FERMI, dark matter, dwarf galaxies and dark satellites of the Milky Way

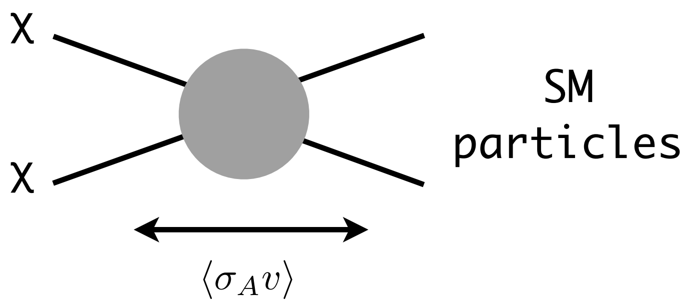
Savvas M. Koushiappas

BROWN

Many thanks to Alex Geringer-Sameth

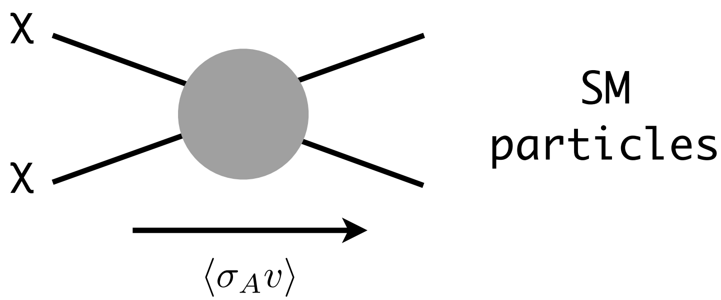
Indirect detection

If it annihilated in the early universe...



$$\hat{\mathbf{L}}[f] = \mathbf{C}[f] \quad \rightarrow \quad \Omega_M$$

...it must annihilate today

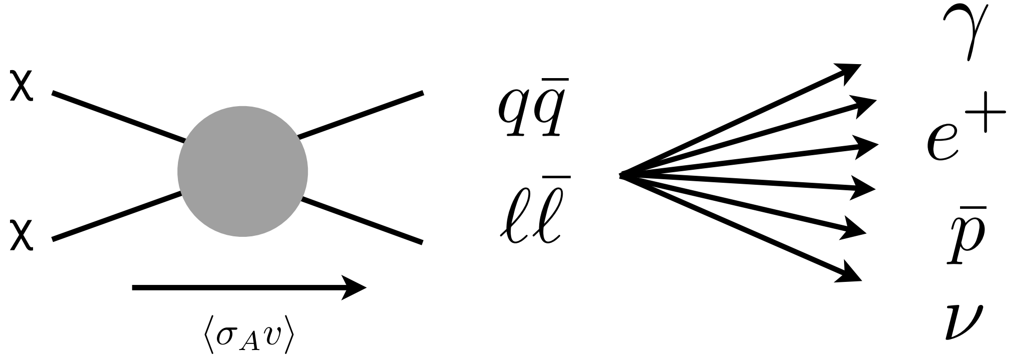


Indirect detection

Two facts:

1. Experiments produce data (AMS-02, IceCube, Fermi, VERITAS, etc.).

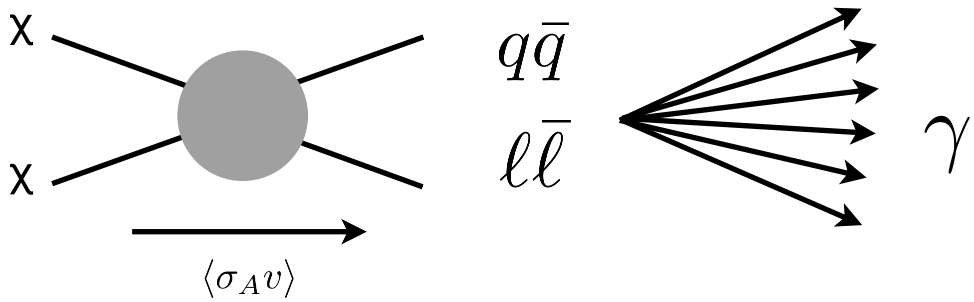
2. We are now sensitive to WIMPs with an annihilation cross section required to explain (naively) the observed relic abundance.



$$\frac{d\Gamma}{d\Omega(\theta)} \propto \Phi_{\rm PP} \int_{\rm los} n^2[r(\theta)]$$

The object we would like to constrain

$$\Phi_{\rm PP} \equiv \frac{\langle \sigma v \rangle}{M_\chi^2}$$



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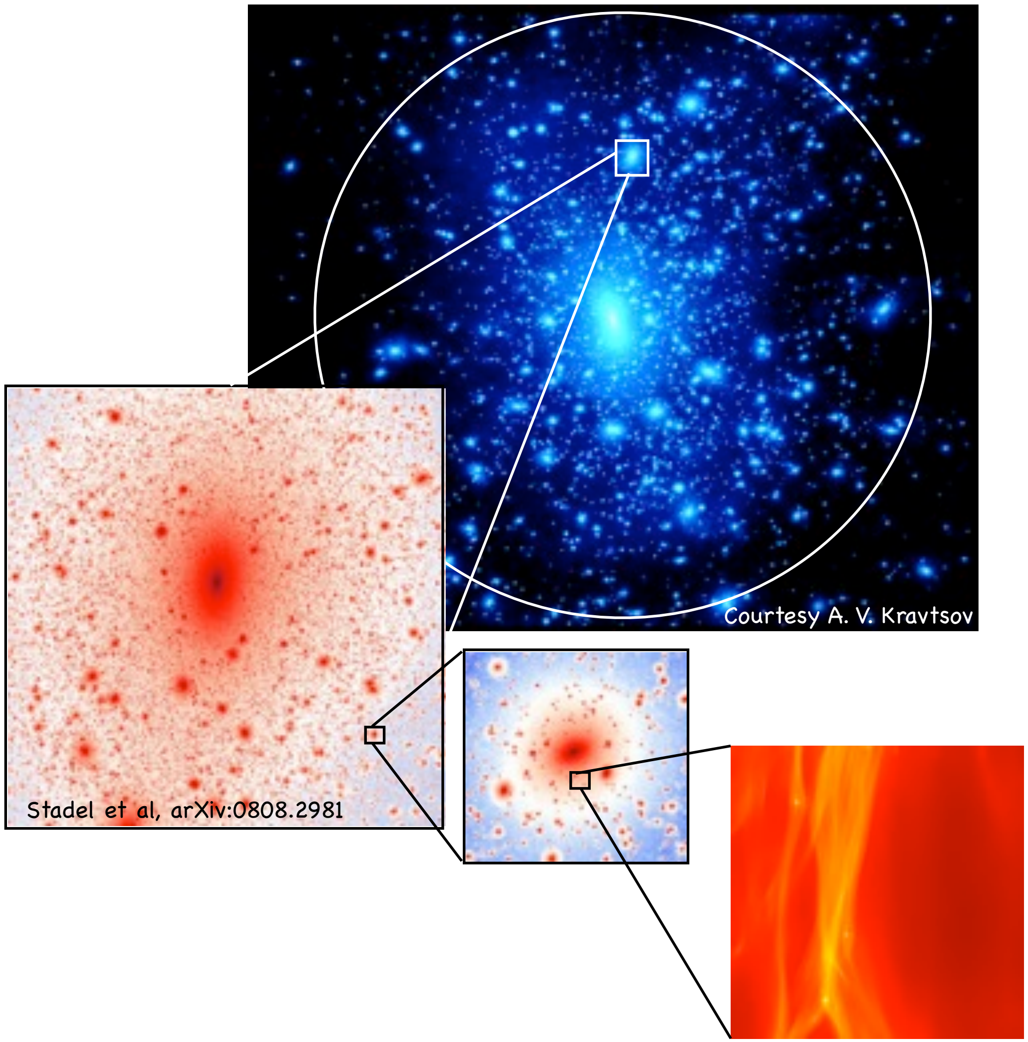
J

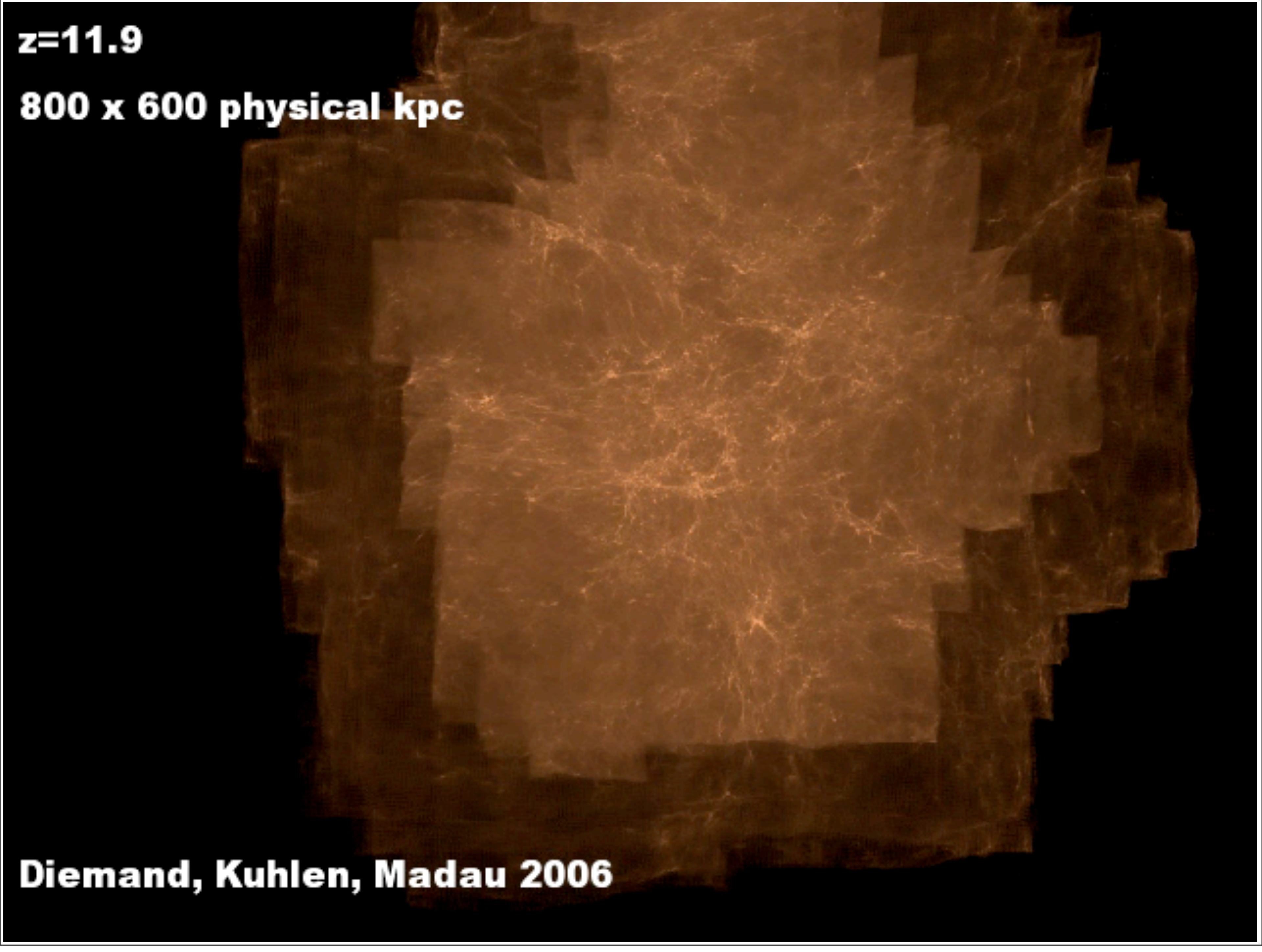
- High signal from high density regions
- Introduces systematic uncertainties

Cold dark matter particle => rich structure in the dark matter distribution



The interpretation of Fermi measurements relies on our understanding of the distribution of dark matter

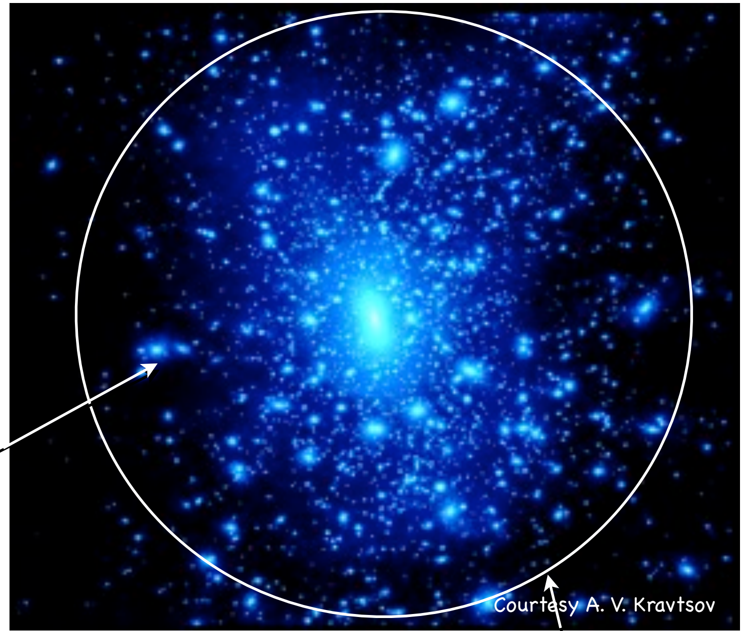
$$\Gamma \propto \int n_\chi^2 d^3 r$$


z=11.9
800 x 600 physical kpc
Diemand, Kuhlen, Madau 2006

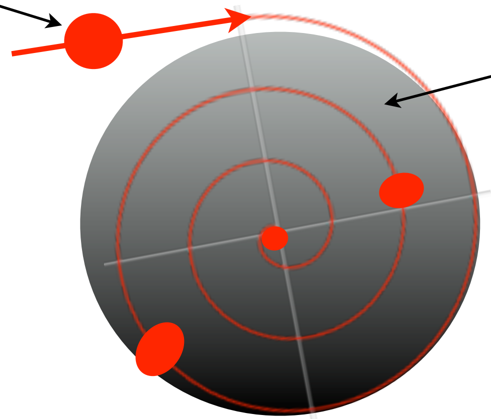
Searches for photons

$$\Gamma_{\gamma, \mathrm{e}^+, \bar{\mathrm{p}}} \sim \int_V n^2 dV$$

The spectrum of dark matter subhalo properties originates from the host assembly history



Accreted subhalo



Koushiappas, Zentner & Walker, PRD 69, 043501 (2004), but see also Baltz, Tayor & Wai, ApJ 659, L125 (2006), Kuhlen, Diemand & Madau , arXiv:0805.4416

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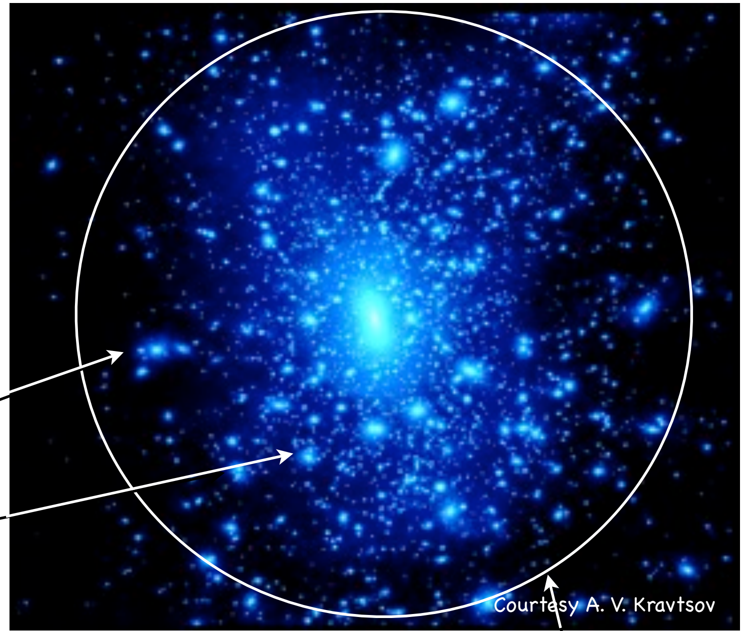
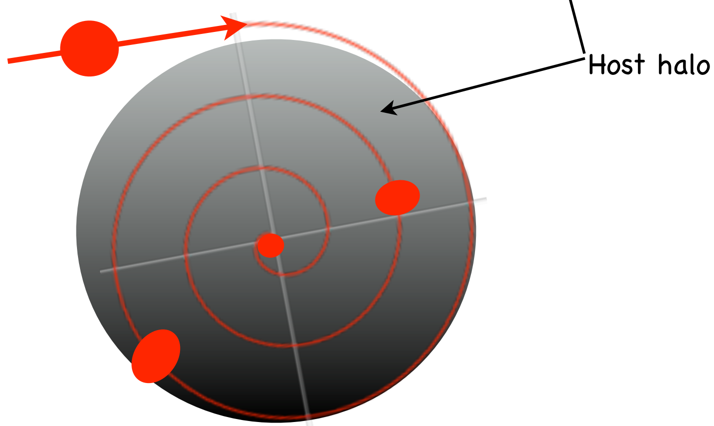


