Searching for the QCD Axion with Gravitational Microlensing

David J. E. Marsh, Helsinki, May 2017

Quevillon, DJEM & Fairbairn 1701.04787
Quevillon, DJEM, Fairbairn & Rozier (FMQR, to appear)

The Strong CP Problem

Axion Review: DJEM Phys Rept (2016)

The QCD topological term induces a neutron EDM:

$$\mathcal{L} \supset \frac{\theta_{\rm QCD}}{32\pi^2}{\rm Tr}G_{\mu\nu}\widetilde{G}^{\mu\nu} \Rightarrow d_n \approx 3.6\times 10^{-16}\theta_{\rm QCD}\, e{\rm cm}$$

This is measured to be small. Fine tuning due to axial anomaly:

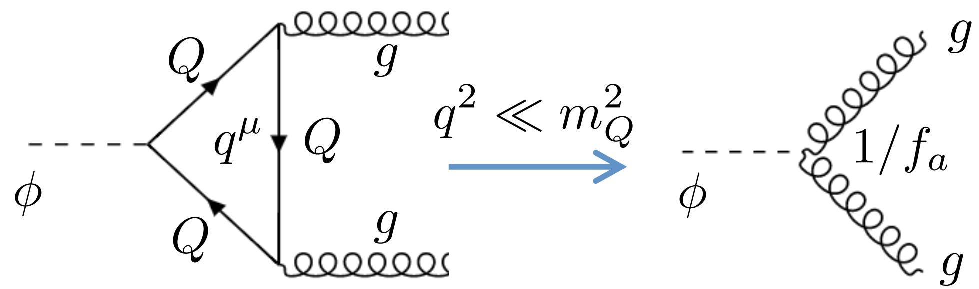
$$|d_n| \leq 3.0\times 10^{-26}\, e{\rm cm}$$

Pendlebury et al (2015), 90% C.L.

$$\theta_{\rm QCD} = \tilde{\theta}_{\rm QCD} + \arg\det M_u M_d$$

Solution: make θ the Goldstone boson of $U(1)_A$ with SSB at scale f_a:

This talk: consider "KSVZ" axion only:



QCD instantons give rise to a non-perturbative potential:

$$V(\phi) - -m_\pi^2 f_\pi^2\sqrt{1-4z\sin^2(\phi/2f_a)}; \quad z = \frac{m_u m_d}{(m_u+m_d)^2}$$

Key Axion Scales

Axion Review: DJEM Phys Rept (2016)
Relic density: Lyth (1992), Kawasaki et al (2012)

The axion mass is fixed by f_a, which is bounded by stellar cooling:

$$m_a \approx 6\,\mu\text{eV}\,\frac{10^{12}\ \text{GeV}}{f_a} \qquad f_a \gtrsim 10^9\ \text{GeV}$$

Axion DM is formed by "vacuum realignment". Crucial epochs:

$$T_{\rm SSB} \approx f_a \qquad m_a = m_{a,0}\left(\frac{T}{\Lambda_{\rm QCD}}\right)^{-n} \qquad 3H(T_0) = m_a(T_0)$$

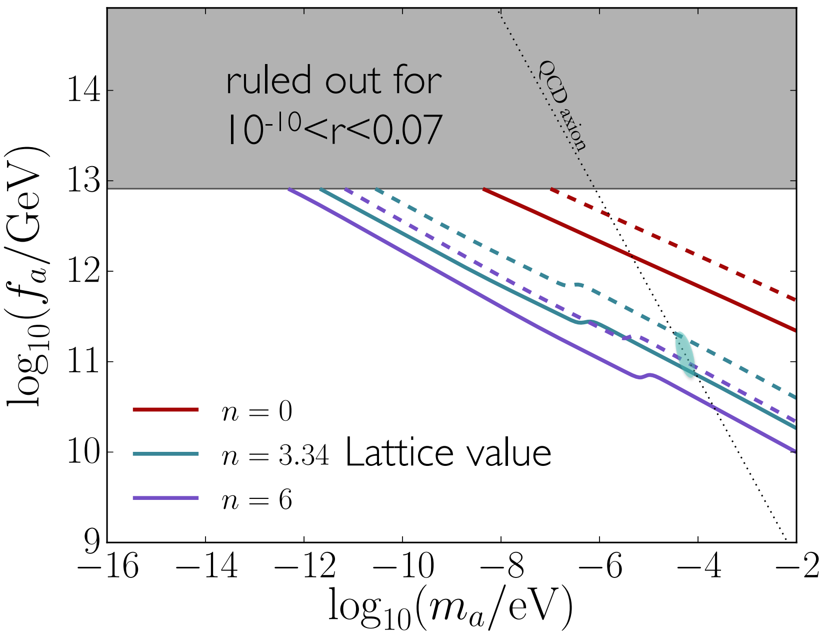
Initial conditions. Non-thermal relic density

Consider the case with SSB after inflation (f_a<H_I ish):

- Axion window if primordial tensors are ever detected.
- Kibble mechanism smooths perts until T_0 when strings decay.

→ Large amplitude, white noise, isocurvature perts @ $k(T_0)$.

Axion Relic Density and Minicluster Mass



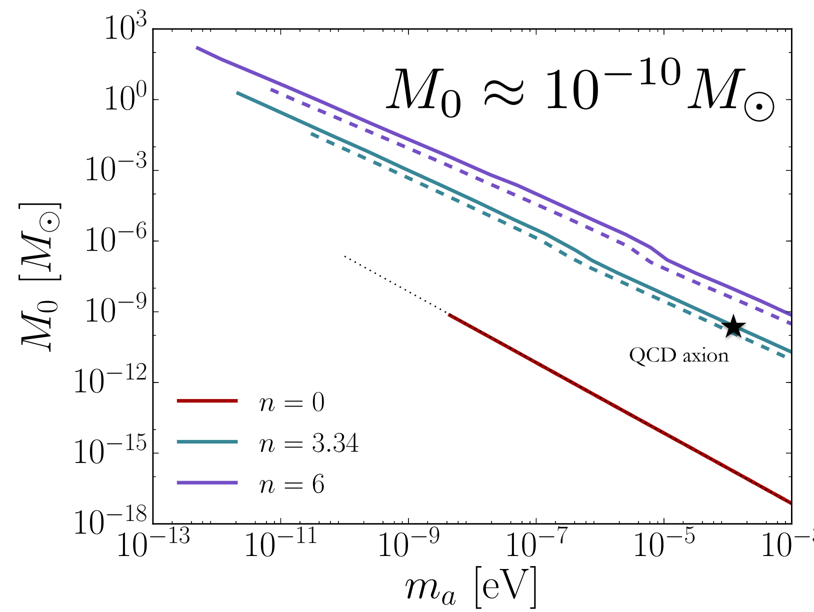
Axion → matter when $m(T_0)>H(T_0)$. Crucial epoch! Mass in horizon at this time → minicluster at z_{eq}: Hogan & Rees (1988)

$$M_0 = \bar{\rho}_{a,0}\frac{4}{3}\pi\left(\frac{\pi}{a(T_1)H(T_1)}\right)^3$$

DM relic density, $\Omega_c h^2=0.12$ → narrow mass window:

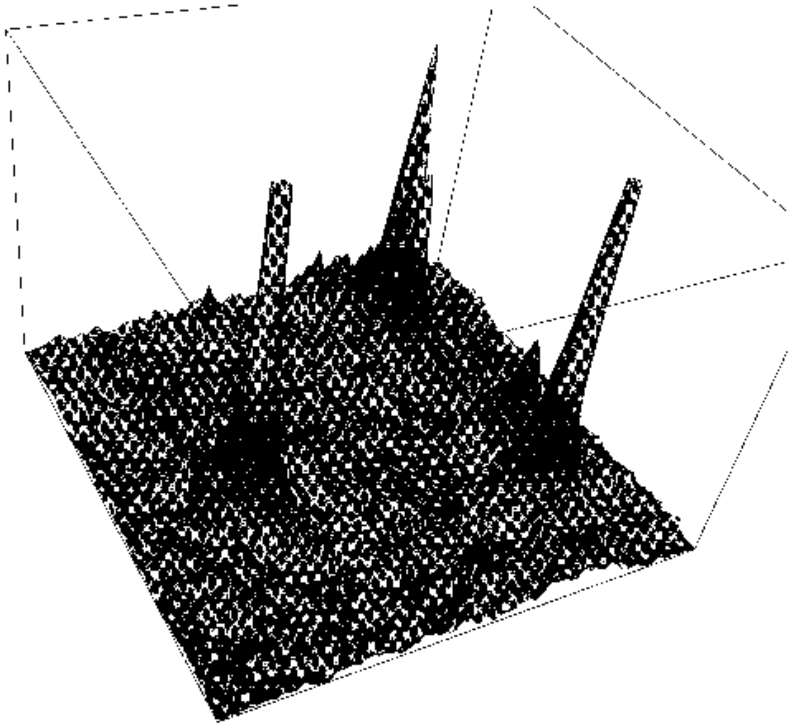
$$50 \lesssim \frac{m_a}{\mu\mathrm{eV}} \lesssim 200$$

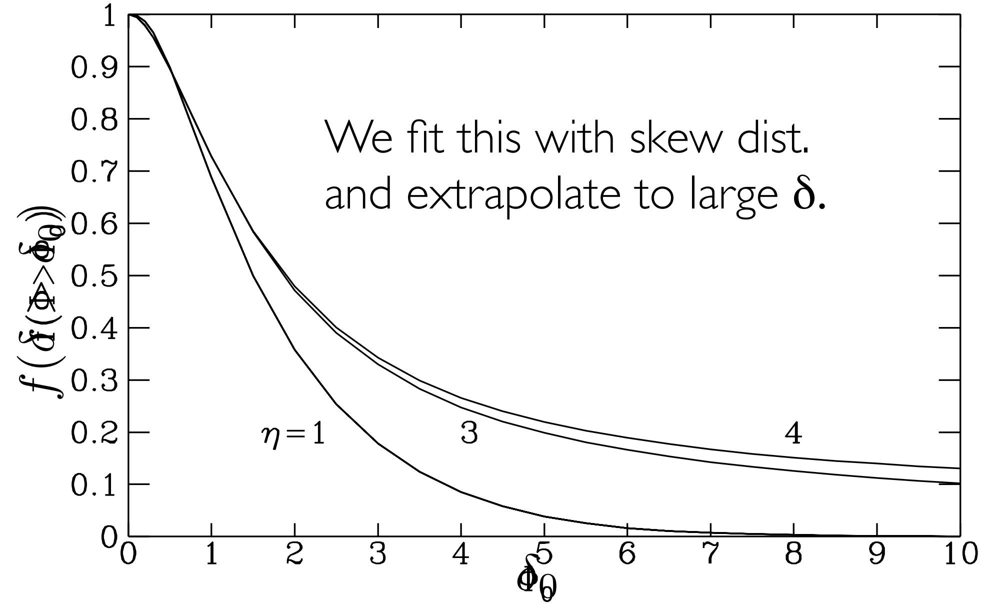
(defect decay, anharmonics)



Simulations: Kolb & Tkachev (1990's)

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





Minicluster formation simulated without gravity or phase transition.

