Future spectroscopic survey and dark matter constraints from dwarf spheroidal galaxies

(In preparation)

Koji Ichikawa

In collaboration with
Kohei Hayashi , Masahiro Ibe, Miho N. Ishigaki,
Shigeki Matsumoto and Hajime Sugai.

KAVLI IPMU

PPP2015, Kyoto, Sep. 14-18, 2015

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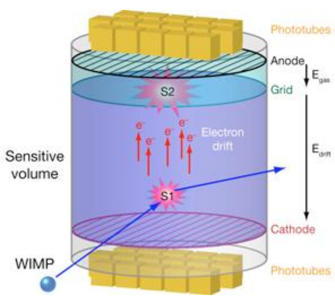
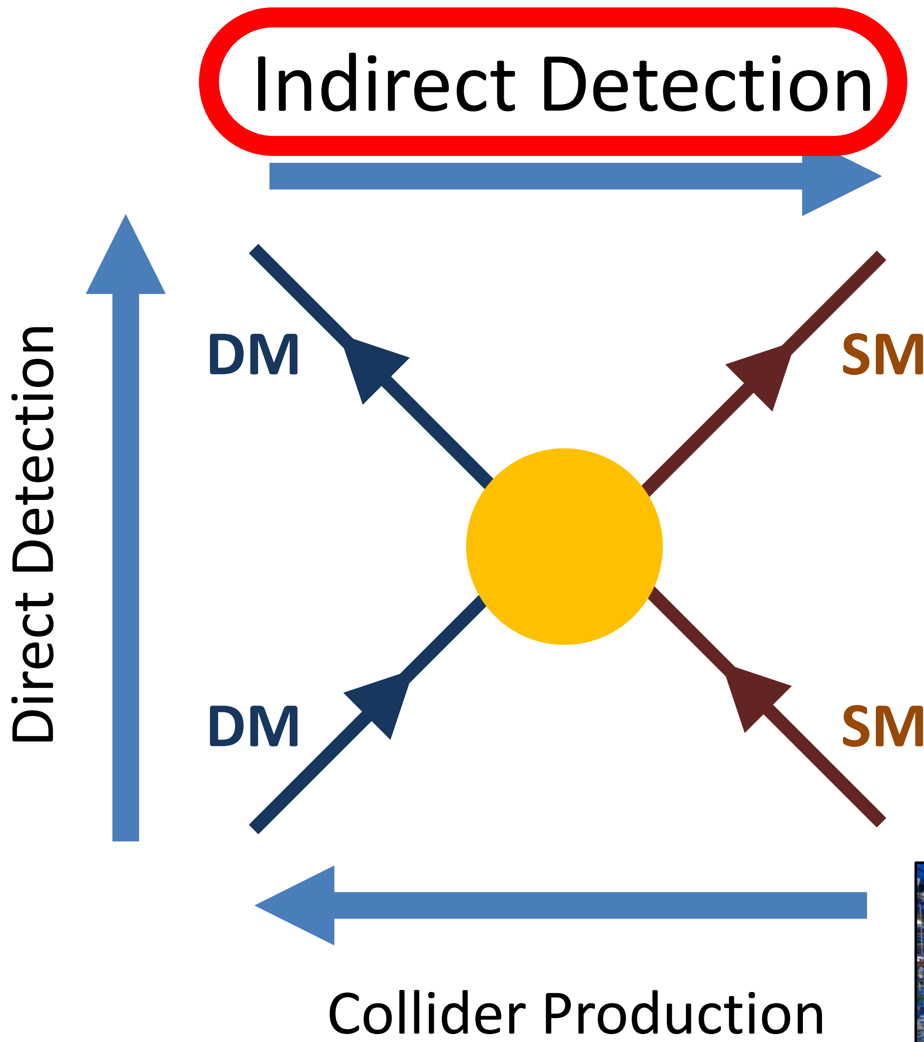
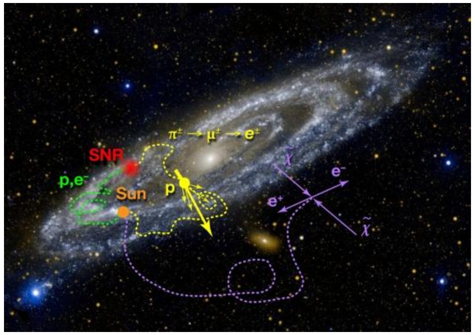
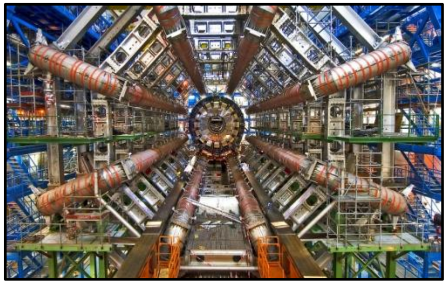
Dark Matter Search