These two may have the same mass, but different history



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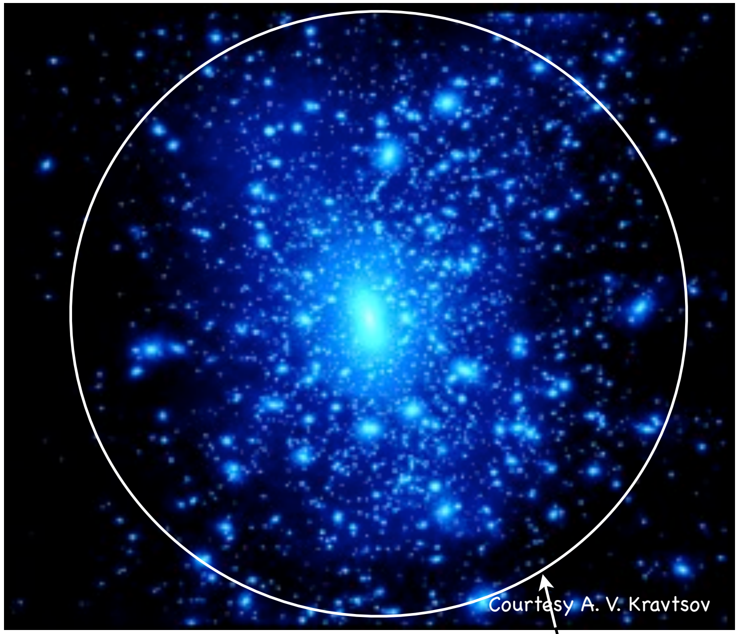

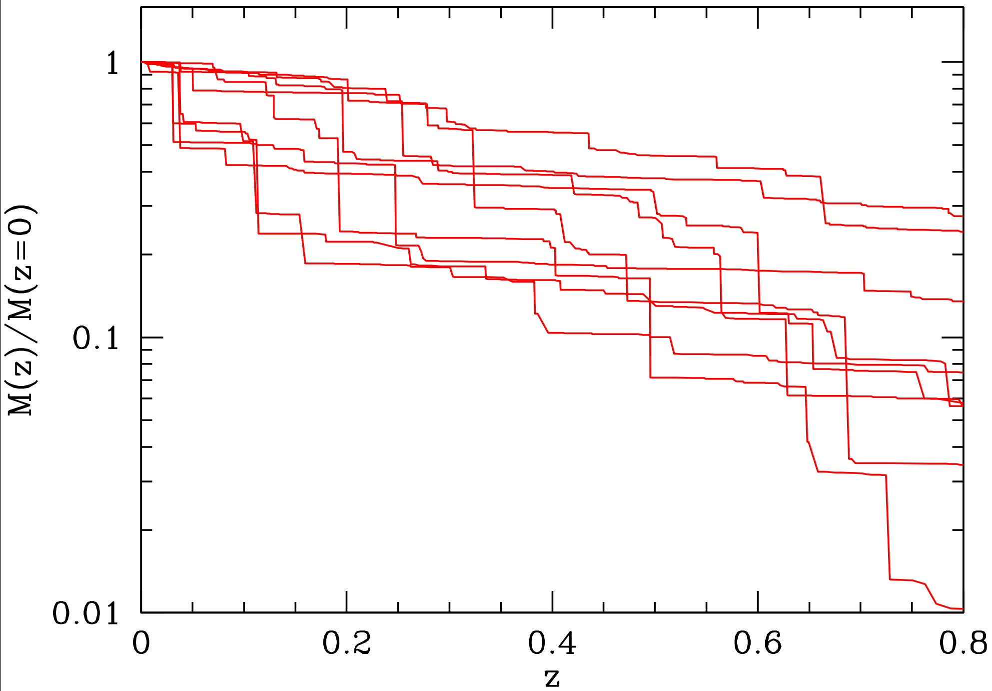

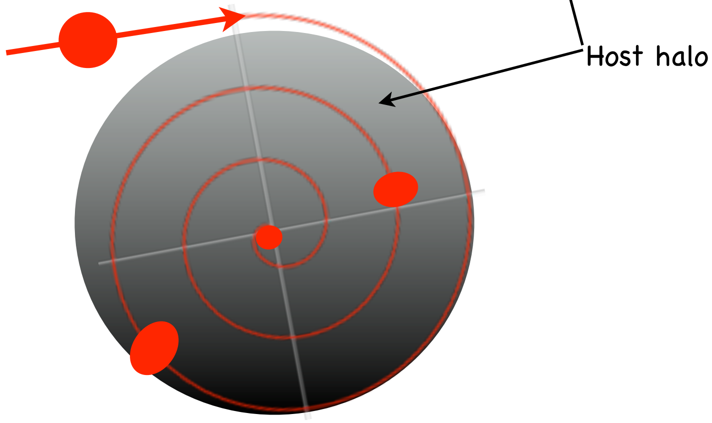

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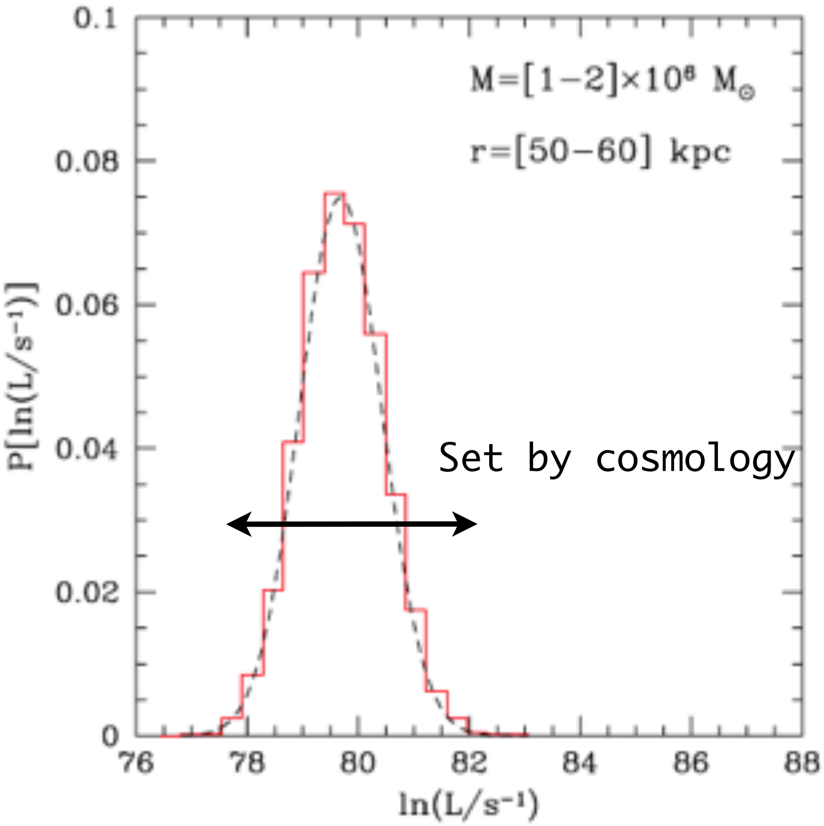
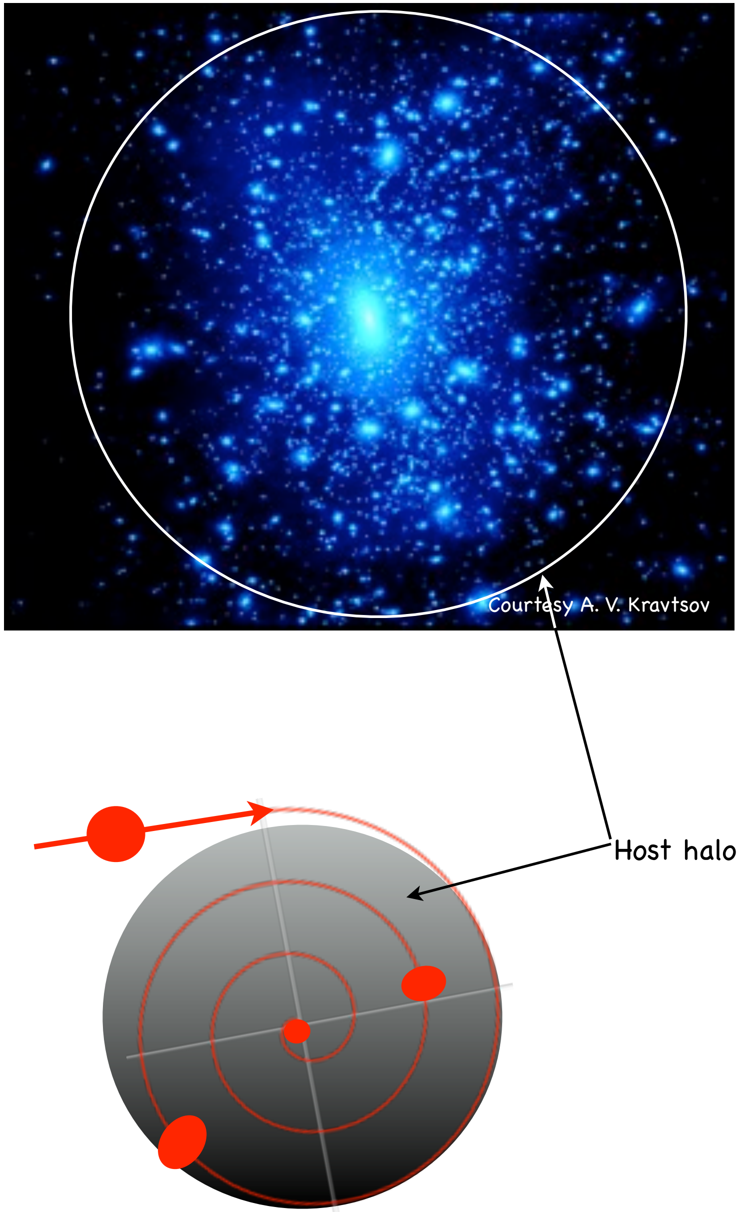


Koushiappas, Zentner, Kravtsov, PRD 82:083504(2010)



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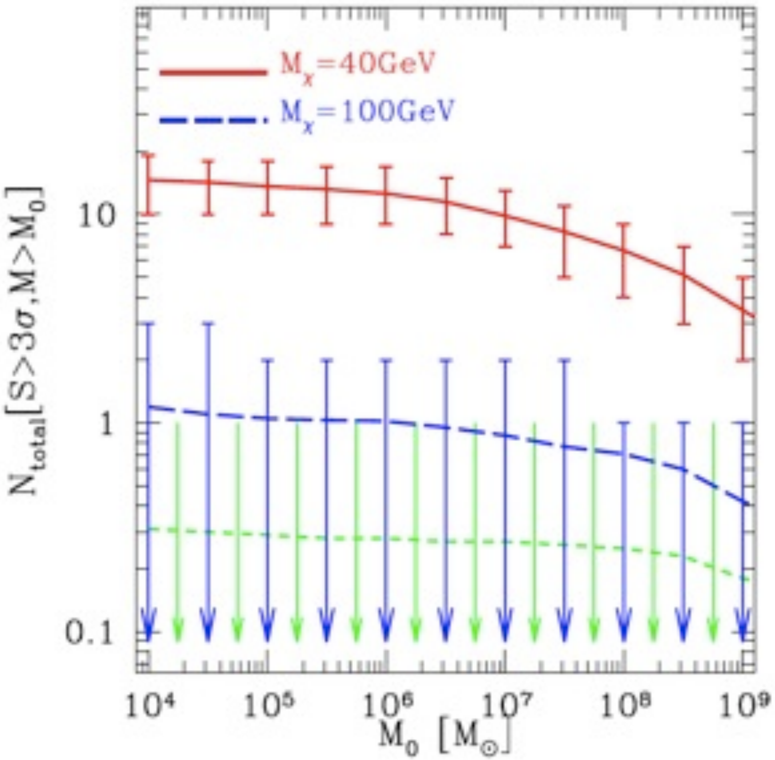

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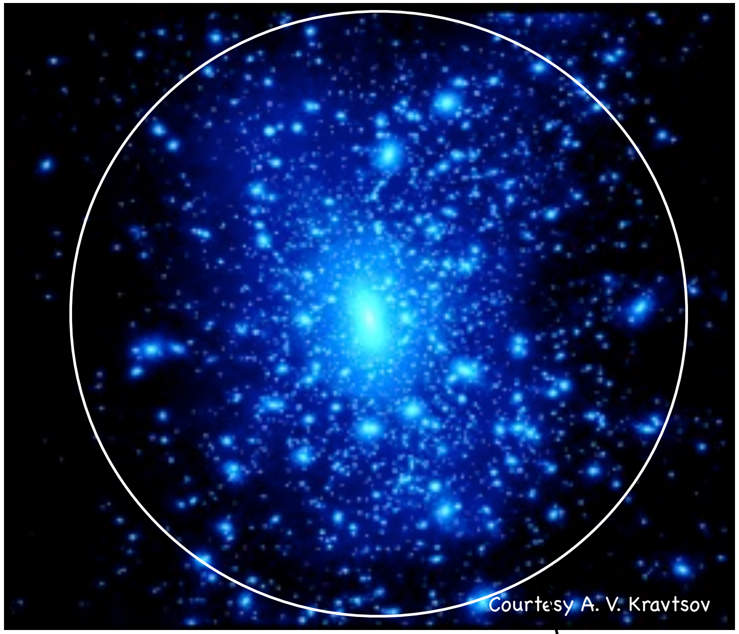

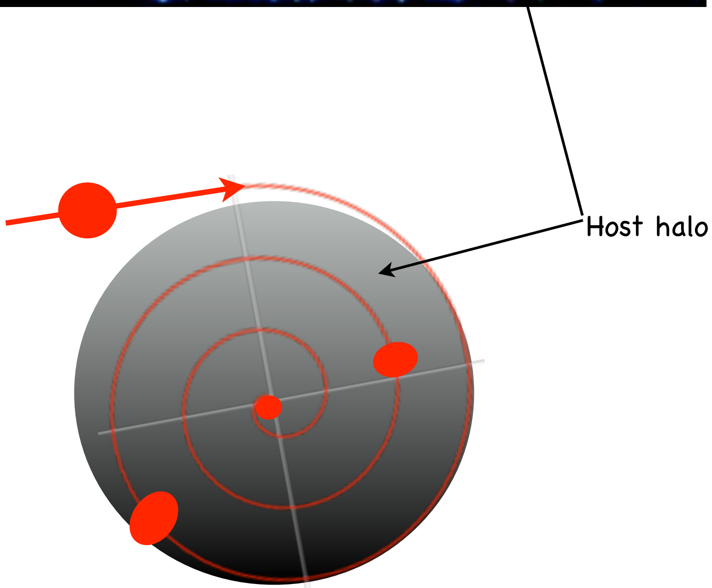

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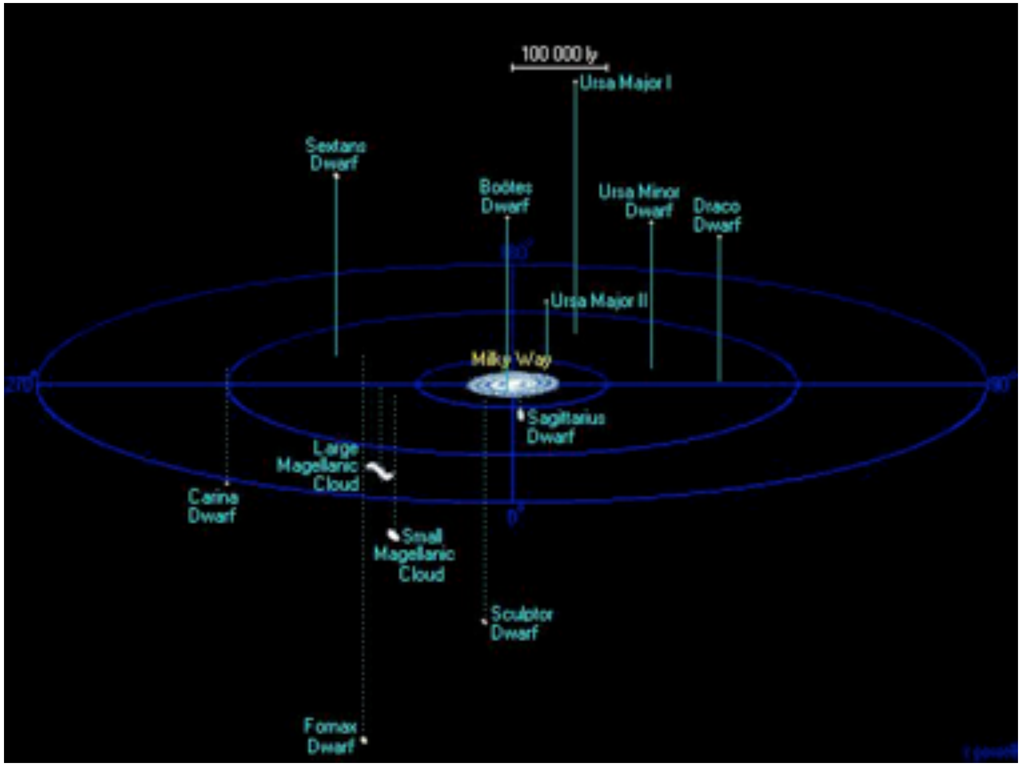
Look nearby, in high density regions: Dwarf galaxies



