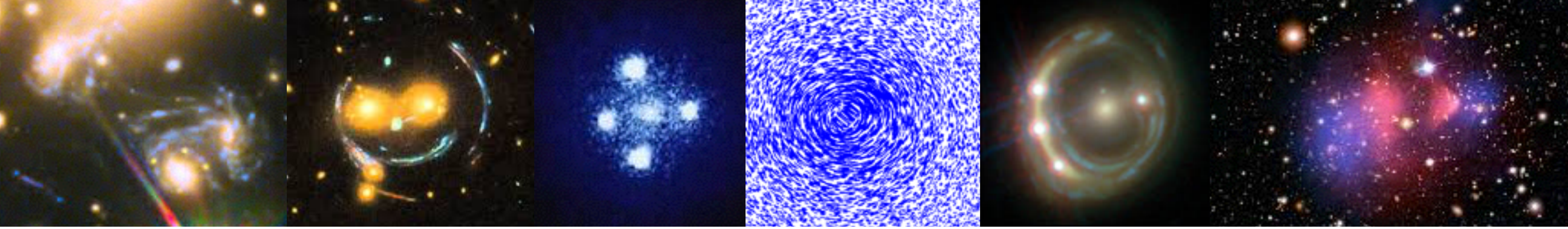

PHY-765 SS18 Gravitational Lensing Week 15

Course Summary and Q&A

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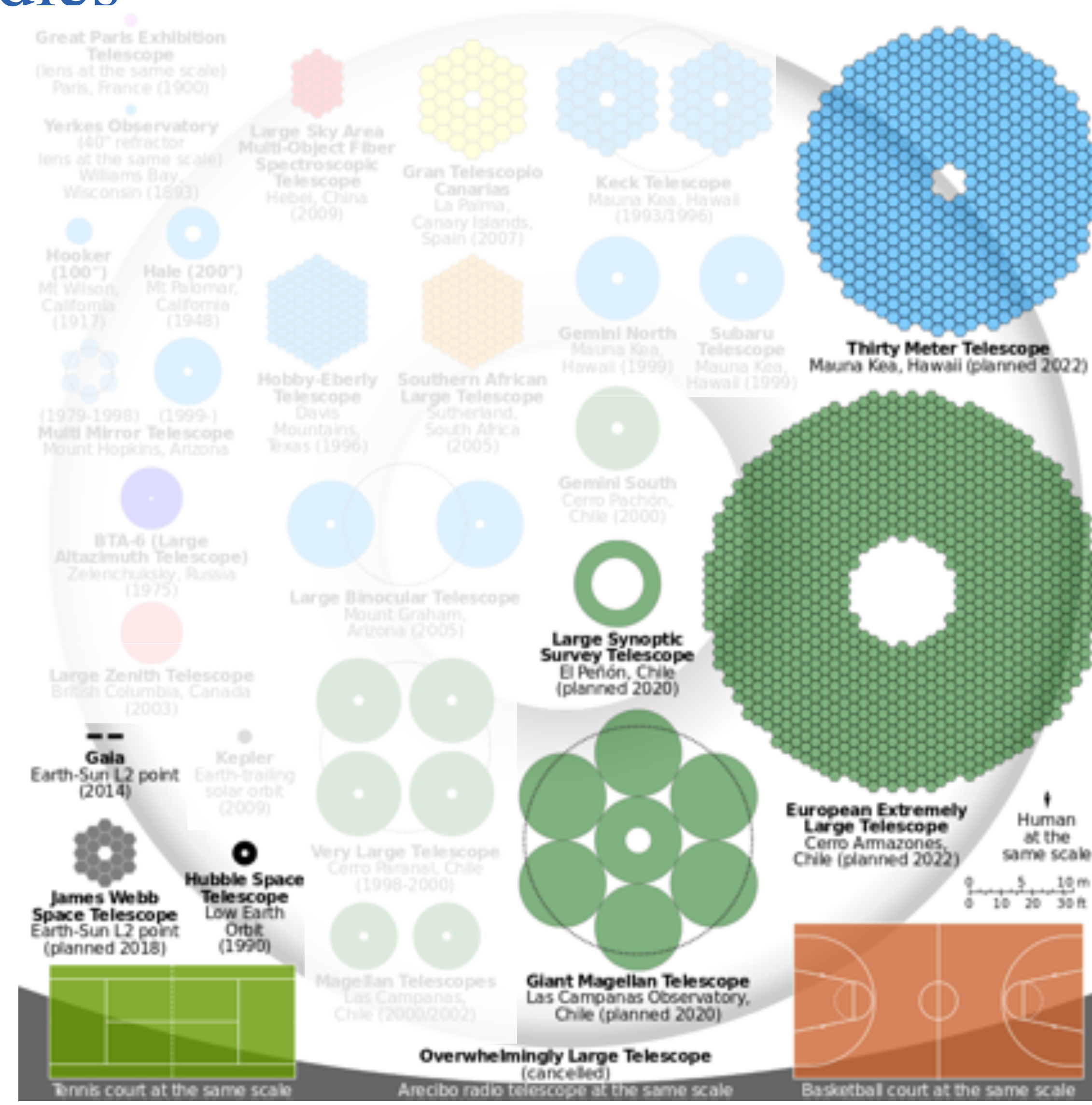
Last week

- (Incomplete) Overview of The Future of GL:

Ongoing (Now)
  - HST: Source follow-up and lensing clusters
  - OGLE/MicroFUN: Monitoring campaign of microlensing events
  - Gaia: Billions of points source; QSO lens ‘contaminants’
  - SDSS: Spec surveys incl. BAO studies
  - DES: Large-area imaging survey

Early ‘20s
  - LSST: Large-area imaging survey
  - JWST: Individual objects

Late ‘20s
  - WFIRST: Large-area survey
  - ELTs: “HST from the ground”



- ✓ Cluster lensing
- ✓ QSO lensing
- ✓ Galaxy-Galaxy lensing
- ✓ Star-Star microlensing
- ✓ Exoplanet searches with microlensing
- ✓ Wide-field weak lensing
- ✓ Power Spectrum lensing analysis

The aim of today

Summarize:

Course Topics &

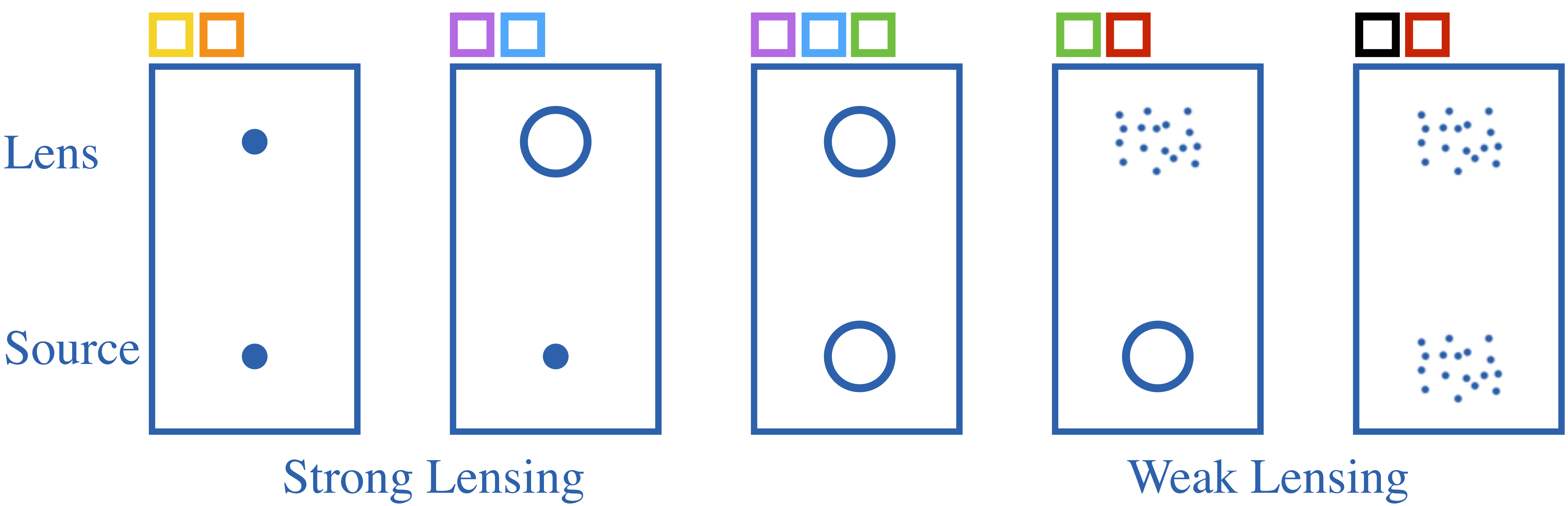
(some of) The Course Essentials

The Course Topics

Week 1: Introduction

Week 2: Basic Lens Geometry

Cluster lensing	Week: 4, 5, 6, 10, 14
QSO lensing	Week: 3, 4, 5, 6, 10, 14
Galaxy-Galaxy lensing	Week: 3, 4, 6, 10, 14
Star-Star microlensing	Week: 7, 8, 14
Exoplanet searches with microlensing	Week: 7, 8, 14
Wide-field weak lensing	Week: 6, 12, 13, 14
Power Spectrum lensing analysis	Week: 12, 13, 14



