M31 GAMMA-RAY EMISSION – A CLOSER LOOK AT DIFFERENT EXPLANATIONS (MILLISECOND PULSARS & DARK MATTER)

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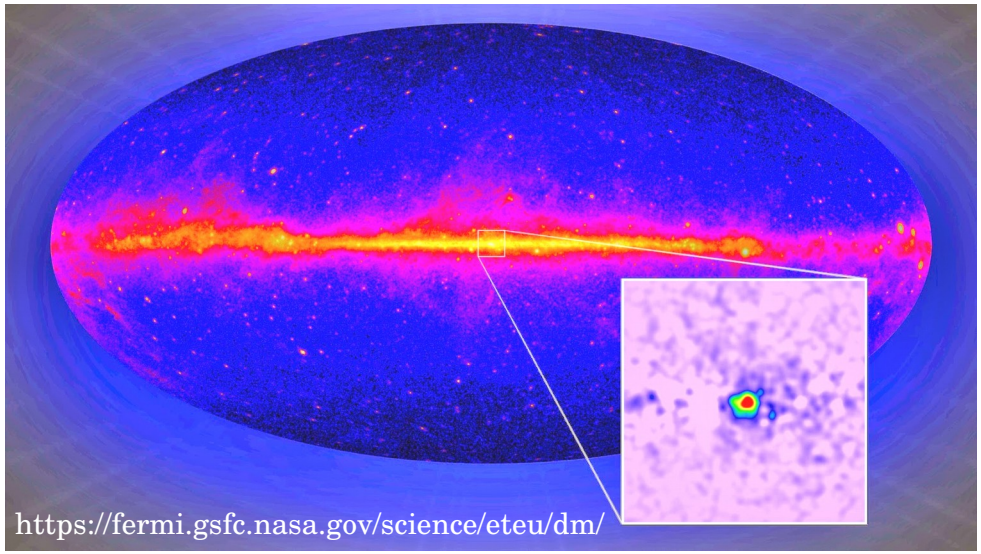
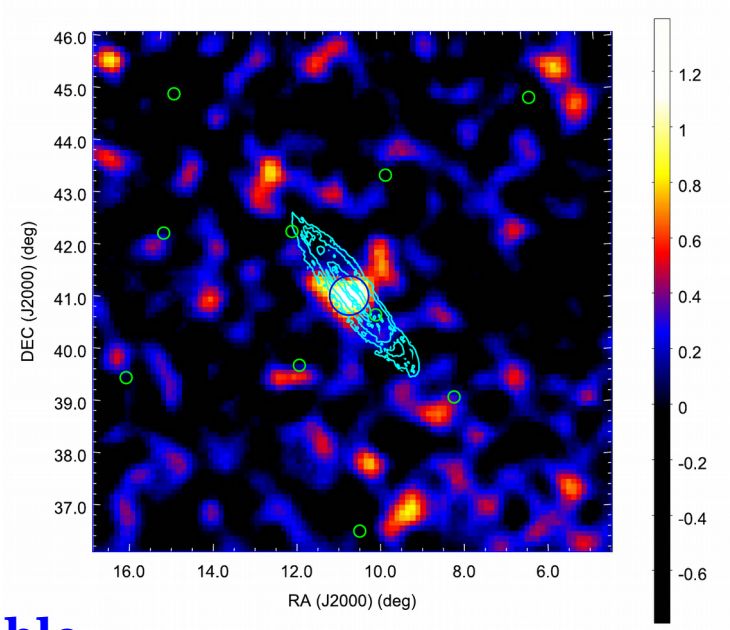
Observation of M31 as Extended Source

- M31 detected in gamma-rays with 5.3σ in two year Fermi LAT data (Abdo+, 2010)
  → only marginal detection of spatial extension (1.8σ)
- Now: more detailed analysis with 88 months of Pass 8 SOURCE class events (cf. Ackermann+ 2017, Astrophys. J., 836, 208)



