Cosmic Shear from Scalar-Induced Gravitational Wave

Devdeep Sarkar
Center for Cosmology, UC Irvine

Based on:
D.S., Paolo Serra, Asantha Cooray (UCI), Kiyotomo Ichiki (Tokyo), and Daniel Baumann (Princeton),
Phys. Rev. D, 77, 103515 (2008) [arXiv: 0803.1490]

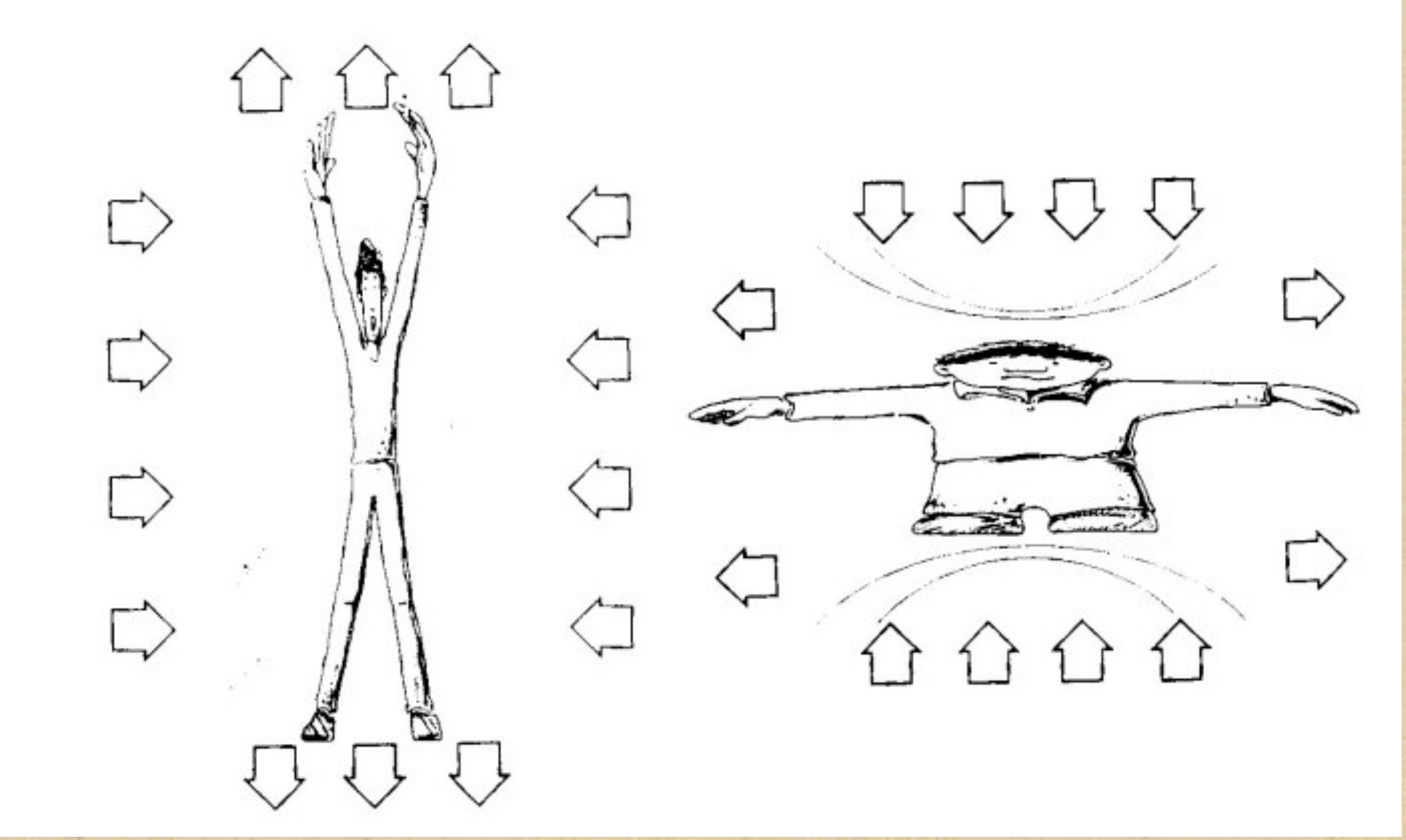
UC Irvine Astro Grad Seminar Oct 08, 2008