Fraction of MCs with density δ:

$$\rho = \delta^3(1+\delta)\rho_{\mathrm{eq}}$$

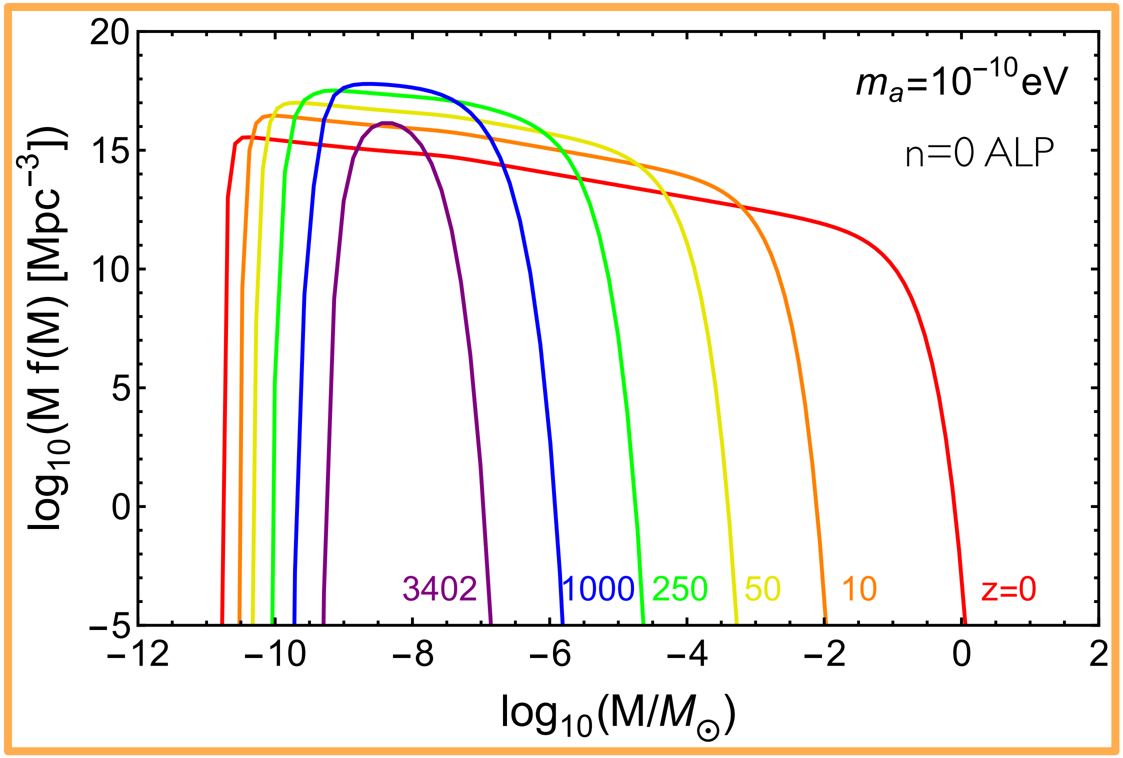
The fraction of DM in miniclusters, f_{MC}, is not predicted.
Our goal: constrain f_{MC} observationally.

So what happens next?

FMQR

As cosmologists, we asked: how do miniclusters form structure?
We computed the simplest thing, the Press-Schechter mass function:

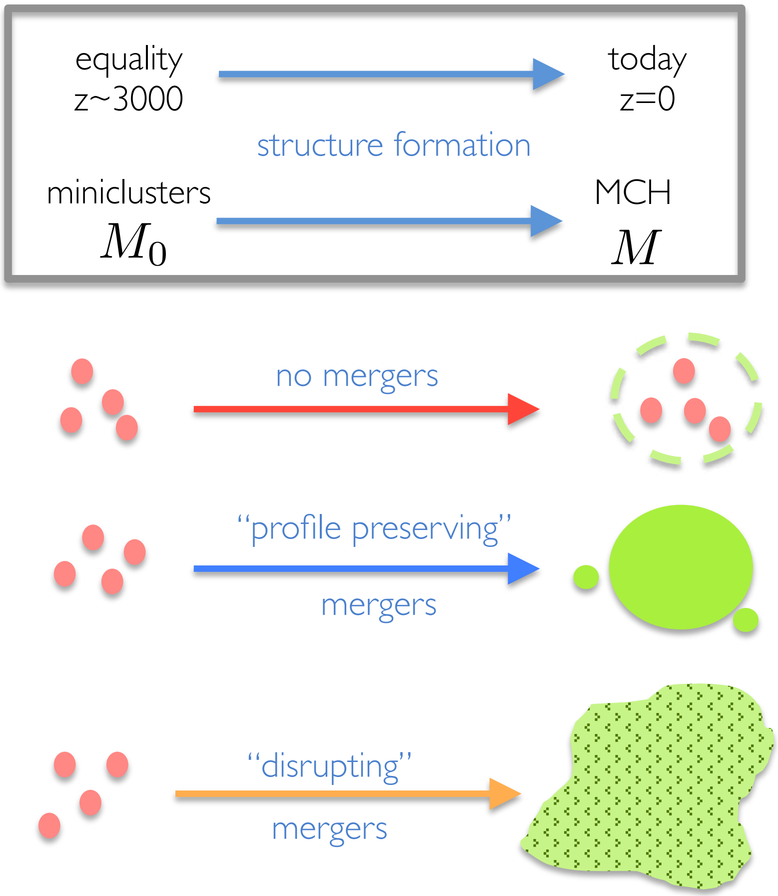
Miniclusters will cluster and form halos (MCHs) on small scales. Contribute to the substructure mass function in the MW.



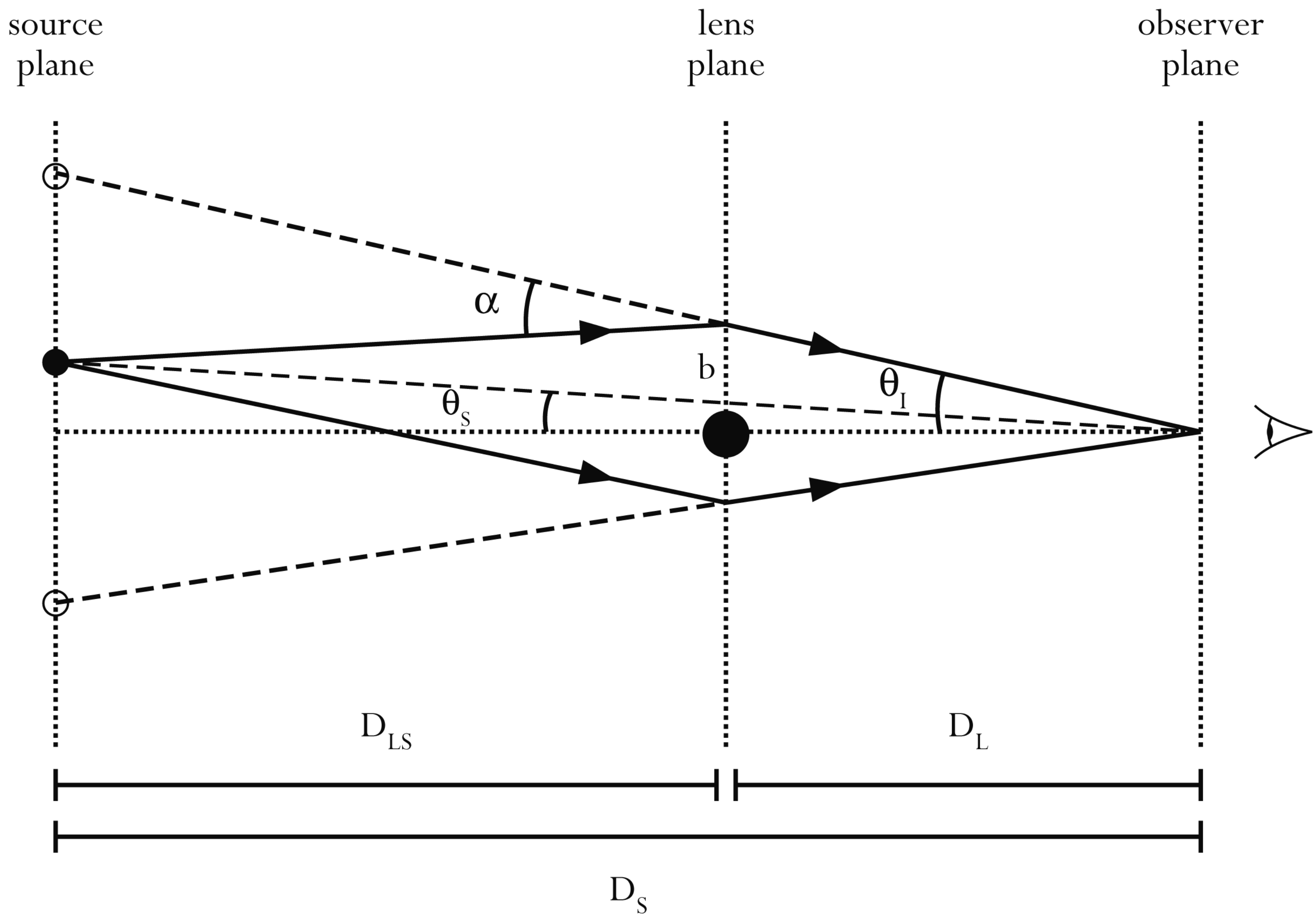
How can we search for MCHs? Like MACHOs? The density is crucial.
Problem: Kolb & Tkachev only give us density in initial mass function.