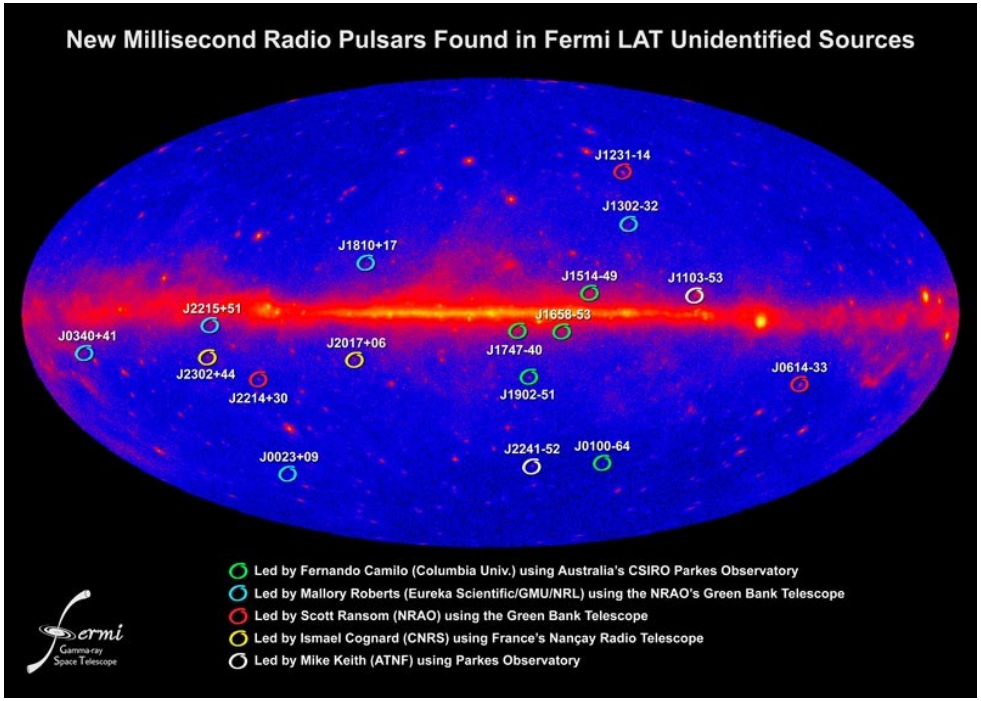


Milky Way (MW) Galactic Center Excess ⟷ **of comparable origin?** ⟷ M31 extended emission

obstructed view on Galactic Center due to position in galactic plane (gas, star-formation regions, SNRs, etc.)

– external viewpoint
– 10 times lower star formation rate than MW
– extended emission seems uncorrelated with M31's disk (unlike MW)

Millisecond Pulsar (MSP) Model Description



There are a number of MSPs detected in the Milky Way!

Toy model for MSP number density:

$$n_{\mathrm{MSP}}(r) = A \underbrace{\langle \rho_*(r) \rangle_{d_1}}_{\text{"primordial" MSPs}} + B \underbrace{\langle \rho_*^2(r) \rangle_{d_2} / \sigma}_{\text{"dynamically" formed}}$$

scales with mass

depends on stellar encounter rate

Main input for our analysis:

– constrain primordial formation with <u>local</u> distribution of MSPs (Winter+, '16)
  → luminosity function

– estimate dynamical formation by properties of globular clusters (Hui+, '11)