Lens Geometry

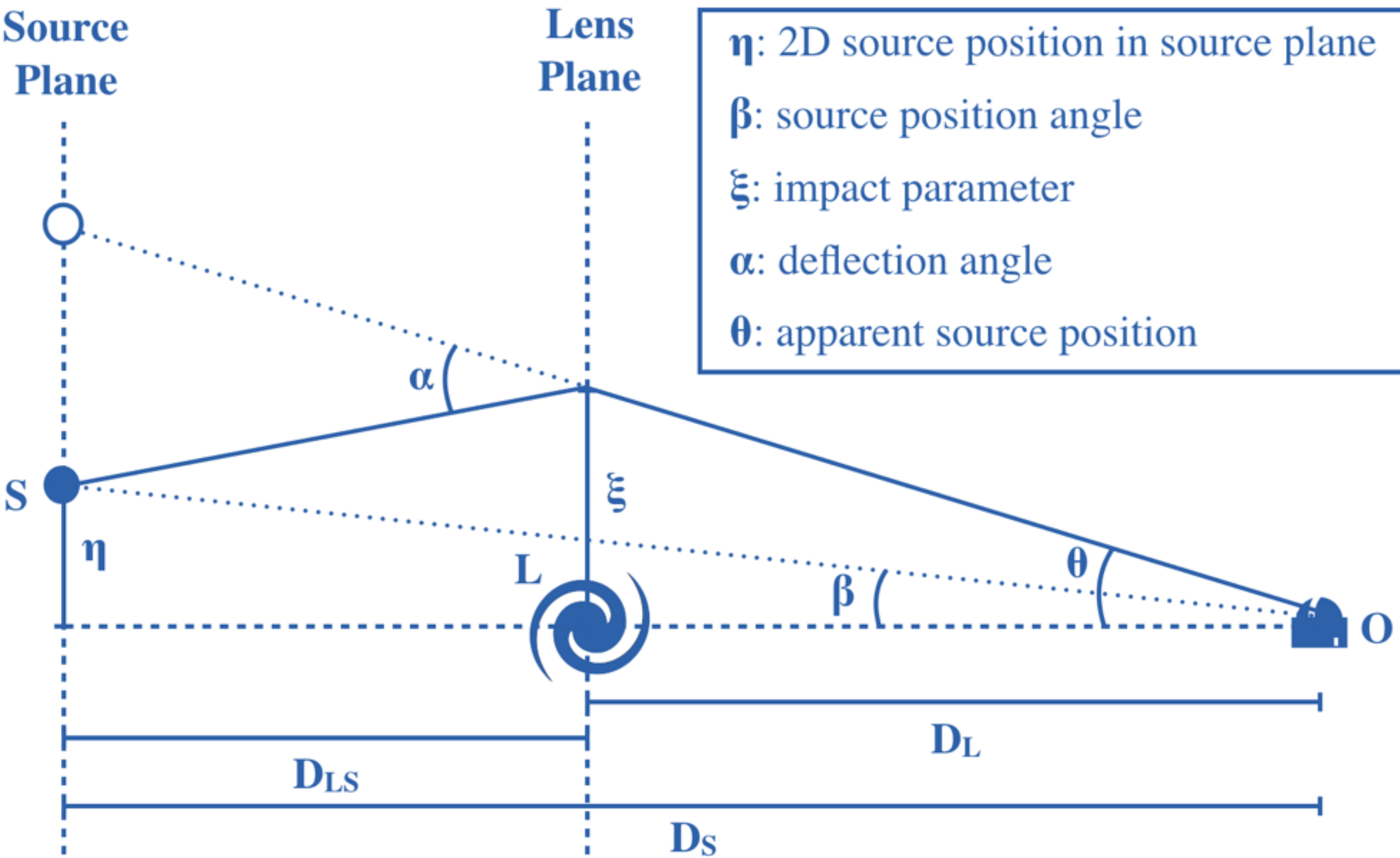
η: 2D source position in source plane

β: source position angle

ξ: impact parameter

α: deflection angle

θ: apparent source position



The Lens Equation

$$\boxed{\boldsymbol{\beta} = \boldsymbol{\theta} - \boldsymbol{\alpha}(\boldsymbol{\theta})}$$

- Obtained from geometrical consideration of GL (deflection angles)
- Provides (non-linear) mapping from source plane to lens/image plane
- The deflection angle, α, is governed by the lens' surface mass distribution

$$\kappa(\boldsymbol{\theta}) \equiv \frac{\Sigma(D_{\rm L}\boldsymbol{\theta})}{\Sigma_{\rm cr}} \qquad \Sigma_{\rm cr} \equiv \frac{c^2}{4\pi G}\frac{D_{\rm S}}{D_{\rm L}D_{\rm LS}}$$

- The point mass lens (PML):

$$\boldsymbol{\beta} = \boldsymbol{\theta} - \frac{4MGD_{\rm LS}}{c^2 D_{\rm S} D_{\rm L}}\frac{\boldsymbol{\theta}}{|\boldsymbol{\theta}|^2} \qquad \theta_E \equiv \sqrt{\frac{4MG}{c^2}\frac{D_{\rm LS}}{D_{\rm S}D_{\rm L}}}$$

LE Consequences 1: Multiple Images

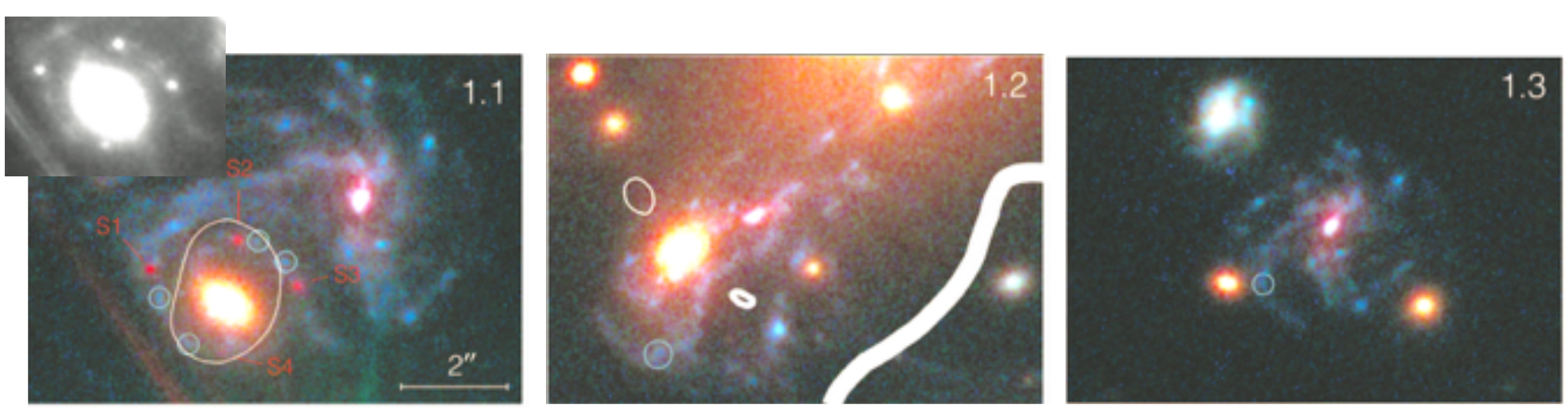
- The PML:

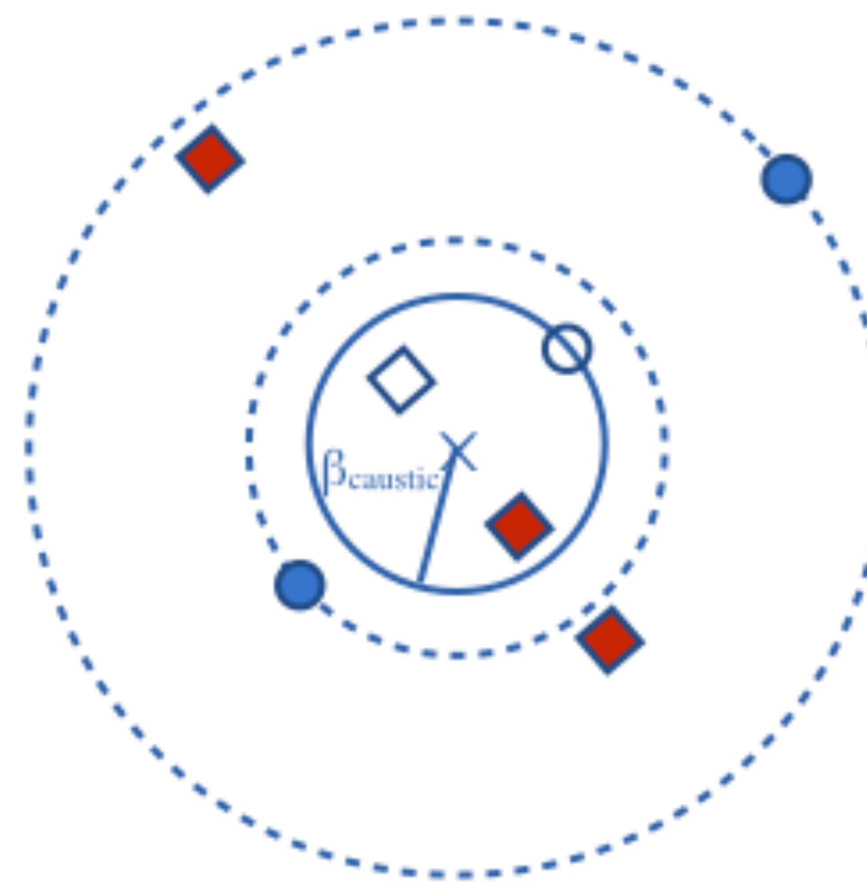
$$\theta_{\pm} = \frac{\beta}{2}\left[1 \pm \sqrt{1 + \frac{4\theta_E^2}{\beta^2}}\right]$$

- Considered Isothermal Sphere (IS) - both spherical and cored version

$$\boldsymbol{\beta} = \boldsymbol{\theta} - \frac{\theta_0}{\theta^2}\left[\sqrt{\theta^2 + \theta_{\rm core}^2} - \theta_{\rm core}\right]\boldsymbol{\theta} \qquad \theta_E = \theta_0\sqrt{1 - 2\frac{\theta_{\rm core}}{\theta_0}}$$

- Defined caustics and critical curves
  - Critical curves are where images fall if source is on the caustic
  - Where pairs of images are created/destroyed
  - Caustic is where
- SN Refsdal: Multiple Images at it's best





LE Consequences 2: Time Delays

- The arrival (travel) time of light from multiple images differ due to
  - change in the gravitational potential (The Shapiro time delay)
  - geometry as the light travels along different paths

Only depends on distances; no lens details

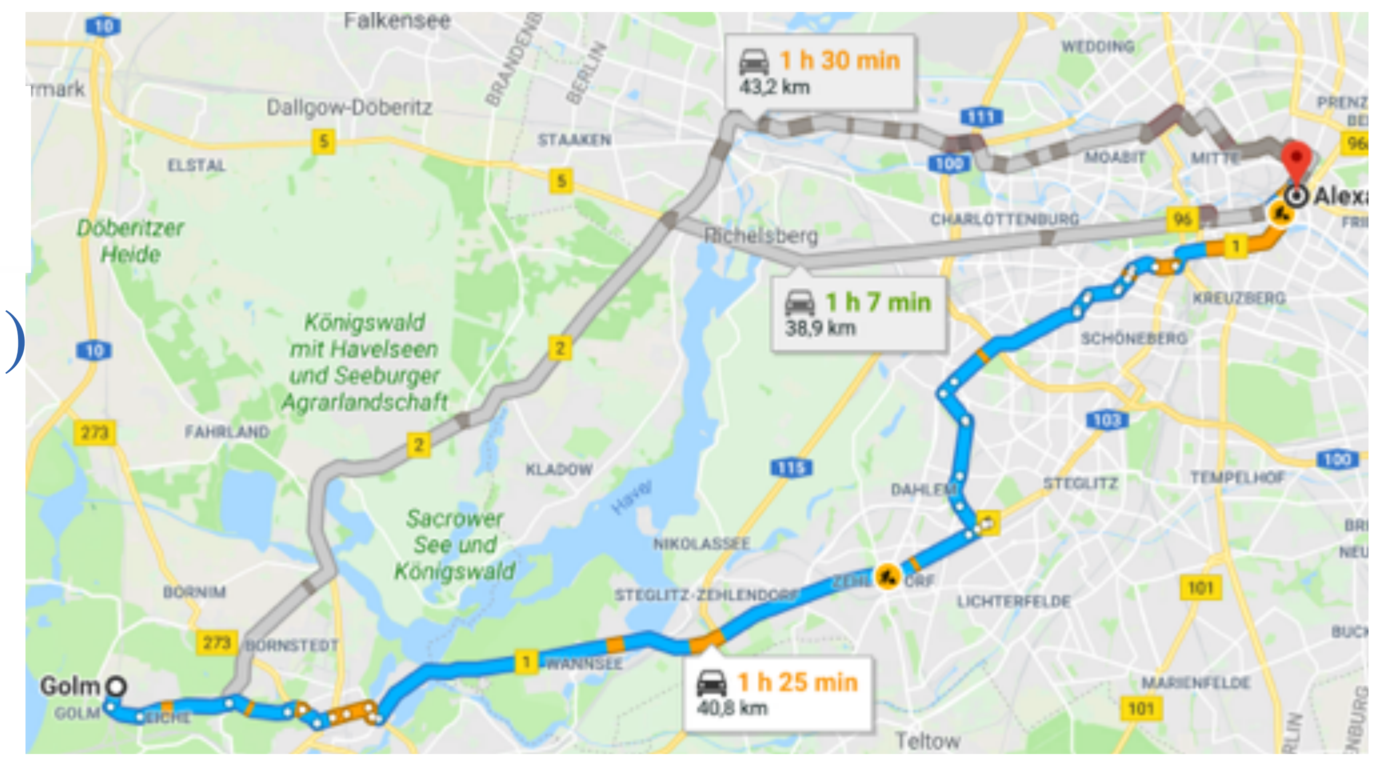
$$\Delta t = \frac{D_{\rm L} D_{\rm S}}{c D_{\rm LS}} \left[\frac{(\boldsymbol{\theta} - \boldsymbol{\beta})^2}{2} - \frac{\Phi(\boldsymbol{\theta})}{c^2} \right]$$

Only depends on lens mass distribution

- For the PML:

$$t_+ - t_- \simeq -(1 + z_{\rm L}) \frac{D_{\rm L} D_{\rm S}}{c D_{\rm LS}} 2c^2 \theta_E \beta$$

  - Light passing closest to the lens (t_-) is delayed the most
  - Light from image θ_+ arrive first

