Prospects on the indirect dark matter detection and a future spectroscopic survey of dwarf spheroidal galaxies

(In preparation)

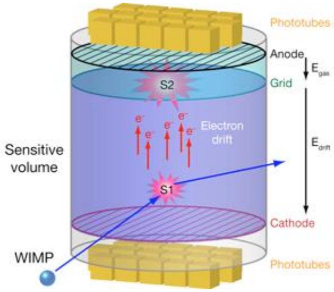
Koji Ichikawa

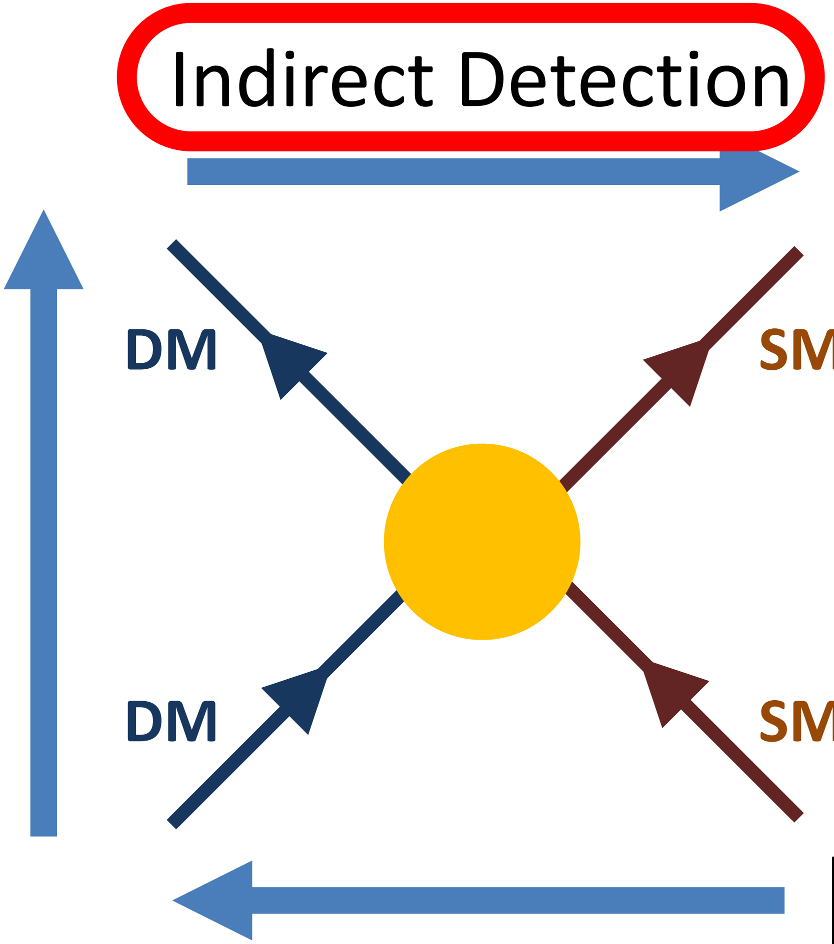
In collaboration with
Kohei Hayashi , Masahiro Ibe, Miho N. Ishigaki,
Shigeki Matsumoto and Hajime Sugai.