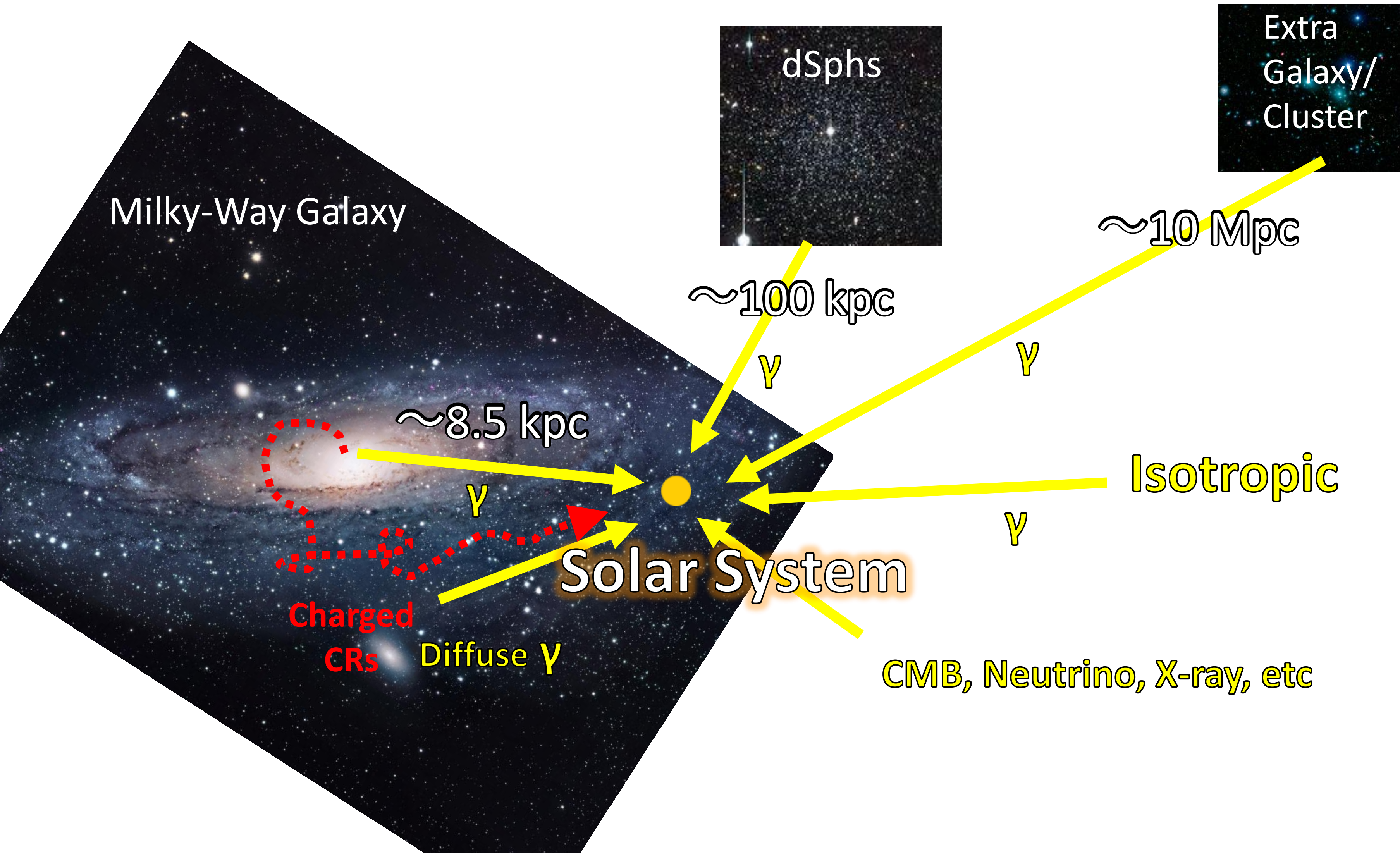




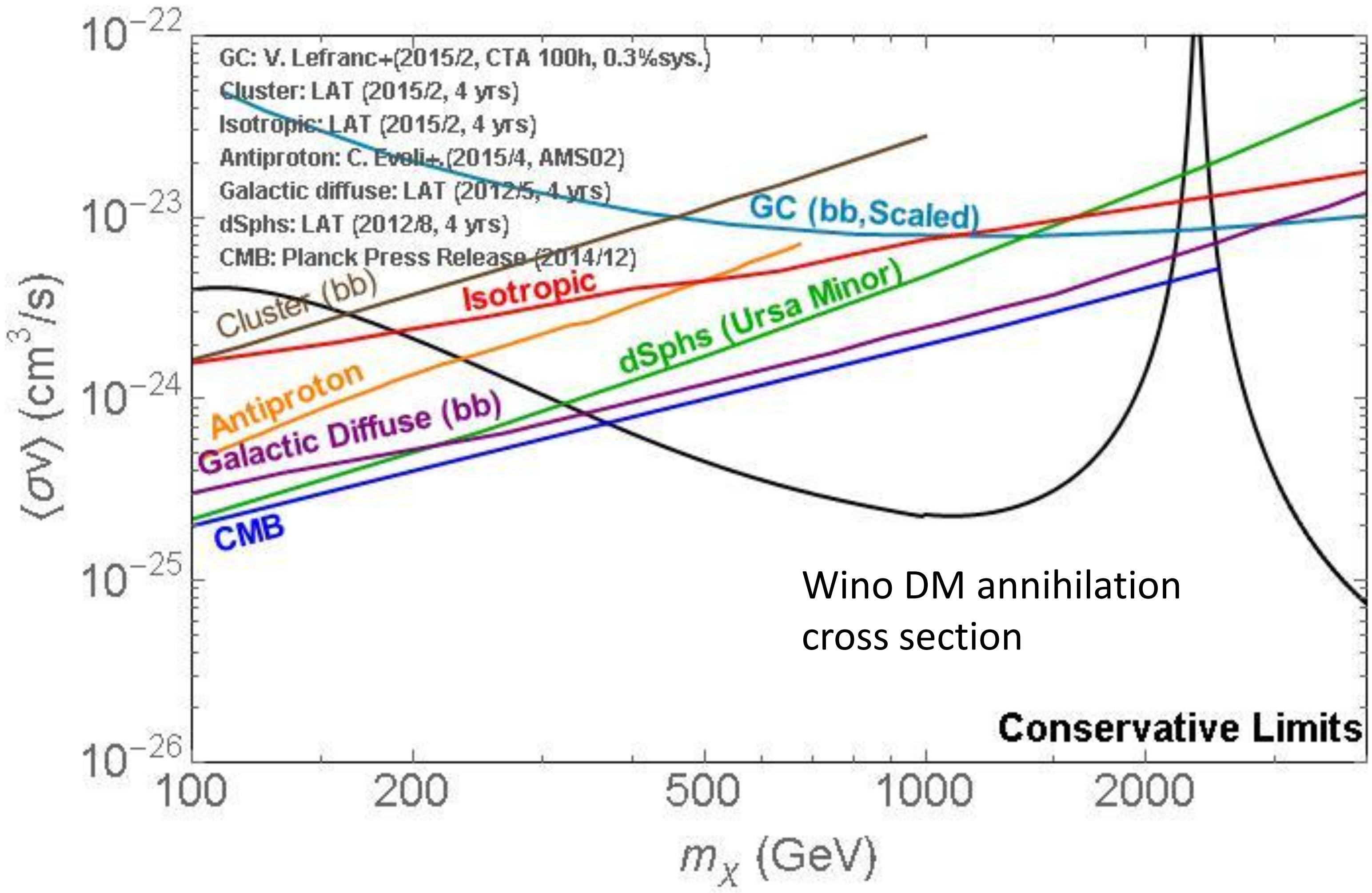




Signal Target



Current(slightly old) observational limit



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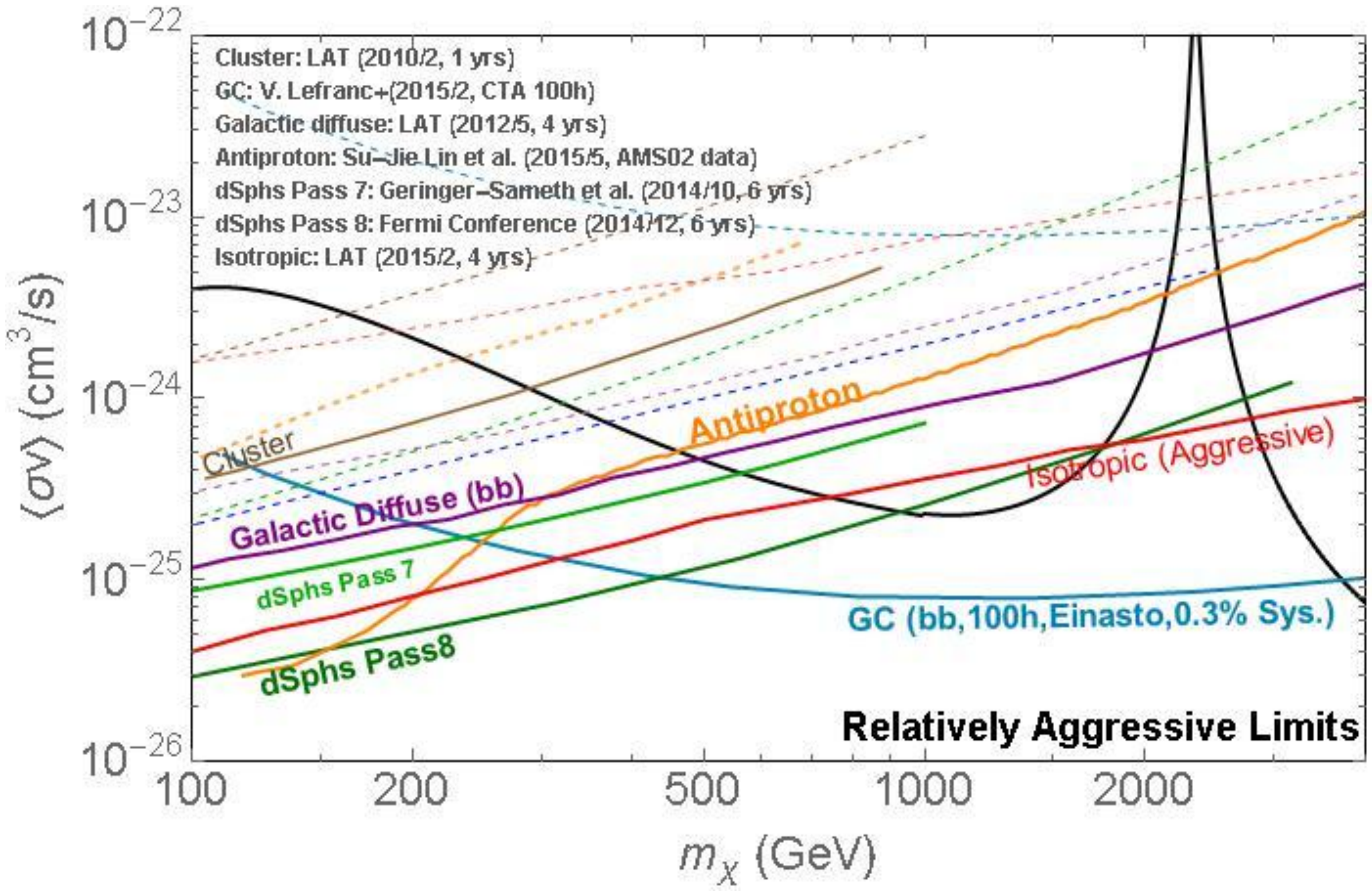

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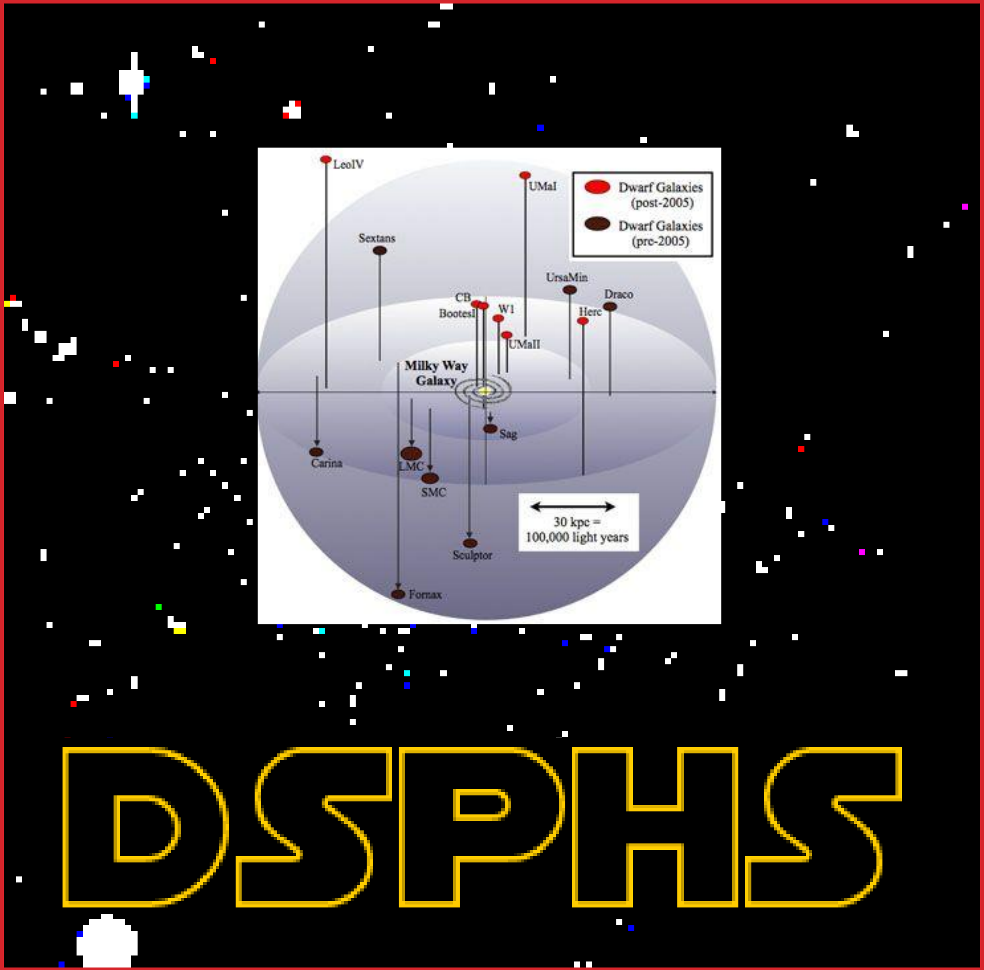
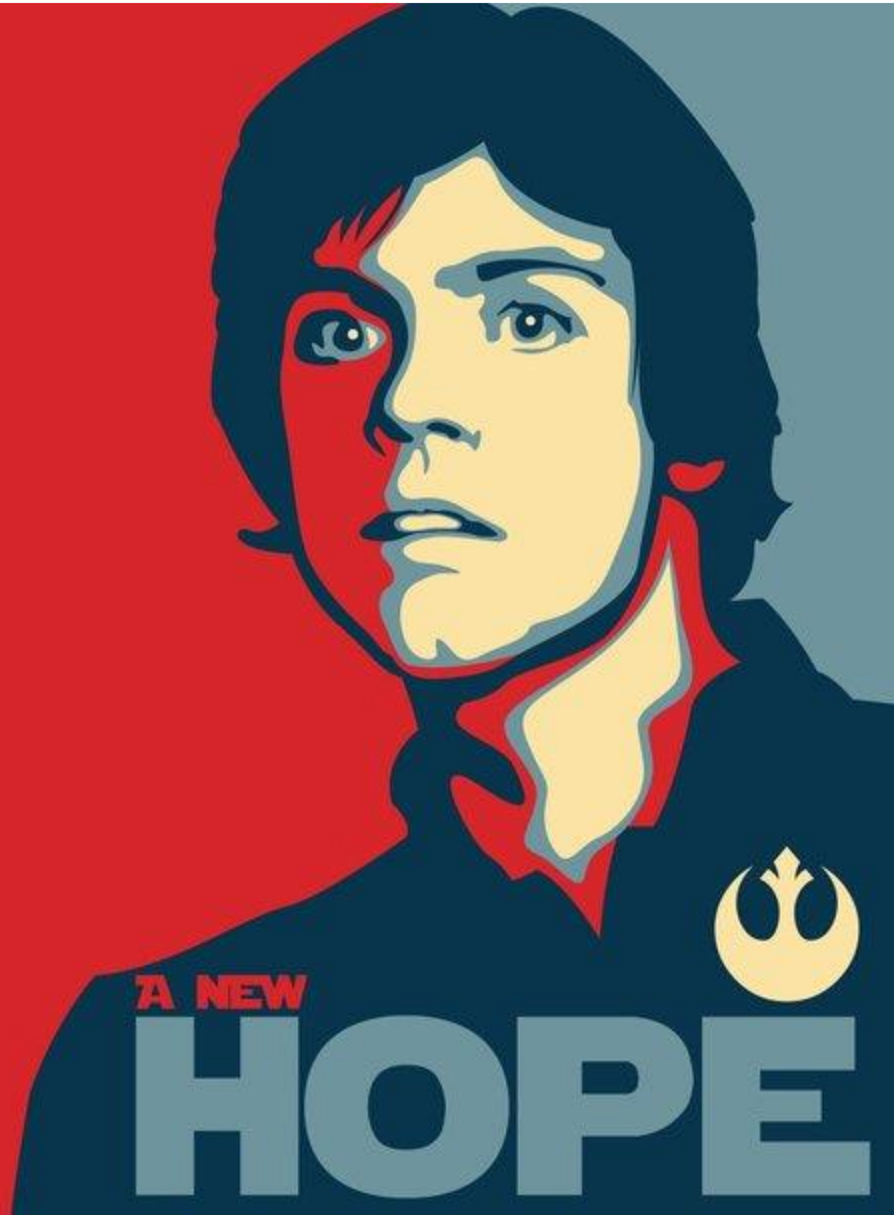
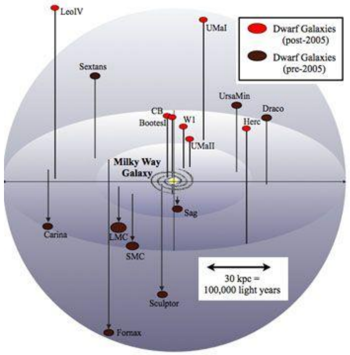