Mergers and Density Profiles

Is the MCH mass function even relevant for the observations?
Do miniclusters merge as they form MCHs? We took some guesses:



Gravitational Microlensing



Gravitational Microlensing

Griest (1991)

For distances and masses of interest, cannot resolve multiple images, only the overall magnification:

$$A(u) = \frac{u^2+2}{u(u^2+4)^{1/2}} \qquad R_{\mathrm{E}}(x, M) = 2[GMx(1-x)d_s]^{1/2}$$

Define the "microlensing tube" where A>1.34:

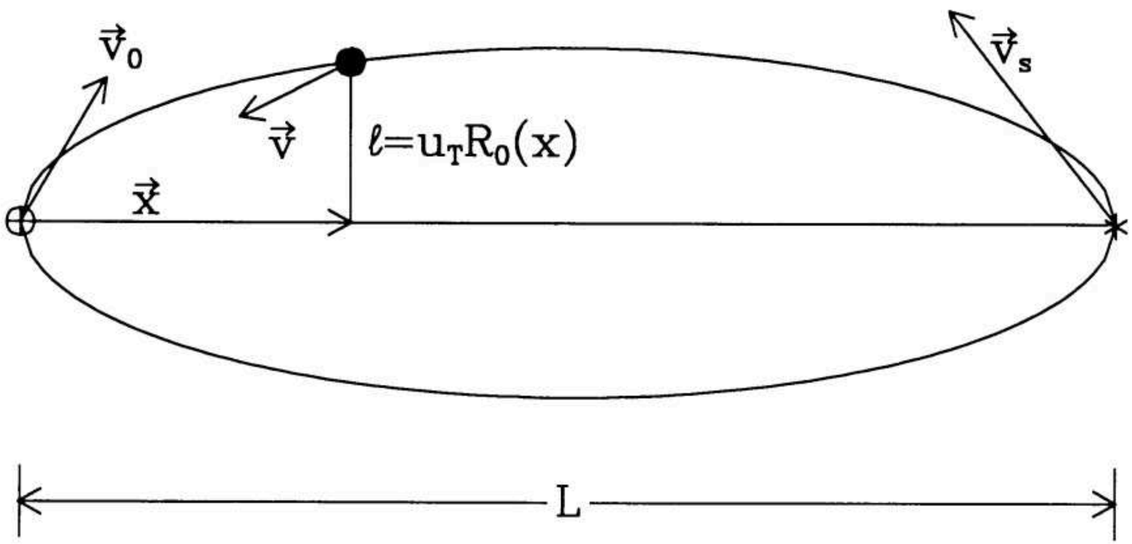


FIG. 1.—Microlensing "tube," variables, and velocities. The observer is marked ⊕, the source by an asterisk, and the dark matter object by a filled circle. A dark matter object inside the tube constitutes an "event".

For a given host halo model, we can now compute the event rate for microlensing…

Lensing with non-point sources

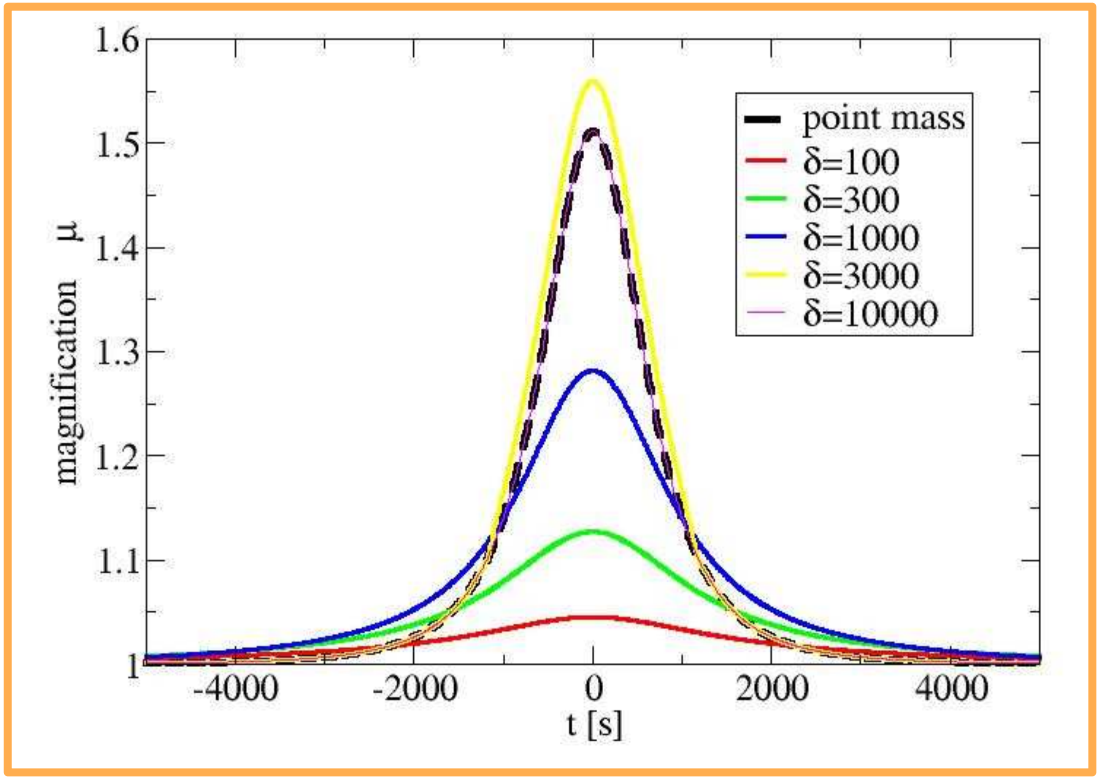
Model miniclusters as NFW density profile and use eqns:

$$A = [(1 - B)(1 + B - C)]^{-1}$$

$$C = \frac{1}{\Sigma_c \pi \ell} \frac{\mathrm{d}M(\ell)}{\mathrm{d}\ell} \; ; \; B = \frac{M(\ell)}{\Sigma_c \pi \ell^2} \; ; \; \Sigma_c = \frac{1}{4\pi G d_s x(1-x)}$$

Plot the "light curve" as lens crosses line of sight.

As concentration increases, miniclusters do more lensing.



Lensing with non-point sources

Model miniclusters as NFW density profile and use eqns:

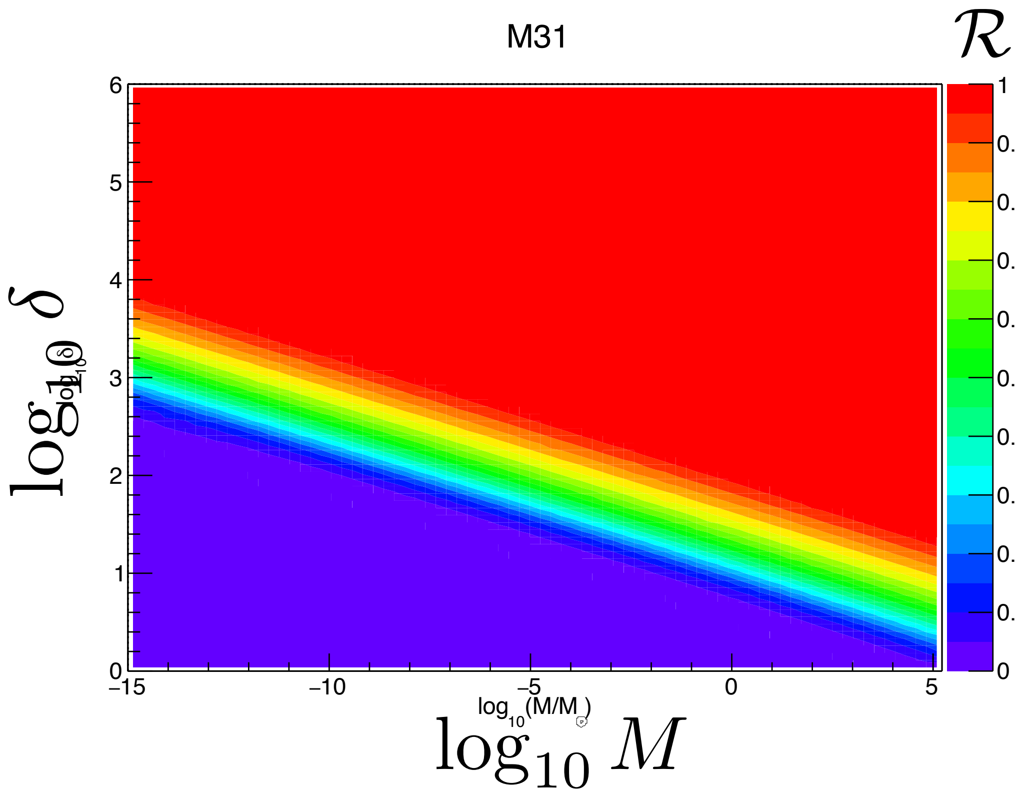
$$A = [(1 - B)(1 + B - C)]^{-1}$$

$$C = \frac{1}{\Sigma_c \pi \ell} \frac{\mathrm{d}M(\ell)}{\mathrm{d}\ell} \; ; \; B = \frac{M(\ell)}{\Sigma_c \pi \ell^2} \; ; \; \Sigma_c = \frac{1}{4\pi G d_s x(1-x)}$$

The lensing tube has the same shape, but is rescaled:

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

Behave like point mass when scale radius << R_E



Lensing with Distributions

Green (2016)
FMQR

For a distribution of lenses, we integrate over the mass function:

$$\frac{\mathrm{d}\Gamma}{\mathrm{d}\hat{t}} = \frac{32 d_s}{\hat{t}^4 v_c^2} \int_0^\infty \left[\frac{\mathrm{d}n}{\mathrm{d}\ln M} M \int_0^1 \rho_{\mathrm{host}}(x) R_{\mathrm{E}}^4 e^{-4R_{\mathrm{E}}^2/(\hat{t}^2 v_c^2)} \right] \mathrm{d}M$$

Similarly for a distribution of density profiles.
Integrate the event rate with $R_E \rightarrow R_{MC}$ over $dn/d\delta$ (from fit):

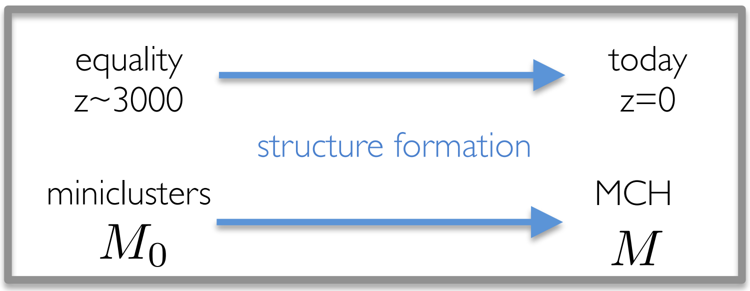
$$\frac{\mathrm{d}\Gamma}{\mathrm{d}\hat{t}} = \int_0^\infty \mathrm{d}\delta \frac{\mathrm{d}n}{\mathrm{d}\delta} [\cdots]_{\mathrm{MC}}$$

How do we combine these two formulae to treat MCHs?
Problem: Kolb & Tkachev only give us density in initial mass function.
What kind of smoothing is the mass function assuming?