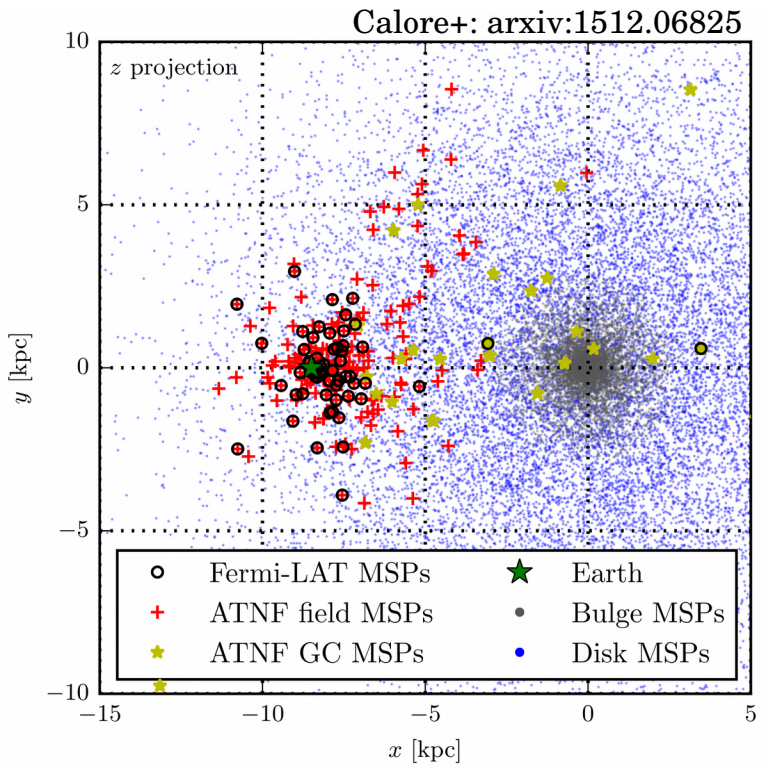
Check prediction of our model with:

– Galactic Center Excess features (Calore+, '15; Ackermann+, '17)

– M31 extended emission

Primordial Formation in MW Bulge

Situation in the MW:



information about local distribution of MSPs:

$$\langle L_b^{\rm prim} \rangle = \frac{M_b}{M_{MW}} \int_{L_{\rm min}}^{L_{\rm max}} L_\gamma \left(\frac{dN}{dL_\gamma} \right)_{MW} dL_\gamma$$

