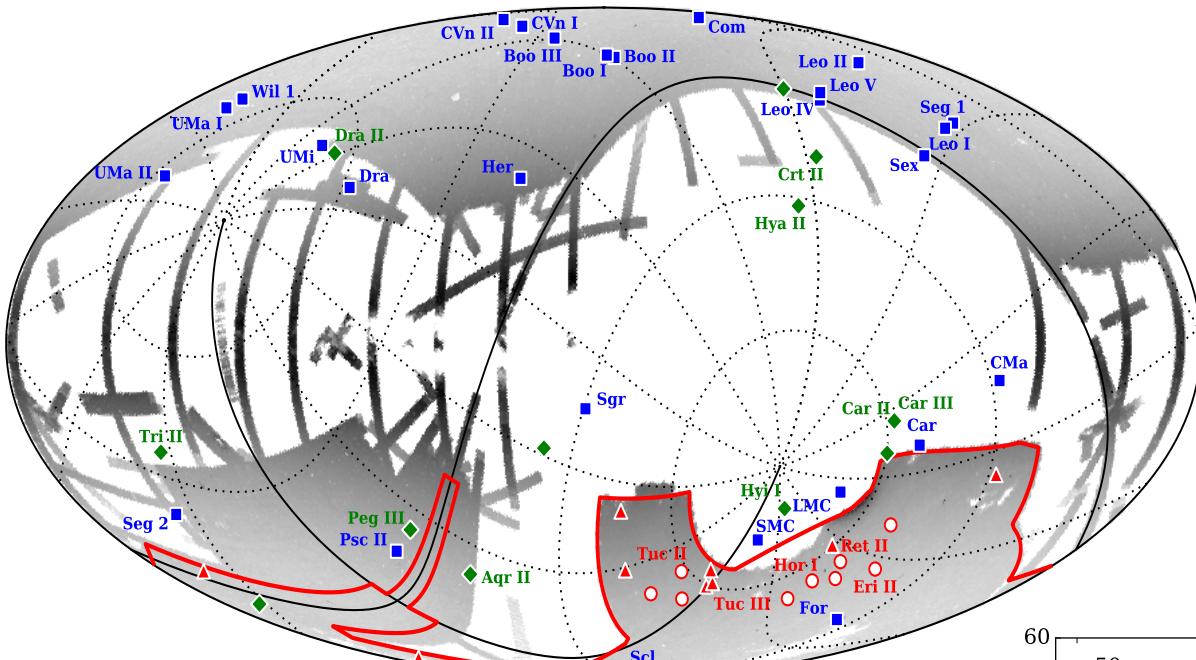


Probing Dark Matter Particle Properties with dark matter phase space information in the Milky Way satellites

Mei-Yu Wang
Carnegie Mellon University

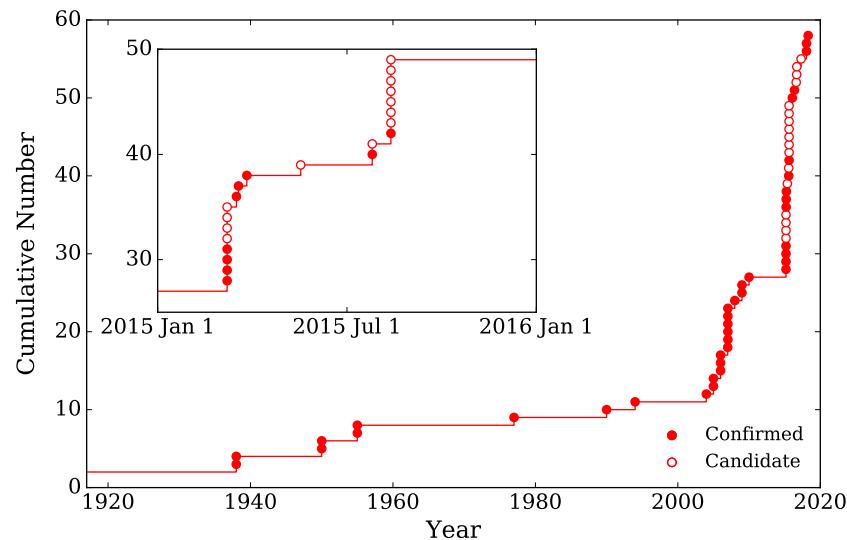
LSST DM Workshop, U Chicago/KICP, August 5-7, 2019

Discoveries of Milky Way dwarf satellite galaxies

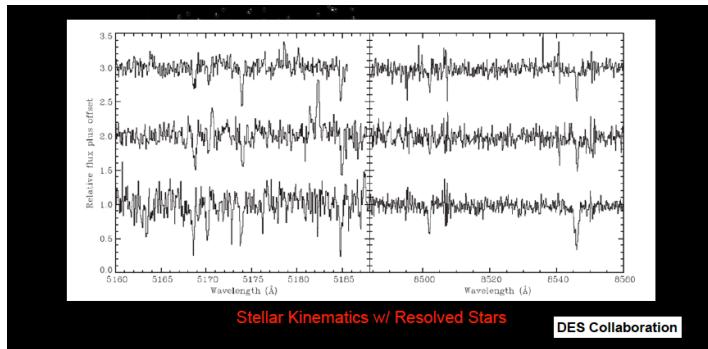
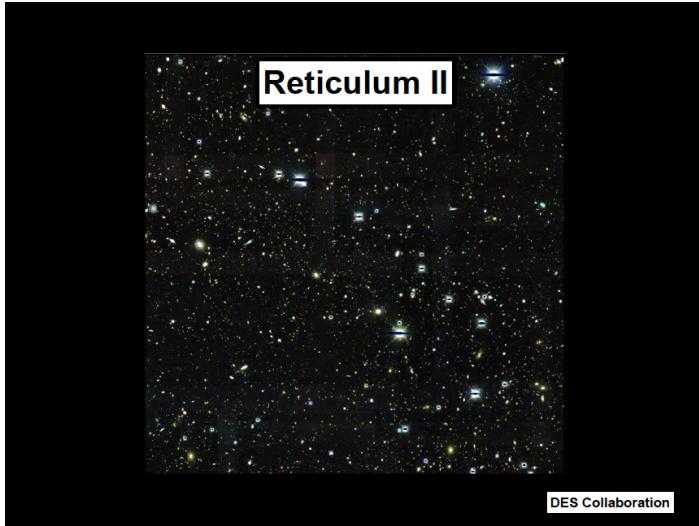


