Student Seminar, ASIAA
May 4, 2017

Galaxy Clusters as Cosmic Lenses

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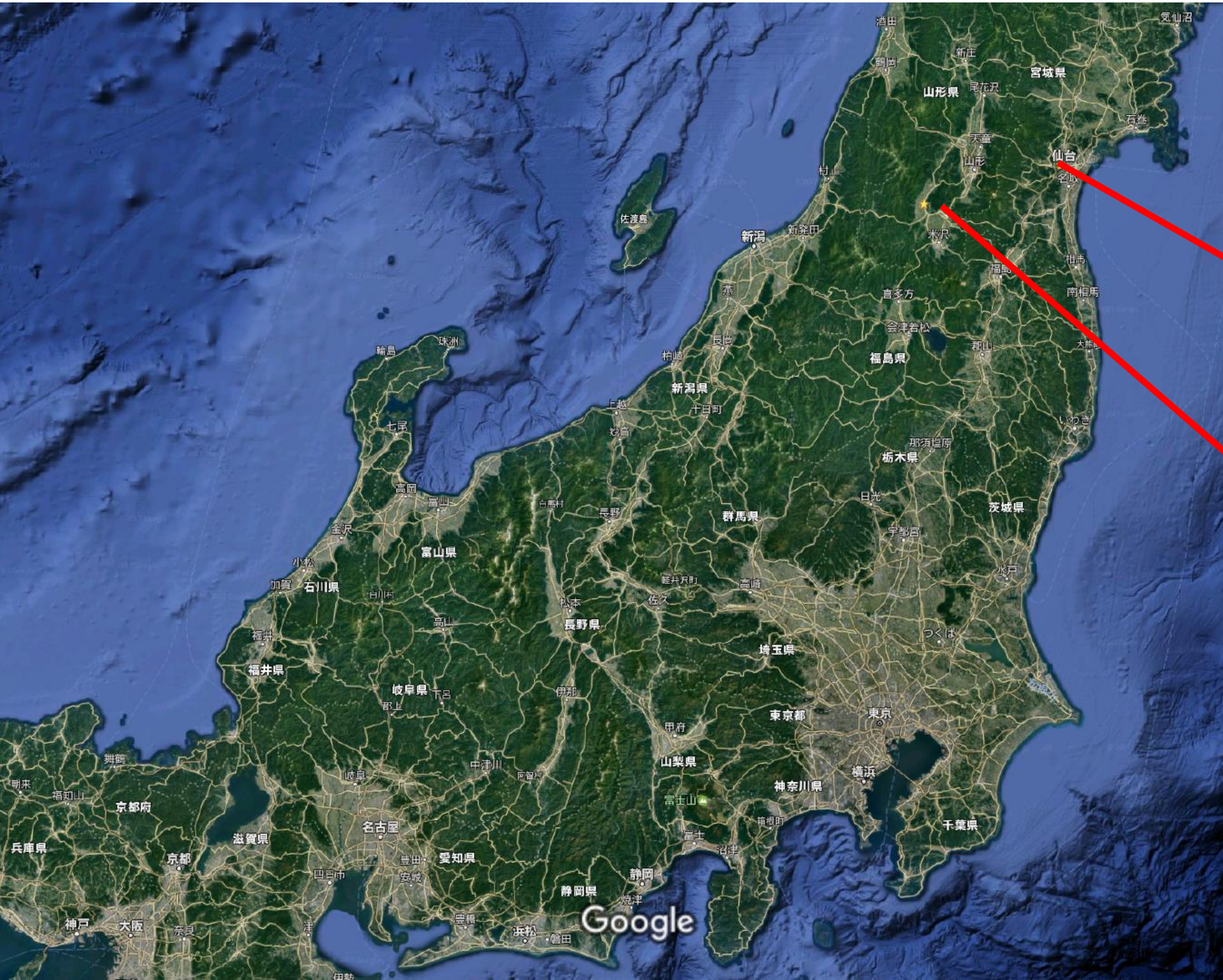
梅津 敬一

Who am I?

Where am I from?

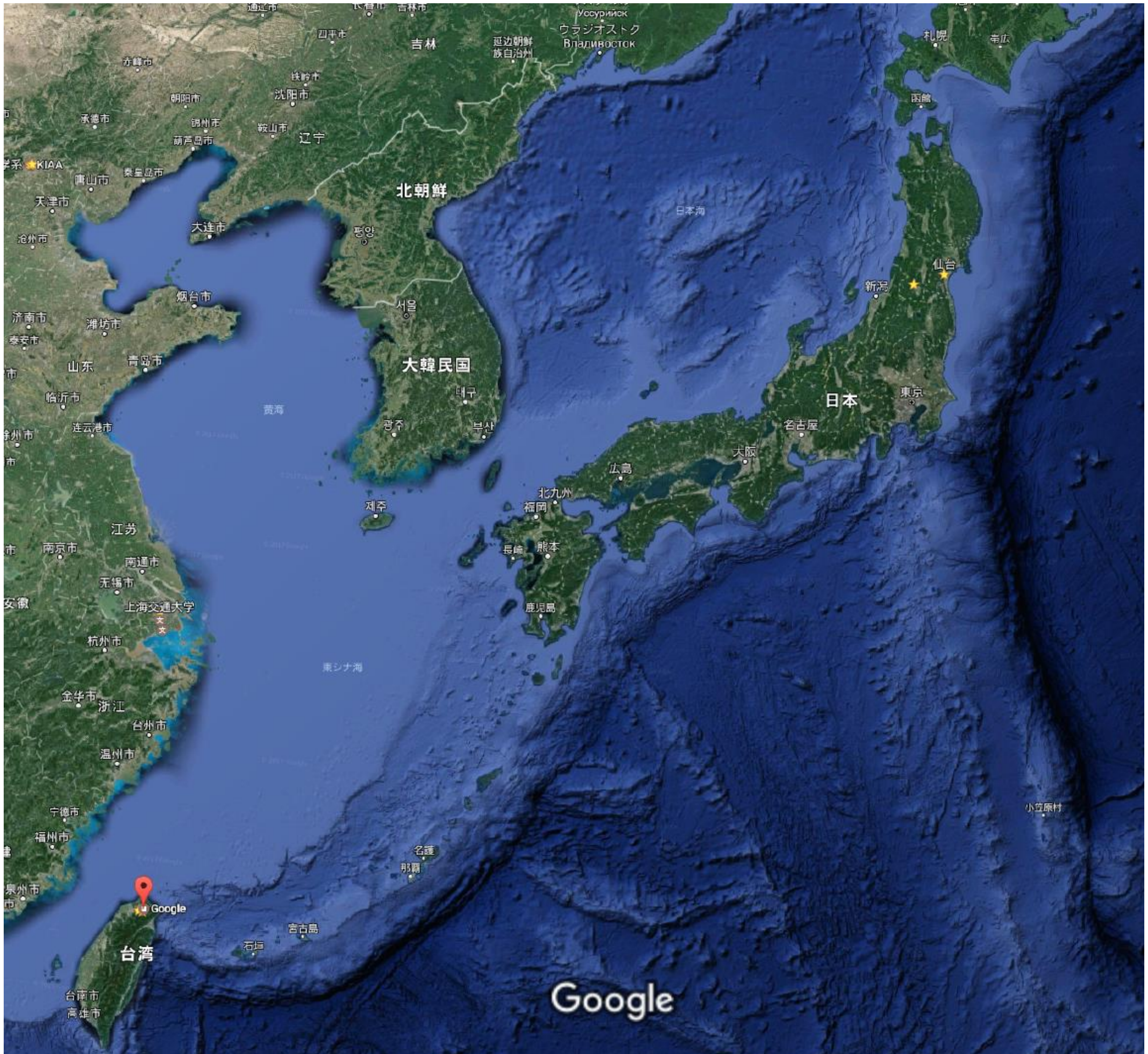


東北大学@
宮城県仙台市

山形県長井市
出生

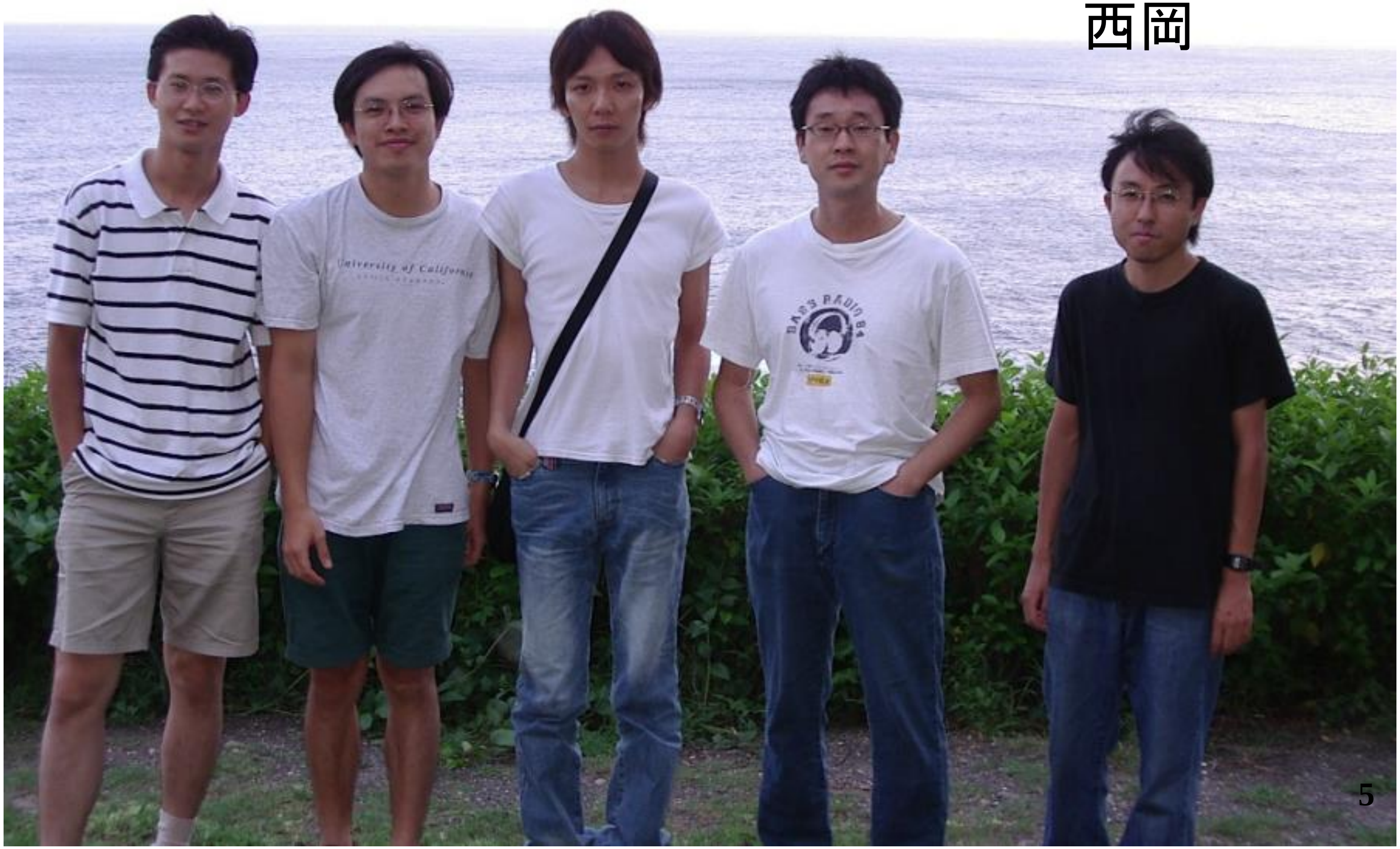
Where am I from?

2001年6月、我移到台湾来



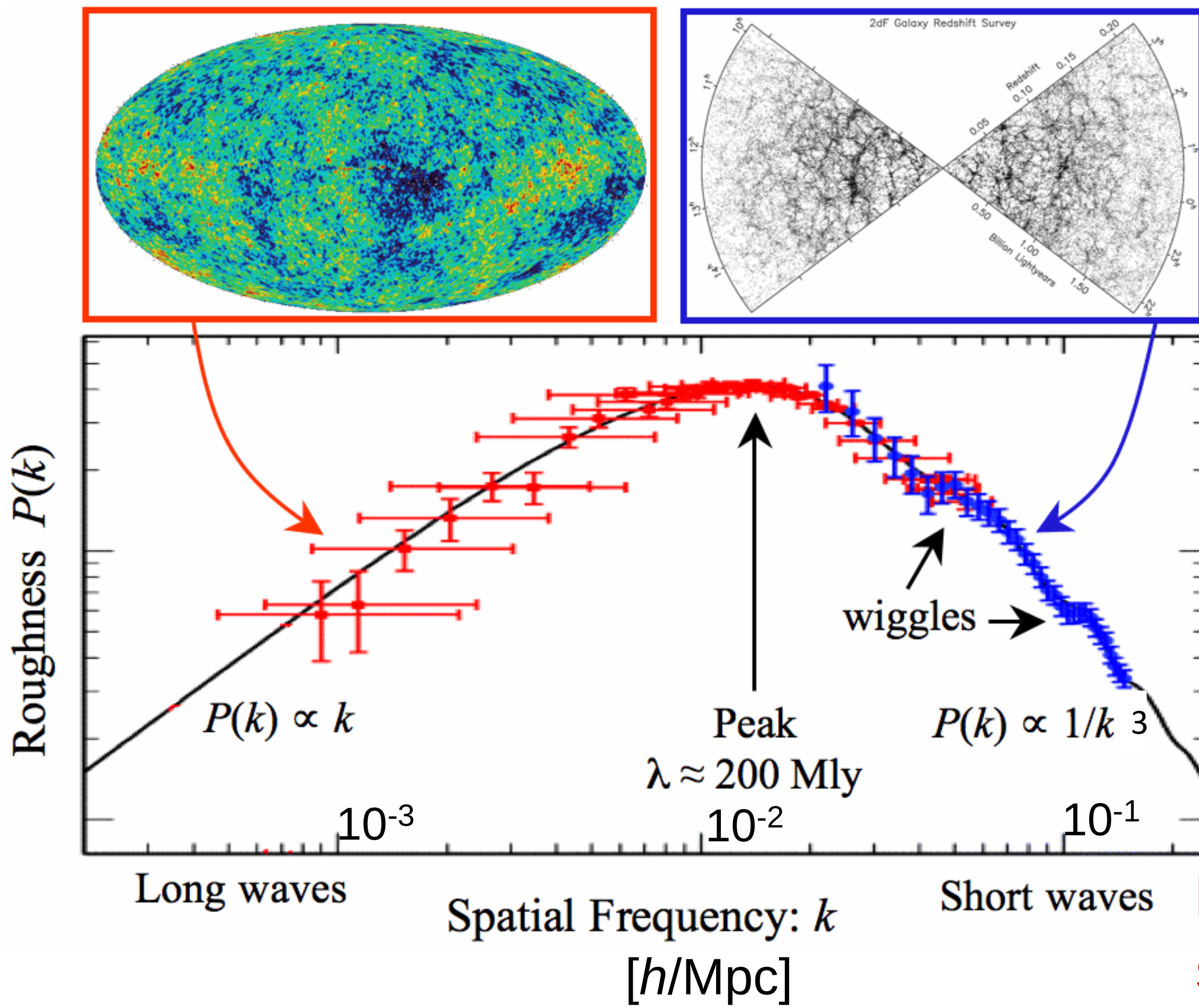
Looking back to 2003 (14年前)..

