Dark matter constraints from dwarf spheroidal galaxies and future spectroscopic survey

(In preparation)

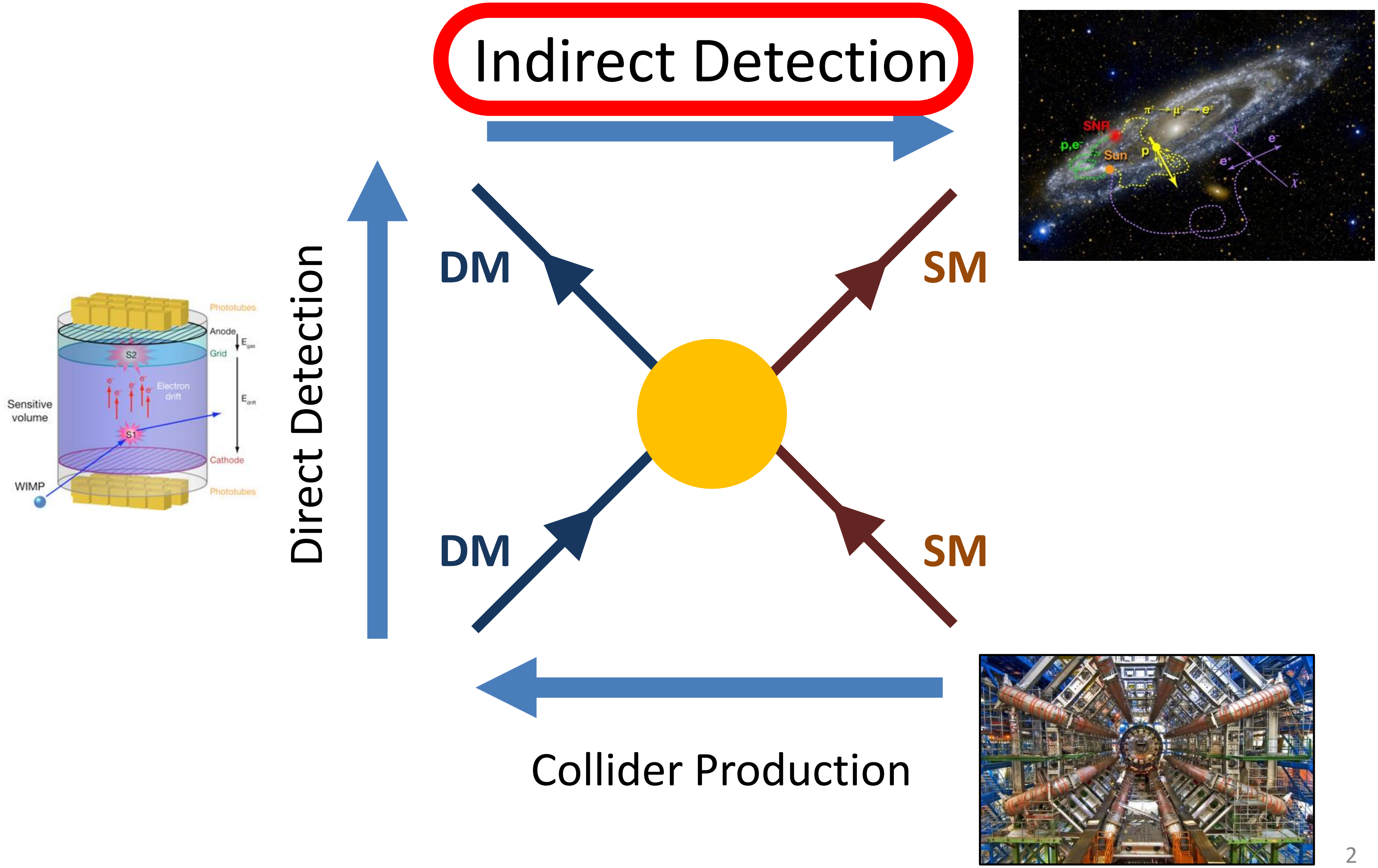
Koji Ichikawa

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

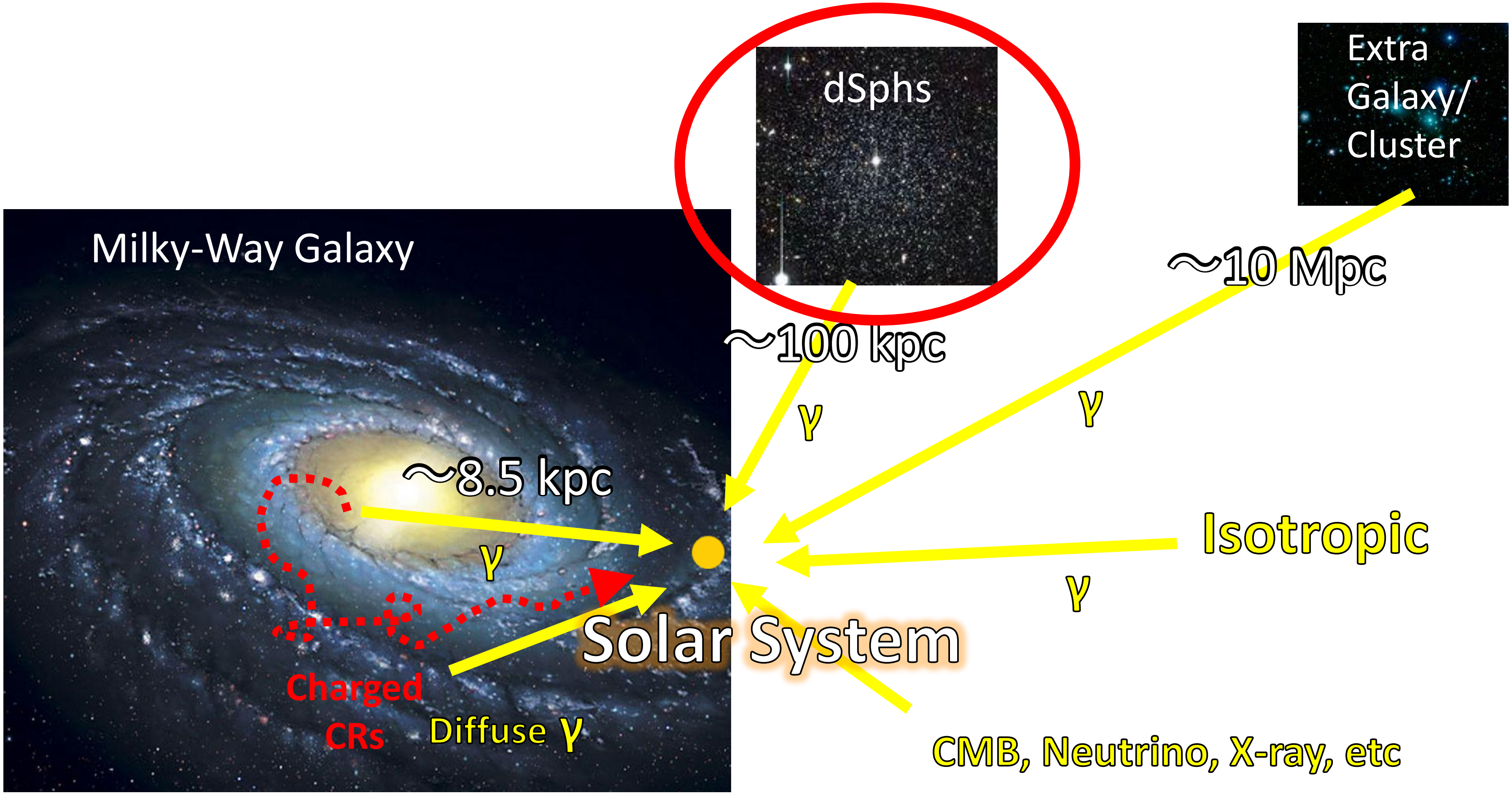
KAVLI IPMU

Workshop on Astrophysics of Dark Matter
Kashiwa, Oct. 13-16, 2015

Dark Matter Search



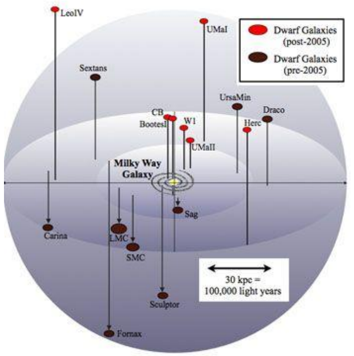
Signal Target



Dwarf spheroidal galaxies

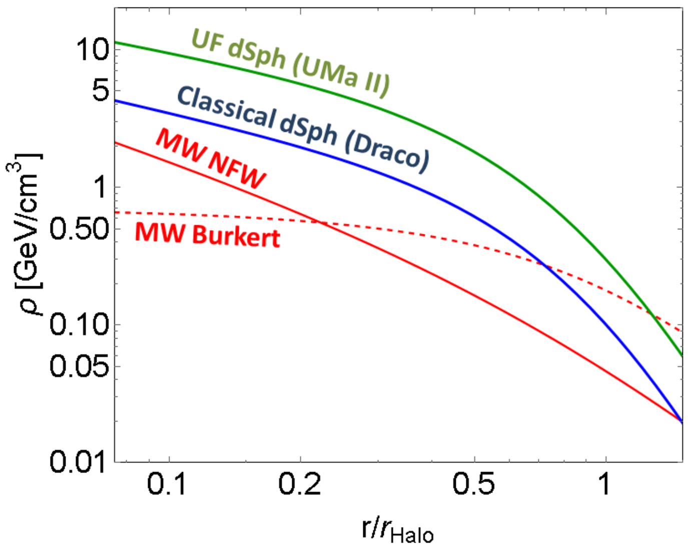
dSphs: **= Clean & DM Rich Target**

