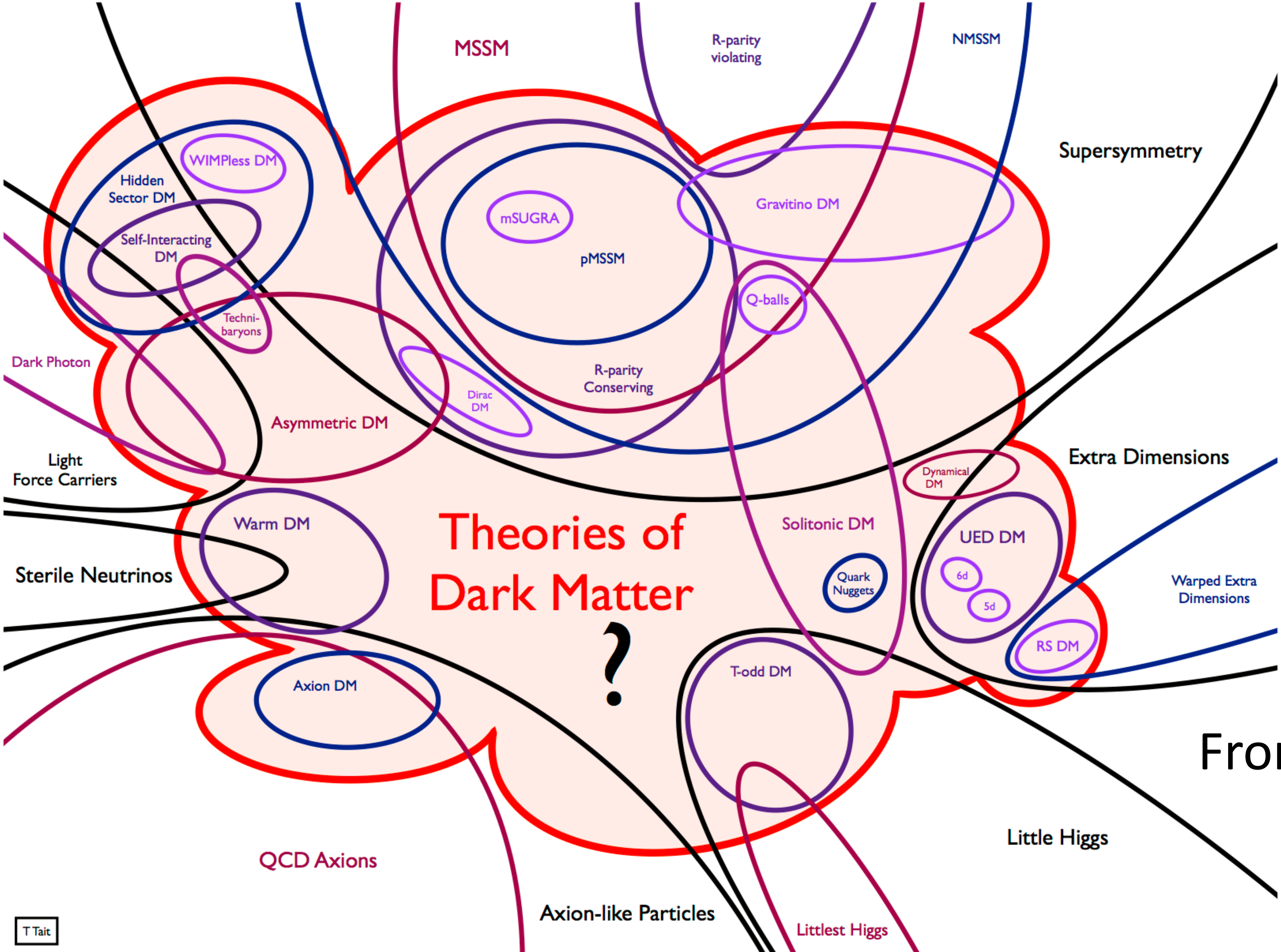
Future Astrophysical tests of the Dark Sector

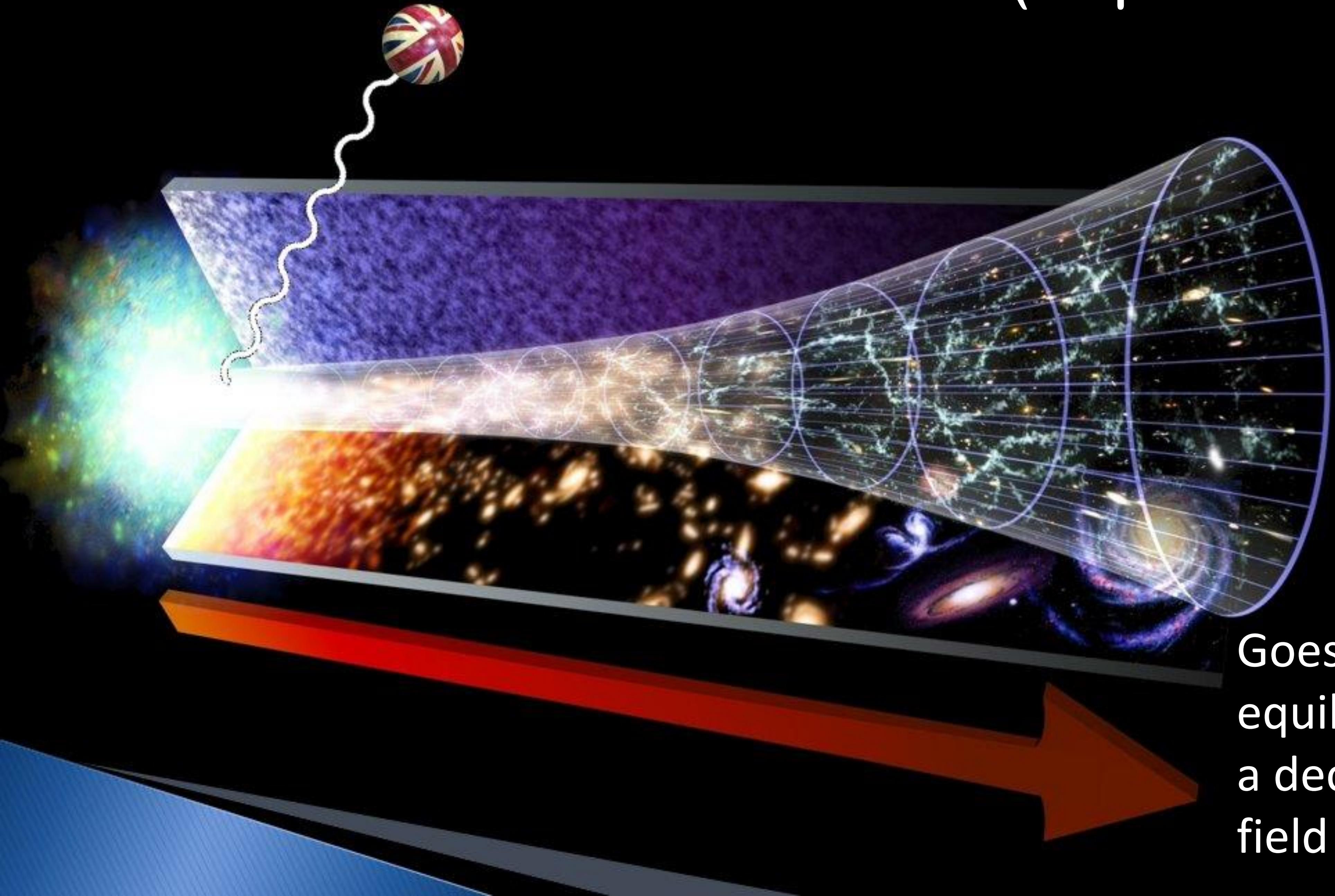
Malcolm Fairbairn

CERN – August 2017



From Tim Tait

The Brexiton (Enqvist 2017, Rajantie 2017)



Goes out of thermal equilibrium then acts as a decoupled spectator field while it decays

1. Is there a small scale crisis?
2. Testing small scales (proposed by B/as)
3. New experimental searches for axions
4. testing DM with future telescopes.
5. Noise in LIGO detectors
6. Origin of supermassive Primordial BHs
7. How robust are Lyα constraints on DM
8. Triple systems (beyond GR)
9. Recycling GR tests for DM models.
10. Model independent tests of Screening.
11. Halo profiles in DM made of BHs.
12. Galileon self-acceleration - is a wrong-sign Kinetic term Okay?
13. Coordinate systems for cosmological

Dwarf Spheroidals, cored or not?

Microlensing with Axion miniclusters

Collapse of Axion Stars

Part I

Dwarf Spheroidal Galaxies, Cored or not?

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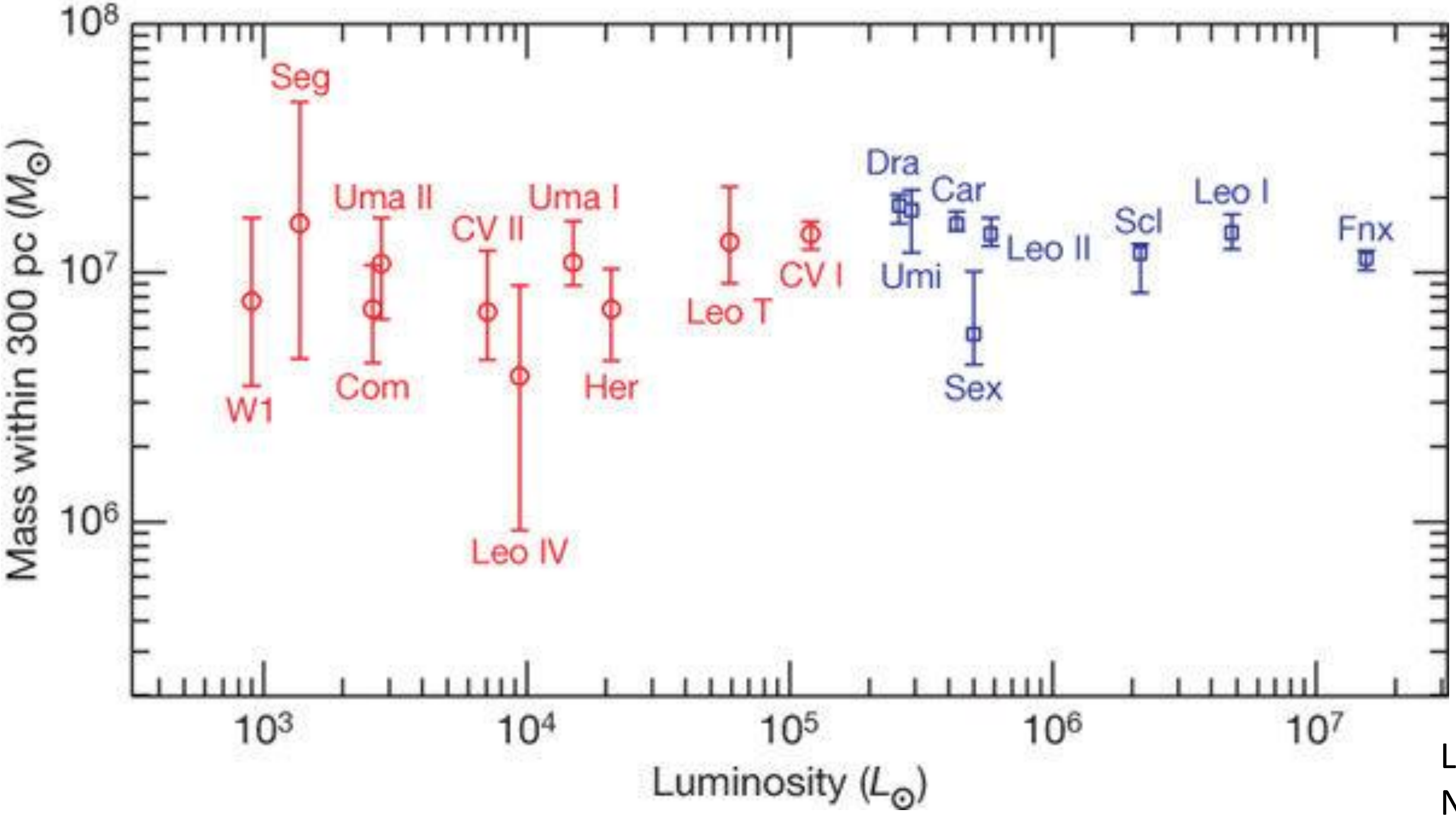
dSphs - Dwarf Spheroidal Galaxies

Dwarf Spheroidal Galaxies have HUGE mass to light ratios baryons are therefore only tracers of potential



Louis E. Strigari et al
Nature 454, 1096

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

Hope to obtain this by fitting data

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

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

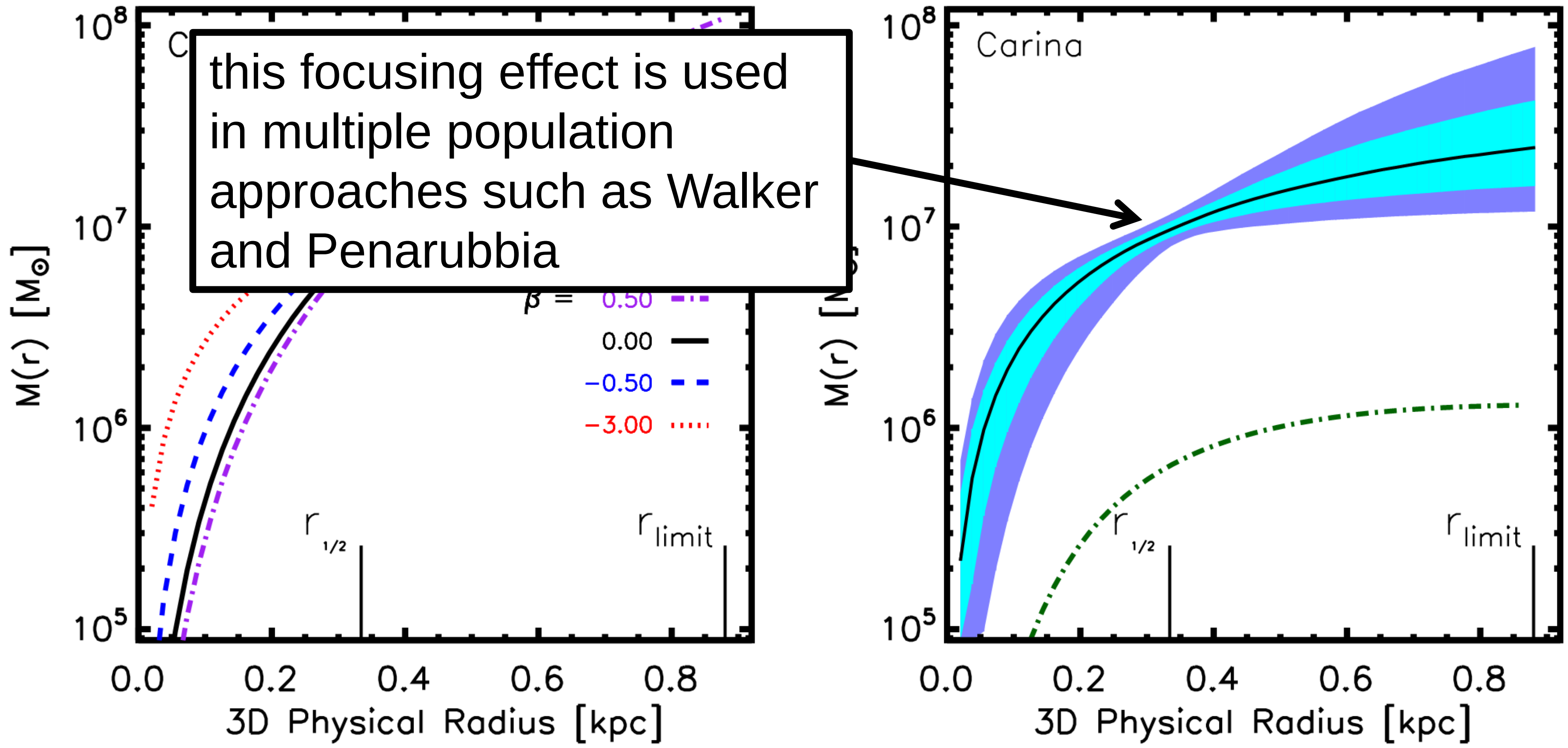
Tangential Velocity Dispersion

Radial Velocity Dispersion

line of sight dispersion then $\Sigma\langle v_z^2\rangle(R) = 2\int_R^\infty (1 - \beta\frac{R^2}{r^2})\frac{\nu\langle v_r^2\rangle r}{\sqrt{r^2 - R^2}}dr$

β degeneracy problem – could be a cusp, could be a core!

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



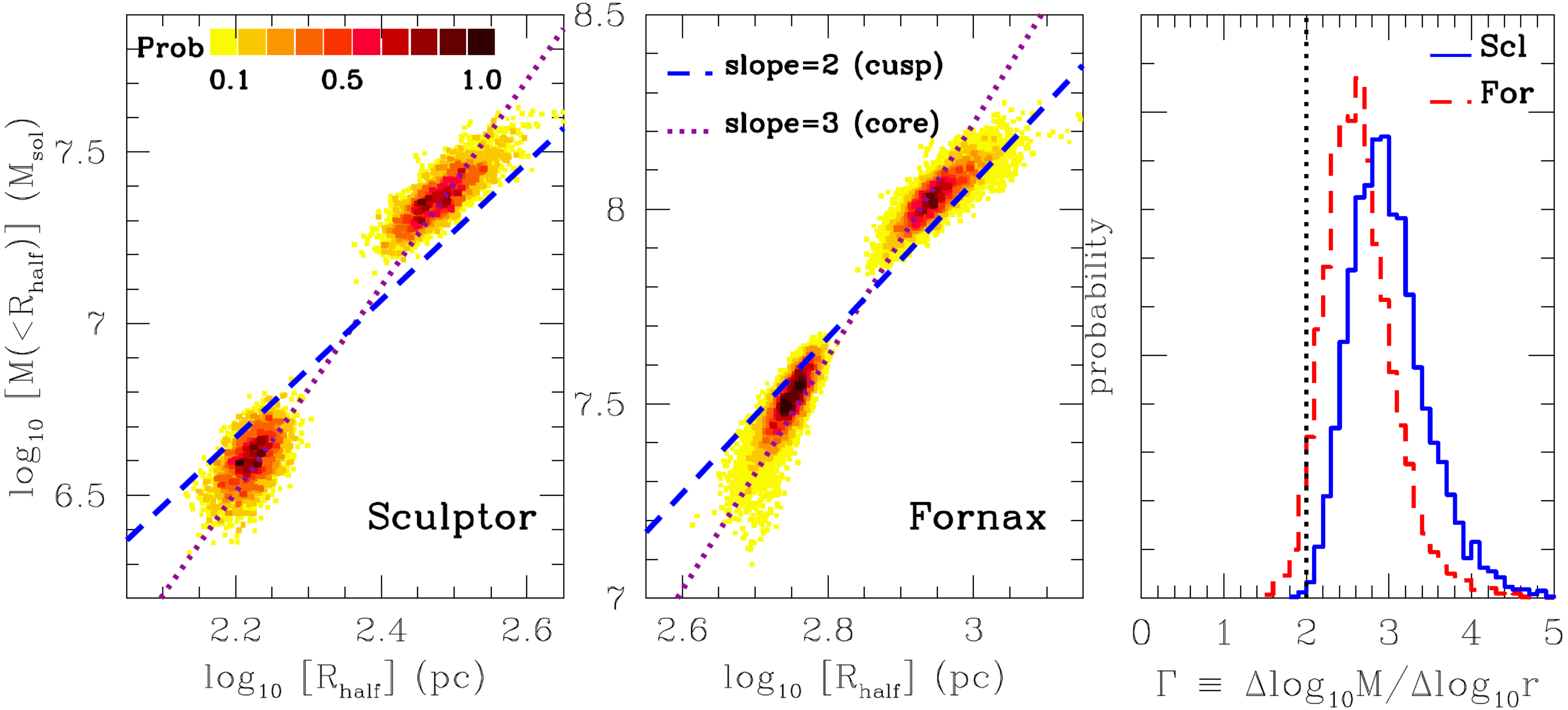
Plots from Wolf et al 0908.2995

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

So many people think dSph galaxies are cored and this goes against predictions of cold dark matter.
The classic paper astro-ph/9909386