副所長



ΛCDM: Standard Structure Formation Paradigm

Matter power-spectrum density, *P*(*k*)



$$\delta := \frac{\rho - \overline{\rho}}{\overline{\rho}} = \frac{1}{(2\pi)^3} \int d^3k\, \tilde{\delta}(\boldsymbol{k}) e^{i\boldsymbol{k}\cdot\boldsymbol{\chi}}$$

$$\langle \tilde{\delta}(\boldsymbol{k}) \tilde{\delta}^*(\boldsymbol{k}') \rangle = (2\pi)^3 \delta^3_{\rm D}(\boldsymbol{k} - \boldsymbol{k}') P(\boldsymbol{k})$$

$P(k) \propto k$^n_s with n_s~1 @ k << k_{eq} (peak)

Turn-over @ k ~ k_{eq}

$P(k) \propto k$^(n_s-4) @ k >> k_{eq}

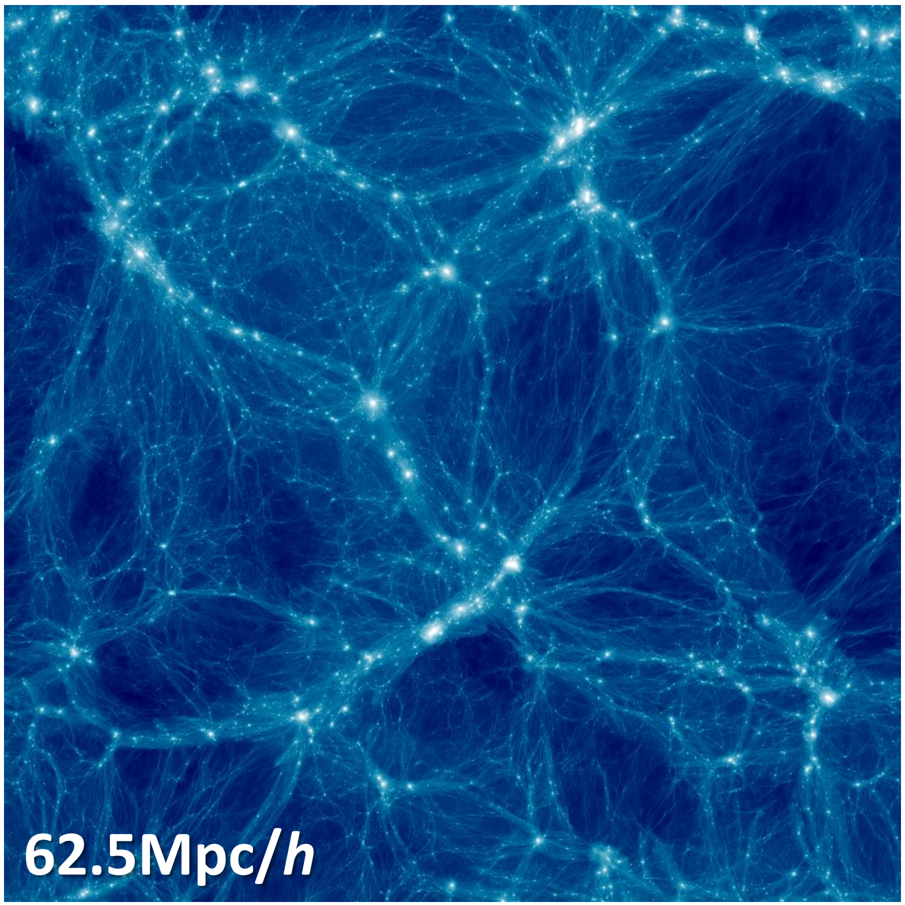
Nonlinear @ k>>0.1*h*/Mpc

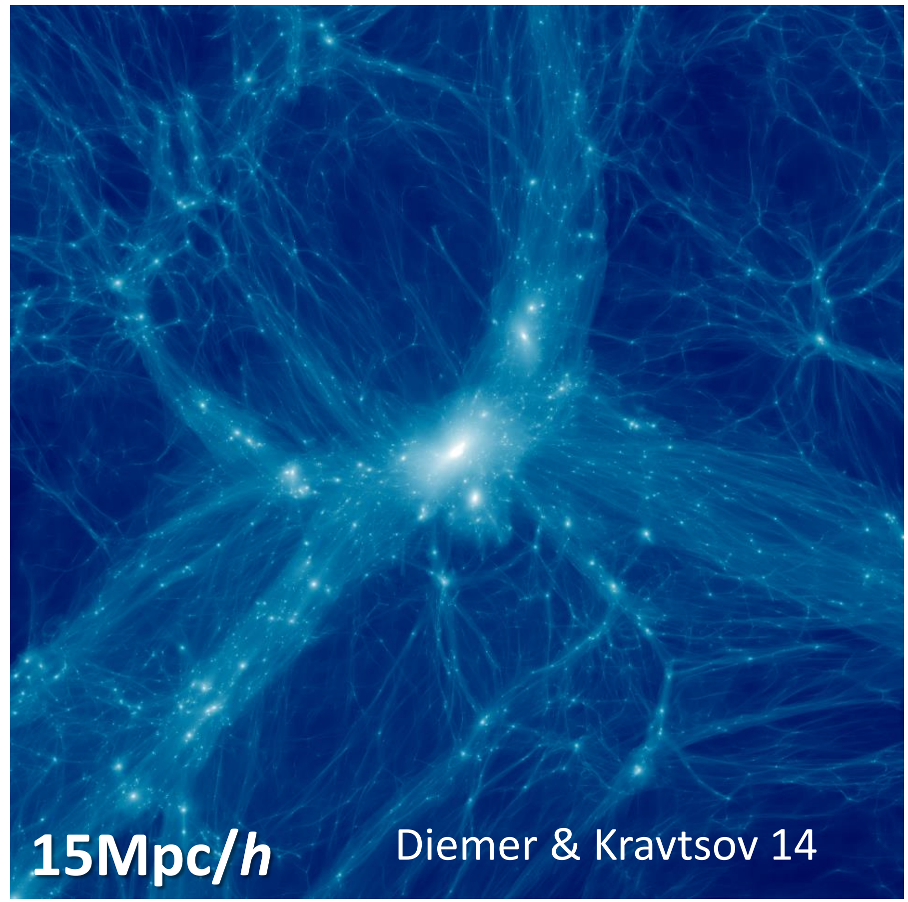
How about smaller scales, λ<10Mpc/*h*?

Galaxy Clusters

Galaxy clusters: Largest class of DM halos

Space-time abundance of rare massive clusters (M=10^{14-15} M_{sun}) is "exponentially" sensitive to cosmology AND their mass calibration

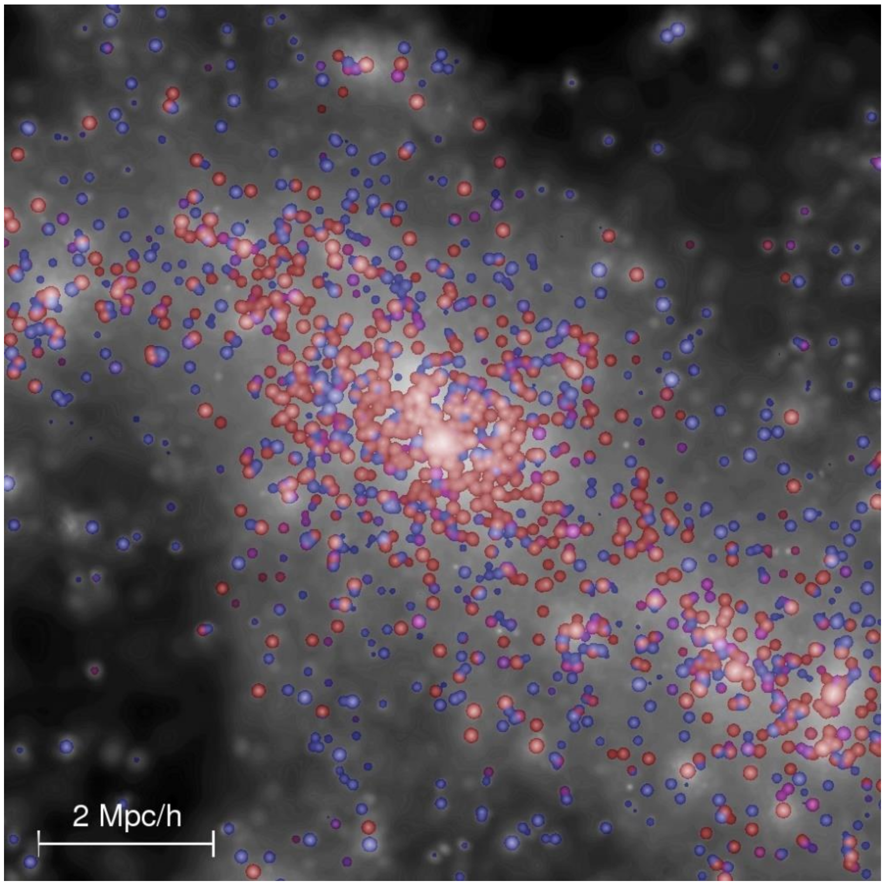


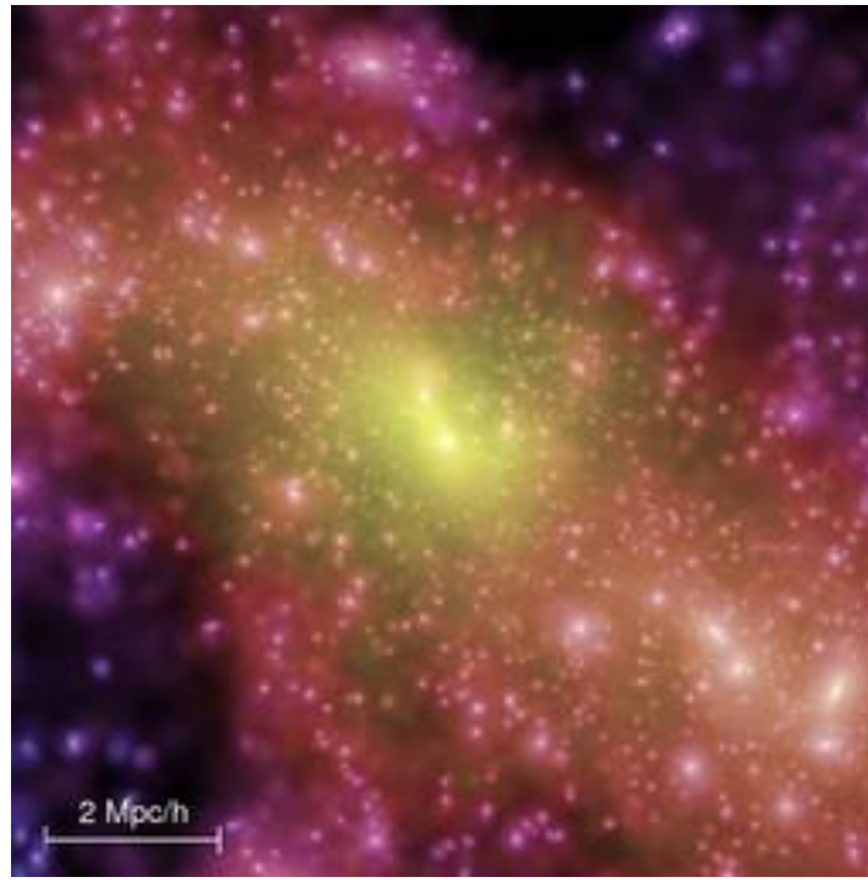


What are clusters made of?