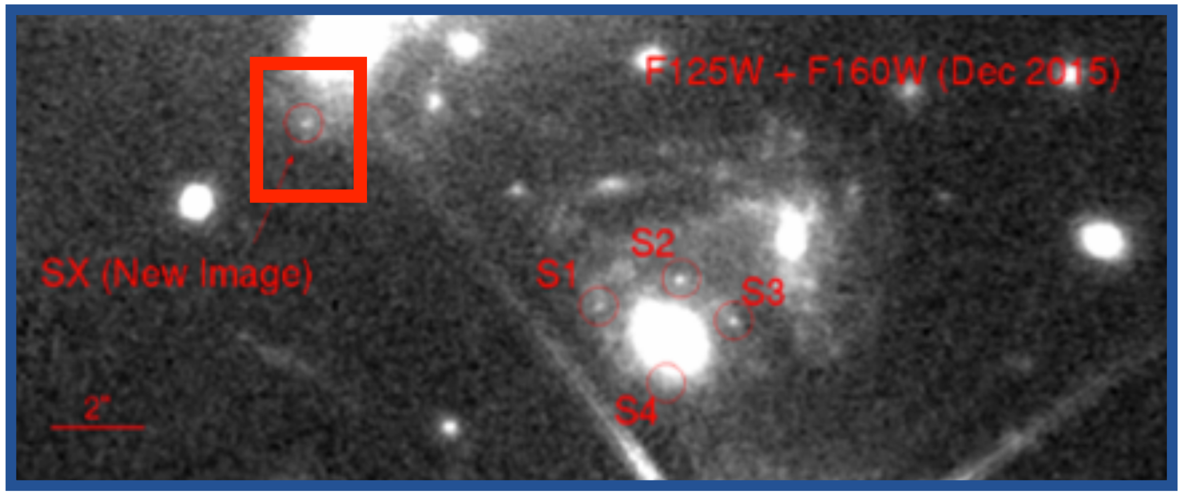


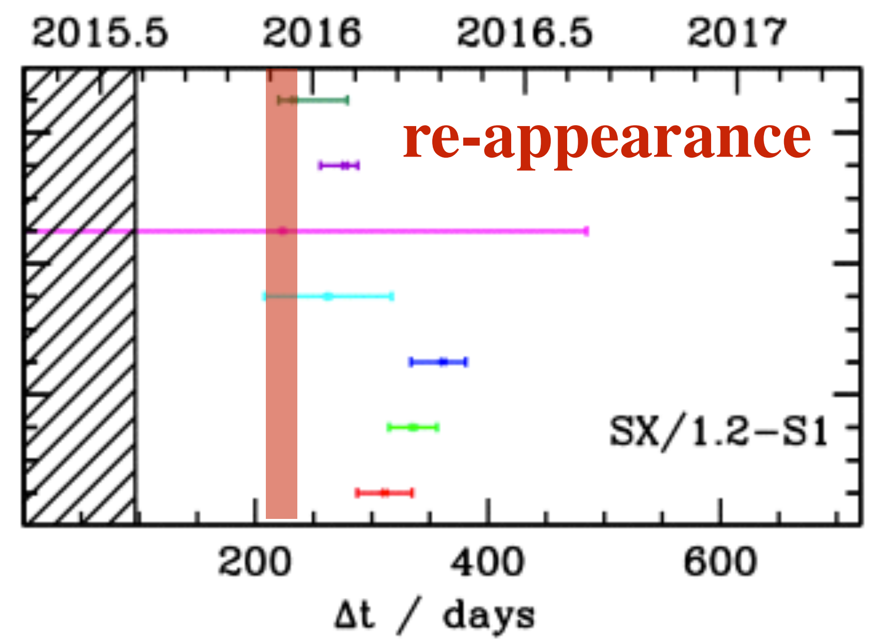
Geometry ~ route taken
Gravitational potential ~ traffic along route

LE Consequences 2: Time Delays

- SN Refsdal Reappearance December 11 2015

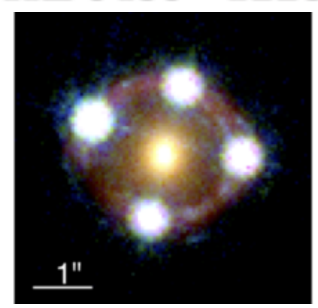
Treu+2016

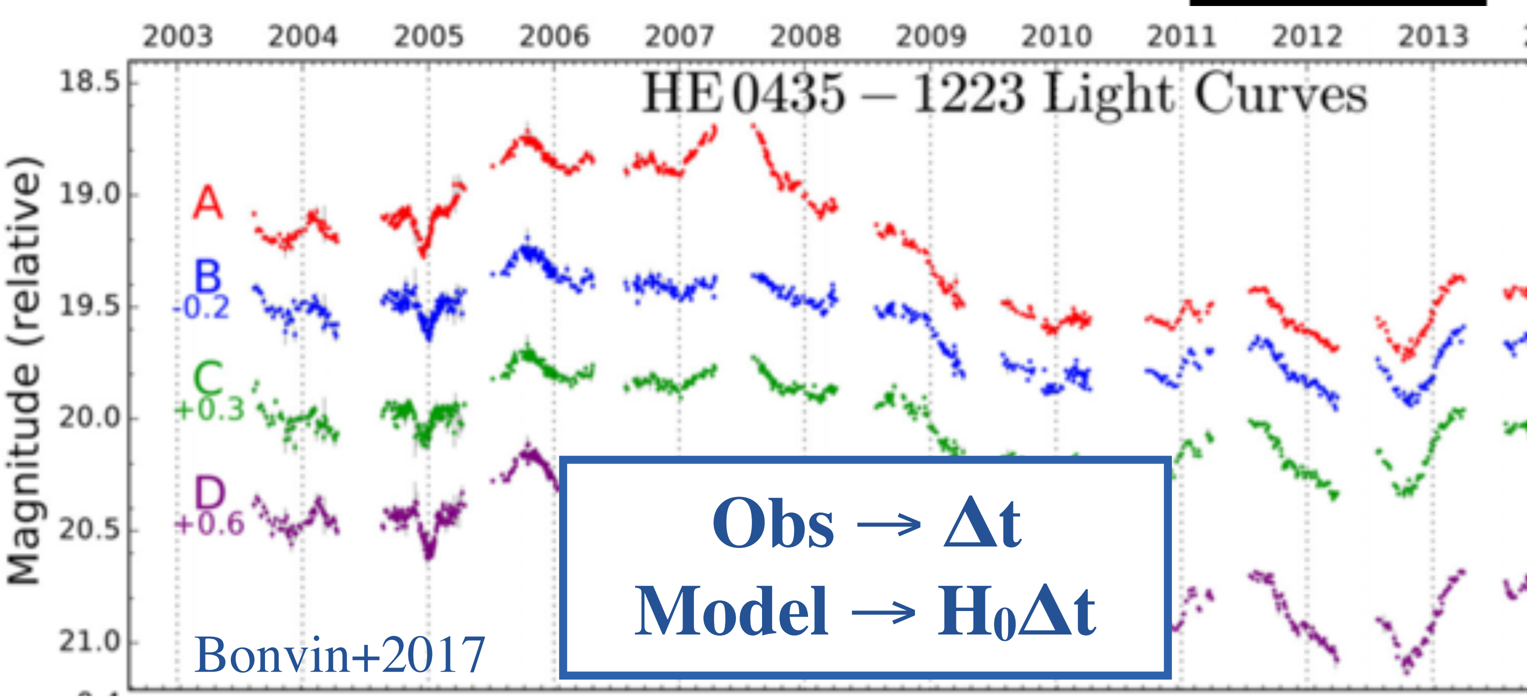




- COSMOGRAIL & H0LiCOW

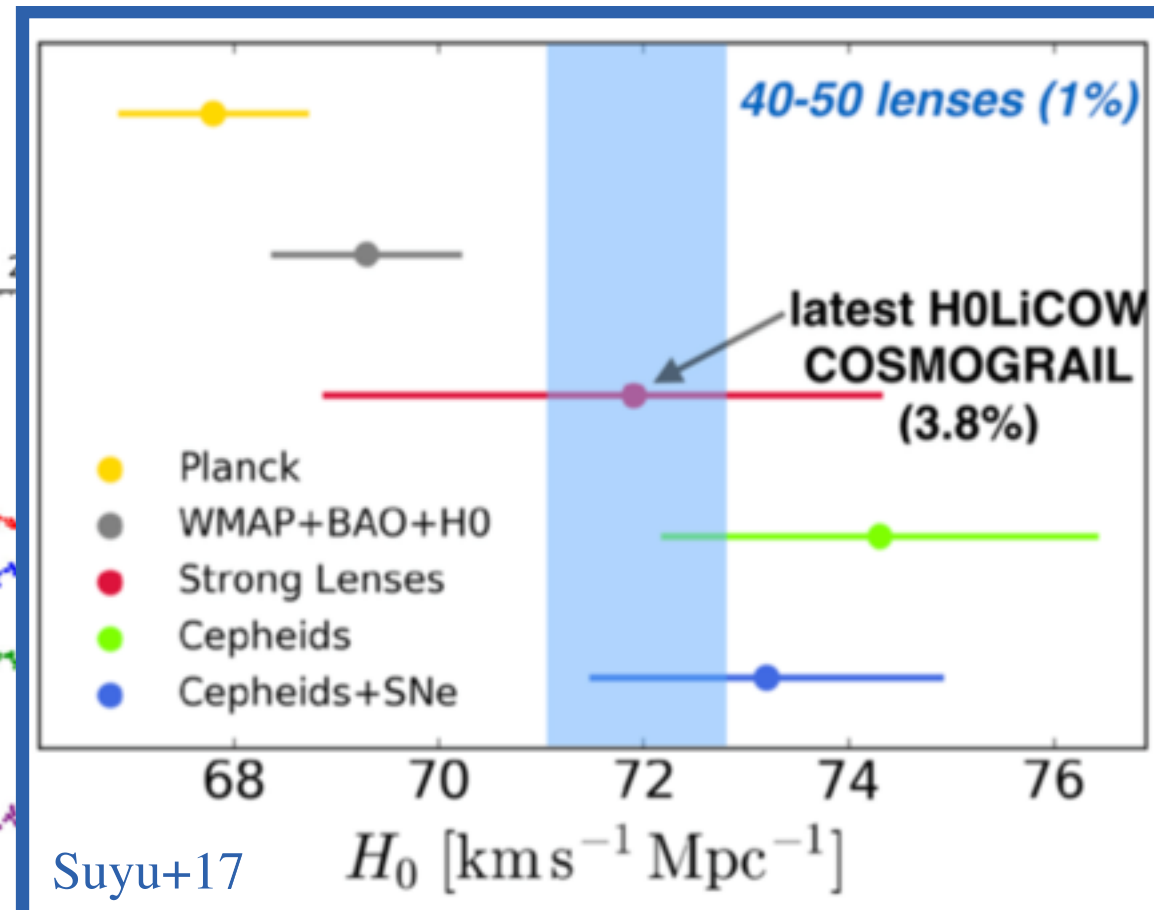
HE 0435−1223





Bonvin+2017

Obs → Δt
Model → $H_0\Delta t$



Suyu+17

LE Consequences 3: Magnification

- Introduced the Jacobian Matrix

$$\mathcal{A}(\boldsymbol{\theta}) = \frac{\partial \boldsymbol{\beta}}{\partial \boldsymbol{\theta}} = \begin{pmatrix} \frac{\partial \beta_i}{\partial \theta_i} & \frac{\partial \beta_i}{\partial \theta_j} \\ \frac{\partial \beta_j}{\partial \theta_i} & \frac{\partial \beta_j}{\partial \theta_j} \end{pmatrix}$$