1. **Neighbor** galaxies: 10~100kpc
2. Large Mass to Luminosity ratio = **DM rich**
3. **Clean** (no strong gamma-ray source)



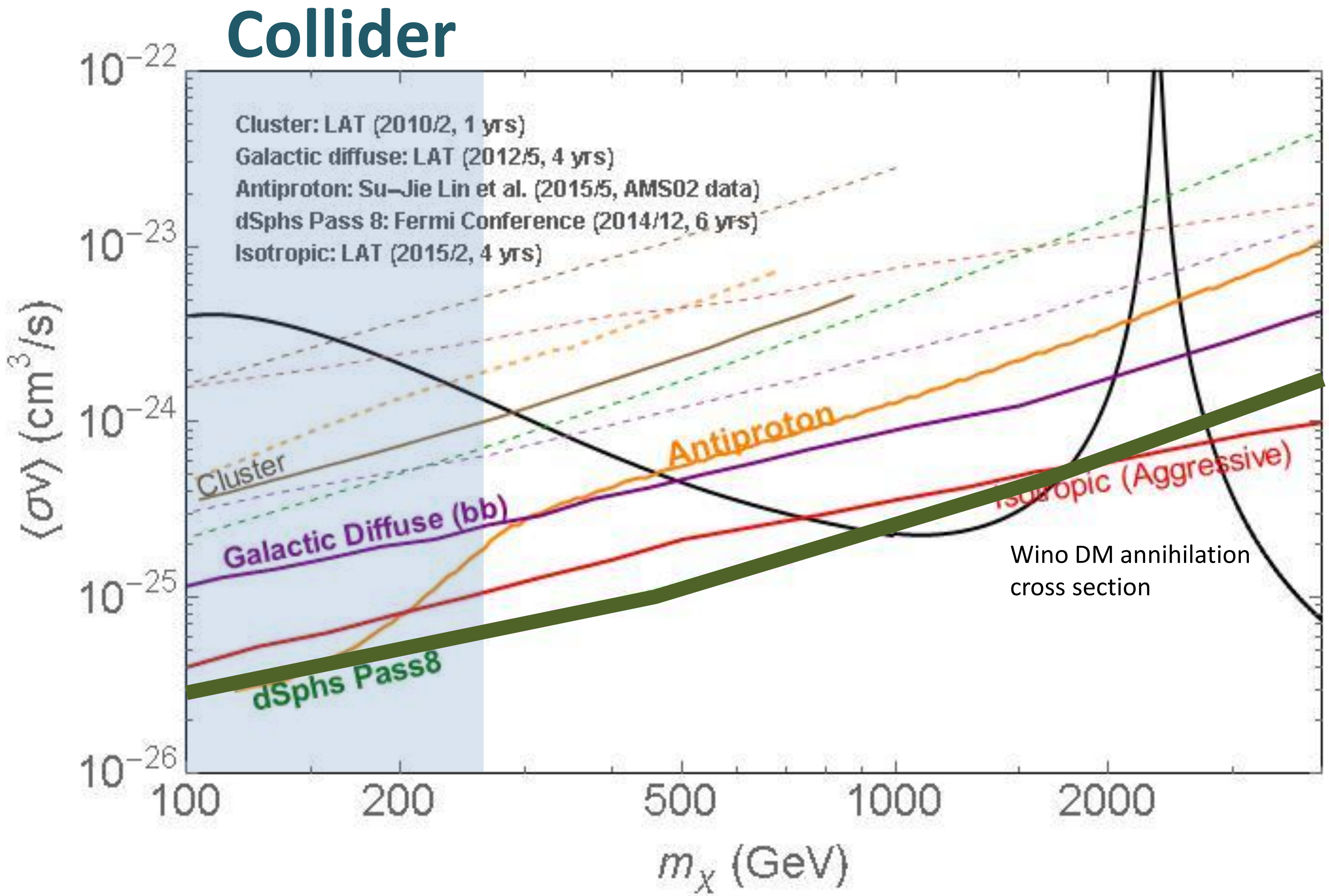
	Classical	Ultra-faint
#dSphs	8	>20
M/L ($M_\odot/L_\odot$)	10-100	100-1000
Distance (kpc)	60-250	10-60
#Obs Stars	150-2500	20-100
Characteristics	Brighter, farther	Darker, closer

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



arXiv:0908.2995v6 [astro-ph.CO]

Current(slightly old) obs limit (ex. Wino)