Agenda

- ABC's of Gravitational Waves
- Primary GWB vs Scalar-Induced GW
- Why Cosmic Shear?
- Gravitational Lensing 201
- Method and Results
- Conclusion

Motivation

To have a deep understanding of...



credit: http://www.lnl.infn.it/~auriga/

ABC's of Gravitational Waves

Einstein's Field Equations:

$$G_{\mu\nu} = R_{\mu\nu} - \frac{1}{2} R g_{\mu\nu} = 8\pi G T_{\mu\nu}$$

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Second order differential equations for metric tensor

$$g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu} \; ; \quad |h_{\mu\nu}| << 1$$

Flat Background
diag(-1,+1,+1,+1)

Small Perturbation

trace reversed

$$\bar{h}_{\mu\nu} = h_{\mu\nu} - \frac{1}{2}\eta_{\mu\nu}h$$

ABC's of Gravitational Waves

Under Lorentz (or Einstein or Hilbert or Fock) Gauge:

$$\partial_\mu \bar{h}^\mu_\lambda = 0$$

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Linearized Einstein Equation becomes:

$$\Box \bar{h}_{\mu\nu} = -16\pi G T_{\mu\nu}$$

$$(\Box \equiv -\partial_t^2 + \partial_x^2 + \partial_y^2 + \partial_z^2)$$

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In Vacuum...

$$\boxed{\Box \bar{h}_{\mu\nu} = 0}$$

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ABC's of Gravitational Waves

Weak-Field limit for a Stationary Spherical Source:

ABC's of Gravitational Waves

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$$h_{00} = -2\Phi$$

$$h_{i0} = 0$$

$$h_{ij} = -2\Phi\delta_{ij}$$

ABC's of Gravitational Waves

Weak-Field limit for a Stationary Spherical Source:

$$h_{00} = -2\Phi$$

$$h_{i0} = 0$$

$$h_{ij} = -2\Phi\delta_{ij}$$

And hence… the metric becomes:

$$ds^2 = -(1 + 2\Phi)dt^2 + (1 - 2\Phi)(dx^2 + dy^2 + dz^2)$$

ABC's of Gravitational Waves

Consider the solution:

$$\bar{h}_{\mu\nu} = C_{\mu\nu} e^{ik_\sigma x^\sigma}$$

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constant, symmetric, (0,2) tensor

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10 independent components

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$$\Box \bar{h}_{\mu\nu} = 0 \Rightarrow k_\sigma k^\sigma = 0 \Rightarrow \omega^2 = \delta_{ij} k^i k^j$$

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(the wave vector is orthogonal to $C^{\mu\nu}$)

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4 equations
6 components
remain

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ABC's of Gravitational Waves

The solution:

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Get rid of coordinate freedom ($x^\mu \rightarrow x^\mu + \zeta^\mu$)...

4 more constraints... leaves 2 components

These two numbers represent the physical information characterizing our plane wave in this gauge.

ABC's of Gravitational Waves

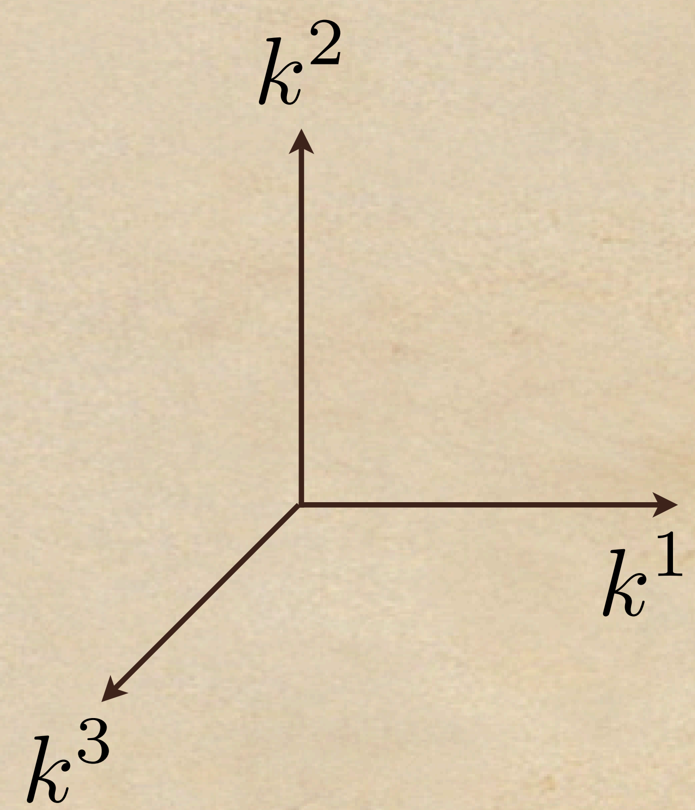
The solution:

$$\bar{h}_{\mu\nu} = C_{\mu\nu} e^{i k_\sigma x^\sigma}$$

Explicit construction...

$$k^\mu = (\omega, 0, 0, k^3) = (\omega, 0, 0, \omega)$$

$$C_{\mu\nu} = \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & C_{11} & C_{12} & 0 \\ 0 & C_{12} & -C_{11} & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix}$$



Transverse Traceless gauge
(radiation gauge)

ABC's of Gravitational Waves

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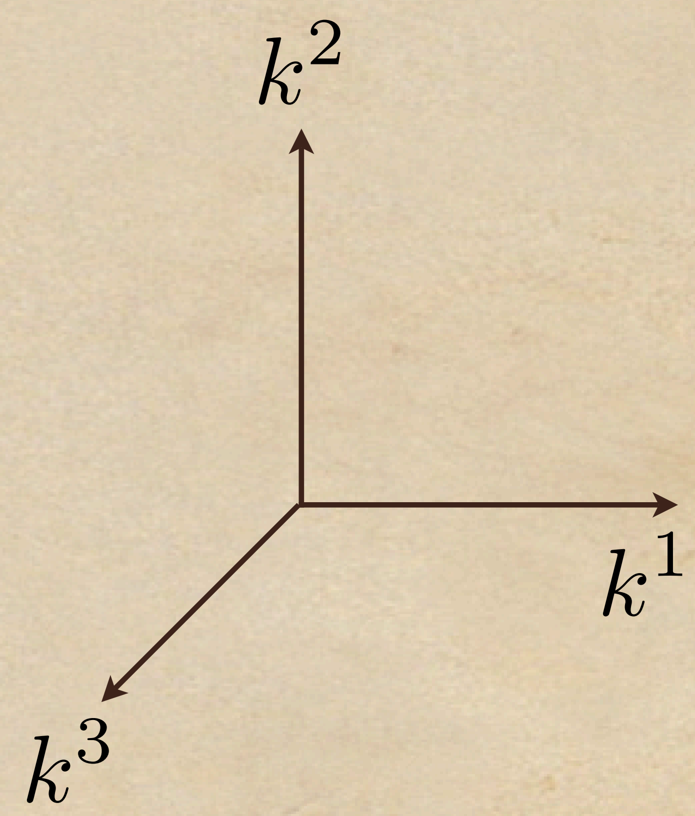

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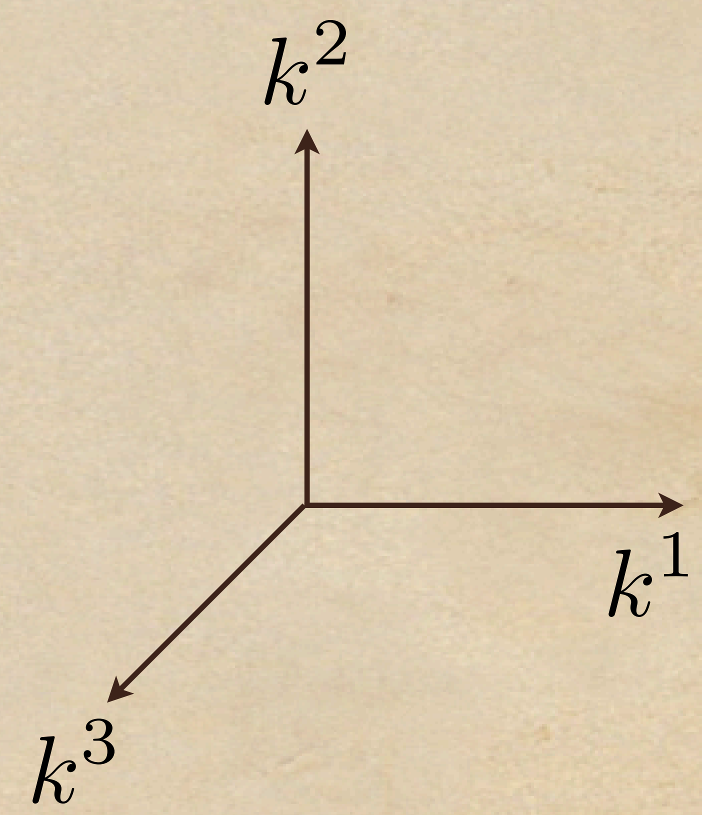
Consider particles with separation S^μ