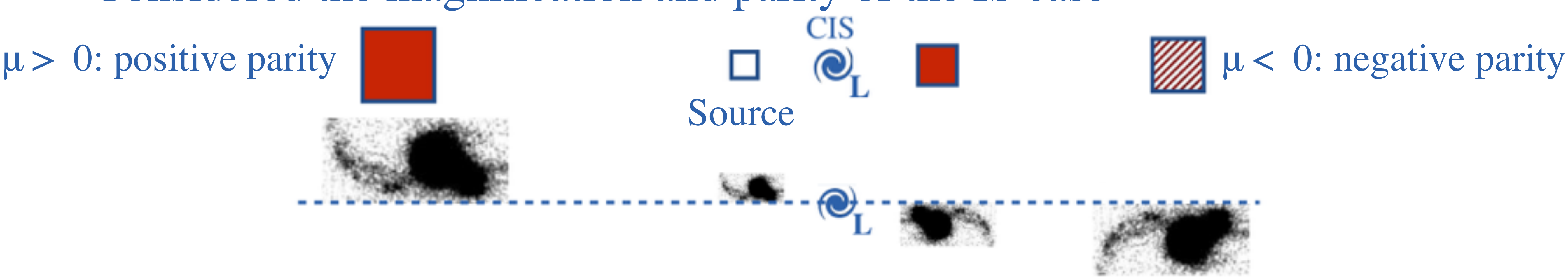
- Related this to the deflection angles and the gravitational potential

$$\mathcal{A}(\boldsymbol{\theta}) = \begin{pmatrix} 1 - \frac{\partial \alpha_i}{\partial \theta_i} & -\frac{\partial \alpha_i}{\partial \theta_j} \\ -\frac{\partial \alpha_j}{\partial \theta_i} & 1 - \frac{\partial \alpha_j}{\partial \theta_j} \end{pmatrix} = \begin{pmatrix} 1 - \frac{\partial^2 \psi}{\partial \theta_i^2} & -\frac{\partial^2 \psi}{\partial \theta_i \partial \theta_j} \\ -\frac{\partial^2 \psi}{\partial \theta_j \partial \theta_i} & 1 - \frac{\partial^2 \psi}{\partial \theta_j^2} \end{pmatrix} \equiv (\delta_{ij} - \boldsymbol{\Psi}_{ij})$$

- Defined the distortion tensor ($\boldsymbol{\Psi}_{ij}$), convergence (κ) and shear (γ)
- And from that the magnification of

$$\mu \equiv \frac{1}{\det \mathcal{A}(\boldsymbol{\theta})} = \frac{1}{(1-\kappa)^2 - \gamma^2} \quad ; \quad \gamma^2 \equiv \gamma_1^2 + \gamma_2^2$$

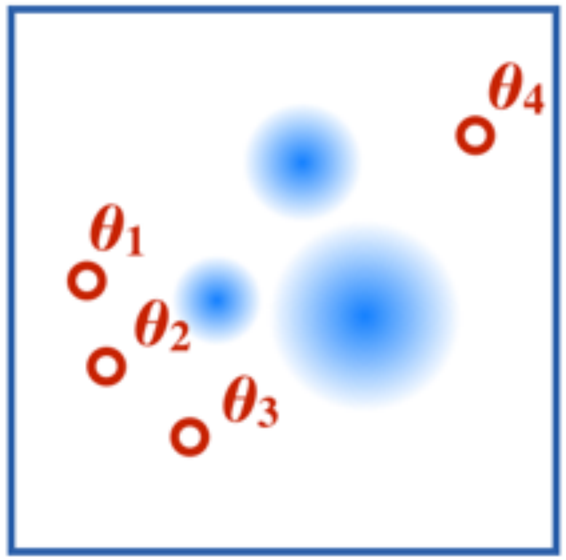
- Considered the magnification and parity of the IS case

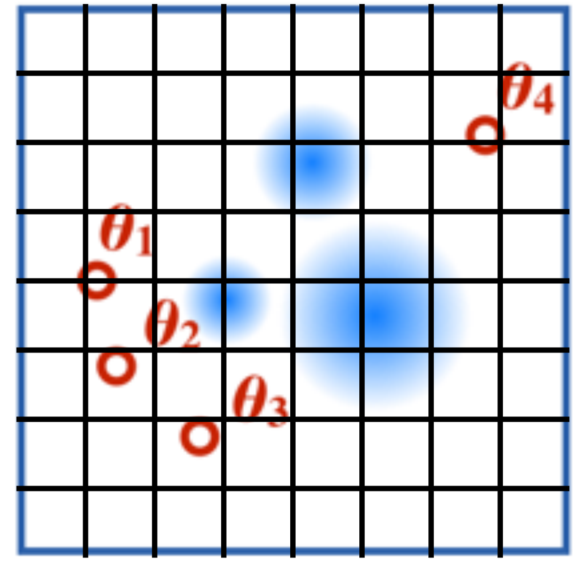


Modeling Lenses for Scientific Purposes

- Two approaches: Parametric & non-parametric

Parametrize matter profile/distribution (e.g. NFW or IS) and re-produce source positions

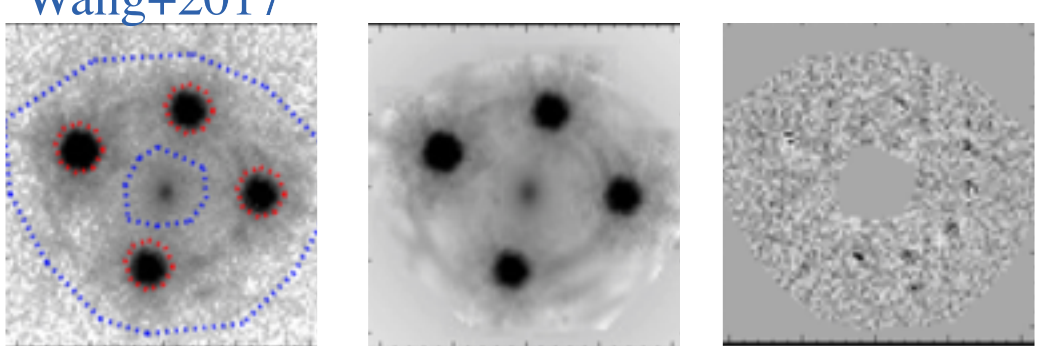


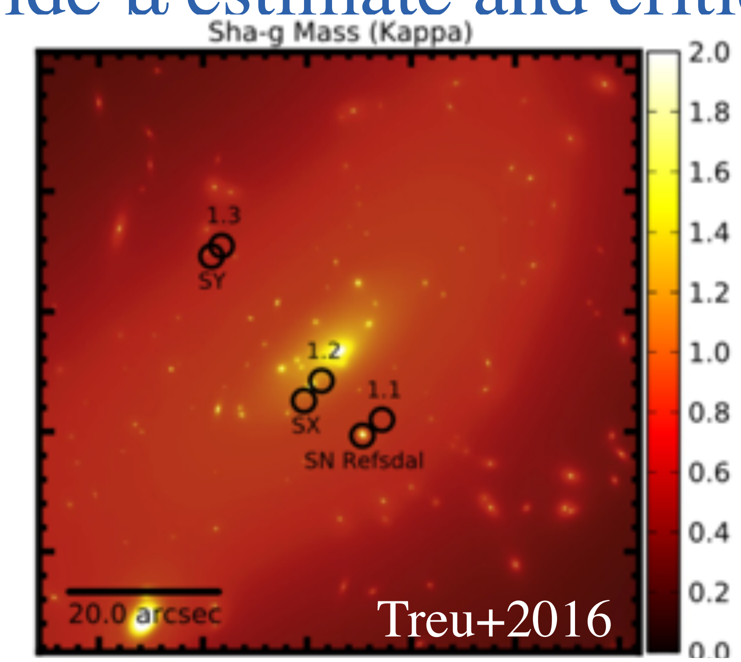


Model pixelated surface brightness distribution iteratively by “molding” lens mass distribution