Dwarf spheroidal galaxies

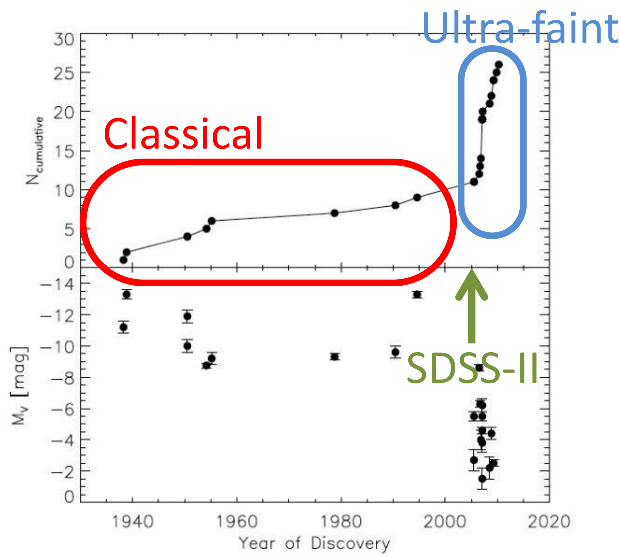
dSphs:

1. **Neighbor** galaxies: 10~100kpc
2. Large Mass to Luminosity ratio = **DM rich**
3. Fewer gas containment



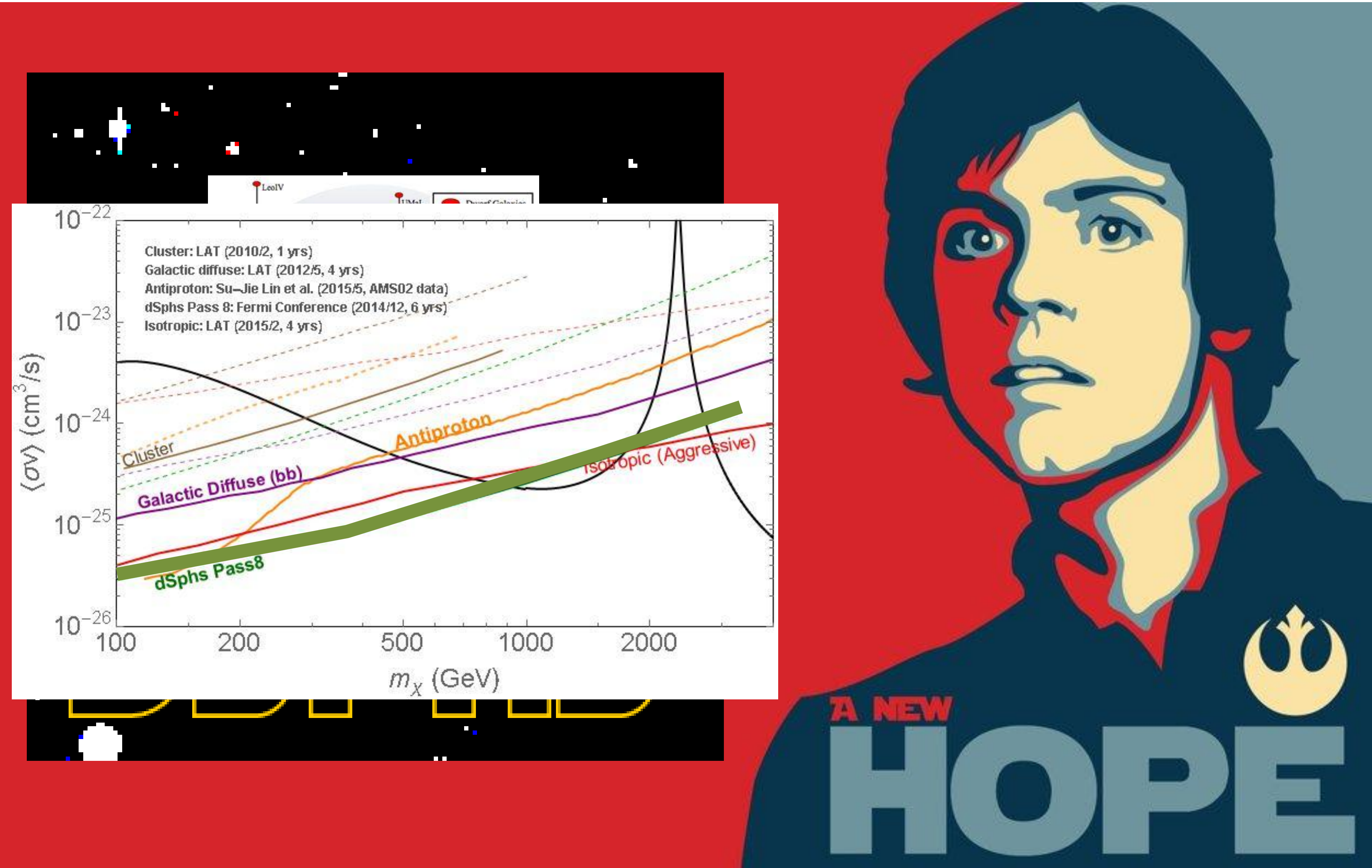
	Classical	Ultra-faint
#dSphs	8	>20
M/L ($M_\odot/L_\odot$)	10-100	100-1000
Distance (kpc)	60-250	10-60
#Obs Stars	150-2500	20-100
Characteristics	Brighter, farther	Darker, closer

See, e.g. Wolf et al (2010)



arXiv:0908.2995v6 [astro-ph.CO]

Current observational limit



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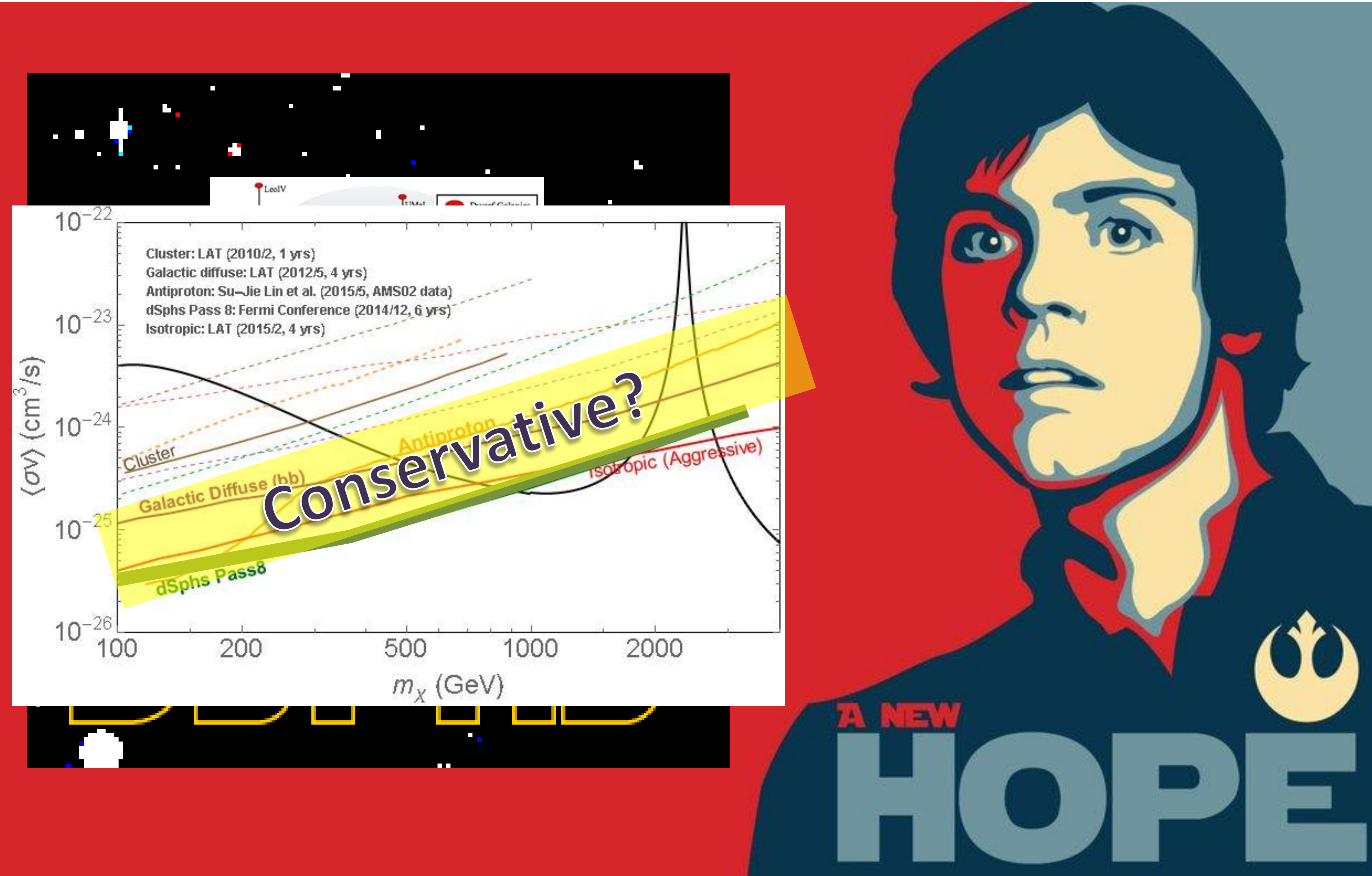


Signal Flux

$$\Phi(E,\Delta\Omega) = \left[\frac{\langle\sigma v\rangle}{8\pi m_{\tilde{w}}^2}\sum_f \mathrm{Br}(\tilde{w}^0\tilde{w}^0 \to f)\left(\frac{dN_\gamma}{dE}\right)_f\right]\left[\int_{\Delta\Omega} d\Omega \int_{l.o.s.} dl\,\rho^2(l,\Omega)\right]$$

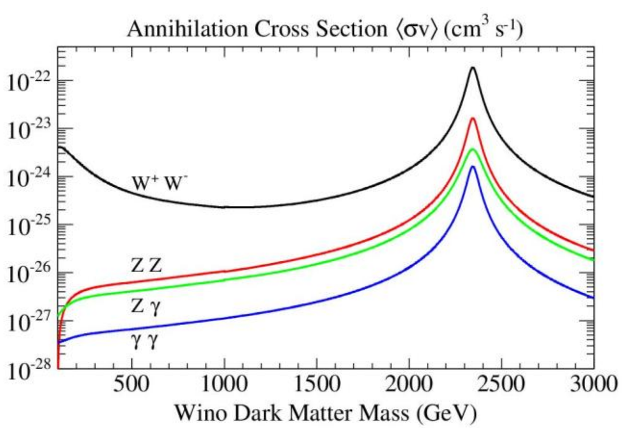
Particle Physics Factor

Astrophysics Factor (J-factor)

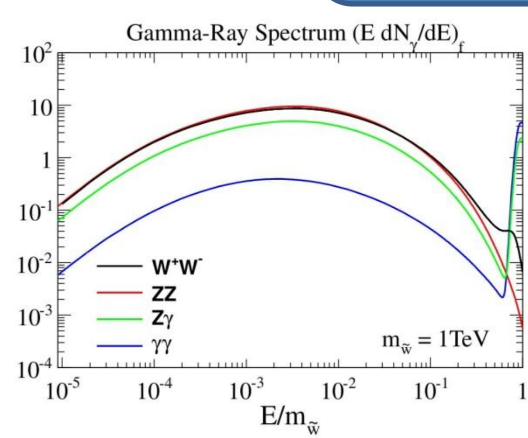
$f = WW, ZZ, \gamma\gamma, Z\gamma$ Error: 1-10 % level