mass of bulge inside: 2 kpc (~ 16°)

$$L^{\rm prim}_{\rm MW\,bulge} = 2.0^{+3.2}_{-1.3} \times 10^{37}\ {\rm erg\,s^{-1}}$$

from Ackermann+, 2017 (arXiv: 1704.03910):

$$L^{\rm obs}_{\rm GCE,tot,\ \lesssim 20^\circ} = 2.2^{+1.5}_{-1.9} \times 10^{37} {\rm erg\ s^{-1}}$$

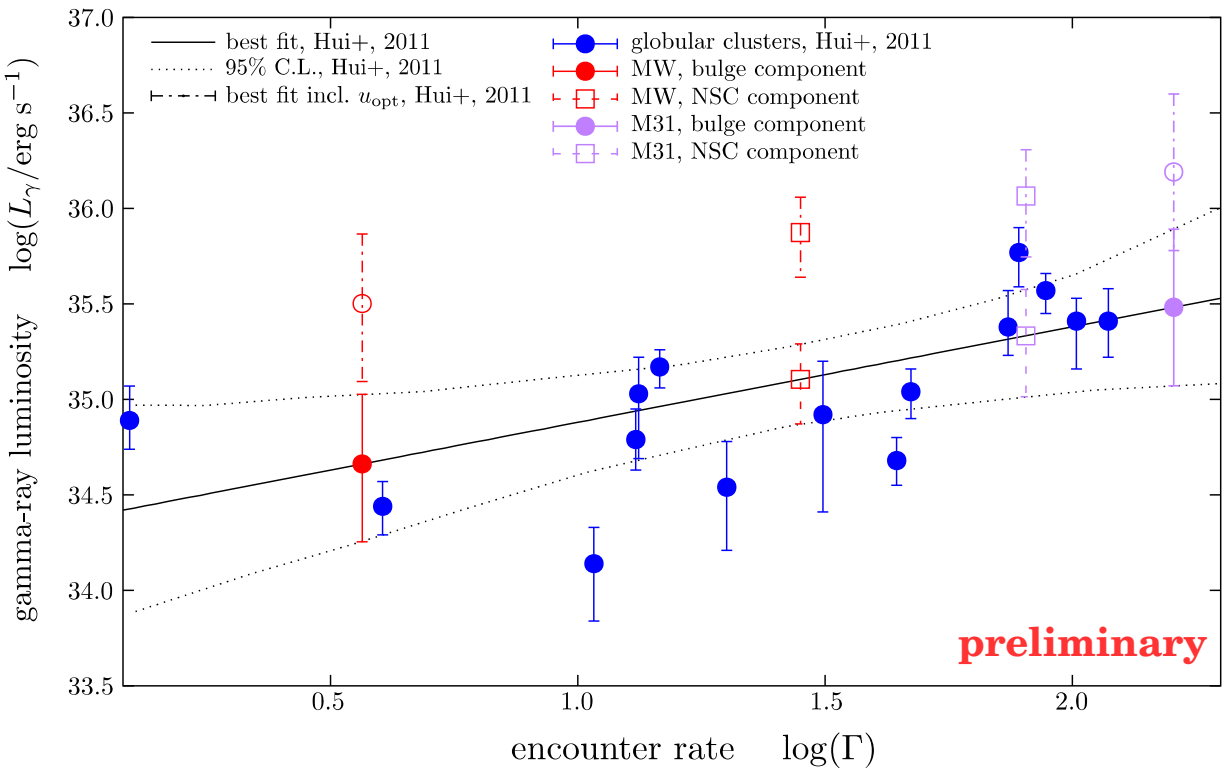
$$L_\gamma^{\rm prim} \sim L^{\rm obs.}_{\rm GCE,\ \leq 20^\circ}$$

