Dwarf Spheroidals and Dark Matter

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Self Interacting Dark Matter

Plan of Talk

1. Dark Matter indirect detection
2. Self interacting dark matter
3. Dwarf Spheroidal Galaxies
4. Reproducing density profiles
5. Breaking the beta degeneracy with Theia

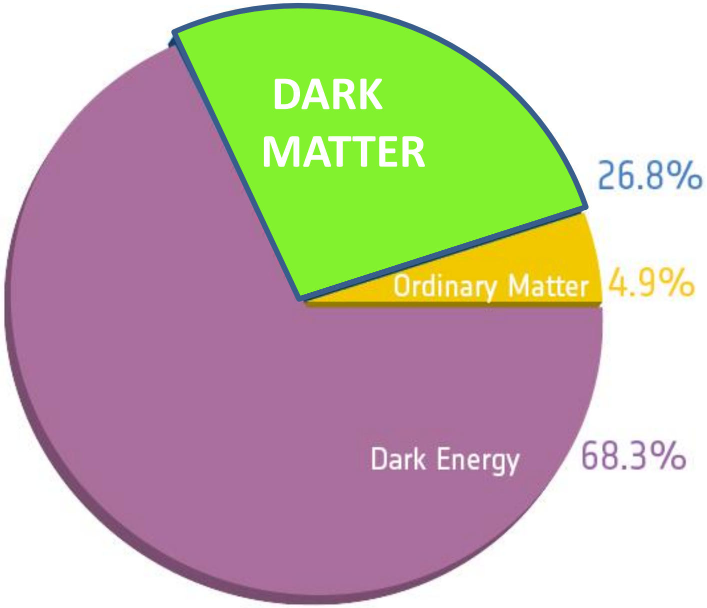
Dark Matter: One of the Biggest Problems in the Universe

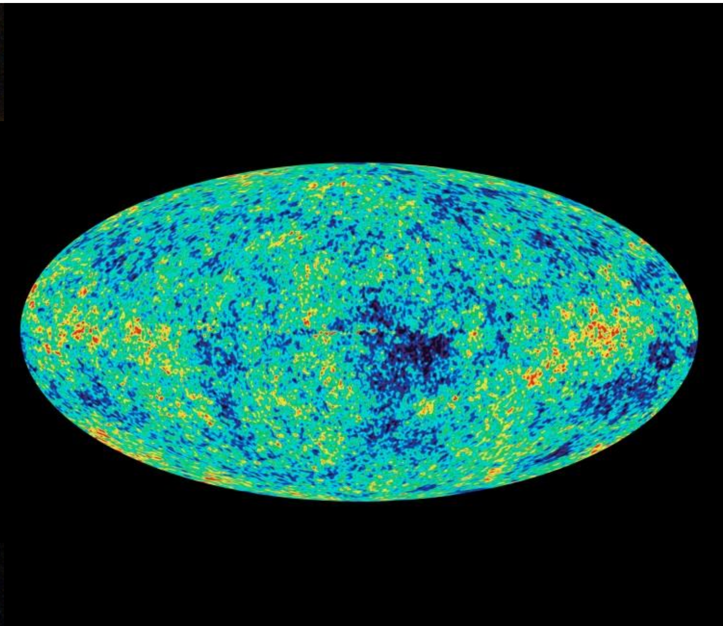
Huge amount of Evidence for Dark Matter

Galaxies, Clusters of Galaxies, Expansion of Universe, fluctuations in the CMB, etc

Thought to be an elusive particle not yet detected

New physics at the LHC energy scale can explain the dark matter in the Universe if it is a Weakly Interacting Massive Particle (WIMP) or similar





Thermal Relics Work !
(at least for the dark matter bit)

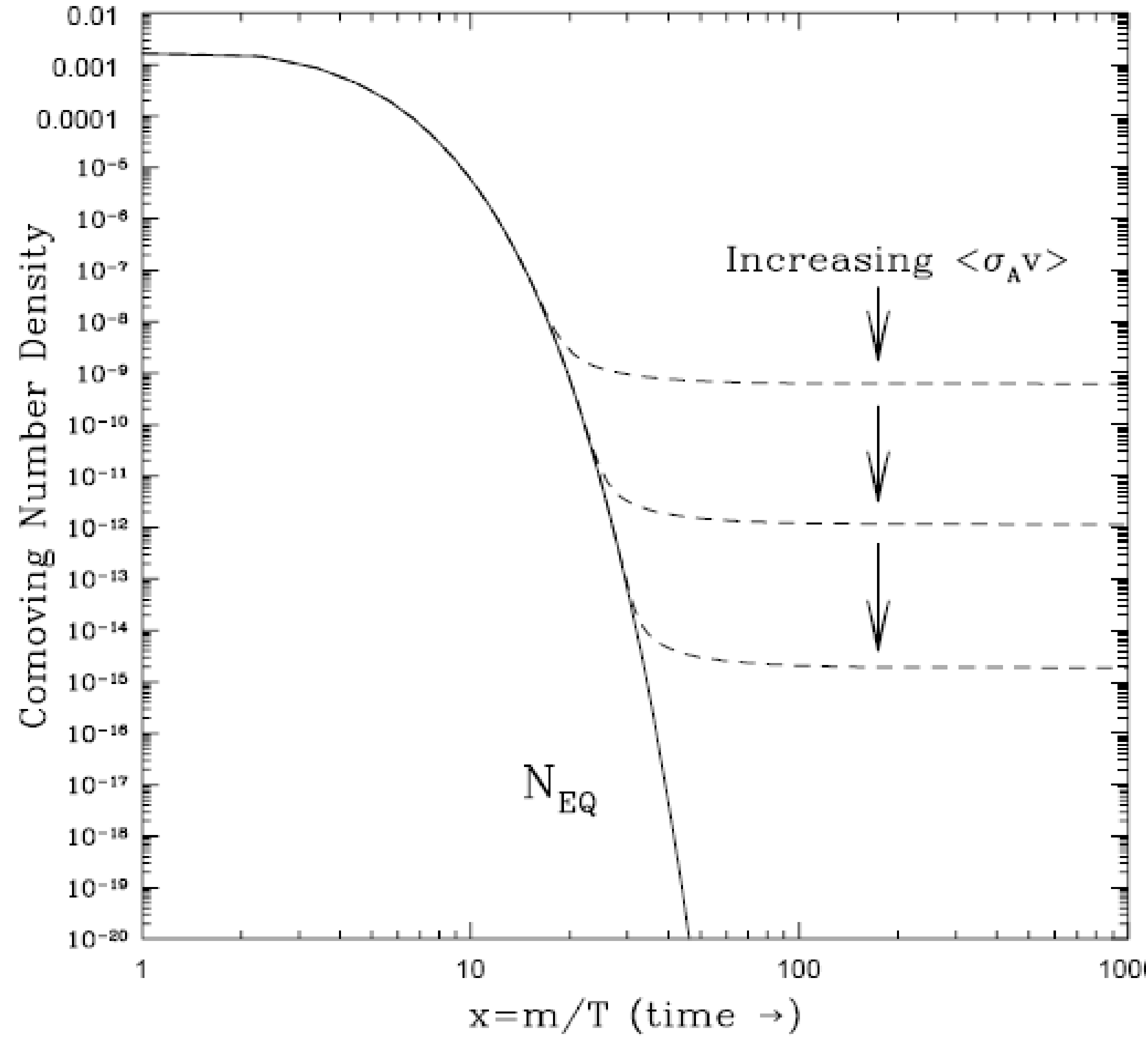
$$\sigma_{\mathrm{weak}} \simeq \frac{\alpha^2}{m_{\mathrm{weak}}^2}$$

$$\alpha \simeq \mathcal{O}(0.01)$$

+

$$m_{\mathrm{weak}} \simeq \mathcal{O}(100\,\mathrm{GeV})$$

$$\Omega_\chi \sim 1$$



$$\frac{dn}{dt} = \langle \sigma v \rangle \left(\frac{\rho}{m_\chi} \right)^2$$

Right amount of dark matter if dark matter mass 100 MeV < M < 100 TeV

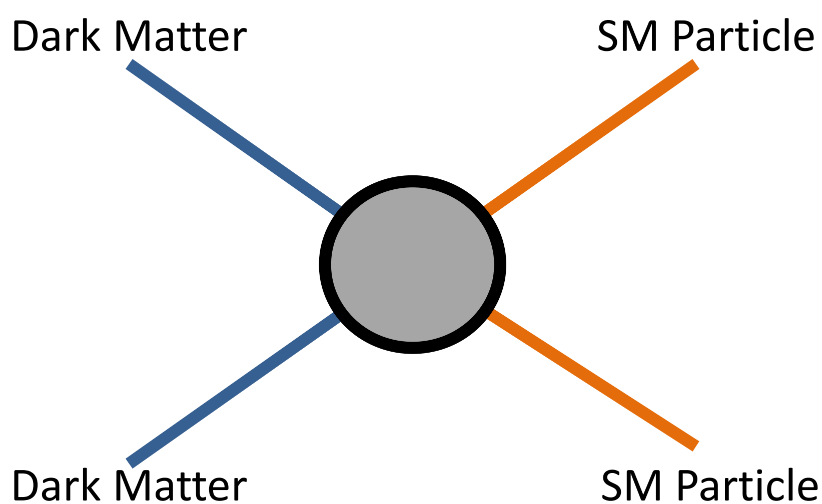
Ways to Detect Dark Matter – *Make, Shake and Break*

***Make** – collider production*

***Shake** – direct detection scattering*

Today concentrate on this –

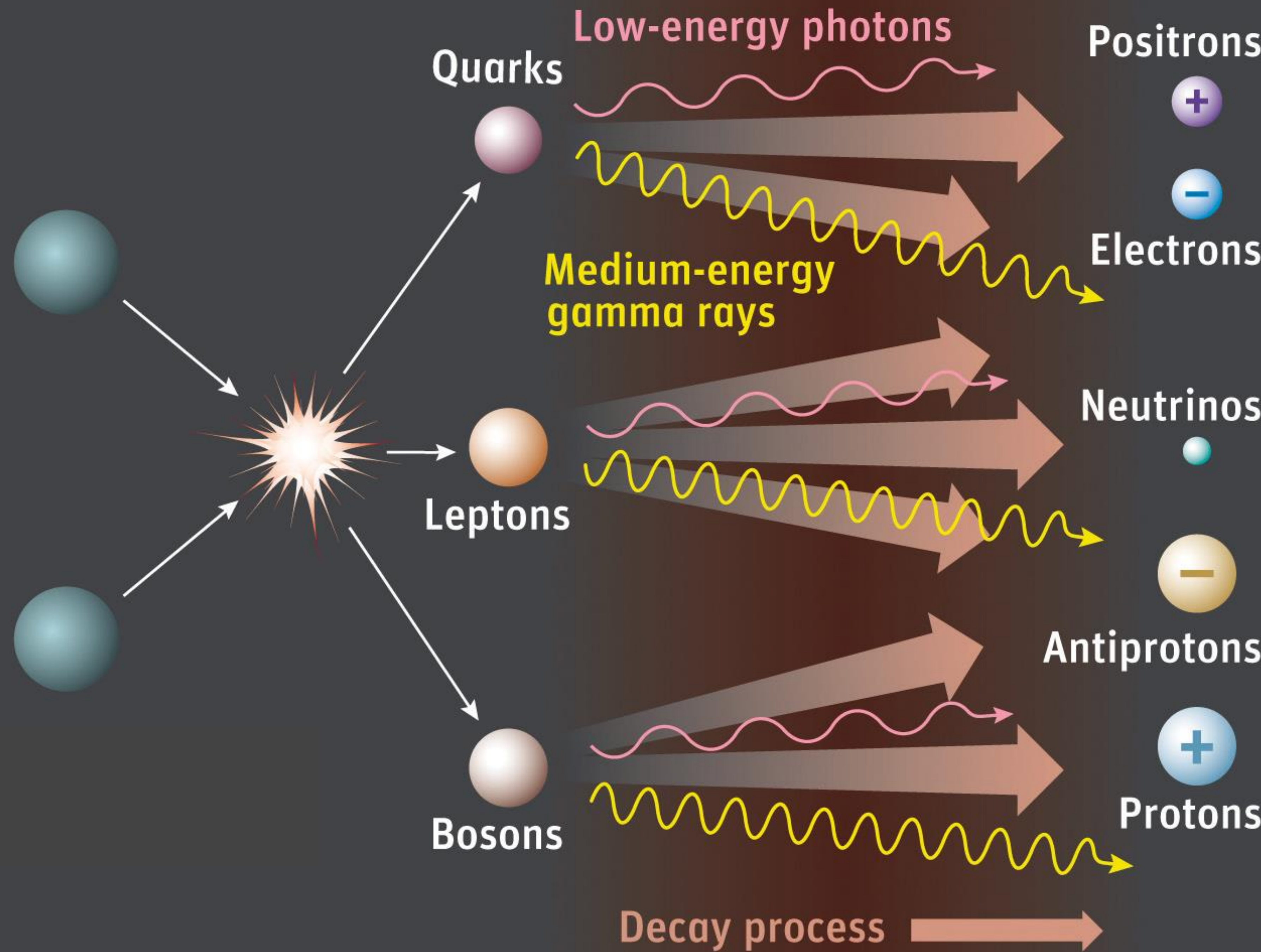
Indirect Detection



***Break** – indirect detection of annihilation*

Dark Matter indirect detection

Dark Matter Self-Annihilation



Rate of self-annihilation of Dark Matter

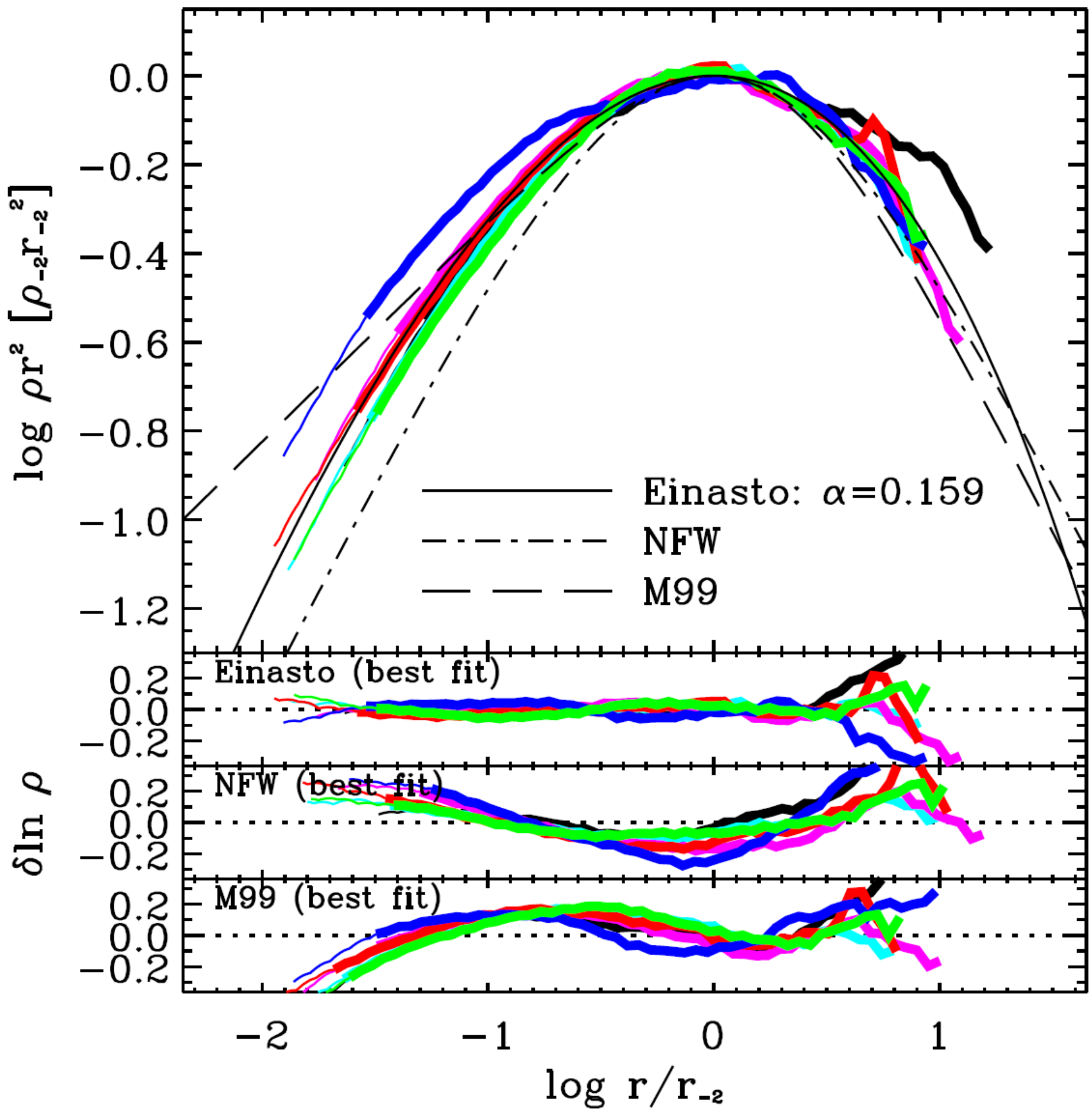
But how well do we know this
at the Galactic Centre?

$$\frac{dn}{dt} = \langle \sigma v \rangle \left(\frac{\rho}{m_\chi} \right)^2$$

We think we might know this

And we have some ideas about this

Simulations show halos denser in middle.



$$\rho(r) = \rho_{-2} e^{-\frac{2}{\alpha}\left[\left(\frac{r}{r_{-2}}\right)^{\alpha} - 1\right]}$$

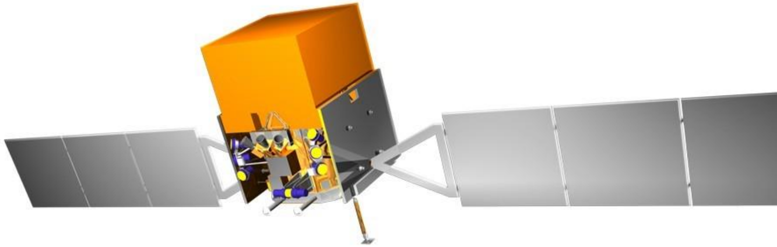
Can parametrise Dark Matter density using a profile such as ‘$\alpha\beta\gamma$’or ‘Zhao’ profile

$$\boxed{\rho(r) = \frac{\rho_0}{\left(\frac{r}{r_s}\right)^{\gamma}\left[1+\left(\frac{r}{r_s}\right)^{\alpha}\right]^{(\beta-\gamma)/\alpha}}}$$

