Axions

Malcolm Fairbairn

APS+L Woerden – October 2017

It’s very nice to be here,

Thank you for the invitation and the organisation.

- Axion phenomenology lightning introduction
- Probing QCD axion with microlensing
- (if time) Ultra Light Axions

Axion Phenomenology Lightning Introduction

Axions as Dark Matter

What is this? Leads to CP violation (neutron EDM)

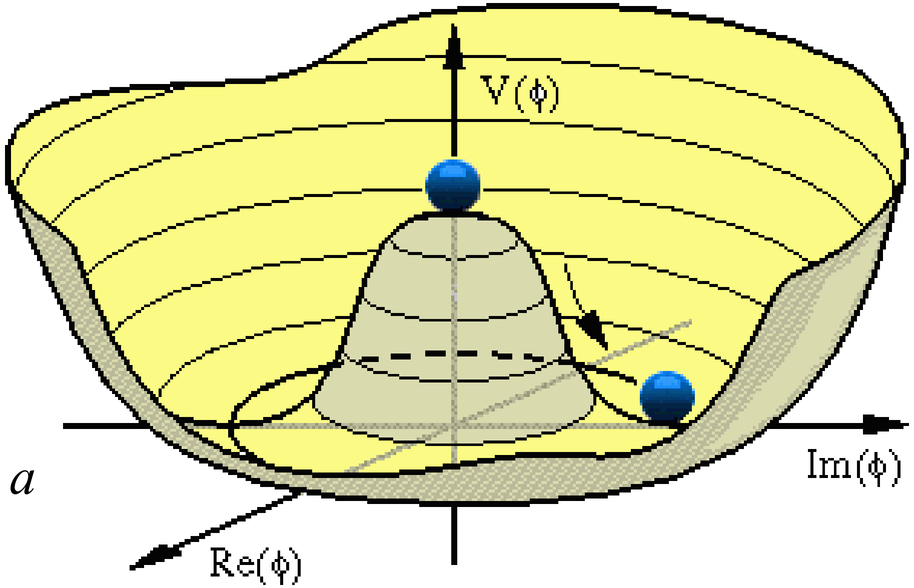
$$S = \int d^4x \left[-\frac{1}{4g^2} G^{a,\mu\nu} G^a_{\mu\nu} + \frac{\theta}{32\pi^2} G^{a,\mu\nu} \tilde{G}^a_{\mu\nu} + i\bar{\psi} D_\mu \gamma^\mu \psi + \bar{\psi} M \psi \right]$$

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

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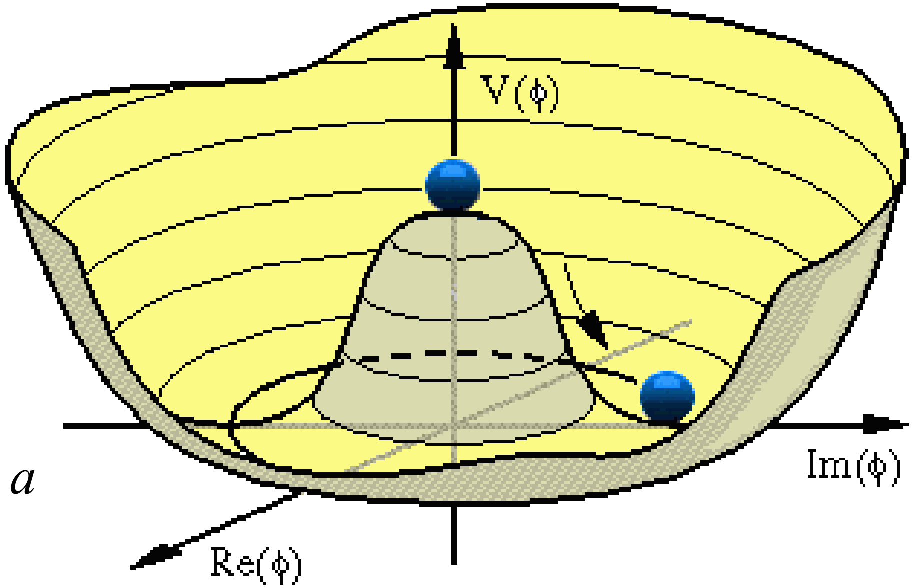

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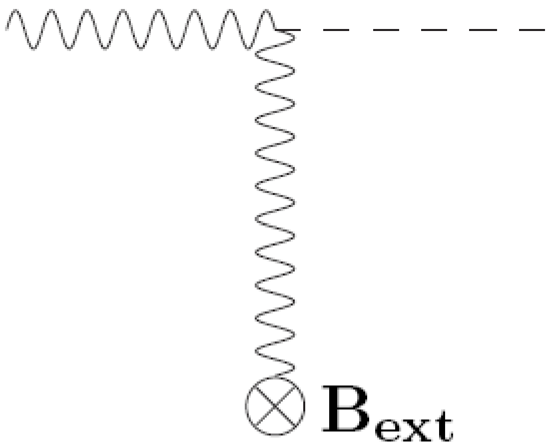
Phenomenological consequences:- coupling to photons

$$\mathcal{L} = \frac{1}{2}(\partial^\mu \psi \partial_\mu \psi - m^2 \psi^2) - \frac{1}{4}\frac{\psi}{M} F_{\mu\nu}\widetilde{F}^{\mu\nu} - \frac{1}{4}F_{\mu\nu}F^{\mu\nu}$$

Consider axion production in magnetic field of nucleon in sun



$$\frac{d\epsilon}{dt} \sim \frac{T^7}{M^2} \quad ; \quad M \sim f_a$$

Existance of sun alone suggests M > 10^8GeV

Lagrangian and mixing

$$\mathcal{L} = \frac{1}{2}(\partial^\mu \psi \partial_\mu \psi - m^2\psi^2) - \frac{1}{4}\frac{\psi}{M}F_{\mu\nu}\widetilde{F}^{\mu\nu} - \frac{1}{4}F_{\mu\nu}F^{\mu\nu}$$

can linearise solutions when refractive index close to unity

$$i\partial_z \Psi = -(\omega + \mathcal{M})\Psi \quad ; \quad \Psi = \begin{pmatrix} A_x \\ A_y \\ a \end{pmatrix}$$

mixing matrix:-

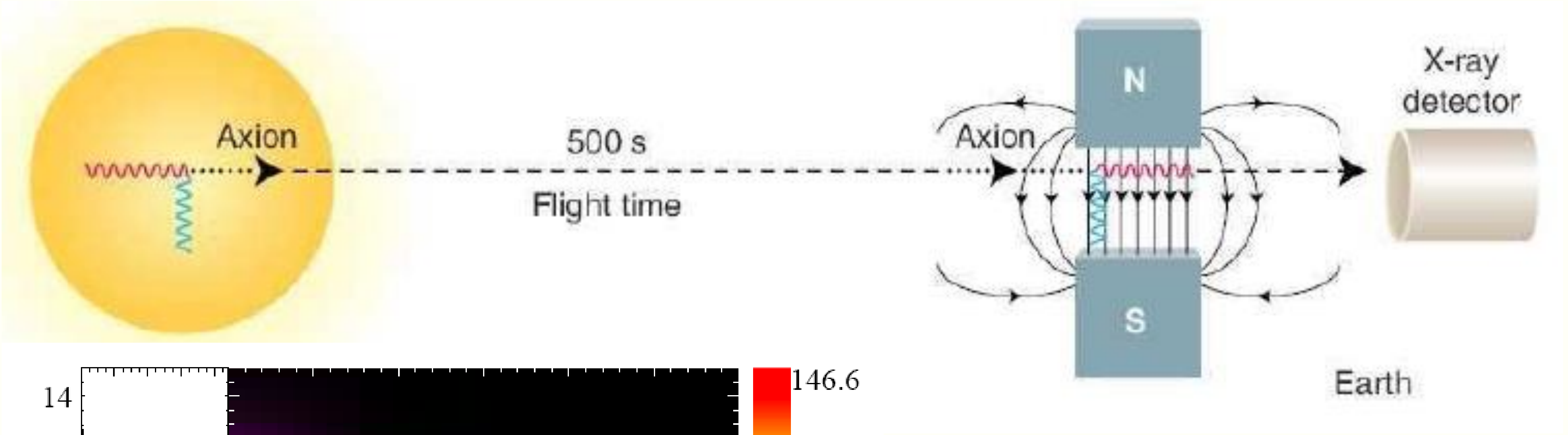
$$\mathcal{M} \equiv \begin{pmatrix} \Delta_p & 0 & \Delta_{Mx} \\ 0 & \Delta_p & \Delta_{My} \\ \Delta_{Mx} & \Delta_{My} & \Delta_m \end{pmatrix}$$

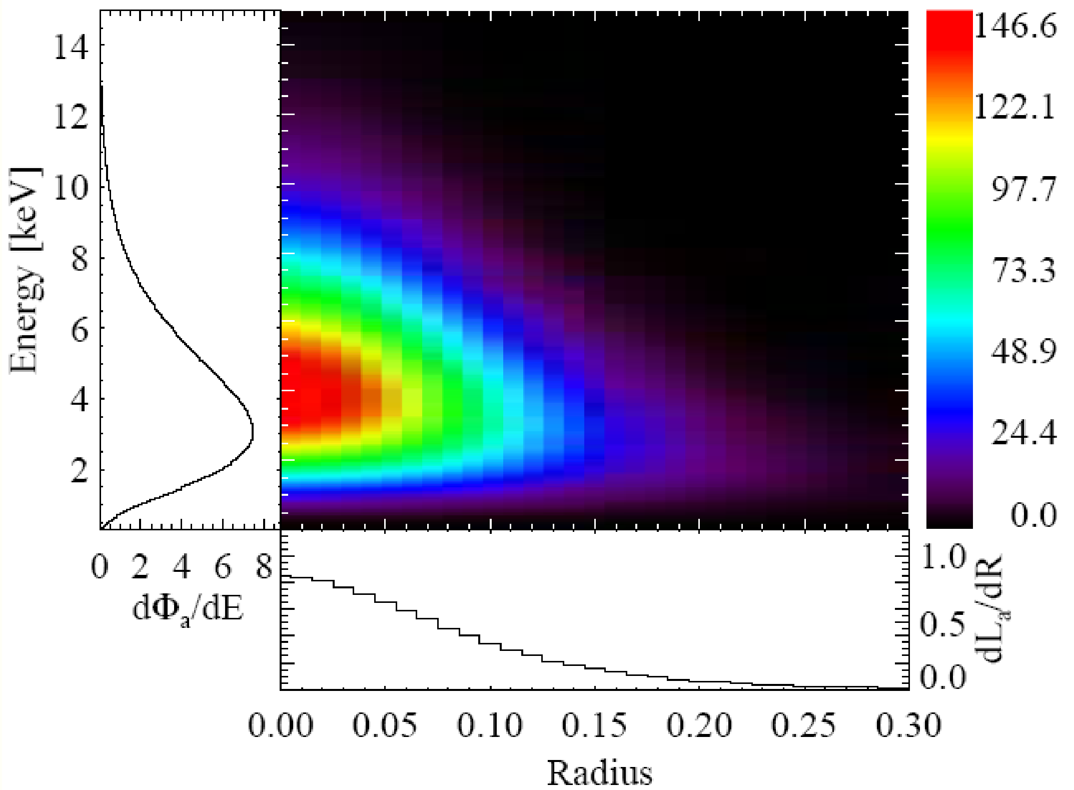
$$\Delta_{Mi} = \frac{B_i}{2M}$$

$$\Delta_m = \frac{m^2}{2\omega}$$

$$\Delta_p = \frac{\omega_p^2}{2\omega}$$

Search for Solar axions





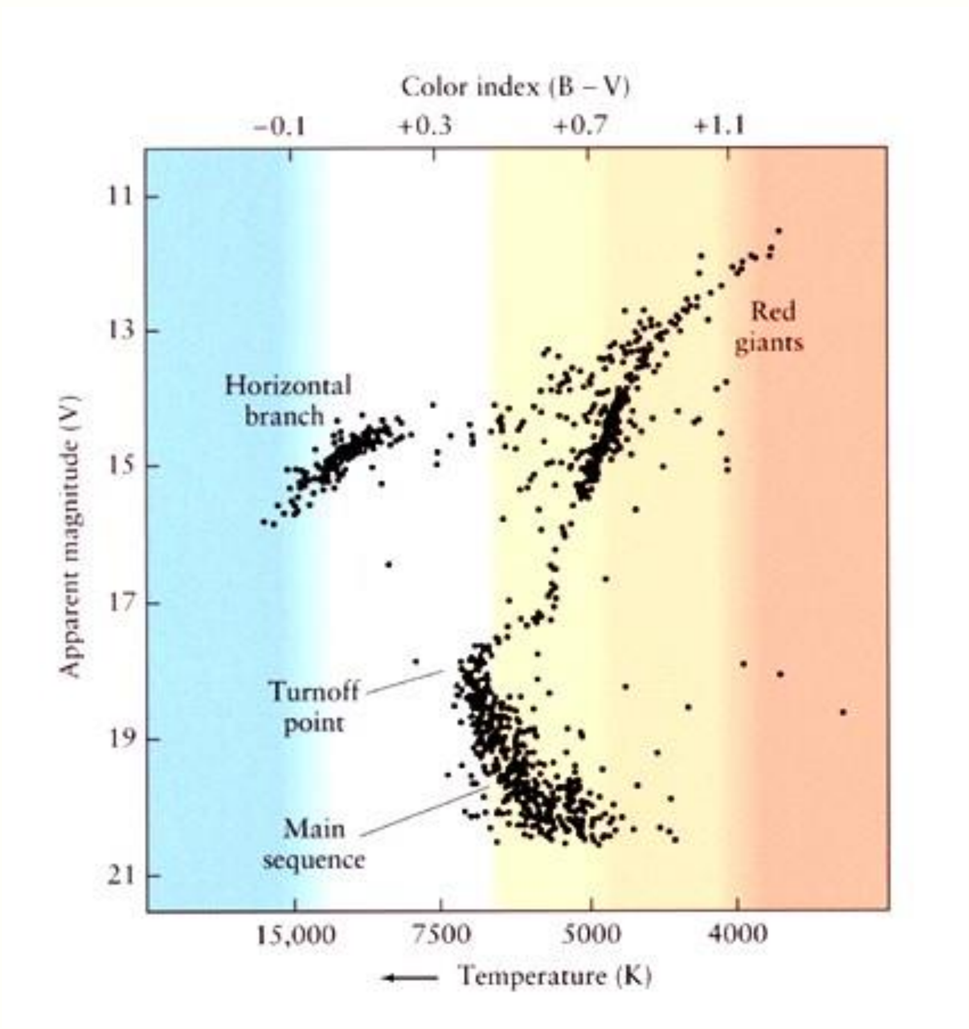
look for axions produced in the sun and turn them back into photons down here

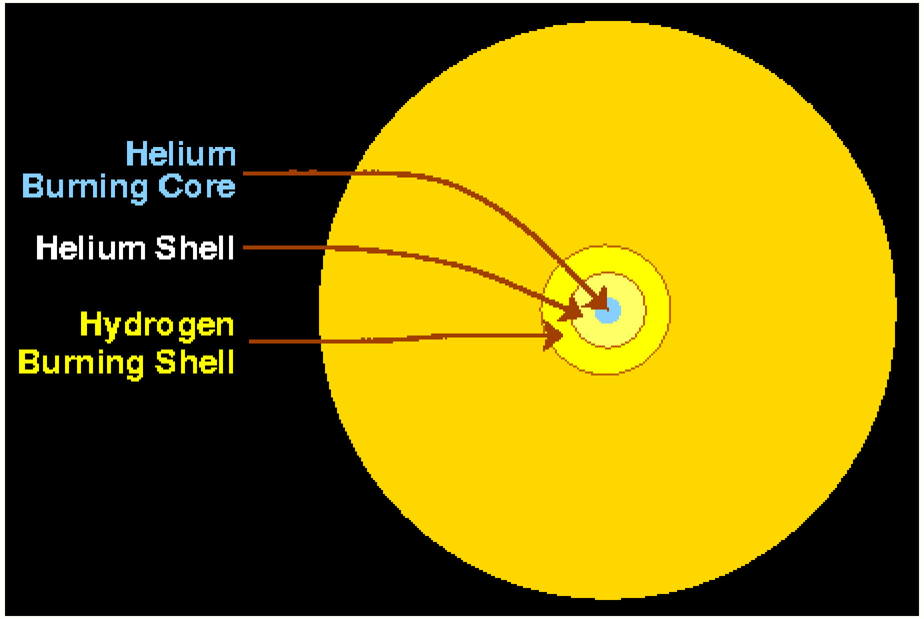
CAST: cern-axion-solar-telescope

Horizontal Branch Stars

Horizontal Branch Stars

Helium burning in core leads to huge central luminosity – temperature gradient is saturated – convective core.