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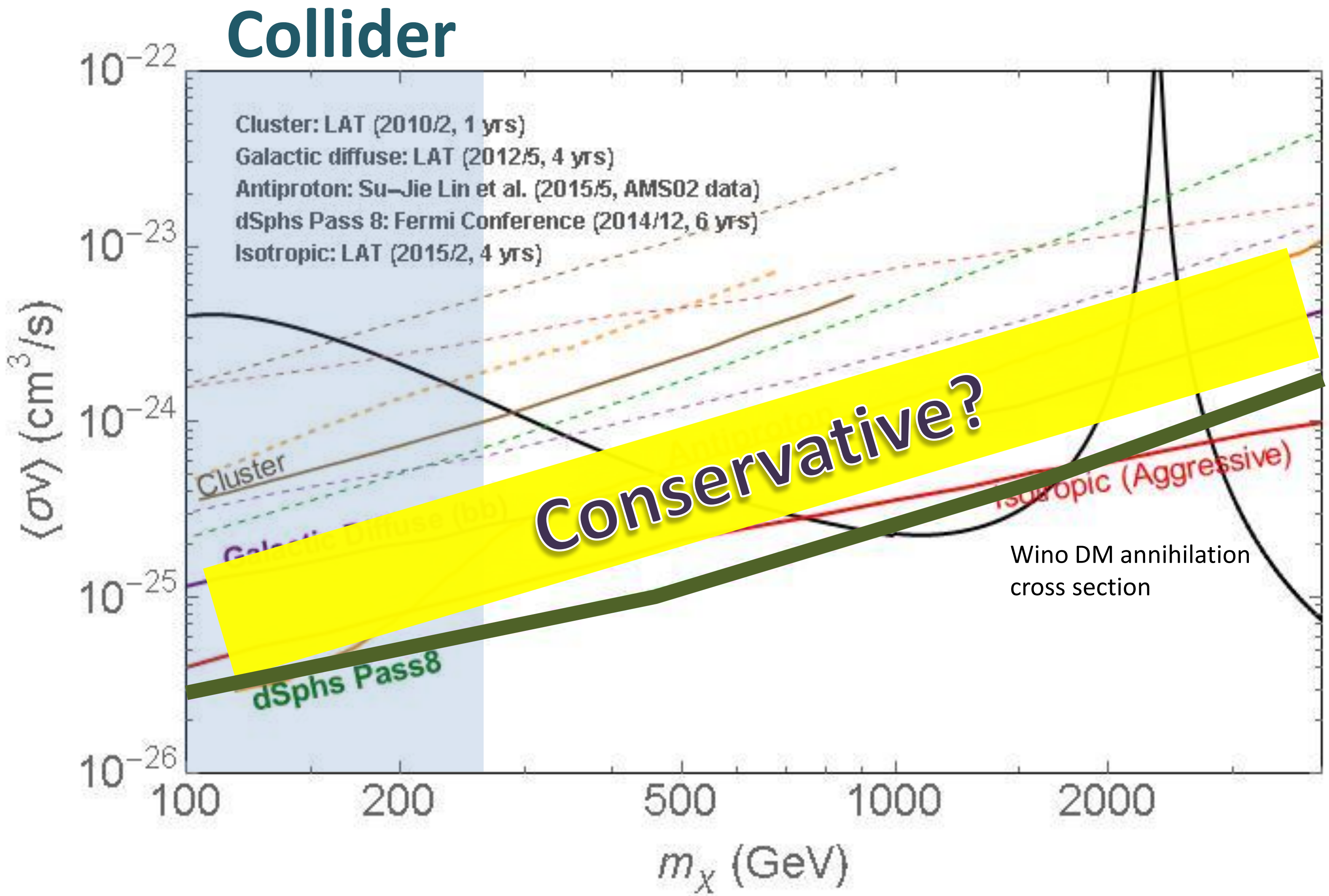
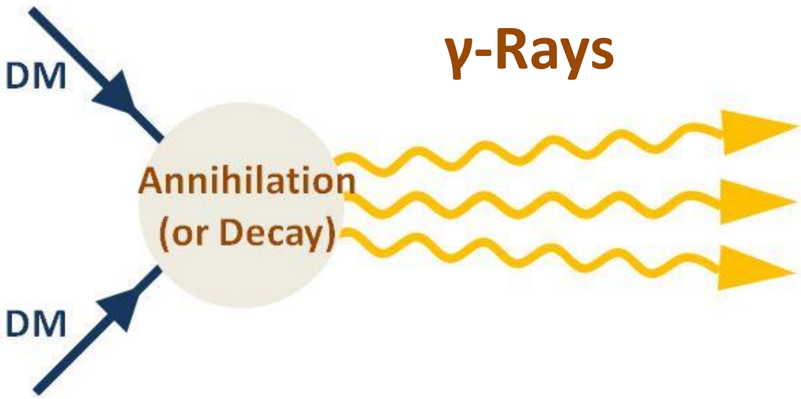


We Should Precisely Determine The dSph DM Halo Shape

Dwarf galaxy



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

Observed γ-Ray Flux

DM Property

Halo Profile (J-factor)

J-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

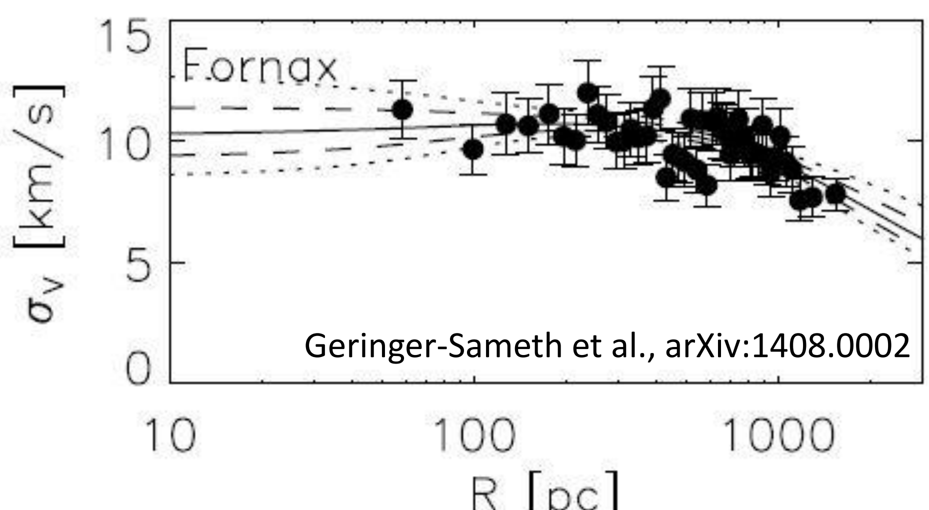
Stellar Density Profile: ν(r)

Jeans equation for stars

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

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

Fit



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

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

Astrophysical Factor

DM Density profile

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

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

Fit

		long. (deg.)	lat. (deg.)	dist. (kpc)	α_s (deg.)	$\log_{10}[J(0.5°)/(\mathrm{GeV}^2\mathrm{cm}^{-5}\mathrm{sr})]$
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*

Factor 1.6 ~ 2 unc. :Conservative?

Hidden Systematics…

- **Non Spherical?**

  => 0.2～0.4 uncertainty

  Axisymmetric: Hayasi and Chiba., arXiv: 1206.3888

- Foreground Contamination?

  N < 100: O(1) uncertainty

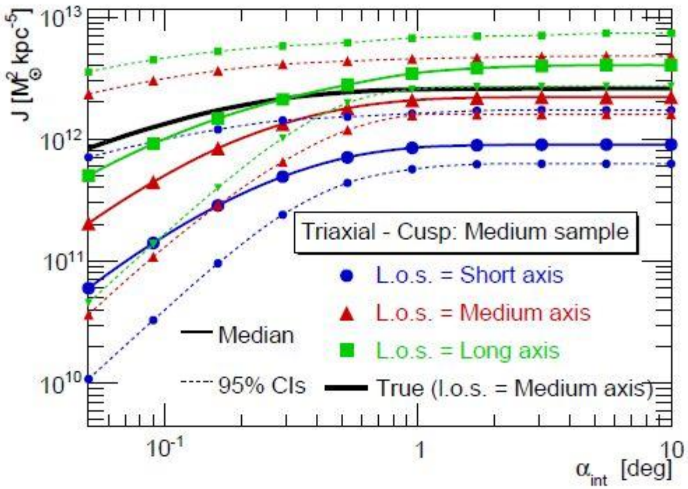
  N ～1000: < 0.4

- Prior Bias?/Cut?