- About 20 sources (most of them discovered in the last 7 years)
- High mass-to-light ratio (i.e., dark matter dominated)
- No known astrophysical background

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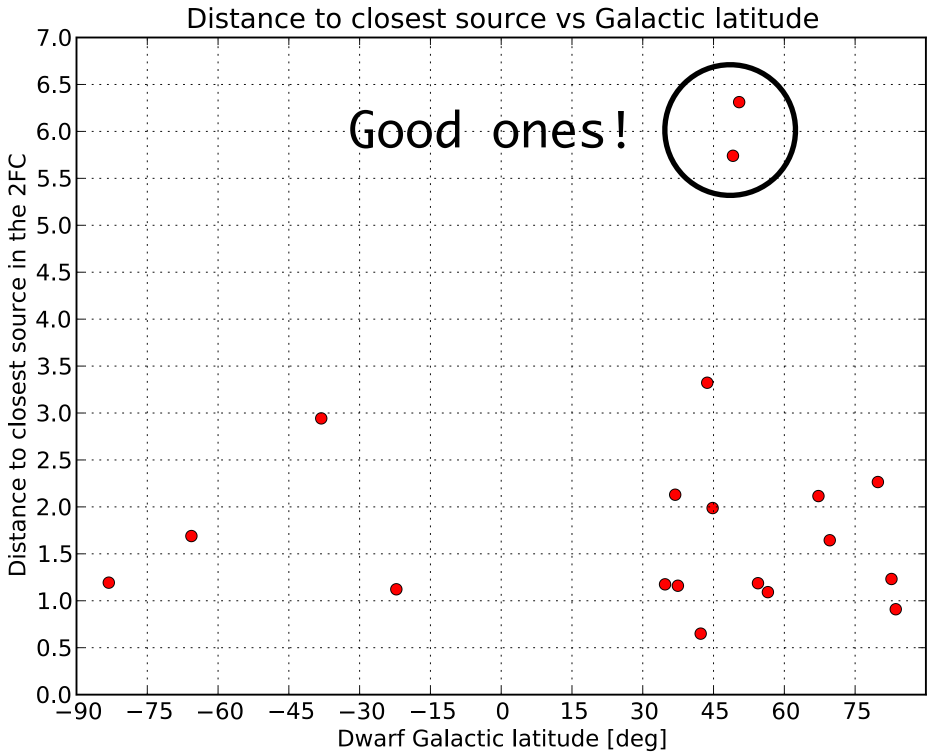

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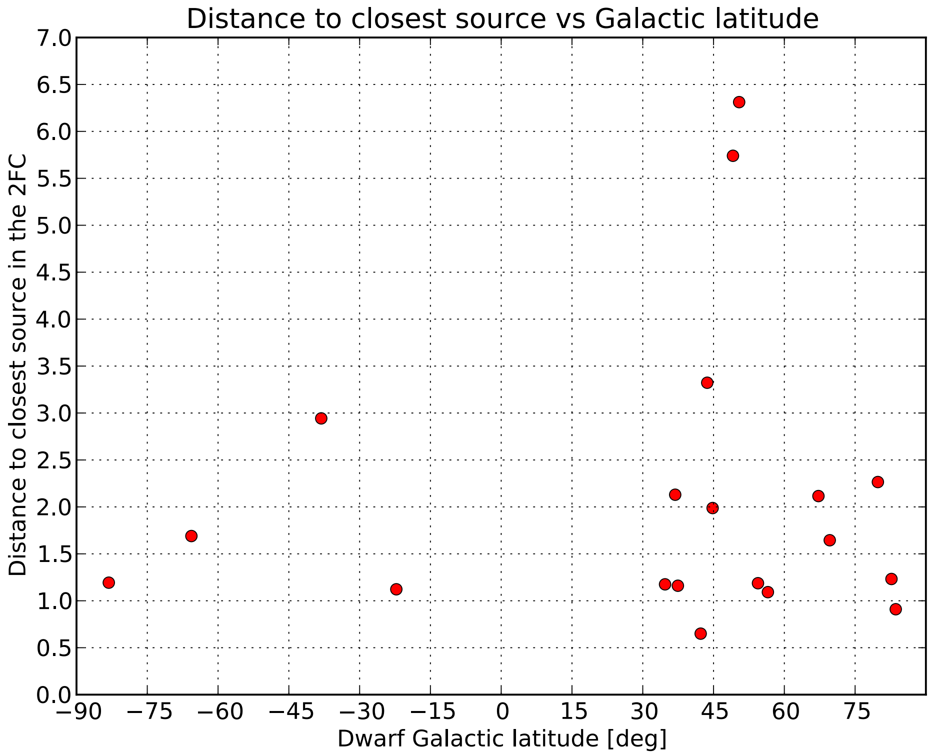

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Look nearby, in high density regions: Dwarf galaxies

Recall, we need $\Gamma \propto f(n^2[r(\theta)])$

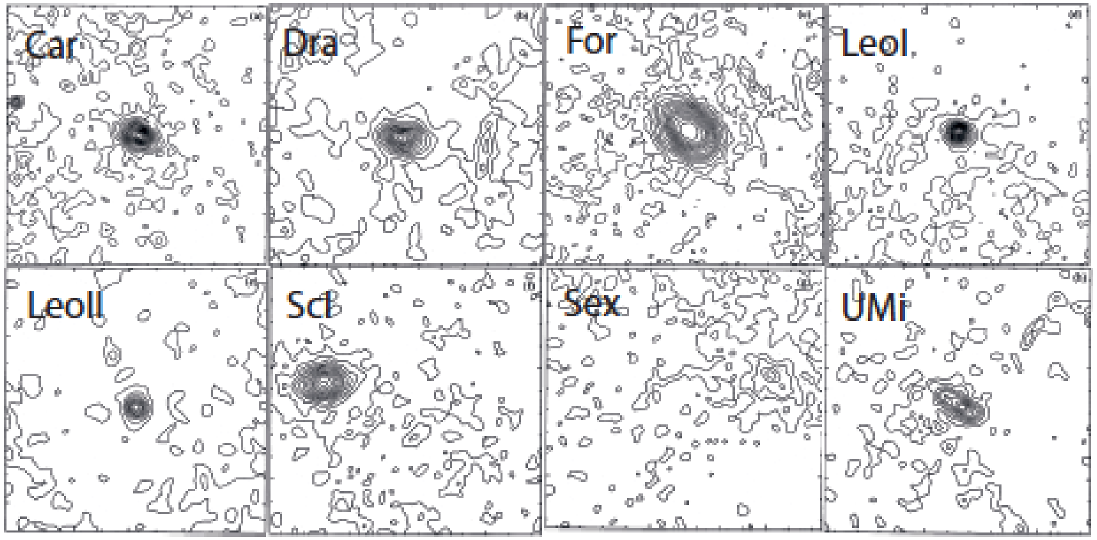
$$n(r) \propto f(\mathbf{v})$$

$$\mathbf{v} \propto g(\sigma_\perp)$$

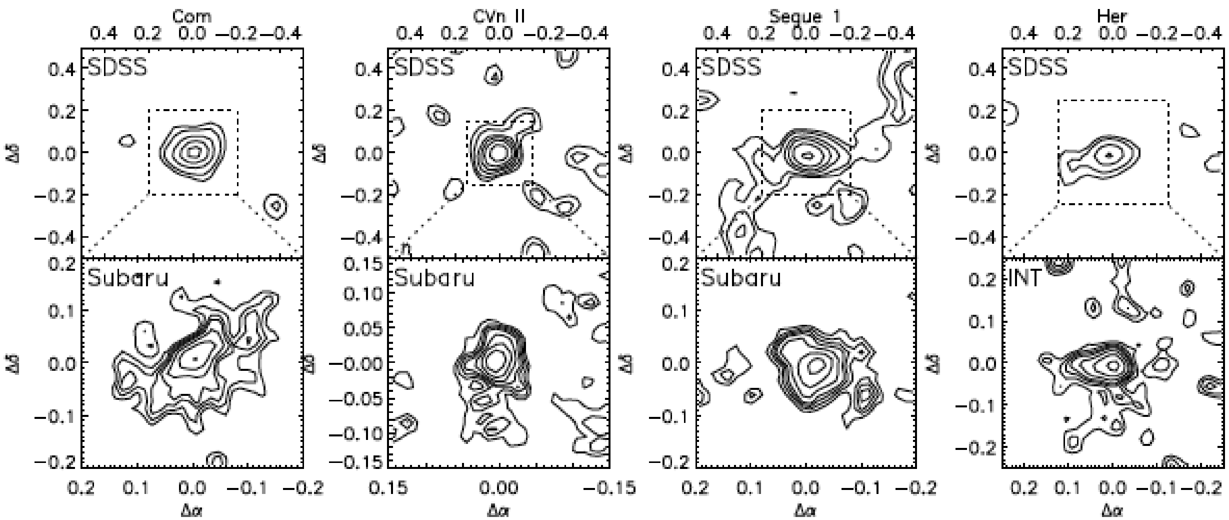
Obtain this from stellar kinematics

- About 20 sources (most of them discovered in the last 7 years)
- High mass-to-light ratio (i.e., dark matter dominated)
- No known astrophysical background

Dwarf galaxies discovered as stellar overdensities



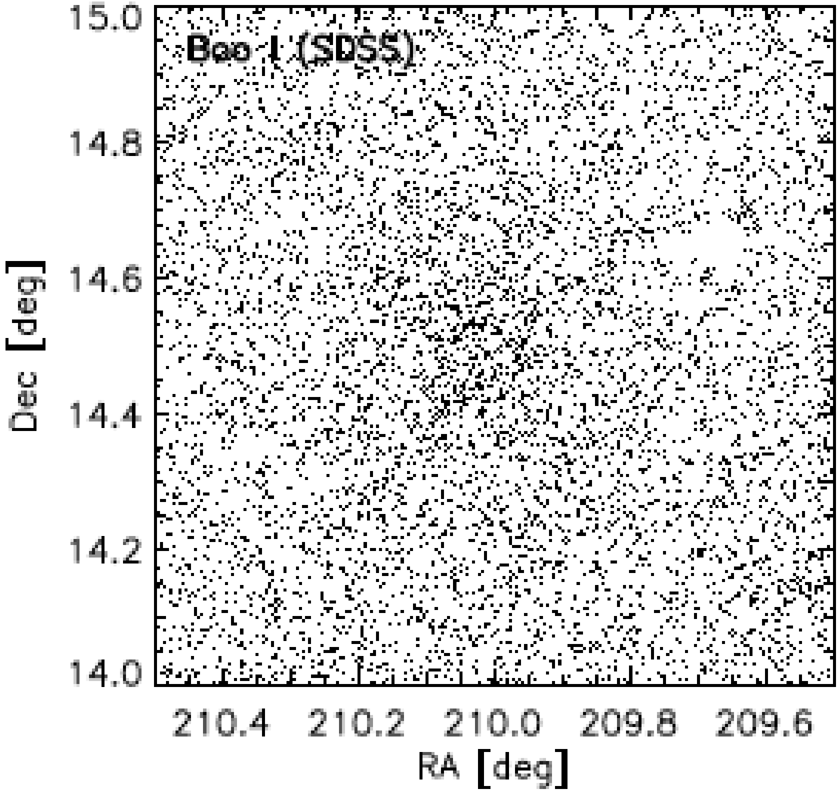
Irwin & Hatzidimitriou MNRAS 277, 1354 (1995)



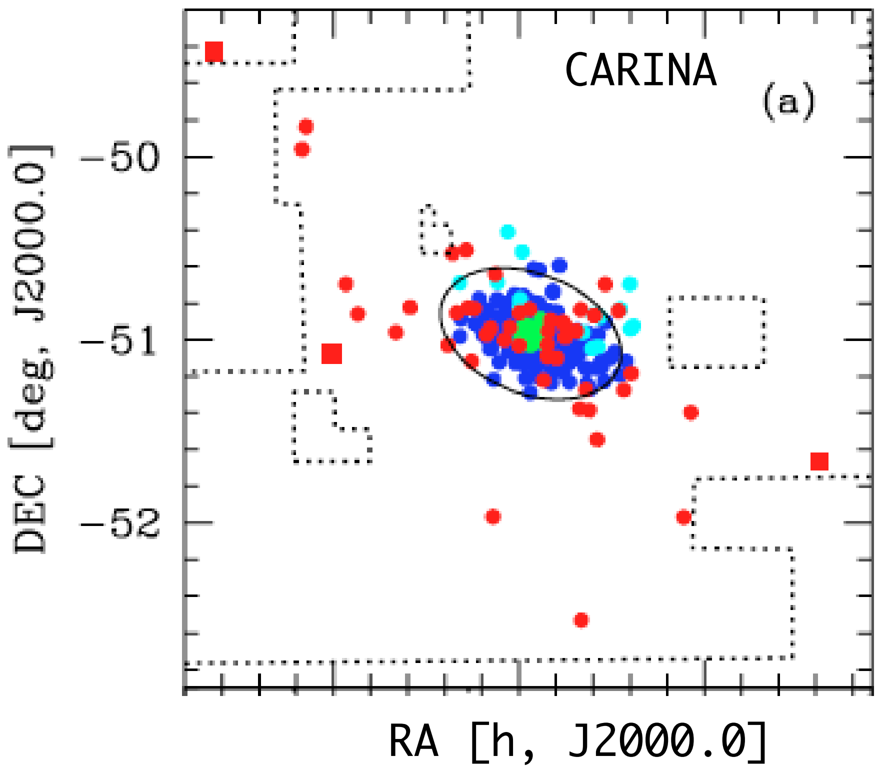
Belokurov et al. (2007)

From Walker, 1205.0311

Dwarf galaxies discovered as stellar overdensities



Martin et al. (2008)

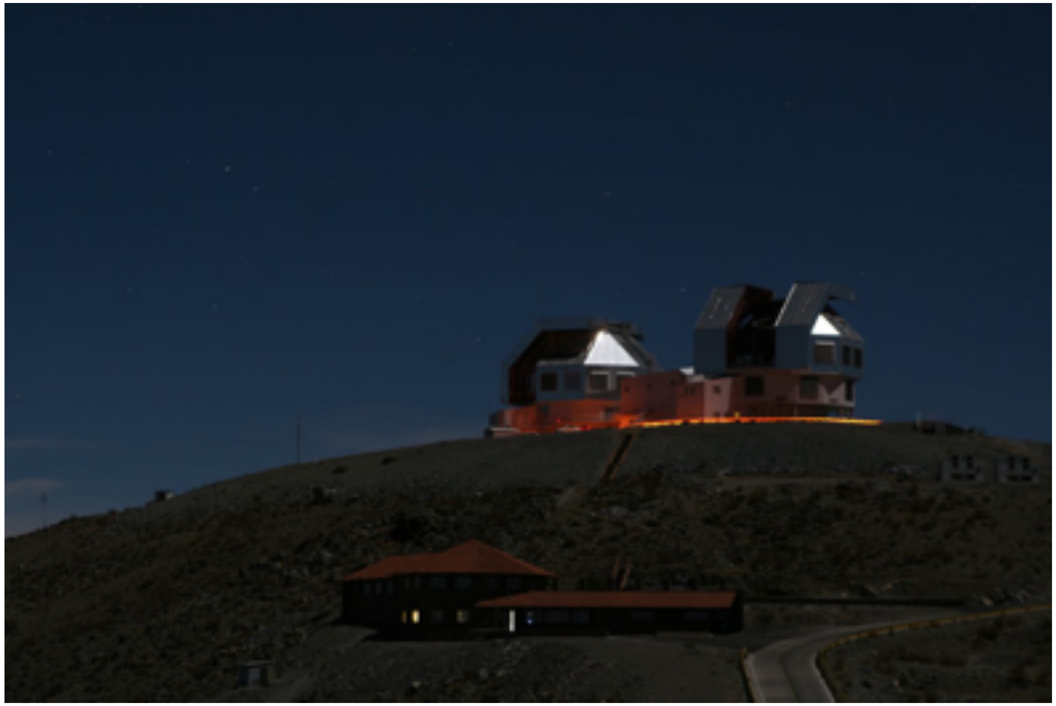


Munoz et al. (2006)