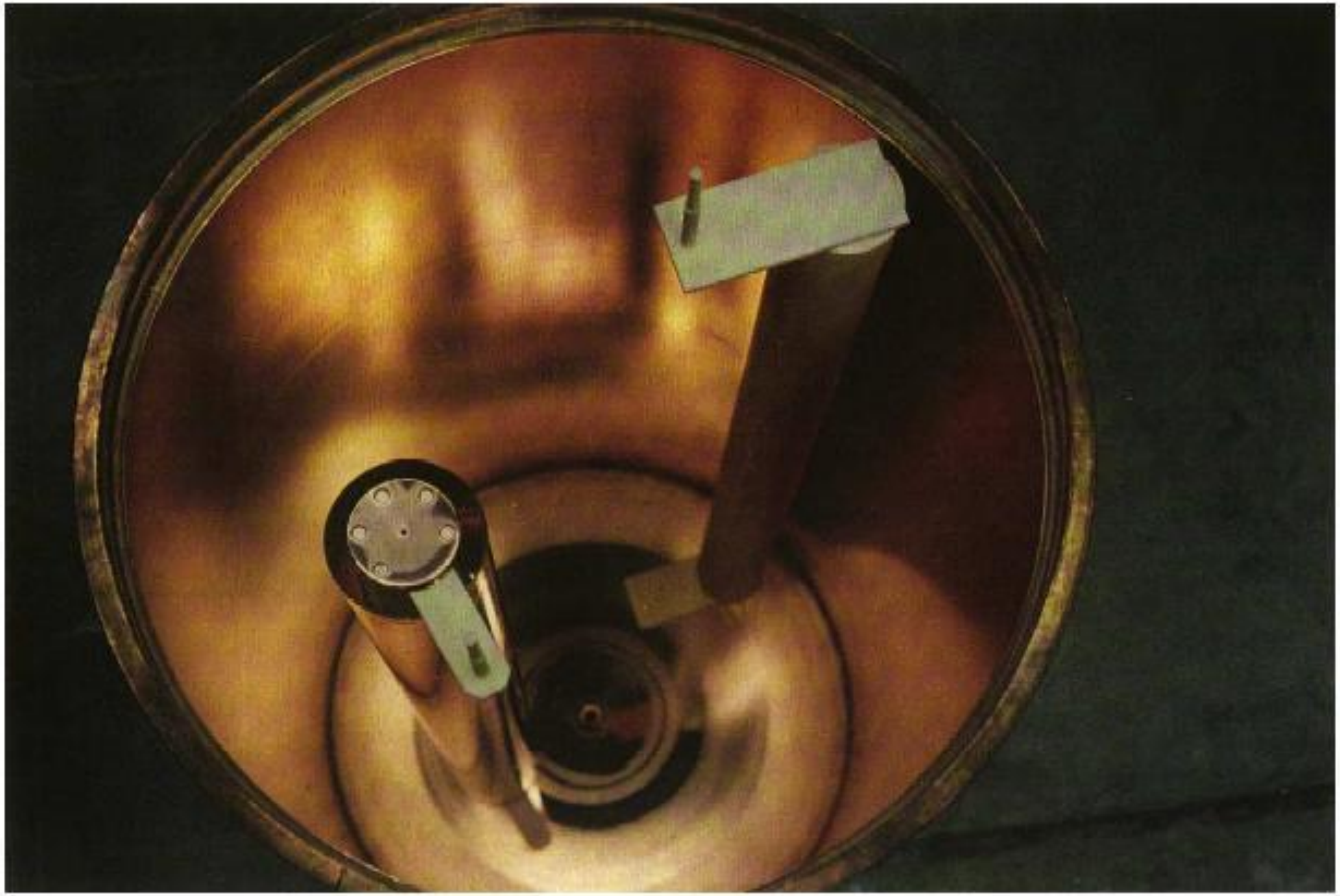
Presence of axion could easily allow energy to escape from this central region

Vacuum Resonant mixing in periodic field

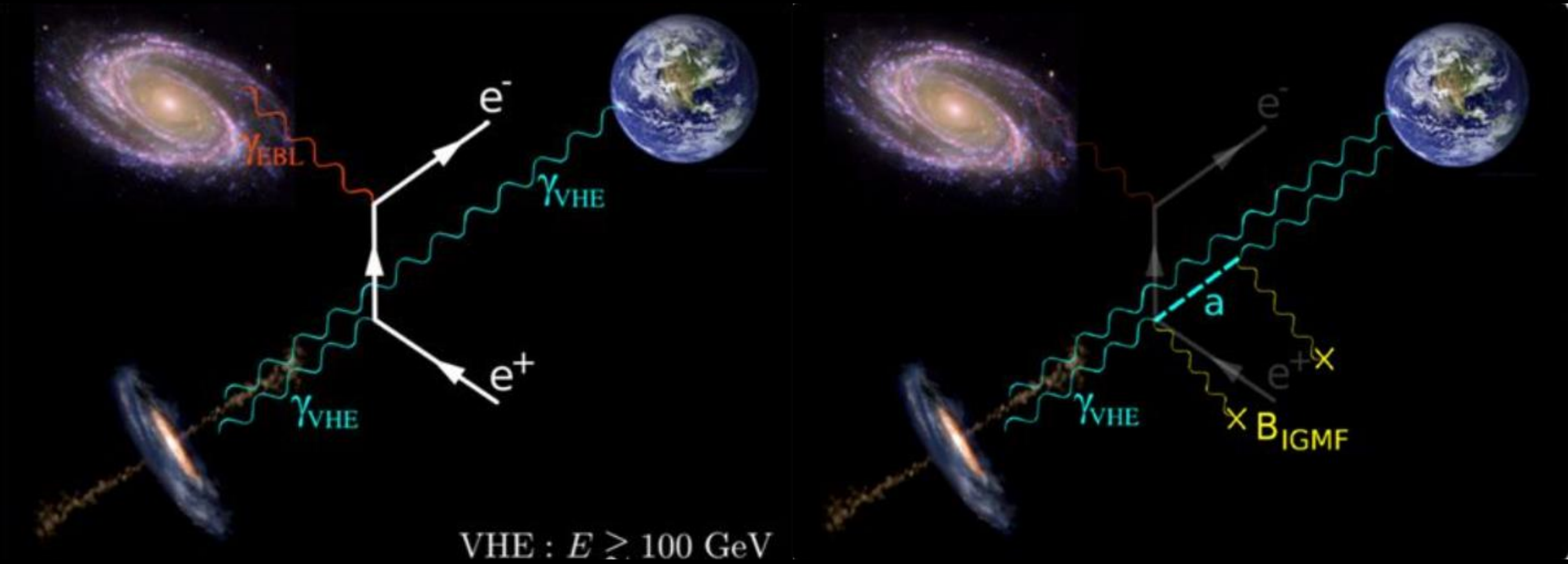
$$P^{(cos)}_{\gamma_{||}\to a} = \left| \int_0^L dt_1 \Delta_M \cos\left(\frac{t_1}{l_0}\right) e^{i\Delta_m t_1} \right|^2 =$$

$$\frac{P^{(cos)}_{\gamma_{||}\to a}}{P^{(const)}_{\gamma_{||}\to a}} \approx \frac{1}{\left(\Delta_m^2 l_0^2 - 1\right)^2}$$

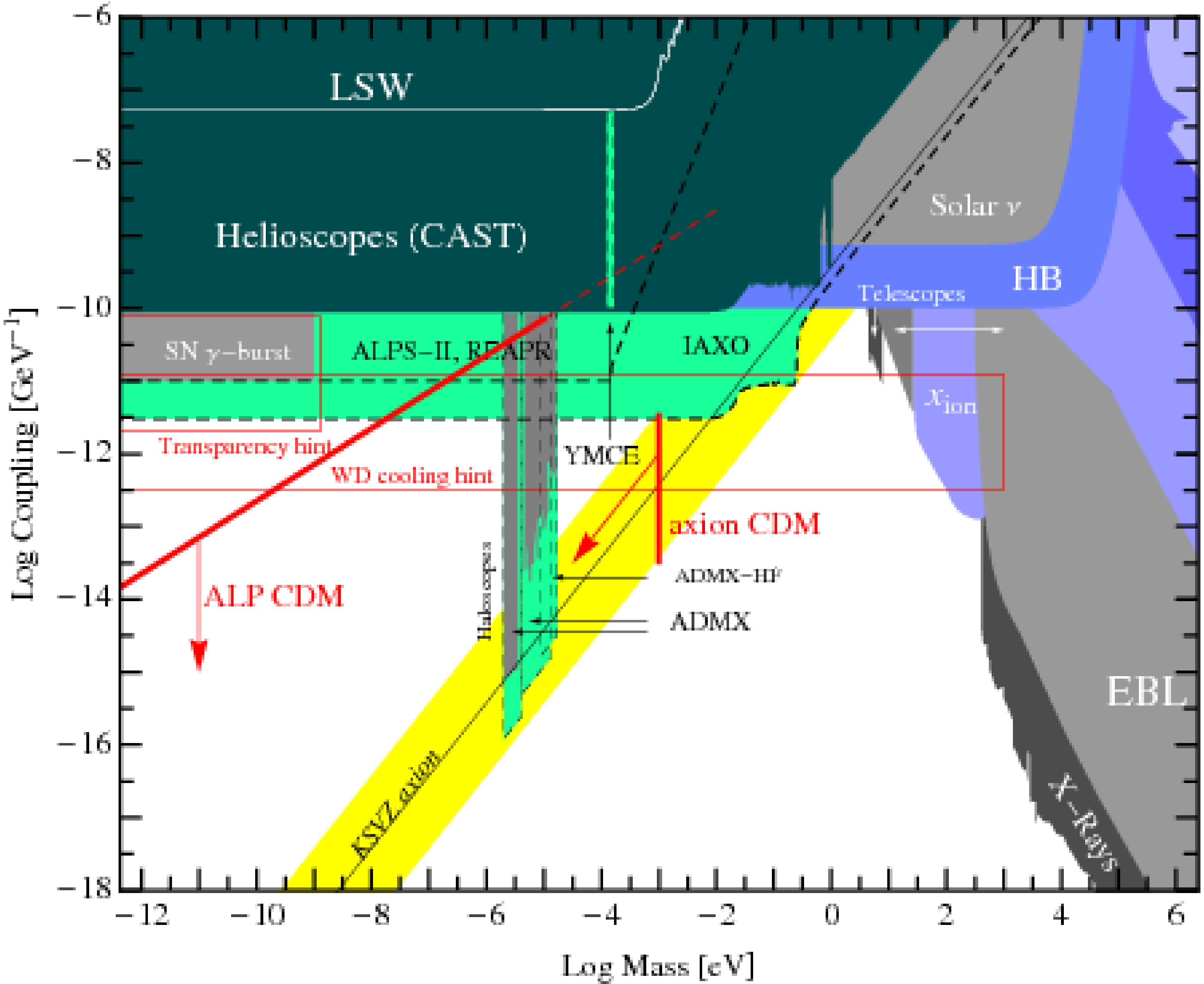
ADMX – Axion Dark Matter Experiment PRD 69-11101(2004)



Possible Hints for anomalous Transparency of Universe? Might be due to Axions. Controversial.

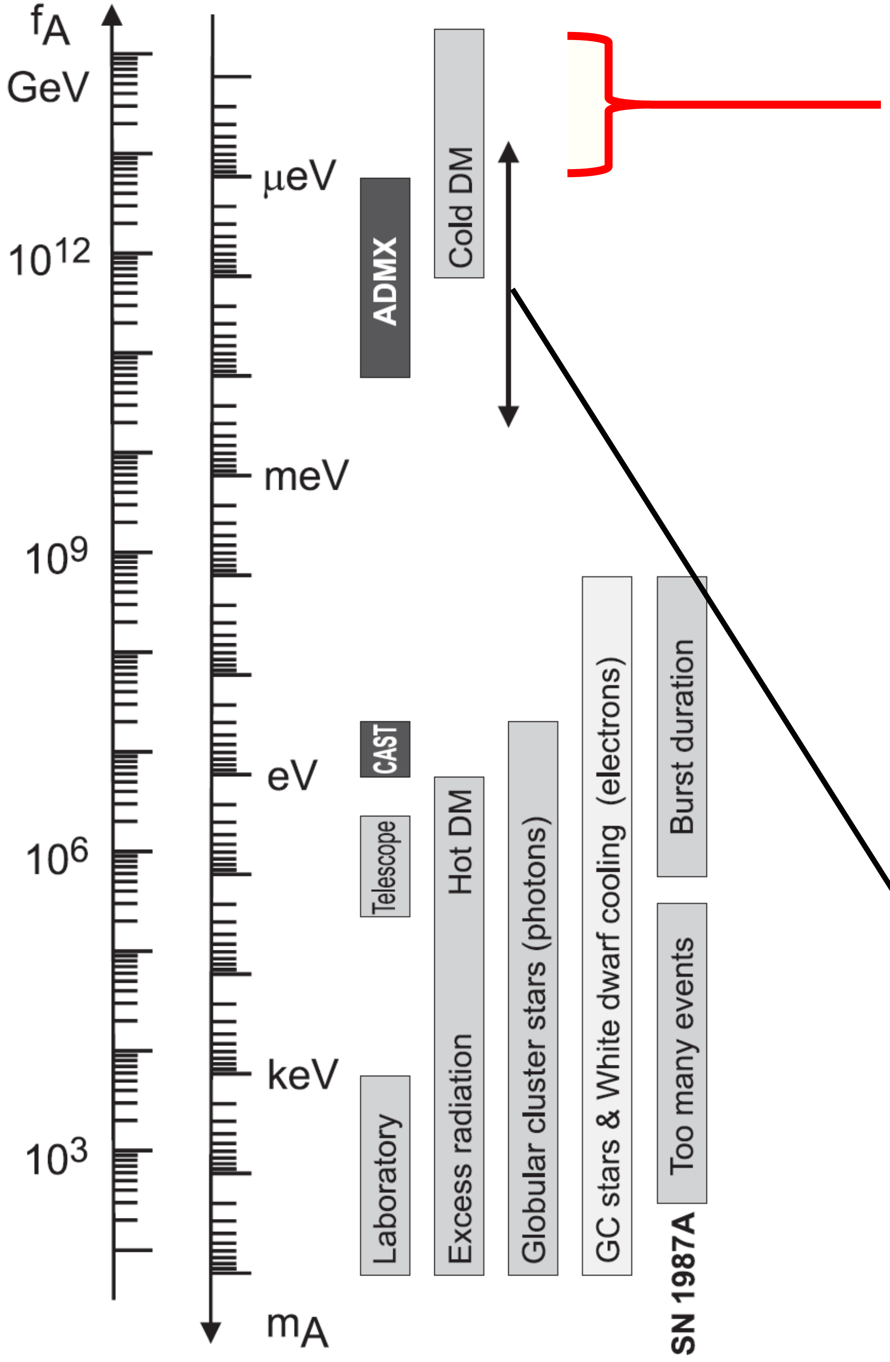


See Work by Horns and Meyer and more recently Troitsky et al. Pictures are from Ringwald.