Discrete galaxies

Underlying dark matter (~mass)



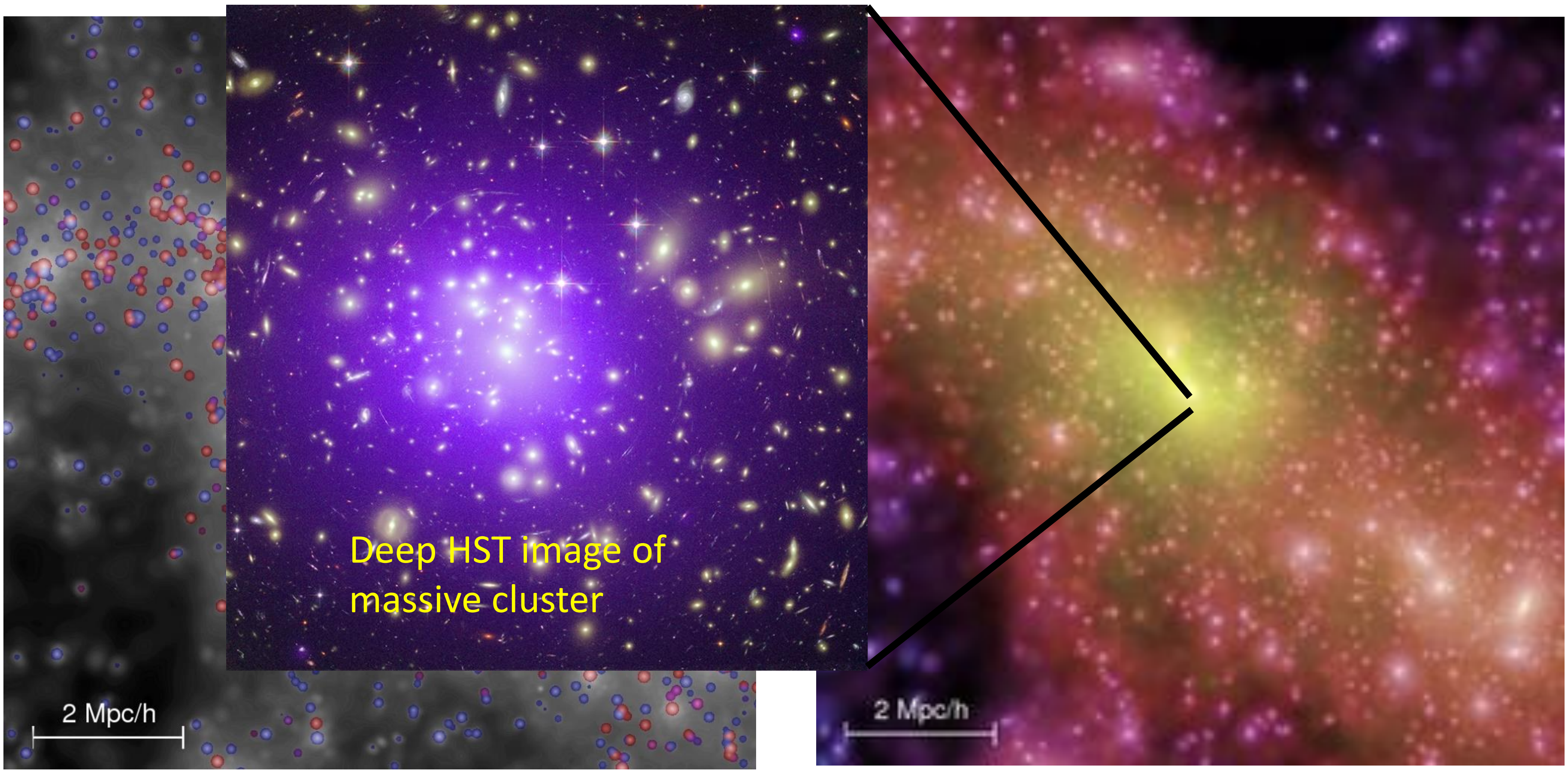


Millennium Simulation

What are clusters made of?

Discrete galaxies

Underlying dark matter (~mass)



Millennium Simulation

Clusters of Galaxies

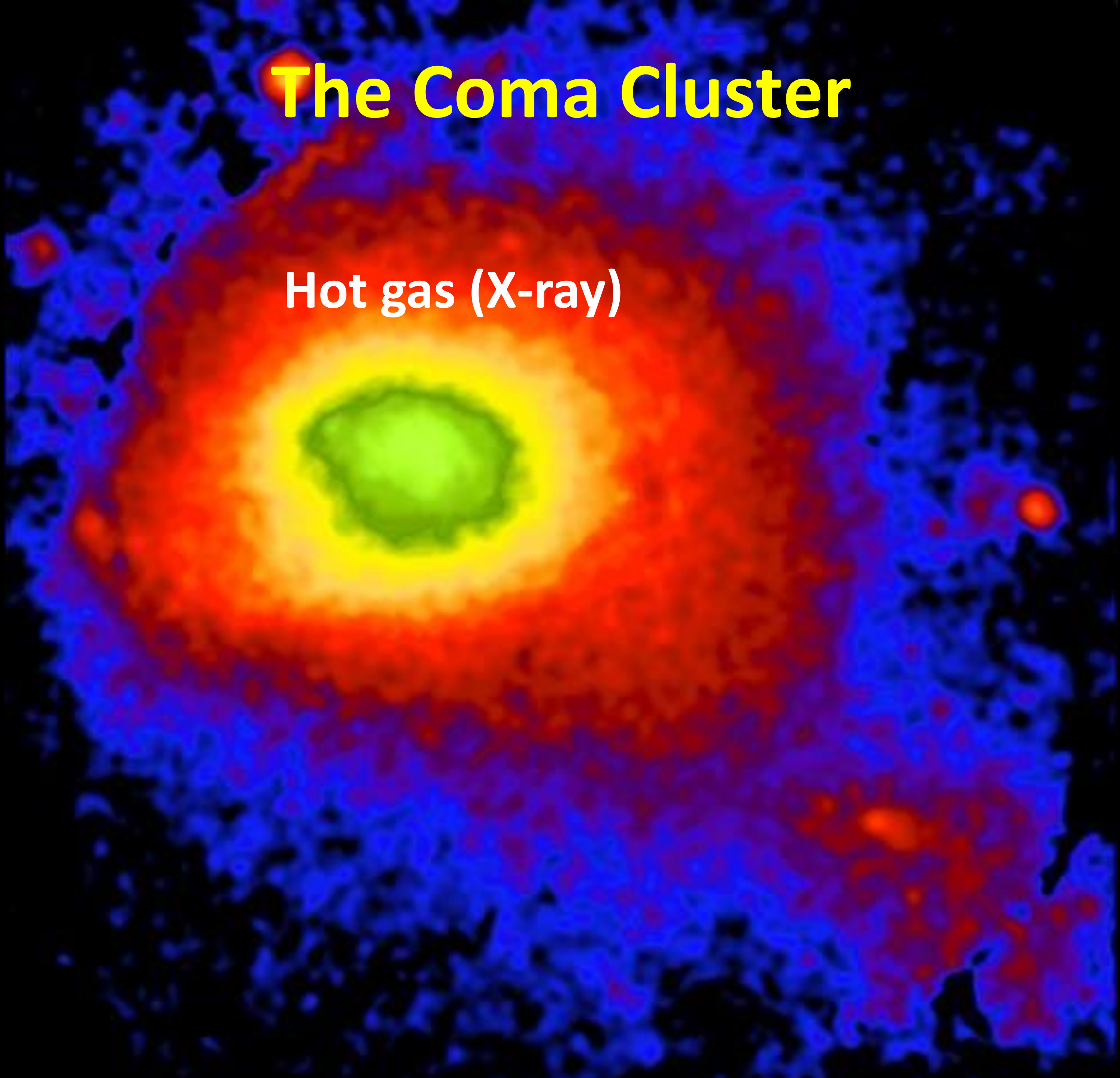
Cluster A1689

Clusters of Galaxies

Cluster A2744: Massive merging cluster

The Coma Cluster

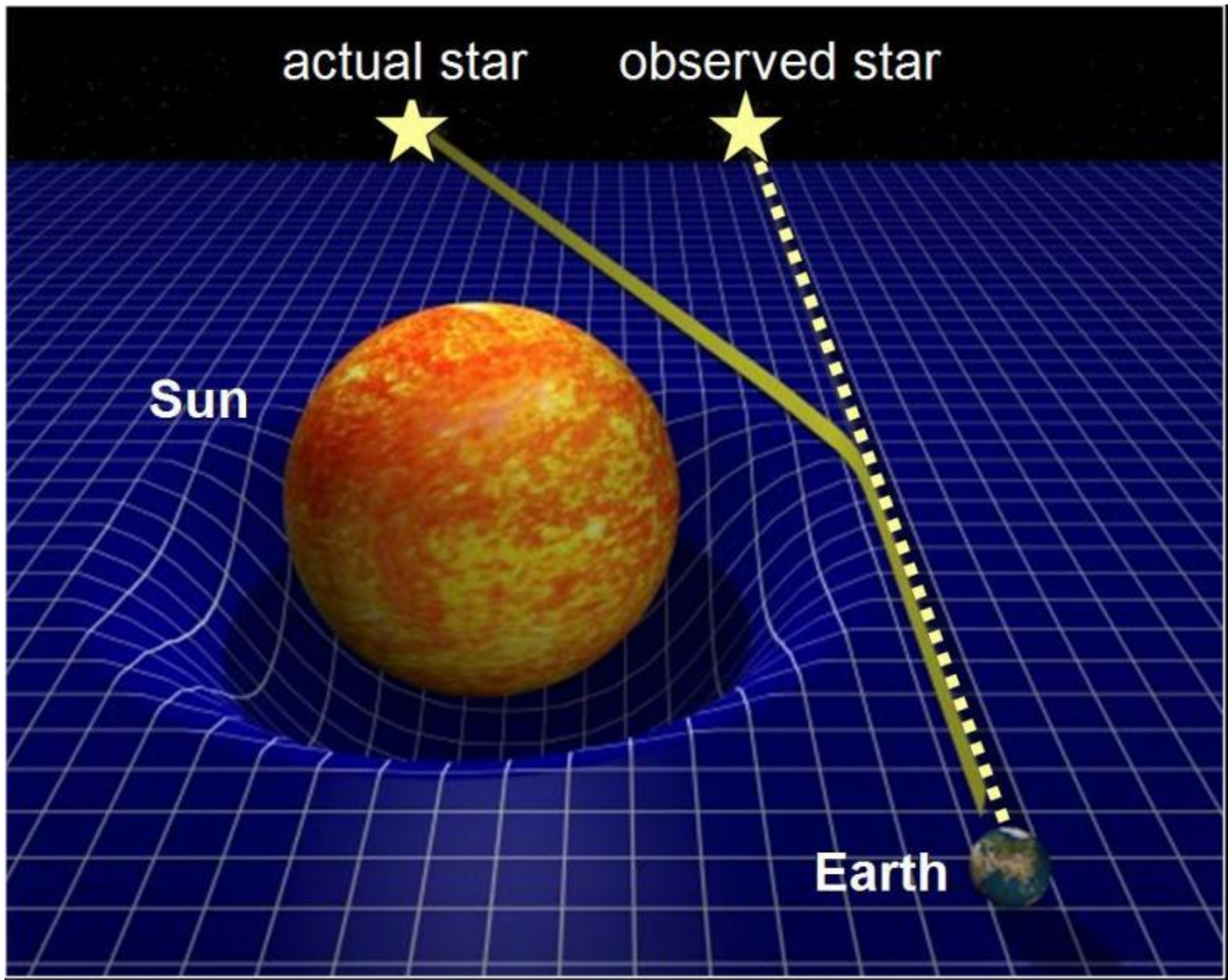
The Coma Cluster



Gravitational Lensing

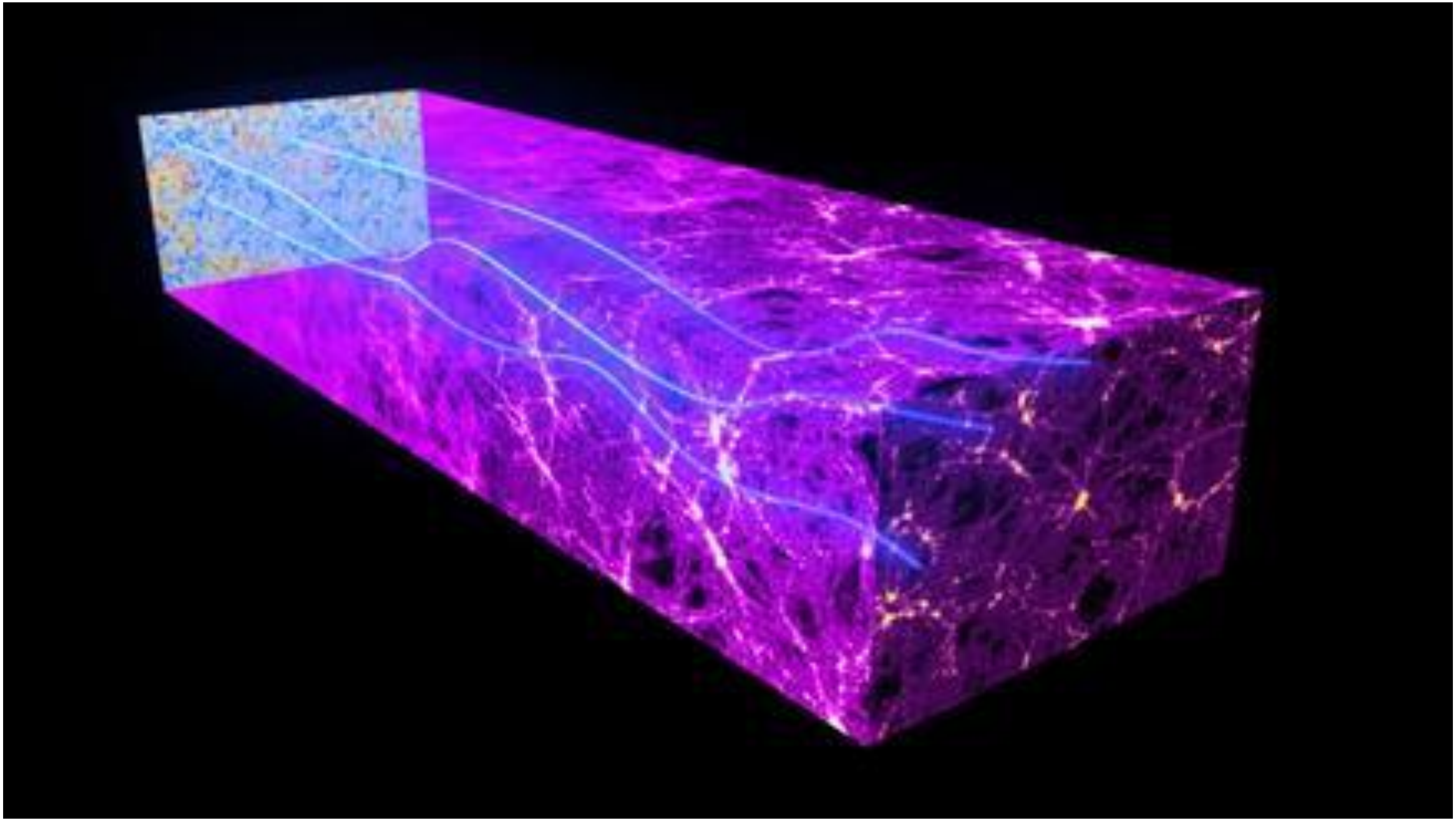
Gravitational Bending of Light

Einstein's gravity (General Relativity):
Mass distorts space-time, and light follows a curved path (geodesic)



Photons: travelers in the cosmos

Photons are traveling through the clumpy universe.



