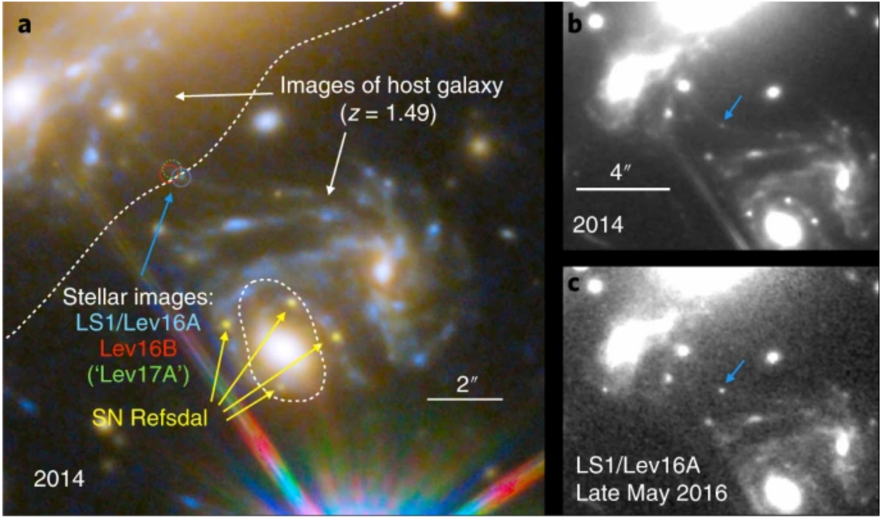
Uncovering Dark Matter Substructure with Caustic Lensing Events

Raghuveer Garani

Caustics

MACS J1149 Lensed Star 1: Icarus

Kelly et al. Nature Astronomy volume 2 (2018)



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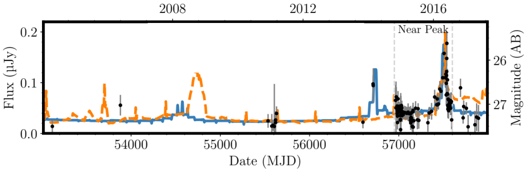
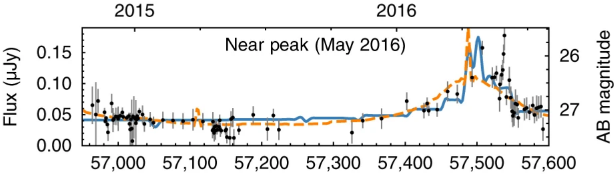
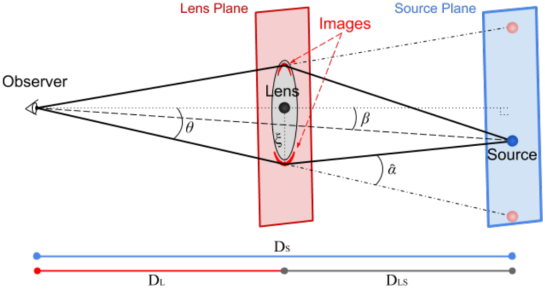




- Asymmetric light curve
- Slow increase followed by a dramatic drop

Gravitaional lensing

Point mass lens



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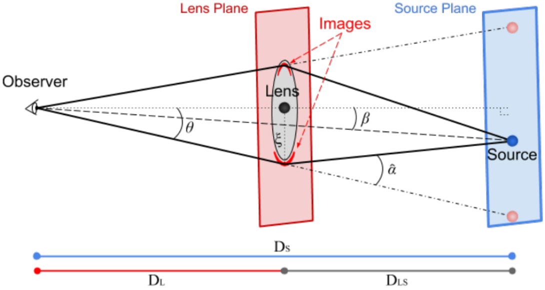
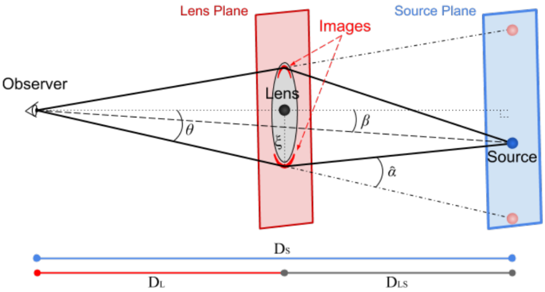


$$\beta = \theta - \frac{\theta_E^2}{\theta} \quad \text{with} \quad \theta_E = \sqrt{4GM\frac{D_{LS}}{D_L D_S}}$$

