The Nature of Dark Matter unveiled

through Synergy of Astrophysics and Particle Physics

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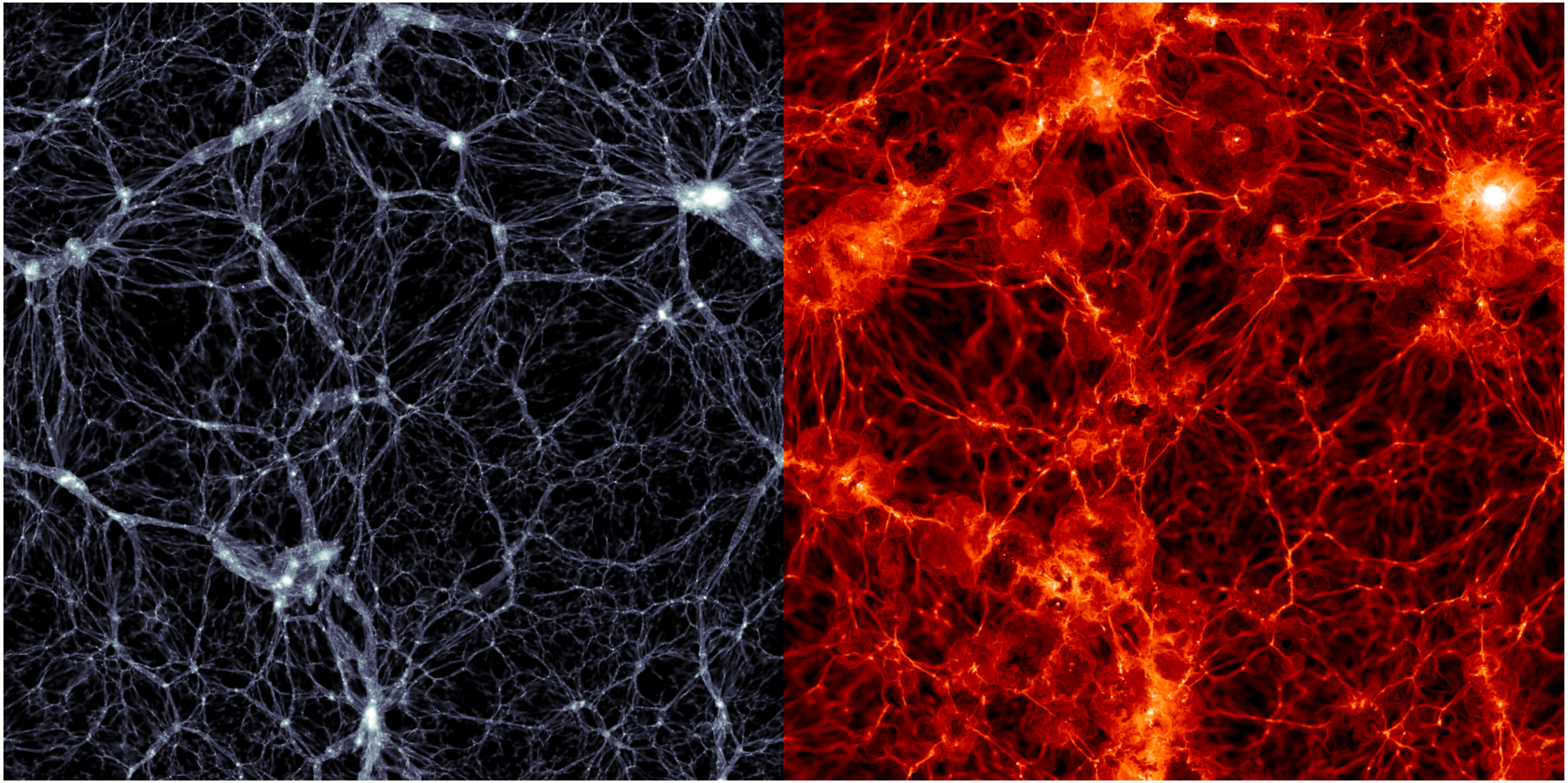
Outline

- Beyond cold dark matter: feedback OR non-standard DM?
- Accurate inference of dark matter distribution in **nearby galaxies** via advanced dynamical modeling
- The local dark matter density in the **Solar Neighborhood**
- Shape of dark matter halo from dynamical modeling of stars+gas in isolated local **dwarf galaxy WLM**
- Astrophysical constraints on dark matter particle properties from **local dwarf galaxies**

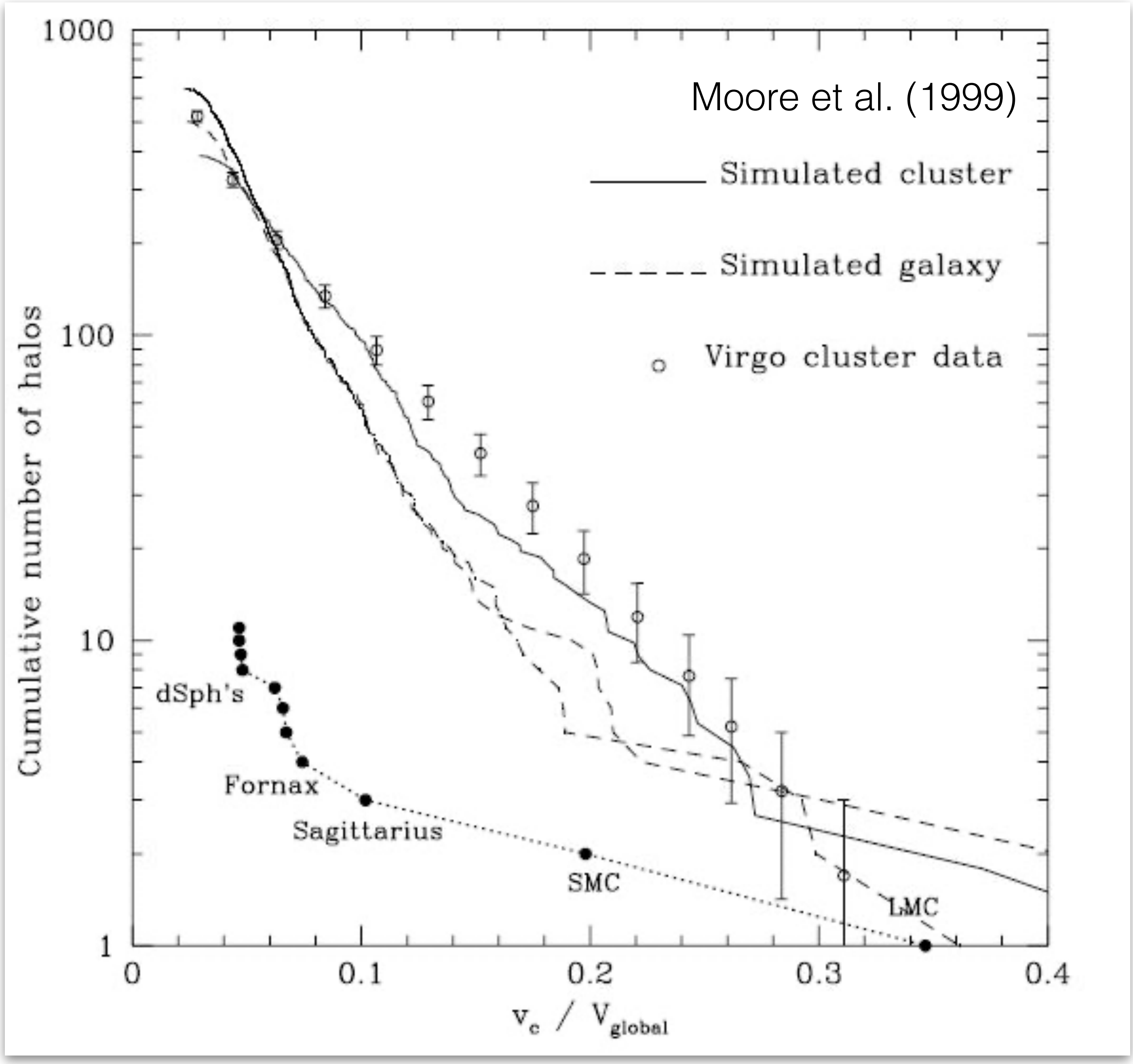
Beyond cold dark matter

Cold dark matter



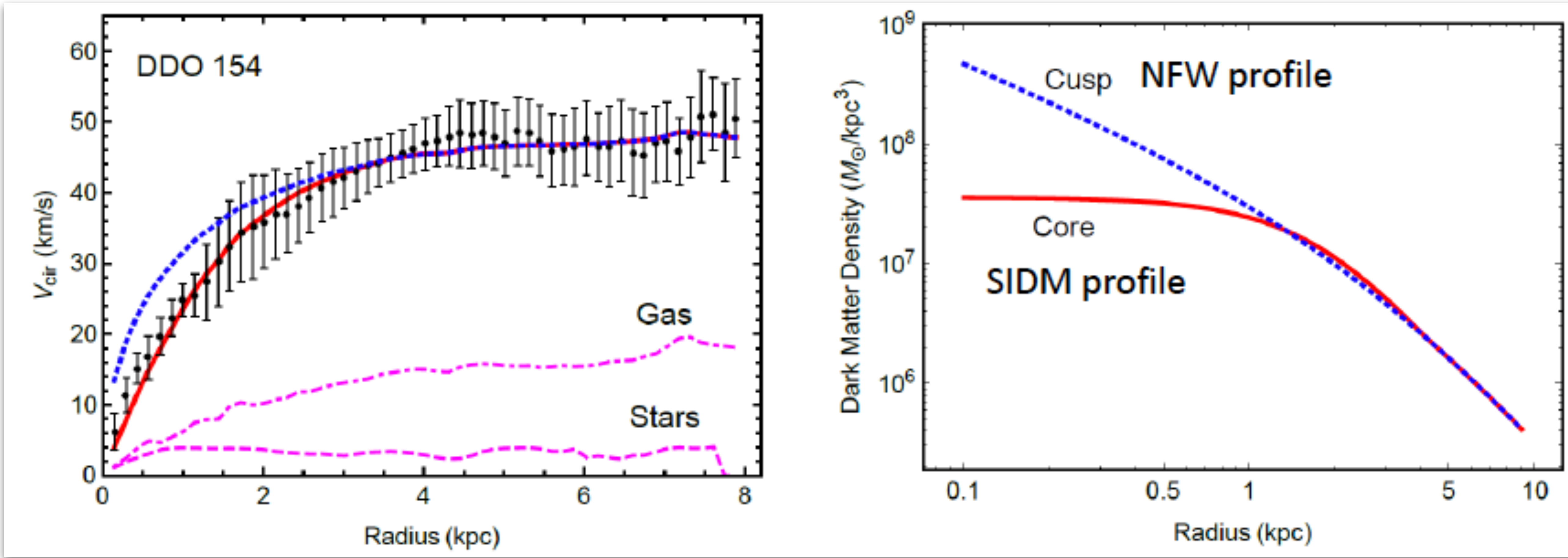
- ΛCDM has been successful at describing how large scale structures in the universe arise
- notable problems have been identified at galactic scales

‘Missing Satellite’ problem



- ΛCDM predicted orders of magnitude more low-mass subhalos than the observed **number of luminous satellite galaxies** around the Milky Way and Andromeda

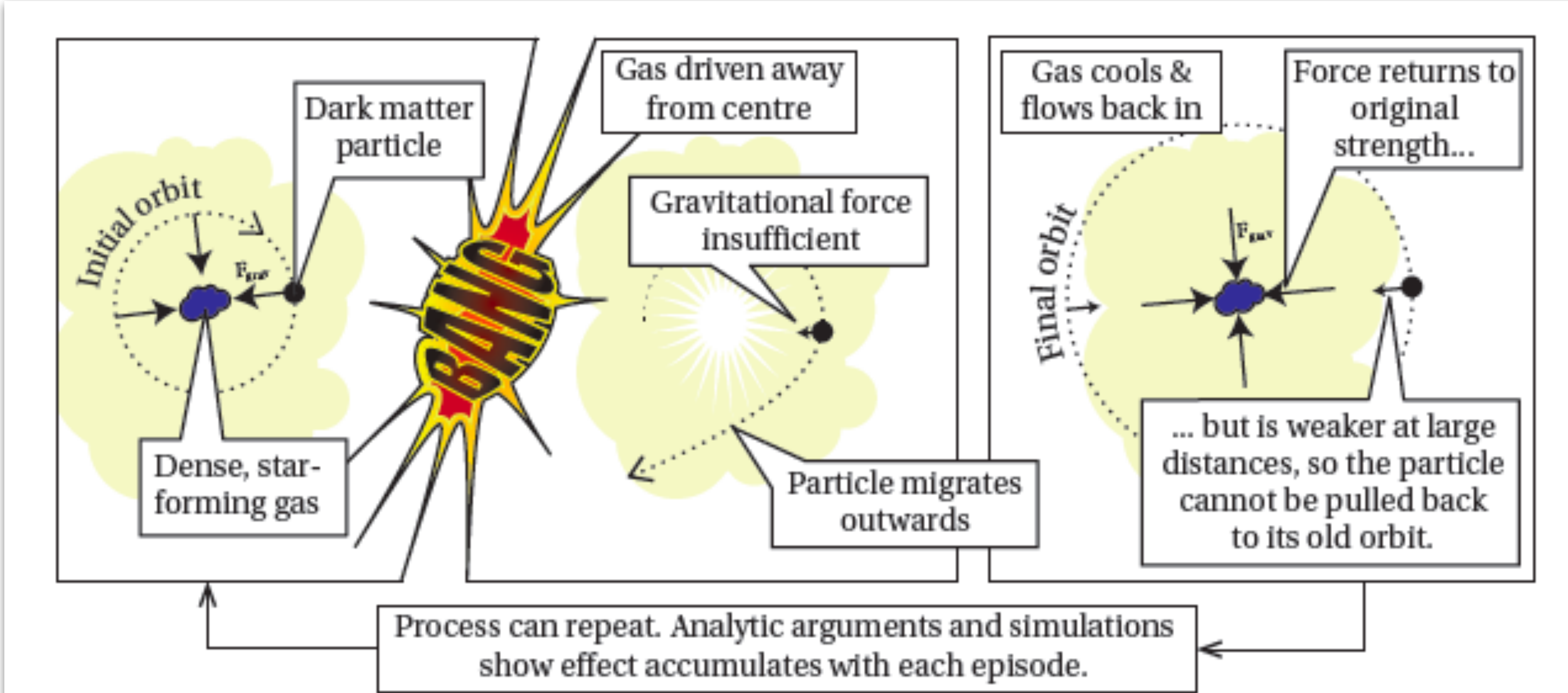
‘Core-Cusp’ problem



Credit: Sean Tulin

- The **density profile** of CDM halos is self-similar with a steep inner cusp, but (low-mass) galaxies show indications of shallower density profiles with an innner core

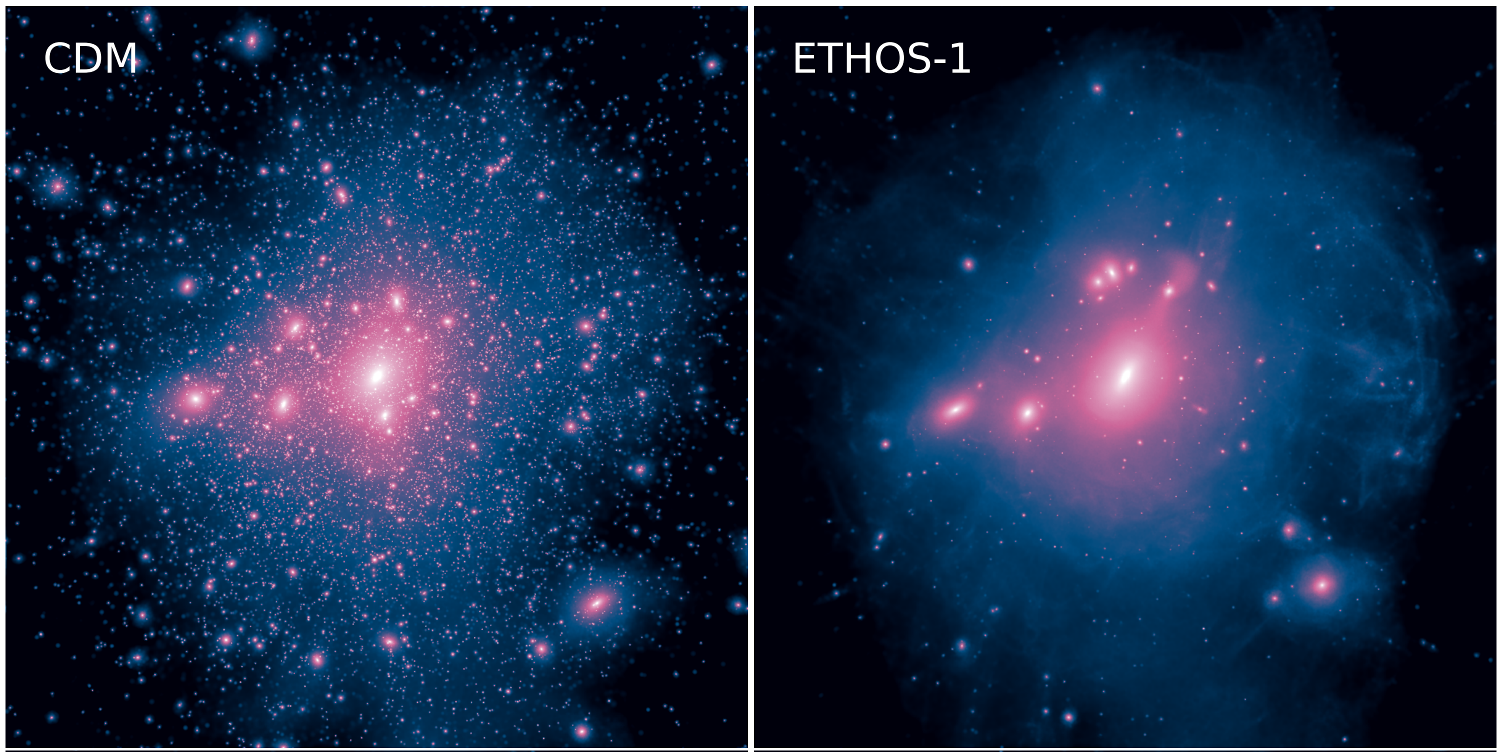
Cold dark matter with feedback?



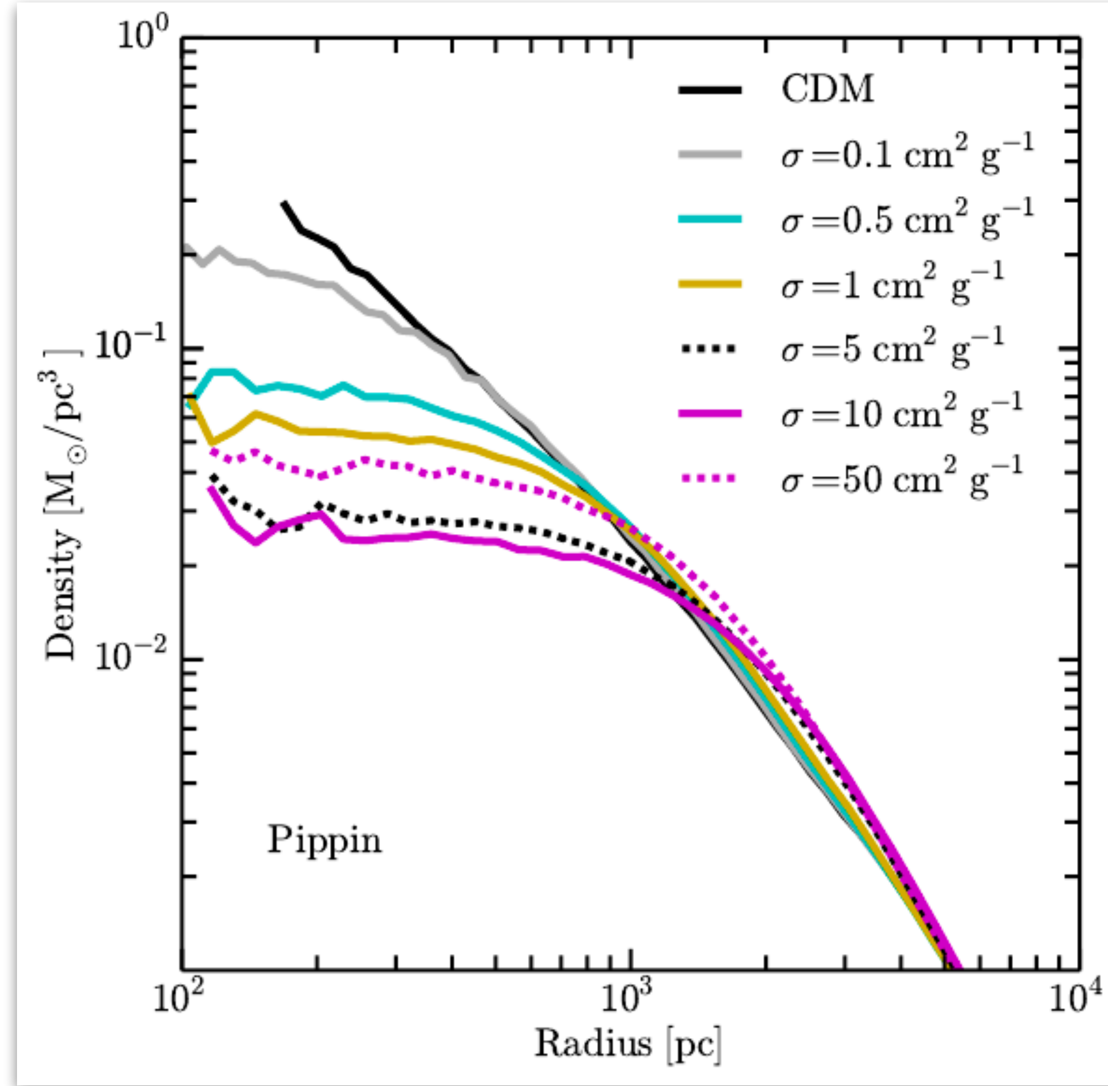
Pontzen & Governato (2012)

- Baryonic feedback processes: supernovae, stellar radiation, reionization, ram pressure stripping, etc.
- Can halt and even **prevent star formation**: dark satellites
- Can cause **non-adiabatic expansion**: density cusps to cores

OR non-standard dark matter?