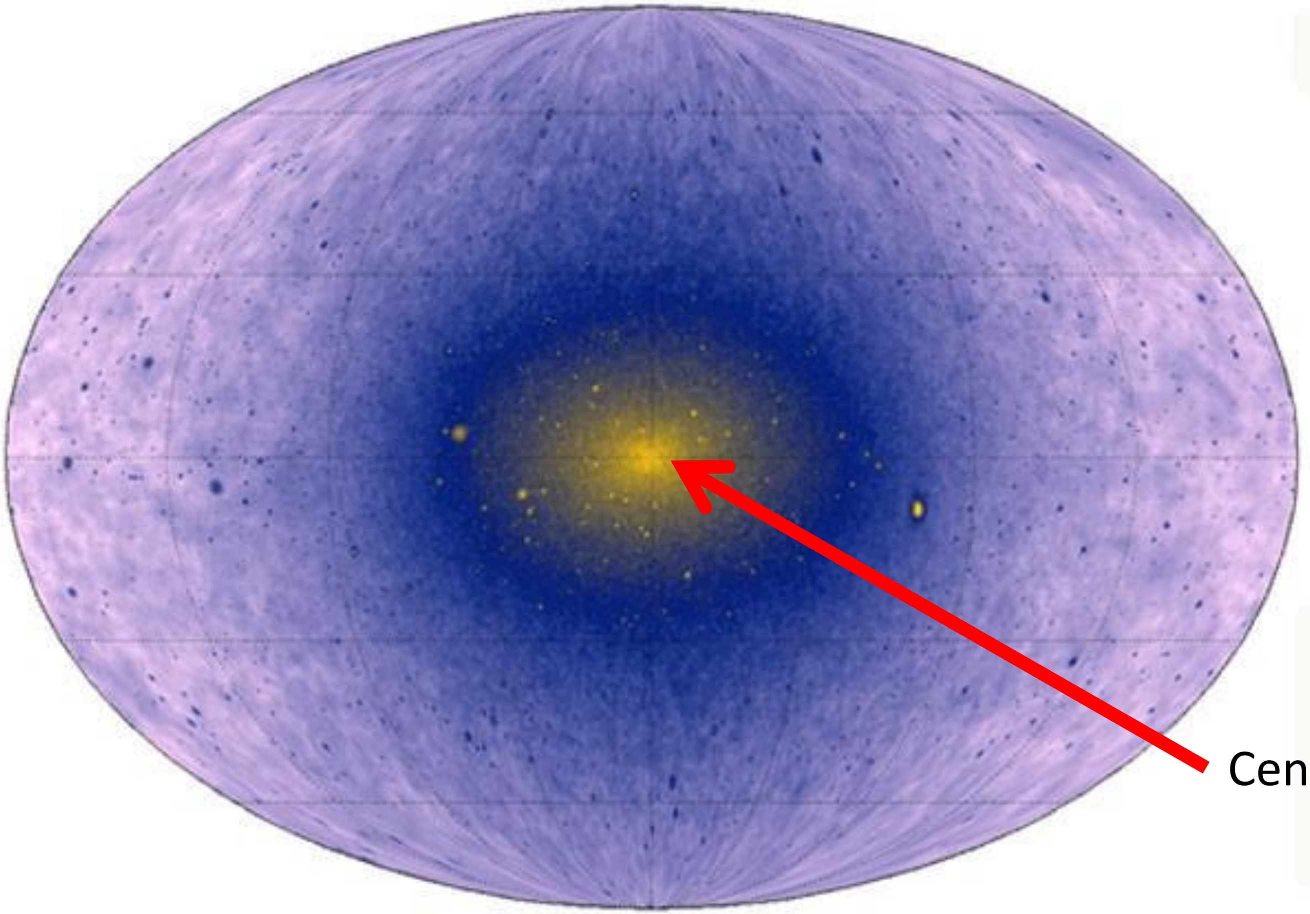
where γ is inner slope, β is outer slope and α gives rate of change between slopes

typically γ is around 1 without baryons, can be more or less with baryons

Can try to detect annihilation of dark matter with itself at Galactic Centre

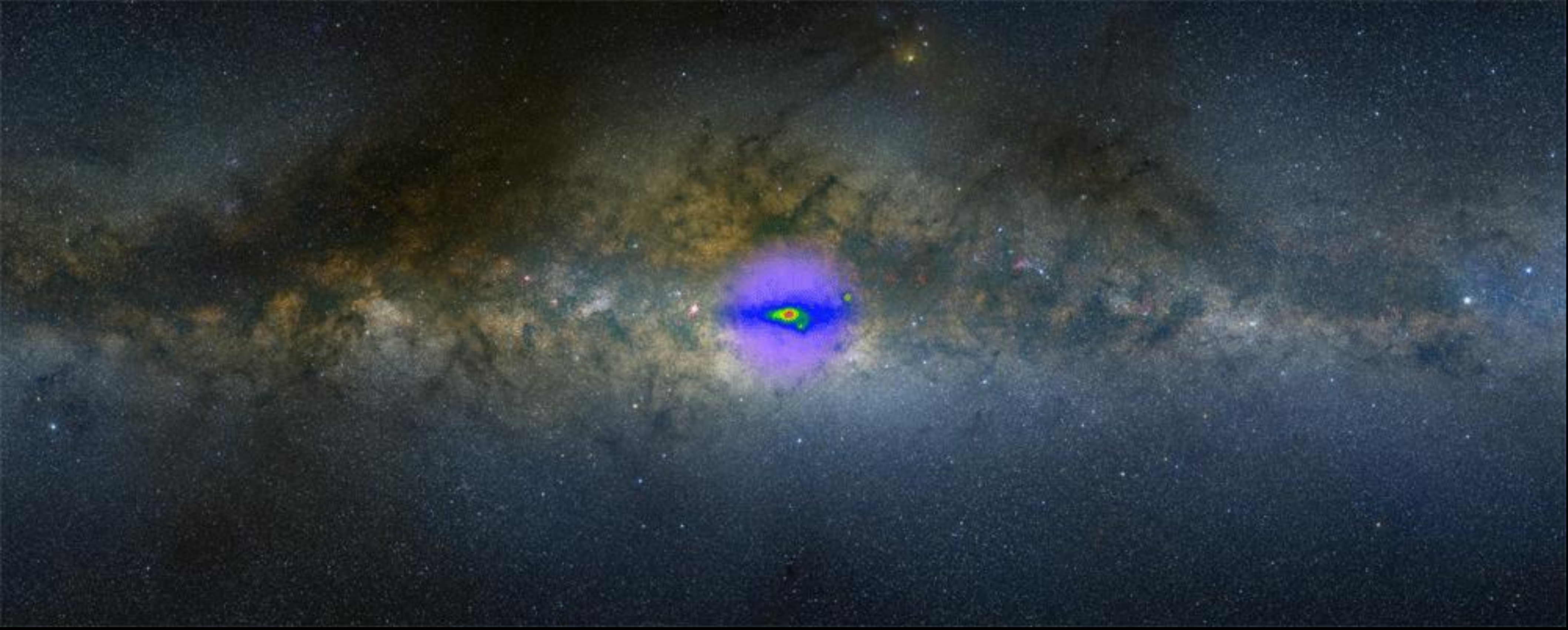


FERMI – gamma ray telescope



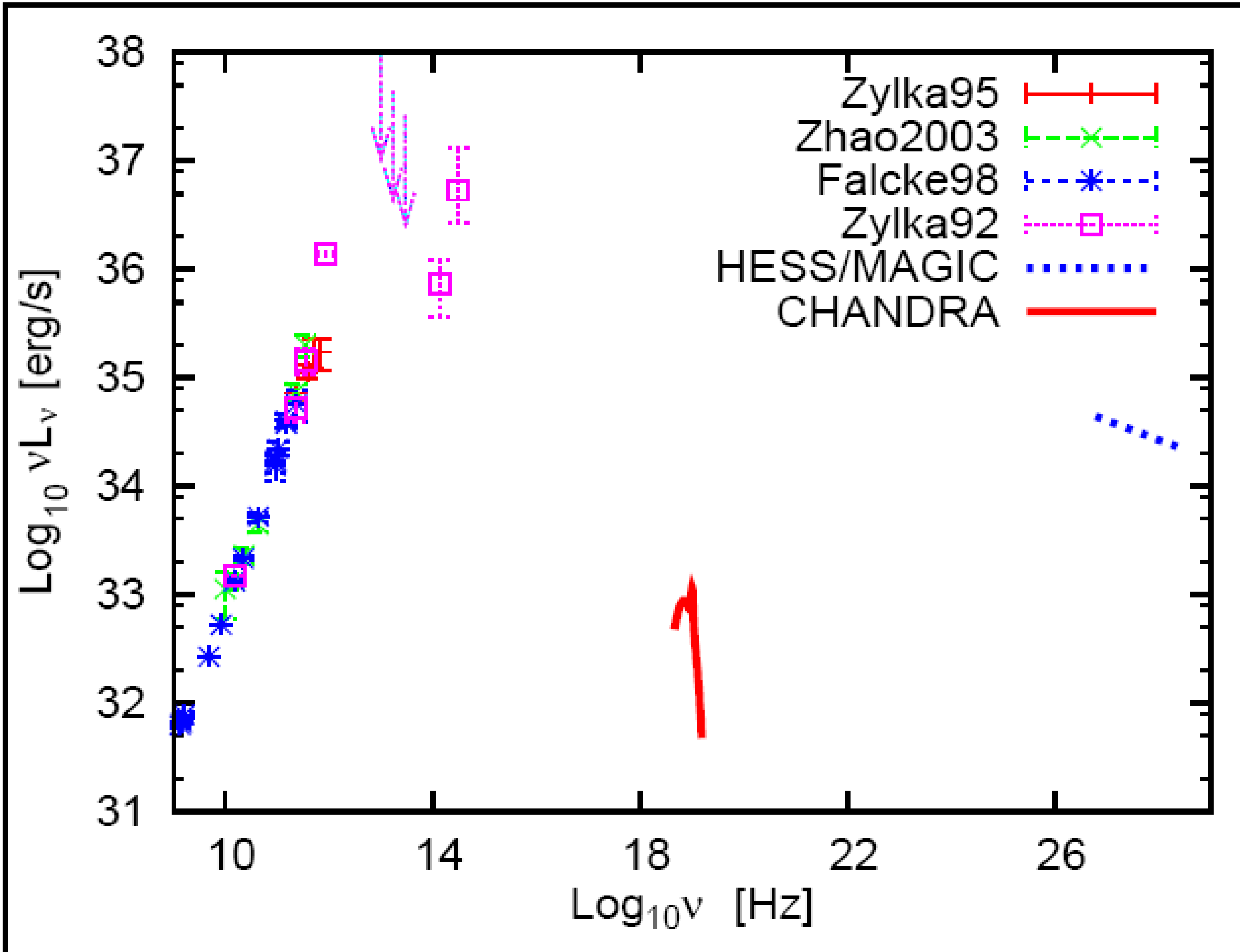
Centre of the milky way

Simulated pre launch map of gamma rays from dark matter annihilation seen by Fermi telescope

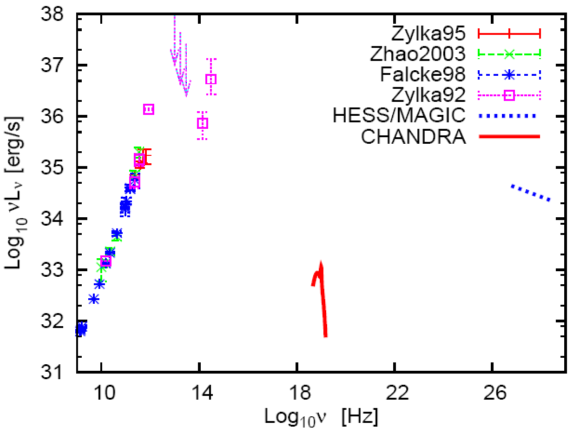


- Galactic Centre Excess detected by Fermi Gamma Ray Telescope
- Consistent with 30 GeV DM annihilating into b quarks
- Approximately right density profile, annihilation cross section
- May also be consistent with Millisecond pulsars
- Next Fermi data release may clarify the situation

Flux centred on Sagittarius A*



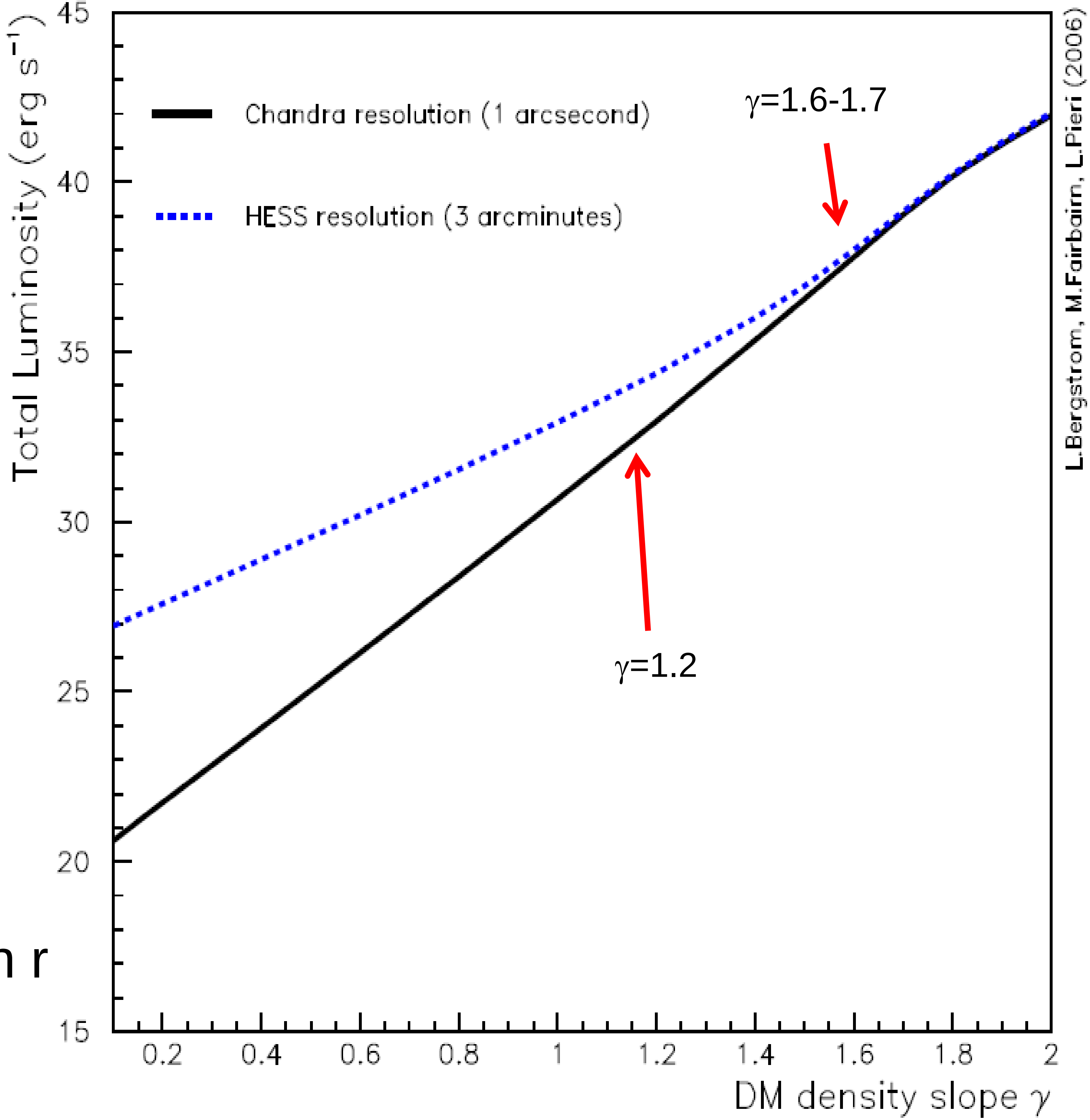
The Galactic Centre Coincidence



Comparison of actual flux with DM ann. flux

Same Vertical scale

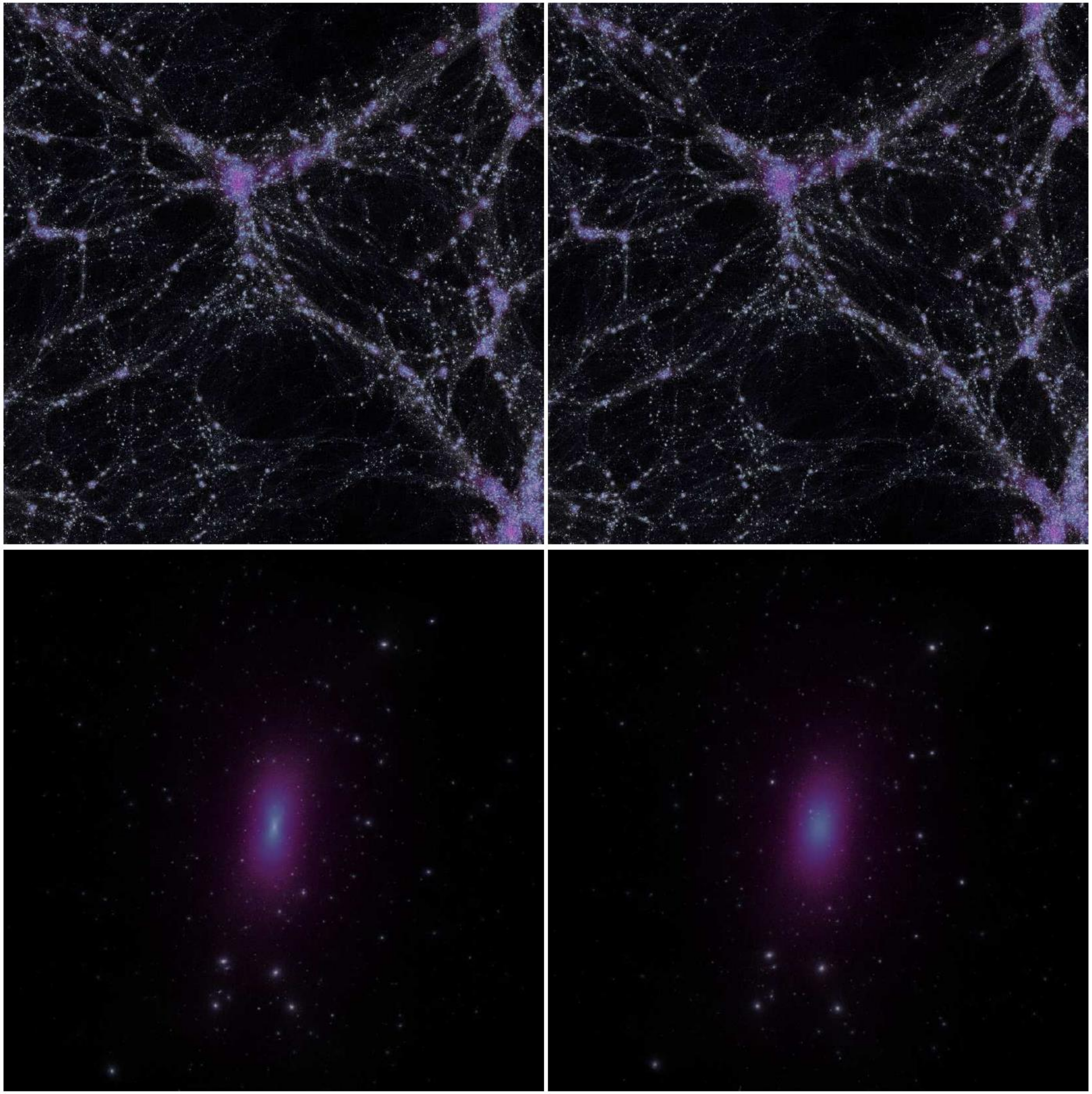
$$\gamma = -\,d \ln \rho \,/\, d \ln r$$



Self interacting Dark Matter

- Dark Matter may interact with itself
- typical cross section to get astrophysical effect (and therefore also constraint) is about ~ cm^2 / g
- This is around 10^{12} times weak interaction
- around 10^{21} times LUX bound at 30 GeV
- May solve “missing satellites problem”
- May solve “too big to fail problem”
- May solve “dsph core problem”
- None of these may actually be a problem

What happens when you replace CDM with SIDM?