Gravitaional lensing

Point mass lens



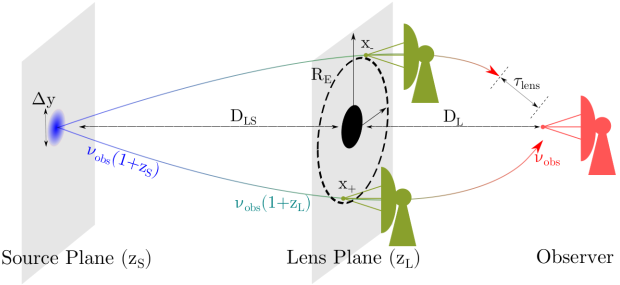
$$\beta = \theta - \frac{\theta_E^2}{\theta} \quad \text{with} \quad \theta_E = \sqrt{4GM\frac{D_{LS}}{D_L D_S}}$$

$$\text{Magnification :} \quad \mu = |\frac{\theta}{\beta}\frac{d\theta}{d\beta}|$$

Critical curve: $\mu^{-1} = 0 \implies \theta = \theta_E$

Gravitational lensing

In generality



Gravitational lensing

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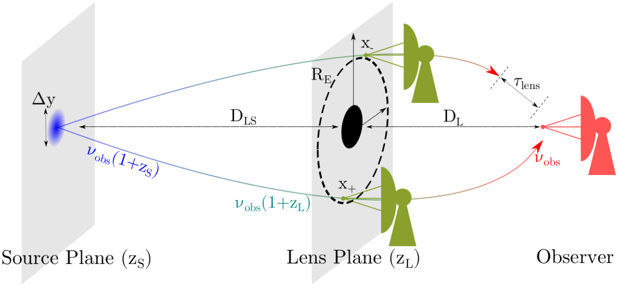


$$F(\vec{y},\lambda) = \frac{(1+z_l)}{i\lambda}\frac{D_L D_S}{D_{LS}}\int d^2\mathbf{x} \quad \exp\left(2\pi i c\frac{(1+z_l)\tau(\mathbf{x};\mathbf{y})}{\lambda}\right)$$

$$\tau(\mathbf{x};\mathbf{y}) = \frac{D_L D_S}{c D_{LS}}\left(\frac{1}{2}(\mathbf{x}-\mathbf{y})^2 - \phi(\mathbf{x})\right)$$

Gravitational lensing

Outline of the calculation

- Magnification $= |F(\vec{y}, \lambda)|^2$

$$\tau(\mathbf{x};\mathbf{y}) = \frac{D_L D_S}{c D_{LS}} \left(\frac{1}{2}(\mathbf{x}-\mathbf{y})^2 - \phi(\mathbf{x}) \right)$$

- Lensing equation: Minimize time delay function, $\partial\tau(\mathbf{x};\mathbf{y})$
- Gravitational potential encoded in $\phi(\mathbf{x})$. For point mass lens $\rightarrow \int drU(r) \sim \ln|\mathbf{x}|$
- Caustics: Expand τ around critical curve
- $q = 1/\partial_1^3\tau(x_0)$ and $\omega \sim$ Gravitational radius/wavelength