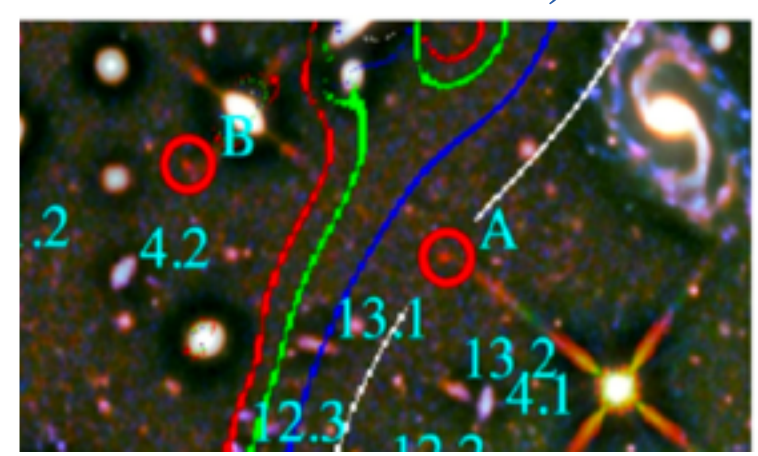
- Lens models and their mass (κ) maps are useful for, e.g.
- Finding high-z galaxies (provide u estimate and critical curve locations)
- Determining lens masses
- Predict $H_0\Delta t$ time-delays

Wang+2017



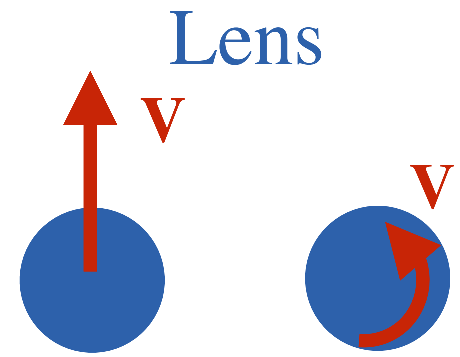


Treu+2016

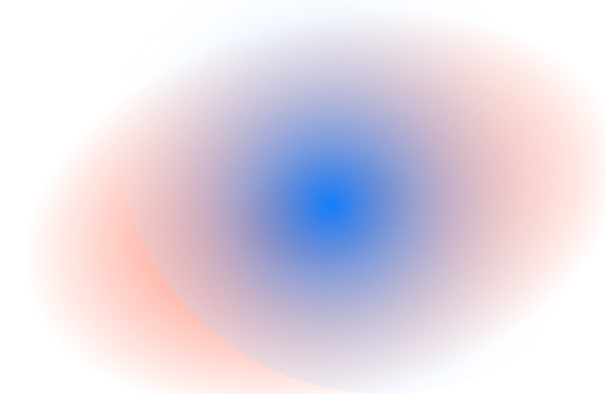


Zitrin+2014

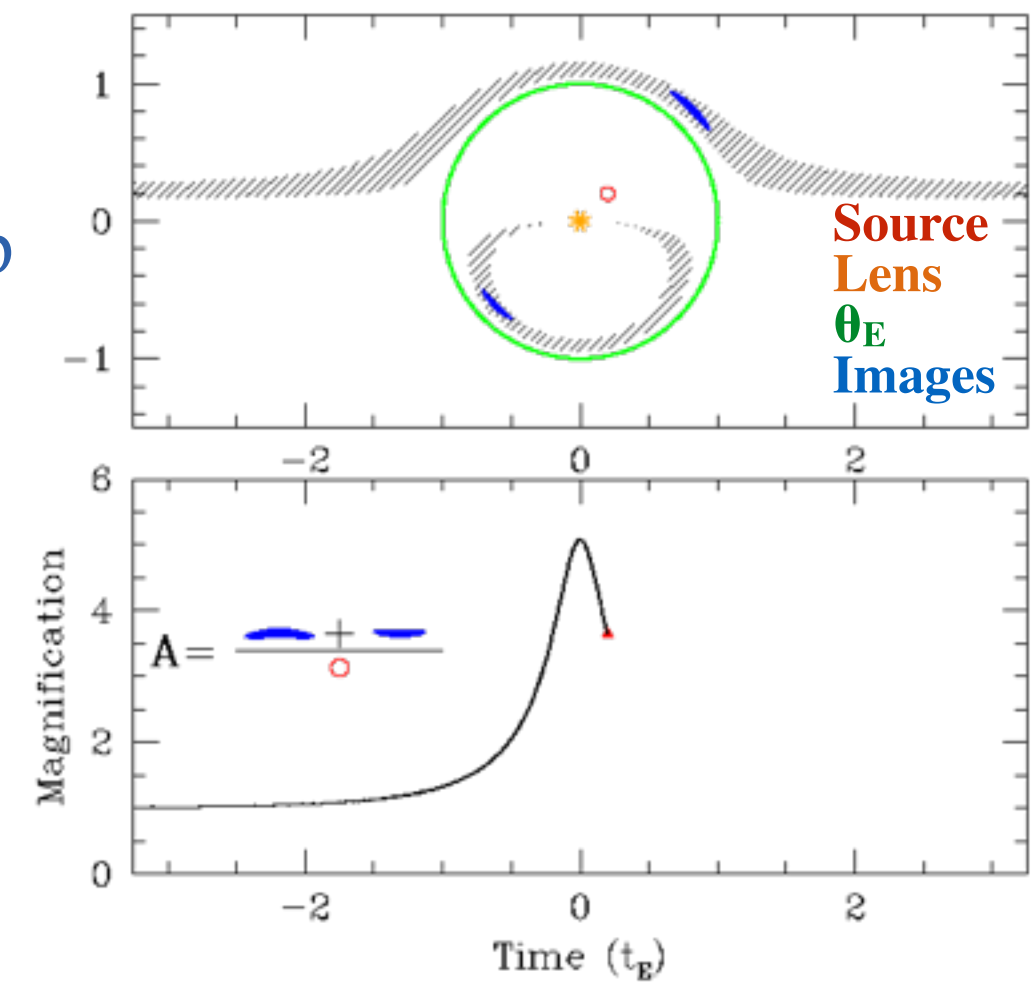
Microlensing



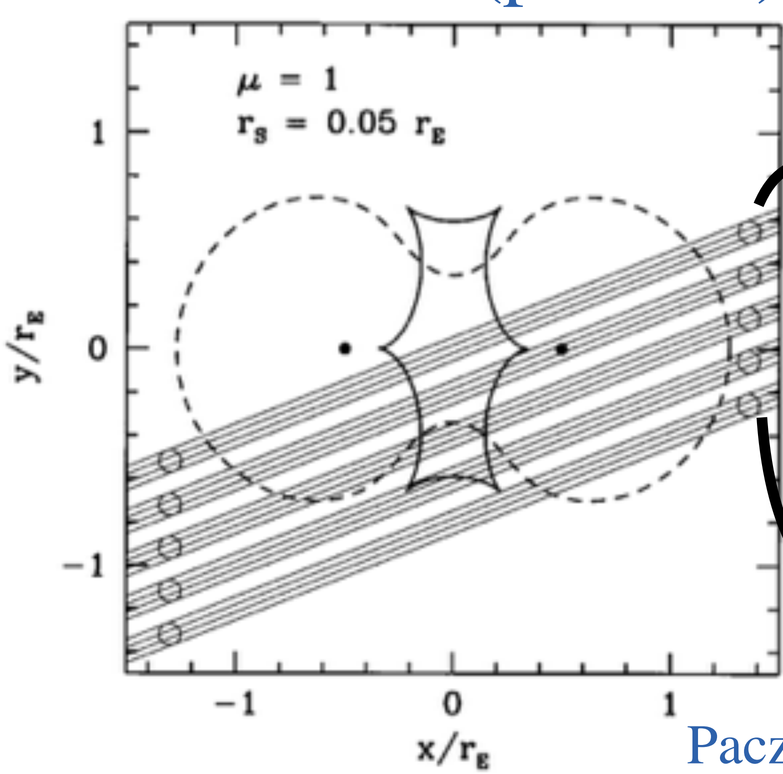
- Galactic and extra galactic micro lensing
- Can be thought of as "unresolved strong lensing"
- Observe variations in μ, i.e., the source brightness
- For the PML we have $$\mu_{\pm} = \frac{1}{1-(\theta_{\mathrm{E}}/\theta_{\pm})^4}$$