Gravitational Bending Angle

Bending angle: small transverse excursion of photon momentum ($|\Psi|/c^2 \ll 1$)

$$\delta\hat{\alpha} \approx \frac{\delta p_\perp}{p_\parallel} = -\frac{2}{c^2}\underbrace{\nabla_\perp \Psi(\chi_\parallel, \chi_\perp)}\delta\chi_\parallel$$

Gravitational field of deflecting matter

$$\hat{\alpha}^{\mathrm{GR}} = 2\hat{\alpha}^{\mathrm{Newton}} \rightarrow \frac{4GM}{c^2 r} = 1.''75\left(\frac{M}{M_{sun}}\right)\left(\frac{r}{R_{sun}}\right)^{-1}$$

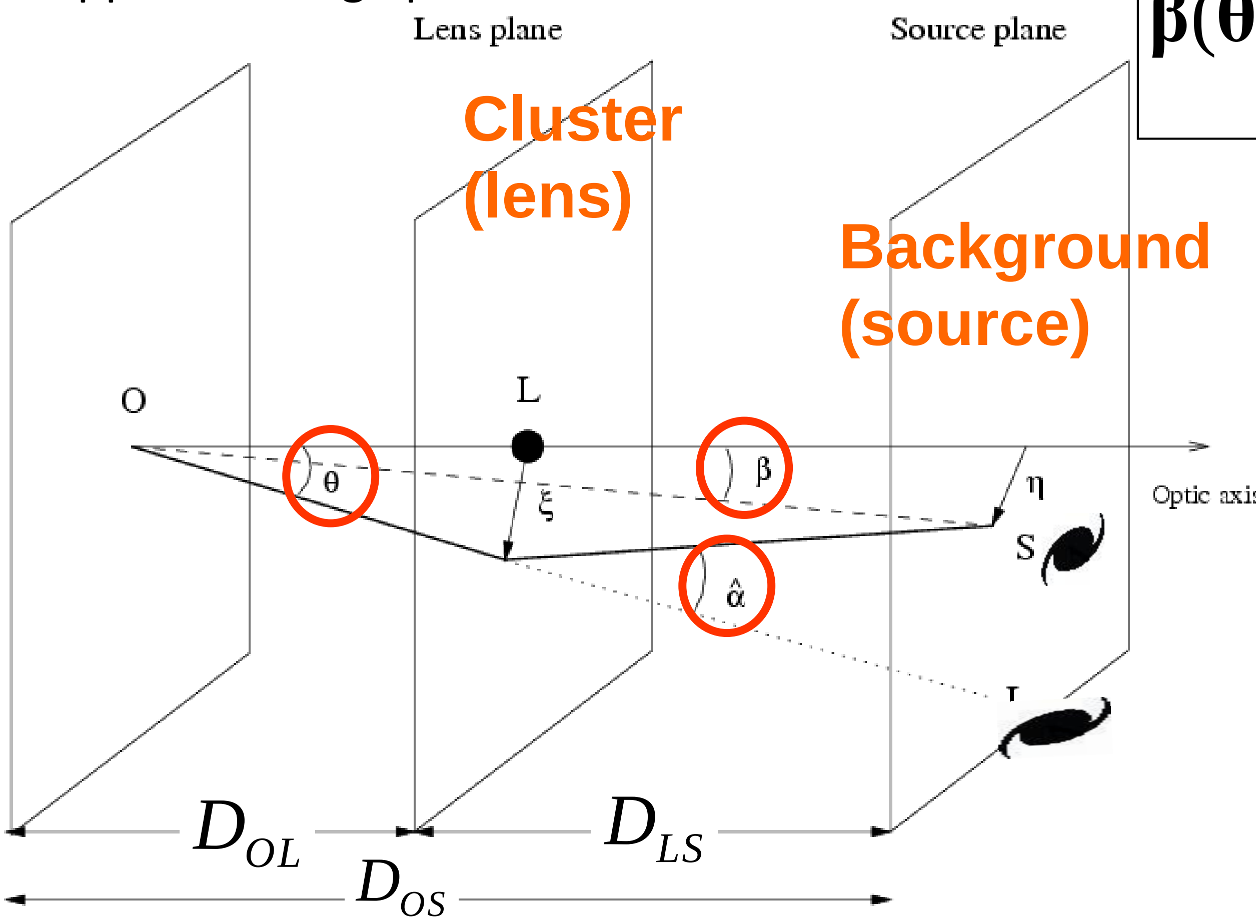
First test with the total eclipse in 1919

Lens Equation

β: true (but unknown) source position

θ: apparent image position

$$\boldsymbol{\beta}(\boldsymbol{\theta}) - \boldsymbol{\theta} = \frac{D_{LS}}{D_{OS}} \int \delta\hat{\boldsymbol{\alpha}}(\boldsymbol{\theta})$$



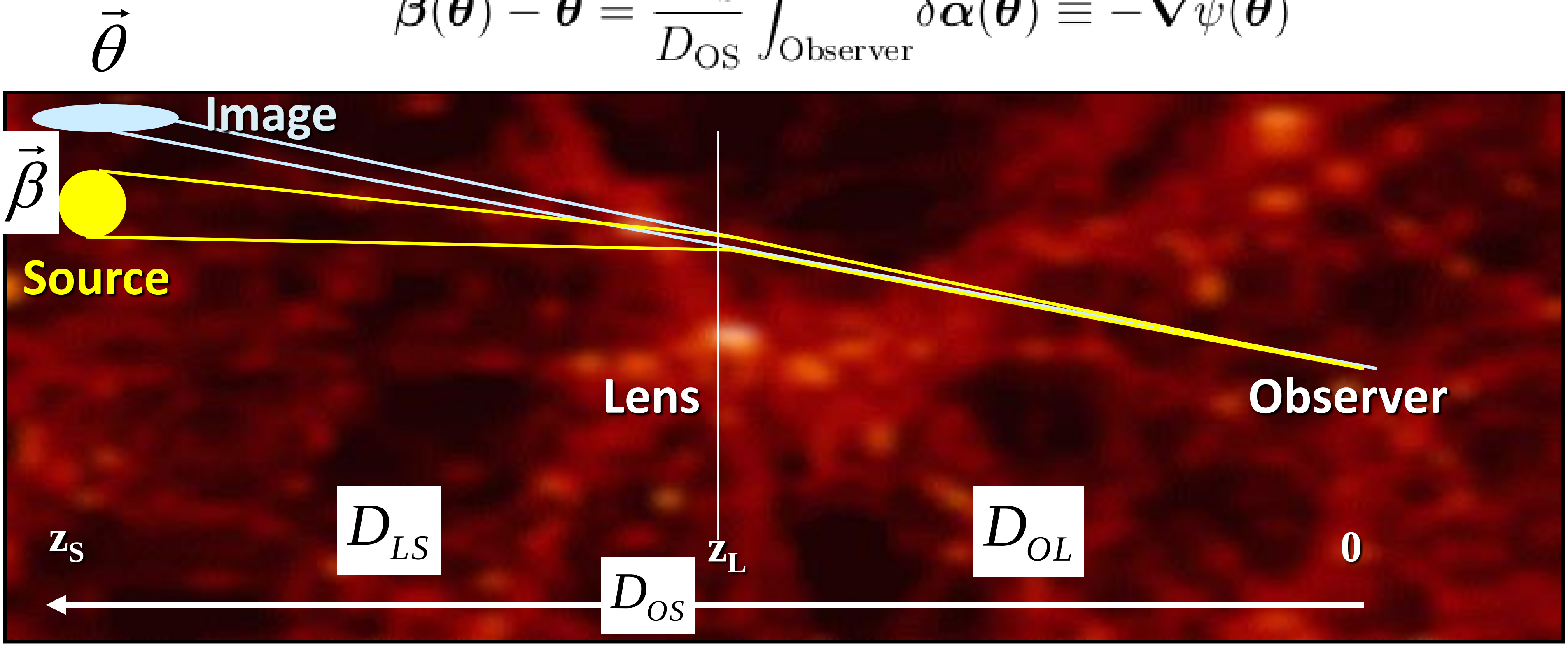
Angular diameter distances:

D_{OL}, D_{LS}, D_{OS} ~ $O(c/H_0)$

For a rigid derivation of cosmological lens eq., see, e.g., Futamase 95

Deflection and Distortion

$$\boldsymbol{\beta}(\boldsymbol{\theta}) - \boldsymbol{\theta} = \frac{D_{\rm LS}}{D_{\rm OS}} \int_{\rm Observer}^{\rm Source} \delta \hat{\boldsymbol{\alpha}}(\boldsymbol{\theta}) \equiv -\boldsymbol{\nabla} \psi(\boldsymbol{\theta})$$



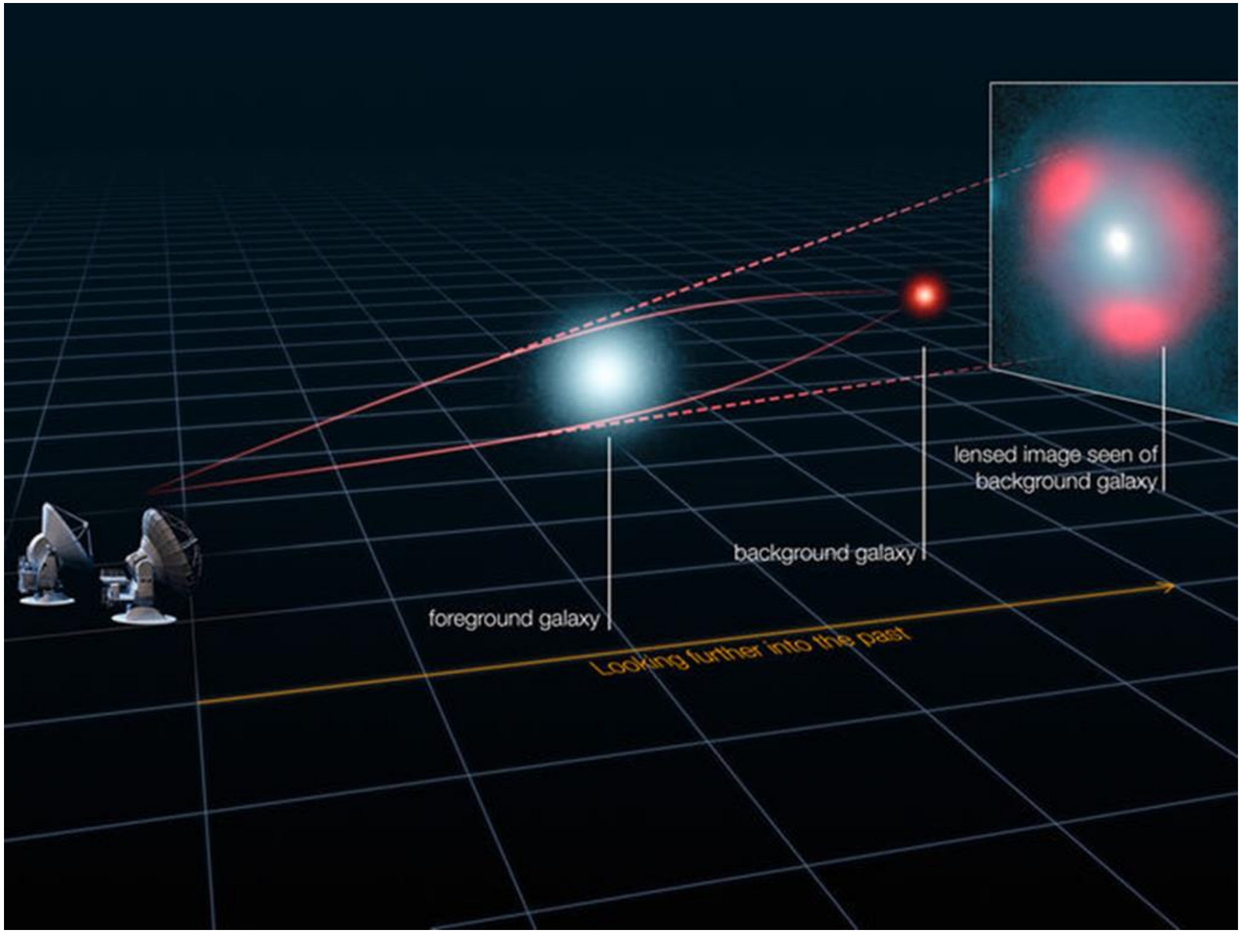
Deformation of an image

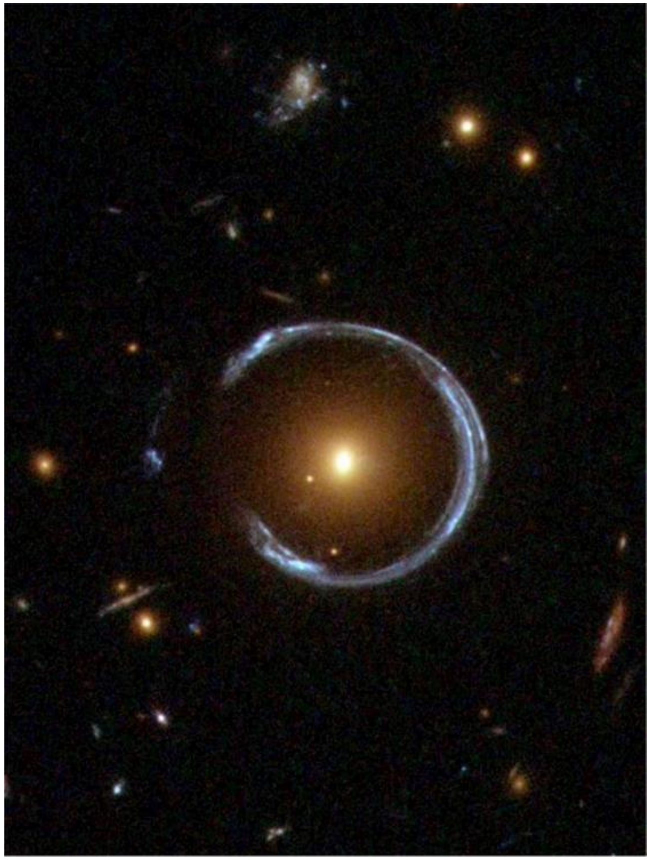
$$\delta\beta_i = (\delta_{ij} - \psi_{,ij})\delta\theta_j + O(\delta\theta^2)$$

