Foreground effect on the J-factor estimation of the dwarf spheroidal galaxies

Koji Ichikawa

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

KAVLI IPMU

arXiv:1608.01749 (submitted in MNRAS)
MNRAS, 461, 2914 (1603.08046 [astro-ph.GA])

TevPa2016, Sep. 12, 2016

Non-Sphericity + Foreground effect on the J-factor estimation of the dwarf spheroidal galaxies

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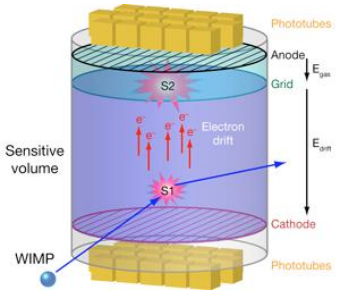
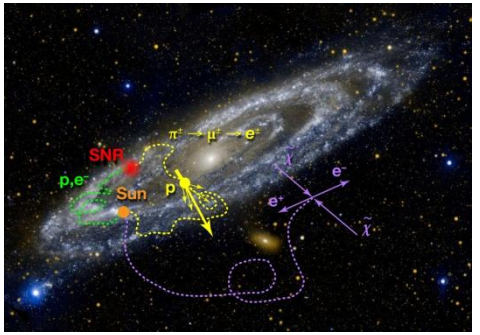
Dark Matter Search



Indirect Detection



Direct Detection

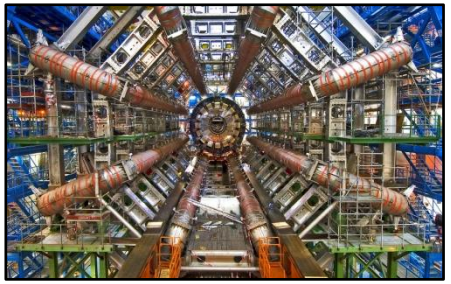
DM

SM

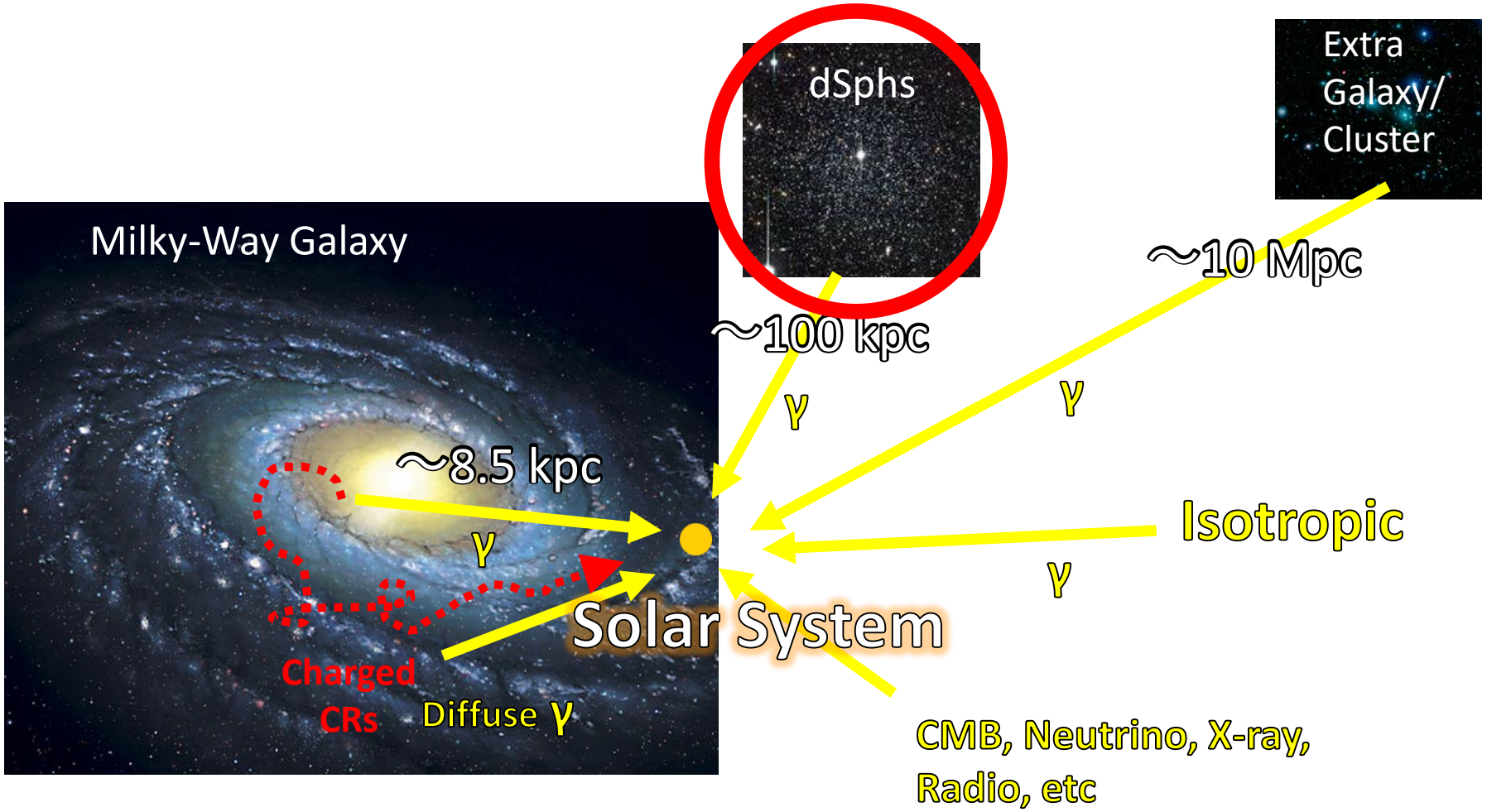
DM

SM

Collider Production



Indirect Detection



Dwarf spheroidal galaxies

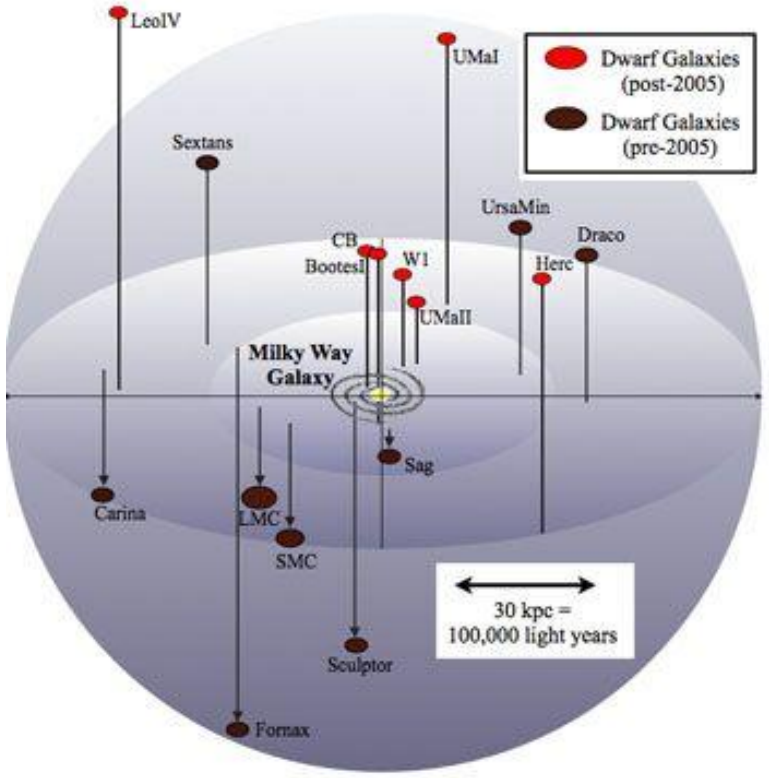
dSphs:

1. **Satellite** galaxies: d= 10~100kpc
2. **Clean** (no strong gamma-ray source)
3. **DM rich**

dSph Type

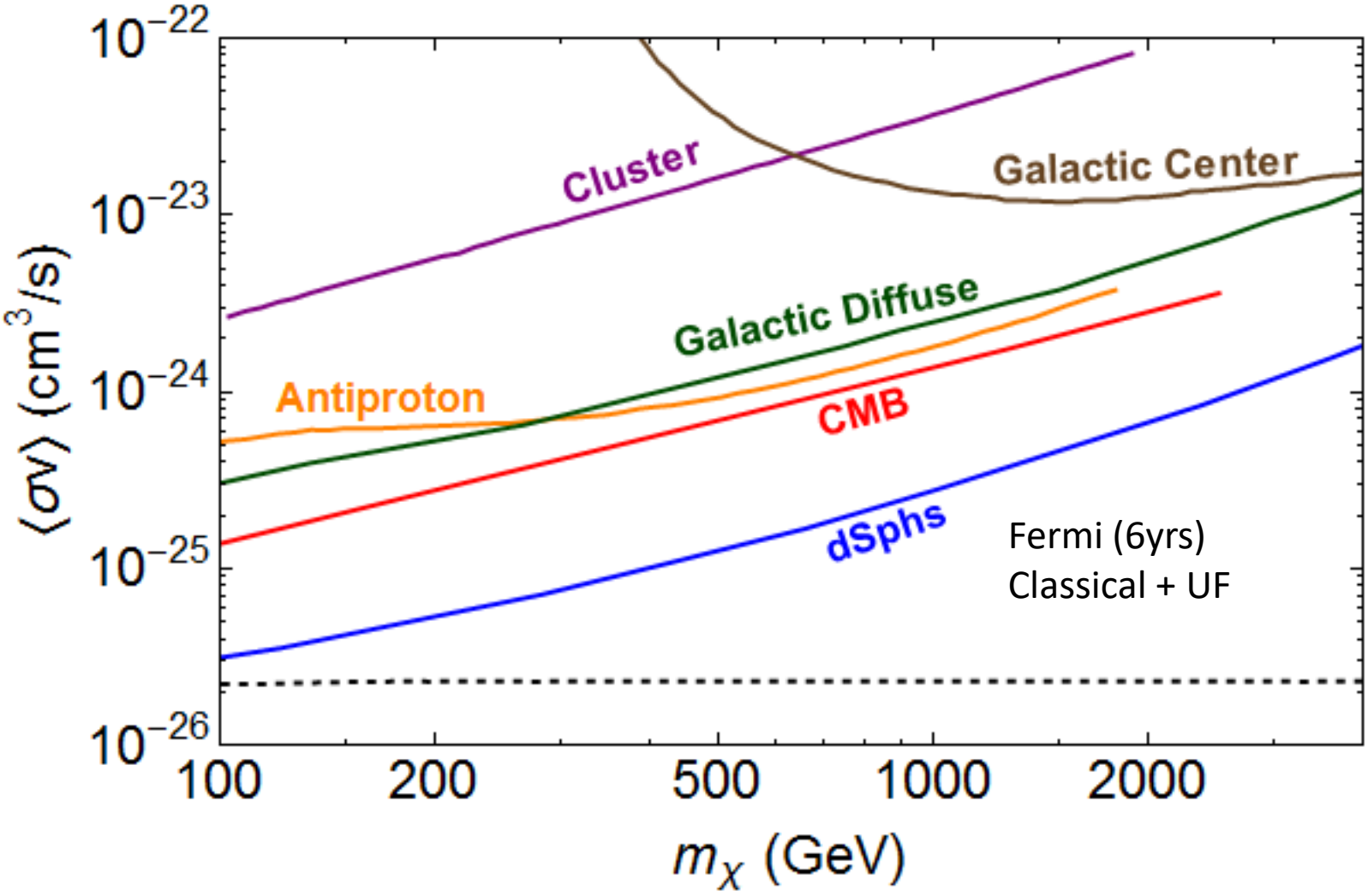
	Classical	Ultra-faint
#dSphs	8	>20
M/L ($M_\odot/L_\odot$)	10-100	100-1000
Distance (kpc)	60-250	10-60
#Obs Stars	150-2500	20-100
Characteristics	Brighter, farther	Darker, closer

