Robust estimate of the dark matter halo of the Milky-way's dwarf spheroidal galaxies

Koji Ichikawa

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

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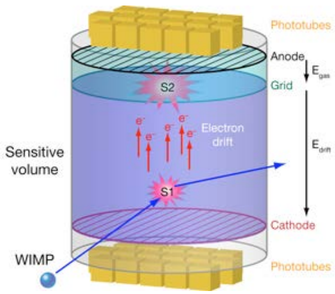
arXiv:1608.01749 (submitted in MNRAS)
MNRAS, 461, 2914 (1603.08046 [astro-ph.GA])

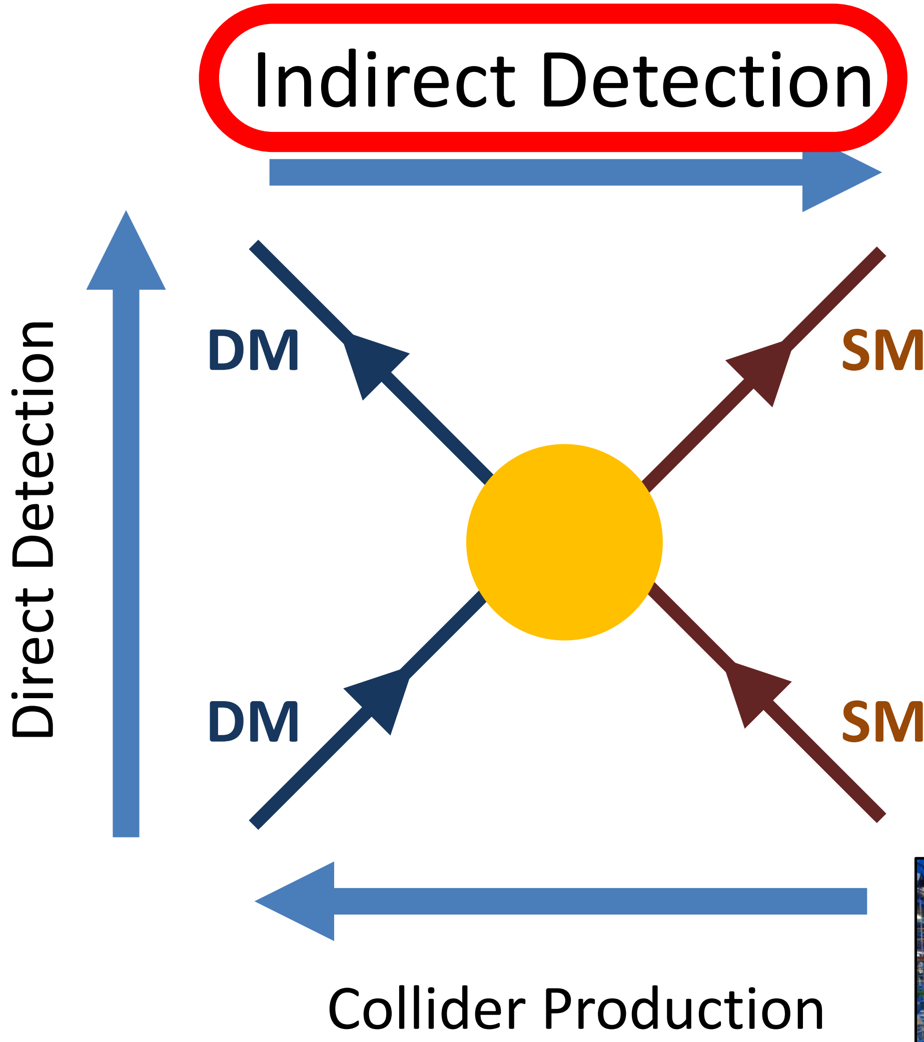
KAVLI IPMU

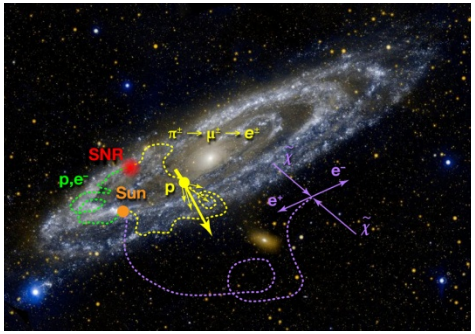
Kashiwa, Dec. 16, 2016

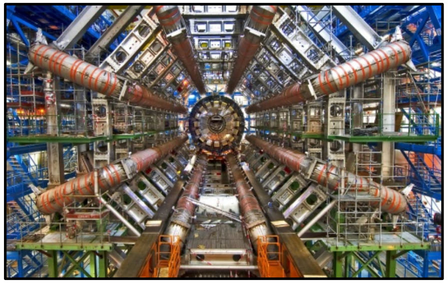
Contents

Dark Matter Search

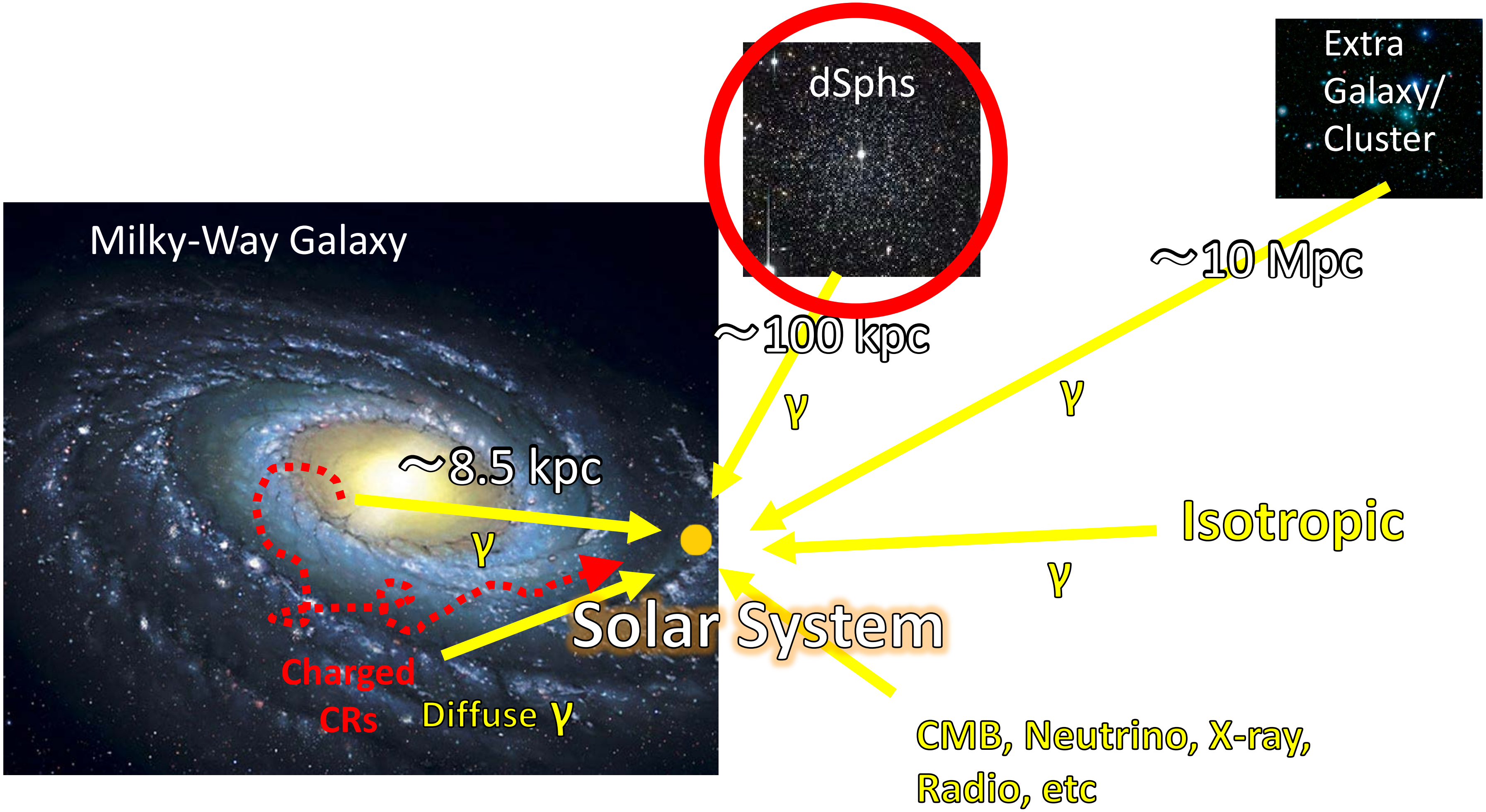








Indirect Detection



Dwarf spheroidal galaxies

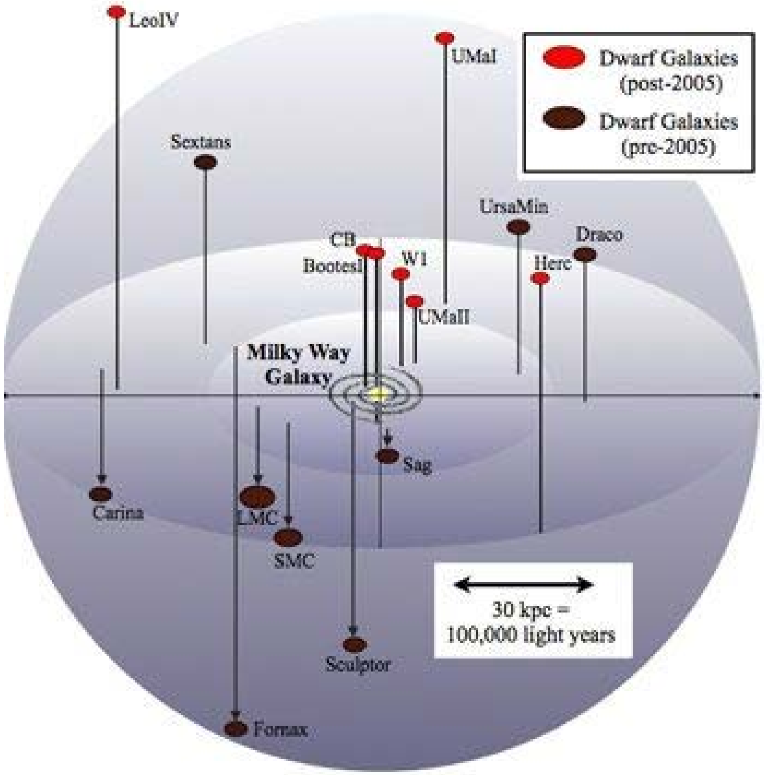
dSphs:

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

dSph Type

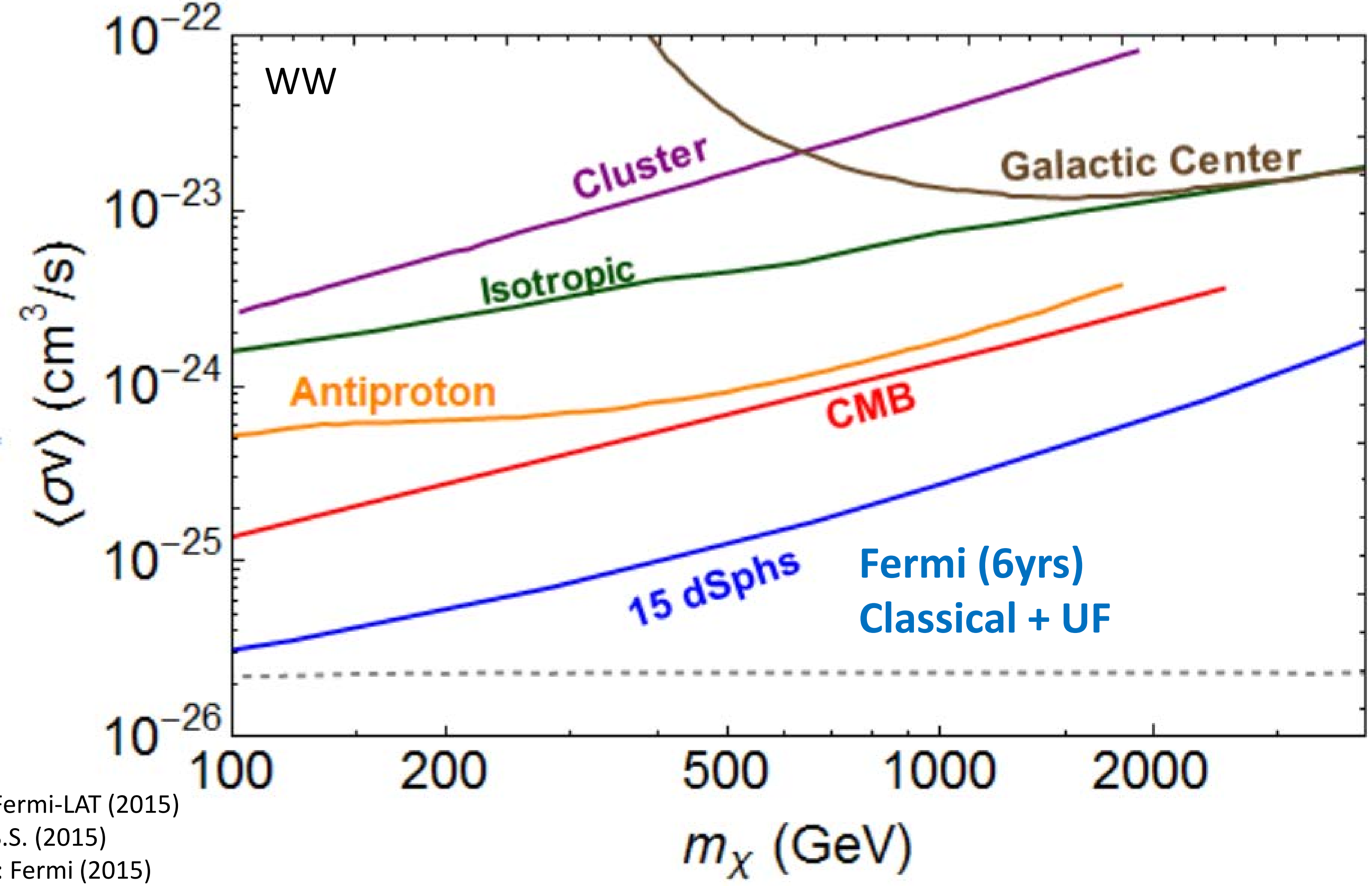
	Classical	Ultra-faint
#dSphs	8	>20
M/L ($M_\odot/L_\odot$)	10-100	100-1000
Distance (kpc)	60-250	10-60
#Obs Stars	150-2500	20-100
Characteristics	Brighter, farther	Darker, closer

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



MNRAS, 406 (2010) 1220

dSph = Strong Probe



Cluster: Fermi-LAT (2015)
GC: H.E.S.S. (2015)
isotropic: Fermi (2015)
antiproton: Hong-Bo Jin+(2015)
CMB: Plank (2014)

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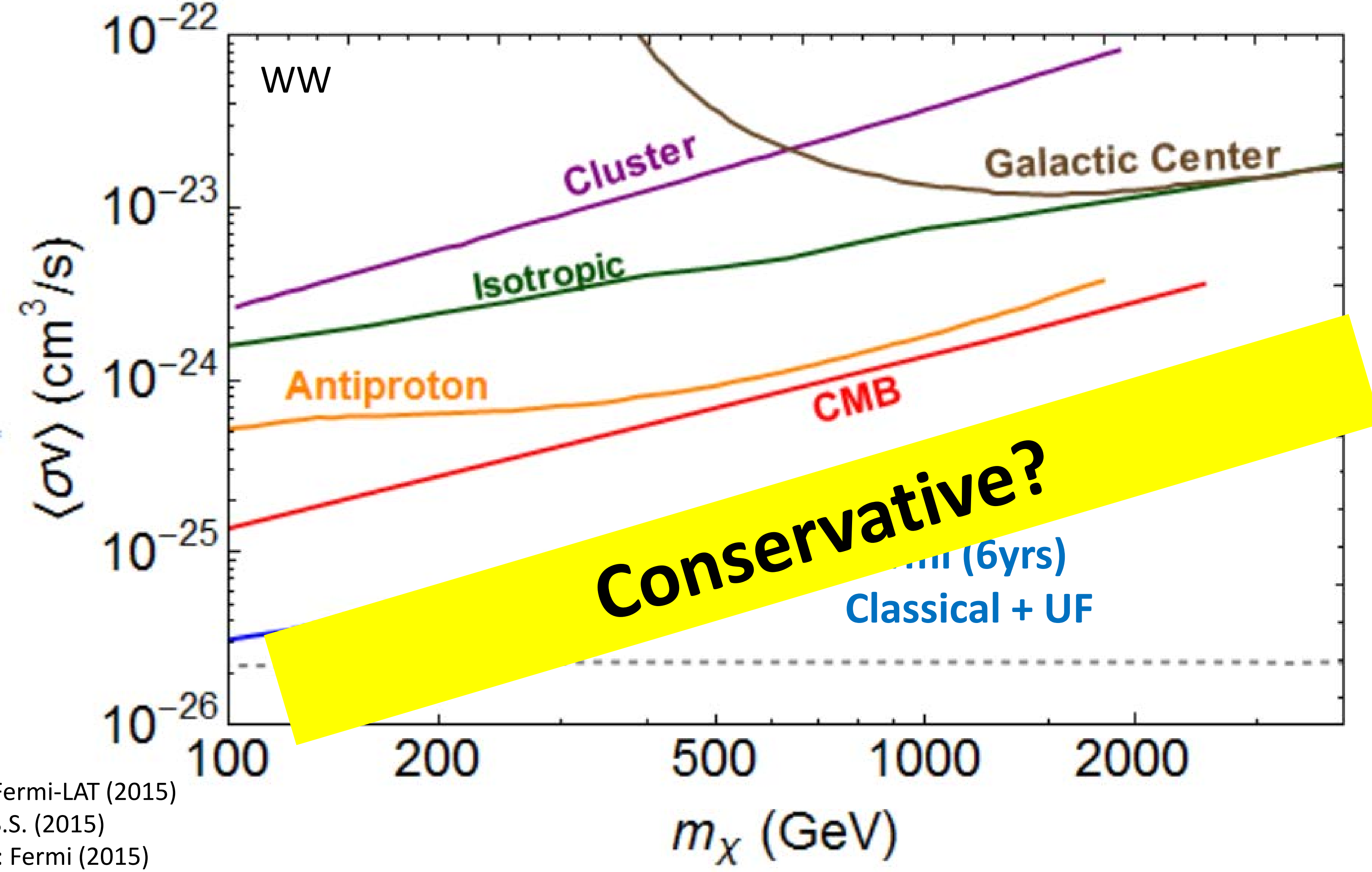