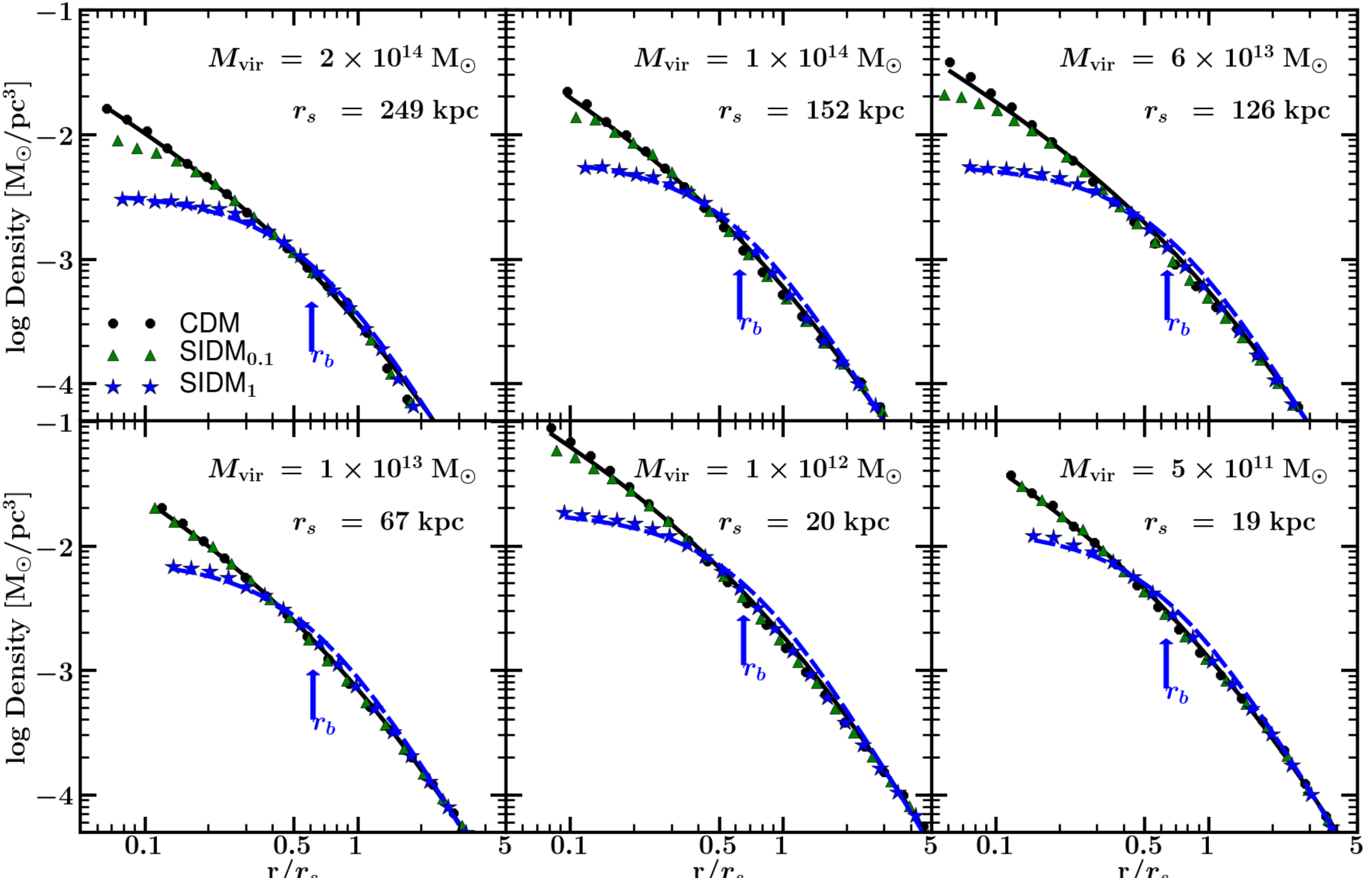
Self interacting simulations with σ=1 cm^2/g

Rocha et al 1208.3025

No difference on large scales

Individual galaxies more cored and spherical with higher velocity dispersion

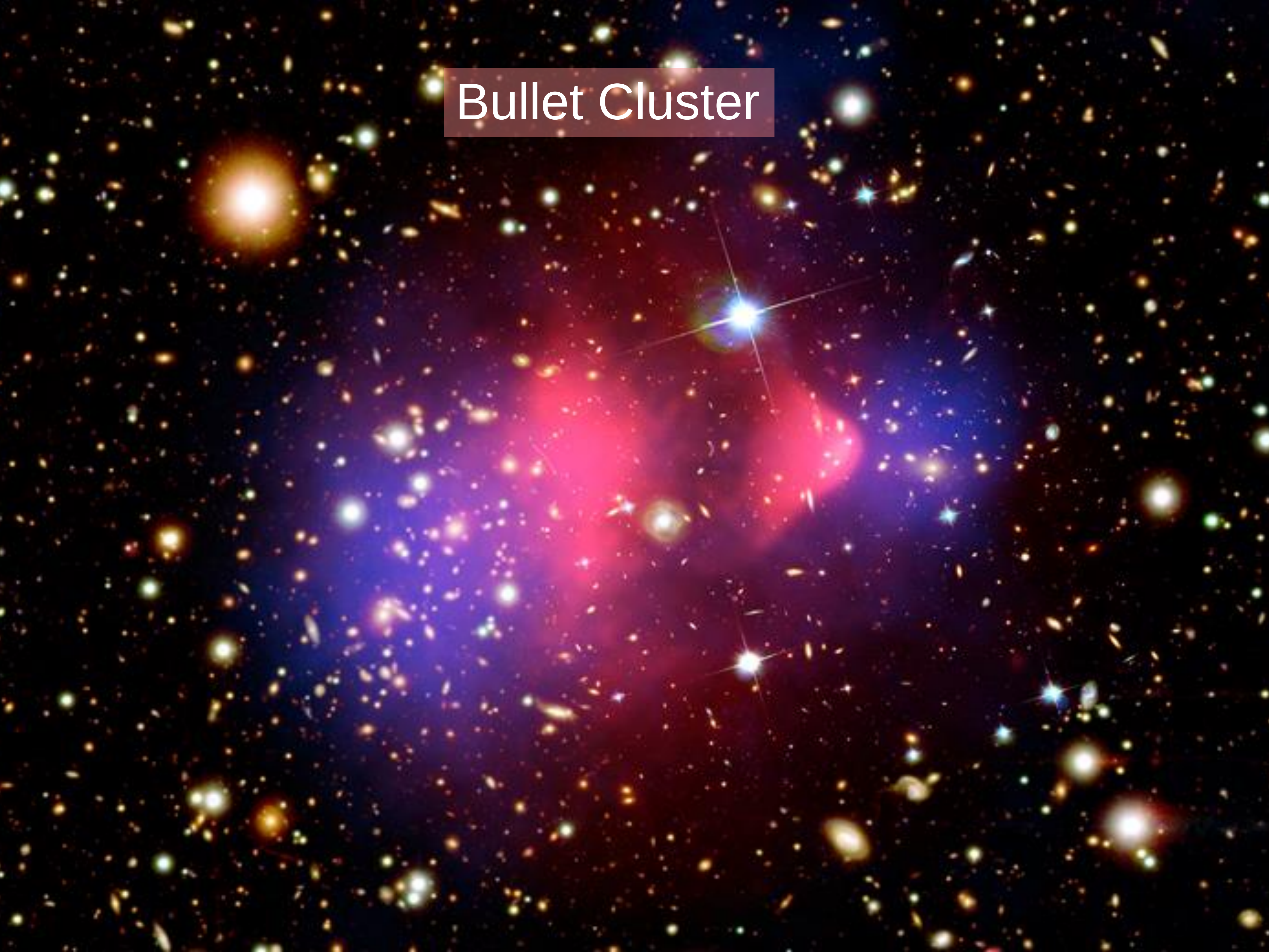
N-body simulations show cores are more pronounced in SIDM rather than CDM
Rocha et al 1208.3025



Strong constraints on σ/m come from Bullet Cluster and
Elliptical Galaxy NGC-720

$$\Gamma_k = \int d^3v_1 d^3v_2 f(v_1) f(v_2) \left(n_X v_{\rm rel} \sigma_T\right) \left(v_{\rm rel}^2 / v_0^2\right)$$

Bullet Cluster



Short range vs. Long range self interactions

For a potential

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

You expect the perturbative cross section (easy to work with)

$$\sigma_T^{\mathrm{Born}} = \frac{8\pi\alpha_X^2}{m_X^2 v^4}\left(\log\left(1 + m_X^2 v^2/m_\phi^2\right) - \frac{m_X^2 v^2}{m_\phi^2 + m_X^2 v^2}\right)$$

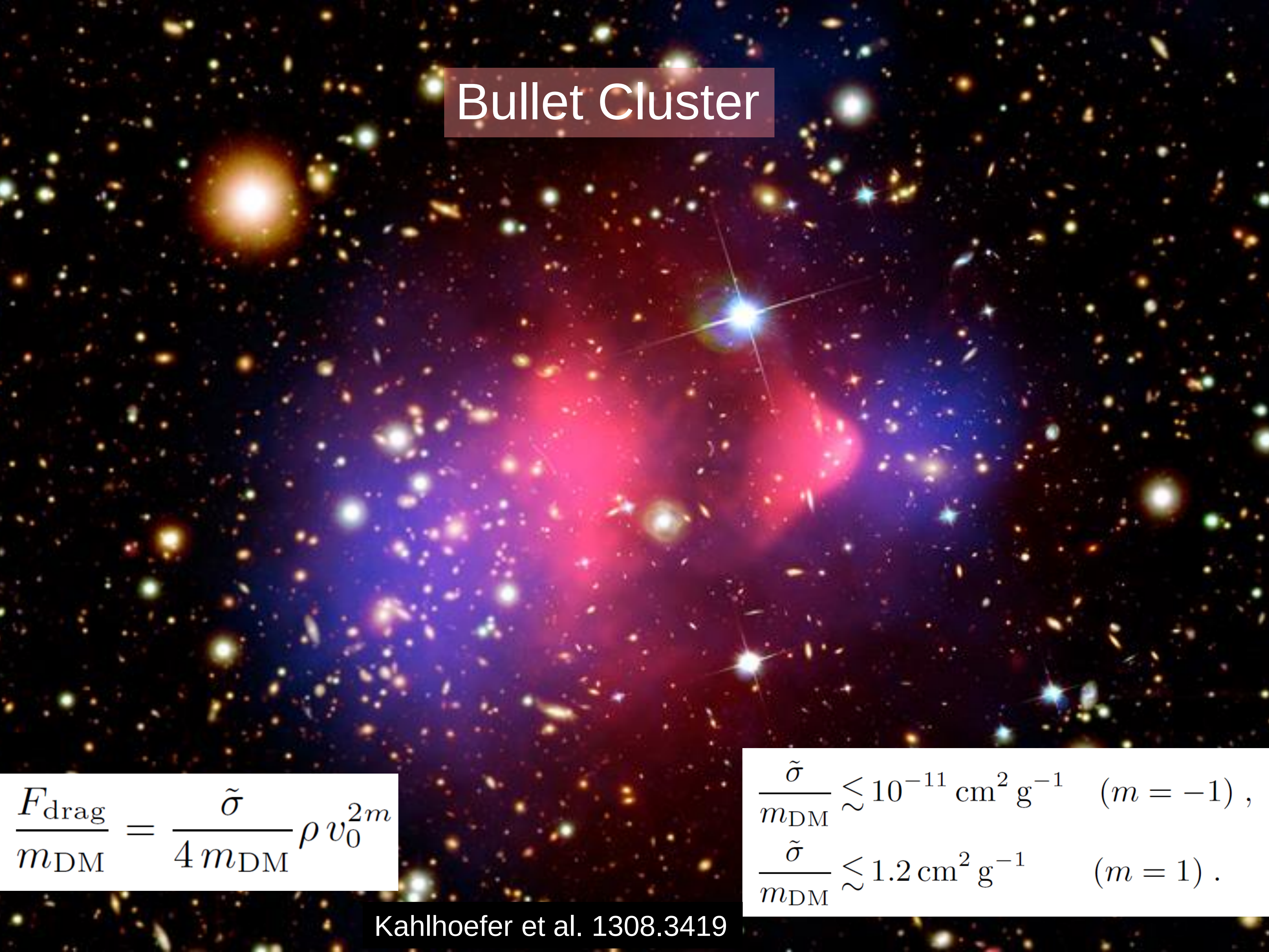
However for real astrophysical systems, things can get non-perturbative, need to use classical expressions from fitting numerical modelling of individual classical scattering in potentials

$$\sigma_T^{\mathrm{clas}} = \begin{cases} \frac{4\pi}{m_\phi^2}\beta^2 \ln\left(1 + \beta^{-1}\right) & \beta \lesssim 10^{-1} \\ \frac{8\pi}{m_\phi^2}\beta^2/\left(1 + 1.5\beta^{1.65}\right) & 10^{-1} \lesssim \beta \lesssim 10^3 \\ \frac{\pi}{m_\phi^2}\left(\ln\beta + 1 - \frac{1}{2}\ln^{-1}\beta\right)^2 & \beta \gtrsim 10^3 \end{cases}$$

$$\beta \equiv 2\alpha_X m_\phi/(m_X v^2)$$

Also many resonant effects (see e.g. Zurek 1302.3898)

Bullet Cluster



$$\frac{F_{\rm drag}}{m_{\rm DM}} = \frac{\tilde{\sigma}}{4\, m_{\rm DM}} \rho\, v_0^{2m}$$

$$\frac{\tilde{\sigma}}{m_{\rm DM}} \lesssim 10^{-11}\,\mathrm{cm}^2\,\mathrm{g}^{-1} \qquad (m=-1)\,,$$

$$\frac{\tilde{\sigma}}{m_{\rm DM}} \lesssim 1.2\,\mathrm{cm}^2\,\mathrm{g}^{-1} \qquad (m=1)\,.$$