Ringwald
arXiv:1210.5081

Probing QCD Axion with microlensing



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

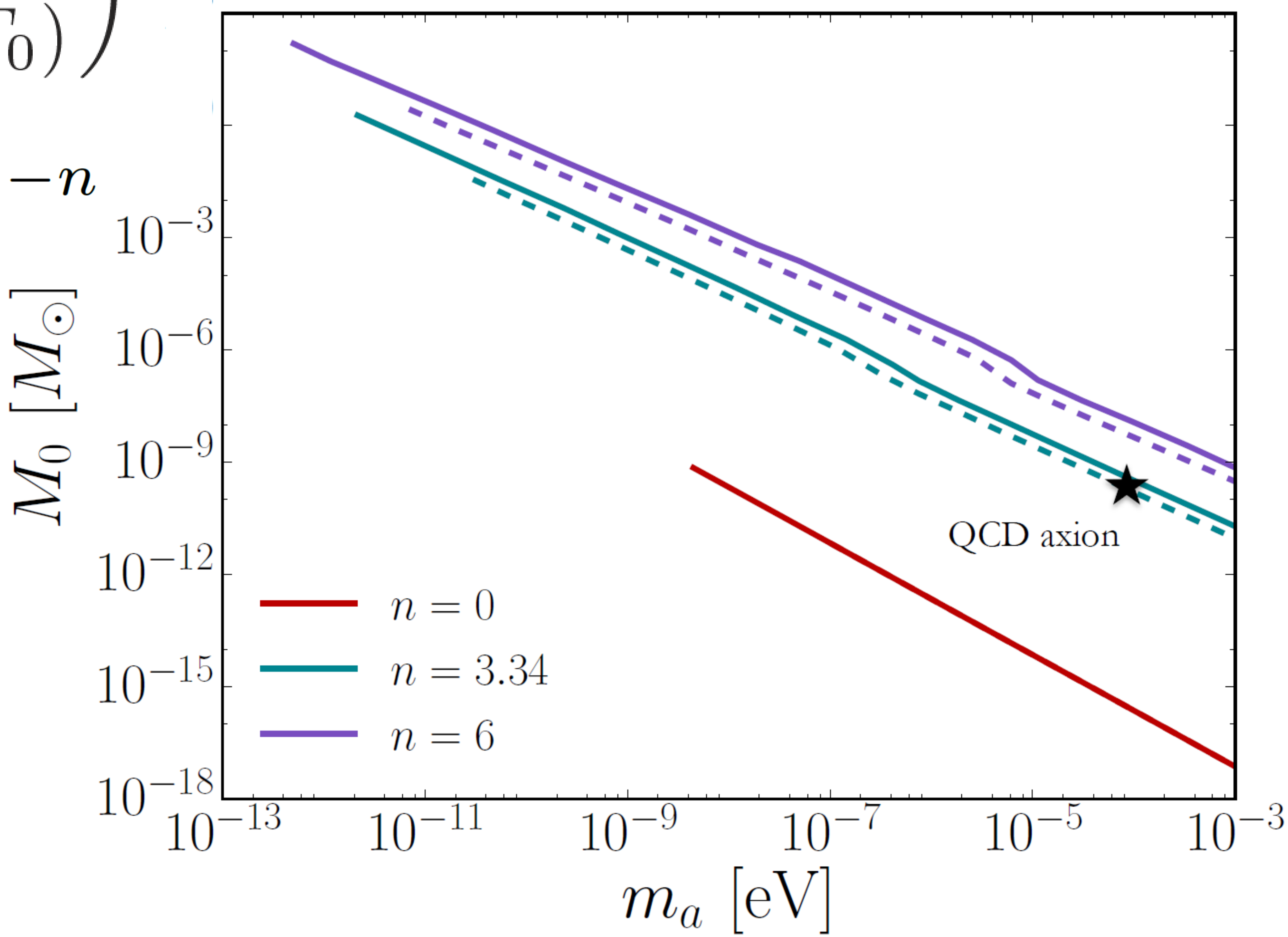
$$M_0 = \bar{\rho}_a \frac{4}{3}\pi \left(\frac{\pi}{a(T_0)H(T_0)} \right)^3$$

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

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

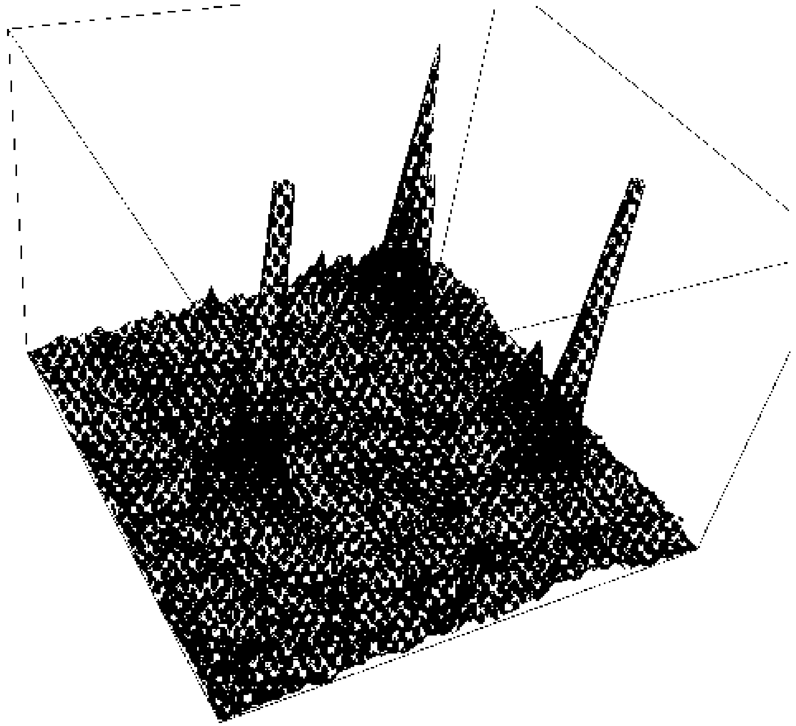
T_0 depends upon n

Mass inside horizon = M_0

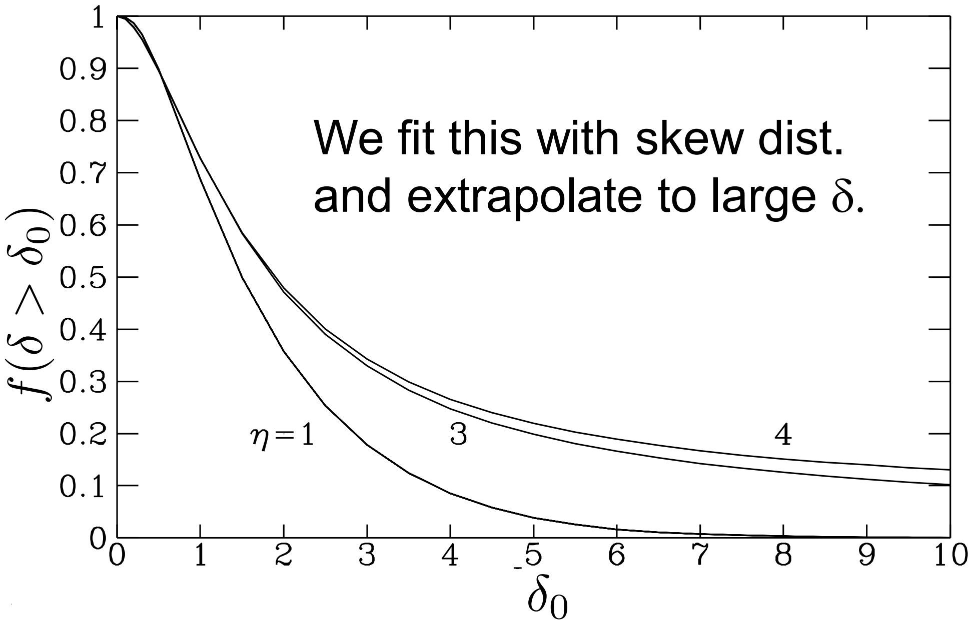


Simulations: Kolb & Tkachev (1990s)

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



Minicluster formation simulated without gravity or phase transition.



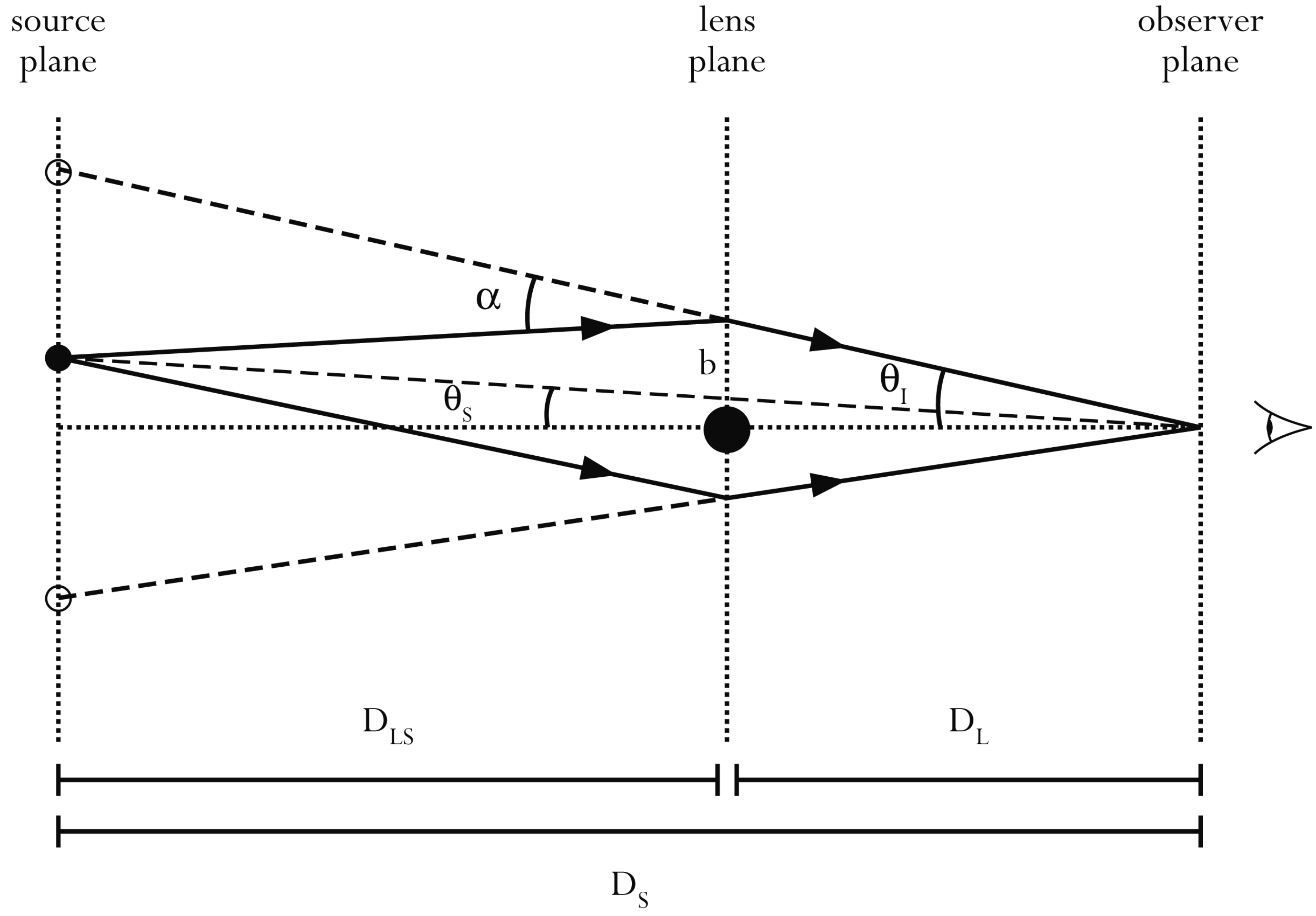
Fraction of MCs with density δ:

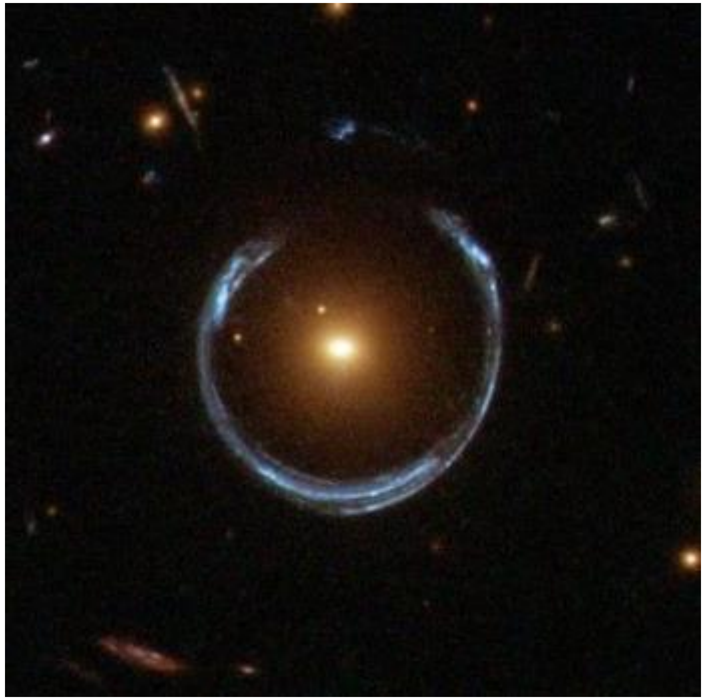
$$\rho_c = 140\delta^3(1+\delta)\rho_a(1+z_{eq})^3$$

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

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

Gravitational Lensing





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

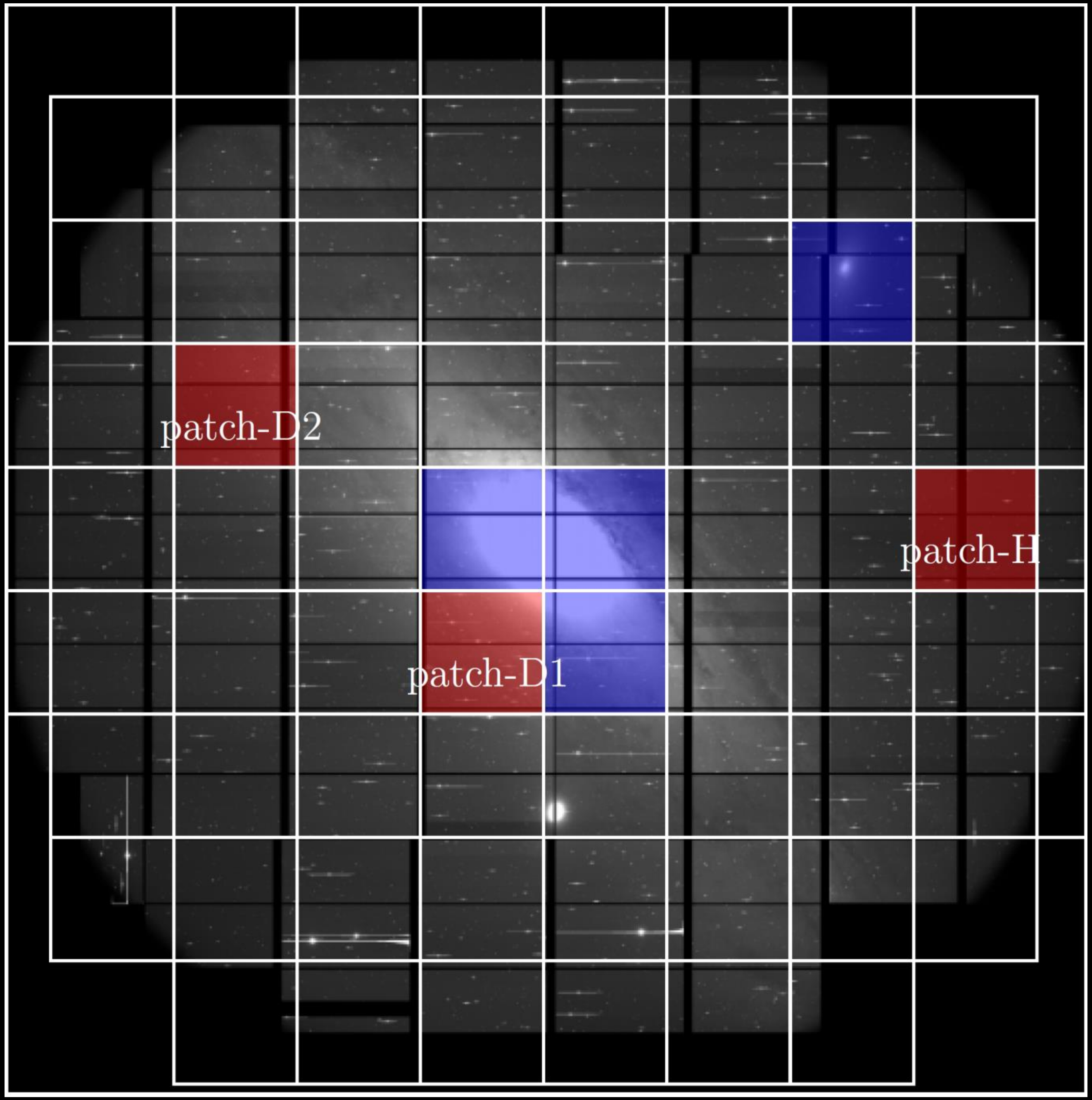
Subaru Hyper Suprime Cam (HSC)