Observational evidence for self-interacting cold dark matter

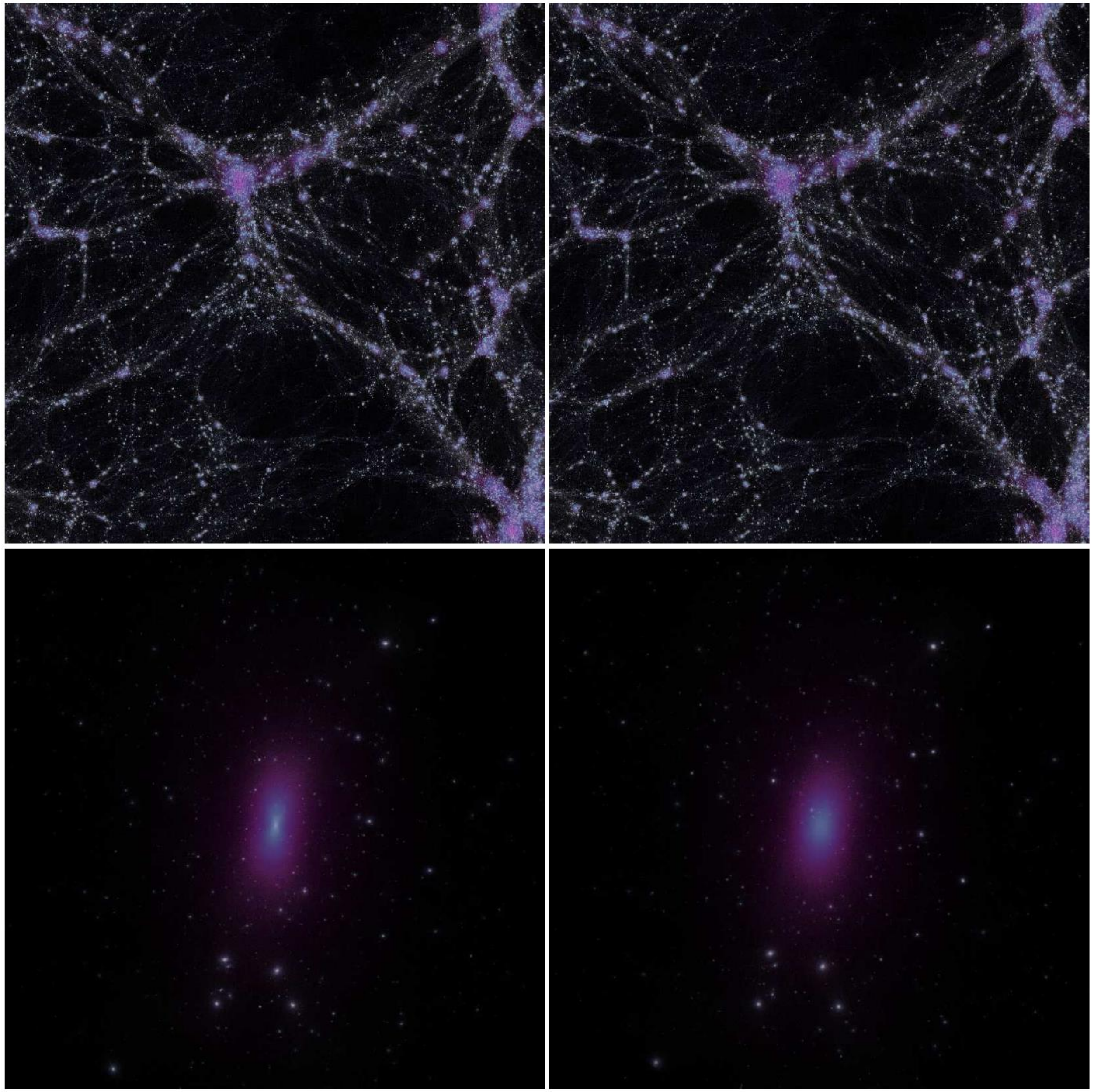
David N. Spergel and Paul J. Steinhardt
Princeton University, Princeton NJ 08544 USA

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^{22} times PANDA bound at 30 GeV

What happens when you replace CDM with SIDM?



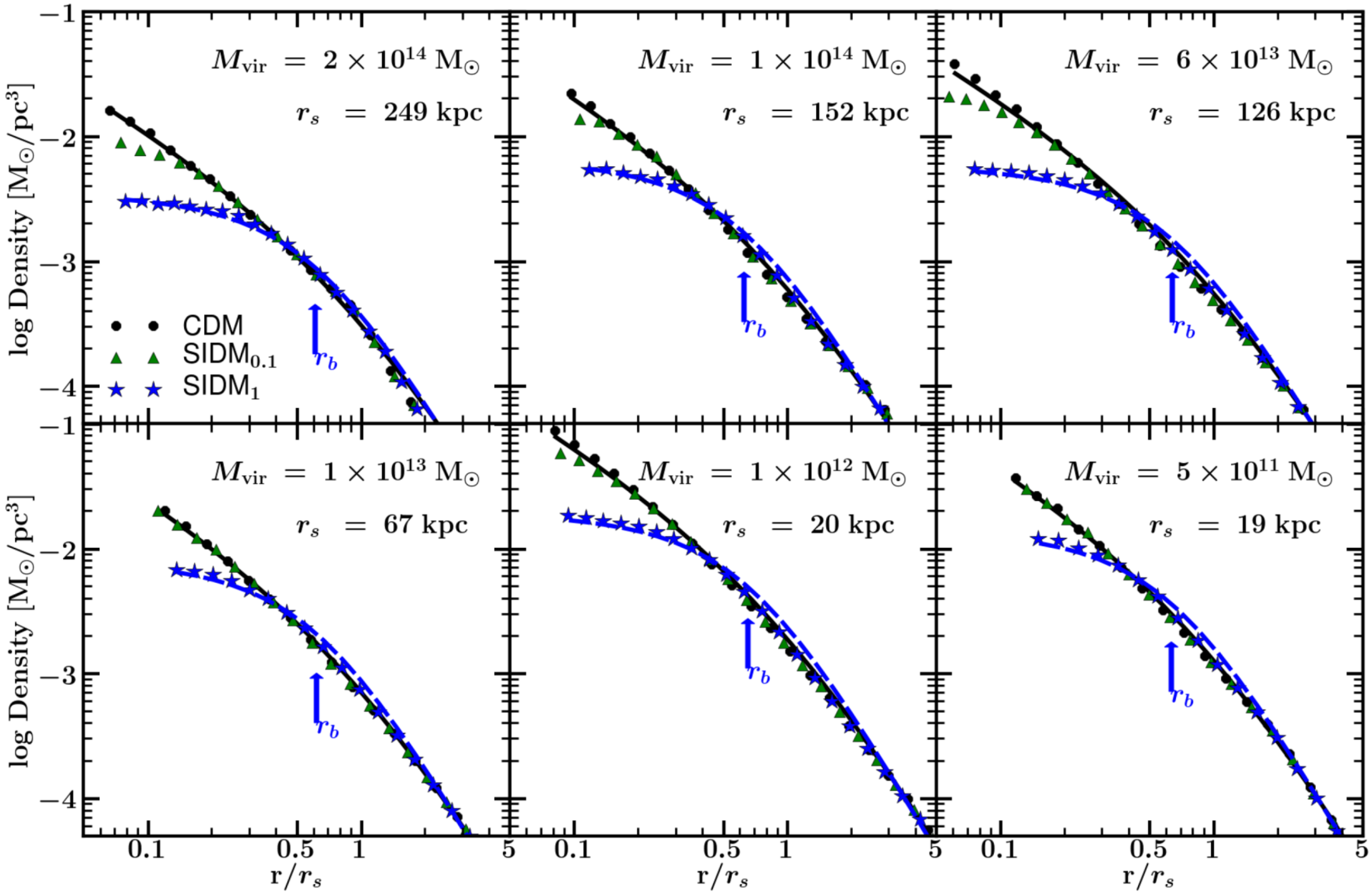
Self interacting simulations with $\sigma = 1\ cm^2/g$

Rocha et al 1208.3025

No difference on large scales

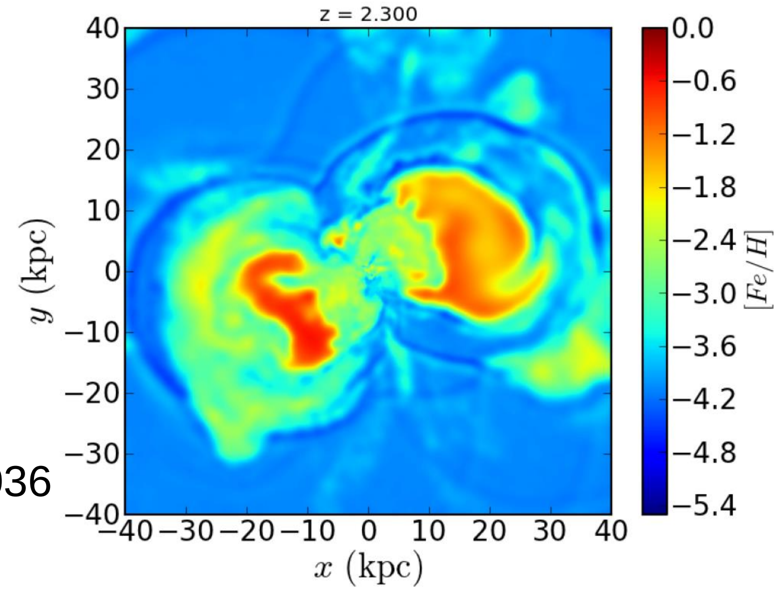
Individual galaxies more cored and spherical with higher velocity dispersion

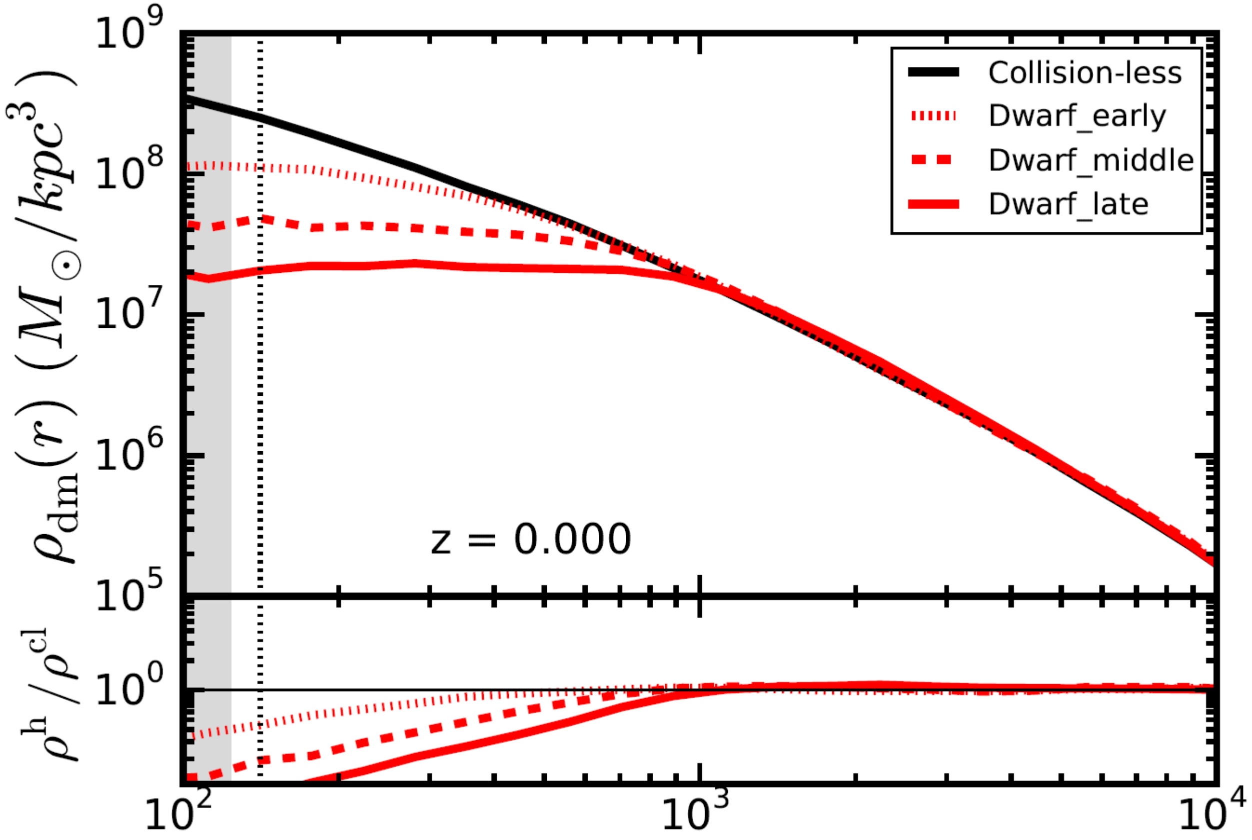
N-body simulations show cores are more pronounced in SIDM rather than CDM
Rocha et al 1208.3025



Baryonic Feedback can also affect Dark Matter Density

Onorbe et al
arXiv:1502.02036





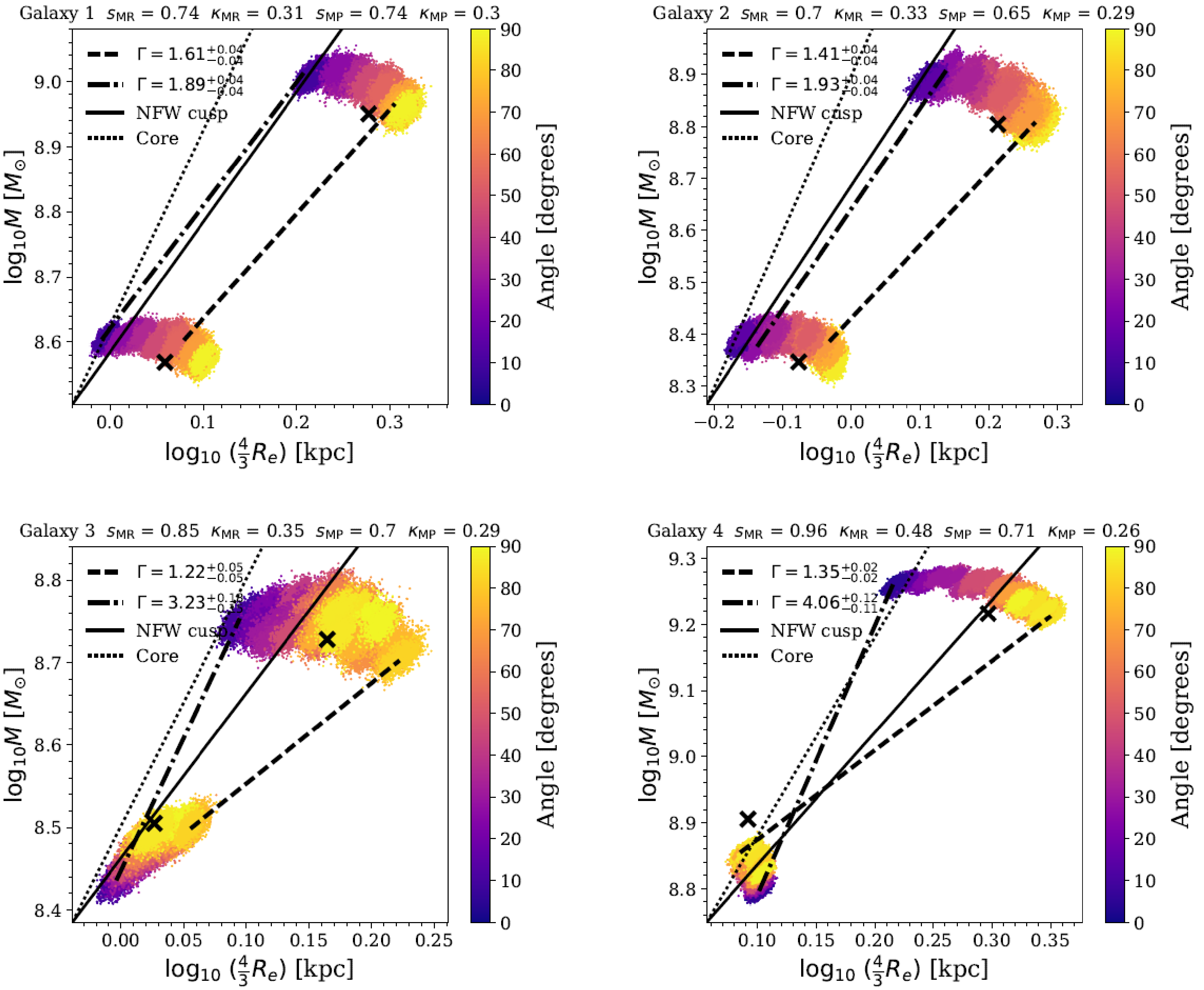
Seeing a definitely cored profile does not necessarily mean new physics

Seeing a definitely cuspy profile can rule out new physics

The core - cusp problem: a matter of perspective

Anna Genina, Bentez-Llambay, Frenk, Cole, Fattahi, Navarro, Oman, Sawala, Theuns

Based on 53 dwarf galaxies in the APOSTLE LCDM cosmological hydrodynamics simulations of analogues of the Local Group.



Can also use Higher Moments of Boltzmann Equation

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

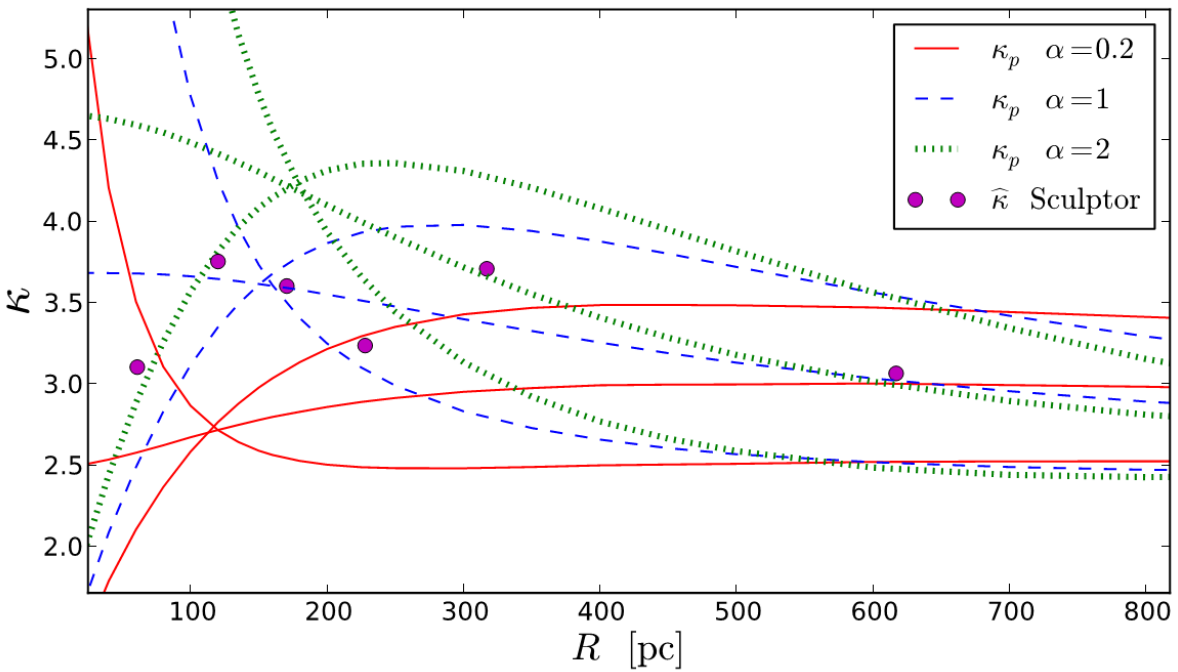
$$\frac{d(\nu\overline{v_r^2 v_t^2})}{dr} - \frac{1}{r}\nu\overline{v_t^4} + \frac{4}{r}\nu\overline{v_r^2 v_t^2} + \nu\sigma_t^2\frac{d\Phi}{dr} = 0$$

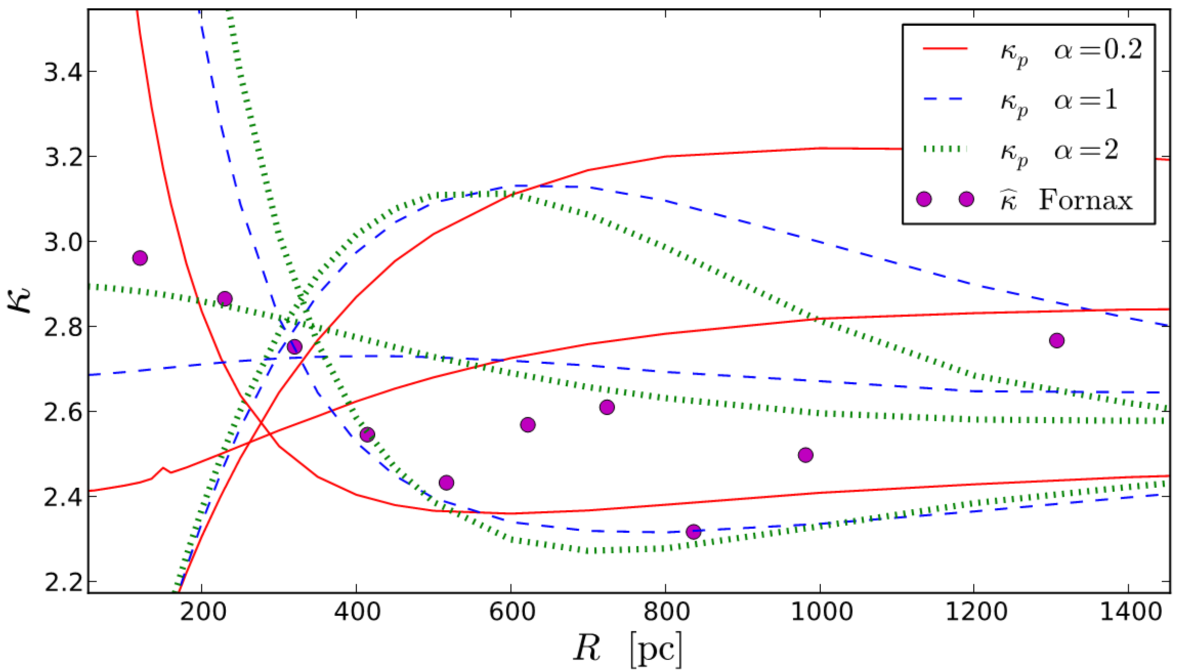
Now you have a new, higher moment anisotropy parameter which can be expressed in several ways, including