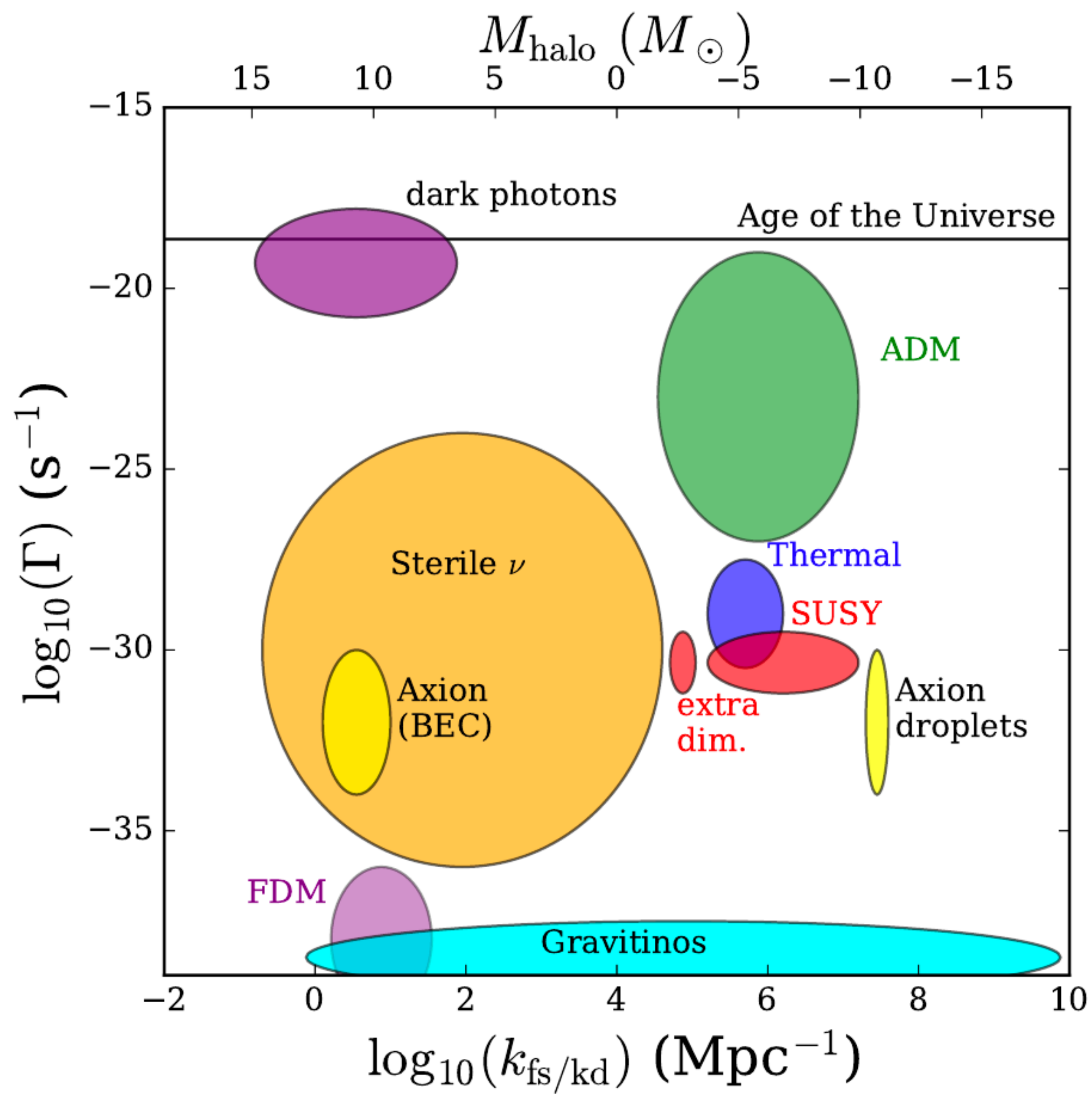
Vogelsberger et al. (2015)



Elbert et al. (2015)

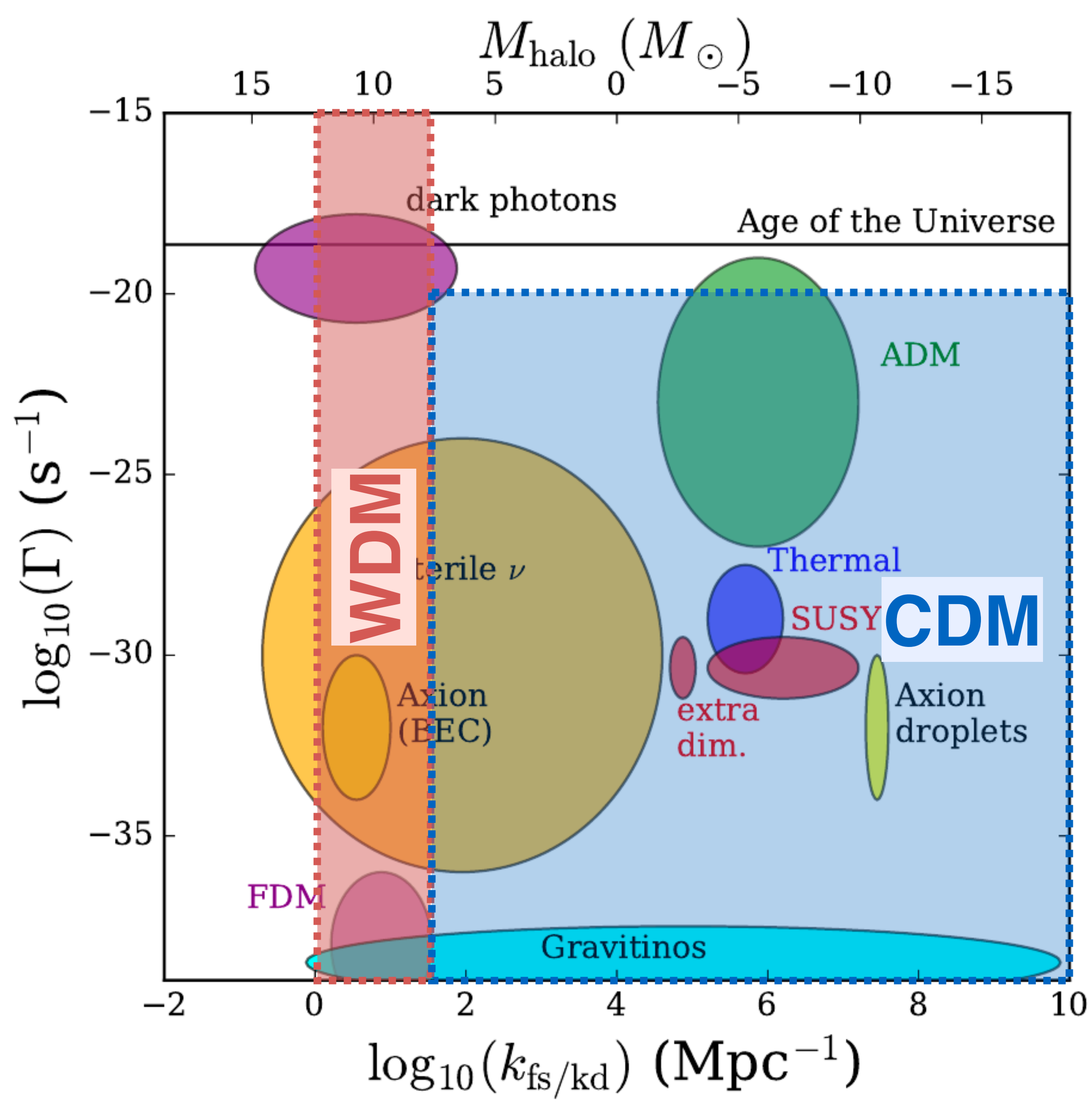
- E.g., self-interacting (SIDM) or ultra-light axion DM (BECDM)
- Structure formation at small scales is **suppressed**
- Particle **self-interactions** can create central density cores

Feedback or non-standard DM?



Buckley & Peter 2018

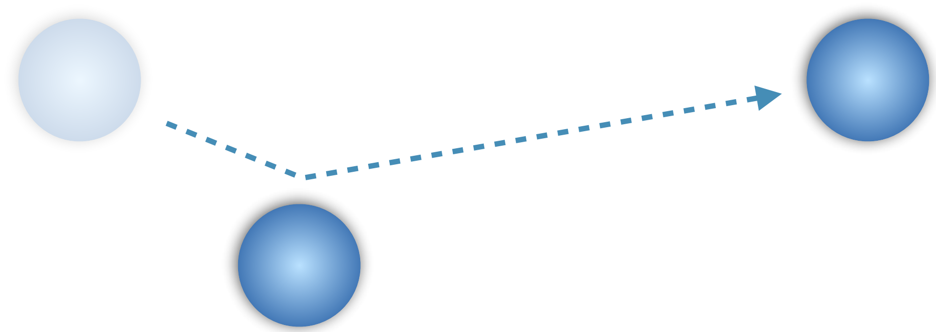
Feedback or non-standard DM?

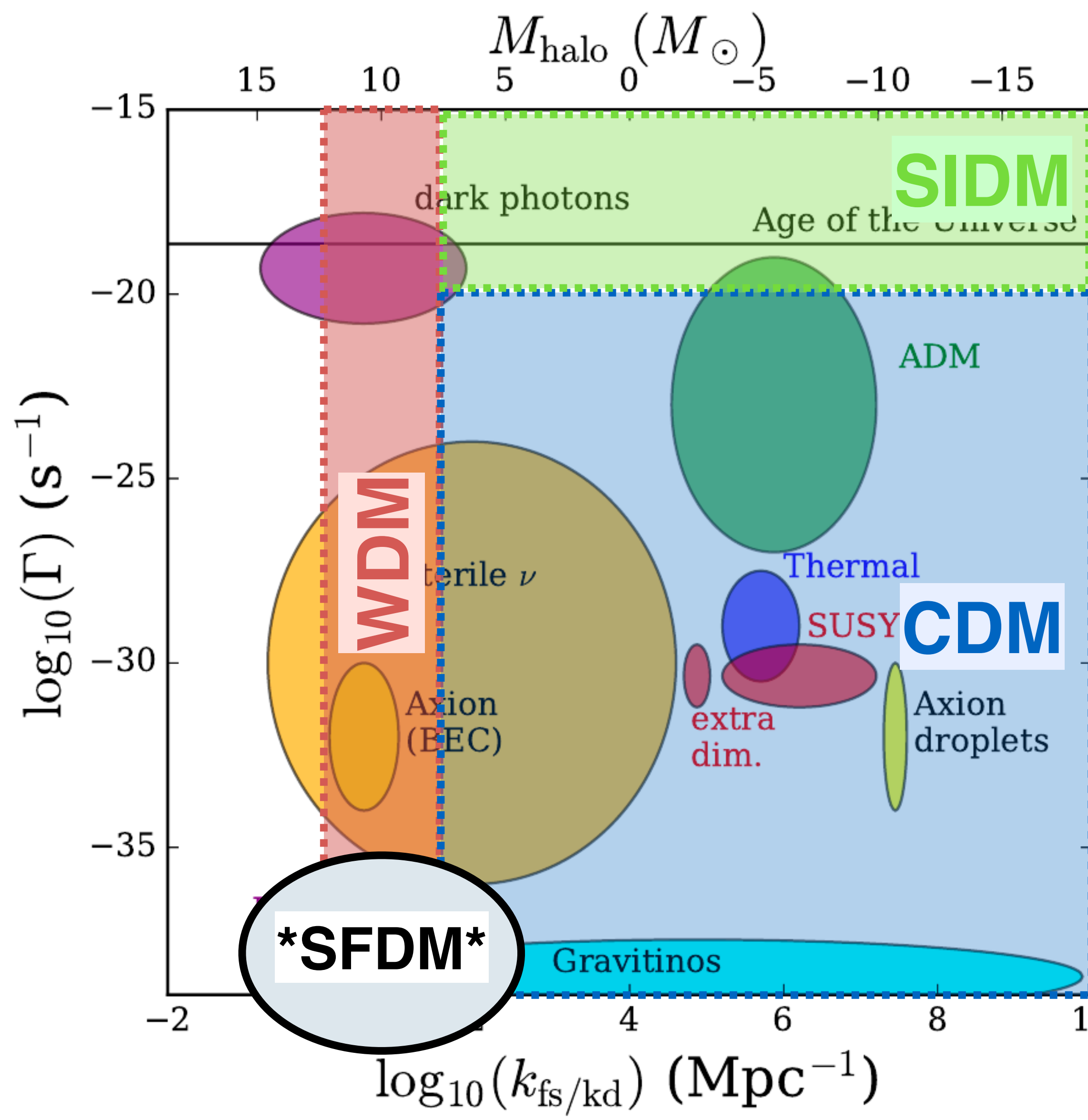


Buckley & Peter 2018

Feedback or non-standard DM?

SIDM = self-interacting DM





Buckley & Peter 2018

Feedback or non-standard DM?

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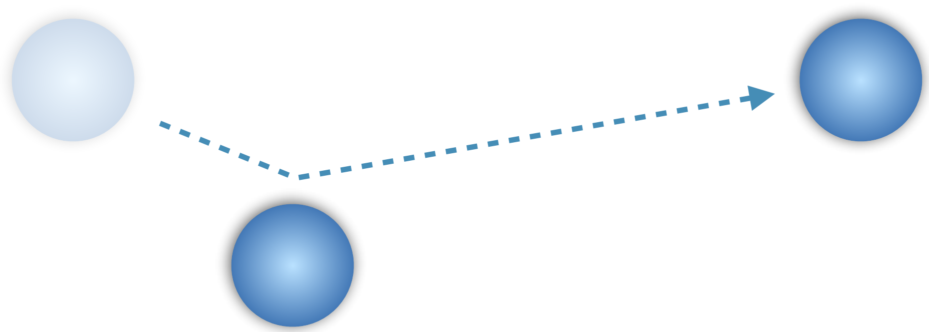
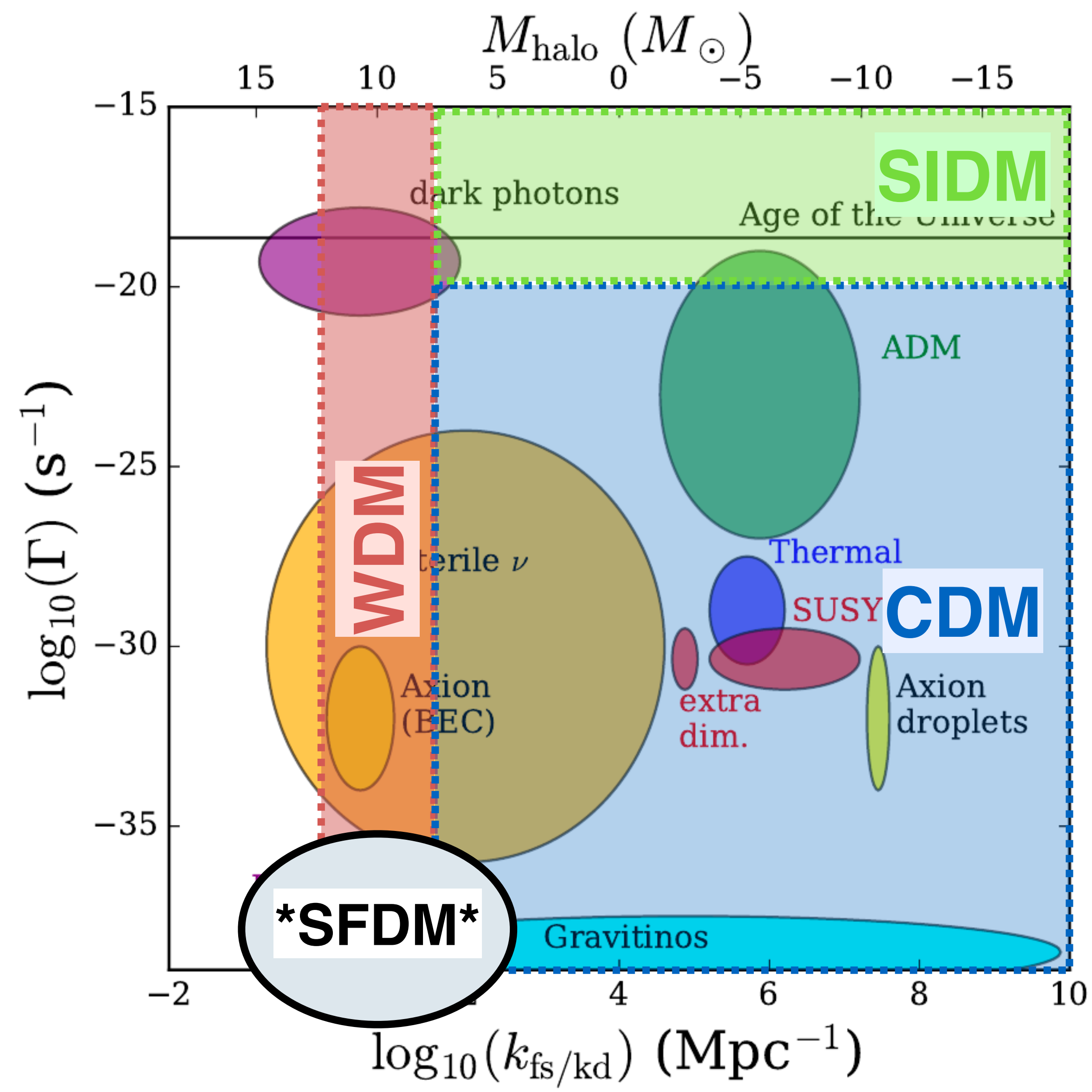


SFDM = scalar field DM

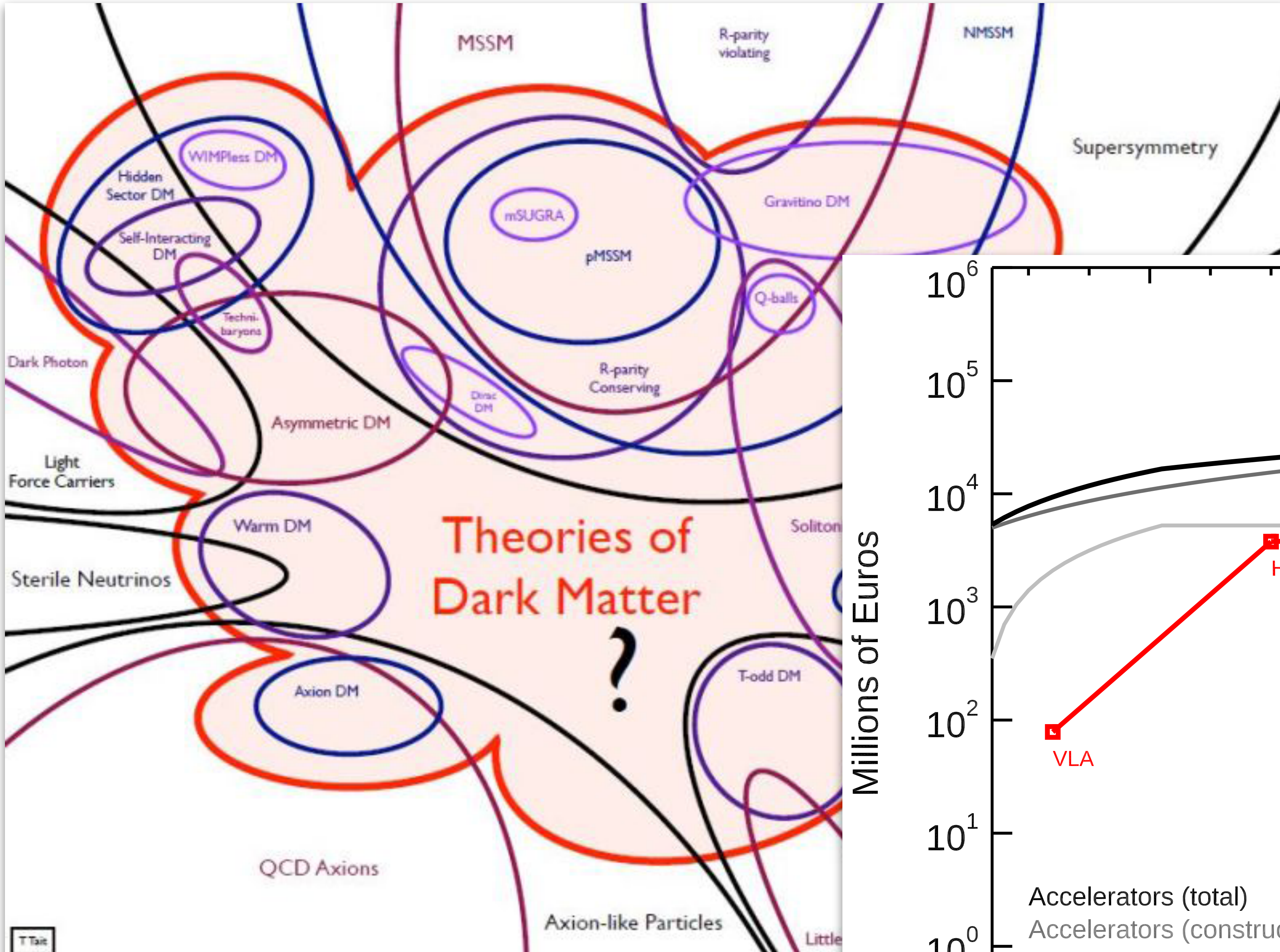
e.g., ULA (ultra-light axion), BECDM (Bose-Einstein-condensate DM), “Fuzzy” DM, “Wave” DM

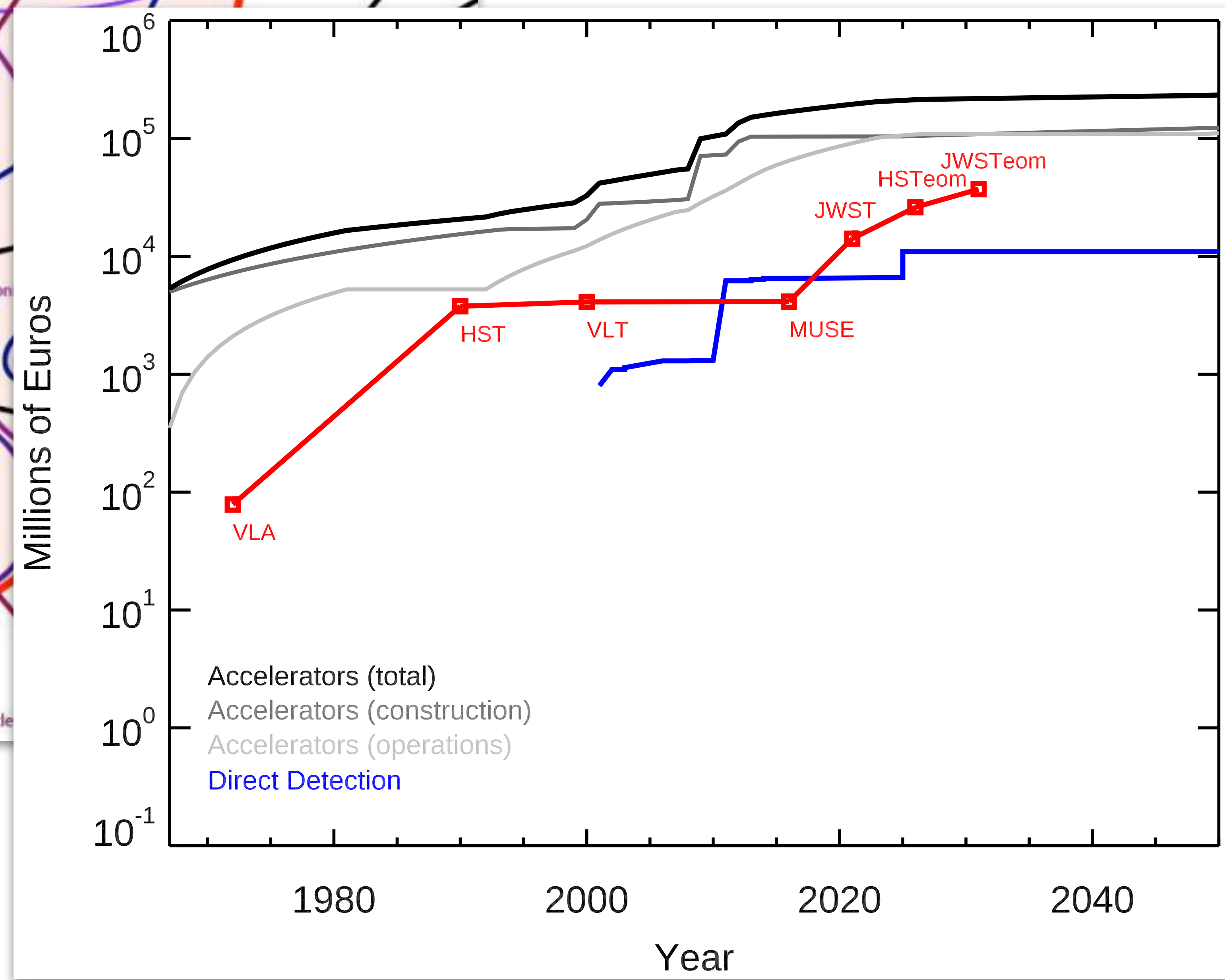
$$m_\psi \sim \mathcal{O}(10^{-22}\mathrm{eV}) \qquad \lambda \sim \frac{h}{m_\psi v} \sim [kpc]$$



Buckley & Peter 2018

Nature of DM: theory & experiments





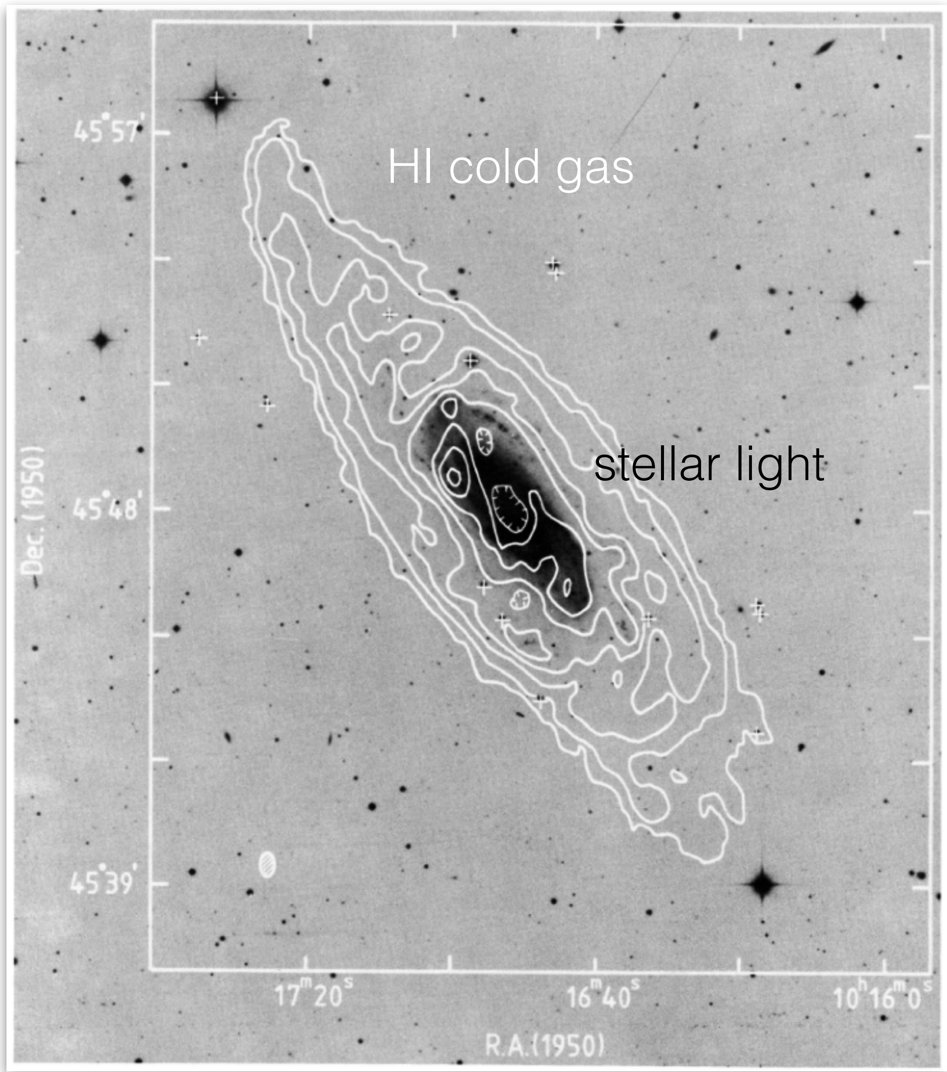
- Large investments from Particle Physics… and Astrophysics?