From Walker, 1205.0311

How to go from kinematic data to a limit

Matthew Walker (CfA) at Magellan



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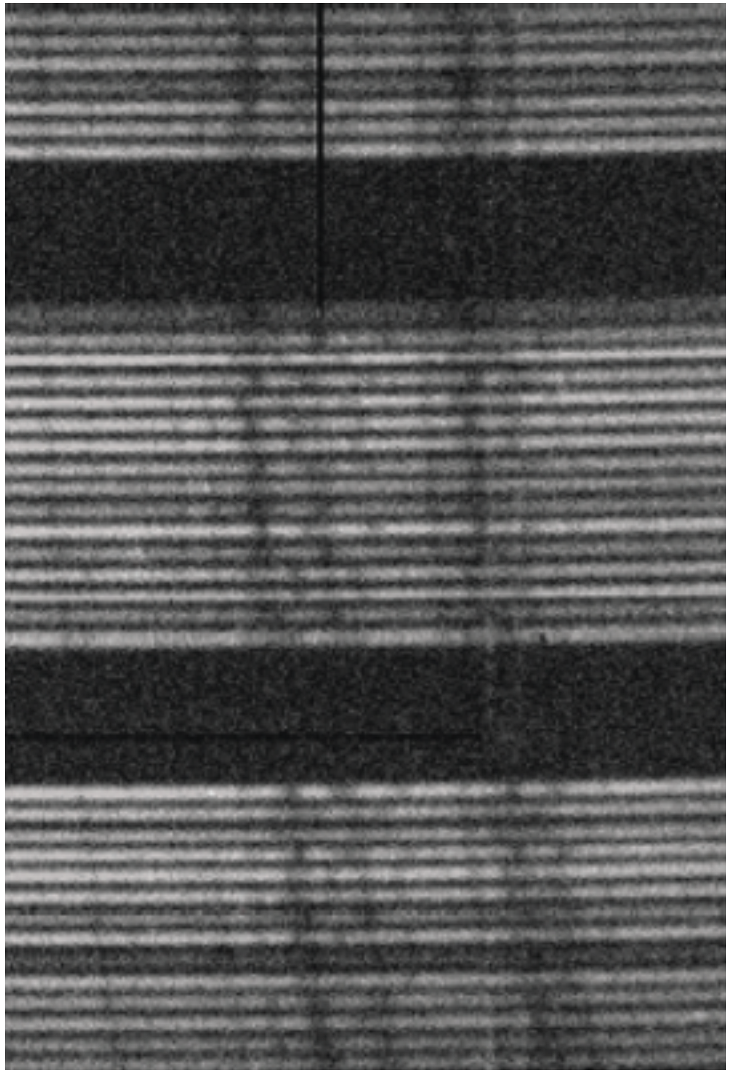


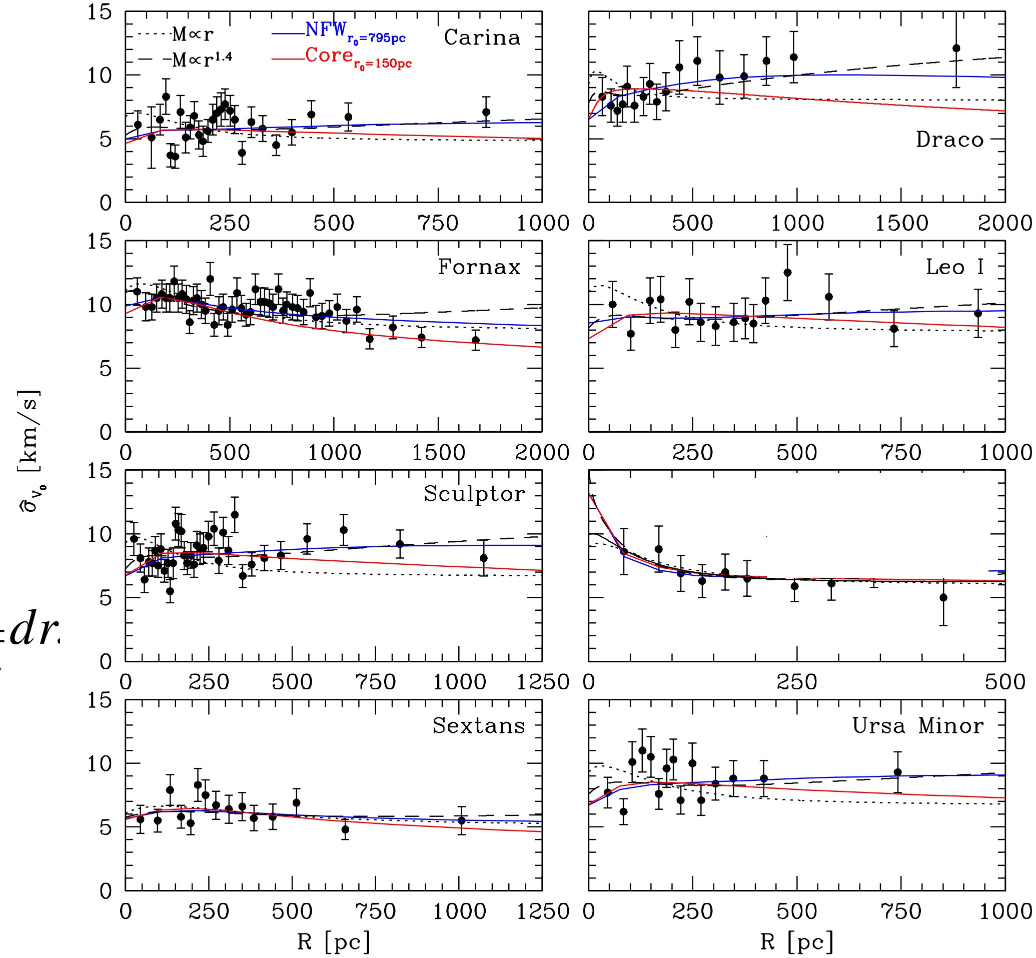
Kinematic data

$$\frac{1}{\nu}\frac{d}{dr}(\nu\langle v_r^2\rangle)+2\frac{\beta_a\langle v_r^2\rangle}{r}=-\frac{GM(r)}{r^2}$$

$$\nu\langle v_r^2\rangle=\frac{1}{f(r)}\int_r^\infty f(s)\nu(s)\frac{GM(s)}{s^2}ds$$

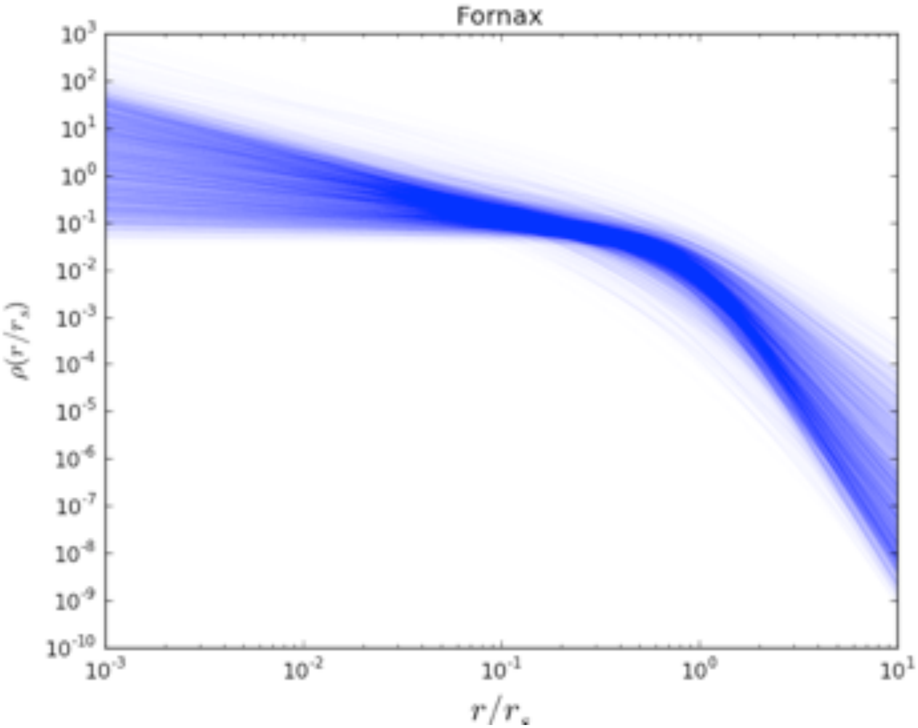
$$\sigma^2(R)\Sigma(R)=2\int_R^\infty\left(1-\beta_a\frac{R^2}{r^2}\right)\frac{\nu\langle v_r^2\rangle r}{\sqrt{r^2-R^2}}dr.$$

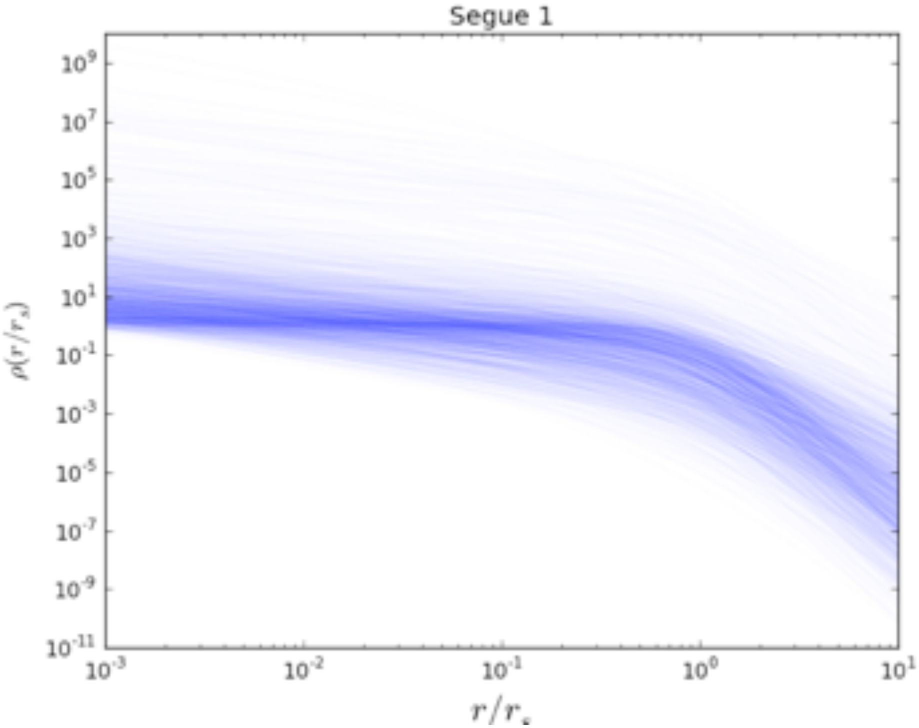
$$\rho(r)=\rho_s\left(\frac{r}{r_s}\right)^{-\gamma}\left[1+\left(\frac{r}{r_s}\right)^{\alpha}\right]^{\frac{\gamma-\beta}{\alpha}}$$



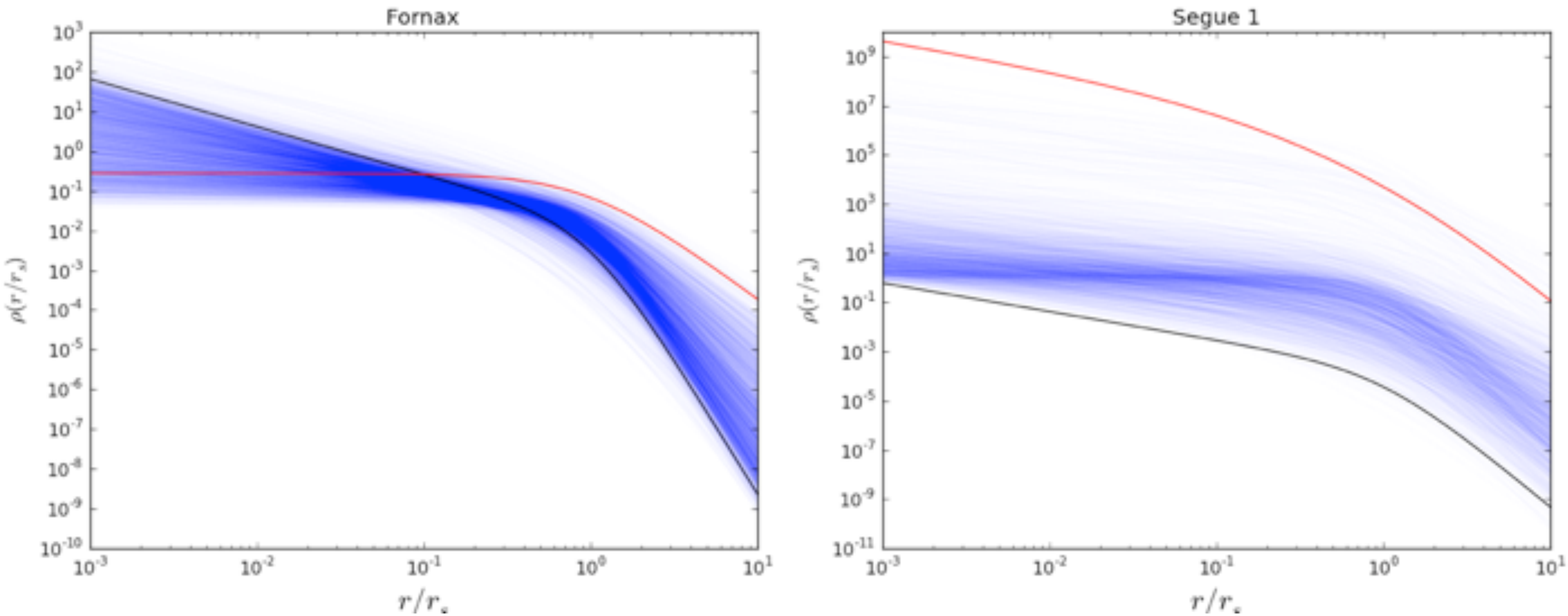
Given ρ_s, r_s, α, β, γ + assumption on β ⟶ get $\Sigma(R)\sigma^2(R)$

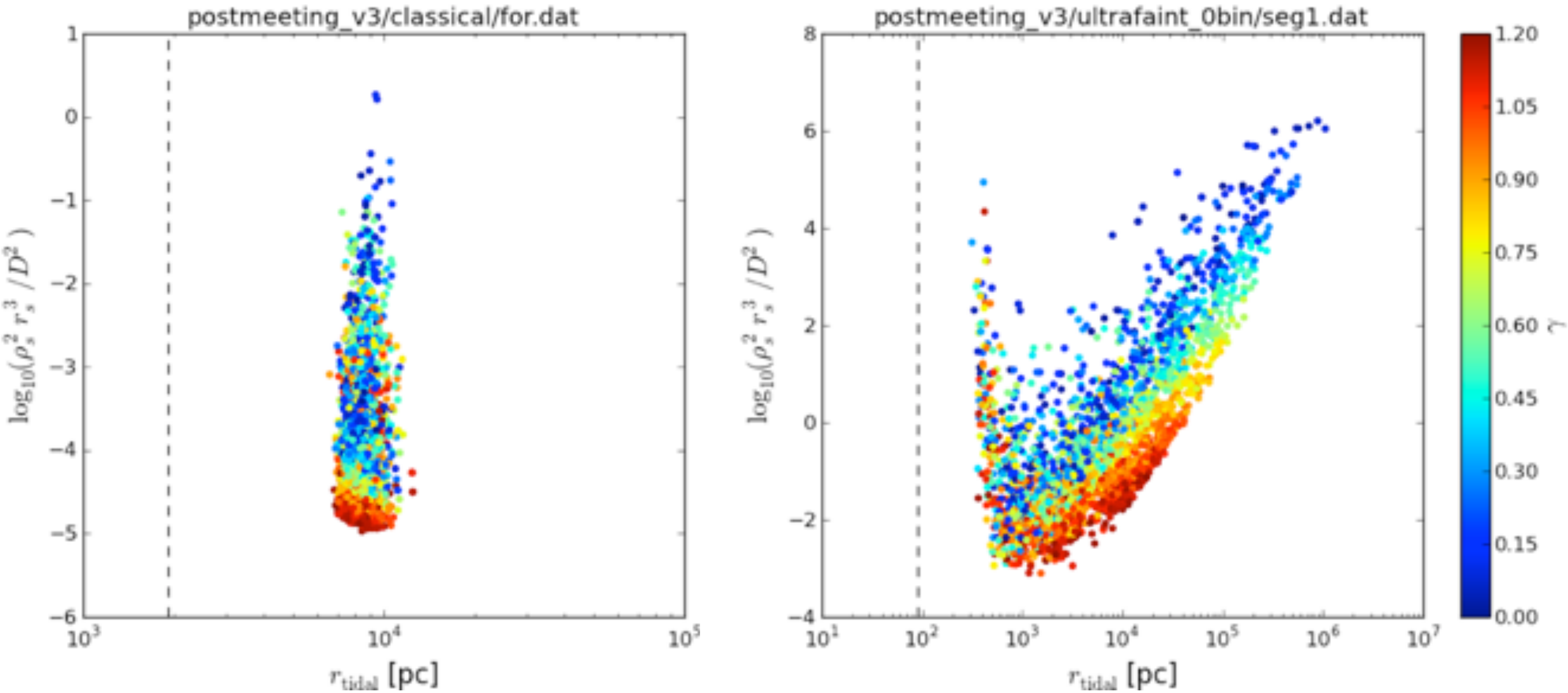
Kinematic data





Kinematic data





postmeeting_v3/classical/for.dat
postmeeting_v3/ultrafaint_0bin/seg1.dat
$\log_{10}(\rho_s^2\, r_s^3\, /D^2)$
$r_{\rm tidal}$ [pc]
γ
1.20
1.05
0.90
0.75
0.60
0.45
0.30
0.15
0.00

Problem we would like to solve:

- We have a dark matter particle with some mass and annihilation cross section
- We have N dwarf galaxies (taken to be sources)
- We have independent experiments that look at them