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

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

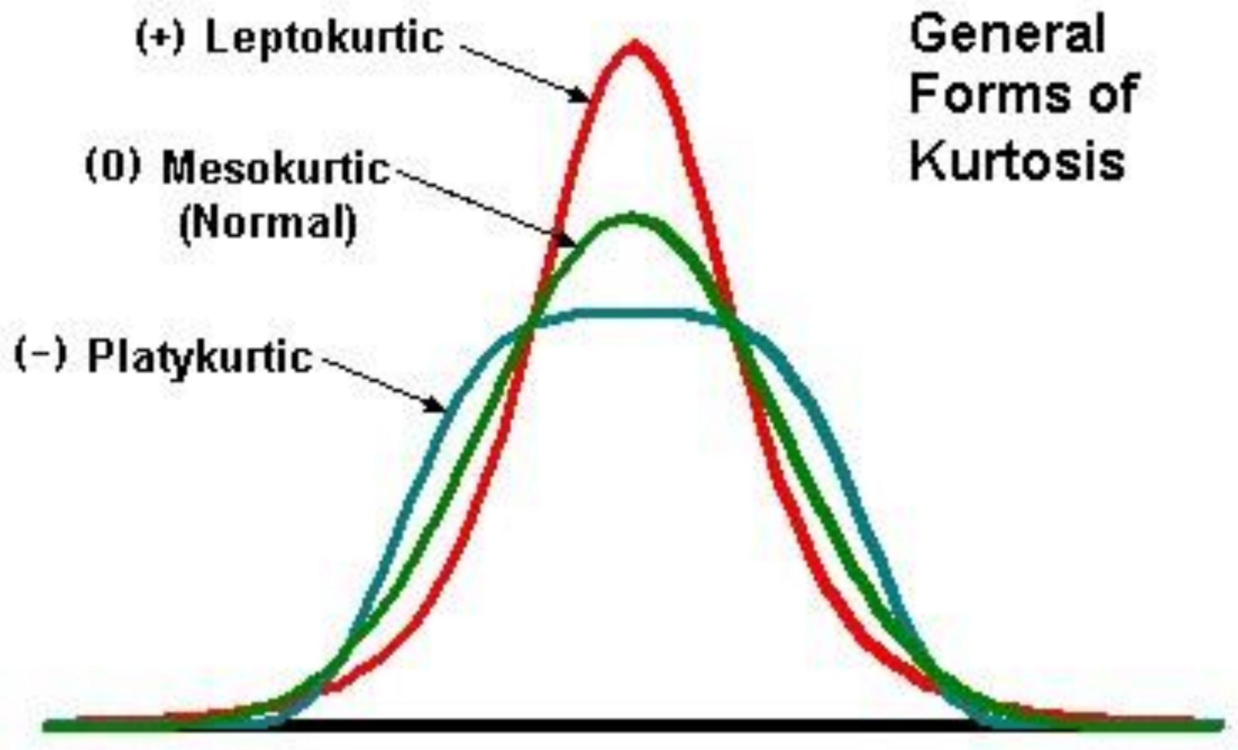

From now on all results will refer to Sculptor Galaxy….
… there is a good reason





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

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

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

Where the * denotes the following weighting:-

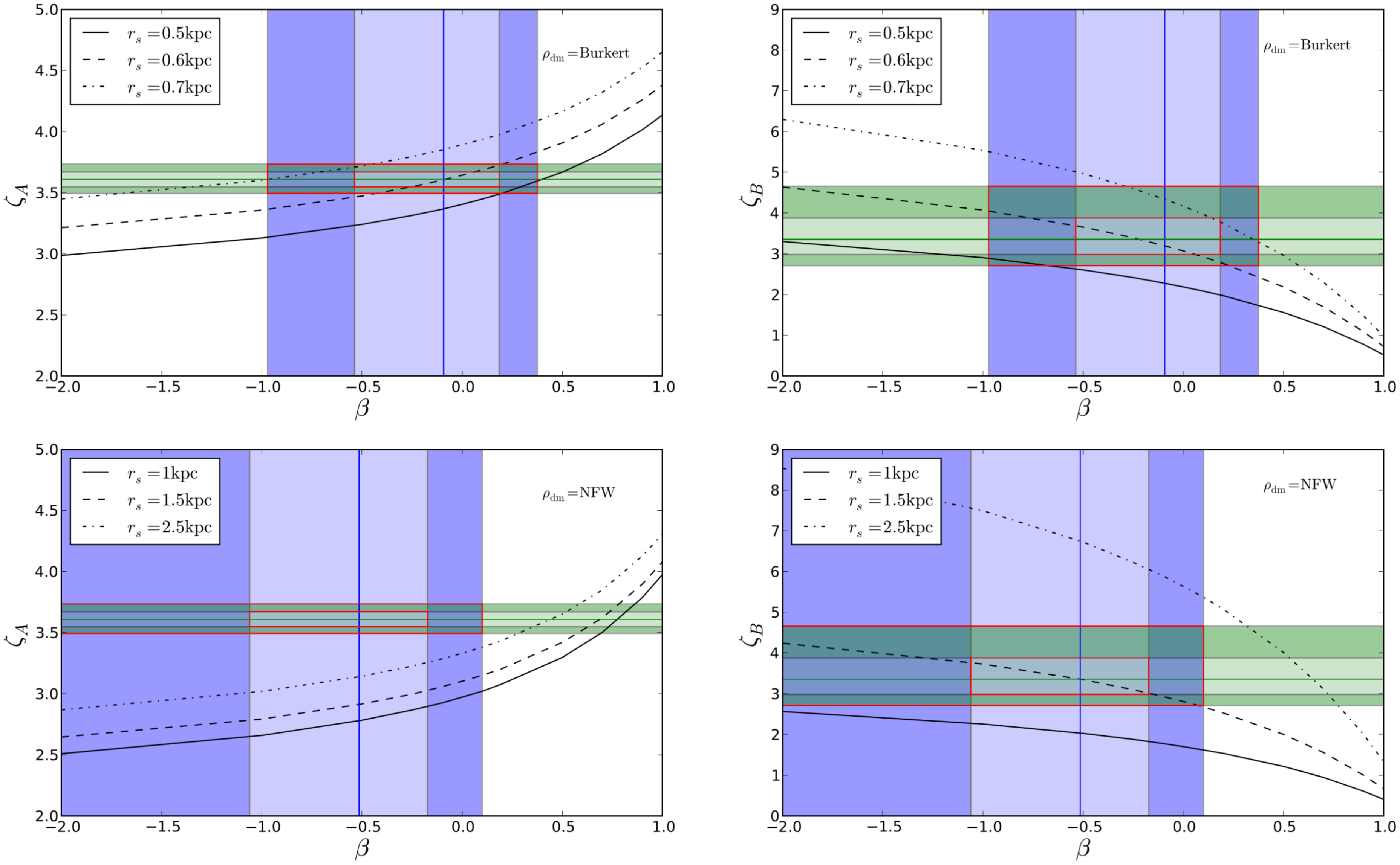
$$X_\star \equiv \frac{1}{N_{\rm tot}} \int_0^\infty X(R) \Sigma(R) R \, {\rm dR}$$

WHY DEFINE IN THIS WAY?

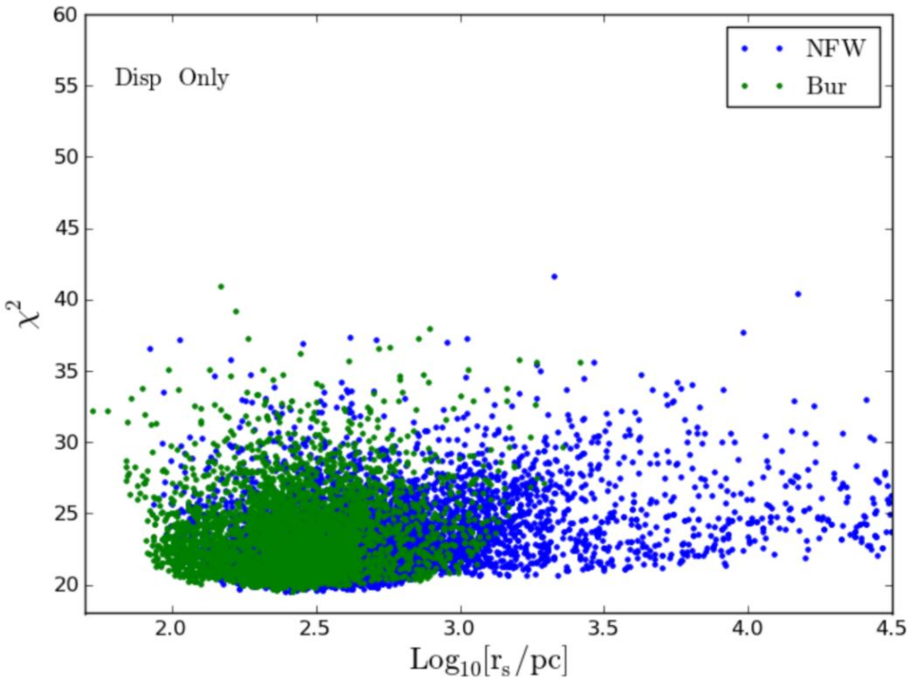
1. The weighting concentrates on the radii where the data is strongest
2. The normalisation removes 2nd order information, which is fitted separately

Richardson and Fairbairn arXiv:1401.6195

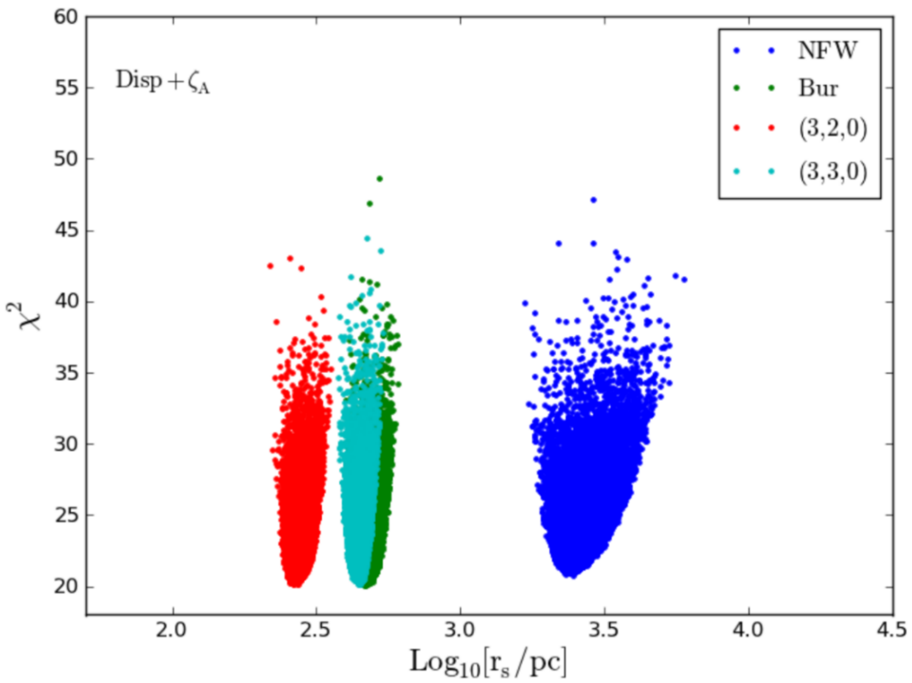
What can we do with these Normalised Virial Estimators?

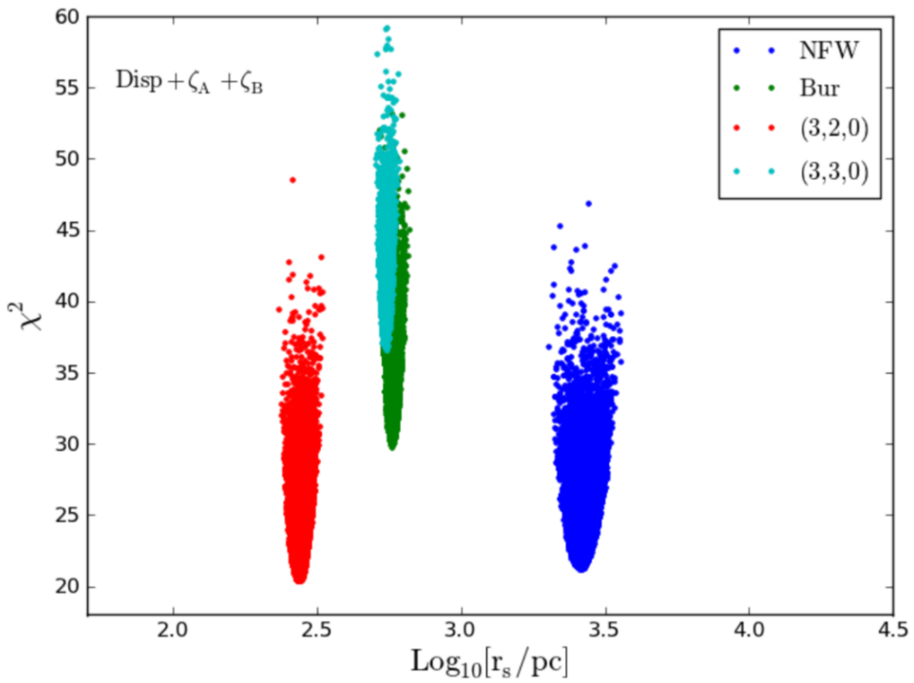


This is just an example where β = constant for Sculptor

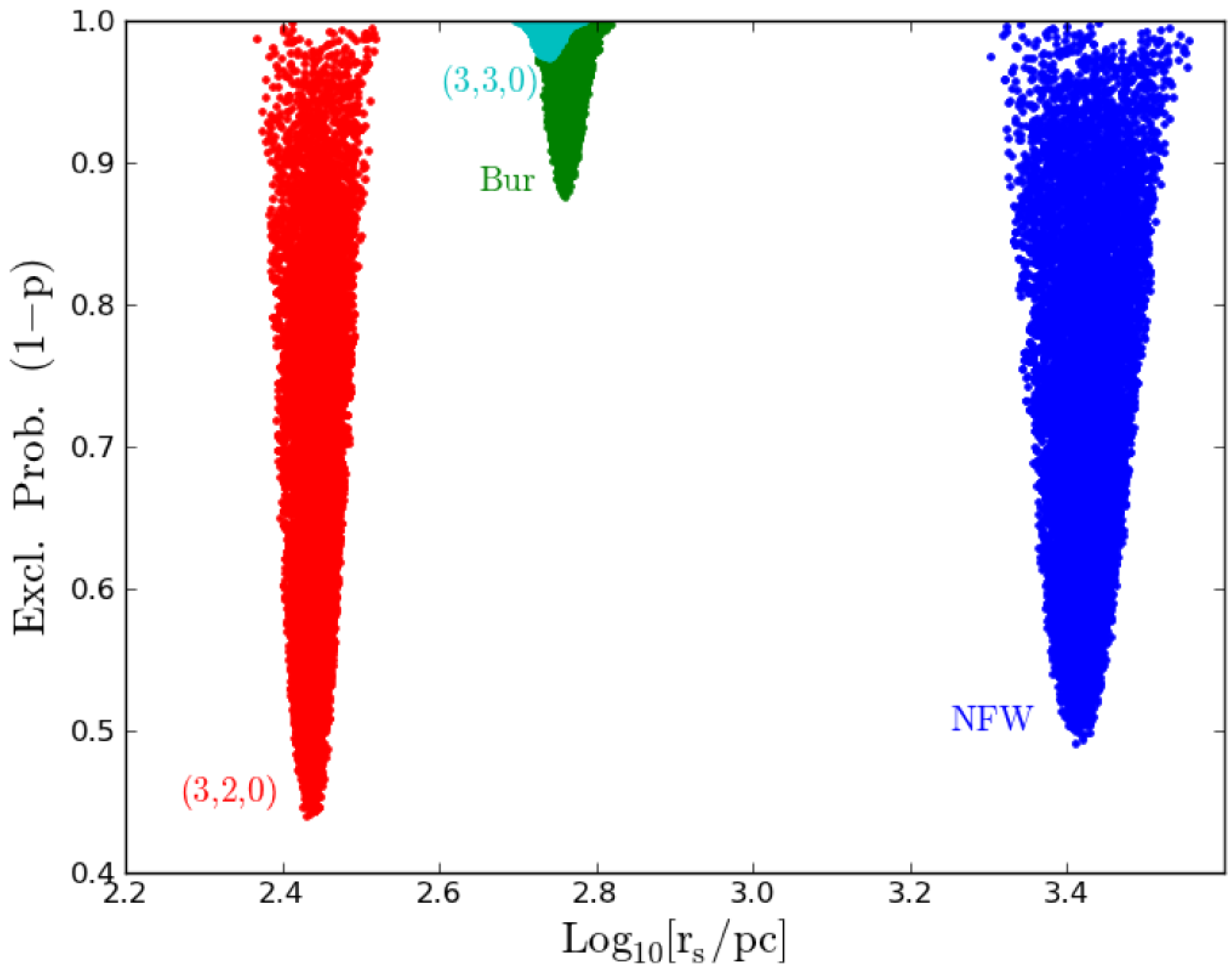


In particular ζ_A, which is more robust to statistics than $\zeta_{B,}$ really picks out the scale radius of a given profile. Here has more freedom.