Plot credit: Alex Drlica-Wagner

- **Past:** Sloan Digital Sky Surveys (SDSS) : ~20
- **Now:** Dark Energy Survey (DES), Pan-STARRS, SMASH, MagLite, Gaia, HSC...
- **Future:** Large Synoptic Survey Telescope (LSST)



Measuring the DM contents of Milky Way dwarf galaxies



- Measuring velocity of individual star in the systems to infer dark matter content (dynamical mass)

Spherical Jeans Equation :

$$r \frac{d(\rho_\star \sigma_r^2)}{dr} = -\rho_\star(r) G M(r)/r - 2\beta(r) \rho_\star \sigma_r^2$$

DM subhalo profile

$$\sigma_{los}^2(R) = \frac{2}{I_\star(R)} \int_R^\infty \left[1 - \frac{\beta(r)}{r^2} \frac{R^2}{r^2} \right] \frac{\rho_\star(r) \sigma_r^2 r}{\sqrt{r^2 - R^2}} dr,$$

Line-of-sight velocity dispersion

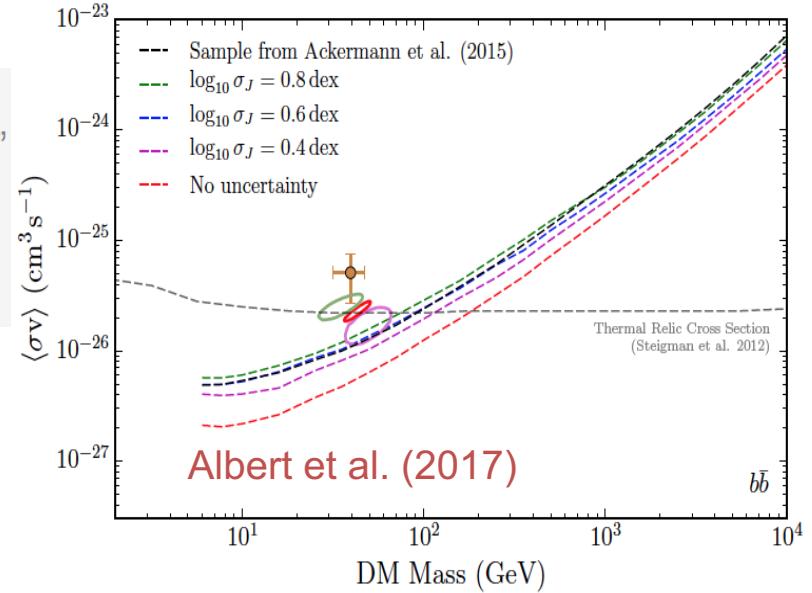
Orbital anisotropy

2D & 3D stellar density profiles

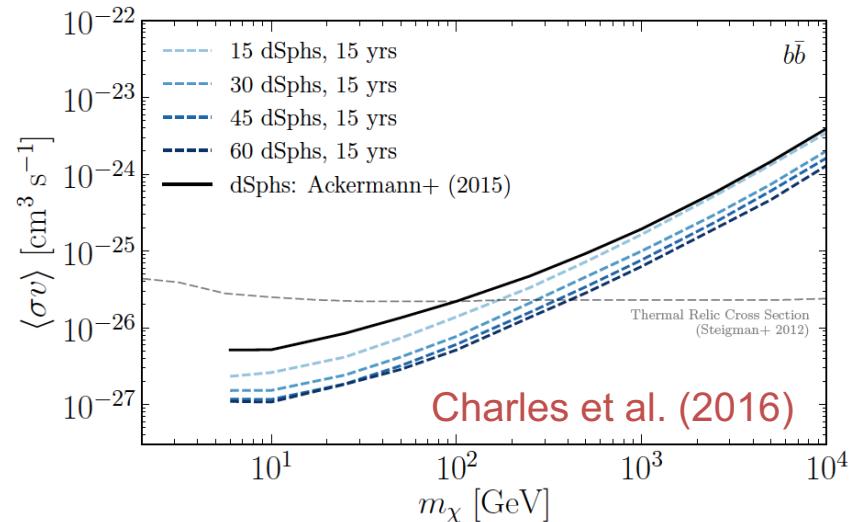
Effects of J-factor on WIMP annihilation cross section limits

$$\frac{dF(\hat{\mathbf{n}}, E)}{d\Omega dE} = \frac{\langle \sigma v \rangle}{8\pi M_\chi^2} \frac{dN_\gamma(E)}{dE} \int_{\ell=0}^{\infty} d\ell [\rho(\ell \hat{\mathbf{n}})]^2$$