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

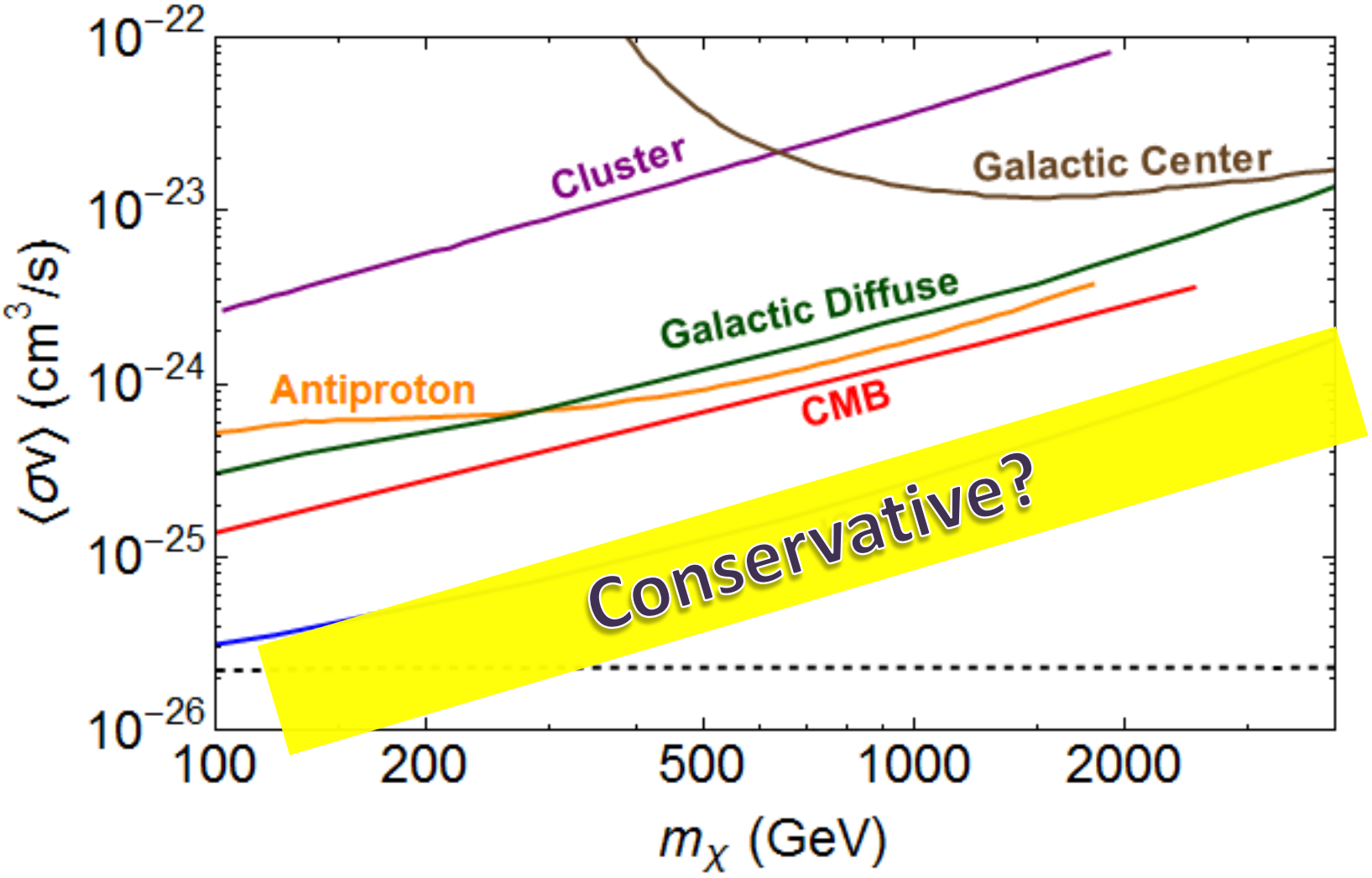


MNRAS, 406 (2010) 1220

dSph = Strong Probe

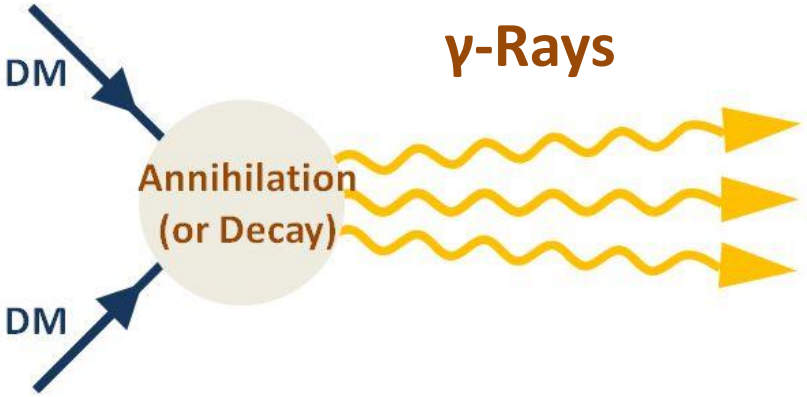


dSph = Strong Probe



Signal Flux

Dwarf galaxy



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

Observed γ-Ray Flux

DM Property

Halo Profile (J-factor)

→ J-factor is determined by

stellar kinematics of dSph

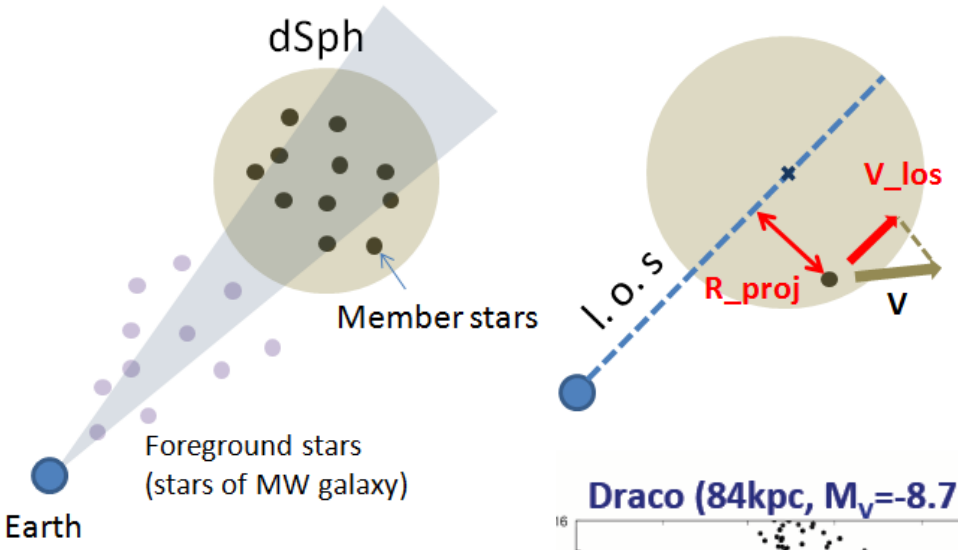
Observables

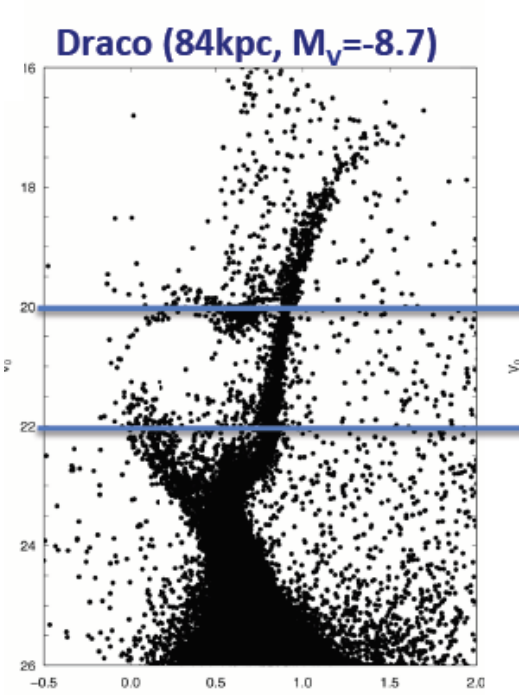
❖ By photometry (V ~ 26)
Distance from center: **R_{proj}**
Luminosity, Color

❖ By spectroscopy (V ~ 20)
Recession velocity: **v_{los}**
Metalicity

❖ Data size {R_{proj}, v_{los}}
Classical: O(100-1000)
UF: < O(50)

Binned v_{los} data w.r.t. R_{porj}
=> Dispersion curve $\sigma_{los}(R_{proj})$.
(v_{los} cannot be directly used for fit.)





Spectroscopy
V ~ 20 →

Photometry
V ~ 26 →

Dispersion Curve

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

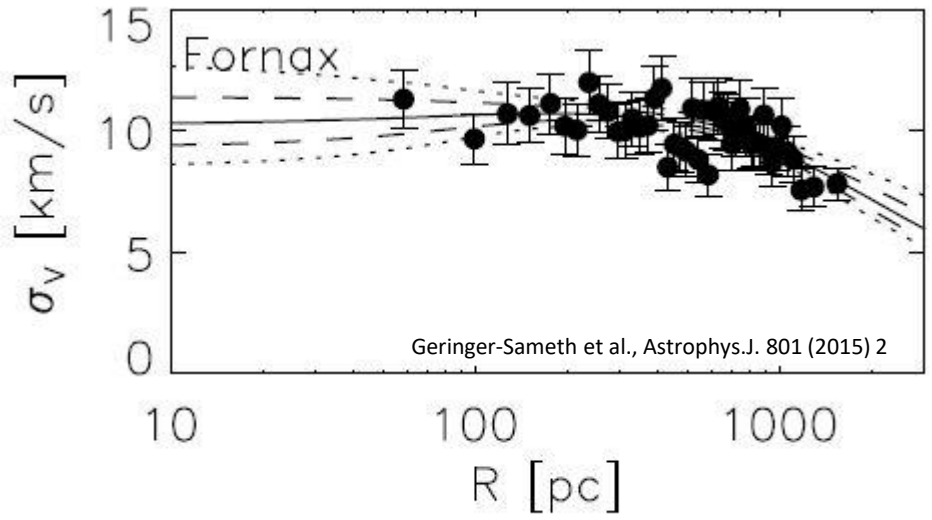
Stellar Density Profile: v(r)

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



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

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

Current Status

Is the fit model accurate enough?

does the fit really converge?