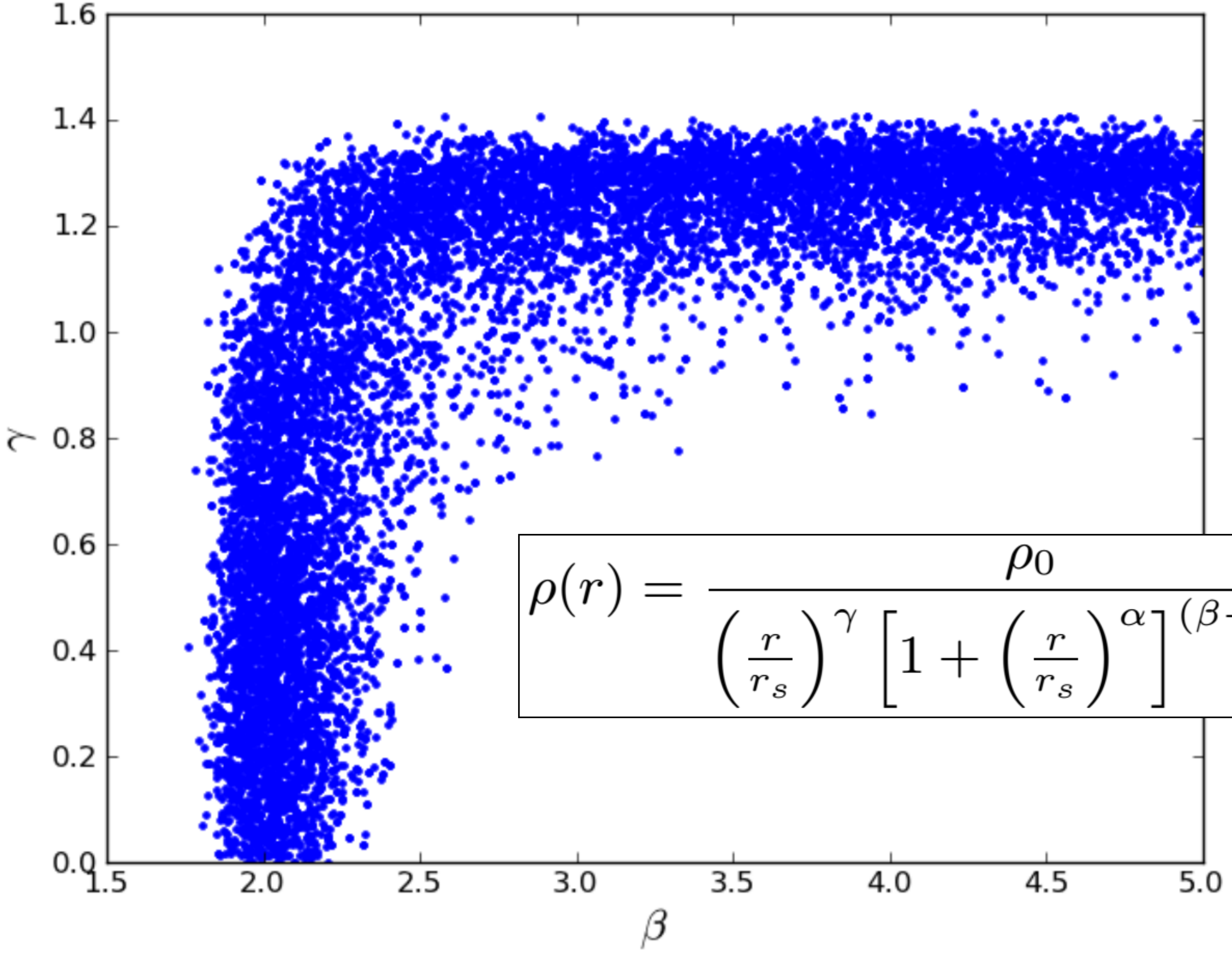




Both NFW and Isothermal (with small core) better fits than cored Burkert or cored 3,3,0 profiles

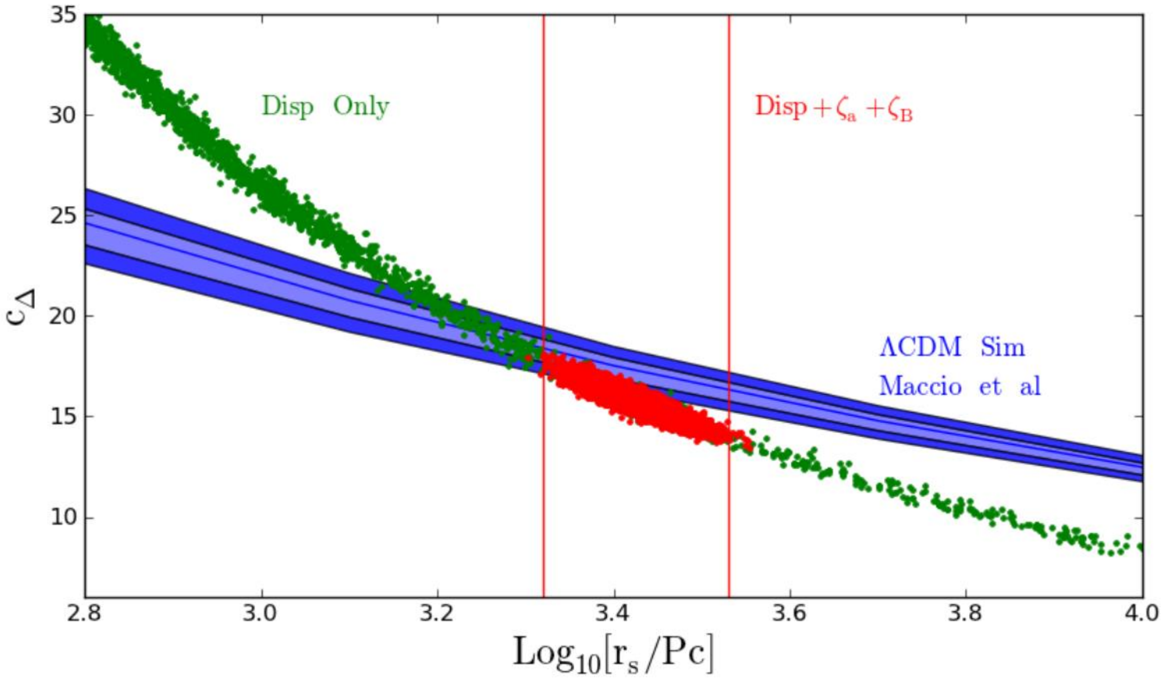


What Happens if we allow the density profile more Freedom?

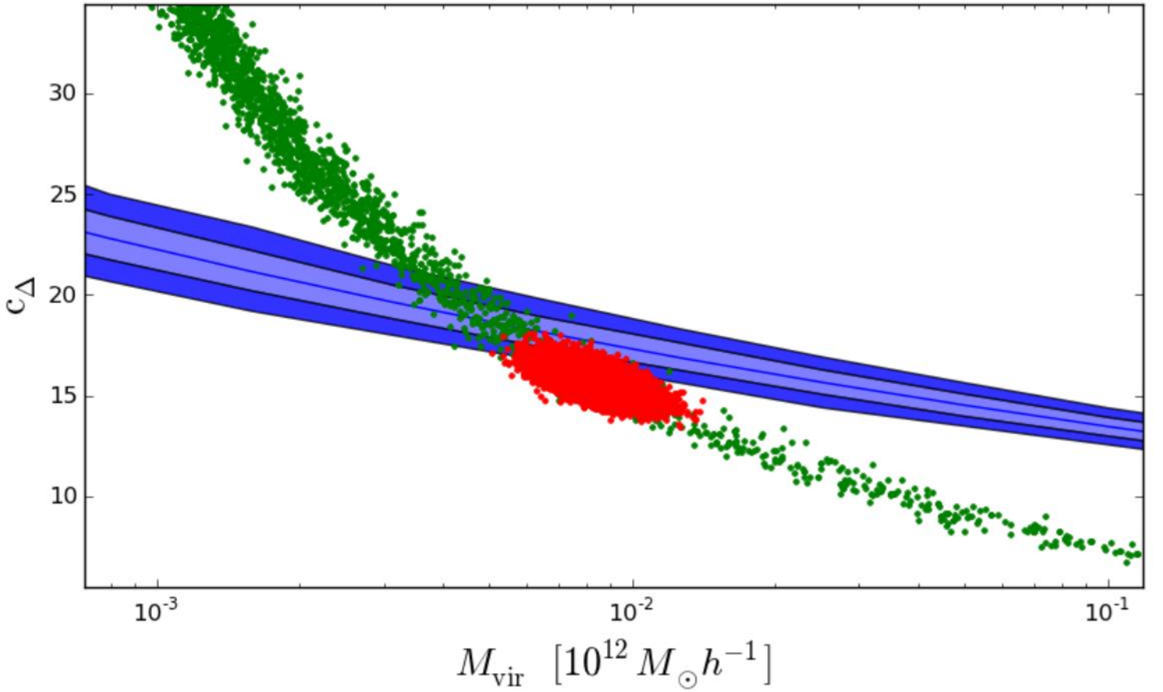


$$\rho(r) = \frac{\rho_0}{\left(\frac{r}{r_s}\right)^{\gamma}\left[1 + \left(\frac{r}{r_s}\right)^{\alpha}\right]^{(\beta-\gamma)/\alpha}}$$

When β is a more general function of r and you assume NFW profiles, you obtain close to exactly what is expected from simulations



One can start to see the power of ζ_A and ζ_B

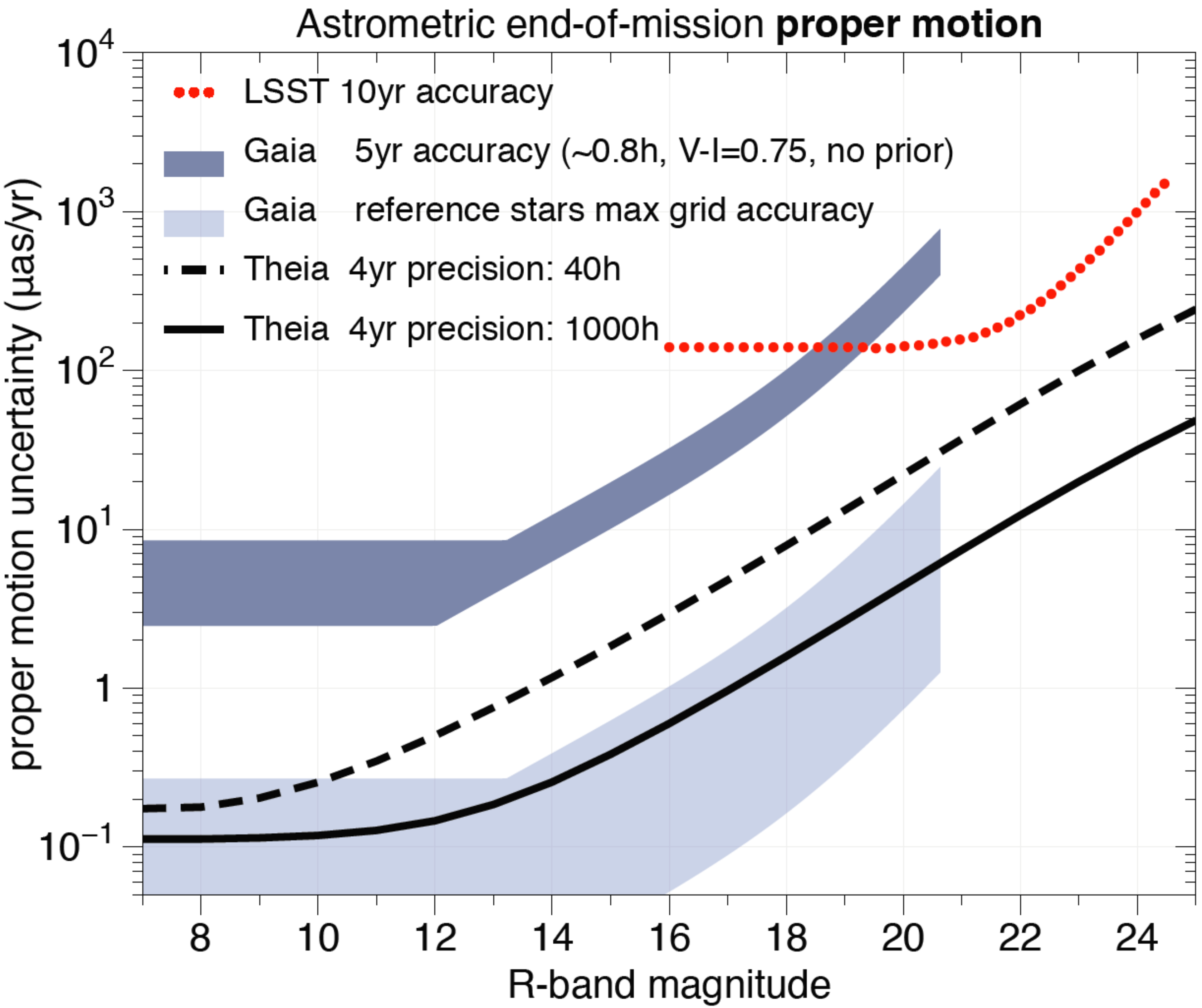


See more recent work by Read and Steger 2017

Future direct MEASUREMENT of β???

Gaia can't really do this

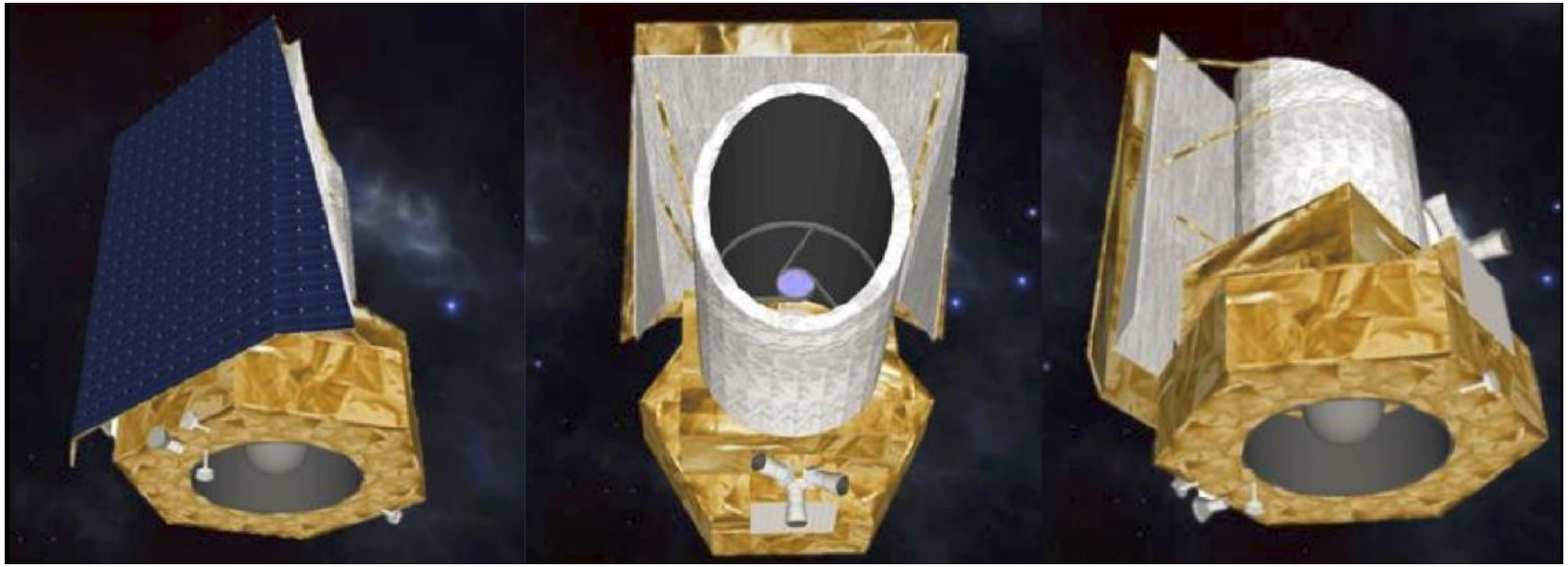
Theia probably can…

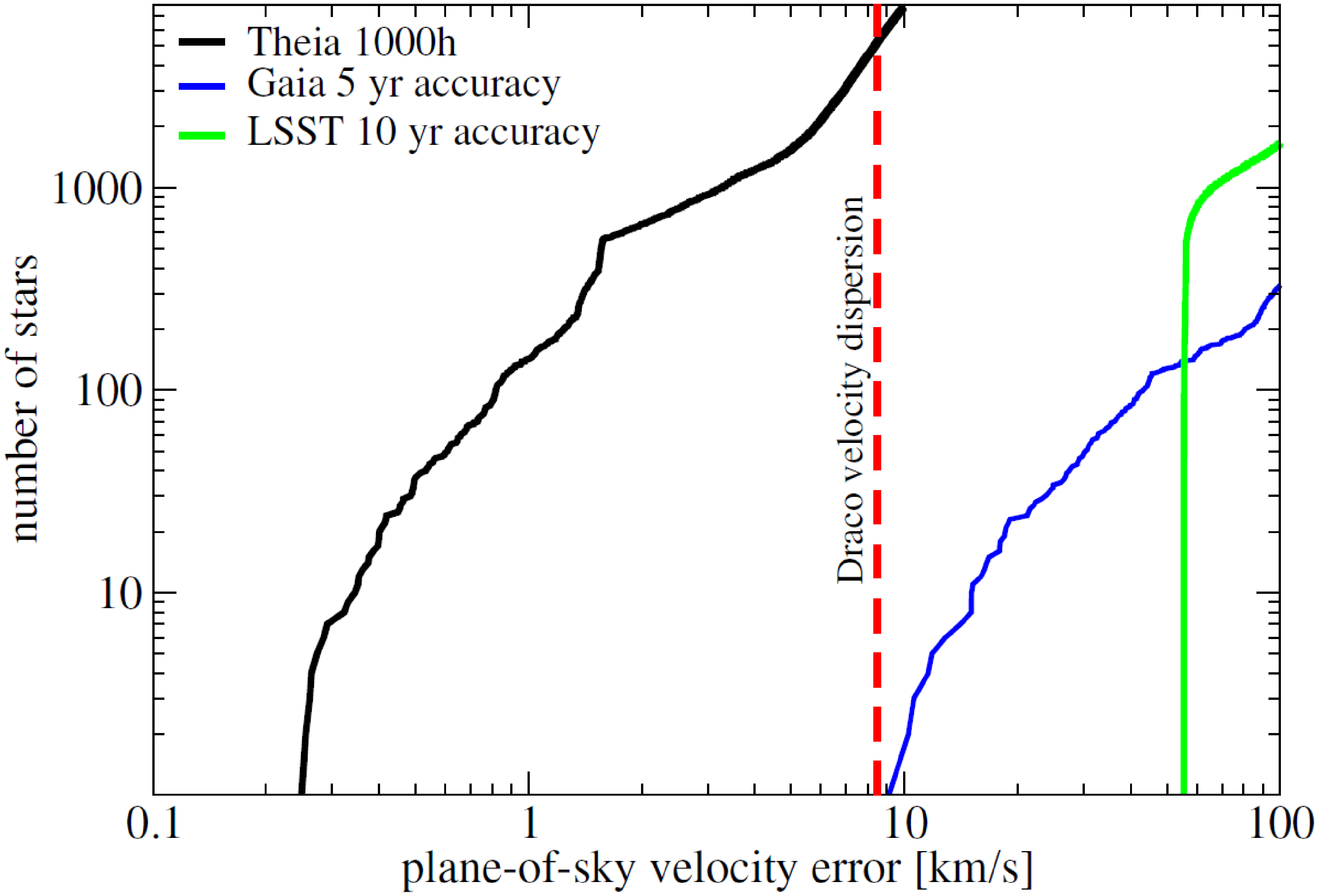


Theia: Faint objects in motion or the new astrometry frontier

The Theia Collaboration *

July 6, 2017





Theia 1000h
Gaia 5 yr accuracy
LSST 10 yr accuracy
Draco velocity dispersion
number of stars
1000
100
10
0.1
1
10
100
plane-of-sky velocity error [km/s]

Conclusions on Dwarf Spheroidals

- Many particle models are created to solve the "core problem" of dwarf spheroidals, e.g. ultra low mass bosons.
- Unfortunately it is not clear that such a problem exists. Many techniques are being developed to find out if this is true or not.

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Part II

Detecting Axion Mini-clusters through Microlensing

Axions as Dark Matter

What is this?