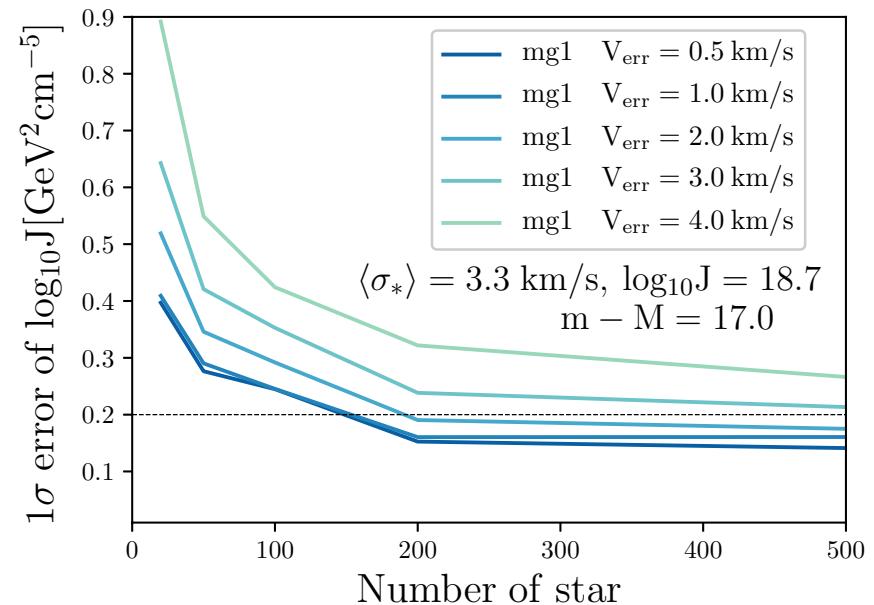
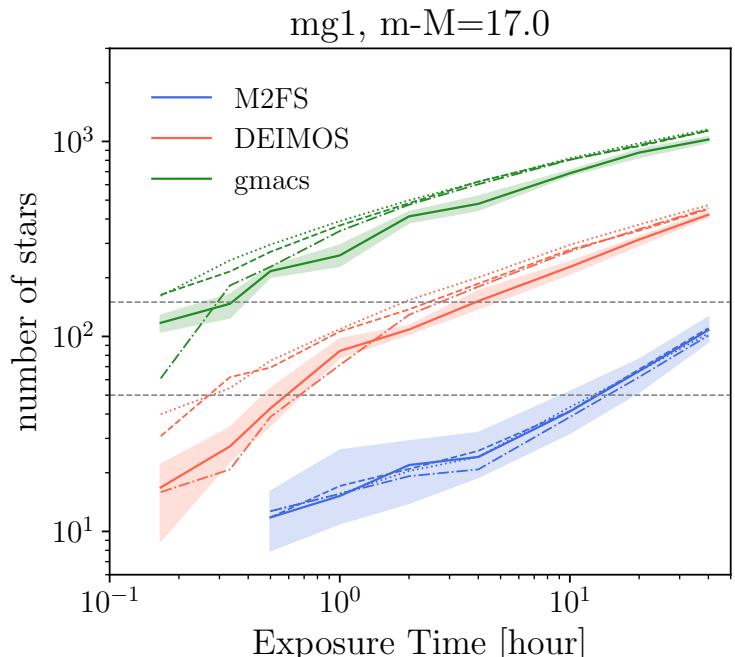
Annihilation cross section
Dark matter particle mass
“J-factor”



- Magnitude of J-factor**
 - Spatial proximity
 - Stellar velocity dispersion (higher the values, higher the DM content)
- Uncertainties of J-factor**
 - Stellar velocity measurement sample size
 - Velocity measurement precision