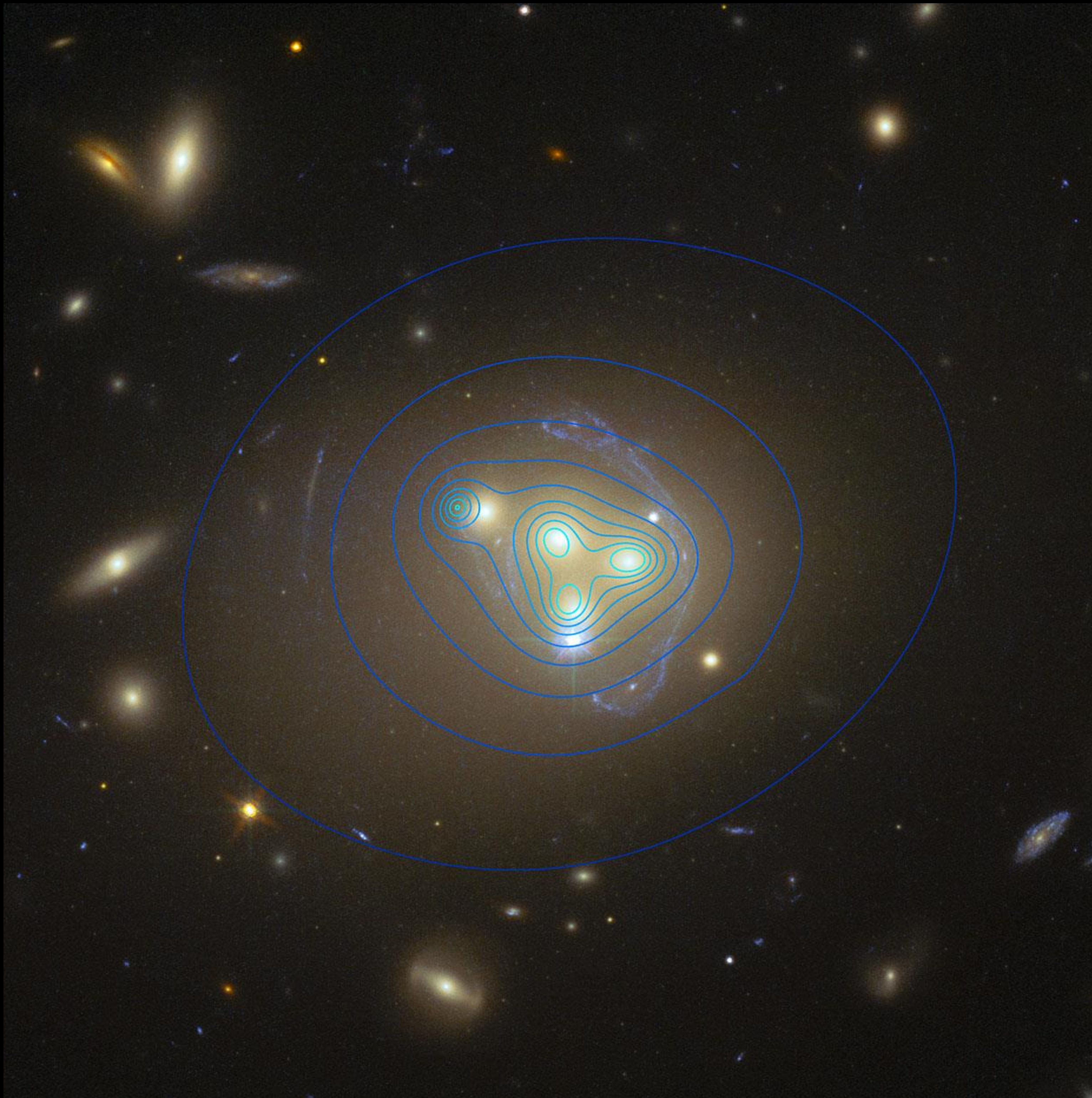
Kahlhoefer et al. 1308.3419

4 large elliptical Galaxies at the centre of Cluster Abell 4827

Mass appears displaced from galaxy

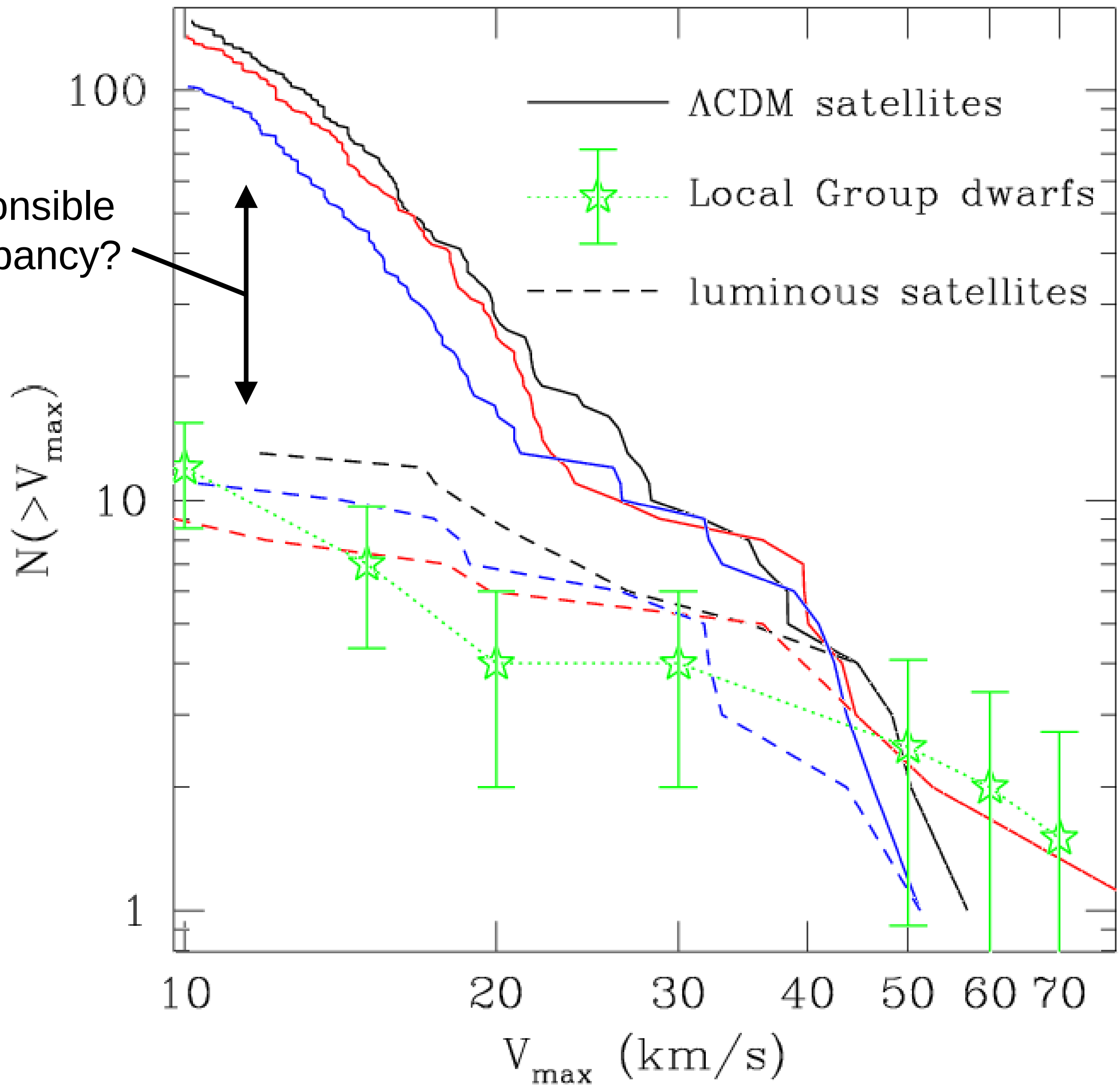
Could be a signal of dark matter self interaction – dark matter pressure…

Massey et al arXiv:1504.03388

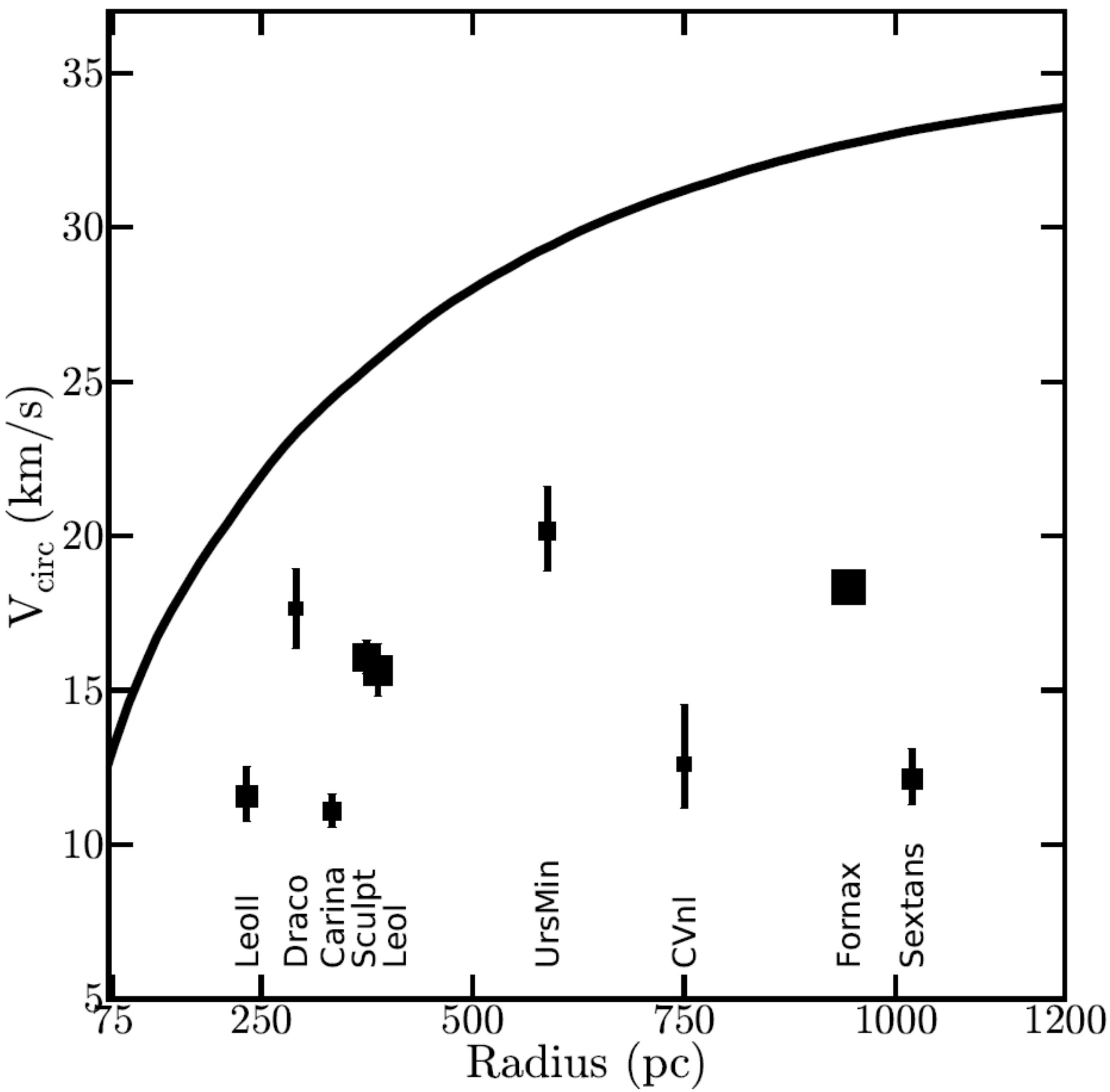


Velocity function of luminous satellites

What is responsible
or this discrepancy?



The Too big to fail Problem



(Boylin-Kolchin et al 2012)

line is rotation curve of typical largest sub halo of simulated Milky Way Galaxy

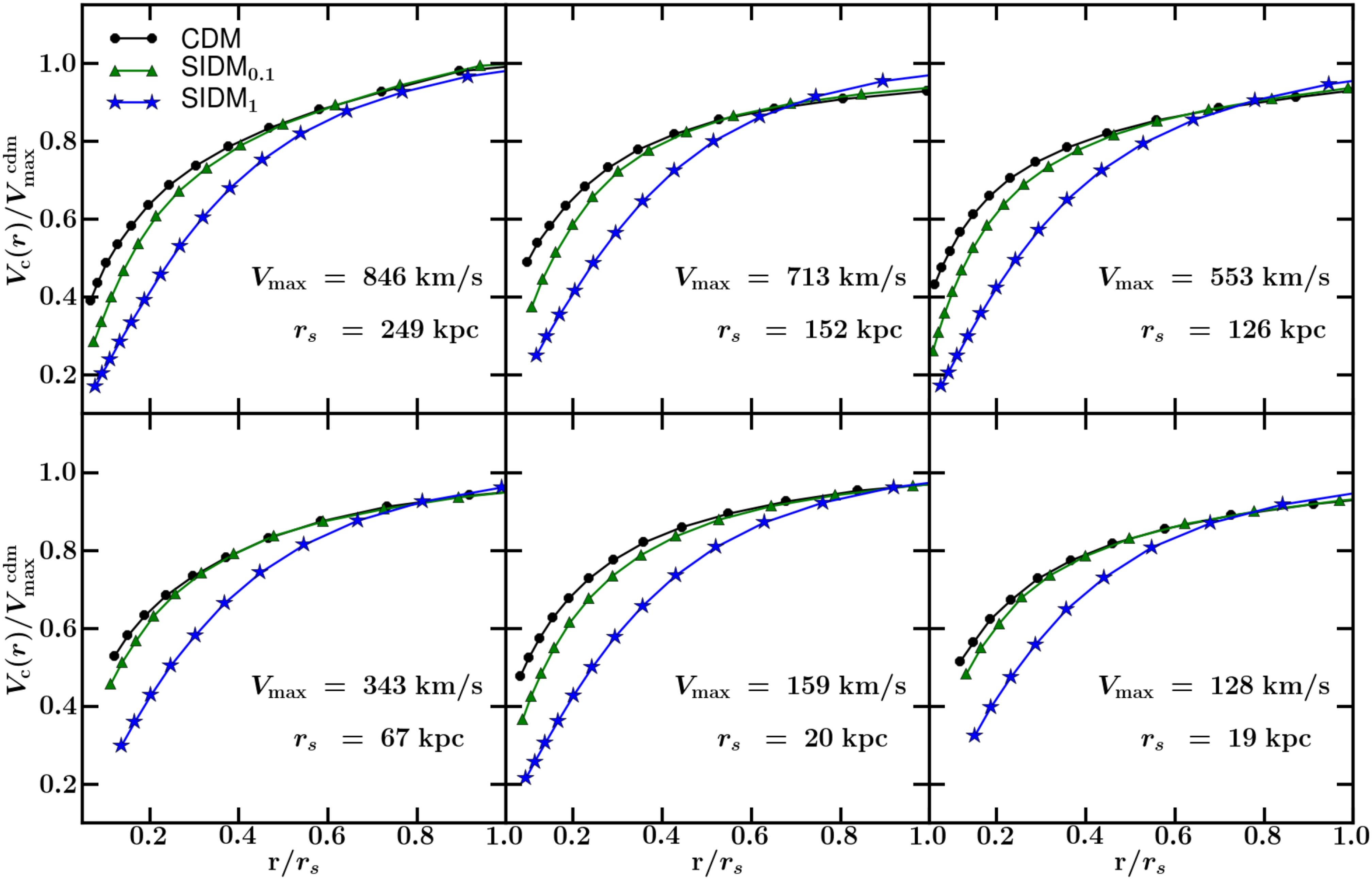
data points are observed circular velocities of largest sub halos at their half light radii

None of them are close to being large enough

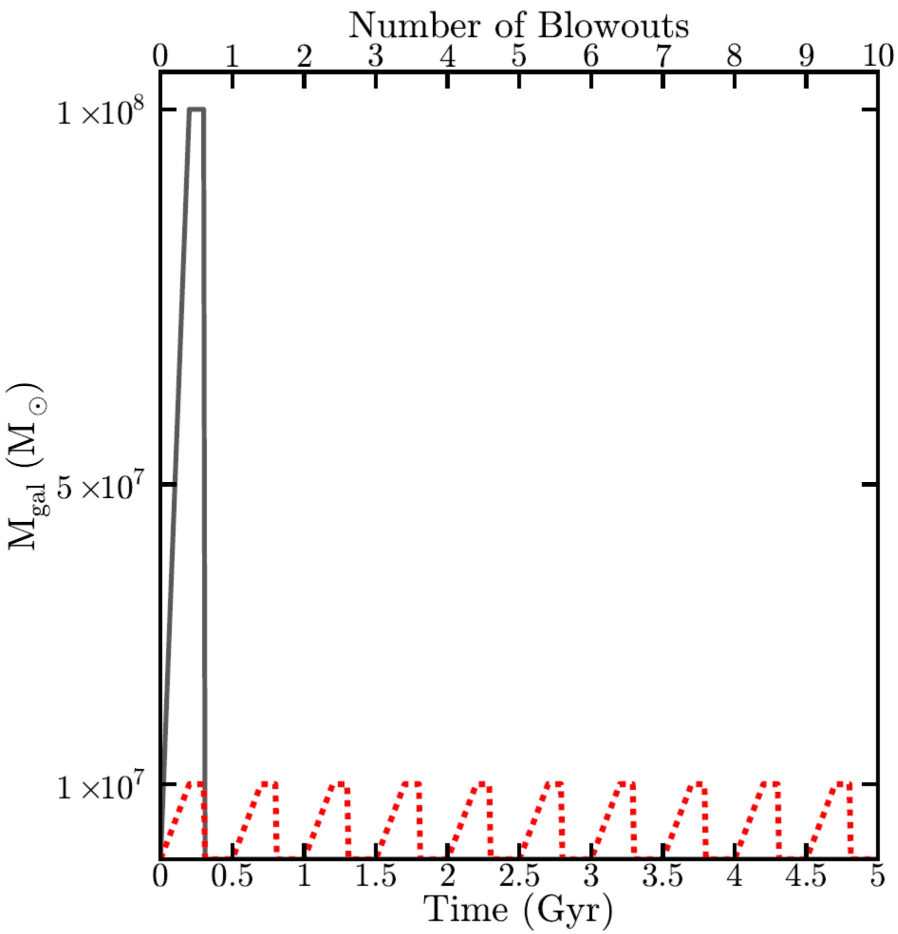
Possible solution is that they posess large cores

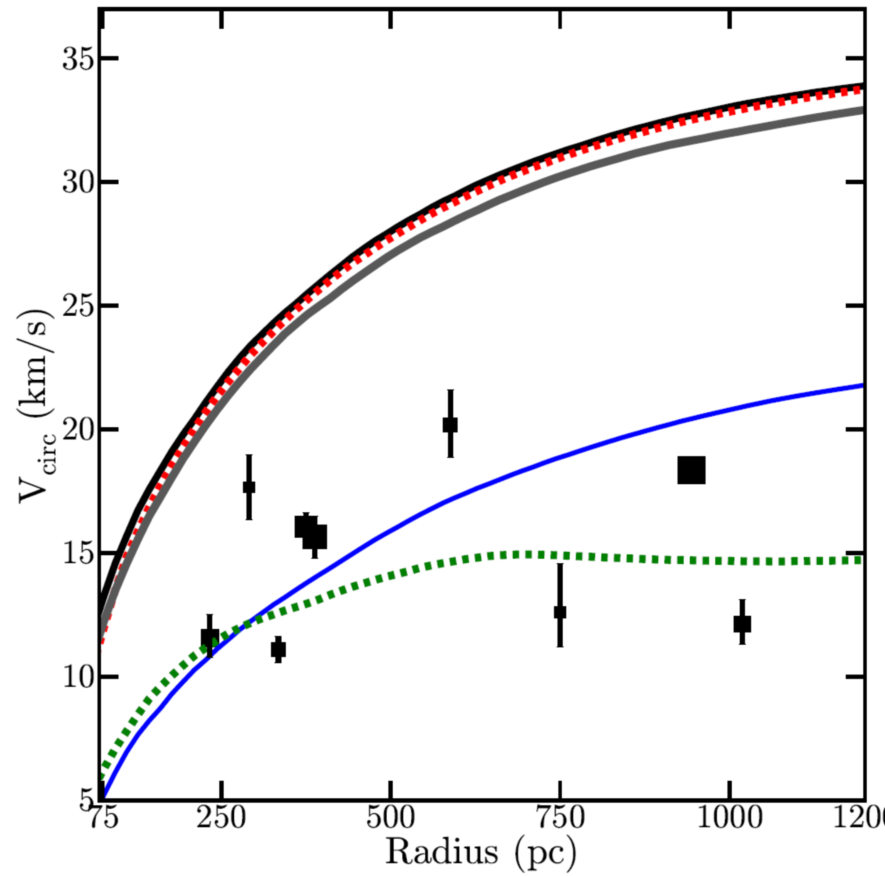
The Too big to fail Problem

Circular velocity is certainly affected by self interactions, maybe enough? Rocha et al 1208.3025



The Too big to fail Problem



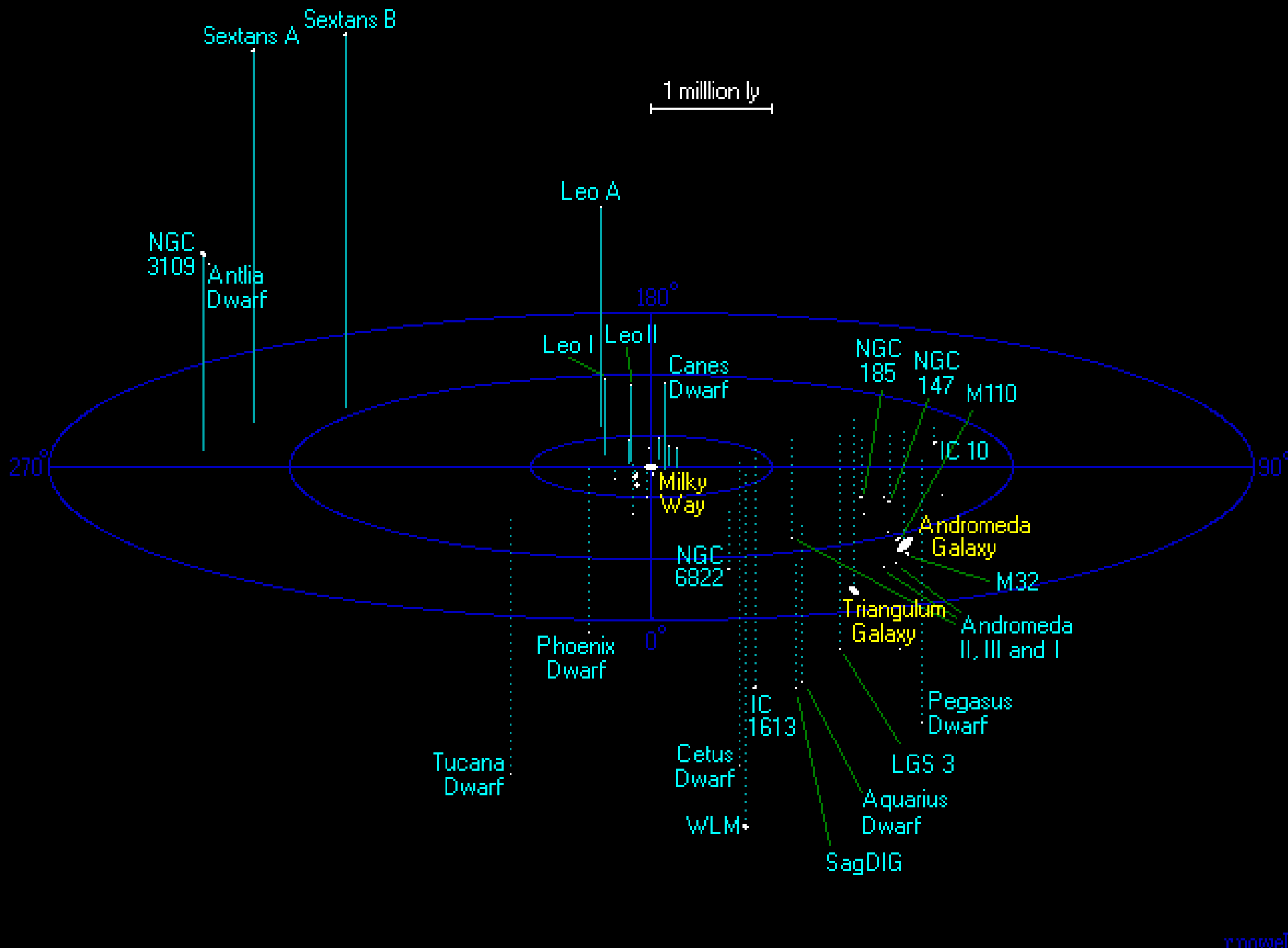


non-adiabatically “blowing out” central potential (mimic cycles of star formation) helps although strength of this effect is perhaps too weak (Garrison-Kimmel et al 1301.3137)