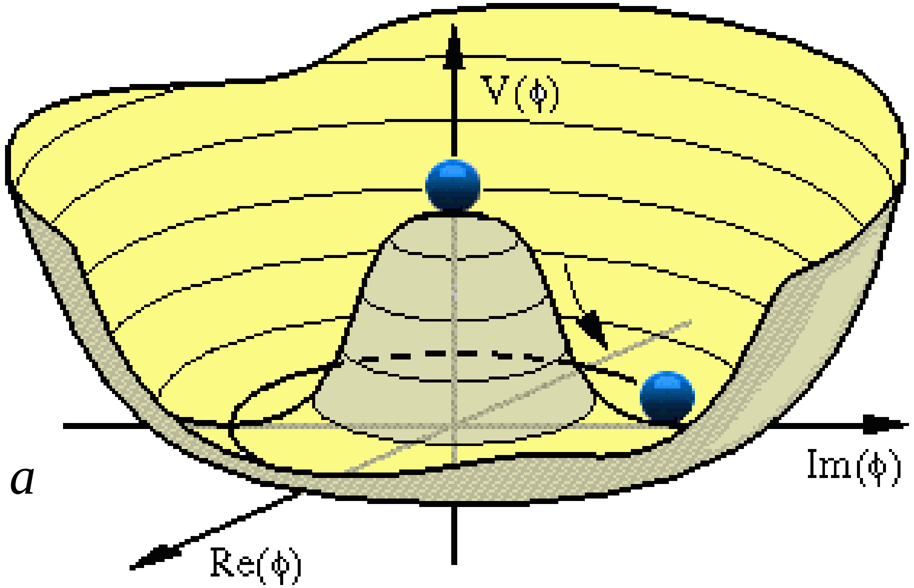
$$S = \int d^4x \left[-\frac{1}{4g^2} G^{a,\mu\nu} G^a_{\mu\nu} + \frac{\theta}{32\pi^2} G^{a,\mu\nu} \tilde{G}^a_{\mu\nu} + \imath \bar{\psi} D_\mu \gamma^\mu \psi + \bar{\psi} \mathrm{M} \psi \right]$$

Gluon kinetic energy

quark kinetic energy

quark mass

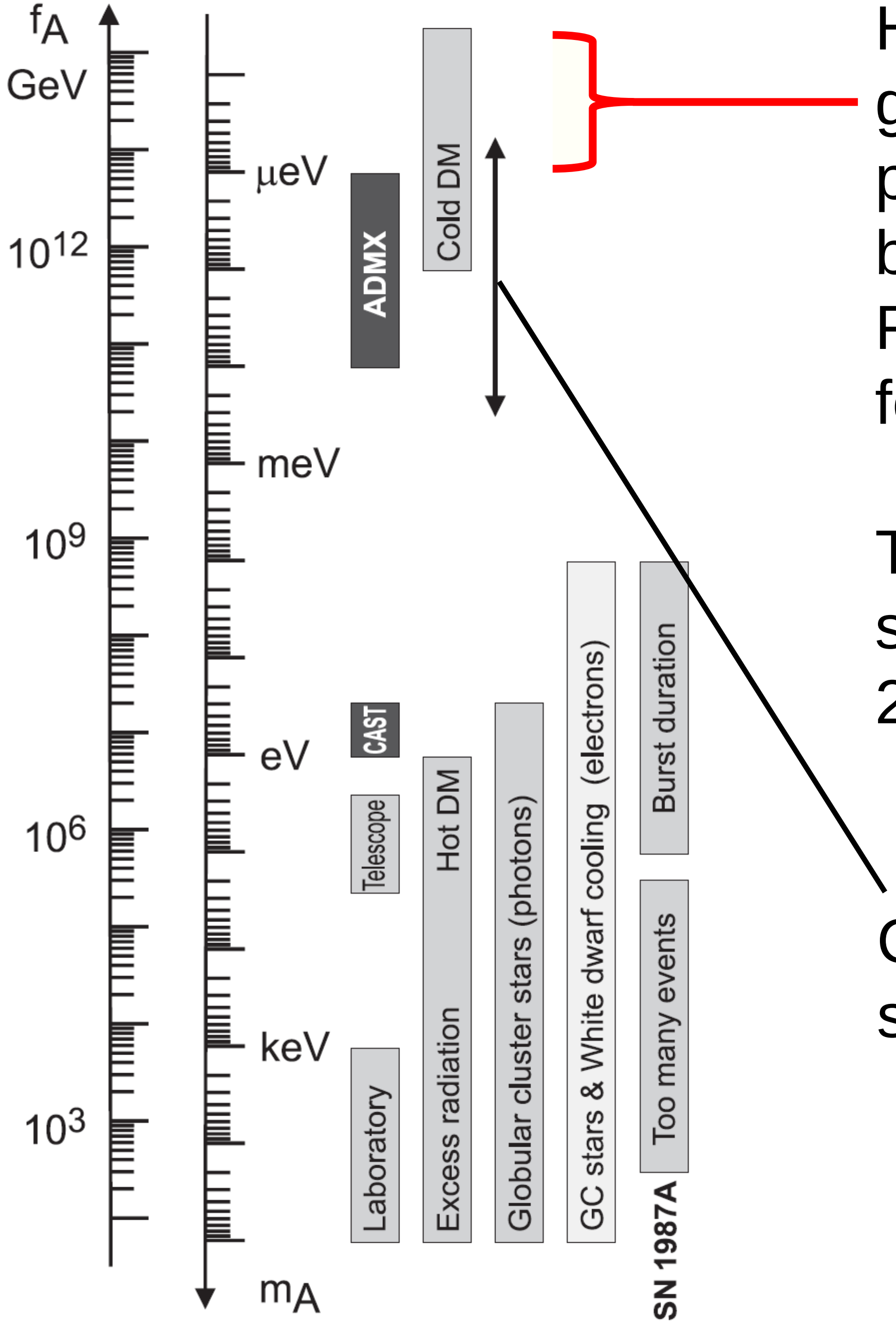
$$\theta \longrightarrow \theta - a/f_a$$



Promote θ to field a

$$m_a^2 \sim \frac{f_\pi^2 m_\pi^2}{f_a^2}$$

Also induces coupling to photons



Here you can get good dark matter, but generically you get too many isocurvature perturbations if PQ symmetry was broken before inflation (although see Hogan, Fairbairn and Marsh and Ballesteros et al for ways around this.)

Tuning required to fix this worse than strong CP problem in first place (Mack 2009)

Can also get good relic abundance if PQ symmetry broken after inflation.

What Happens Step by Step

1. PQ phase transition after inflation – lots of different values in different regions
2. Field smooths itself out on horizon scale in the style of Kibble Mechanism
3. Axion acquires a mass, leading to big over-densities from place to place
4. Field now collapses to form (very) dense miniclusters with typical mass equal to that inside horizon
5. All of these isocurvature perturbations physics occurs on very small scales, on large scales they fall into adiabatic perturbations
6. We then try to observe the small scale miniclusters today with lensing

U(1) PQ symmetry broken by axion mass after inflation

Relic abundance then set by different value of the axion field in different regions of the Universe

Generic answer (from particle data group) is given by

$$\Omega_A^{\rm real} h^2 \approx 0.11 \left(\frac{41\ \mu{\rm eV}}{m_A}\right)^{1.19}$$

On its own suggests that the axion mass is about 40 micro-eV but there is a range over perhaps a couple of orders of magnitude because the contribution from the decay of topological defects is uncertain.

Correlations in this field are on length scale of horizon at phase transition – very small- much smaller than cosmological Planck/galaxy scales etc.

U(1) PQ symmetry broken by axion mass after inflation

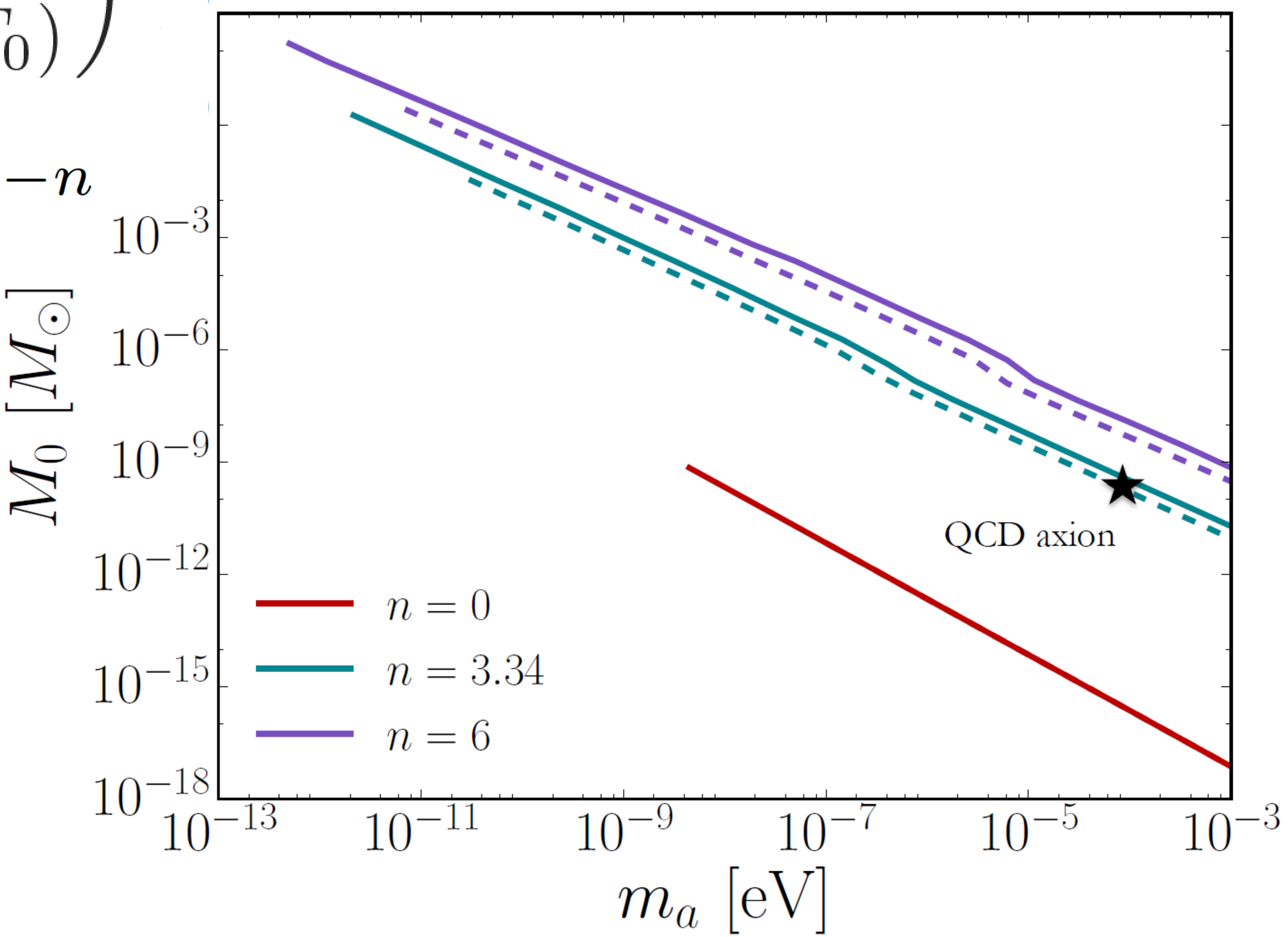
$$M_0 = \bar{\rho}_a \frac{4}{3}\pi \left(\frac{\pi}{a(T_0)H(T_0)} \right)^3$$

$$m_a(T) = m_{a,0}(T/T_c)^{-n}$$

For QCD instantons, Theory and lattice simulations suggest that n=3.34. Wantz and Shellard, 0910.1066. Borsanyi et al., 1508.06917, 1606.07494.

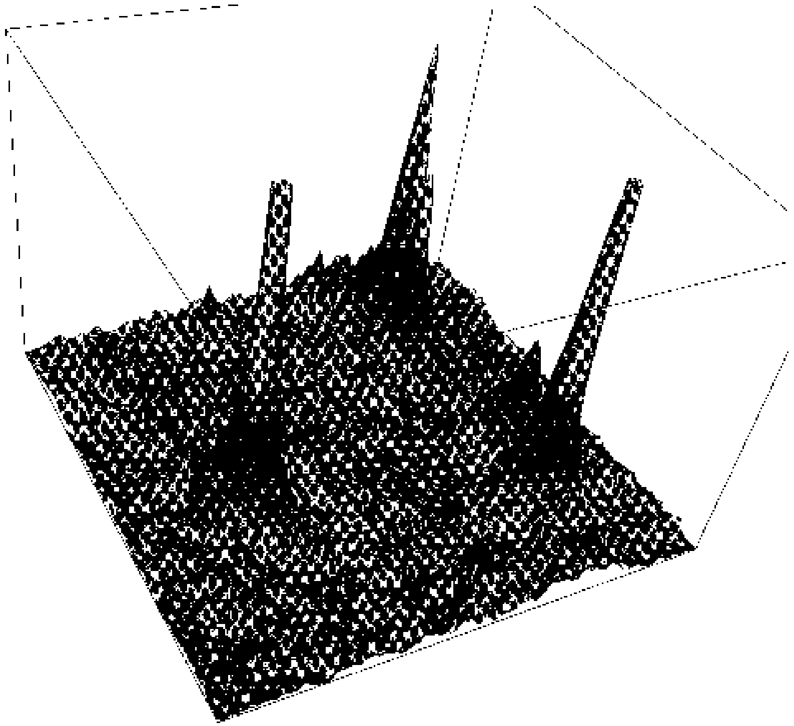
T_0 depends upon n

Mass inside horizon = M_0

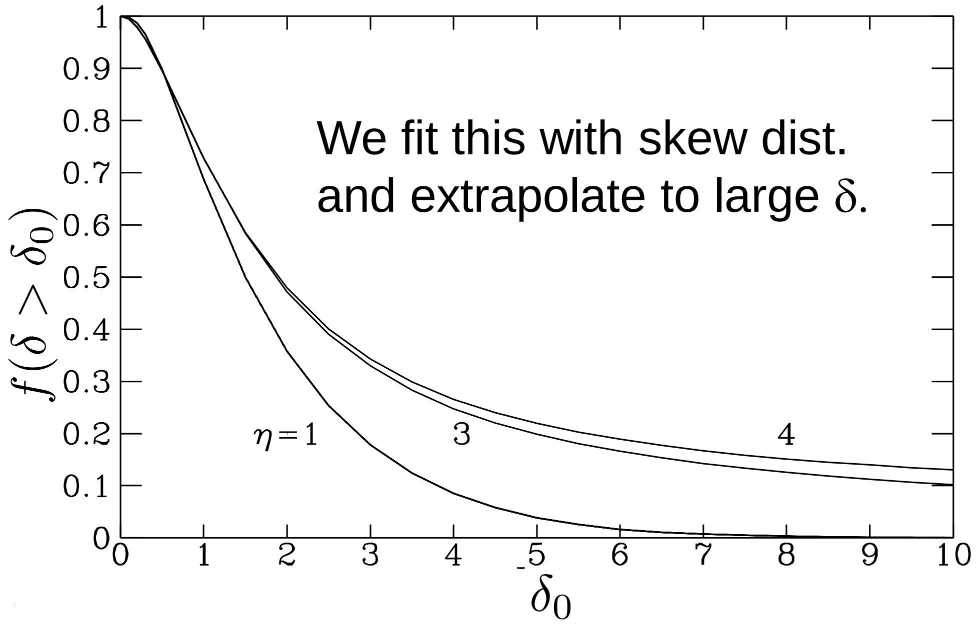


Simulations: Kolb & Tkachev (1990s)

See also Zurek et al (2007); Hardy (2016)



Minicluster formation simulated without gravity or phase transition.



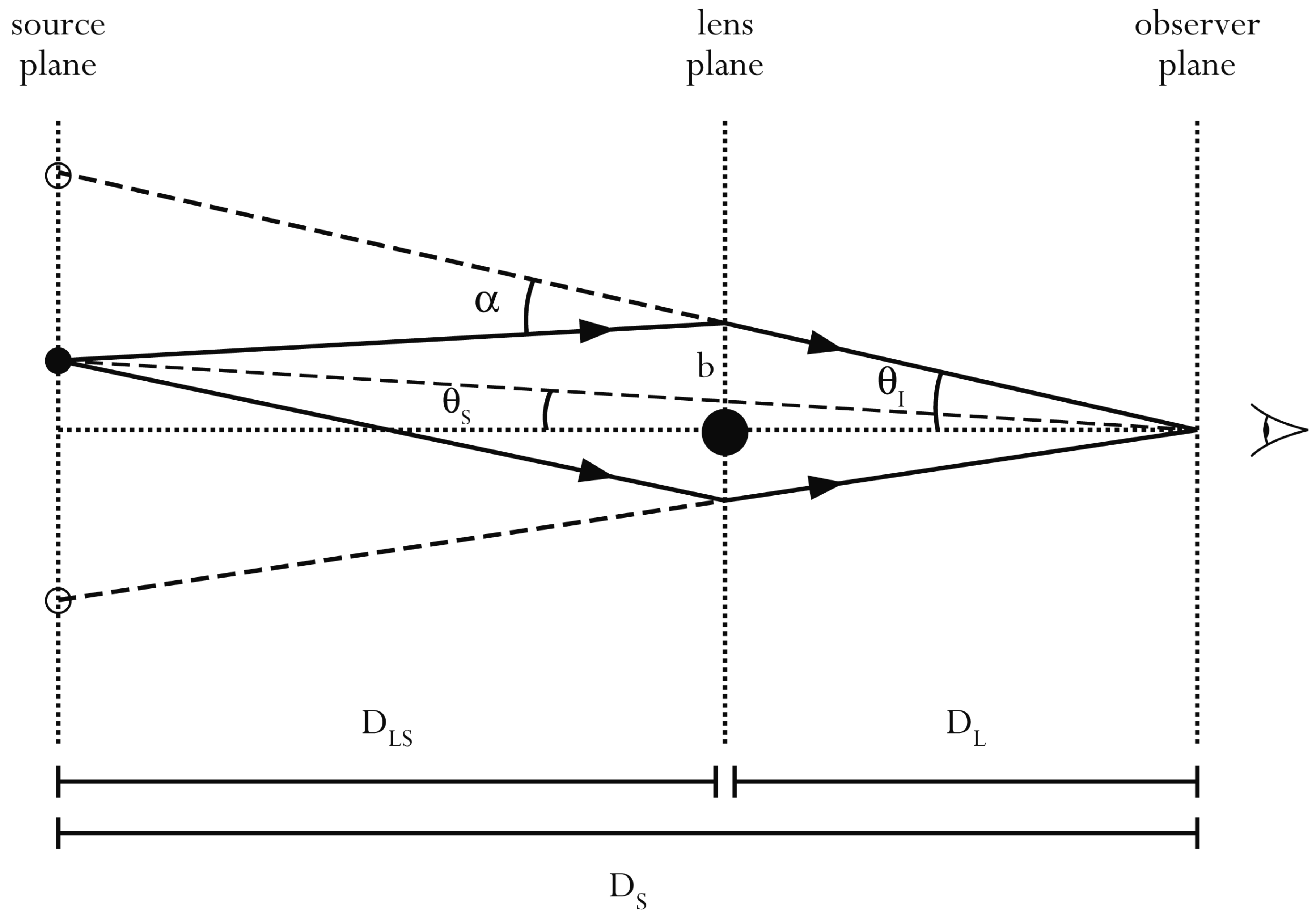
Fraction of MCs with density δ:

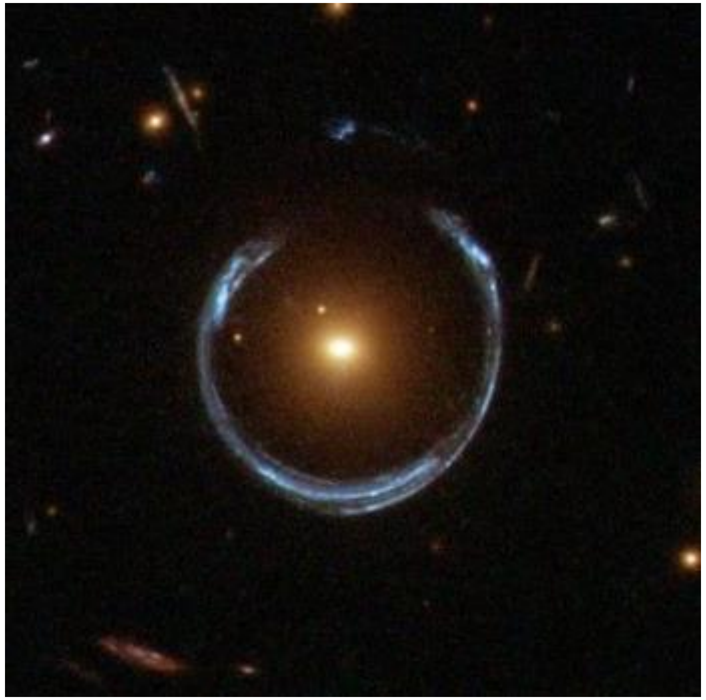
$$\boxed{\rho_c = 140\delta^3(1+\delta)\rho_a(1+z_{eq})^3}$$

The fraction of DM in miniclusters, f_{MC}, is not predicted.