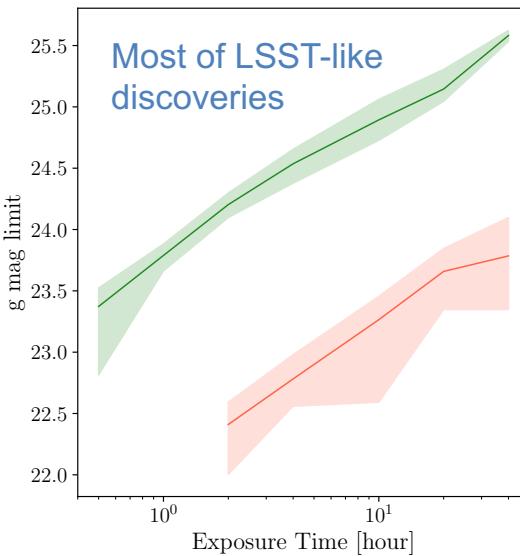
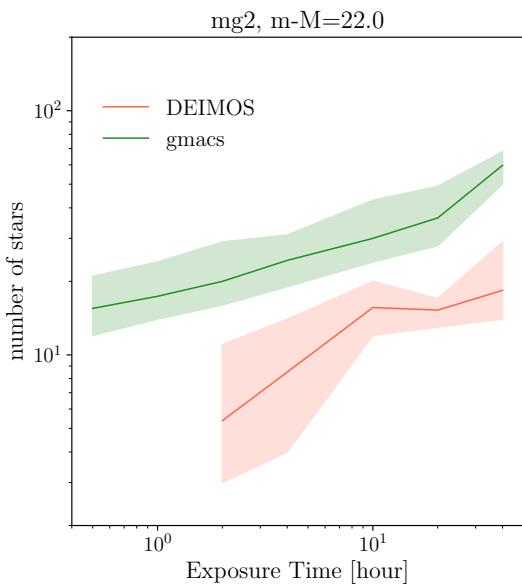
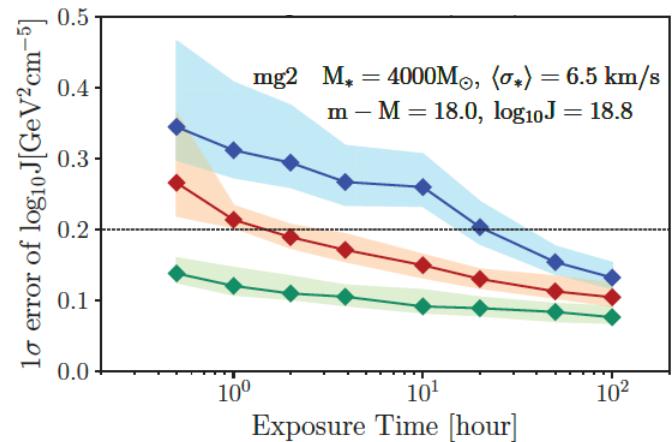
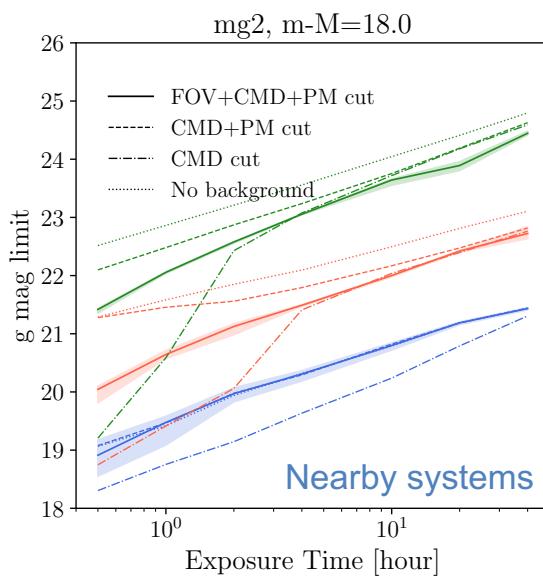
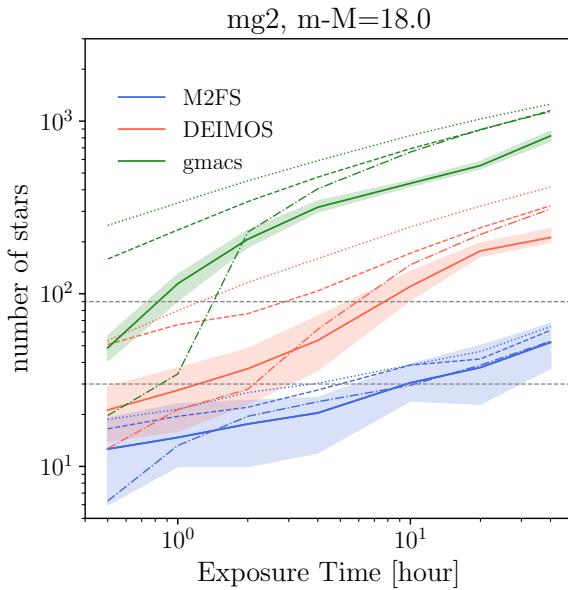


Improving J-factor measurements with current & future spectroscopic follow-up facilities



Instrument/Telescope	Multiplexing	Mirror Size [meter]	Systematic Error [km/s]
DEIMOS/Keck	40	10	2.0
IMACS/Magellan	50	6.5	1.5
M2FS/Magellan	256	6.5	0.9
GIRAFFE/VLT	123	8.2	0.5
GMACS/GMT	50	23.5	2.0

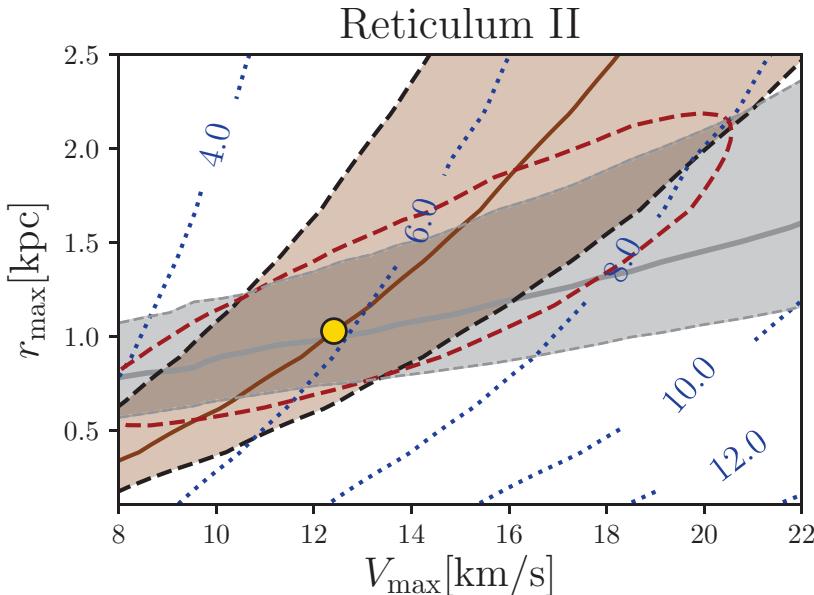
MYW, Drlica-Wagner, Li, Strigari (2019),
in preparation