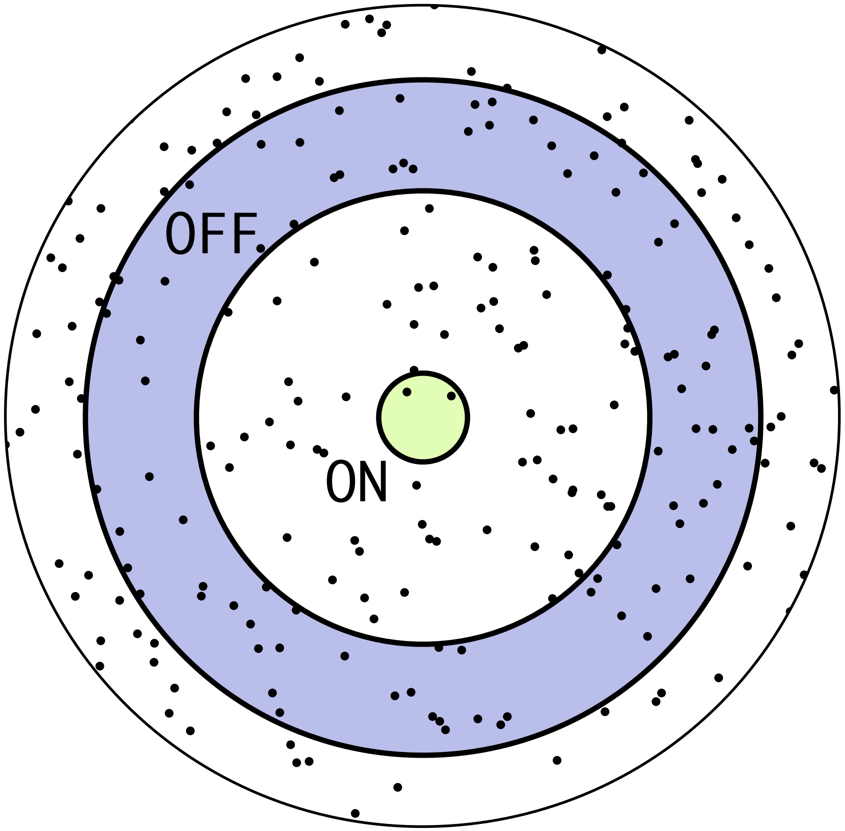
Analysis methods

ON/OFF

Profile likelihood

Photon weighting

ON/OFF
(ACTs)



Pros

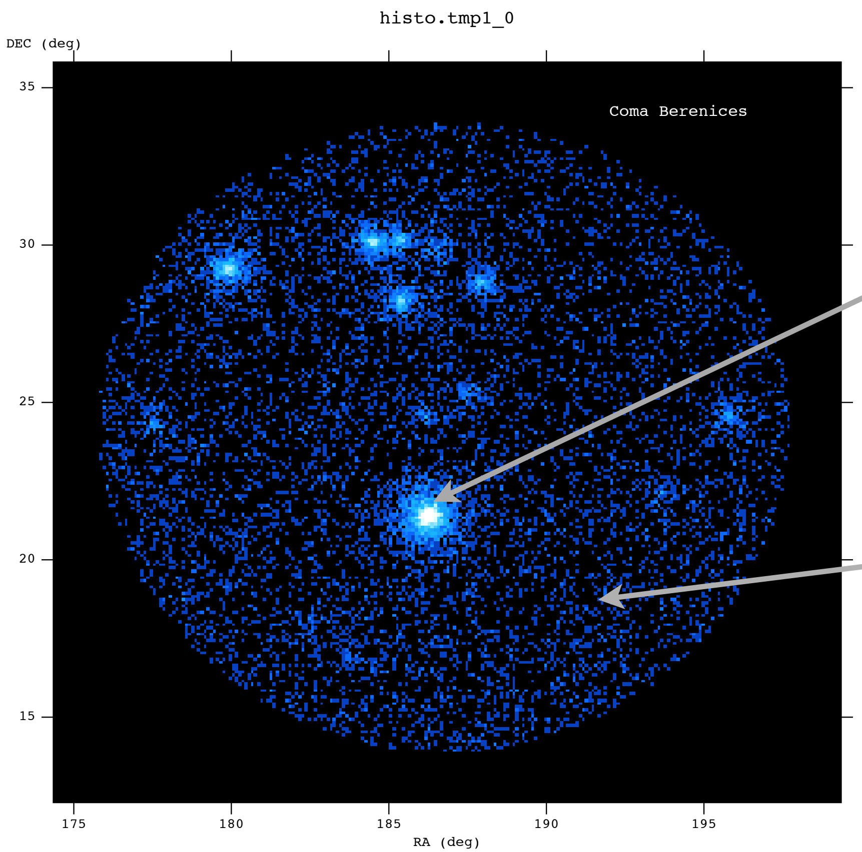
- Model independent

Cons

- One dwarf at a time
- Assumptions on PDFs
- Ignores energy/spatial info
- Ignores DM spectrum
- Choice of ON radius/energy range
- Nearby sources

Profile likelihood method
(e.g Fermi collaboration studies)

1. Construct a theoretical model which in principle characterizes the background
2. Compute the signal/noise ratio (and place bound)



Background at this source

Computed by how much one understands this

Profile likelihood method
(e.g Fermi collaboration studies)

1. Construct a theoretical model which in principle characterizes the background
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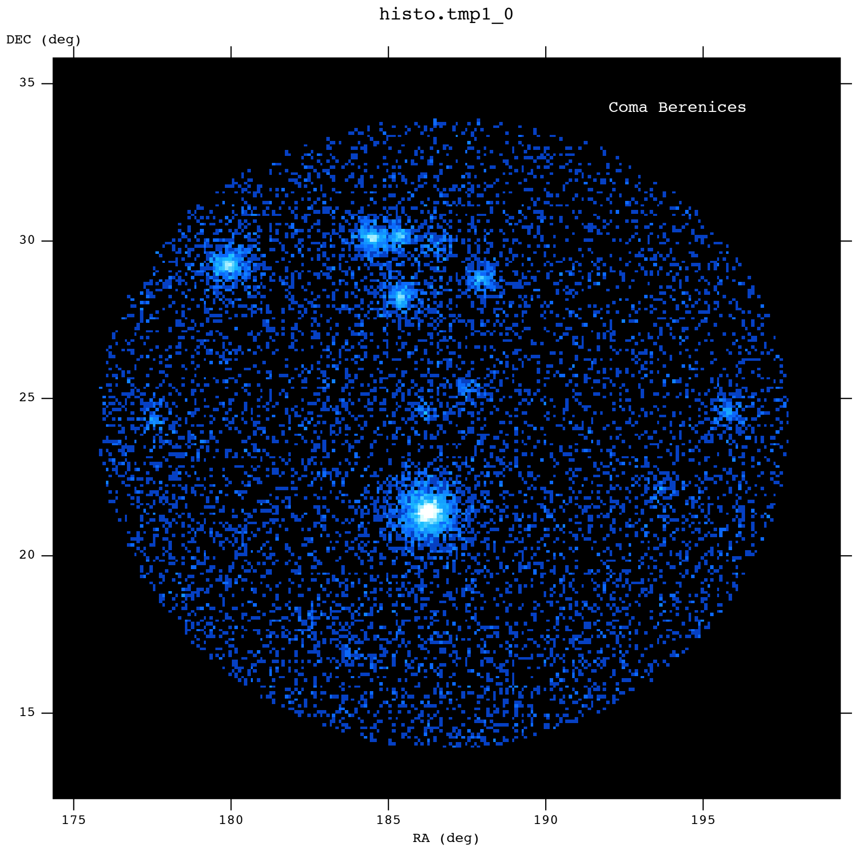
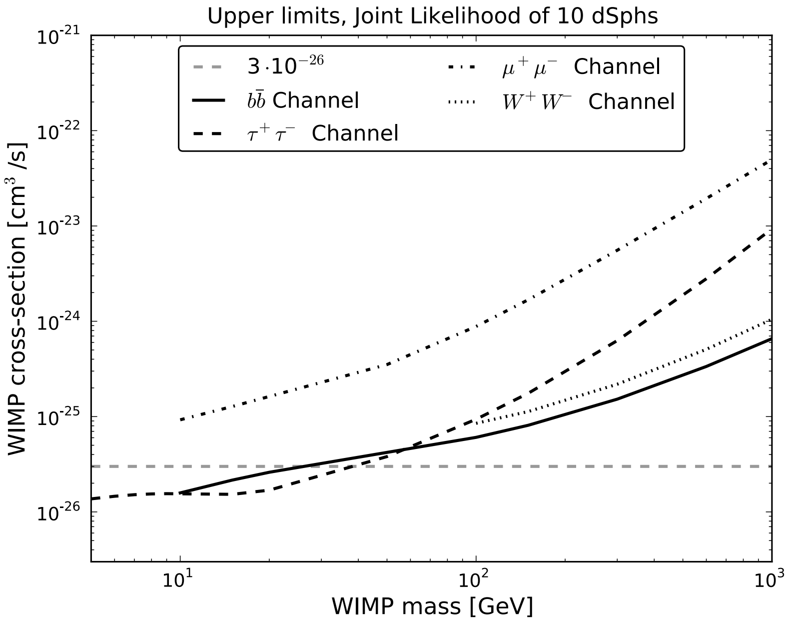


Pros
- Combined analysis of dwarfs is easy
- Uses all information available
- Handles sources, complicated fields of view

Cons
- Model dependent (free parameters)
- Time consuming

Profile likelihood method
(e.g Fermi collaboration studies)

1. Construct a theoretical model which in principle characterizes the background
2. Compute the signal/noise ratio (and place bound)



$$L(D|\mathbf{pw},\{\mathbf{p}\}) = \prod_i L_i^{LAT}(D|\mathbf{pw},\mathbf{p}_i) \times \frac{1}{\ln(10)\, J_i \sqrt{2\pi}\sigma_i} e^{-\left(\log_{10}(J_i) - \overline{\log_{10}(J_i)}\right)^2/2\sigma_i^2}, \quad (1)$$

- Fixed size of Region of Interest
- No spatial information
- No spectral information

Photon weighting

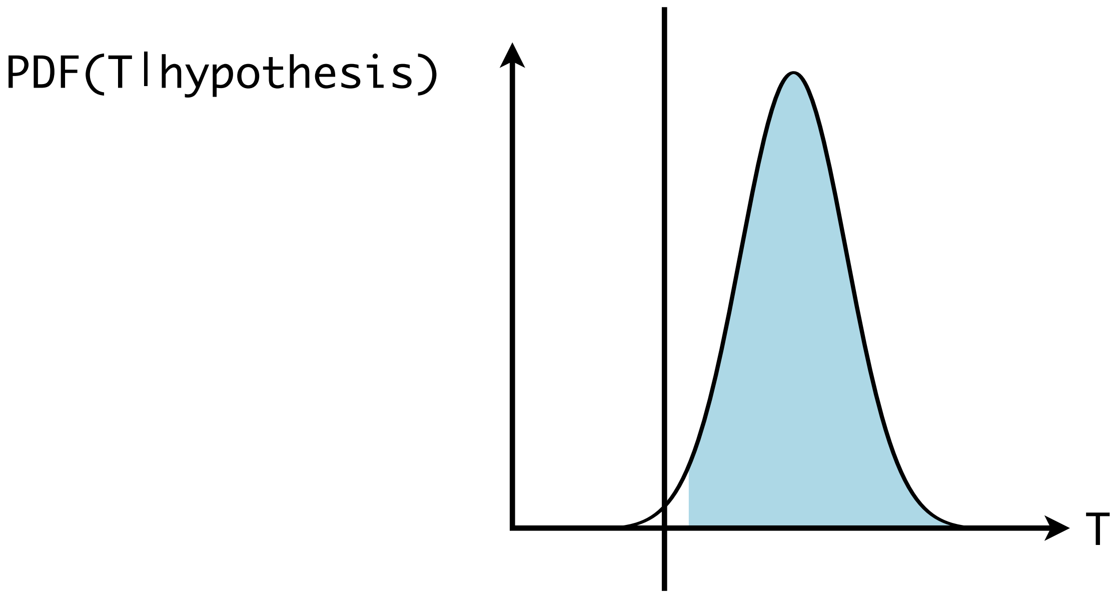
Alex Geringer-Sameth & Koushiappas, PRL 107,241303, 2011 & PRD 86, 021302(R) 2012.

Searches/Limits = Hypothesis testing

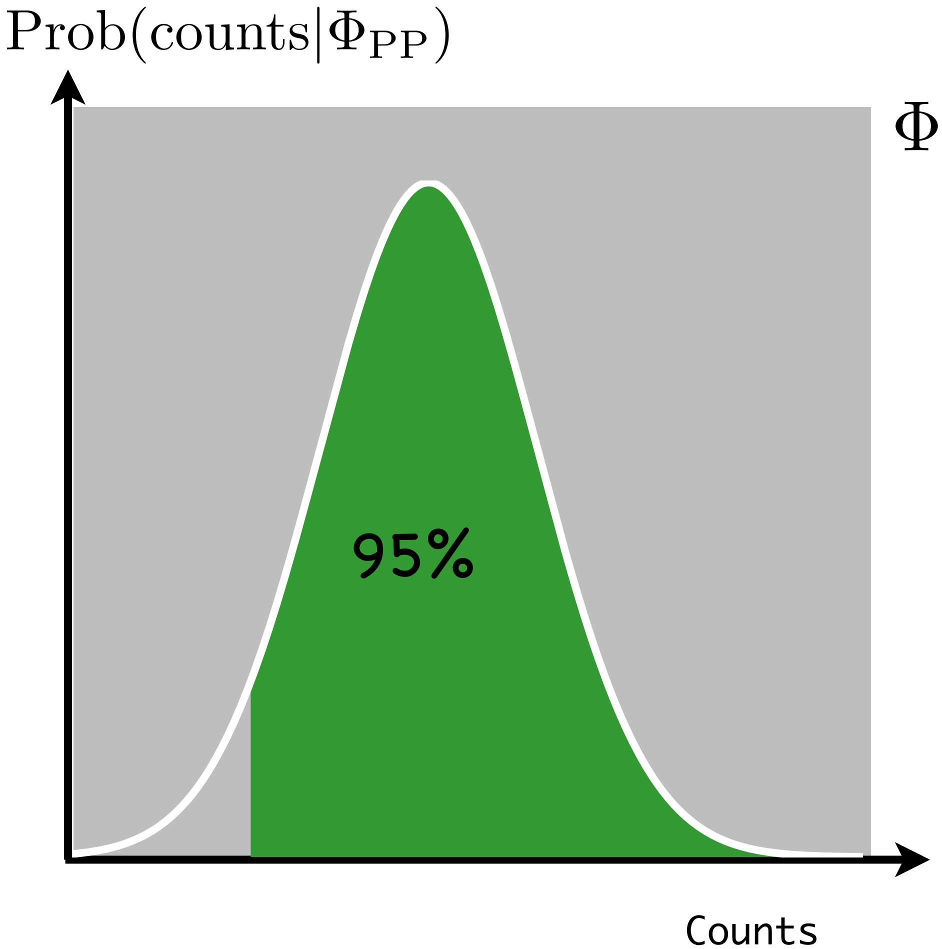
Data ⟶ Test statistic, T

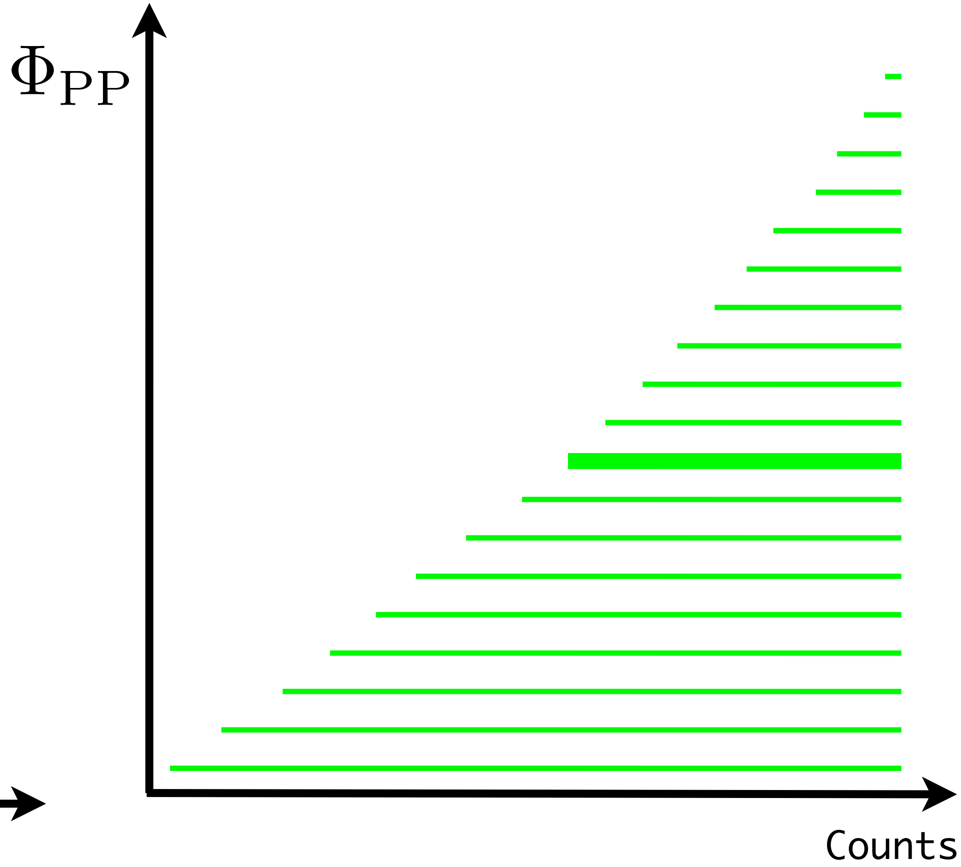
(many numbers) (one number)

e.g. T = { number of photons (ON/OFF)
LR (profile likelihood)