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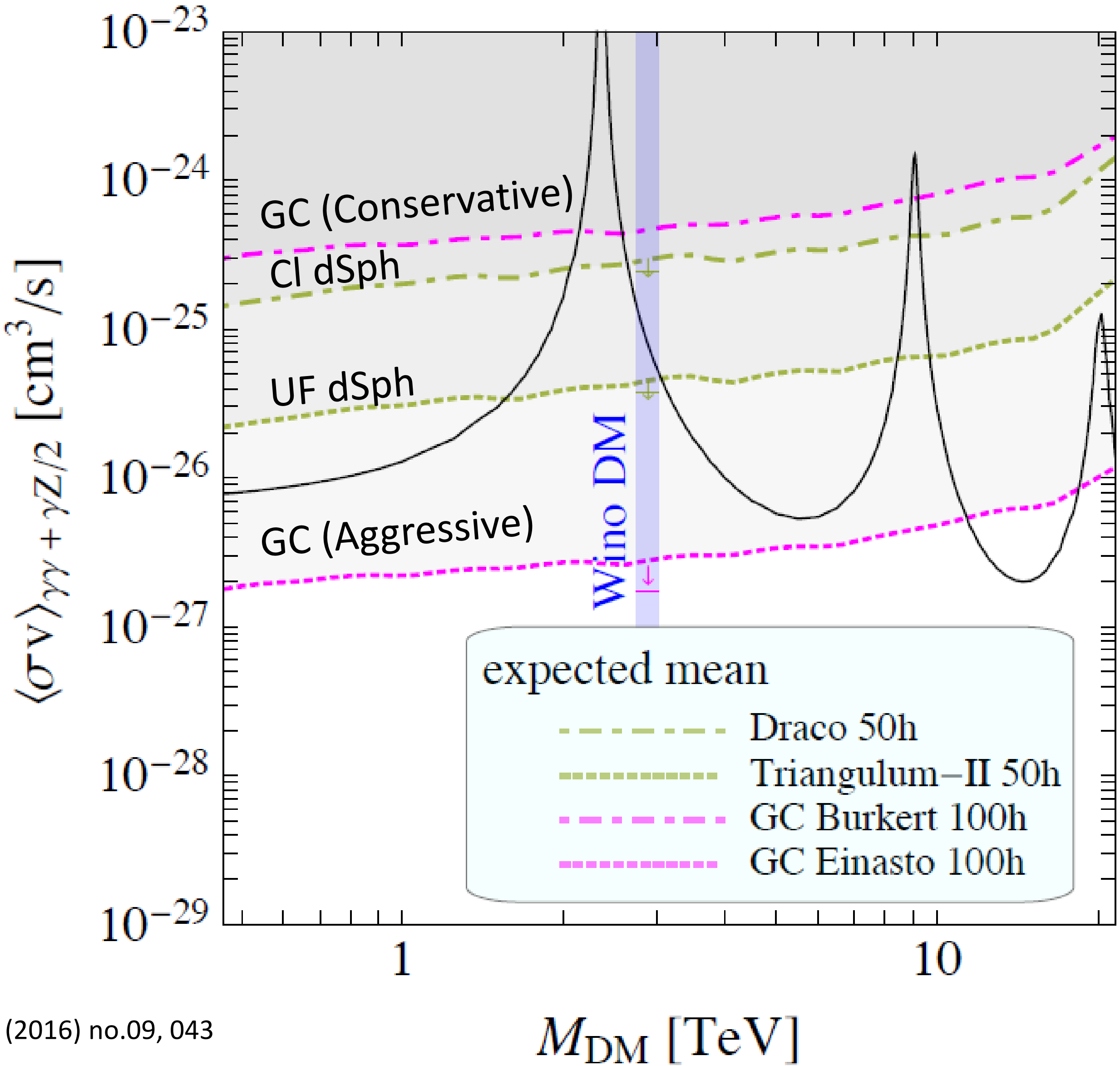
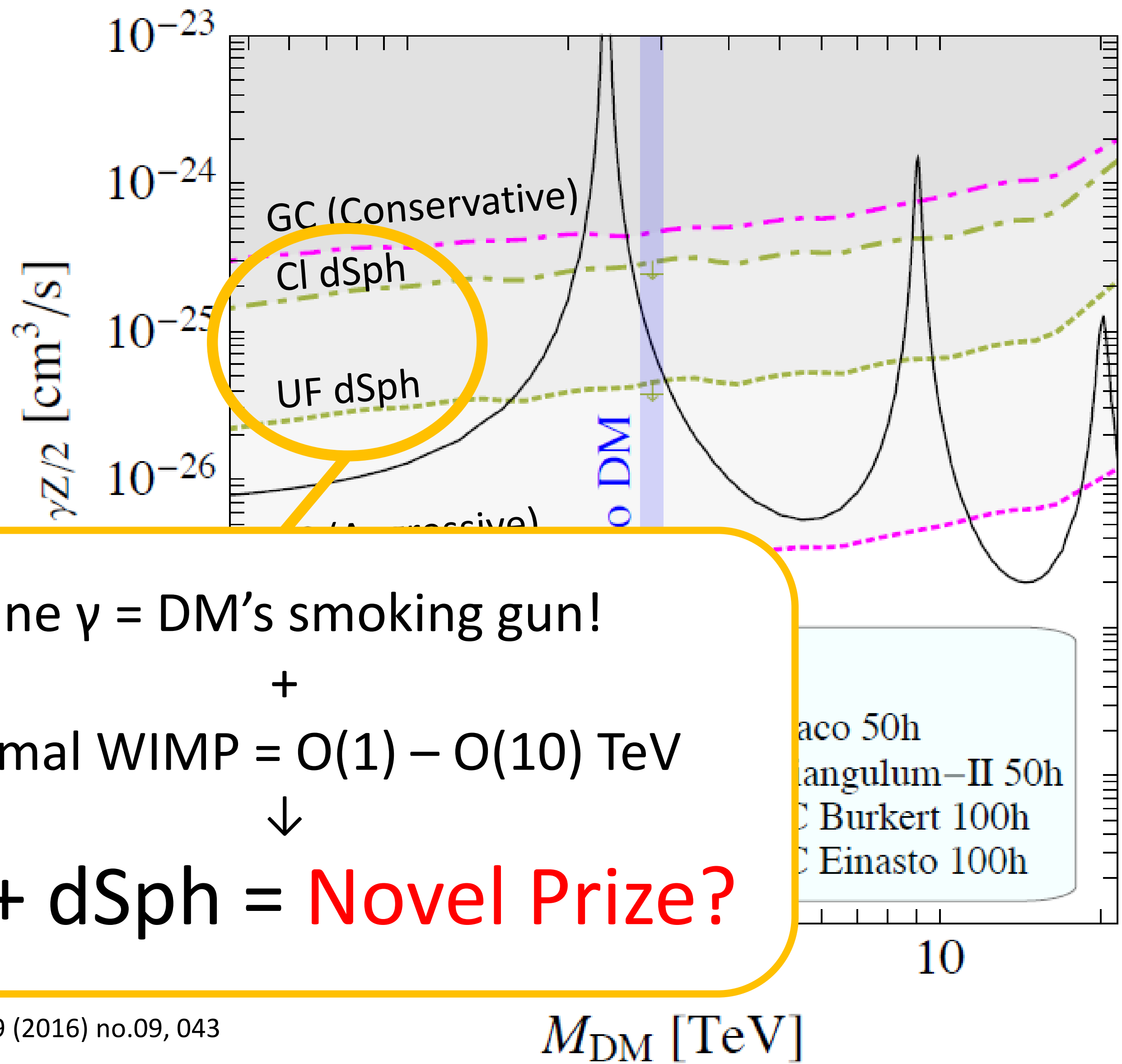
O(1) TeV Line Search = CTA !



Lefranc et al. JCAP 1609 (2016) no.09, 043

O(1) TeV Line Search = CTA !



Line γ = DM's smoking gun!