Large uncertainty: Next Slide

$$J \simeq \frac{1}{D^2}\int_{\mathrm{Vol}} r^2\rho^2(r)\mathrm{d}r$$



Hryczuk and Iengo (2012)
arXiv:1111.2916v4 [hep-ph]



Cirelli et al. (2012)
arXiv:1012.4515 [hep-ph]

Astrophysical Factor

DM Density profile

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

$\rho_s(r/r_s)^{-1}(1+r/r_s)^{-2}$ Cusp

$\rho_s(1+r/r_s)^{-1}(1+r/r_s)^{-2}$ Cored

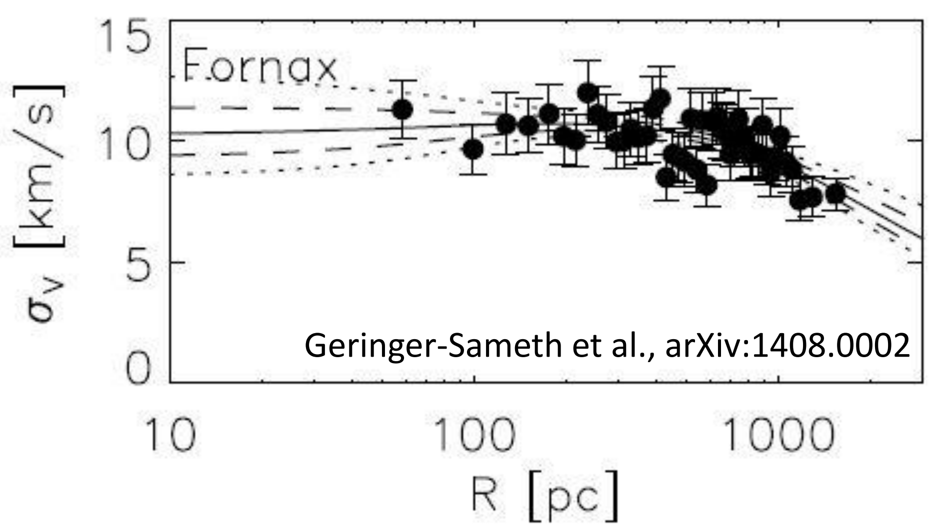
Stellar Density Profile: ν(r)

Jeans equation for stars

$$\frac{1}{\nu}\frac{d}{dr}(\nu \bar{v_r^2}) + 2\frac{\beta(r)\bar{v_r^2}}{r} = -\frac{GM(r)}{r^2}$$

$\sigma_{\mathrm{l.o.s}}^{2\,(\mathrm{Theory})}$ ⟷ $\sigma_{\mathrm{l.o.s}}^{2\,(\mathrm{obs})}$

Fit



$$P(\theta|D) \propto P(D|\theta)P(\theta)$$

$$\sim \prod_{i}^{\mathrm{samples}} \exp\left[-\frac{(\sigma^2_{\mathrm{obs}}(r_i) - \sigma^2_{\mathrm{theory}}(r_i,\theta))^2}{2\delta^2}\right]$$

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Fit

		long. (deg.)	lat. (deg.)	dist. (kpc)	α_s (deg.)	$\log_{10}[J(0.5°)/(\mathrm{GeV^2cm^{-5}sr})]$
Classical: Well-determined	Draco	86.4	34.7	76	$0.25^{+0.15}_{-0.09}$	18.8 ± 0.16
	Ursa Min.	105.0	44.8	76	$0.32^{+0.18}_{-0.12}$	18.8 ± 0.19
	Sculptor	287.5	-83.2	86	$0.25^{+0.25}_{-0.13}$	18.6 ± 0.18
	Sextans	243.5	42.3	86	$0.13^{+0.07}_{-0.05}$	18.4 ± 0.27
Ultra-faint: Not well-determined. Prior dependence	Segue 1	220.5	50.4	23	$0.40^{+0.86}_{-0.27}$	*19.5 ± 0.29*
	Ursa Maj. II	152.5	37.4	32	$0.32^{+0.48}_{-0.19}$	*19.3 ± 0.28*
	Willman 1	158.6	56.8	38	$0.25^{+0.54}_{-0.17}$	*19.1 ± 0.31*
	Coma B.	241.9	83.6	44	$0.25^{+0.54}_{-0.17}$	*19.0 ± 0.25*

Conservative?

Hidden Systematics…

- Prior Bias?/Cut?

$$P(\theta|D) \propto P(D|\theta)P(\theta)$$

$$\sim \prod_i^{\text{samples}} \exp\left[-\frac{(\sigma^2_{\text{obs}}(r_i) - \sigma^2_{\text{theory}}(r_i,\theta))^2}{2\delta^2}\right]$$

ex: $P(v_{\max}) \propto v_{\max}^{-n} dv_{\max}$

- Non Spherical?

=> 0.2〜0.4 uncertainty

- Foreground Contamination?
- Member Star Sampling Bias?

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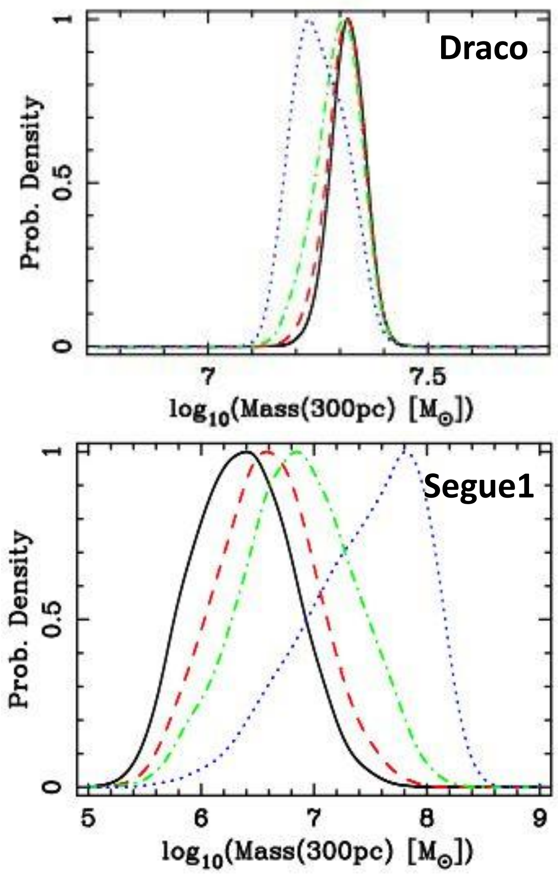

Martinez et al., arXiv: 0902.4715

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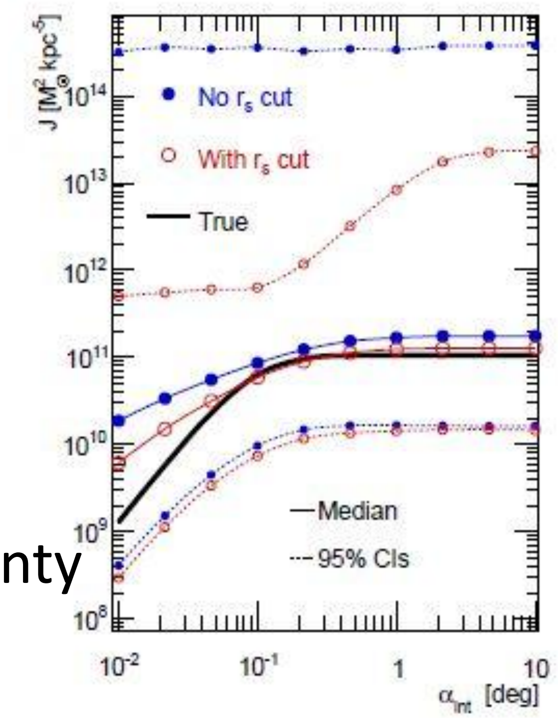
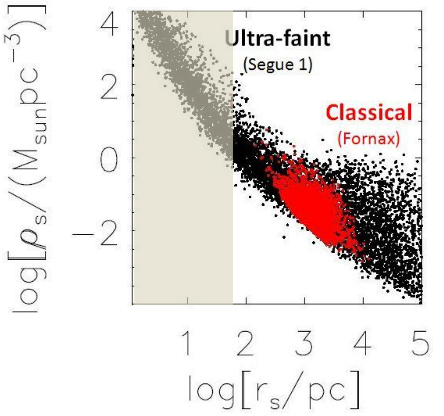


Bonnivard et al., arXiv: 1407.7822



Geringer-Sameth et al., arXiv:1408.0002

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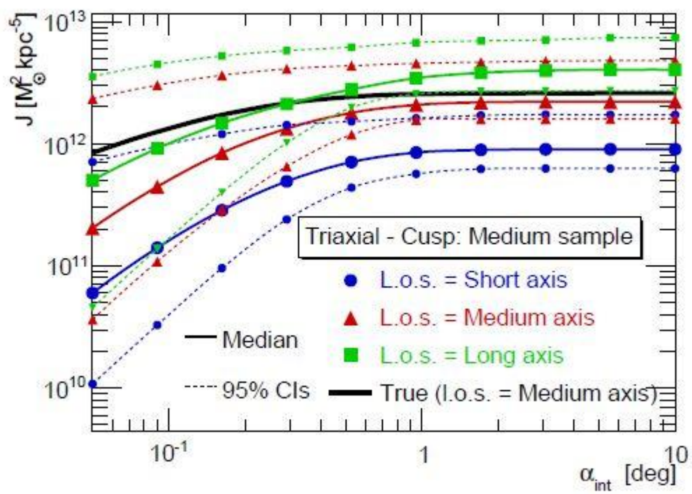
ex: $P(v_{\max}) \propto v_{\max}^{-n} dv_{\max}$

Galaxy	Spherical $\log_{10} J^{GS15}(\theta_{\max})$ [GeV^2 cm^{-5}]	軸対称 $\log_{10} J(\theta_{\max})$ [GeV^2 cm^{-5}]
Carina	$17.92^{+0.19}_{-0.09}$	$17.98^{+0.26}_{-0.16}$
Fornax	$17.84^{+0.11}_{-0.06}$	$17.97^{+0.08}_{-0.06}$
Sculptor	$18.57^{+0.07}_{-0.05}$	$18.51^{+0.14}_{-0.09}$
Sextans	$17.92^{+0.35}_{-0.29}$	$17.76^{+0.36}_{-0.38}$
Draco	$19.05^{+0.22}_{-0.21}$	$18.84^{+0.29}_{-0.31}$
Leo I	$17.84^{+0.20}_{-0.16}$	$17.31^{+0.27}_{-0.25}$
Leo II	$17.97^{+0.20}_{-0.18}$	$17.03^{+0.32}_{-0.30}$

By K. Hayashi (Preliminary)