<u>Our goal</u>: ***constrain f_{MC} observationally.***

Gravitational Lensing





$$R_{\mathrm{E}}(x, M) = 2\left[GMx(1-x)d_s\right]^{1/2}$$

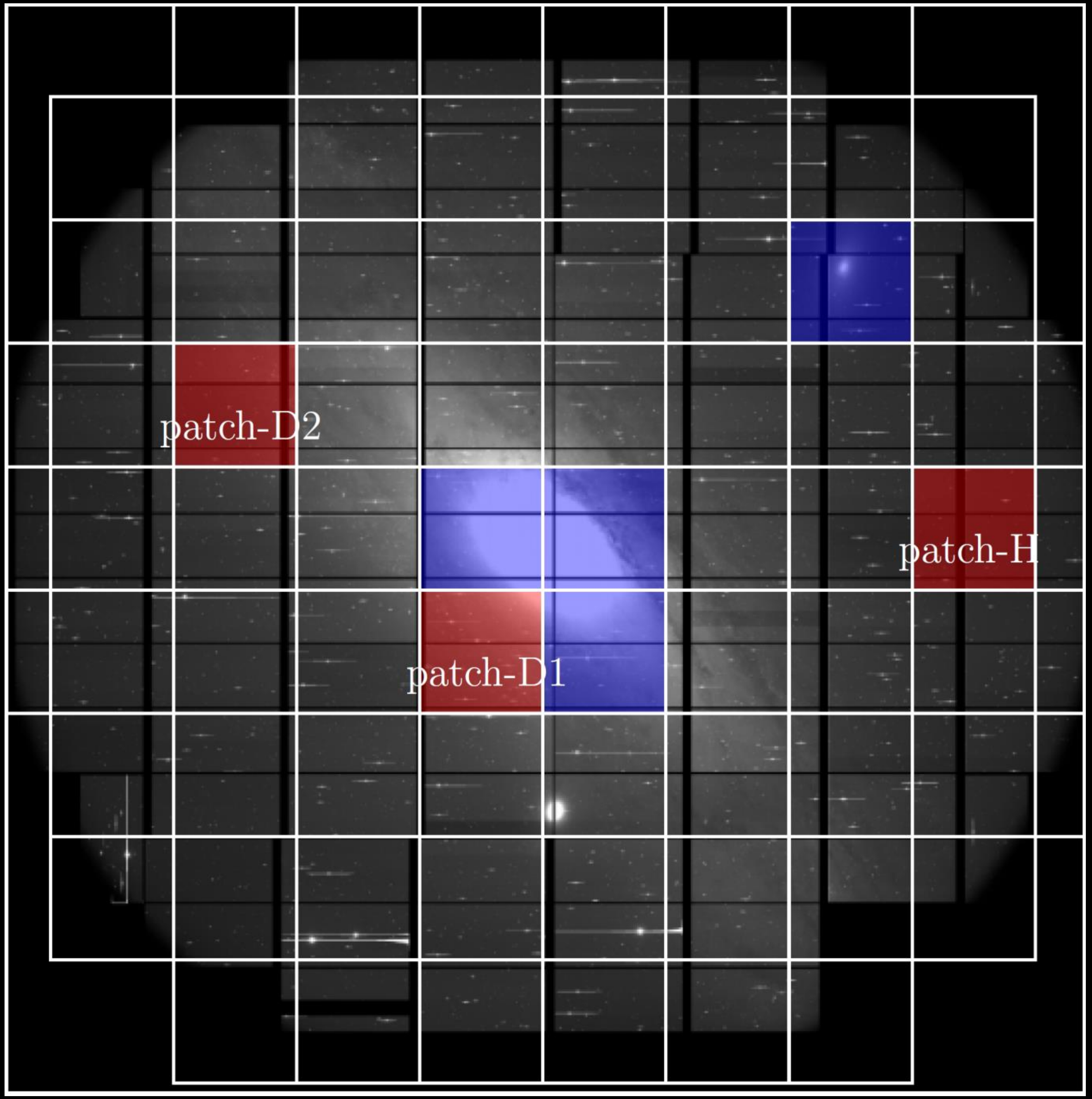
Subaru Hyper Suprime Cam (HSC)

1.5 degree coverage on sky, can cover whole of Andromeda Galaxy (M31)

Blue patches excluded due to too many objects

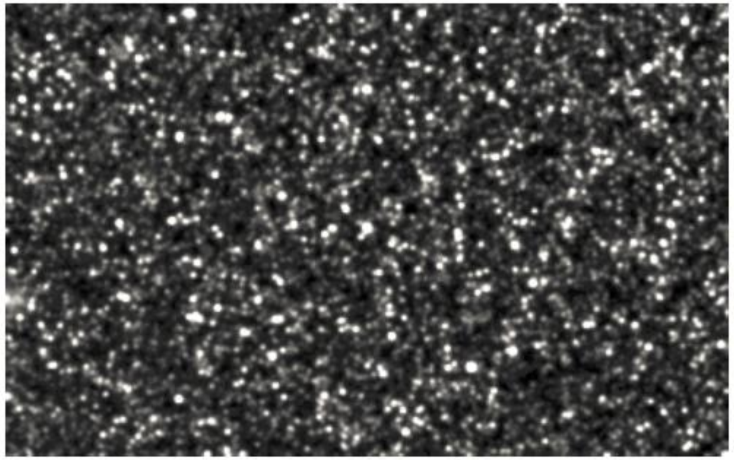
D1 representative of inner disk
D2 outer disk
H halo

Niikura et al, 1701.02151

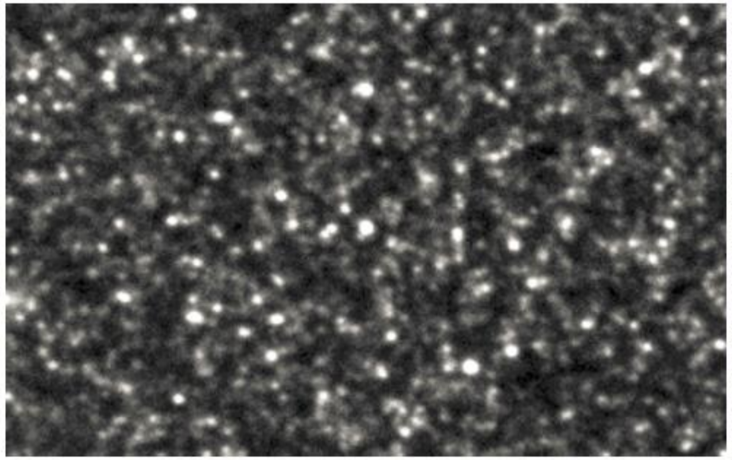


Subaru Hyper Suprime Cam (HSC)

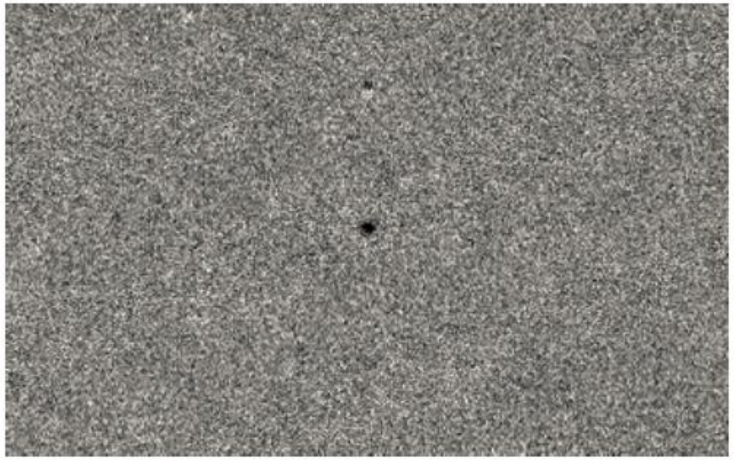
Has only collected 7 hours of data – already has very strong constraints on lensing events



Good stacked image



representative target image

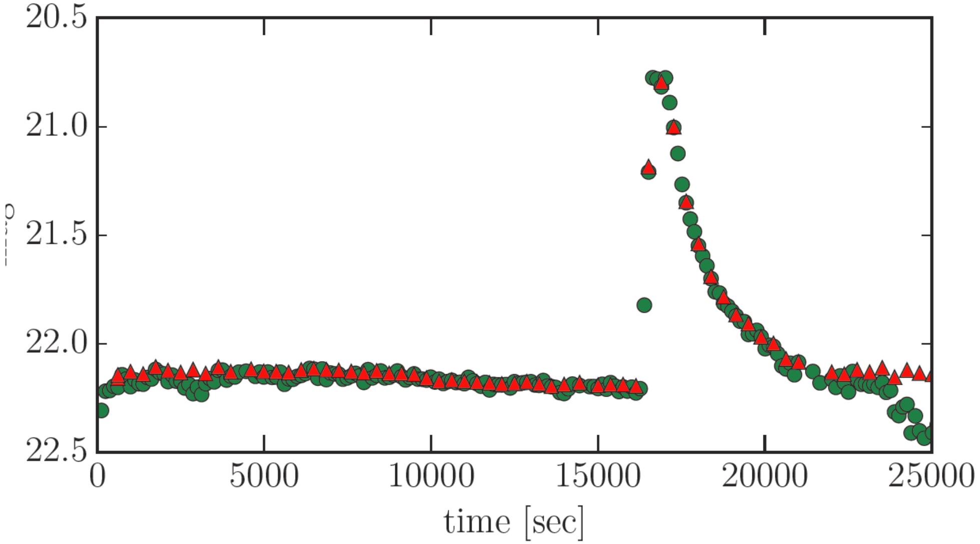


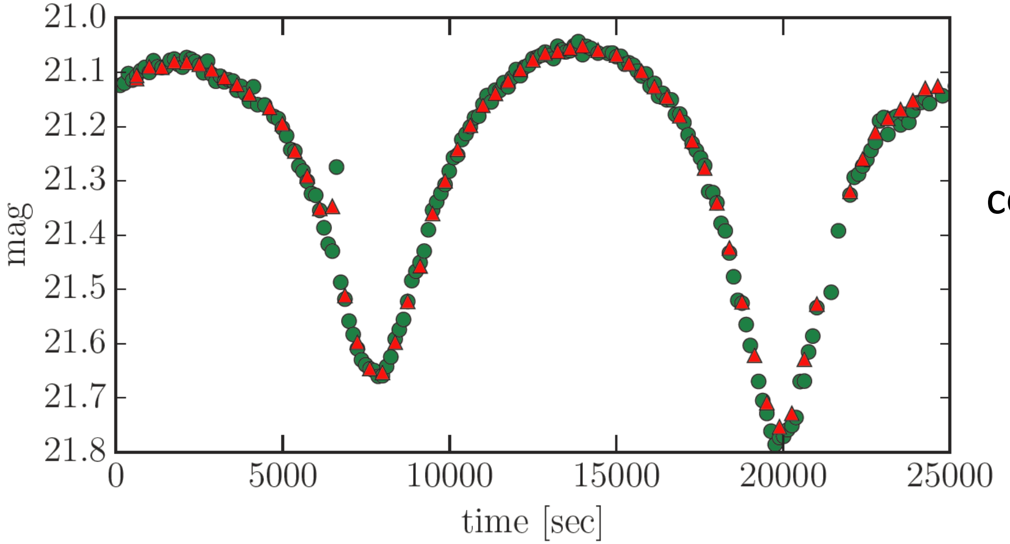
difference – change in one star’s flux

Subaru Hyper Suprime Cam (HSC)

Niikura et al, 1701.02151

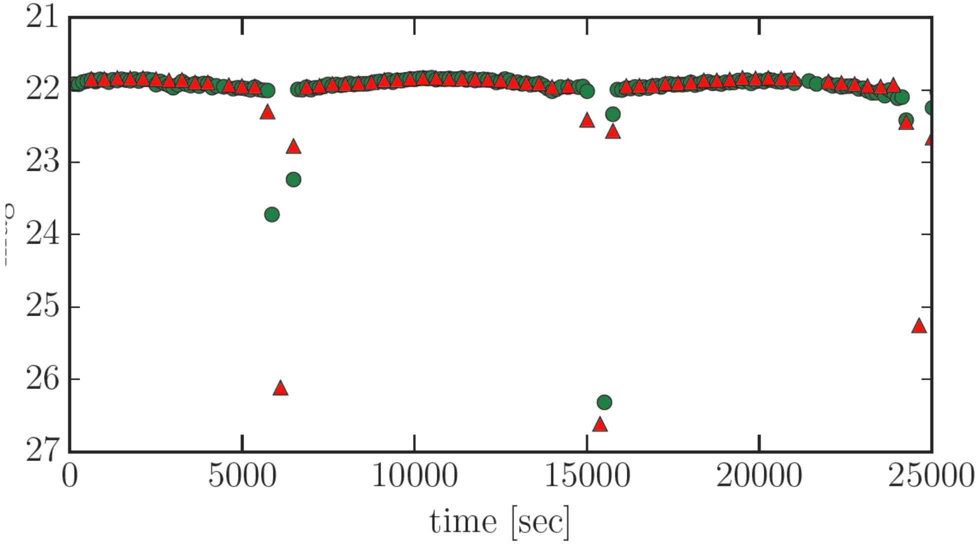
Stellar flare?

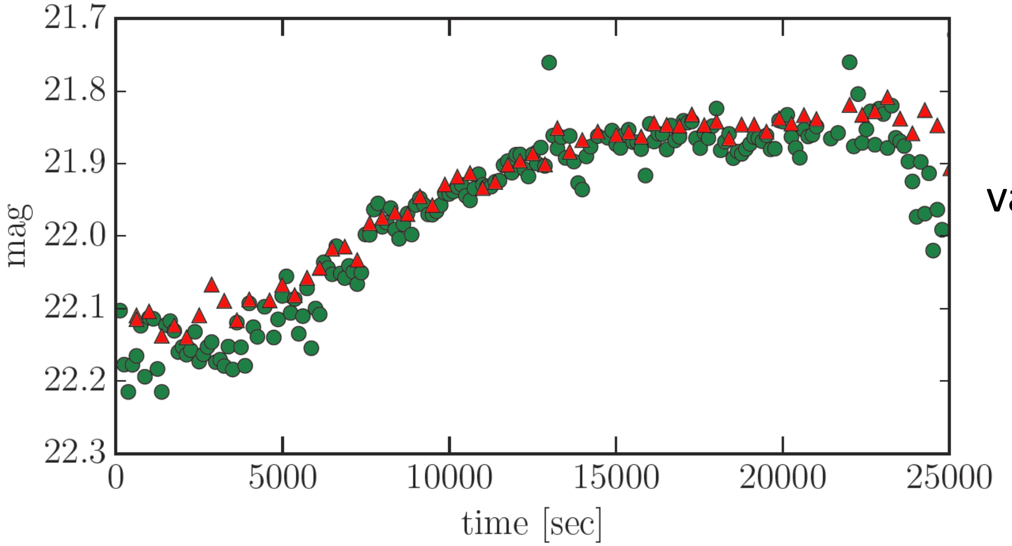




contact binary?

Eclipsing Binary?

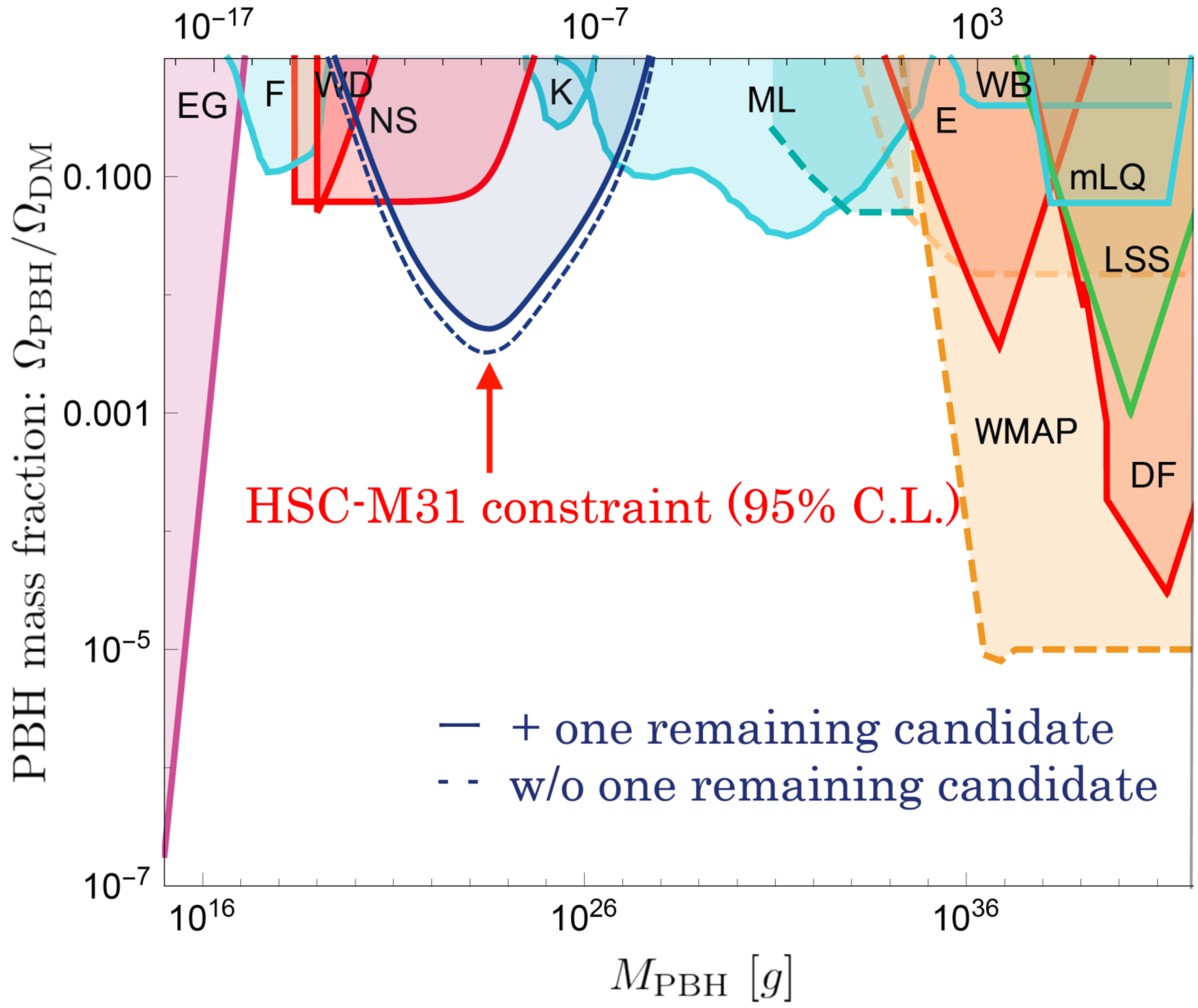




variable star?

HSC constraint on Primordial Black Holes

Niikura et al, 1701.02151



Magnification in the point mass vs. the extended mass case

Most haloes are very diffuse and therefore cause no lensing

Magnification for a distributed source

$$\mu = \left[(1 - B)\,(1 + B - C)\right]^{-1}$$

$$C = \frac{1}{\Sigma_c \pi r} \frac{dM(r)}{dr} \; ; \; B = \frac{M(r)}{\Sigma_c \pi r^2} \; ; \; \Sigma_c = \frac{c^2 D_S}{4\pi G D_L D_{LS}}$$

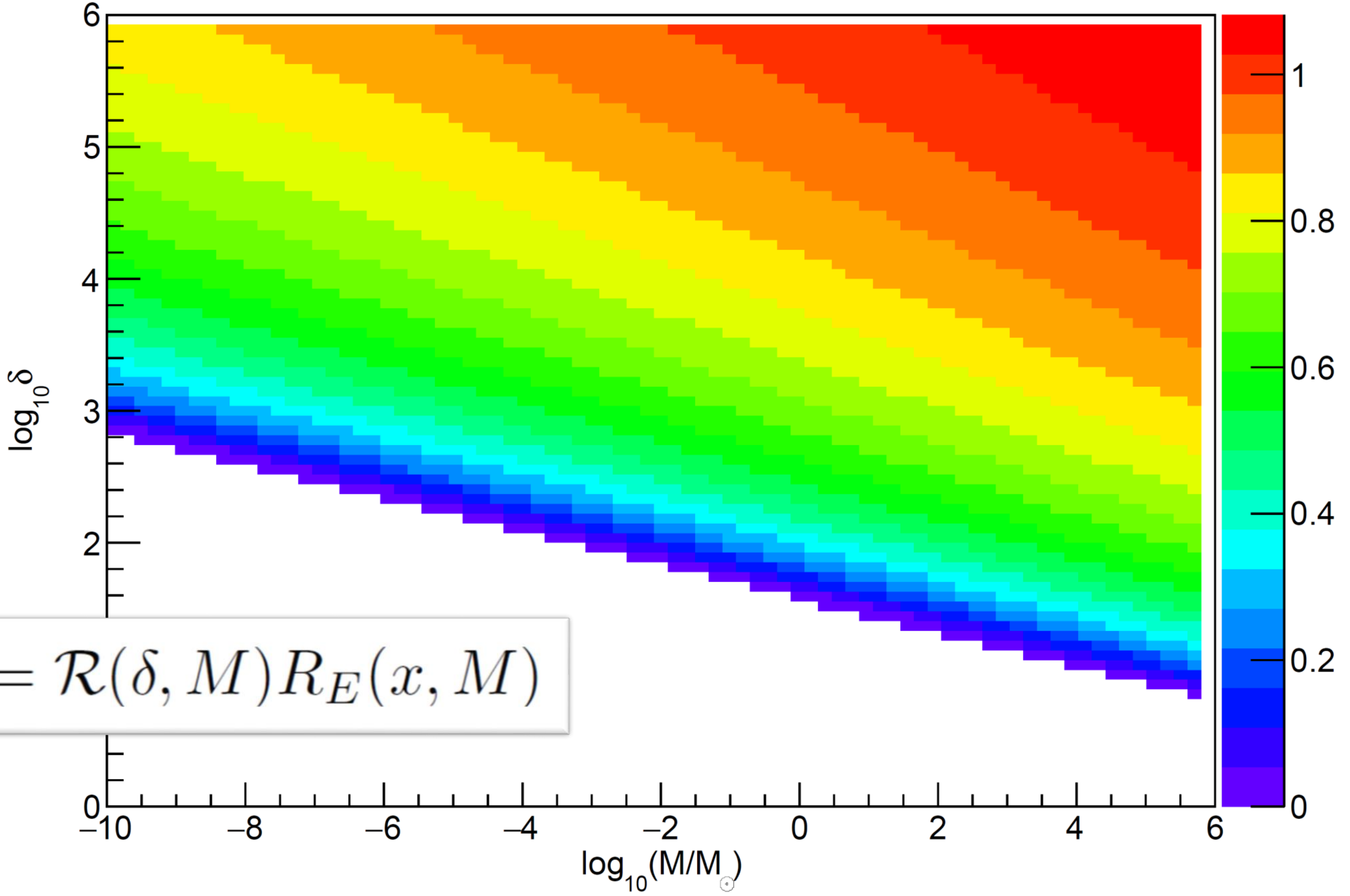
We have distributed density which, while dense, is not a point mass.

For each halo we need to integrate inwards to find value of *r* where μ=1.34.