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

Blue patches excluded due to too many objects

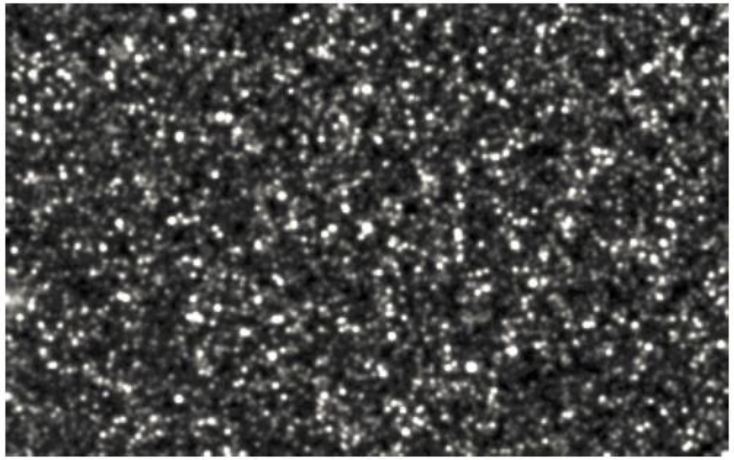
D1 representative of inner disk
D2 outer disk
H halo

Niikura et al, 1701.02151

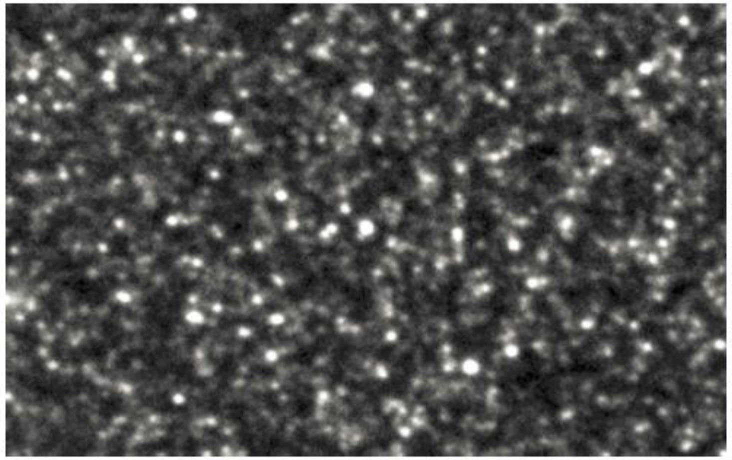


Subaru Hyper Suprime Cam (HSC)

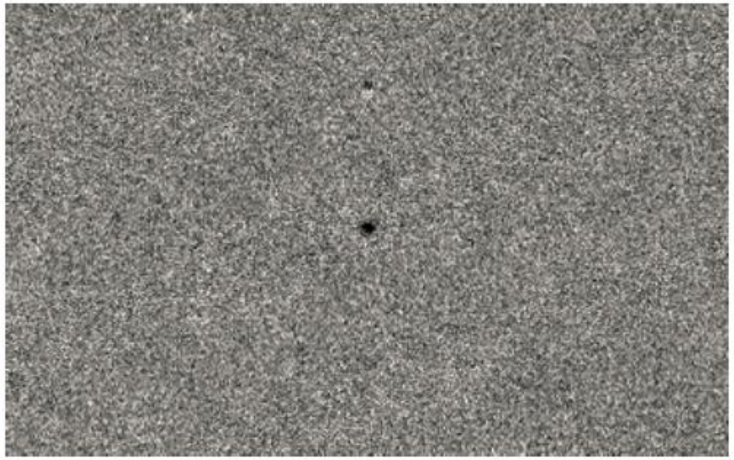
Has only collected 7 hours of data – already has very strong constraints on lensing events



Good stacked image



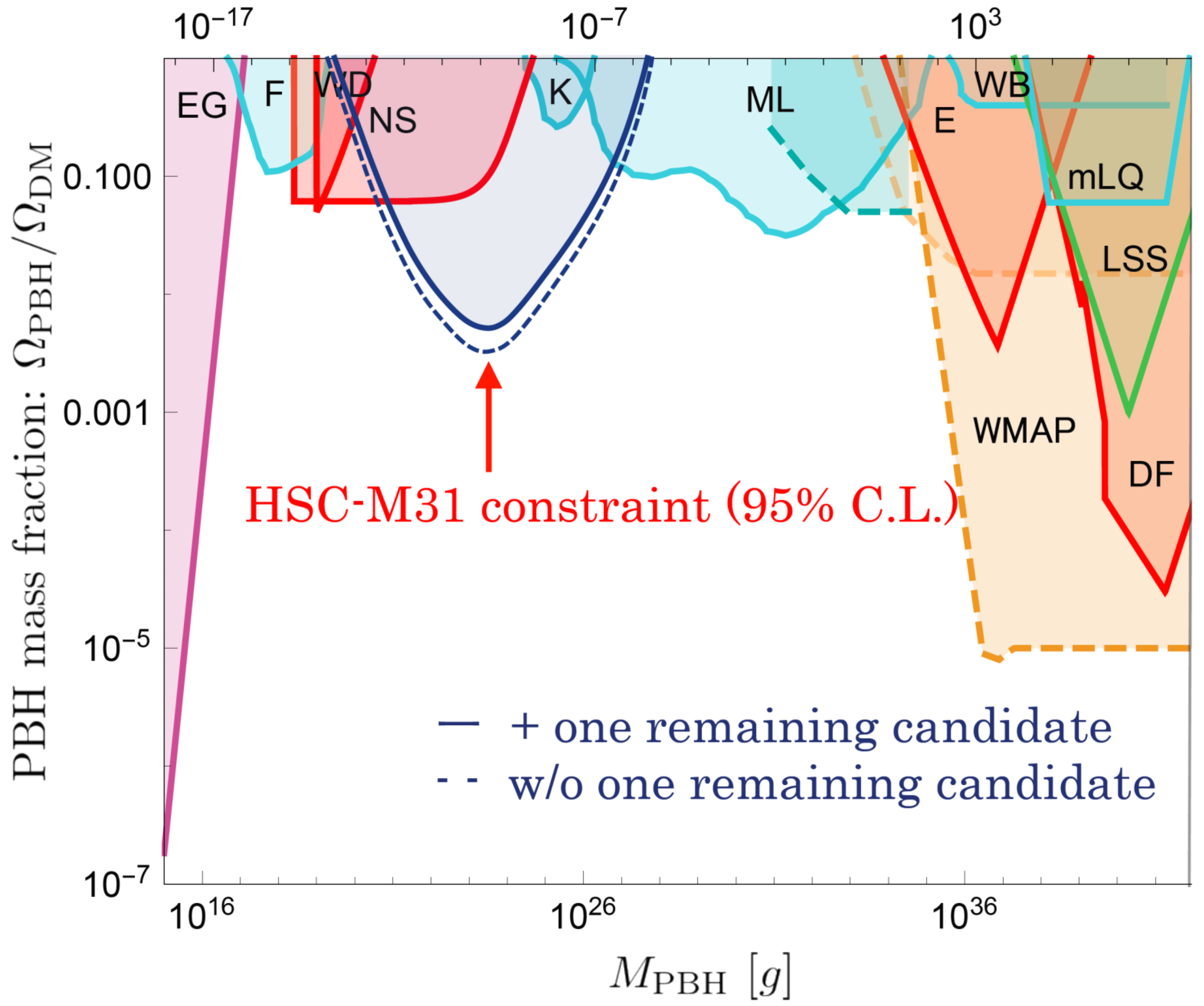
representative target image



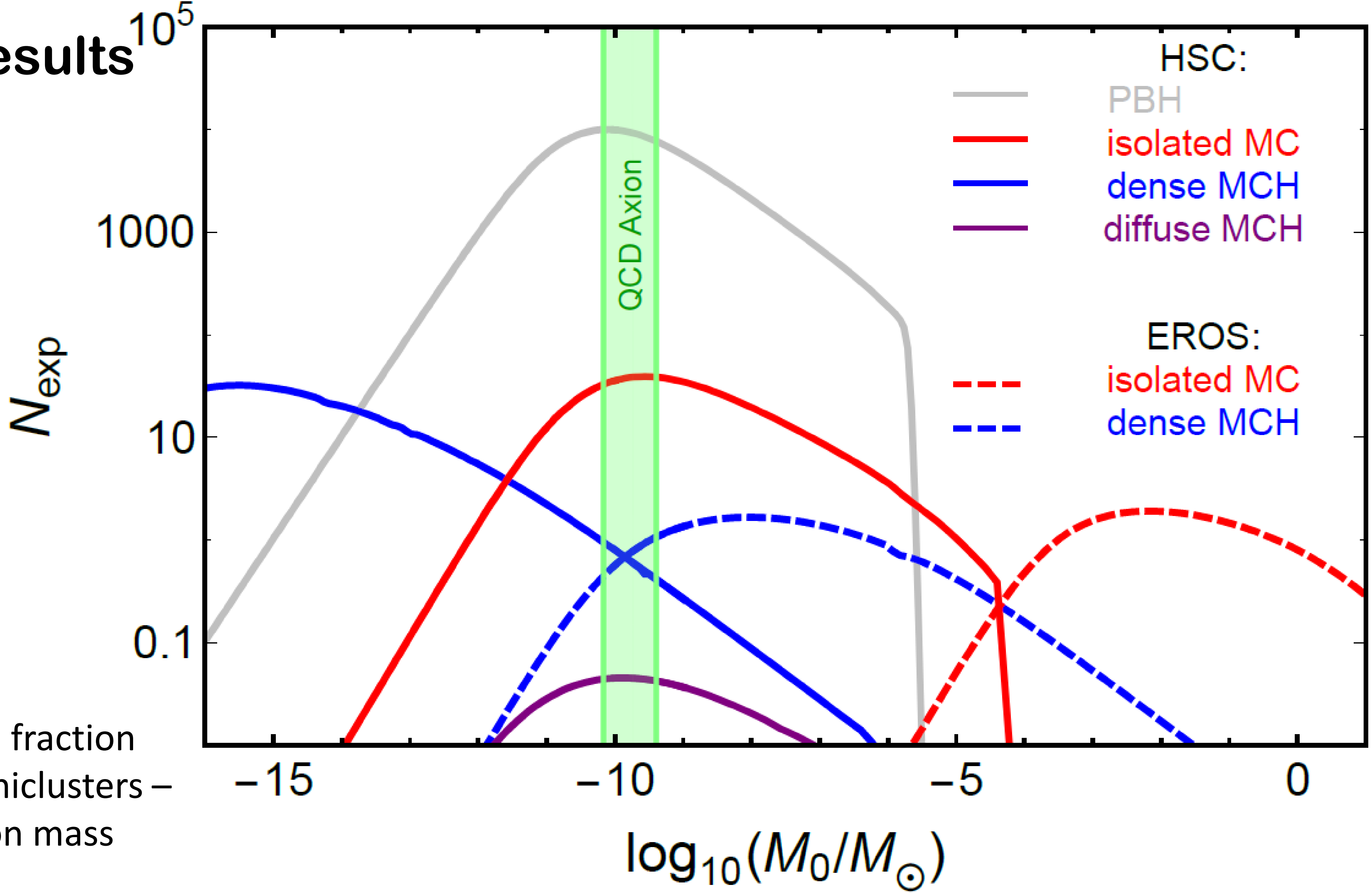
difference – change in one star's flux

HSC constraint on Primordial Black Holes

Niikura et al, 1701.02151

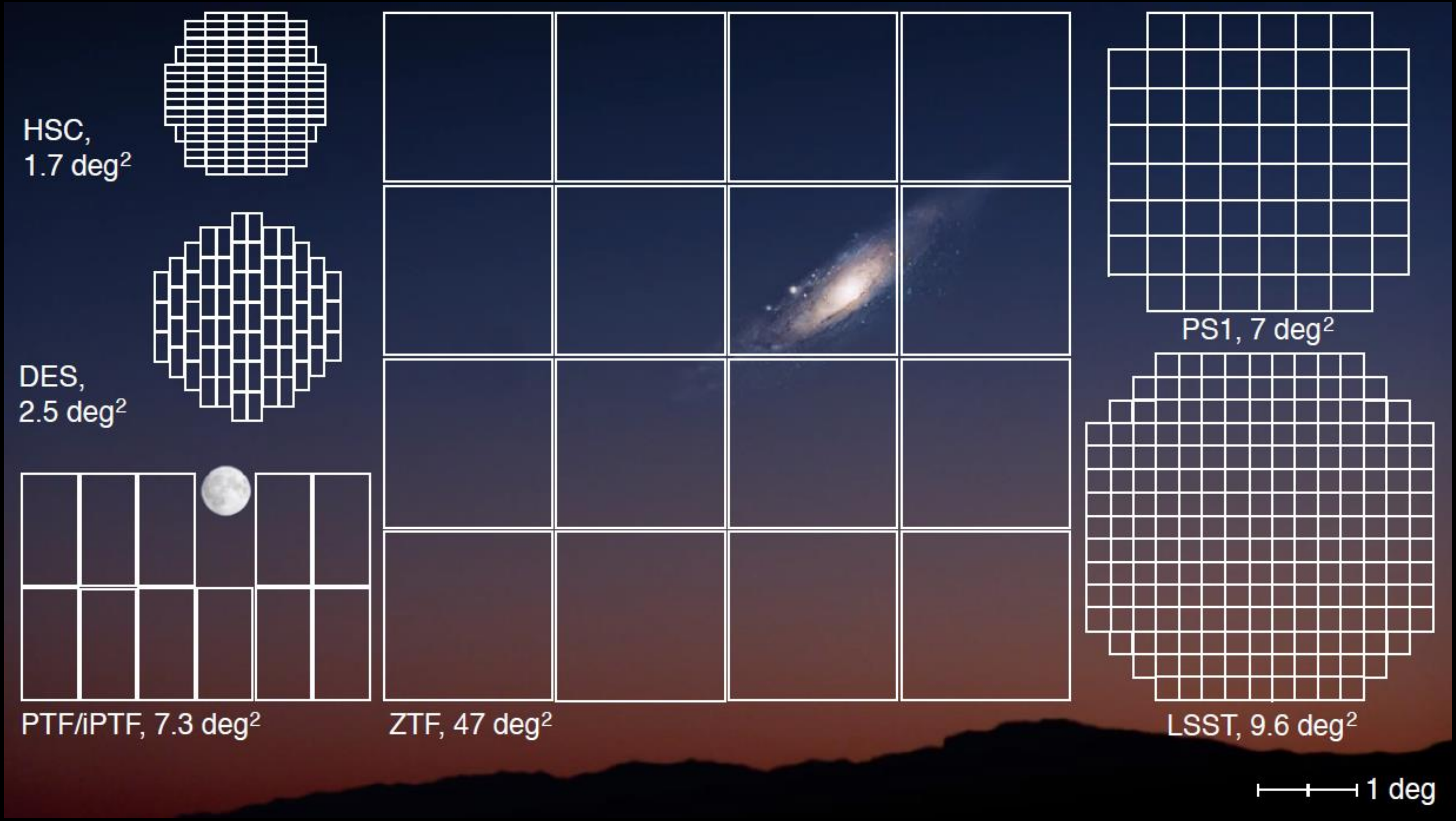


Our Results



Only small fraction can be miniclusters – depends on mass

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 QCD 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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New Probes of Ultra Light Axions