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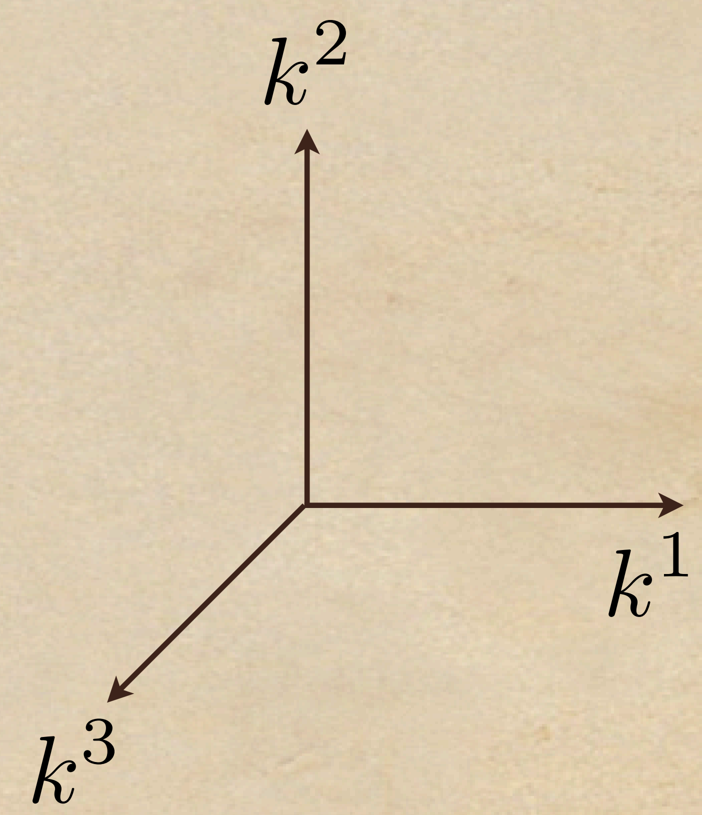
Consider particles with separation S^μ

The geodesic deviation Equation:

$$\frac{\partial^2}{\partial t^2} S^\mu = \frac{1}{2} S^\sigma \frac{\partial^2}{\partial t^2} h^\mu_\sigma$$

This implies that ONLY S^1 and S^2 will be affected!



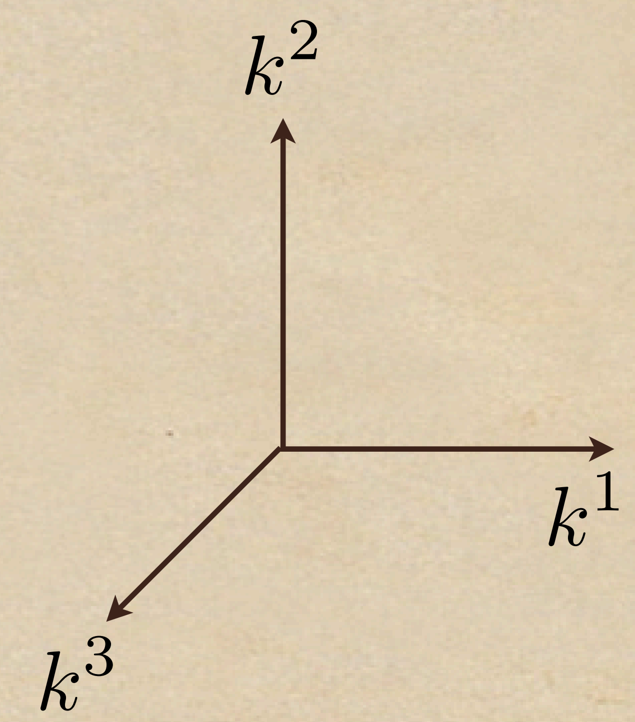
$k^\mu = (\omega, 0, 0, k^3) = (\omega, 0, 0, \omega)$