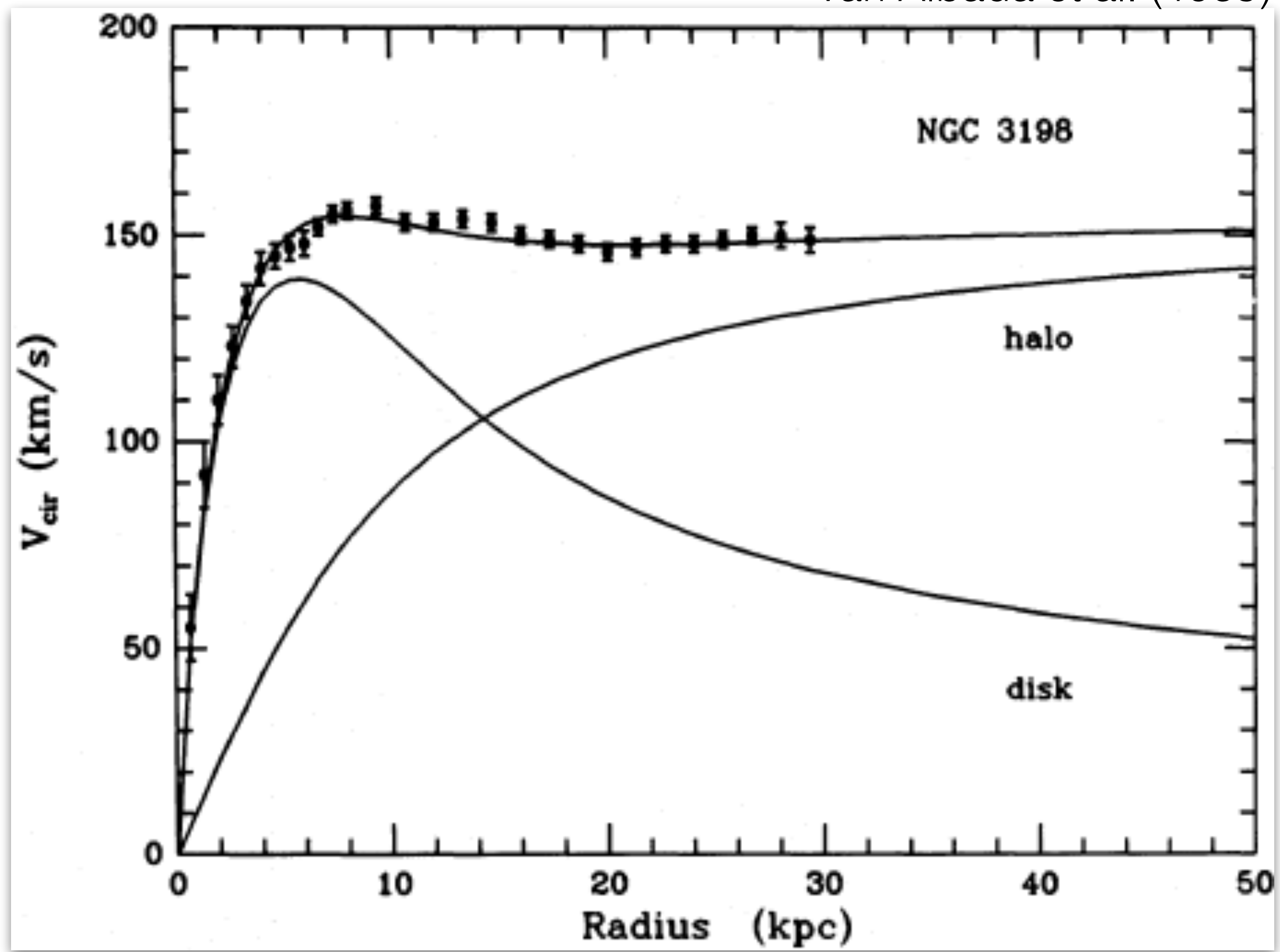
Dark matter in nearby galaxies

Dark Matter in Galaxies

$$\frac{GM_{\rm tot}(<R)}{R} = -R\frac{\partial\Phi}{\partial R} = v_c^2(R)$$

van Albada et al. (1985)



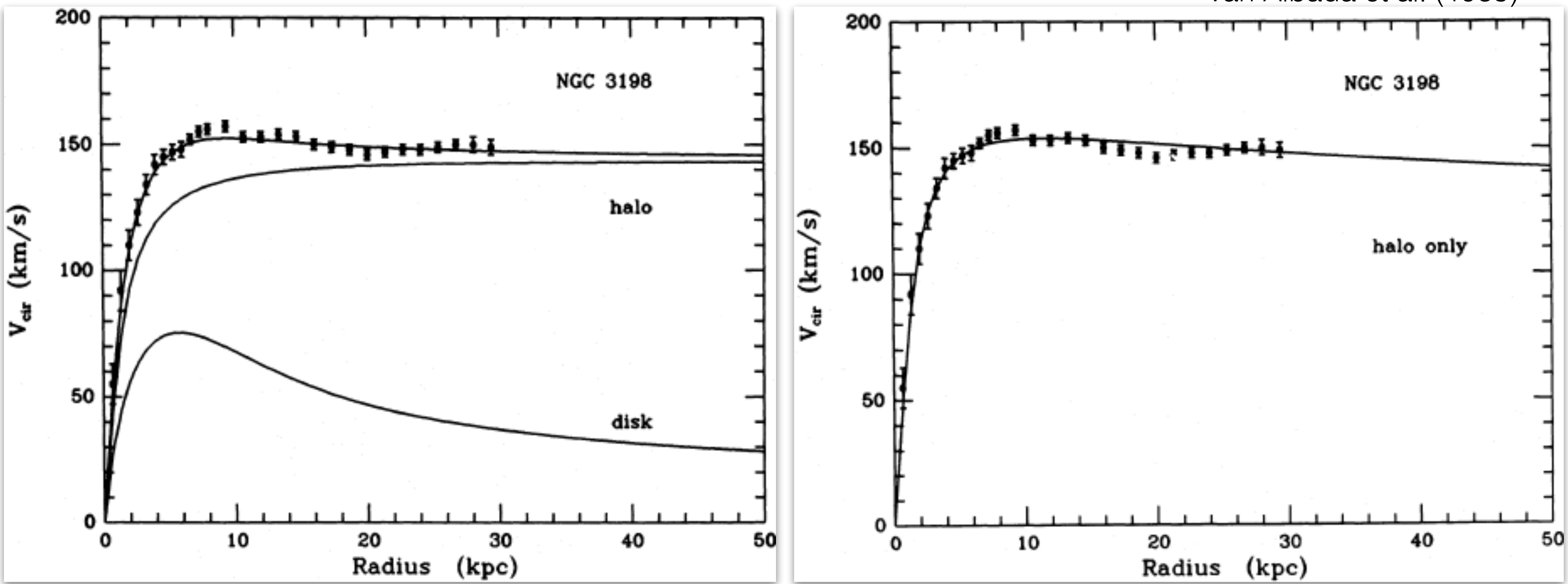


- To disentangle luminous and dark mass requires stellar mass-to-light ratio …

Disk-halo degeneracy

$$\frac{GM_{\rm tot}(<R)}{R} = -R\frac{\partial\Phi}{\partial R} = v_c^2(R)$$

van Albada et al. (1985)

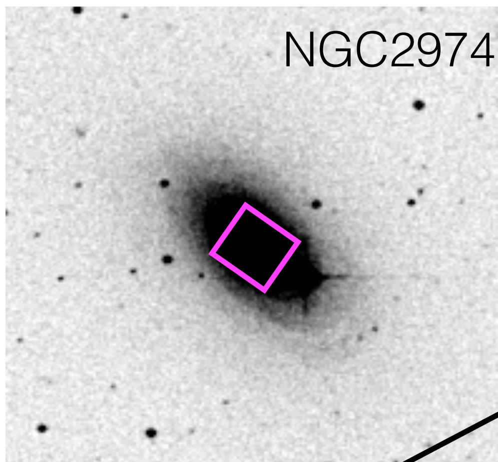


- ... + resolution, correction non-circular motions, deprojection, non-spherical halo, and presence of cold gas!

Mass-anisotropy degeneracy

tracer density

velocity anisotropy: σ_ϕ/σ_R, σ_z/σ_R, ...?

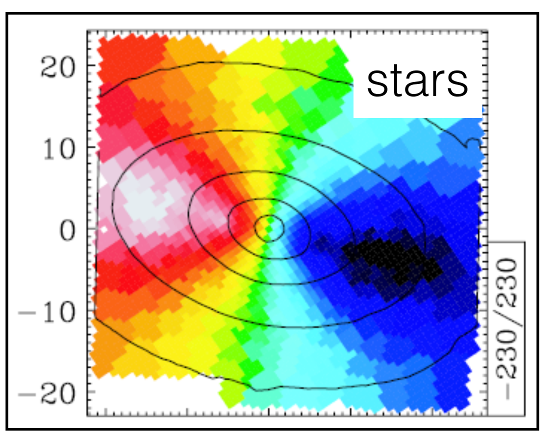


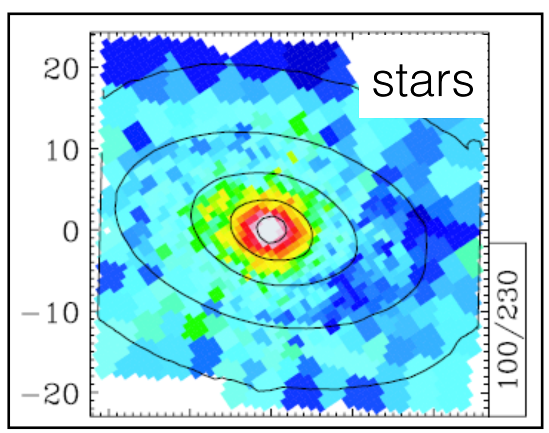
$$v_c^2(R) = \overline{v_\phi}^2 + \sigma_R^2 \left[\frac{\partial \ln (\nu \sigma_R^2)^{-1}}{\partial \ln R} + \dots \right]$$

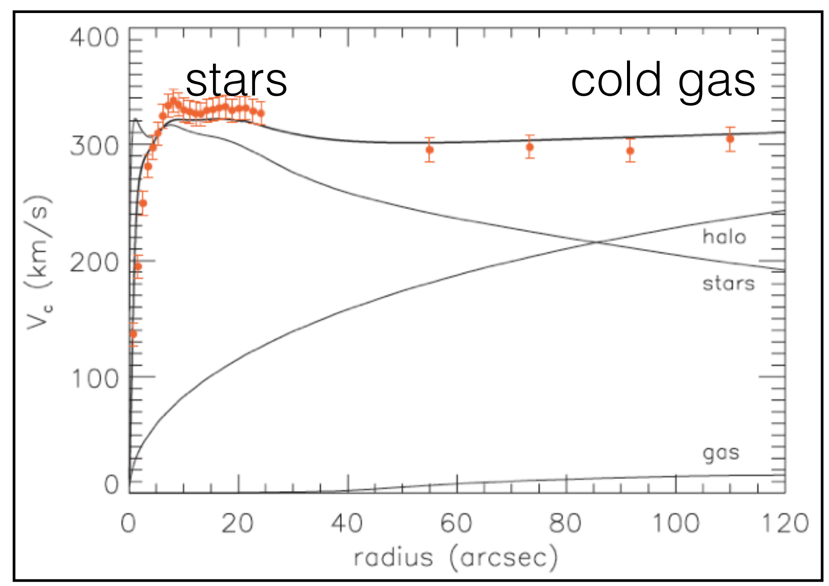
mean velocity

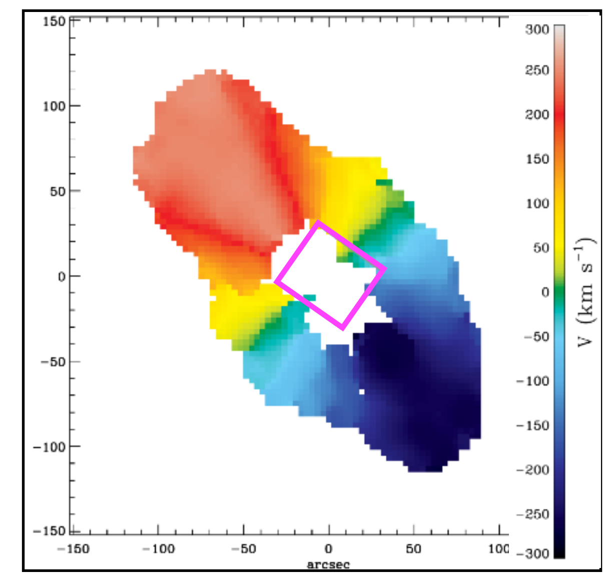
velocity dispersion

Weijmans et al. (2008)





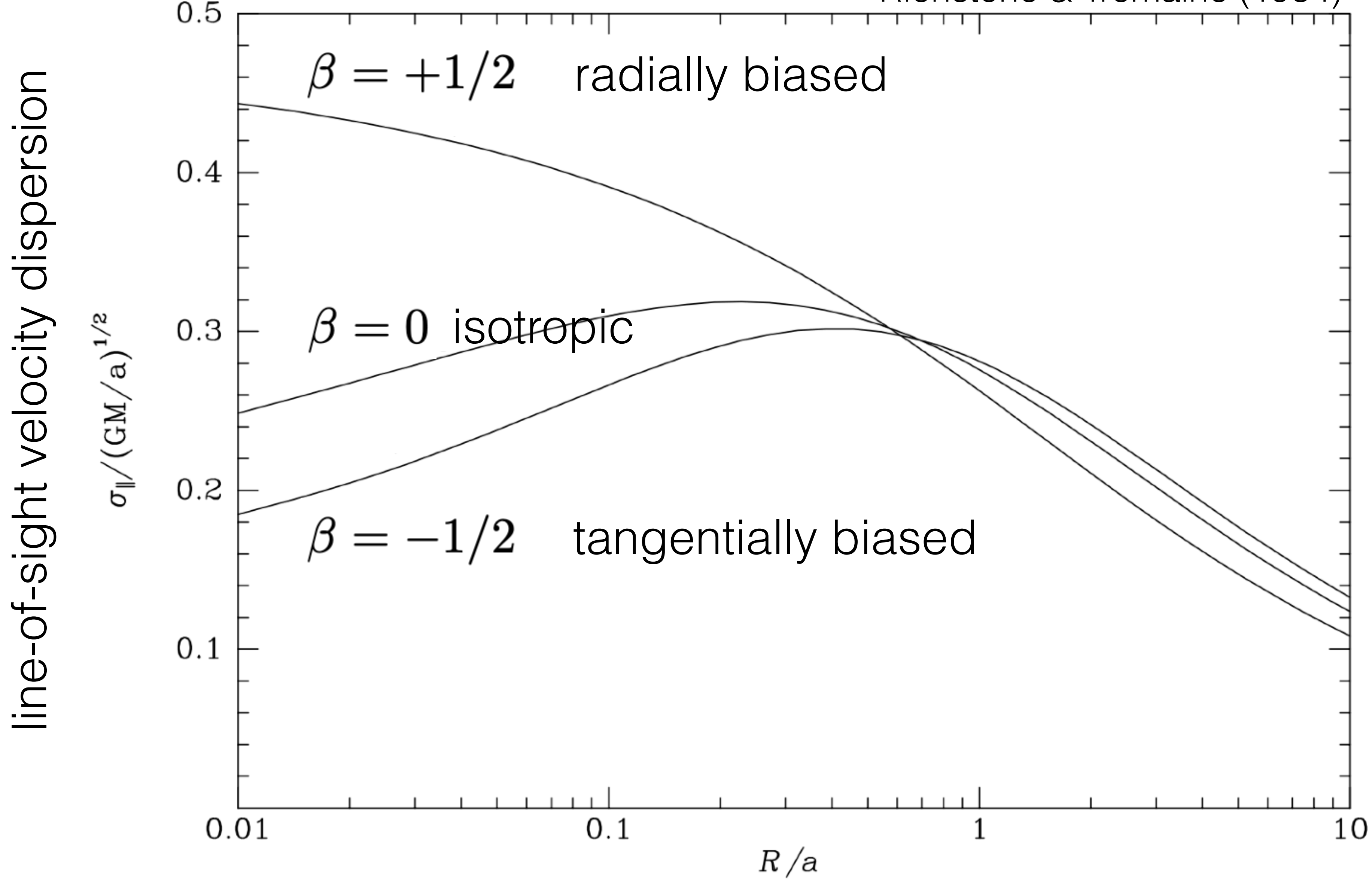


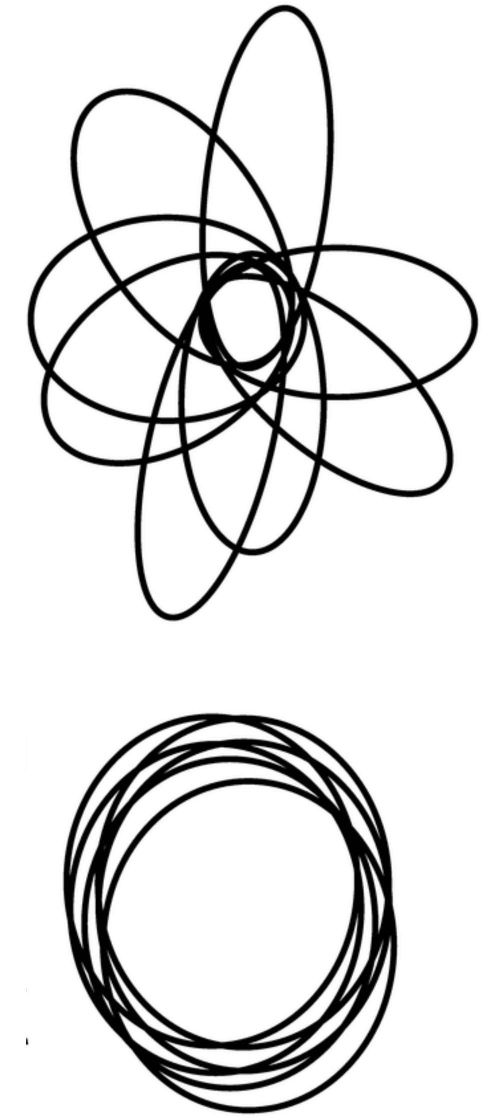


- All galaxies per definition contain stars, but for robust DM inference need more advanced data and models

Mass-anisotropy degeneracy

Richstone & Tremaine (1984)



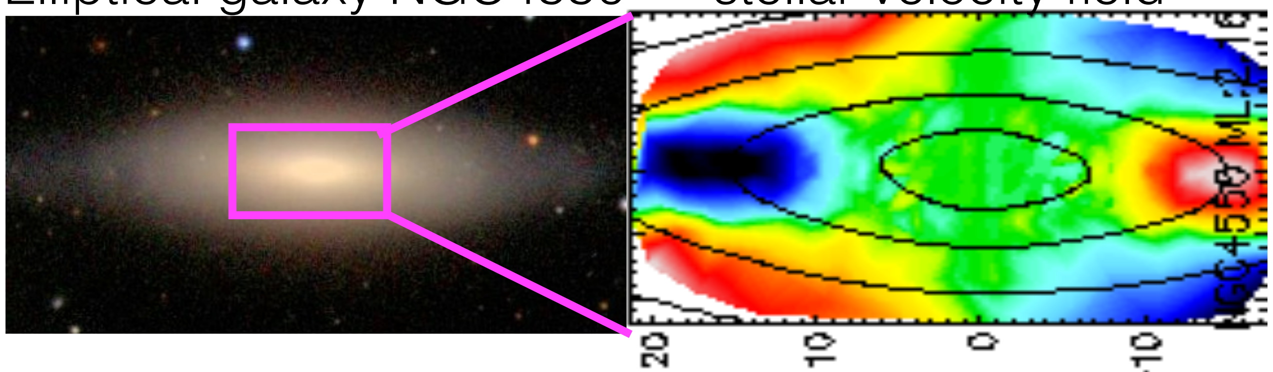


- radial variation in observed line-of-sight velocity dispersion due to change in mass *or* in velocity anisotropy
- to break this mass-anisotropy degeneracy need **advanced dynamical models** with higher-order velocity moments

Schwarzschild orbit-based model

vdBosch, vdVen et al. (2008), vdVen, vdBosch et al. (2008)

Elliptical galaxy NGC4550 stellar velocity field



Emsellem et al. (2004)

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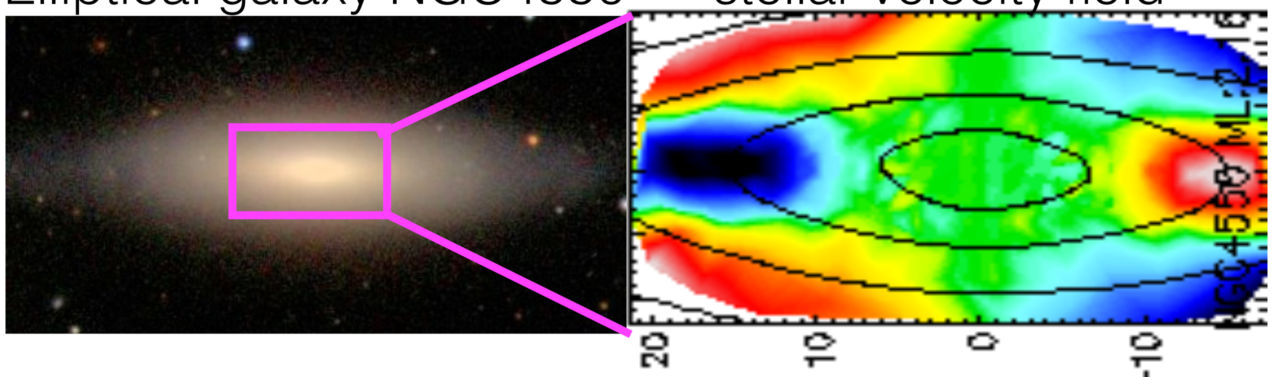

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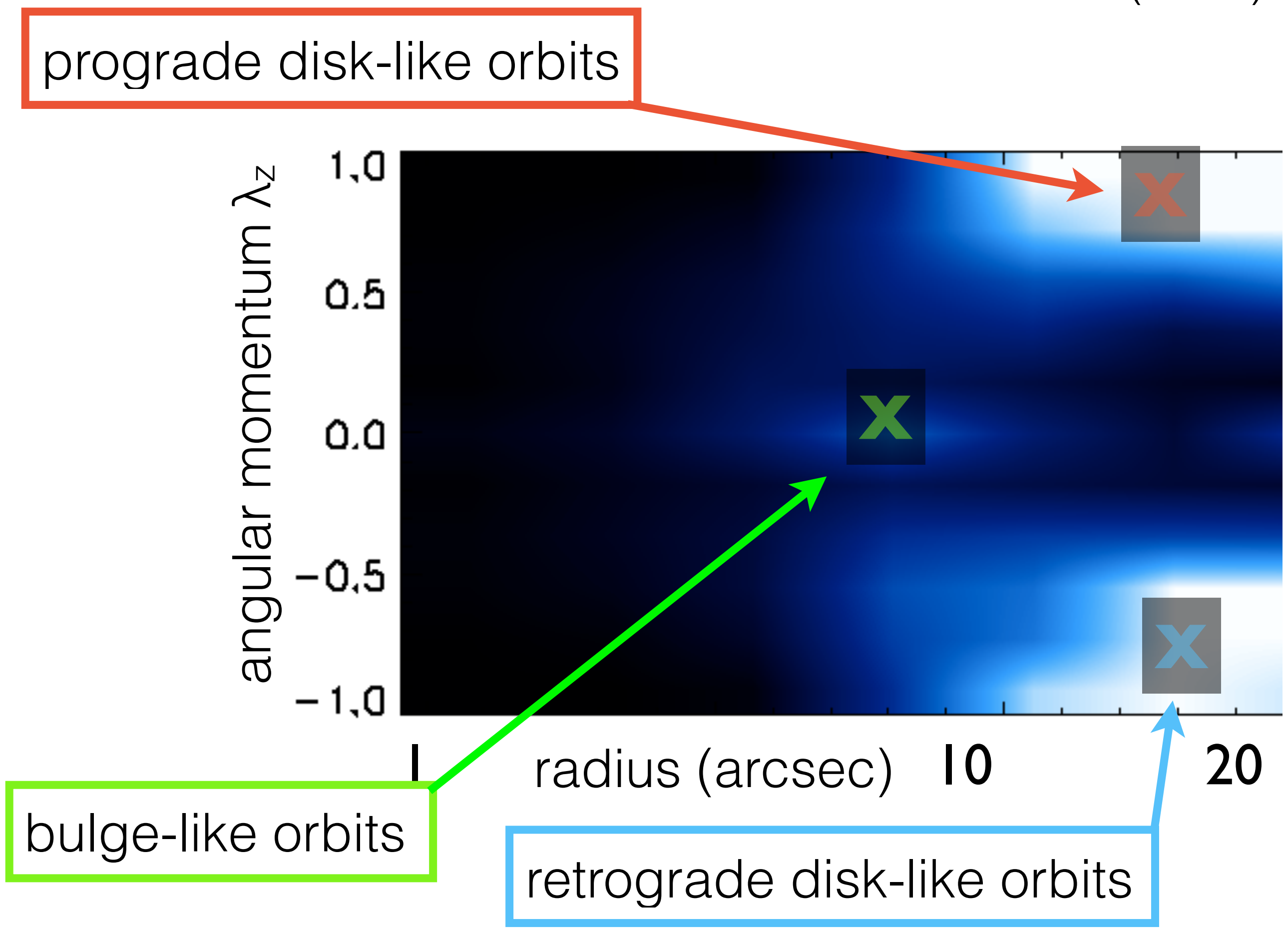