\+

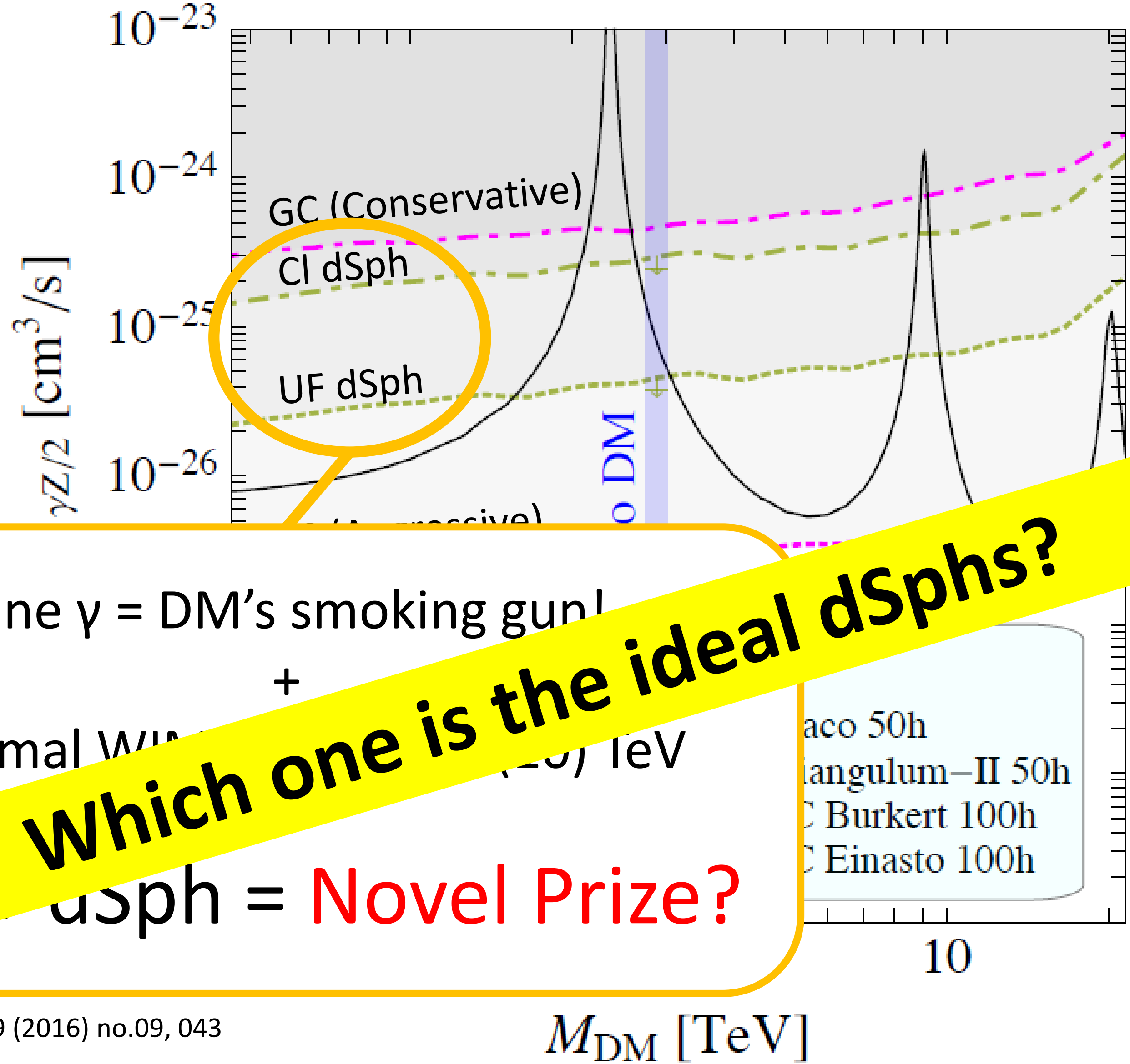
Thermal WIMP = O(1) – O(10) TeV

↓

CTA + dSph = Novel Prize?

Lefranc et al. JCAP 1609 (2016) no.09, 043

O(1) TeV Line Search = CTA !



Line γ = DM's smoking gun!

+

Thermal WI… TeV

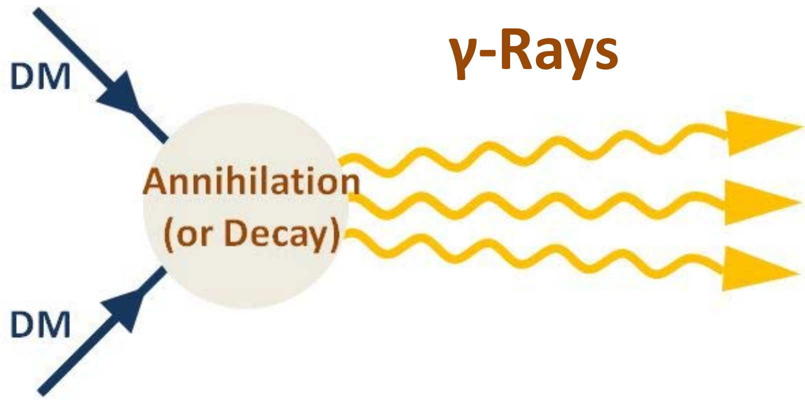
… dSph = Novel Prize?

Which one is the ideal dSphs?

Lefranc et al. JCAP 1609 (2016) no.09, 043

Signal Flux

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

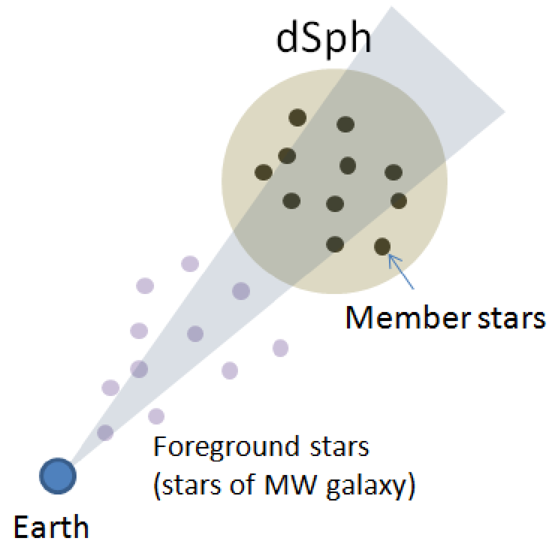
DM Property

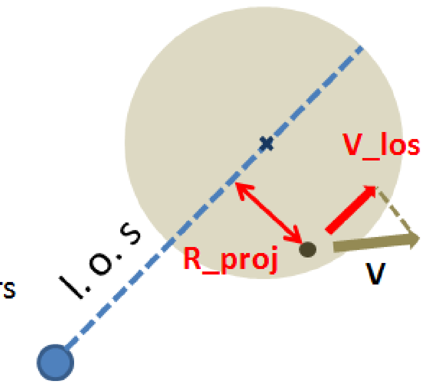
Halo Profile (J-factor)

→ J-factor is determined by **stellar kinematics of dSph**

Observables

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

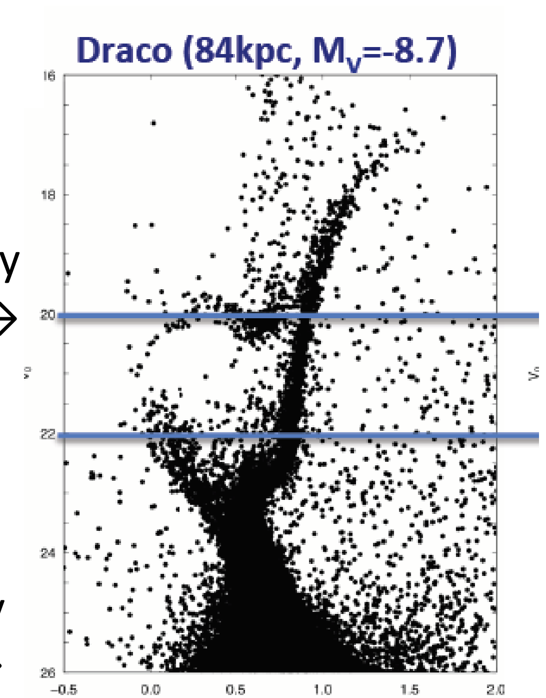




Recession velocity: v_{los}
Metalicity
=> By spectroscopy (V ~ 20)

Data set {R_{proj}, v_{los}} is typically
O(100-1000) for classical dSphs and
< O(50) for UF-dSphs

Spectroscopy
V ~ 20 →



Photometry
V ~ 26 →

- v_{los} cannot be directly used for fit.
- binned v_{los} data w.r.t. R_{porj} gives a dispersion curve $\sigma(R_{proj})$.

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

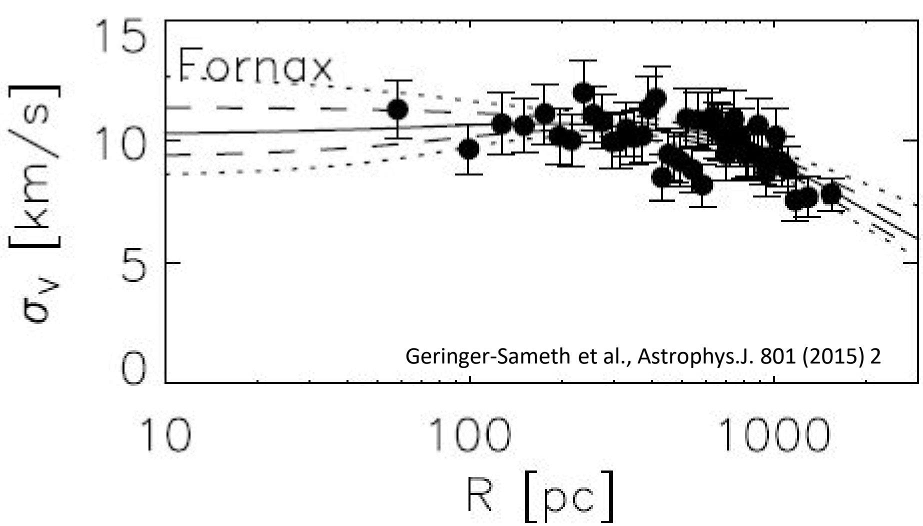
Stellar Density Profile: ν(r)

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



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

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

Current Status

Is the fit model accurate enough?

