Einstein's Microscope:

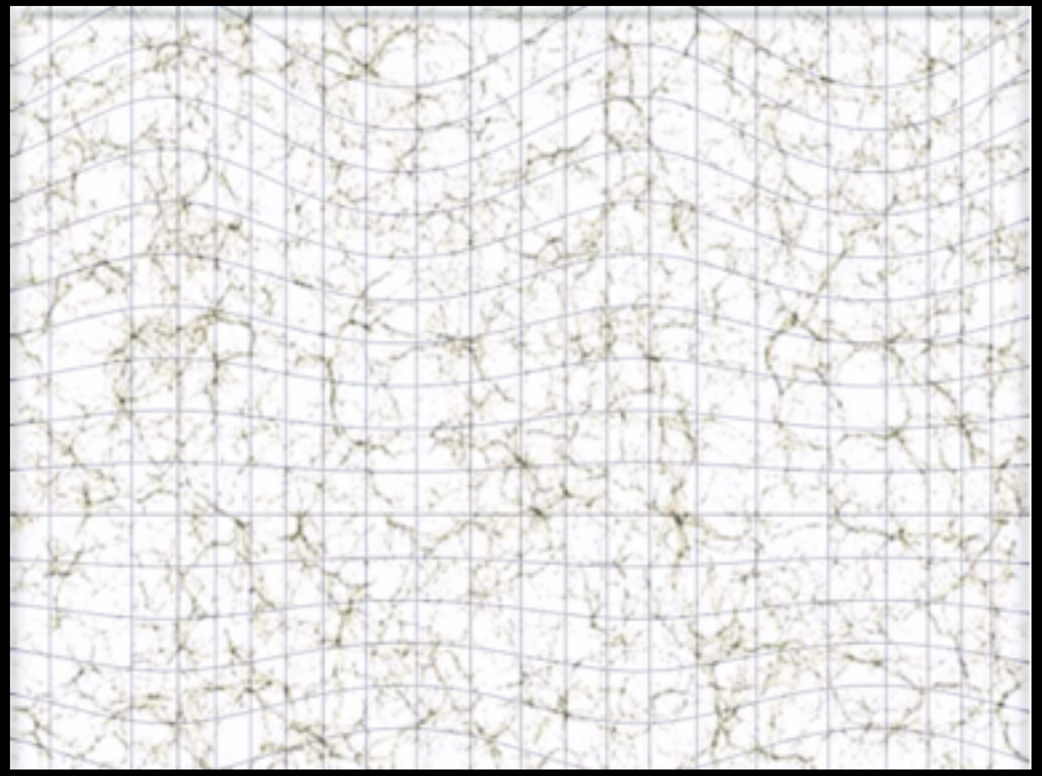
Uncovering Small-Scale Dark Matter Structures with Novel Gravitational Lensing Probes

Liang Dai
Institute for Advanced Study

Seminar @ University of Wisconsin-Madison
Feb 2020

Research Overview: Inflation & Cosmology

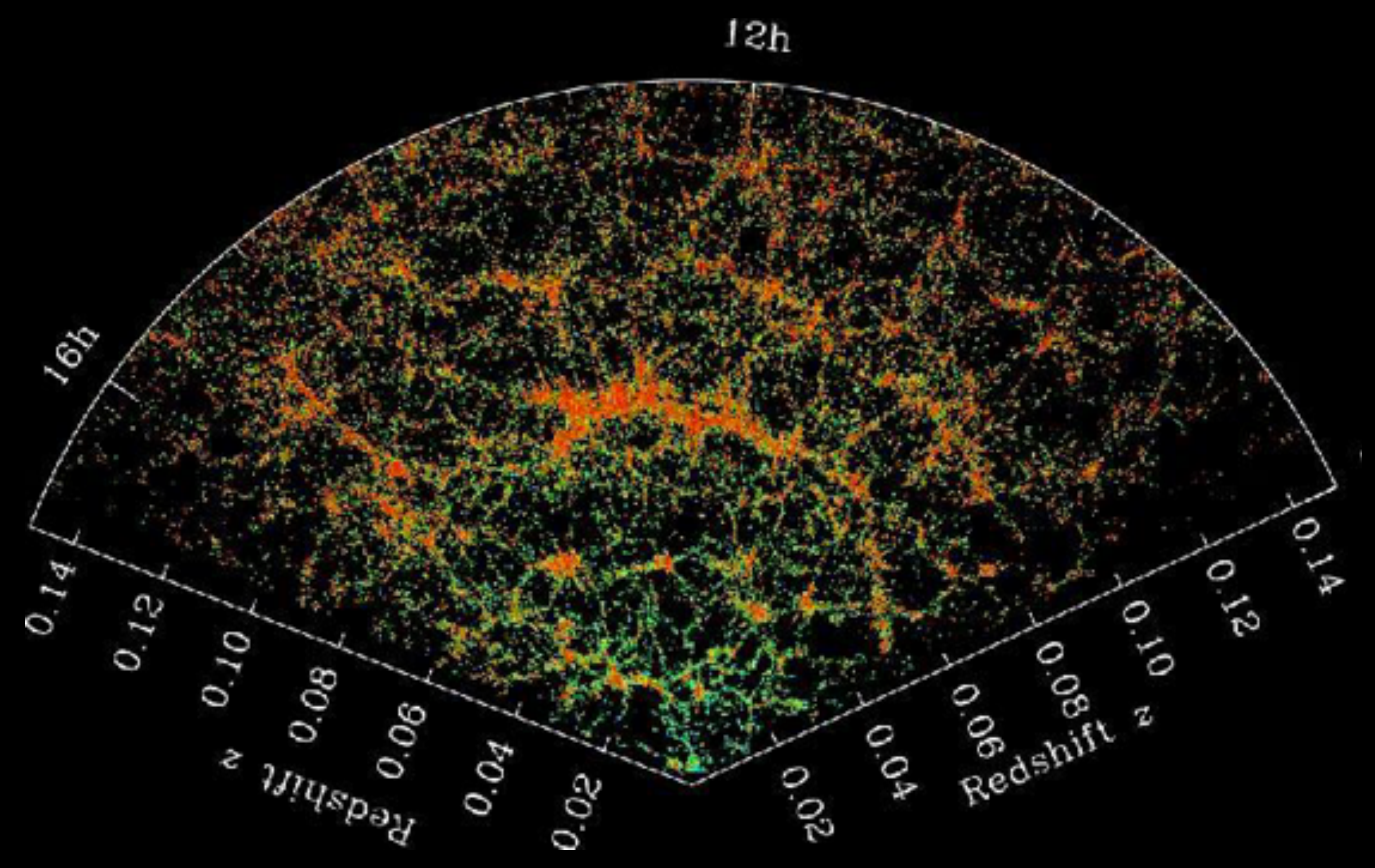
Inflationary (primordial) gravitational waves



LD, Jeong & Kamionkowski 13'a
LD, Jeong & Kamionkowski 13'b
Chluba, LD, Grin, Amin & Kamionkowski 15'

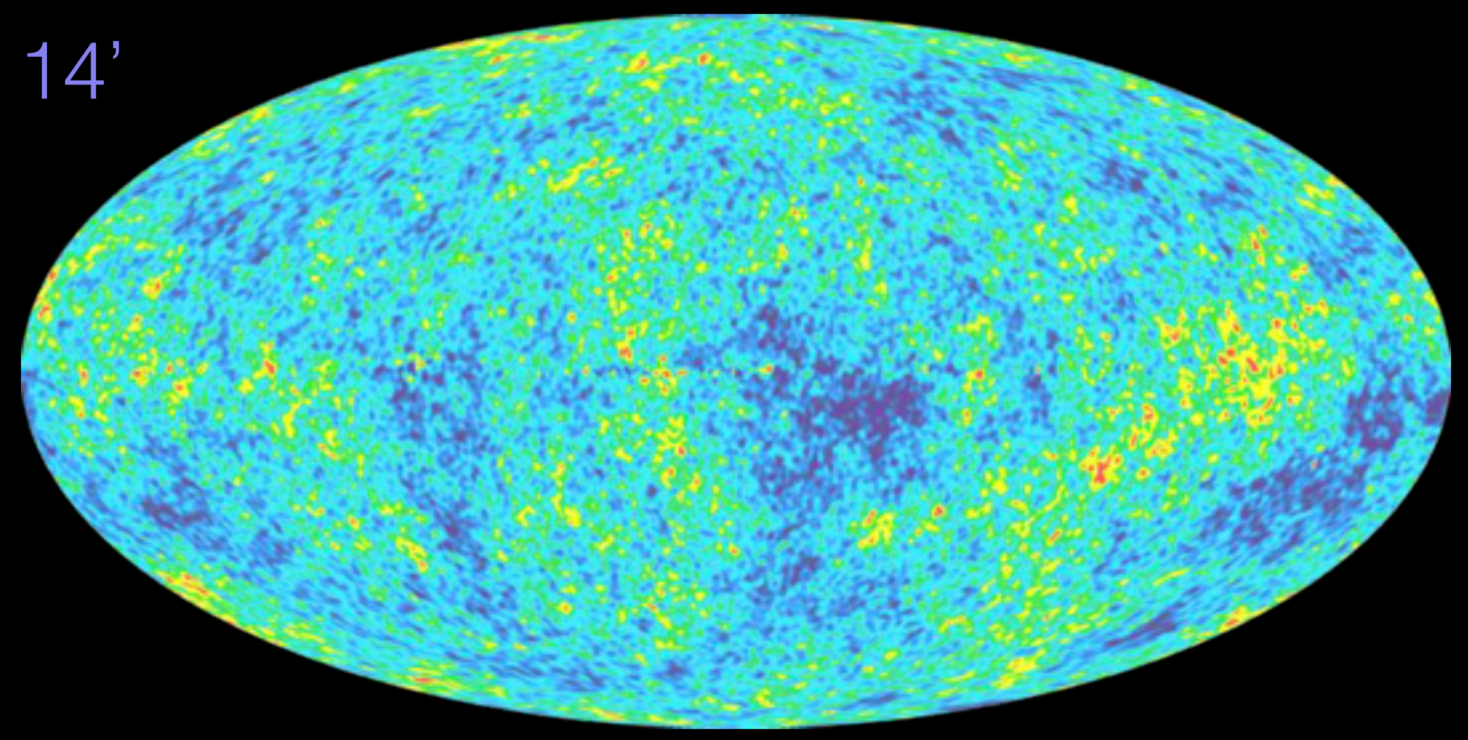
Relativistic theory of large-scale structure clustering

LD, Pajer & Schmidt 15'a
LD, Pajer & Schmidt 15'b



Cosmic Microwave Background (CMB): weak lensing, SZ effect, aberration, etc.

Jeong, Chluba, LD, Kamionkowski & Wang 14'
LD 14'
Chluba, LD & Kamionkowski 14'
Chluba & LD 14'
LD & Chluba 14'

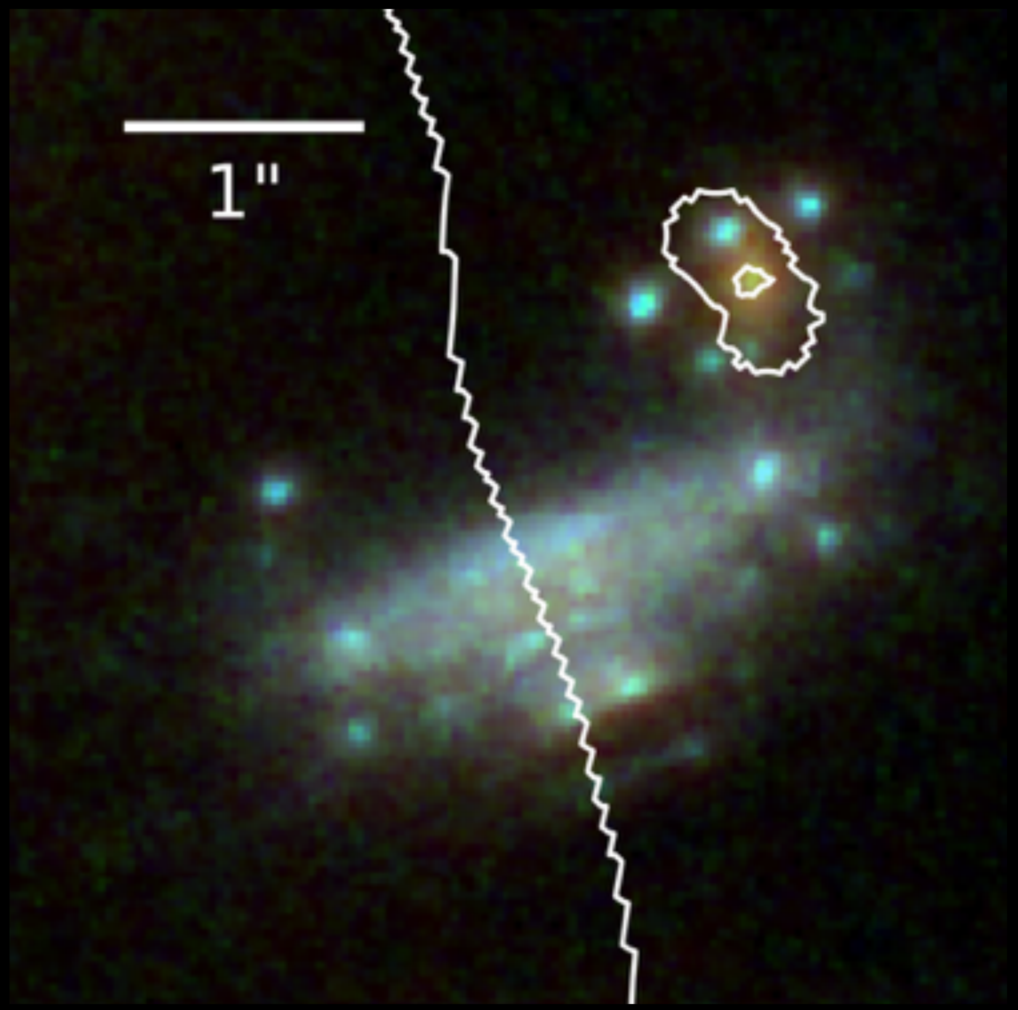


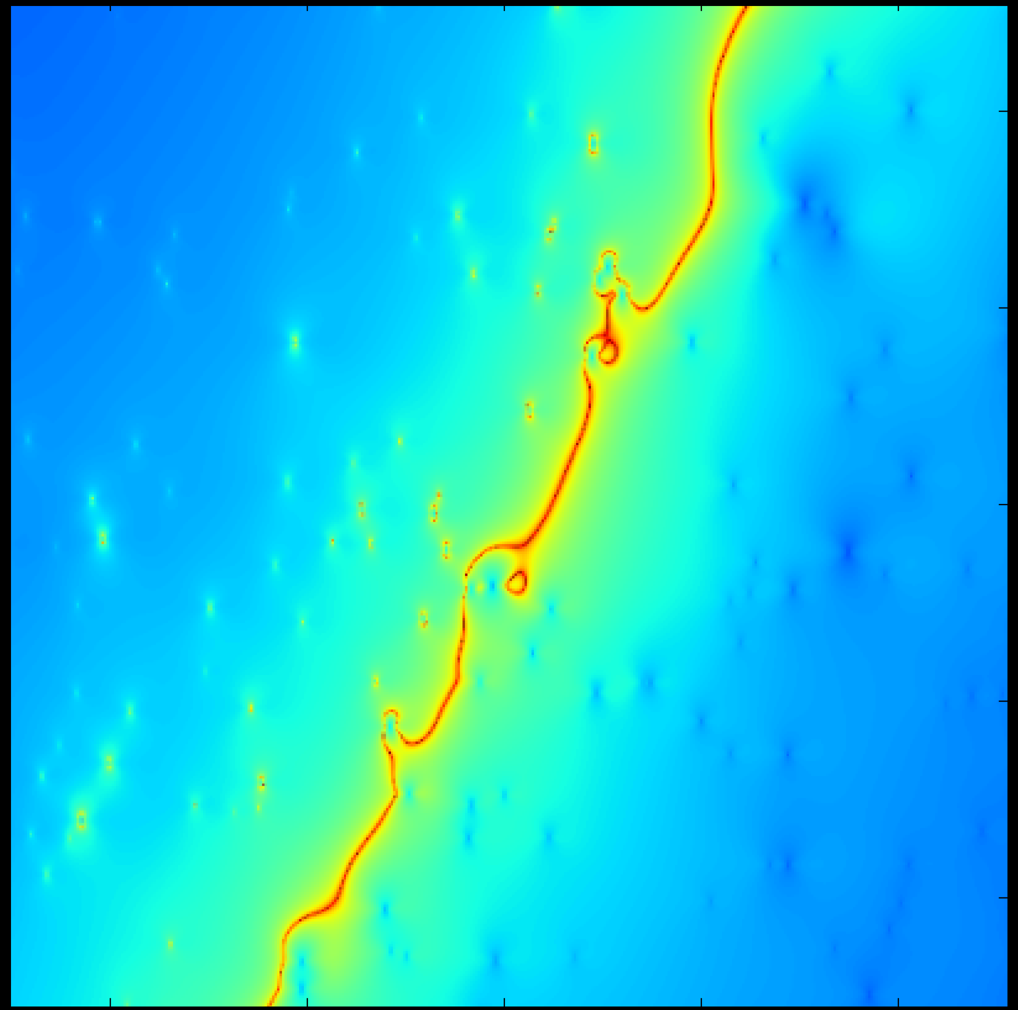
Research Overview: Gravitational Lensing & Gravitational Waves (GWs)

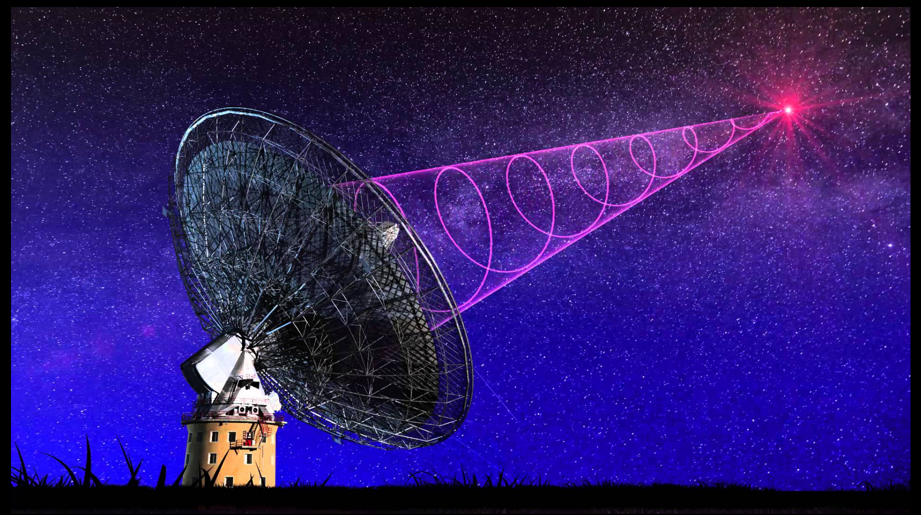
Cosmological Highly Magnified Sources

Novel and practical probes of non-luminous DM subhalos, minihalos, and compact dark matter

Venumadhav, LD & Miralda-Escudé 17'
LD, Venumadhav, Kaurov & Miralda-Escudé 18'
Kaurov, LD, Venumadhav ++ 19'
LD & Miralda-Escudé 19'
LD, Kaurov, Sharon ++ 2001.00261



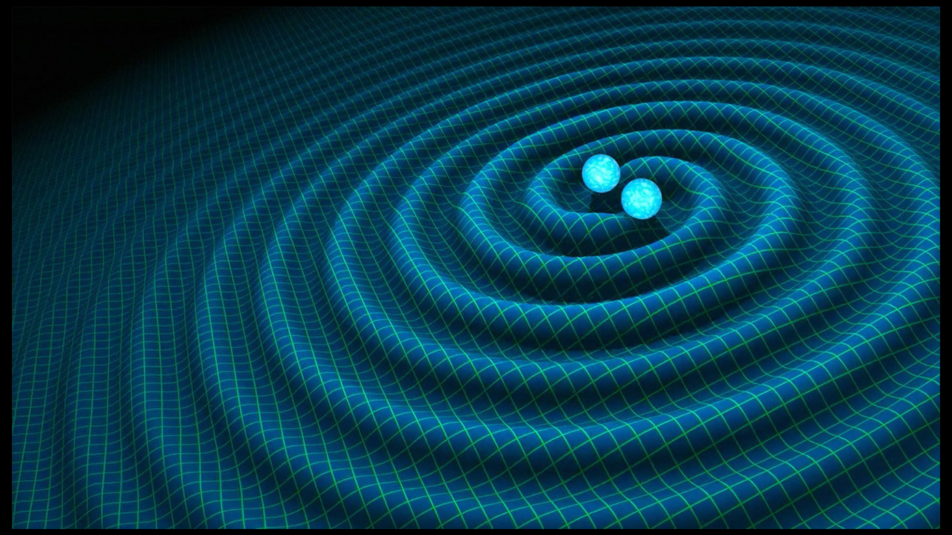




Lensing of Fast Radio Bursts (FRBs)

Muñoz, Kovetz, LD & Kamionkowski 16'
LD & Lu 17'

Lensing of Astrophysical GWs



LD, Venumadhav & Sigurdson 17'
LD & Venumadhav 1702.04724
LD, Li Zackay, Mao & Lu 18'

GW Data Analysis & Methodologies

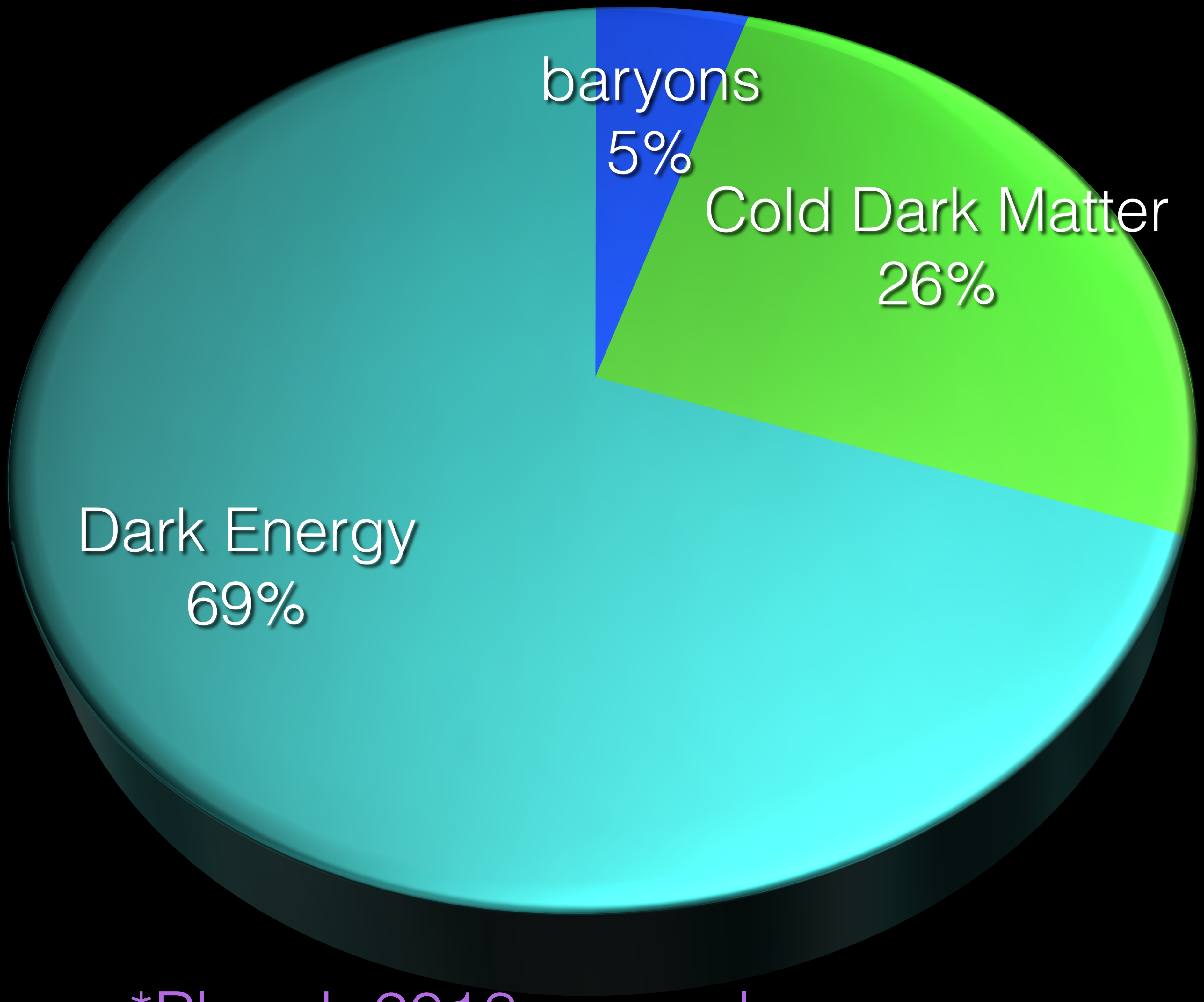
Zackay, Venumadhav, LD ++ 19'
Venumadhav, Zackay, Roulet ++ 19'
Roulet, LD, Venumadhav ++ 19'
Zackay, LD & Venumadhav 1910.09528
Zackay, LD & Venumadhav 1806.08792
LD, Zackay, & Venumadhav 1806.08793
Radice & LD 19'

Outline

- Introduction
- Highly magnified cosmological sources
- Applications of highly magnified sources: Probing small-scale dark matter structures
- Lensing of gravitational waves
- Conclusion