See also recent nature paper on disequilibrium modelling (tidal stripping) Ural

dSphs - Dwarf Spheroidal Galaxies

dSphs - Dwarf Spheroidal Galaxies

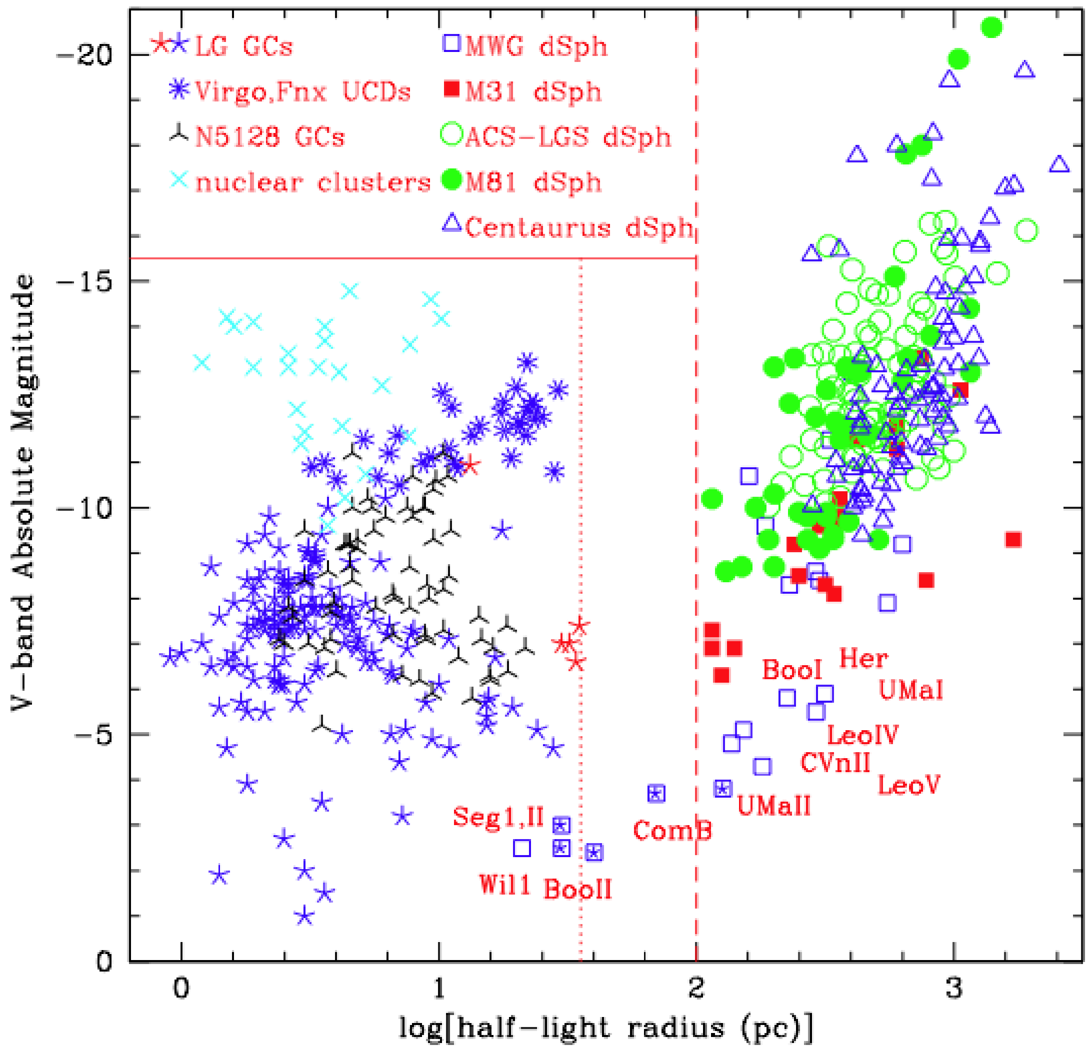


Dwarf spheroidals: basic properties

$$L = 2\times10^3 L_\odot - 2\times10^7 L_\odot \quad \sigma_0 \sim 7-12\,\mathrm{km\,s^{-1}} \quad r_0 \approx 130-500\,\mathrm{pc}$$

Low luminosity, gas-free satellites of Milky Way and M31

Large mass-to-light ratios (10 to 100), smallest stellar systems containing dark matter?



Luminosities and sizes of Globular Clusters and dSph

Gilmore et al 2009

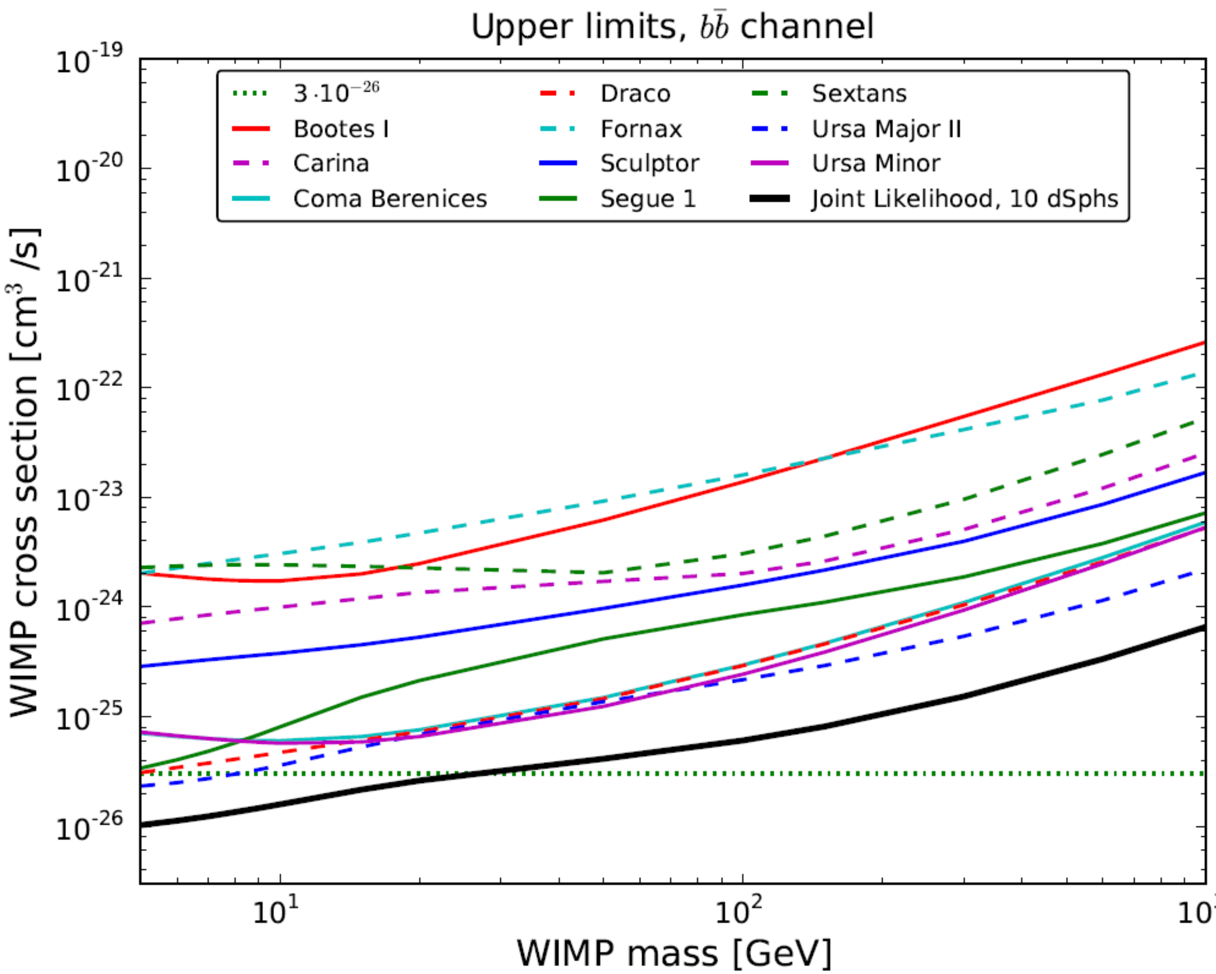
What can Inner Density Profile of dSph galaxies tell us?

Expected WIMP annihilation signal

Is dark matter self interacting?

To some extent, is dark matter warm/hot-cold/mixed/decaying

Fermi constraints on gamma ray emission from Dwarf Spheroidals



arXiv:1108.3546

However, this makes assumptions about the density distribution that many people question.

What can Inner Density Profile of dSph galaxies tell us?

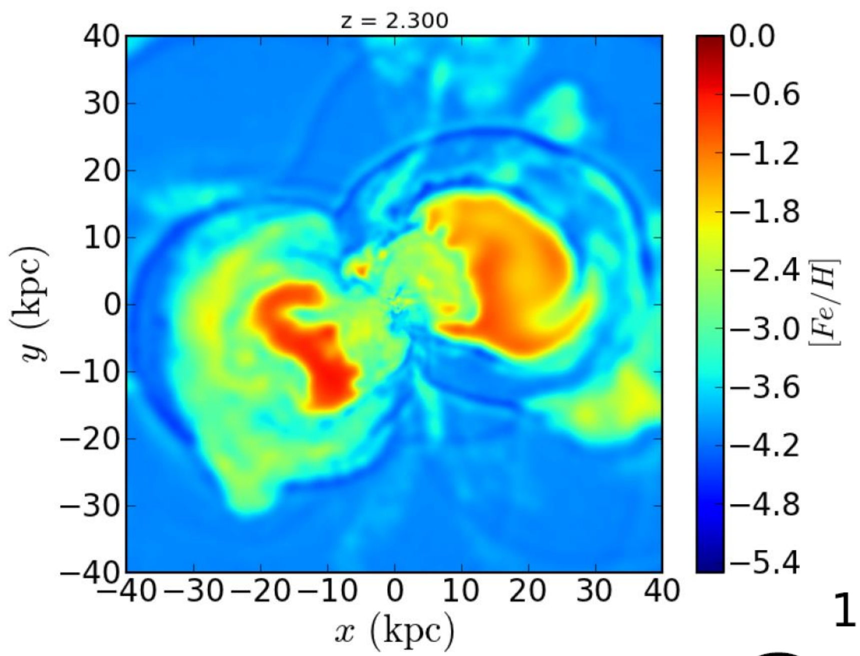
Expected WIMP annihilation signal

Is dark matter self interacting?

To some extent, is dark matter warm/hot-cold/mixed/decaying

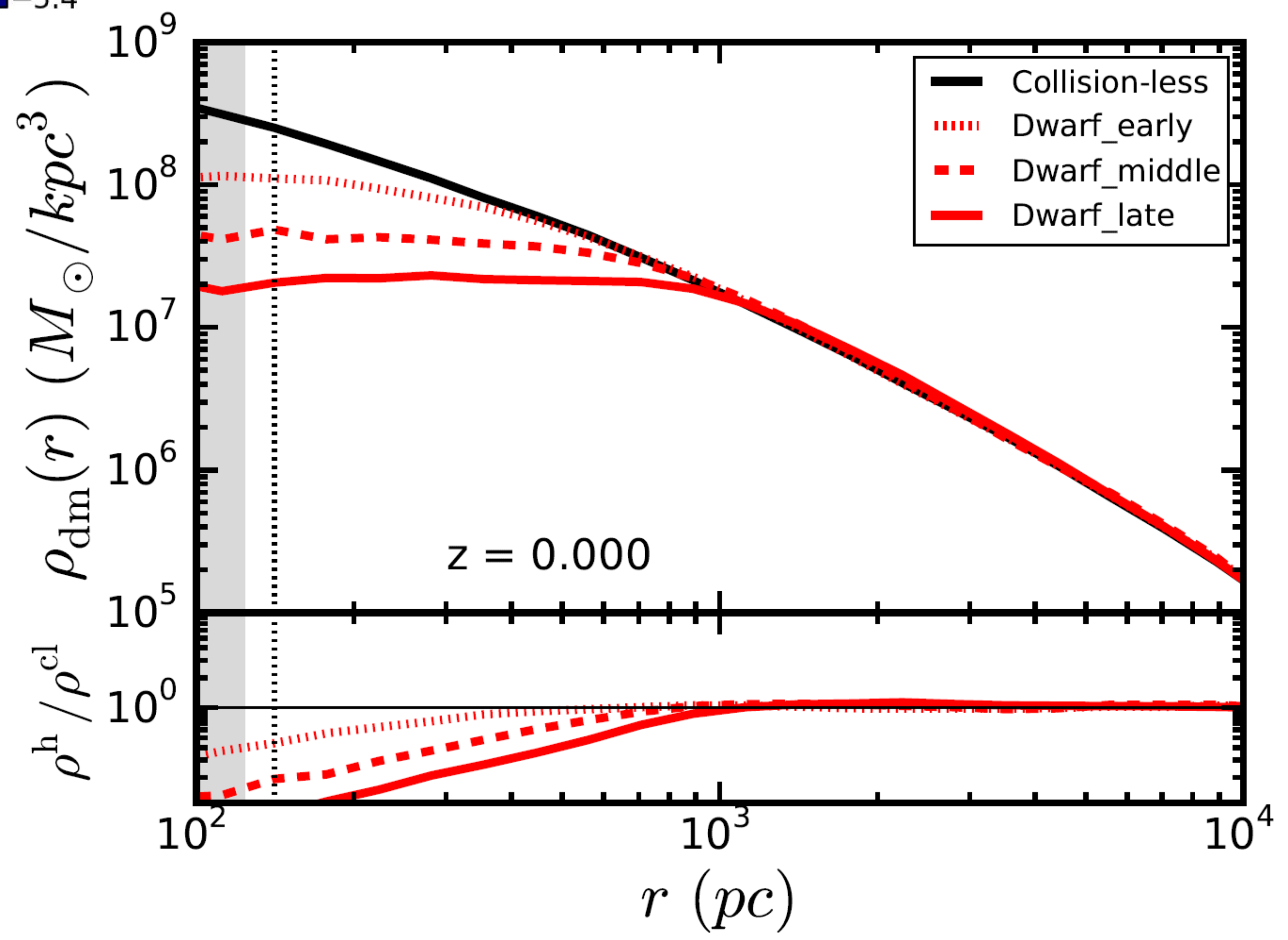
BORING HEALTH WARNING:-

Gastrophysical effects can affect inner densities as well as sexy new physics



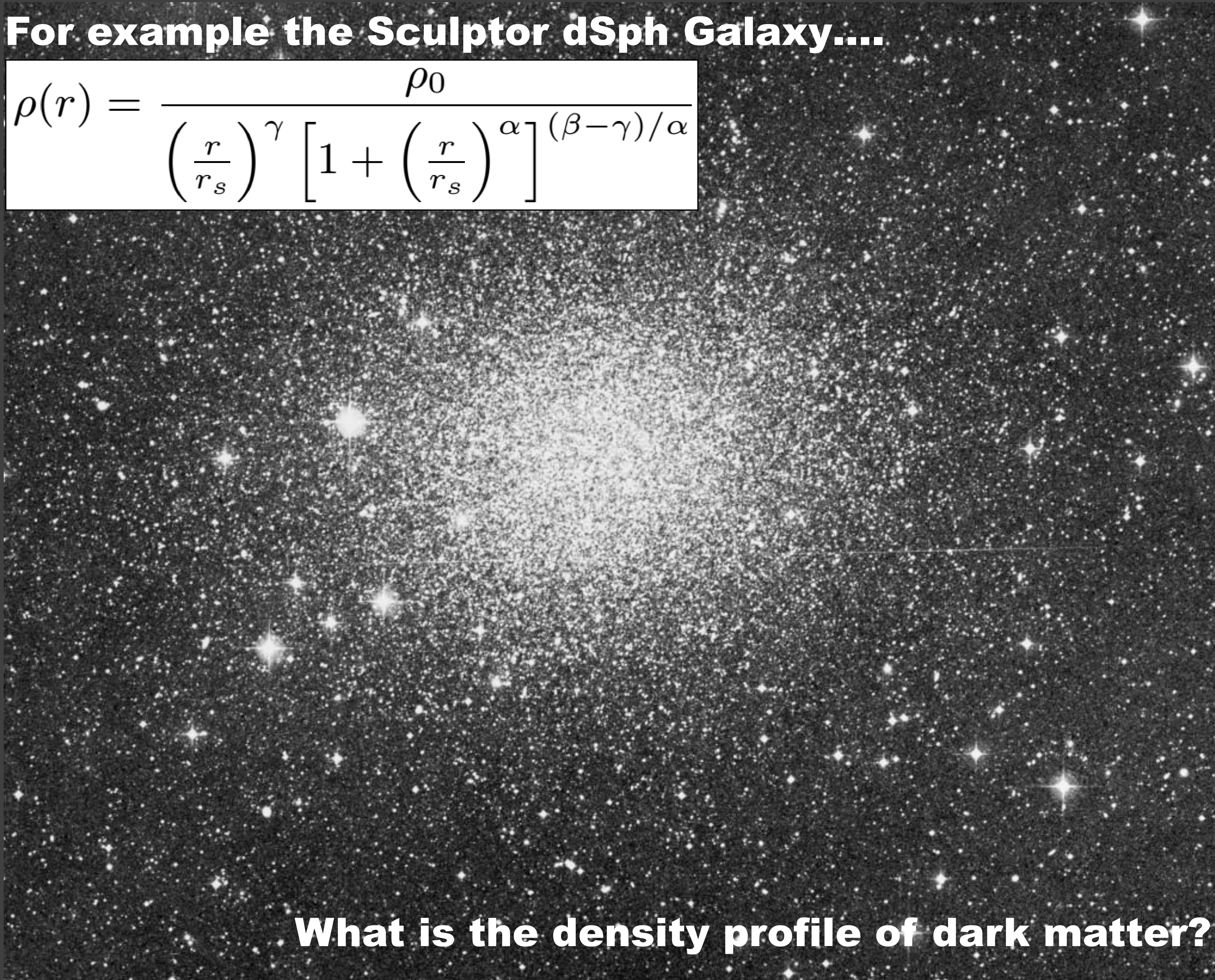
Baryonic Feedback can also affect Dark Matter Density

Onorbe et al
arXiv:1502.02036



For example the Sculptor dSph Galaxy....

$$\rho(r) = \frac{\rho_0}{\left(\frac{r}{r_s}\right)^{\gamma}\left[1+\left(\frac{r}{r_s}\right)^{\alpha}\right]^{(\beta-\gamma)/\alpha}}$$



What is the density profile of dark matter?