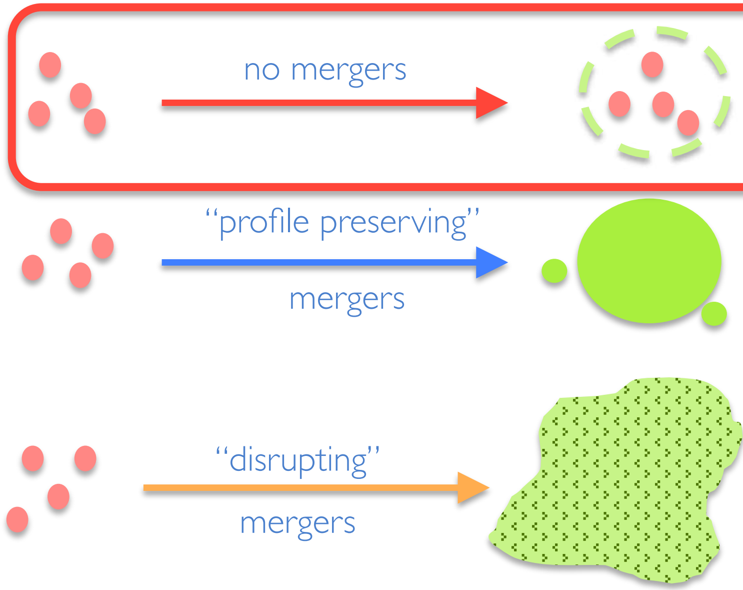
Mergers and the Lensing Mass Function

FMQR

A full treatment would allow lensing on multiple time scales.
The way to treat approximate the signal depends on the mergers:



Modeling of minicluster mass function and density profiles



Effective mass function	NFW concentration	Model name
Dirac-delta (M_0)	$c(\delta, M_0)$	isolated miniclusters
Press-Schechter	$c(\delta, M)$	dense MCH
“Cut” Press-Schechter	Assumed negligible $M>M_0$	diffuse MCH

For a single time scale, the best approximation depends on the survey.

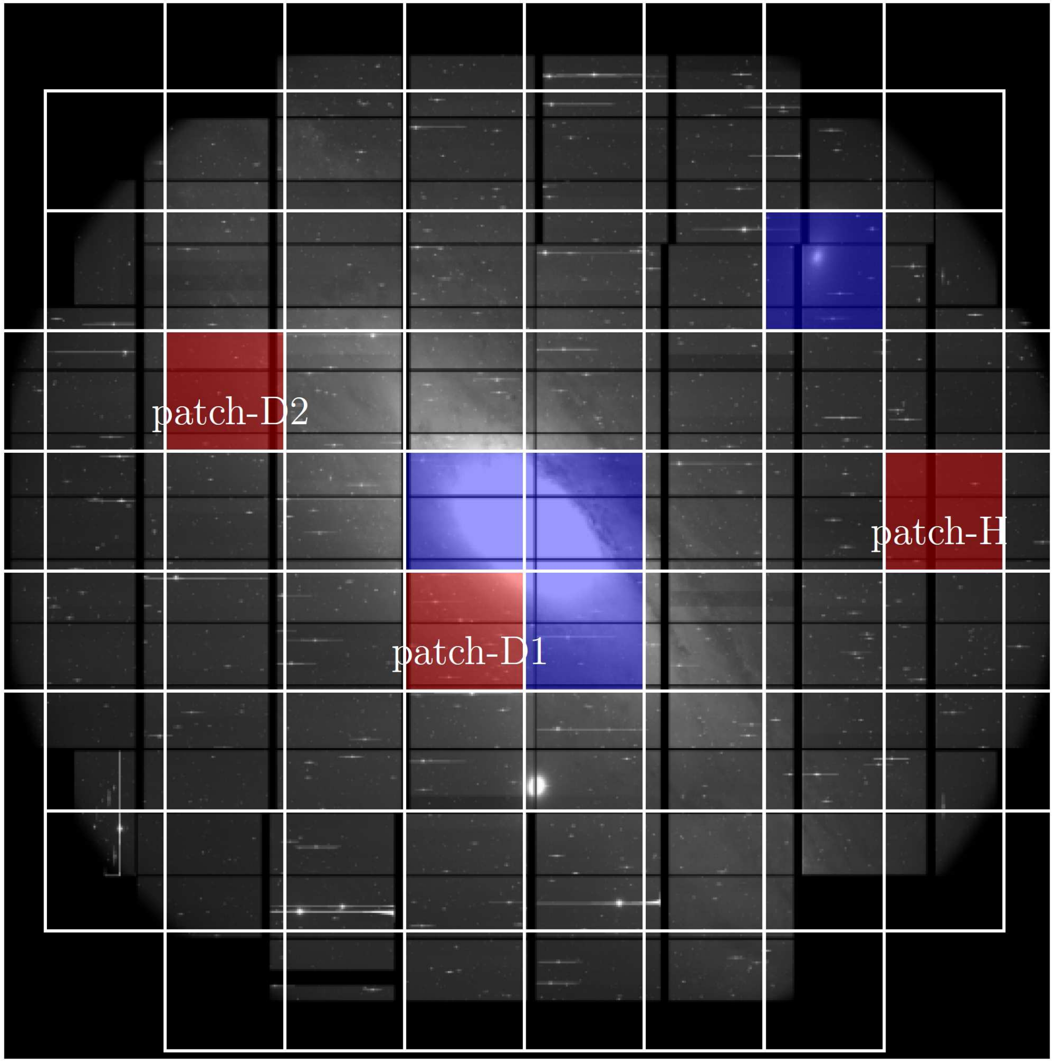
Subaru Hyper Suprime Cam

Niikura et al (2017)

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

Use of "pixel lensing" allows for high cadence observations.

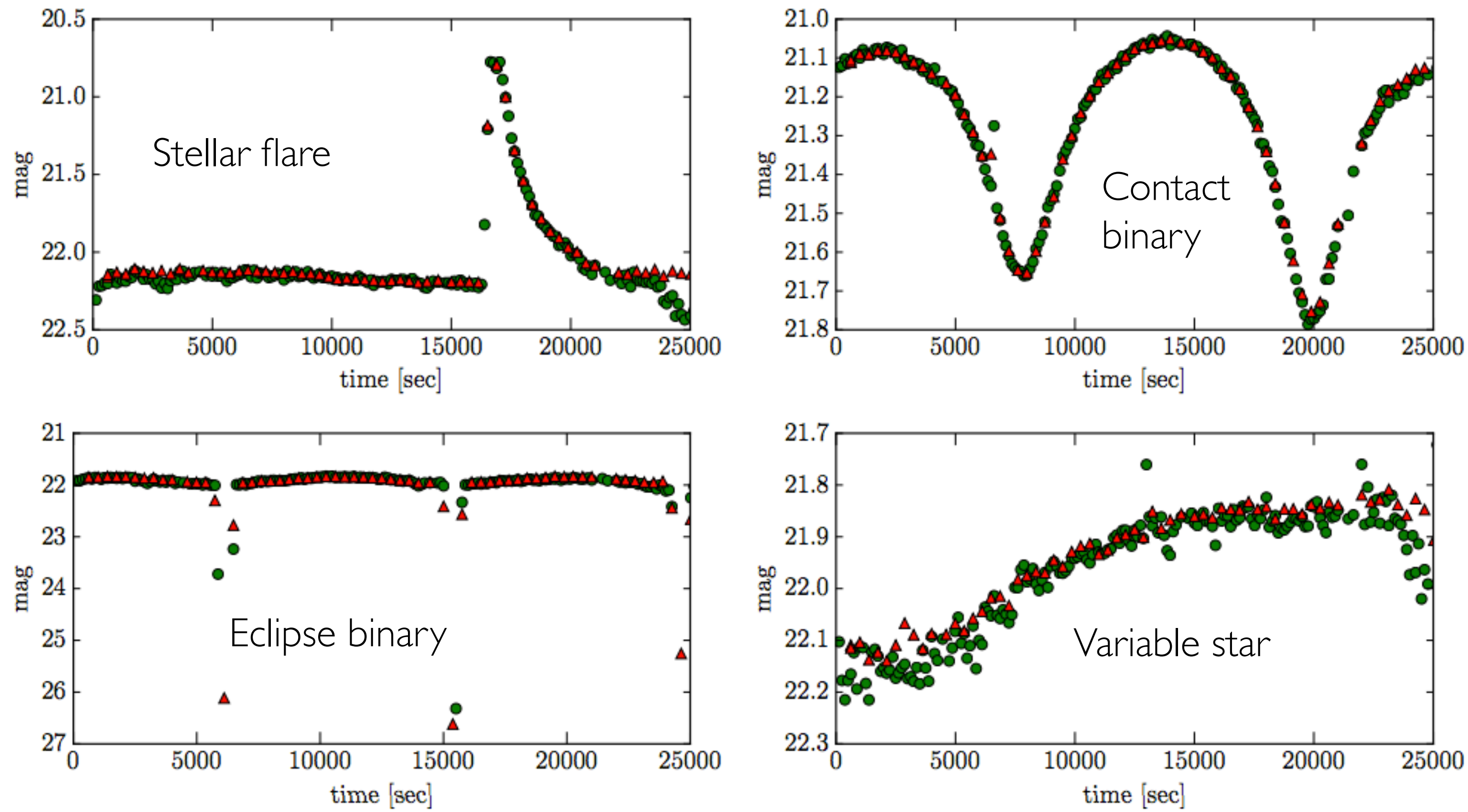
HSC has collected only 7 hours of lensing data



Transient Survey

Niikura et al (2017)