Dark Matter in the Universe

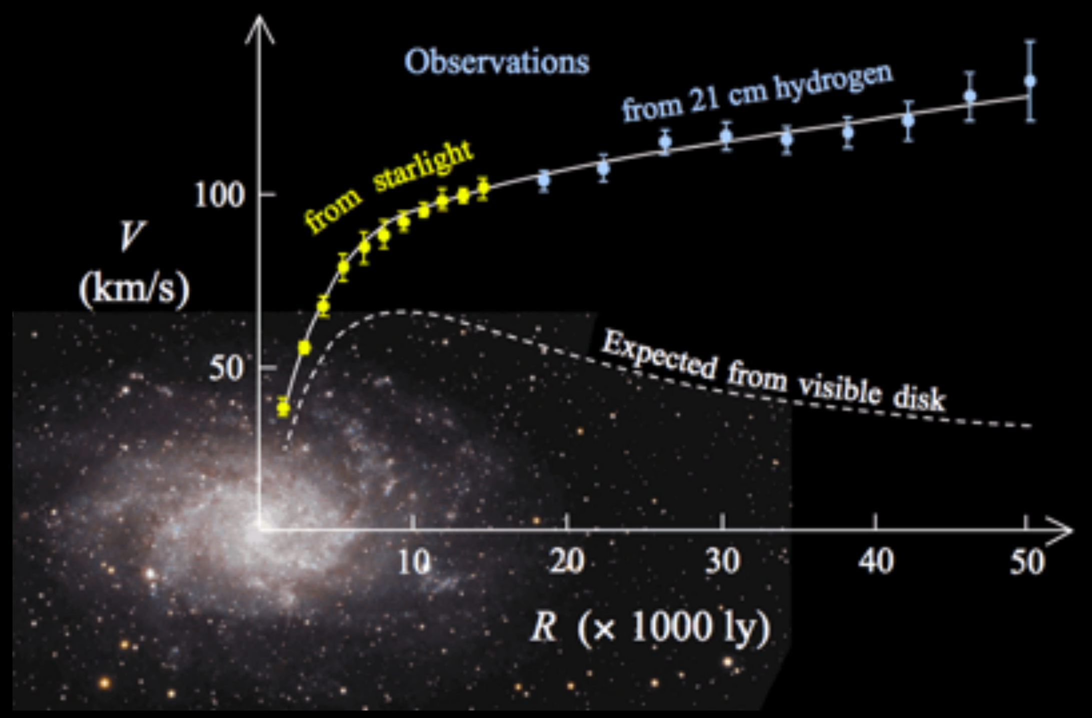
Cosmic Energy Budget



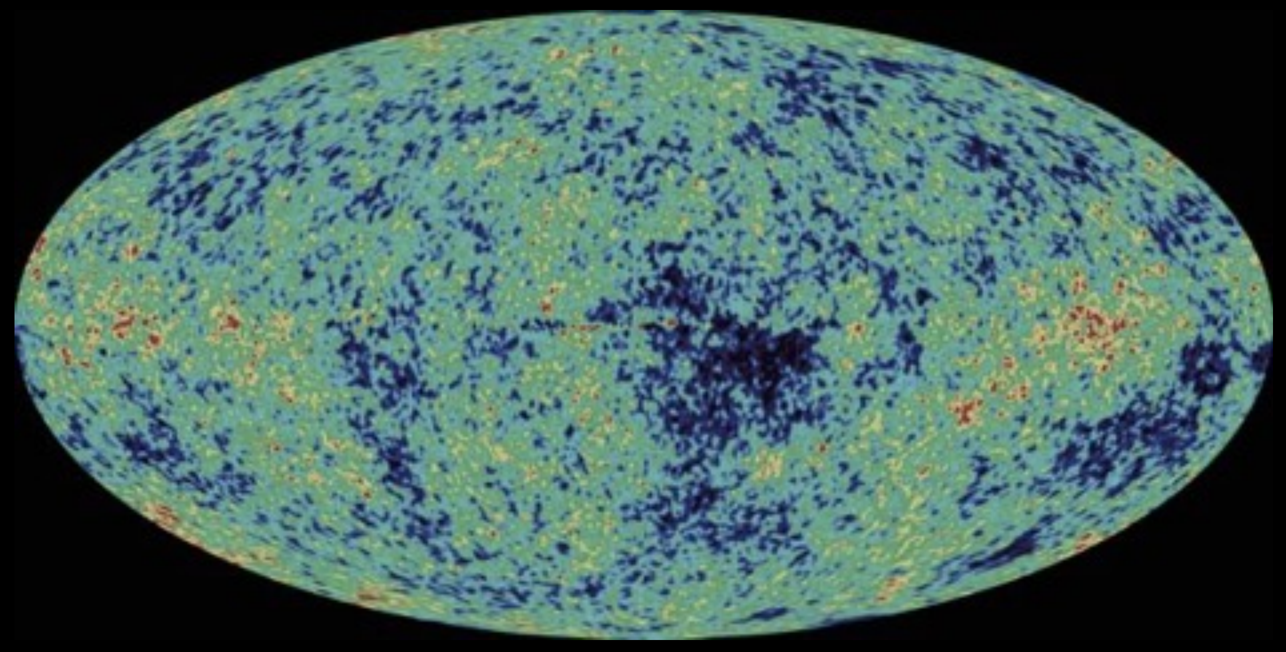
*Planck 2018 cosmology

… and trace amount of photons and neutrinos …

intracluster dynamics



galaxy rotation curves

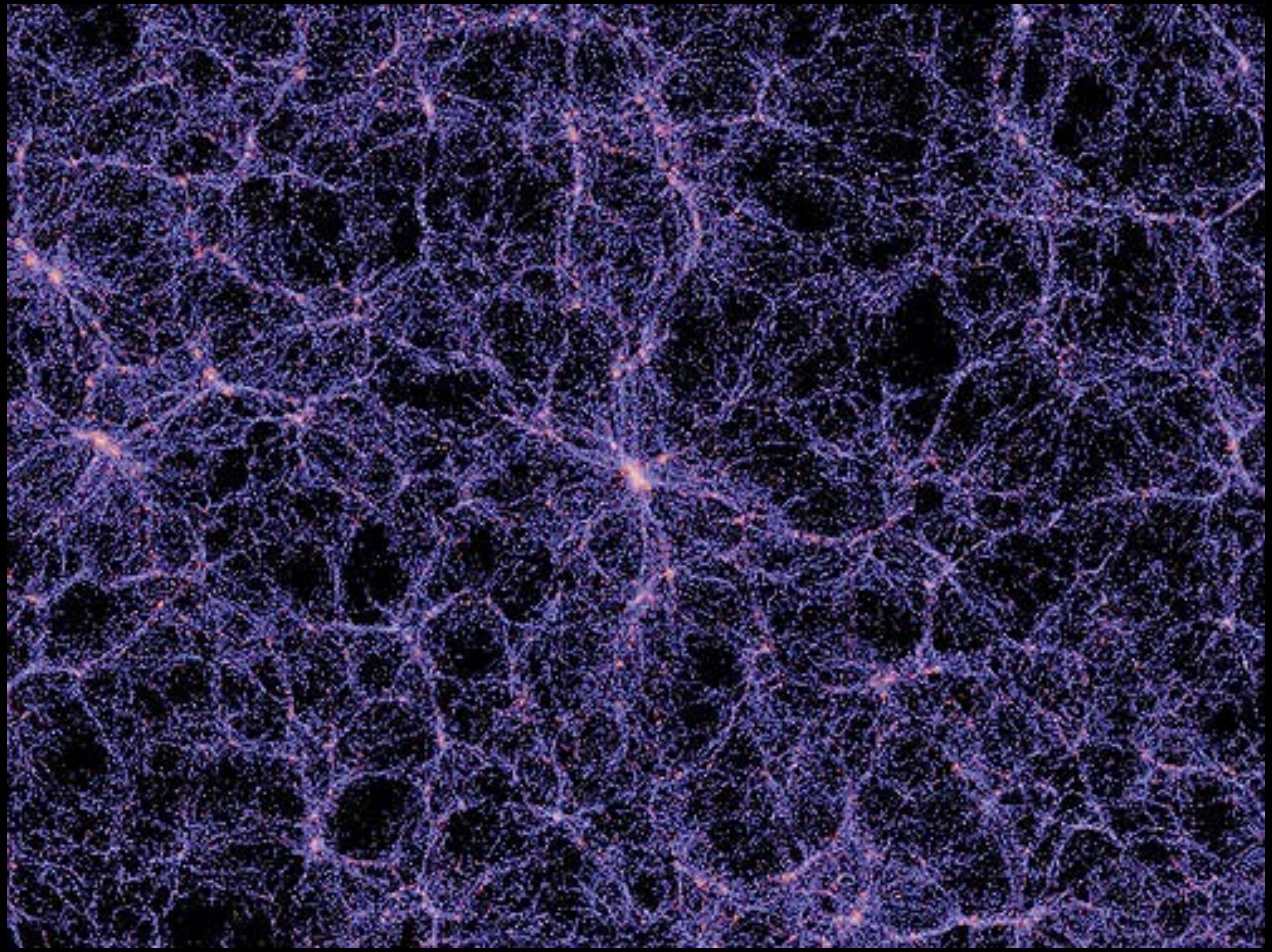


acoustic peaks in CMB power spectrum

Dark Matter Substructure

On large scales, microscopic details not important:

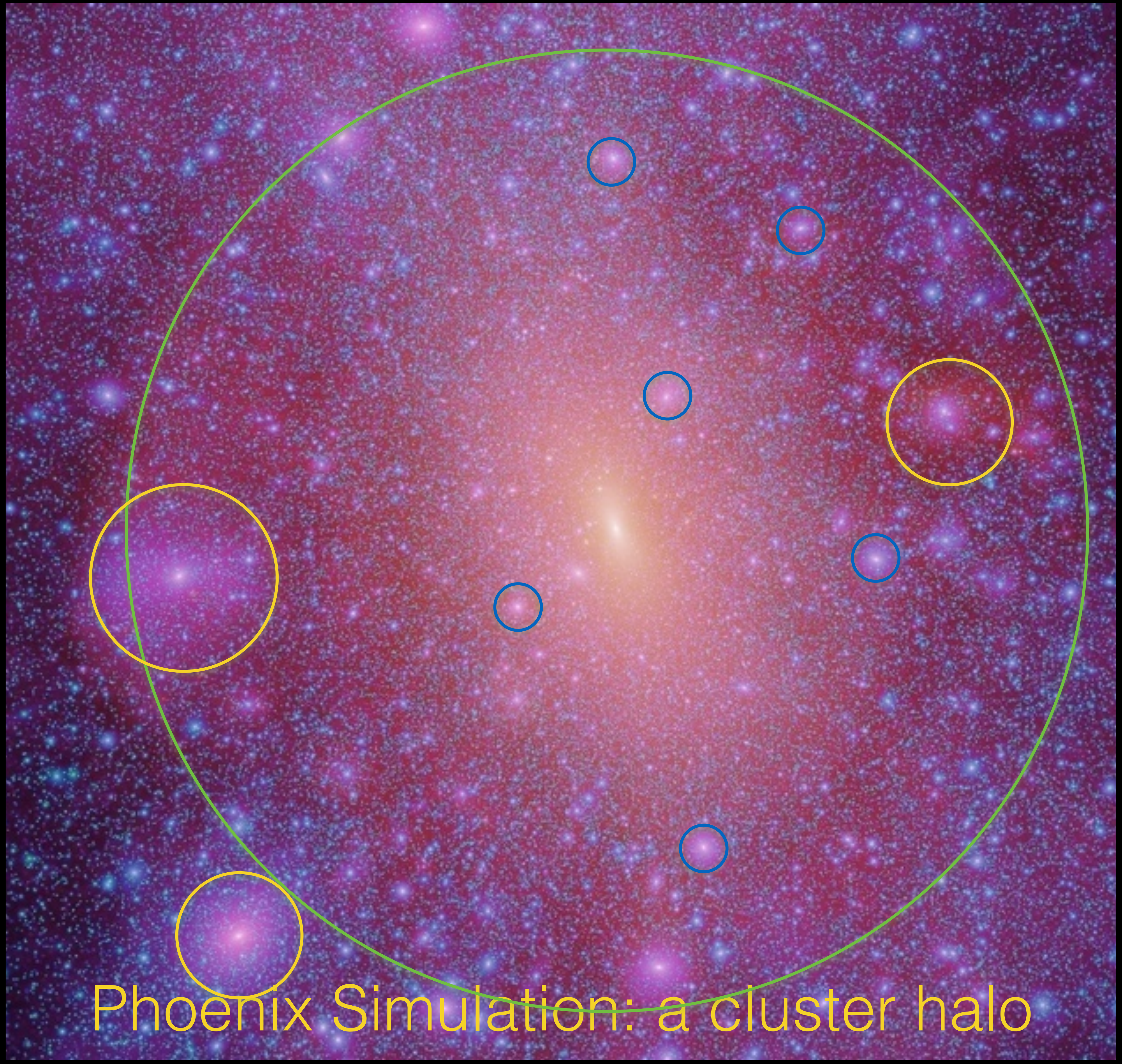
non-relativistic matter that self-gravitates



Millennium Simulation

Collapsed objects called halos host galaxies/clusters

Are there small (sub-)halos that host few or no stars?



Phoenix Simulation: a cluster halo

Different Possibilities on Small Scales

We are still not sure about the underlying nature of the DM …

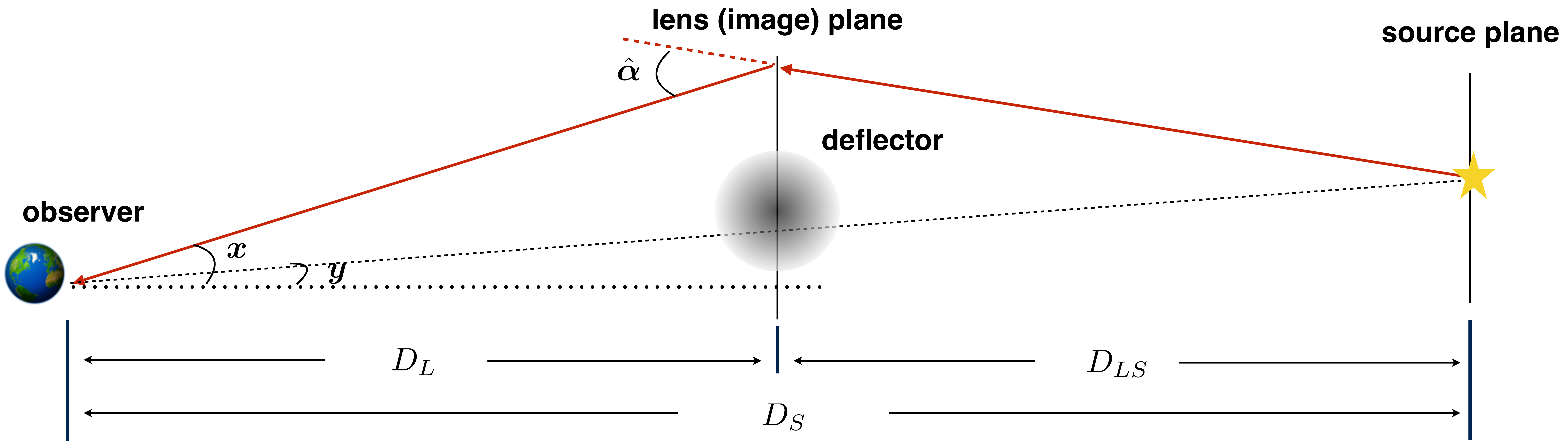
Cold Dark Matter ?
WIMP? axion? …

Warm Dark Matter ?
massive neutrinos? …

Fuzzy Dark Matter ?
ultralight scalar particles?
(from string theory)

Compact Objects ???
black holes? QCD matter?

Geometric Lensing



lens equation $$\boldsymbol{y} = \boldsymbol{x} - \frac{D_{LS}}{D_S}\hat{\boldsymbol{\alpha}}(\boldsymbol{x}) = \boldsymbol{x} - \hat{\boldsymbol{\alpha}}(\boldsymbol{x})$$

image deformation $$\frac{\partial \boldsymbol{y}}{\partial \boldsymbol{x}} = \begin{bmatrix} 1-\kappa-\gamma_1 & -\gamma_2 \\ -\gamma_2 & 1-\kappa+\gamma_1 \end{bmatrix}$$

(signed) magnification factor $$\mu = 1/\left[(1-\kappa)^2 - (\gamma_1^2+\gamma_2^2)\right]$$

κ is **convergence** and is proportional to lens surface density

γ_1 and γ_2 are image **shear**

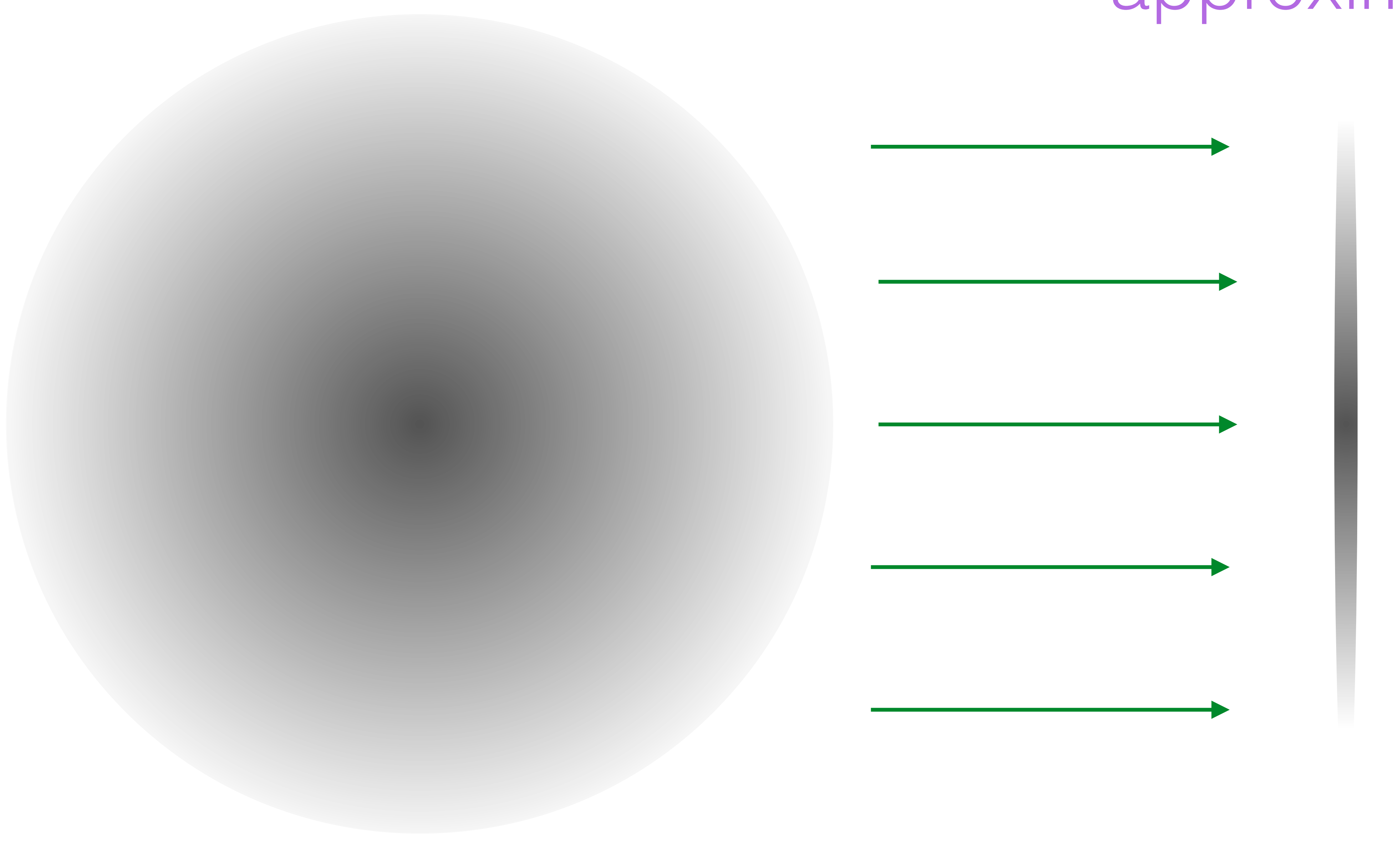
Extended Lens

Critical lens surface density

$$\Sigma_c \sim \frac{1}{4\pi\, G\, D}$$

extended lens

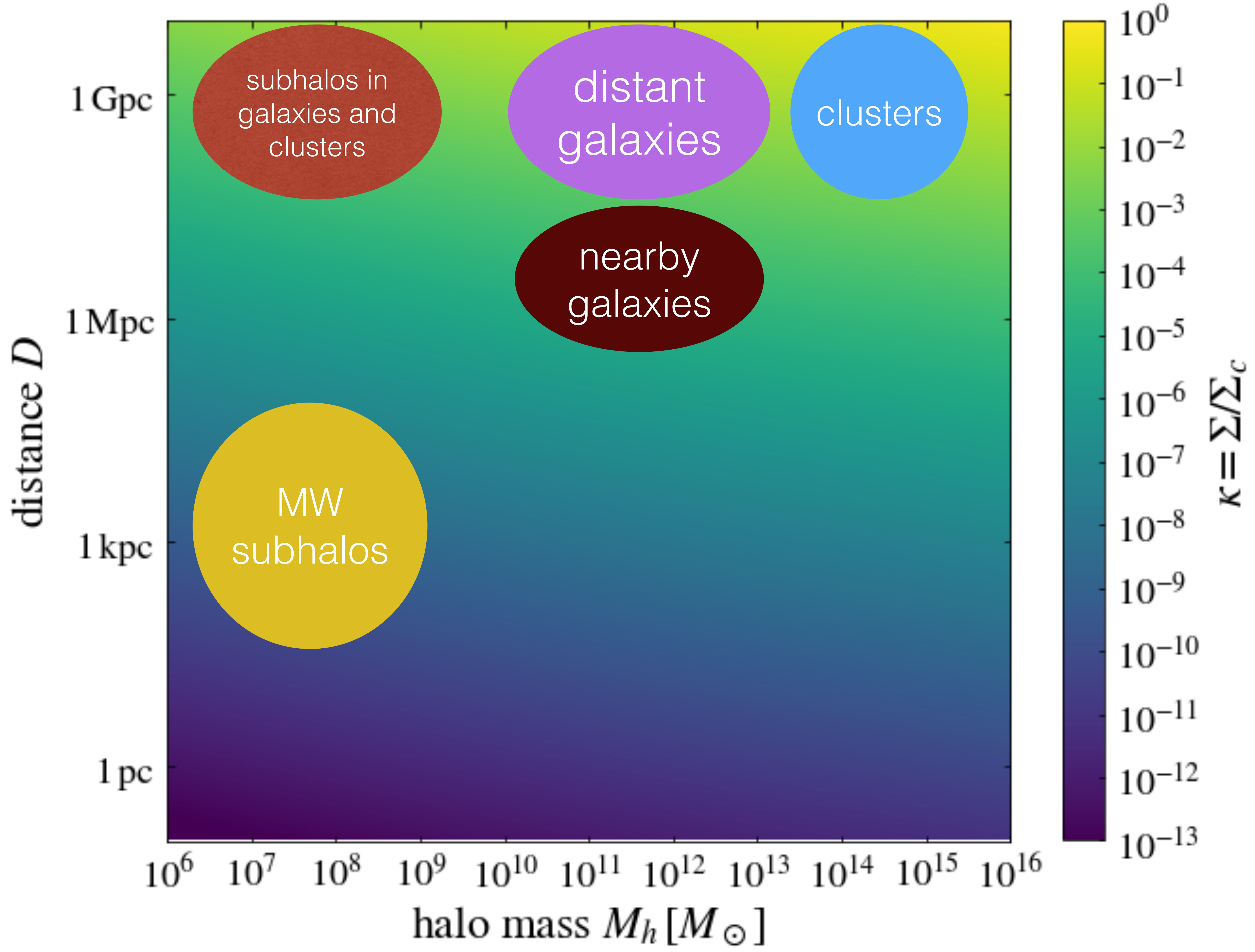
“thin sheet” approximation



“collapse” along the line of sight

Lensing convergence

$$\kappa = \Sigma/\Sigma_c$$



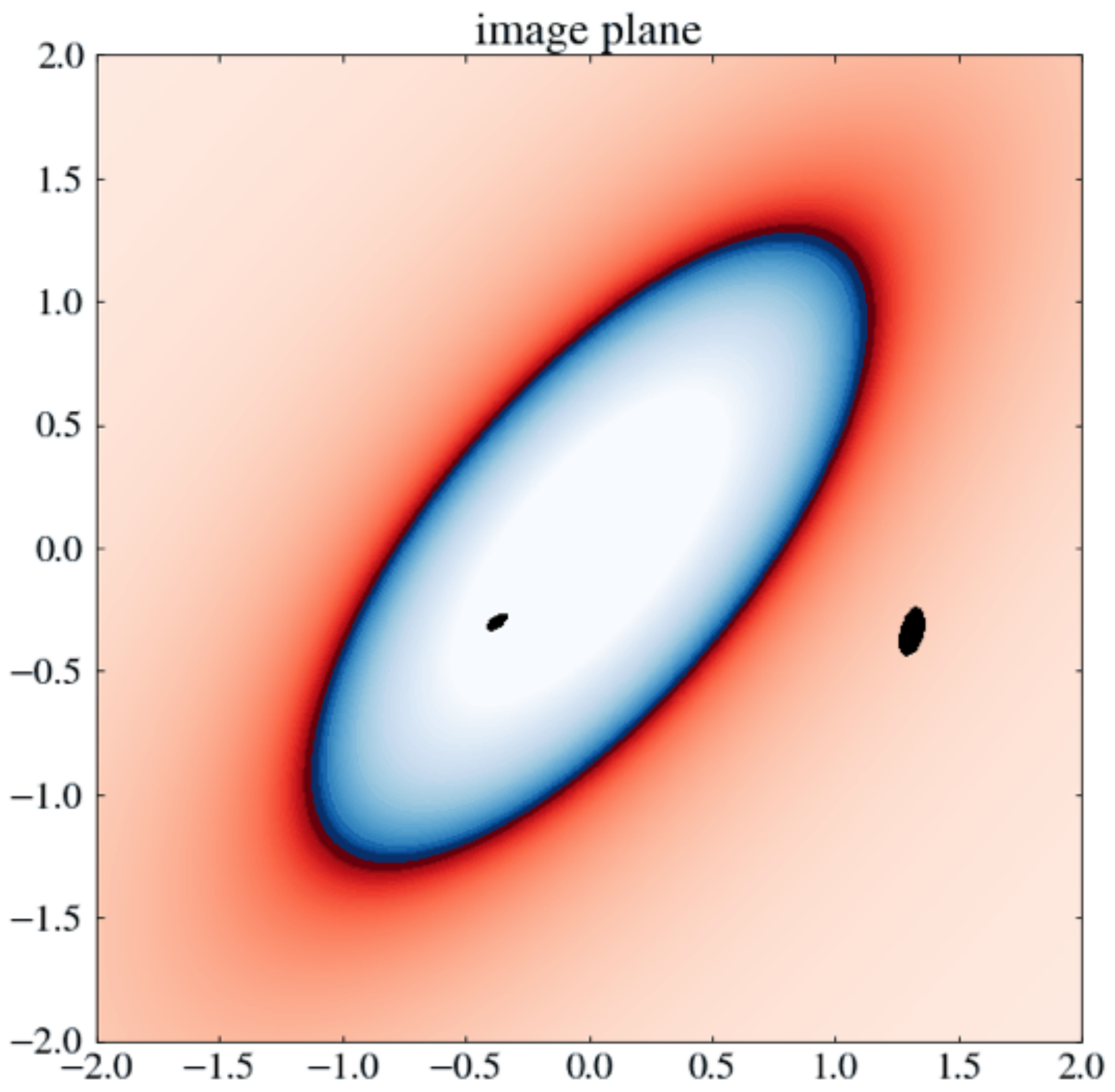
Difficult to be super-critical !