→ GCE „eaten up“ by primordial MSPs

Dynamical Formation in MW Bulge

Dynamically formed MSPs:

Treat bulge and nuclear stellar cluster (NSC) of MW as sort of globular cluster!
→ compare with analysis of encounter rate vs. luminosity in globular clusters



stellar encounter rate:

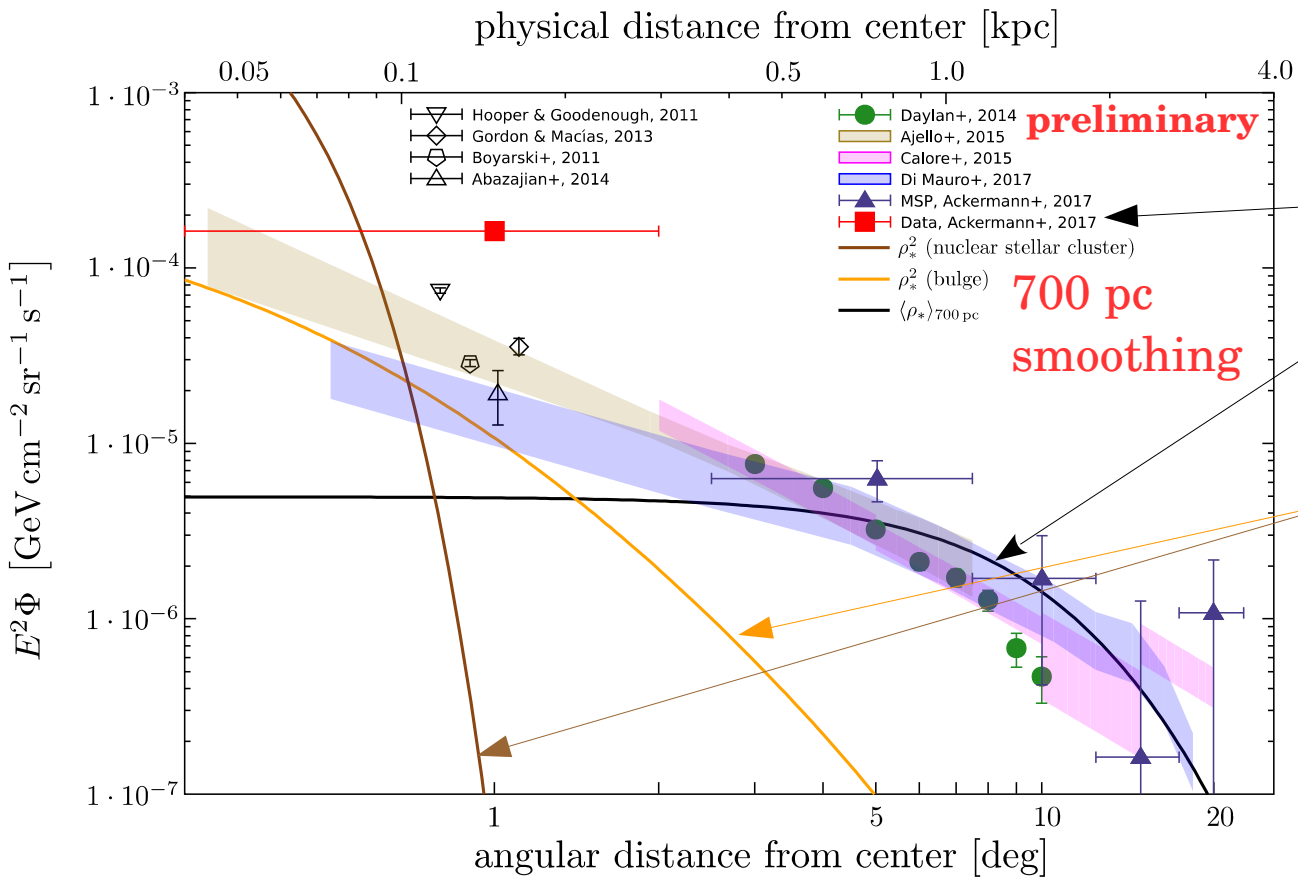
$$\Gamma \sim \int \frac{\rho_*^2}{\sigma} \mathrm{d}V$$