In practise the corresponds to outer image having magnification of 1.17.

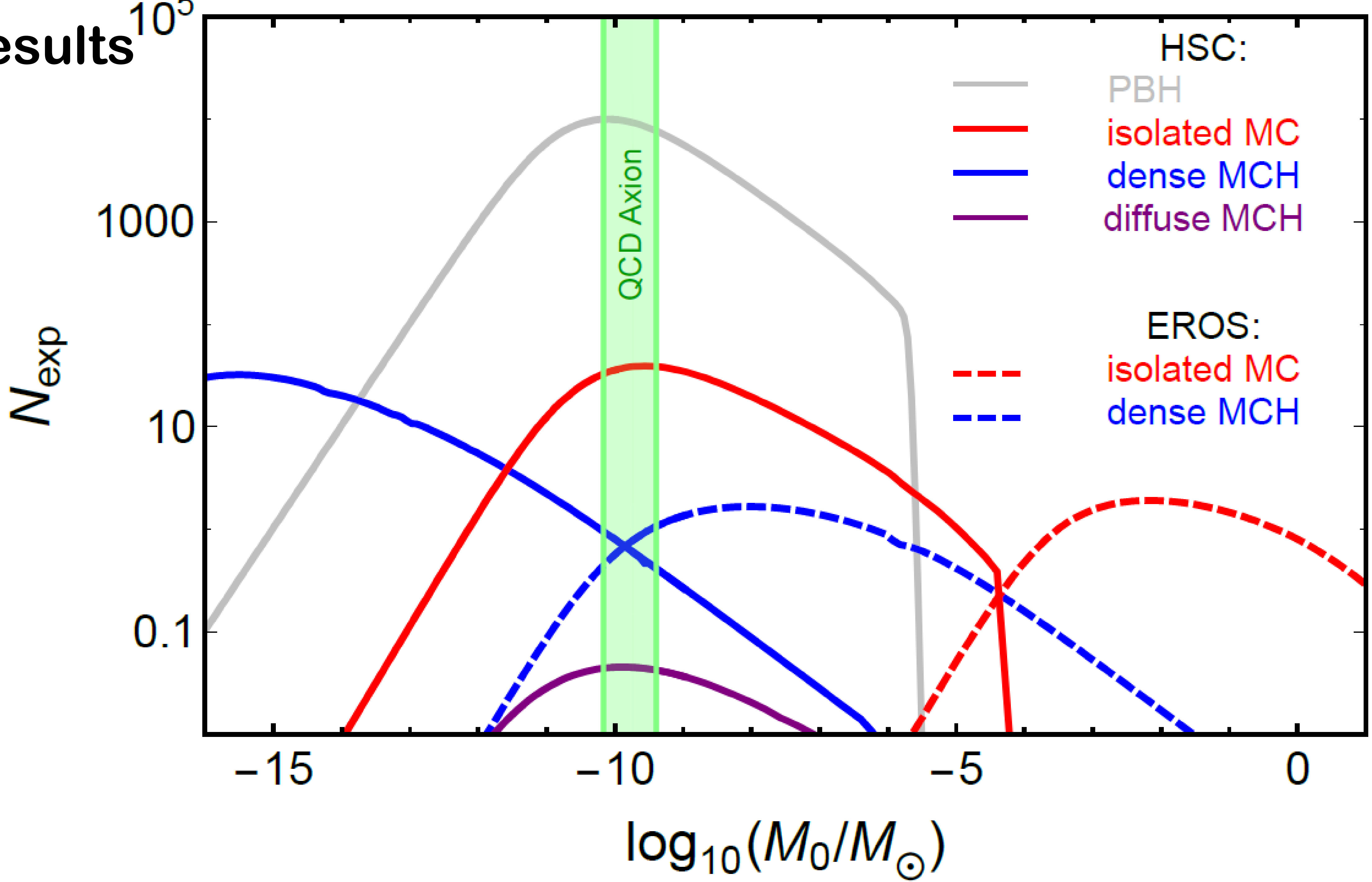
Effective diameter / Einstein diameter

Most haloes are very diffuse and therefore do not cause enough lensing



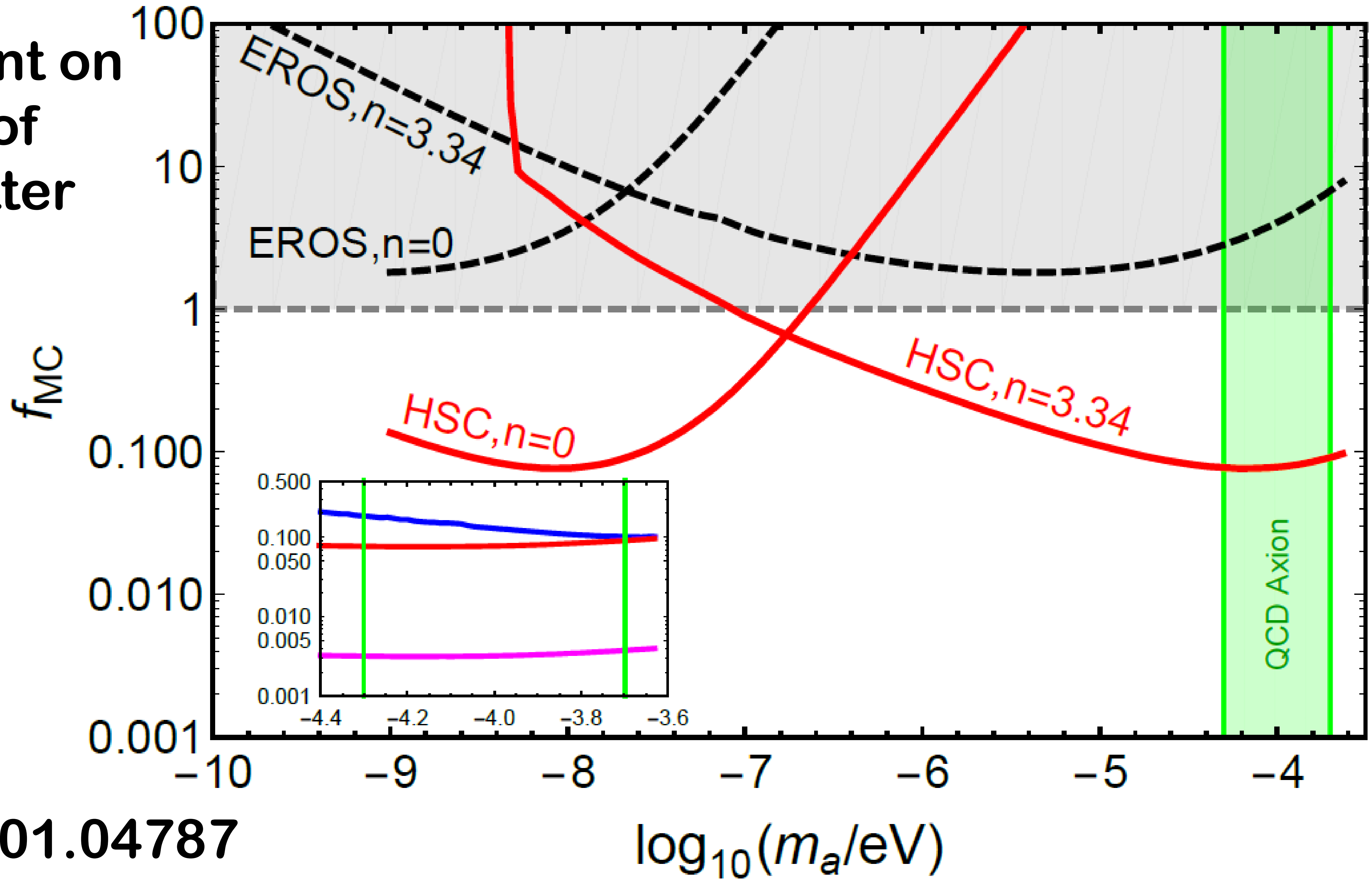
$$R_{\mathrm{MC}}(x, M, \delta) = \mathcal{R}(\delta, M) R_E(x, M)$$

Our Results



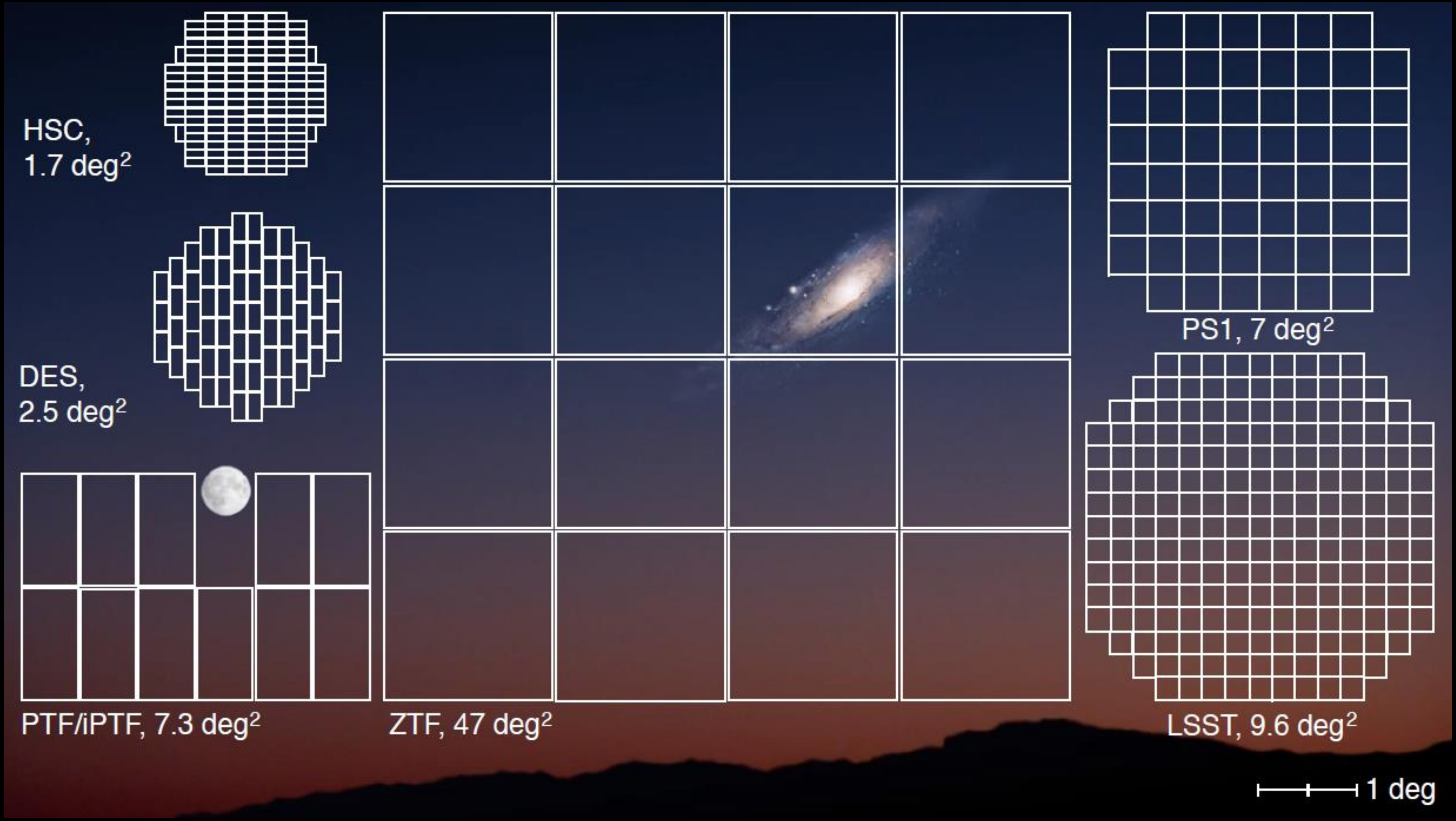
10^5
1000
10
0.1
N_{exp}
−15
−10
−5
0
$\log_{10}(M_0/M_\odot)$
QCD Axion
HSC:
PBH
isolated MC
dense MCH
diffuse MCH
EROS:
isolated MC
dense MCH

Constraint on fraction of dark matter



arXiv:1701.04787

Upcoming Surveys - many of which plan much more exposure than HSC



What do we need to know to further exploit this discovery channel?

- What fraction of the axion dark matter ends up in miniclusters?
- What is the expected distribution of over-densities for the halos?
- Is the minicluster-axion mass relation we assume correct?
- What is the subsequent evolution of the halos (tidal disruption? Friction?)
- What is the precise density profile of the halos (shouldn’t be too critical)

Conclusions on Axion Microlensing

- Gravitational Microlensing seems to be about to experience a renaissance
- Microlensing is a promising discovery channel for axion miniclusters
- With assumptions we have made, QCD axion can be searched for in this channel
- Those assumptions need to be checked, re-investigated and updated!

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Part III

Axion Stars evolution

Black hole formation from axion stars

Thomas Helfer,[1] David J. E. Marsh,[1] Katy Clough,[1] Malcolm Fairbairn,[1] Eugene A. Lim,[1] and Ricardo Becerril[2]

[1] *King's College London, Strand, London, WC2R 2LS, United Kingdom*

[2] *Instituto de Física y Matemáticas, Universidad Michoacana de San Nicolás de Hidalgo, Ciudad Universitaria, CP 58040 Morelia, Michoacn, Mexico.*





N.B. there are two David Marshes,
both of whom were at oxford at
the same time,
both of whom work on axions,
one of them is German and the
other is a scouser.

WE SIMULATED AXION STARS USING GR-CHOMBO

GRChombo: Numerical Relativity with Adaptive Mesh Refinement

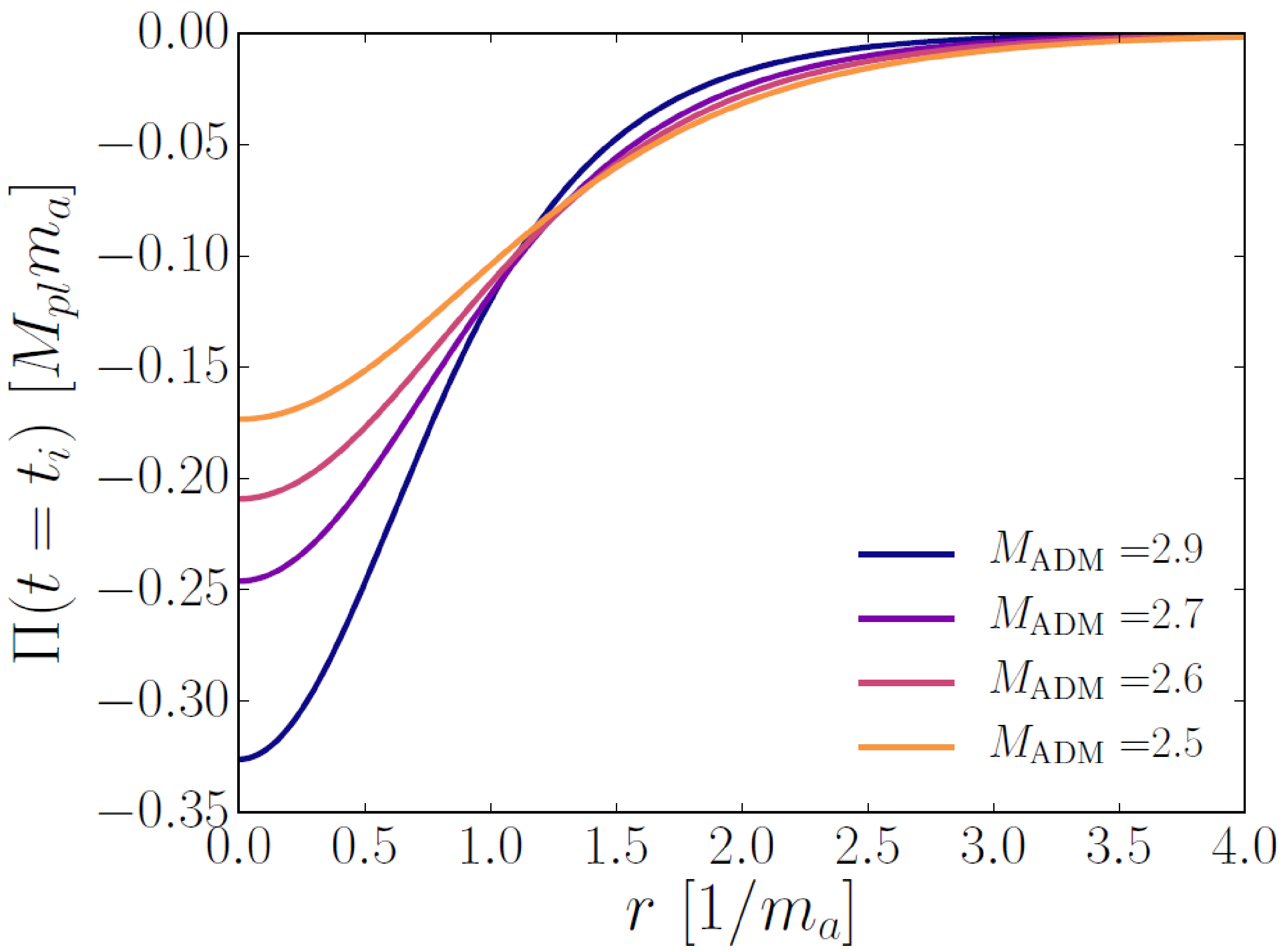
http://grchombo.github.io/

Katy Clough[1], Pau Figueras[2], Hal Finkel[3], Markus Kunesch[2], Eugene A. Lim[1], Saran Tunyasuvunakool[2]

GRChombo's features include:-

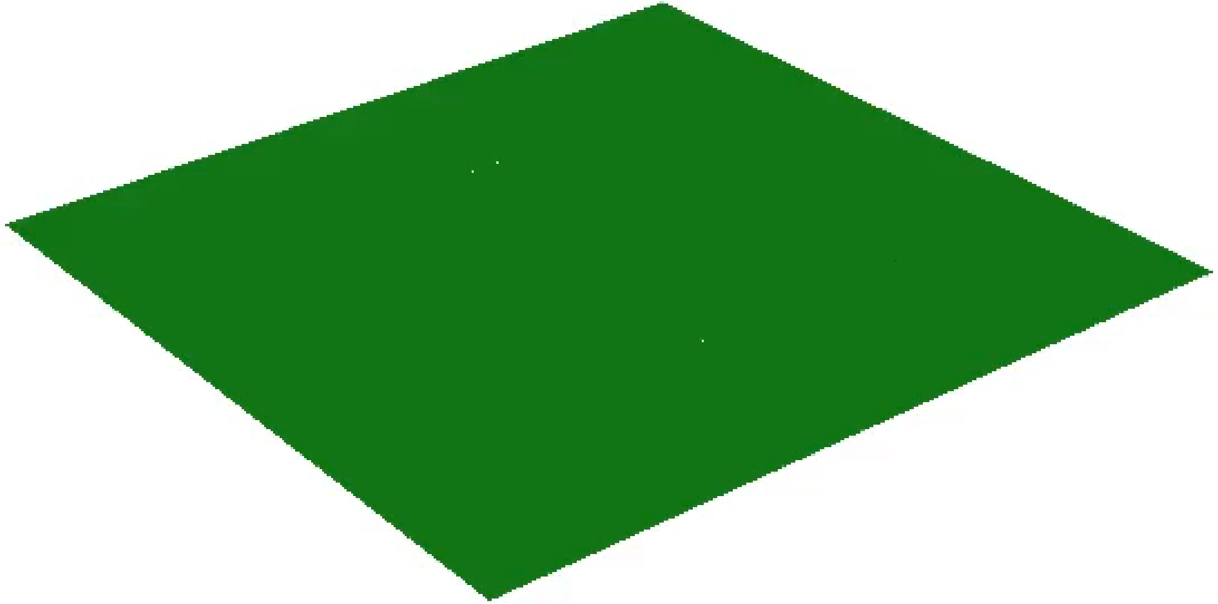
- full adaptive mesh refinement (AMR) with block structured Berger-Rigoutsos grid generation which supports non-trivial "many-boxes-in-many-boxes" meshing hierarchies
- massive parallelism through the Message Passing Interface (MPI)
- GRChombo evolves the Einstein equation with the standard BSSN formalism
- option to turn on CCZ4 constraint damping if required
- can stably and accurately evolve vacuum black hole spacetimes such as binary black hole mergers, and non-vacuum spacetimes such as scalar collapses into black holes
- I only understand the previous bullet point (and this one)

Initial Conditions



Set the potential zero,
Give momentum equal to that obtained from full relativistic solution in the harmonic case