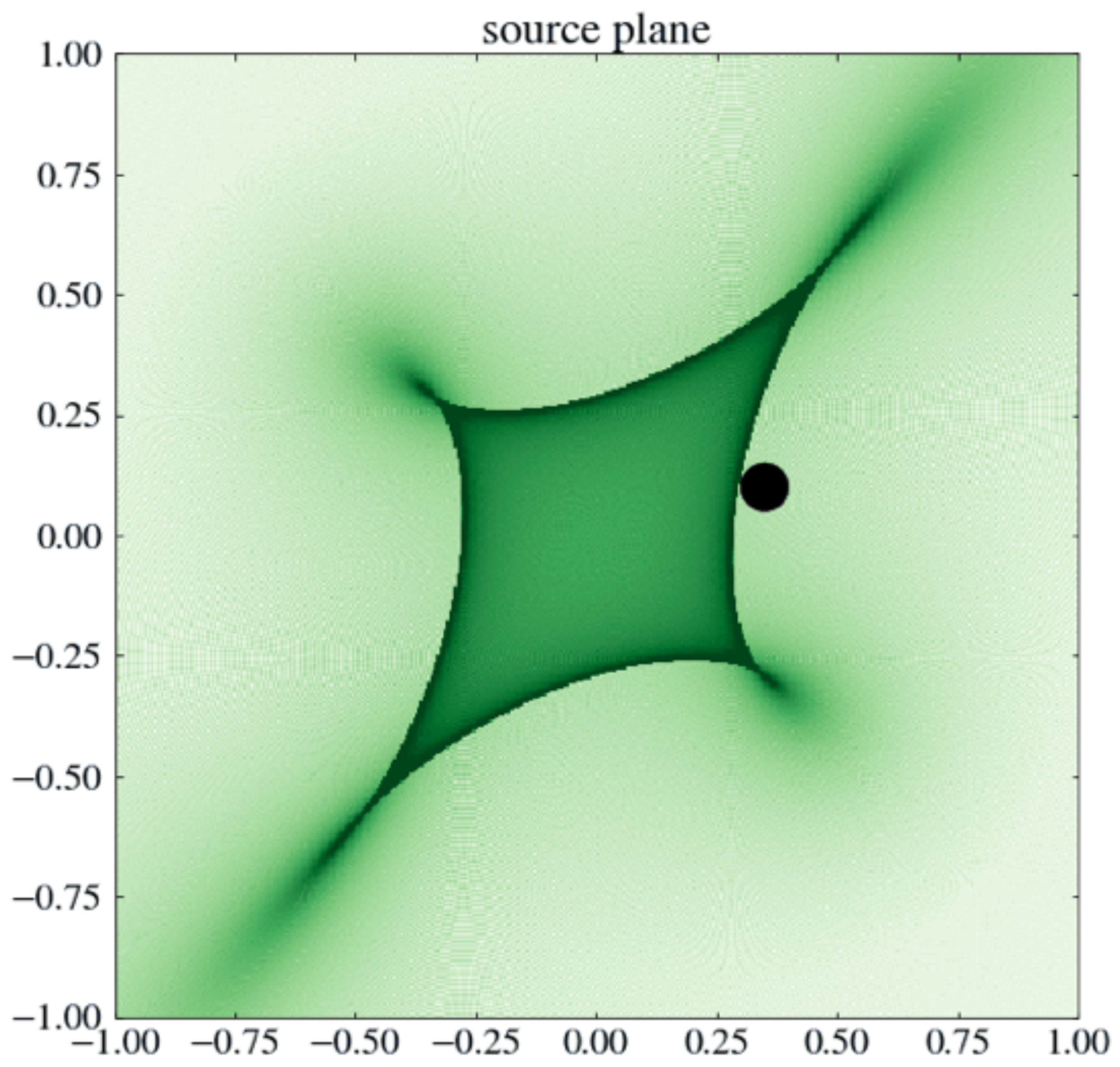
Caustics & Critical Curves

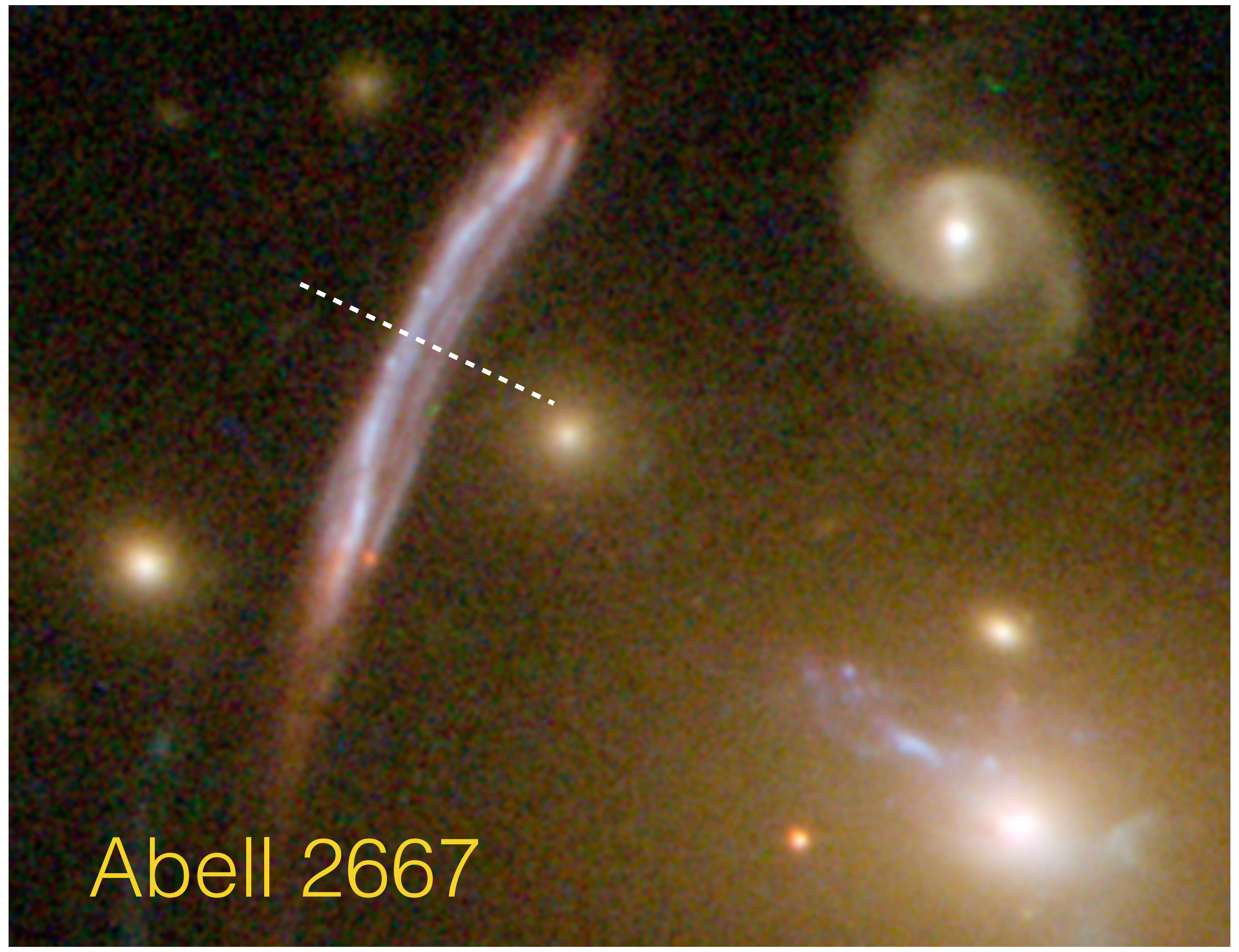
$$\boldsymbol{y} = \boldsymbol{y}(\boldsymbol{x}) = \boldsymbol{x} - \boldsymbol{\alpha}(\boldsymbol{x})$$

Change in the **topology** of images:
It is studied using catastrophe theory in mathematics

(e.g. Blandford & Narayan 1986)





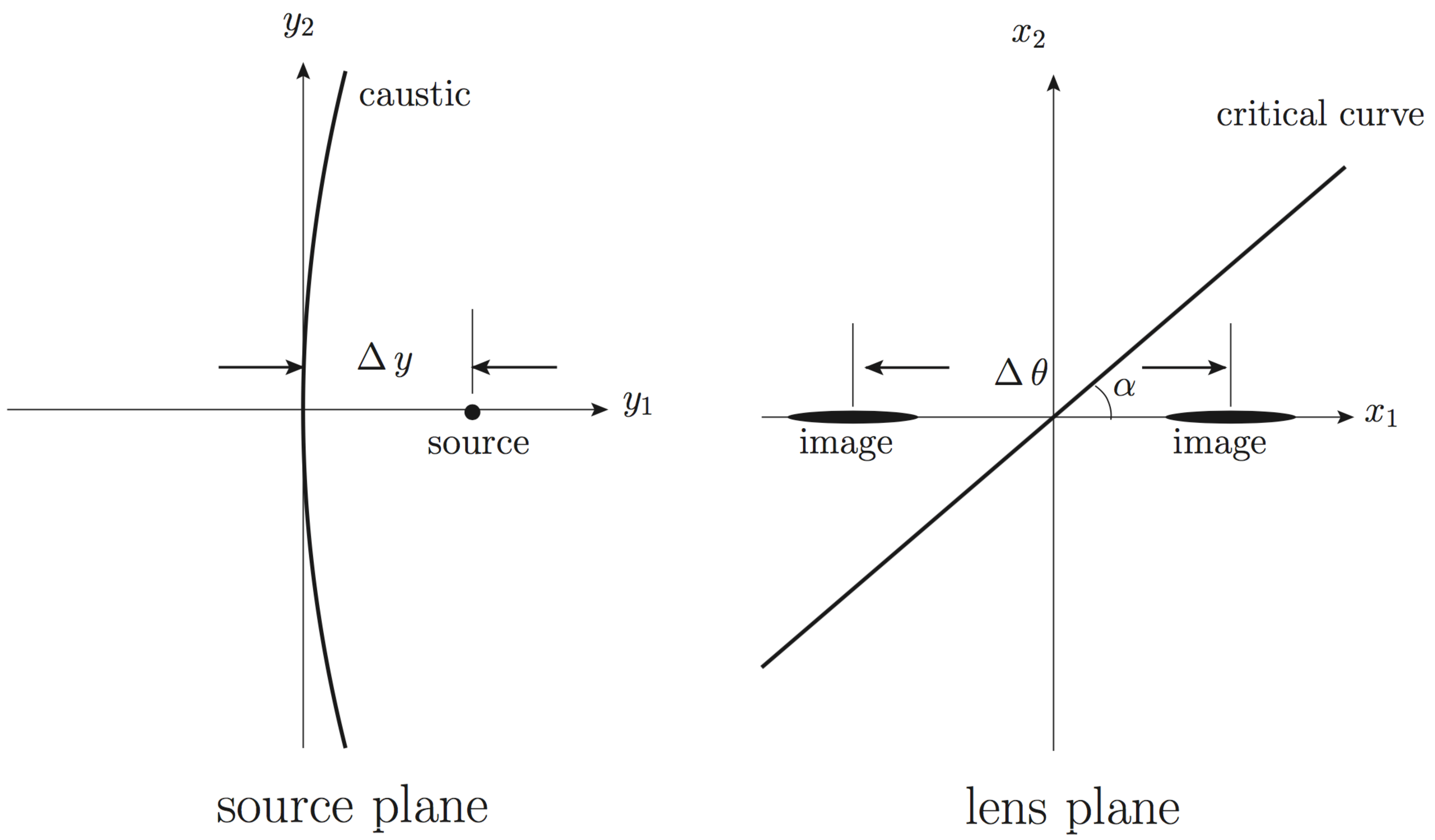


An example of lensed galaxy

Outline

- Introduction
- Highly magnified cosmological sources
- Applications of highly magnified sources: Probing small-scale dark matter structures
- Lensing of gravitational waves:
- Conclusion

Caustic Transit of Compact Sources



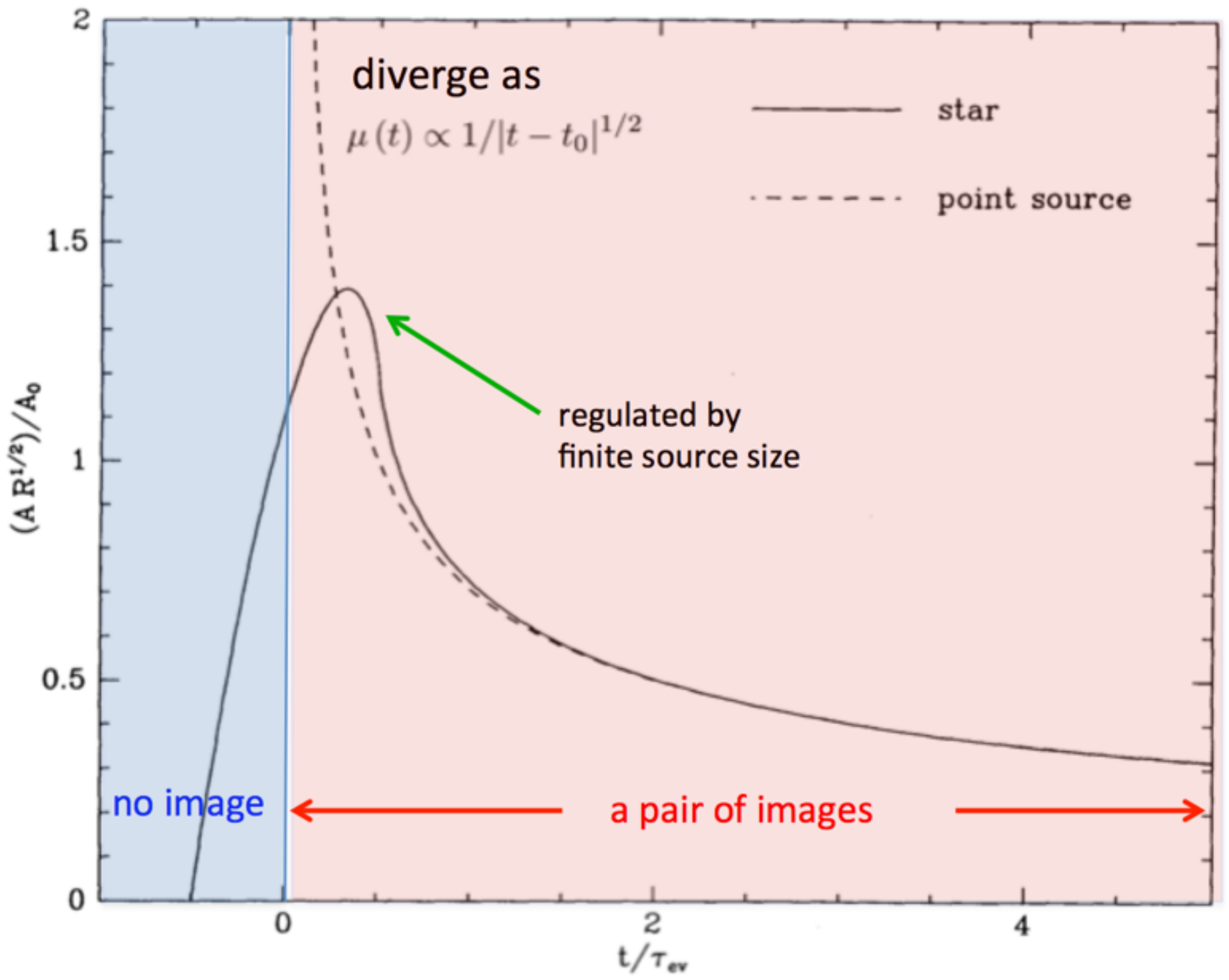
$$\mu \sim \theta_C / \Delta\theta$$

$$\Delta\theta \sim 10 - 100\,\mathrm{mas}$$

$$\theta_C \sim 10''$$

$$\mu \sim \frac{\theta_C}{\Delta\theta} \sim \mathrm{few} \times 10^{2-3}$$

Miralda-Escudé 91'

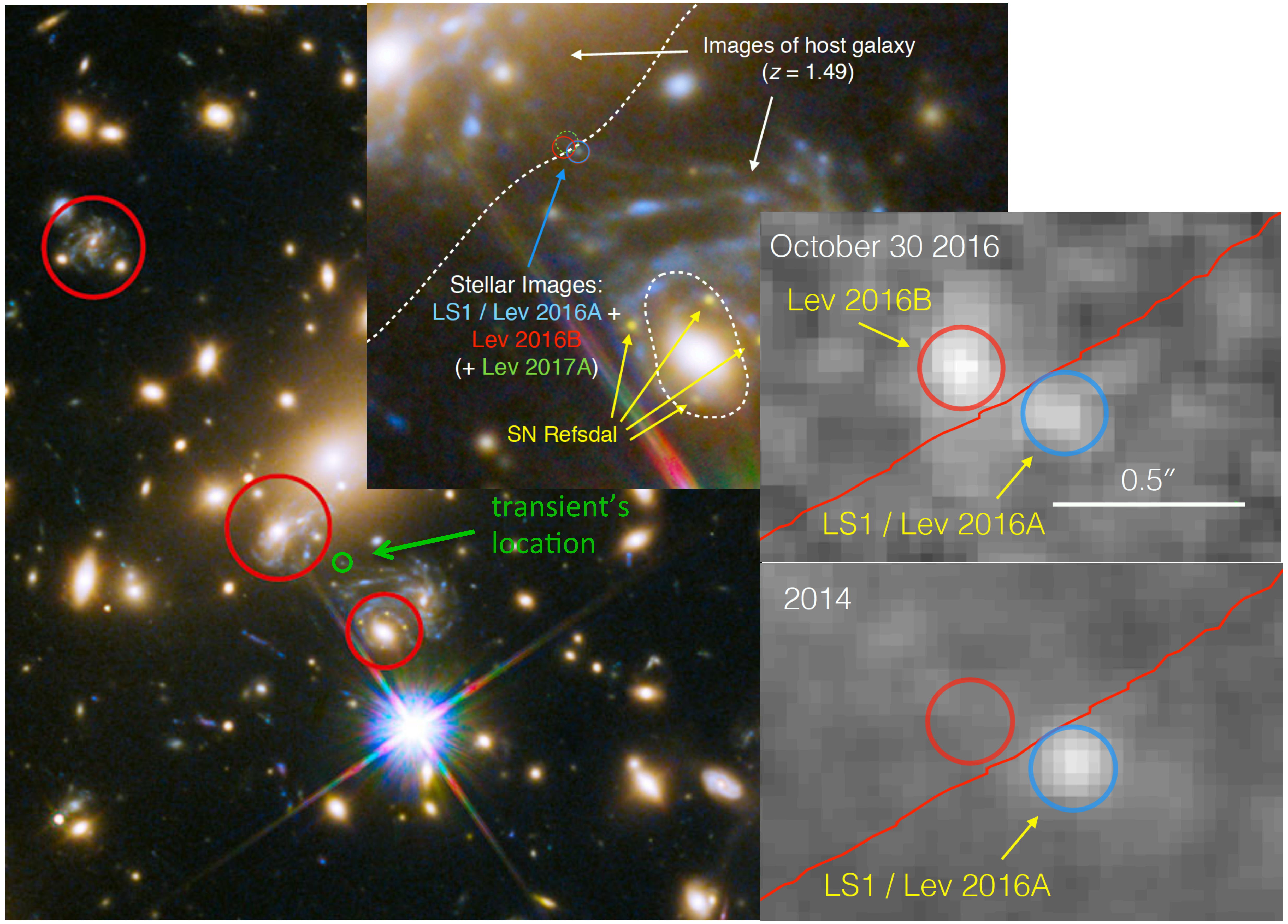


finite source size $\mu_{\rm pk} \propto R_S^{1/2}$

wave diffraction $\mu_{\rm pk} \propto \lambda^{-1/3}$

Caustic Transiting Stars Detection by HST

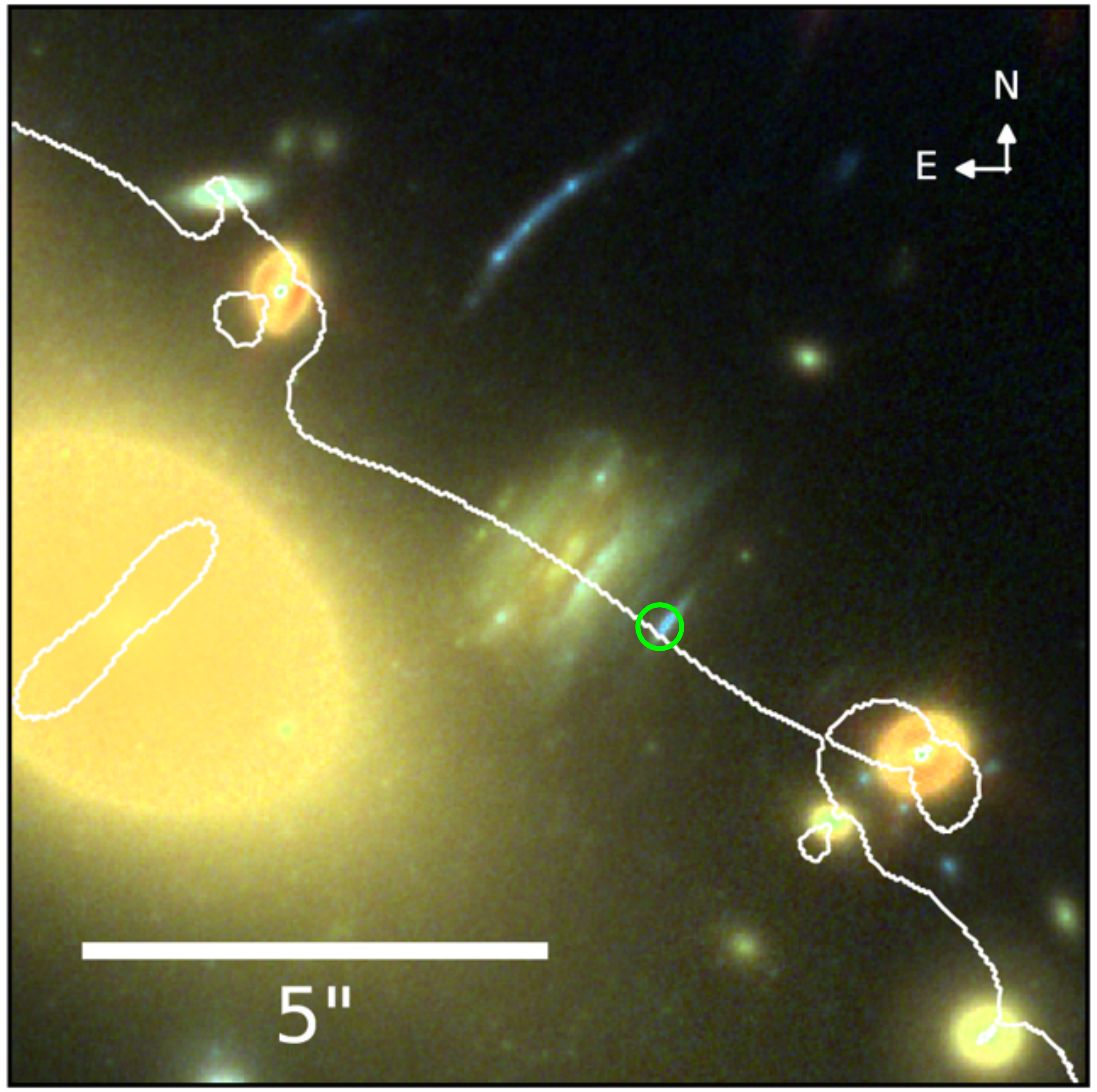
Kelly++ 17'



MACS J1149.5+2223 (z_S=1.49, z_L=0.544)

Chen++ 19'

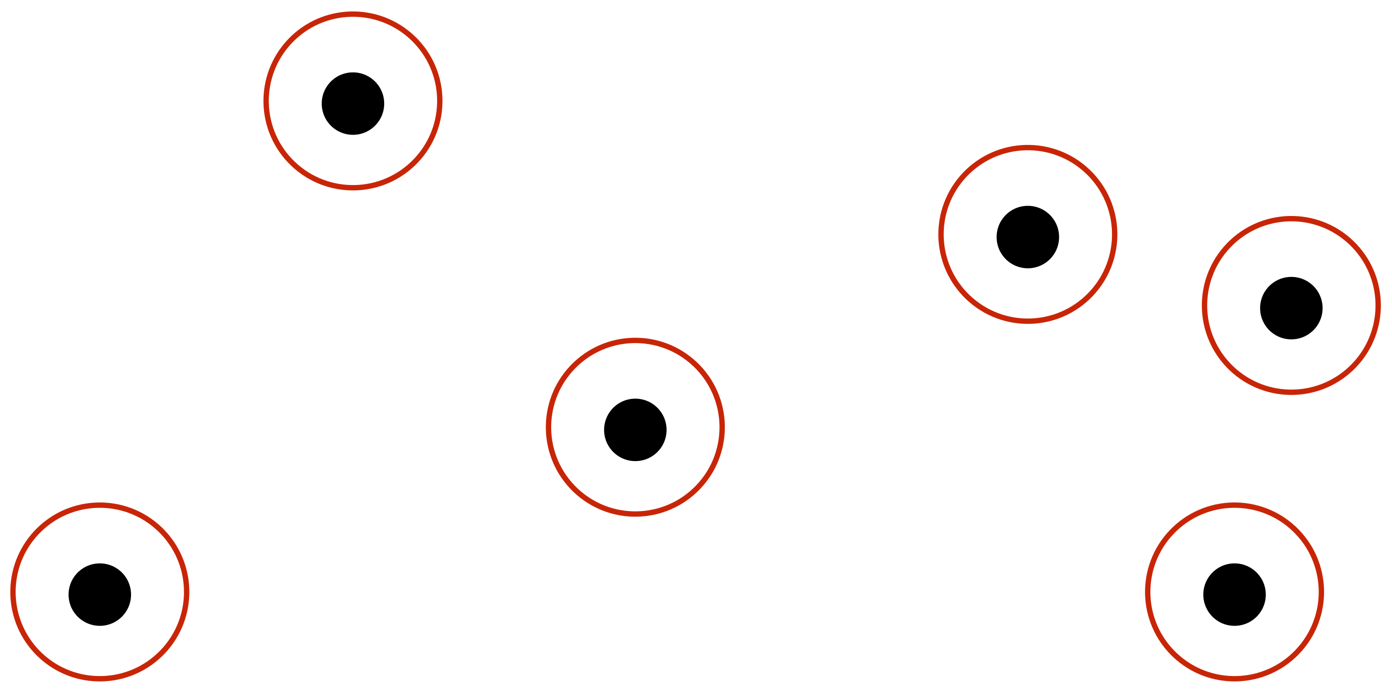
Kaurov, LD, Venumadhav++ 19'



MACS J0416.1-2403 (z_S=0.94, z_L=0.397)