How do you work out how much DM in Dwarf Spheroidals?

Use the Jeans equation and the line of sight stellar dispersion

Cannot observe this directly for stars so free parameter

Can obtain this by fitting data

$$\frac{1}{\rho}\frac{\partial}{\partial r}\left(\rho\sigma_R^2\right) + 2\frac{\beta\sigma_R^2}{r} = -\frac{GM}{r^2}$$

$$\beta \equiv 1 - \frac{\sigma_t^2}{\sigma_r^2}$$

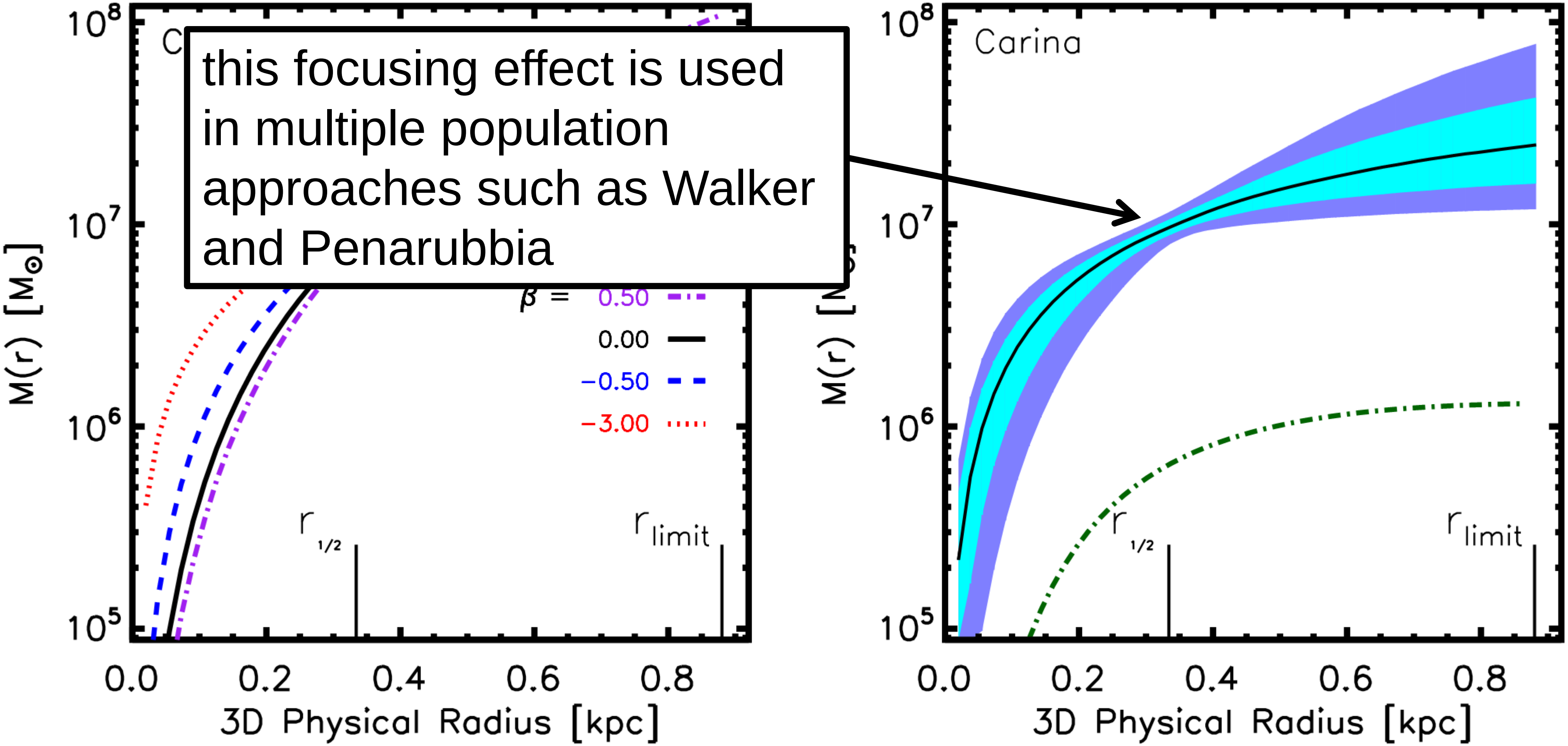
Tangential Velocity Dispersion

Radial Velocity Dispersion

line of sight dispersion then $\Sigma(R) = \int_{-\infty}^{\infty} \nu(r) dz = 2\int_R^{\infty} \frac{\nu(r) r}{\sqrt{r^2 - R^2}} \mathrm{d}r$

β degeneracy problem

this focusing effect is used in multiple population approaches such as Walker and Penarubbia



Plots from Wolf et al 0908.2995

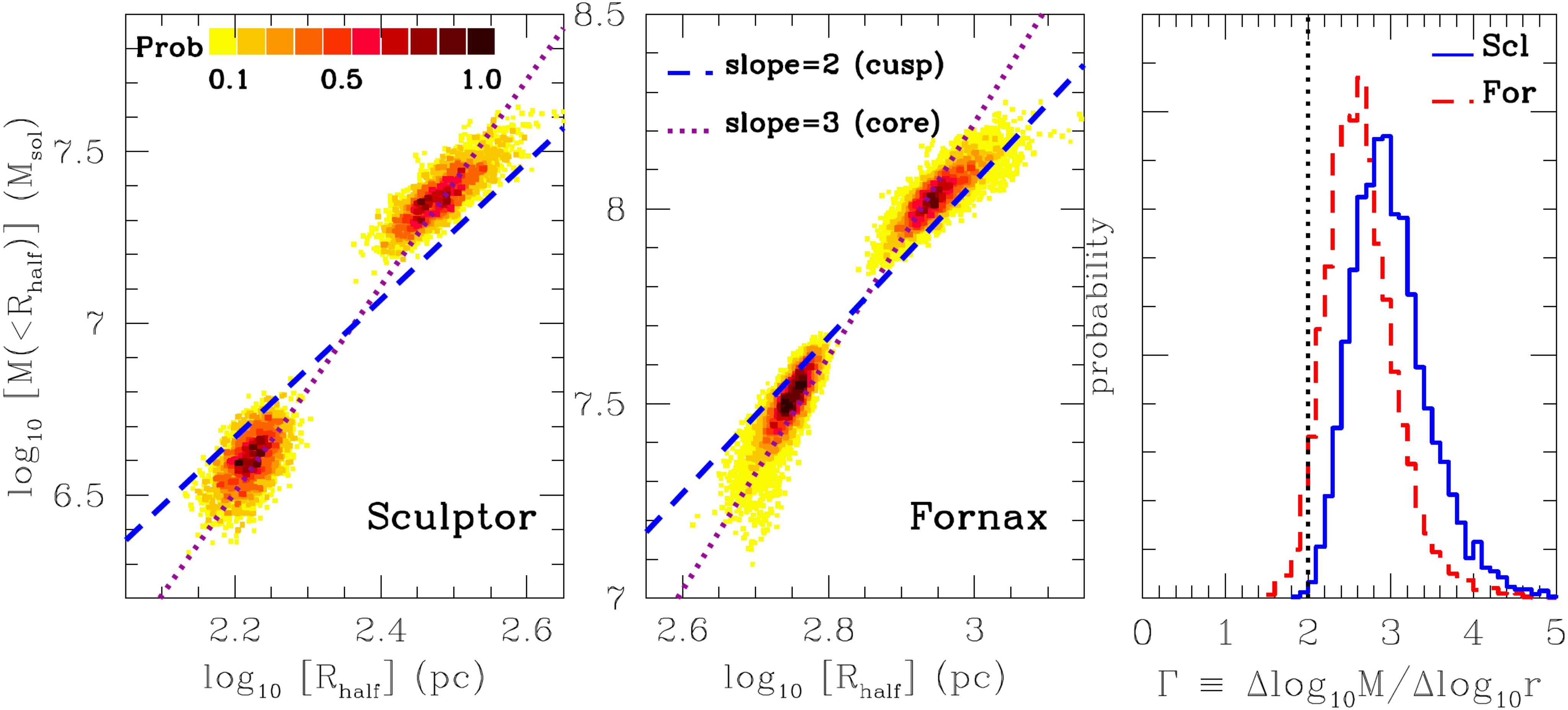
Only really sure of the enclosed mass at the half light radius.

Maybe this is enough for J-factors….

Example of core detection:-
Walker and Penarrubia Method

Split population into two using metallicity and then
look for radius at which enclosed mass degeneracy shrinks :-

two different radii, two different masses, can infer density profile.



arXiv:1108.2404

Can also use Higher Moments of Boltzmann Equation

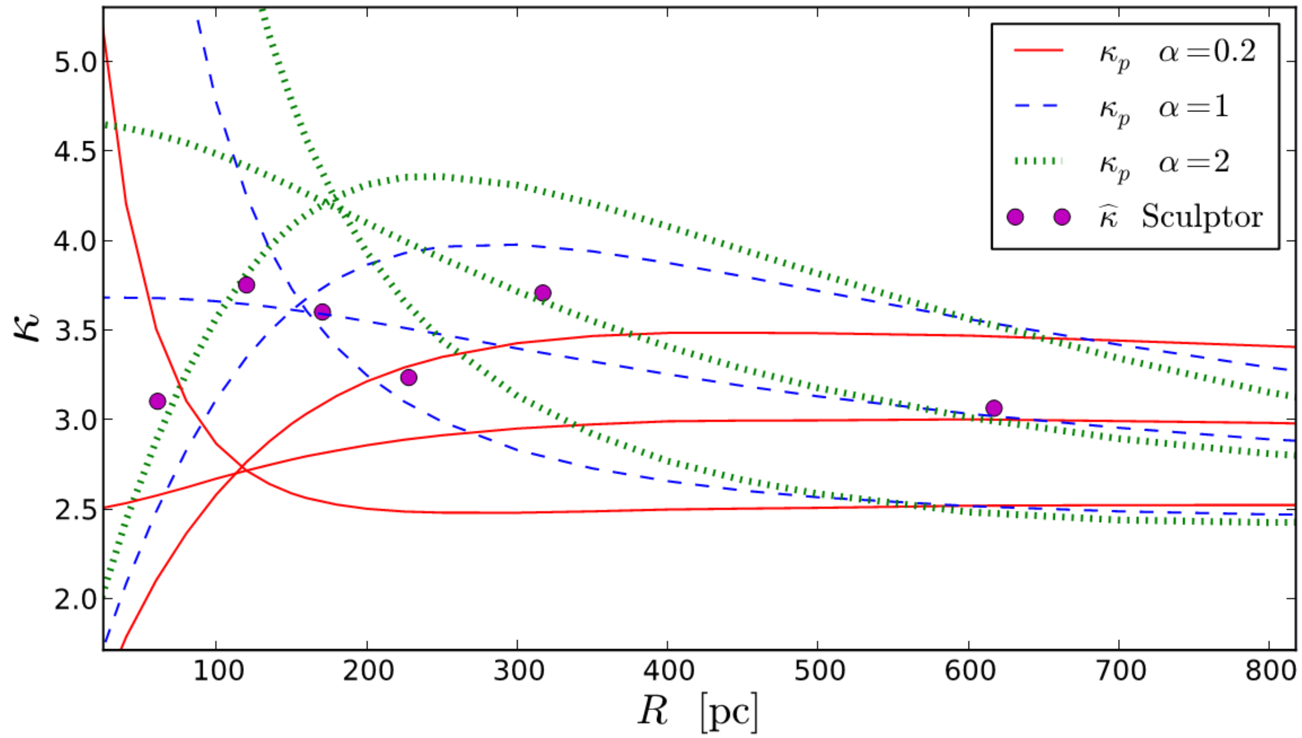
$$\frac{d(\nu\overline{v_r^4})}{dr} - \frac{3}{r}\nu\overline{v_r^2 v_t^2} + \frac{2}{r}\nu\overline{v_r^4} + 3\nu\sigma_r^2\frac{d\Phi}{dr} = 0$$

$$\frac{d(\nu\overline{v_r^2 v_t^2})}{dr} - \frac{1}{r}\nu\overline{v_t^4} + \frac{4}{r}\nu\overline{v_r^2 v_t^2} + \nu\sigma_t^2\frac{d\Phi}{dr} = 0$$

Now you have a new, higher moment anisotropy parameter which can be expressed in several ways, including

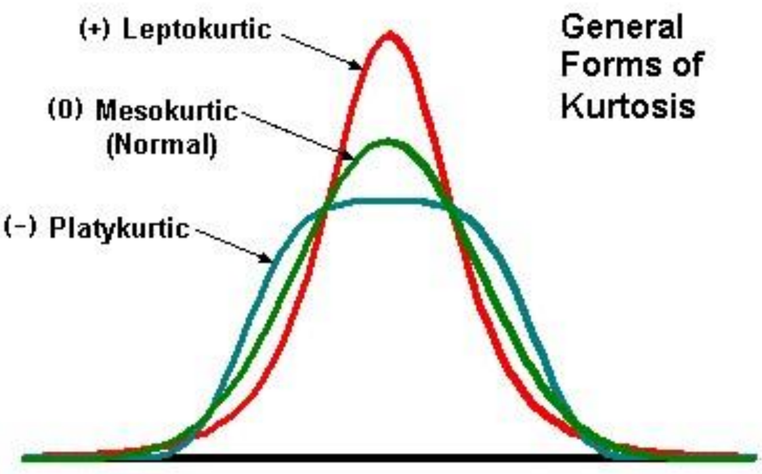
$$\beta' = 1 - \frac{3}{2}\frac{\langle v_r^2 v_t^2\rangle}{\langle v_r^4\rangle}$$

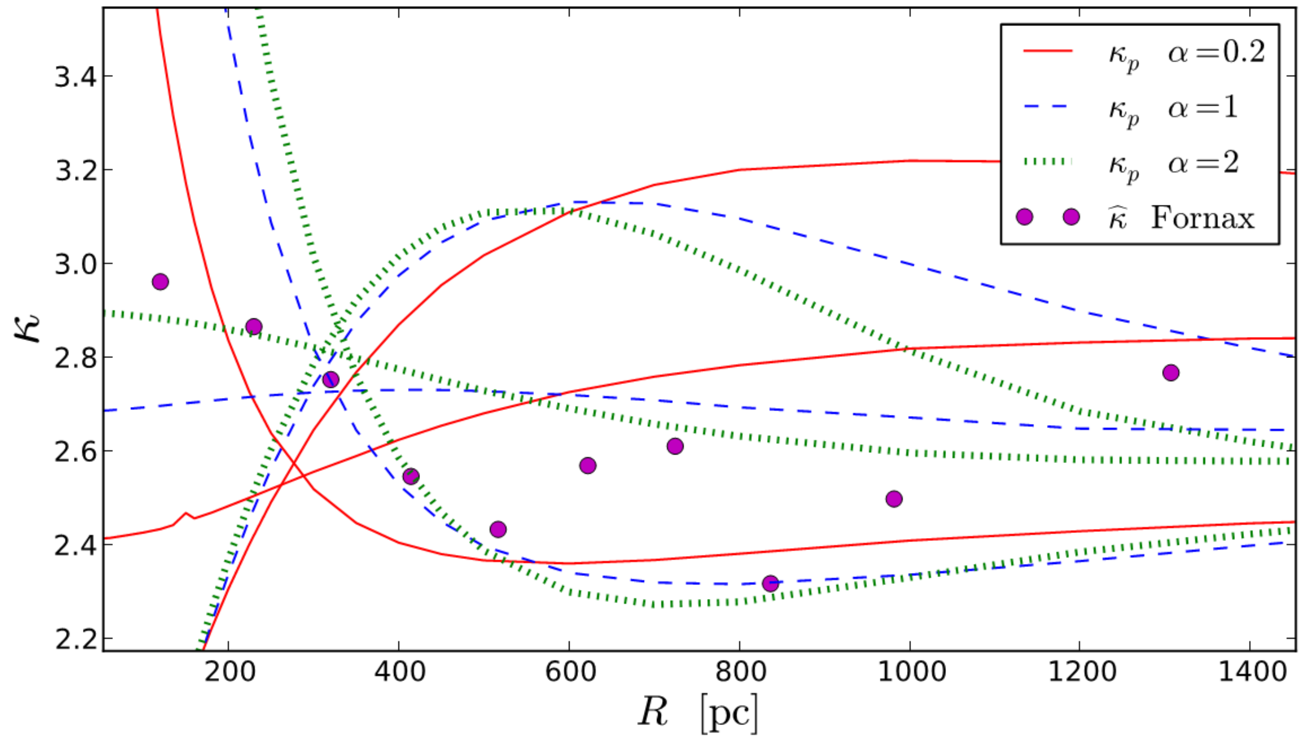
MF with Tom Richardson, see also Amorisco and Evans, Lokas, Mamon, Merrifield and Kent, Napolitano et al etc…



Actually there is a good reason, Sculptor is quite Leptokurtic

i.e. $\kappa > 3$





Using Virial Estimators

The projected virial theorem takes you from $2K_z + W_z = 0$ to (Merrifield and Kent)

$$\int_0^\infty \Sigma\langle v_z^2\rangle R\mathrm{dR} = \frac{2}{3}\int_0^\infty \nu\frac{\mathrm{d}\Phi}{\mathrm{dr}}\mathrm{r}^3\mathrm{dr}$$

This actually alone gives up more or less same information about enclosed mass at half light radius as full second order Jeans analysis.