  N < 100: > O(1) uncertainty

Galaxy	$\log_{10} J^{GS15}(\theta_{\max})$ [GeV^2 cm^{-5}]	$\log_{10} J(\theta_{\max})$ [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-san (Preliminary)



Bonnivard et al., arXiv: 1407.7822

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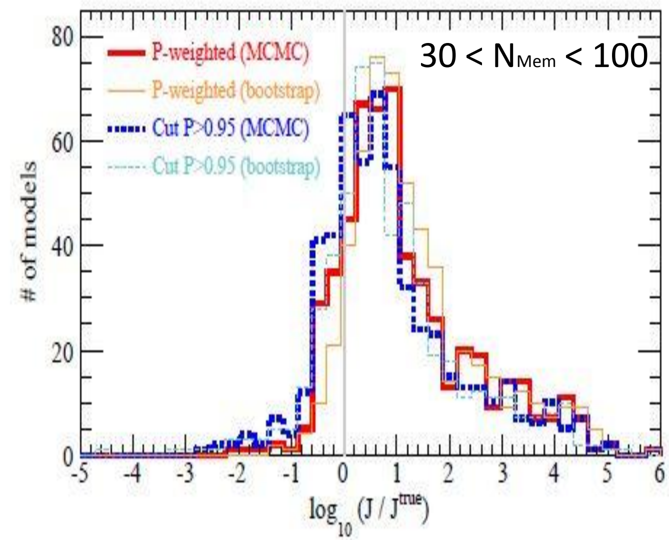
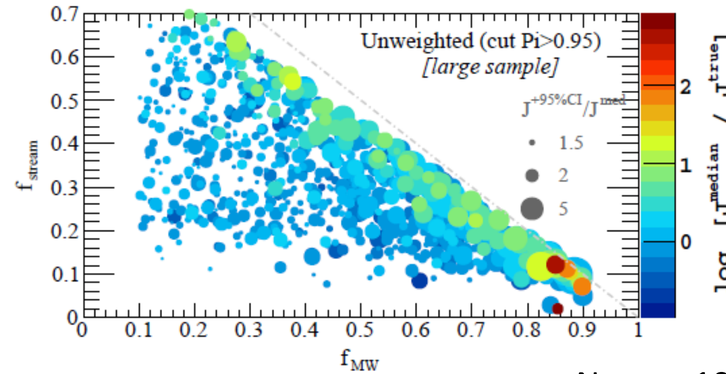


Bonnivard et al., arXiv:1506.08209



N_{mem} 〜 1000

Bonnivard et al., arXiv:1504.02048

Hidden Systematics…

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- **Prior Bias?/Cut?**

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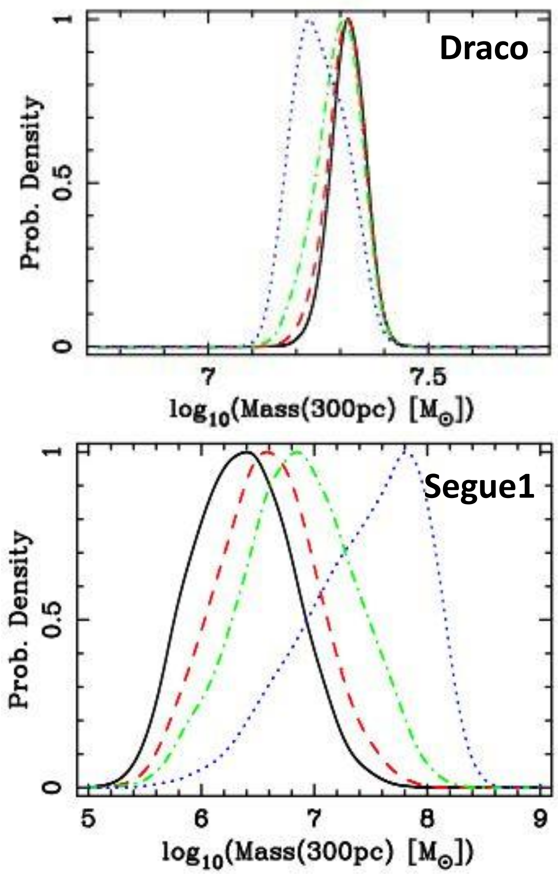


Martinez et al., arXiv: 0902.4715

Hidden Systematics…

- Non Spherical?

  => 0.2～0.4 uncertainty

  Axisymmetric: Hayasi and Chiba., arXiv: 1206.3888

- Foreground Contamination?

  N < 100: O(1) uncertainty

  N ～1000: < 0.4

- Prior Bias?/Cut? (For Ultra faint dSphs)

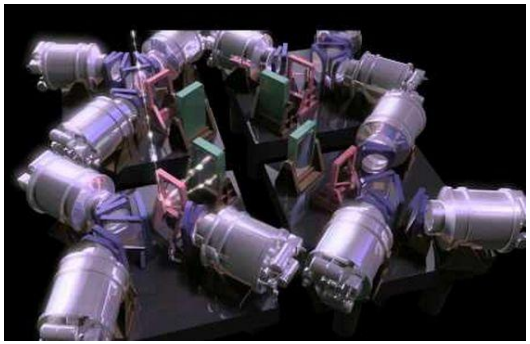
  N < 100: > O(1) uncertainty

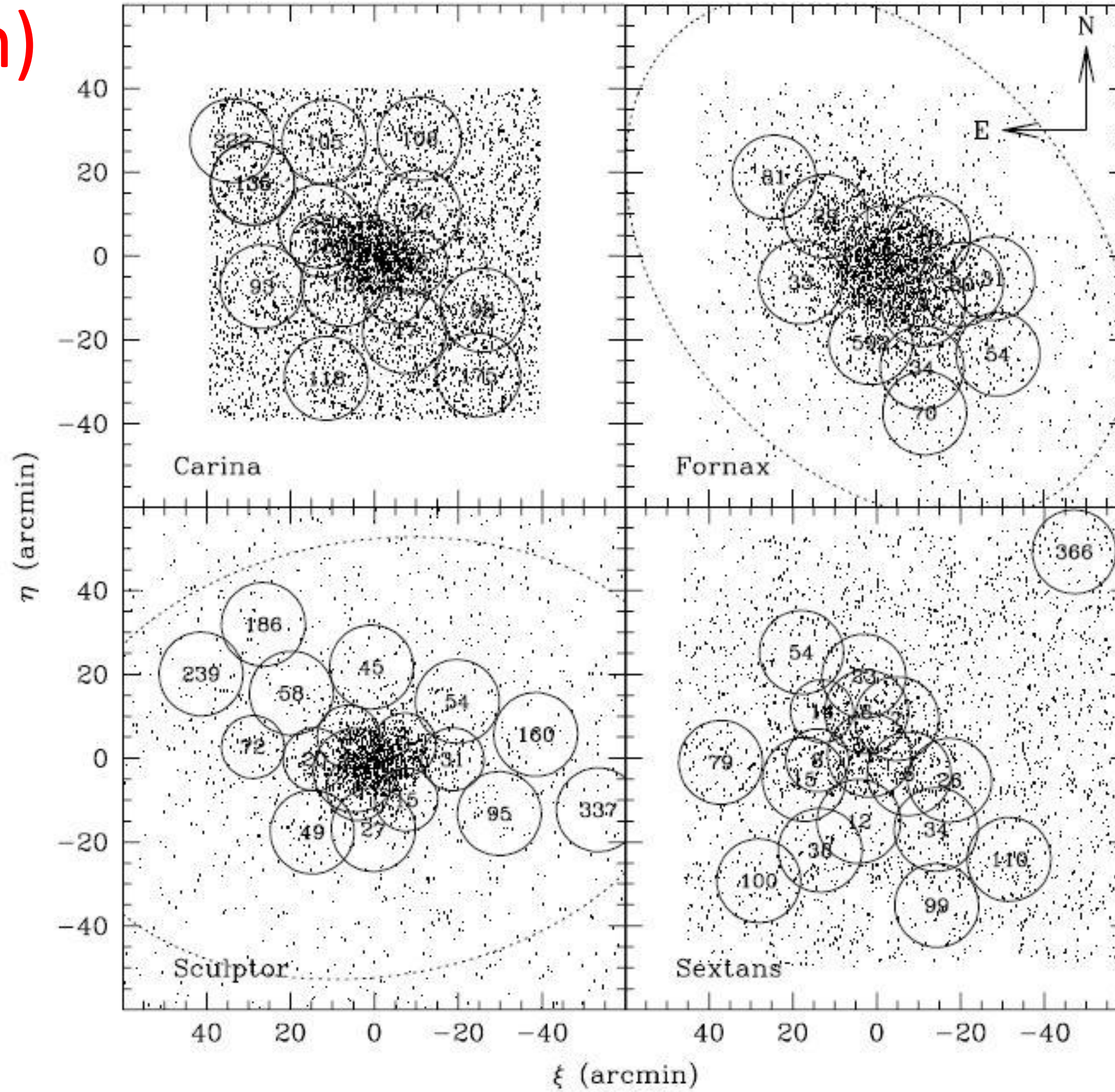
How to Reduce Them? -> **Increase #N_{Mem}!**