Stellar Microlenses Near Critical Curve

Isolated microlenses



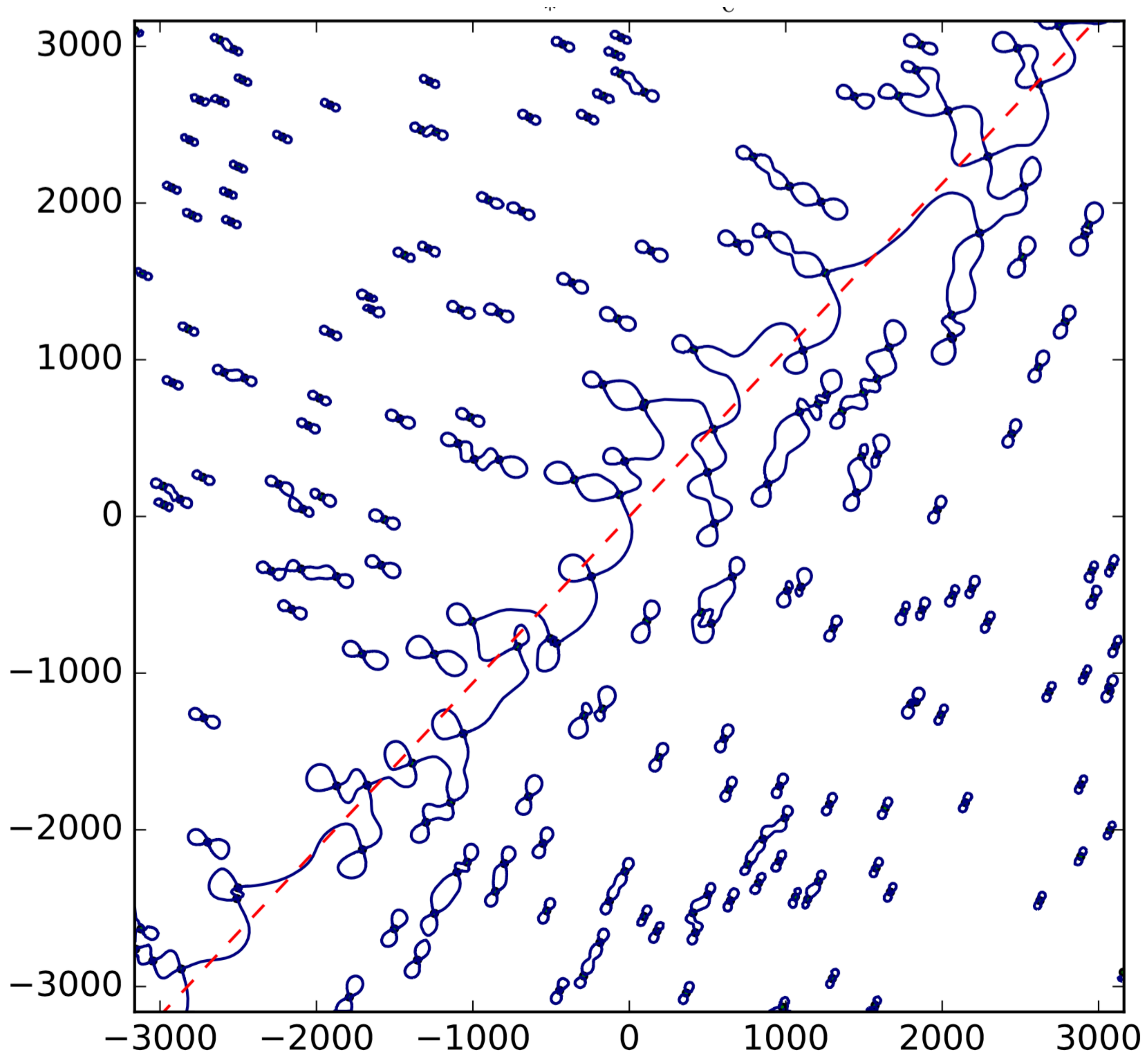
$$\theta_E = \left[\frac{4\,G\,M}{c^2}\,\frac{D_{LS}}{D_L\,D_S} \right]^{1/2} \sim 10^{-6}\,\mathrm{arcsec}$$

Nominal microlensing optical depth is small for intracluster stars

$$\kappa_{\rm ICS} \sim \mathrm{few} \times 10^{-3}\text{–}10^{-2}$$

Microlenses superimposed near a macro critical curve

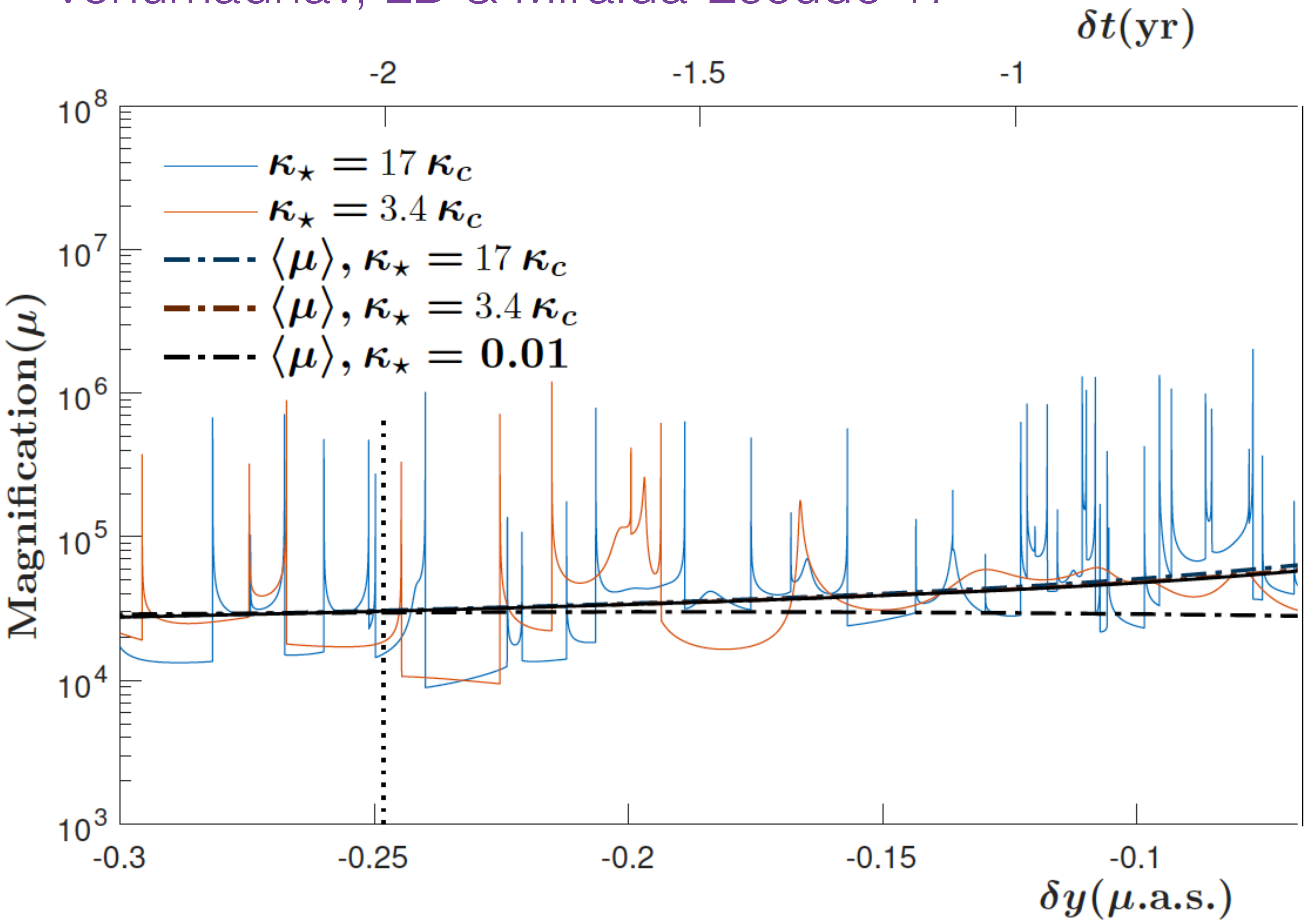
Venumadhav, LD & Miralda-Escudé 17'
Diego++ 17'; Oguri++ 18'



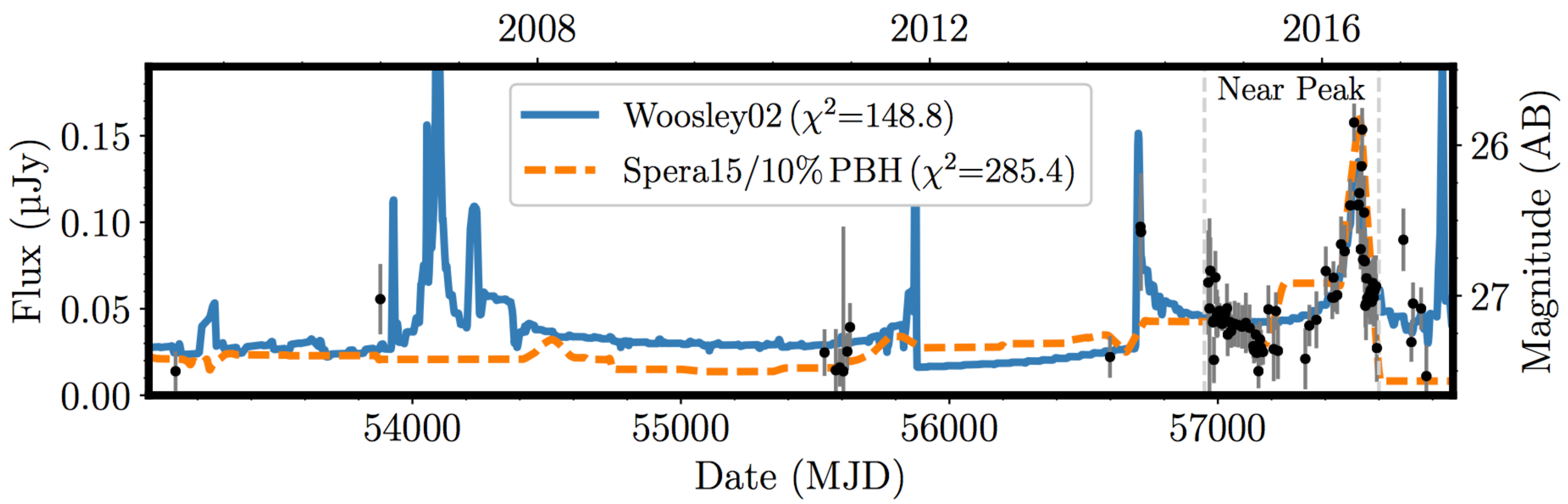
Strongly coupled microlensing: macro critical curve disrupted !

Microlensing Flux Variability

Venumadhav, LD & Miralda-Escudé 17’

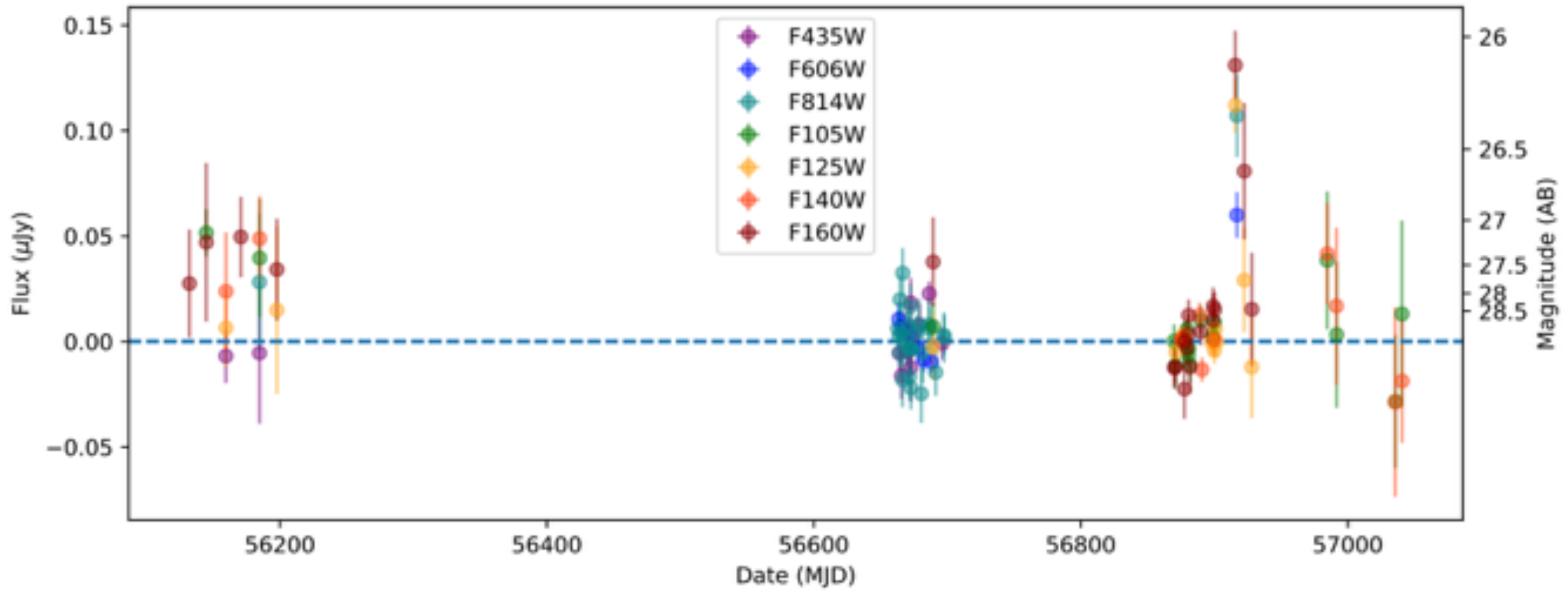


Kelly++ 17’ MACS J1149.5+2223



Chen++ 19’ MACS J0416.1-2403

Kaurov, LD, Venumadhav++ 19’

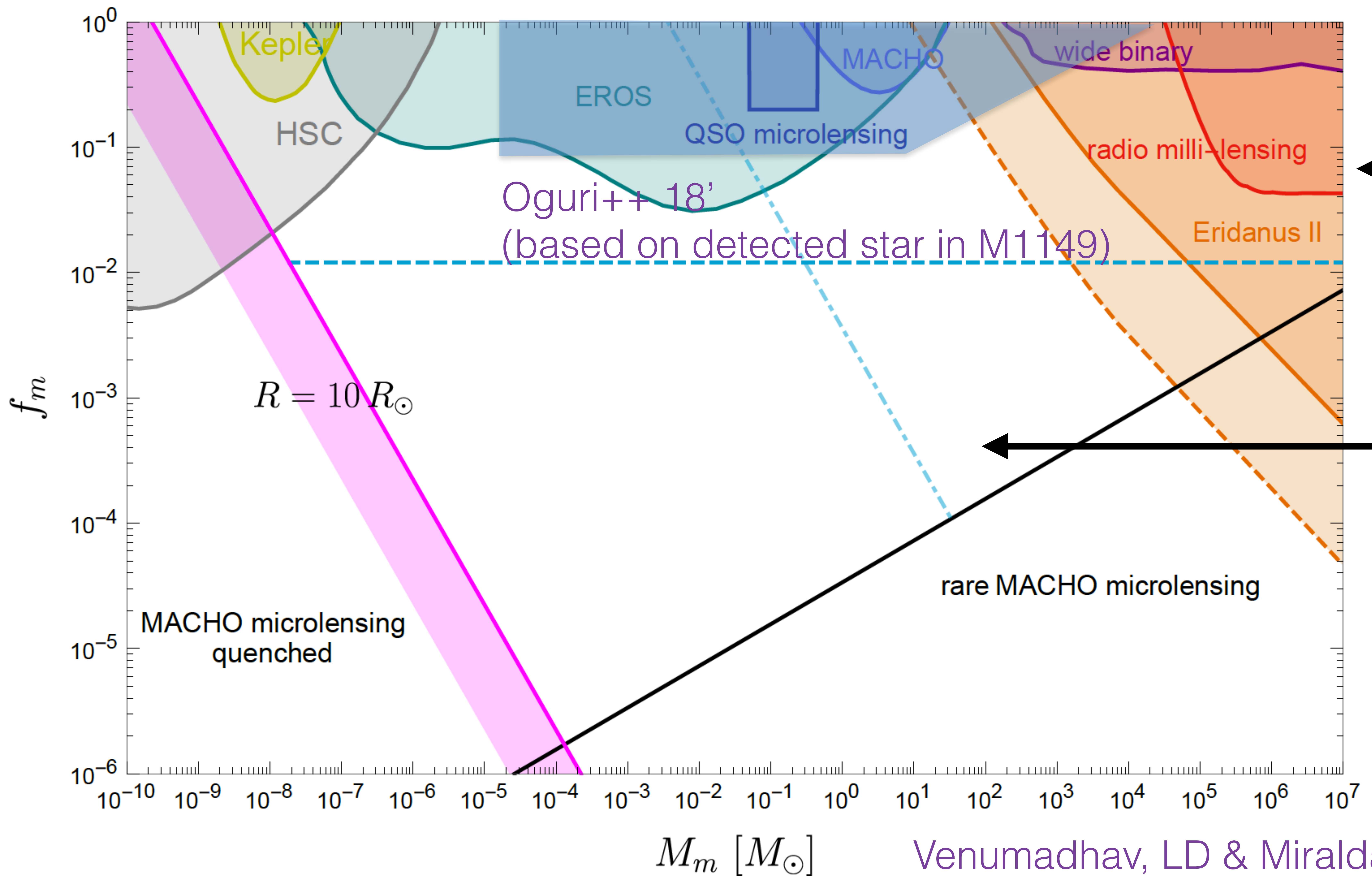


Phenomenological implications

[1] Enhanced detectability: intermittent **micro caustic crossings** with peak magnifications $\boldsymbol{\mu_{pk} \sim 10^4}$

[2] Ample opportunity to follow-up: micro caustic transits **one to few times per year**; variability persists for **tens of thousands of years**.

Sensitive Probe of Compact Dark Matter



Venumadhav, LD & Miralda-Escudé 17'

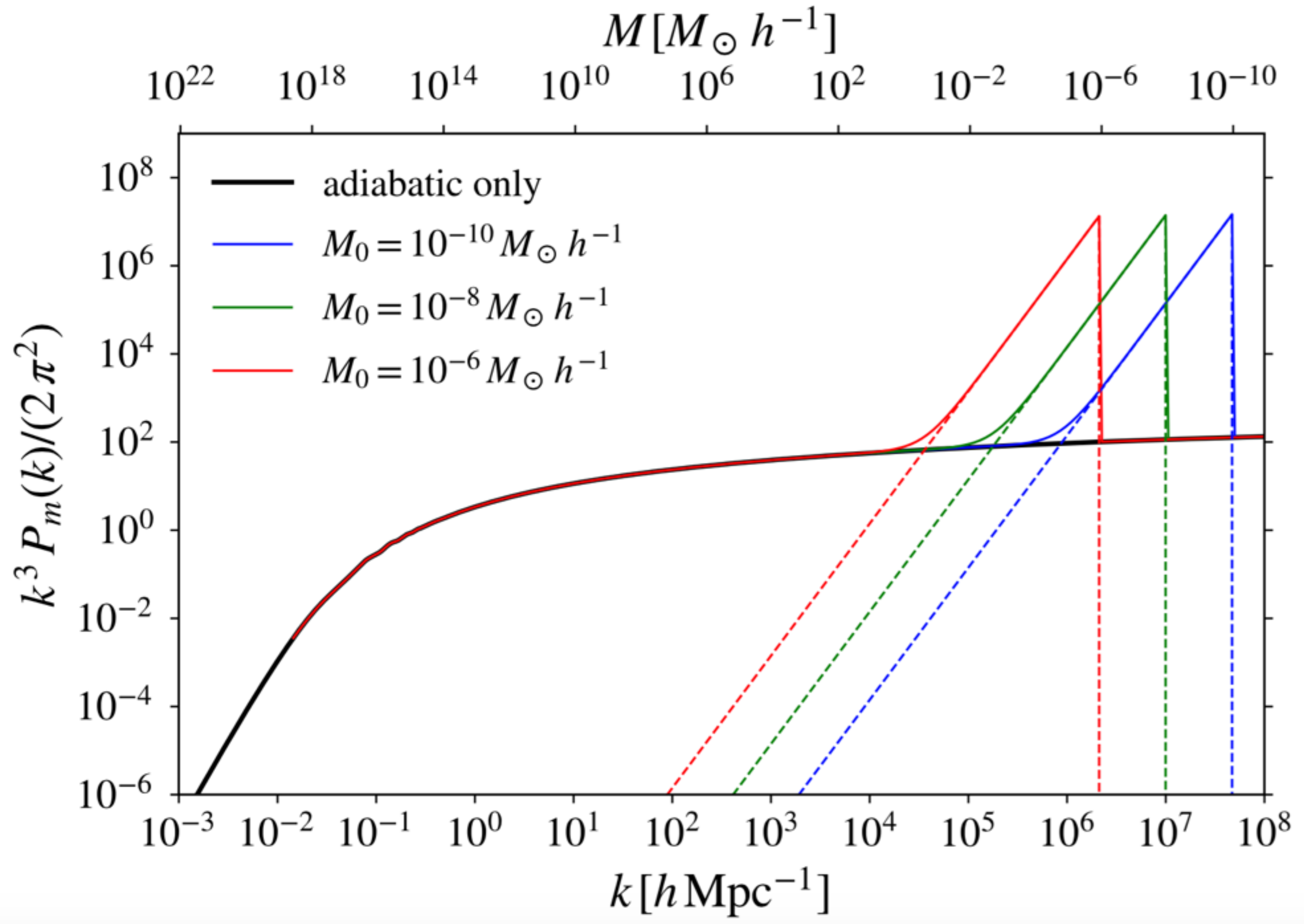
Primordial BHs, nuclear nugget DM, ultra compact halos, etc.

surface density of compact DM larger than that of stars

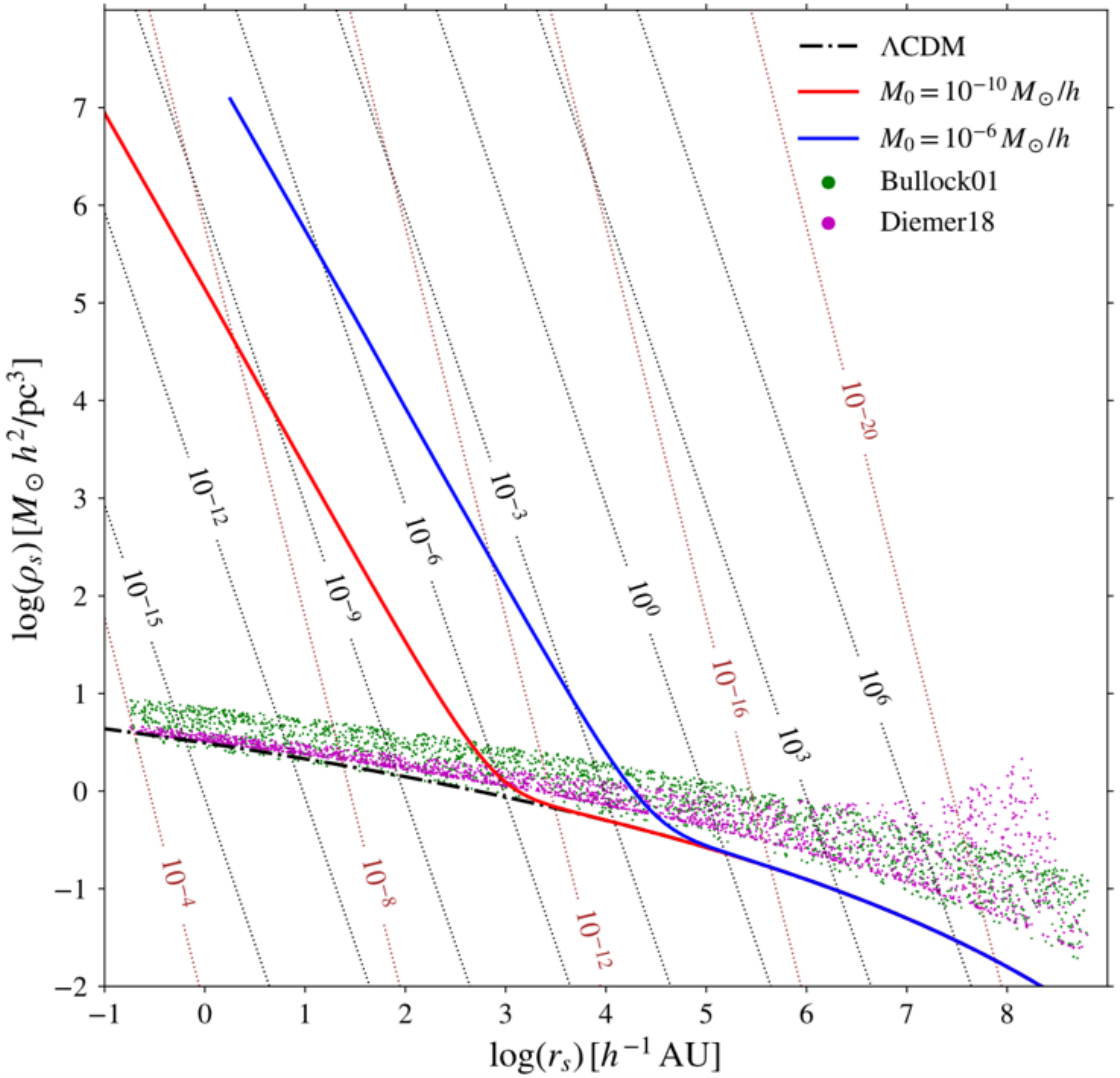
Need to measure microlensing statistics
(e.g. magnification distributions, temporal correlation functions of variability)

Axion Minihalos From Isocurvature Fluctuations

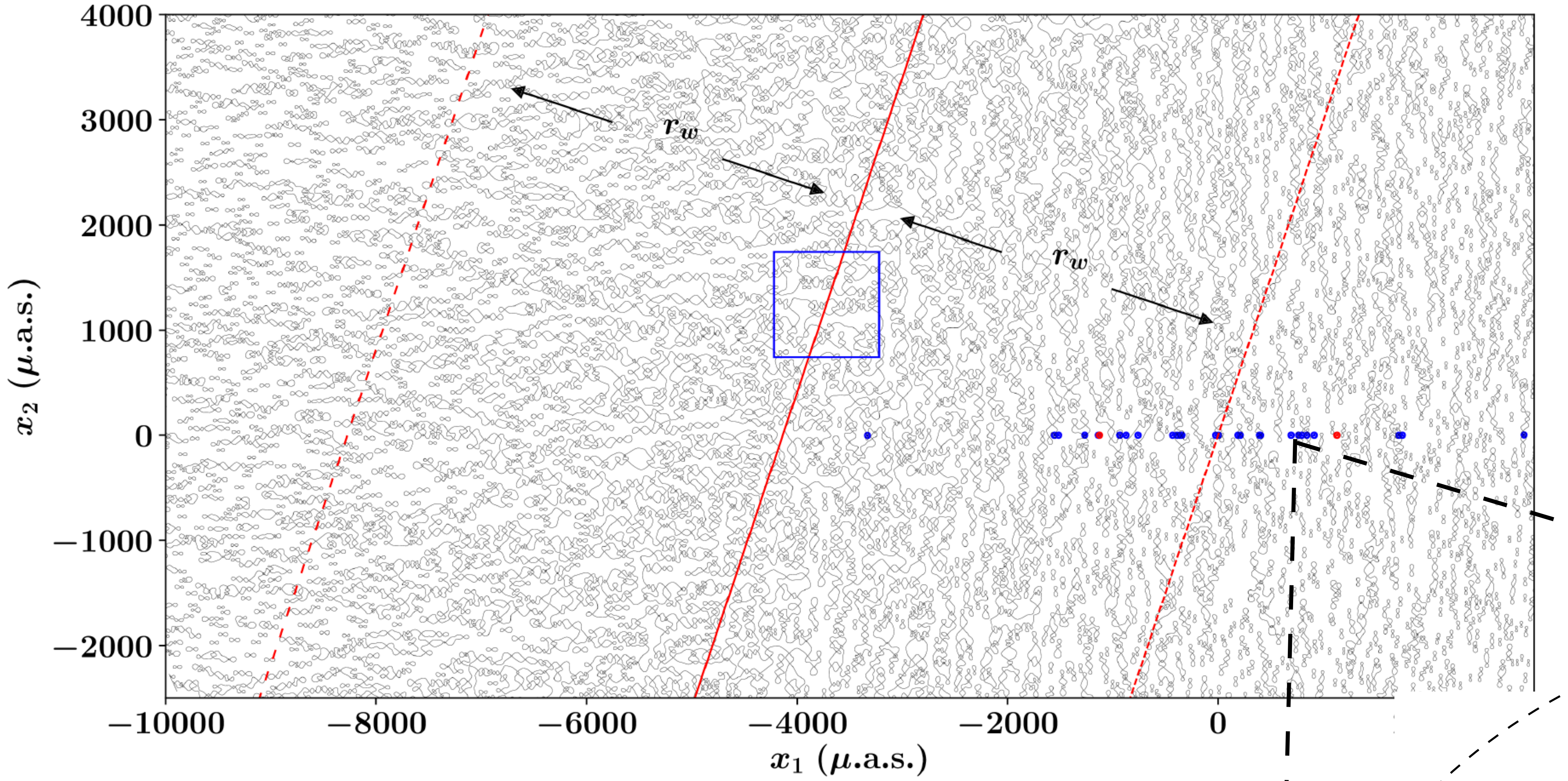
LD & Miralda-Escudé 19'