Is the data pure enough?

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Is the fit model accurate enough?	Spherical Assumption
does the fit really converge?	Biased by a prior
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Non Sphericity

Most of the studies assume **spherical profile**.

But…

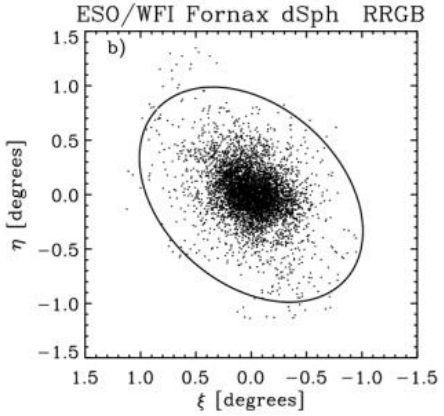
1. Stellar distributions of dSphs are not spherical.

2. Simulation suggest axisymmetric profile.

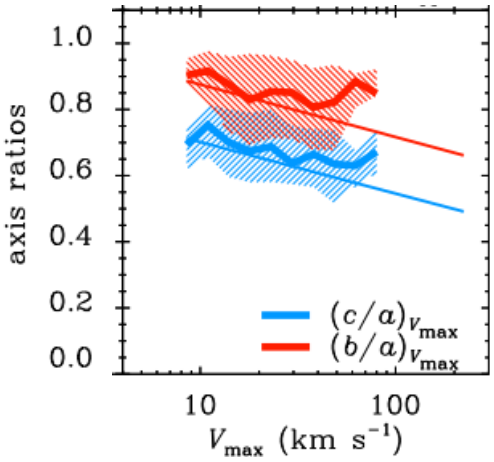
3. Non-Spherical fit include spherical possibility.

→ non-spherical fit

is more conservative



G. Battaglia et al. Astron.Astrophys. 459



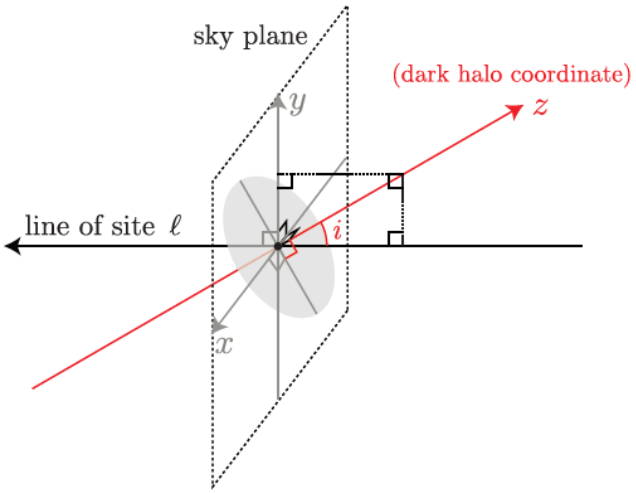
C. Vera-Ciro, et al. MNRAS 439 (2014).

K. Hayashi and M. Chiba 2012, 2015b,
K. Hayashi, KI, S. Matsumoto, M. Ibe, M. N. Ishigaki, H. Sugai, arXiv:1603.08046 [astro-ph.GA]

Axisymmetric fit

Assumptions

1. Dynamical equilibrium.
2. DM dominate system.
3. Collisionless system.
4. Axisymmetry in both stellar and DM components.
5. Constant velocity anisotropy.



Parameters

Halo Size	ρ0
Halo Radius	b_{halo}
Halo Shape	α
Axis-ratio	**Q**
Inclination	**i**
Velocity anisotropy βz	

$$\rho(R,z) = \rho_0 \left(\frac{m}{b_{\rm halo}}\right)^{\alpha} \left[1 + \left(\frac{m}{b_{\rm halo}}\right)^2\right]^{-(\alpha+3)/2}$$