- **Non Spherical?** Axisymmetric: Hayasi and Chiba., arXiv: 1206.3888

=> 0.2〜0.4 uncertainty



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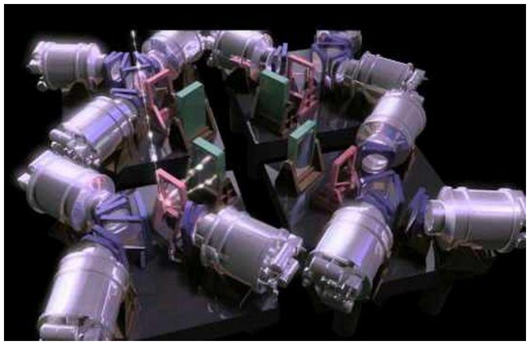
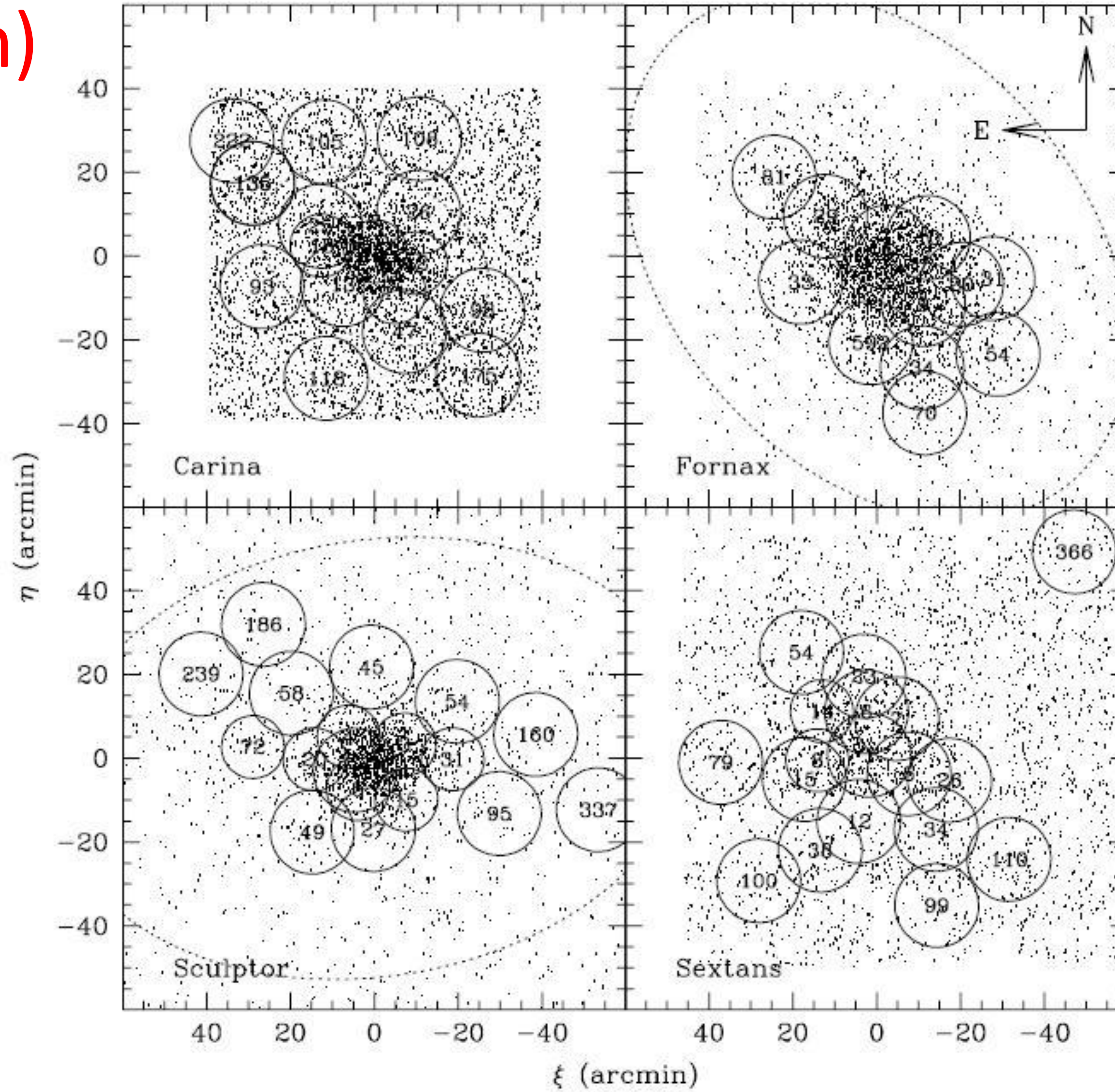
- Member Star Sampling Bias?

Prime Focus Spectroscopy

FoV 1.3 deg (diam)

with 2394 Fiber





MMFS (M. G. Walker et al,. (2007))

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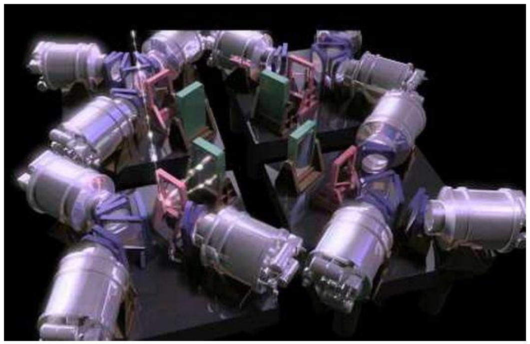

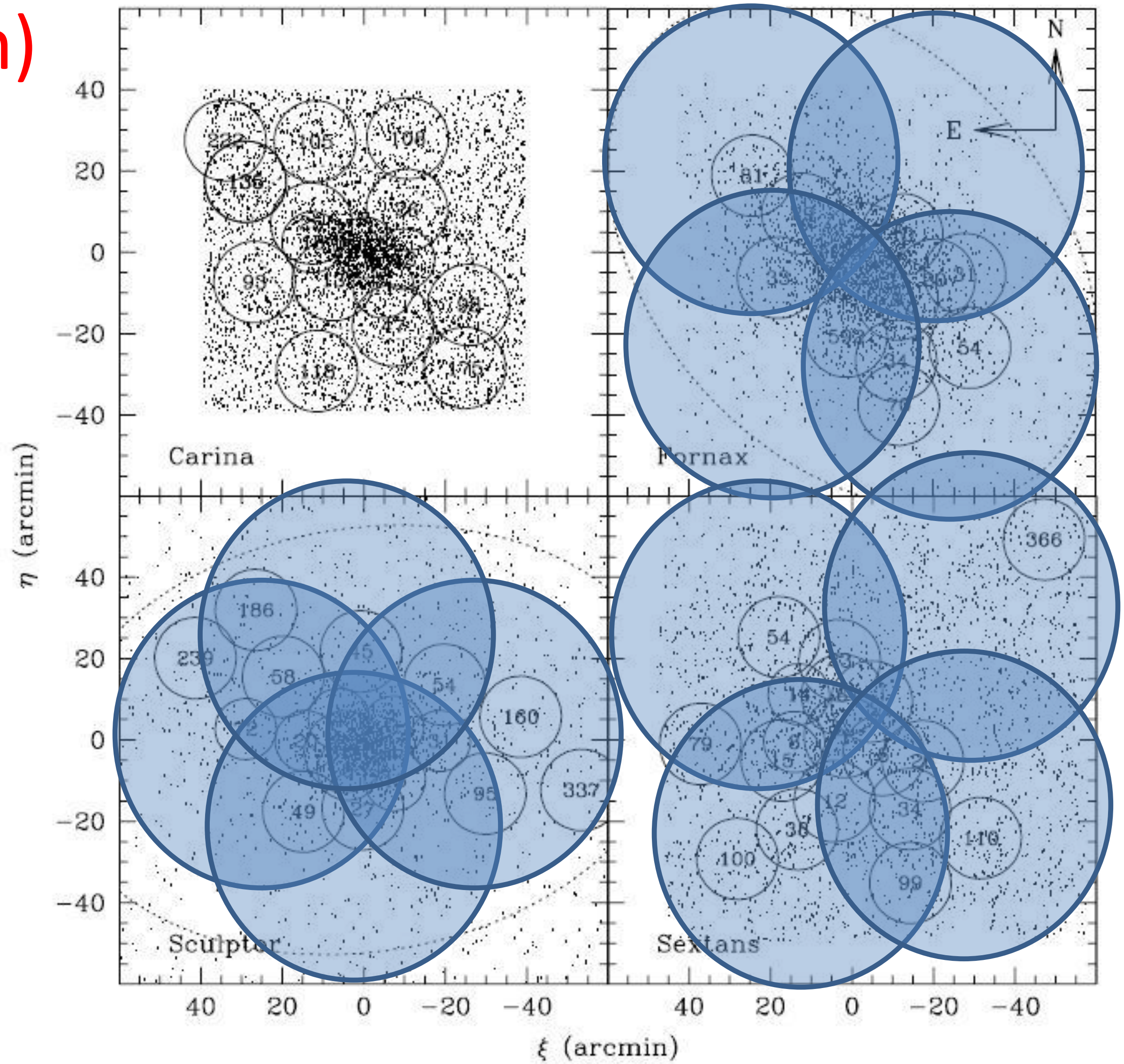

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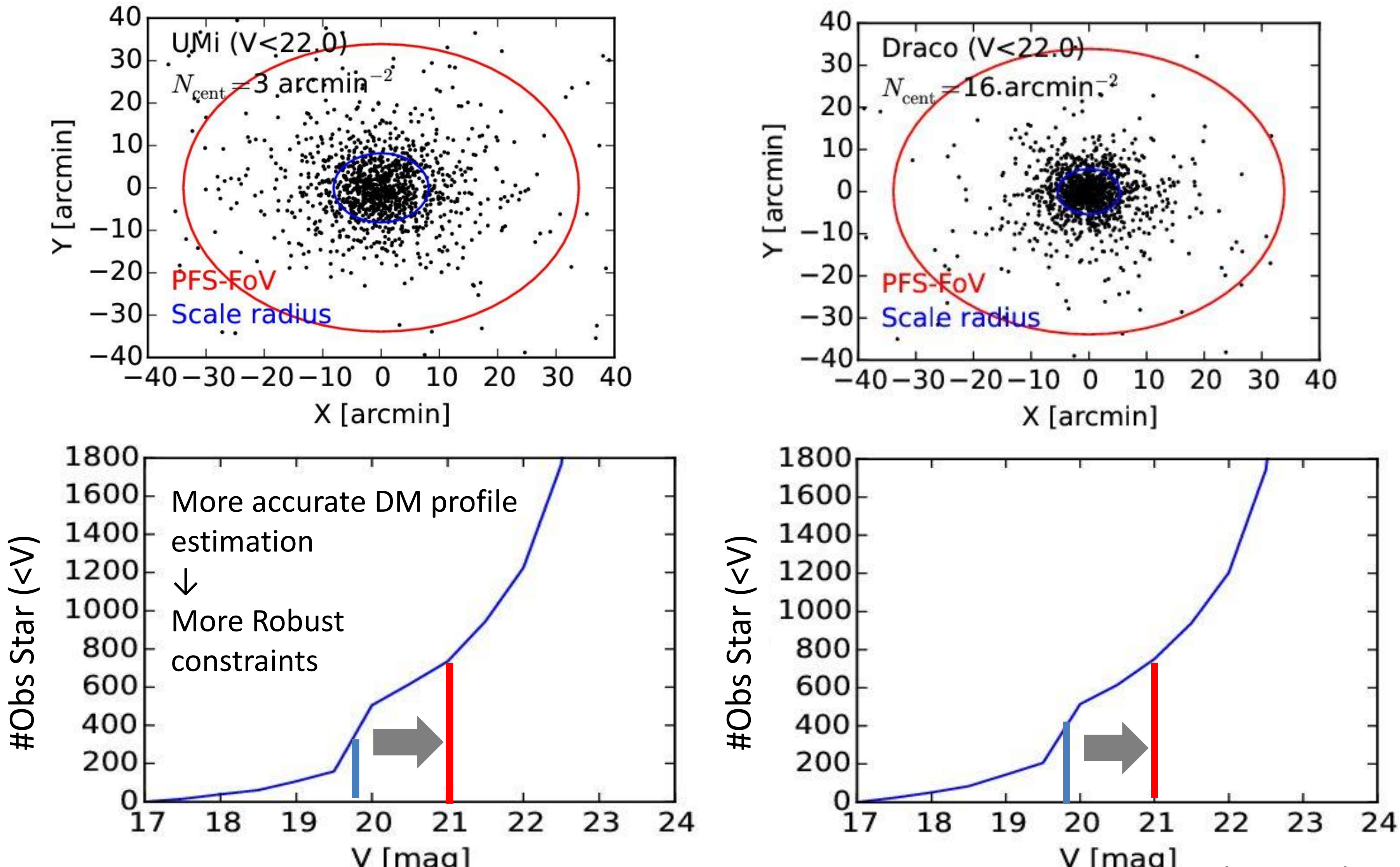


by M. Ishigaki

Strategy

1. Mock Observable:

(R, v, Metalicity, Luminosity)