Prime Focus Spectrograph

FoV 1.3 deg (diam)

with 2394 Fiber

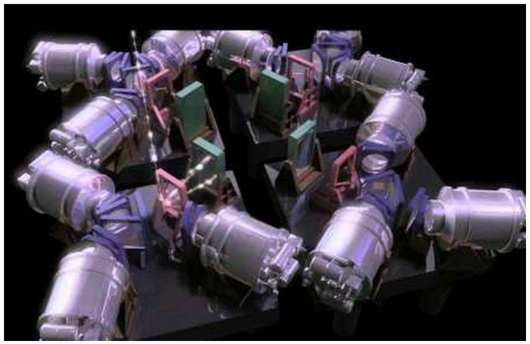


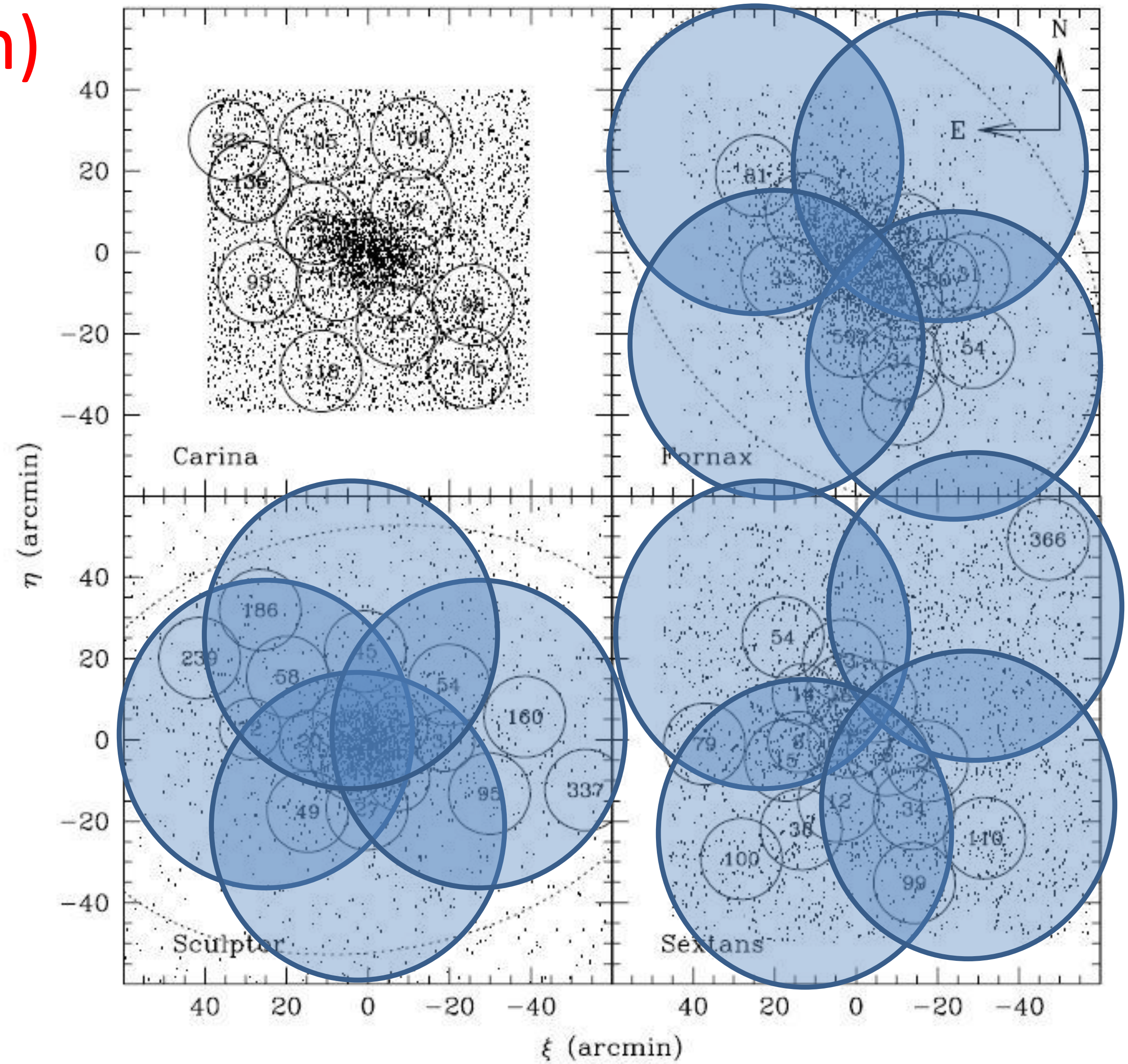


MMFS (M. G. Walker et al,. (2007))