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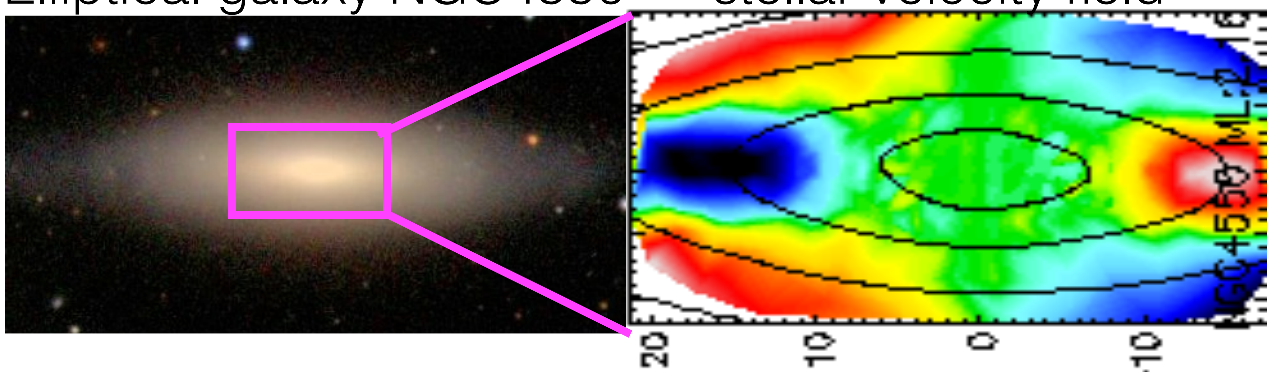
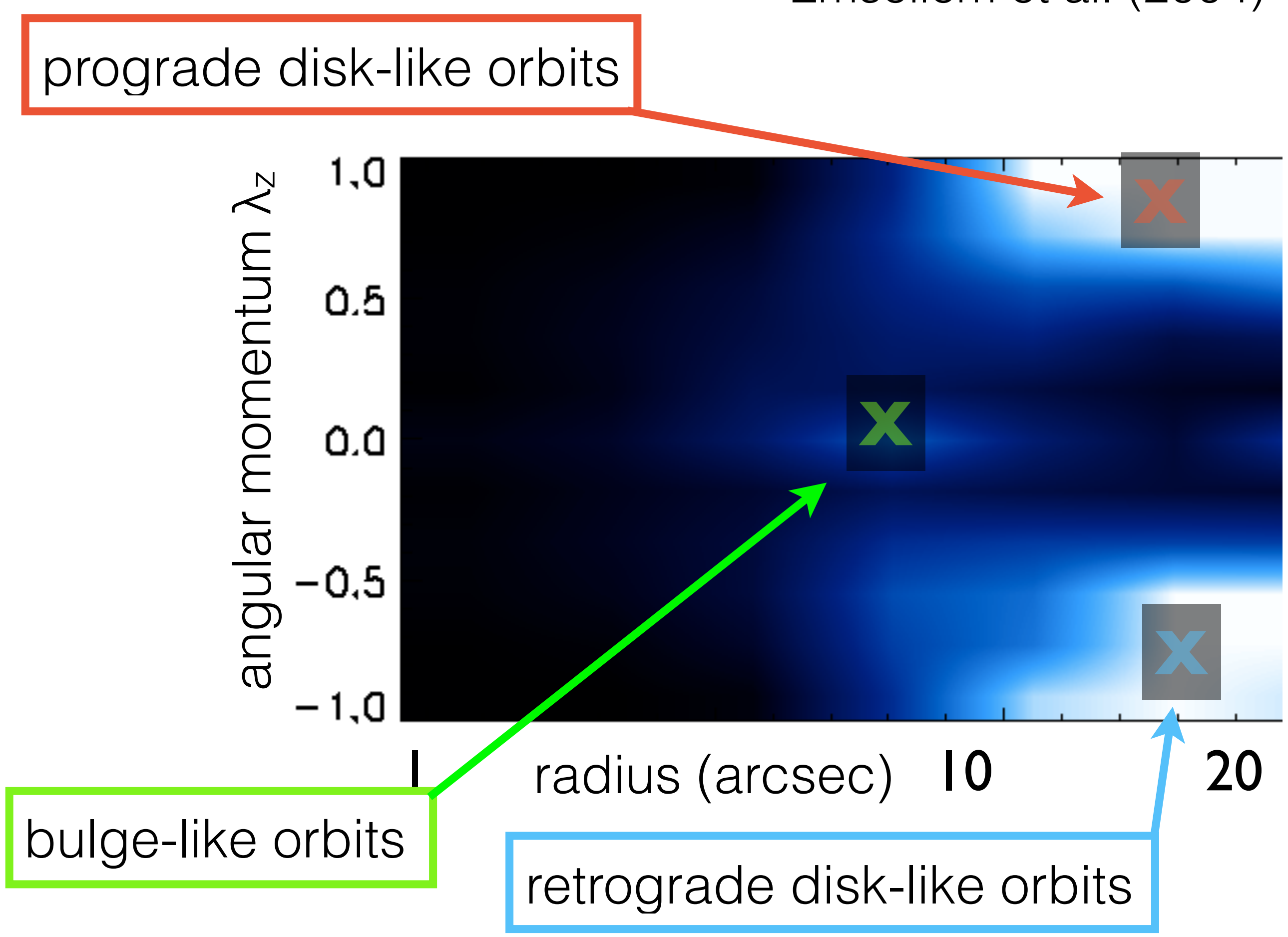
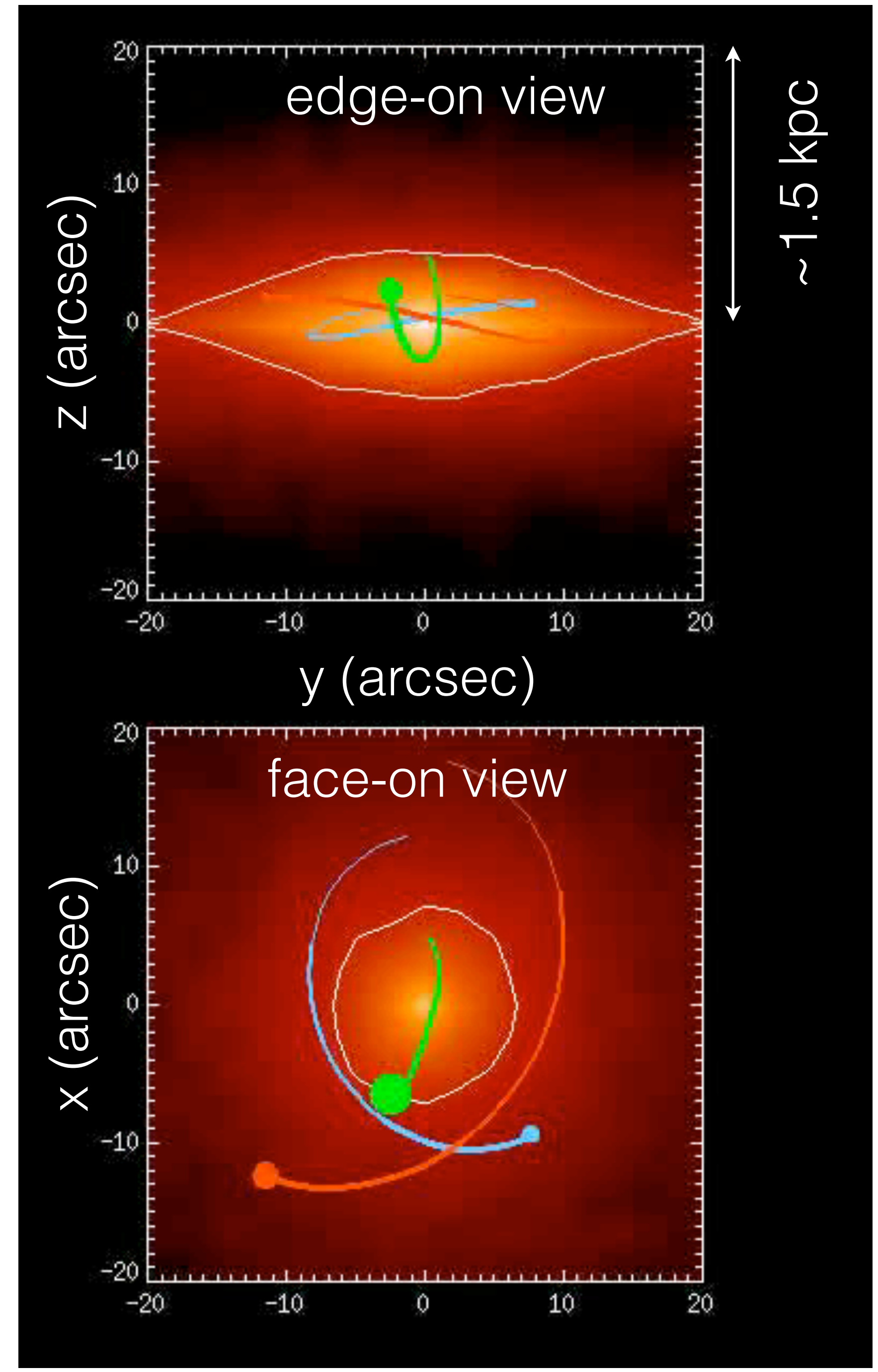
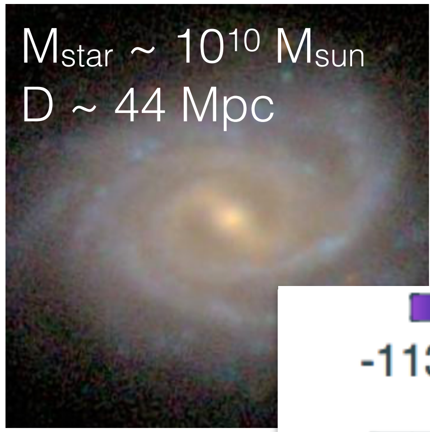


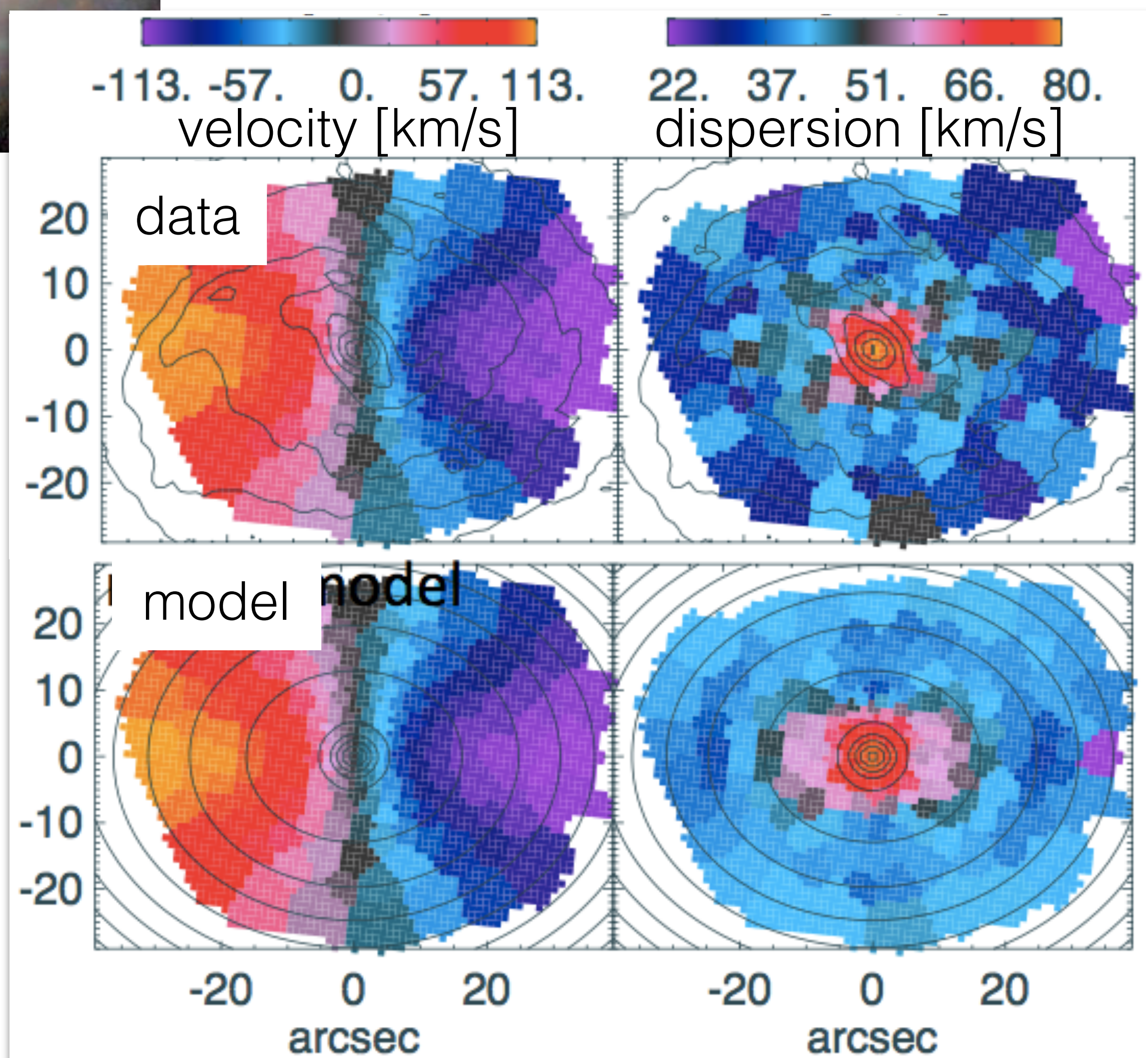


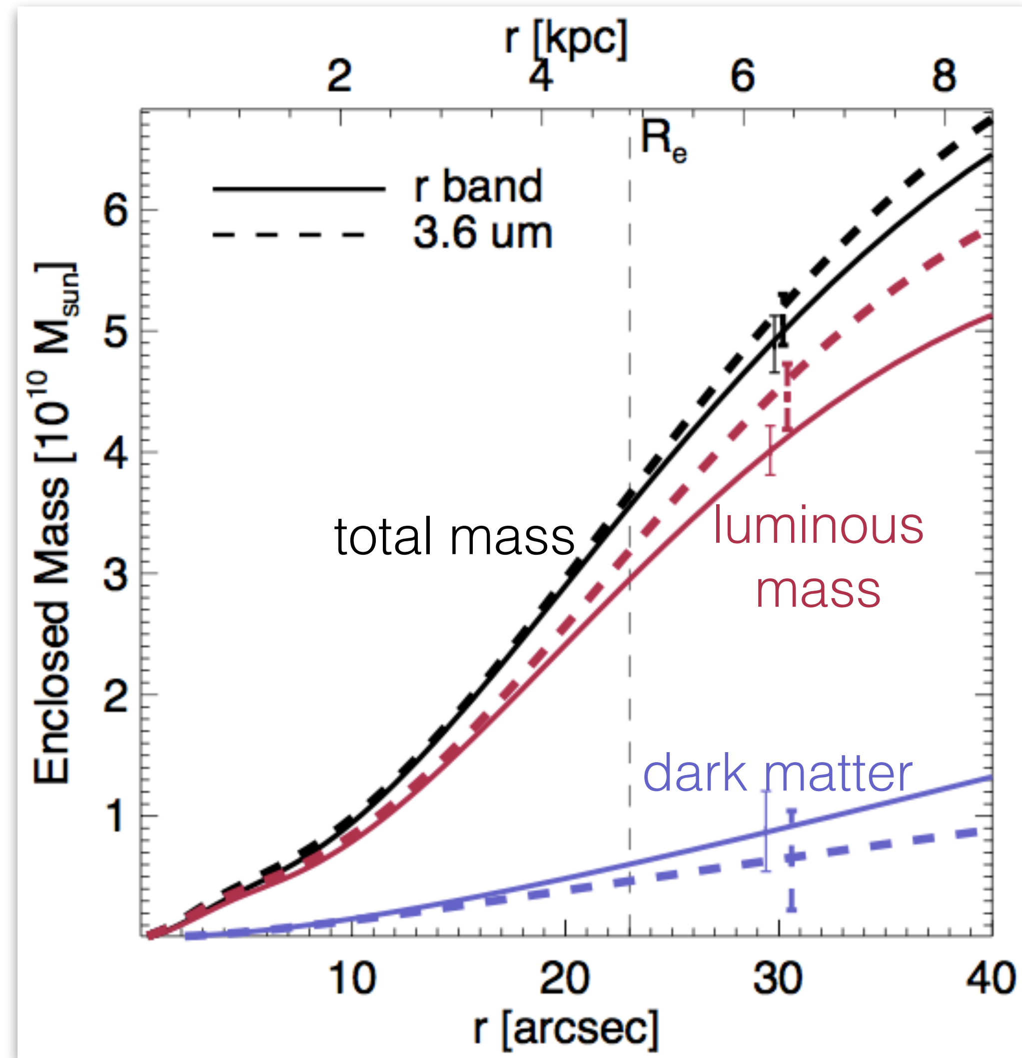


Assembly and mass recovery



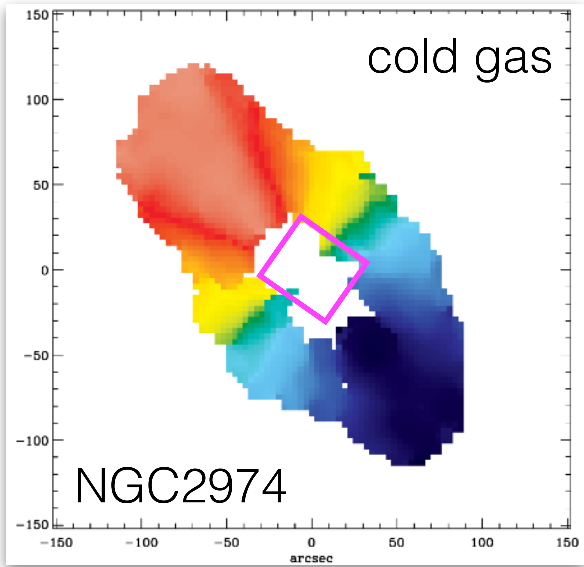
Zhu, vdBosch, vdVen, et al. (2017); Zhu, vdVen, et al. (2018);
Zhu, vdVen, Leaman et al. (2020); Zhu, vdVen, Leaman et al. (2021)



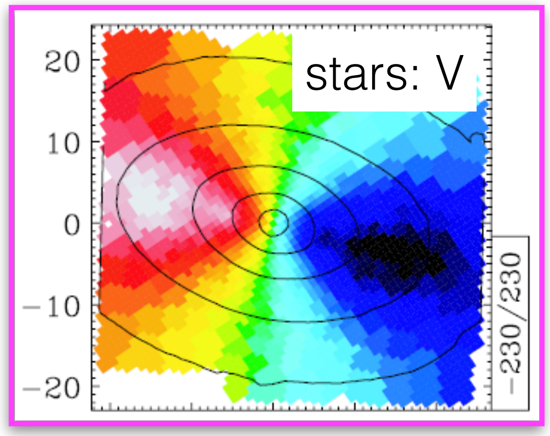


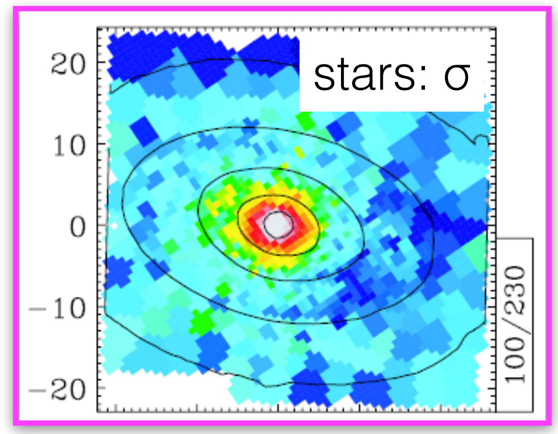
- Advanced (population-)orbit models of hundreds nearby galaxies
- Recovery assembly history *and* accurate (<10% uncertainty) inference of luminous and **dark matter distribution**

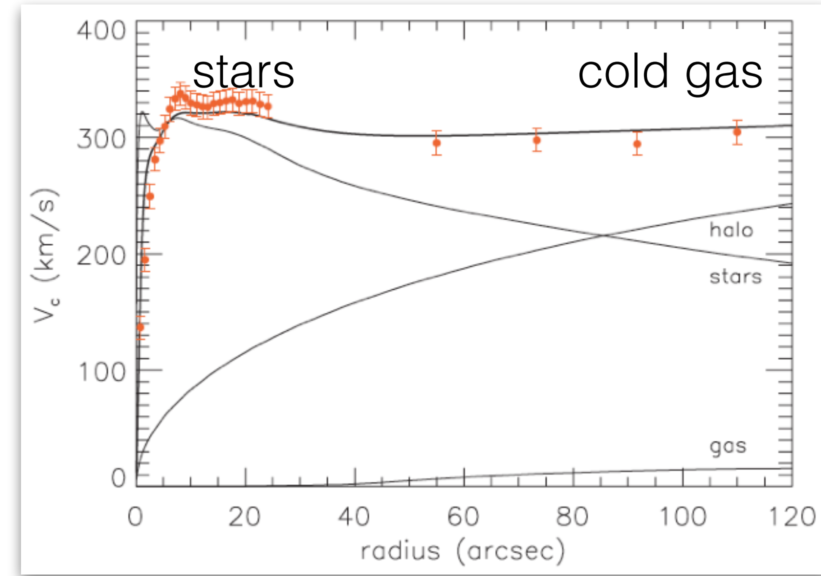
Luminous tracers of dark matter



Weijmans et al. (2008)







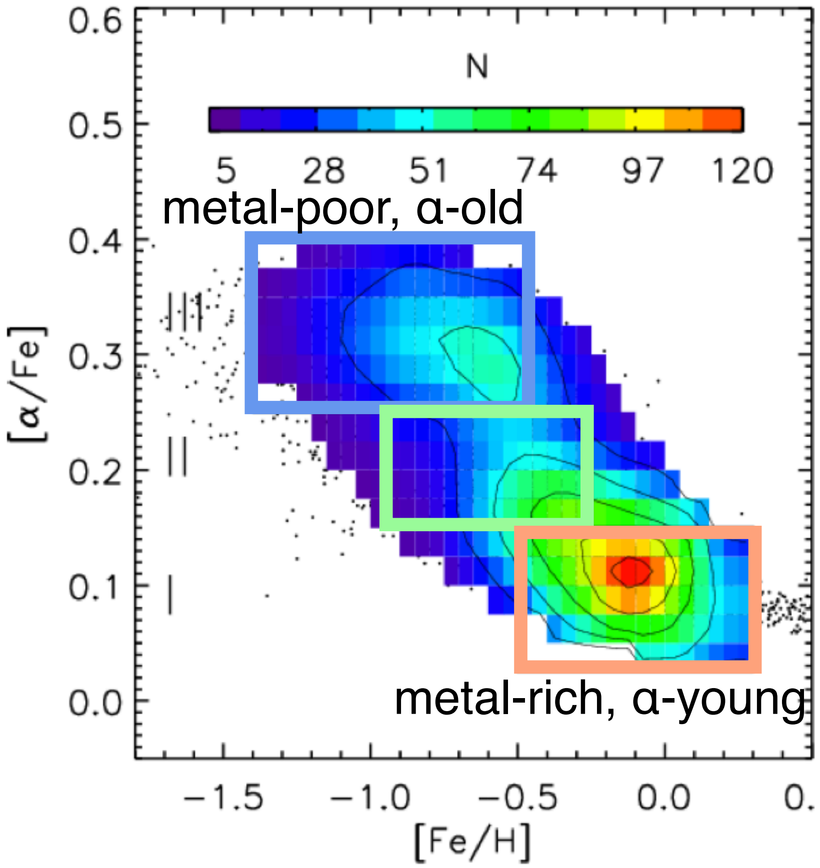
- **Cold gas**: directly circular velocity, but restricted to disk plane, sensitive to perturbations, and needs mass-to-light ratio to break disk-halo degeneracy
- **Hot stars**: everywhere, but needs advanced data and models to break mass-shape-anisotropy degeneracy
- **Local Group**: stars are resolved, positions and distances, line-of-sight velocities and proper motions, chemical properties and even (proxies for) ages ...