KAVLI IPMU

TeVPa2015, Kashiwa, Oct. 26-30, 2015

Dark Matter Search





Indirect Detection

Direct Detection

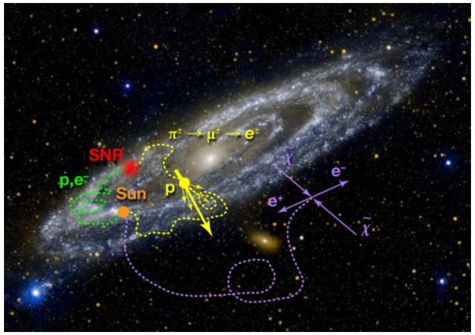
DM

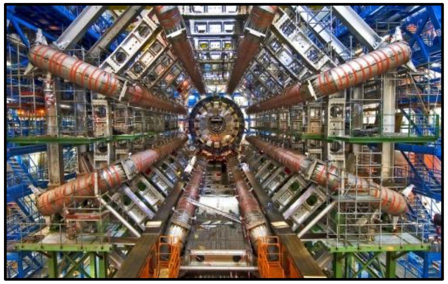
DM

SM

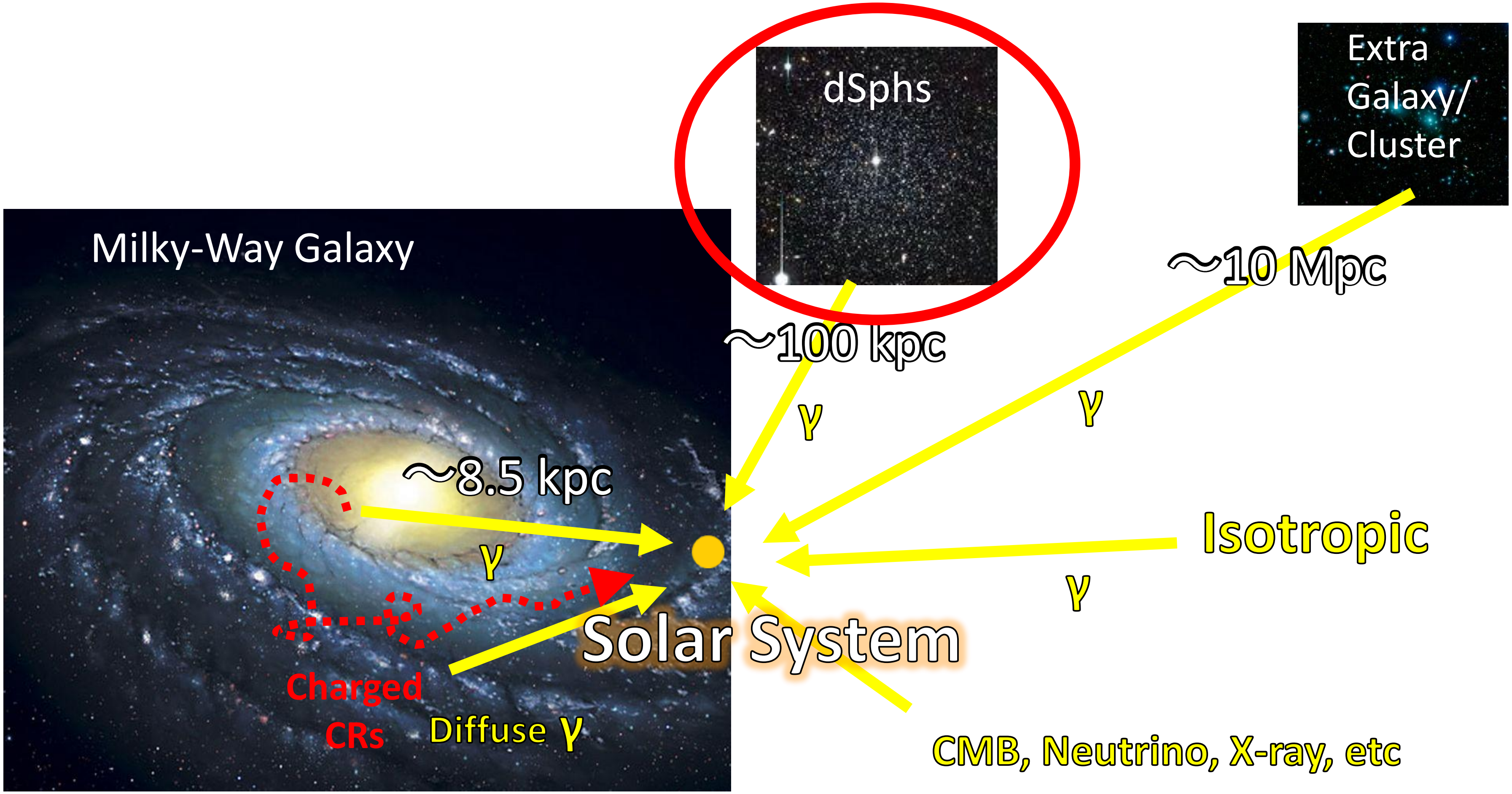
SM

Collider Production





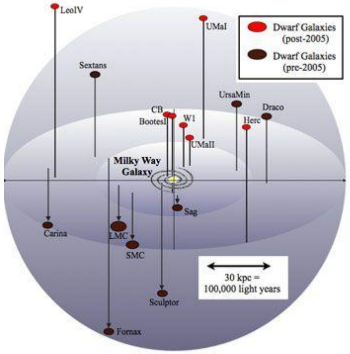
Signal Target

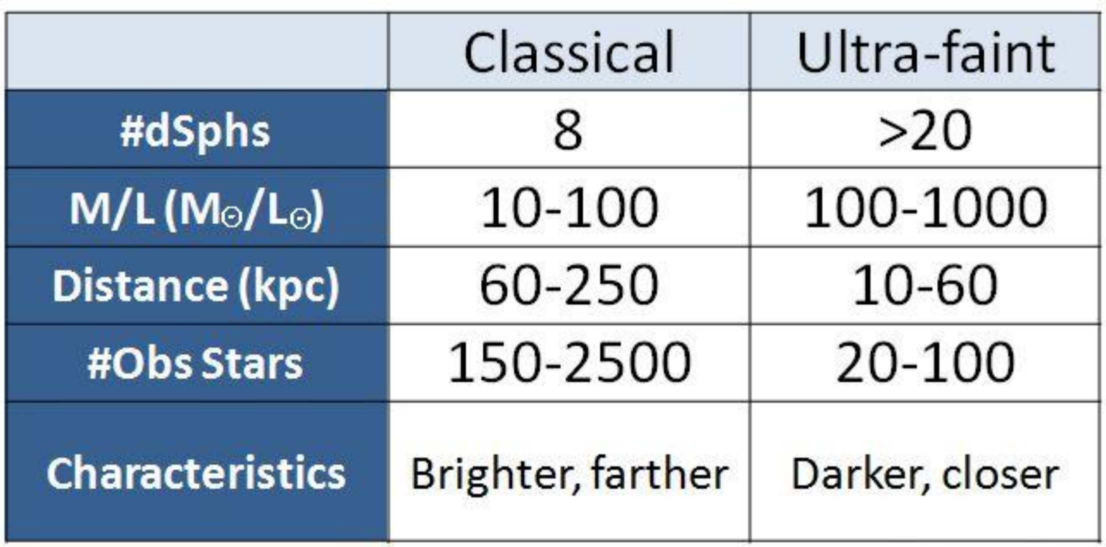


Dwarf spheroidal galaxies

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

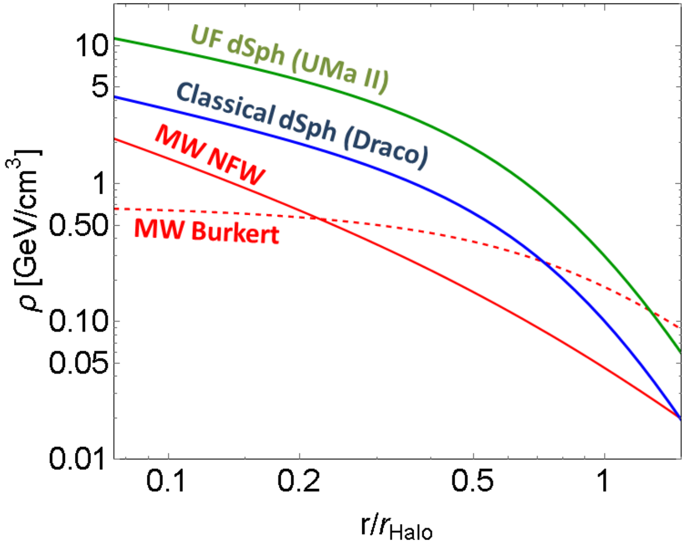
1. **Neighbor** galaxies: 10~100kpc
2. Large Mass to Luminosity ratio = **DM rich**
3. **Clean** (no strong gamma-ray source)





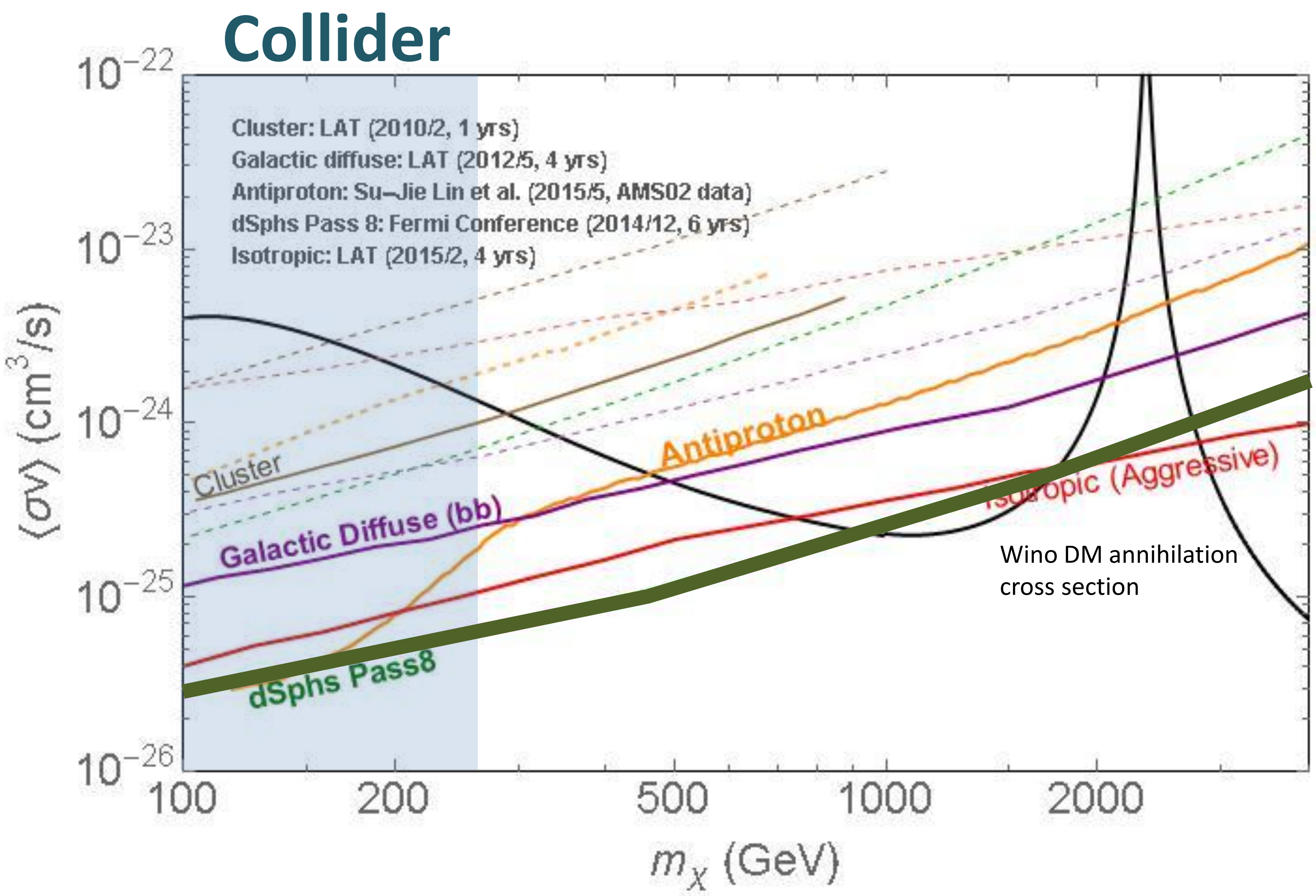
	Classical	Ultra-faint
#dSphs	8	>20
M/L ($M_\odot/L_\odot$)	10-100	100-1000
Distance (kpc)	60-250	10-60
#Obs Stars	150-2500	20-100
Characteristics	Brighter, farther	Darker, closer

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



arXiv:0908.2995v6 [astro-ph.CO]

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



Wino DM annihilation cross section

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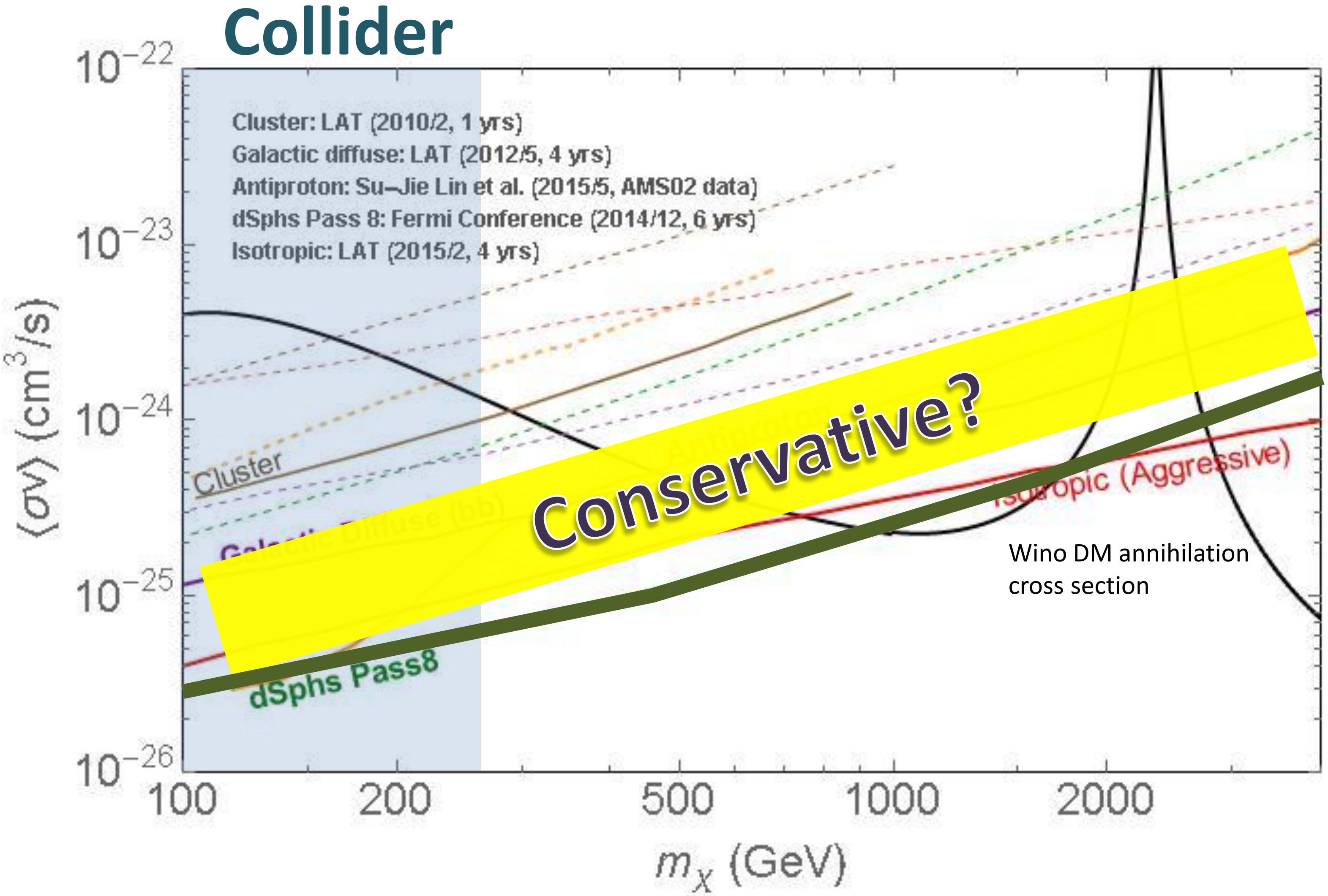
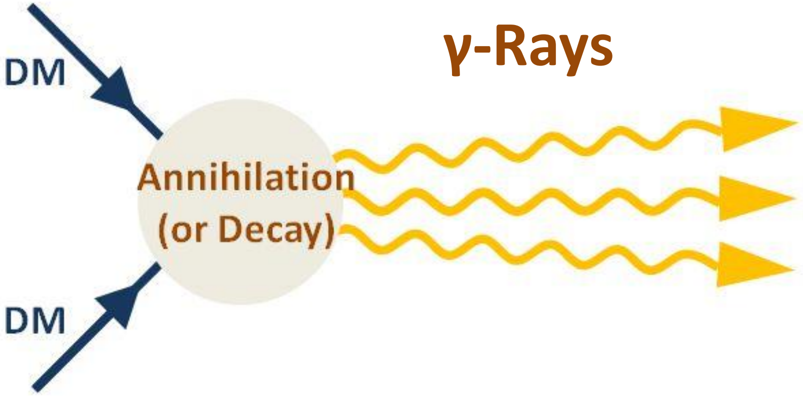