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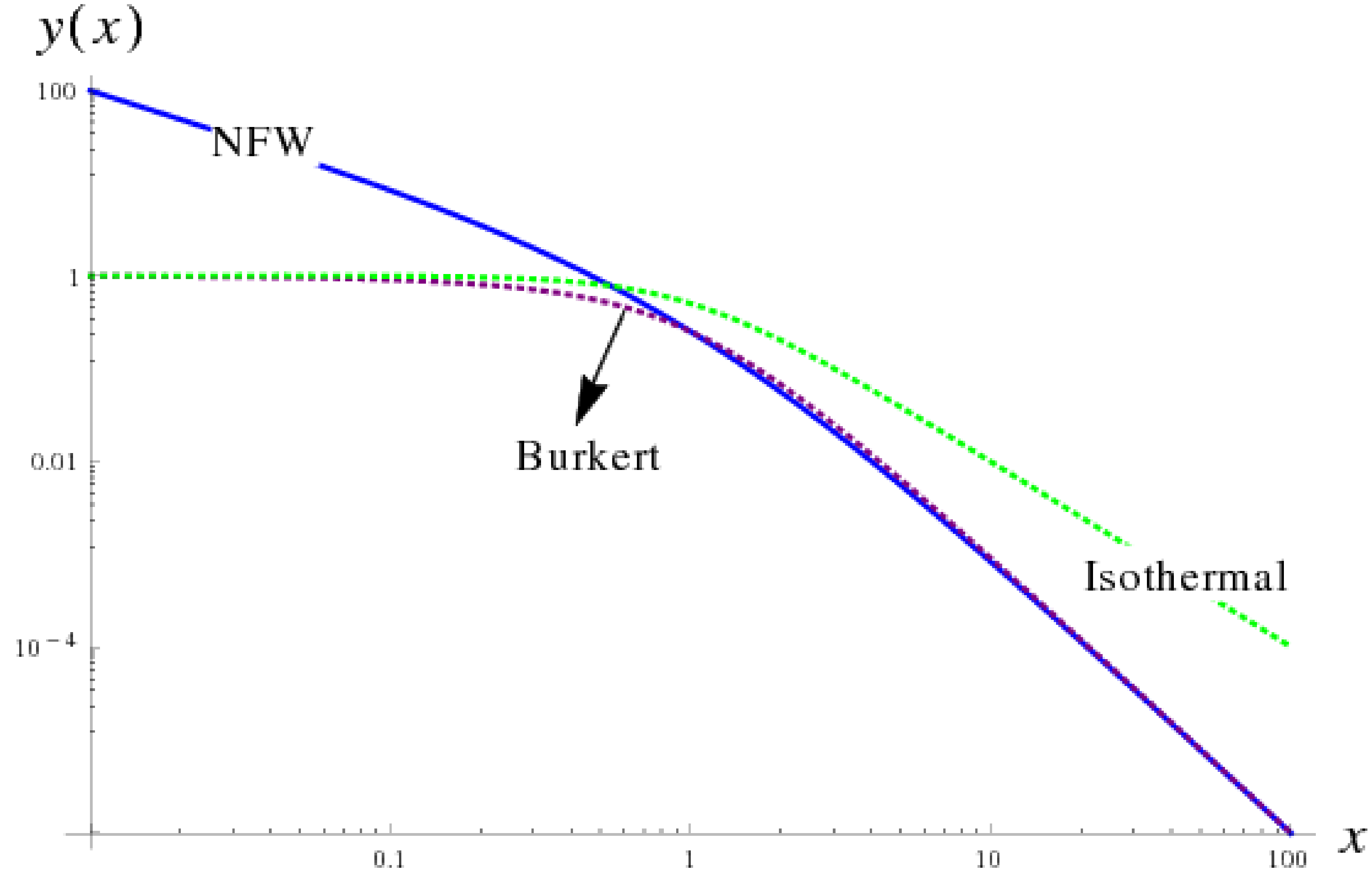
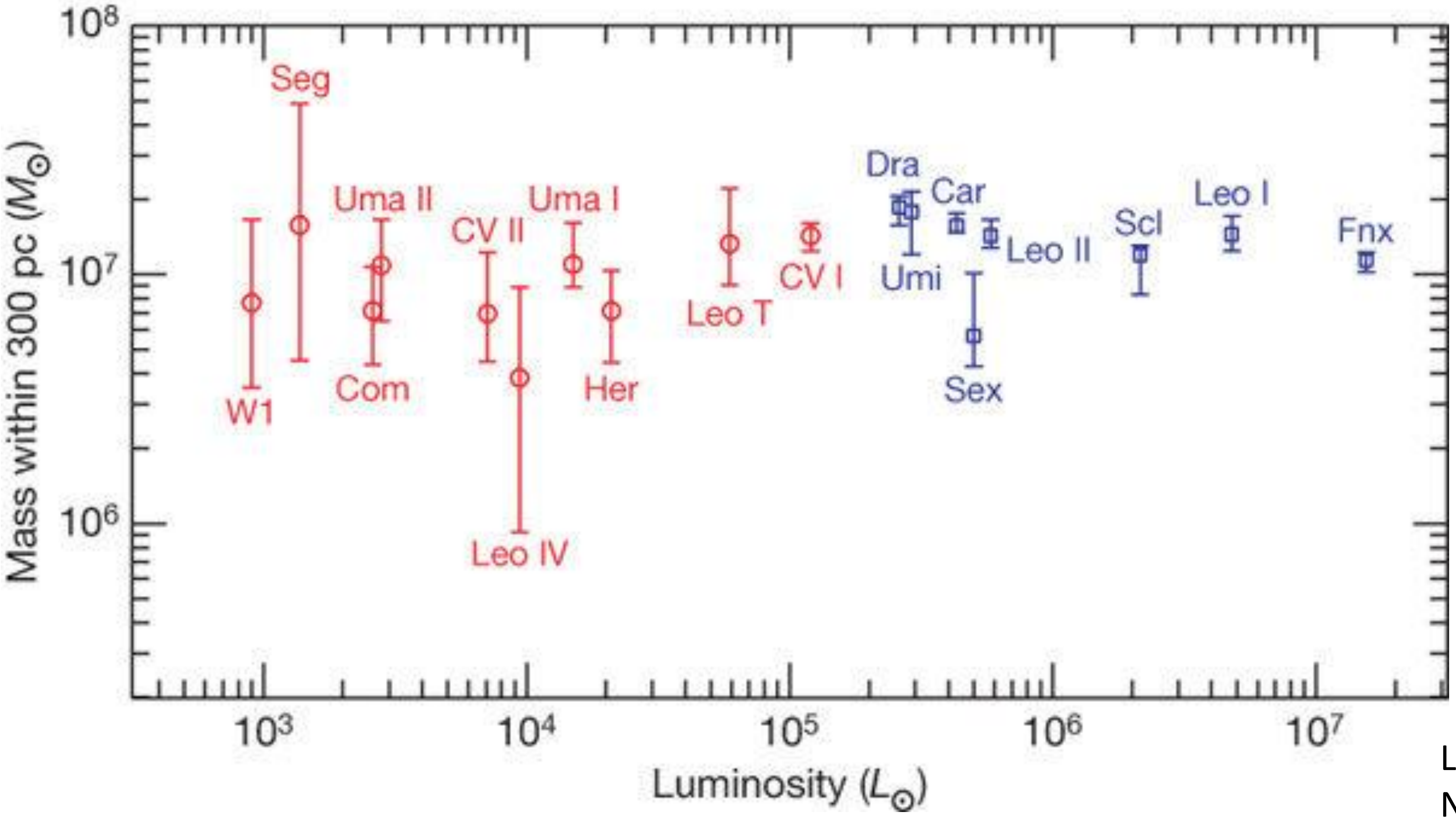
Cusps vs. Cores – would like to know



N-body simulations predict cuspy profiles like NFW.
Exotic models (Self interacting DM and ULA) predict cores.
Milky Way no good for this, central region baryon dominated.

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

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

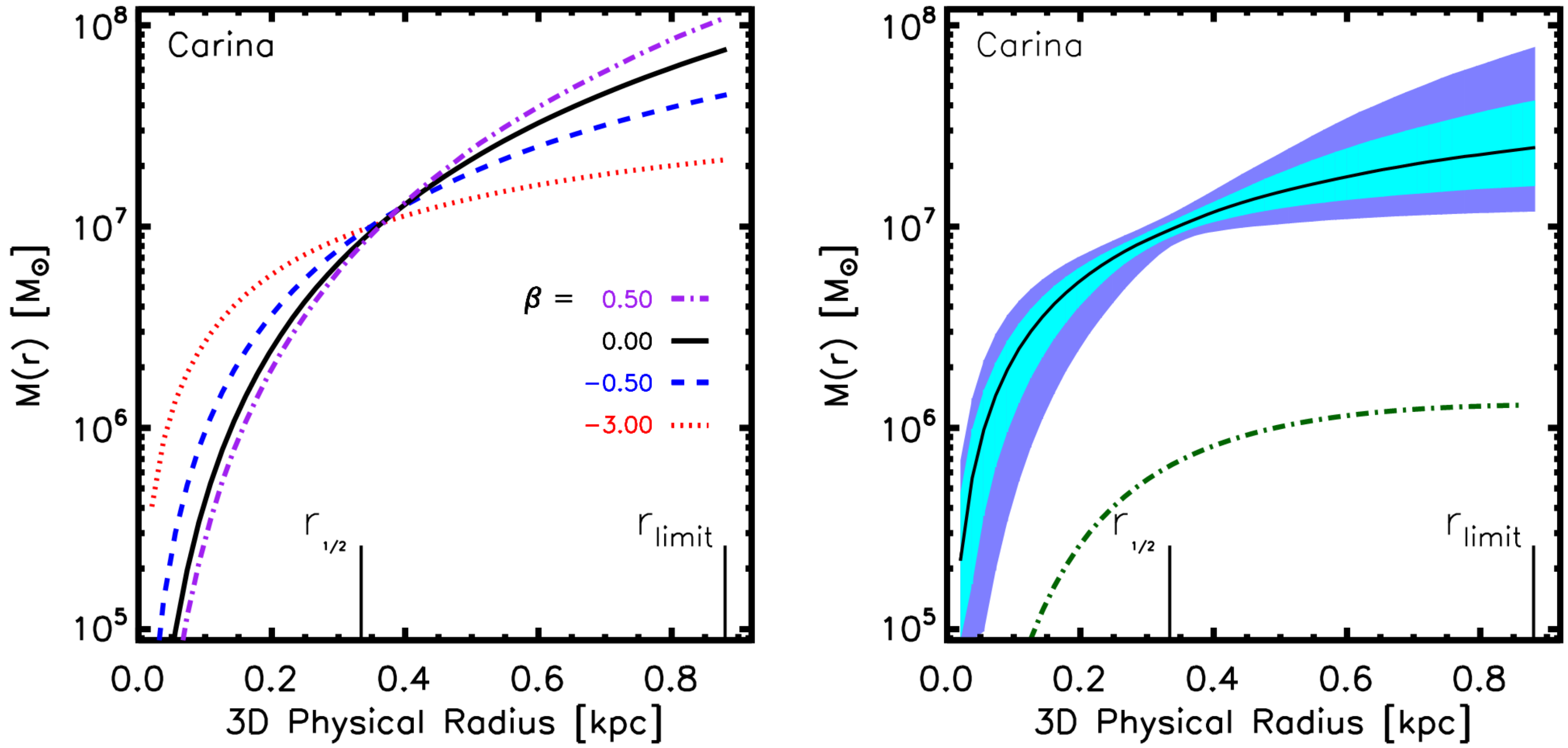
$$\beta \equiv 1 - \frac{\sigma_t^2}{\sigma_r^2}$$

Tangential Velocity Dispersion

Radial Velocity Dispersion

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

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



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….

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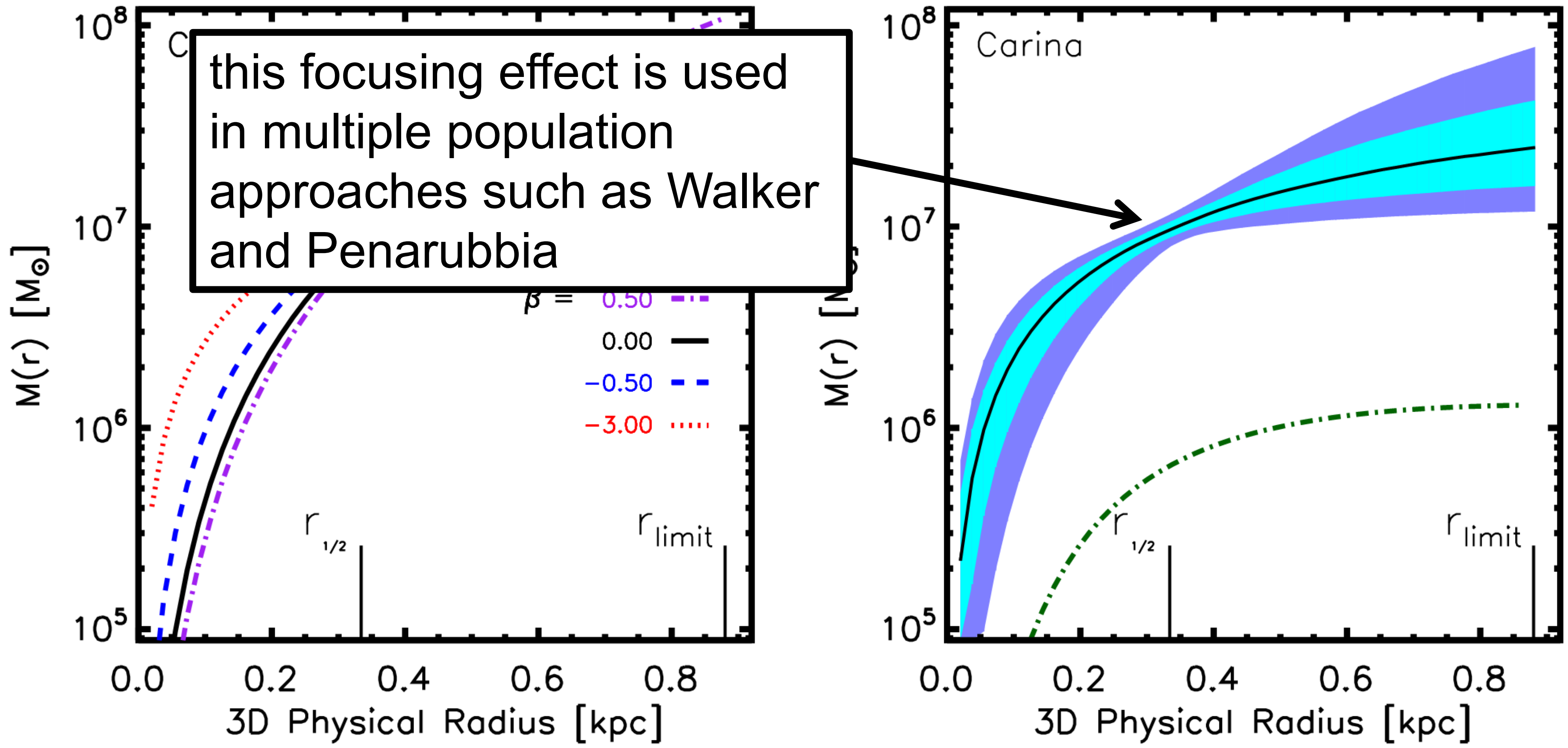