Magnification, μ

$$\mu^{-1} = \det\left(\frac{\partial \boldsymbol{\beta}}{\partial \boldsymbol{\theta}}\right) = |1 - \nabla\nabla\psi|$$

Einstein Ring

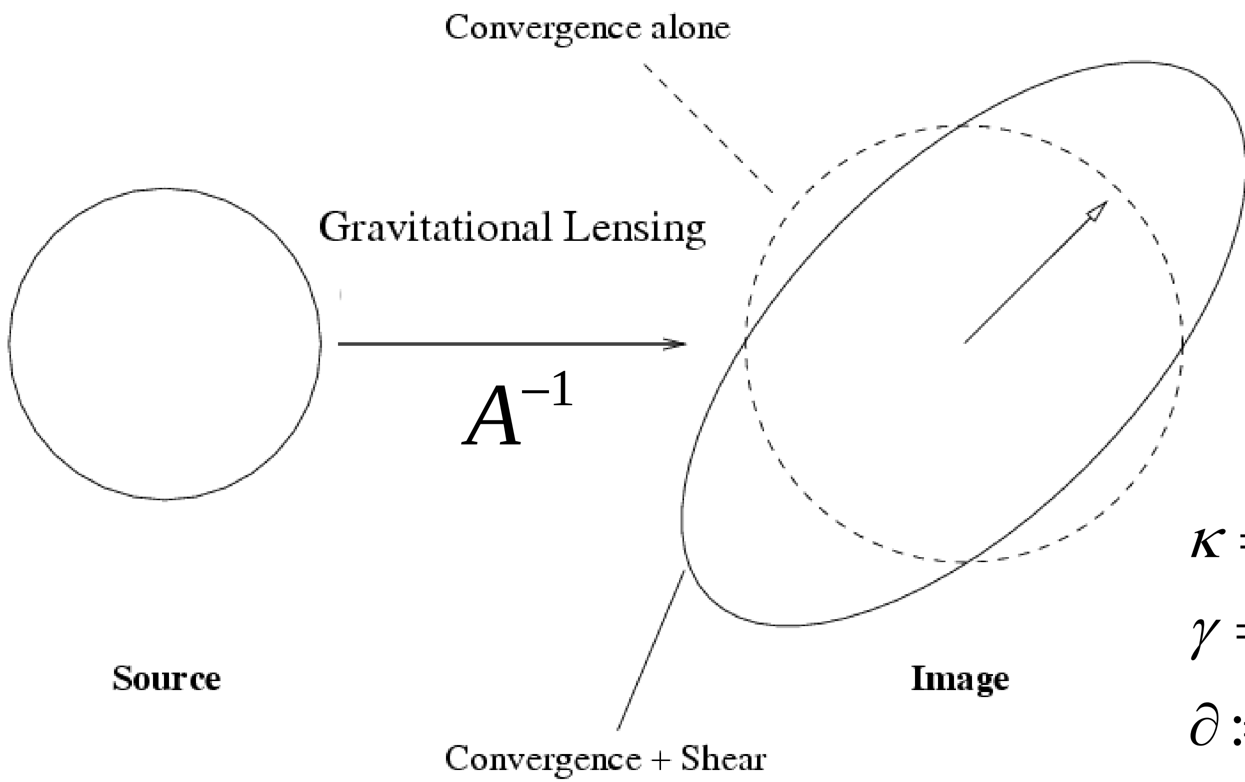




Hubble Space Telescope

Einstein Ring Examples

Convergence (κ) and Shear (γ)



$$\kappa = \partial\partial^* \Psi / 2 = \Delta\Psi / 2$$

$$\gamma = \partial\partial\Psi / 2$$

$$\partial := \partial_x + i\partial_y = e^{i\phi}\partial_r$$

$$\mathcal{A}(\boldsymbol{\theta}) = \begin{pmatrix} 1-\kappa-\gamma_1 & -\gamma_2 \\ -\gamma_2 & 1-\kappa+\gamma_1 \end{pmatrix} = (1-\kappa)\begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} - \begin{pmatrix} \gamma_1 & \gamma_2 \\ \gamma_2 & -\gamma_1 \end{pmatrix},$$

Convergence, κ

κ: weighted line-of-sight projection of density contrast $\delta = \delta\rho/\rho$

$$\kappa = \frac{3H_0^2\Omega_m}{2c^2}\int_0^{\chi_s} d\chi \, \frac{r(\chi)r(\chi_s - \chi)}{r(\chi_s)}\frac{\delta}{a} = \int_{\mathrm{Observer}}^{\mathrm{Source}} d\Sigma \, \Sigma_{\mathrm{crit}}^{-1}$$

Surface mass density field

$$\Sigma(\boldsymbol{\chi}_\perp) = \int_0^{\chi_s} d\chi \, a(\rho - \overline{\rho}) = \int_{\mathrm{Observer}}^{\mathrm{Source}} dl \, \delta\rho$$

Critical surface mass density

$$\Sigma_{\mathrm{crit}} = \frac{c^2}{4\pi G}\frac{D_{\mathrm{OS}}}{D_{\mathrm{OL}} D_{\mathrm{LS}}}$$

- **Strong lensing**: $\Sigma \sim \Sigma_{crit}$ @ cluster cores
- **Weak lensing**: $\Sigma \sim 0.1\, \Sigma_{crit}$ @ outside cores
- **Cosmic lensing**: $|\Sigma| \lesssim 0.01\, \Sigma_{crit}$ @ LSS

Shear and Convergence

Shear tensor

Linear Stokes parameters

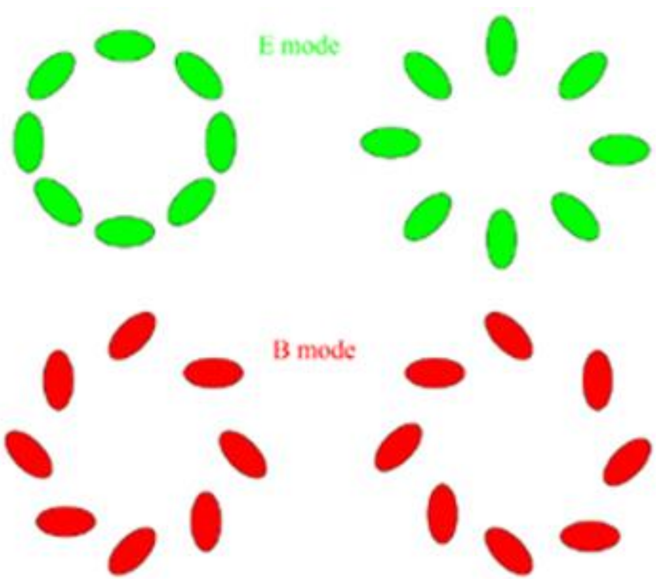
$$\Gamma_{ij} = \begin{bmatrix} +\gamma_1 & \gamma_2 \\ \gamma_2 & -\gamma_1 \end{bmatrix} \Leftrightarrow \begin{bmatrix} +Q & U \\ U & -Q \end{bmatrix}$$

Shear-to-mass relation

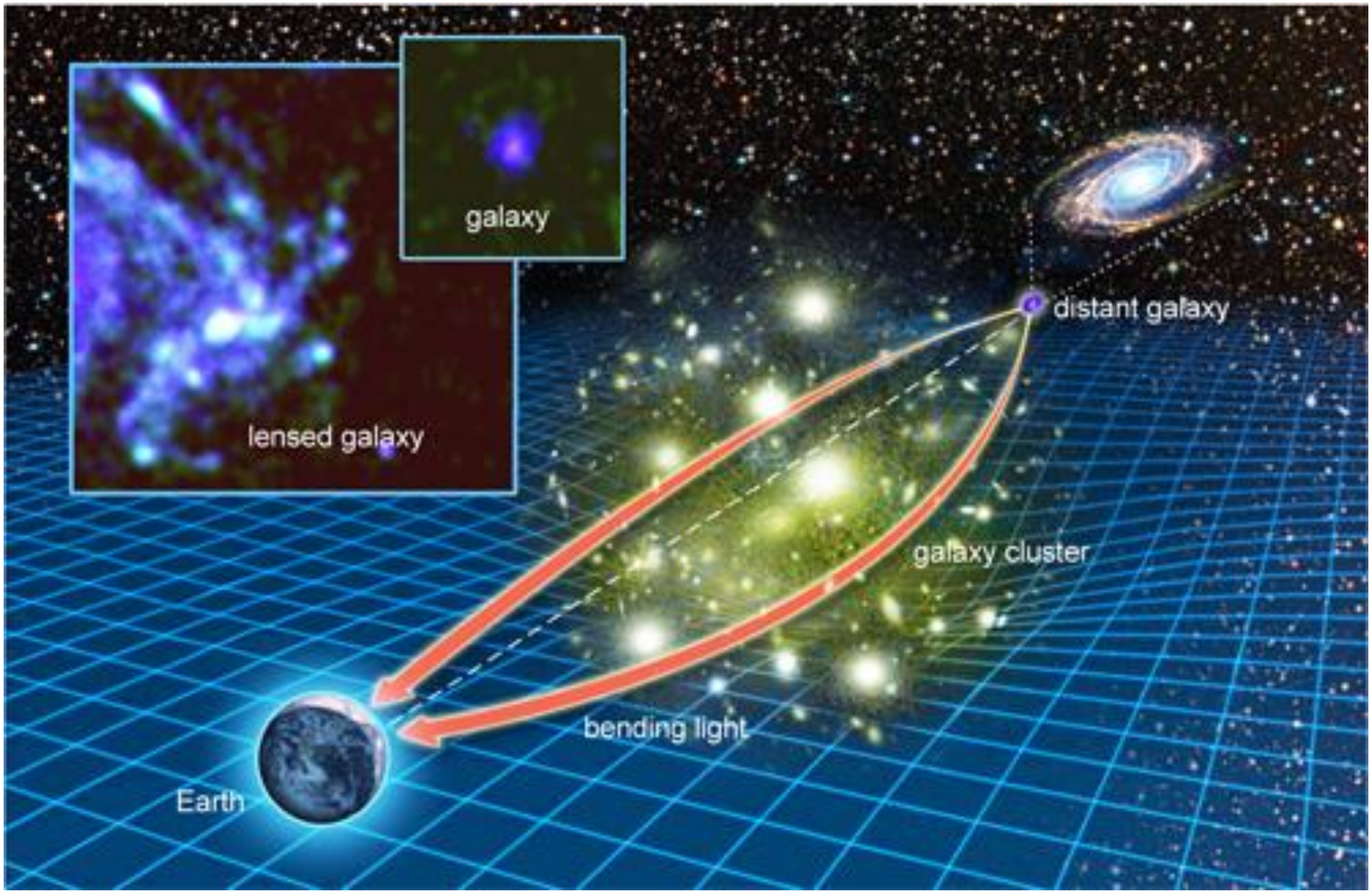
E mode

$$\Delta\kappa = \partial_i \partial_j \Gamma_{ij} \Leftrightarrow E$$

Kaiser & Squires (1993)