Wino DM annihilation cross section

We Should Precisely Determine The dSph DM Halo Shape

Dwarf galaxy



DM

DM

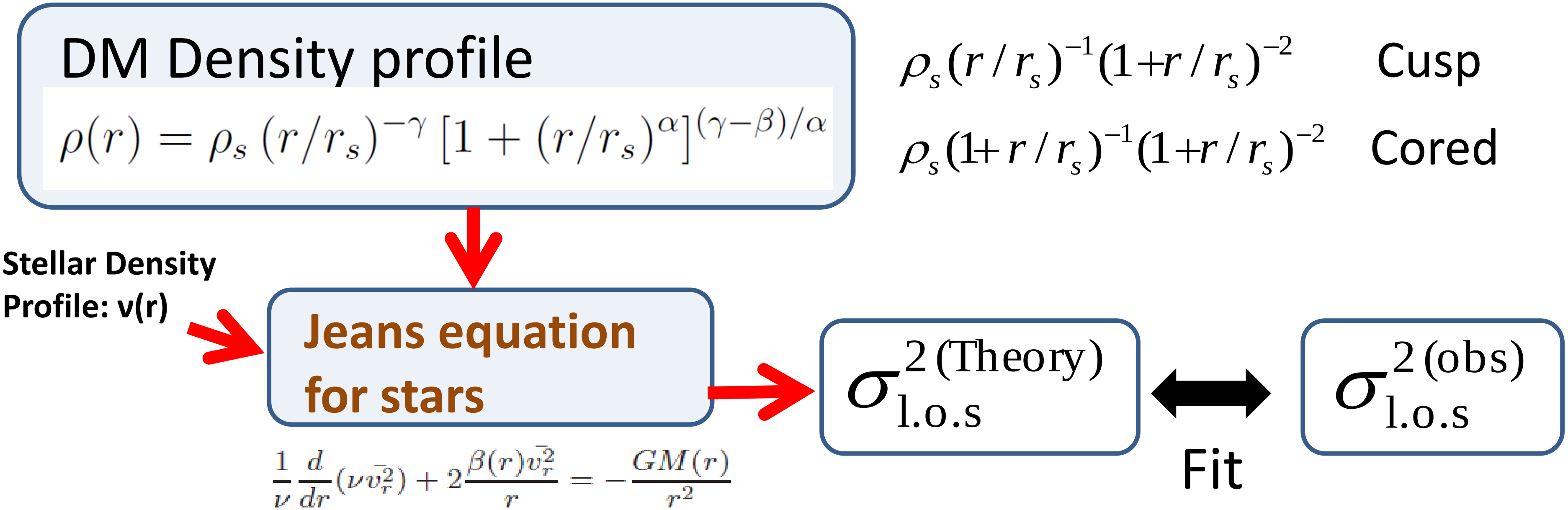
Annihilation
(or Decay)

γ-Rays

$$\underbrace{\Phi(E,\Delta\Omega)}_{\text{Observed }\gamma\text{-Ray Flux}} = \underbrace{\left[\frac{\langle\sigma v\rangle}{8\pi m_{\rm DM}^2}\sum_f {\rm Br}({\rm DM\ DM}\to f)\left(\frac{dN_\gamma}{dE}\right)\right]}_{\text{DM Property}} \boxed{\underbrace{\left[\int_{\Delta\Omega} d\Omega \int_{\rm l.o.s} dl\,\rho^2(l,\Omega)\right]}_{\text{Halo Profile}}}$$

(J-factor)

J-Factor



DM Density profile

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

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

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

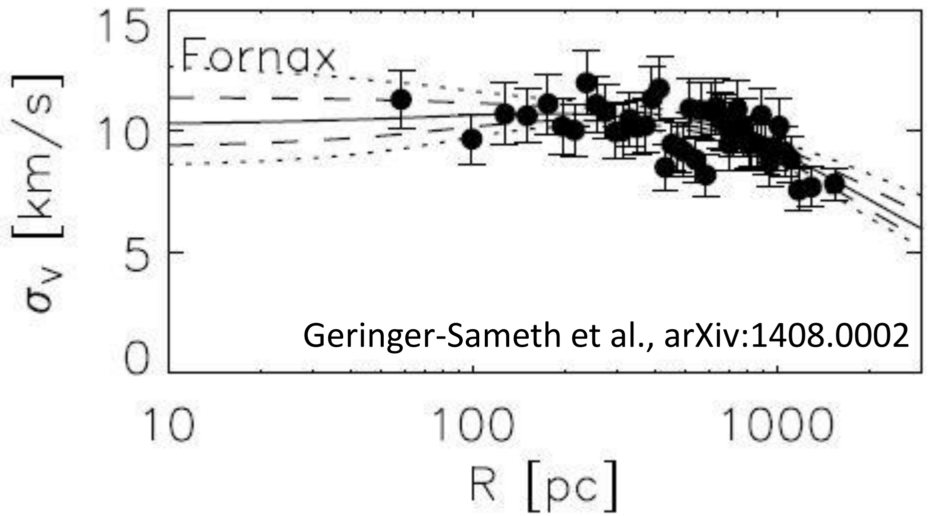
Stellar Density Profile: ν(r)