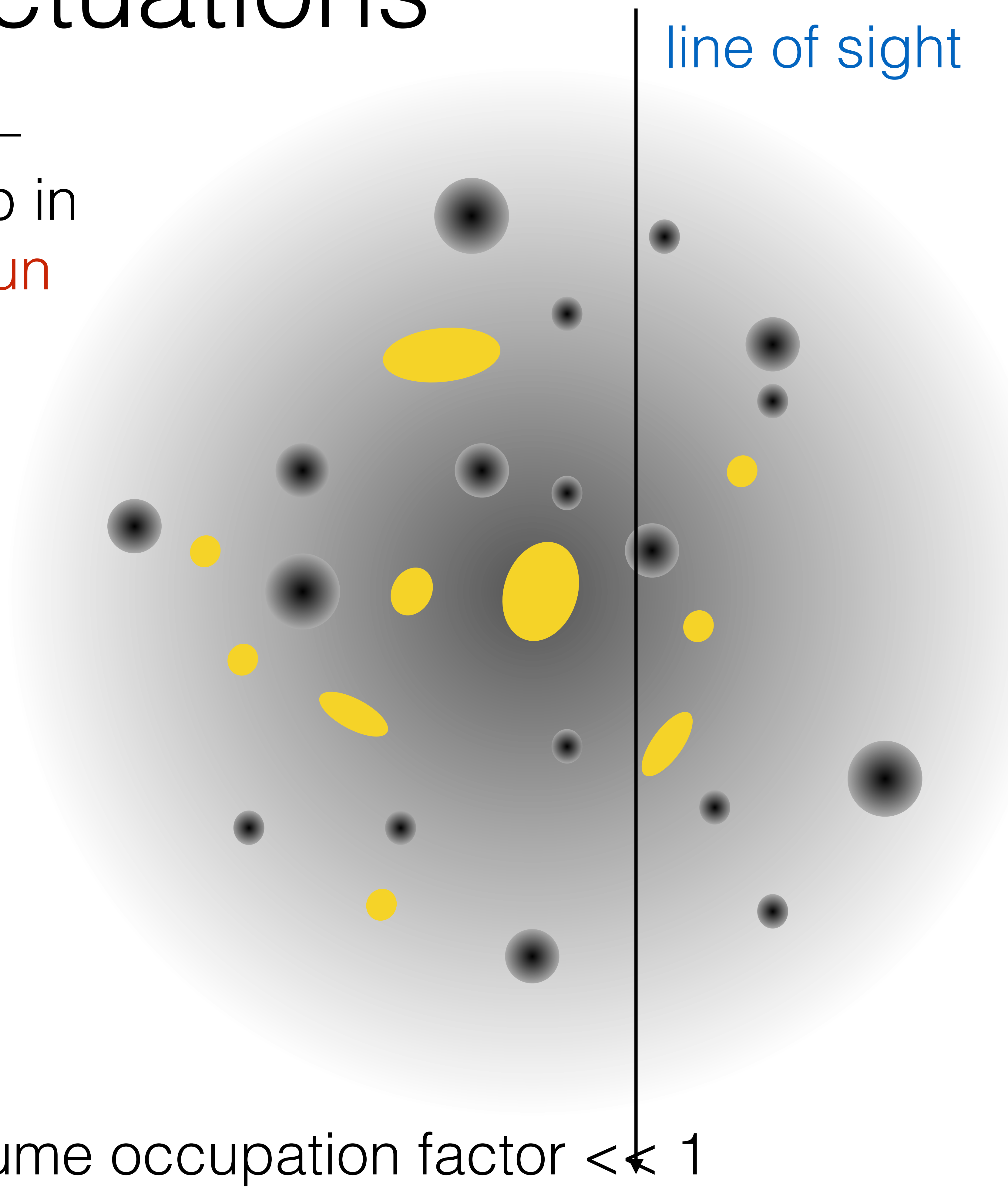
Dense (sub-)planetary minihalos from during **z ~ 20 — 3000**



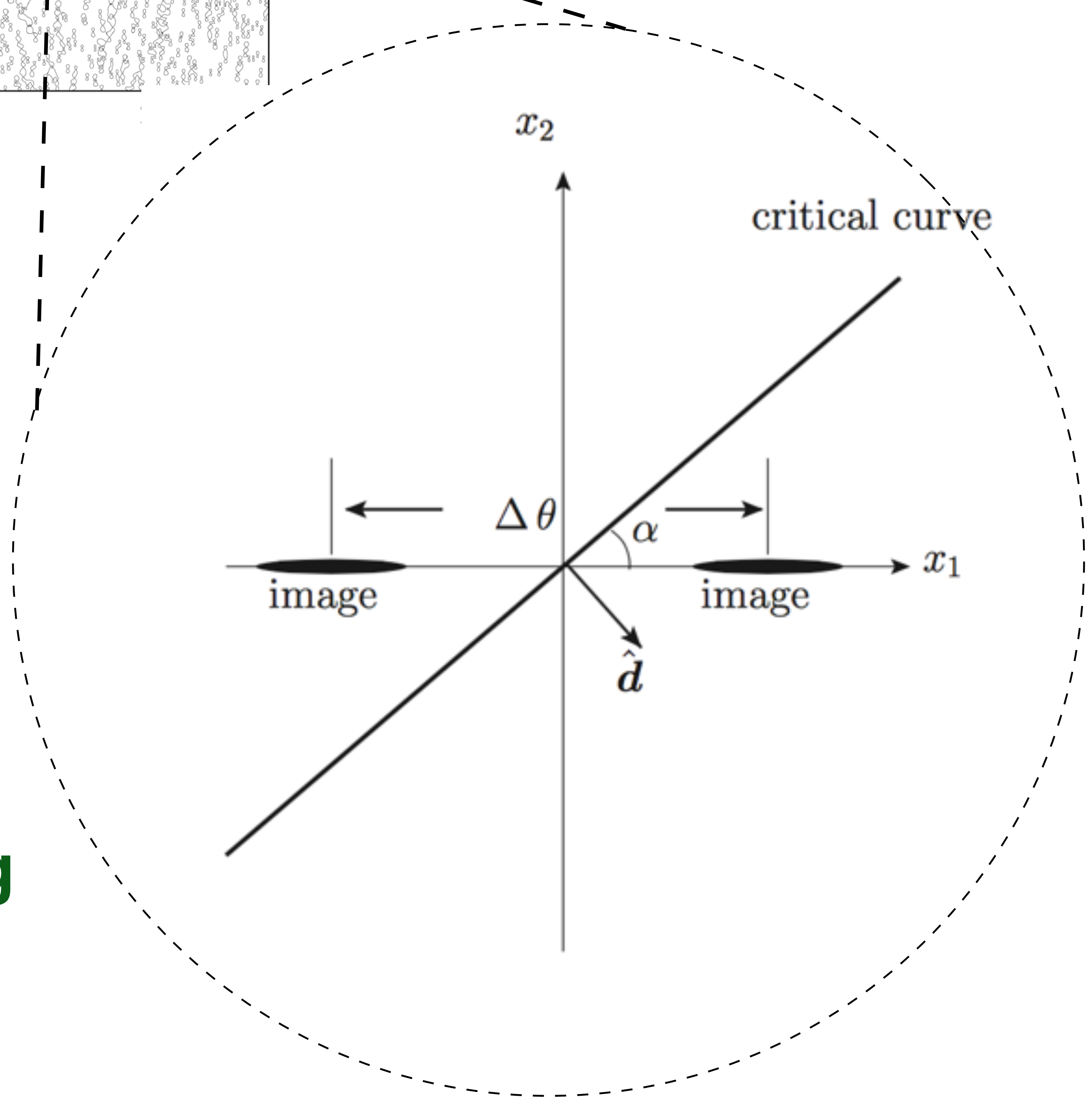
Fine-scale Surface Density Fluctuations



After cluster forms, few % — tens of % of mass locked up in mini-halos ~ 10^{-10}—10^{-4} Msun



a network of micro critical curves form near the macro critical curve



micro caustic crossing

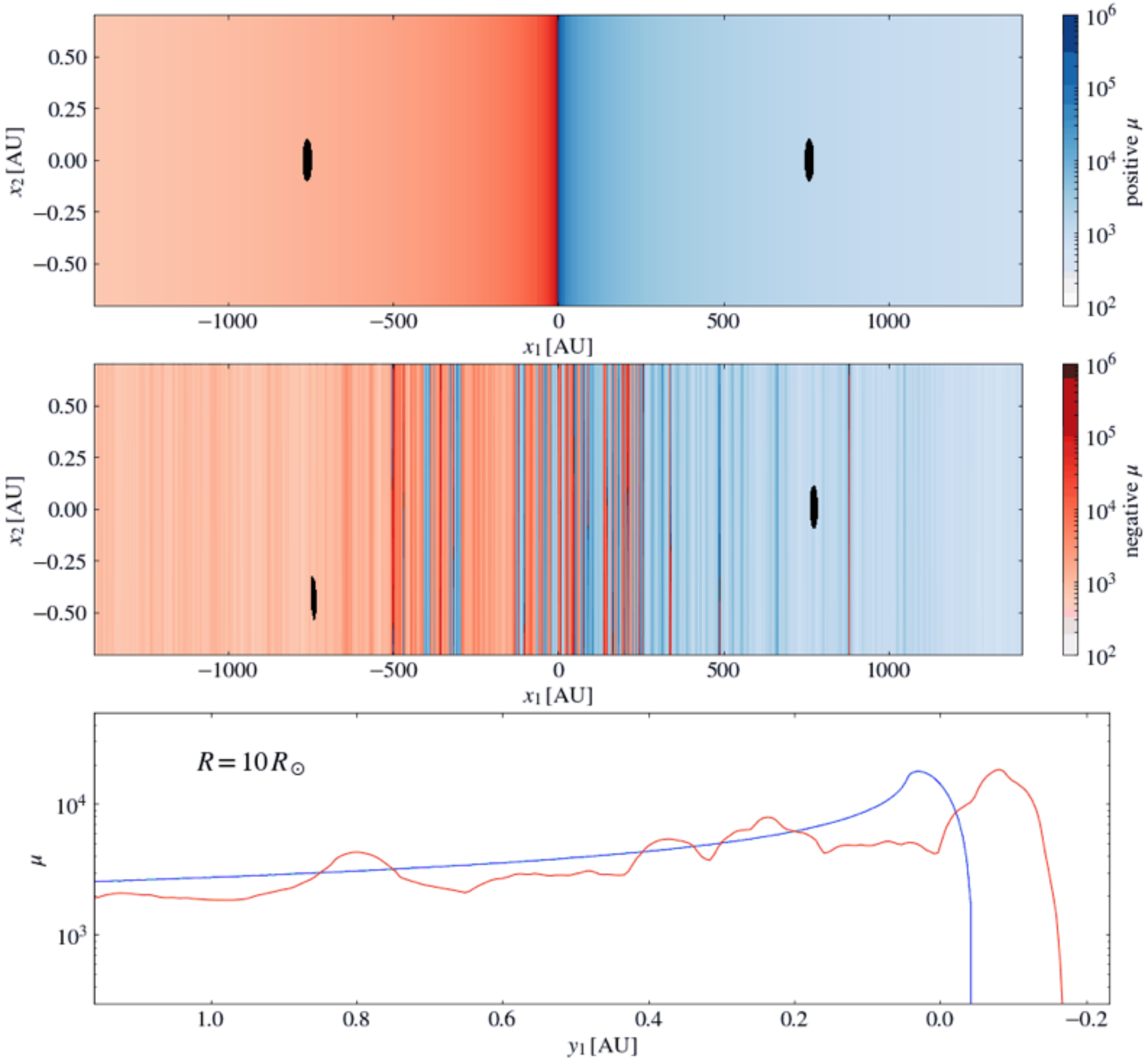
volume occupation factor << 1
but area covering factor >> 1

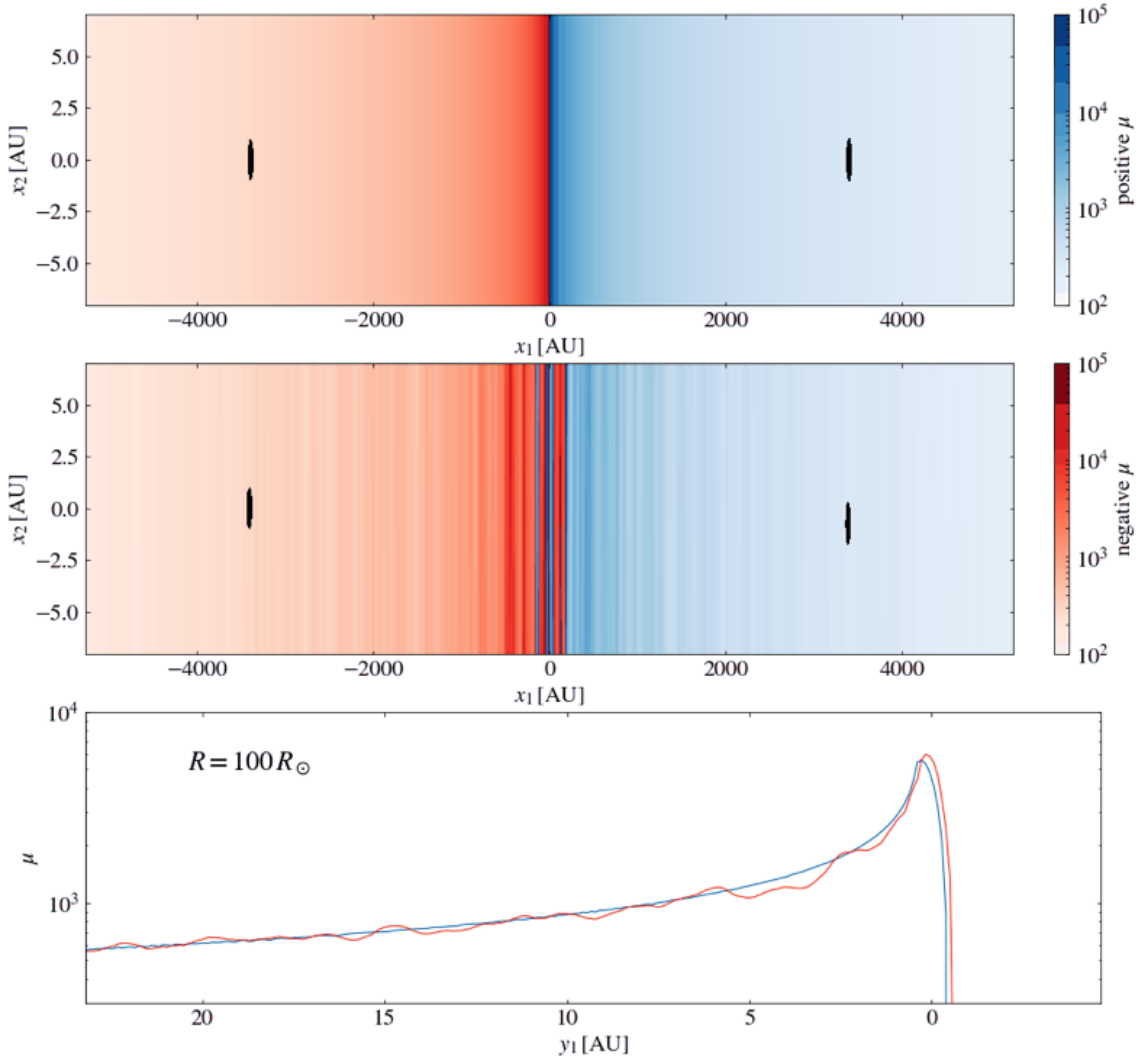
gaussian fluctuations in convergence
~ 10^{-4}—10^{-3} on scales ~10^{2}—10^{4} AU

Effects on Light Curves

time to traverse 1 AU = $6\,\mathrm{d}\left(\dfrac{v_t}{300\,\mathrm{km/sec}}\right)$

We should do high-cadence monitoring around the times of microlensing peaks !

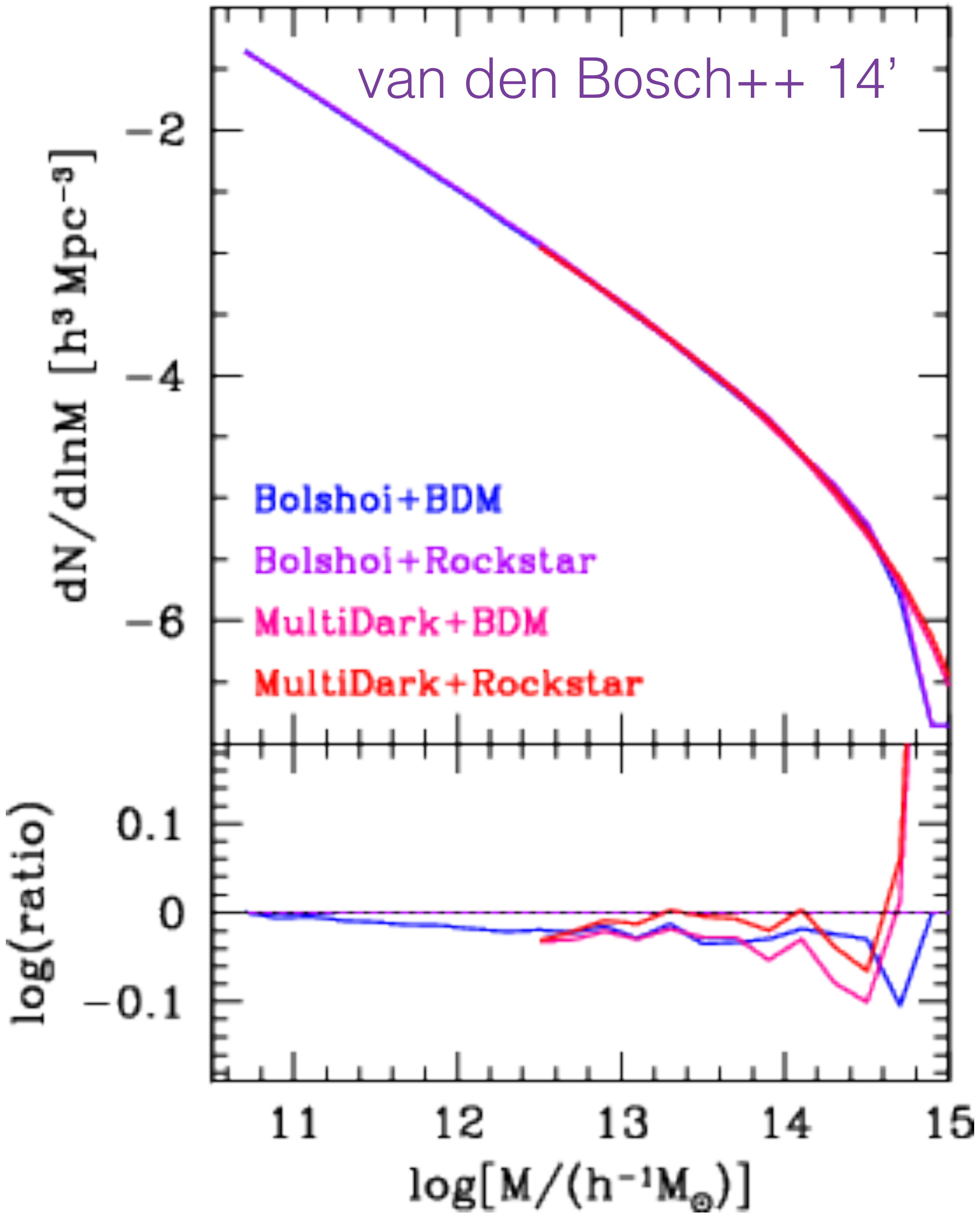




Outline

- Introduction
- Highly magnified cosmological sources
- Applications of highly magnified sources: Probing small-scale dark matter structures
- Lensing of gravitational waves
- Conclusion

Probe DM Subhalos?

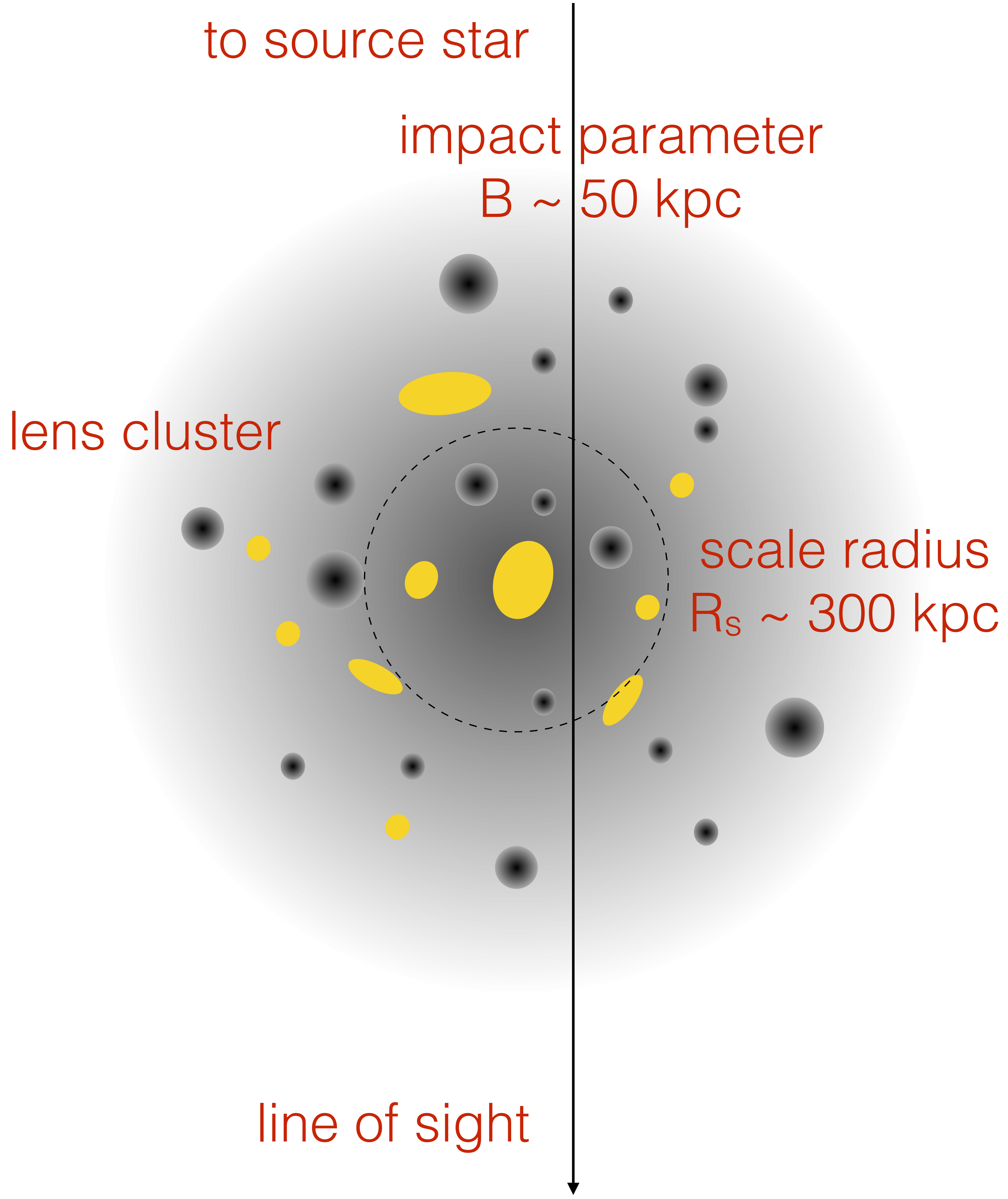


Mo++ 10'