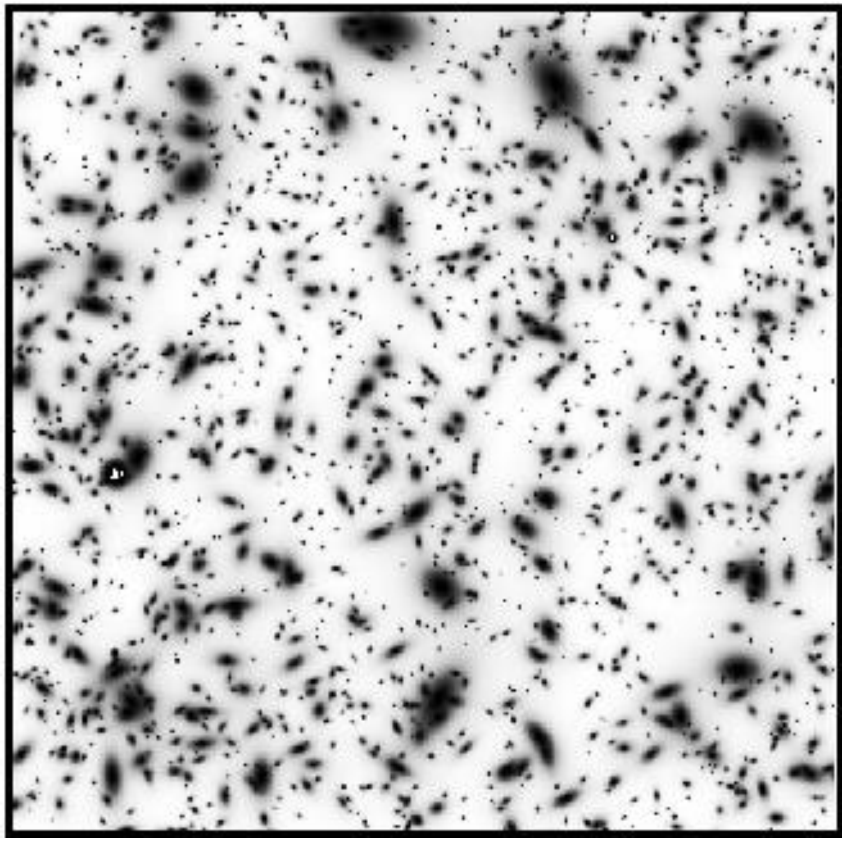


Gravitational Lensing by Galaxy Clusters

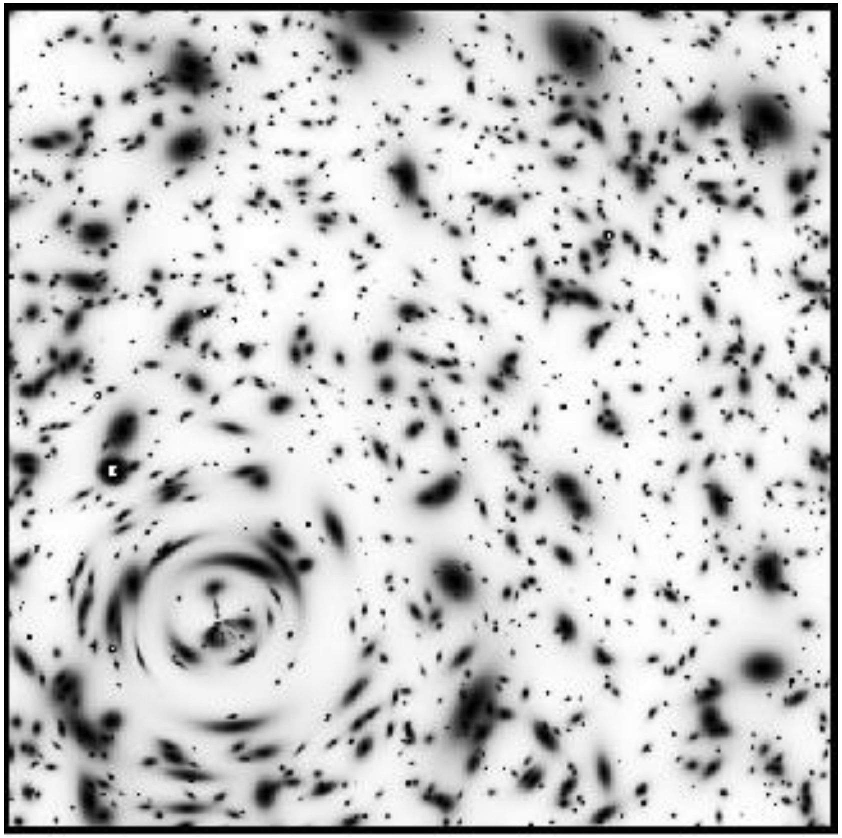


Observable Lensing Effects

No lensing

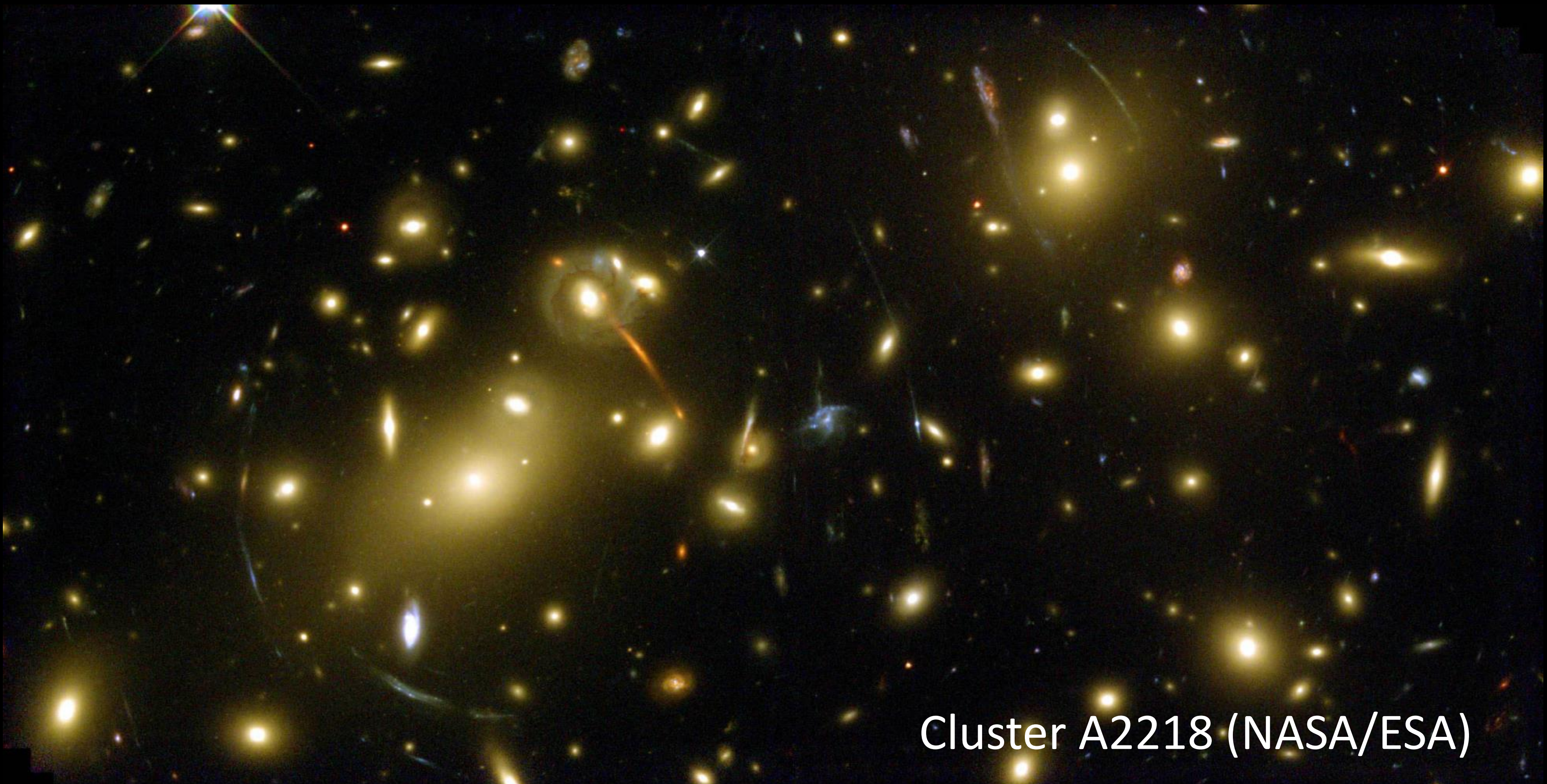


With lensing



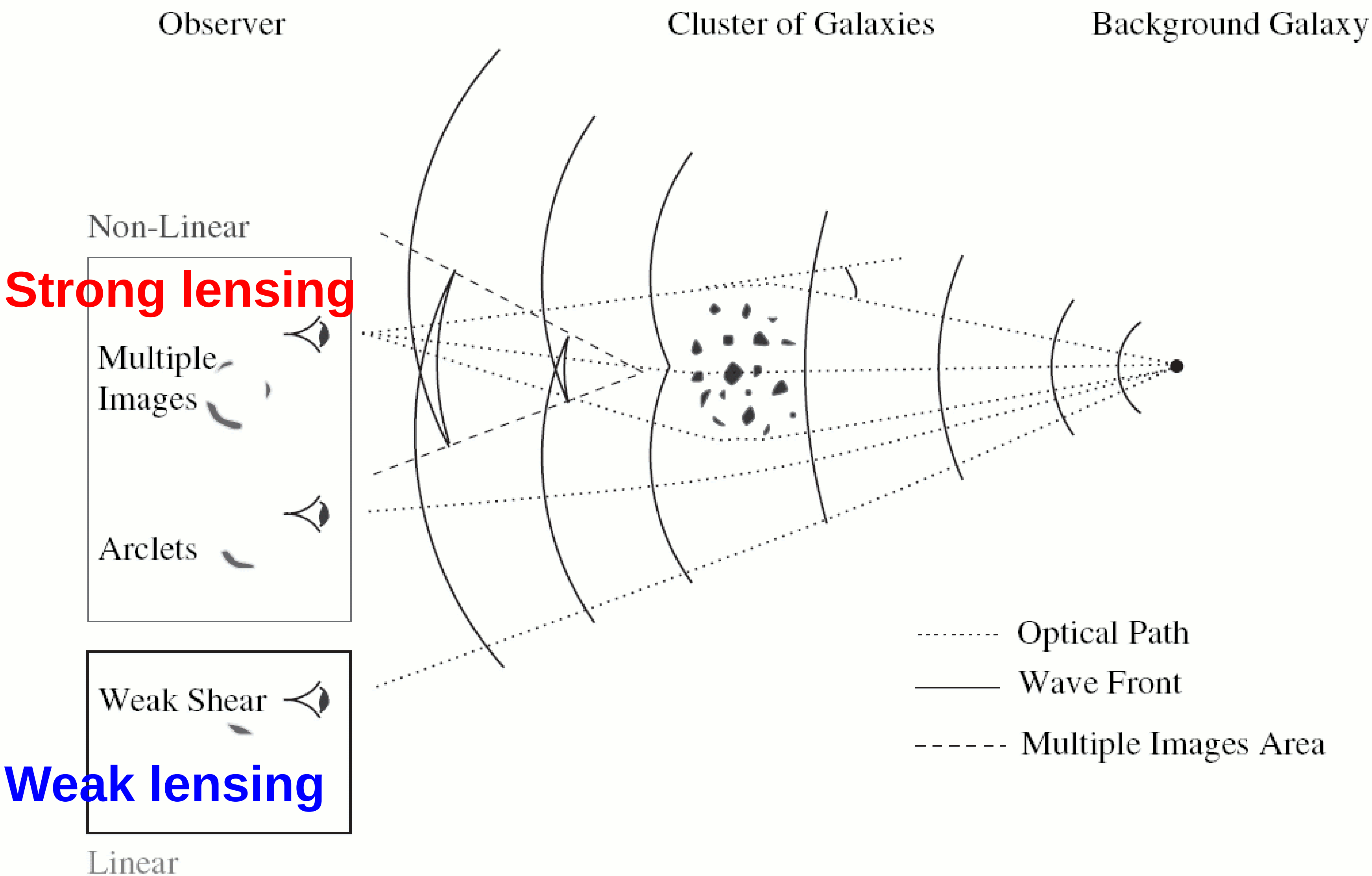
Computer simulation

Gravitational Shear

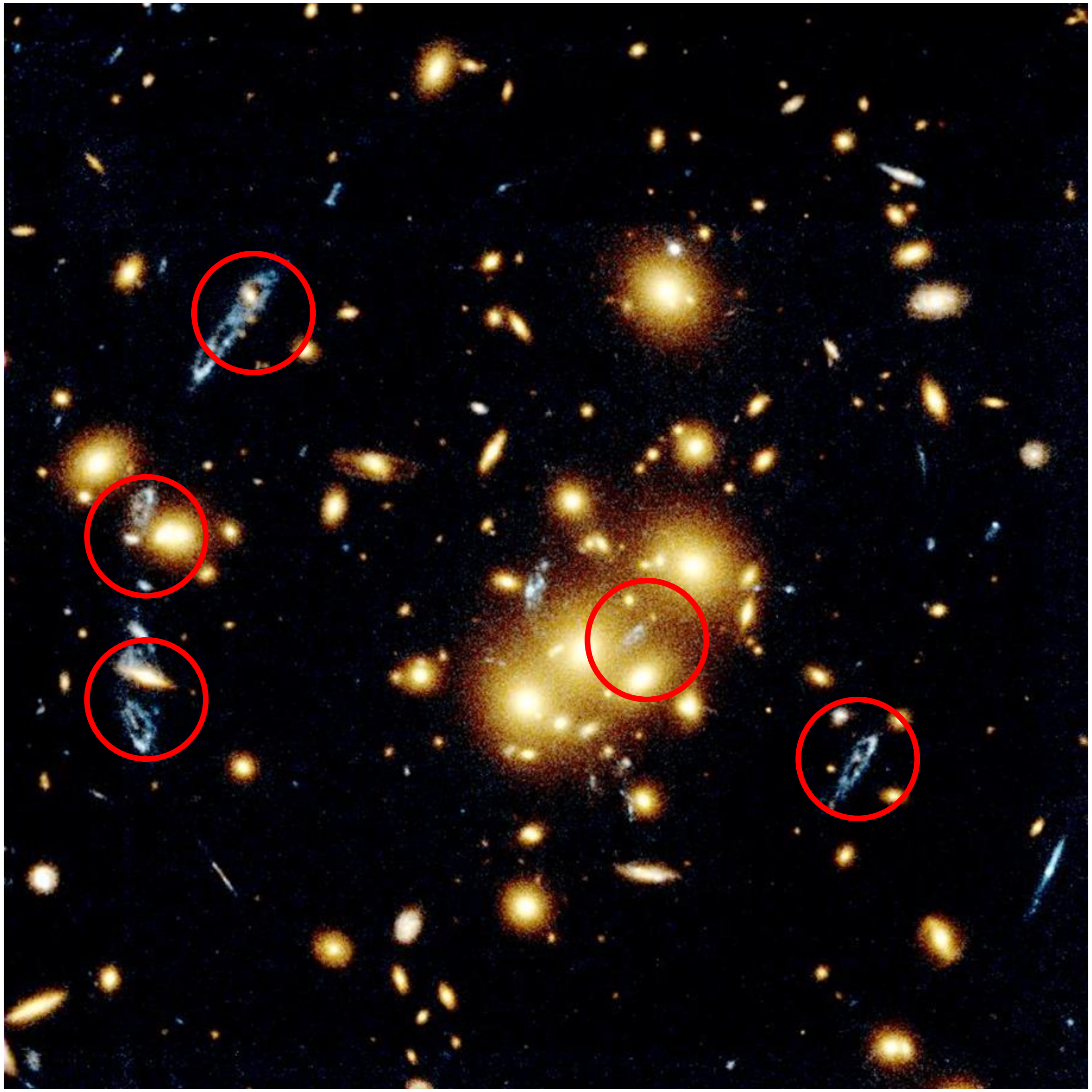



Gravitational Magnification
MACSJ1149 (z=0.54)
Zheng+CLASH. 2012, Nature, 489, 406