Jeans equation for stars

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

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

Fit

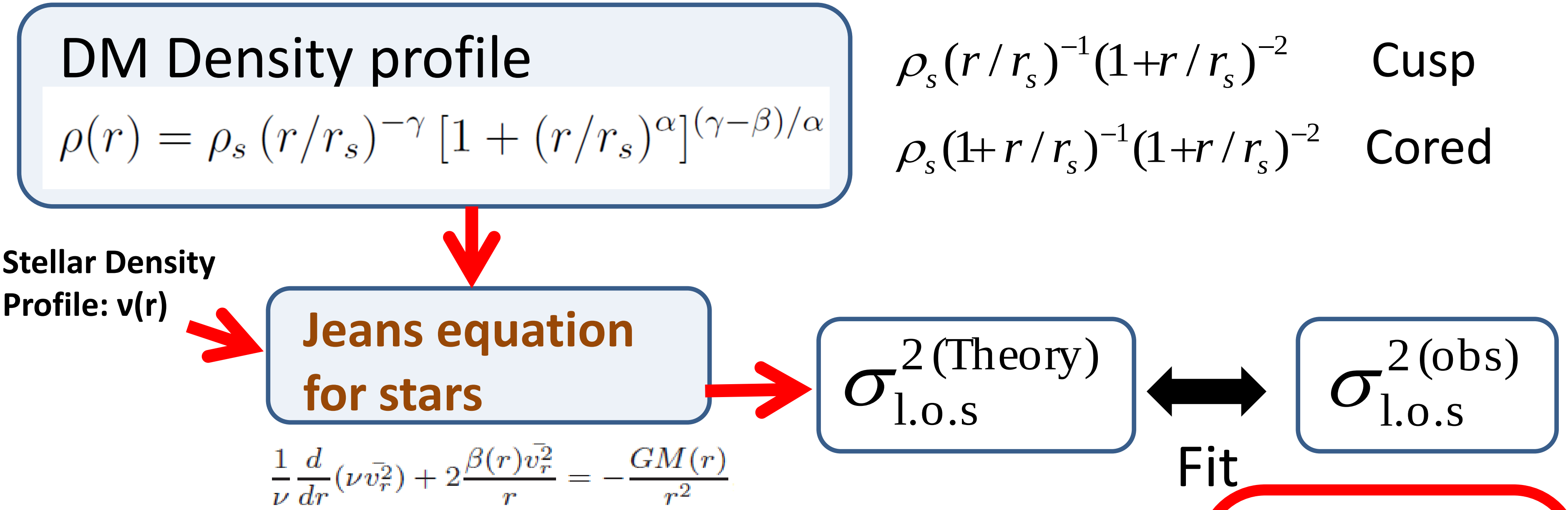


Geringer-Sameth et al., arXiv:1408.0002

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

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

Astrophysical Factor



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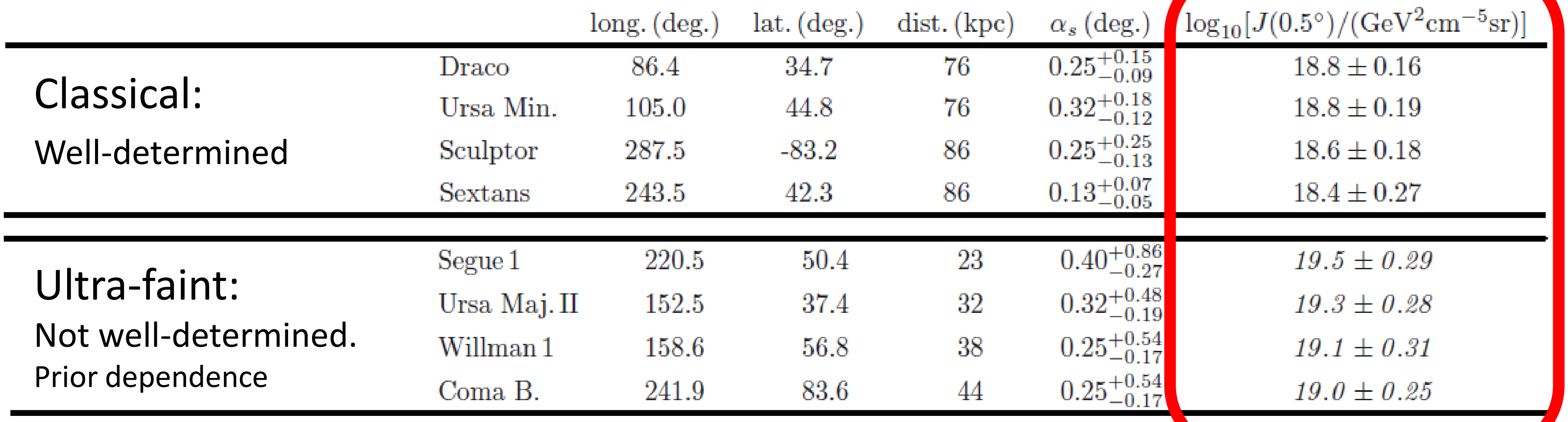
$\sigma^{2\,(\mathrm{Theory})}_{\mathrm{l.o.s}}$

Fit

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



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

Factor 1.6 ~ 2 unc. :Conservative?

Hidden Systematics…

- **Non Spherical?**

  => 0.2〜0.4 uncertainty

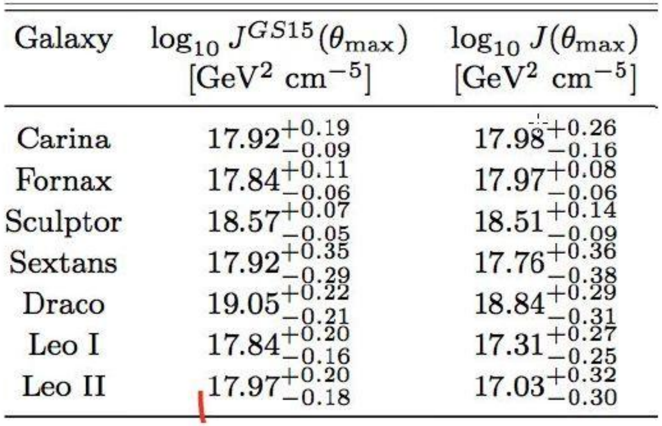
  Axisymmetric: Hayasi and Chiba., arXiv: 1206.3888

- Foreground Contamination?

  N < 100: O(1) uncertainty
  N 〜1000: < 0.4

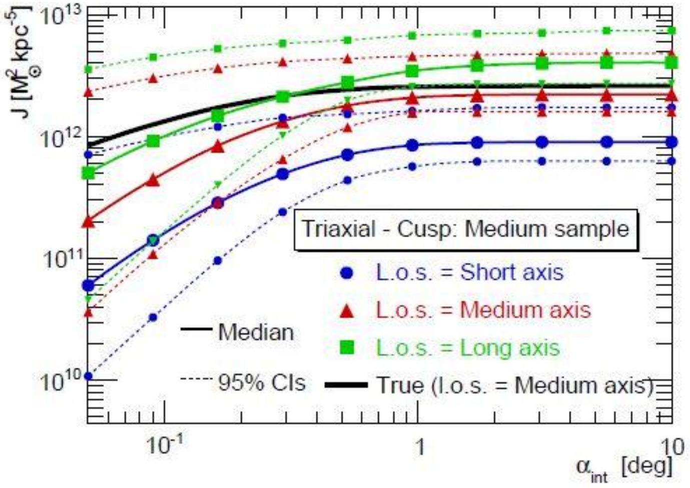
- Prior Bias?/Cut?

  N < 100: > O(1) uncertainty



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

Hidden Systematics…

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  Axisymmetric: Hayasi and Chiba., arXiv: 1206.3888

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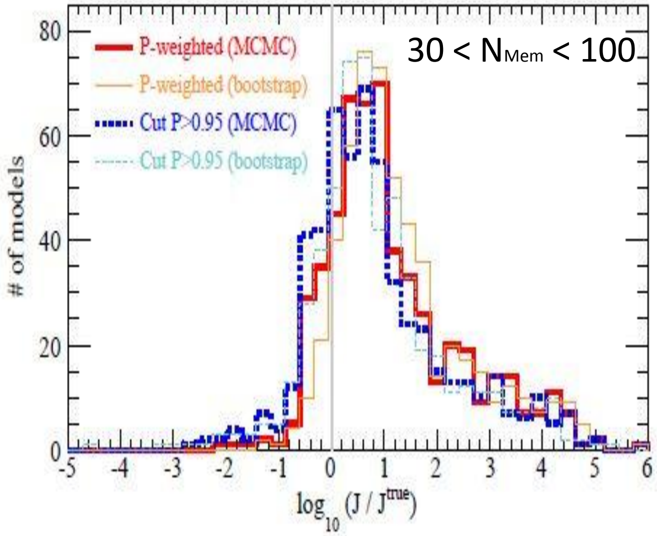
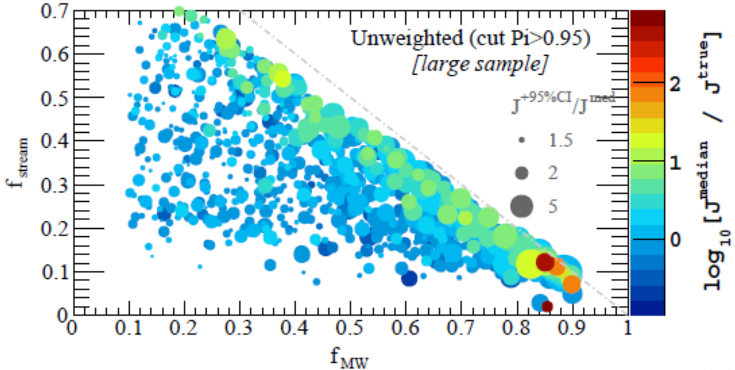


$30 < N_{Mem} < 100$

Bonnivard et al., arXiv:1506.08209



N_{mem} 〜 1000

Bonnivard et al., arXiv:1504.02048

Hidden Systematics…

- Non Spherical?

  => 0.2〜0.4 uncertainty

  Axisymmetric: Hayasi and Chiba., arXiv: 1206.3888

- Foreground Contamination?

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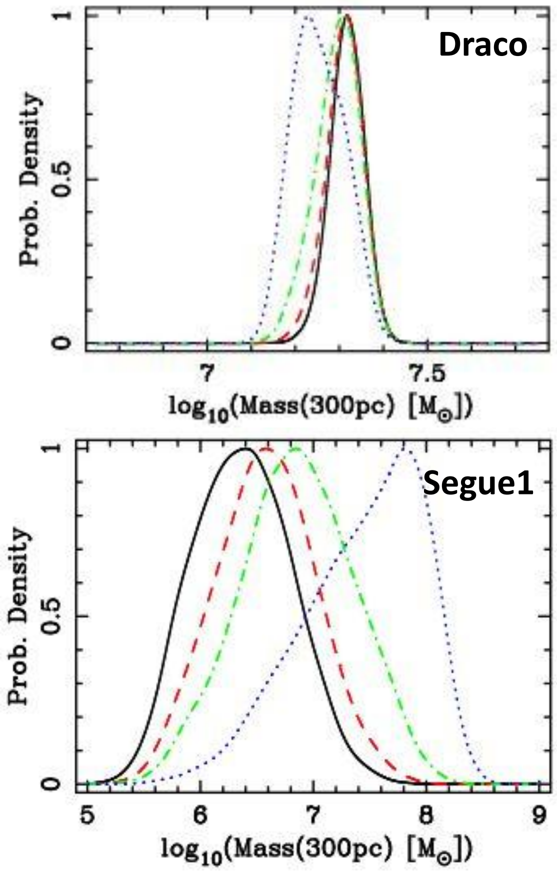