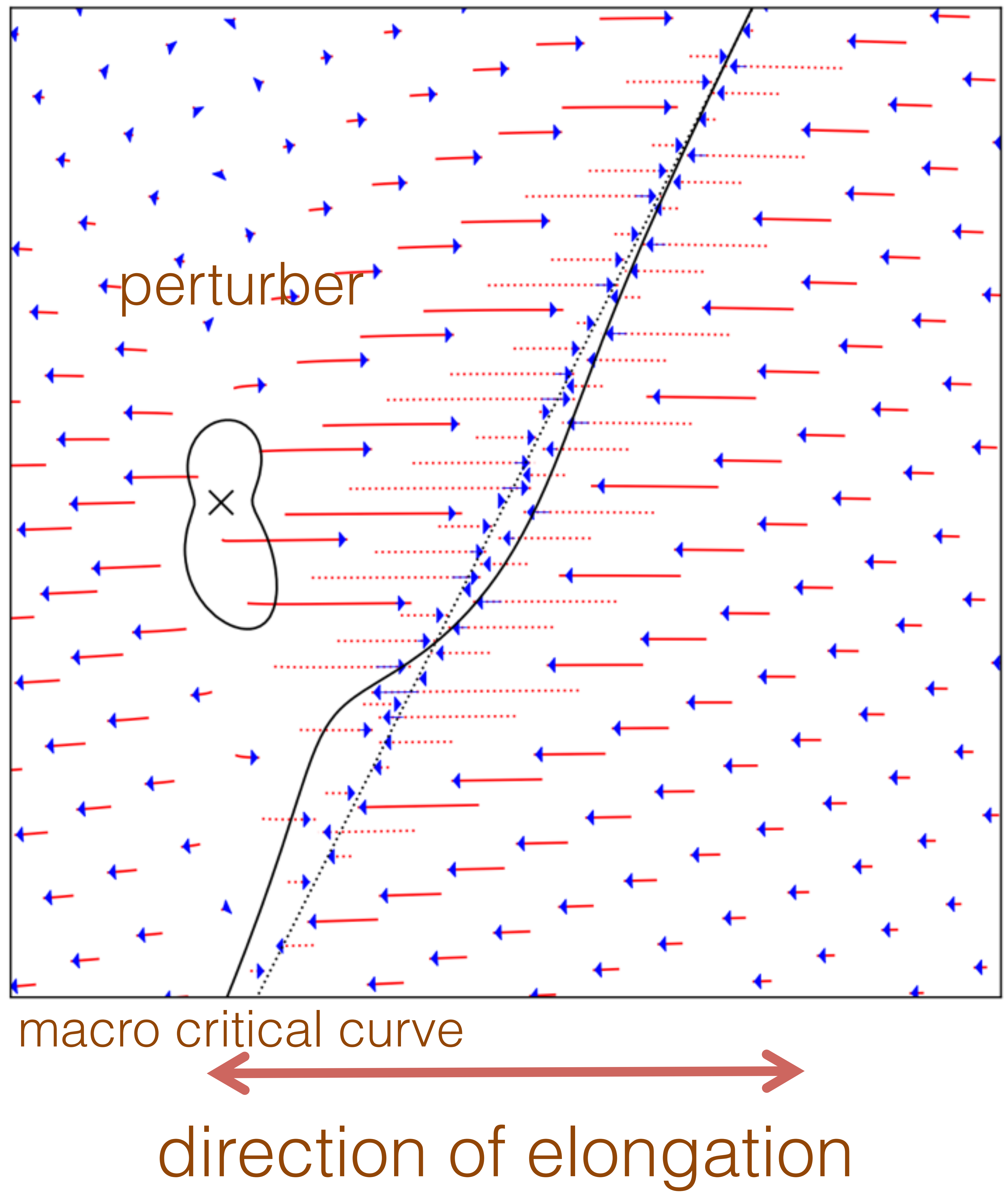
$$\frac{dN}{d\log m} \propto m^{-0.9}$$

1—10% mass locked up in subhalos

Astrometric Signals of Subhalos



LD, Venumadhav, Kaurov & Miralda-Escudé 18’

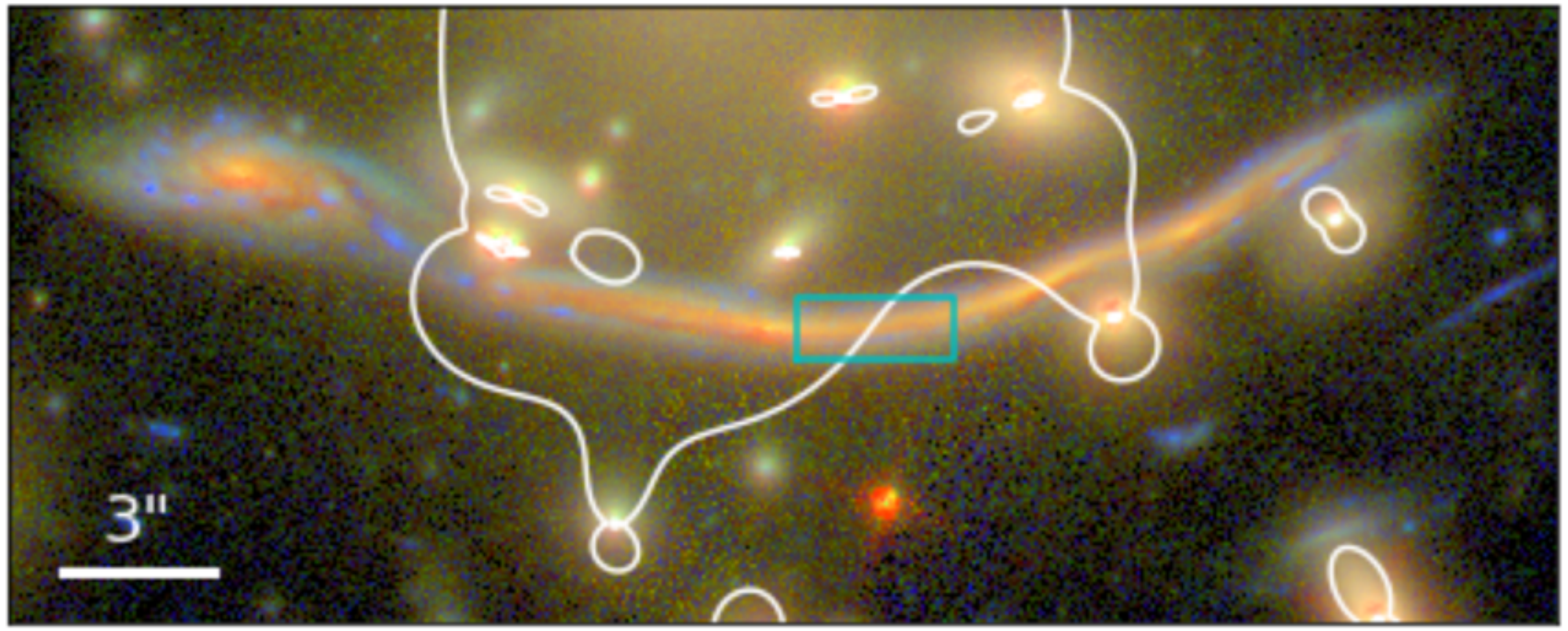


Multiple Stars Along Critical Curve

The "Dragon" in Abell 370 at z = 0.725

Richard++ 09'

- Consider an caustic straddling arc, which is highly stretched across the critical curve
- Prefer large arc width along the critical curve
- Multiple highly magnified stars or star clusters may be detectable

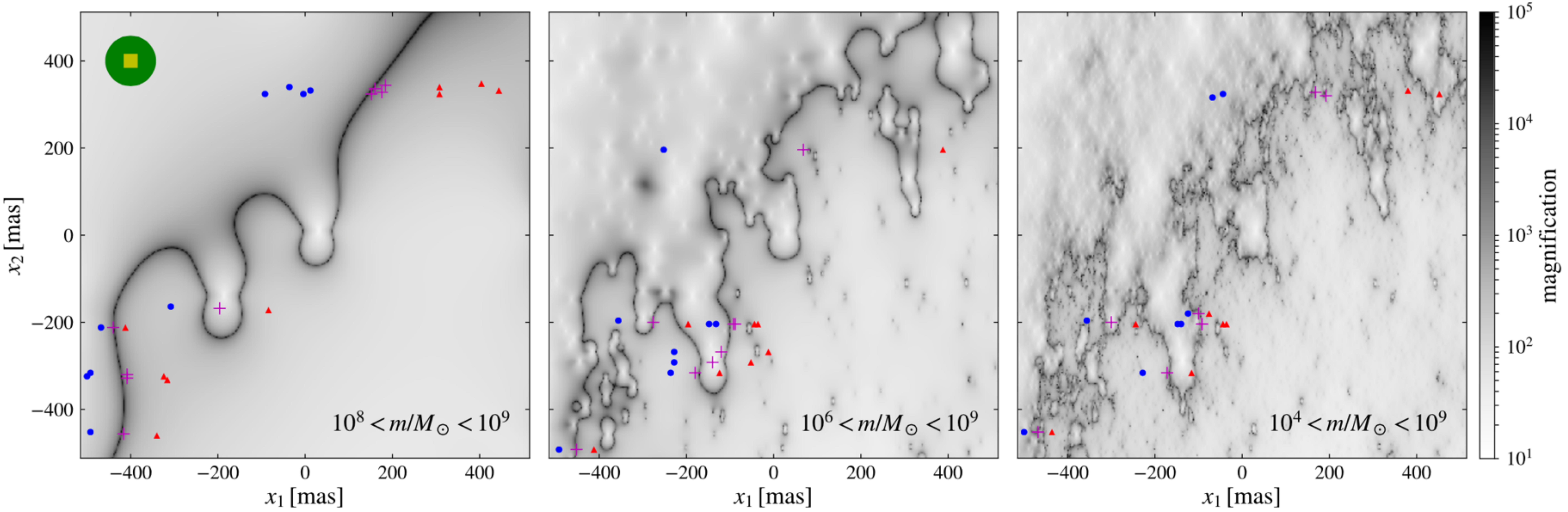


“Dragon” of Abell 370

JWST PSF (~1.5 μm)

NIRCam pixel (32 mas)

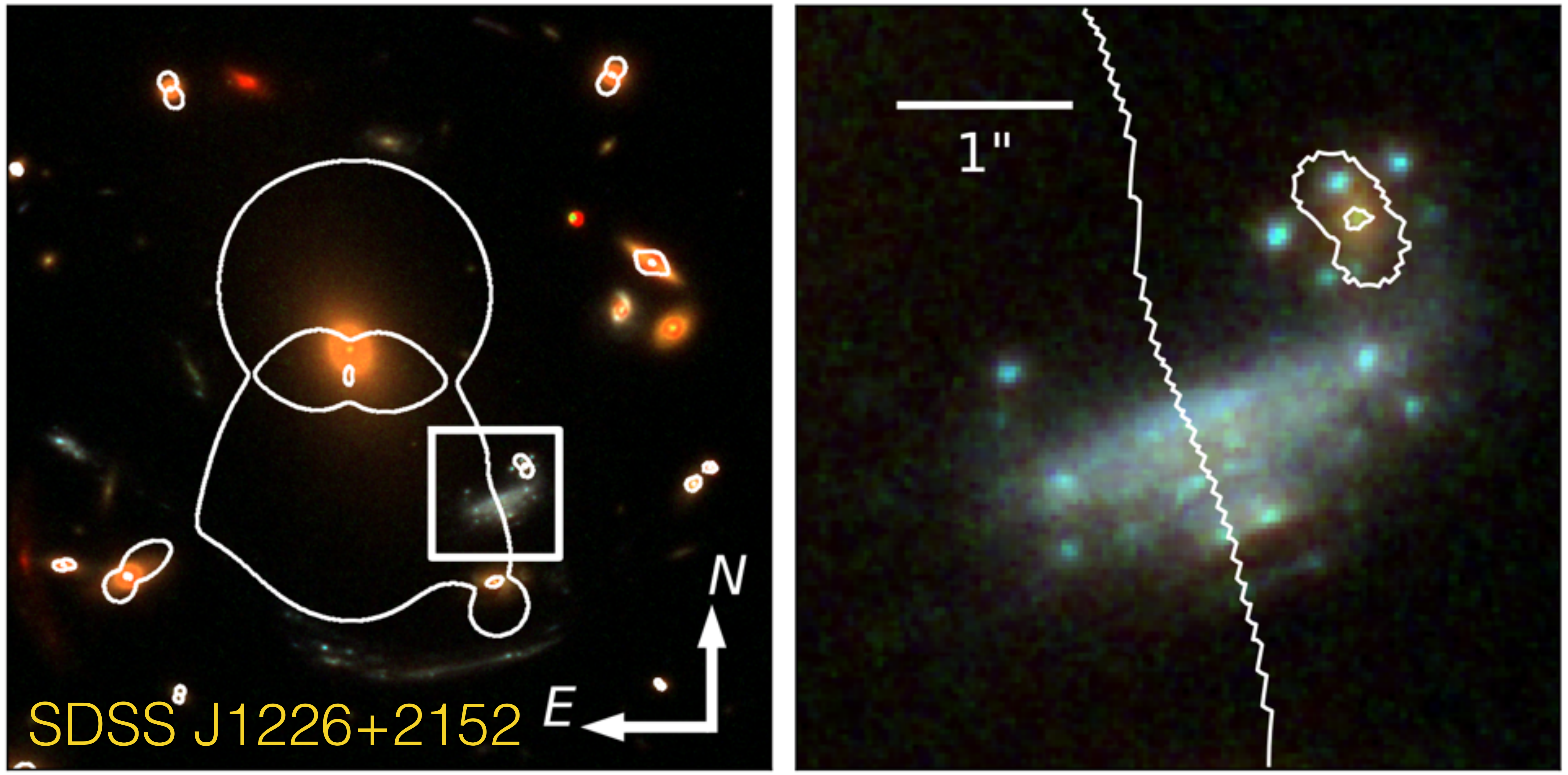
LD, Venumadhav, Kaurov & Miralda-Escudé 18’

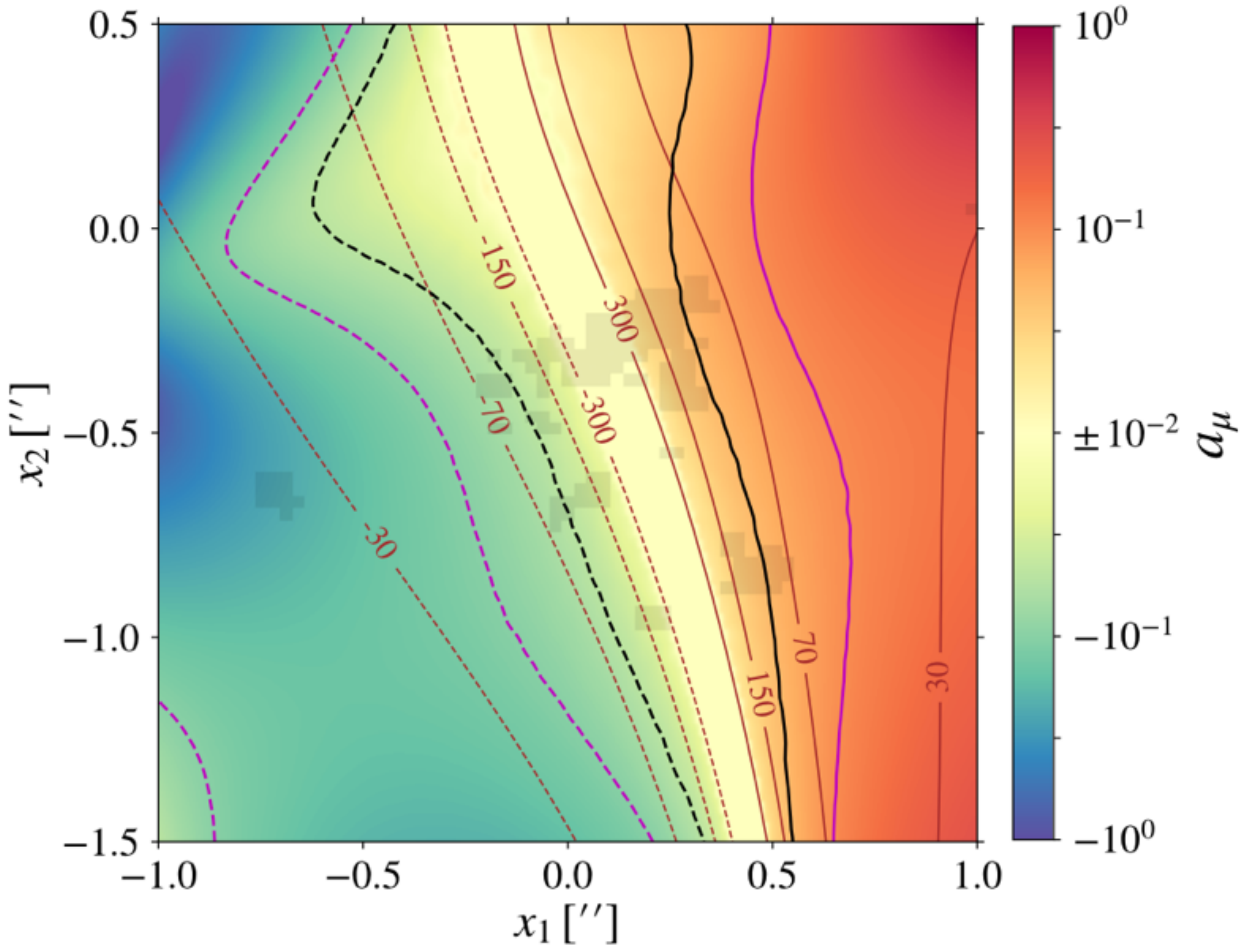


Can probe a population of DM subhalos in the mass range 10^6–10^8 Msun

Photometric Signals of Subhalos

LD, Kaurov, Sharon++ 2001.00261





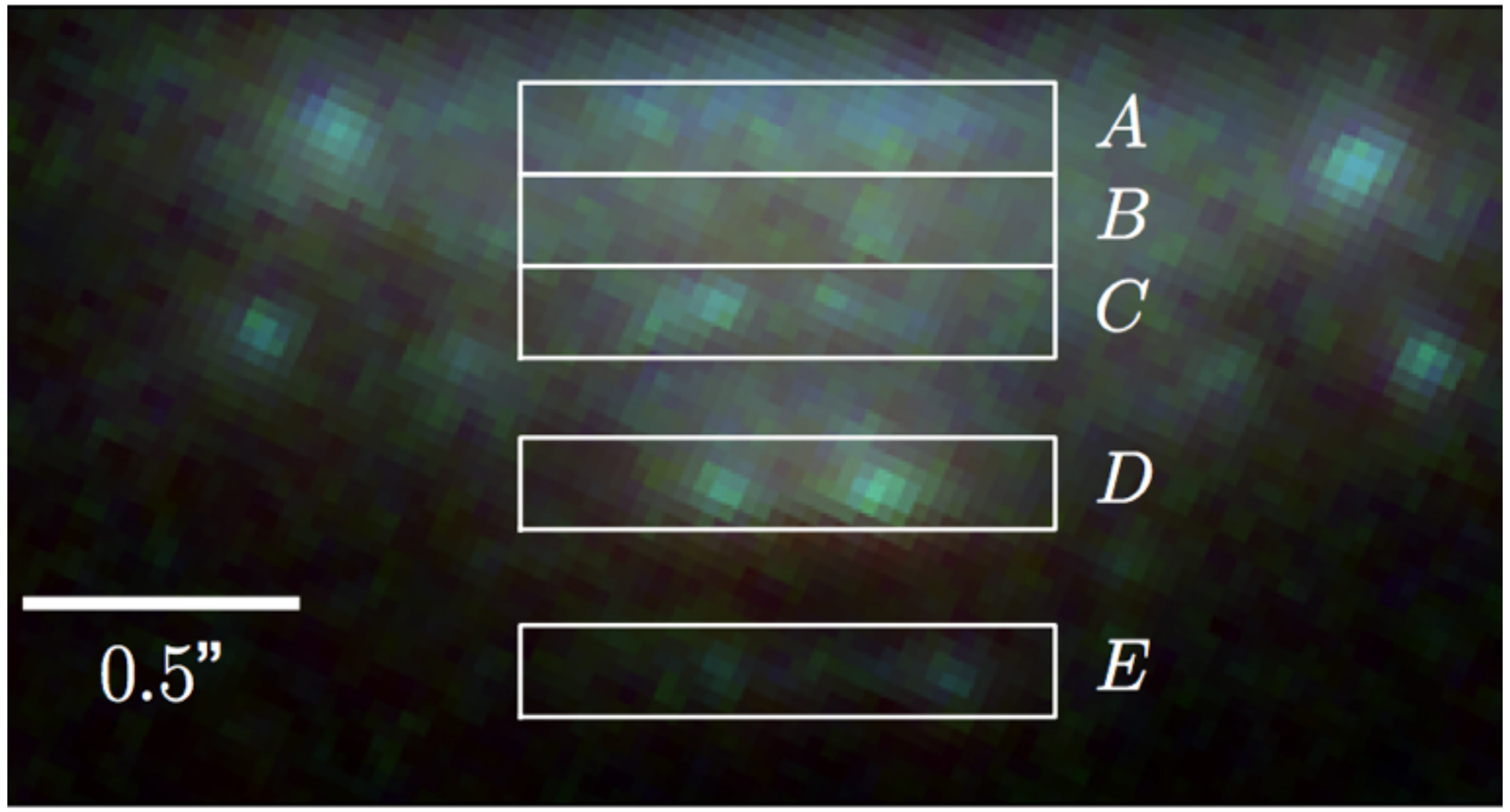
Smooth lens model:
cluster DM halo, BCG, member galaxies & their DM halos

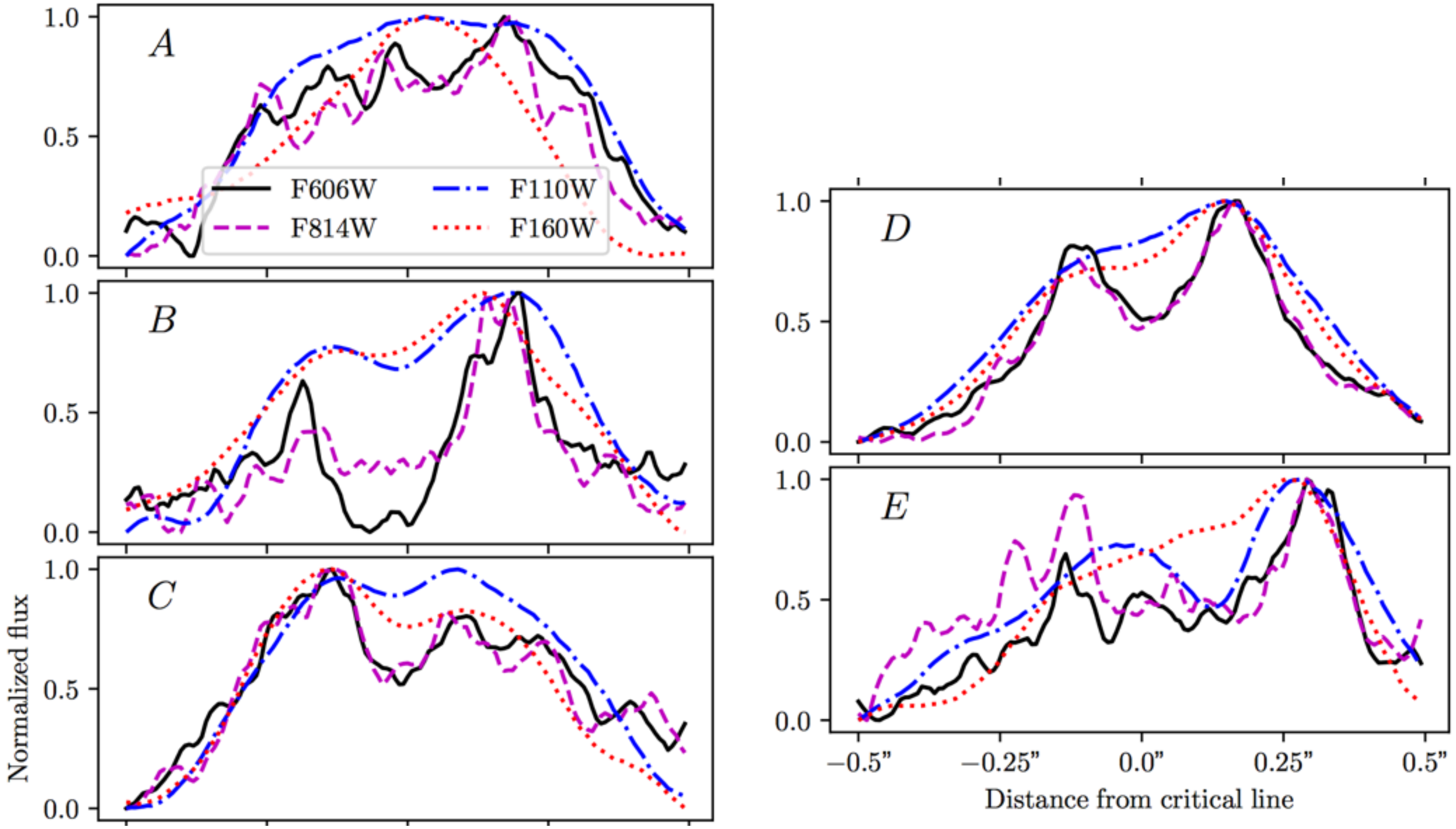
Magnification asymmetry between **a close pair of highly magnified images** should be smaller than ~ 1/magnification

Magnification asymmetry $a_\mu = 2\,\frac{|\mu| - |\mu'|}{|\mu| + |\mu'|}$

SDSS J1226+2152: Flux Asymmetries

LD, Kaurov, Sharon++ 2001.00261





All close images pairs are not equally bright !

[1] Asymmetries similar in 4 different HST filters.
[2] Asymmetries are much larger than few percent.
[3] Asymmetries do not seem to have changed very much over 6 years.

Compact Young Star Clusters

NGC 3603

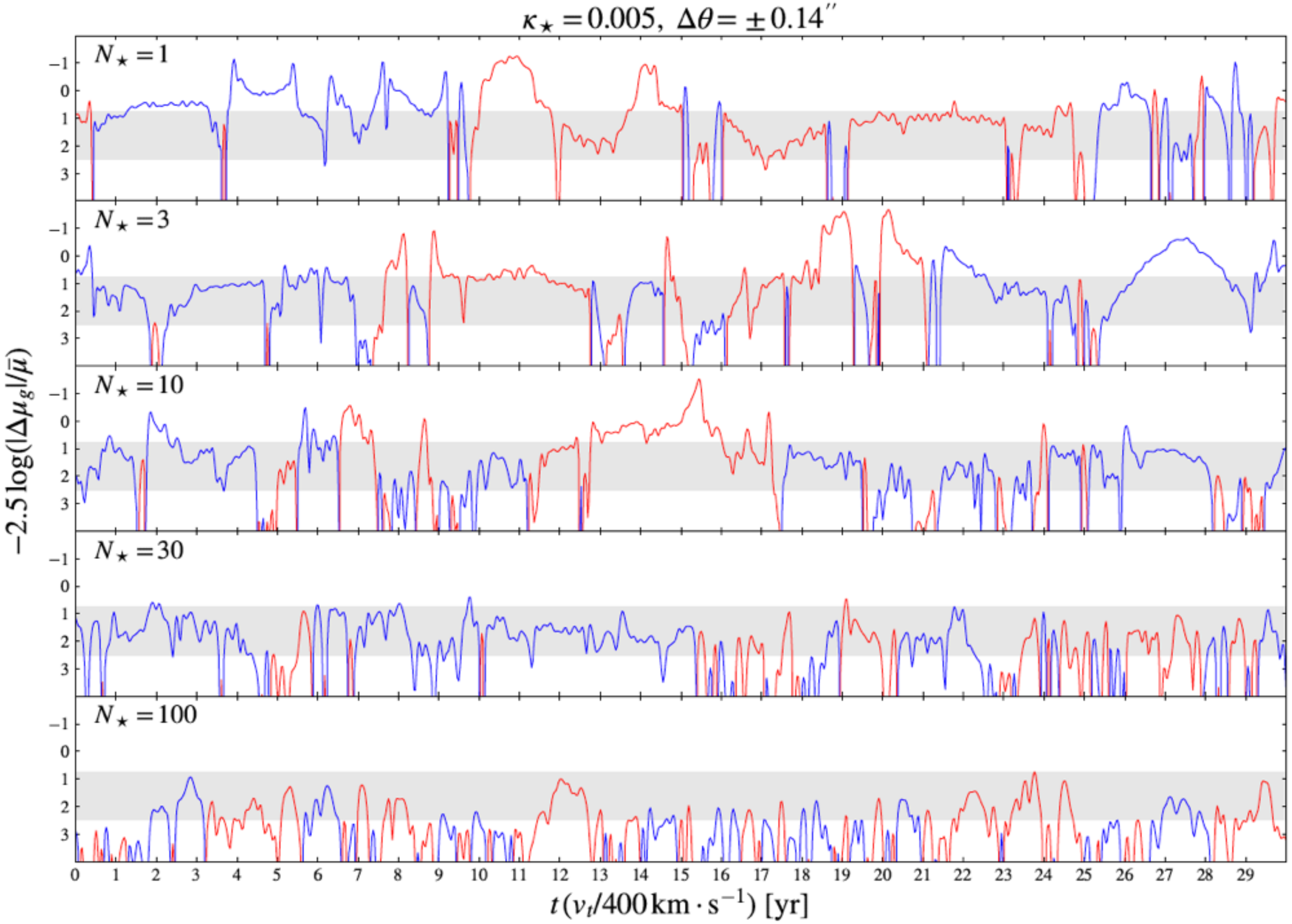
Compact sources must be smaller than **~ a few pc**

More likely to be clusters of stars.