Strong and Weak Lensing



Multiple Imaging by Strong Lensing



Cluster CL0024+1654

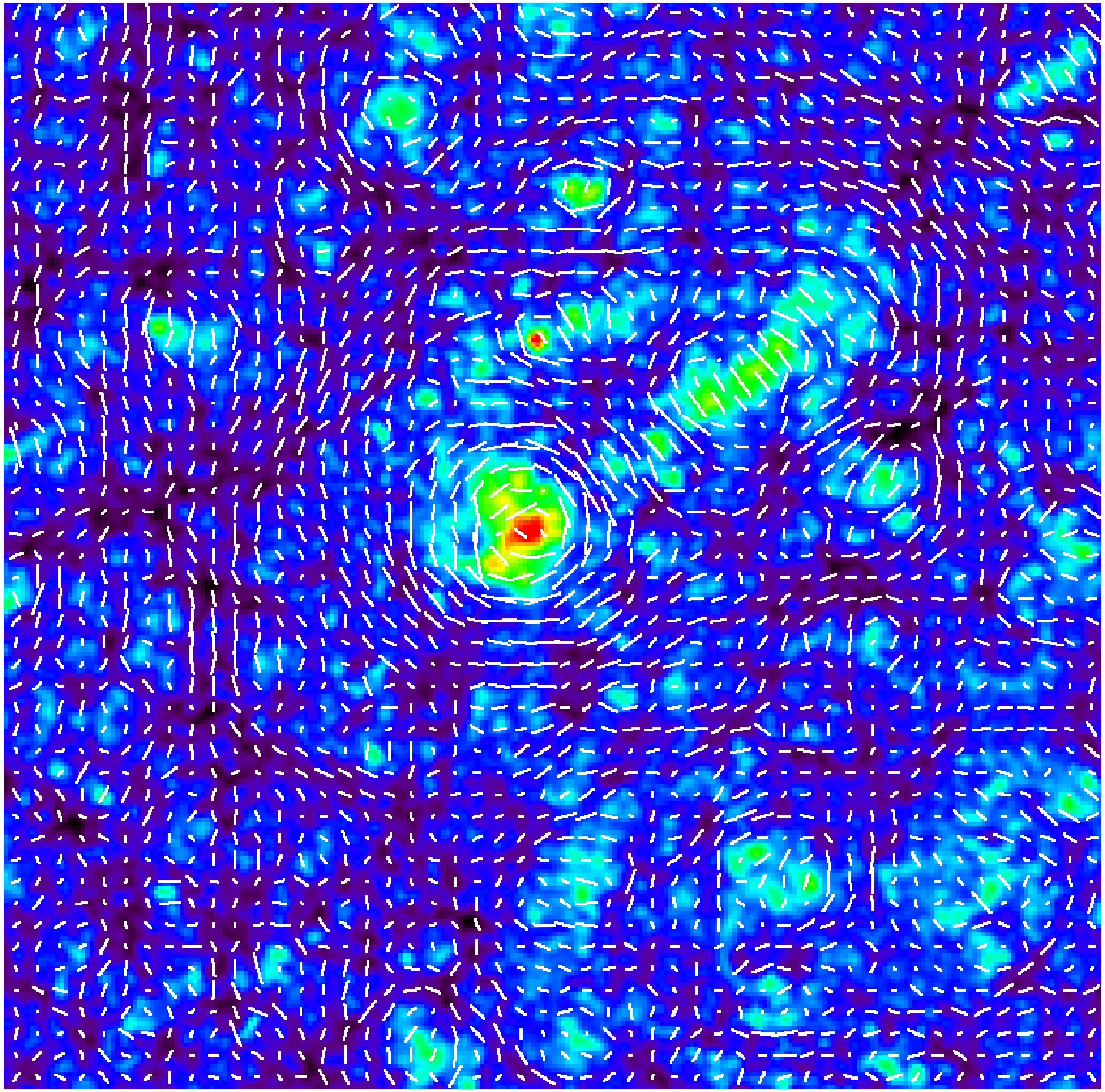
Weak Shear Field

Weak shear is observable

$$\gamma \approx \frac{a-b}{a+b} e^{2i\phi}$$

Cosmic shear: a few %

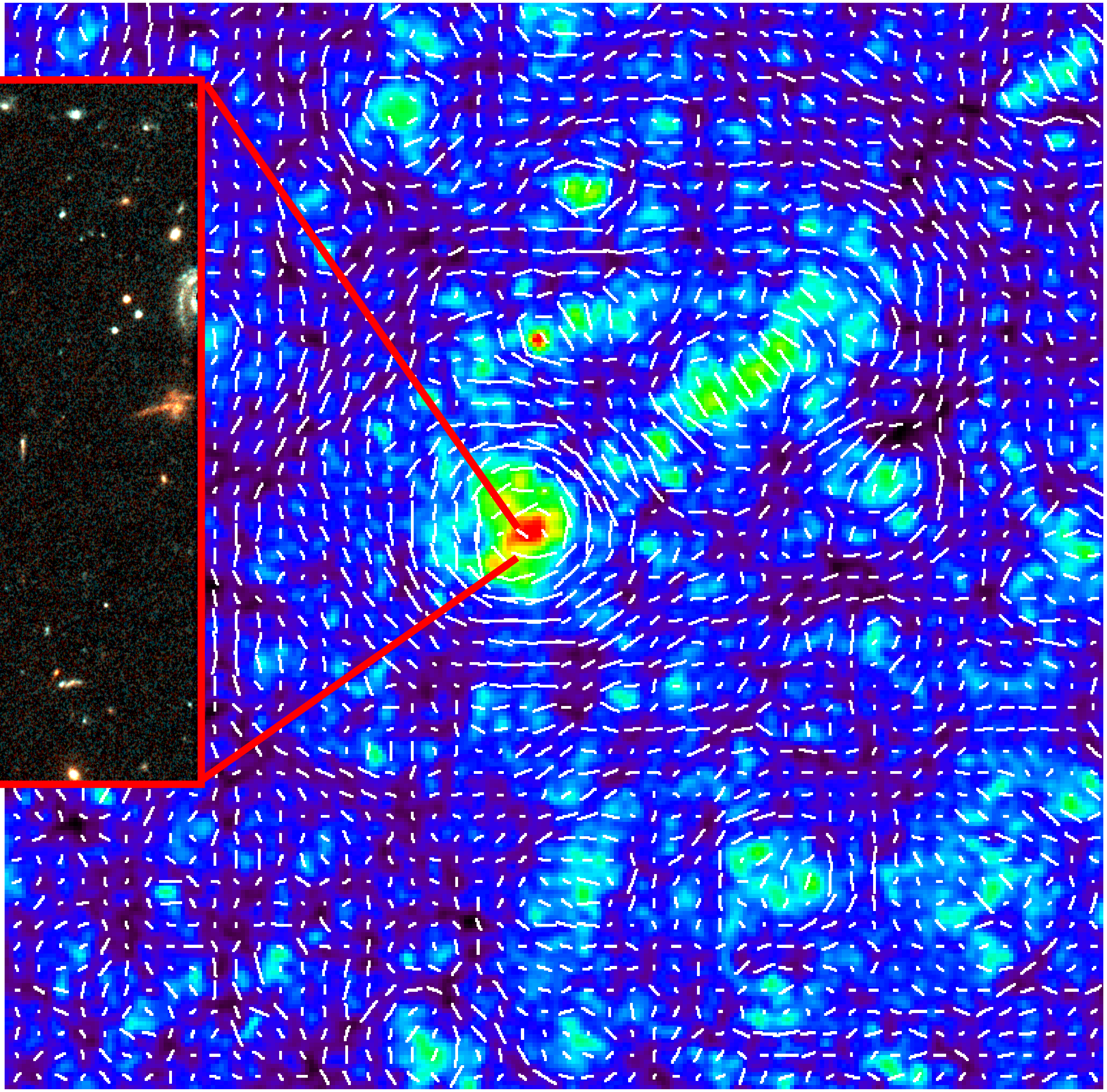
Cluster shear: 10-20%



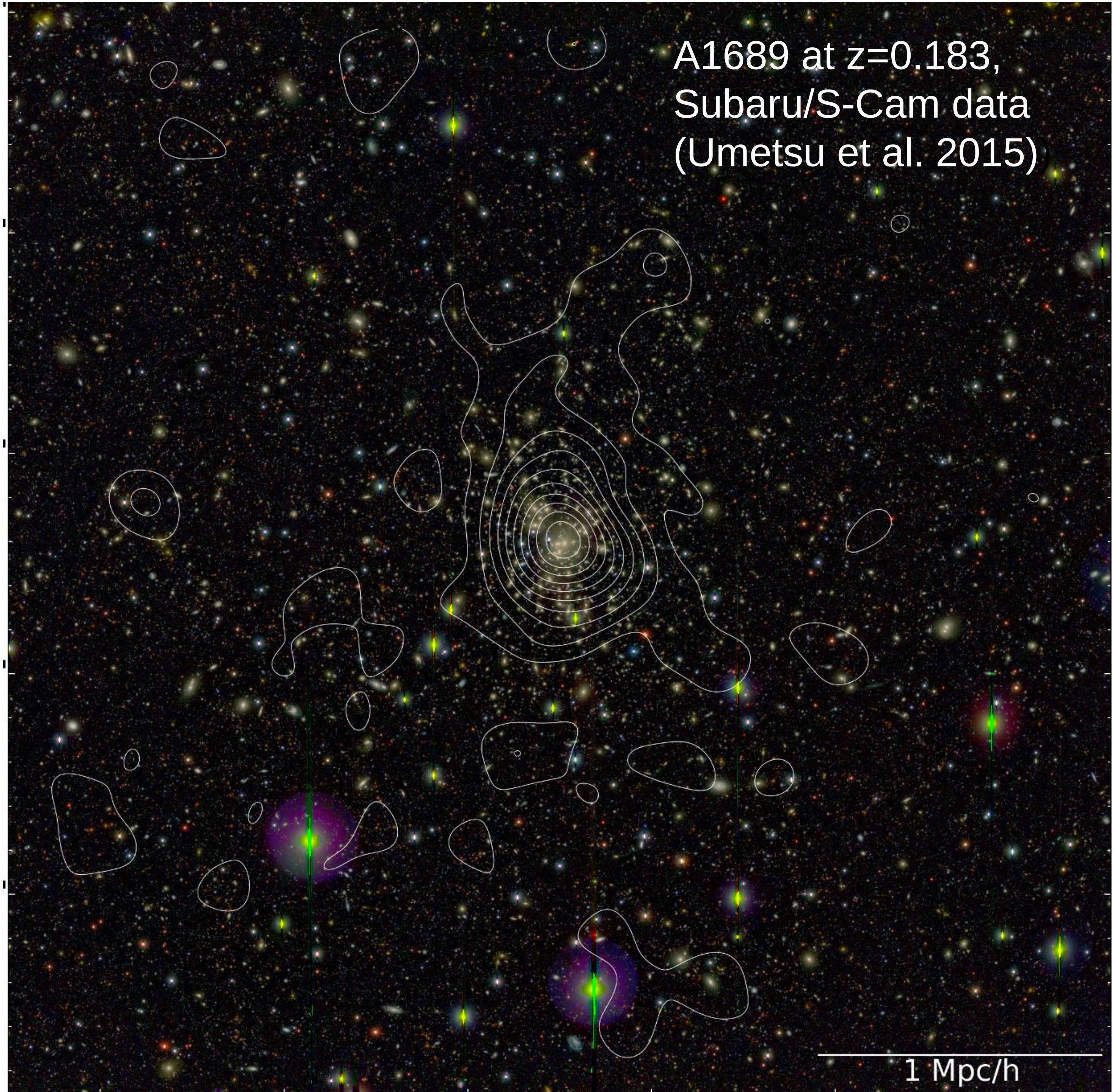
Simulated 3x3 degree field (Hamana 02)

Weak Shear Field

Cluster z = 0.77; Arc z = 4.89:
Photo from H. Yee (HST/ACS)