Enough data?

Is the data pure enough?

Current Status

Is the fit model accurate enough?	Spherical Assumption
Enough data?	O(10) – O(100)
Is the data pure enough?	95%

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Non Sphericity

Most of the studies assume
spherical profile.
But…

1. Stellar distributions of dSphs are not spherical.

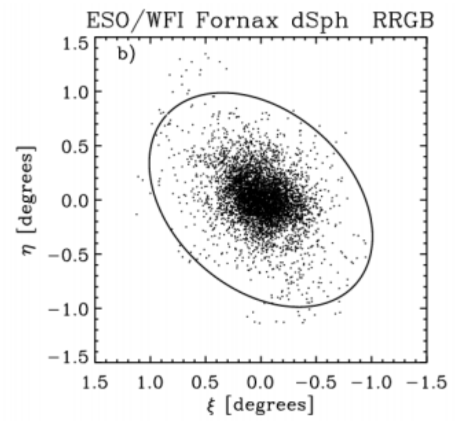
2. Simulation suggest axisymmetric profile.

3. Non-Spherical fit include spherical possibility.

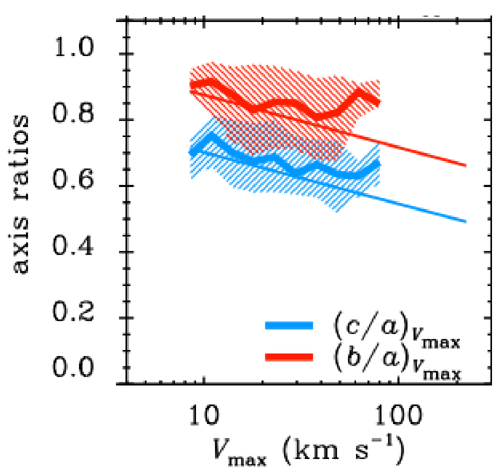
→ non-spherical fit

is more conservative

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]