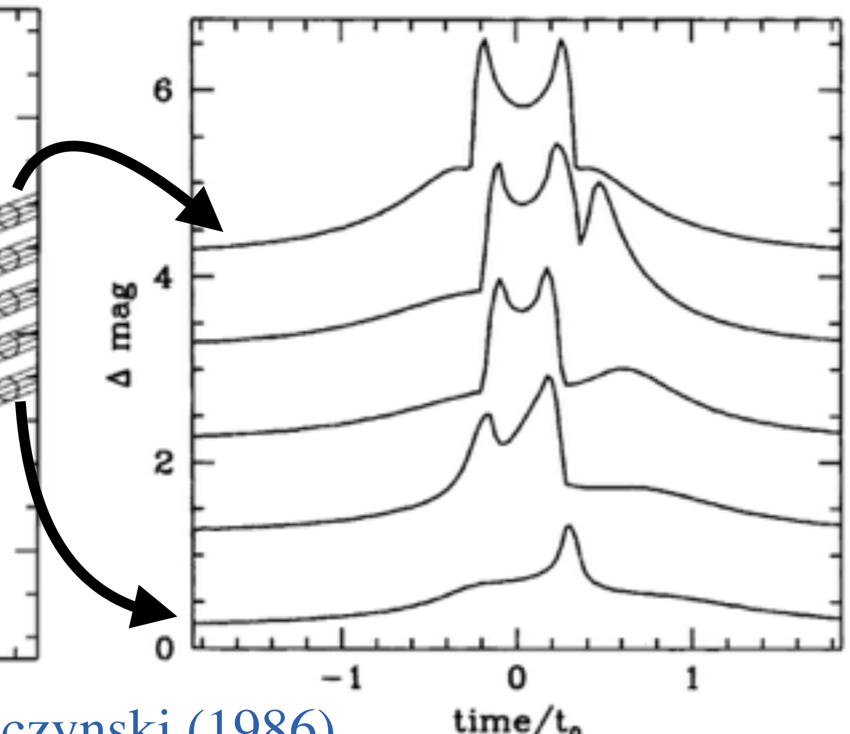


$$\mu = \frac{y^2+2}{y\sqrt{y^2+4}} \quad \text{where} \quad y = \frac{\beta}{\theta_{\mathrm{E}}}$$



- Caustics (patterns) provide magnification map





Paczynski (1986)

Movie credit: B. Scott Gaudi, OSU

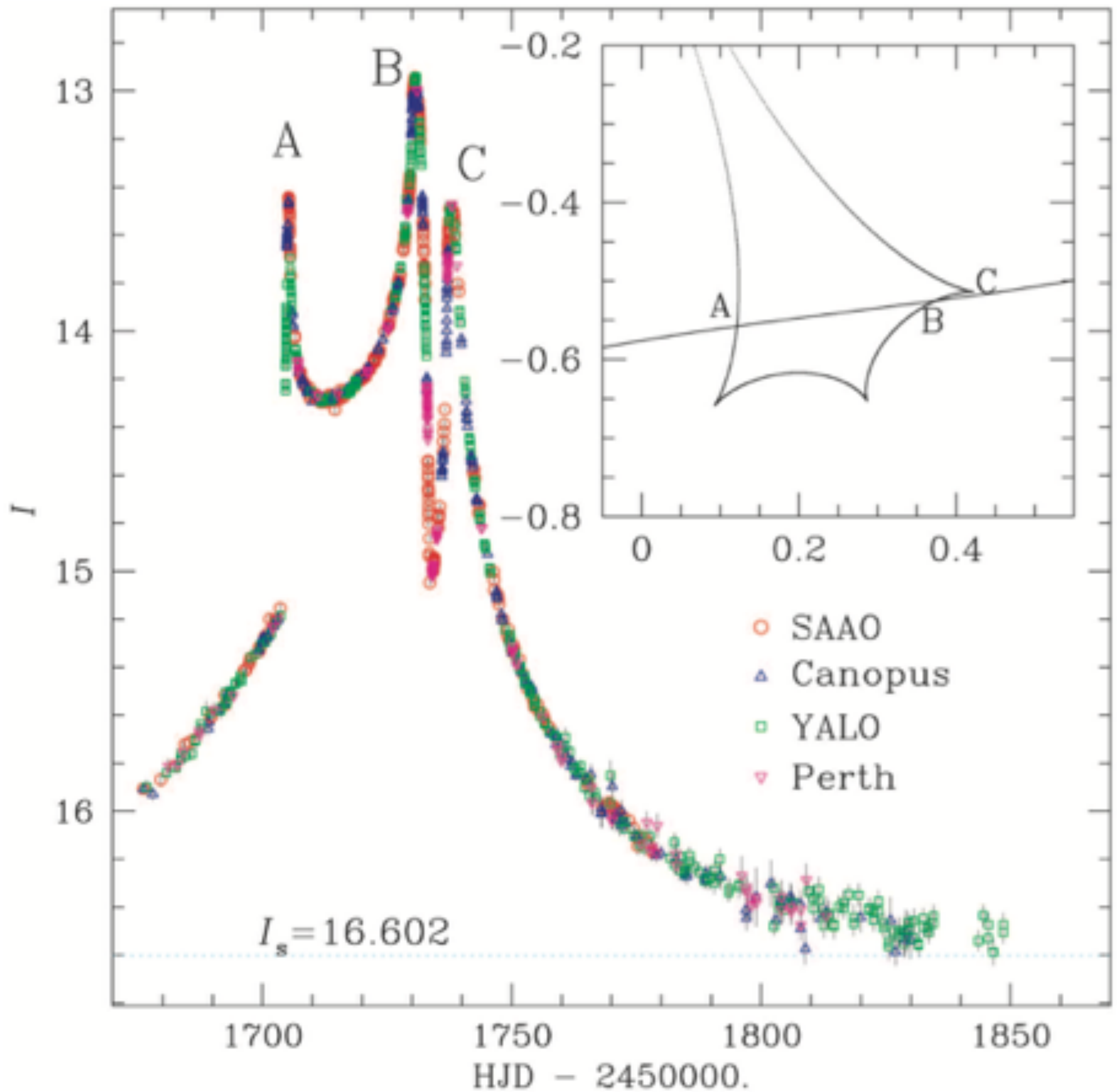
Microlensing

- Particular changes to the magnification curve can indicate double PML
- For an 'x-axis aligned' double PML the magnification is

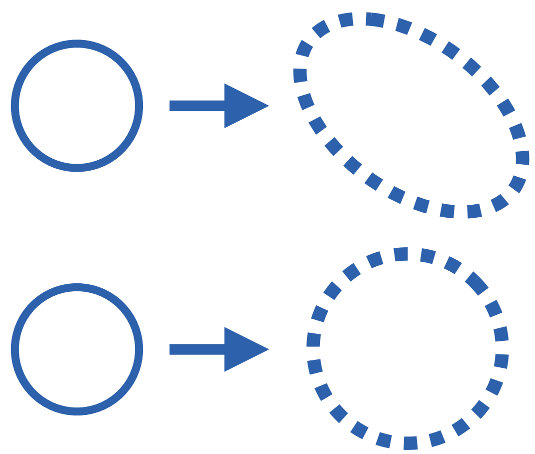
$$\mu = \frac{1}{1 - \frac{1}{x^4}\left(1 + \frac{qx^2}{(x-x_{\rm p})^2}\right)^2} \qquad \Delta\mu_{\rm p} \simeq \frac{2\mu_0^2 q}{x^2(x-x_{\rm p})^2}$$

- Here the subscript 'p' refers to **p**erturbe
- … or **pl**anet
- So if a planet (around lens) is close to lensed image position, $\Delta\mu_{\rm p}$ is large
- Looked at a range of such events:

An+00



Weak Lensing



- Characterizing source image distortions from lensing
  - Shearing (γ)
  - Scaling (κ)
- Idealized weak lensing ($\kappa = 0$, $\gamma 2 = 0$) reveals ellipse nature of distortion

$$1 = \frac{(1-\gamma_1)^2}{\beta_0^2}\theta_1^2 + \frac{(1+\gamma_1)^2}{\beta_0^2}\theta_2^2$$

- Ellipticity can be described by 2nd order surface brightness moments

$$q_{ij} \equiv \int d^2\theta \, \mathcal{S}^{\mathrm{obs}}(\boldsymbol{\theta})\theta_i\theta_j$$