Dark Matter in the Solar Neighborhood

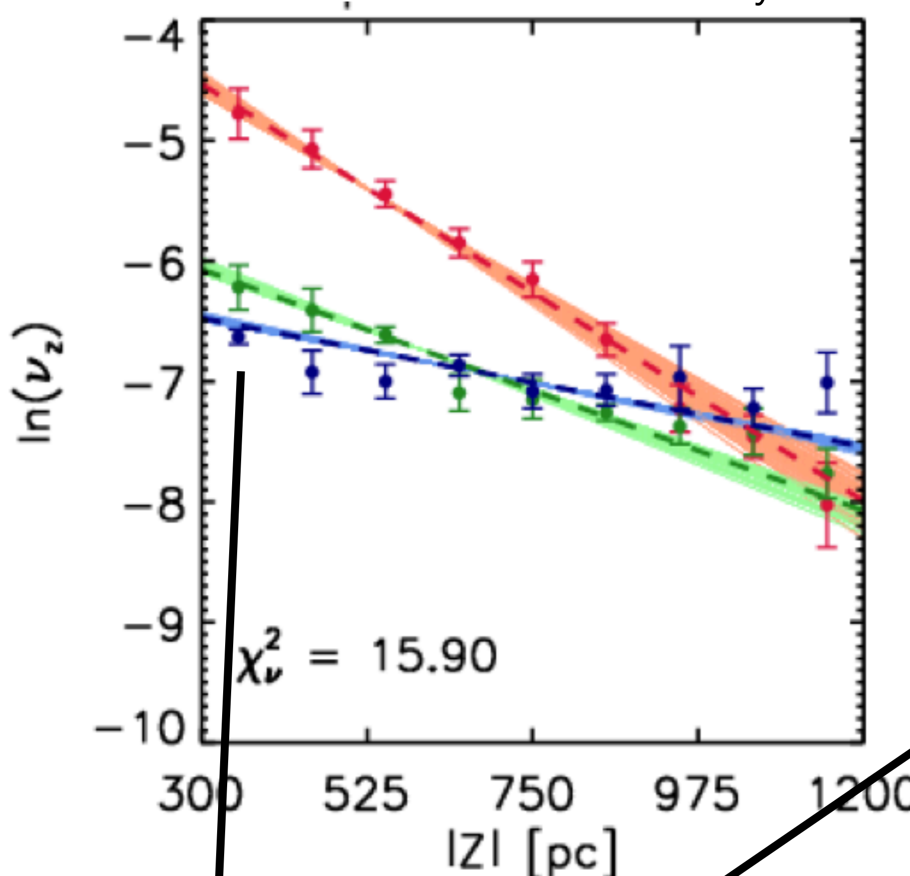
Vertical Jeans equation

Zhang, Rix, vdVen, et al. (2013)

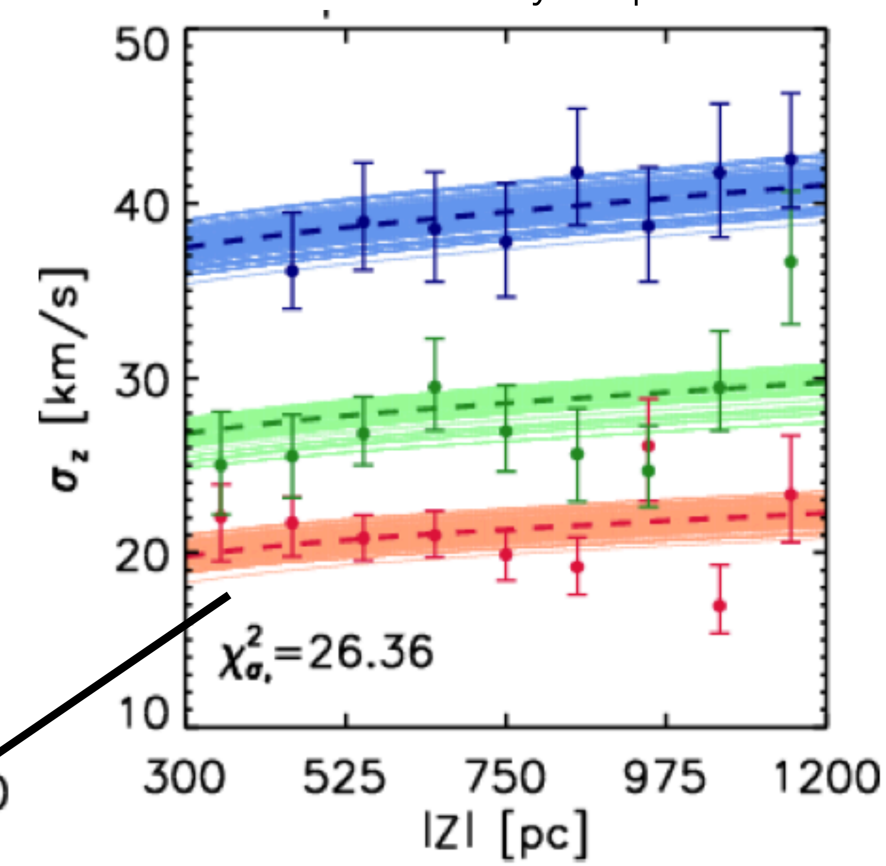
9,000 SDSS/SEGUE K-dwarf stars



vertical number density



vertical velocity dispersion



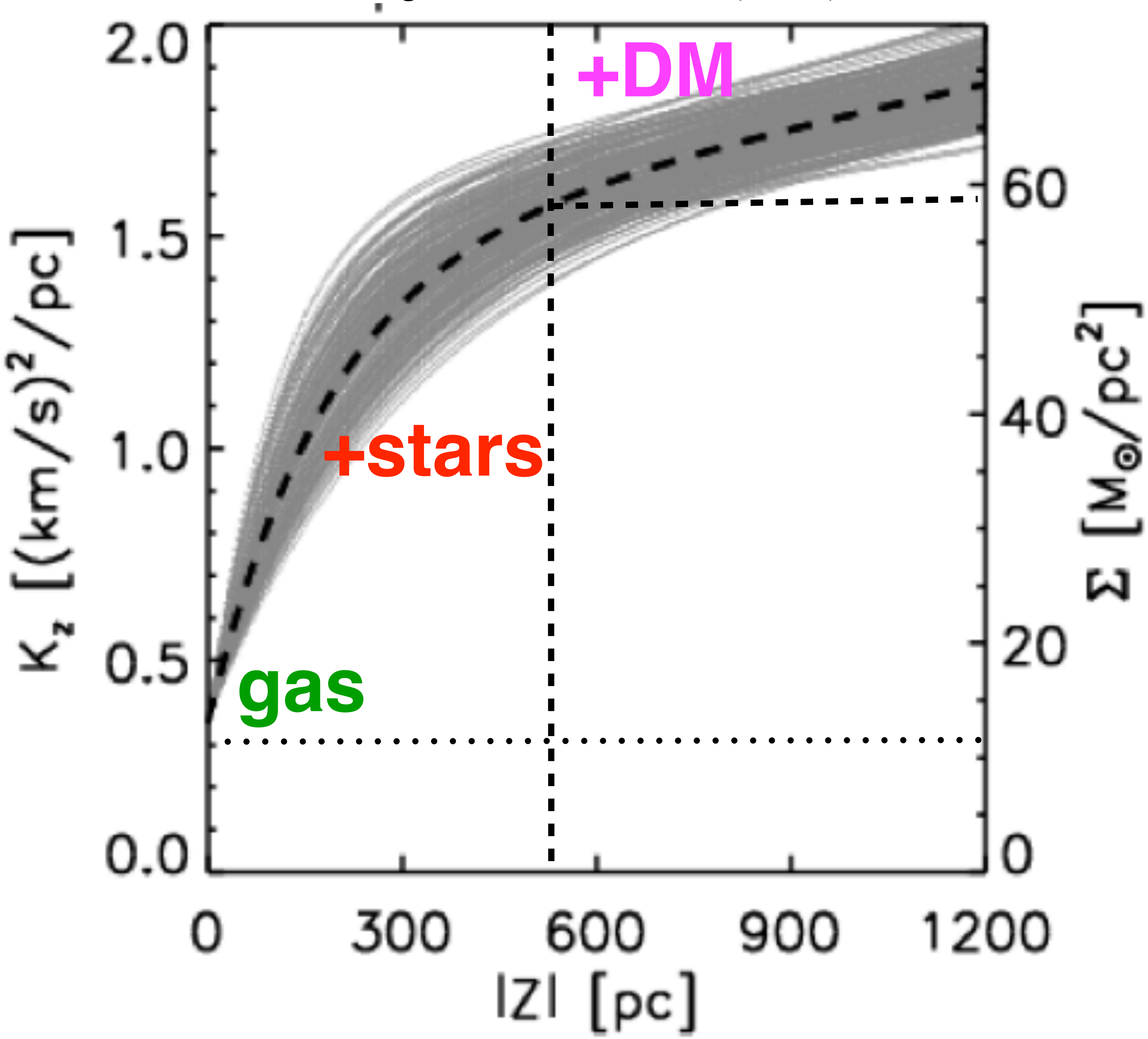
$$-\left.\frac{\partial\Phi(R,z)_\odot}{\partial z}\right|_{R=R_0} = K_z(z) = \frac{1}{\nu}\frac{\mathrm{d}}{\mathrm{d}z}\left(\nu\sigma_z^2\right)$$

Poisson's equation

$\rho_{tot} = \rho_{gas} + \rho_{stars} + \rho_{DM}$

Gas, stars and dark matter

Zhang, Rix, vdVen, et al. (2013)

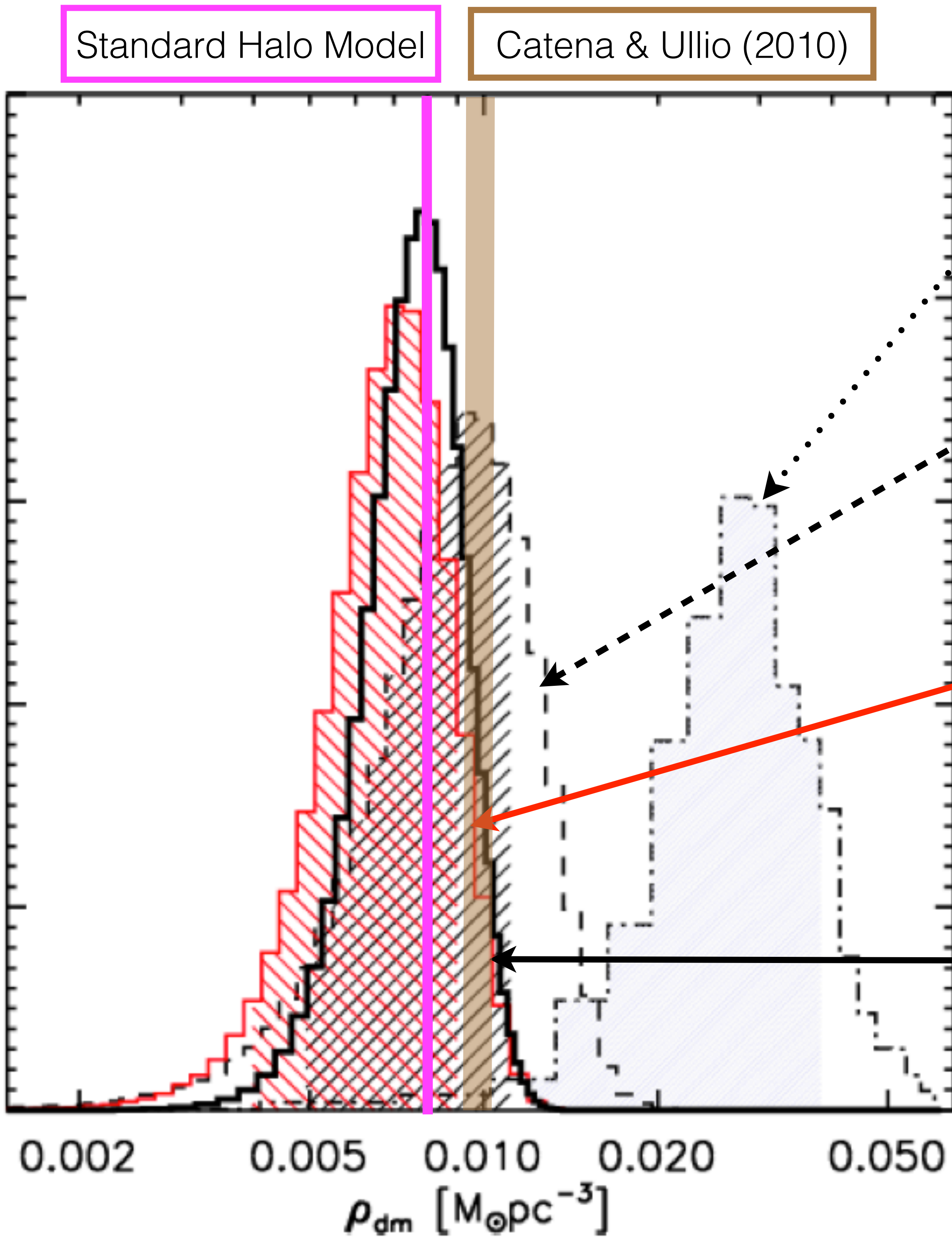


$\rho_{gas}+\rho_{stars}+\rho_{DM}$

$\sim\rho_{gas}+\rho_{stars}$

$\sim\rho_{gas}$

Local dark matter density



Garbari et al. (2012)
~2,000 K-type dwarf stars

Bovy & Tremaine (2012)
~400 giant stars
(from Moni Bidin et al. 2012,
but corrected for $d\langle V_\phi \rangle/dR \neq 0$)

Zhang, Rix, vdVen et al. (2013)
~9,000 K-type dwarf stars

Joint probability:

$$0.0075 \pm 0.0021 \ M_\odot \,\mathrm{pc}^{-3}$$

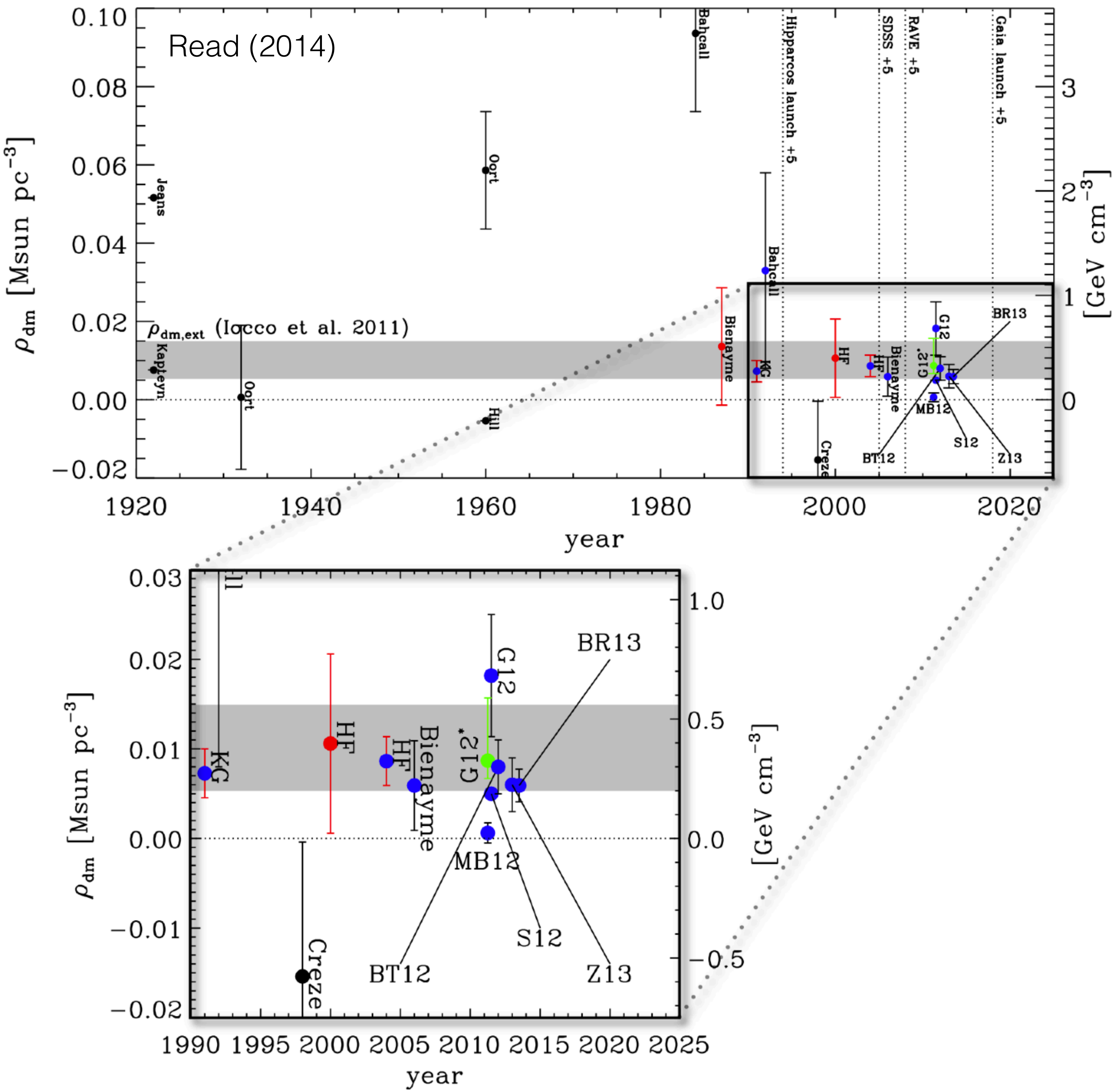
$$(0.28 \pm 0.08 \ \mathrm{GeV\,cm}^{-3})$$

Zhang, Rix, vdVen, et al. (2013)

Local dark matter density

Still **significant uncertainty** due to assumptions on

- intrinsic density of tracers
- velocity anisotropy
- baryonic contributions
- possible dark disks



Local dark matter next steps

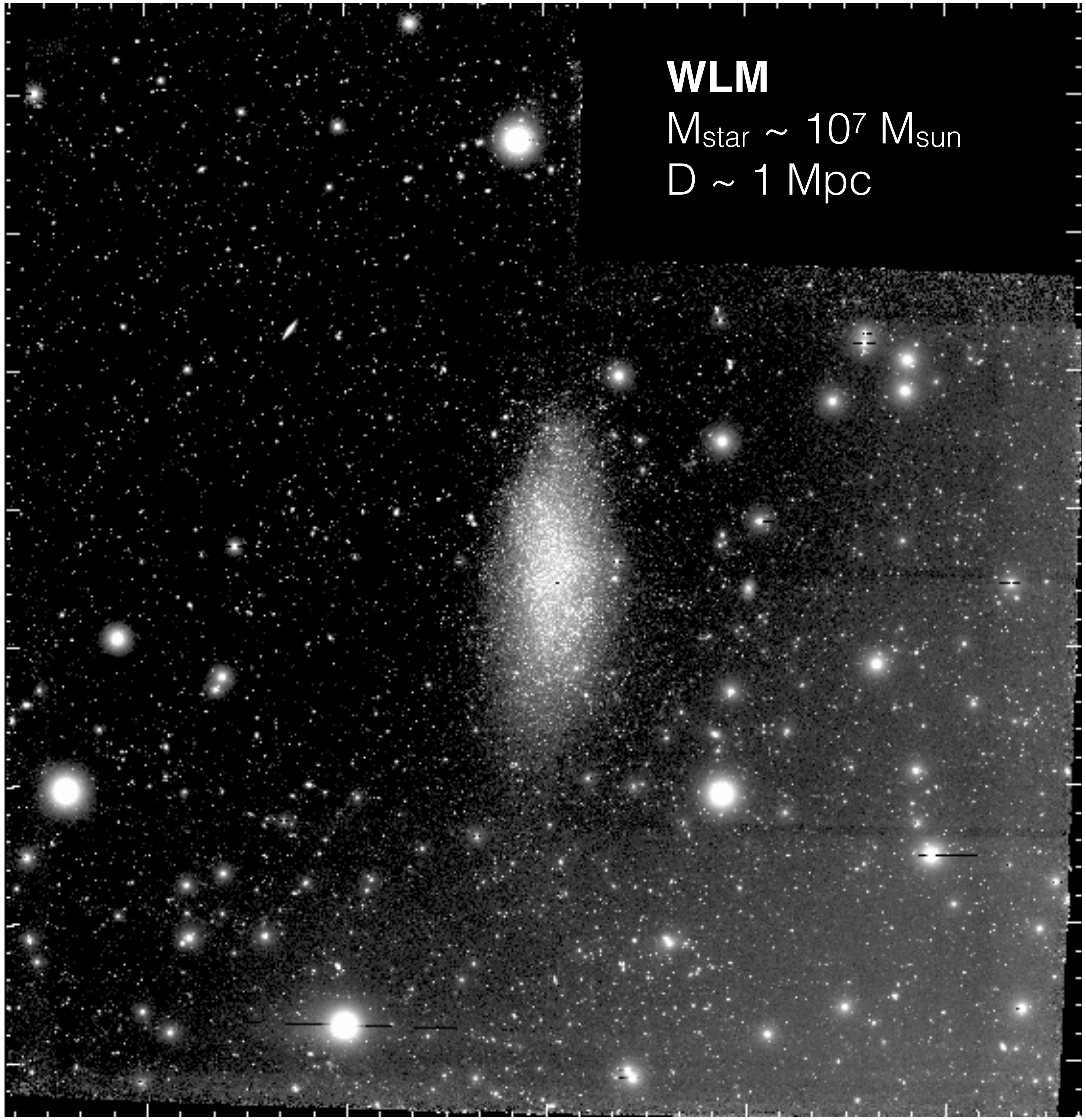
- High quantity and quality discrete (population-)kinematic data from SDSS/APOGEE, Gaia/ESO, …
- Avoid binning and hard cuts via **discrete fitting** including contaminants in Bayesian framework
(e.g., Watkins, vdVen, et al. 2013; Zhu, vdVen, et al. 2016)
- **Beyond Jeans equations** through orbit- and/or distribution-function based (population-)dynamical models
(e.g., Ting, Rix, Bovy & vdVen 2013; Zhu, vdVen, Leaman, et al. 2020)
- … improved robust constraints on **dark matter amount and distribution** in the Local Group

Dark matter in local dwarf galaxy WLM

Isolated Local Dwarf Galaxy WLM

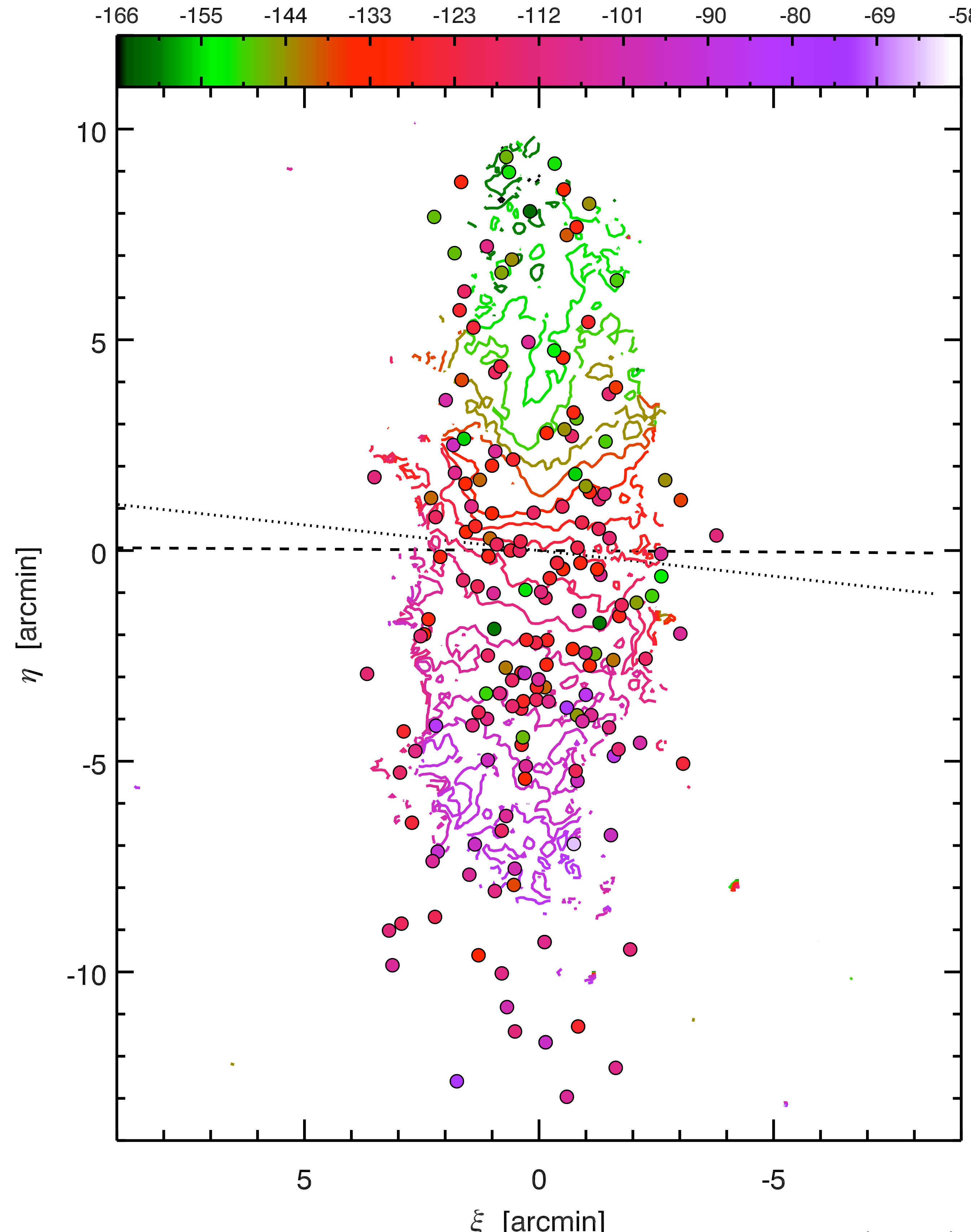
- Isolated dwarf galaxies may have **stellar and gas** kinematics available

- Wish to combine them in a joint dynamical model to break mass-anisotropy-geometry degeneracies



Multi-tracer dynamical models

- VLT+Keck spectroscopy of RGB stars discrete velocities
- For a choice of **orbit structure** and **gravitational potential**, we compute likelihood for each dynamical model to reproduce discrete, on-sky line of sight velocities

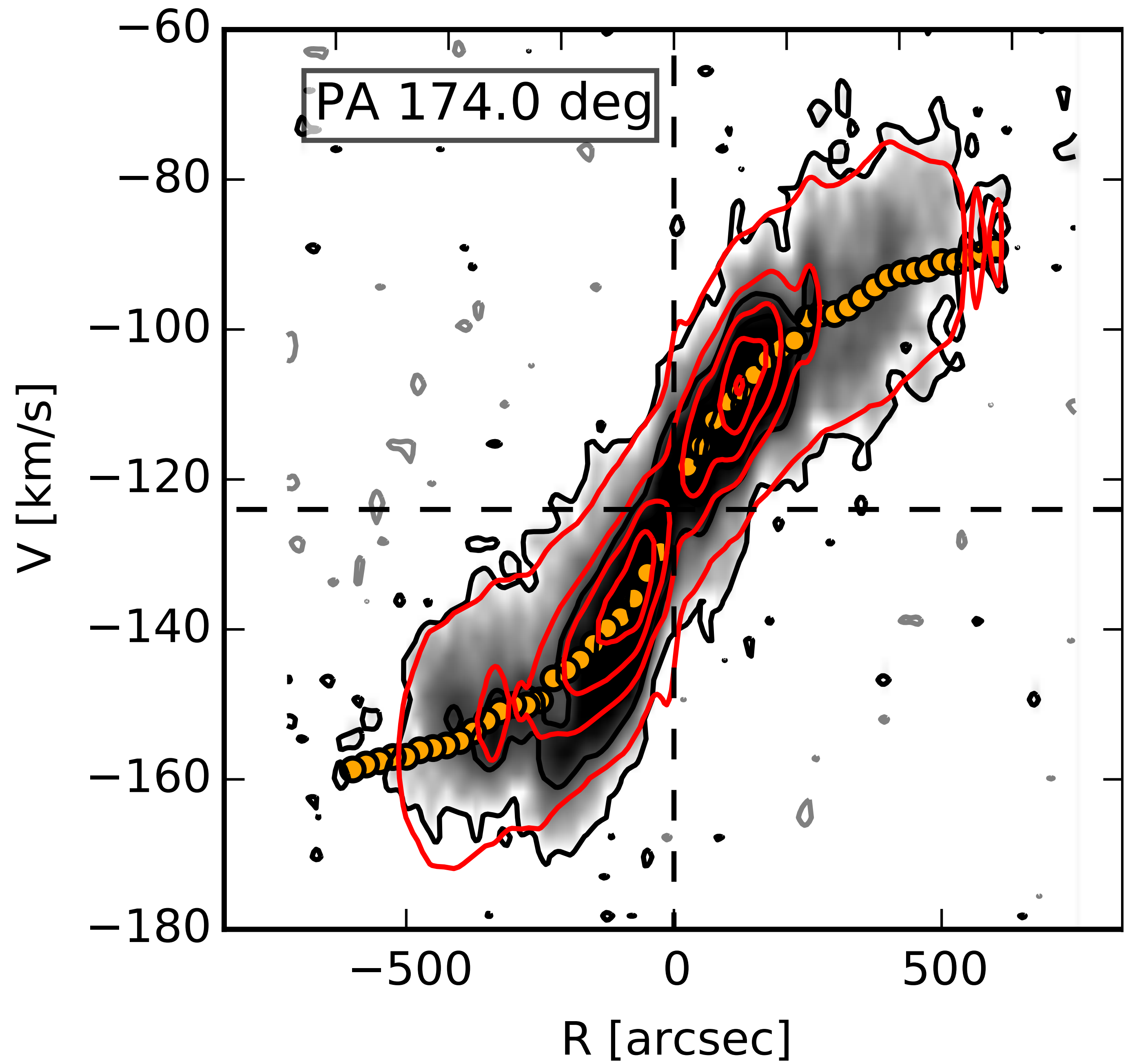


Leaman et al. (2013)

Multi-tracer dynamical models

- For the first time want to combine this model with **gas kinematics**
- HI gas rotation curve independently constrains total potential in Jeans equations.

