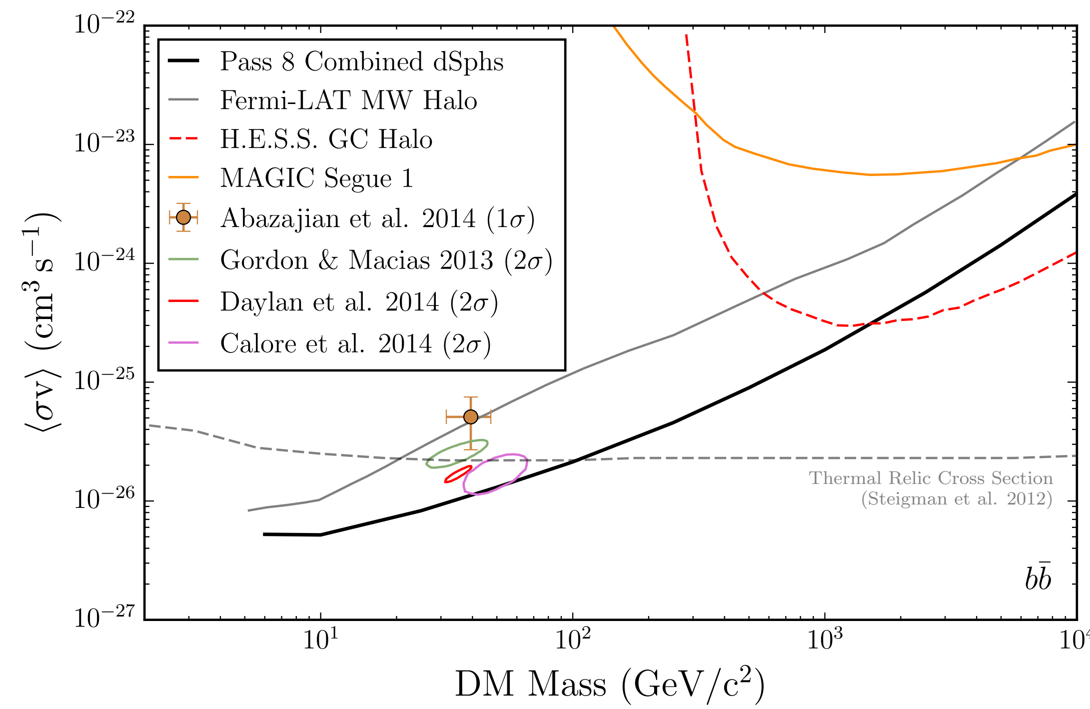
Ratio of velocity dispersions

- Orbital distribution of the Milky Way satellites is more circular than radial (Cautun & Frenk, 2017)
- Most prominent for galaxies closest to Galactic center
- Does this agree with predictions from cosmological simulations (Alex Riley et al. in prep)

Summary

How far can sensitivity go?





Forthcoming Gaia data releases?