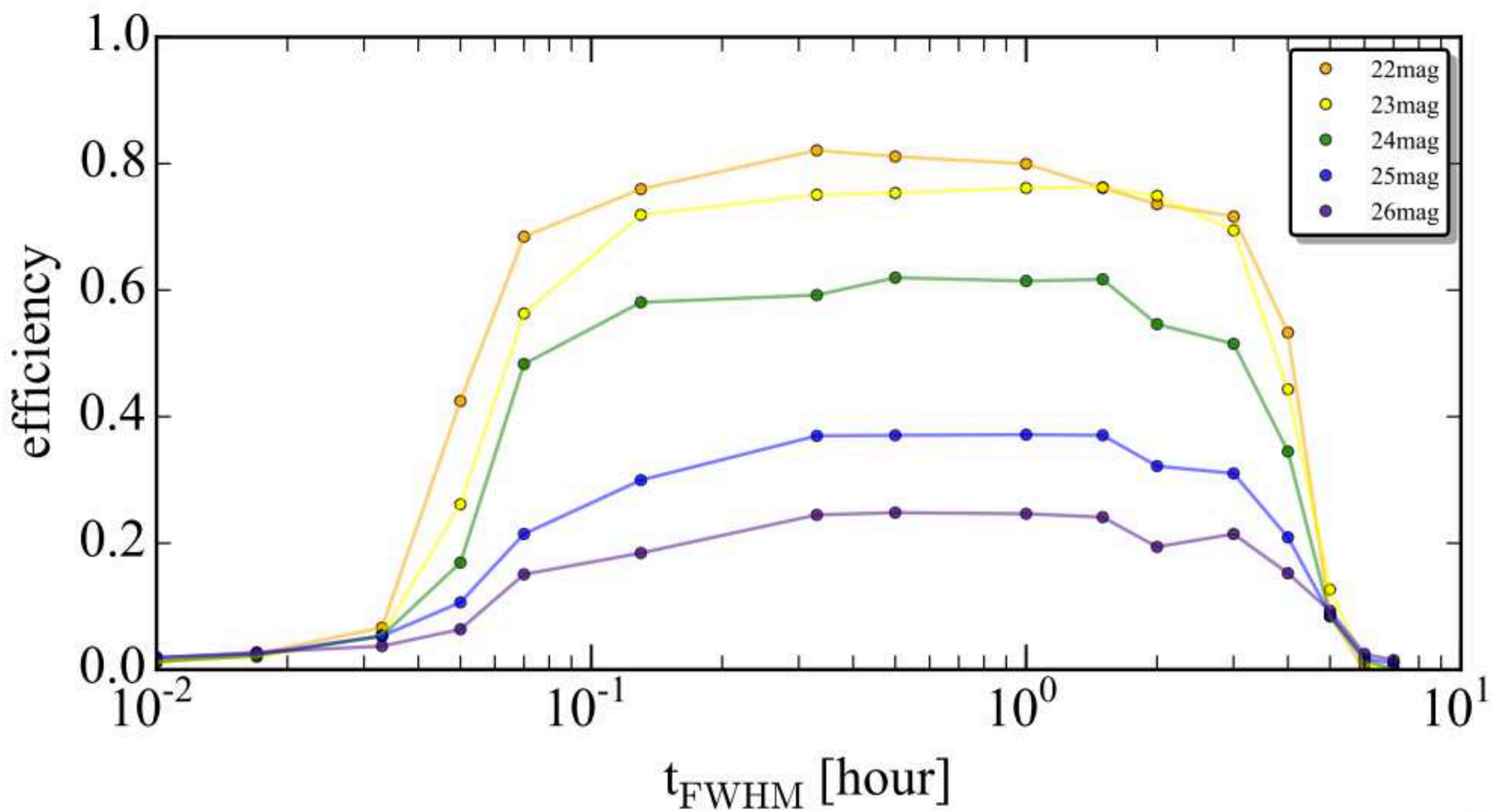
Careful analysis by observers excludes various non-microlensing events by lightcurves:



Lensing Efficiency

Niikura et al (2017)

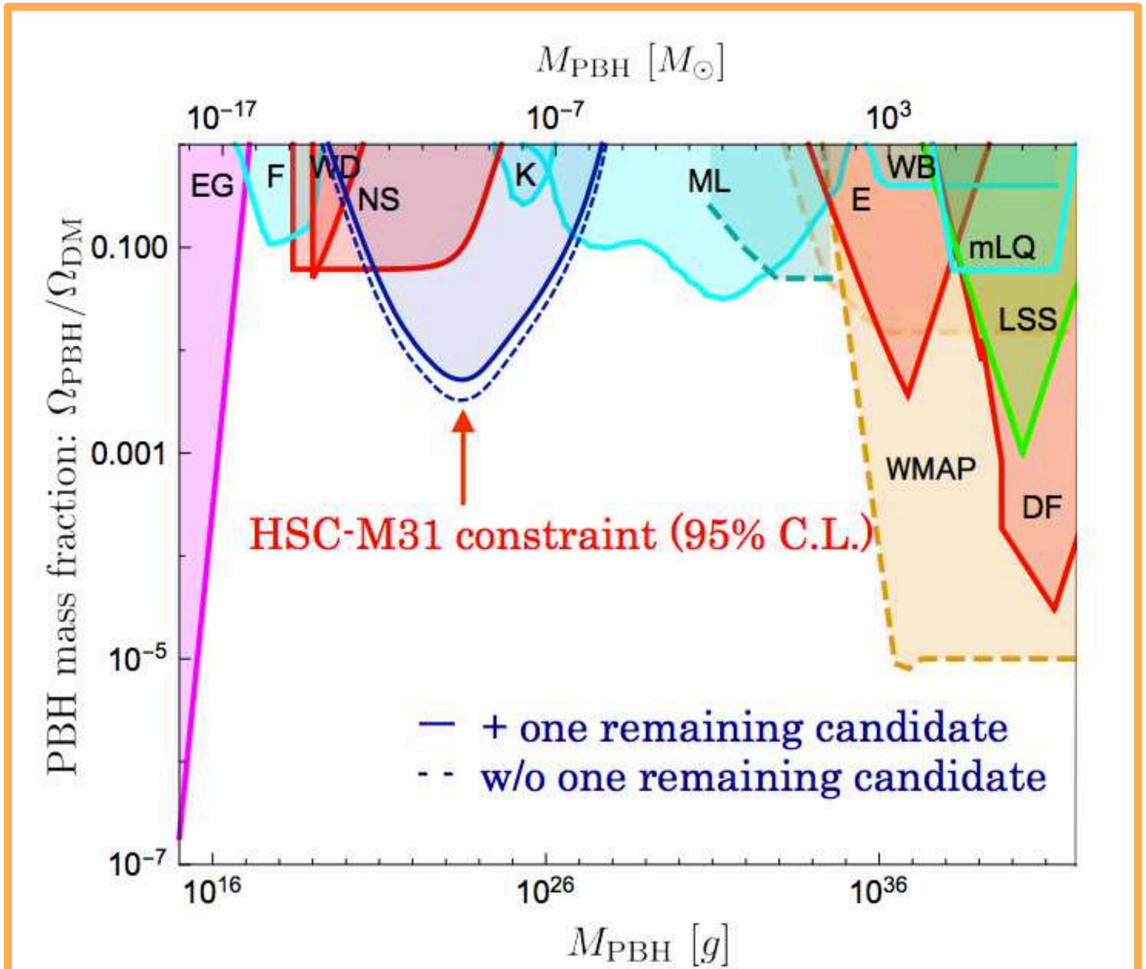
The lensing efficiency sets the range of lens masses accessible.
Fixed by the cadence (2min) and observing time (7hours)



Constraints on DM

Niikura et al (2017)

For point masses (e.g. PBH), tight constraints on the DM fraction:



What luck! The perfect range for searching for miniclusters!

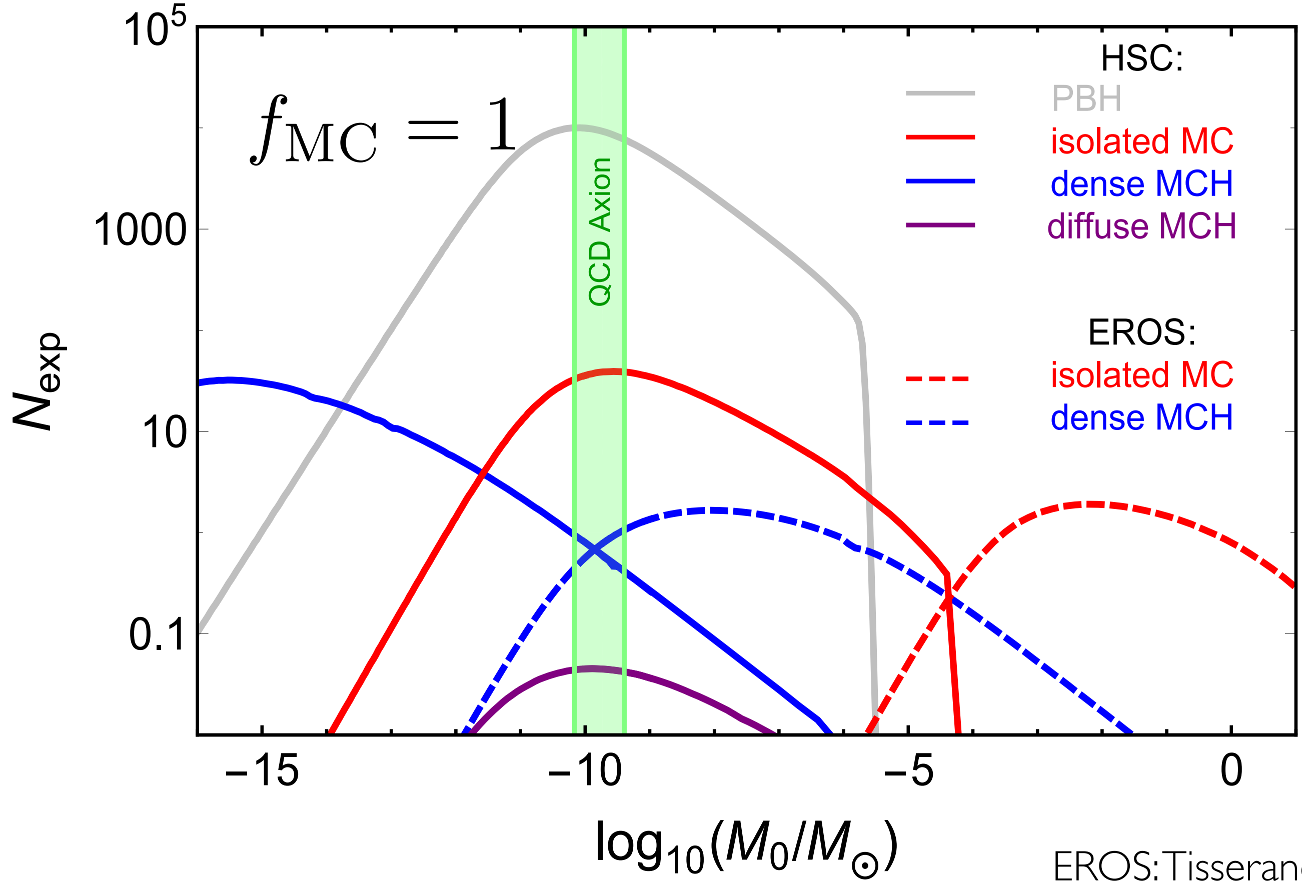
Results: events in EROS and HSC

FMQR

EROS ε: fit from paper.