Martinez et al., arXiv: 0902.4715

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)

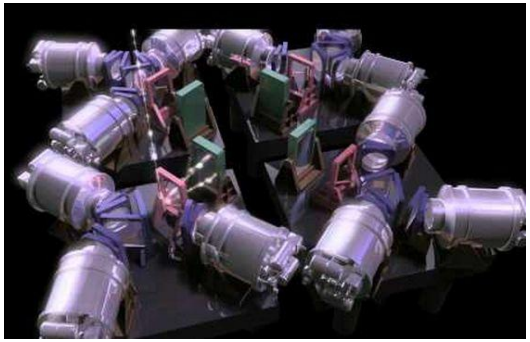
  N < 100: > O(1) uncertainty

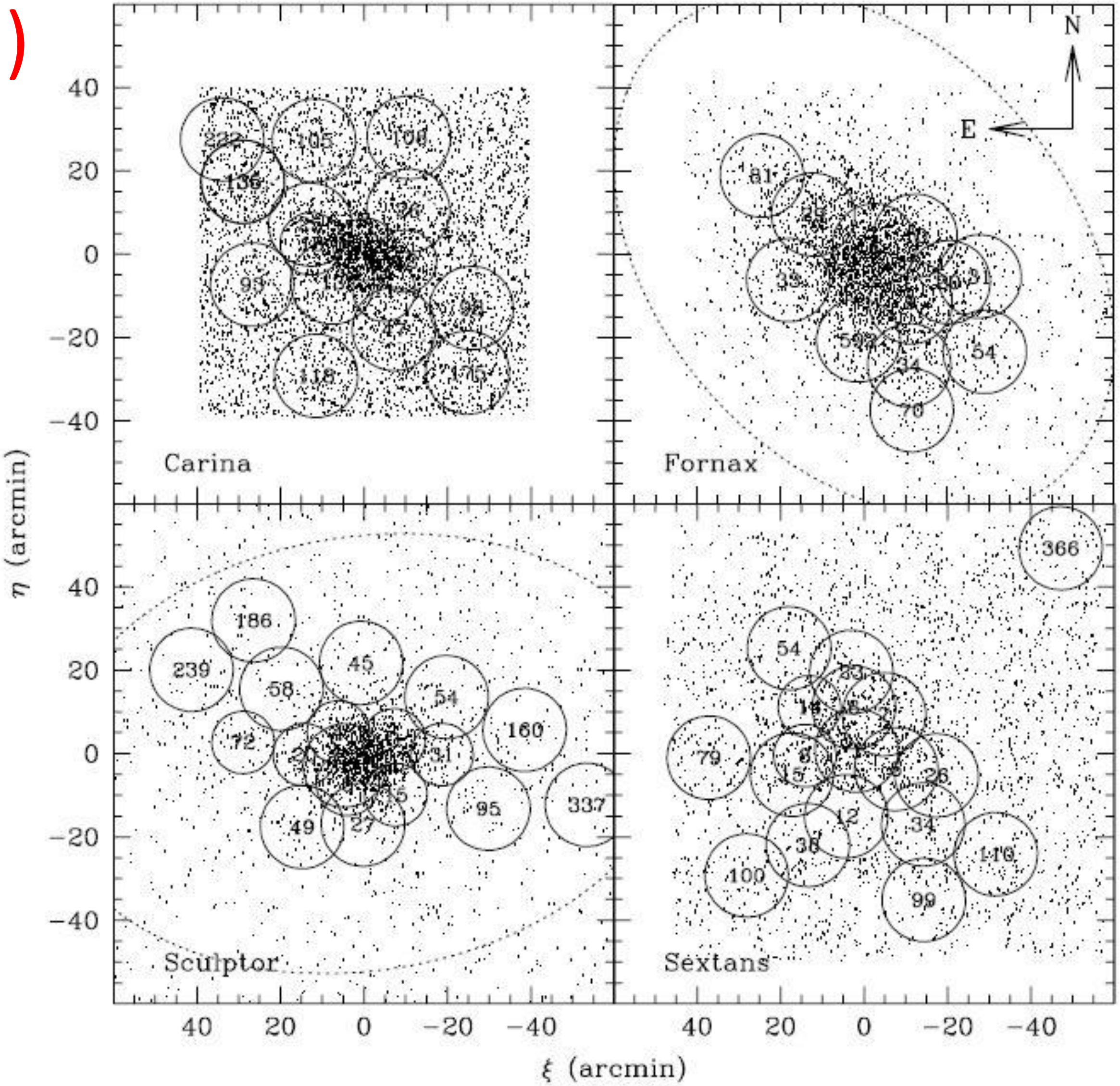
How to Reduce Them? -> **Increase #$\mathbf{N}_{\mathbf{Mem}}$!**

Prime Focus Spectrograph

FoV 1.3 deg (diam)

with 2394 Fiber



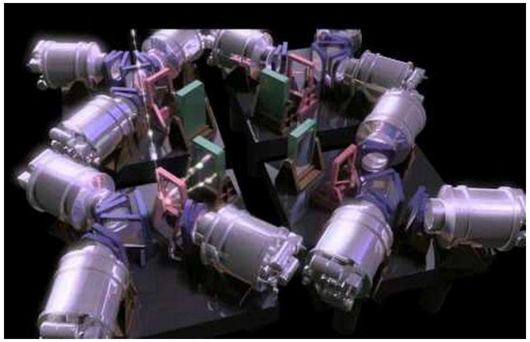


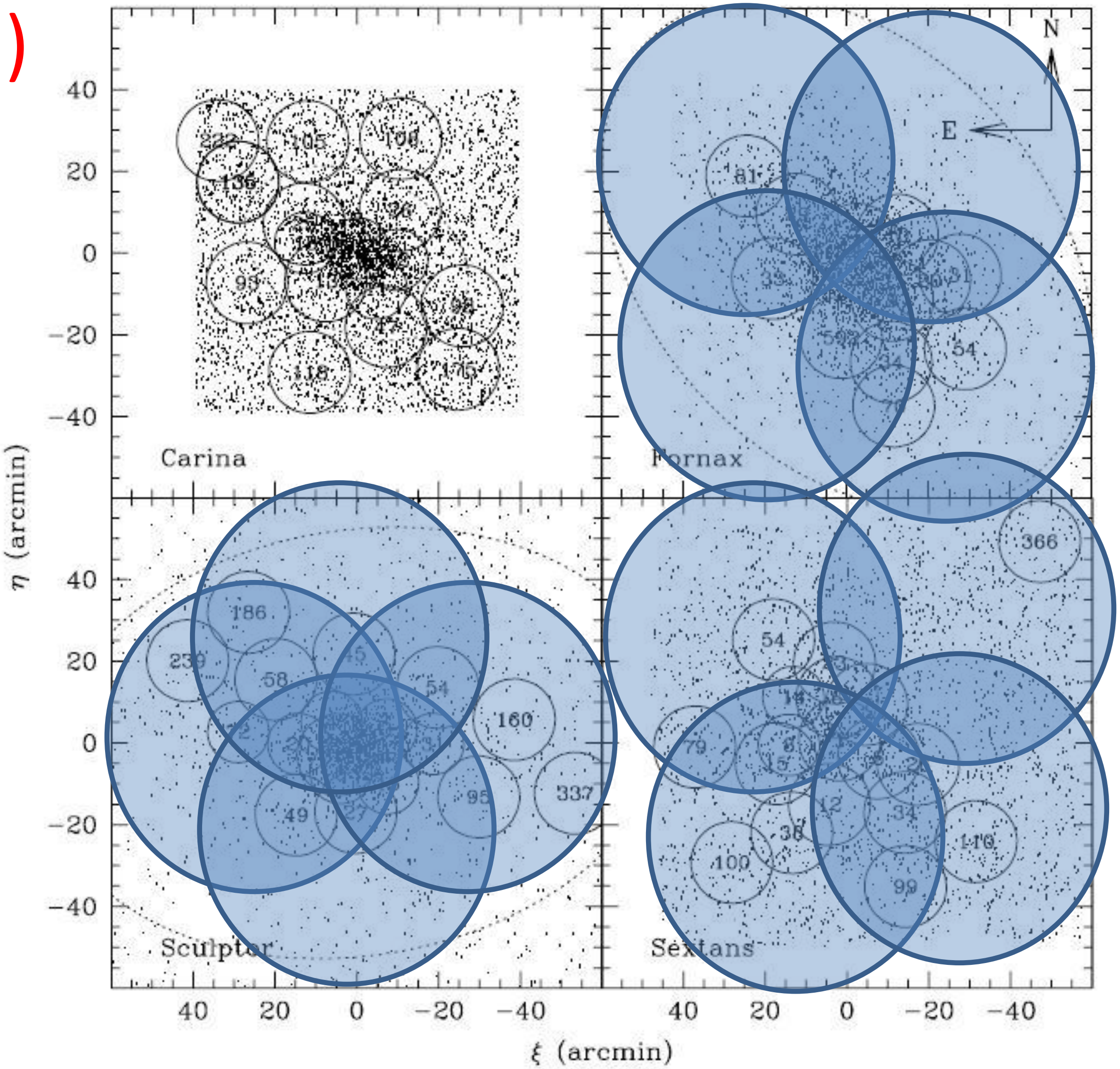
MMFS (M. G. Walker et al,. (2007))