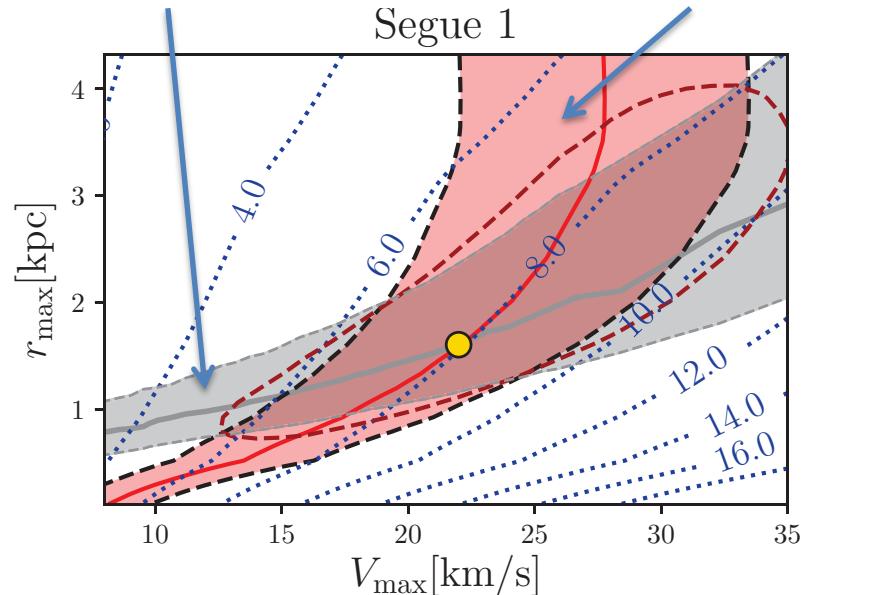
- Applying CMD+ Gaia PM cut to reduce background star contamination
- FOV can be important for nearby dwarf galaxies
- High multiplexing is highly preferred.

Constructing DM velocity distribution in dSphs

Assuming NFW profile



N-body simulation

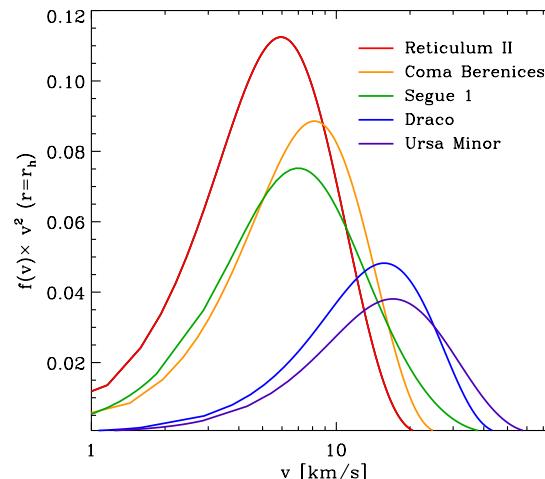


MYW, Cherry, Strigari and Horiuchi (2018)

Boddy, Kumar, Strigari, MYW (2017)

$$f_{\text{DM}}(\epsilon) = \frac{1}{\sqrt{8}\pi^2} \int_{\epsilon}^0 \frac{d^2\rho_{\text{DM}}}{d\Psi^2} \frac{d\Psi}{\sqrt{\epsilon - \Psi}}$$

DM velocity distribution function

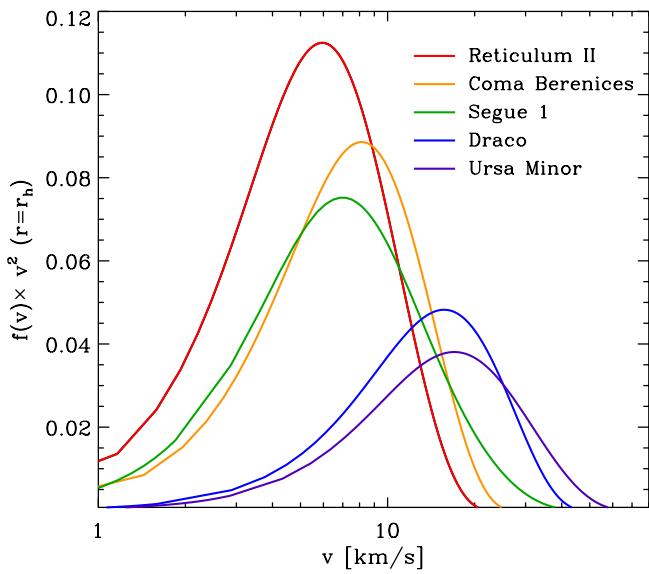


Sommerfeld-enhanced J-factor for Milky Way satellite galaxies

Boddy, Kumar, Strigari, MYW (2017)

$$\frac{d\Phi}{dE_\gamma} = \frac{1}{4\pi} \frac{dN}{dE_\gamma} \int_{\Delta\Omega} d\Omega \int d\ell \int d^3v_1 \frac{f(r(\ell, \Omega), \vec{v}_1)}{m_X} \int d^3v_2 \frac{f(r(\ell, \Omega), \vec{v}_2)}{m_X} \frac{(\sigma_A |\vec{v}_1 - \vec{v}_2|)}{2}$$