$$|F|^2 \sim \mathrm{Ai}^2(-(q\omega^2)^{1/3} y_1)$$

Caustic lensing

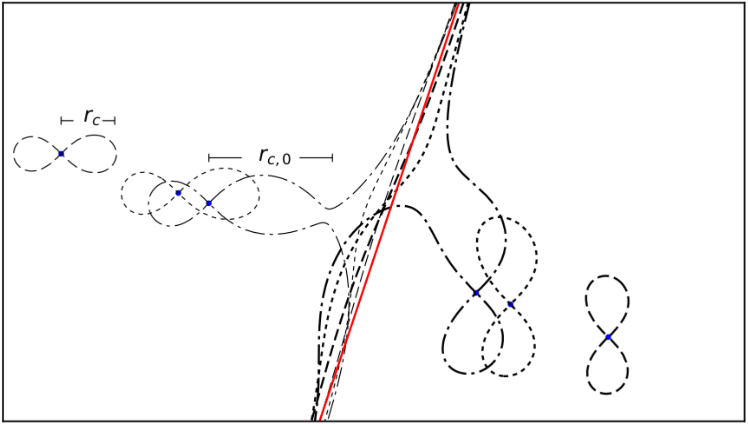
M. Oguri (Glafic): Isothermal sphere

Caustic lensing

M. Oguri (Glafic): With shear

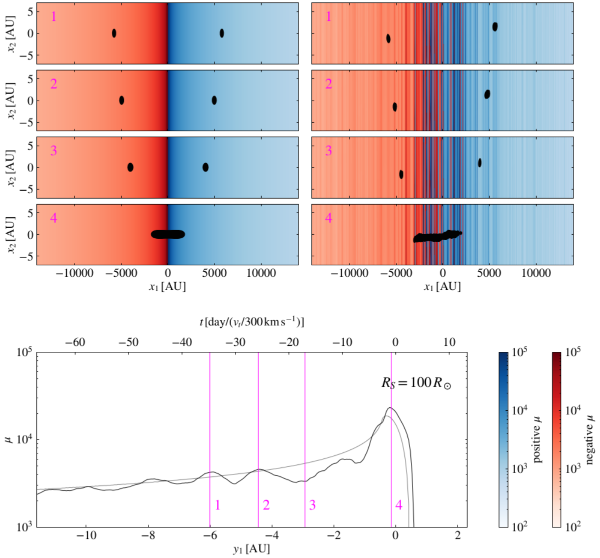
Microlenses in a bigger lens

Venumadhav, Dai & Miralda-Escudé 2018



Microlenses in a bigger lens

Dai & Miralda-Escudé 2020



QCD Axion

Peccei-Quinn '77, Weinberg-Wilczek '78

- Solves more problems than it causes – [unknown]

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$$\left(\theta - \frac{a}{f_a}\right)\frac{\alpha_s}{8\pi}G\tilde{G}$$

- Dark matter?

$$V(a) = \frac{1}{2}m_a^2(T)a^2 + \cdots$$

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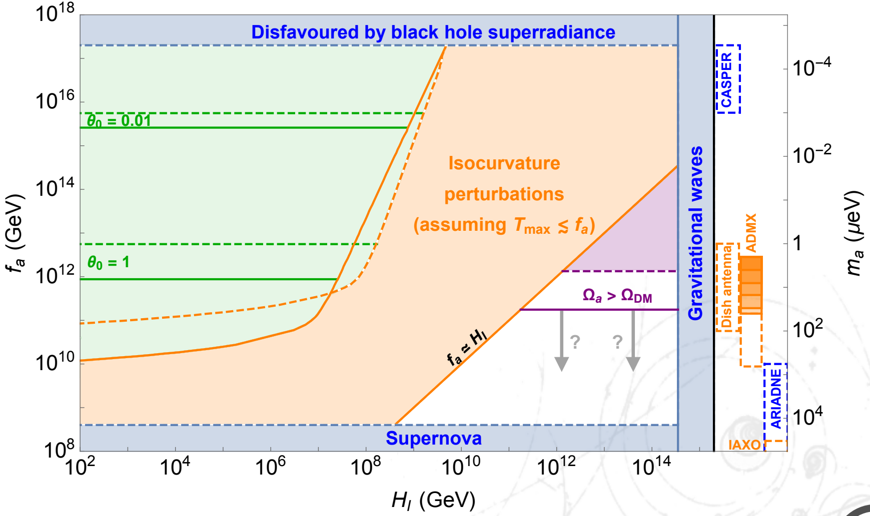
- Post-inflationary ($f_a < \text{Max}[\frac{H_I}{2\pi}, T_{\text{max}}]$): string-network + domain walls $\rightarrow$ relic abundance uncertain

Cosmology of 'The QCD axion, precisely'

Grilli di Cortona, Hardy, Vega, Villadoro '16



QCD axion miniclusters

Tkachev '87, Kolb & Tkachev '93

- $\Phi = \delta\rho/\rho \sim 1$
- Minicluster mass set by $m_a(T_\star) = H(T_\star)$

$$M_{\rm MC} = \pi^2 g_\star(T_\star) T_\star^3 T_{\rm eq}/(30 H^3(T_\star)) \approx 5\times 10^{-12}(\Omega_a h^2)\, M_\odot\ .$$