Almost Stable Solution with large f



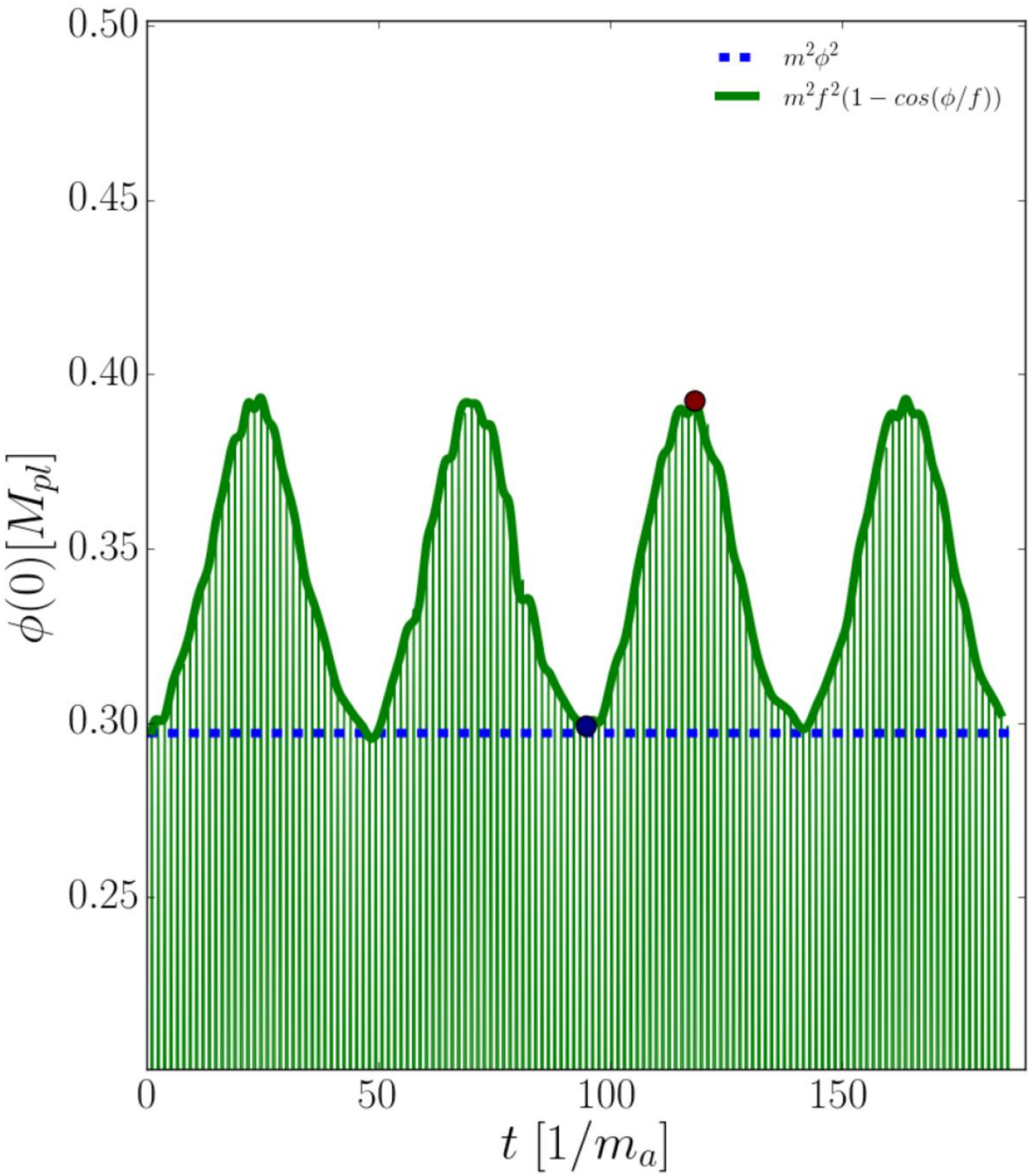
Tried to understand amplitude modulation using perturbative analysis

$$V(\phi) = m_a^2 f_a^2 \left[1 - \cos\left(\frac{\phi}{f_a}\right)\right]$$
$$= \frac{1}{2} m_a^2 \phi^2 - \frac{1}{4!} \frac{\phi^4}{f_a^2} + \dots$$

Understanding the amplitude modulation

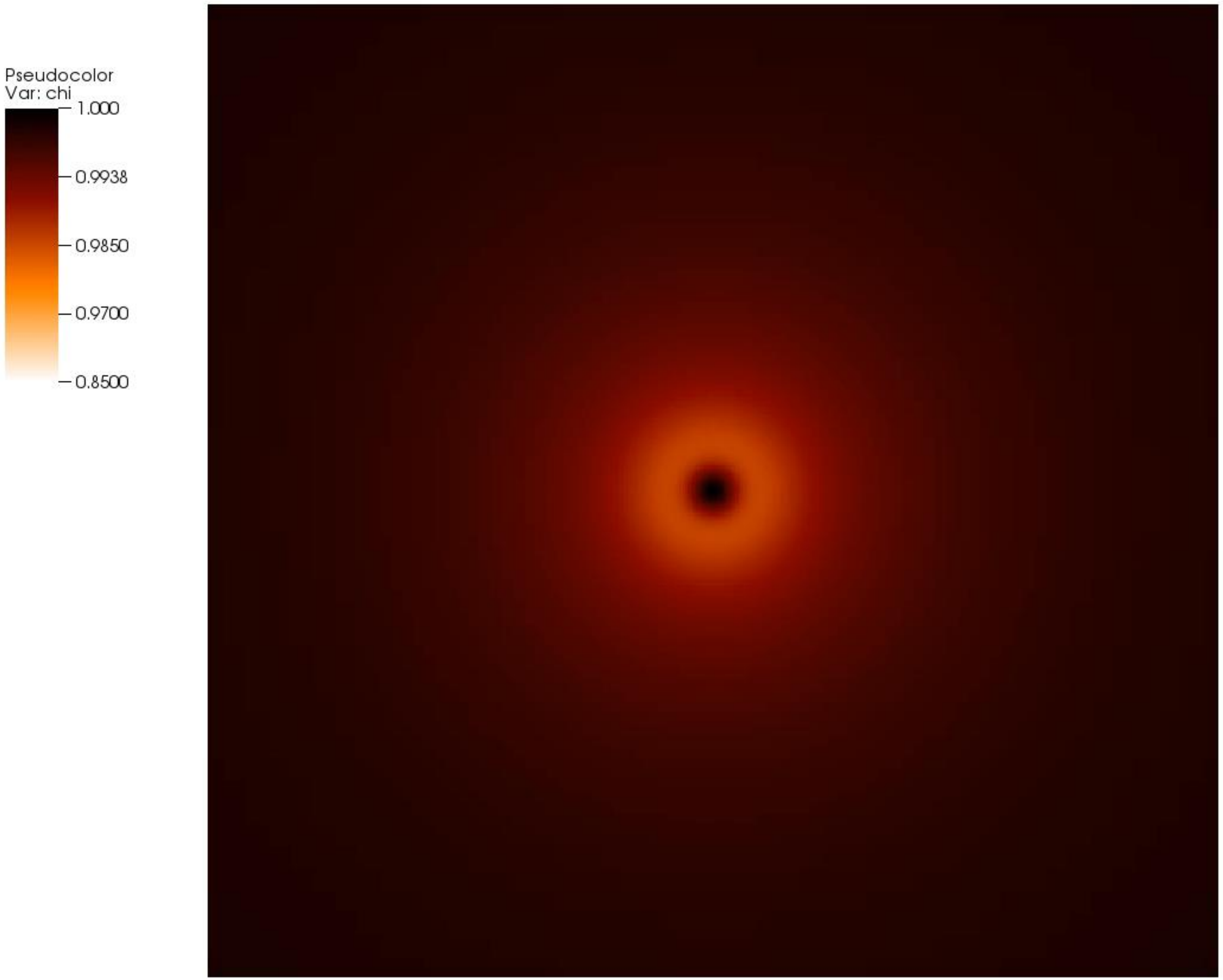
$$V(\phi) = m_a^2 f_a^2 \left[1 - \cos\left(\frac{\phi}{f_a}\right)\right]$$

$$= \frac{1}{2} m_a^2 \phi^2 - \frac{1}{4!}\frac{\phi^4}{f_a^2} + \dots$$



Extra features probably due to spatial gradients.

What happens when we increase the amplitude?



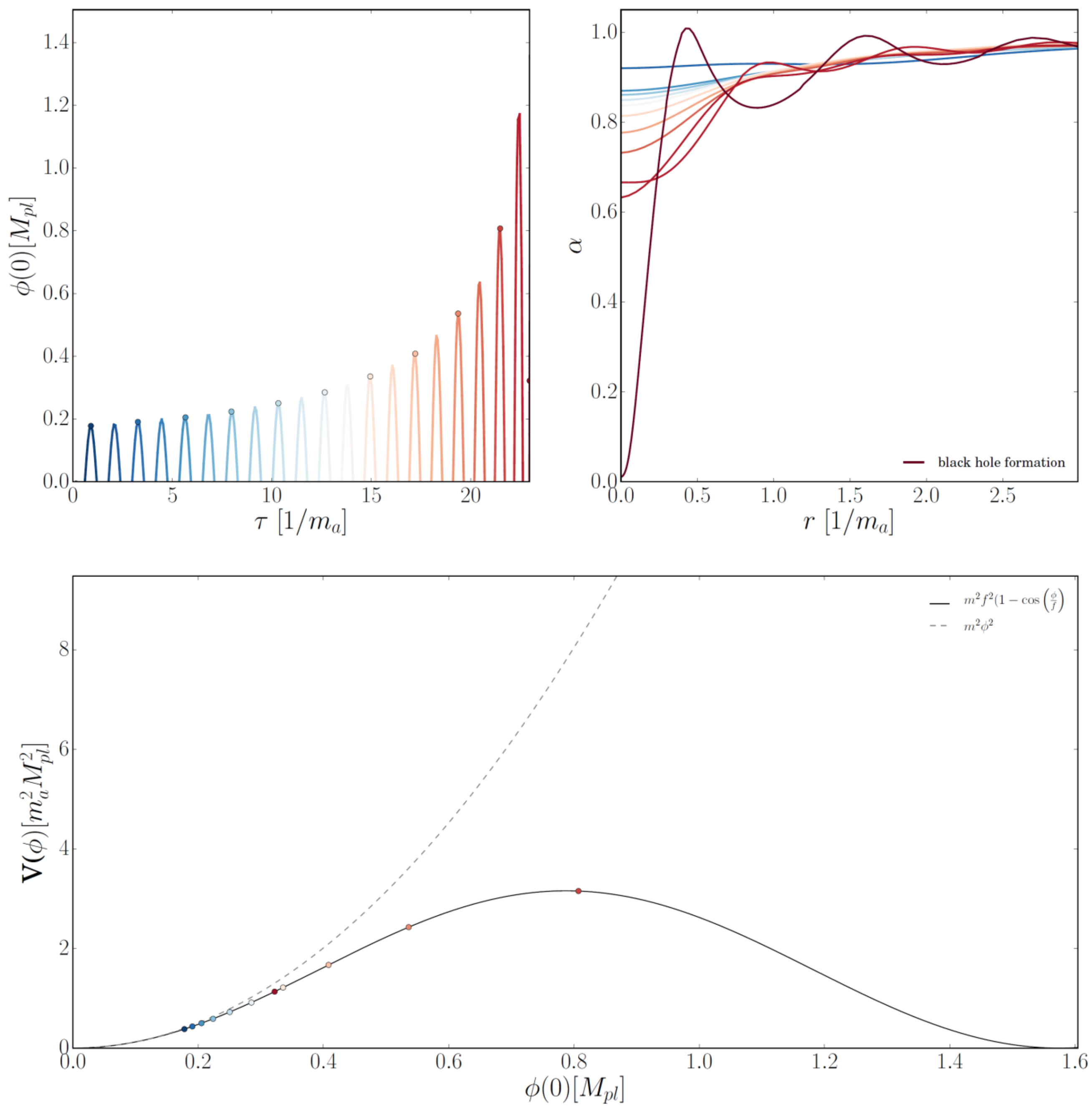
Some of them disperse…

Here, you are looking at the evolution of

$$\chi = \sqrt{\frac{1}{1 - 2V_{Newton}}}$$

What happens when we continue to increase the amplitude/mass?

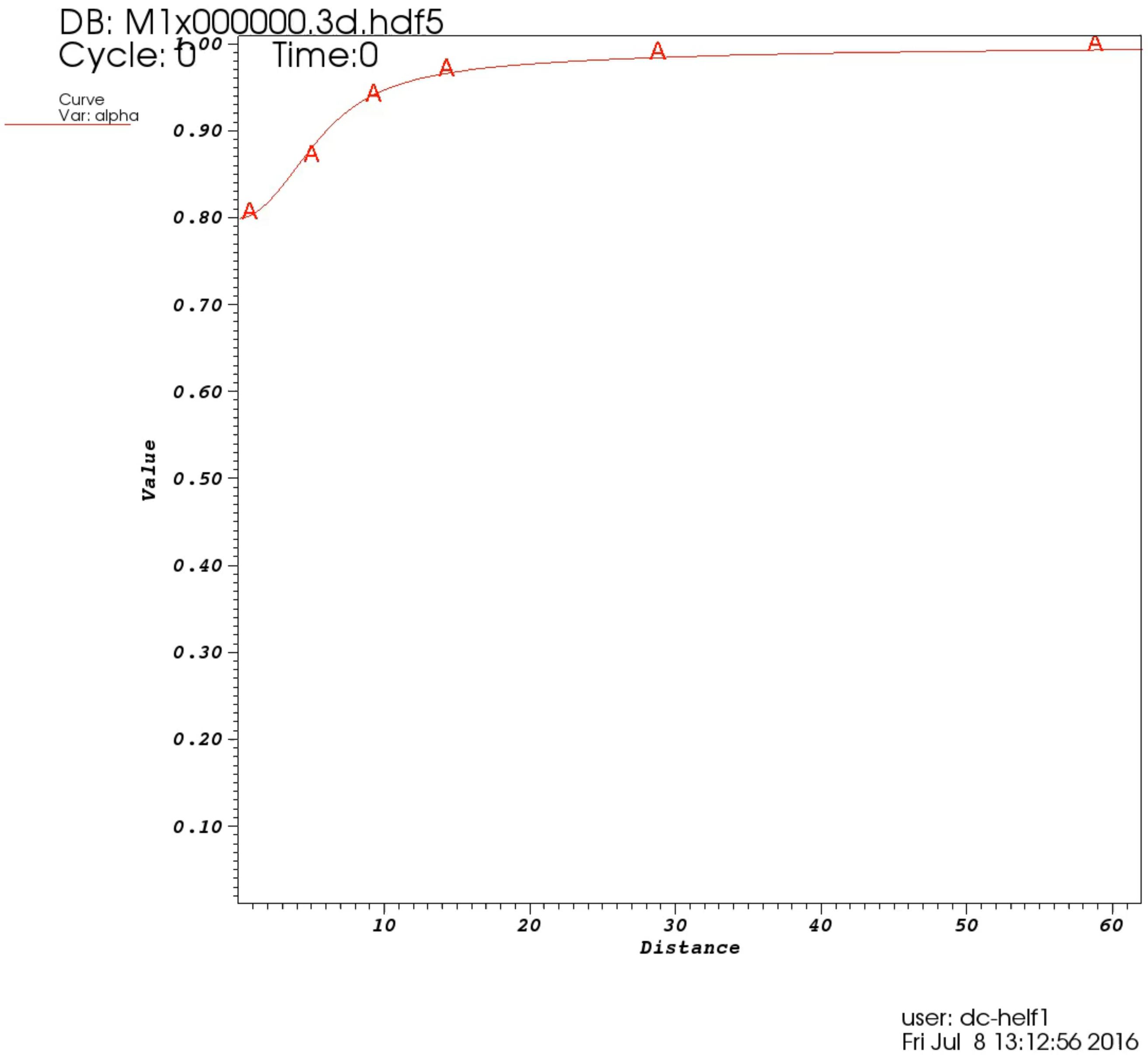
For sufficiently large values, we get a black hole



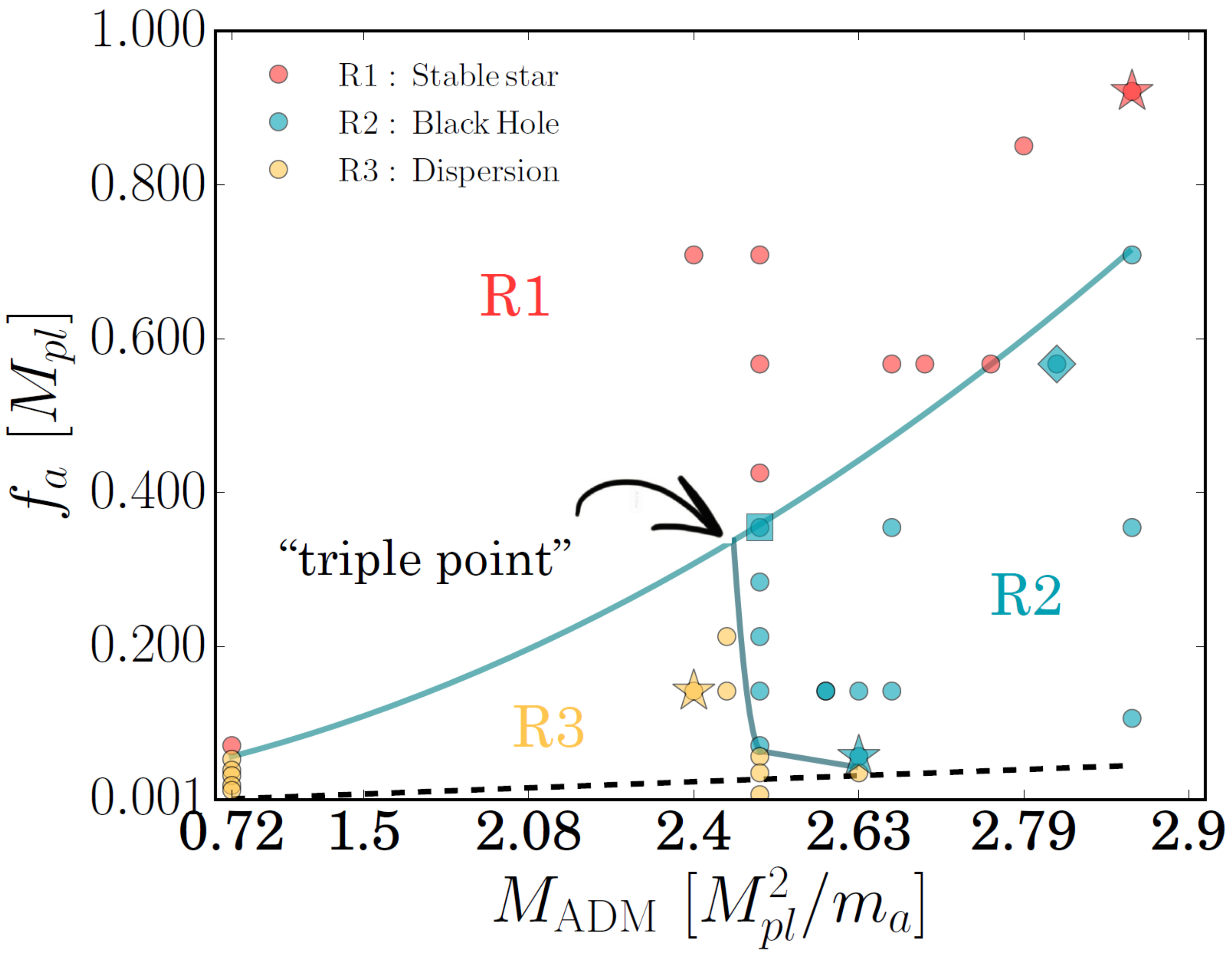
Some of them Collapse

Again, you are looking at

$$\chi = \sqrt{\frac{1}{1 - 2V_{Newton}}}$$



Our Result : We propose an Axion Star Phase Diagram



- **Region 1 (stable)**: Where the maximum axion angle $\phi/f_a \lesssim 0.1\pi$, we find quasi-stable solutions for which the lifetime is much longer than the individual oscillations of the field profile. These solutions differ from the $m^2\phi^2$ model by small modulations and are true axion stars

- **Region 2 (unstable)**: Where the initial ADM mass is sufficiently large, we find collapse to black holes even though the stars' radii are greater than their respective Schwarzchild radii.

- **Region 3 (unstable)**: Where f_a is small (large self-interactions) and the initial field velocity is sufficiently large, we see dispersal of the axion star caused by scalar radiation

What we Did:-

- We did full GR solutions of axion stars
- We identified three regions
  1. Stable solution much like $m^2\phi^2$
  2. Region where dispersal takes place, back to situation 1.
  3. Region where black hole forms.

What next:-

- Implications for cosmology, obviously
- Black hole formation, could this play a role?

King's College London, most central London University

We will be recruiting one or two postdocs in the Autumn

Please apply!

Dark Matter Searches are no place for Dogma.

Could be WIMPs, sterile neutrinos, axions, hidden sector glueballs, KK particles, whatever….

Whenever we come up with an idea to test one of these we should do so. There will be lots of new ways to test these scenarios in the coming Years…

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