Prime Focus Spectrograph

FoV 1.3 deg (diam)

with 2394 Fiber





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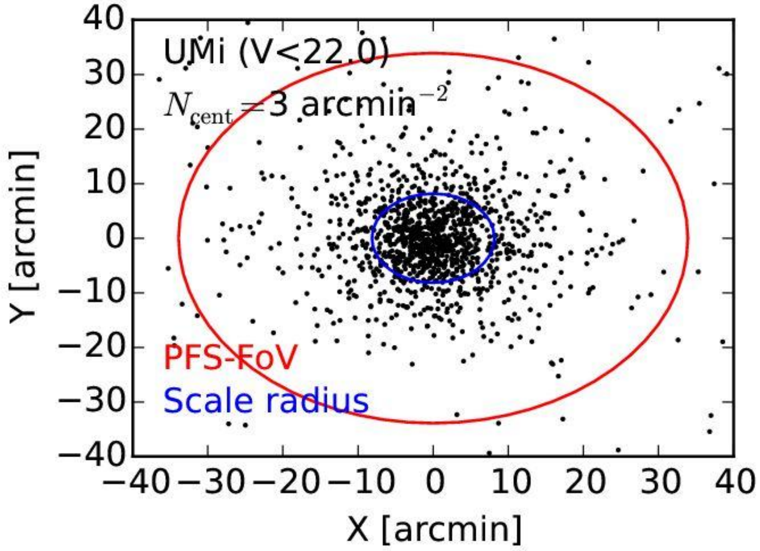
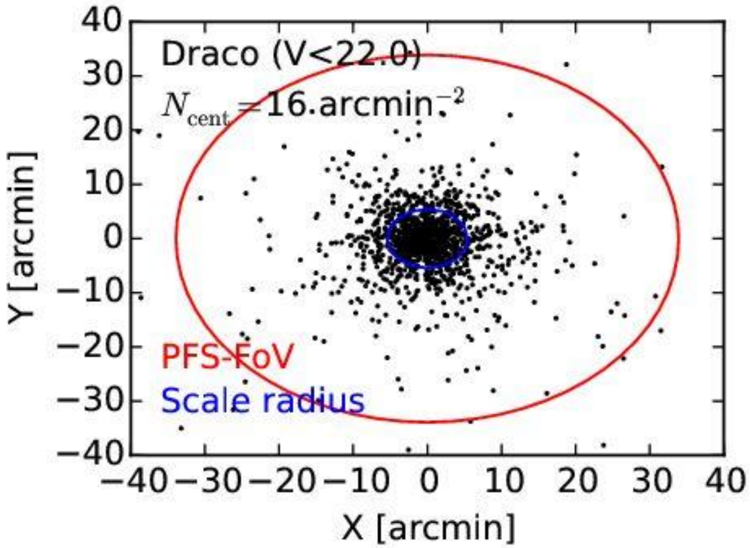
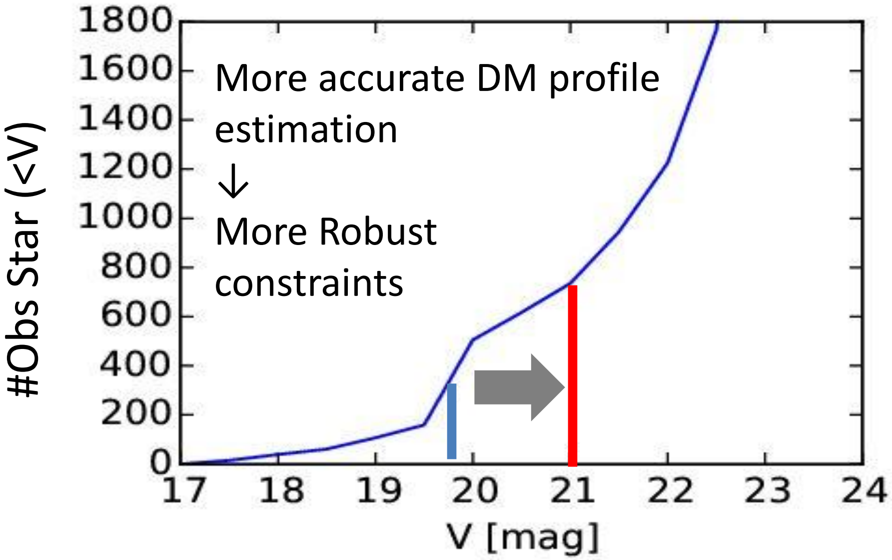
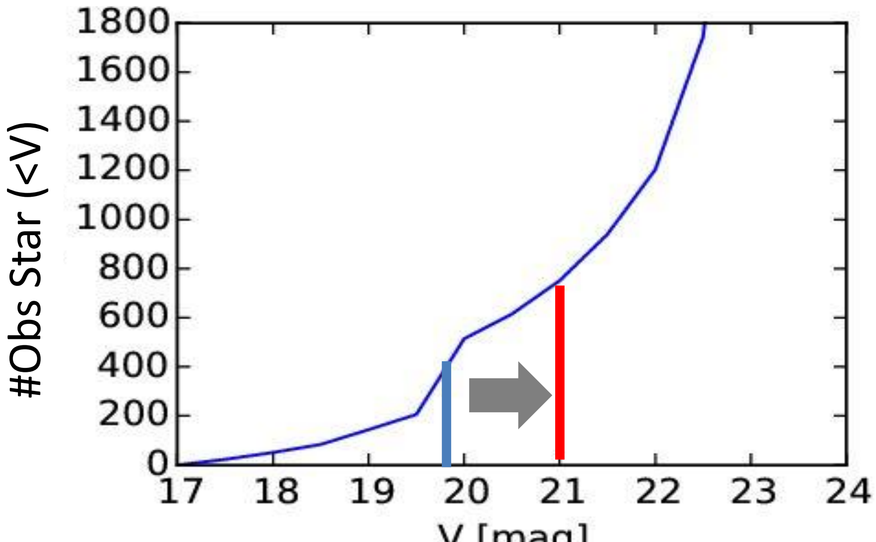
Prime Focus Spectrograph