$$N_{\rm exp} = E \int {\rm d}\hat{t}\,\epsilon(\hat{t})\,\frac{{\rm d}\Gamma}{{\rm d}\hat{t}}$$

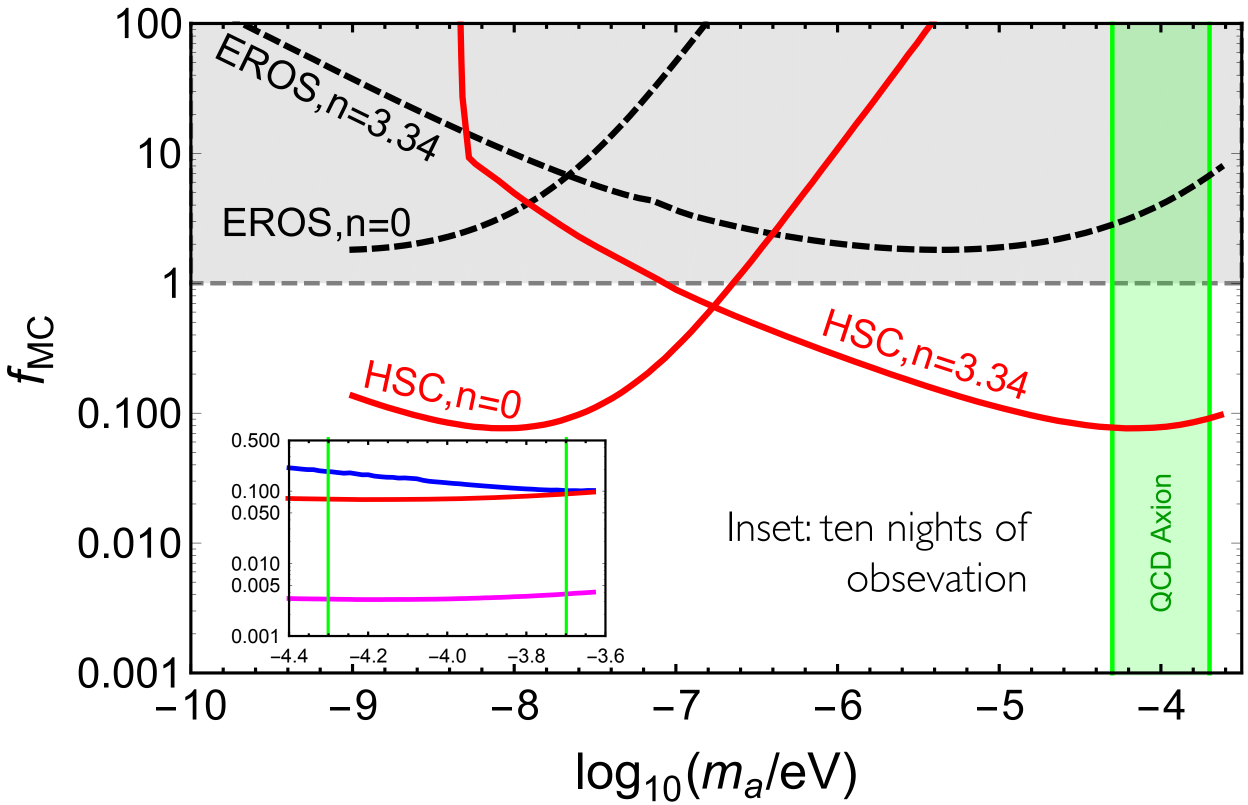
HSC ε: approx from cadence and obs time. Normalise to PBH rate.



EROS: Tisserand et al (2007)
HSC: Niikura et al (2017)

Results: constraints on f_{MC}

No observed events → Poisson stats 95% C.L. exclusion.



We have placed the first observational bound on f_{MC}:

$$f_{\rm MC} < 0.083(m_a/100\mu{\rm eV})^{0.12}$$

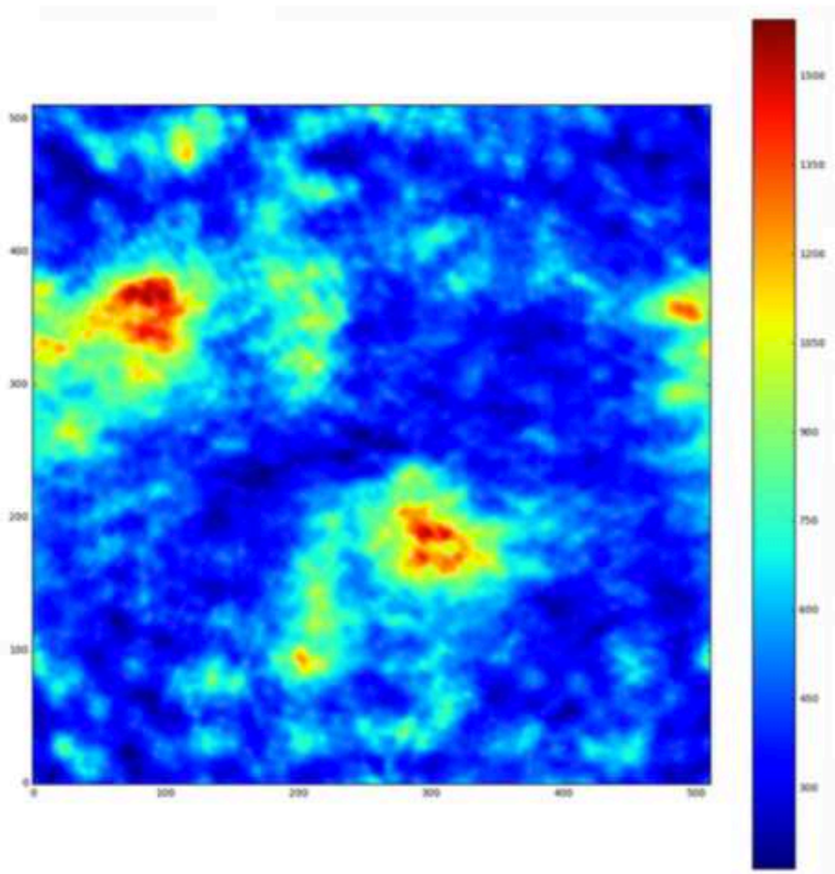
Uncertainties in the Calculation

There are lots of them, we've just made an initial investigation.

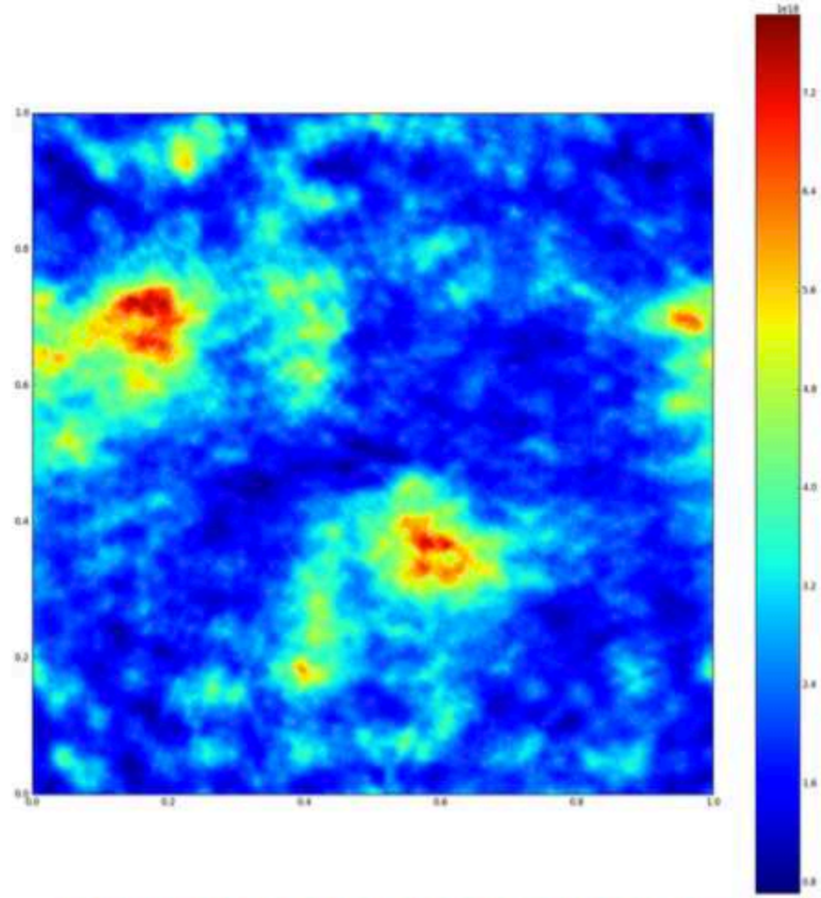
- What is the theory value of f_{MC}? Can we exclude models or make discoveries?
- What about MCHs? Are there mergers? (tidal disruption, friction?)
- True density profile of miniclusters? (not too important)
- Is $M_0(m_a)$ relation correct? (cubic versus spherical volume, cut-off dependence, string correlation or horizon size, relic density unceratinties)
- "Theorists treatment" of observations. Dedicated analysis?
- Any other business? (role of miniclusters and MCHs other than lensing, axion stars etc. etc.)