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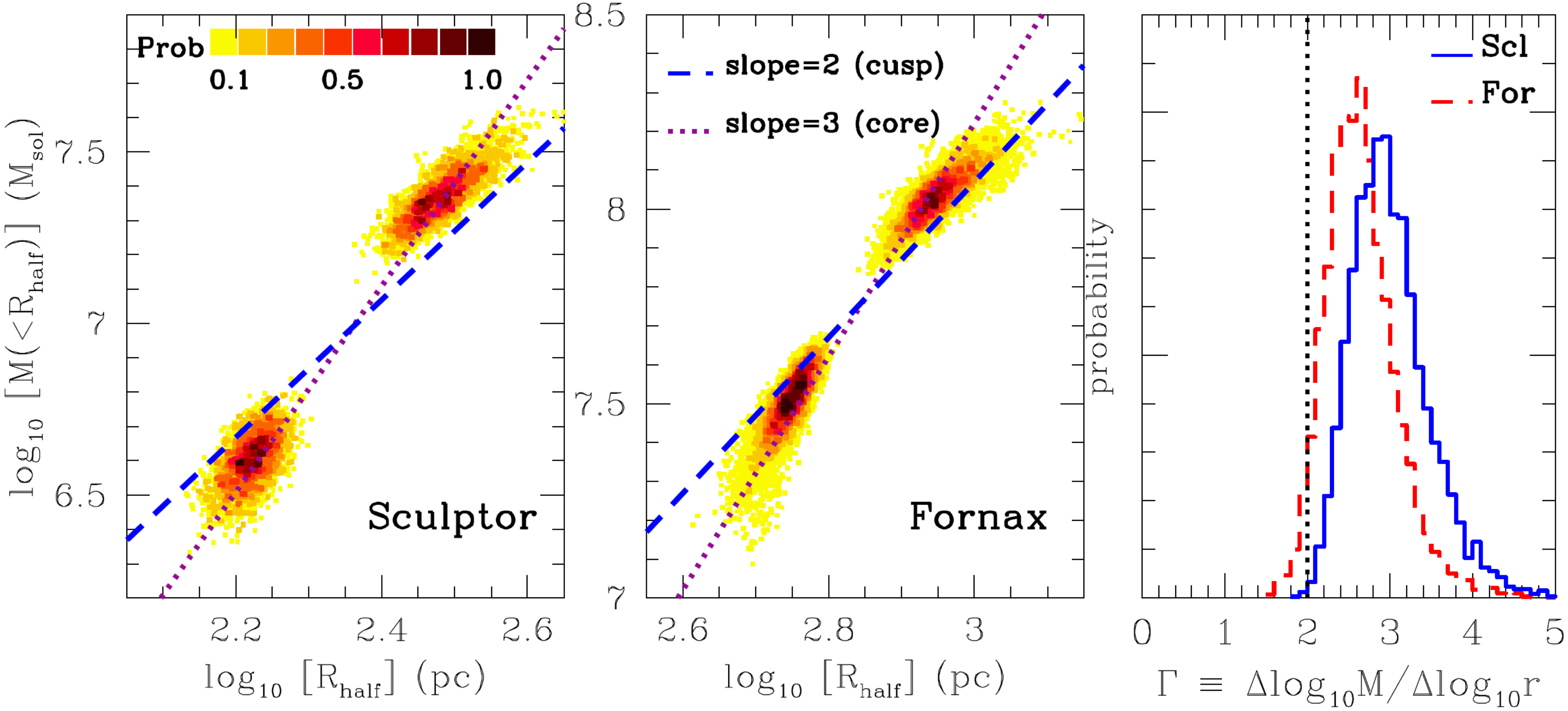
Example of core detection:-
Walker and Penarrubia Method

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.

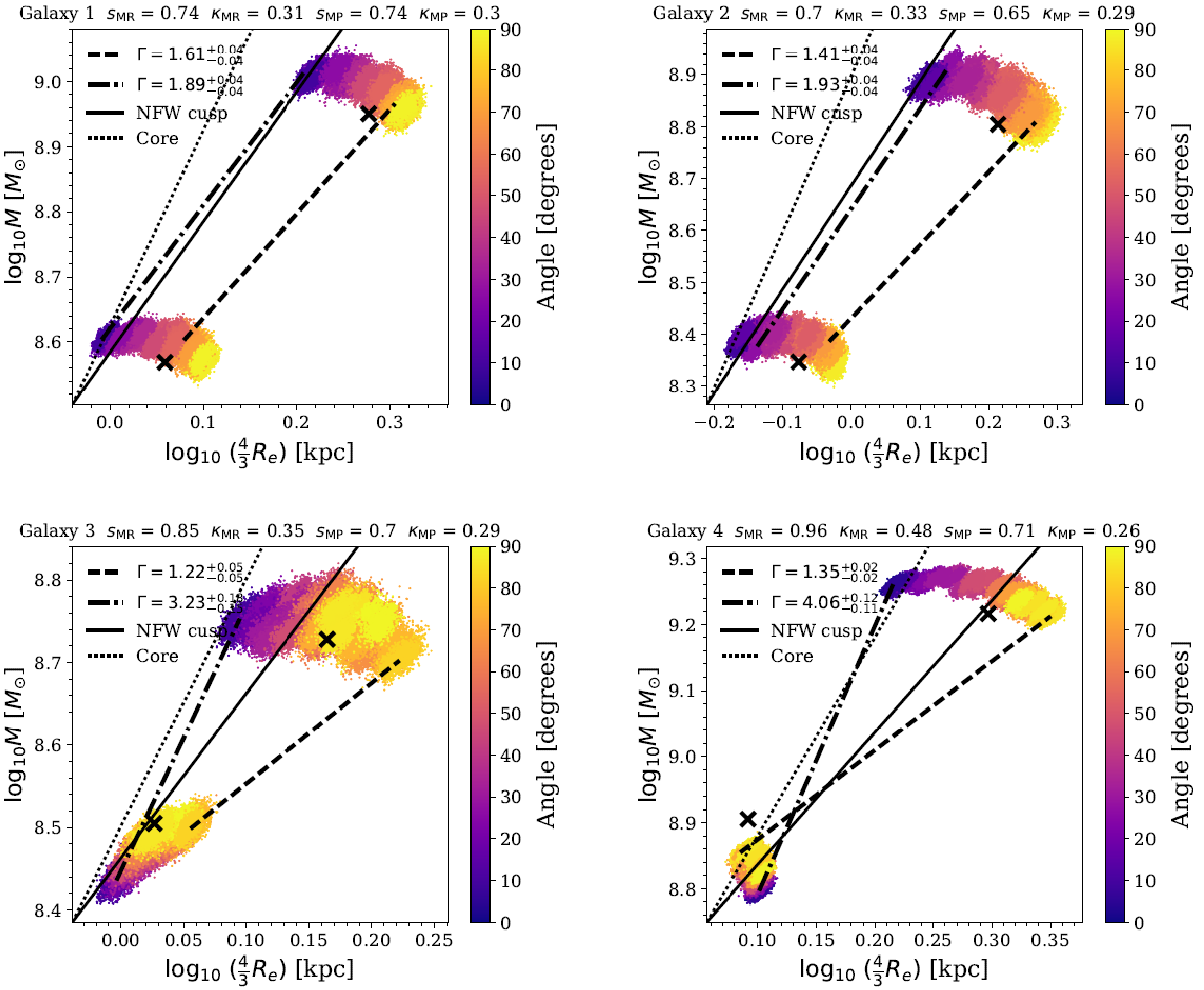


arXiv:1108.2404

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.



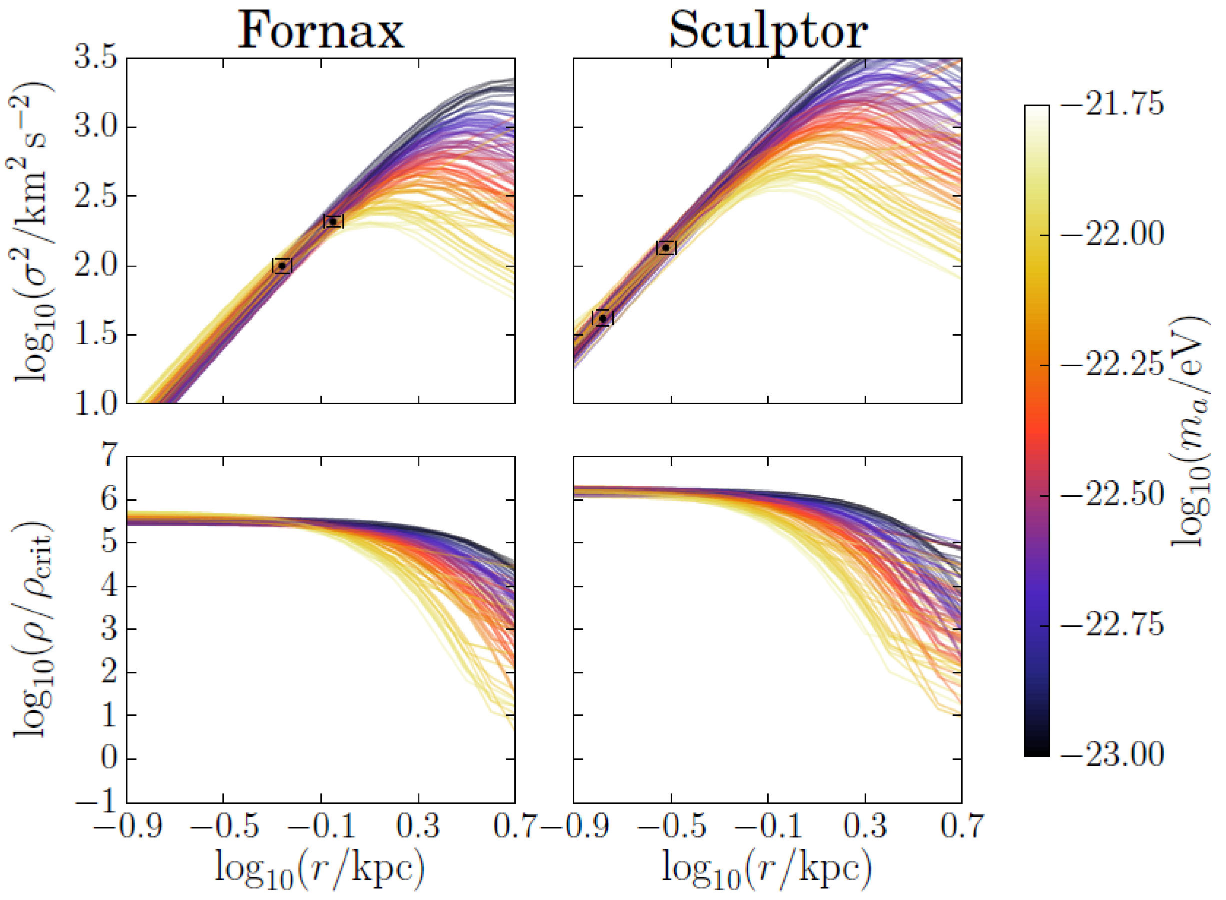
Axion dark matter, solitons, and the cusp-core problem

David J. E. Marsh[1*] and Ana-Roxana Pop[2†]
[1] *Perimeter Institute, 31 Caroline St N, Waterloo, ON, N2L 6B9, Canada*
[2] *Department of Physics, Princeton University, Princeton, NJ 08544, USA*

Ultra-light axions give rise to cored density profiles in smaller galaxies

May explain some of the cores…

Would result in slowly oscillating axion field.



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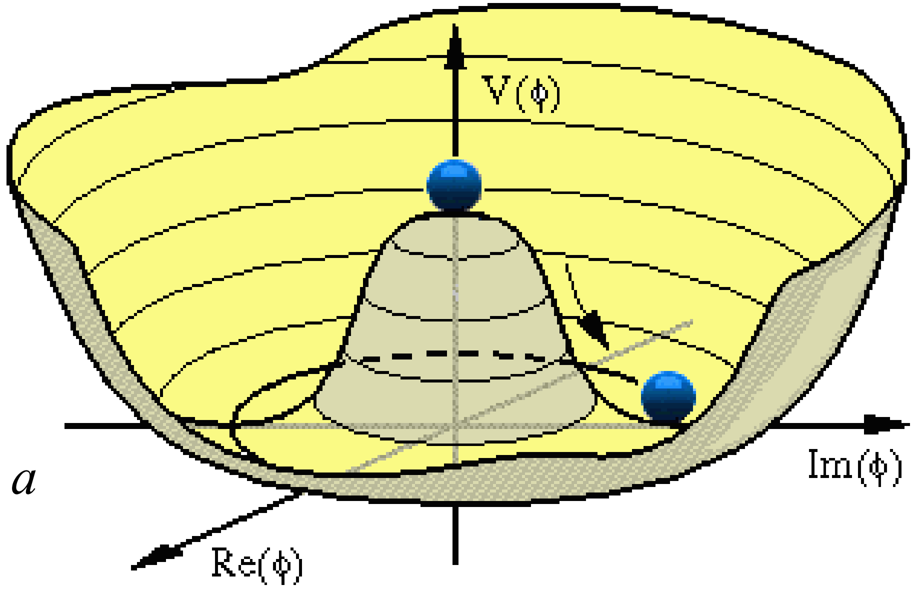
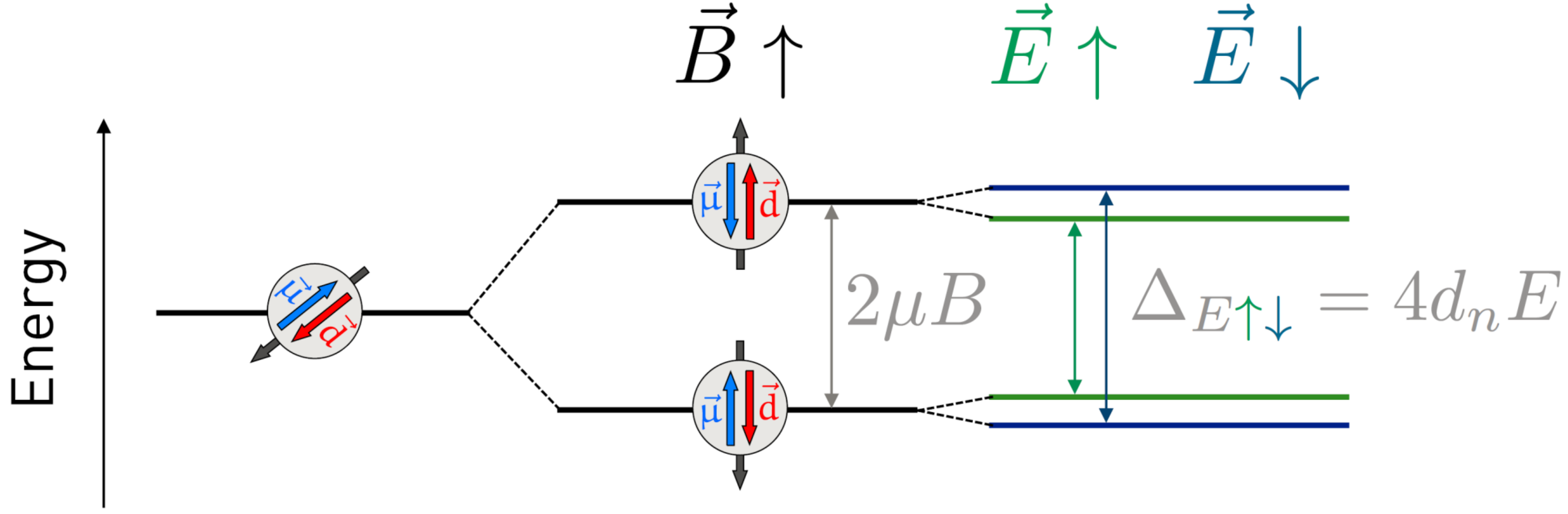


$$m_a^2 \sim \frac{f_\pi^2 m_\pi^2}{f_a^2}$$

Also induces coupling to photons

How to measure the nEDM

$$\mathcal{H} = -\vec{\mu} \cdot \vec{B} - \vec{d_n} \cdot \vec{E}$$

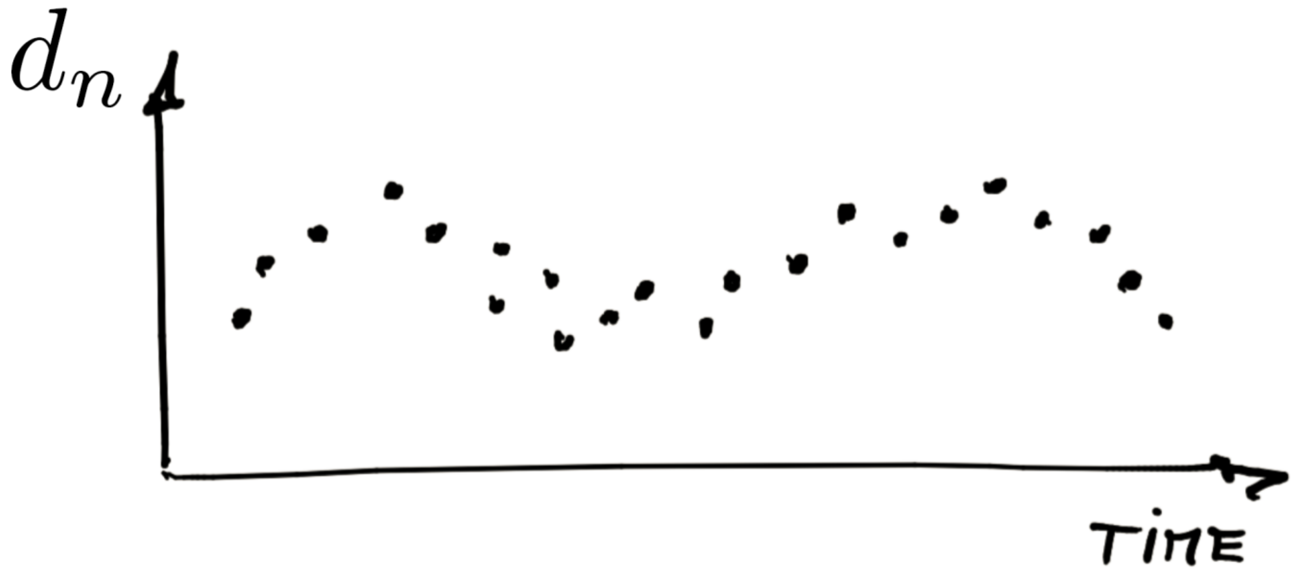


Measure a change in the transition frequency in a presence of an electric field.