Prime Focus Spectrograph

FoV 1.3 deg (diam)
with 2394 Fiber





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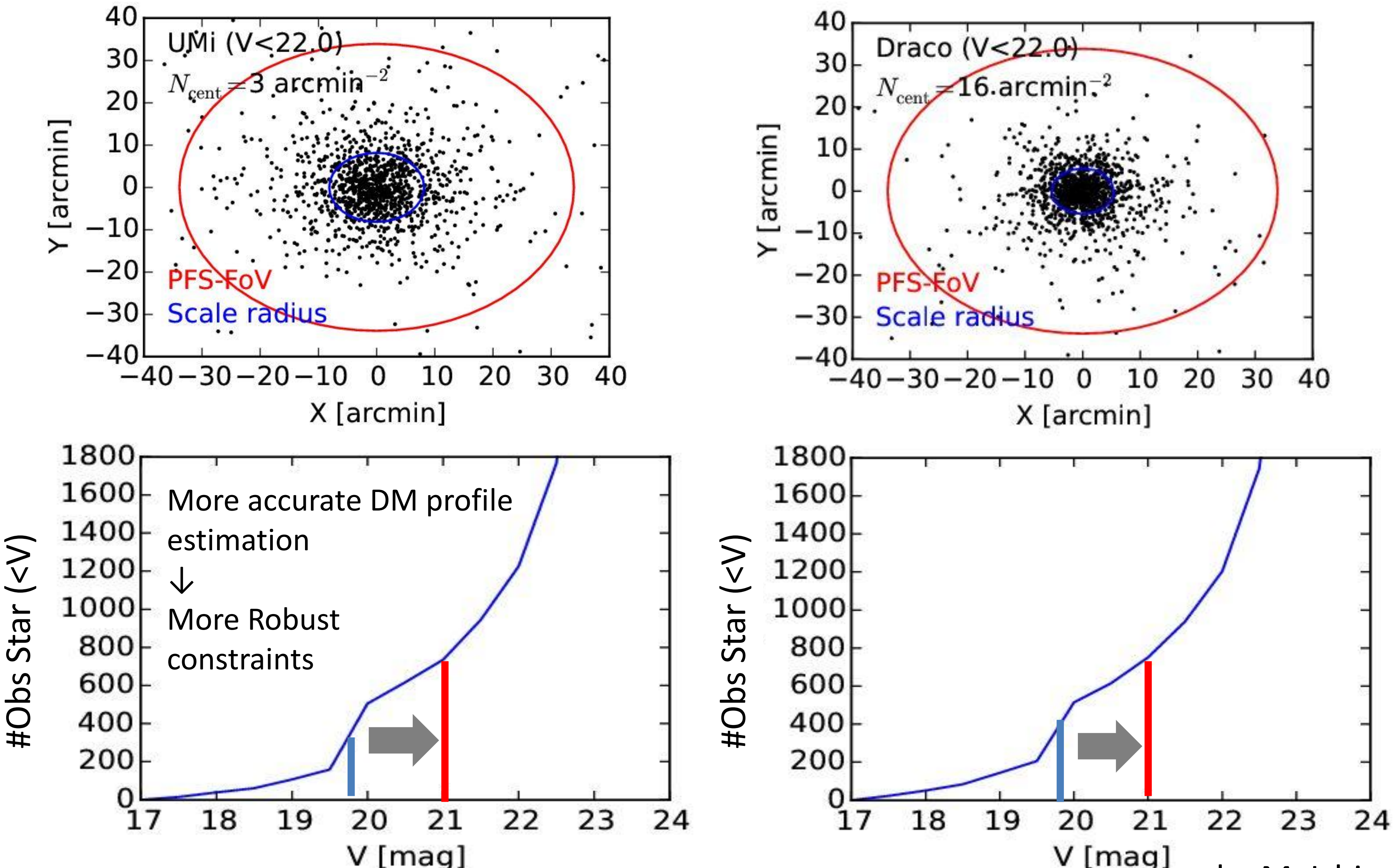
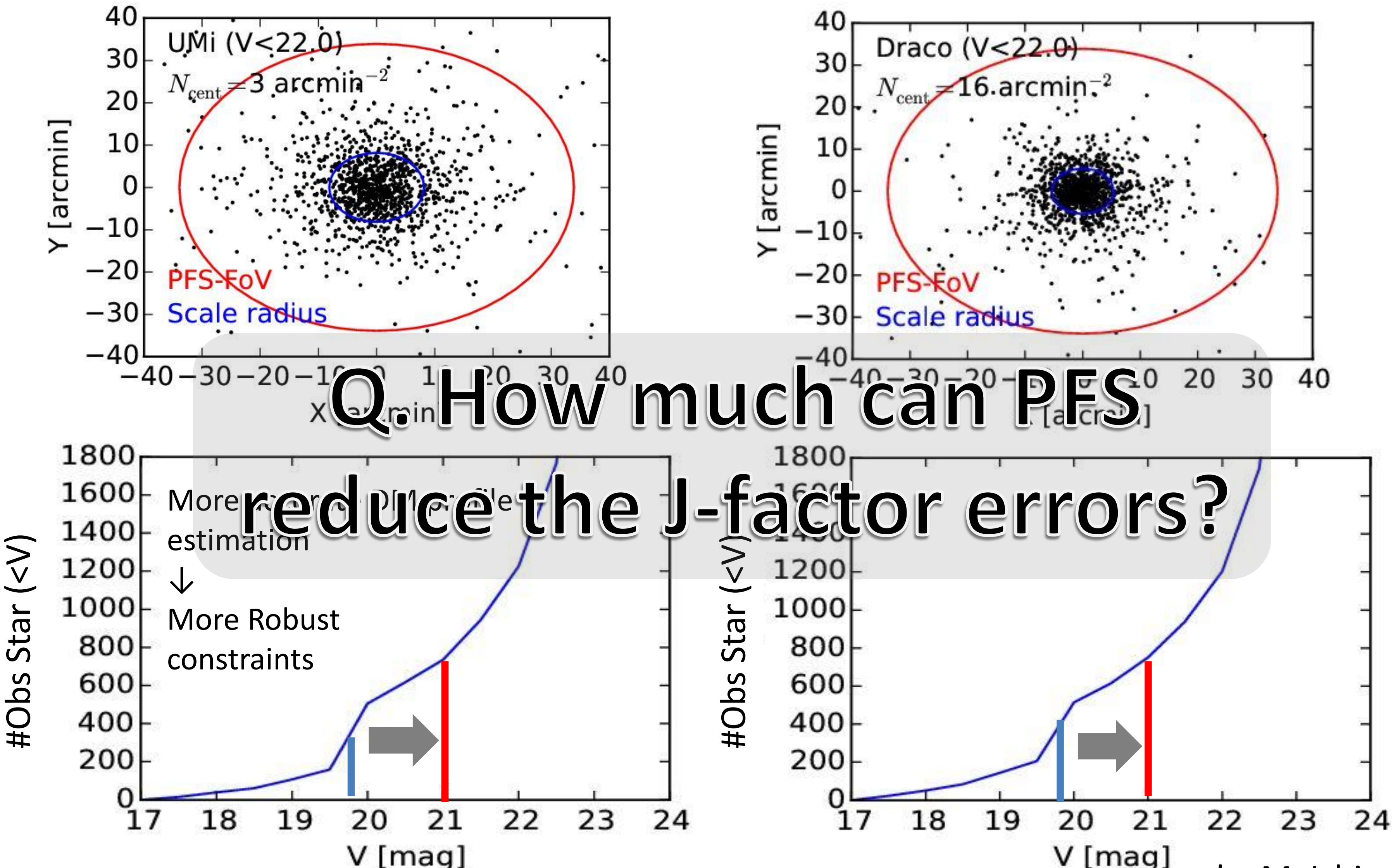


by M. Ishigaki

Prime Focus Spectrograph



Q. How much can PFS reduce the J-factor errors?

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))

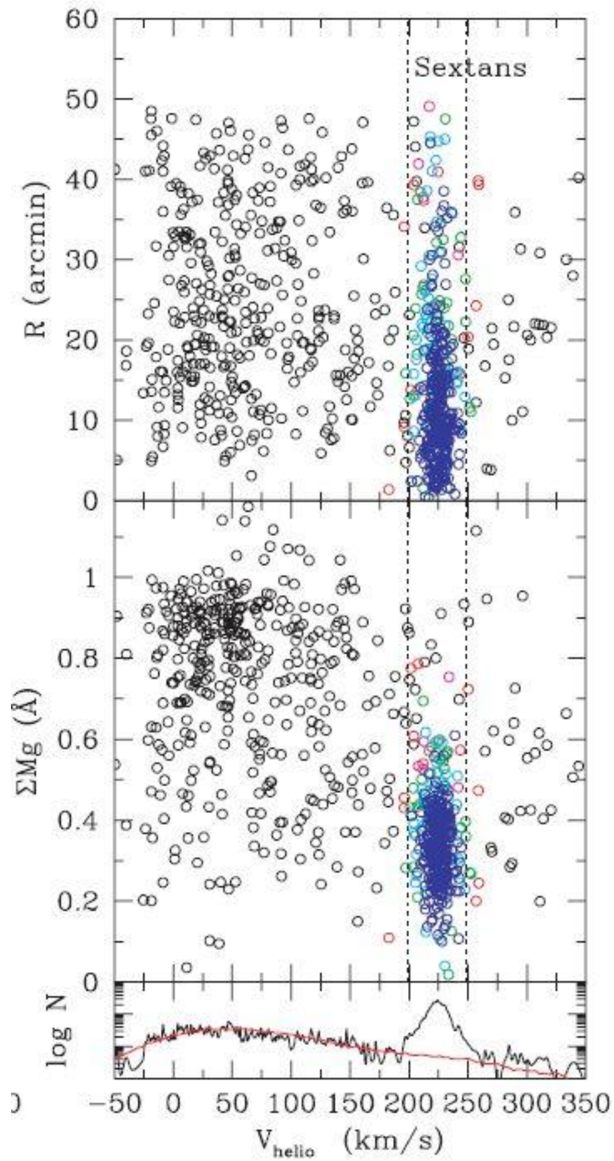
2. Detector Convolution:

⇒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 Stell

⇒Bolt

Foregroun

⇒Besa

2. Dete

⇒1. fix: dv

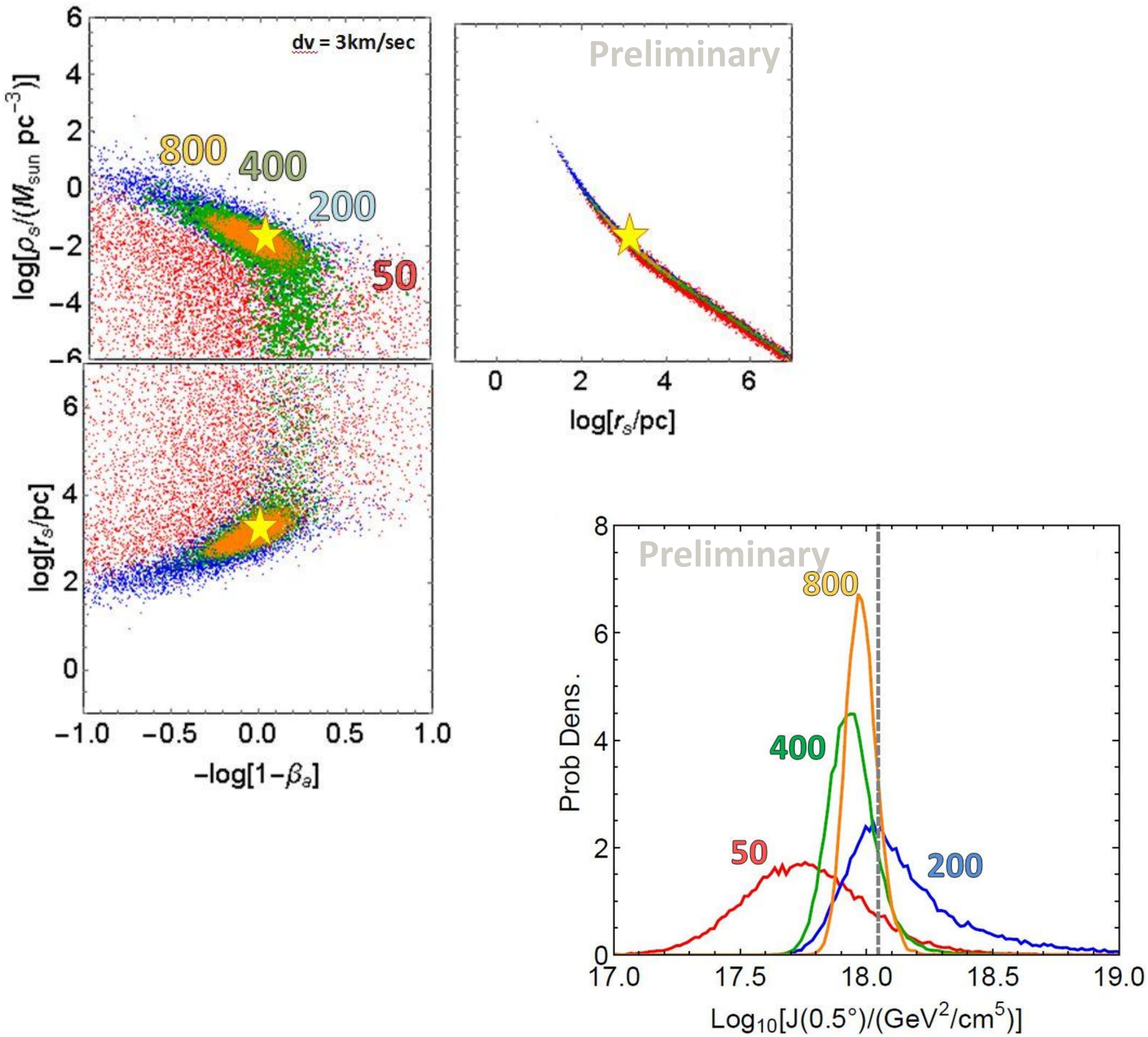
3. Fit:

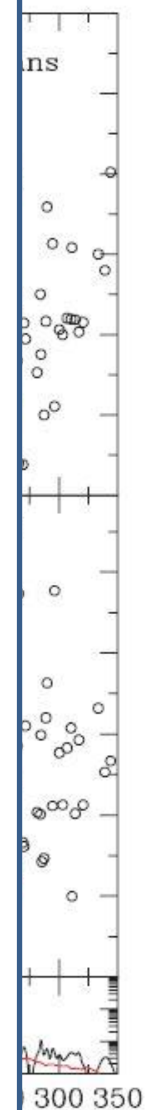
(DM prof

dSph v, fo

⇒Fit to

Fit without Foreground





Walker+, AJ 137 (2009)

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(DM prof

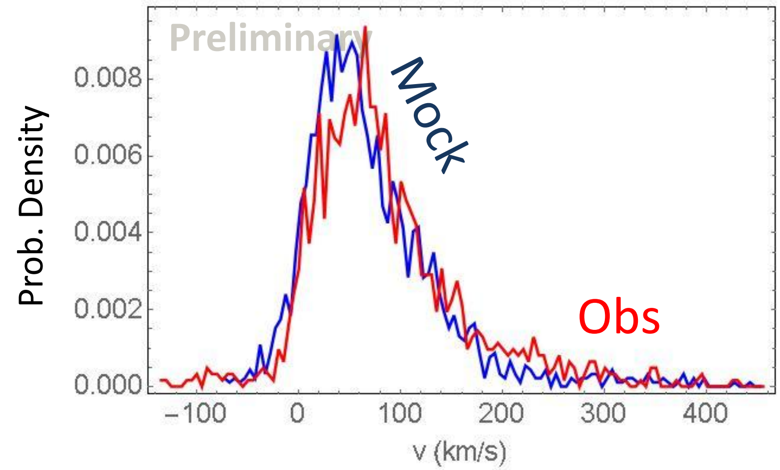
dSph v, f

⇒Fit to

2. Foreground

Besancon Model

Robin+ (2003)



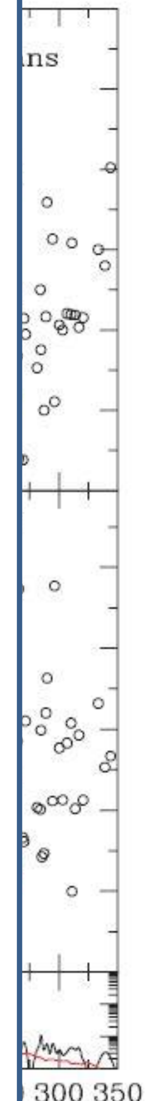
3. Fit

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

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

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

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



Walker+, AJ 137 (2009)

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2. Dete

⇒1. fix: dv

3. Fit:

(DM prof

dSph v, f

⇒Fit to

2. Foreground

Besancon Model

Robin+ (2003)