Simulations: Wiebe, Redondo, Niemeyer

Simulate the PQ phase transition and string decay for i.c.'s:



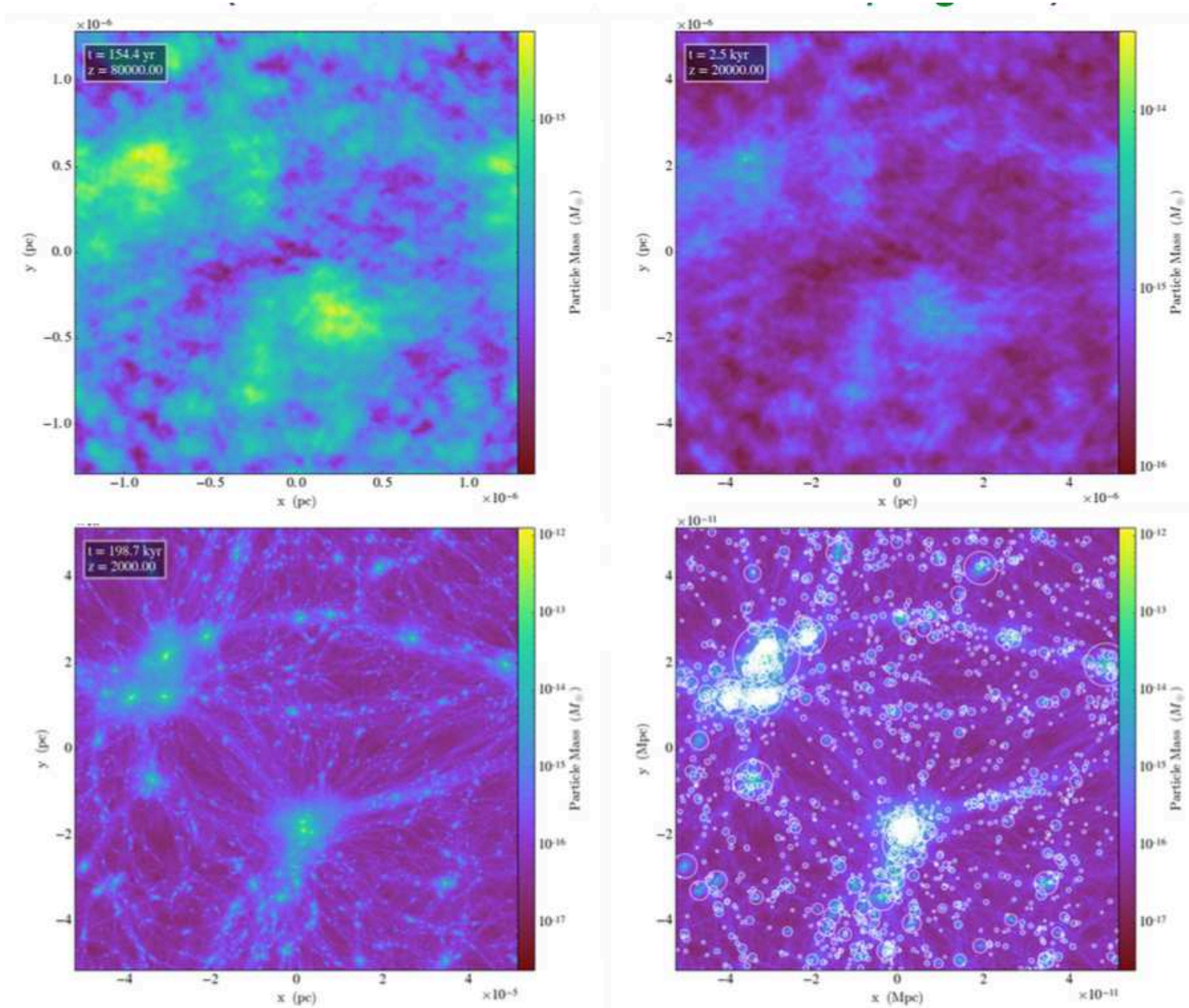
field simulation (input)



N-body initial conditions

Simulations: Wiebe, Redondo, Niemeyer

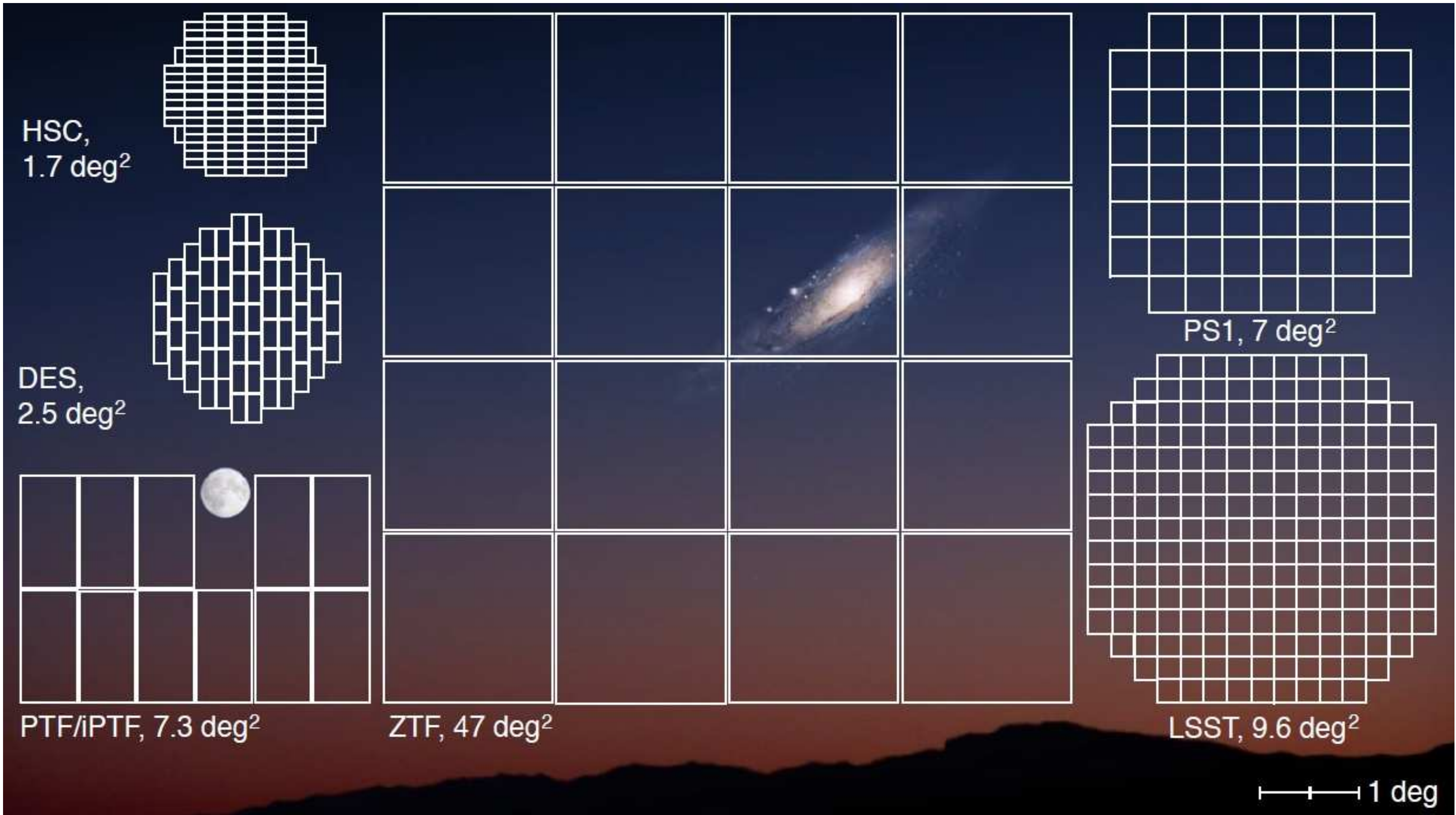
Collapse → dense objects of $M \sim M_0$. Small boxes → cannot get MF.



A Microlensing Renaissance

Image courtesy of Ariel Goobar

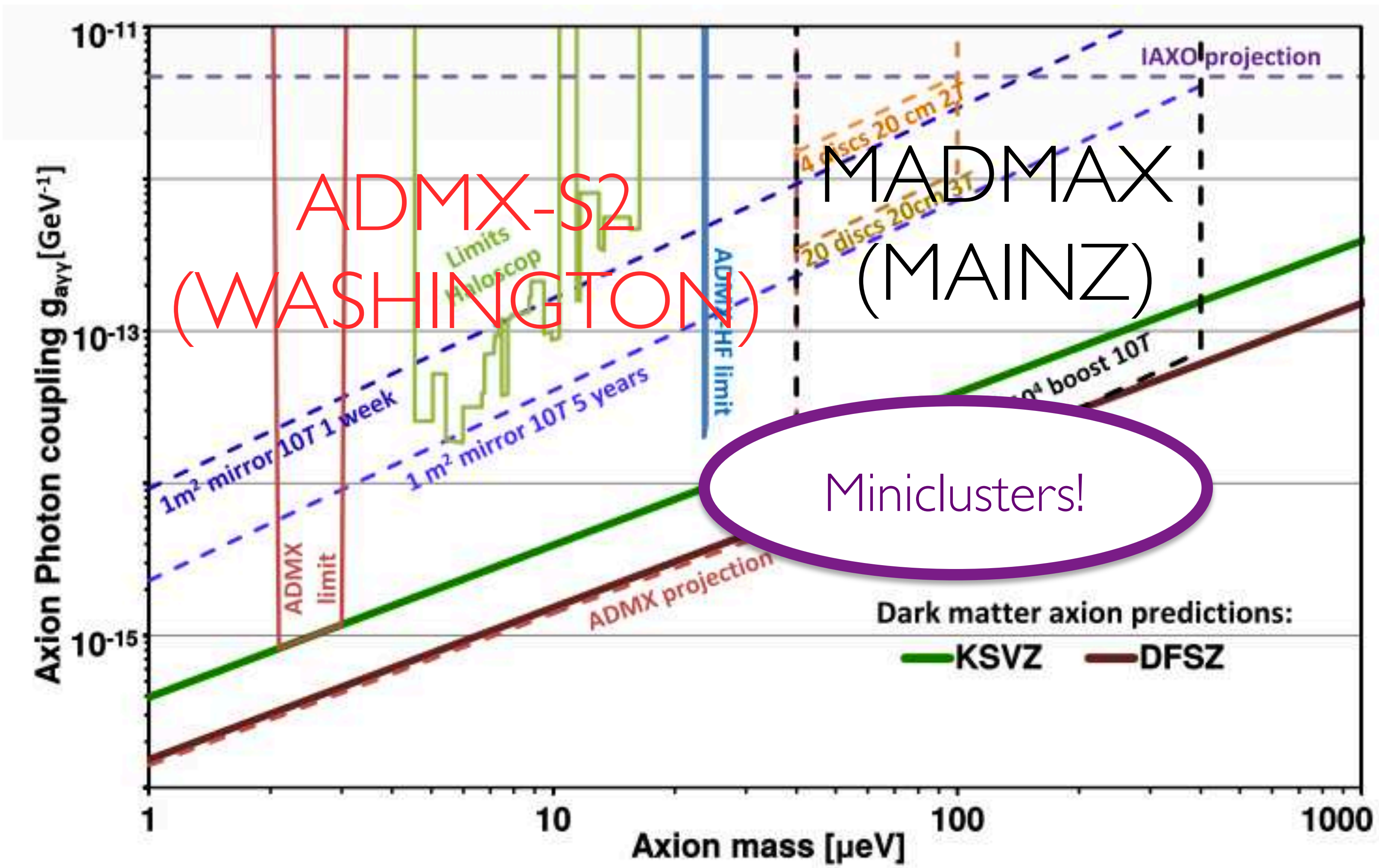
Lots of new surveys with larger exposure than HSC.
Orders of magnitude improvement very possible.