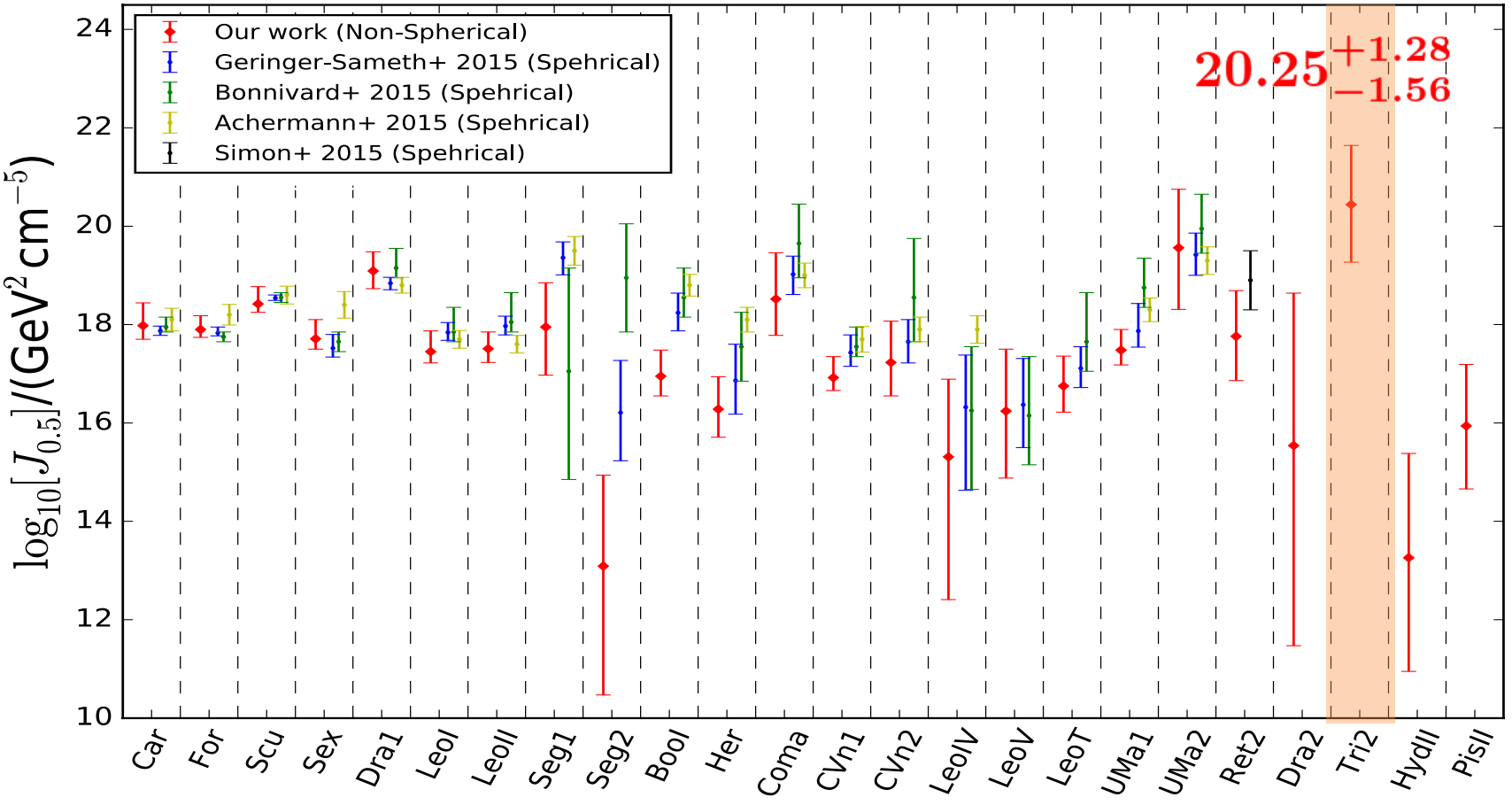
$$m^2 = R^2 + \frac{z^2}{Q^2}$$

$$\beta_z = 1 - \overline{v_z^2}/\overline{v_R^2}$$

Axisymmetric Jeans equations → $\overline{v_{\rm los}^2}(x,y)$

$$\overline{v_z^2} = \frac{1}{\nu(R,z)} \int_z^{\infty} \nu \frac{\partial \Phi}{\partial z} dz \qquad \overline{v_\phi^2} = \frac{1}{1-\beta_z}\left[\overline{v_z^2} + \frac{R}{\nu}\frac{\partial(\nu\overline{v_z^2})}{\partial R}\right] + R\frac{\partial \Phi}{\partial R}$$

Our Fit Results

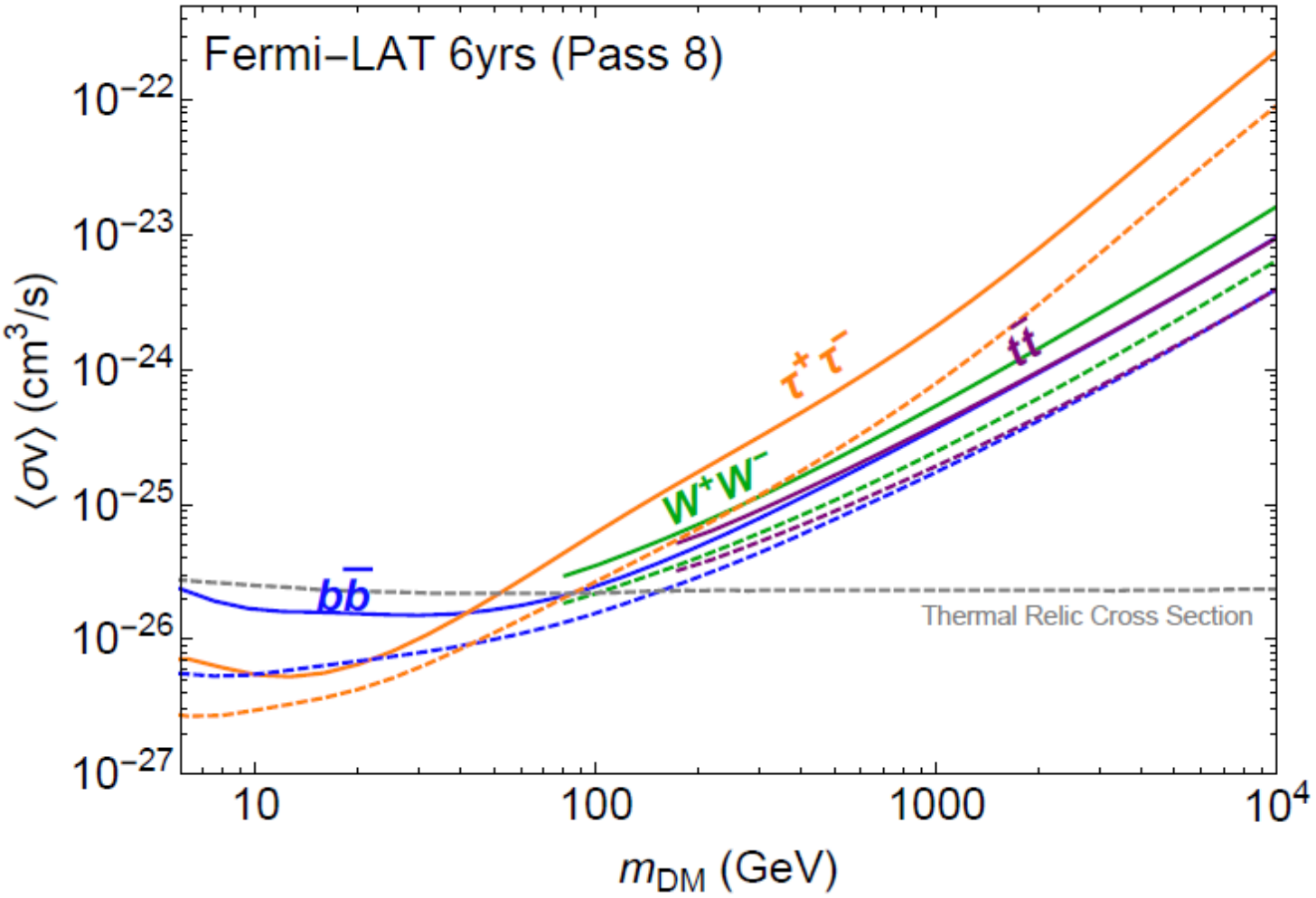


※The fit is still affected by the range of the parameter region.

Empirical condition: r* < rs is required for UF dSph with small J-factors.

- $0 \leq \log_{10}[b_{\mathrm{halo}}/\mathrm{pc}] \leq +5;$
- $-5 \leq \log_{10}[\rho_0/(M_\odot \mathrm{pc}^{-3})] \leq +5;$