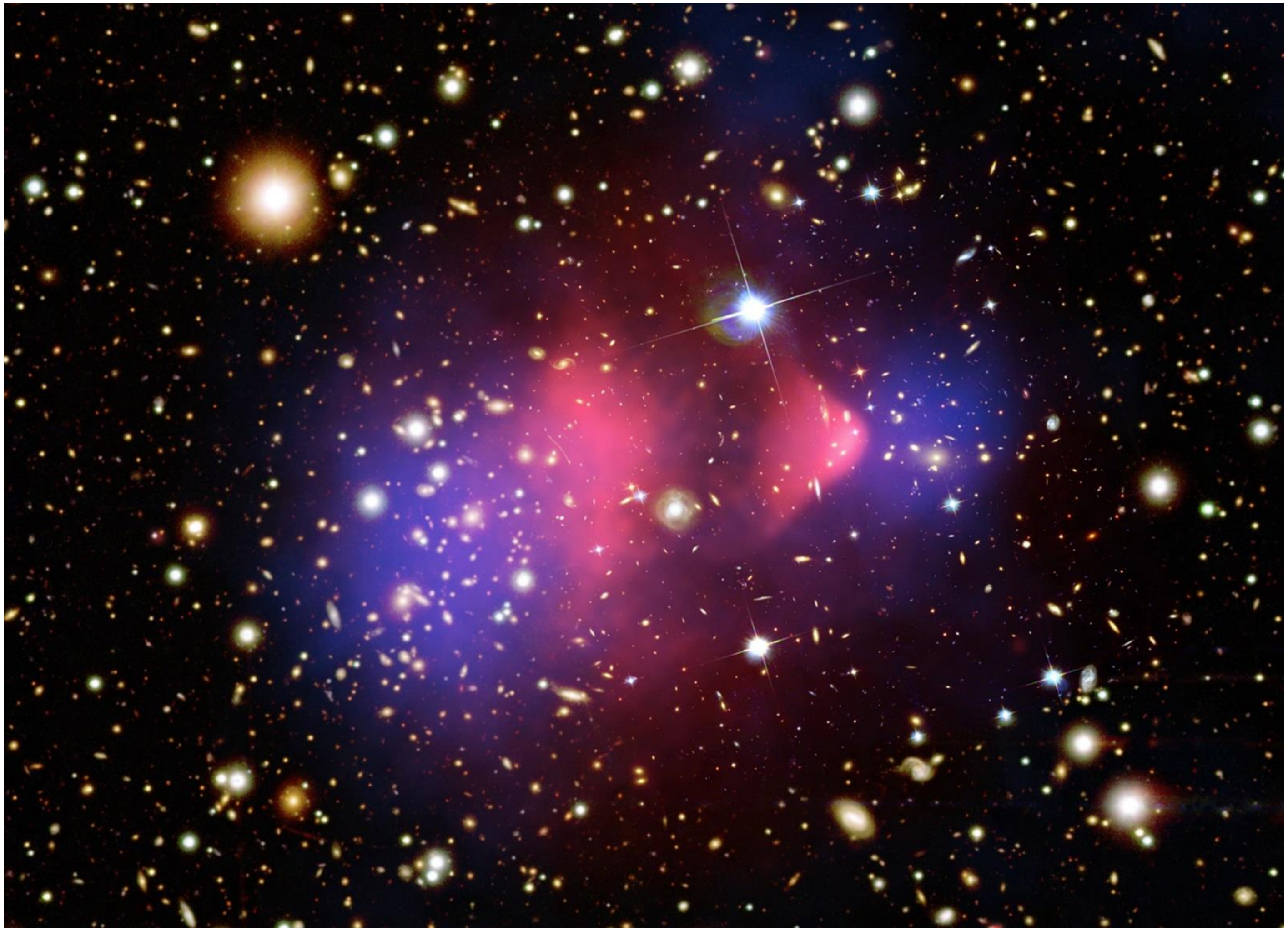


Simulated 3x3 degree field (Hamana 02)


A1689 at z=0.183,
Subaru/S-Cam data
(Umetsu et al. 2015)
1 Mpc/h

Seeing the unseen: Dark Matter

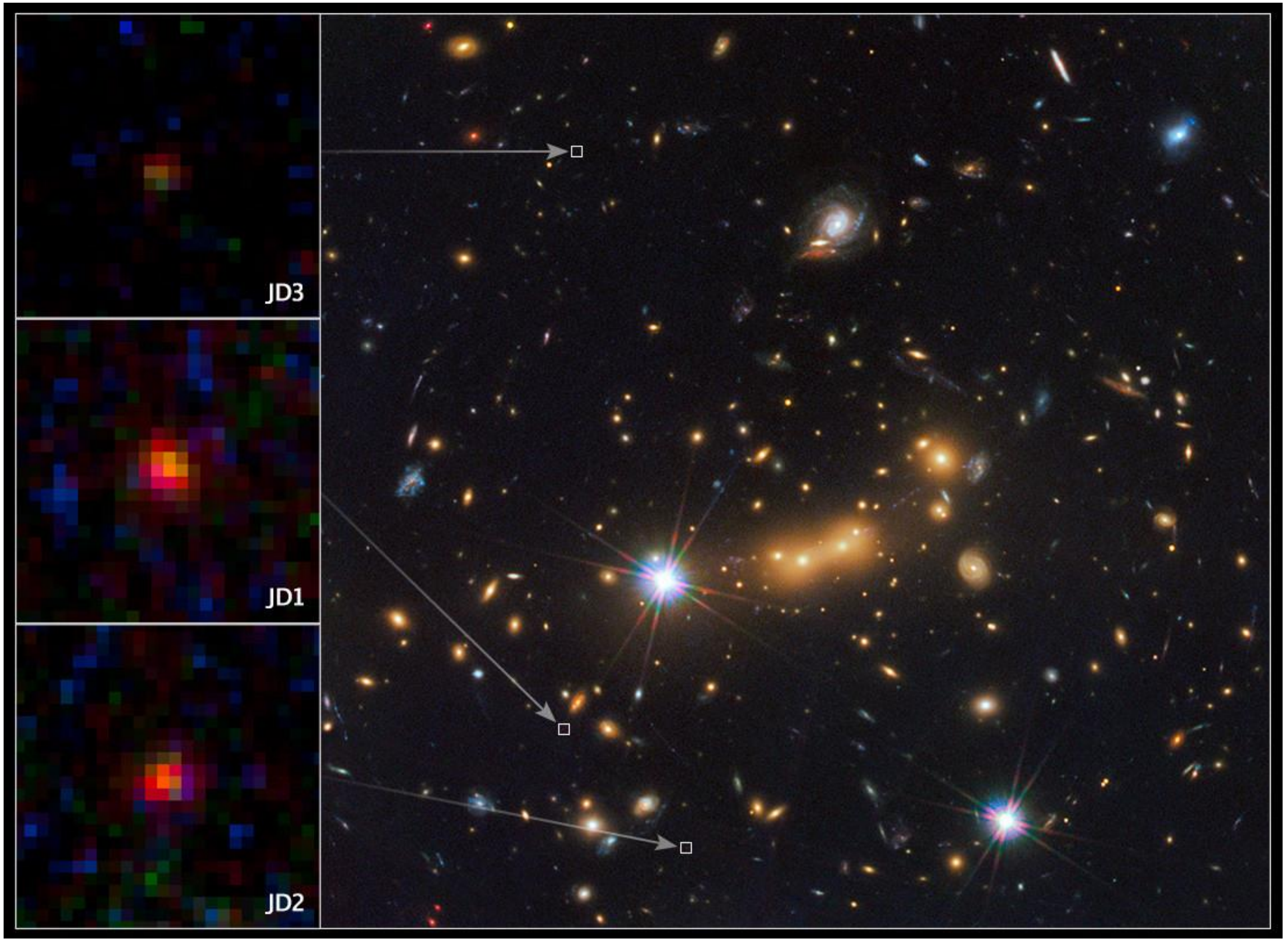
Bullet cluster



Blue: DM
Red: hot gas

Hunting the first galaxies with lensing

Highly magnified distant galaxy (candidate) at z ~ 11



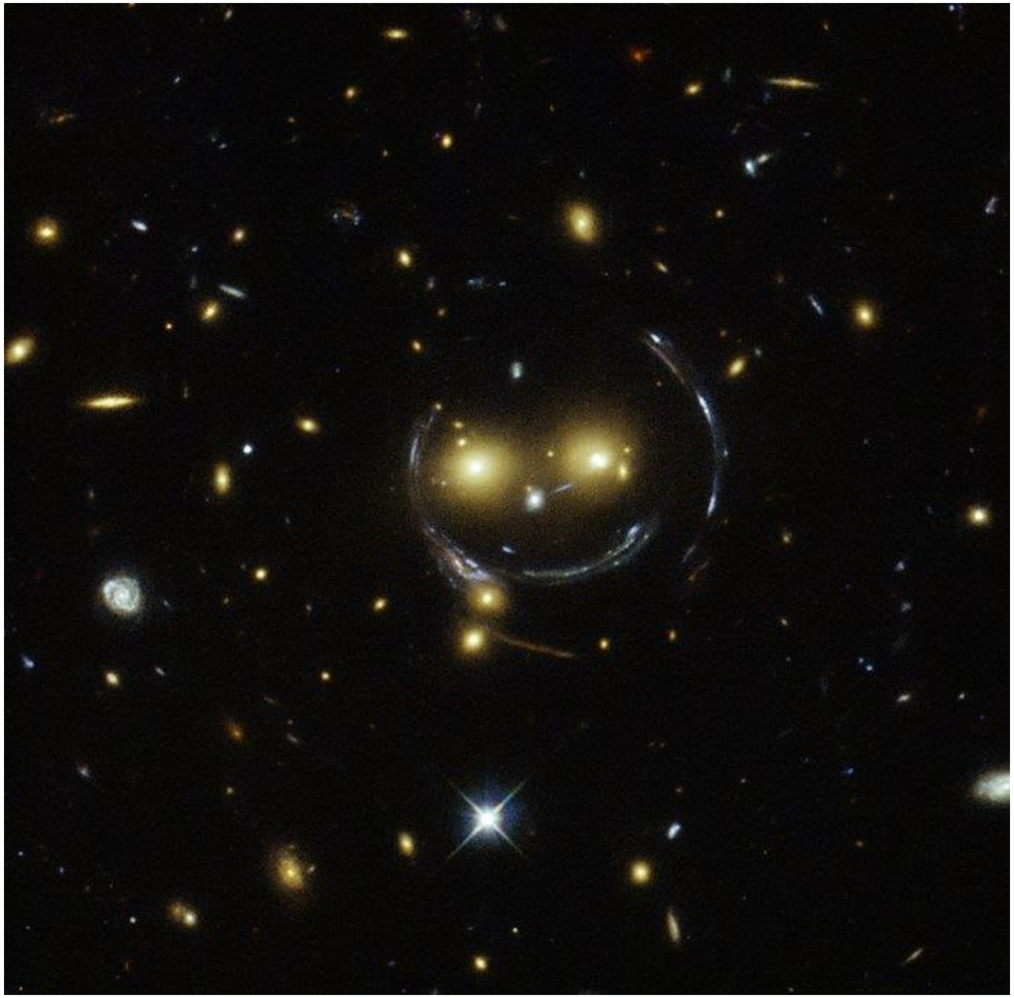
Cluster MACS0647

Multiple images of a supernova!

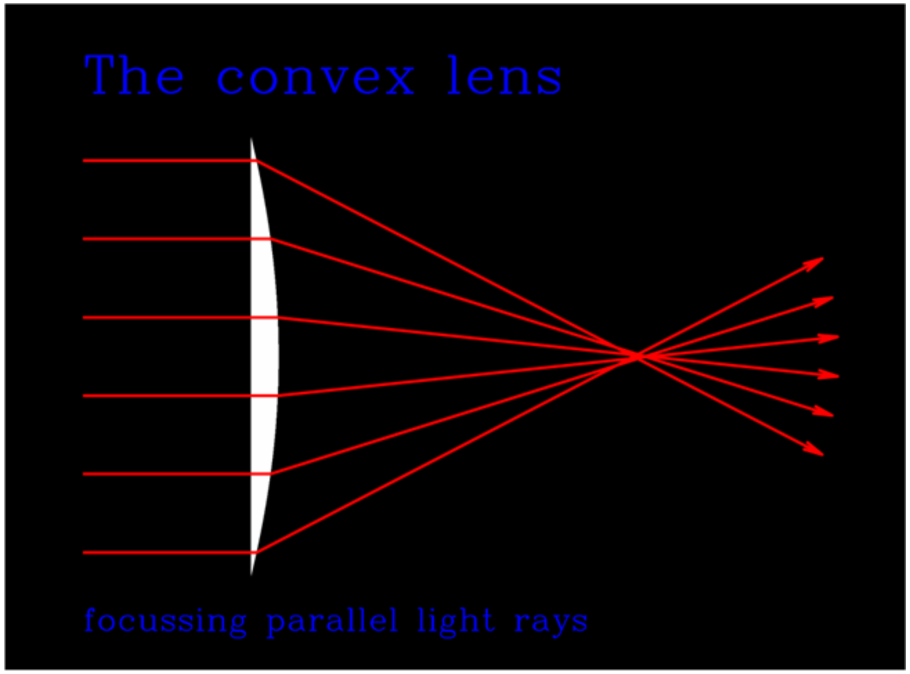
Cluster MACS1149

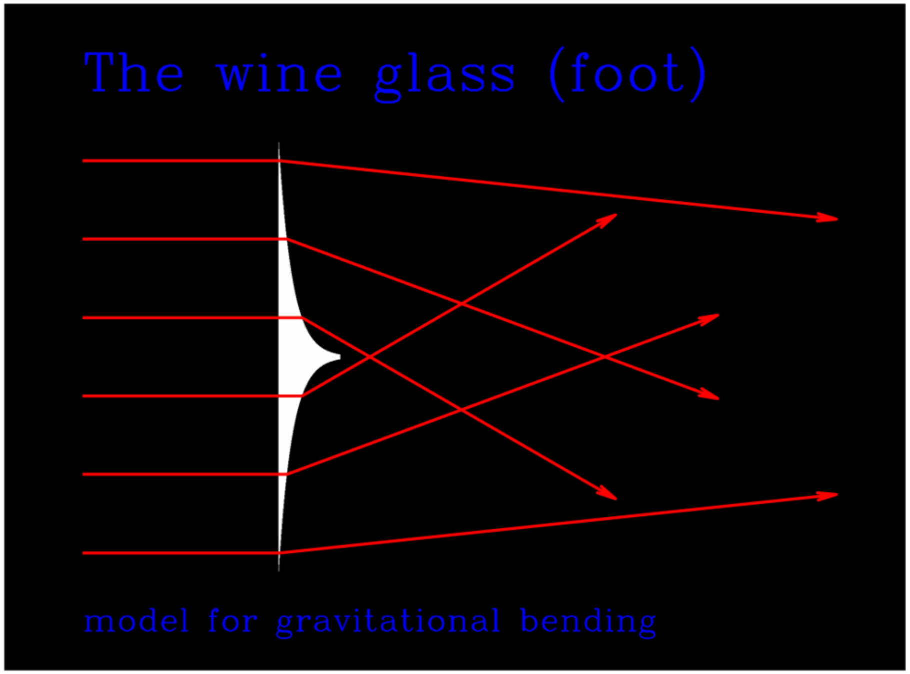
Summary

Gravitational lensing is exciting!!!



凸面 vs. 重力透鏡


The convex lens
focussing parallel light rays


The wine glass (foot)
model for gravitational bending