- contribution of dynamically formed MSPs: less than 5%

$$\left(L^{\rm obs}_{\rm GCE,tot,\ \lesssim 20^\circ} = 2.2^{+1.5}_{-1.9} \times 10^{37} \mathrm{erg\ s^{-1}} \right)$$

MSP Model – Comparison to GCE Radial Profile

Radial profile of MW bulge emission:



maximally expected flux from innermost 2°, includes point sources

primordially formed MSPs (black)

$$L^{\mathrm{prim}}_{\mathrm{MW\,bulge}} = 2.0^{+3.2}_{-1.3} \times 10^{37}\ \mathrm{erg\,s^{-1}}$$

dynamically formed MSPs:

– bulge

– nuclear stellar cluster

- fit $\langle\rho_*\rangle_{d_1}$ to data of Calore+, 2015
- based on globular cluster scaling relation:
  $\longrightarrow$ derive coefficient for dynamical ρ_*^2 components

Finding:
radial profile of GCE in excellent agreement with our model

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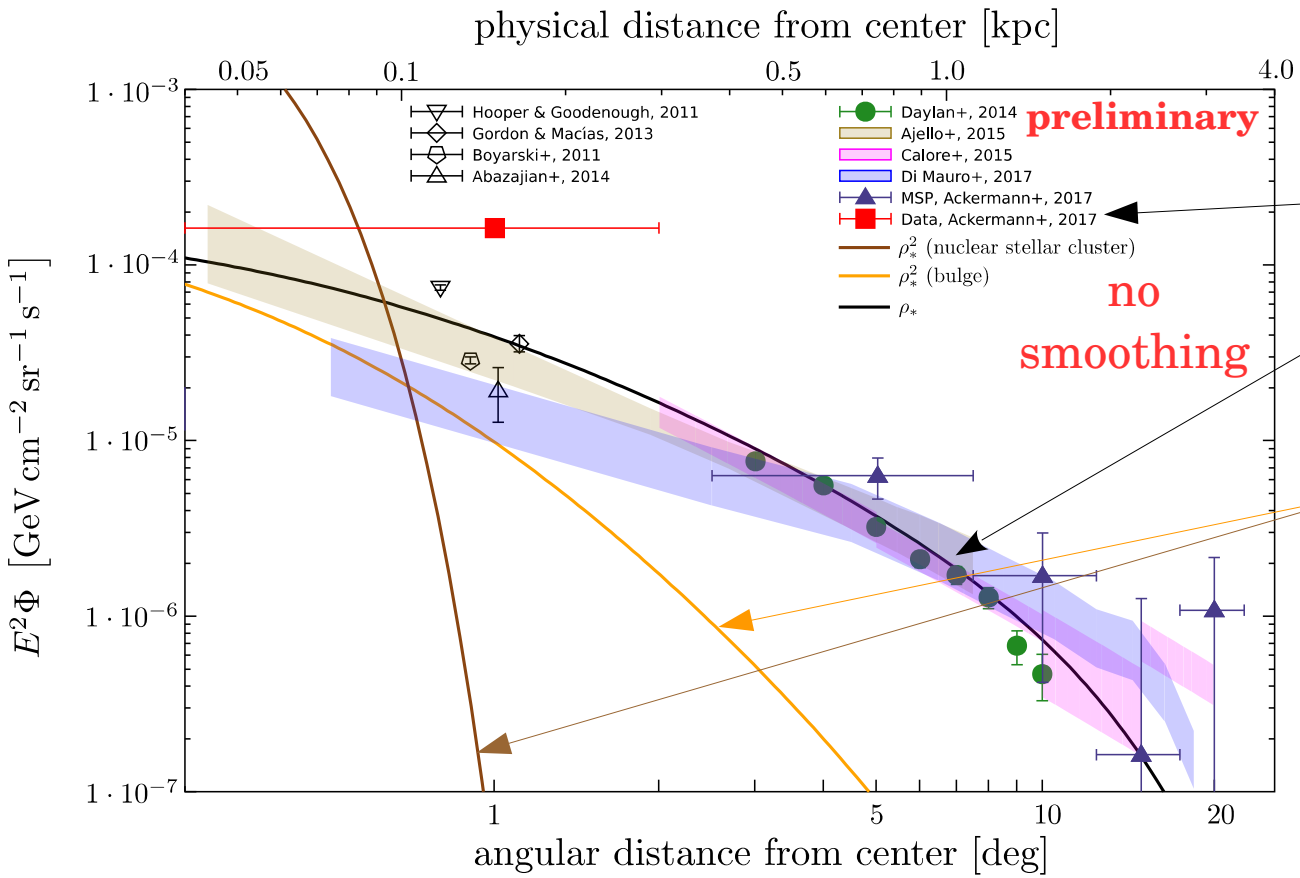

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M31 Emission – Millisecond Pulsar Explanation

Situation in M31:

- assumption: observed emission of M31 from an MSP-like component, then:

$$L^{\text{prim}}_{\text{M31 bulge}} = 7.5^{+12.0}_{-5.3} \times 10^{37} \text{erg s}^{-1} \qquad L^{\text{obs}}_{\text{M31 bulge}} = (28. \pm 4.) \times 10^{37} \text{erg s}^{-1}$$

$$L^{\text{prim}}_{\text{M31, bulge}} \lesssim L^{\text{obs.}}_{\text{M31, bulge}}$$

- dynamical component also less than 5% contribution
- reasonable result as: extended emission includes point sources, black hole activity, etc.
- Test if the MSP scenario can explain the spatial distribution of the emission!

Morphology fit to the M31 data

Template	TS	Δ *LogL*	TS_{GDE2}
Uniform disk	46	–	
Point Source	37	4.3	
NFW (disk centered)	44	0.9	
NFW (infrared position centered)	43	1.2	
IRAC_{1°	41	2.4	
$\text{IRAC}_{0.7^\circ}$	41	2.5	
IRAC	40	2.6	

– map of emission strongly correlated with old stellar populations
– smoothed with 900 pc kernel
– smoothed templates 2.5σ consistent with best fit