Effect on constraints



Our estimation gives 3 times weaker constraints

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➡ Axisymmetric fit

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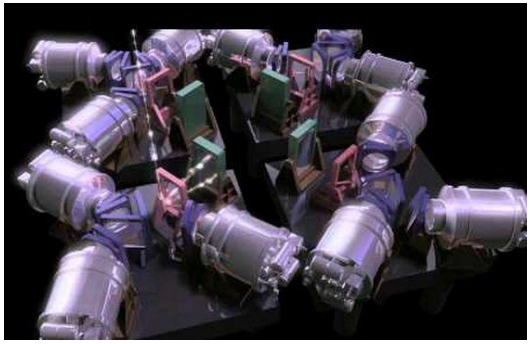
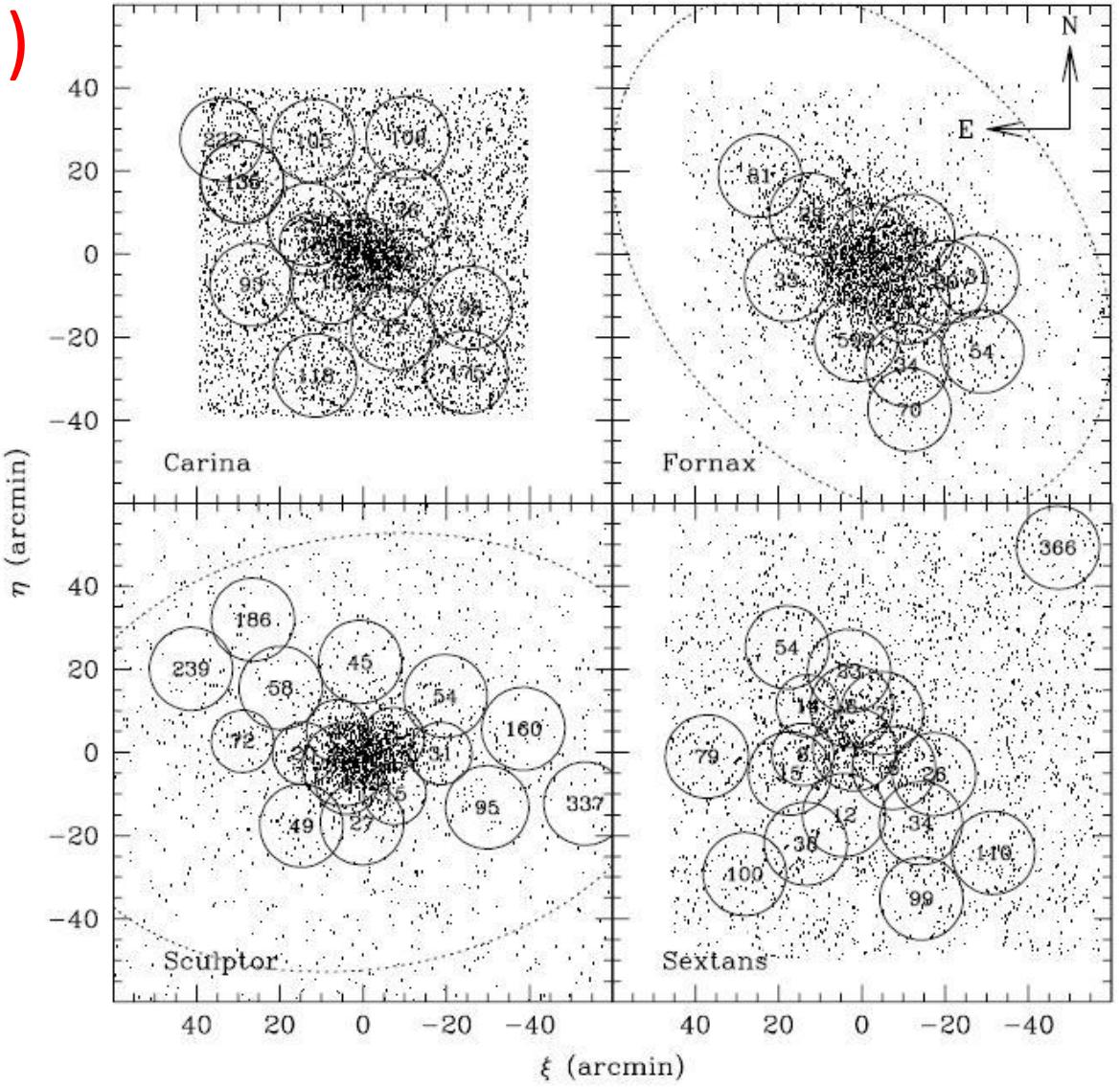
Prime Focus Spectrograph

FoV 1.3 deg (diam)
with 2394 Fiber





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

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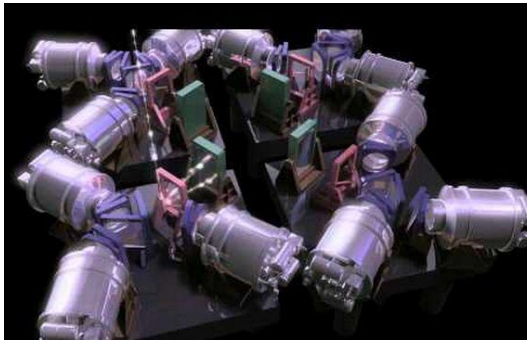
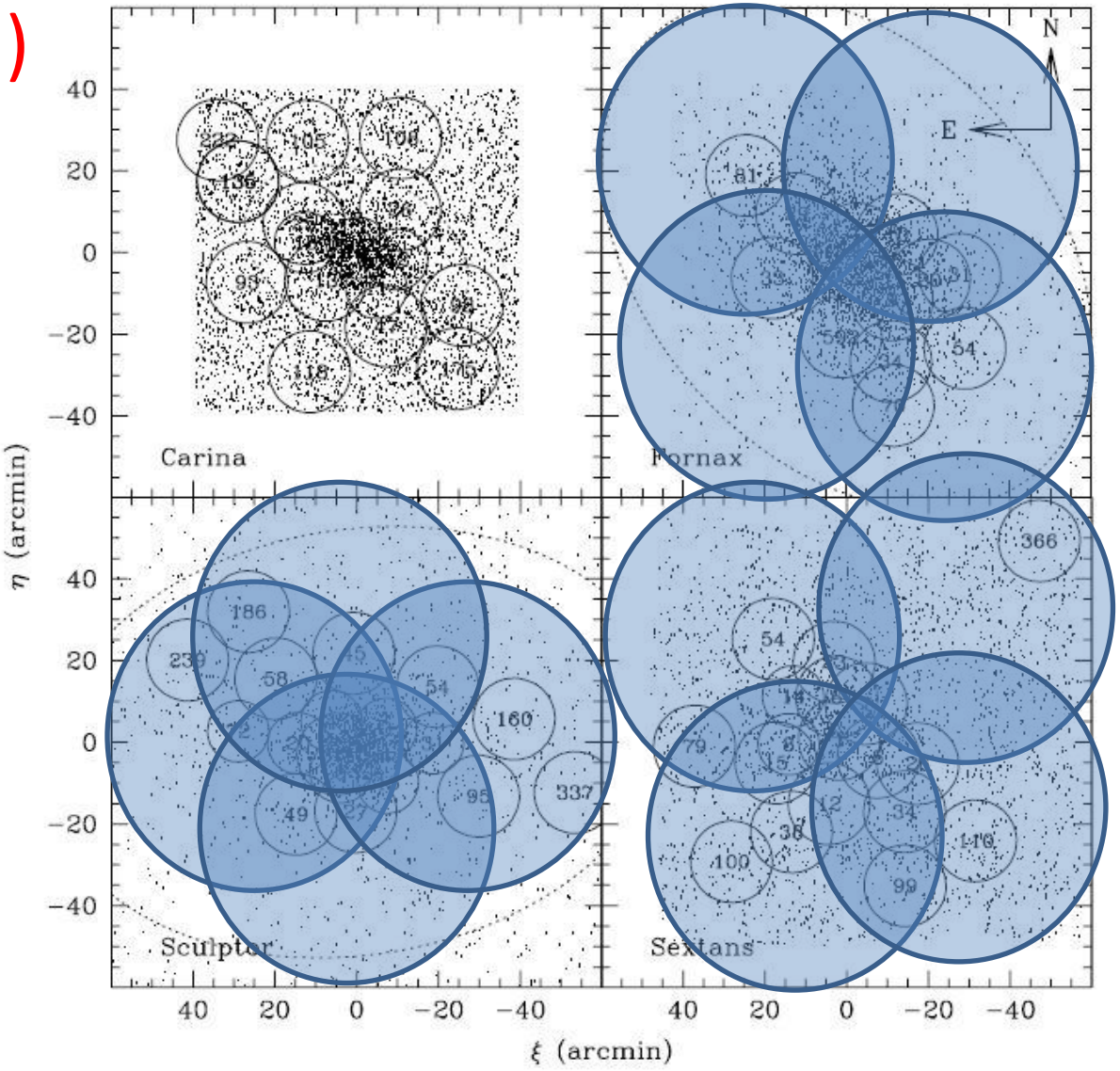




MMFS (M. G. Walker et al,. (2007))

Hidden Systematics…

Prior Bias?/Cut?

N < 100: > O(1) uncertainty

Martinez et al., JCAP 0906 (2009) 014

Non Spherical?