- The minicluster decouples from expansion when $T \sim (1+\Phi)T_{\rm eq}$

$$\rho_c = 140(1+\Phi)\Phi^3 \rho_a(T_{\rm eq}) \approx 4\times 10^8 (1+\Phi)\Phi^3 \left(\Omega_a h^2\right)^4 \frac{\rm M_\odot}{\rm pc^3}\ .$$

- Mass function unknown. Need simulation (survival? mergers?)

$$\frac{d\,F}{d\ln M} = f_{\rm DM} M \delta(M - M_{\rm MC}).$$

Surface density power spectrum

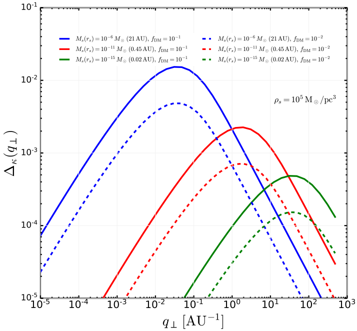
RG, Redi, Tesi; in progress

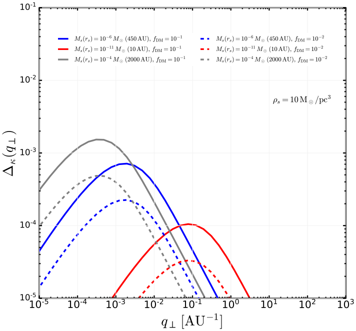
- 2D-projected power spectrum

$$P_\kappa(q_\perp) = \frac{\bar{\Sigma}_{\rm cl}}{\Sigma^2_{\rm crit}} \int \frac{\mathrm{dlnM}}{M} \frac{\mathrm{dF}}{\mathrm{d\,lnM}} |\tilde{\rho}(q_\perp; M)|^2 .$$

- Lensing convergence: $\Delta^2_\kappa(q_\perp) = q^2_\perp P_\kappa(q_\perp)/2\pi \propto$ fluctuations in the light curve!

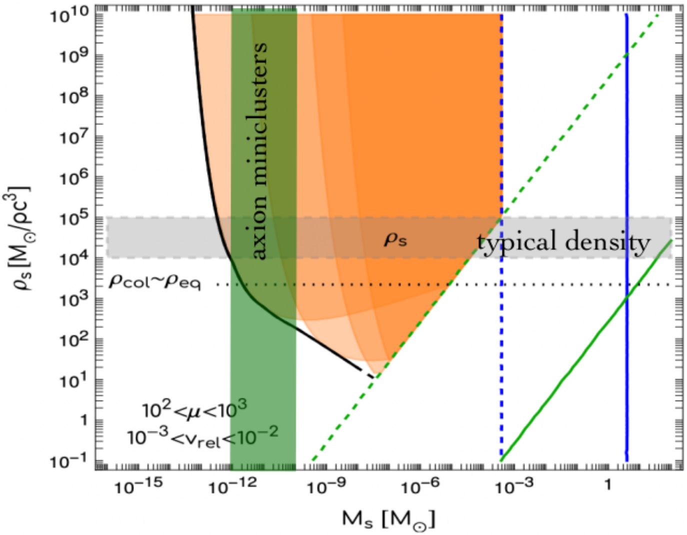
$$\Delta_\kappa(q_\perp \sim \frac{2\pi}{r_s}) \approx 0.6 f^{1/2}_{\rm DM} \left(\frac{2\times 10^4\, M_\odot/pc^2}{\Sigma_c}\right)^{1/2} \left(\frac{M_s}{10^{-6}\, M_\odot}\right)^{1/6} \left(\frac{\rho_s}{140\, \rho_{\rm eq}}\right)^{1/3} .$$