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



Iorio et al. (2017)

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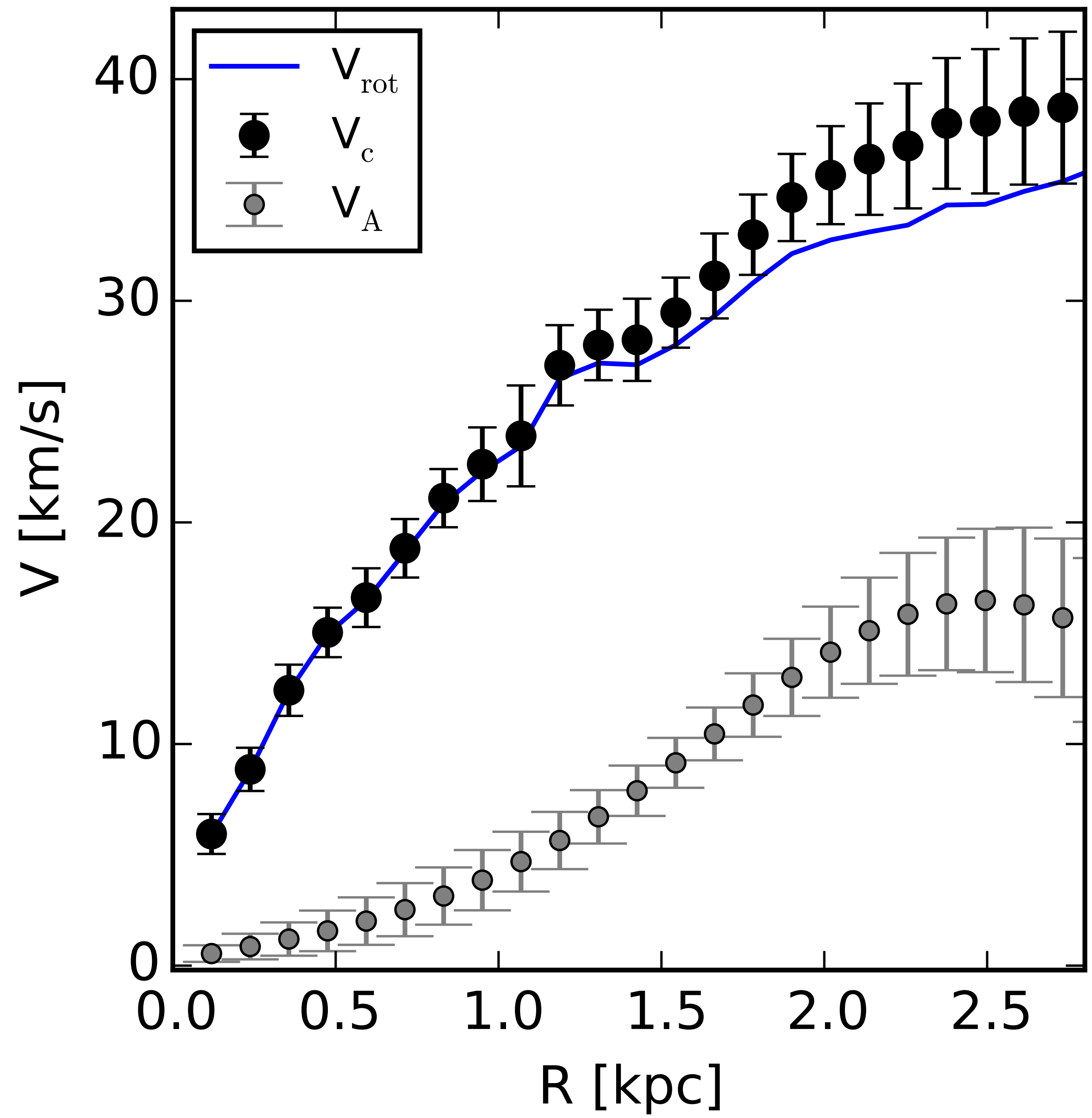


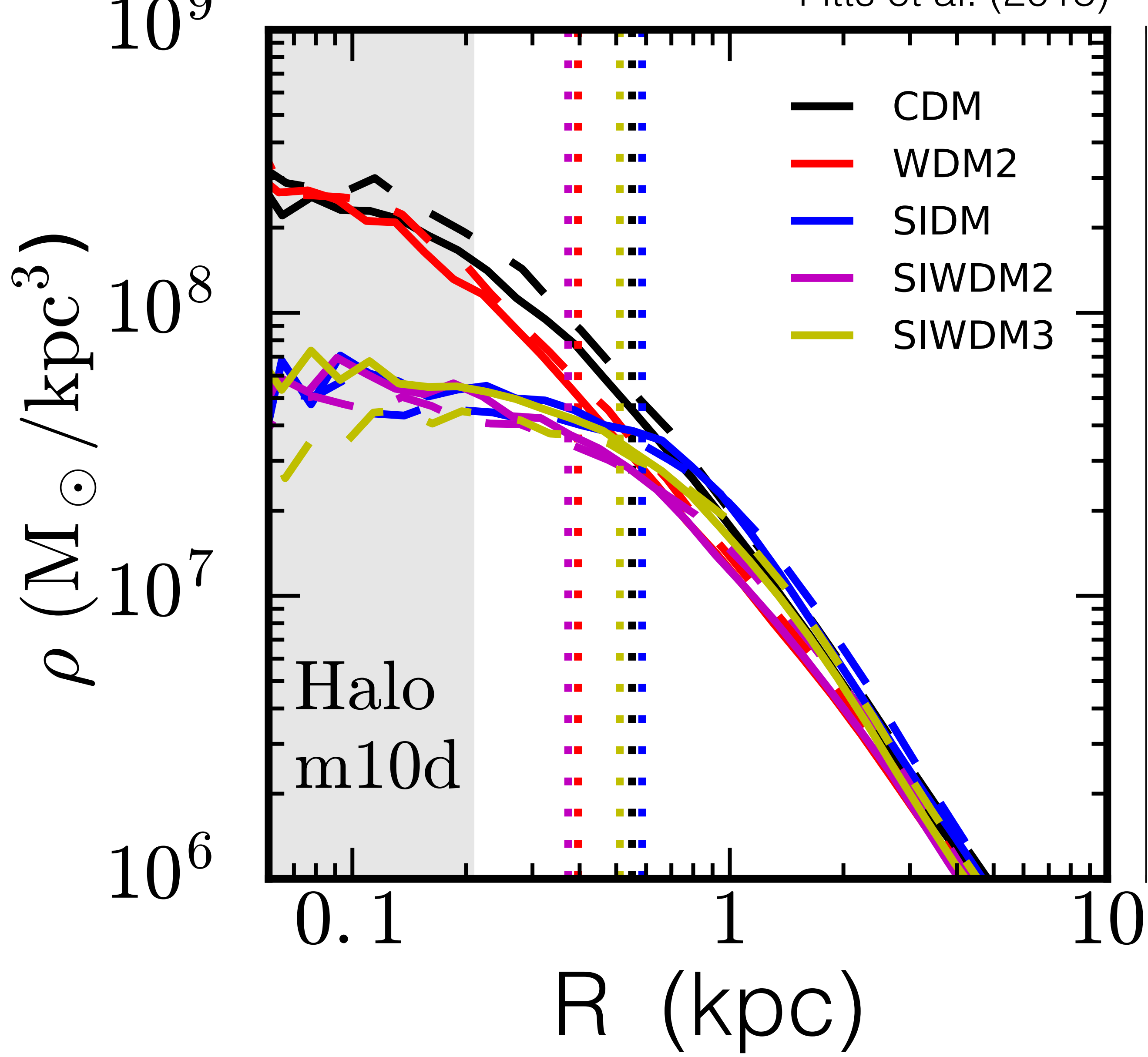
Iorio et al. (2017)

Multi-tracer dynamical models

- DM halo ***profile*** parameterised by axisymmetric generalised NFW profile
- Allows for cored profiles expected due to baryonic feedback or SIDM

$$\rho(r) = \frac{\rho_{\rm s}}{(r/r_{\rm s})^{\gamma}(1+r/r_{\rm s})^{3-\gamma}}$$

Fitts et al. (2018)



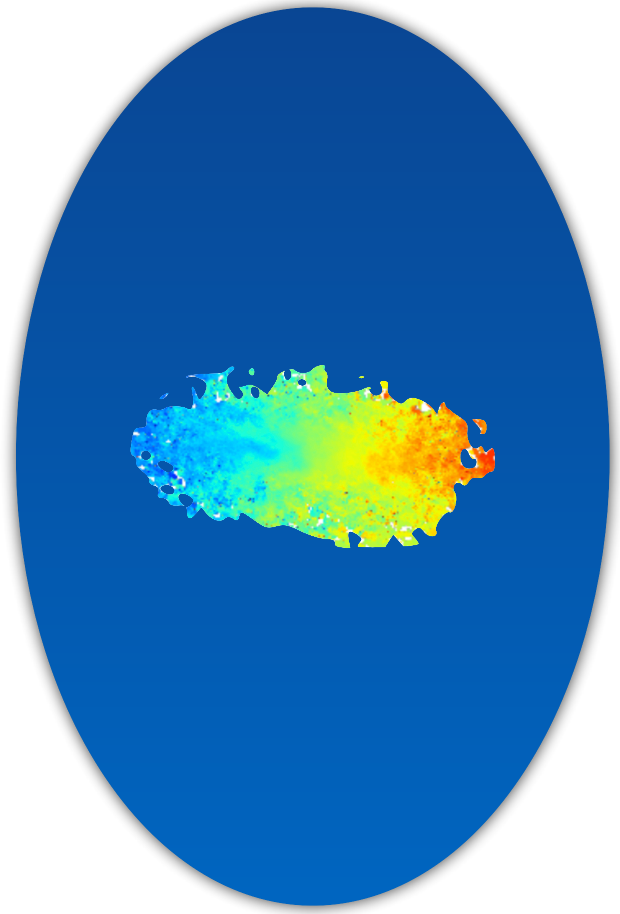
γ = 1; NFW **cusp**

γ = 0; **cored** profile

Multi-tracer dynamical models

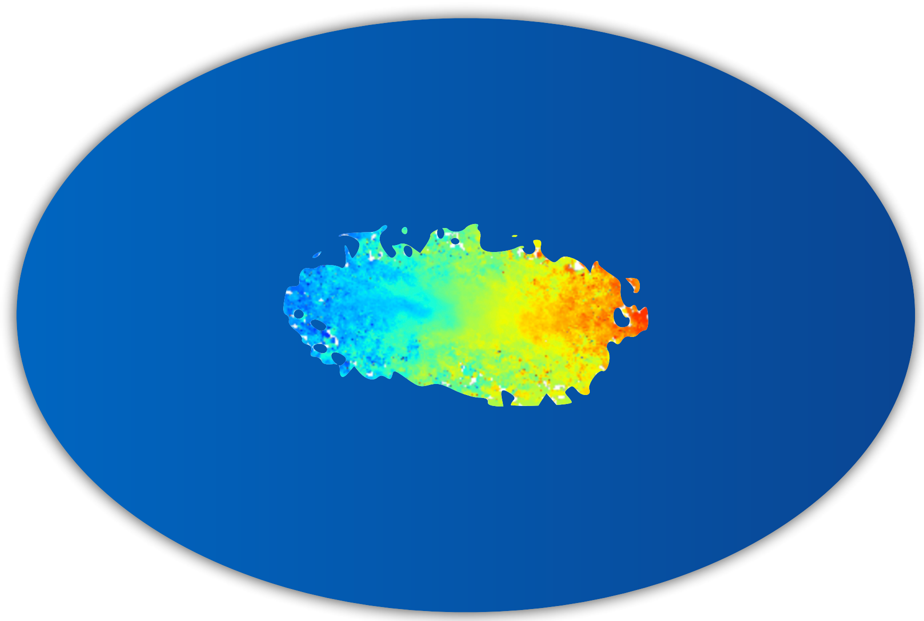
- DM Halo ***shape*** parameterised by short to long axis ratio

$$q_{DM} = c/a$$



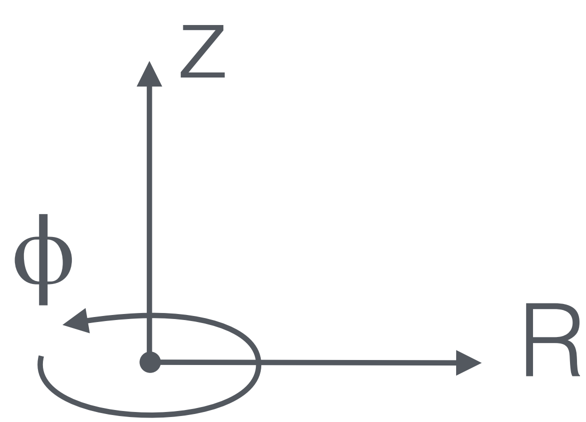
Prolate

$q_{DM} > 1$

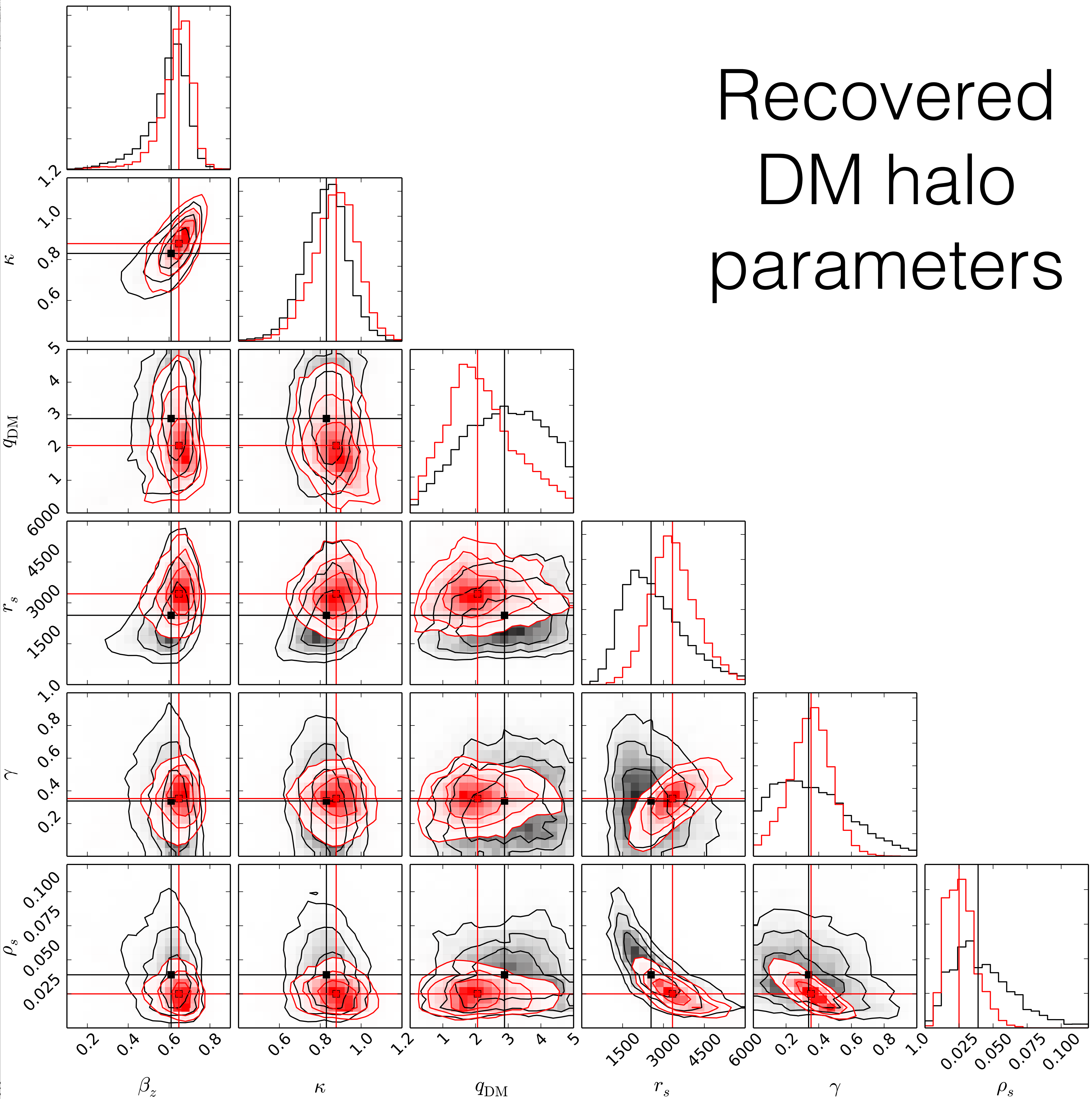


Oblate

$q_{DM} < 1$



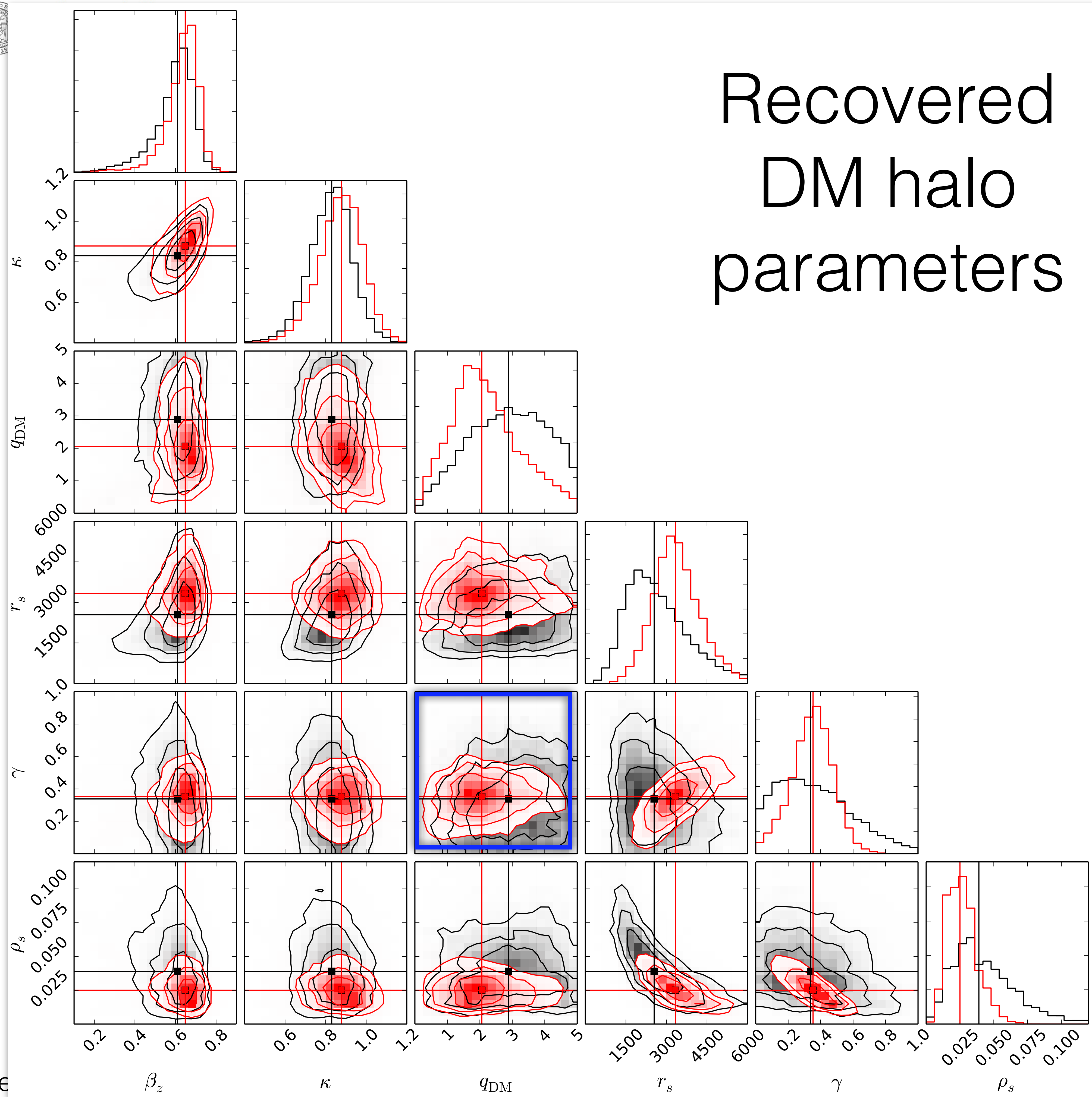
Recovered DM halo parameters



- See factor of 2-3 reduction in uncertainties when using **gas + stars** (red)

Leung, Leaman, et al. (2021)

Recovered DM halo parameters



- Lets focus on DM halo shape (q) and inner density profile slope (γ)

Leung, Leaman, et al. (2021)