- Useful for large scale mass determination
- To measure this ellipticity in the weak lensing regime, needs statistics
  - Cross correlation & power spectrum on density contrasts $\boldsymbol{\delta}(\boldsymbol{x}, t) \equiv \frac{\rho_m(\boldsymbol{x}, t) - \bar{\rho}_m(t)}{\bar{\rho}(t)}$
- The extreme: Cosmic shearing of CMB by integrated foreground mass
  - Probes cosmological parameters and lensing characteristics

Outlook to the (near) future of lensing

- (Incomplete) Overview of The Future of GL:

Ongoing (Now)
  - HST: Source follow-up and lensing clusters
  - OGLE/MicroFUN: Monitoring campaign of microlensing events
  - Gaia: Billions of points source; QSO lens ‘contaminants’
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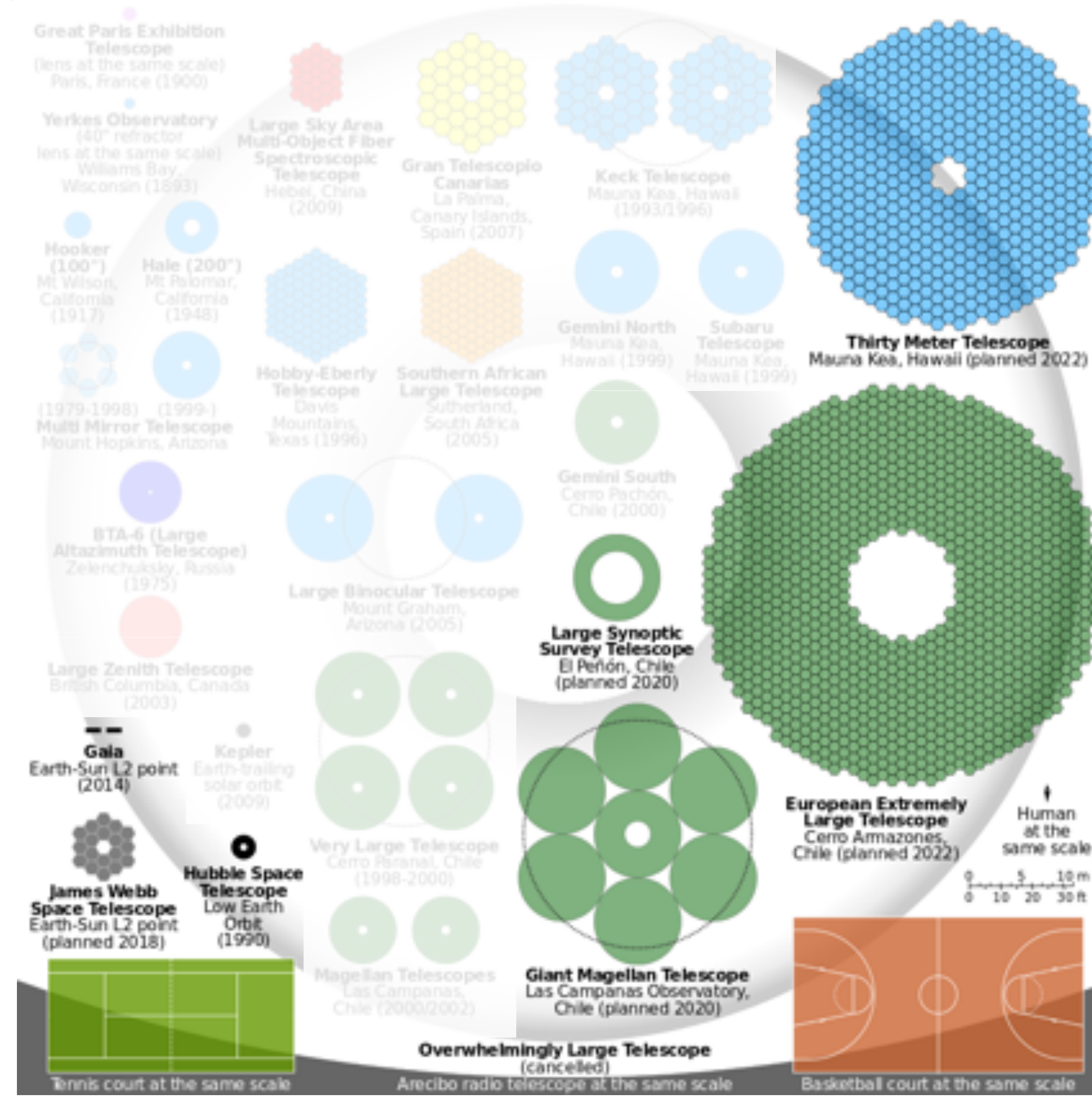
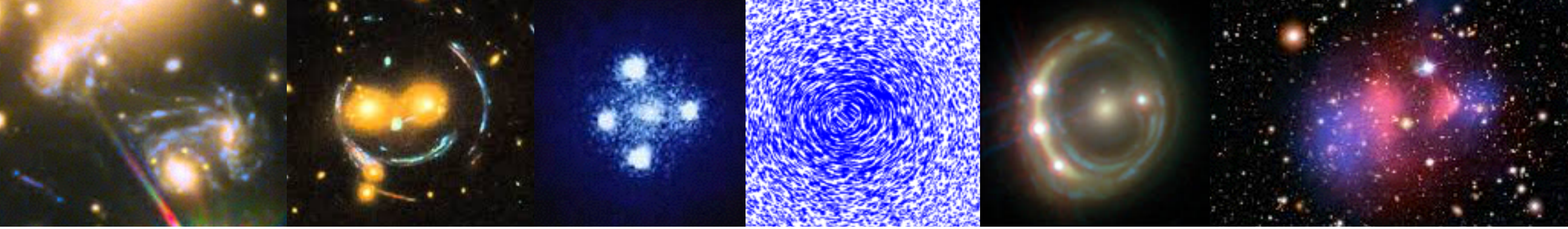
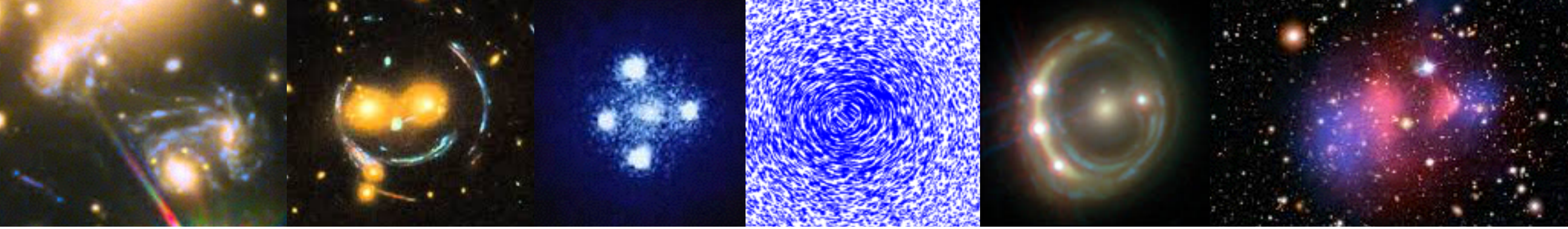


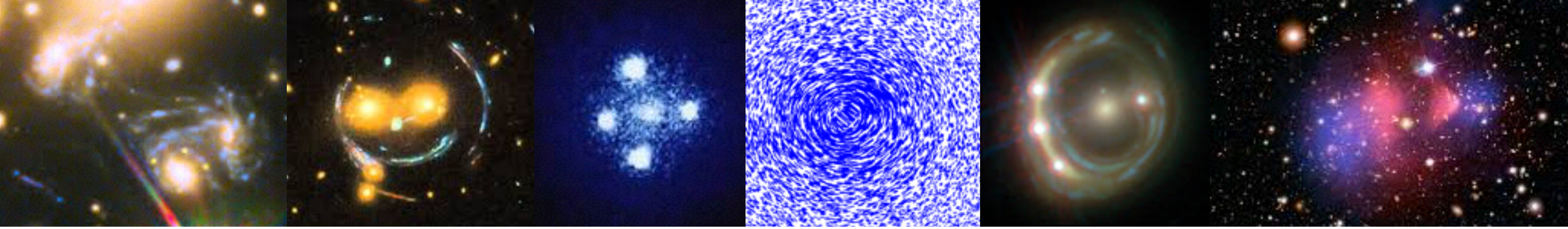
- ☑ Cluster lensing
- ☑ QSO lensing
- ☑ Galaxy-Galaxy lensing
- ☑ Star-Star microlensing
- ☑ Exoplanet searches with microlensing
- ☑ Wide-field weak lensing
- ☑ Power Spectrum lensing analysis



Questions?



Last Week’s Worksheet



This Week’s Worksheet