G. Battaglia et al. Astron.Astrophys. 459

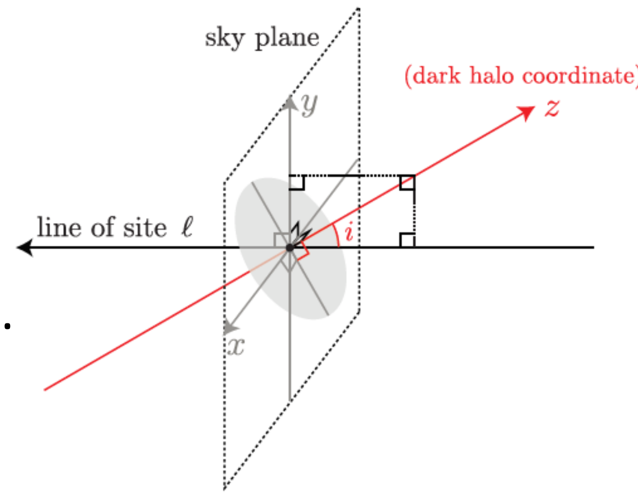


C. Vera-Ciro, et al. MNRAS 439 (2014).

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

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

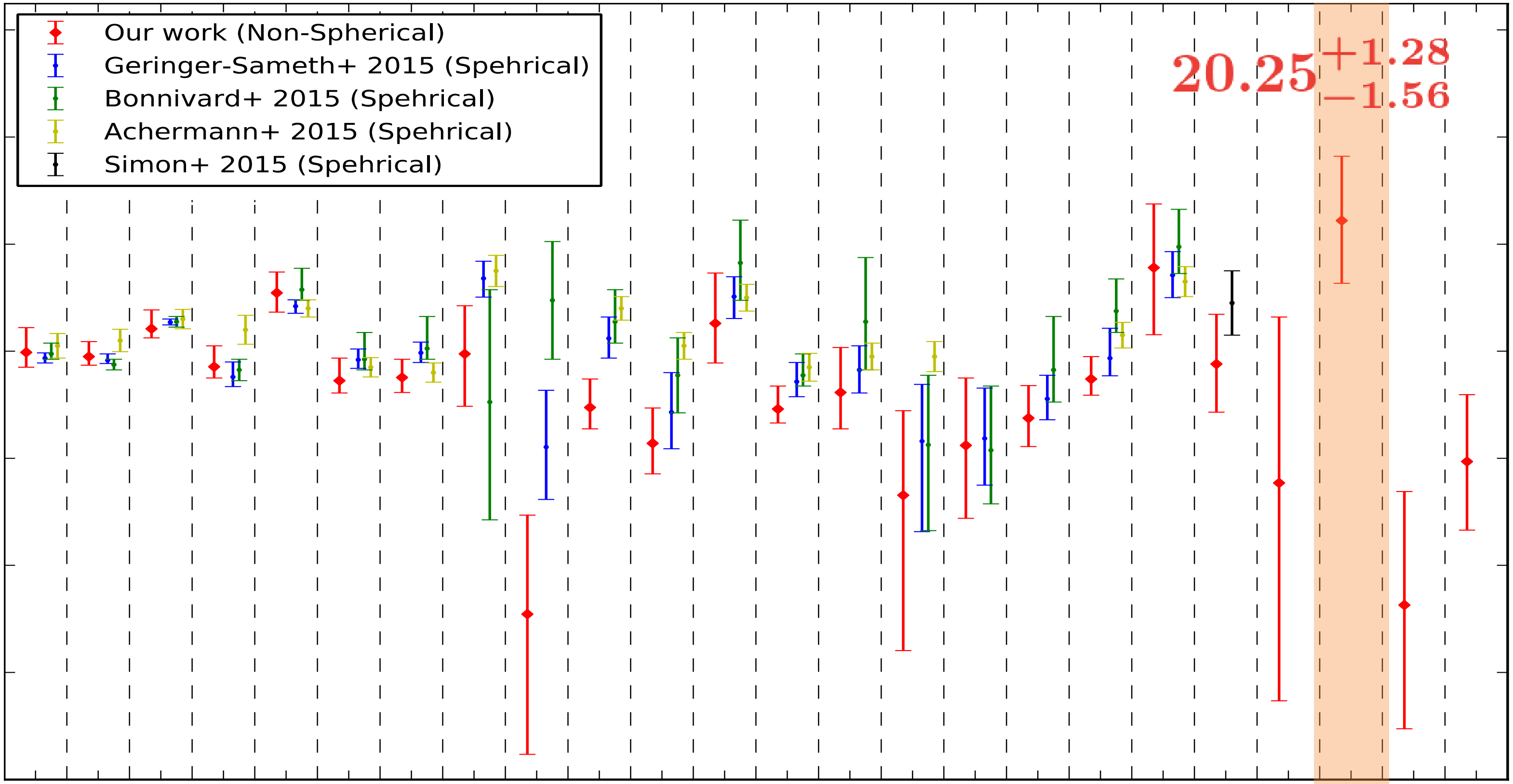
$$m^2 = R^2 + \frac{z^2}{Q^2}$$

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

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

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

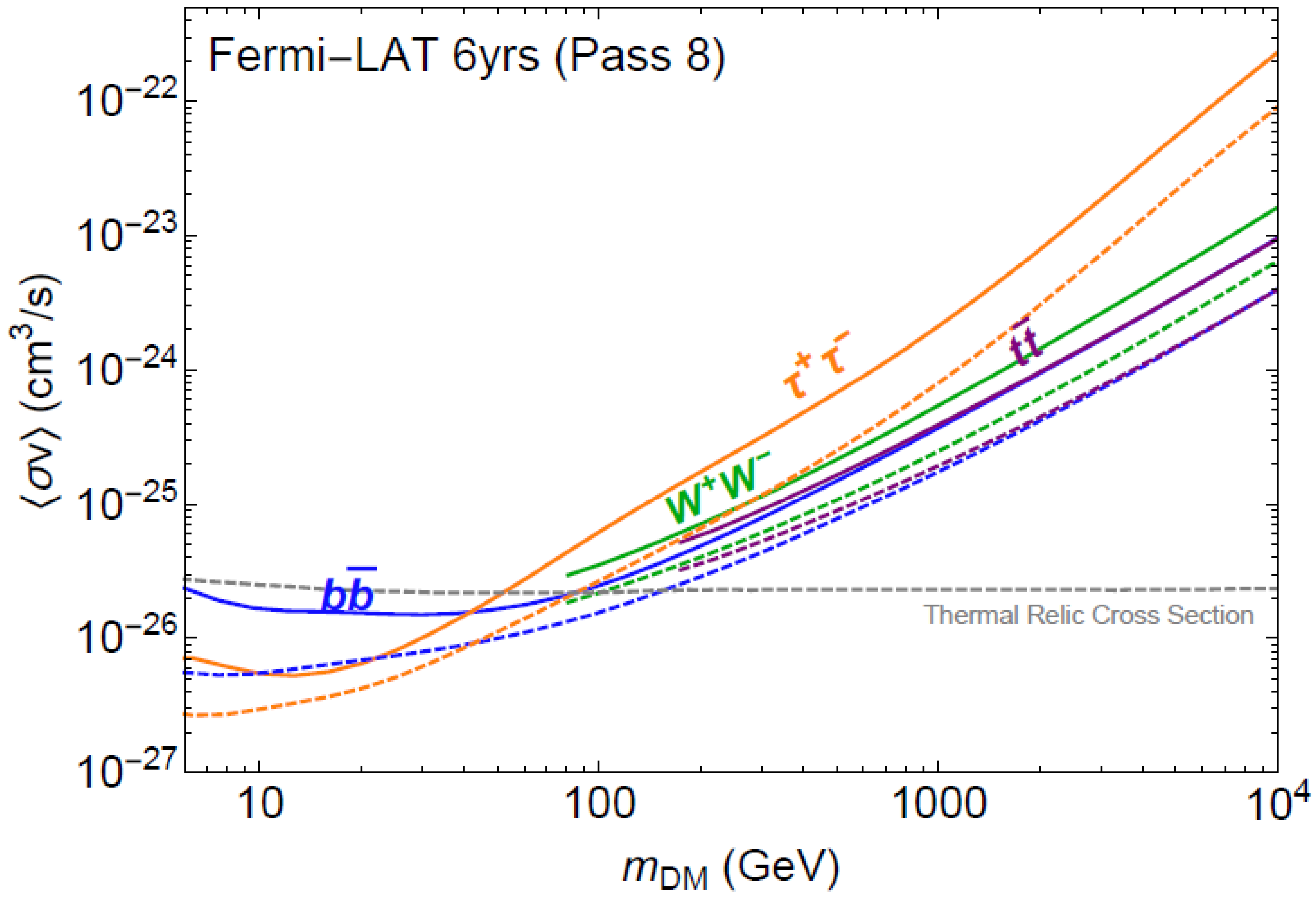
Our Fit Results



※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.

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

Effect on constraints



Our estimation gives 3 times weaker constraints

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Axisymmetric fit

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Current Status

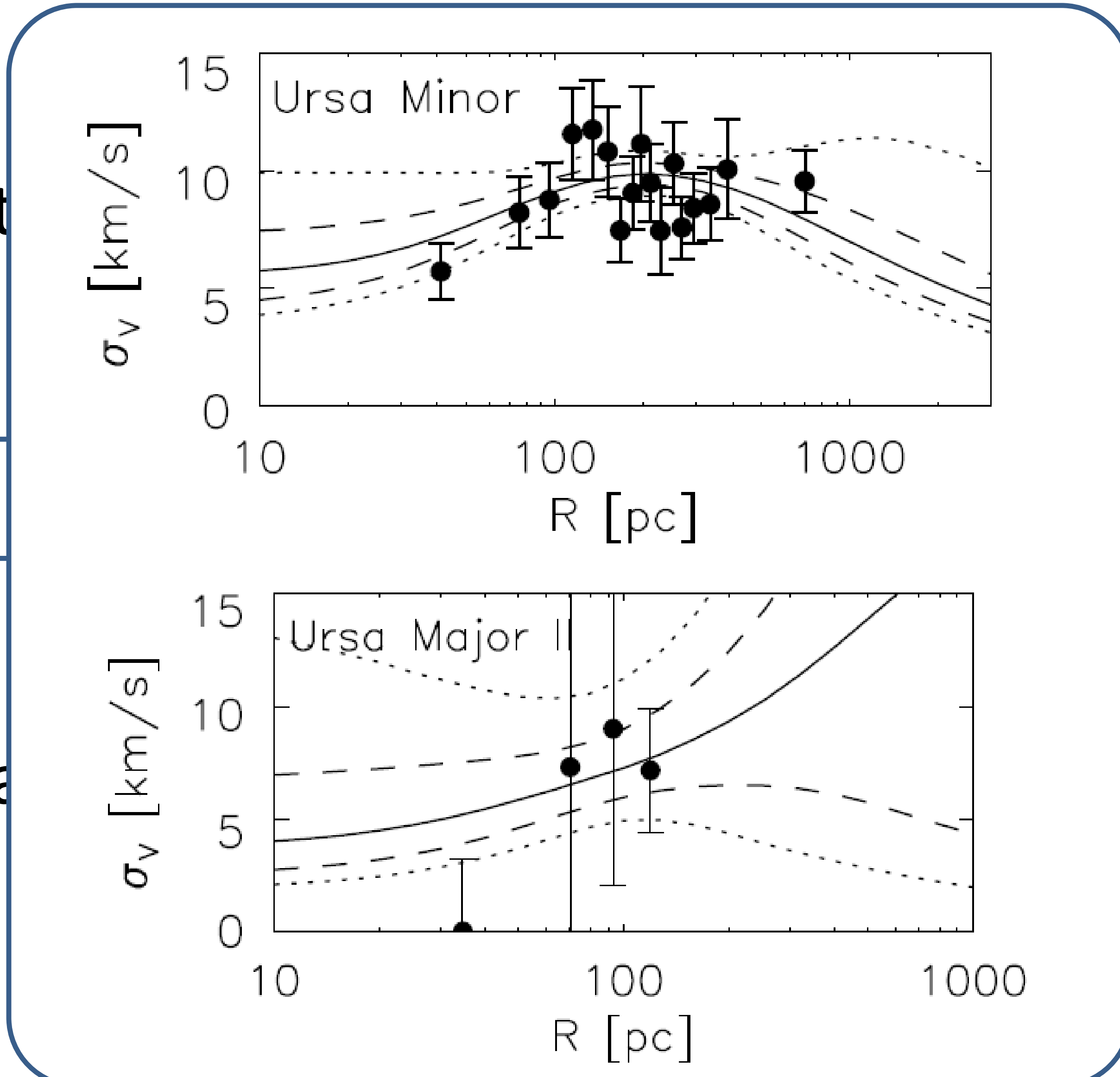
Is the fit

Enough

(100)

cal

tion

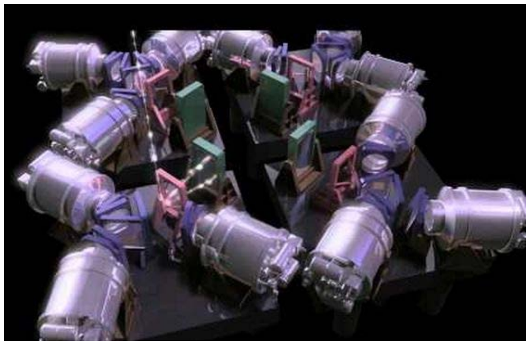


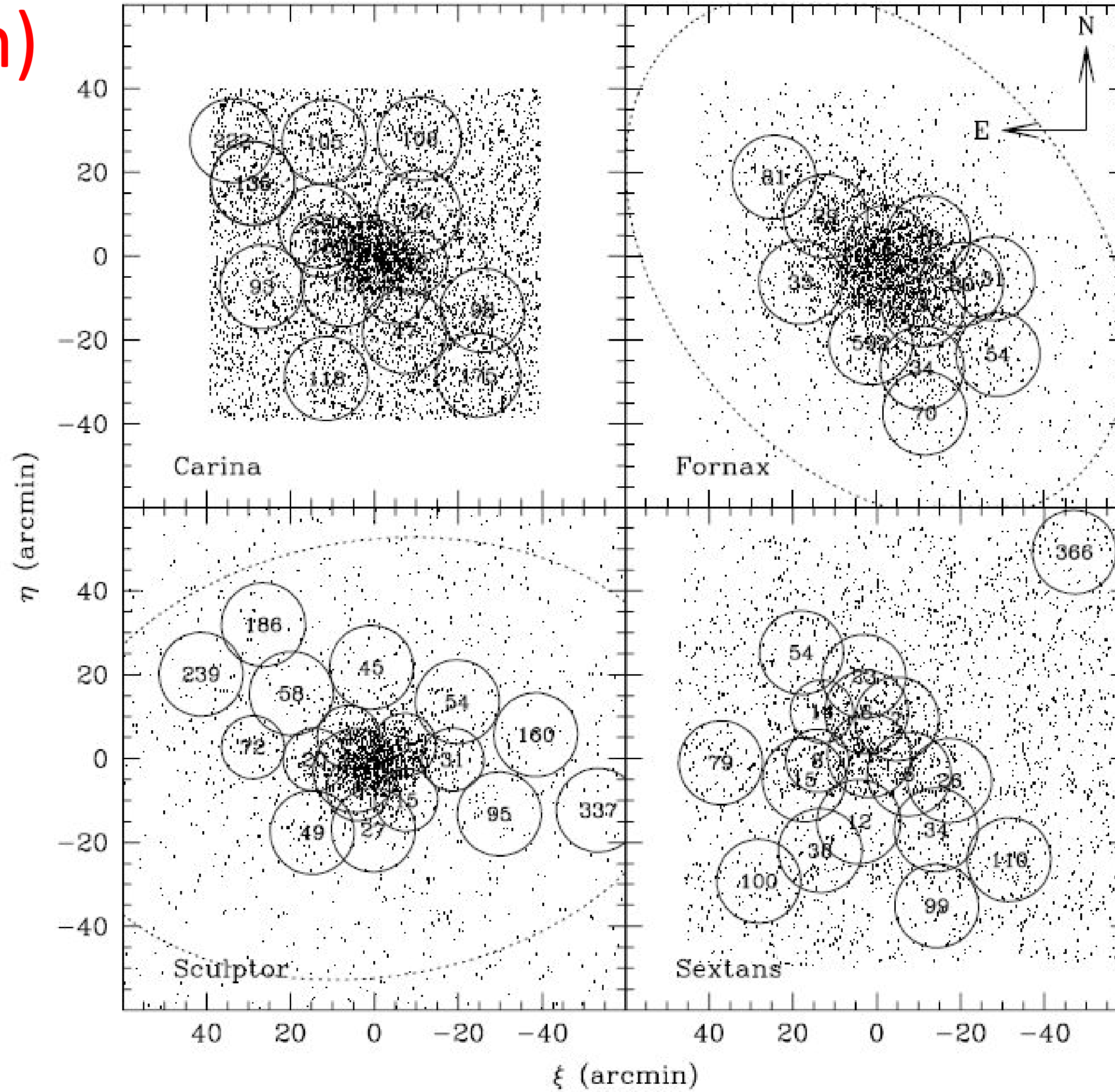
Is the da

Prime Focus Spectrograph

FoV 1.3 deg (diam)