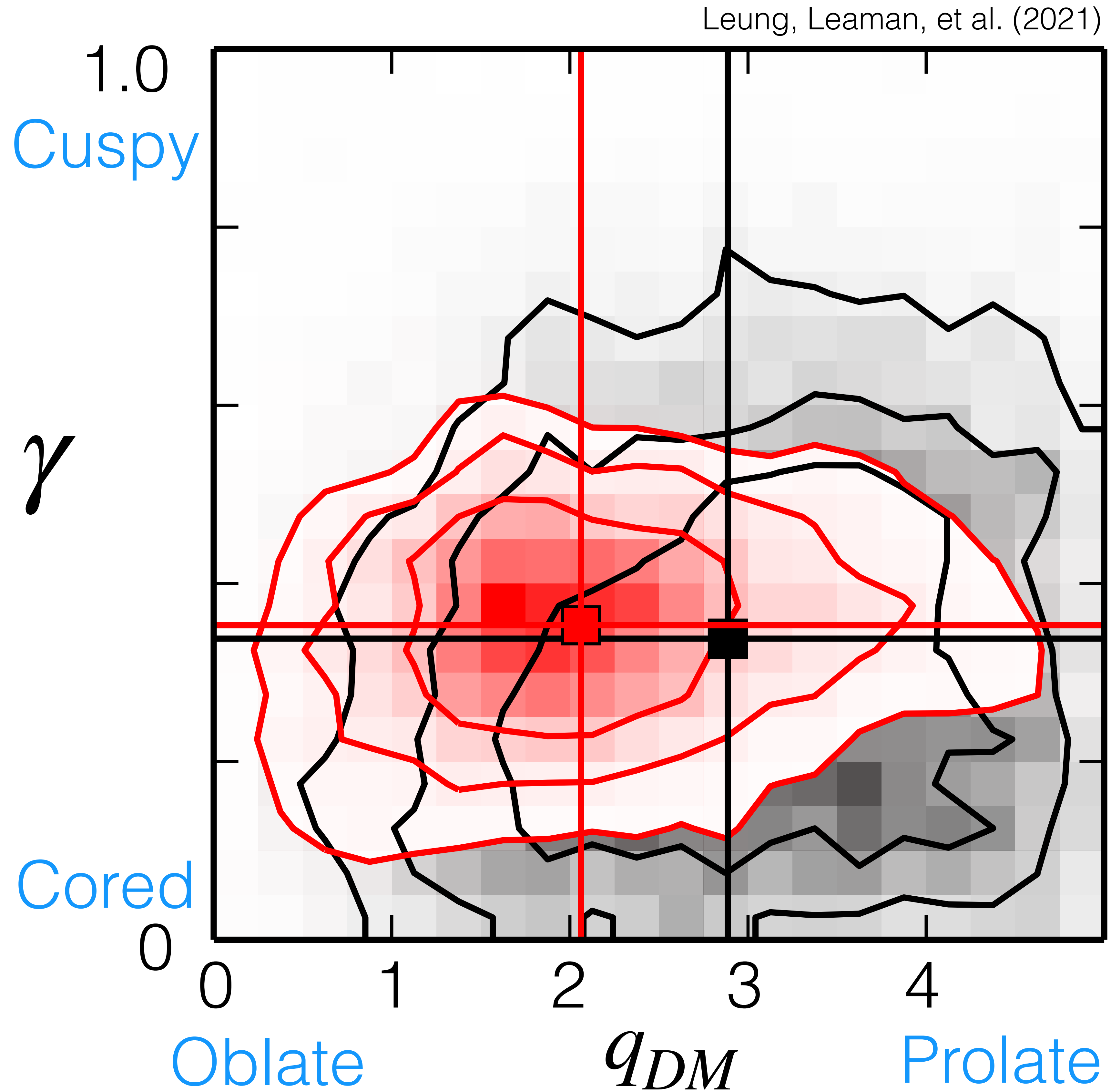
Recovered DM halo parameters

Cored DM halo

$\gamma = 0.3 \pm 0.1$

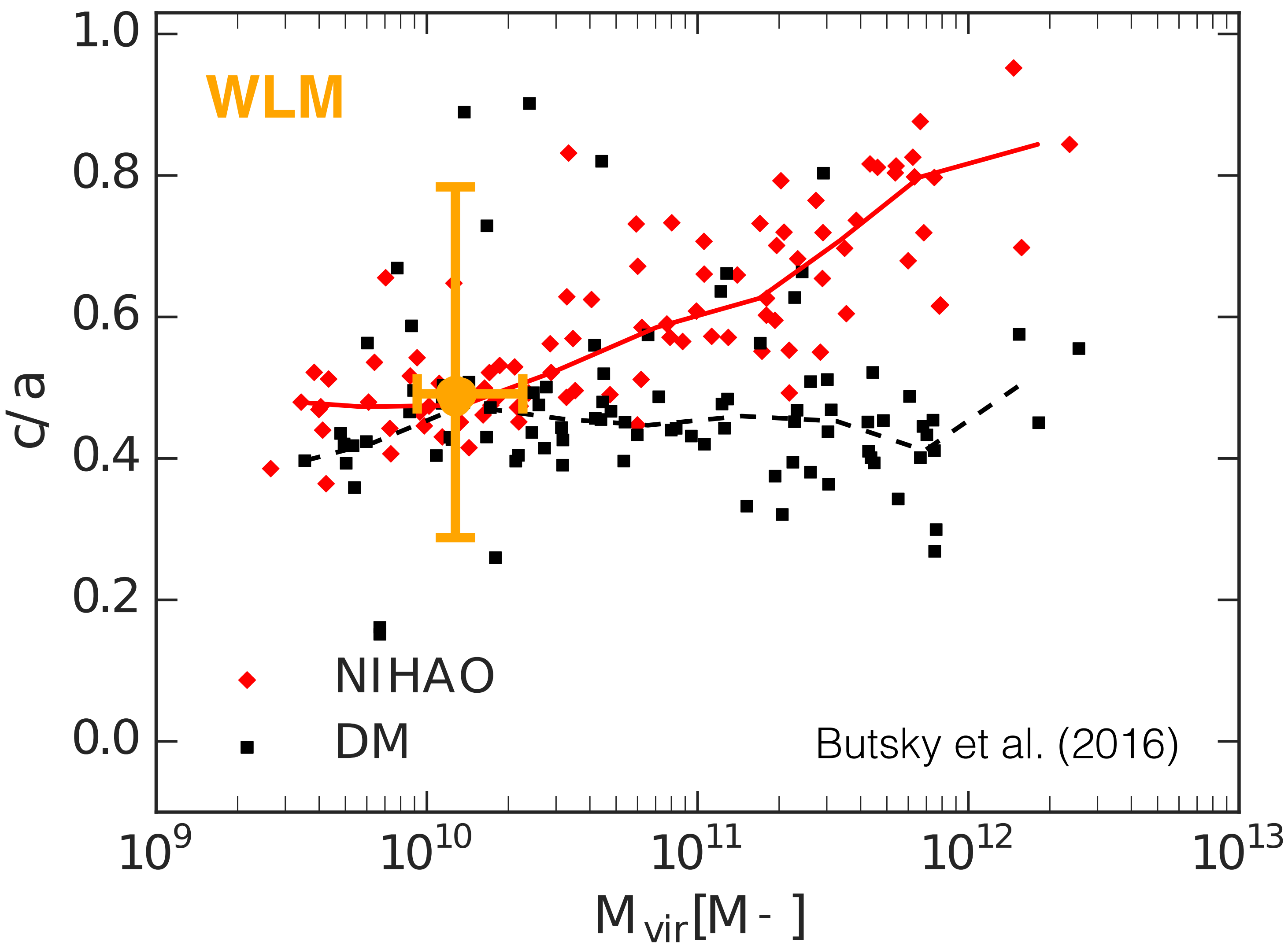
Prolate DM halo

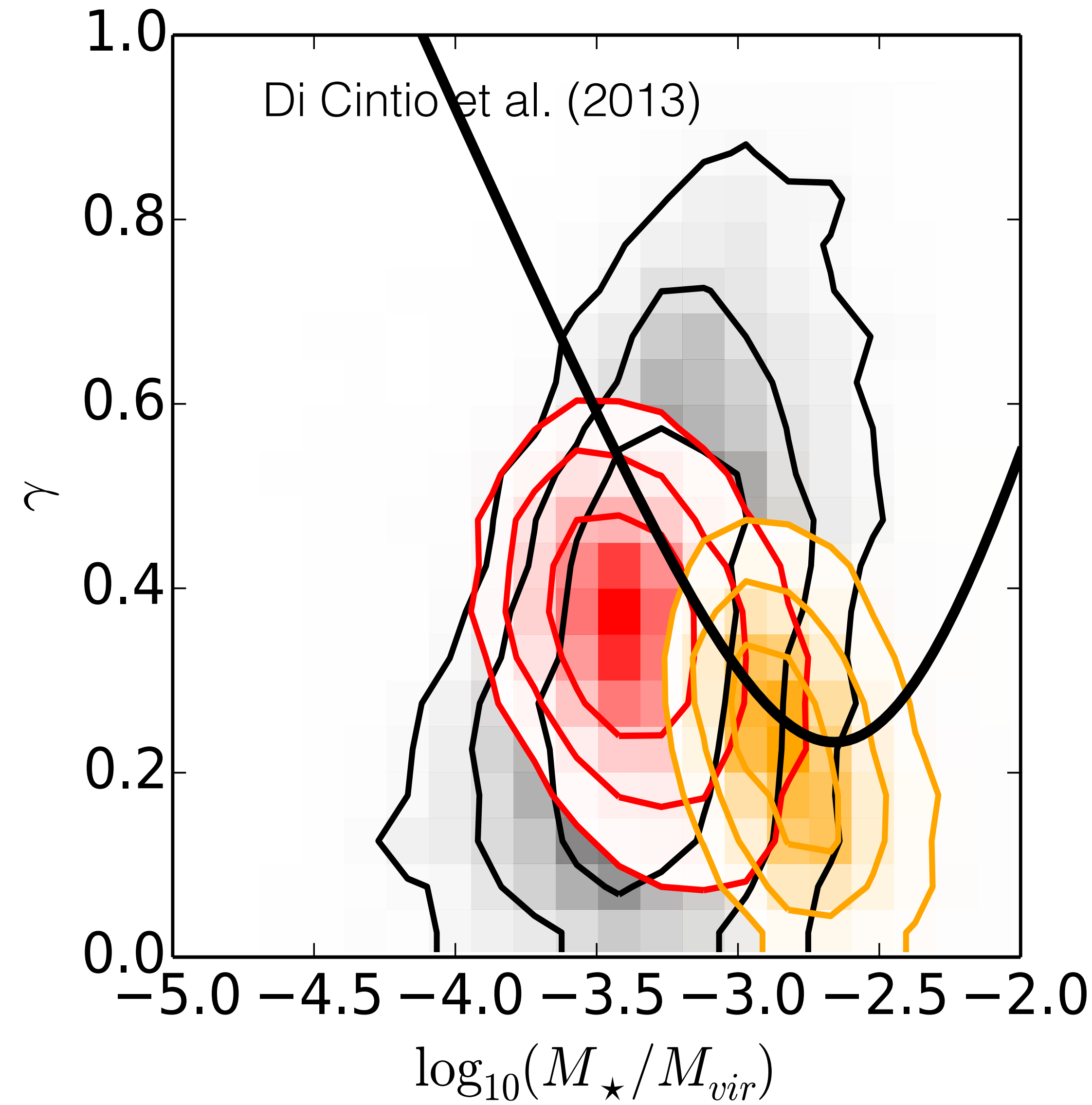
$q_{DM} = 2.1 \pm 0.9$



Baryonic feedback predictions

Leung, Leaman, et al. (2021)





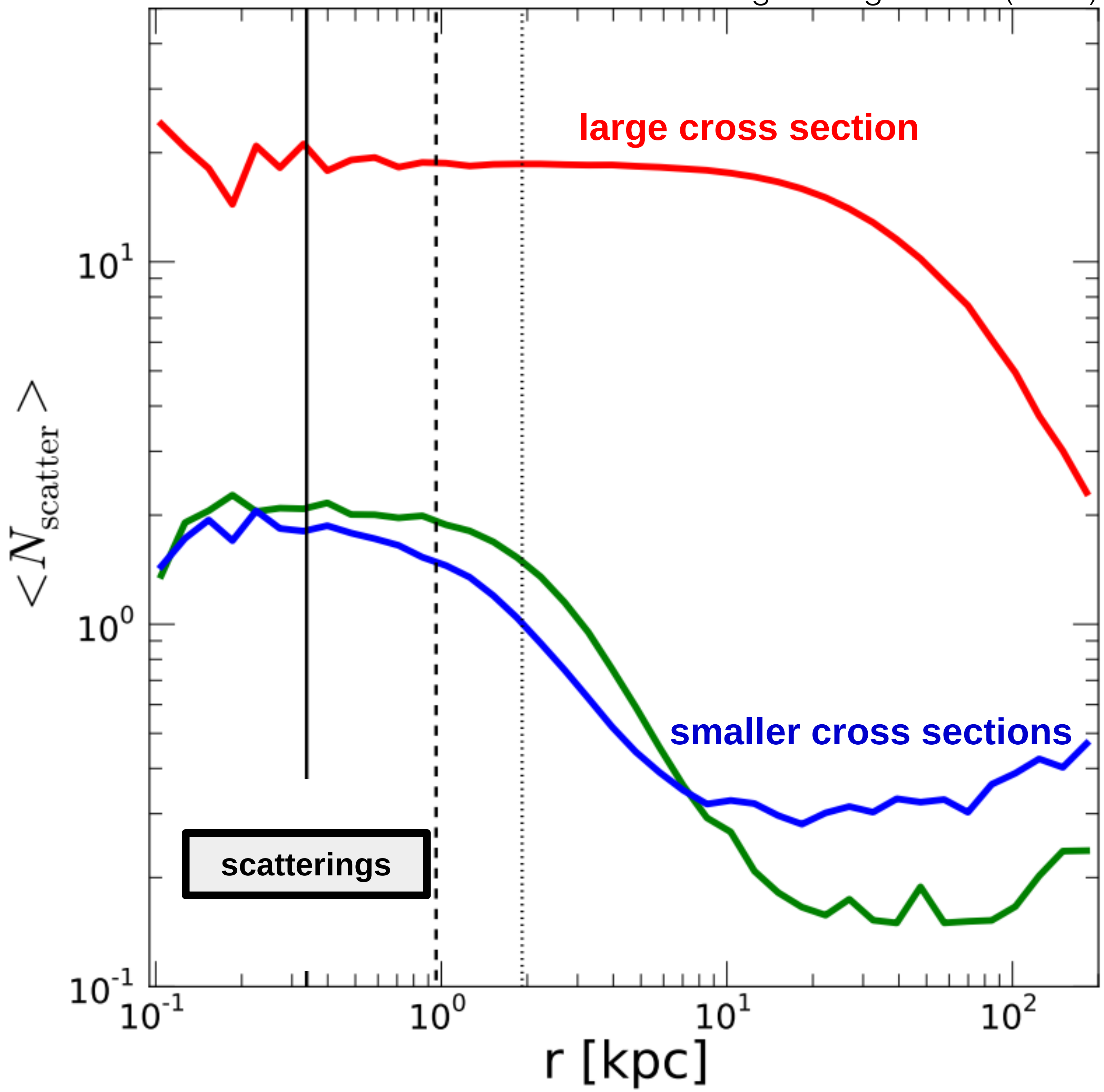
- DM core, mass and **geometry** in excellent agreement with simulations where **CDM** is modified by stellar **feedback**

Separating DM models with galaxy dynamics

Constraints on DM particle properties

- SIDM and BECDM have link between DM core size and viral mass - for a given **particle cross section**

Vogelsberger et al. (2012)

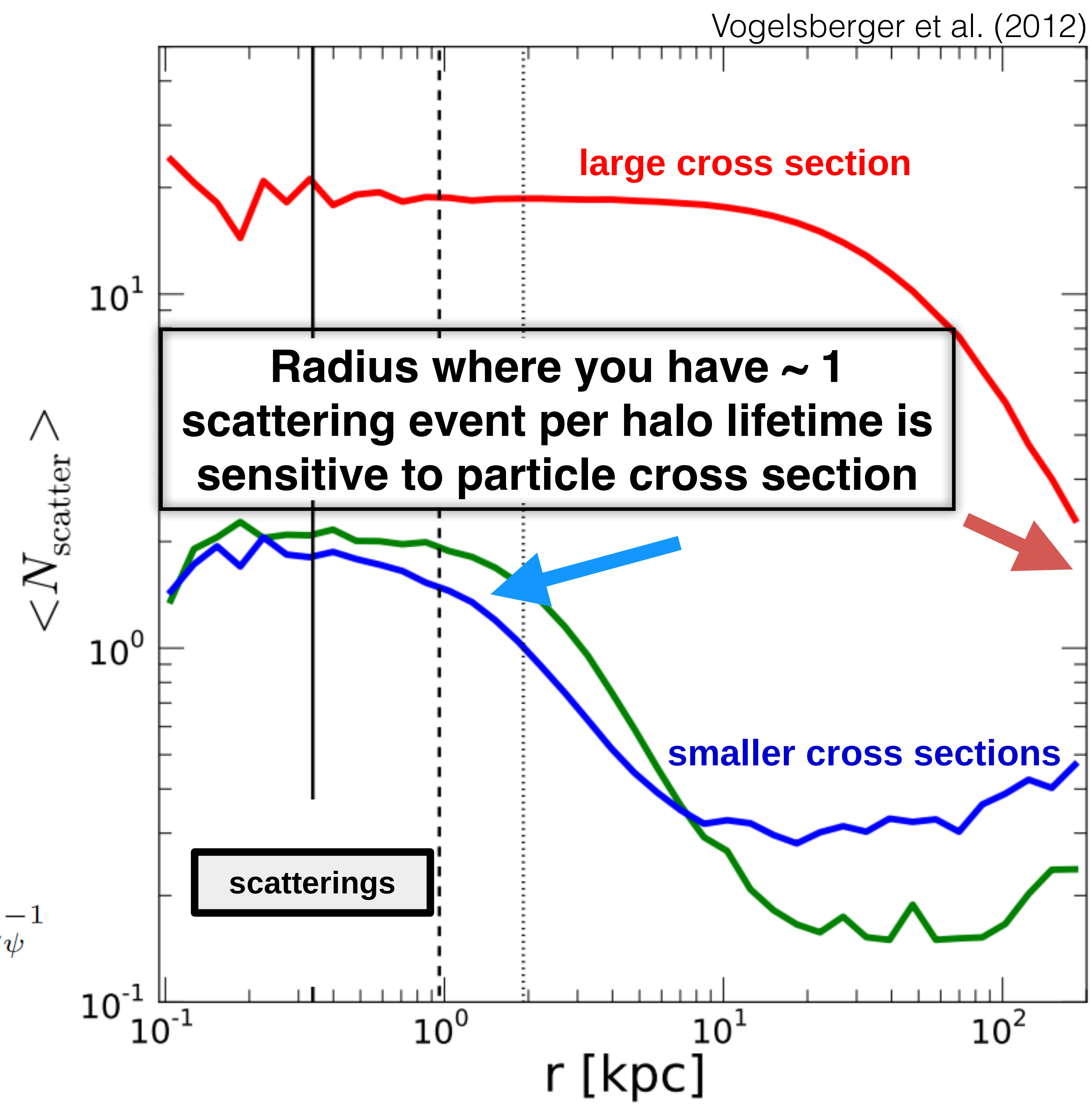


Constraints on DM particle properties

- SIDM and BECDM have link between DM core size and viral mass - for a given **particle cross section**

$$\frac{\langle\sigma v\rangle}{m_X} = \{\rho(r_c)\, t_{halo}\}^{-1}$$

$$r_c = 1.5\mathrm{kpc}\left(\frac{M_{vir}}{10^9 M_\odot}\right)^{-1/3} m_\psi^{-1}$$



Constraints on DM particle properties

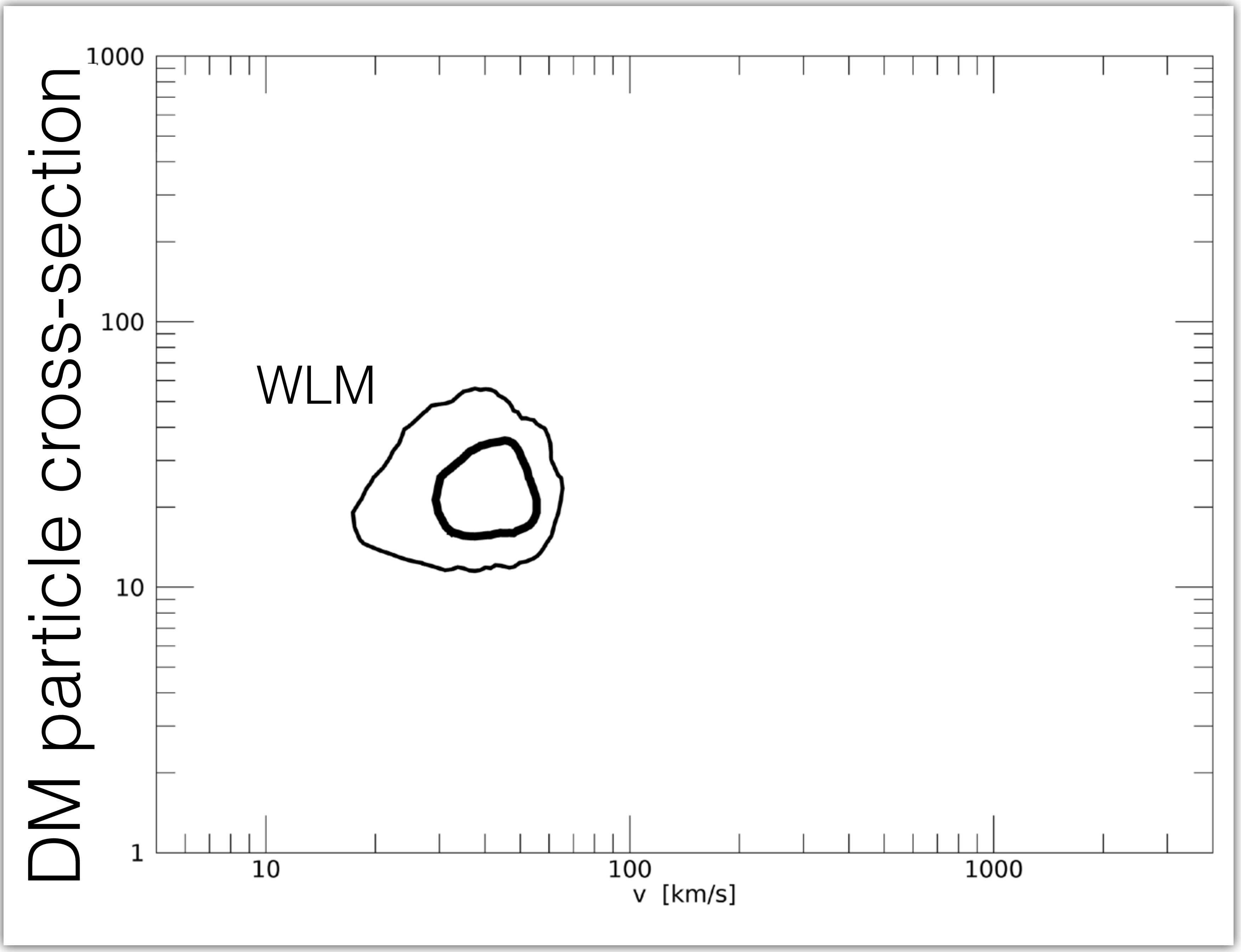
WLM: Leung, Leaman, et al. (2021)

- For SIDM the particle cross section is related to the DM core radius

$$\frac{\langle \sigma v \rangle}{m_X} = \{\rho(r_c) t_{halo}\}^{-1}$$

- For ultra-light axion / BECDM

$$r_c = 1.5\mathrm{kpc}\left(\frac{M_{vir}}{10^9 M_\odot}\right)^{-1/3} m_\psi^{-1}$$



Halo virial velocity

Constraints on DM particle properties

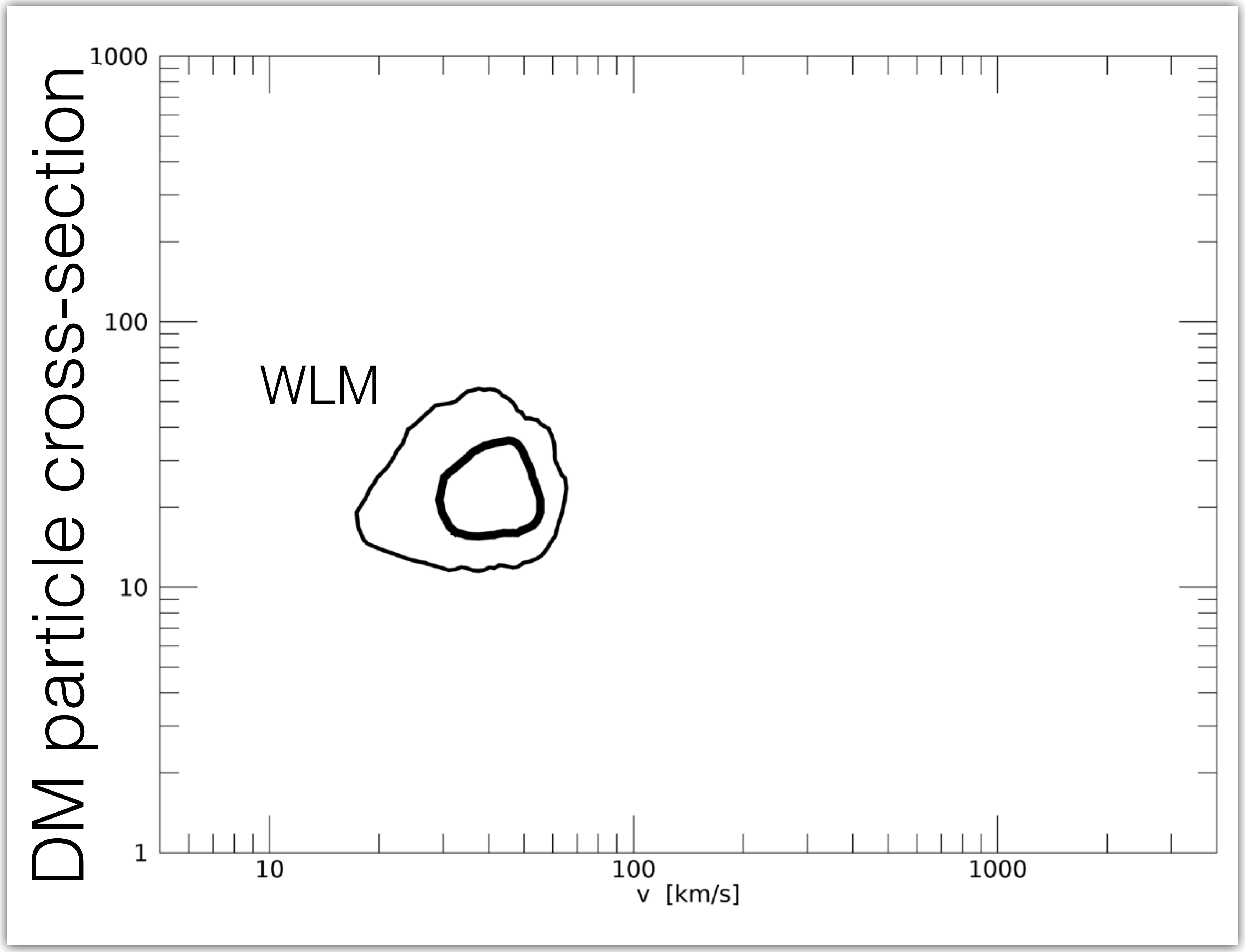
WLM: Leung, Leaman, et al. (2021)

- Joint constraints for velocity independent SIDM:

$$\sigma/m_X = 0.8 - 3.1\ \mathrm{cm^2\ g^{-1}}$$

- For ultra-light axion / BECDM

$$m_\psi = 1.1 - 1.3 \times 10^{-22}\ \mathrm{eV}/c^2$$



Halo virial velocity

Constraints on DM particle properties

Fornax: Leung, Leaman, et al. (2019)
Pegasus: Leaman, et al. (2020)
WLM: Leung, Leaman, et al. (2021)