0.2～0.4 uncertainty

Bonnivard et al., MNRAS, 446 (2015)

Velocity anisotropy? Ullio and Valli, JCAP 1607 (2016)

Etc. (Halo truncation, stability, binary stars…)

In the future…

Increasing #Obs Star can reduce these errors

Foreground Contamination?

N < 100: O(1) uncertainty

N ～1000: < 0.4

Bonnivard et al., MNRAS, 453 (2015)

Remains!

Q. How to treat this FG contamination?

Set up

1. Mock Observable:

dSph Stellar + Foreground

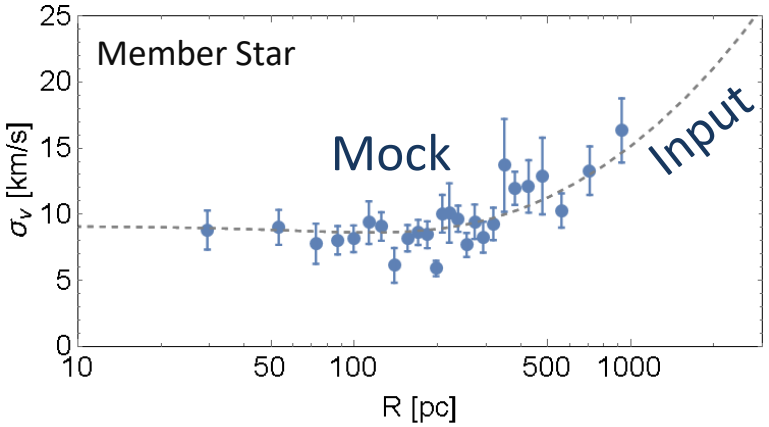
dSph Stellar Mock

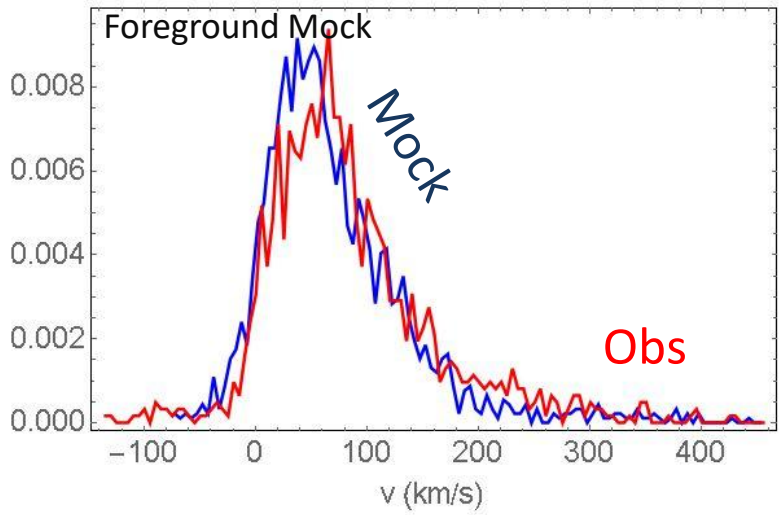
⇒Assign stellar information
(Age, metalicity, luminosity, color, etc)

⇒Assign velocity and distance,
(Boltzmann Equation under DM profile)

Foreground Mock

⇒Besancon Model (Robin+ (2003))





2. Detector:

Prime Focus Spectrograph

$\theta_{\rm ROI}$ [degree]	$i_{\rm max}$ [mag]	dv [km/s]	d[Fe/H]	$d\log_{10}(g/[{\rm cm/s^2}])$	$dT_{\rm eff}$ [K]
0.65, 1.3	21, 21.5	3.0	0.5	0.5	500

Cut Strategy

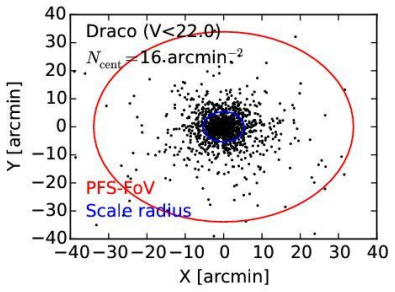
ROI Cut:
0.65 deg radius for 1 pointing

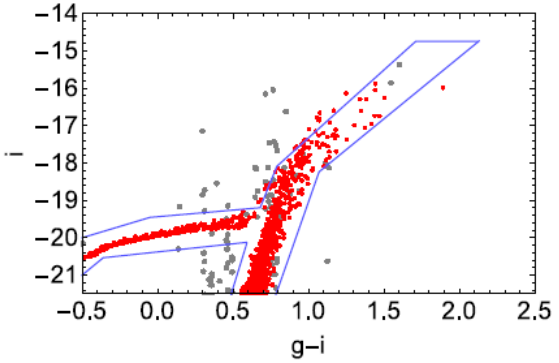
velocity Cut
vLower < v < vUpper

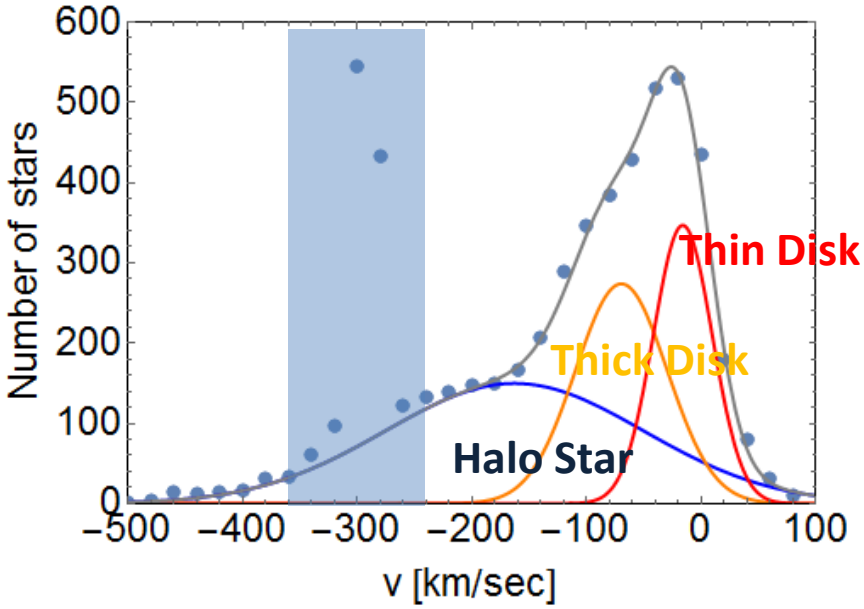
Surface Gravity Cut
$\propto M/4\pi R^2 \propto MT^4/L \propto$ (Luminosity)^(-1)
Eliminate Darker Foreground Star