with 2394 Fiber





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

Prime Focus Spectrograph

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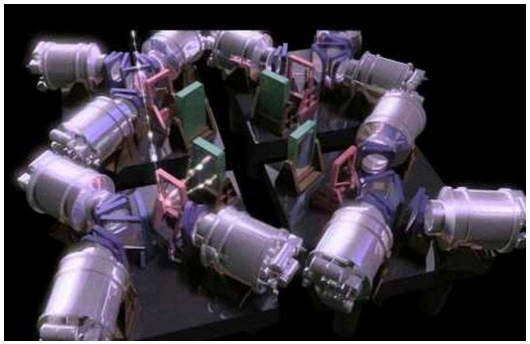

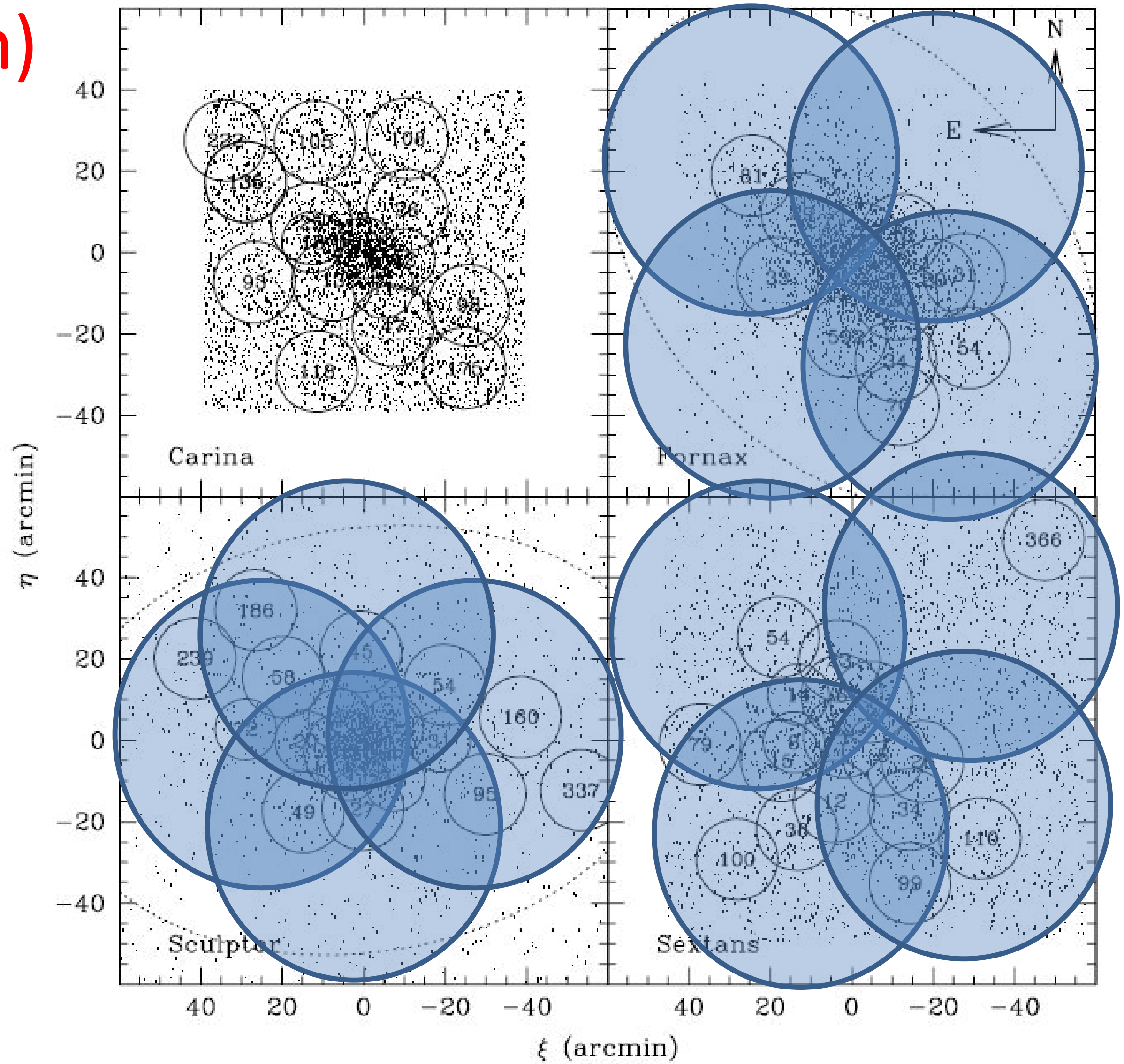

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Hidden Systematics…

Prior Bias?/Cut?

N < 100: > O(1) uncertainty

Non Spherical?

0.2〜0.4 uncertainty

Velocity anisotropy?

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

Remains!

Q. How to treat this FG contamination?

Purpose

Q. How many stars will be observed?

Q. How can we obtain purer dSph member star data?

Q. How can we include the FG contamination in the fit?

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

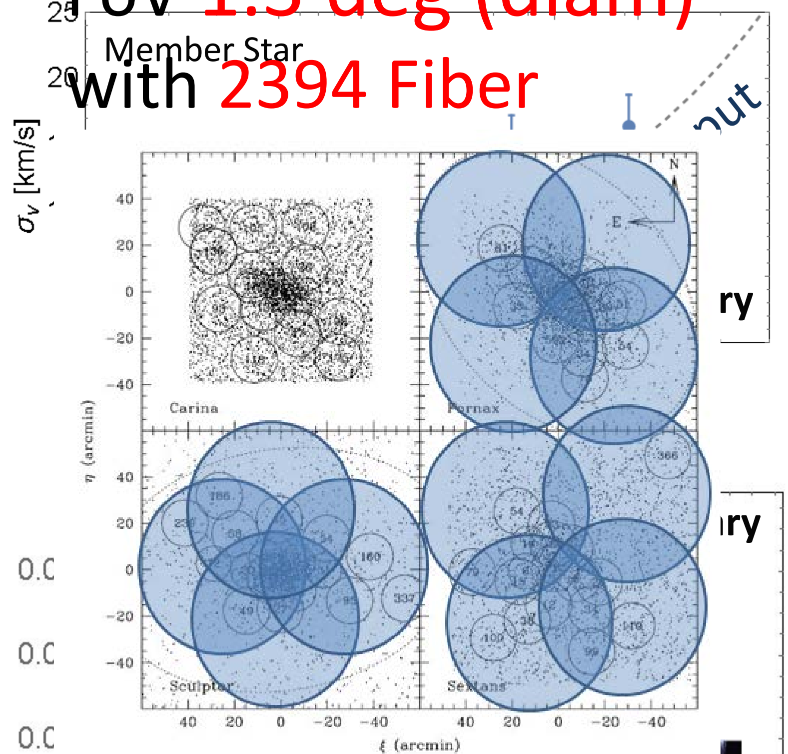
⇒Besancon Model (Robin+ (2003))

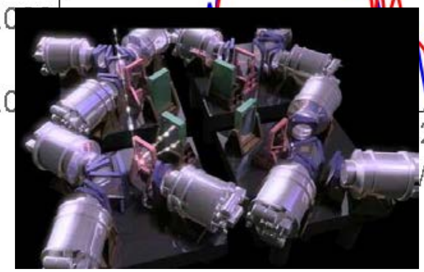
2. Detector:

Prime Focus Spectrograph

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

FoV 1.3 deg (diam)
with 2394 Fiber





Cut Strategy

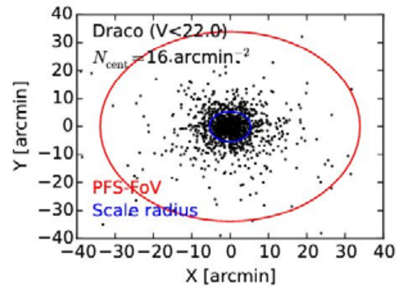
ROI Cut:
0.65 deg radius for 1 pointing

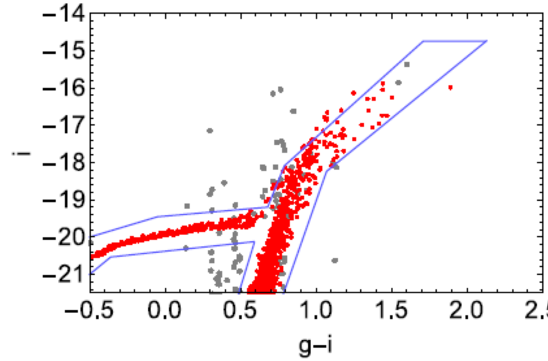
velocity Cut
vLower < v < vUpper

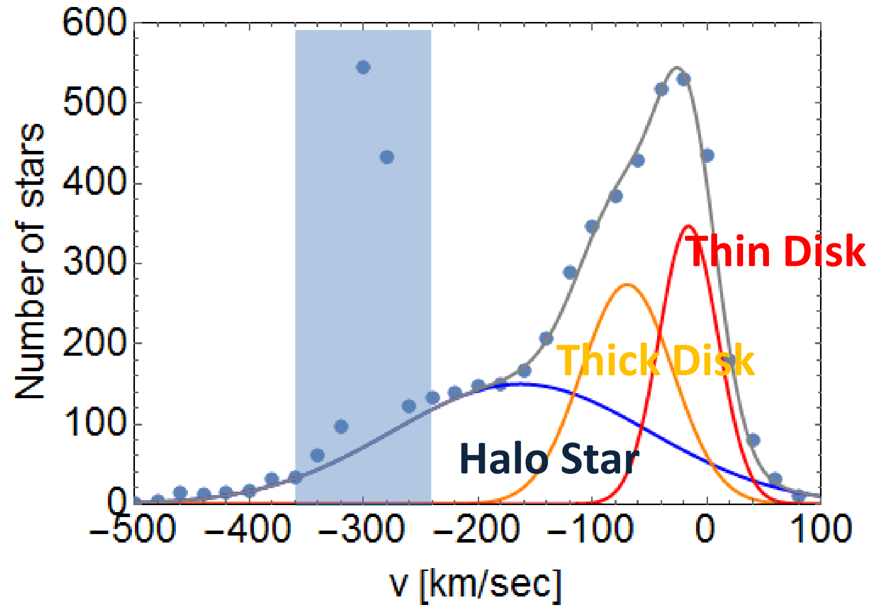
Surface Gravity Cut
$\propto M/4\pi R^2 \propto MT^4/L \propto$ (Luminosity)^(-1)
Eliminate Darker Foreground Star

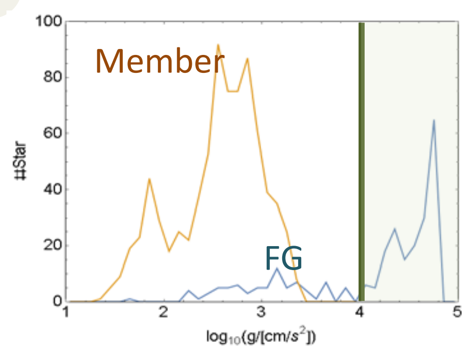
Color –Magnitude Cut

* Teff, Chemical Cut do not so efficient

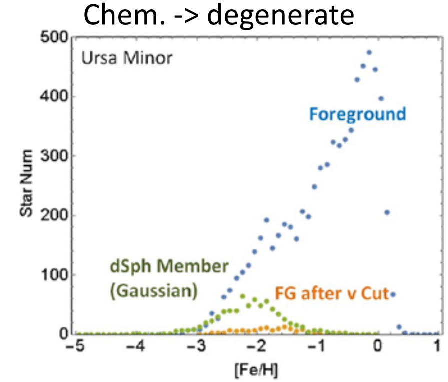








Chem. -> degenerate



#Obs Expectation

	Current	i > 21	i > 21.5	i > 22
Draco	450	900 37	1150 43	-
Ursa Minor	300	1100 33	1400 41	-
Ursa Major 2	20	50 135	115 180	195 220

Fit including FG model

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

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

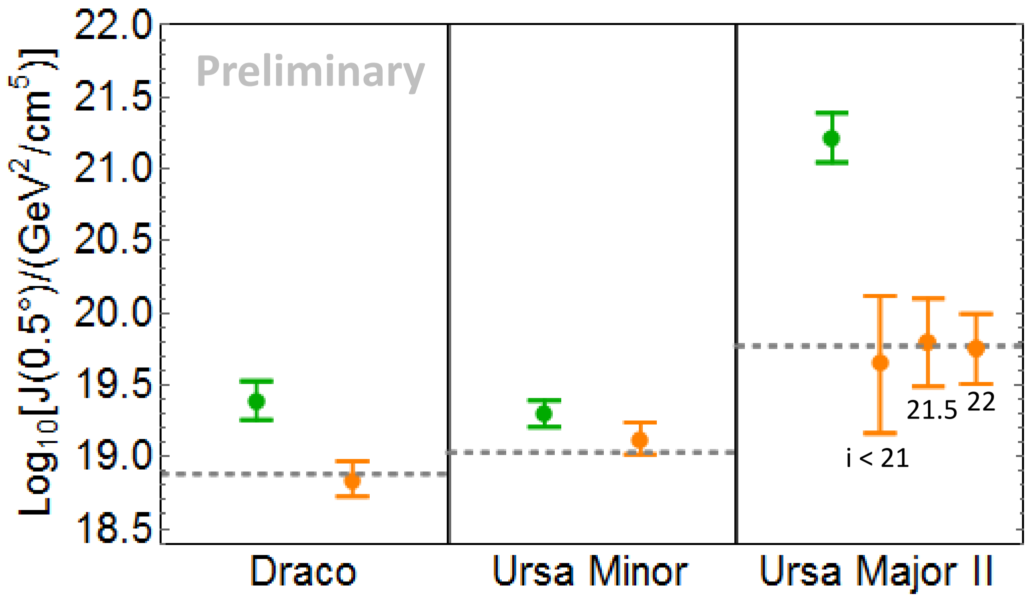
$$f_{\rm FG}(v, R) = 2\pi R N_{\rm FG} e^{-\frac{(v-v_{\rm FG})^2}{2\sigma_{\rm FG}}}$$

FG Parameter

Can be considered to be
Gaussian after several cuts.

Fit Results

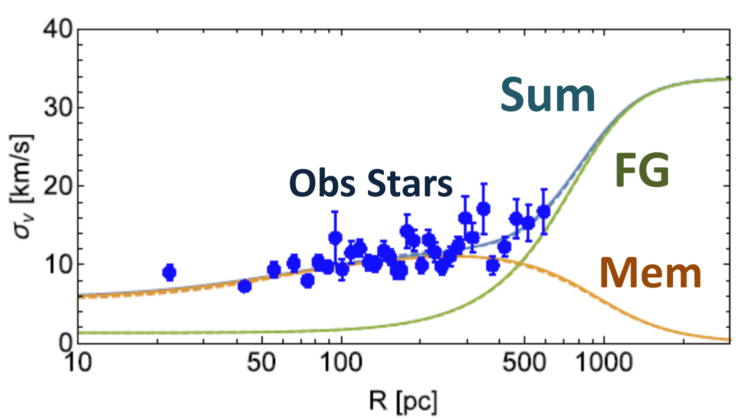
Contaminated
(consider FG as Member star)
5% Contamination biases
dLogJ = ~0.3-0.5
⇒Overestimates sensitivity line
~ 2-3 times stronger

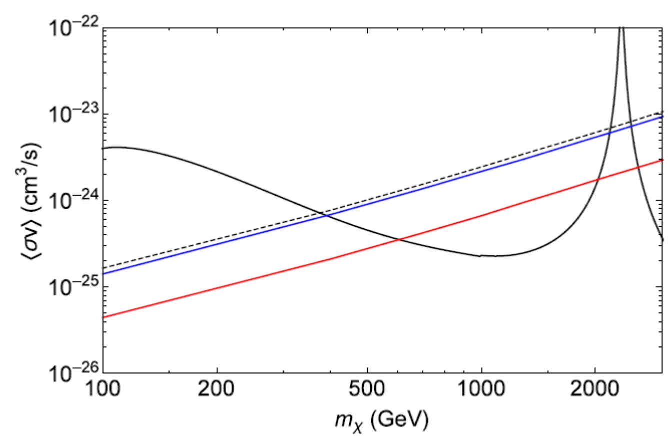


Our Fit

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

Reproduce Ref val.

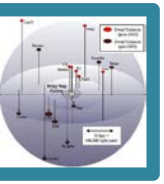




Summary

- Indirect detection is essential for O(1) TeV DM search.
- Gamma-ray observation of dSphs can give robust constraints (～1TeV or More) if dLogJ is small enough.
- However, many hidden systematic errors still exist.
- We give more conservative results by the axisymmetric DM model.
- Prior bias gives too aggressive results.
- Investigation of stellar kinematics (PFS) will play a crucial role.
- Reduction of foreground stars can be achieved by our cut and new likelihood.

Thank You !



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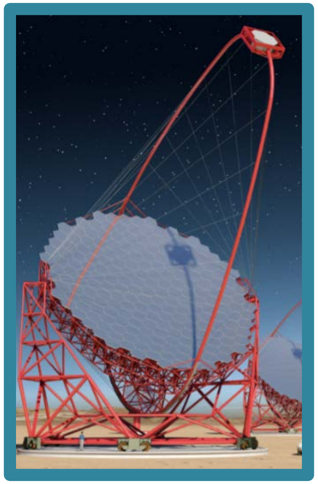

Kashiwa, Dec. 16, 2016