Dark Matter Profiles for M31

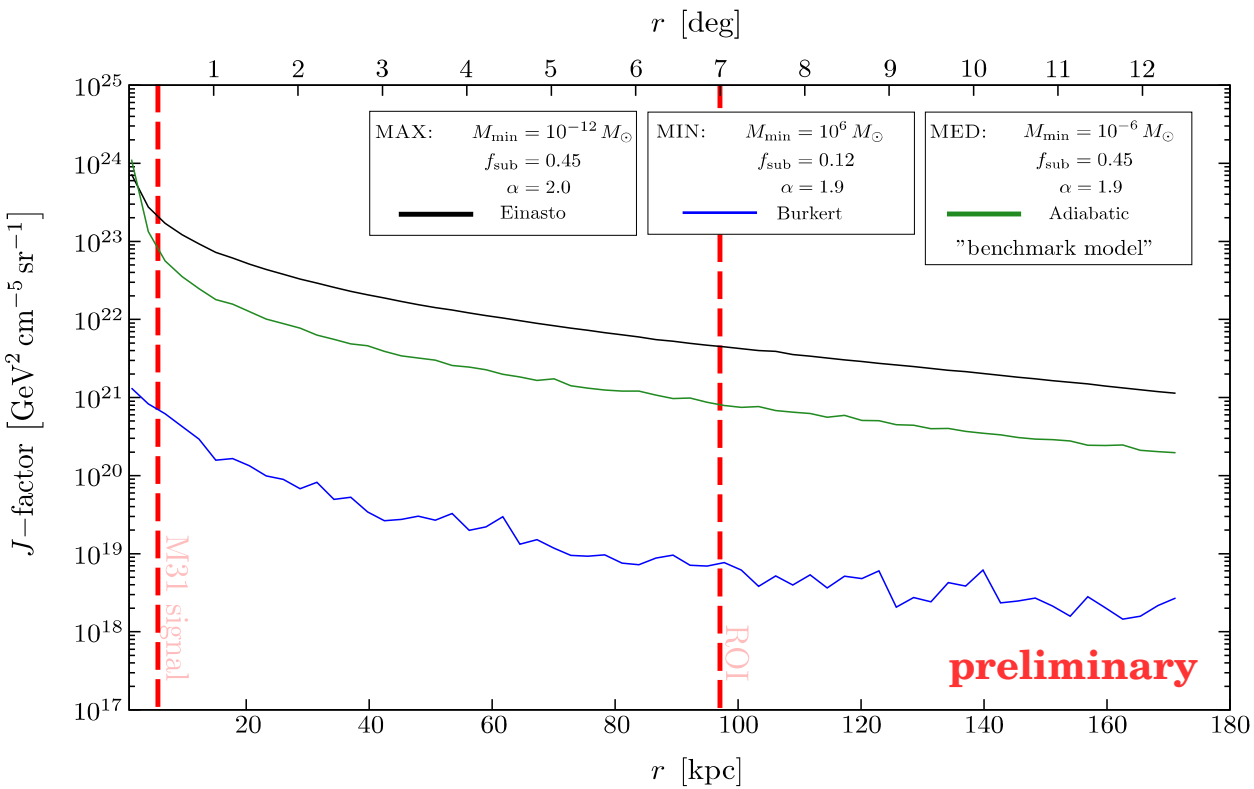
in MW: radial profile of GCE also fit by NFW dark matter density profile (Calore+, '15)

→ True for M31? Which profile should we consider? Subhalos?

translate DM profile uncertainties into:

2 limiting cases + one benchmark model

- **MAX** (Einasto)
- **MED** (adiabatically contracted NFW DM profile, Gnedin+, '11)
- **MIN** (Burkert)