At Fourth order, there are two new virial estimators

$$\int_0^\infty \Sigma\langle v_z^4\rangle R\mathrm{dR} = \frac{2}{5}\int_0^\infty \nu(5-2\beta)\langle \mathrm{v_r^2}\rangle\frac{\mathrm{d}\Phi}{\mathrm{dr}}\mathrm{r}^3\mathrm{dr}$$

$$\int_0^\infty \Sigma\langle v_z^4\rangle R^3\mathrm{dR} = \frac{4}{35}\int_0^\infty \nu(7-6\beta)\langle \mathrm{v_r^2}\rangle\frac{\mathrm{d}\Phi}{\mathrm{dr}}\mathrm{r}^5\mathrm{dr}$$

Again we find that these contain nearly as much information as full fourth order Jeans Equations
Although note, you now have to solve the full Jeans Equation at second order
as you require $\beta(r)$ and $\langle v_r^2\rangle(r)$

Normalised Virial Estimators

We define two new normalised Virial Estimators

$$\zeta_A = \frac{\langle v_z^4 \rangle_\star}{\langle v_z^2 \rangle_\star^2} = \frac{9N_{\rm tot}}{10} \frac{\int_0^\infty \nu(5-2\beta)\langle v_r^2 \rangle \frac{\mathrm{d}\Phi}{\mathrm{dr}} r^3 \mathrm{dr}}{\left(\int_0^\infty \nu \frac{\mathrm{d}\Phi}{\mathrm{dr}} r^3 \mathrm{dr}\right)^2}$$

$$\zeta_B = \frac{\left(\langle v_z^4 \rangle R^2\right)_\star}{\langle v_z^2 \rangle_\star^2 R_\star^2} = \frac{9N_{\rm tot}^2}{35} \frac{\int_0^\infty \nu(7-6\beta)\langle v_r^2 \rangle \frac{\mathrm{d}\Phi}{\mathrm{dr}} r^5 \mathrm{dr}}{\left(\int_0^\infty \nu \frac{\mathrm{d}\Phi}{\mathrm{dr}} r^3 \mathrm{dr}\right)^2 \int_0^\infty \Sigma(R) R^3 \mathrm{dR}}$$

Where the * denotes the following weighting:-

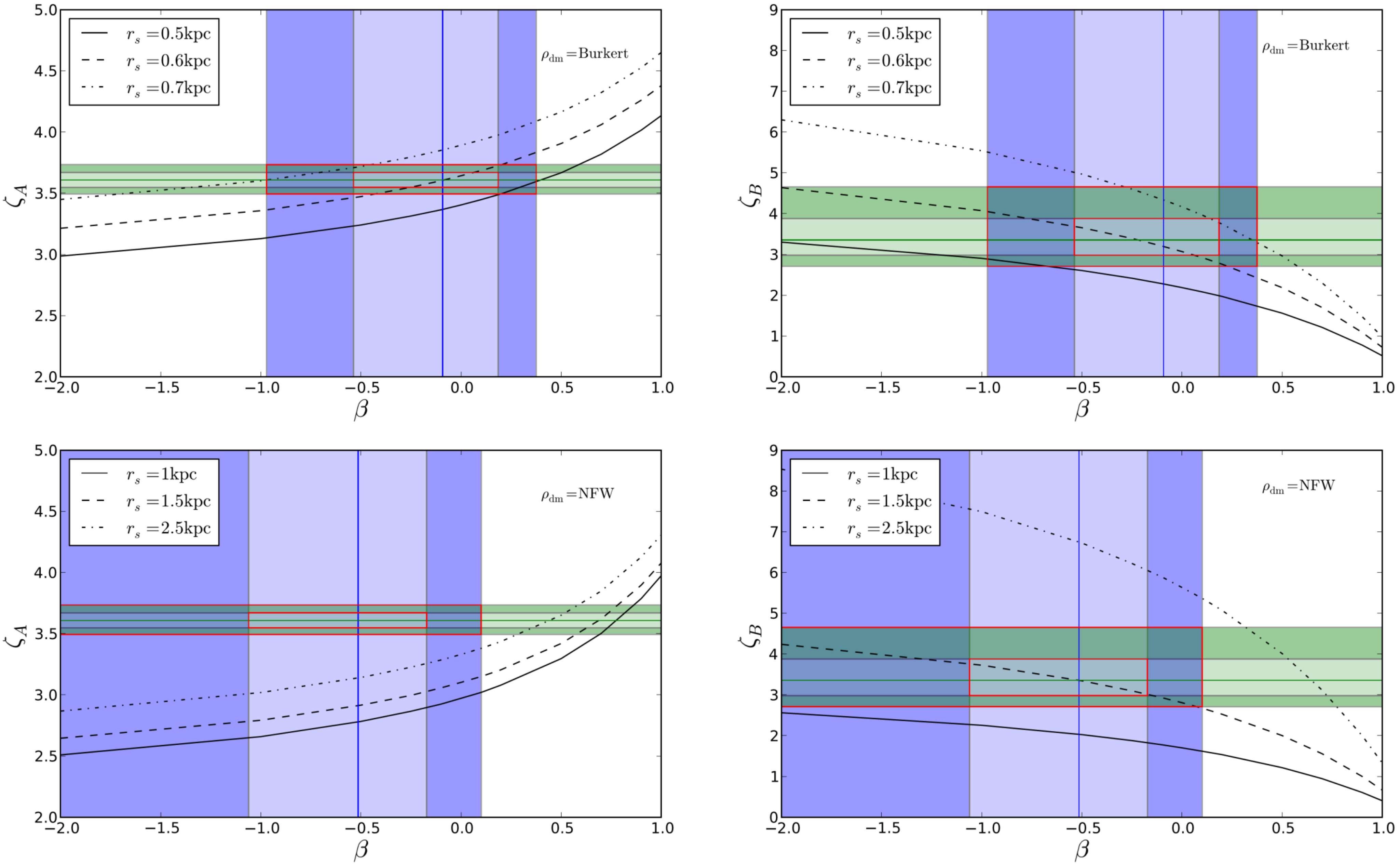
$$X_\star \equiv \frac{1}{N_{\rm tot}} \int_0^\infty X(R)\Sigma(R)R \, \mathrm{dR}$$

WHY DEFINE IN THIS WAY?

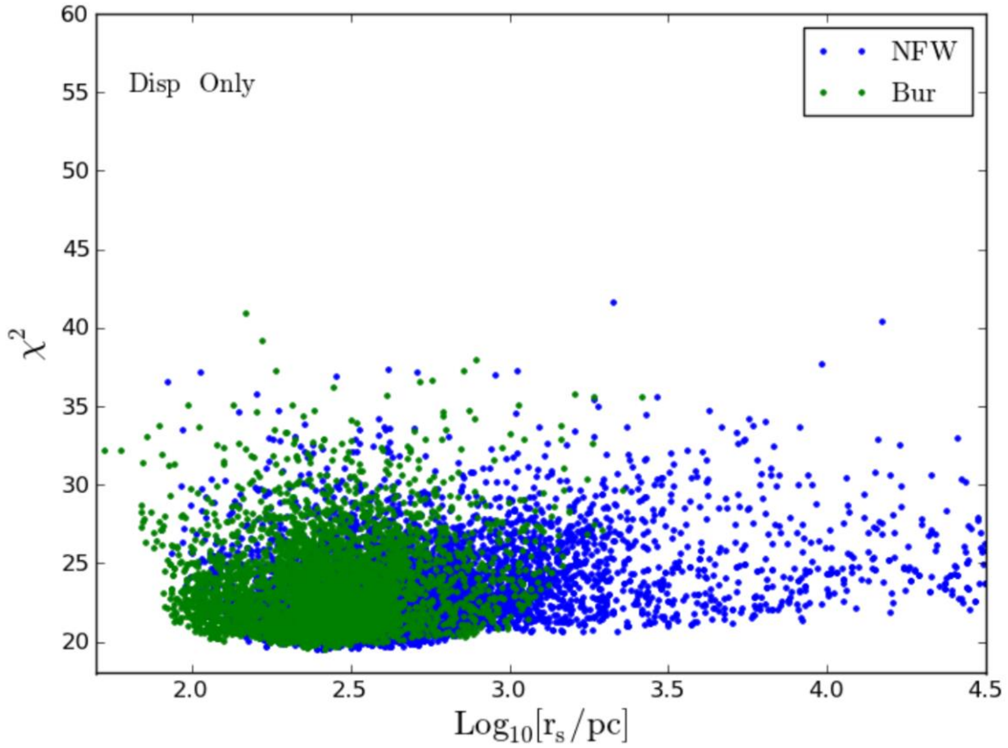
1. The weighting concentrates on the radii where the data is strongest
2. The normalisation removes 2nd order information, which is fitted separately

Richardson and Fairbairn arXiv:14016195

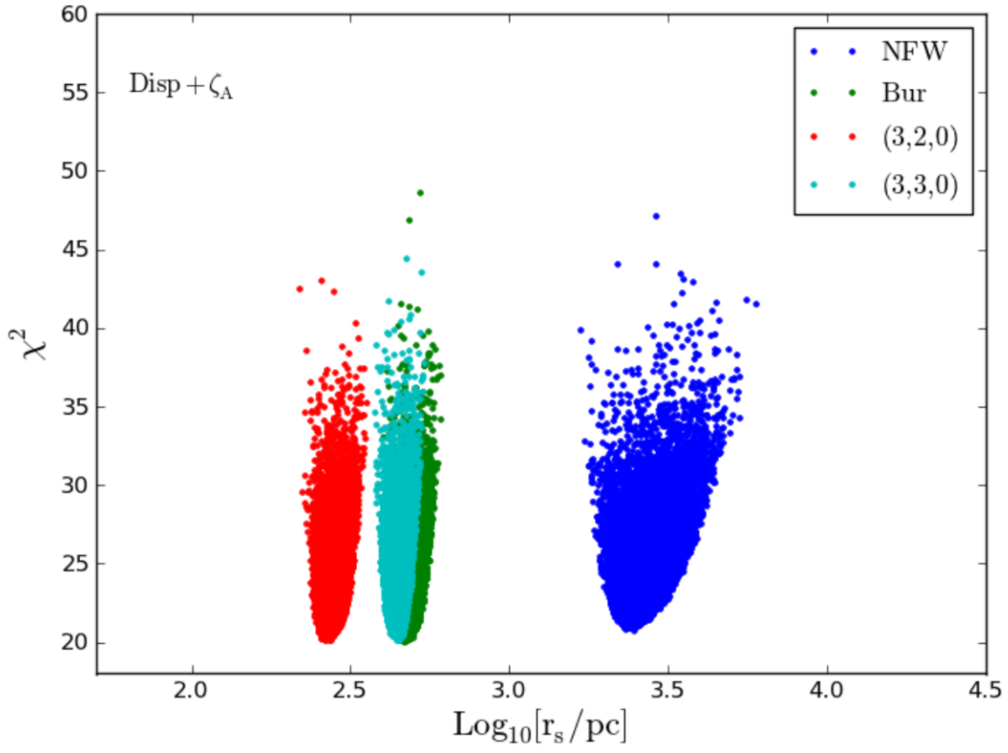
What can we do with these Normalised Virial Estimators?

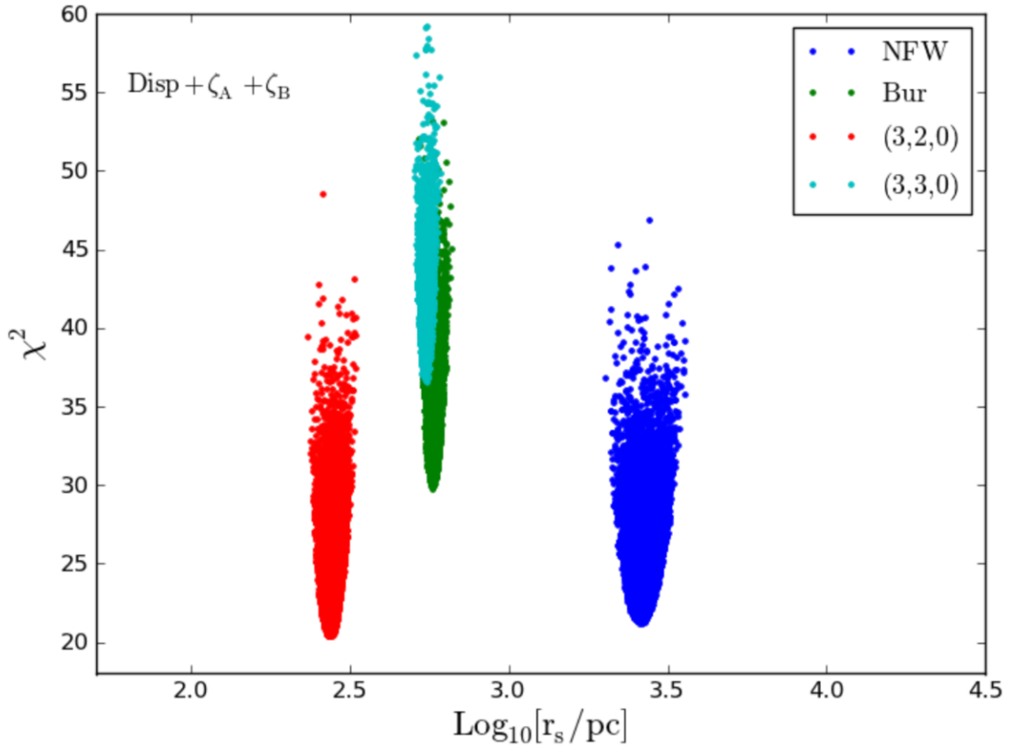


This is just an example where β = constant for Sculptor

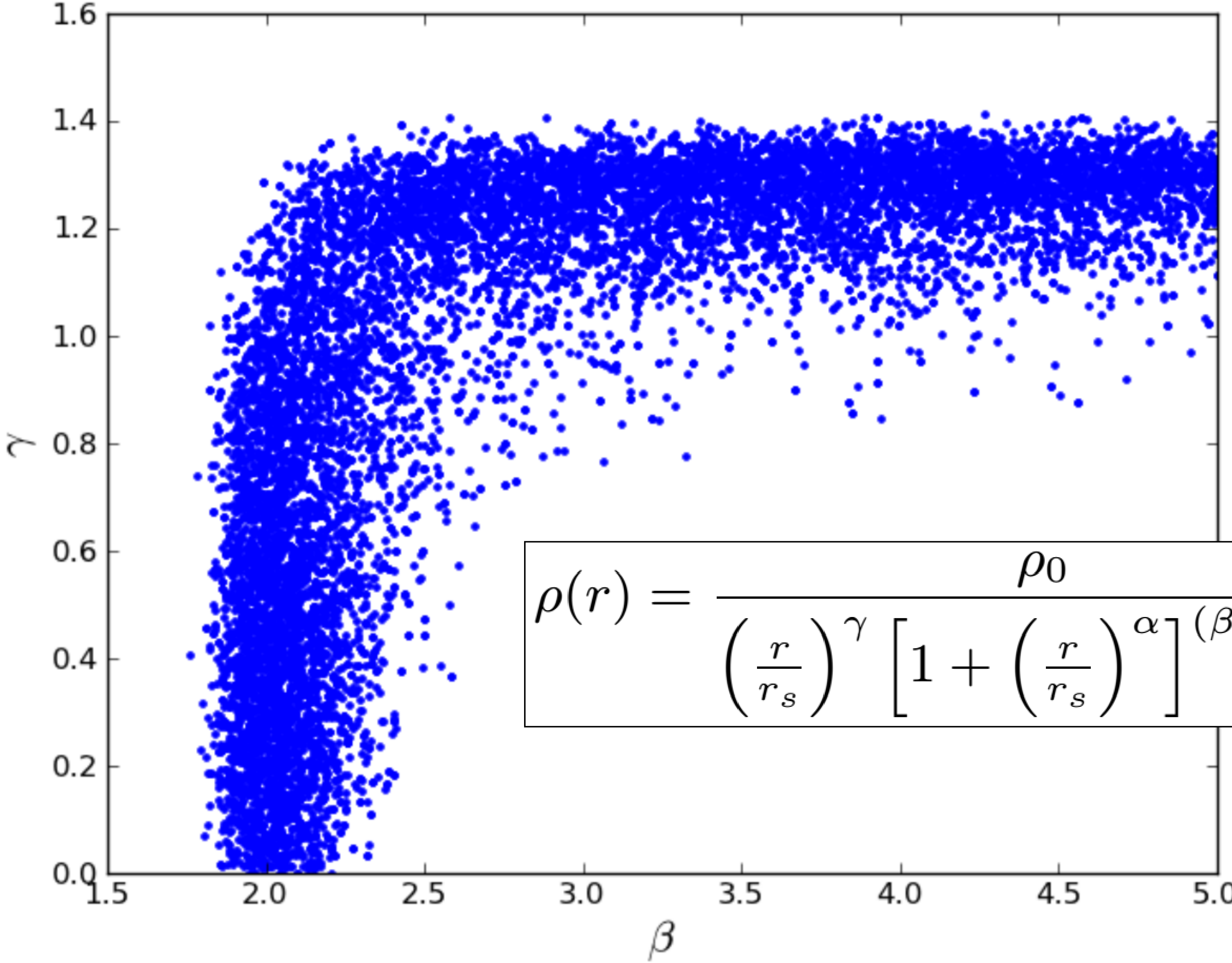


In particular ζ_A , which is more robust to statistics than ζ_B, really picks out the scale radius of a given profile.