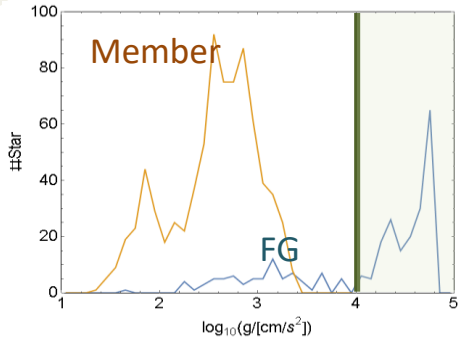
Color –Magnitude Cut

* Teff, Chemical Cut do not so efficient

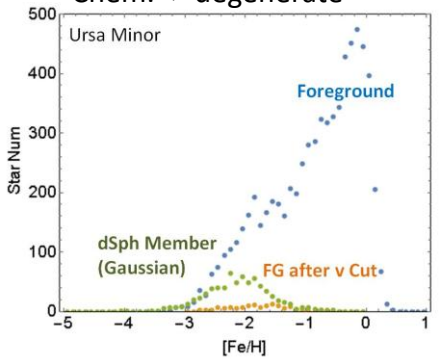








Chem. -> degenerate



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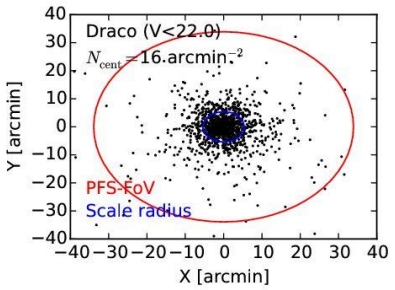
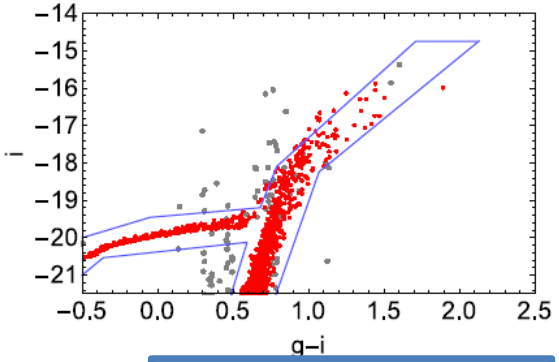
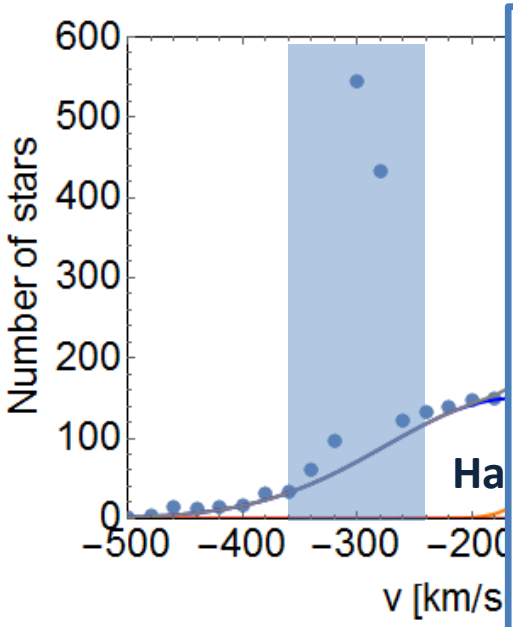
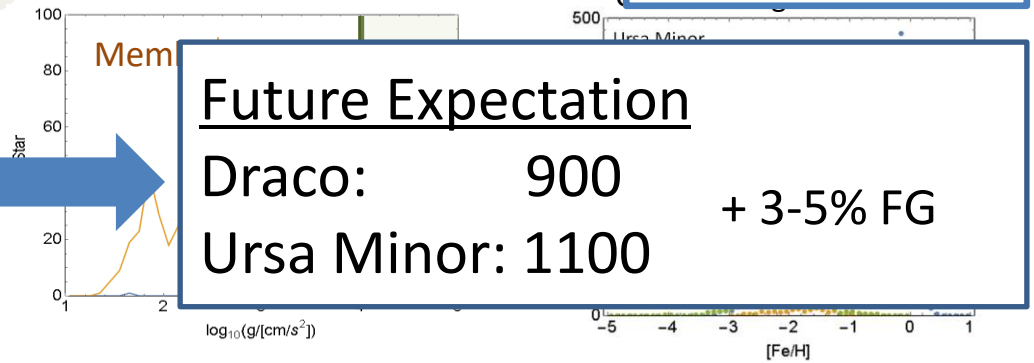






MEM	
ROW	1160
Color	1160
Velocity	1160
g	1100
FG	
ROW	4200
Color	840
Velocity	140
g	40



Current #Star

Draco:	450
Ursa Minor:	300

Future Expectation

Draco:	900
Ursa Minor:	1100

+ 3-5% FG

Fit including FG model

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

Member Fraction

Prob. Dist. Of FG

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

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

Member Parameter
= halo information

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

FG Parameter

Can be considered to be Gaussian after several cuts.

Fit Results

Contaminated
(consider FG as Member star)

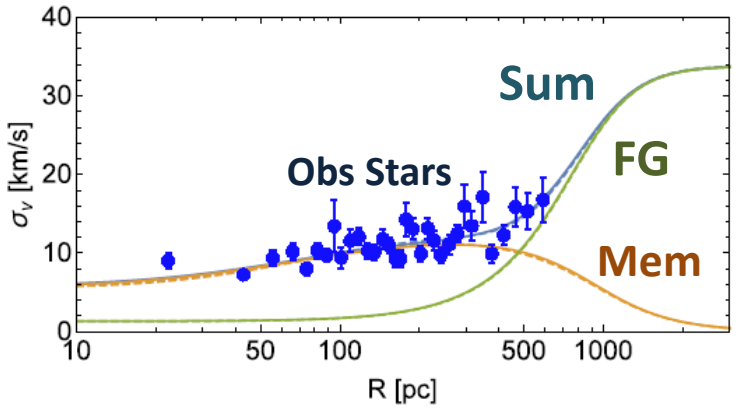
5% Contamination biases
dLogJ = ~0.3-0.5
⇒Overestimates sensitivity line
~ 2-3 times stronger

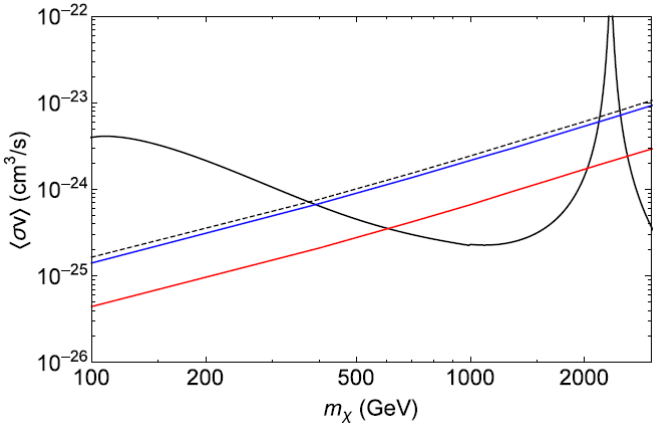
Ursa Minor case	LogJ	dLogJ
Ref (input)	**19.03**	+0.27 -0.19 (Geringer-Sameth et al.,arXiv:1408.0002)
Contaminated	**19.30**	0.07
Out Fit	**19.11**	0.12

Our Fit

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

➡ Reproduce Ref val.





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➡ Axisymmetric fit

does the fit really converge? Biased by a prior

➡ Increase #data

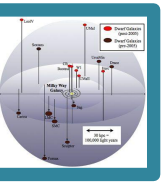
Is the data pure enough? 95%

➡ Member + Foreground fit

Summary

- Indirect detection is essential for O(1) TeV DM search.
- Gamma-ray observation of dSphs can give robust constraints.
- However, many hidden systematic errors still exist.
- We give more conservative results by the axisymmetric DM model.
- To reduce the prior bias in the fit, future investigation of the stellar kinematics (PFS) will play a crucial role.
- We introduce a new likelihood method to reduce the foreground contamination.

Thank You !



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