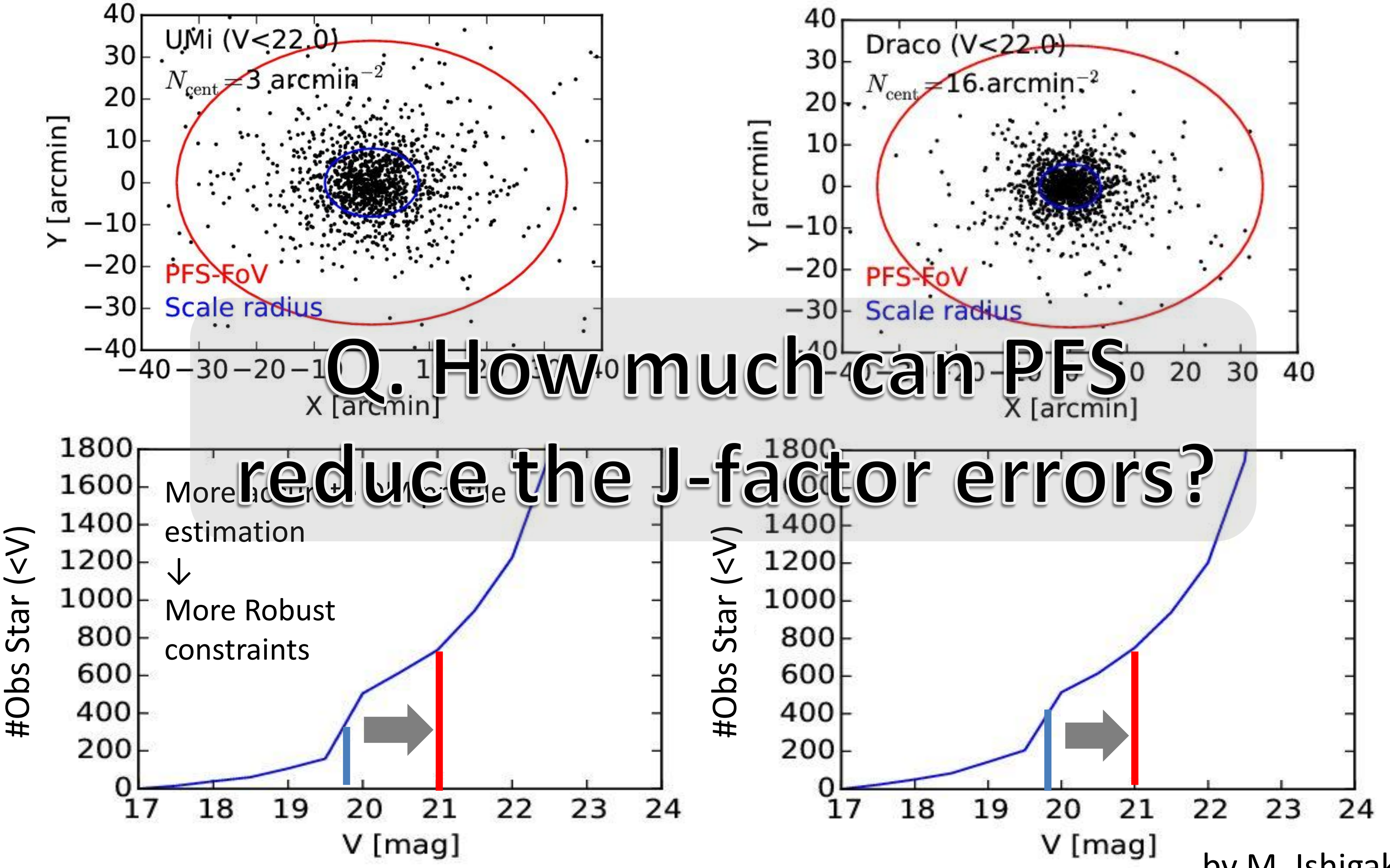



More accurate DM profile estimation
↓
More Robust constraints



by M. Ishigaki

Prime Focus Spectrograph



More accurate DM profile estimation
↓
More Robust constraints

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

by M. Ishigaki

Strategy

1. Mock Observable:

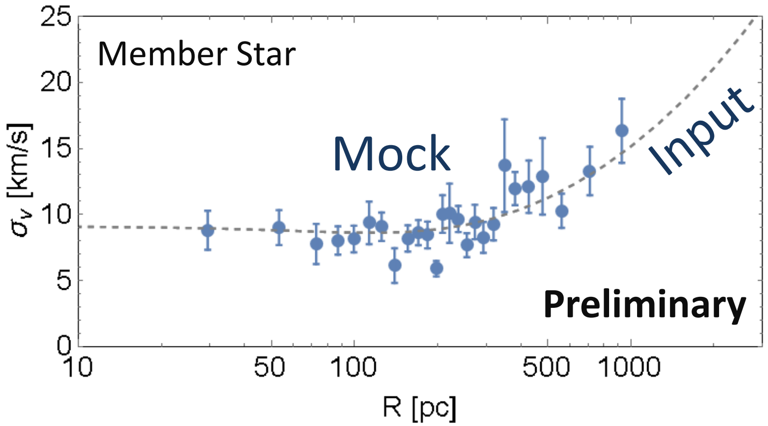
dSph Stellar + Foreground

dSph Stellar Mock

⇒Boltzmann Equation under DM profile

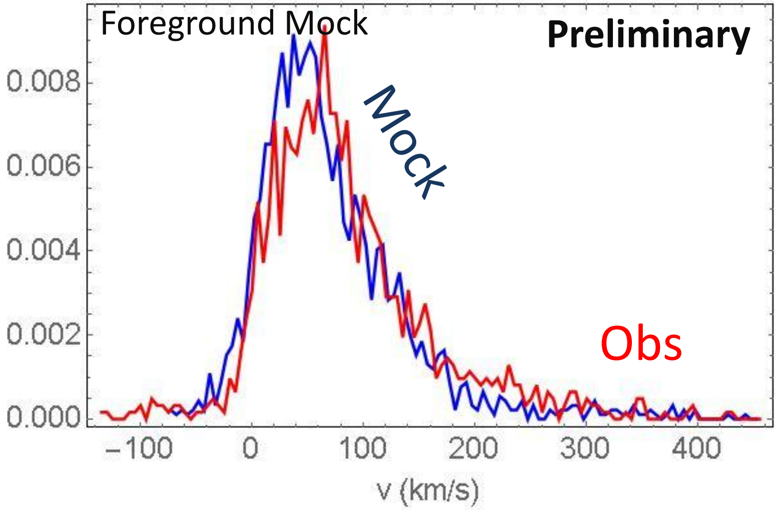
Foreground Mock

⇒Besancon Model (Robin+ (2003))



2. Detector Convolution:

⇒1. fix: dv = 3.0km/s



3. Fit:

by (v, r) probability density. (unbinned)

Stra

1. Moc

dSph St

dSph Stell

⇒Bolt

Foregroun

⇒Besa

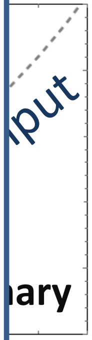
2. Dete

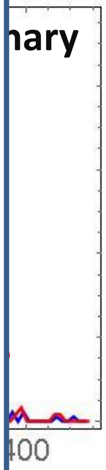
⇒1. fix: dv

3. Fit:

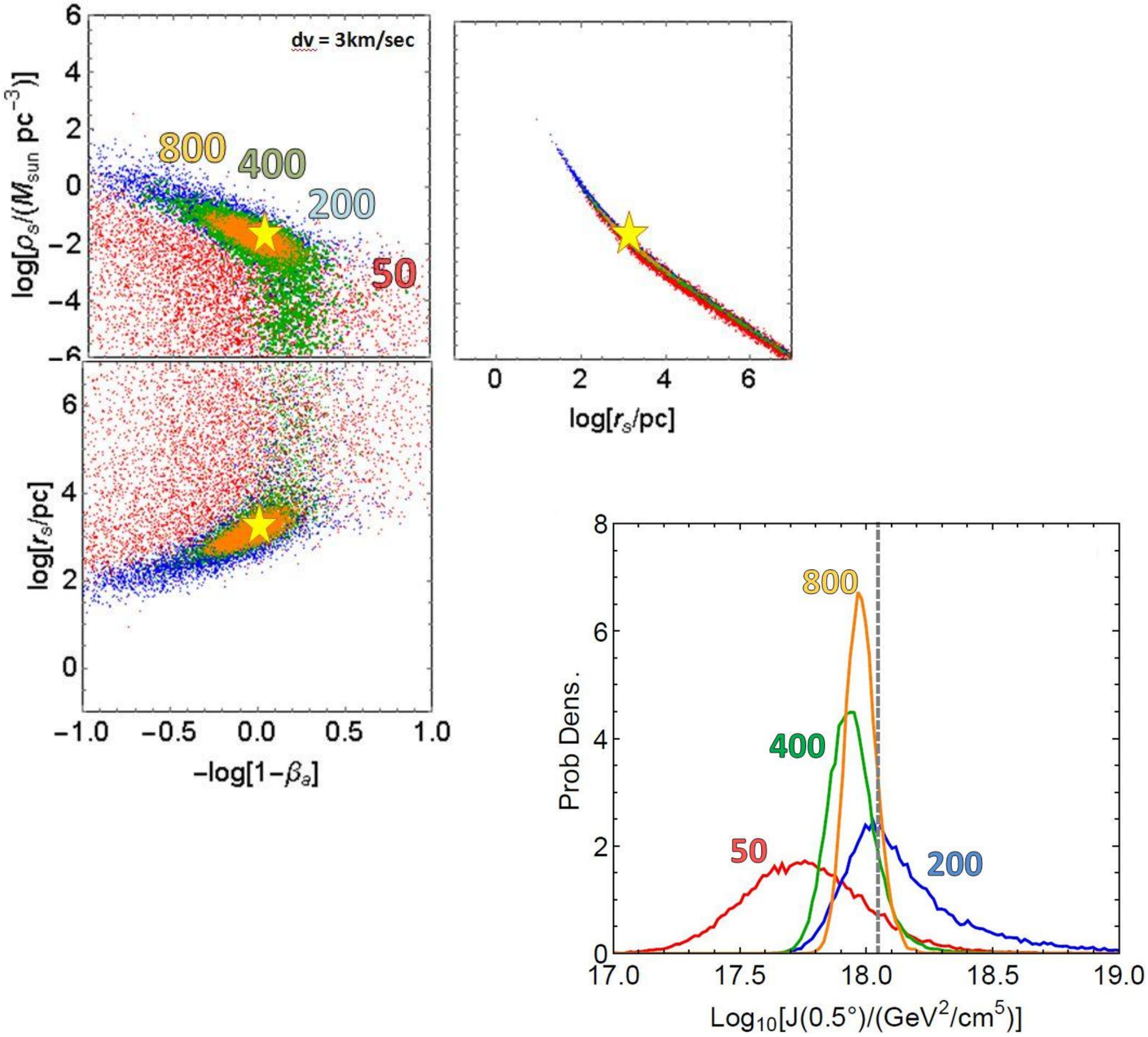
by (v, r)

(unbinn





Fit without Foreground Star

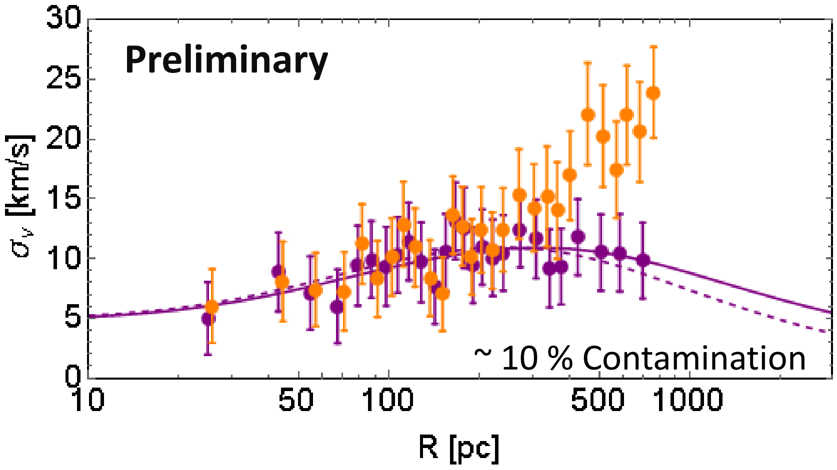


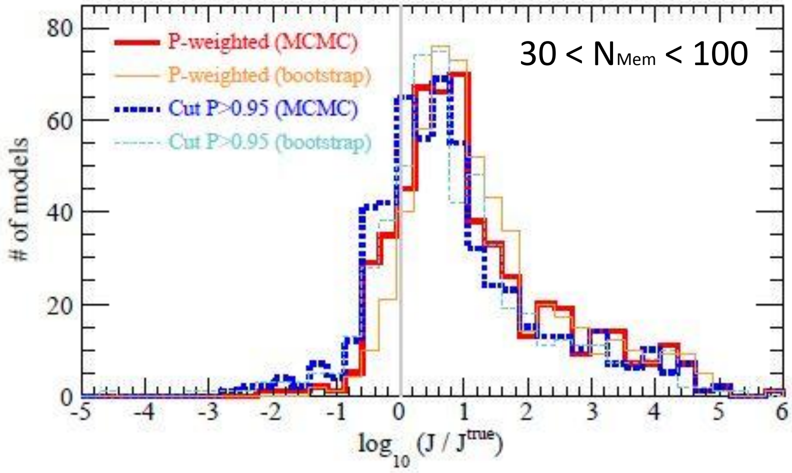
Foreground Contamination

Outer Region = FG dominant

How to reduce the FG?
=> Cut

How to include the FG effect?
=> Model the FG dist.