An Axion Renaissance

Knirck (PATRAS 2017)
CASPEr, ABRACADABRA at low mass

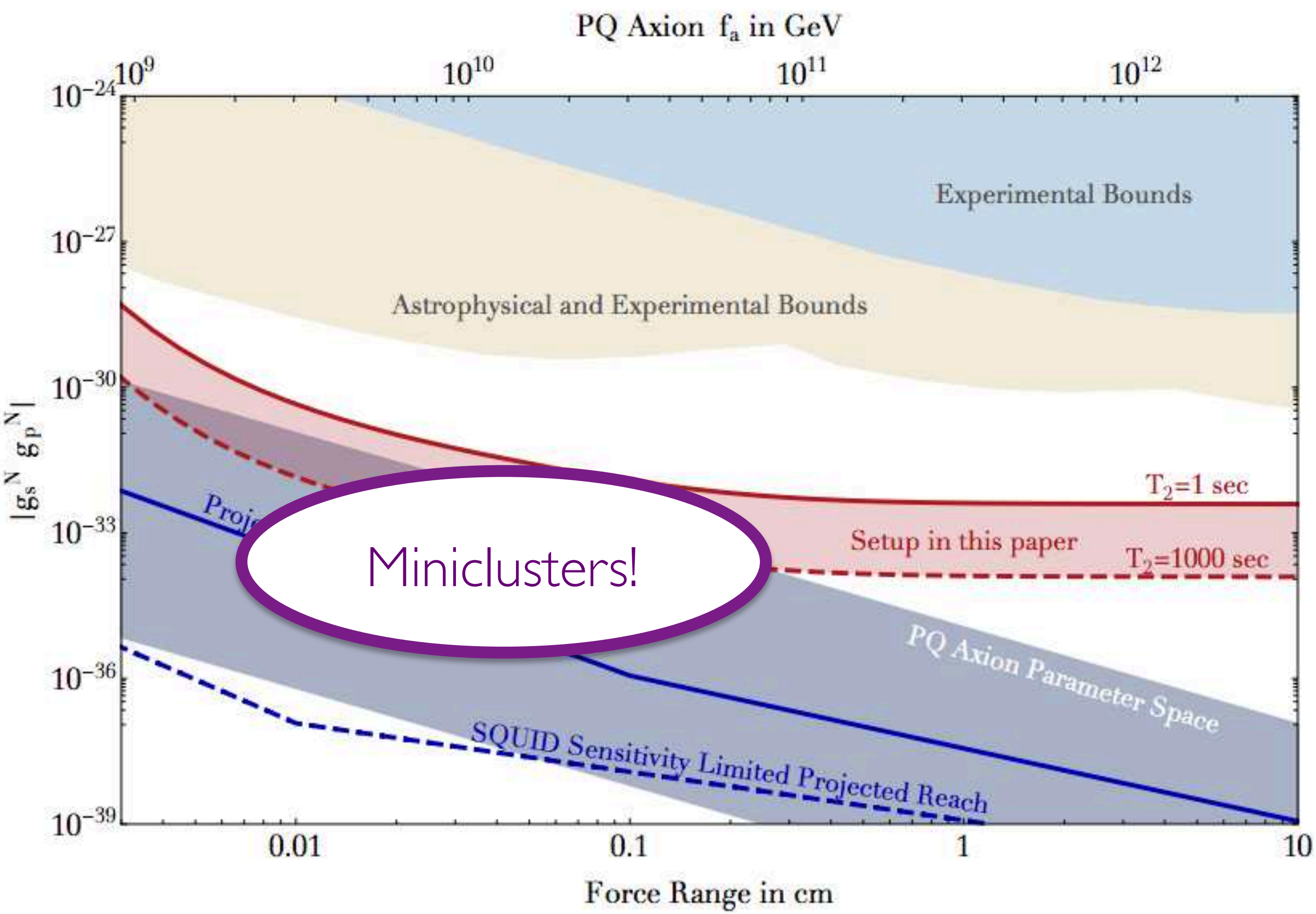
Huge and renewed global effort in axion direct detection.
If f_{MC} is high, rare MC encounters → axion DM detection is limited.



An Axion Renaissance

Arvanitaki and Geraci (2015)
ARIADNE: CAPP (Korea)

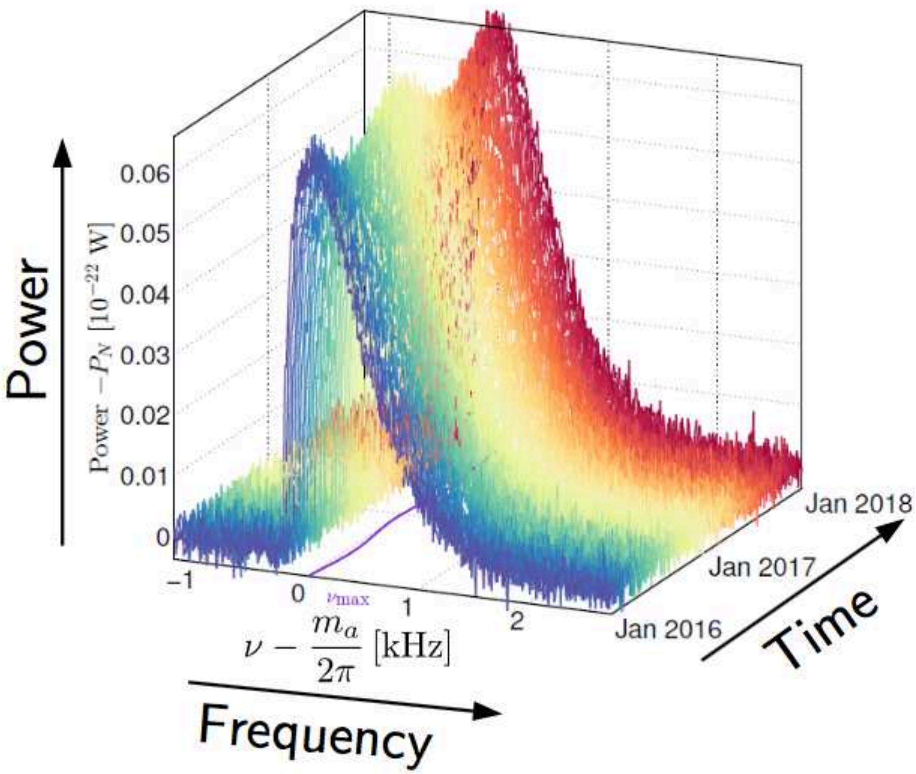
Huge and renewed global effort in axion direct detection.
With force detection, can detect independently of DM fraction.

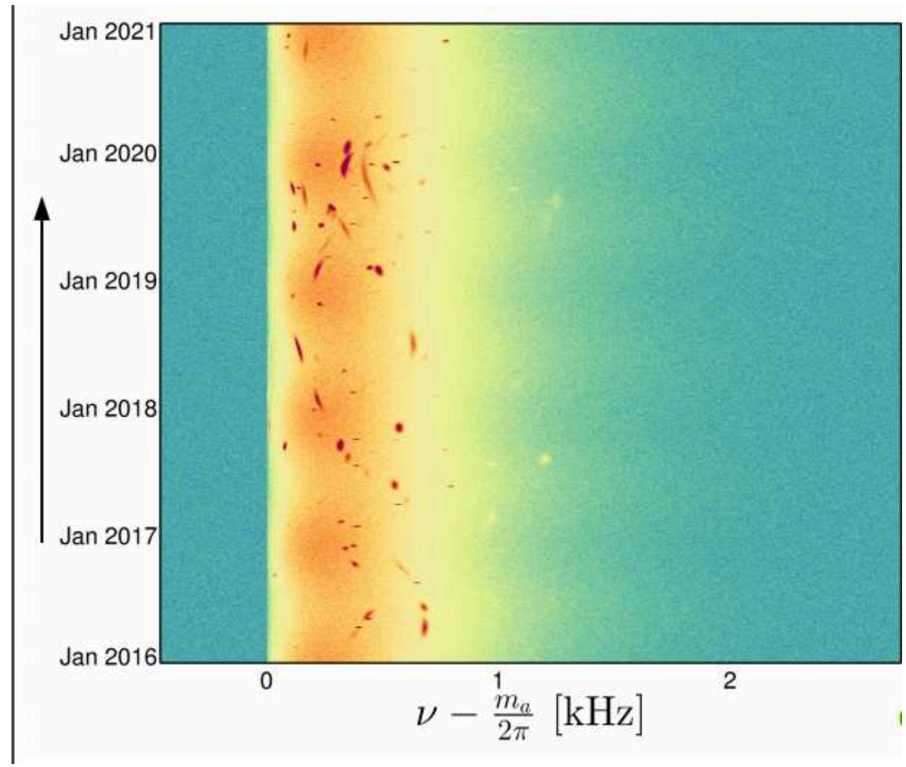


Axion Astronomy

O'Hare & Green (2017)
Tinyakov et al (2015)

Axion direct detection allows to probe the local velocity distribution.
Even a small minicluster fraction can show up via tidal streams.





This is the perfect time to be studying axion DM detection. It is also the perfect time to be thinking about microlensing.

Miniclusters are a fairly generic, but largely overlooked, aspect of axion DM pheno.