Preliminary limits axion Miniclusters

RG, Redi, Tesi; in progress



Outlook

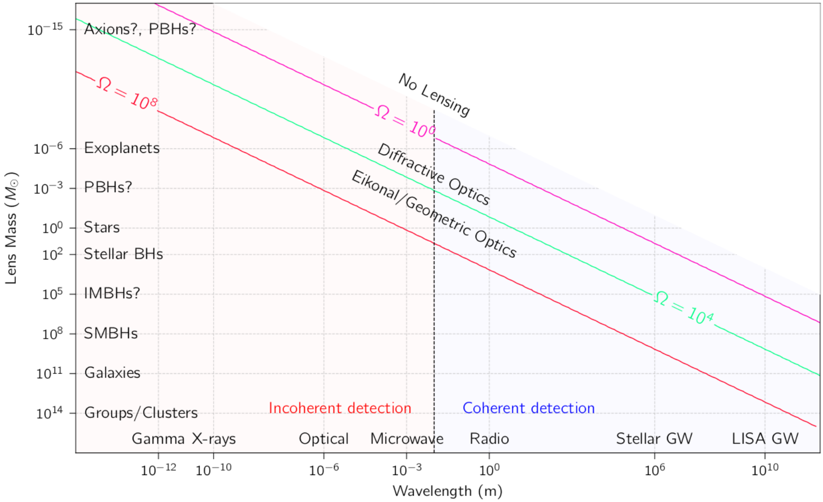
- Photometric lensing or microlensing along the caustics could be powerful probes of small scale structures
- Implement improved lens + microlens models
- Refine caustic calculations in diffraction regime
- Several new suspected caustic lensing events recently obseved
- Can this do better than traditional microlensing for PBH?

LS1 properties

Oguri et al. '18

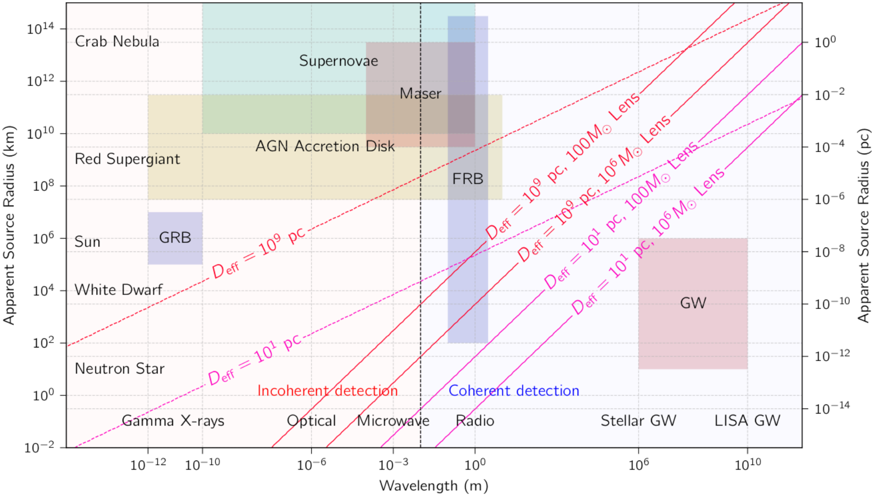
- In ΛCDM MACS J1149 LS1 is $z_l = 0.544$, and the source redshift $z_s = 1.49$
- Physical distances: 6.4 kpc/arcsec at lens and 8.5 kpc/arcsec for the source
- Surface temperature $\sim 11,000$ K, $v \sim 1000 km/s$

Regimes



Axions?, PBHs?
Exoplanets
PBHs?
Stars
Stellar BHs
IMBHs?
SMBHs
Galaxies
Groups/Clusters
No Lensing
Ω = 10⁸
Ω = 10⁰
Ω = 10⁴
Diffractive Optics
Eikonal/Geometric Optics
Incoherent detection
Coherent detection
Gamma X-rays
Optical
Microwave
Radio
Stellar GW
LISA GW
Lens Mass (M☉)
Wavelength (m)

Sources


Crab Nebula
Supernovae
Maser
Red Supergiant
AGN Accretion Disk
FRB
Sun
GRB
White Dwarf
Neutron Star
GW
Incoherent detection
Coherent detection
Gamma X-rays
Optical
Microwave
Radio
Stellar GW
LISA GW
$D_{eff} = 10^9$ pc
$D_{eff} = 10^1$ pc
$D_{eff} = 10^9$ pc, $100M_\odot$ Lens
$D_{eff} = 10^9$ pc, $10^6 M_\odot$ Lens
$D_{eff} = 10^1$ pc, $100M_\odot$ Lens
$D_{eff} = 10^1$ pc, $10^6 M_\odot$ Lens
Apparent Source Radius (km)
Apparent Source Radius (pc)
Wavelength (m)