Multi-dimensional Neyman Construction





Alex Geringer-Sameth & Koushiappas, PRL 107,241303 (2011) 1108.2914

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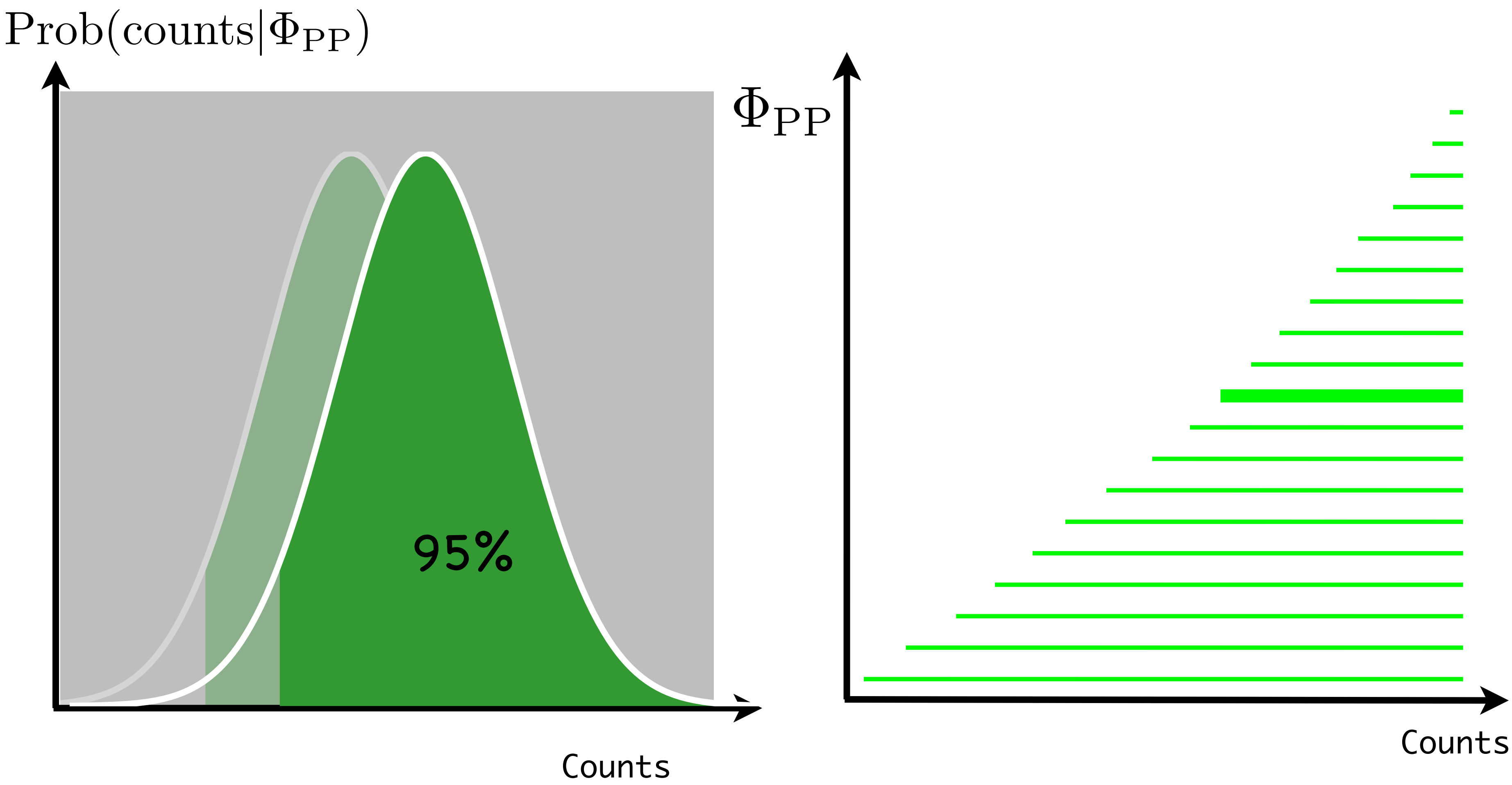

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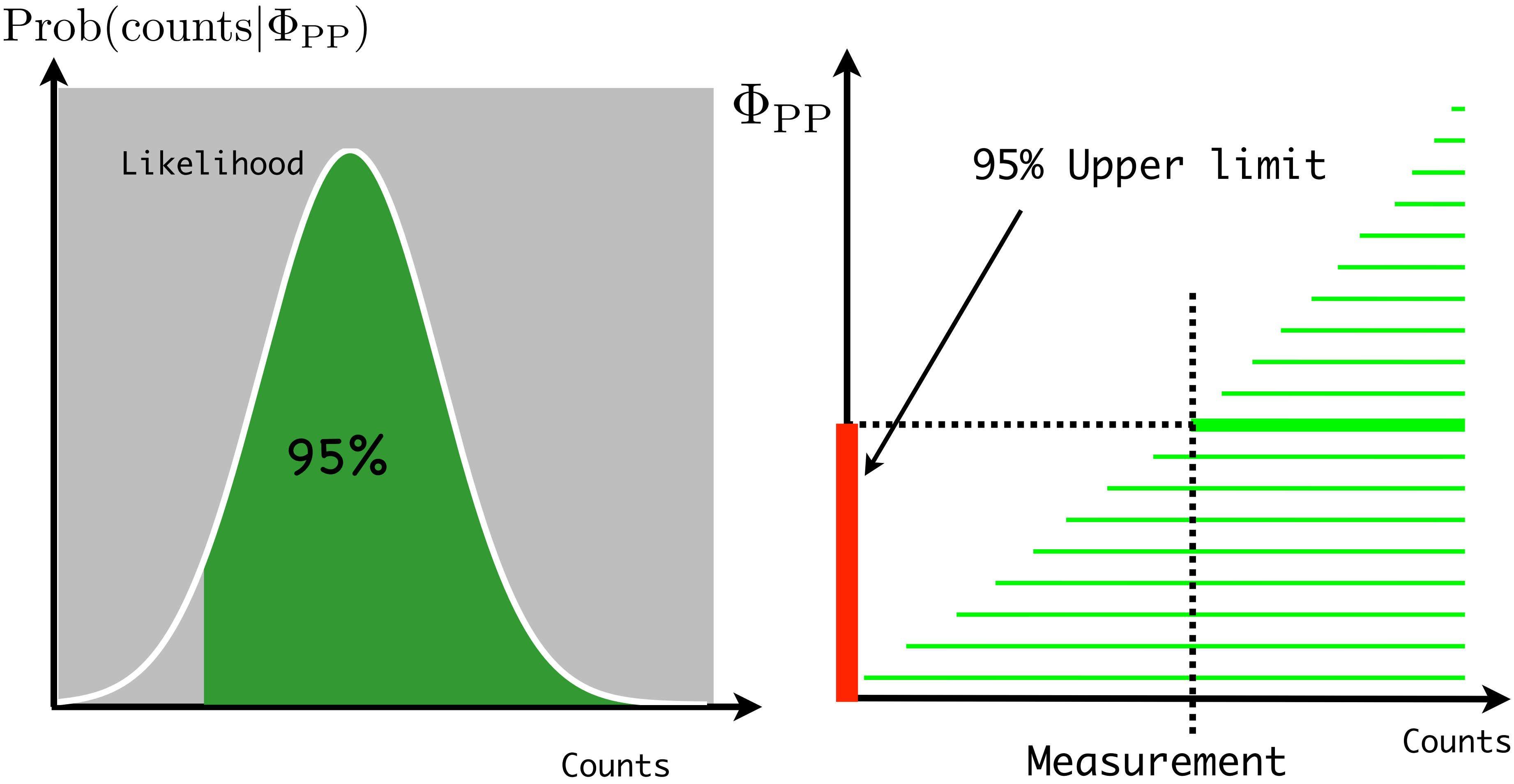
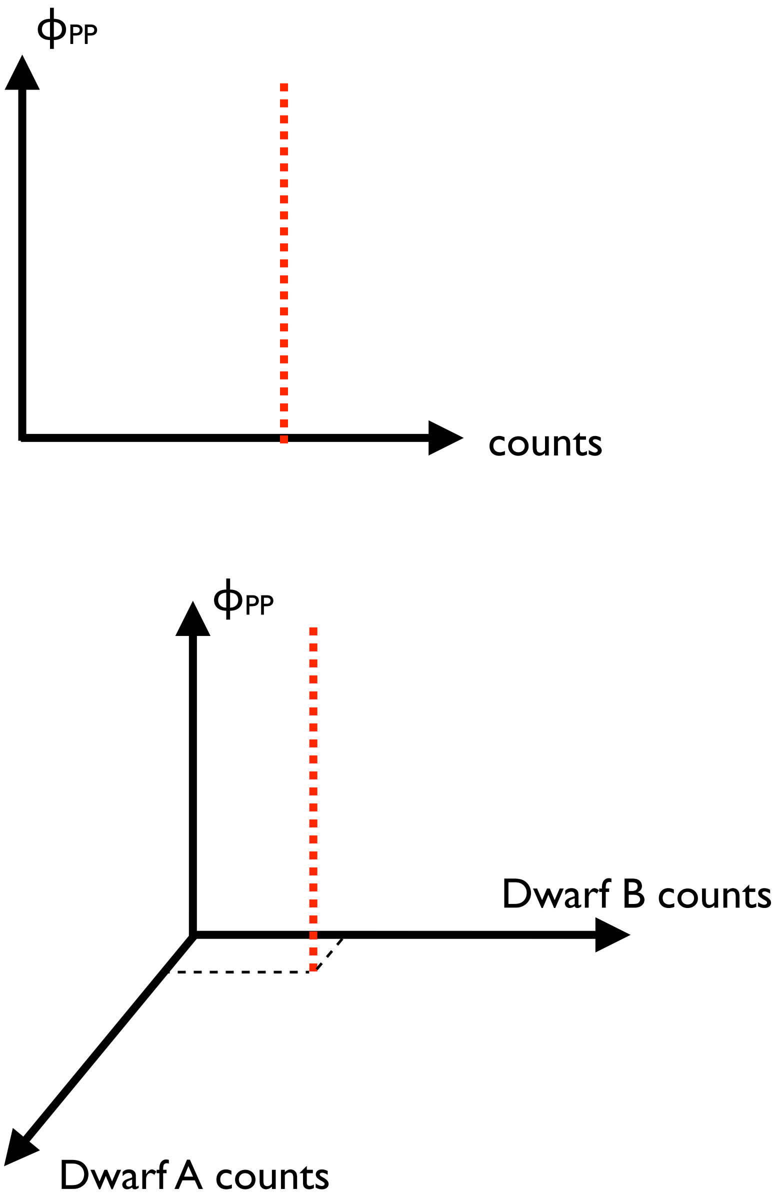
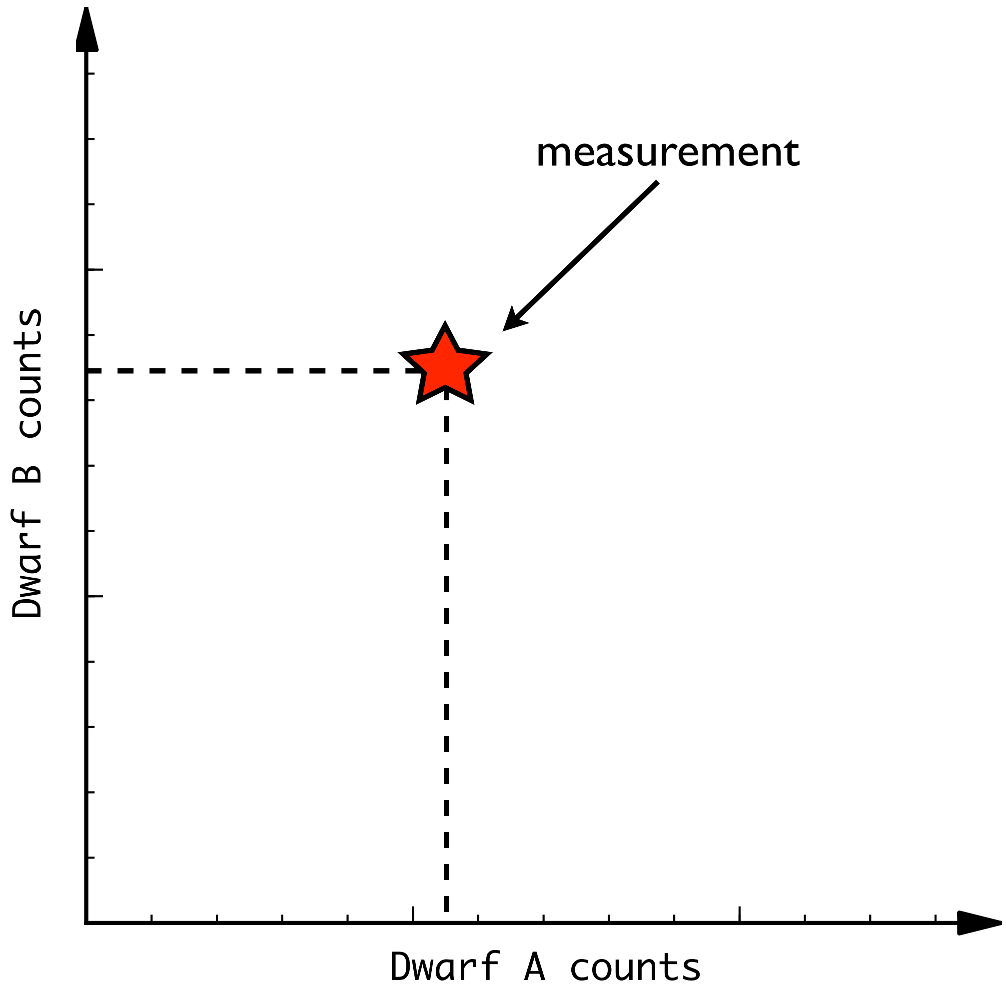


Alex Geringer-Sameth & Koushiappas, PRL 107,241303 (2011) 1108.2914

Combining observations of dwarfs





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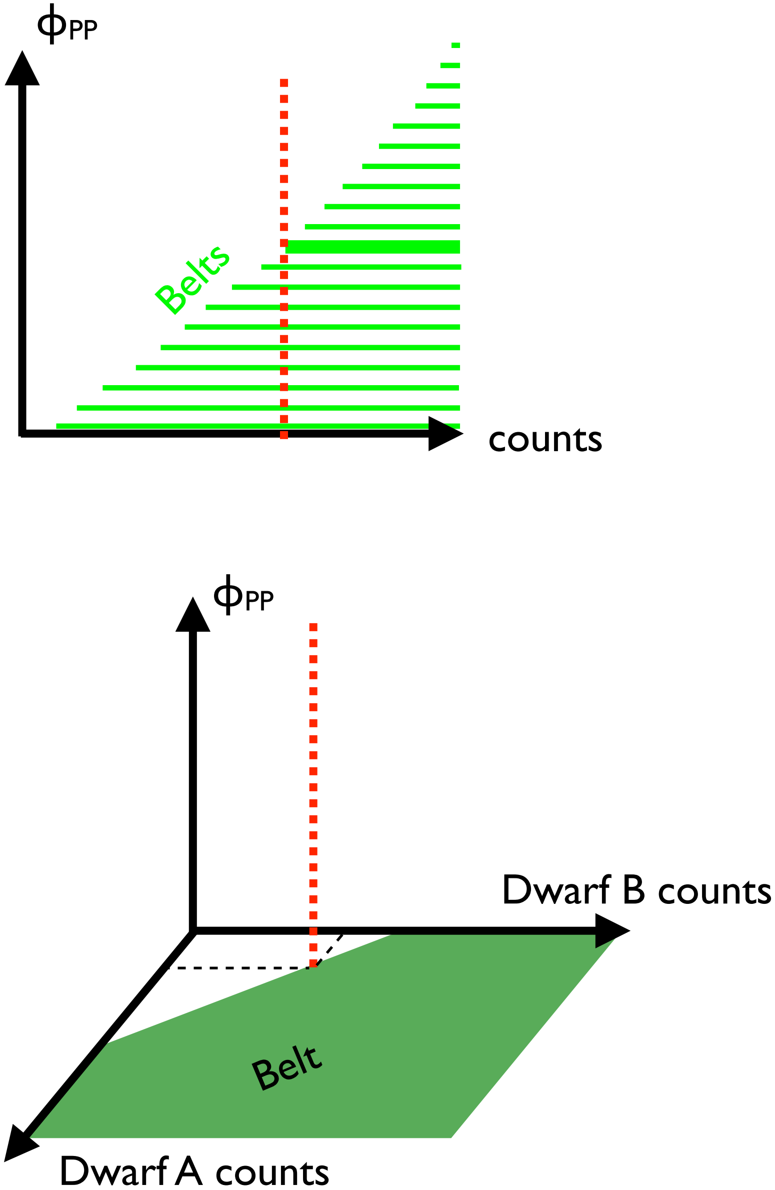