Bonnivard et al., arXiv:1506.08209

Cut Strategy

ROI Cut:
1.3 deg radius for 4 pointing

Color –Magnitude Cut
Gravity Cut
velocity Cut
Teff, Chemical Cut do not so efficient

Current (i ~ 20.)

Member 420
FG 30 (w/o vCut: 130)

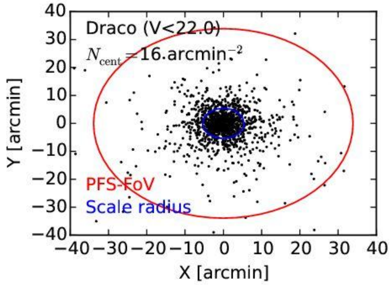
This contamination is ignored
= Biases dLogJ~ 0.1

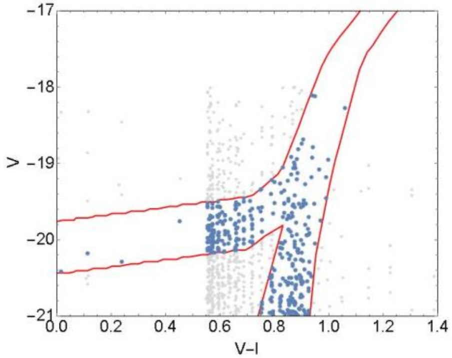
PFS (i < 21)

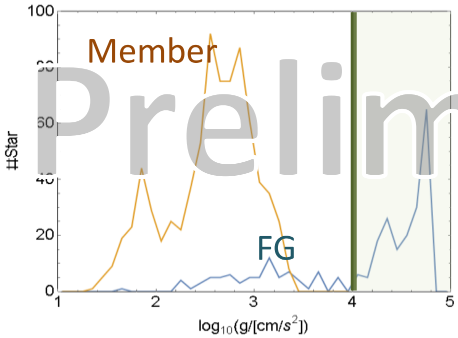
Member 700
FG 80 (w/o vCut: 550)

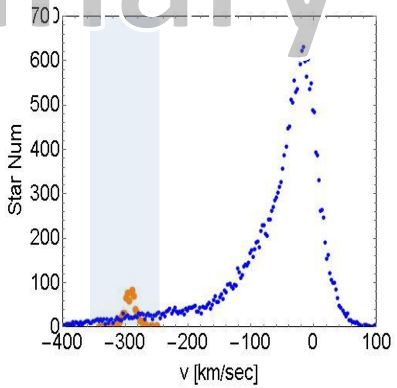
PFS (i < 21.5)

Member 900
FG 100 (w/o vCut: 650)

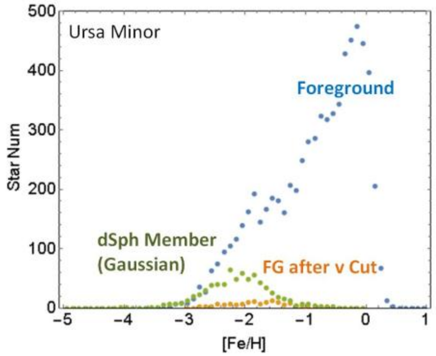








Chem. -> degenerate



Fit including FG model

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

Member Fraction

Prob. Dist. Of FG

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

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

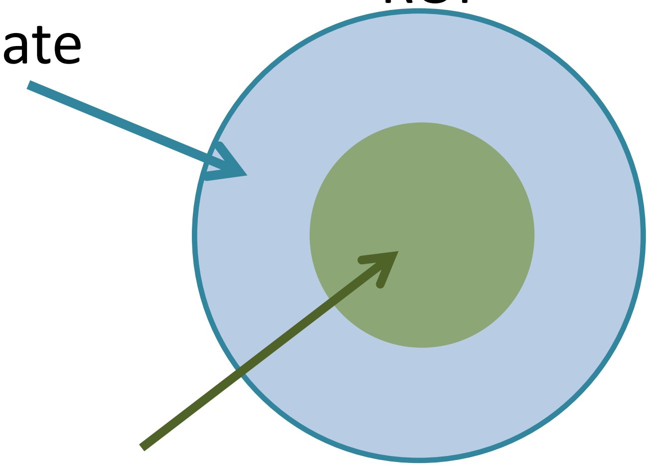
Member Parameter
= halo information

$$f_{\mathrm{FG}}(v,R) = 2\pi R N_{\mathrm{FG}} e^{-\boxed{\frac{(v-v_{\mathrm{FG}})^2}{2\sigma_{\mathrm{FG}}}}}$$

FG Parameter

Can be considered to be
Gaussian after several cuts.

FG func Parameters



ROI

FG Dominate

dSph Dominate

Outer Region Stars

(Data w/o v cut can be used)

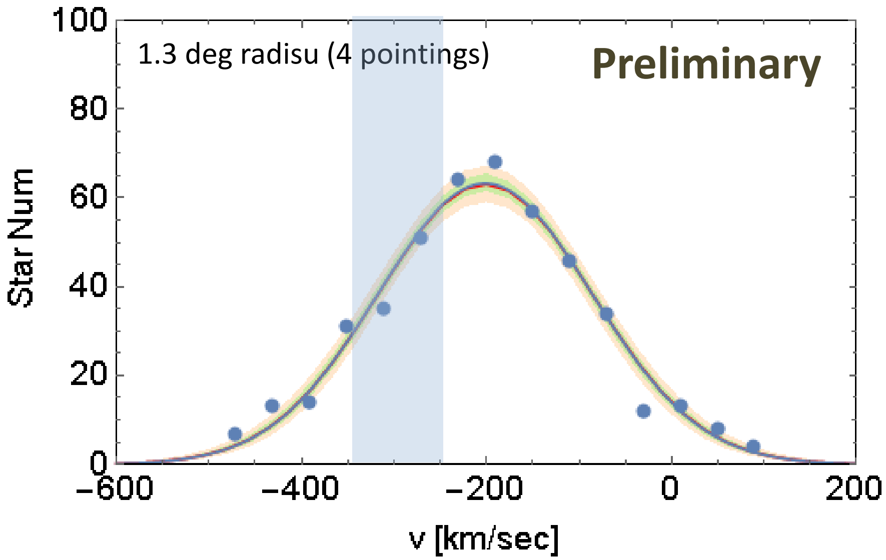
=>

FG func parameter inc. its errors can be determined (errors => prior)

Large ROI

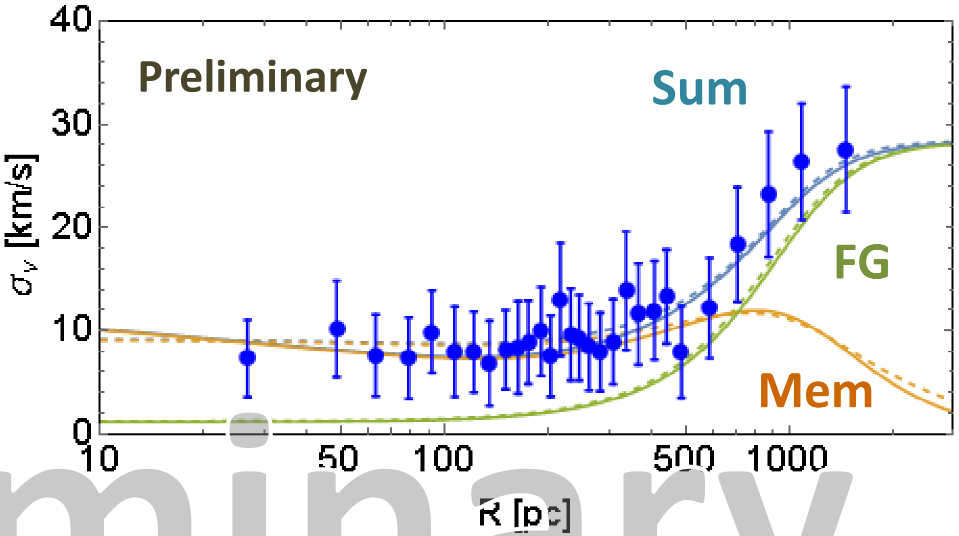
=Large FG sample

= Small error of f_{FG} params



Results

Current Data
(inc. FG contami)
dLog(J) ~ 0.25?
↓
PFS
(inc. FG contami)
dLog(J) < 0.15?



Optimization is on-going…

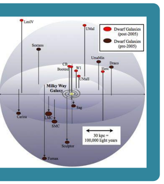
Summary

- 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 important

Thank You !

Koji Ichikawa

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



TeVPa2015, Kashiwa, Oct. 26-30, 2015