Such clusters are not much smaller than a few pc.

Member stars subject to uncorrelated microlensing

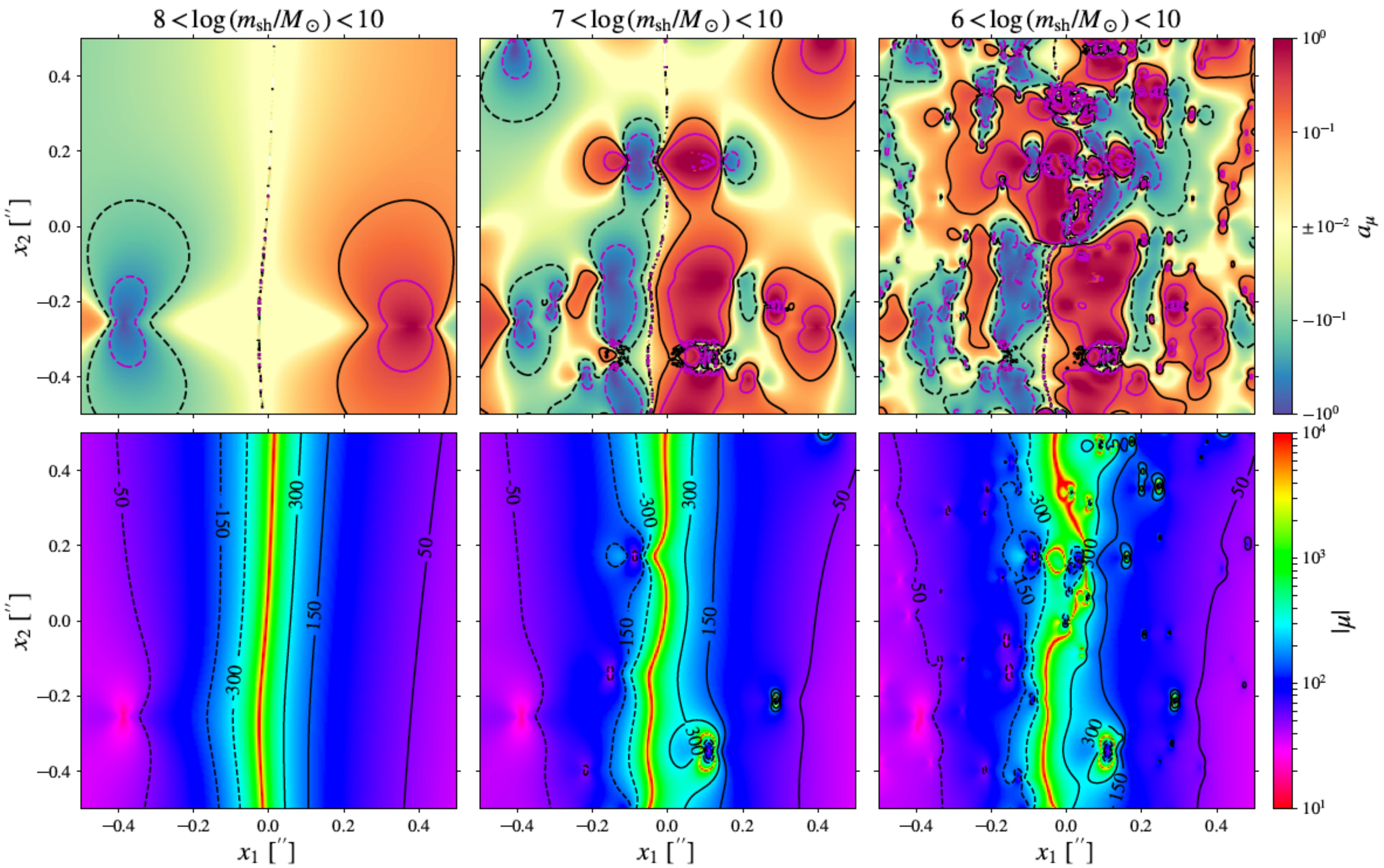
LD, Kaurov, Sharon++ 2001.00261



Microlensing induced flux asymmetry should show **significant variability**

Subhalos Causing Asymmetries?

LD, Kaurov, Sharon++ 2001.00261



Naturally cause **persistent** magnification asymmetries

Enhanced abundance of intervening sub-galactic, invisible subhalos **~ 10^6—10^8 Msun** across the cluster halo.

Unequality of image pairs spoiled at **> 10% level**

Are we seeing the effect of subhalos?

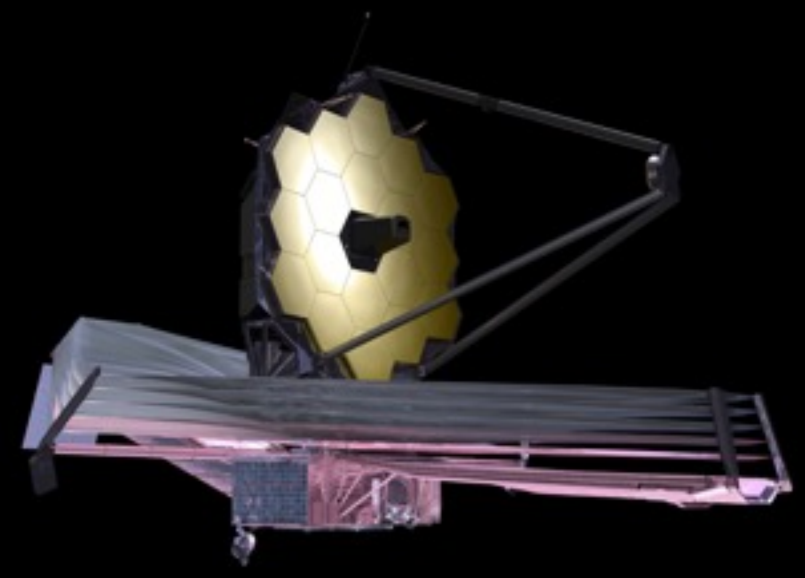
If so, flux asymmetries should be commonly found.

Observational Prospects

Observe more deeply

mag ~ 30;
x3 angular resolution; spatially resolved spectroscopy

HST

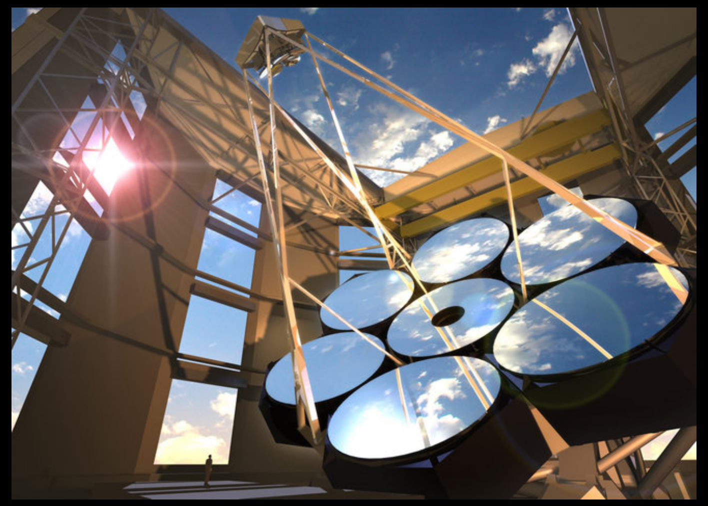


JWST

Astrometry

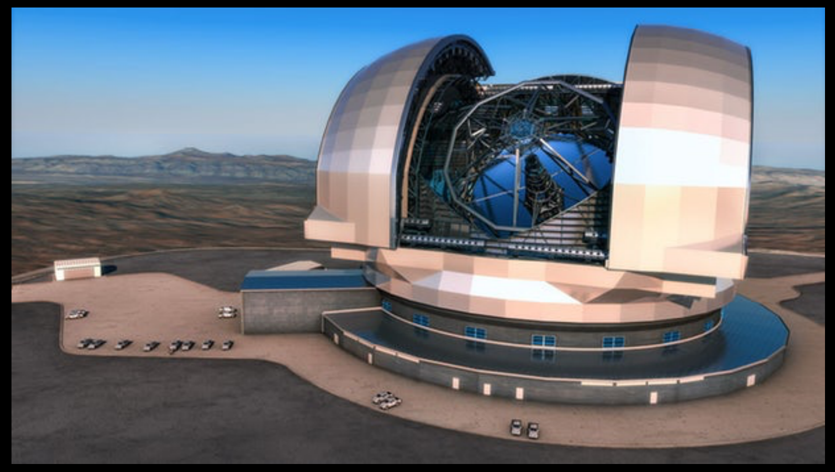
Microlensing follow-up

(dedicated small telescopes?)



GMT

TMT

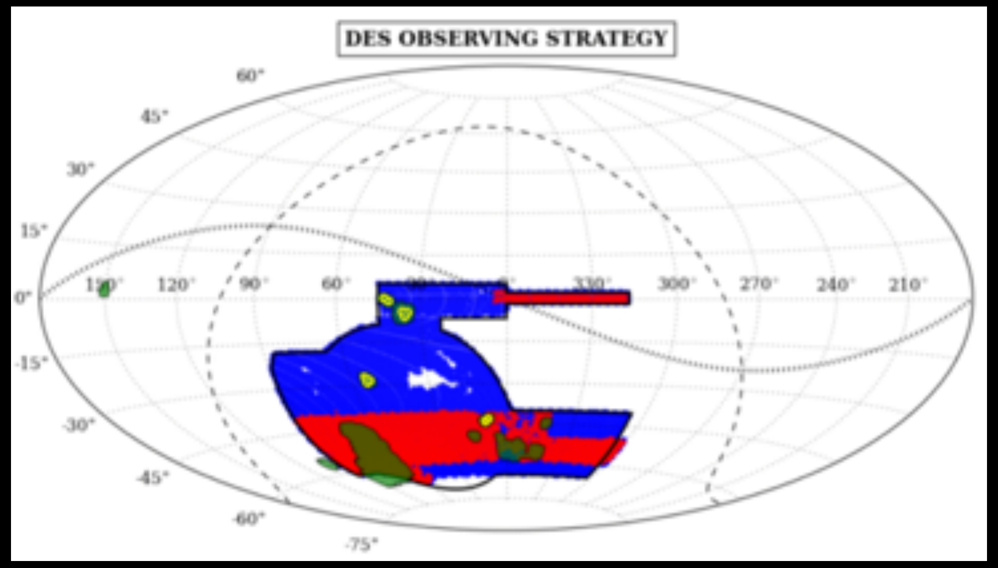


EELT

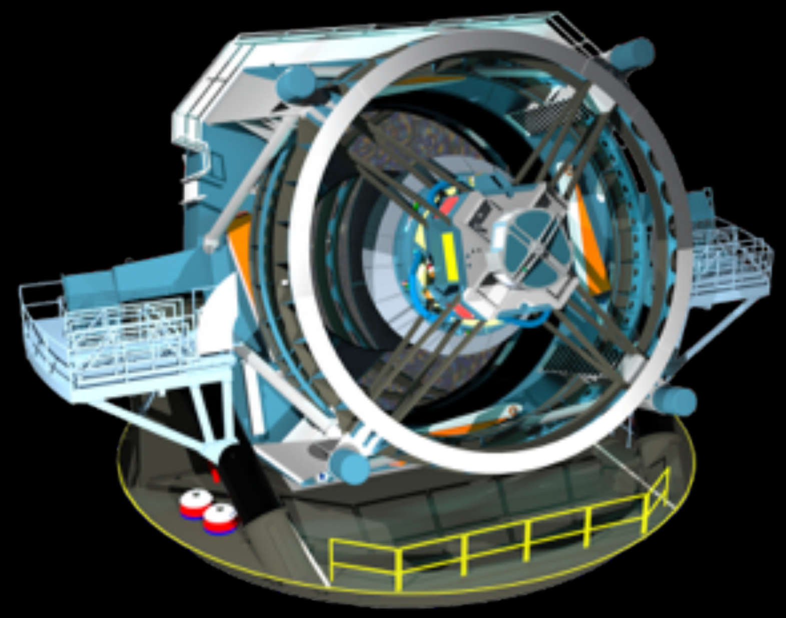
Enlarged catalog of arcs

currently ~ 10 well modeled clusters
+ a few useful arcs

In the era of DES, LSST, etc, much more strong lensing systems



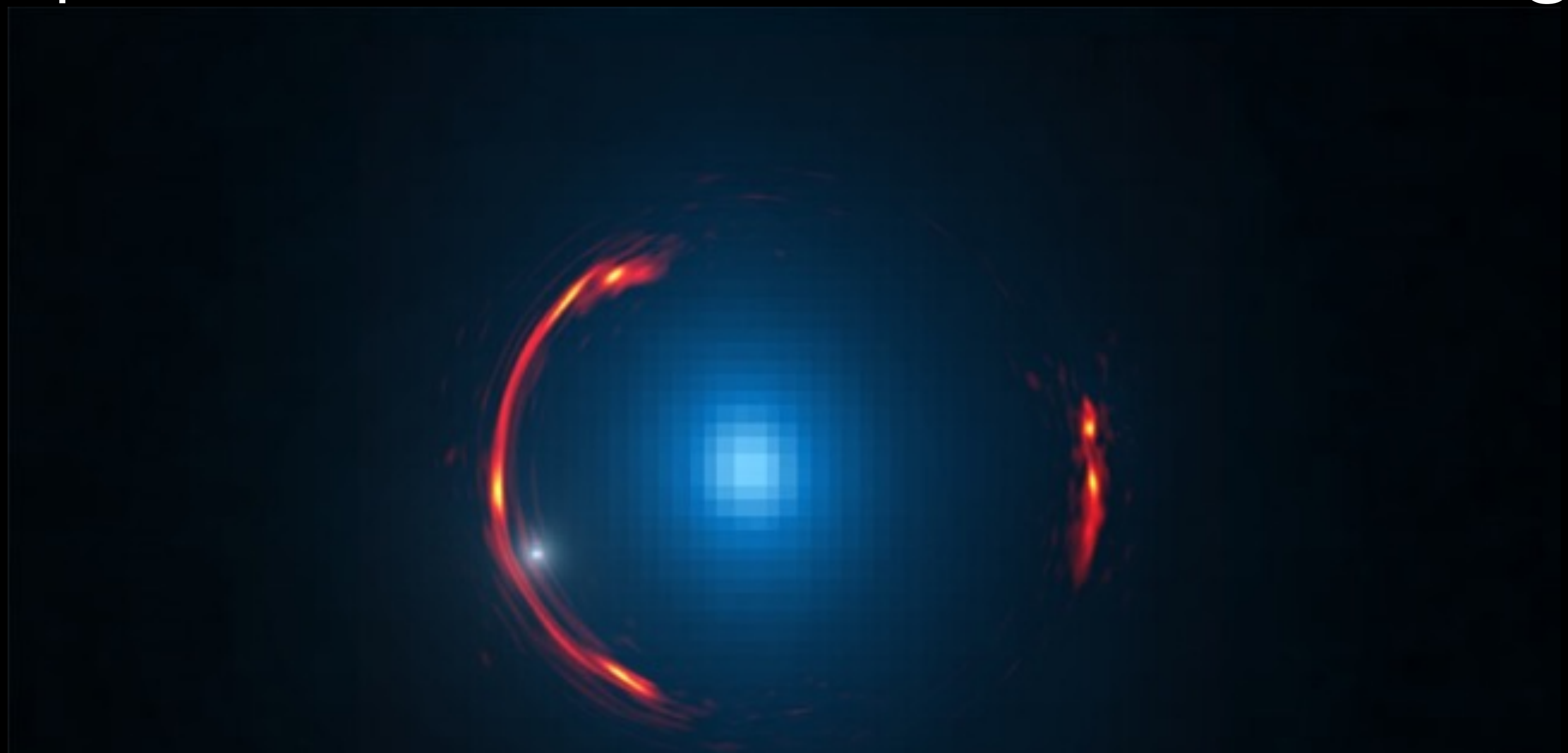
DES



LSST

Other ways to see sources?

Dusty emission from compact star forming complexes at sub-millimeter wavelengths.

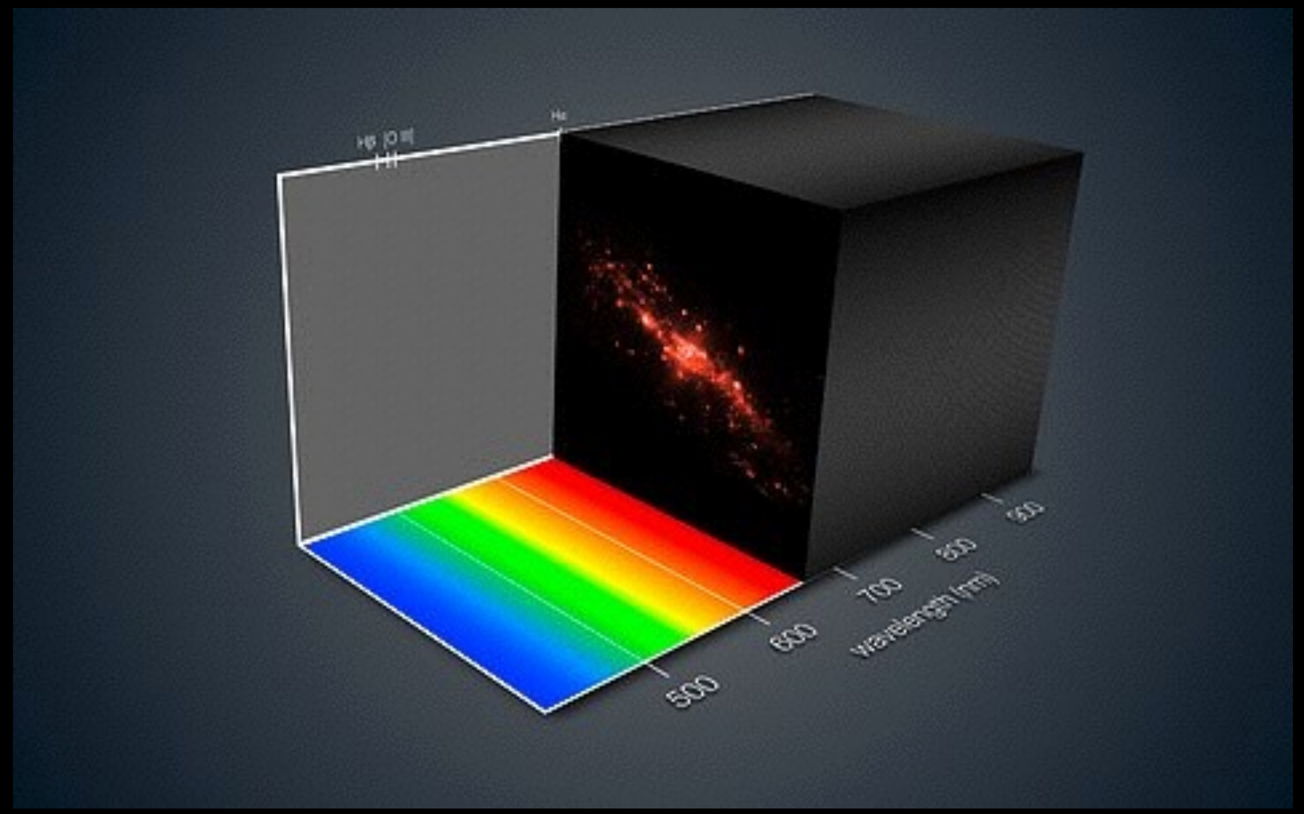


Credit: Y. Hezaveh

Atomic line emission from compact HII regions

Useful for astrometry

Mitigate continuum background

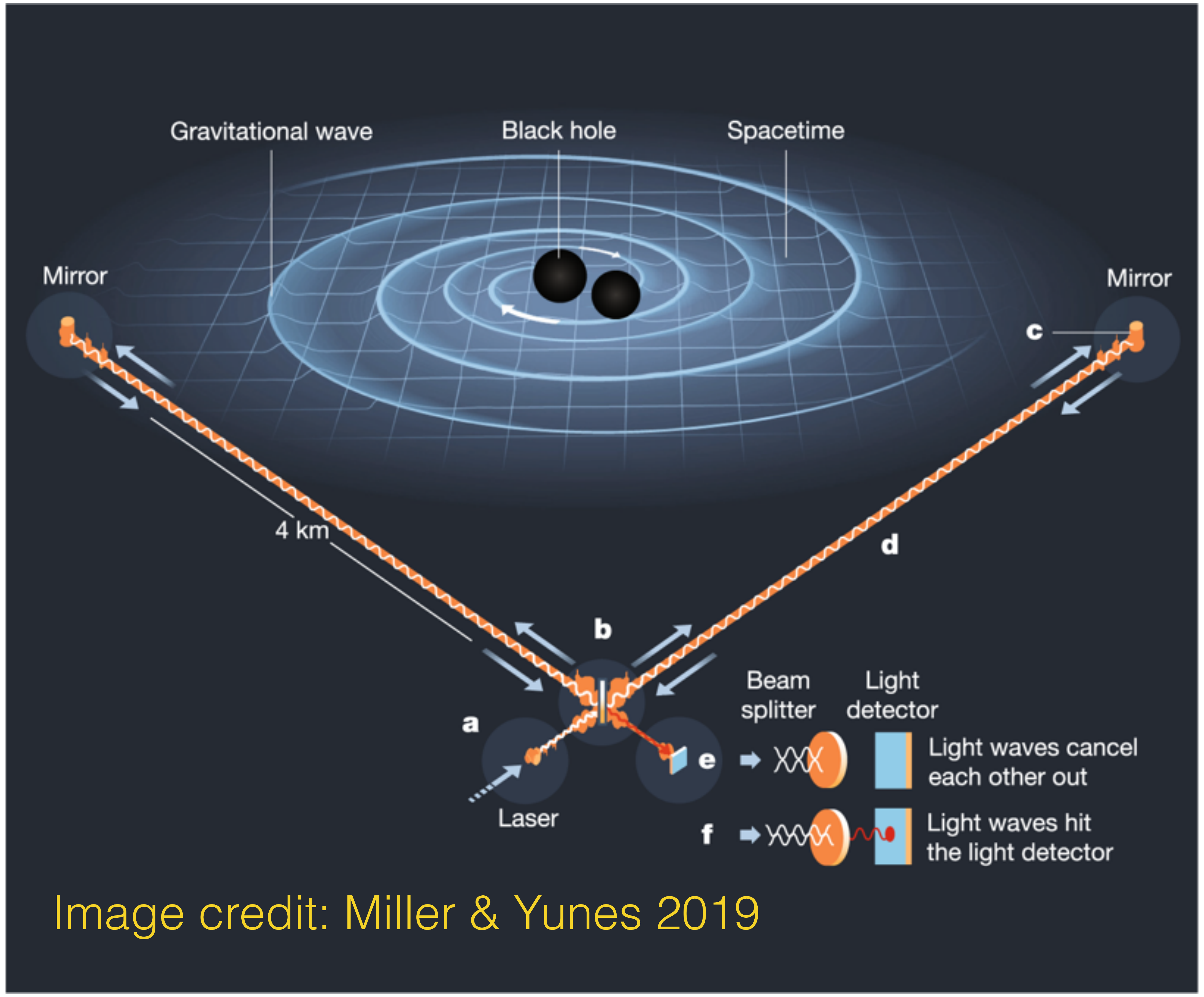


Integral Field Spectrograph

Outline

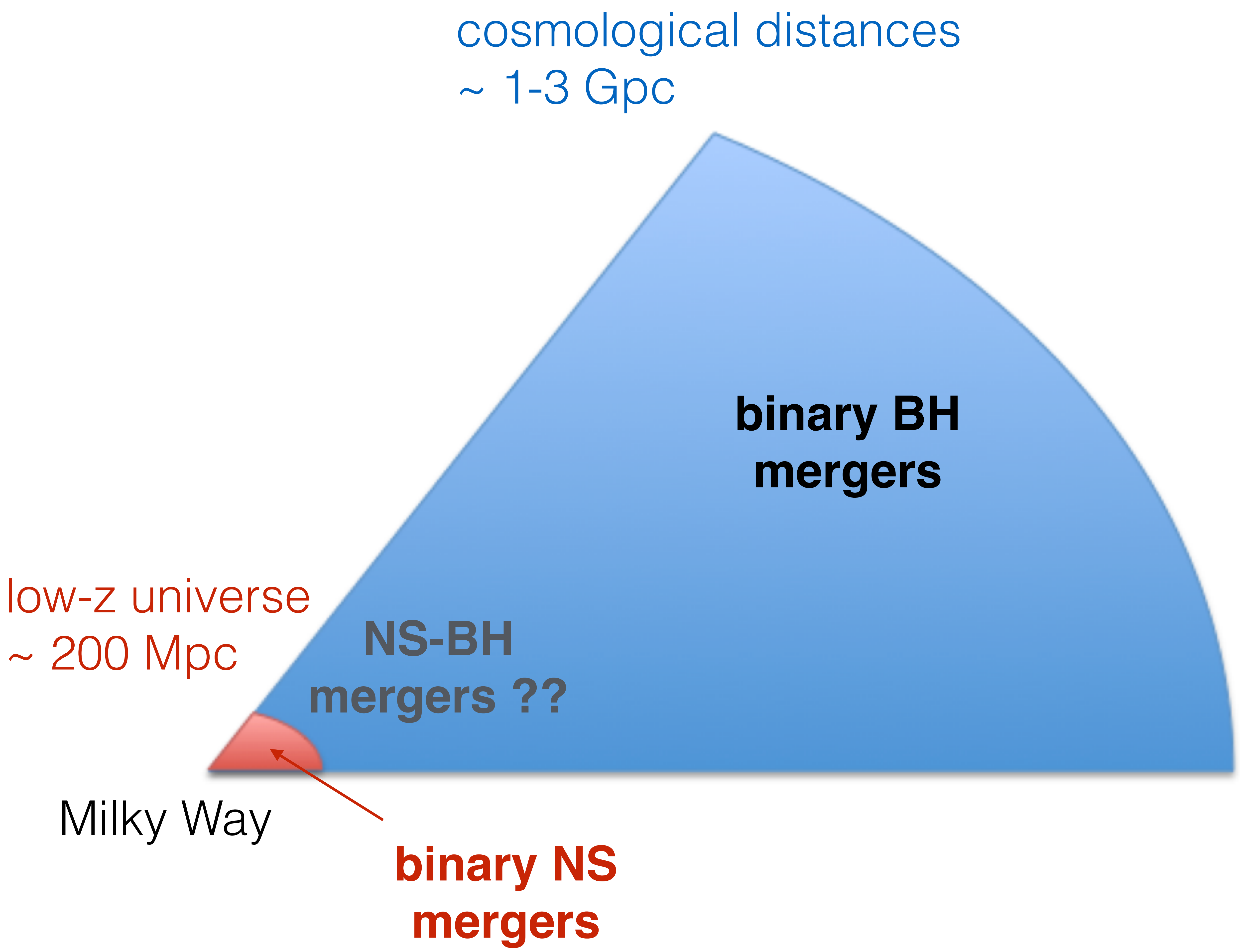
- Introduction
- Highly magnified cosmological sources
- Applications of highly magnified sources: Probing small-scale dark matter structures
- Lensing of gravitational waves
- Conclusion