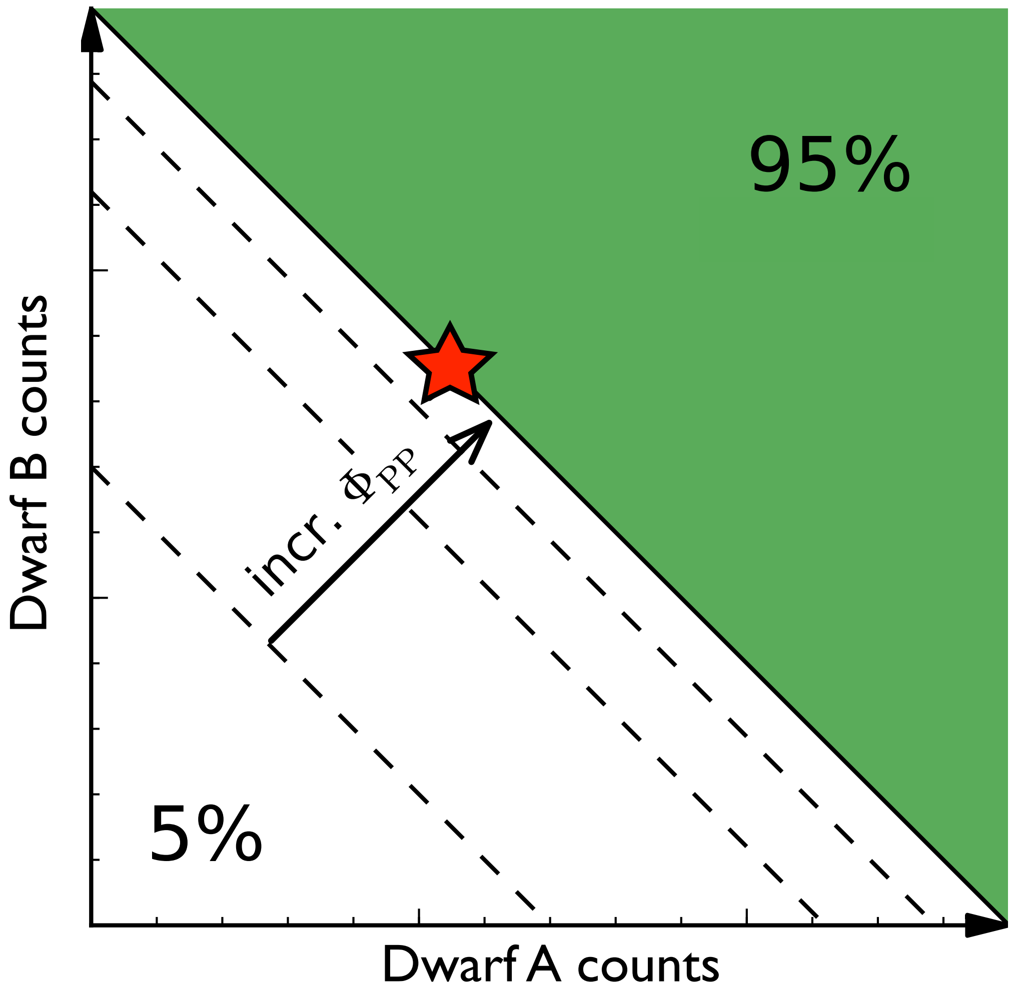

Alex Geringer-Sameth & Koushiappas, PRL 107,241303 (2011) 1108.2914

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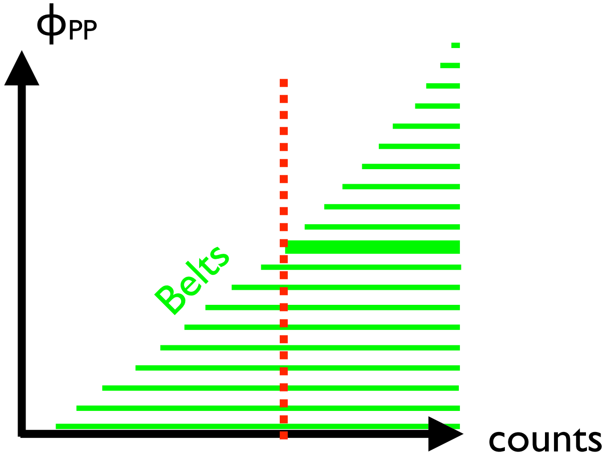

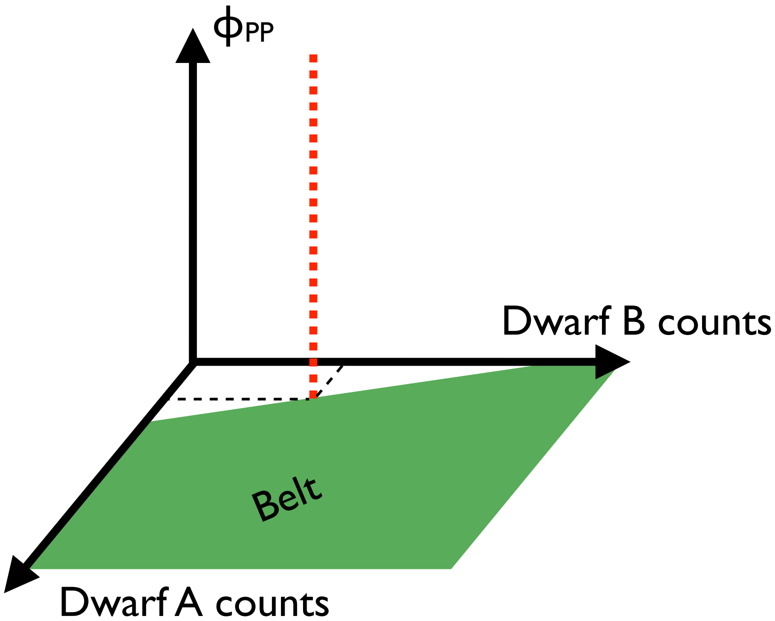

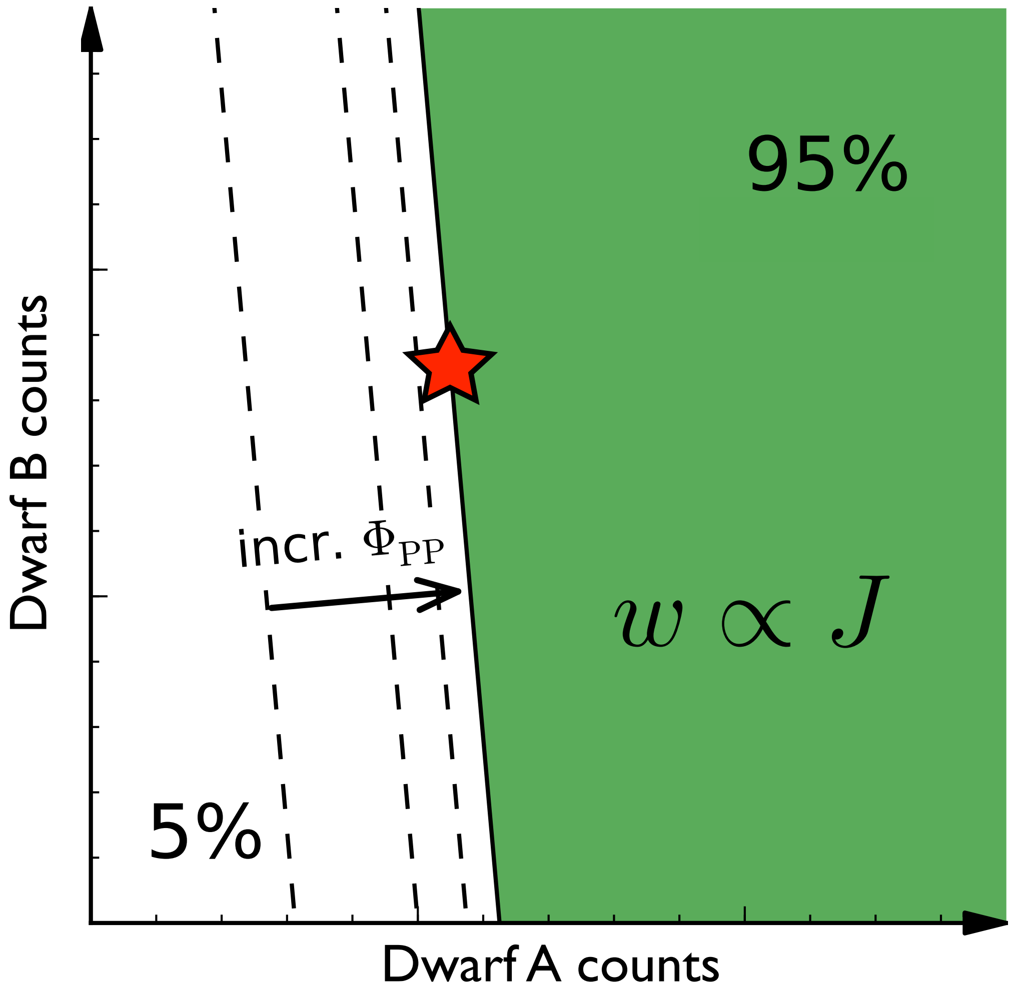

See Sutton, Classical and Quantum Gravity, 26, 245007 (2009)

Alex Geringer-Sameth & Koushiappas, PRL 107,241303 (2011) 1108.2914

Choosing a test statistic

Weight dwarfs according to expected signal and expected background

observed counts

$$T = \sum_{i \in \mathrm{dwarfs}} w_i N_i$$

$$w_i \propto \frac{\mathrm{exposure} \times J}{\mathrm{background}}$$

Geringer-Sameth & SMK, PRL 107,241303, 2011

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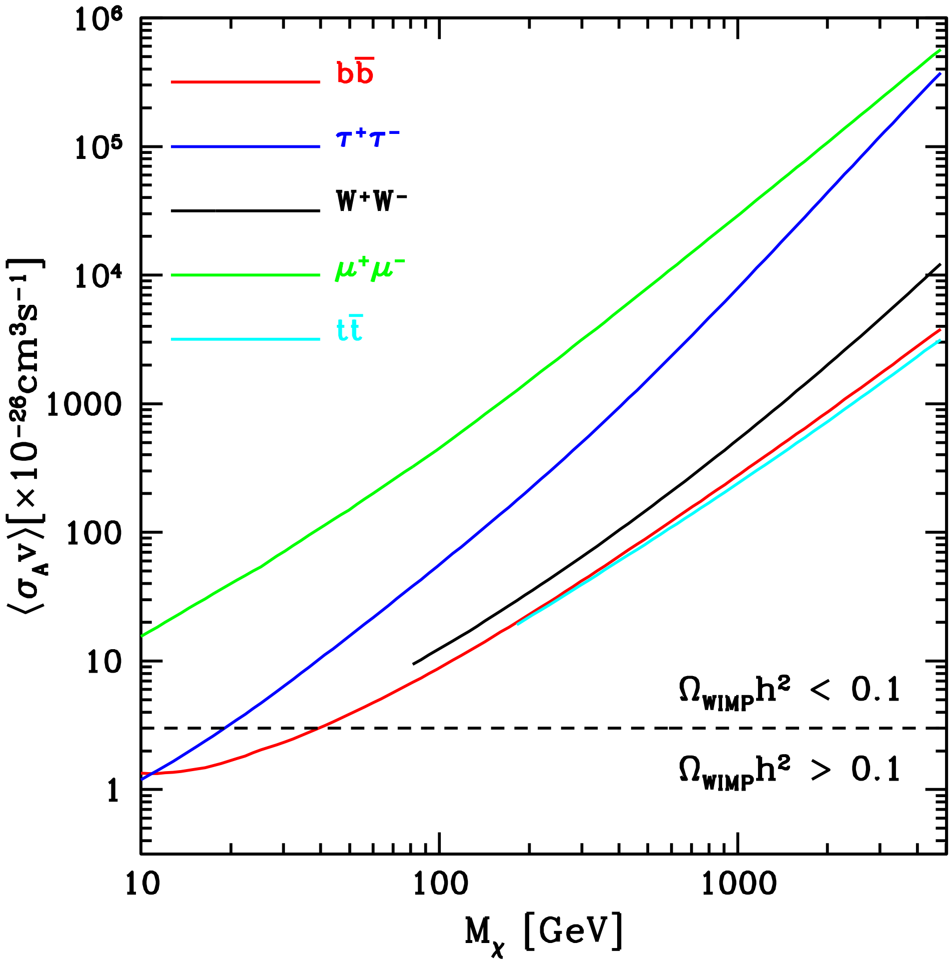

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Include spatial, spectral, instrumental information:

Each photon gets a weight

$$T = \sum_{i \in \text{photons}} w(Q_i)$$

sum over all events from all dwarfs

Weight of photon is based on:

- Which dwarf it came from
- Energy
- Angular separation from location of dwarf

} Q_i

Geringer-Sameth & SMK, PRL 107,241303, 2011

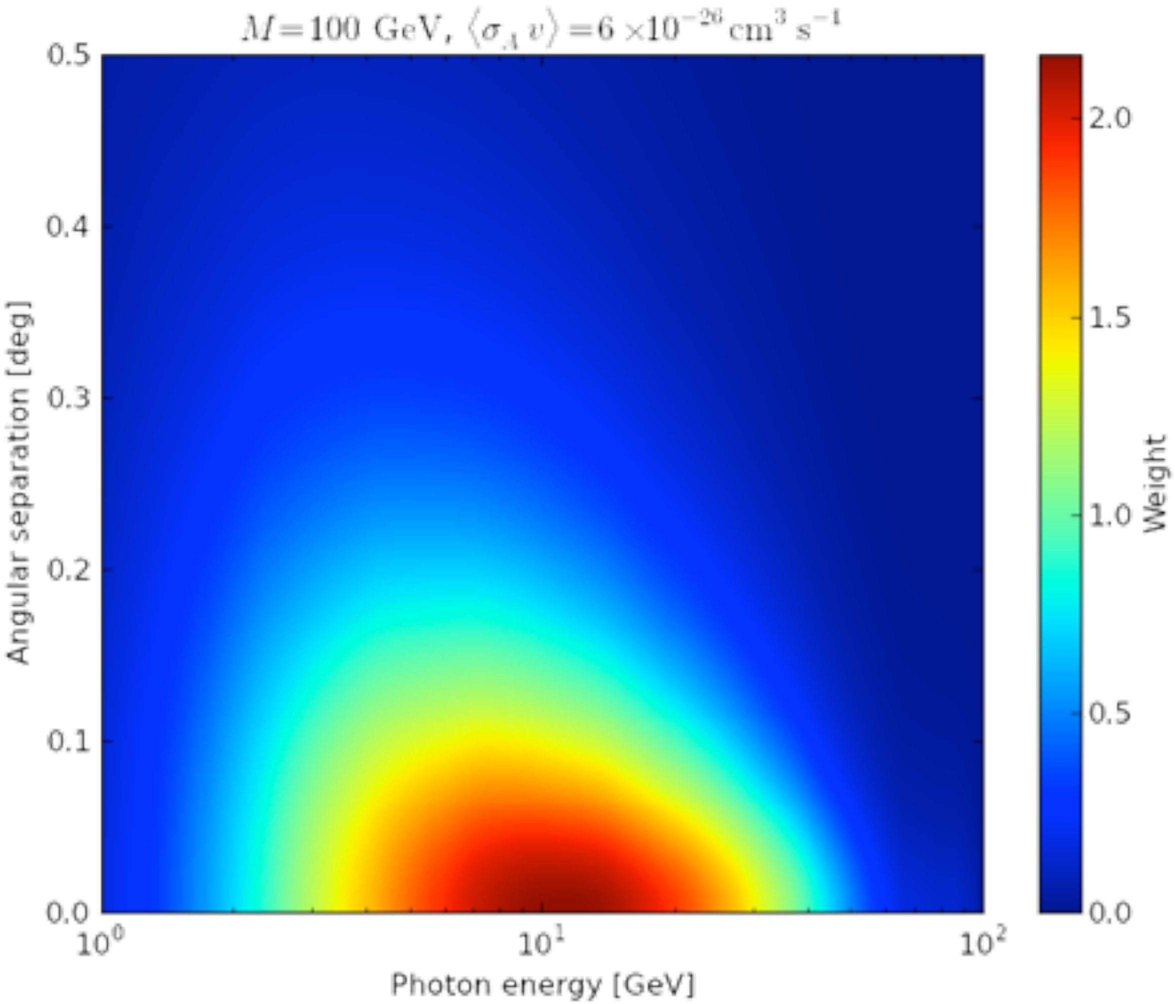
Geringer-Sameth & SMK, PRD 86, 021302(R), 2012