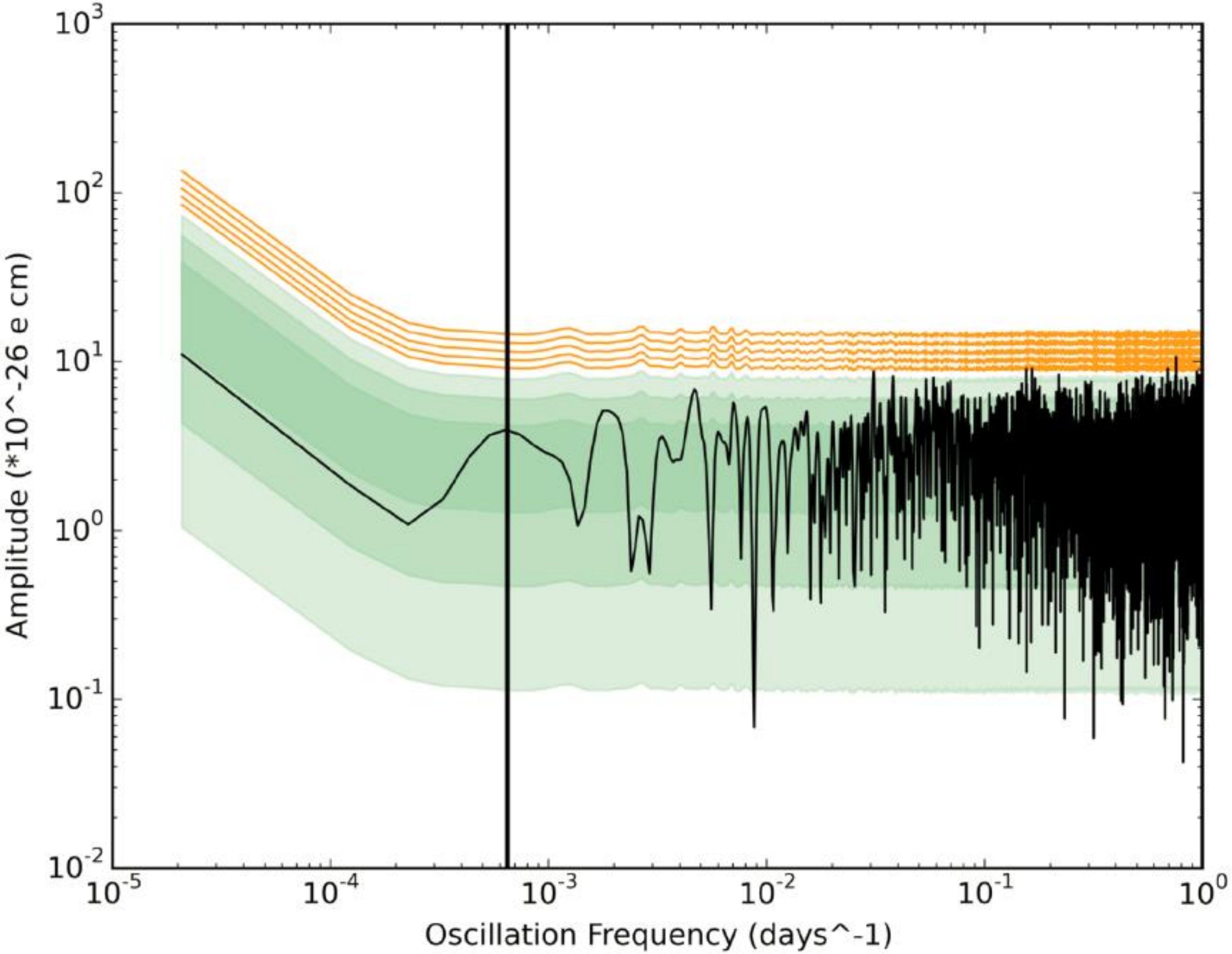
Run-base analysis – ILL data

Work of Nicholas Ayres, University of Sussex, UK

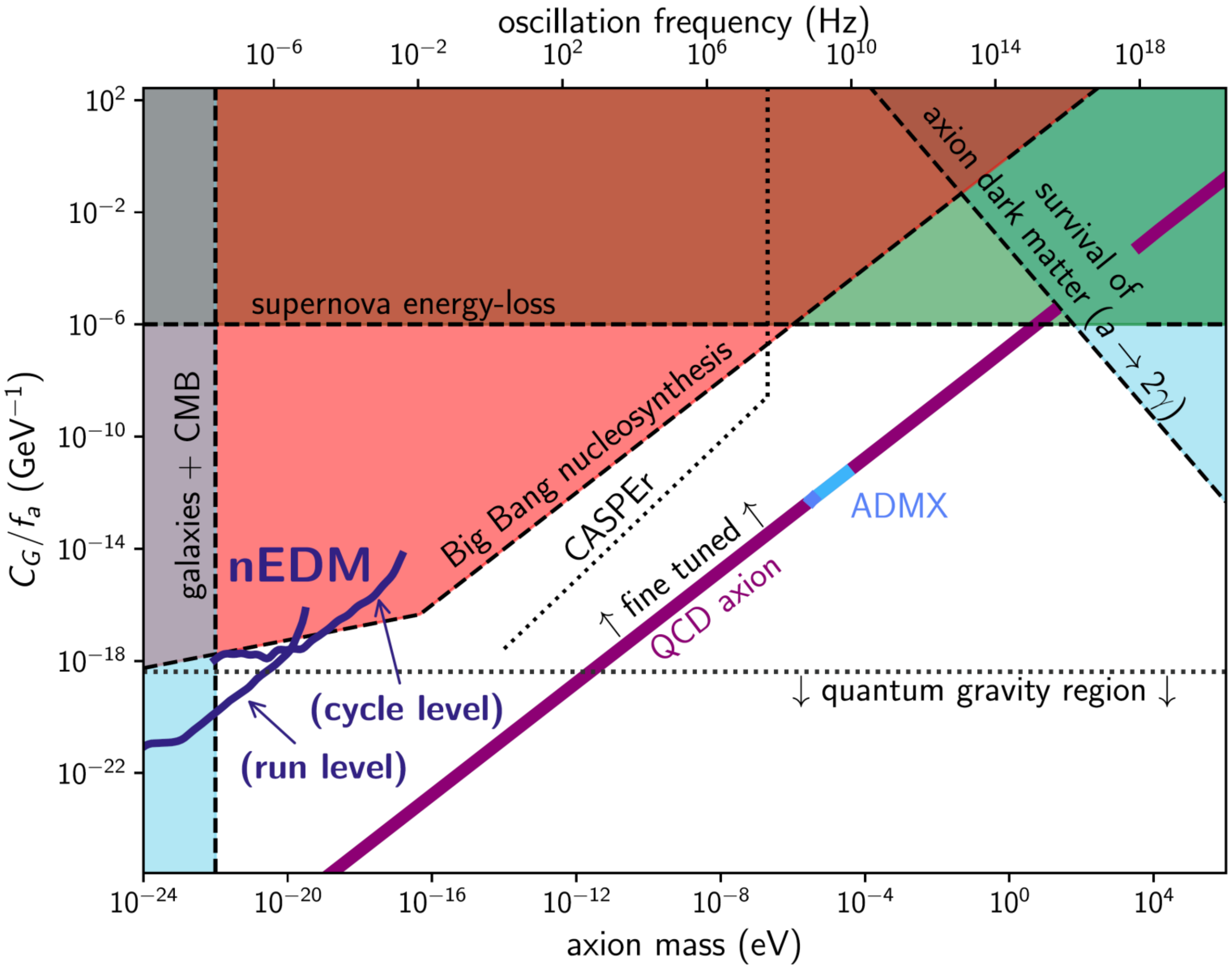
We get an d_n estimate every 1-73 hours.



False-Alarm Thresholds



Limits



oscillation frequency (Hz)
10^−6
10^−2
10^2
10^6
10^10
10^14
10^18
10^2
10^−2
10^−6
10^−10
10^−14
10^−18
10^−22
C_G / f_a (GeV^−1)
supernova energy-loss
axion dark matter survival of (a → 2γ)
galaxies + CMB
Big Bang nucleosynthesis
CASPEr
↑ fine tuned ↑
QCD axion
ADMX
nEDM
(cycle level)
(run level)
↓ quantum gravity region ↓
10^−24
10^−20
10^−16
10^−12
10^−8
10^−4
10^0
10^4
axion mass (eV)

Conclusions on Ultra Light Axions

- Many particle models are created to solve the “core problem” of dwarf spheroidals.
- Unfortunately it is not clear that such a problem exists. Many techniques are being developed to find out if this is true or not.
- If true, may be due to ultra light axions.
- New methods to test regime of ultra light axions are being developed.

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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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King's College London, most central London University

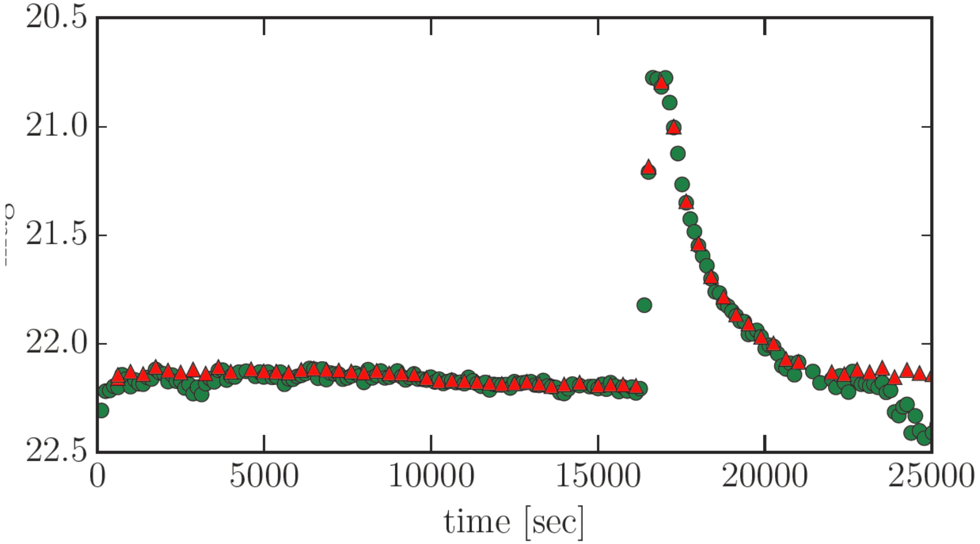
We will be recruiting two or three postdocs in the Autumn

Please apply!

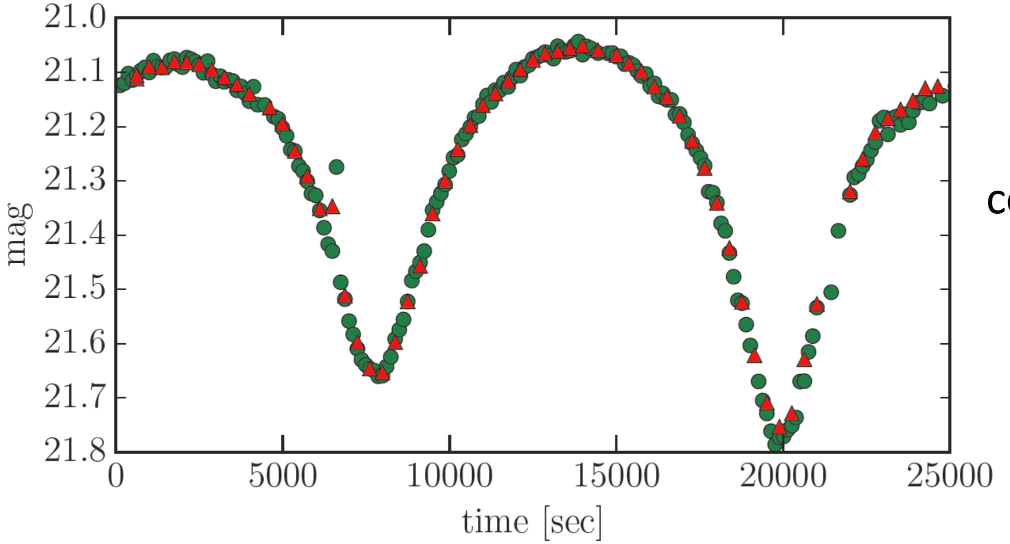
Subaru Hyper Suprime Cam (HSC)

Niikura et al, 1701.02151

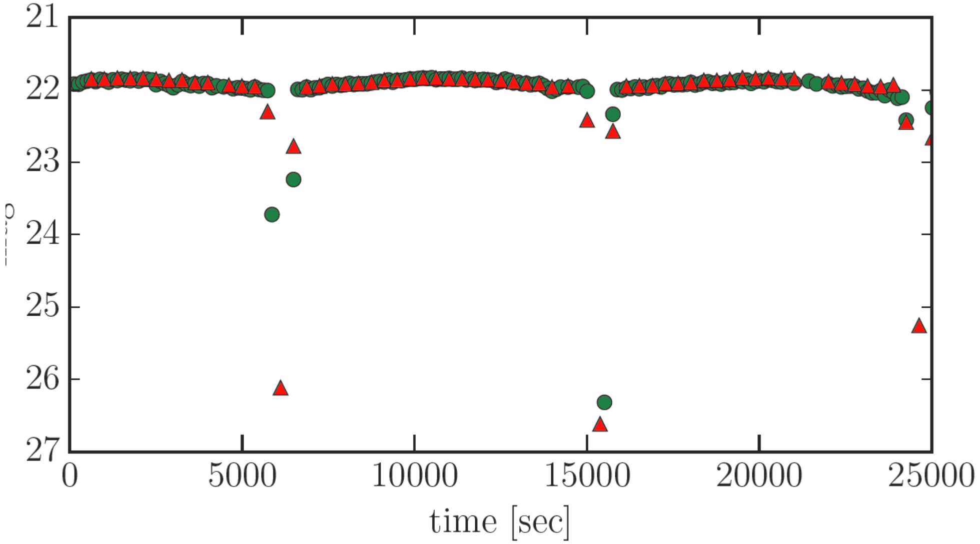
Stellar flare?