Gravitational Wave Radiation

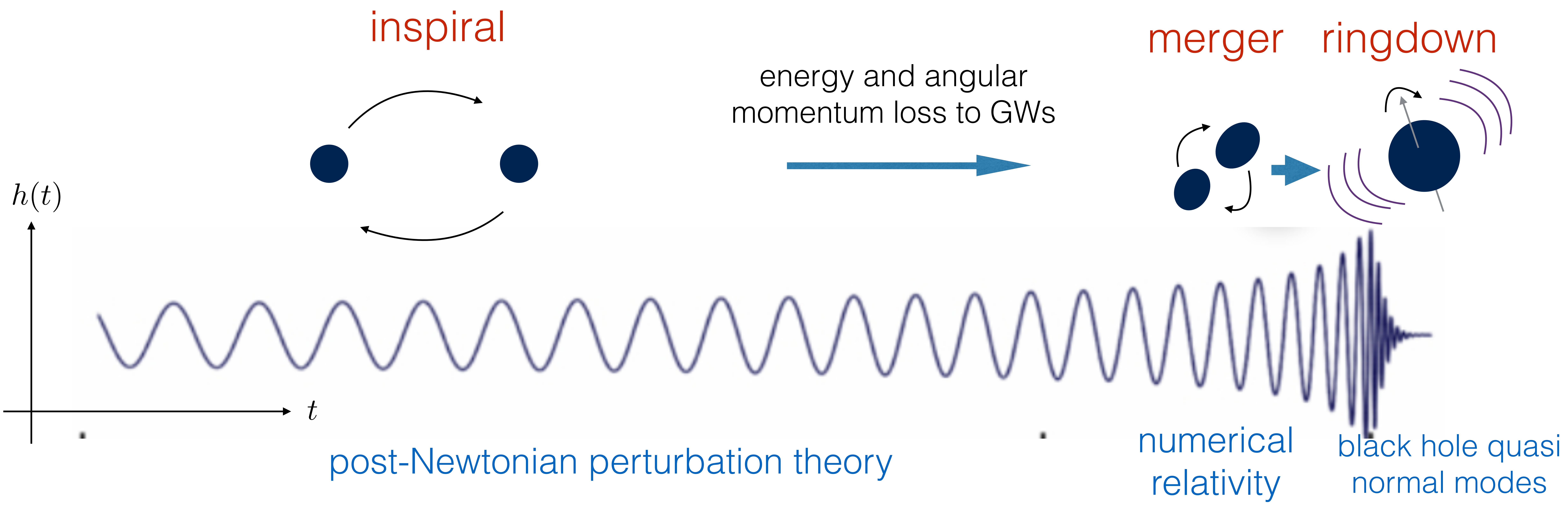


$$h_{ij}(t_{\rm obs}) = \frac{2\,G}{c^4\,r}\,\ddot{Q}_{ij}(t - r/c)$$

mass quadrupole



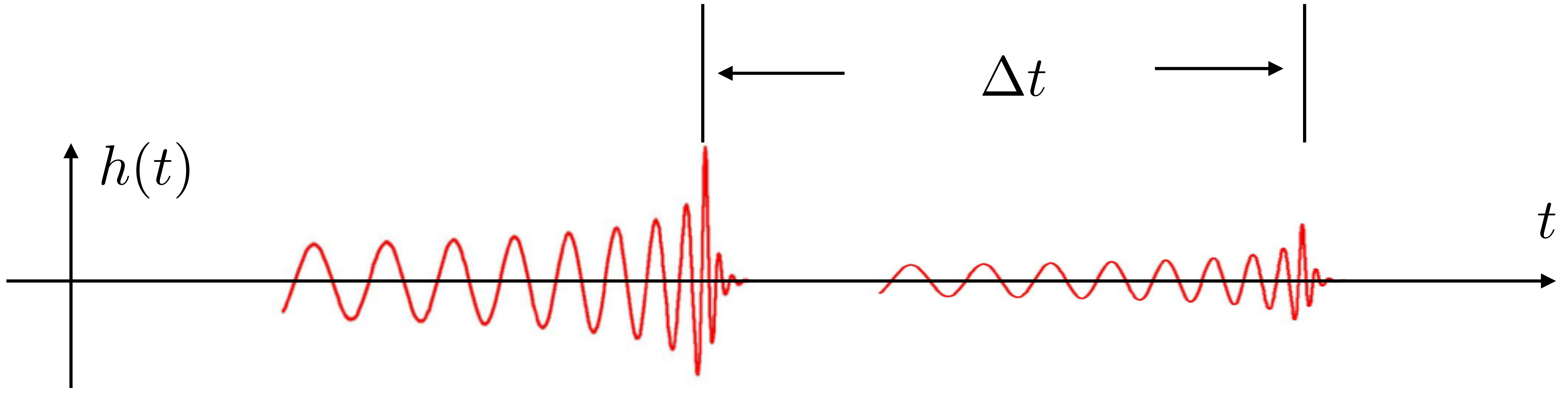
GW Waveform from Compact Binary Masses



Wave frequency (= 2 x orbital frequency) increases as an accelerating pace
Wave amplitude grows until the point of merger

Geometric & Wave Diffractive Lensing

Geometric lensing: characteristic delay time $\sim \dfrac{G\,M_L}{c^3} \gg \dfrac{2\pi}{\omega}$



Multiple images from geometric lensing:

Identical frequency chirping
Delays in arrival times
Different amplifications

Diffractive lensing: characteristic delay time $\sim \dfrac{G\,M_L}{c^3} \lesssim \dfrac{2\pi}{\omega}$

Diffraction integral $$F(\omega) = \frac{\omega}{2\,\pi\,i} \int d^2\boldsymbol{x}\, \exp\left[i\,\omega\,\left(\tau_{\rm geo}(\boldsymbol{x}) + \tau_{\rm gr}(\boldsymbol{x})\right)\right]$$ Schneider, Ehlers & Falco 1992

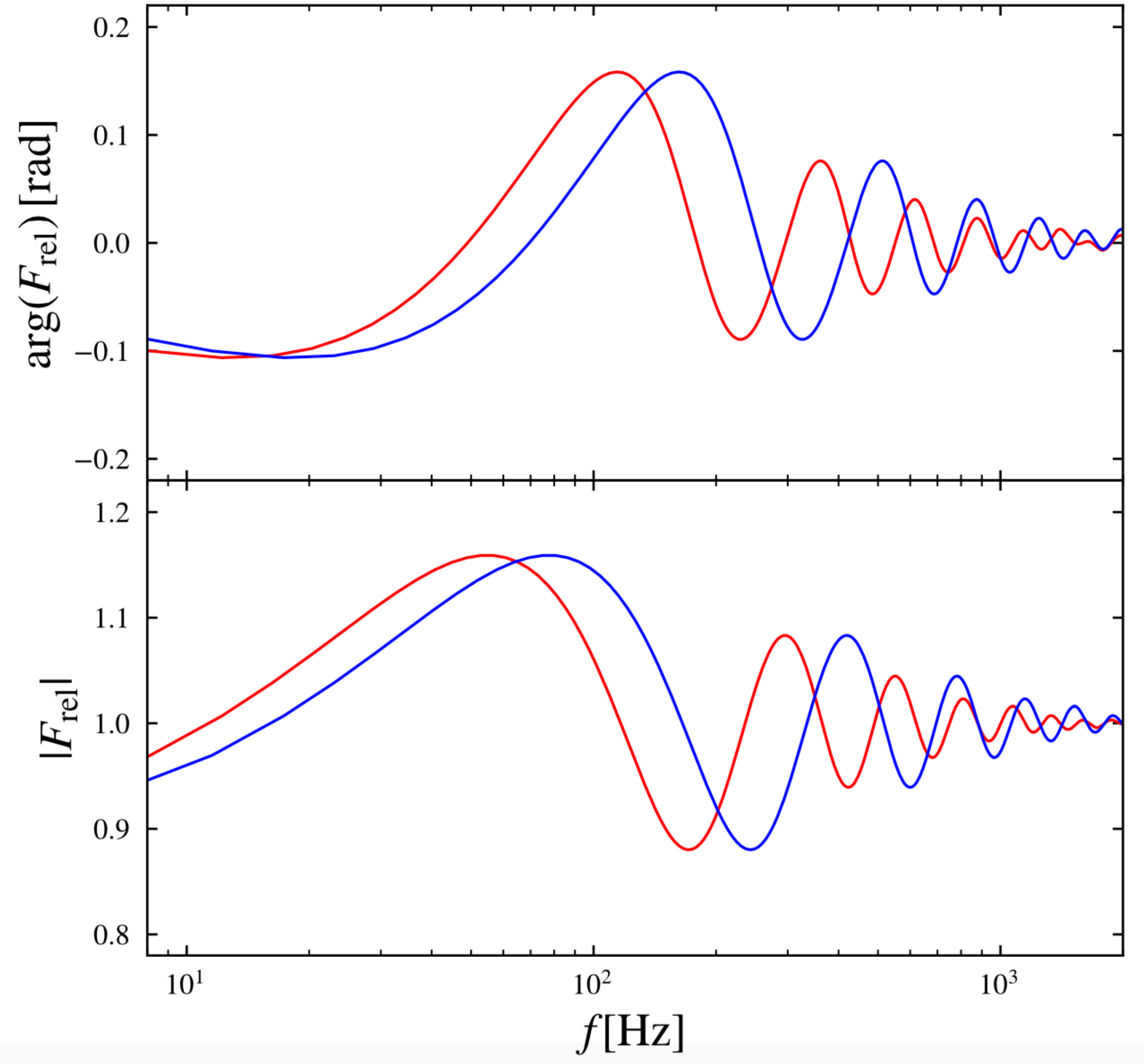
Nakamura 1998 $$h_{\rm obs}(\omega) = F(\omega)\,h(\omega)$$

amplitude and phase distortions

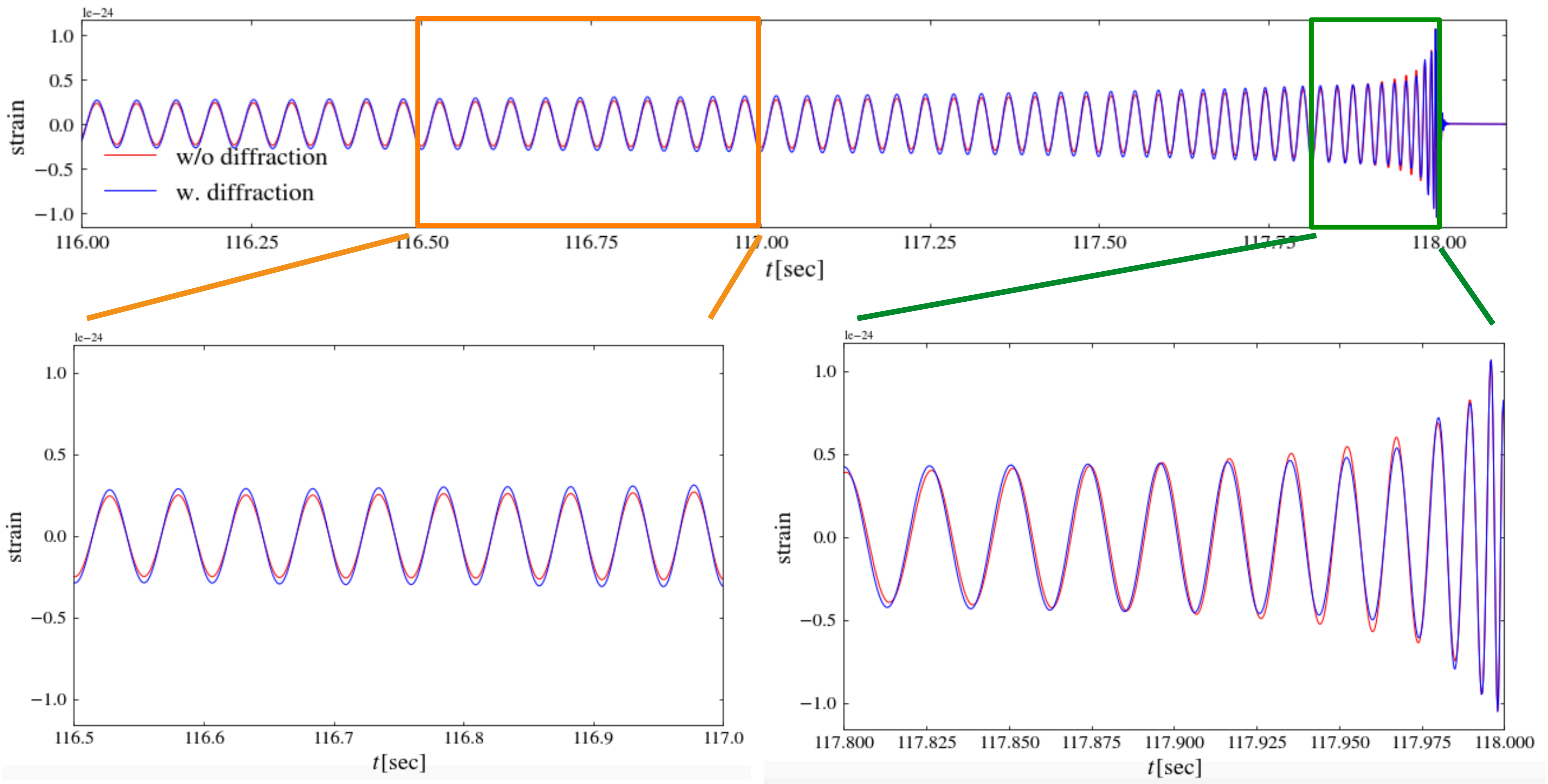
Wave Diffraction by Extended Lenses

Does not require multiple images
Probe **sub-critical lenses**

Effect of an isothermal lens



LD, Li, Zackay, Mao & Lu 18'



Seemingly subtle, diffraction distortions detectable through **maximizing the matched filtering likelihood !**

Practical Difficulties With Templates

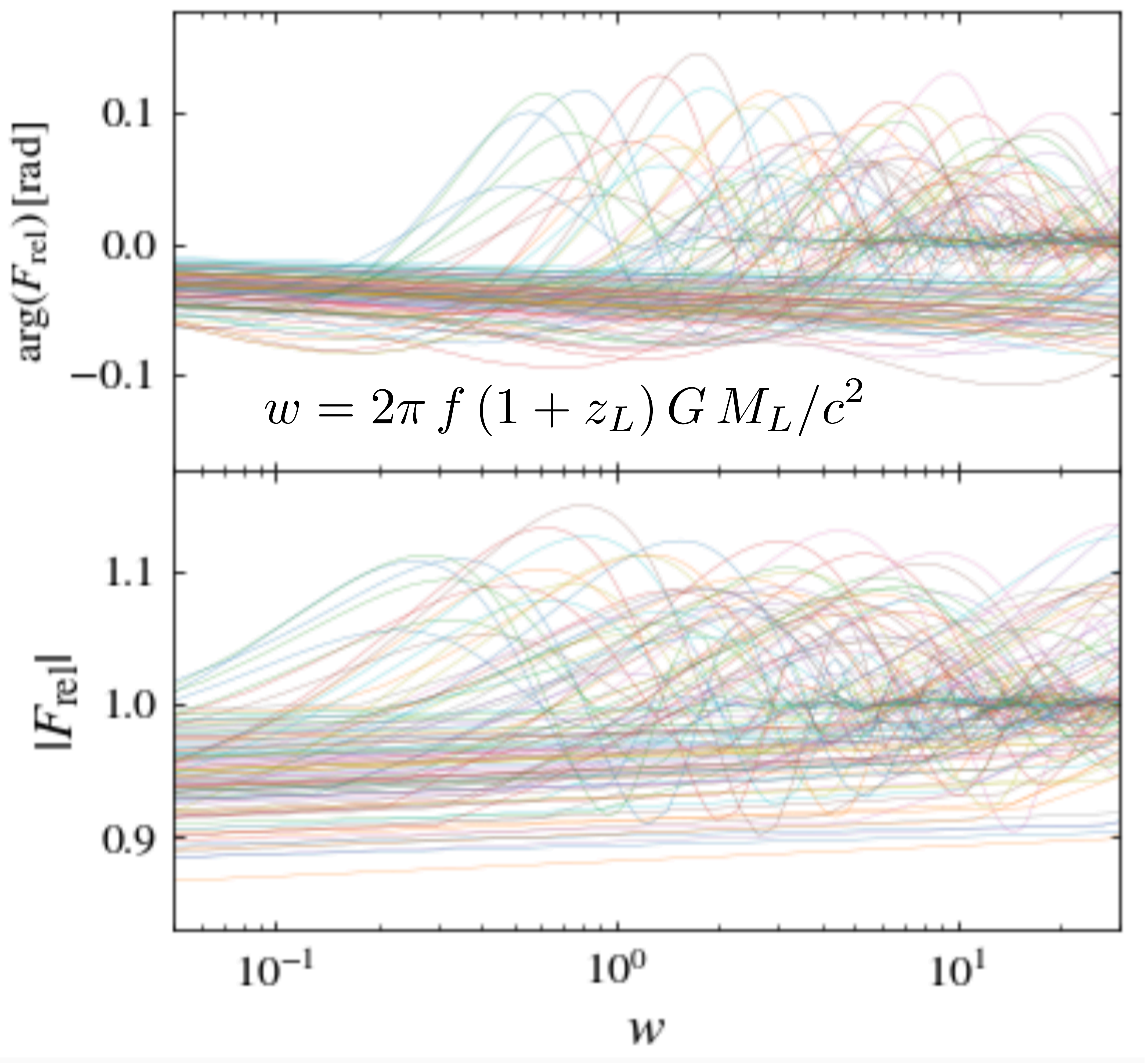
Matched filtering requires the **precise** knowledge of F(f)

In reality, F(f) will depend on too many parameters:

lens profile, distances, impact parameter, etc

These parameters are unknown

Have to search for a large number of templates, but ideally need to mitigate **the look elsewhere effect** as much as possible



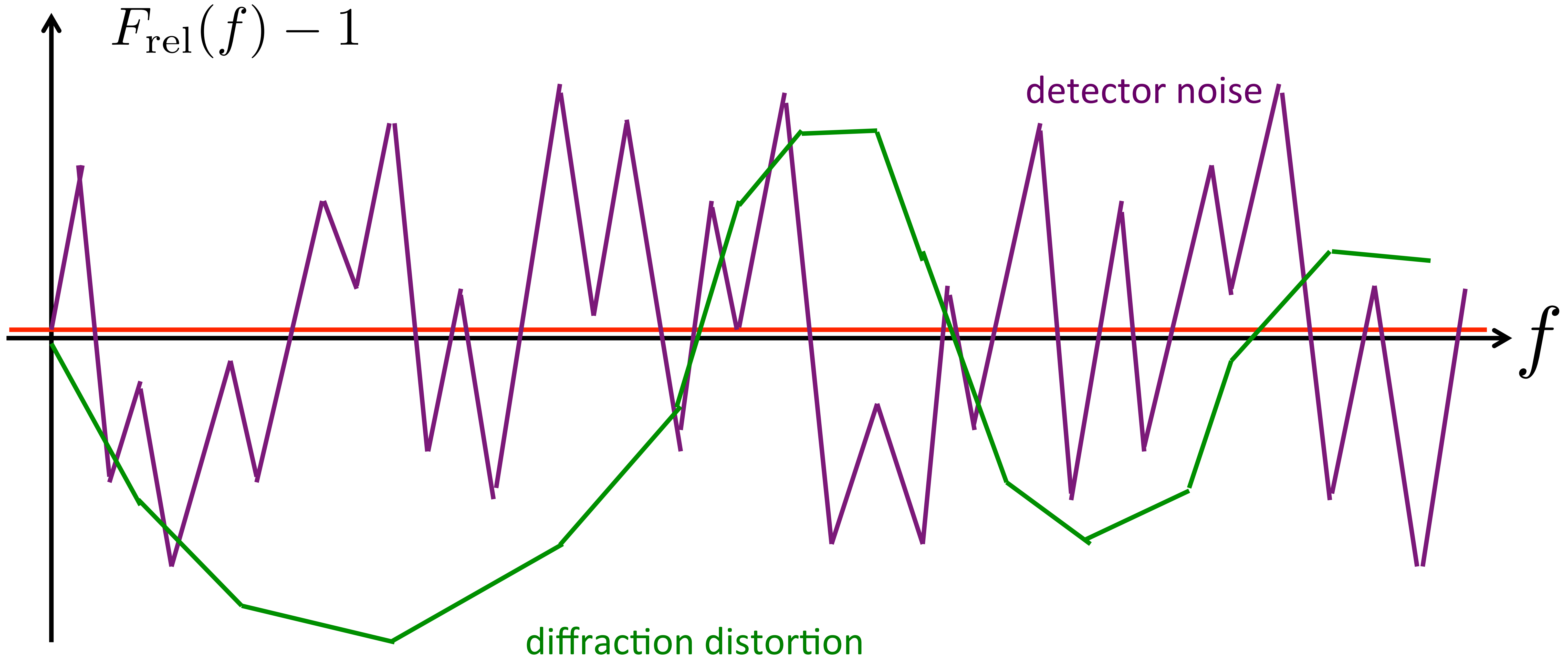
A Practical and Efficient Solution

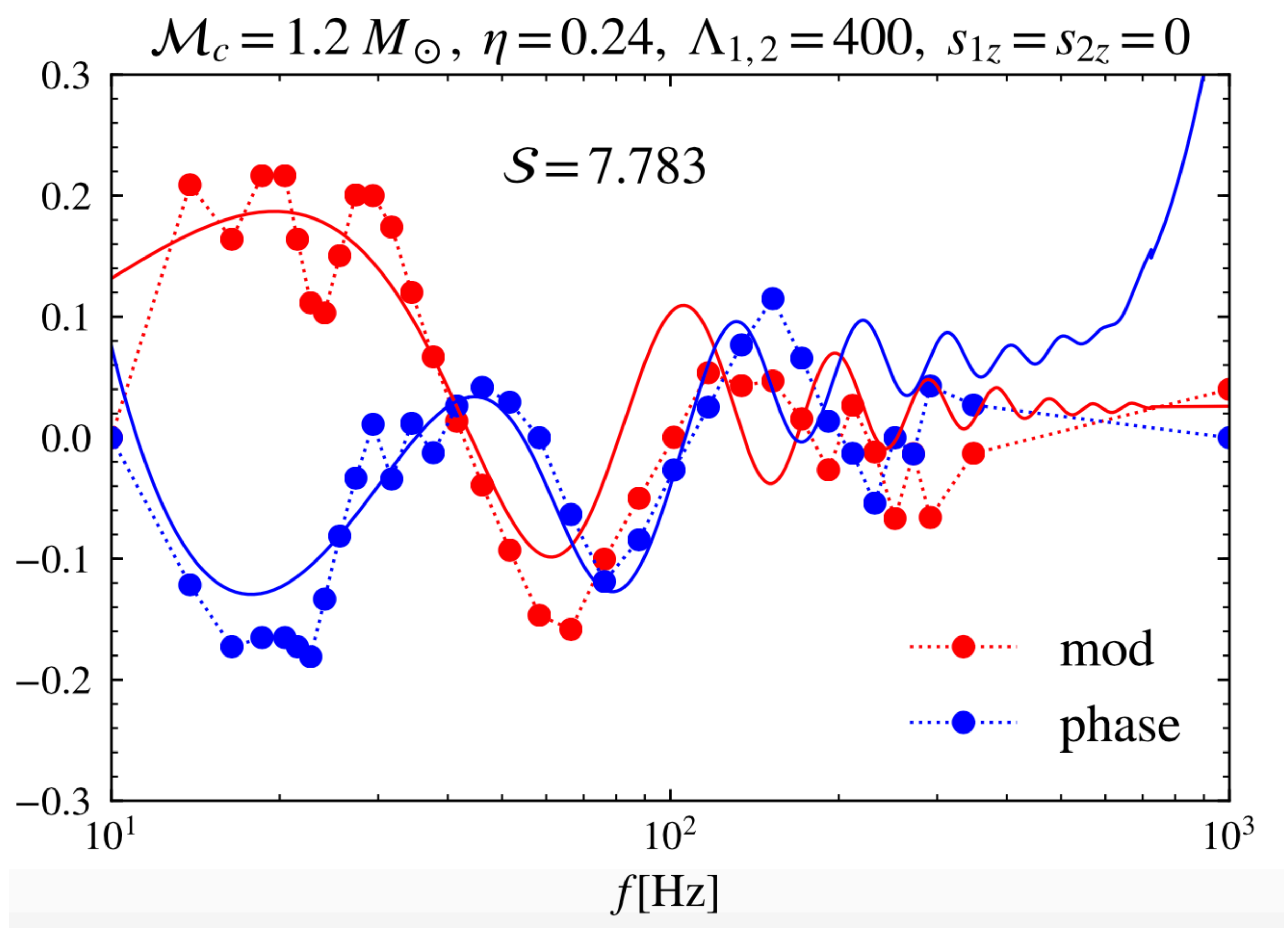
LD, Li, Zackay, Mao & Lu 18'

$$\mathcal{S} := \int \mathcal{D}g(f)\,\mathcal{P}\left[g(f)\right] \prod_{a=1}^{N_d} \frac{P[s_a(f)|g(f)\,h_{\mathrm{BF},a}(f)]}{P[s_a(f)|h_{\mathrm{BF},a}(f)]}$$

model-free amplitude and phase distortion reconstruction

(called Forward and Viterbi algorithms in signal processing)





Summary

- **Extreme magnification** of cosmological sources one of the best ways to probe non-luminous DM structures on small scales. To be thoroughly explored theoretically and observationally.
- Several applications:
  - **Microlensing** by compact halo objects
  - **“Nano-lensing”** by (sub-)planetary mass DM minihalos
  - **Astrometric** and **photometric** imprints of sub-galactic DM halos
- **Wave diffraction** of GWs from distant mergers is a new way to probe sub-galactic DM structures.