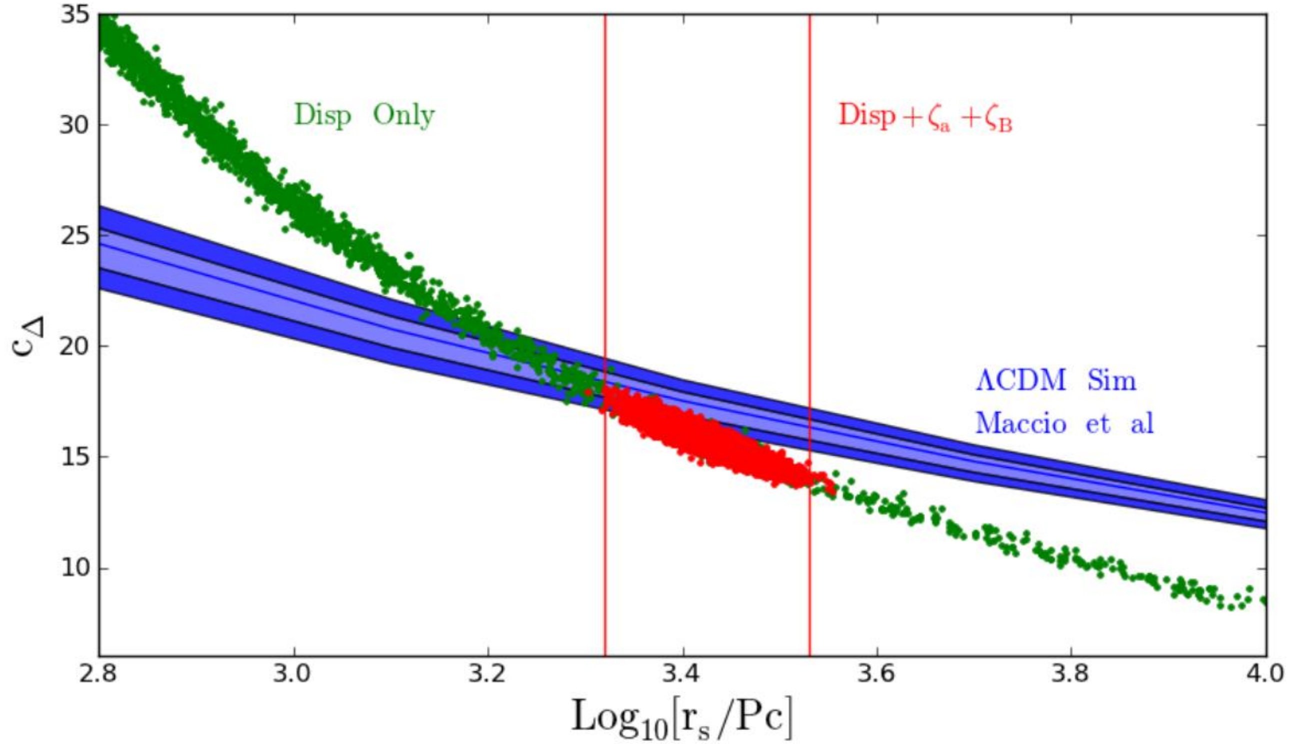


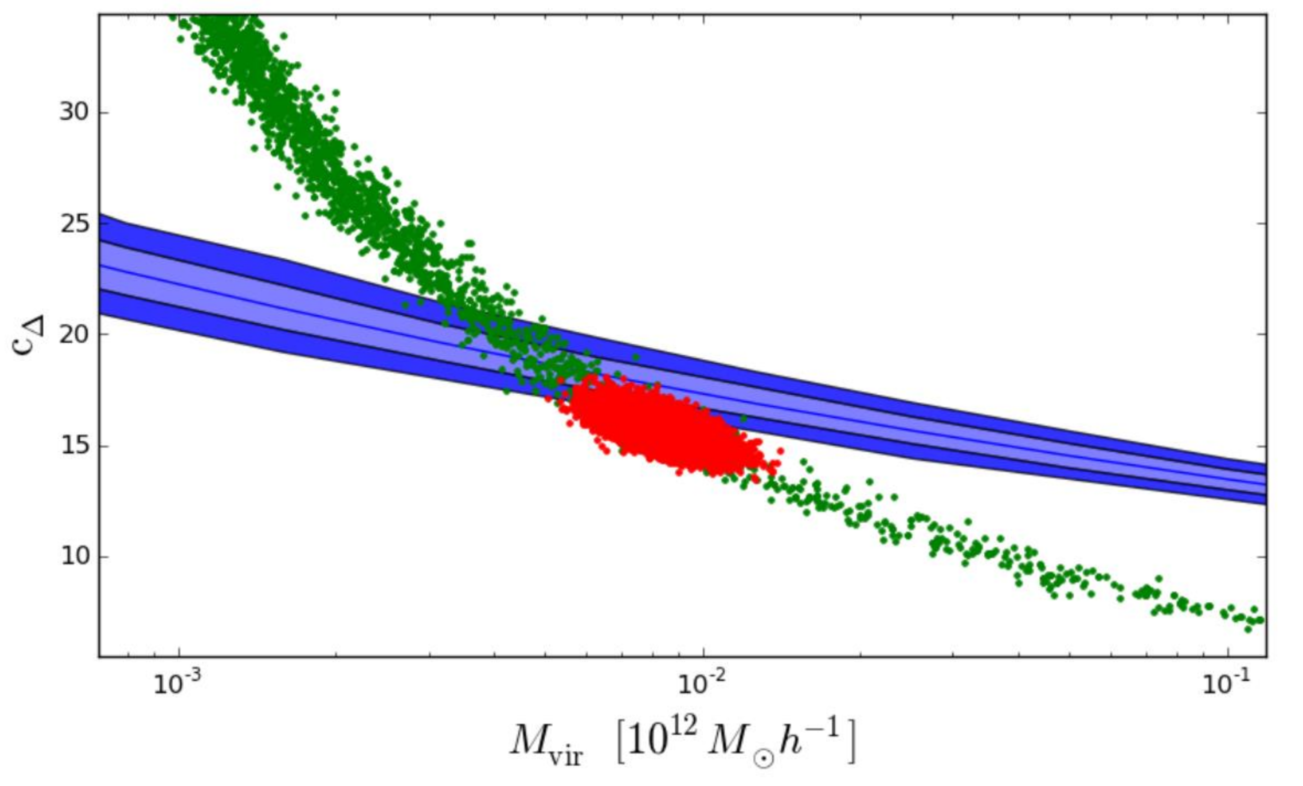
What Happens if we allow the density profile more Freedom?



$$\rho(r) = \frac{\rho_0}{\left(\frac{r}{r_s}\right)^{\gamma}\left[1+\left(\frac{r}{r_s}\right)^{\alpha}\right]^{(\beta-\gamma)/\alpha}}$$

When β is a more general function of r you can fit the Sculptor velocity dispersion better with NFW profiles.





One can start to see the power of ζ_A and ζ_B

Scenes from Spherical/triaxial Working Group at the Gaia Challenge

University of Surrrey, 2013

Remarkably difficult to re-produce the density profile of dwarf spheroidal galaxies.

- Huge industry, very difficult problem to re-create density parameters accurately.

DETERMINING THE NATURE OF DARK MATTER WITH ASTROMETRY

Louis E. Strigari[1,2] James S. Bullock[1], Manoj Kaplinghat[1],

astro-ph/0701581

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

$$\sigma_R^2(R) = \frac{2}{I_\star(R)} \int_R^\infty \left(1 - \beta + \beta\frac{R^2}{r^2}\right) \frac{\nu_\star \sigma_r^2 r dr}{\sqrt{r^2 - R^2}} \,,$$

$$\sigma_t^2(R) = \frac{2}{I_\star(R)} \int_R^\infty (1 - \beta) \frac{\nu_\star \sigma_r^2 r dr}{\sqrt{r^2 - R^2}} \,.$$

If we can determine the variance of velocity at right angles to the line of sight we can in principle break the beta degeneracy problem.

What we did

- Took list of magnitudes of brightest stars in Draco
- Used Theia projected performance provided by Doug etc.
- Obtained tangential velocity errors based upon 2 years of observation
- Applied these tangential velocity errors to mock data set from gaia challenge
- Attempted to reproduce density profile

A reminder – what are we trying to constrain?

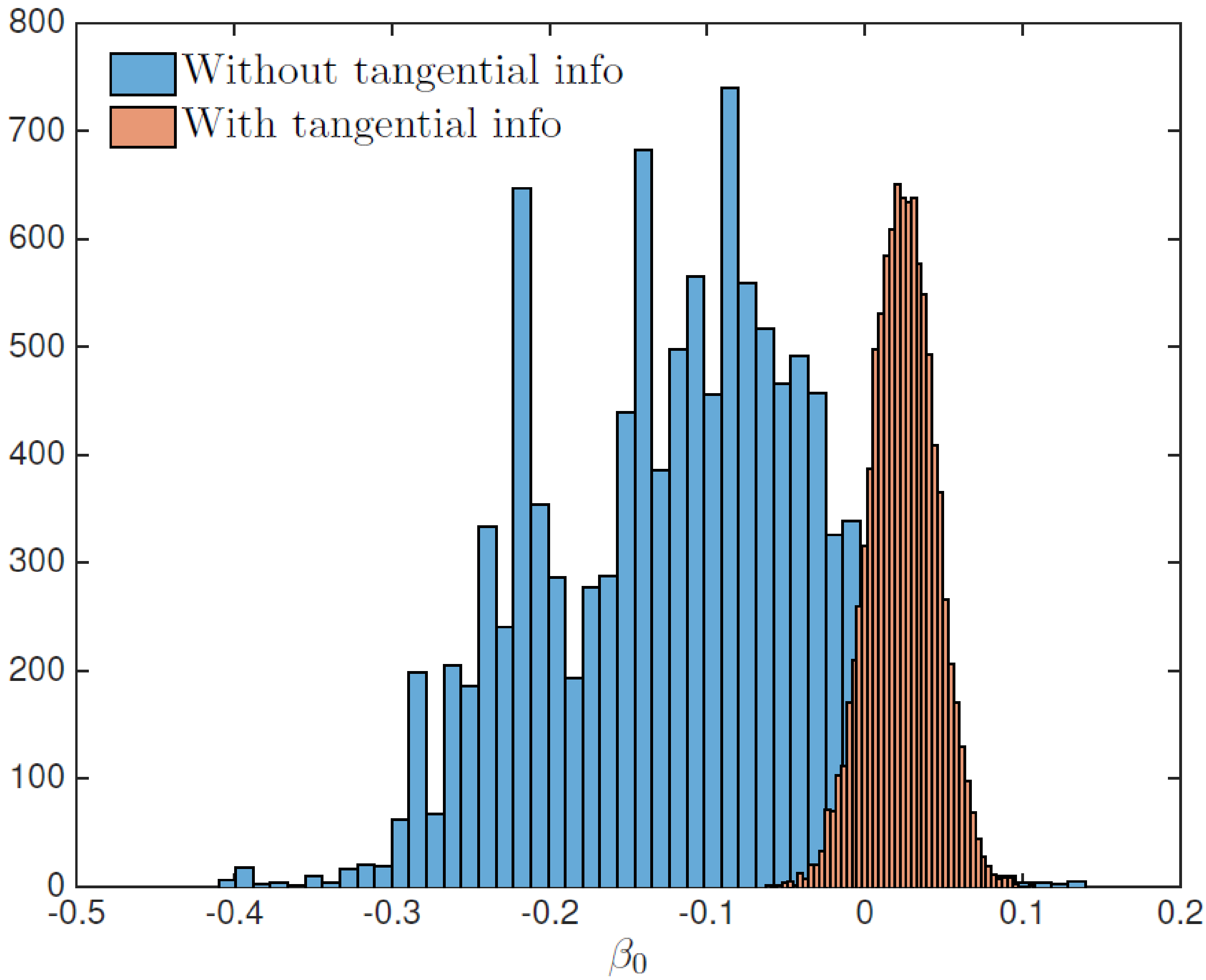
Inner slope of density profile γ

$$\boxed{\rho(r) = \frac{\rho_0}{\left(\frac{r}{r_s}\right)^{\gamma}\left[1+\left(\frac{r}{r_s}\right)^{\alpha}\right]^{(\beta-\gamma)/\alpha}}}$$

Velocity anisotropy parameter β

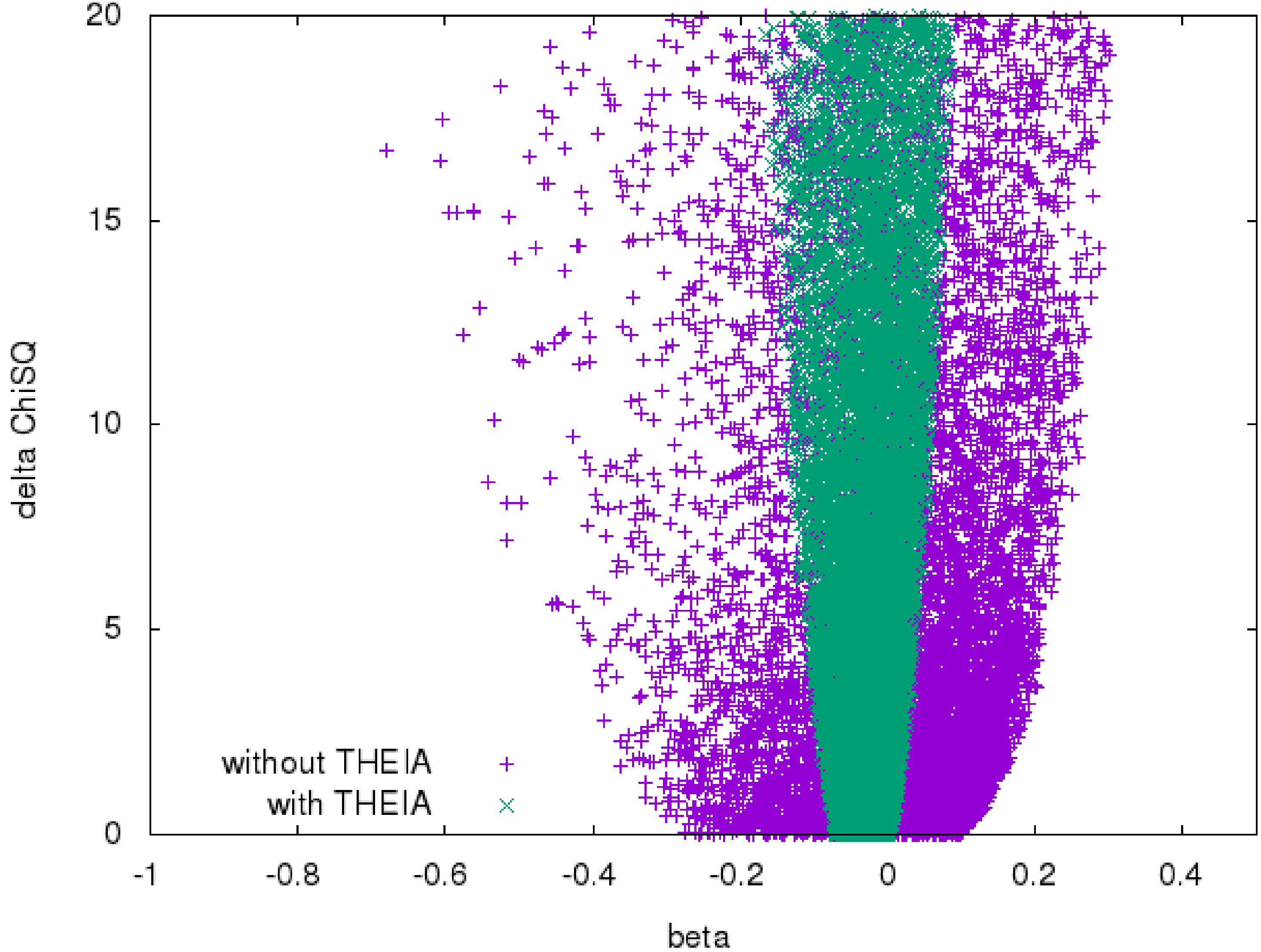
$$\beta \equiv 1 - \frac{\sigma_t^2}{\sigma_r^2}$$

Our Initial estimates for Theia performance (in science case a year ago)

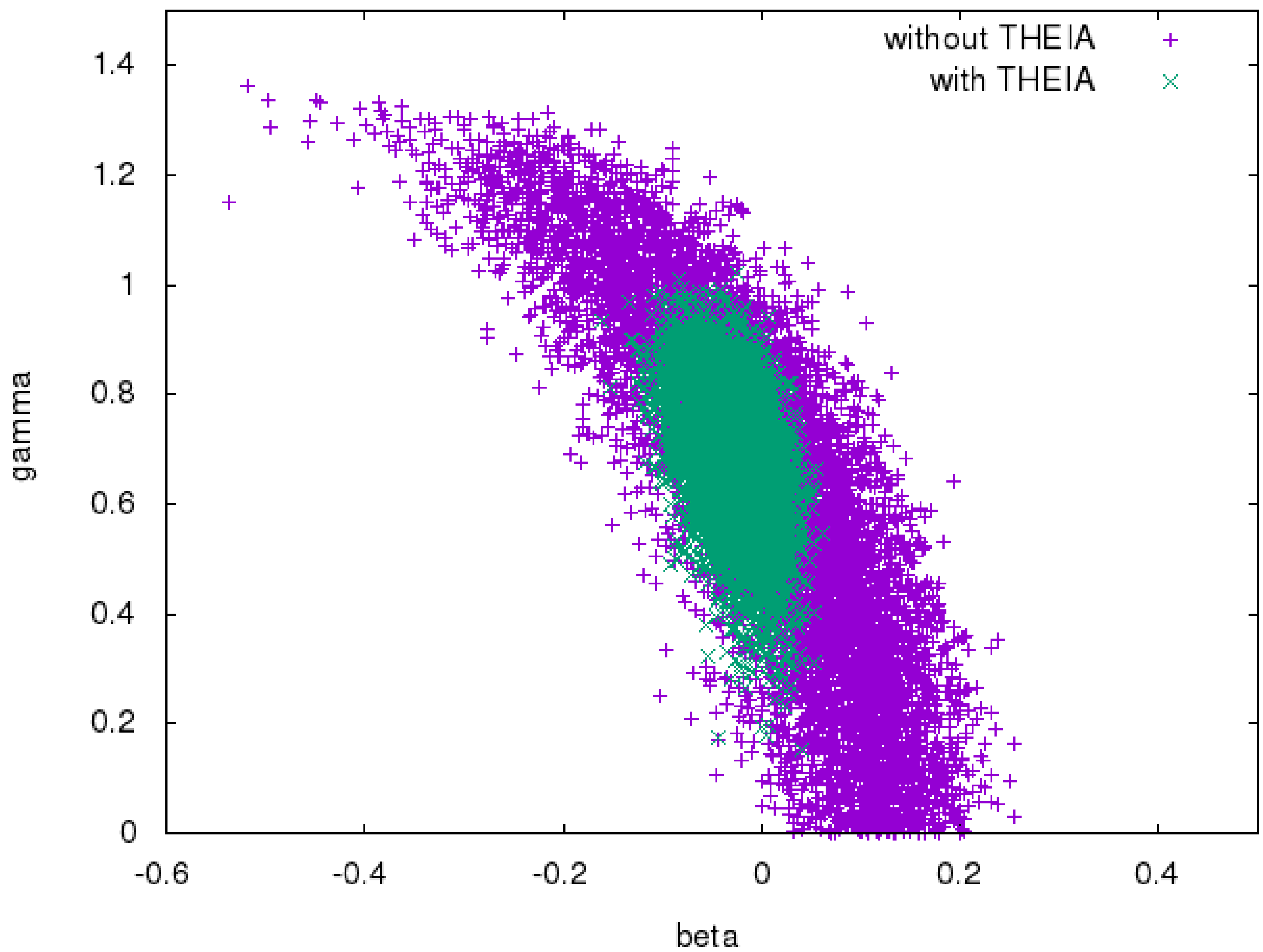


Work with Aaron Vincent and Doug Spolyar

New Analysis of β=0, γ=1 Gaia Mock data set



New Analysis of β=0, γ=1 Gaia Mock data set



Inconsistent with core , but not getting the right value of γ 

"THEIA" has done its job here, we just need to make sure we can do ours now. We will…

To do a better job…

- Need to know Theia predicted performance, or possible range of performances. Also lifetime of mission obviously to convert angular resolution into proper motion.
- Assuming Theia gives us β we then need a reliable way to reproduce the other parameters.
- Need *plenty* of warning for deadlines, fixing and checking and trying new things takes a long time. *(Already answered by Alain Leger in private conversation yesterday !)*

In Summary

- Dwarf Spheroidals excellent Laboratories for fundamental physics
- Understanding density profile critical for annihilation signal and probes of self interacting dark matter
- Velocity anisotropy – β degeneracy makes this hard
- Theia can break this degeneracy