= dSph Stellar + Foreground

dSph Stellar Mock

⇒Boltzmann Equation under DM profile

Foreground Mock

⇒Besancon Model (Robin+ (2003))

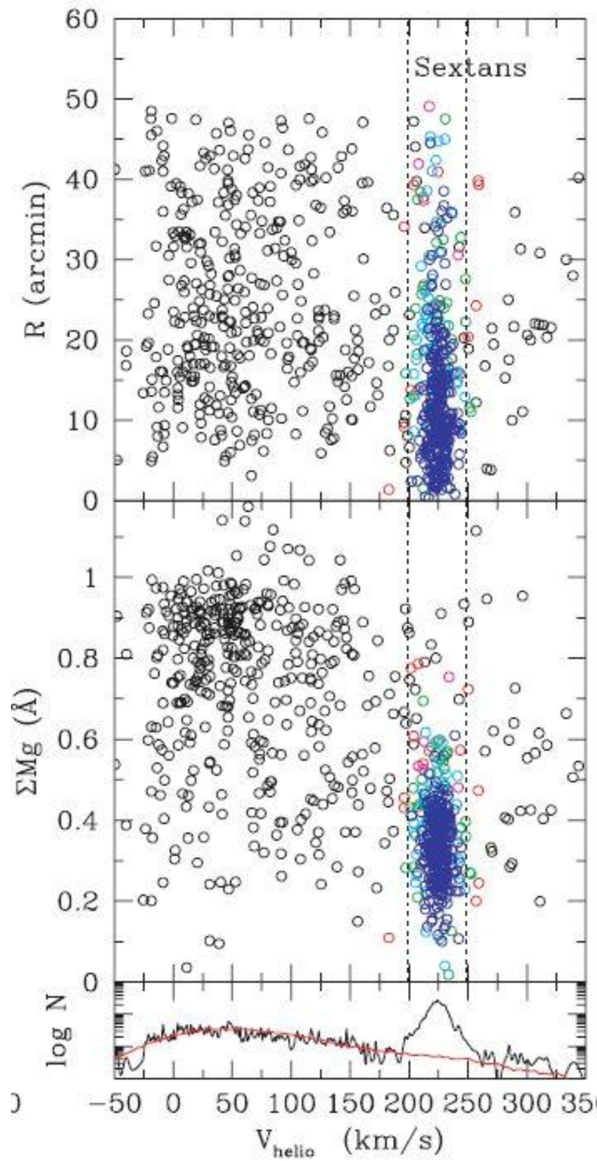
2. Detector Convolution:

⇒1. fix: dv = 3.0km/s

3. Fit:

(DM profile, anisotropy, dSph stellar profile, dSph v, foreground norm + metalicity)

⇒Fit to (v, r) probability density.



Walker+, AJ 137 (2009)

Stra

1. Moc

(R, v, N

= dSph S

dSph Stella

⇒Boltz

Foregroun

⇒Besa

2. Dete

⇒1. fix: dv

3. Fit:

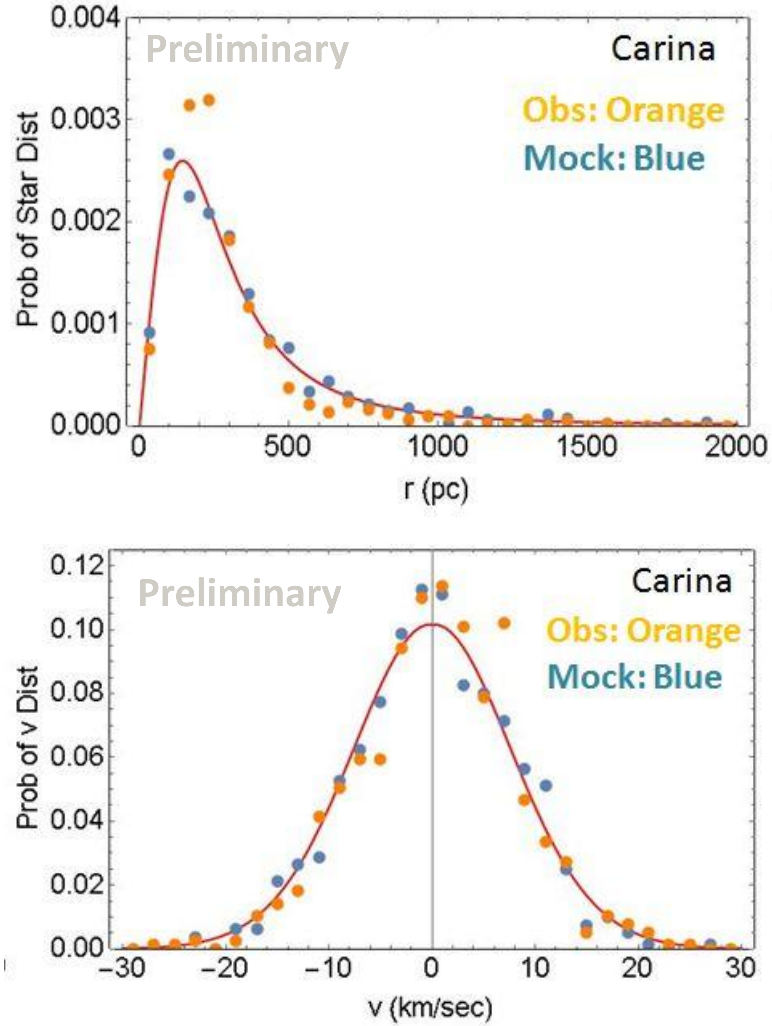
(DM prof

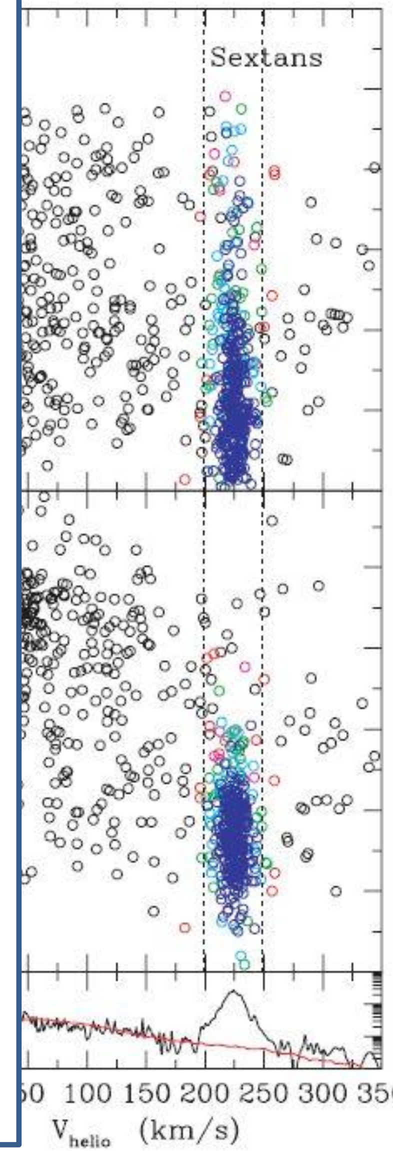
dSph v, fo

⇒Fit to

1. Mock Samples

$\rho_{DM}(r)$, $v_{star}(r)$ => f(r,v)   Cuddeford (1991)





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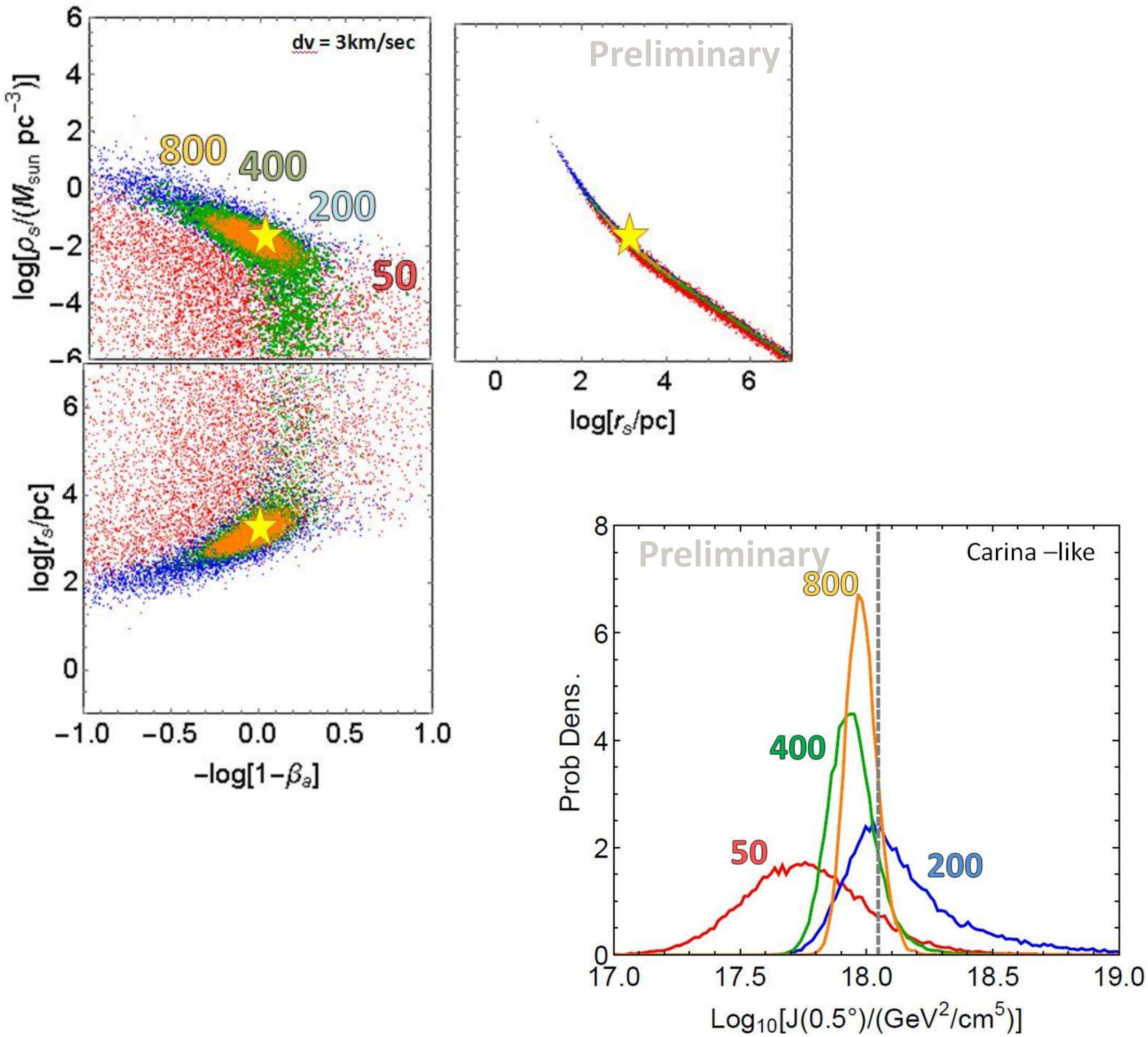
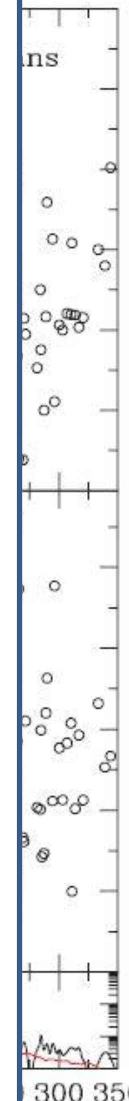
⇒Fit to