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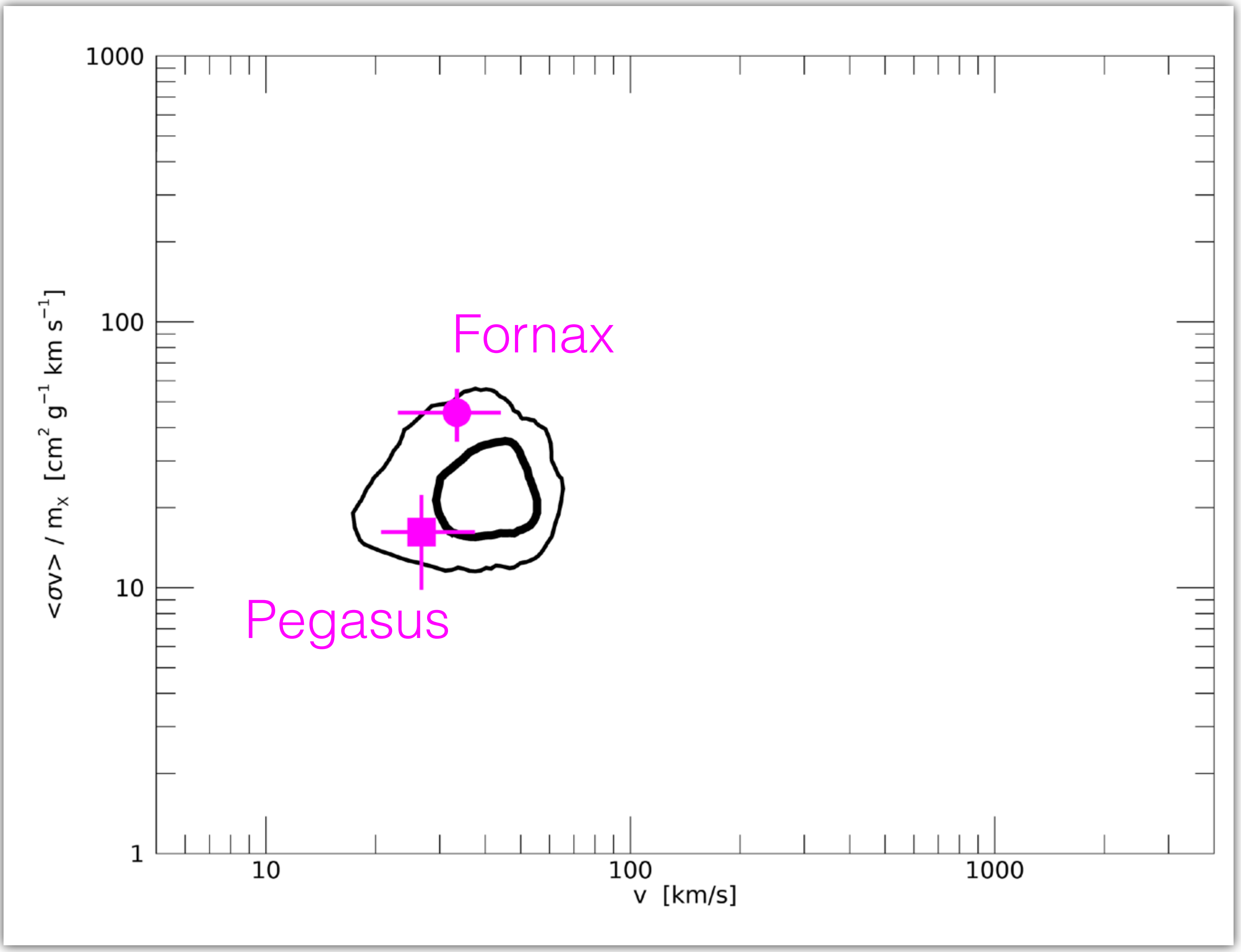

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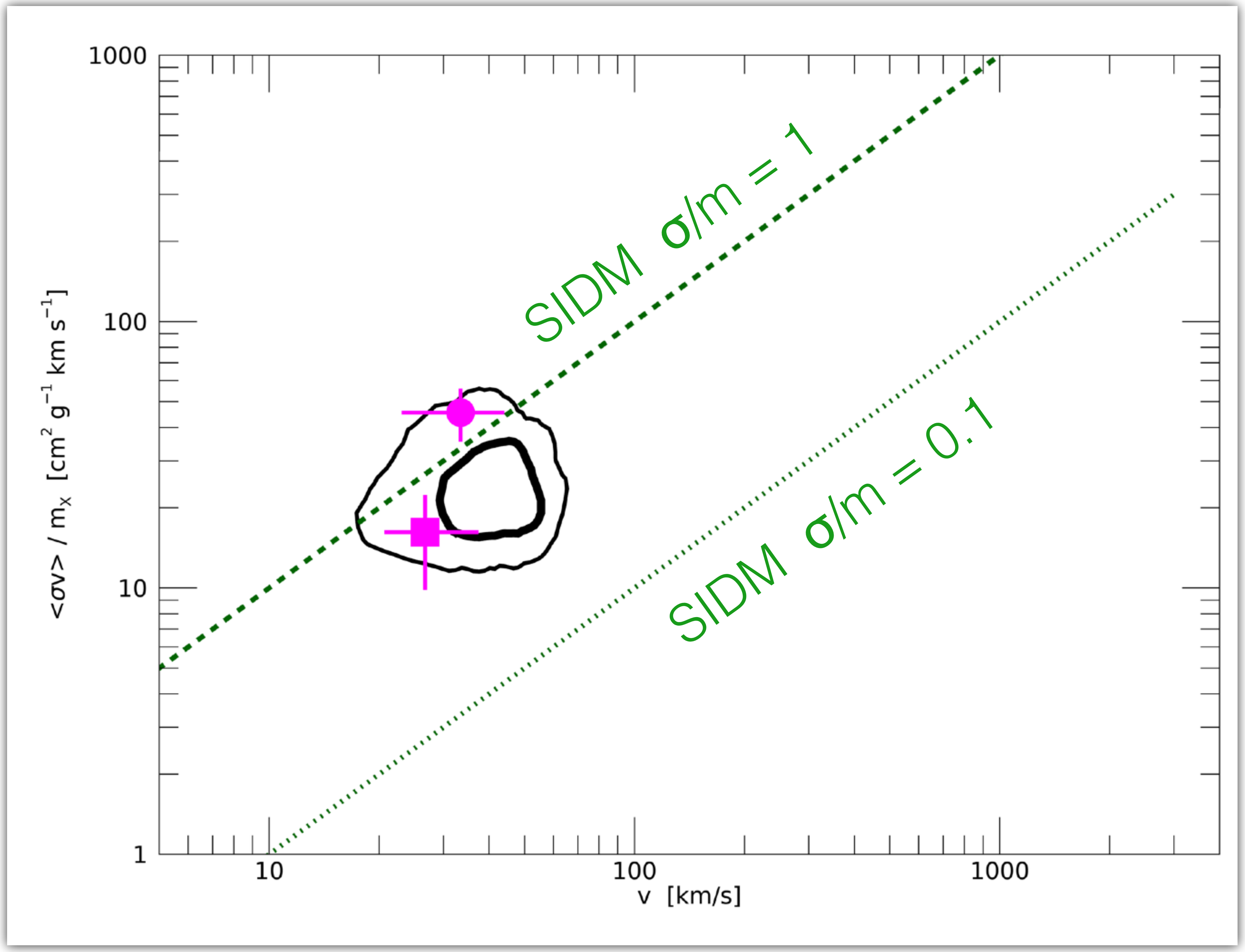

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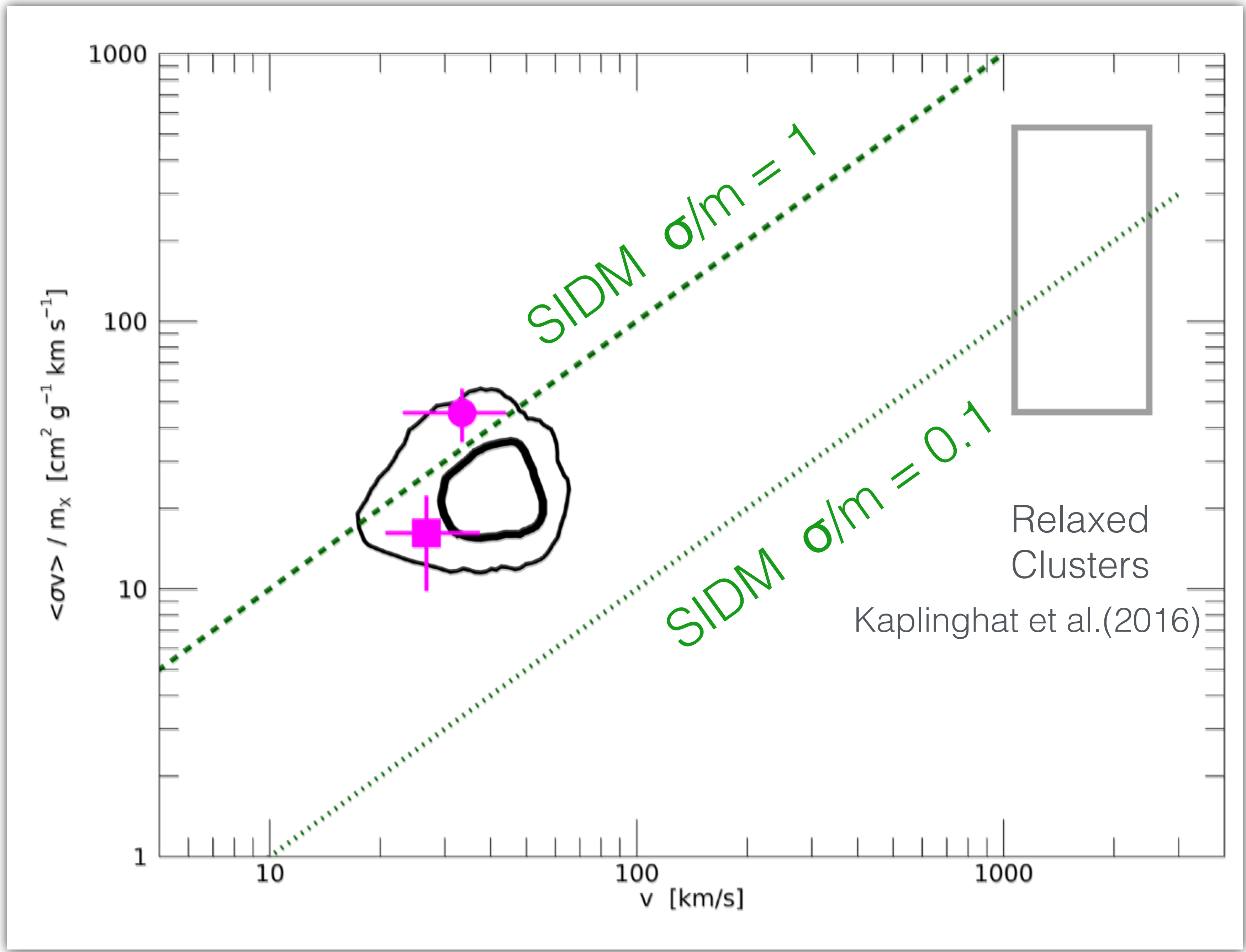

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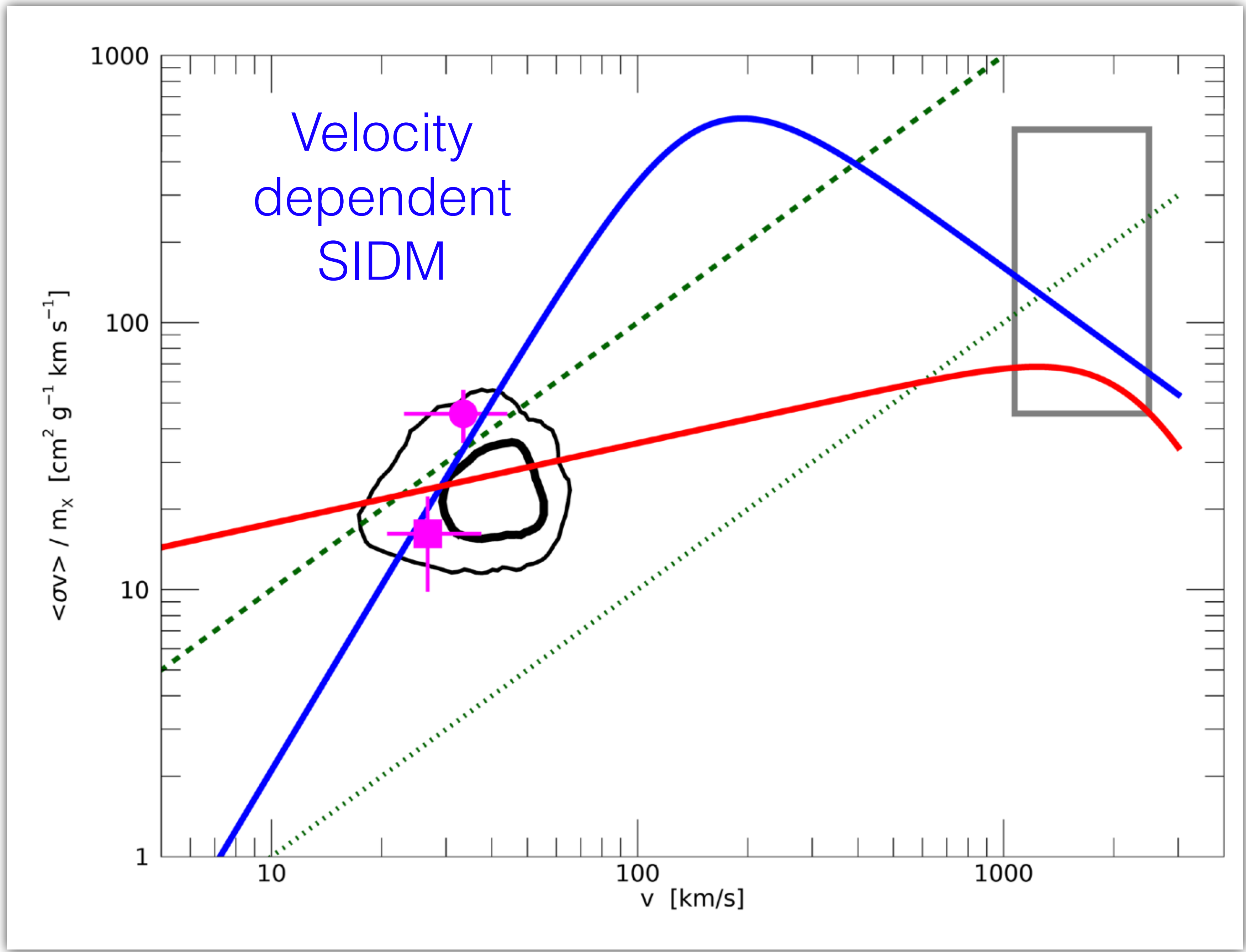
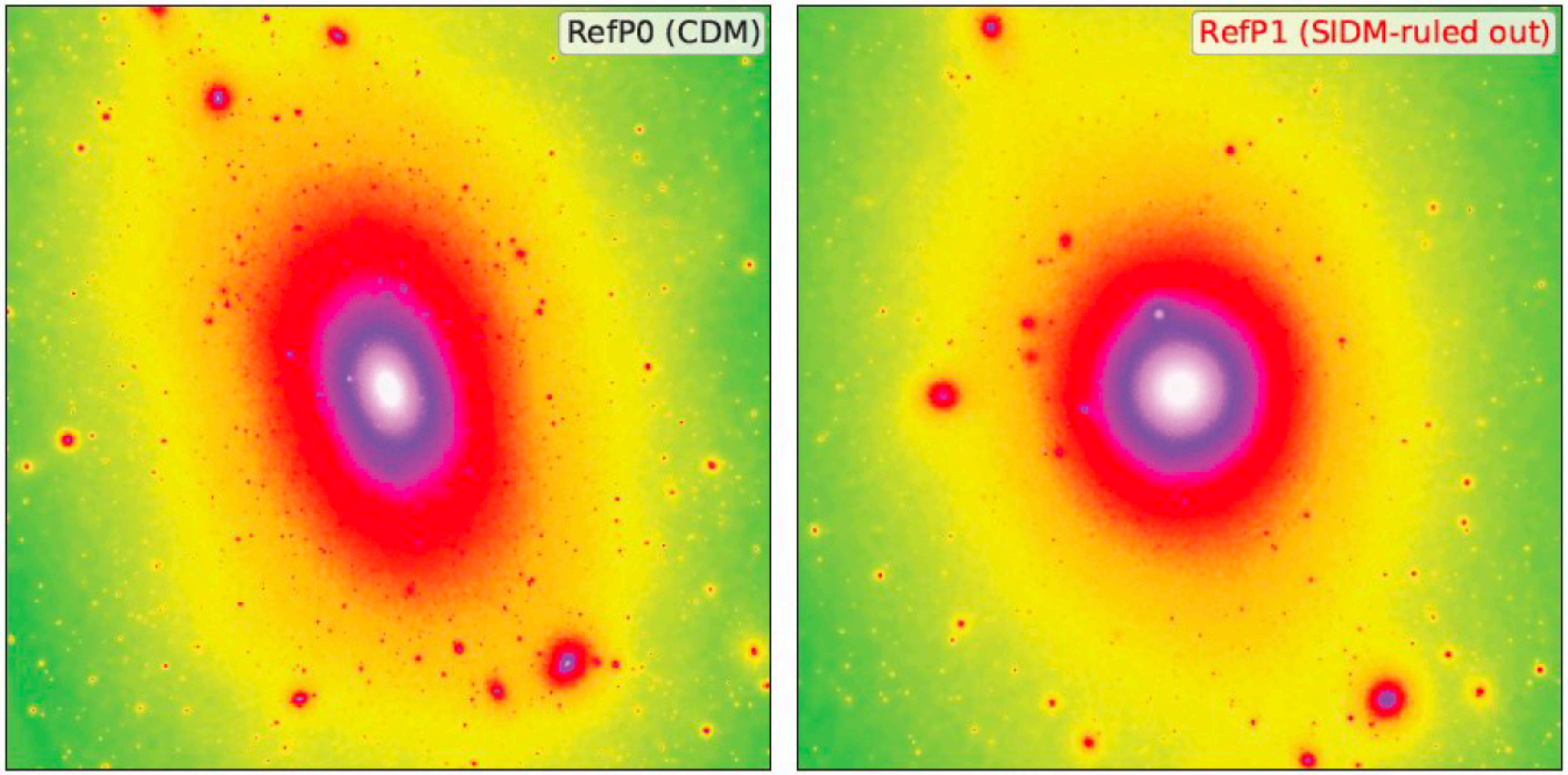


Are prolate, cored DM halos problematic for SIDM?

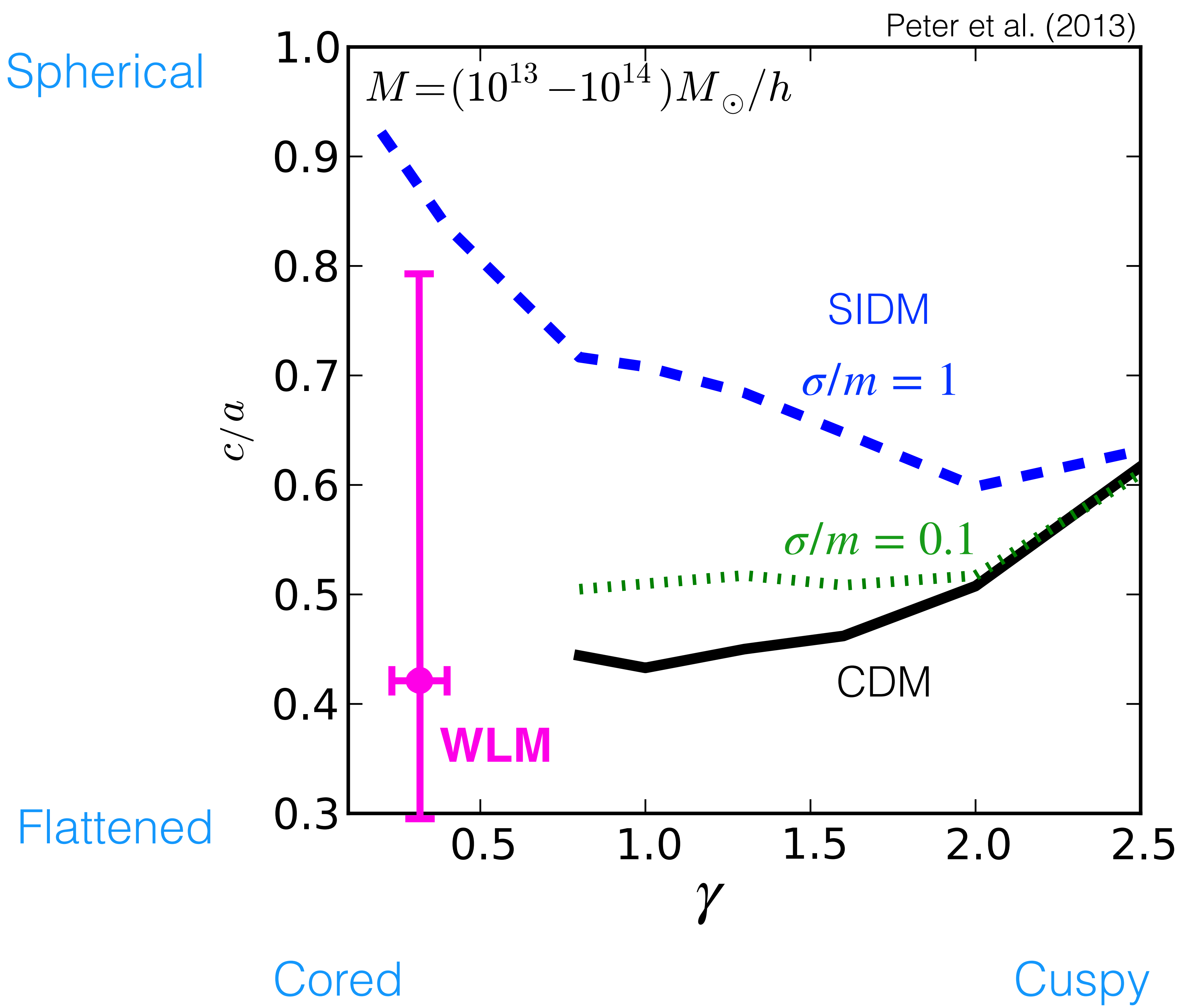
- Particle **interactions** in inner regions can easily create DM cores in SIDM
- But this tends to be an isotropic process and **sphericalizes** the halos

Vogelsberger et al. (2012)



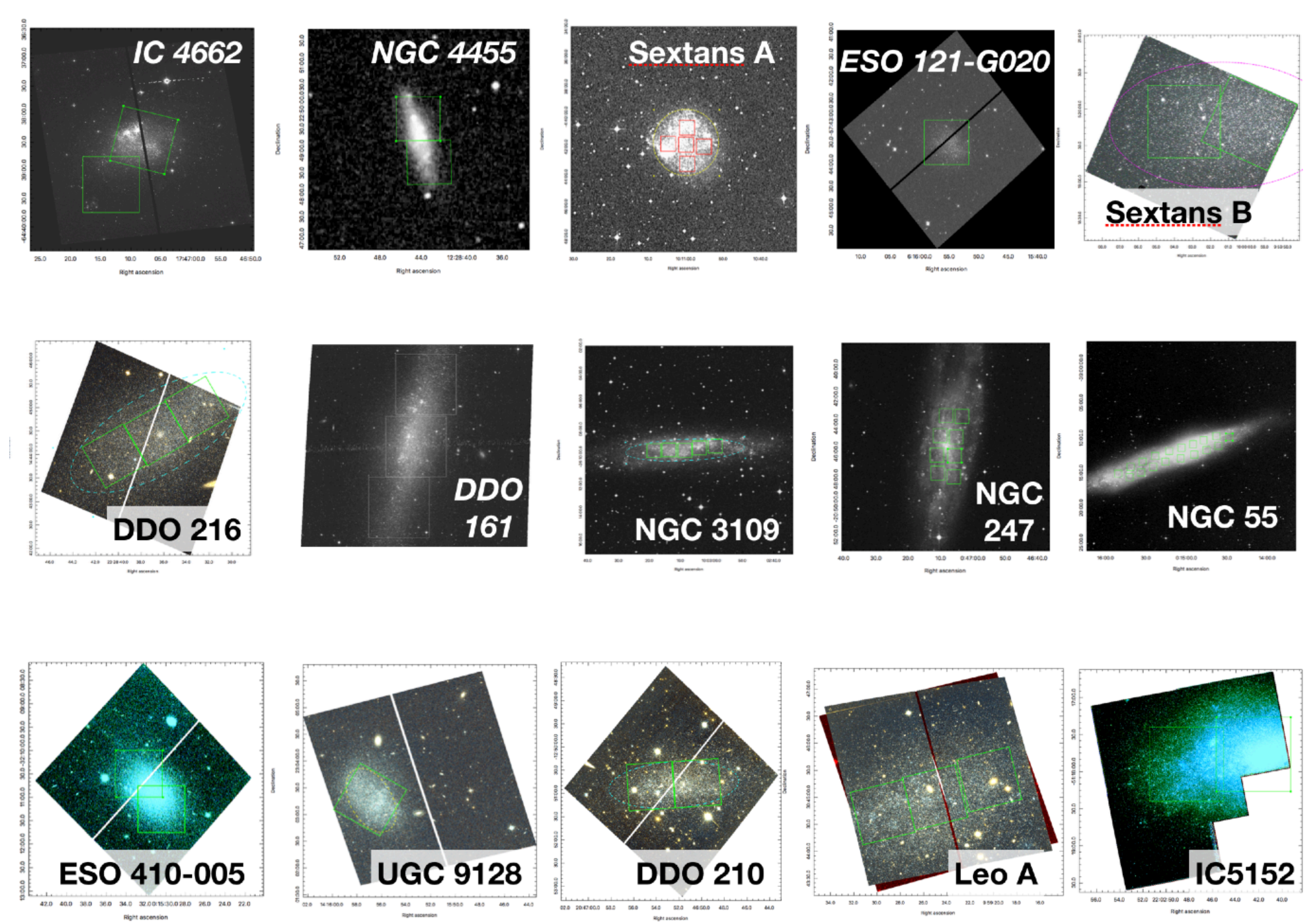
Are prolate, cored DM halos problematic for SIDM?

- Unclear if halos of this mass can have non-spherical geometries **and** an inner density core in SIDM, SFDM



Future targets with MUSE + HST

- MUSE lets us efficiently measure the stellar kinematics in nearby dwarfs.
- ~15 identified with existing HI gas kinematics to form a large program.



Conclusions

- New methods are needed to differentiate CDM+feedback from alternative dark matter theories
- **Advanced dynamical models** are providing more robust inferences of local and extragalactic DM distributions
- Combining gas, stellar and globular cluster orbits let us recover **DM density profile *and* flattening**
- DM particle cross sections inferred from studies of nearby dwarf galaxies together with aspherical DM halos may be problematic for interacting DM models - but **naturally arise in CDM+feedback simulations**

Thanks for your interest!
Questions?