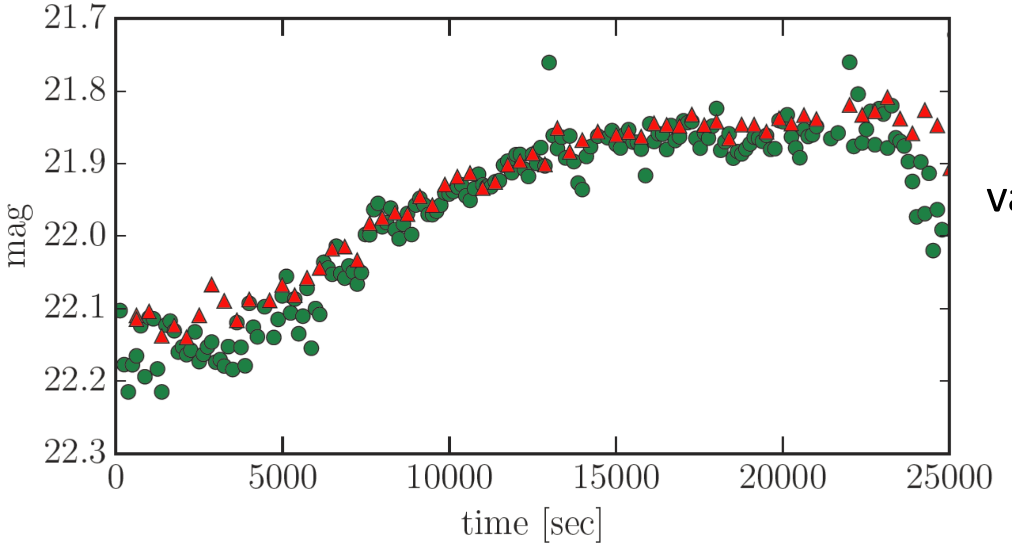
contact binary?



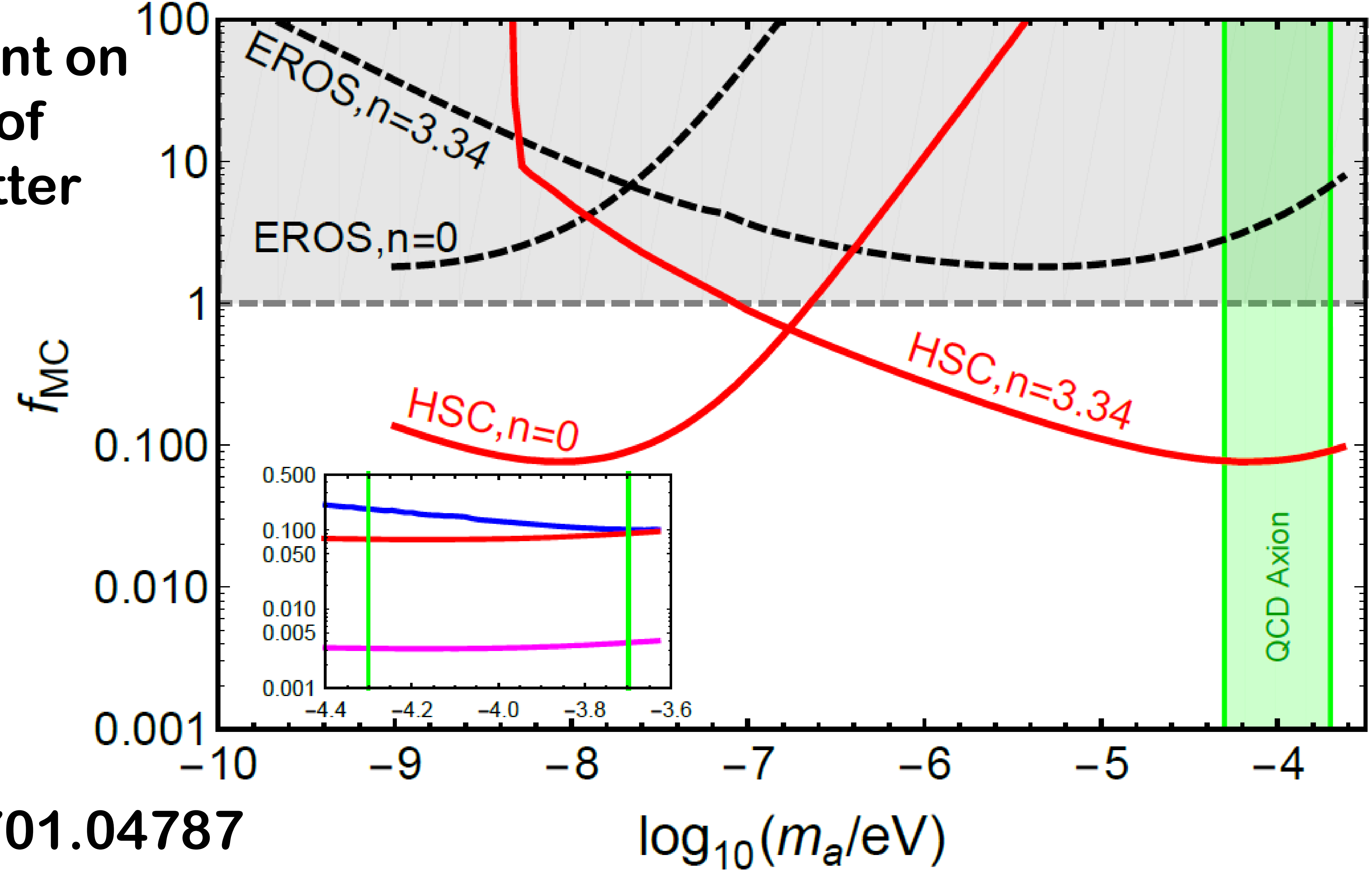
Eclipsing Binary?



variable star?



Constraint on fraction of dark matter



arXiv:1701.04787

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

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

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

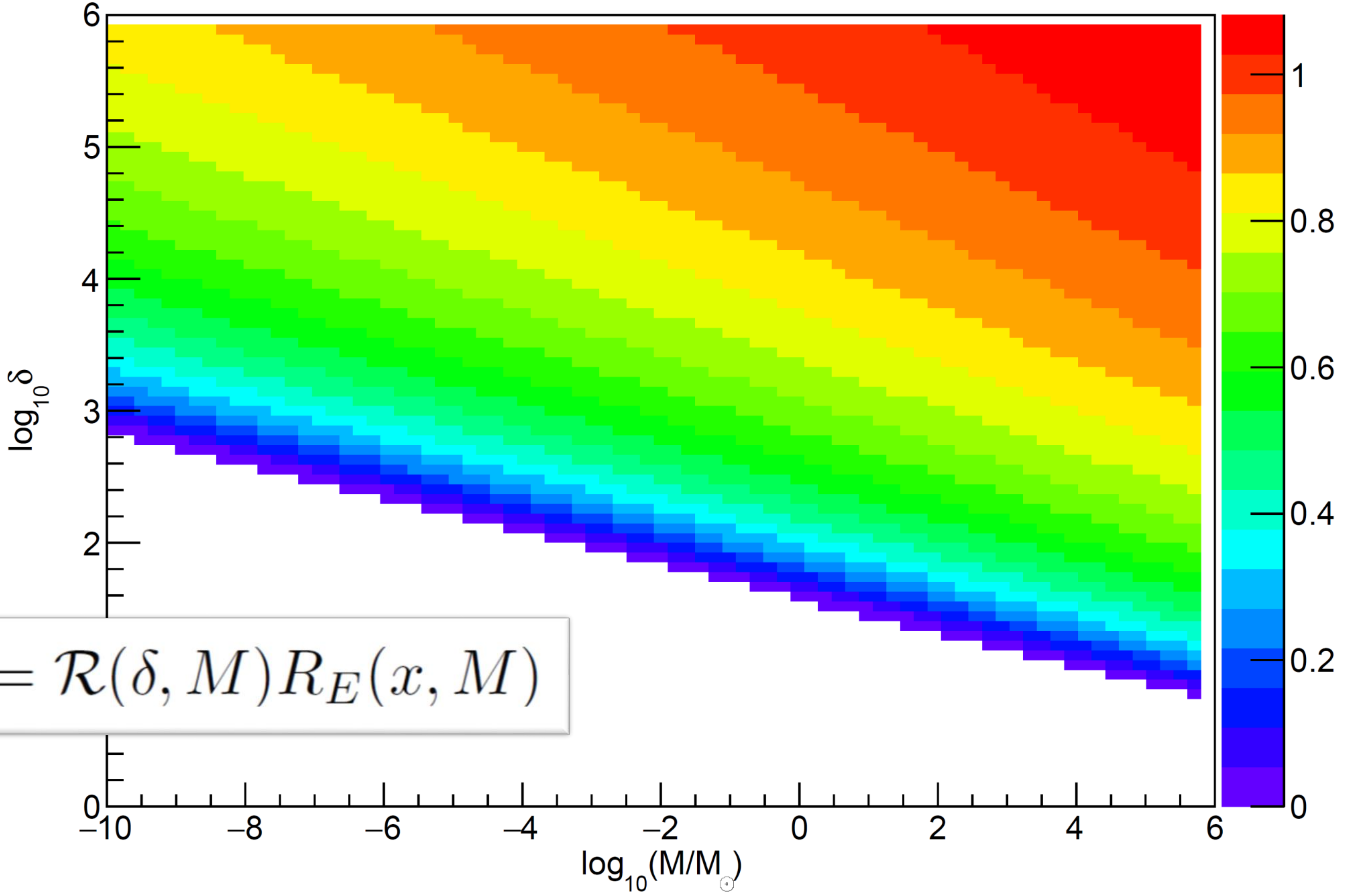
We have distributed density which, while dense, is not a point mass.

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

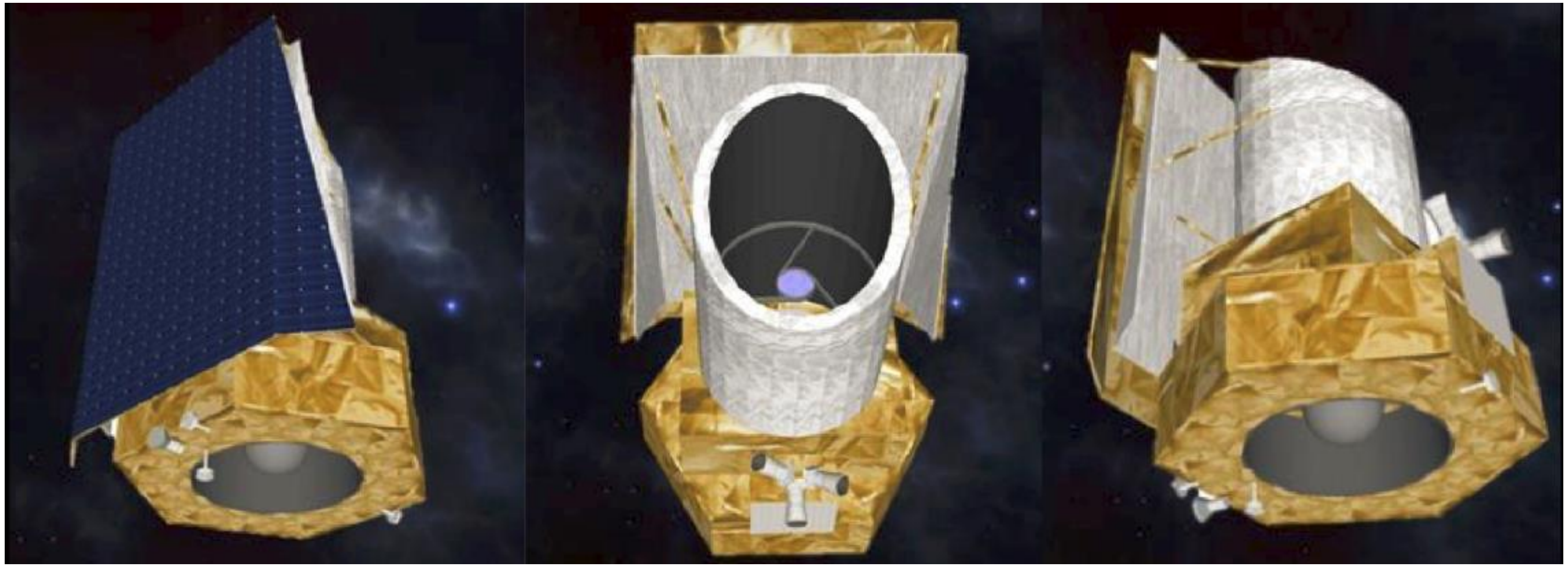


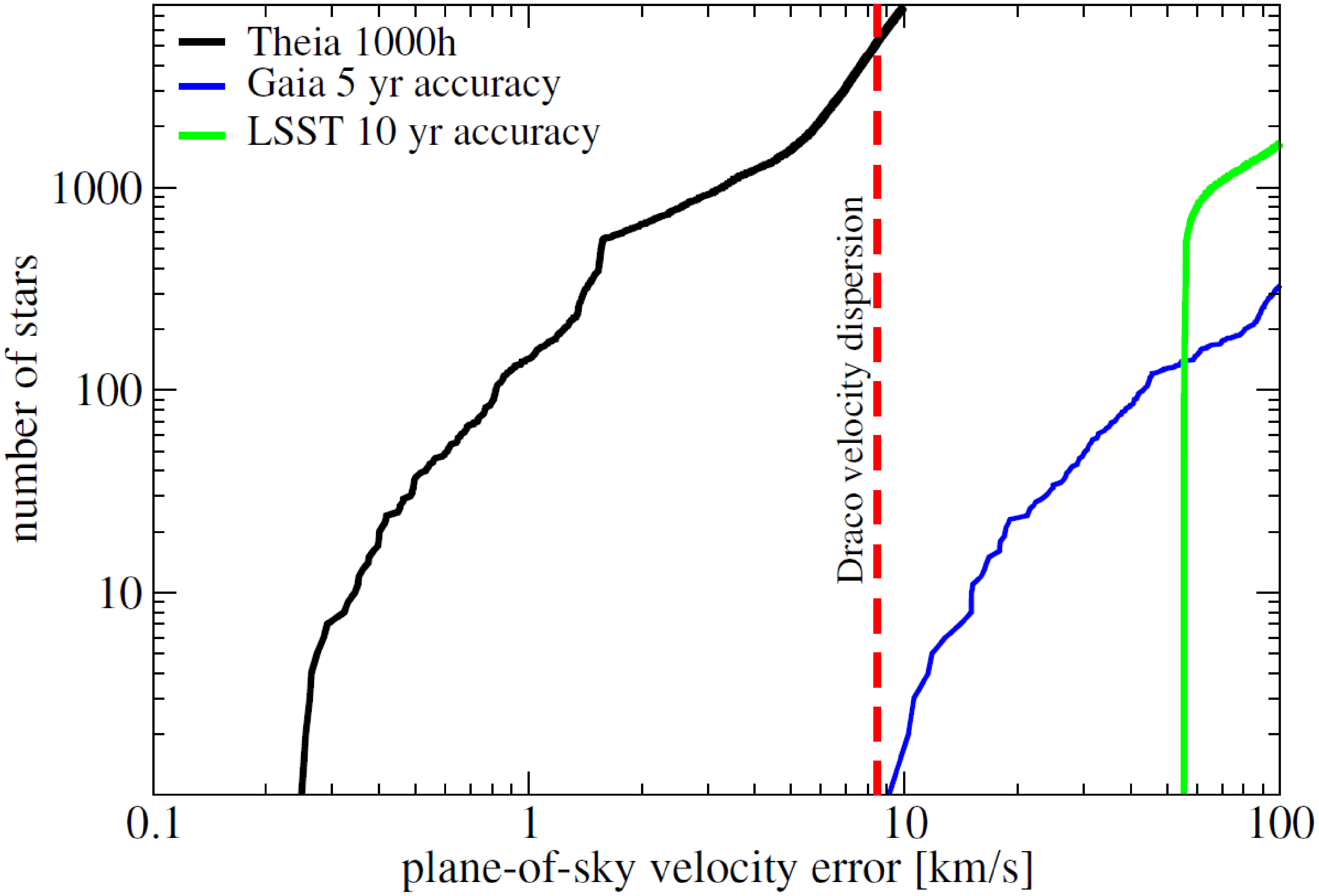
$$R_{\mathrm{MC}}(x, M, \delta) = \mathcal{R}(\delta, M) R_E(x, M)$$

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]