Fit without Foreground





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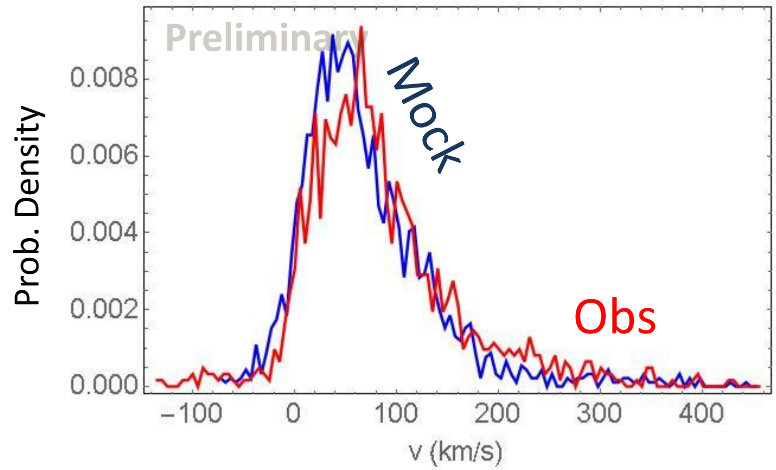
⇒Fit to

2. Foreground

Besancon Model

Robin+ (2003)



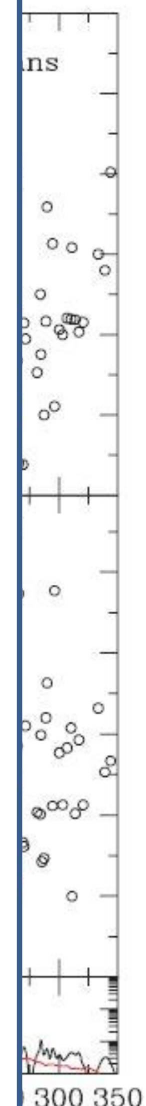
3. Fit

$$-2\sum_i \ln\left(s f_{\rm Mem}(v_i, R_i) + (1-s) f_{\rm FG}(v_i, R_i)\right)$$

$$s = \frac{N_{\rm Mem}}{N_{\rm Mem} + N_{\rm FG}}$$

$$f_{\rm Mem}(v, R) = \frac{2\pi R \Sigma(R)}{\sqrt{2\pi\sigma^2(R)}} e^{-\frac{(v - v_{\rm Mem})^2}{2\sigma^2(R)}}$$

$$f_{\rm FG}(v, R) = 2\pi R N e^{-\frac{(v - v_0)^2}{2(\sigma_0(v - v_0) + \sigma_1)^2}}$$



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2. Foreground

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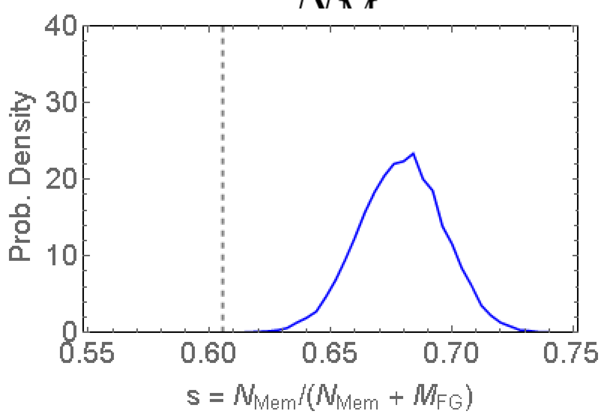
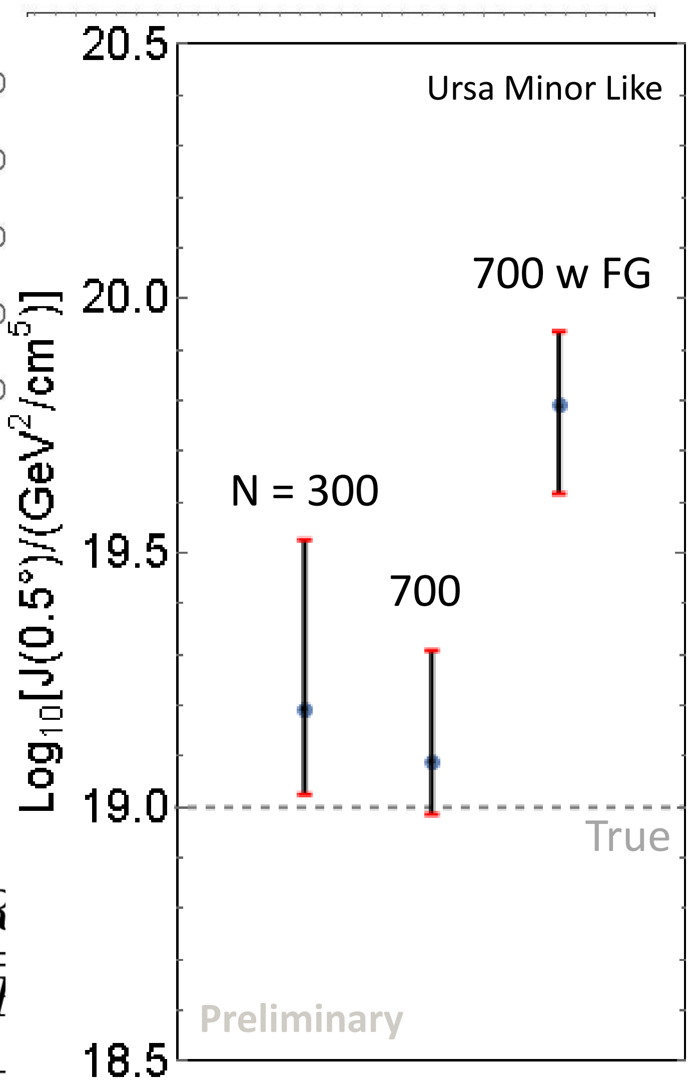
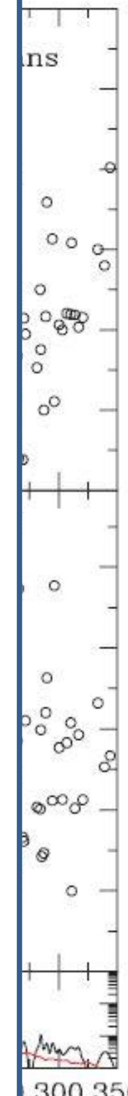




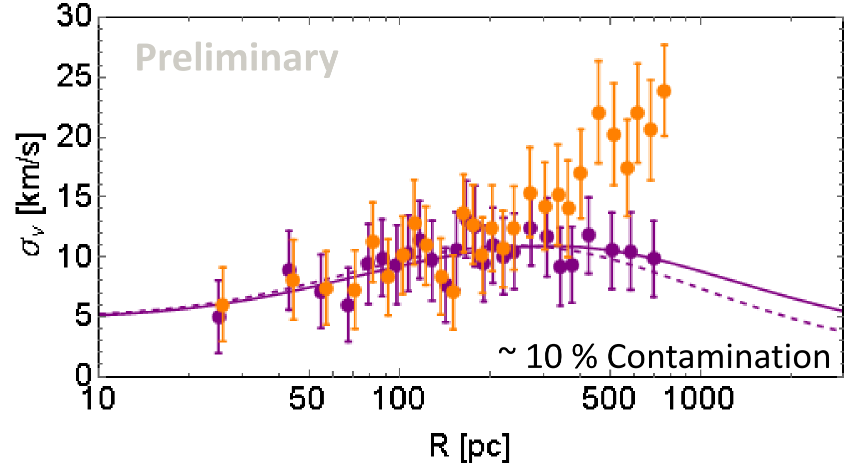


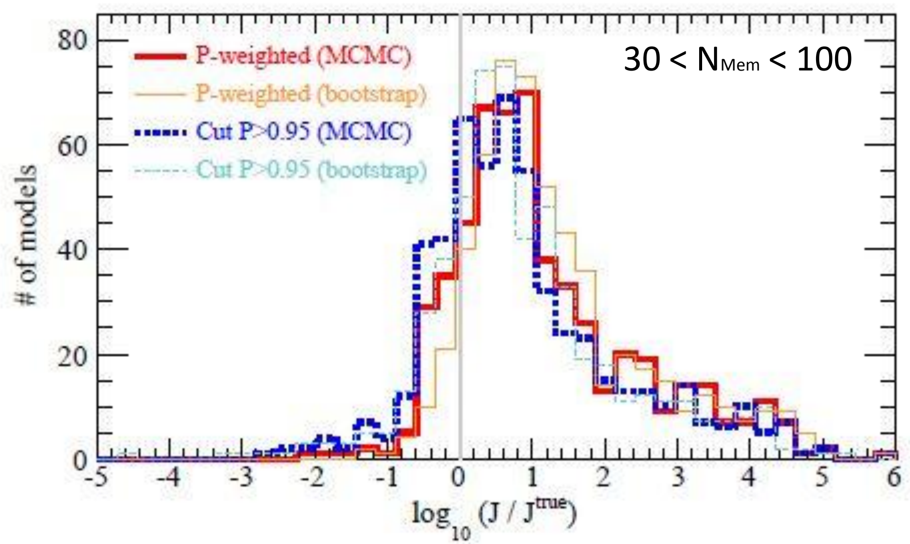
Walker+, AJ 137 (2009)

Foreground Contamination

Outer Region = FG dominant

How to Reduce FG stars?