Choosing weights

$$w_Q = \log\left(1 + \frac{s_Q}{b_Q}\right)$$

signal

background

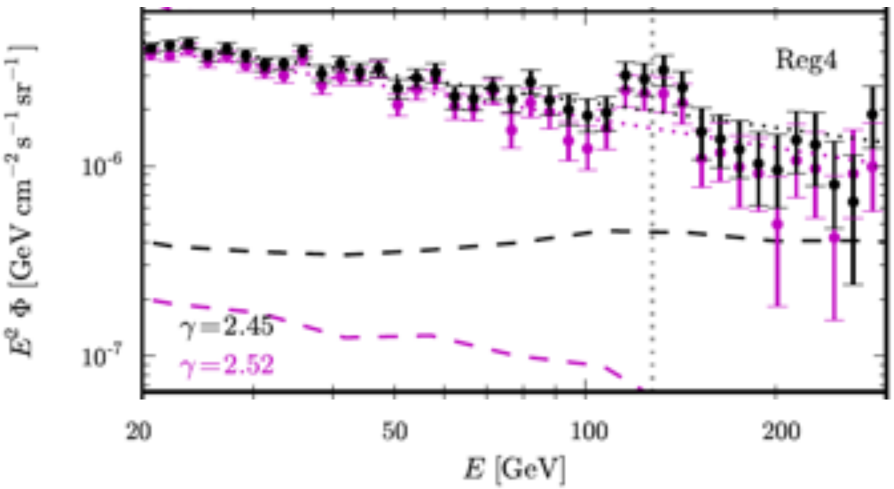


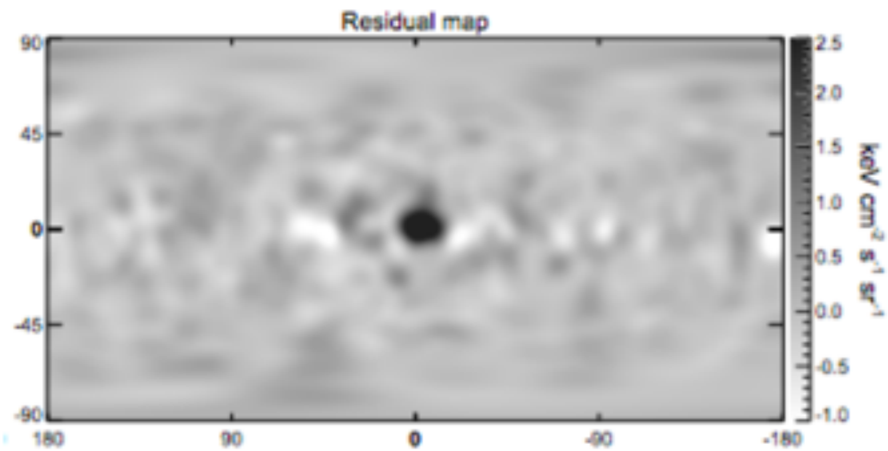
INGREDIENTS

DM annihilation spectrum
+
Instrument response (effective area, PSF)
+
astrophysical background

The 130 GeV line

Weniger, arXiv:1204.2797

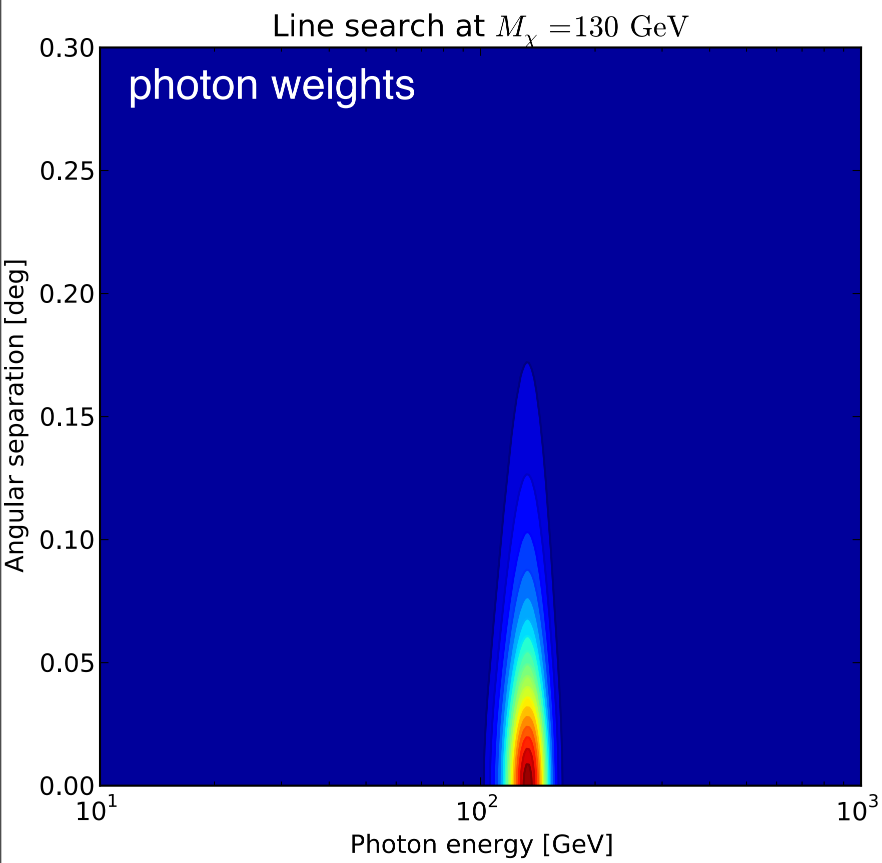


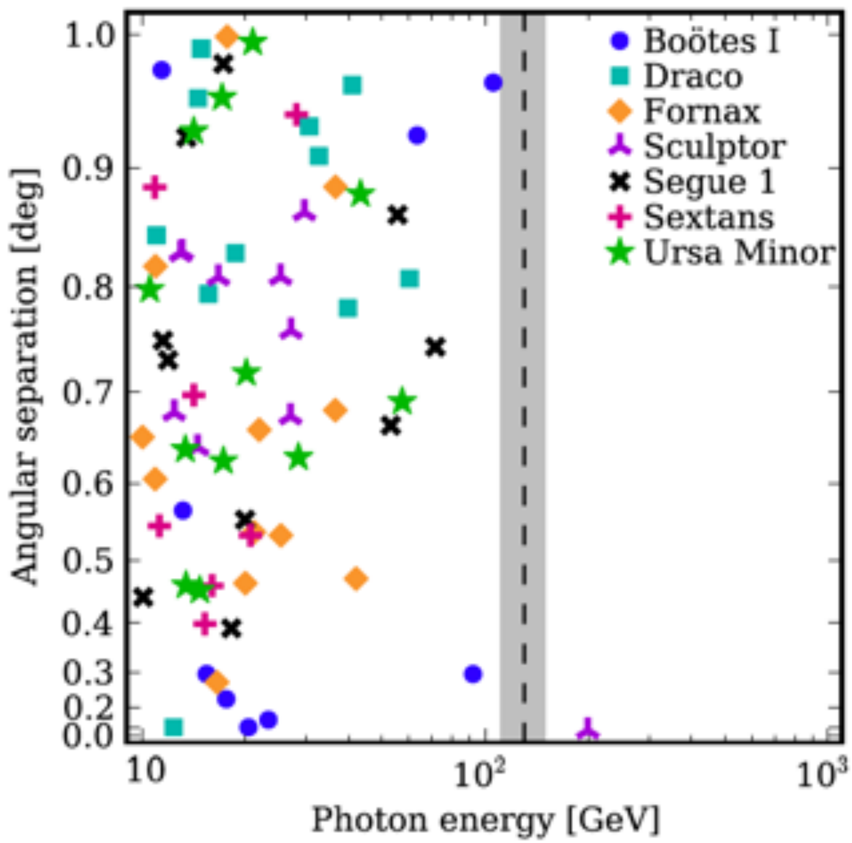


Su & Finkbeiner, arXiv:1206.1616

- Tough to explain with known astrophysics
- Peak is 200 pc away from GC
- Need a very large cross-section
- What about the Earth's limb?
- Could it be systematic?

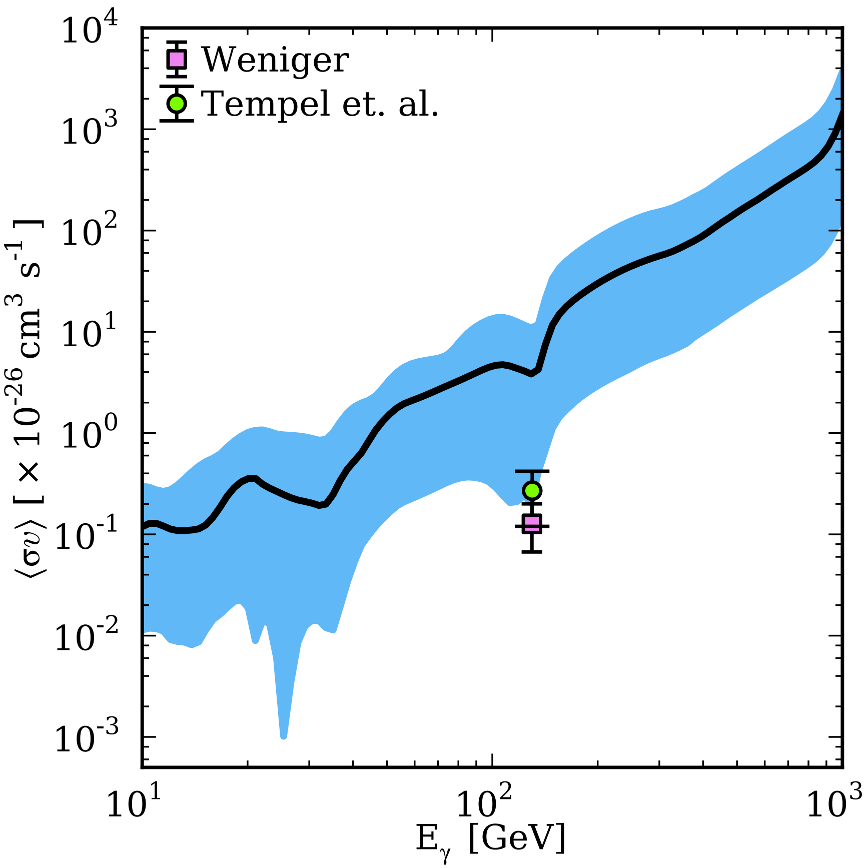
Change DM spectrum: optimal weights for a line search

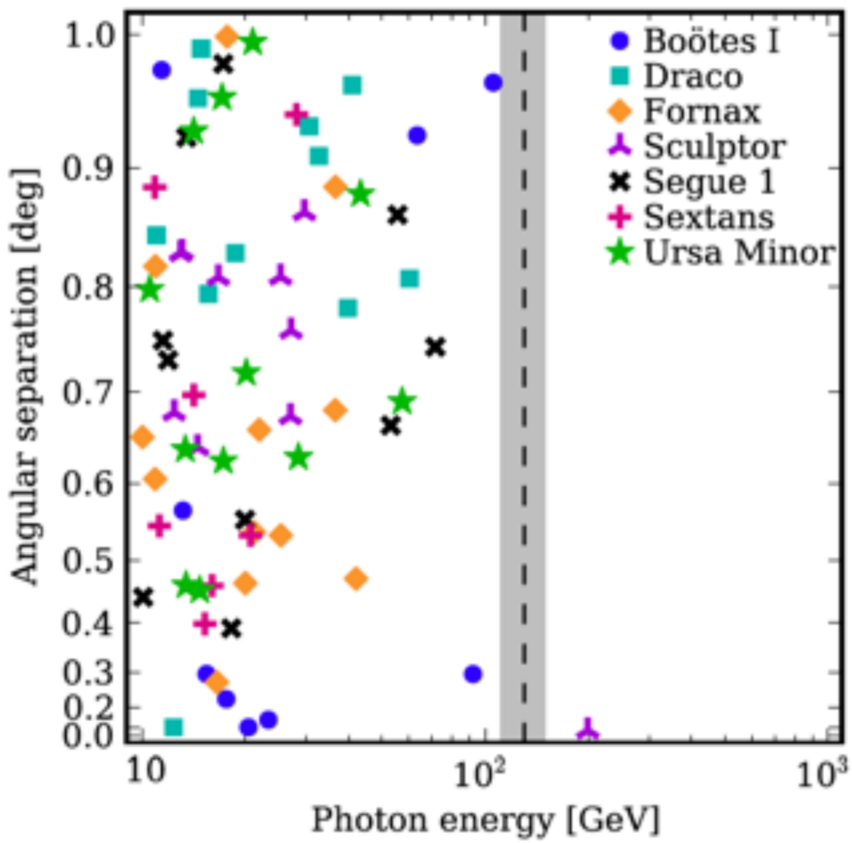




Geringer-Sameth & SMK, PRD 86, 021302(R), 2012

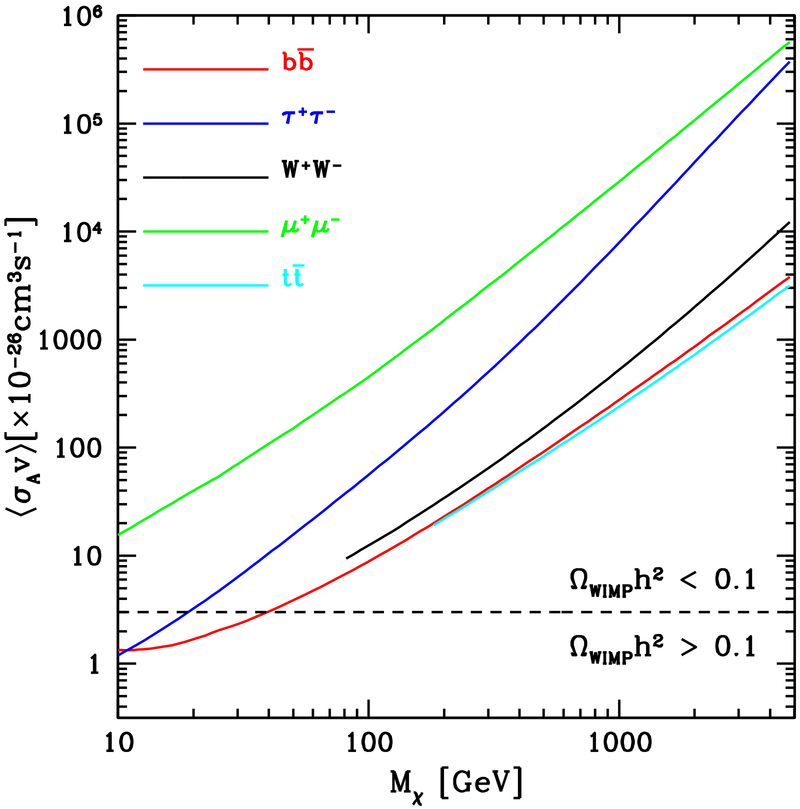
Change DM spectrum: optimal weights for a line search

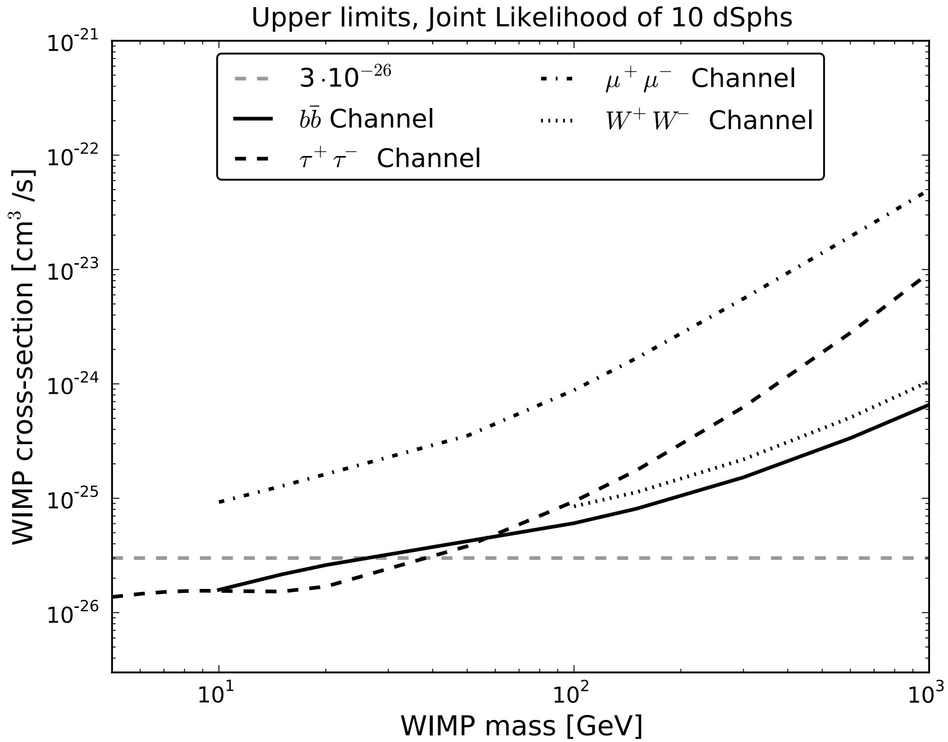




Geringer-Sameth & SMK, PRD 86, 021302(R), 2012

Predicting the future





Stay tuned for results in the high-mass (>TeV) regime using a staked dwarf analysis with ***VERITAS***...