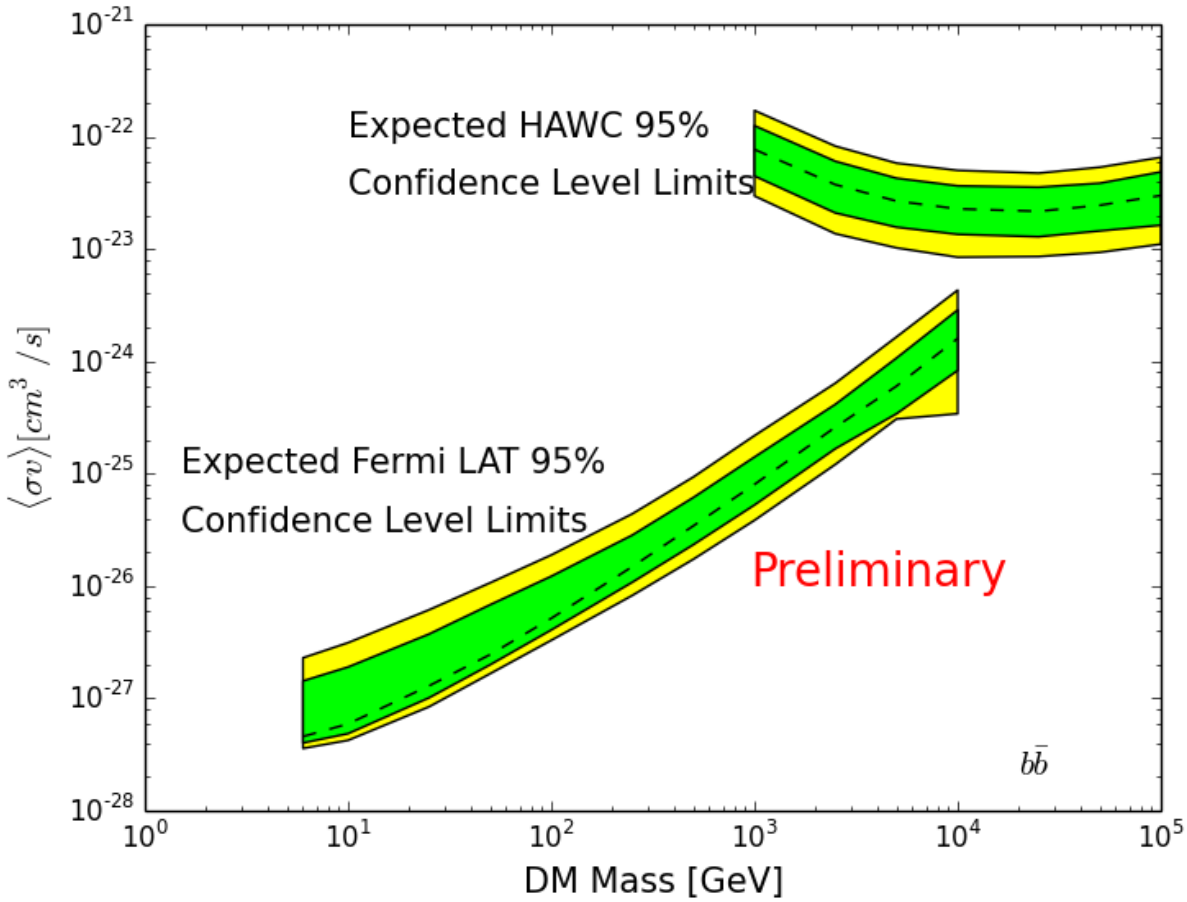


- use CLUMPY for J-factor maps
- from Caterpillar 2015 simulations:
  - fraction of mass in resolved substructures (> 10^4 M_sol): 12%
  - index of subhalo mass function: preferred α = 1.9
- extrapolation to minimal DM halo masses < 10^4 M_sol: fraction in substructure 45%

M31 Emission – Dark Matter Explanation

→ joint work of Fermi-LAT and HAWC to derive upper limits on dark matter annihilation cross-section

- complementary sensitivity ranges of HAWC and Fermi
- derive limits by Monte Carlo simulation of M31 emission (background + DM)
- preliminary results consistent with previous gamma-ray constraints



Conclusions

- According to local information about MSP distribution in MW:
  → Primordially formed MSPs can explain the bulk of the observed emission of the MW bulge.

- The extended emission of M31 is also consistent with emission from primordially formed MSPs, although only at the 2σ limit.
  → Room for additional contributions.

- Joint work within in the LAT and HAWC collaboration on the search/constraints on DM signal from M31.

Backup Slides

Deposited MSPs by Disruption of Globular Clusters

- MSPs deposited in the MW GC region offer an alternative explanation to our 'in situ' scenario
  → significant uncertainties on overall contribution to gamma-ray luminosity (Brandt+, '15)

- NSC has stellar encounter rates comparable to globular clusters, so dynamical formation expected in that region

  ↳ hard to tell apart the two mechanisms, could be of comparable magnitude