Velocity-dependent cross section



$$V(r) = -\frac{\alpha_X}{r} e^{-m_\phi r}$$

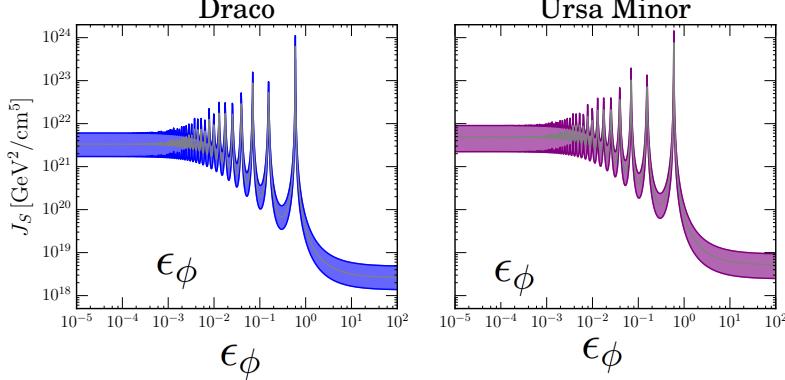
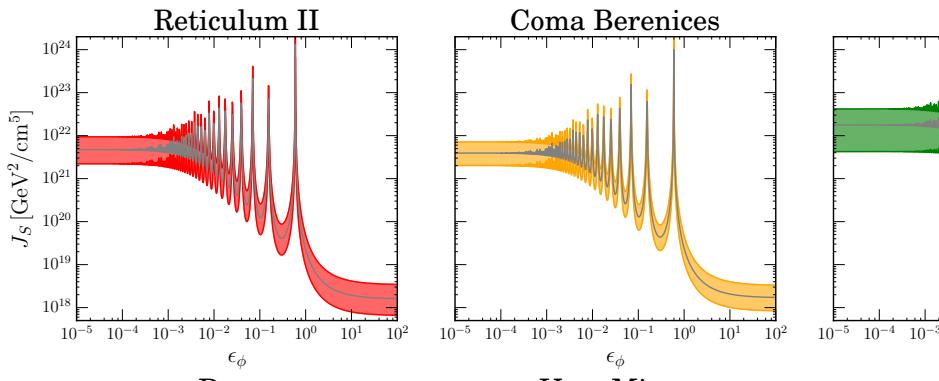
Interaction between DM described by a Yukawa potential

$$S \simeq \frac{\pi}{\epsilon_v} \frac{\sinh\left(\frac{2\pi\epsilon_v}{\pi^2\epsilon_\phi/6}\right)}{\cosh\left(\frac{2\pi\epsilon_v}{\pi^2\epsilon_\phi/6}\right) - \cos\left(2\pi\sqrt{\frac{1}{\pi^2\epsilon_\phi/6} - \frac{\epsilon_v^2}{(\pi^2\epsilon_\phi/6)^2}}\right)}$$

Sommerfeld enhancement factor

Sommerfeld-enhancement can change the order of J-factor among satellite galaxies

Boddy, Kumar, Strigari, MYW (2017)

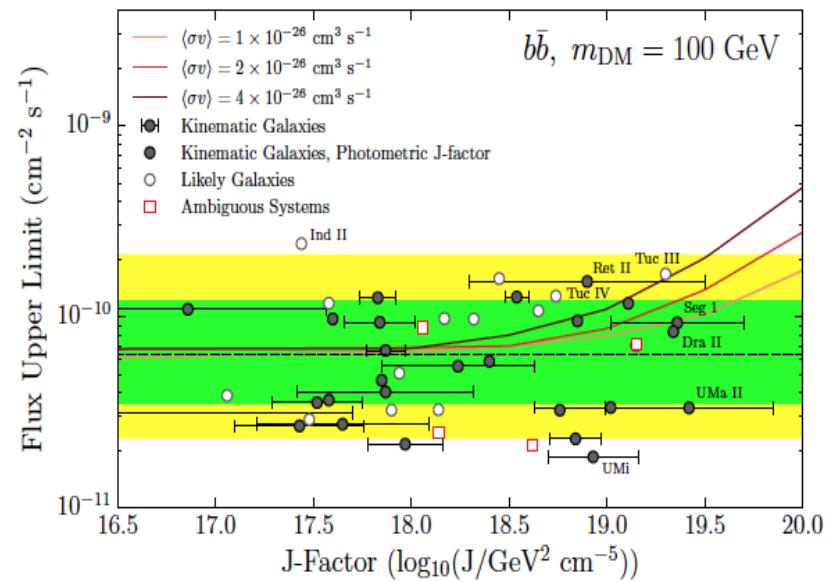


$\epsilon_\phi \gg 1 \rightarrow$ Non-enhanced limit

$\epsilon_\phi \ll 1 \rightarrow$ Coulomb-like potential

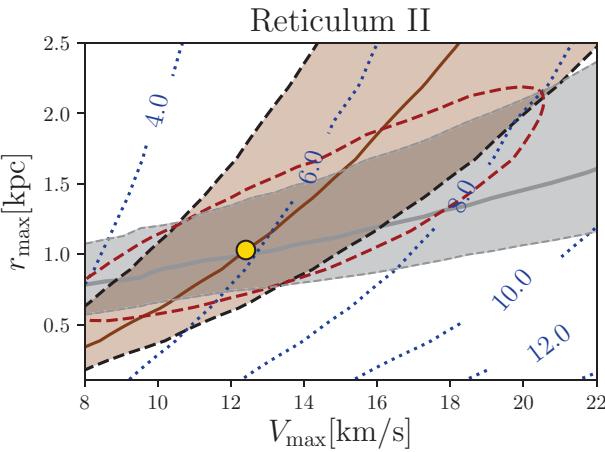
$$\epsilon_\phi \equiv \frac{m_\phi}{\alpha_X m_X}$$

Albert et al. (2017)