Prob. Density

0.00
0.00
0.00
0.00
0.00

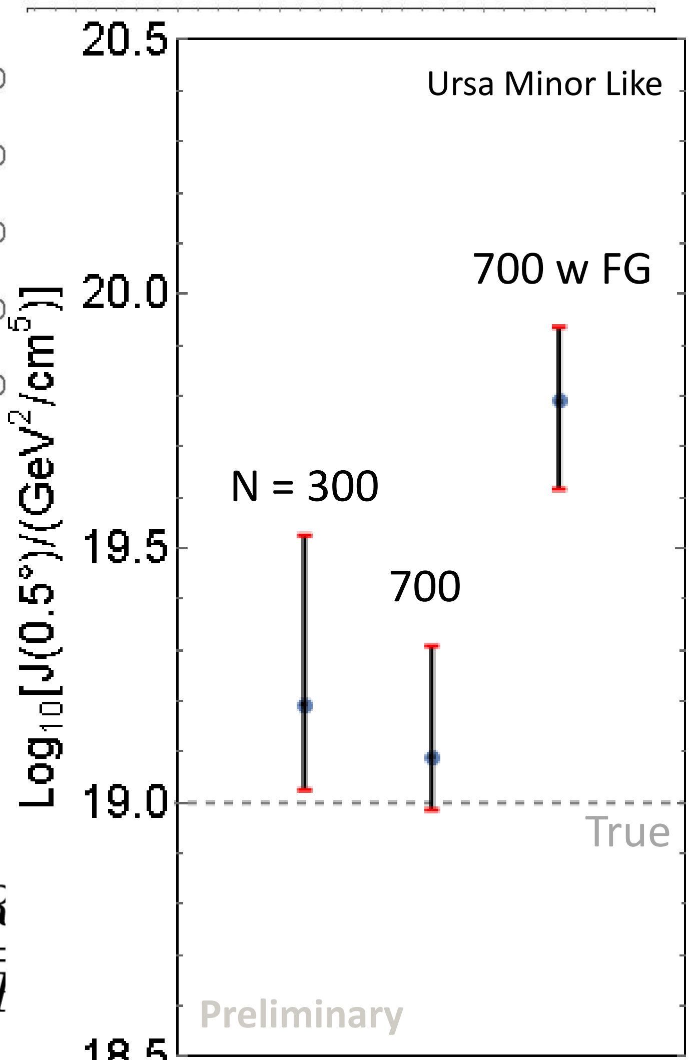
3. Fit

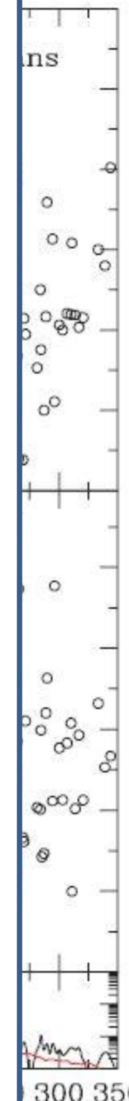
$$-2\sum_i \ln(s f_{\rm Mem}(v_i, R_i))$$

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

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

$$f_{\rm FG}(v, R) = 2\pi R N e^{-}$$



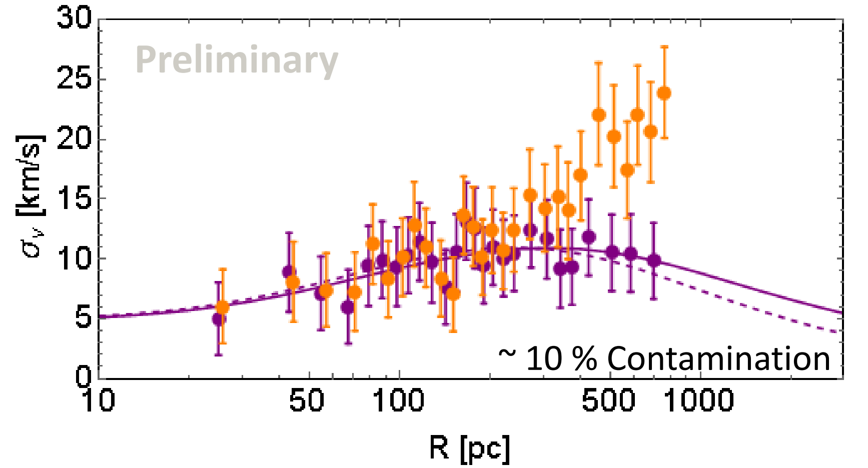


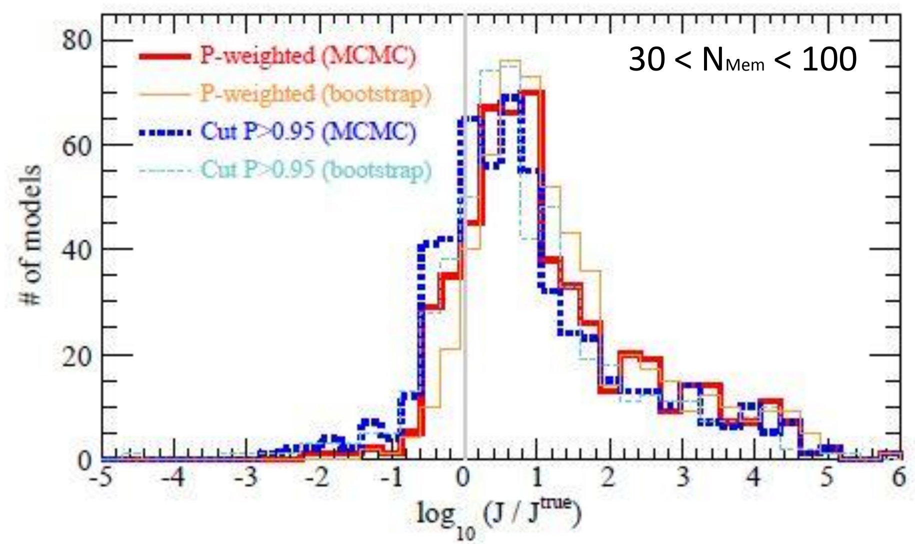
Walker+, AJ 137 (2009)

Foreground Contamination

Outer Region = FG dominant

How to Reduce FG stars?





Bonnivard et al., arXiv:1506.08209

Cut Strategy

Preliminary

Coming Soon!

FG

V Cut (18<V<21):

velocity Cut :

Color Cut:

Gravity Cut:

ROI Cut (0.65 deg):

Members

V Cut (18<V<21):

velocity Cut:

Color Cut:

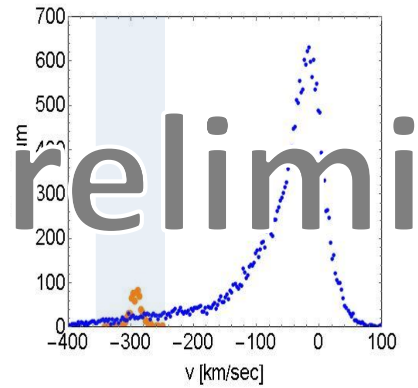
Gravity Cut:

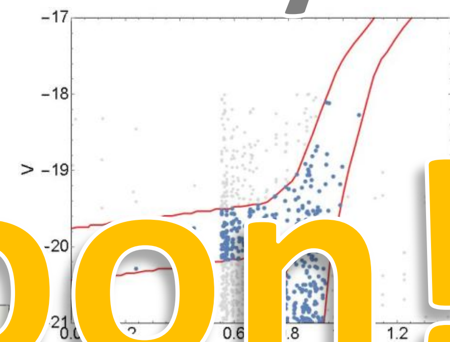
ROI Cut (0.65 deg):

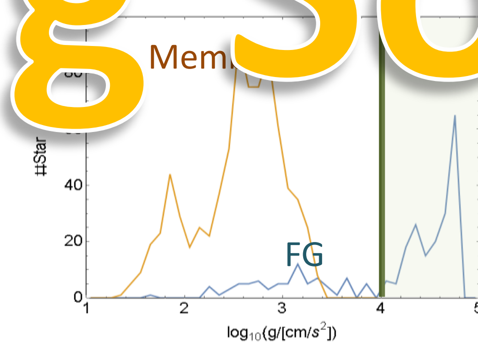
⇒Reduces to O(2) % Contam ?

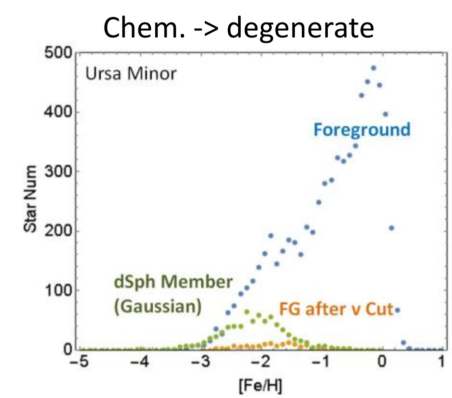
More Wider Range (1.3 deg radius)?

Precise information on FG Distribution can be used?









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 (PFS) will play a crucial role.
- Reduction of foreground stars is necessary

Summary

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Thank You !

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Shigeki Matsumoto and Hajime Sugai.