Bonnivard et al., arXiv:1506.08209

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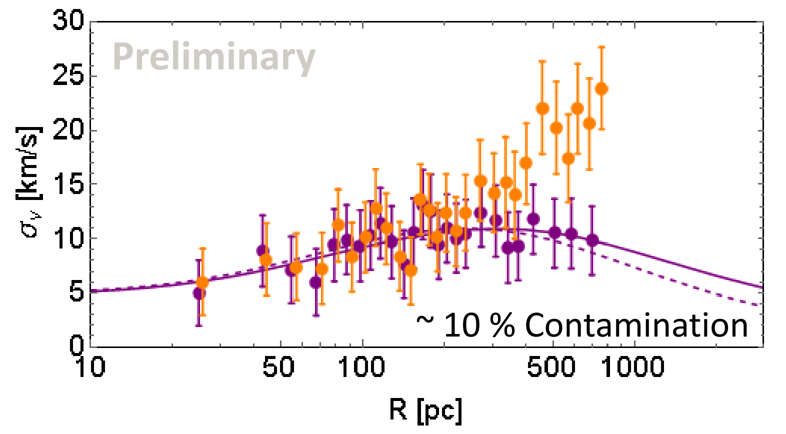

<u>Cut:</u>

1. Velocity … The most effective
2. Color… Not Bad
3. Chemical Component… Degenerate
4. Others?

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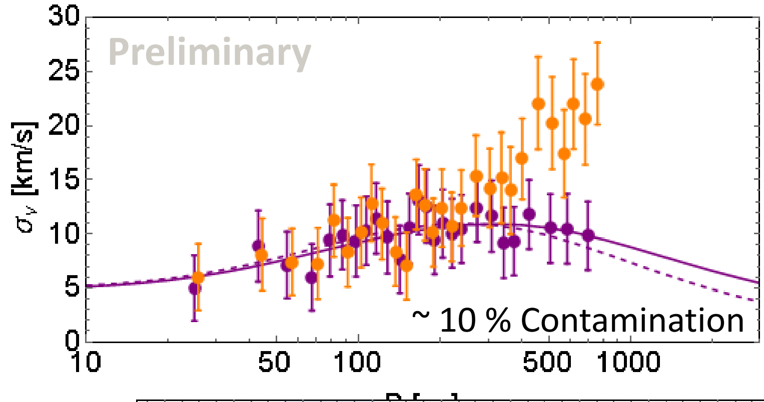

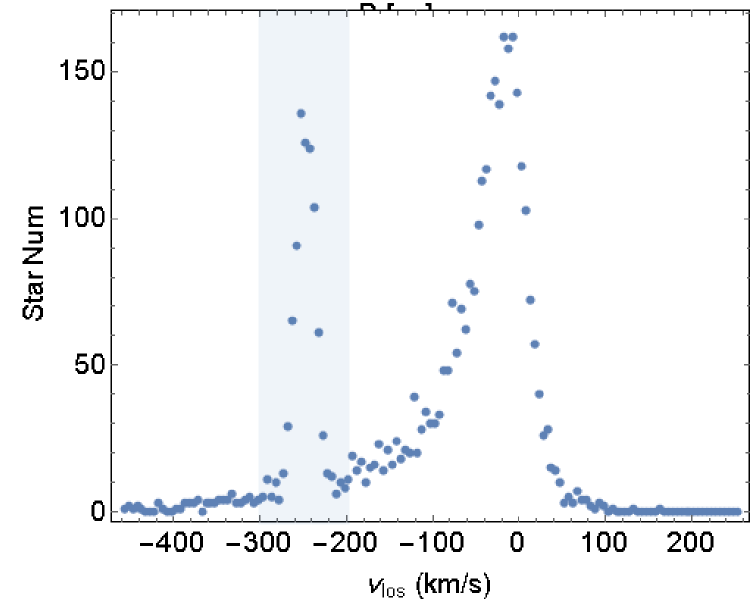

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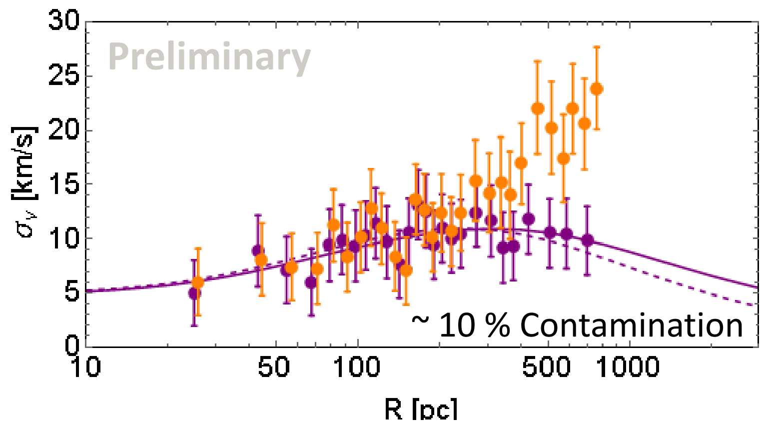

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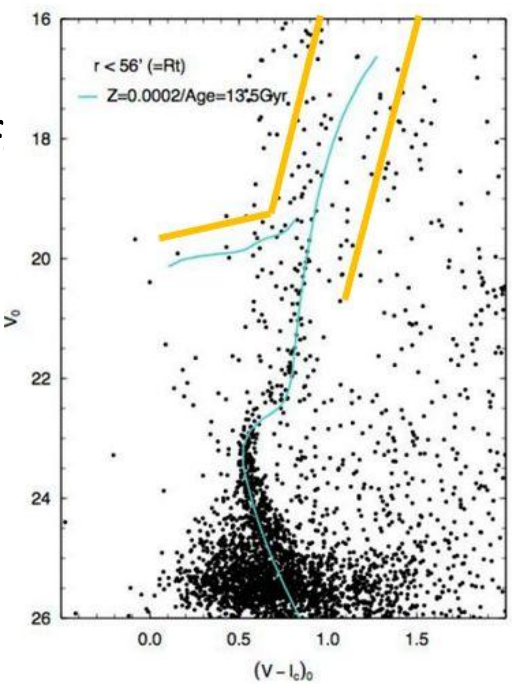
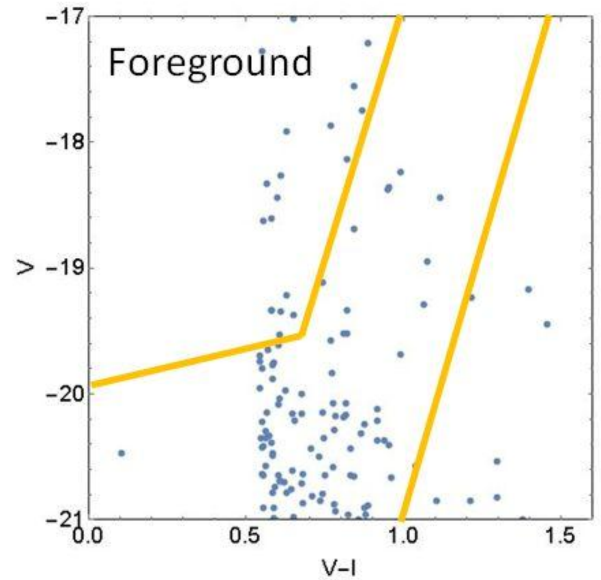
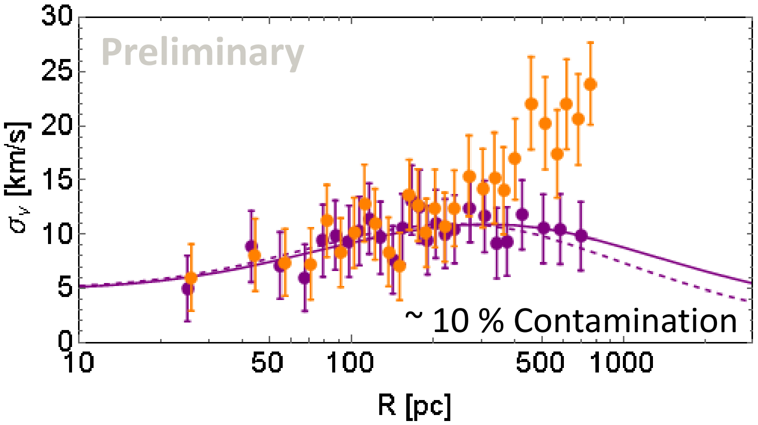




Foreground Contamination

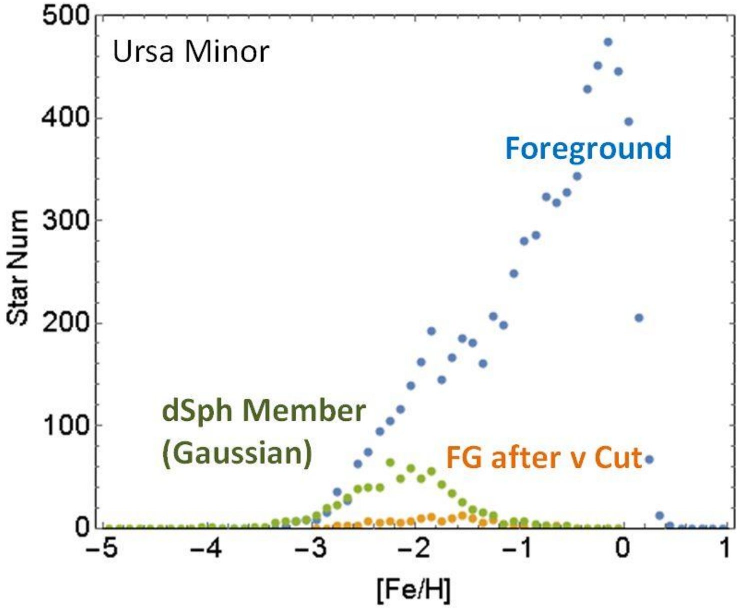
Outer Region = FG dominant

How to Reduce FG stars?



<u>Cut:</u>

1. Velocity … The most effective
2. Color… Not Bad
3. Chemical Component… Degenerate
4. Others?



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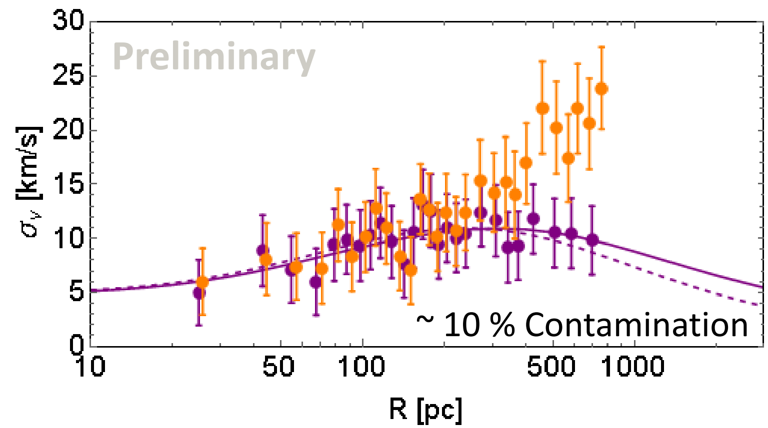
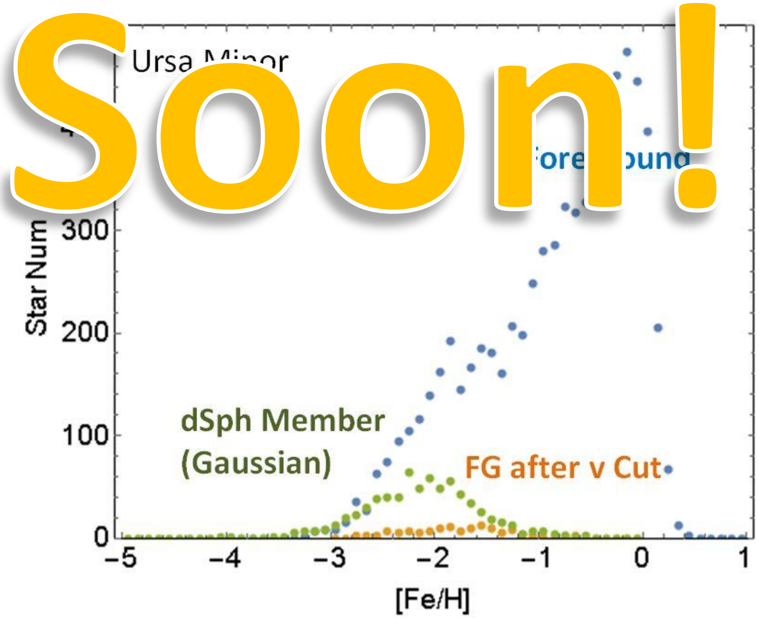


Coming Soon!



Summary

- Indirect detection is essential for DM search.
- Gamma-ray observation of dSph can give robust constraints on the DM annihilation cross section.
- Investigation of stellar kinematics is important.
- PFS will play a crucial role.

Thank You !

Koji Ichikawa

In collaboration with
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Shigeki Matsumoto and Hajime Sugai.