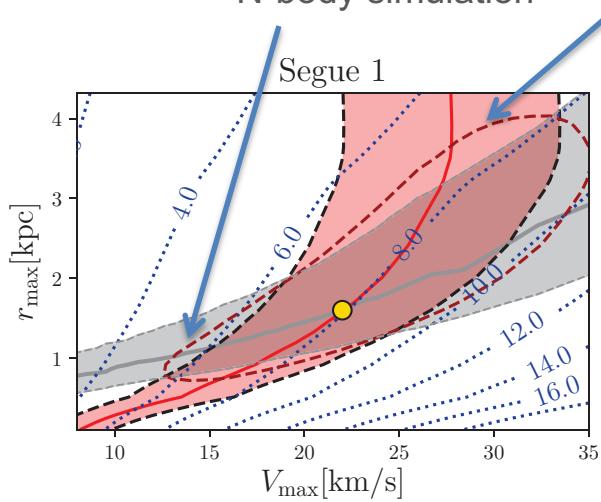


Dark matter velocity dispersion

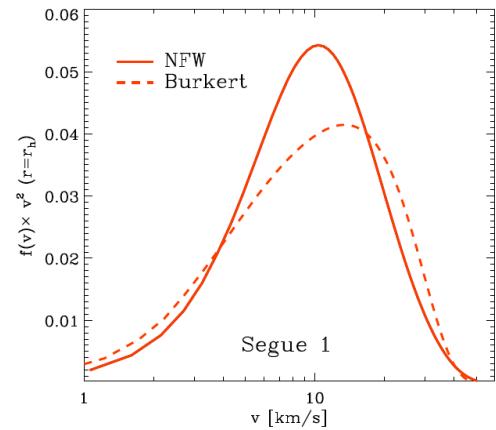
DM velocity dispersion (NFW profiles)



N-body simulation



Stellar kinematics



dSph name	$\langle \sigma_* \rangle$ [km/s]	2D r_h^\dagger [pc]	3D r_h^\ddagger [pc]	$\langle \sigma_{\text{DM}}^{\text{NFW}} \rangle$ [km/s]	$Q_{\sigma_{\text{DM}}}^{\text{NFW}}$
Coma Berenices	$4.6^{+0.8}_{-0.8}$	60.6	78.2	$7.8^{+3.5}_{-2.1}$	$6.9^{+5.6}_{-3.8}$
Pegasus III	$5.4^{+3.0}_{-2.5}$	41.7	54.3	$10.2^{+5.7}_{-6.1}$	$5.9^{+14.6}_{-2.7}$
Horologium I	$4.9^{+2.8}_{-0.9}$	30.0	39.0	$9.7^{+4.6}_{-2.9}$	$15.8^{+13.3}_{-6.6}$
Reticulum II	$3.3^{+0.7}_{-0.7}$	34.8	45.2	$5.9^{+2.4}_{-1.9}$	$25.8^{+18.3}_{-11.7}$
Segue	$3.9^{+0.8}_{-0.8}$	20.9	27.2	$8.2^{+2.2}_{-2.6}$	$34.0^{+30.9}_{-12.4}$
Draco II	$2.9^{+2.1}_{-2.1}$	16.6	21.5	$6.2^{+4.4}_{-2.9}$	$74.8^{+90.9}_{-40.3}$

Eddington Formula

$$f_{\text{DM/star}}(\epsilon) = \frac{1}{\sqrt{8\pi^2}} \int_{\epsilon}^0 \frac{d^2 \rho_{\text{DM/star}}}{d\Psi^2} \frac{d\Psi}{\sqrt{\Psi - \epsilon}}$$

$$\langle \sigma_{\text{DM/star}}^2(r) \rangle = \frac{\int v^4 f_{\text{DM/star}}(v, r) dv}{\int v^2 f_{\text{DM/star}}(v, r) dv}$$

Resonantly produced sterile neutrino mass bound from satellite phase space density

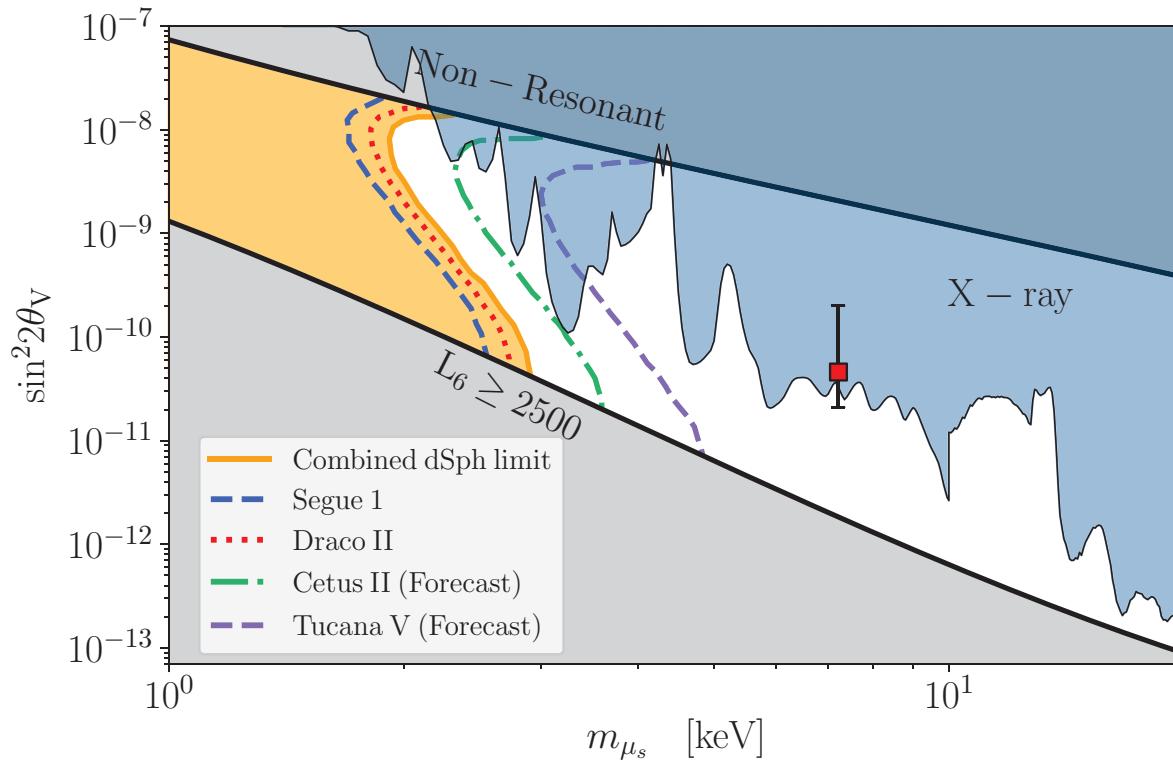
Liouville's theorem:

For dissipationless and collisionless particles, the phase-space density cannot increase $\Rightarrow Q < q_{\max}$

$$Q_{\text{MB}} \equiv \frac{\bar{\rho}}{(2\pi\sigma^2)^{3/2}}$$

Coarse-grained phase-space density

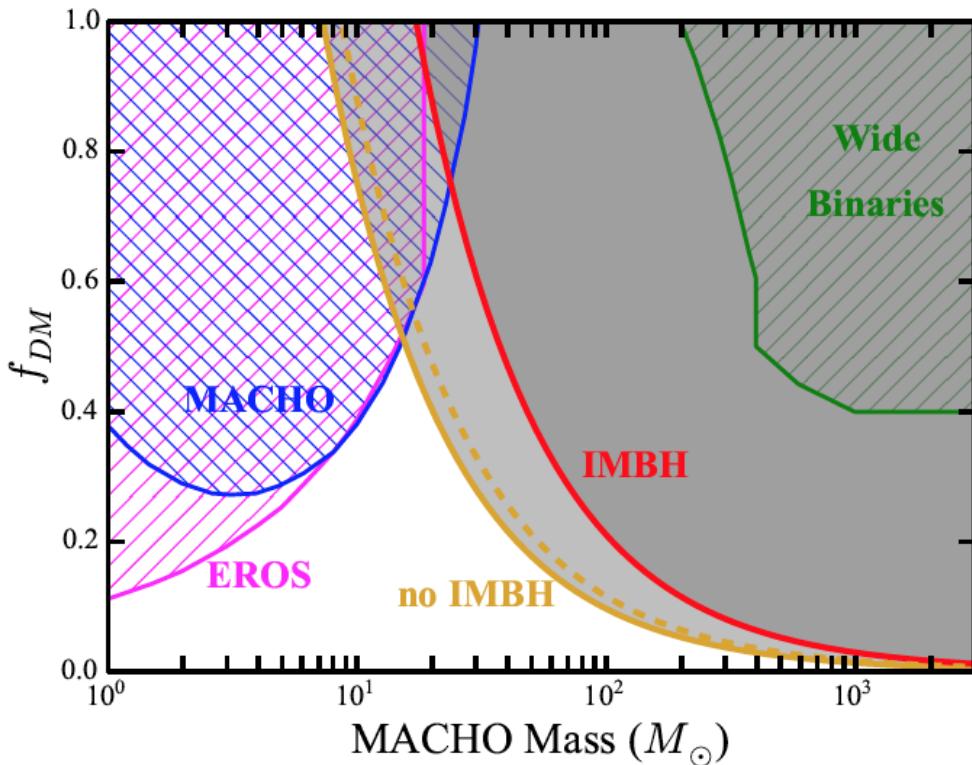
q_{\max} : Fine-grained phase-space density



MYW, Cherry, Horiuchi, and Strigari (2017)

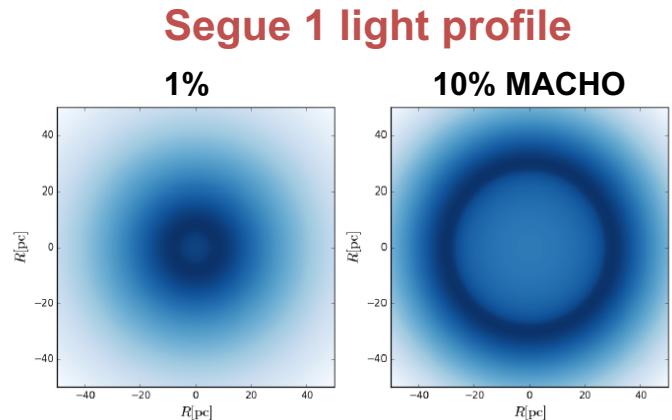
MACHO (MAssive Compact Halo Object) dark matter limits

The star cluster in Eridanus II or any compact dwarf galaxies could be dynamically heated by MACHO and therefore expand/dissolve.



Li et al. (2017), the DES collaboration
Also see Brandt (2016)

$$\frac{dr_h}{dt} = \frac{4\sqrt{2}\pi G f_{DM} m_a}{\sigma} \ln \Lambda \left(\alpha \frac{M_*}{\rho r_h^2} + 2\beta r_h \right)^{-1}$$



Koushiappas & Leob (2017)

Conclusion

- Milky Way satellite galaxies are compelling targets for dark matter searches due to their proximity, high dark matter content, and low astrophysical backgrounds.
- Satellite galaxies stellar kinematic measurement affect the precision of dark matter content determination. It has direct impacts on indirect detection limits of WIMP dark matter model.
- The DM phase space information can be derived from stellar kinematics. It can provide useful constraints on various DM models such as velocity-dependent annihilation channel, sterile neutrino, and MACHO DM.