ABC's of Gravitational Waves

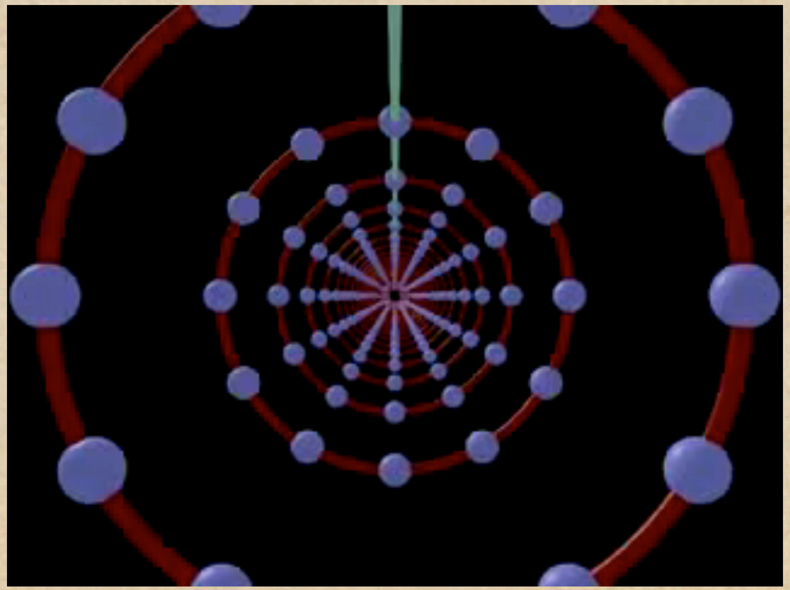
Case (I) $C_\times = 0$

$$S^1 = \left(1 + \frac{1}{2} C_+ e^{ik_\sigma x^\sigma}\right) S^1(0)$$

$$S^2 = \left(1 - \frac{1}{2} C_+ e^{ik_\sigma x^\sigma}\right) S^2(0)$$



Credit: Michael
Penn State Schuylkill



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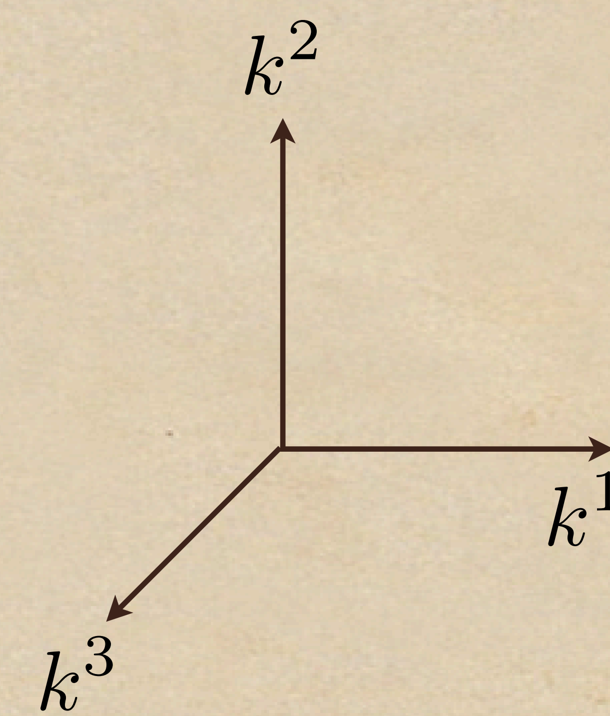

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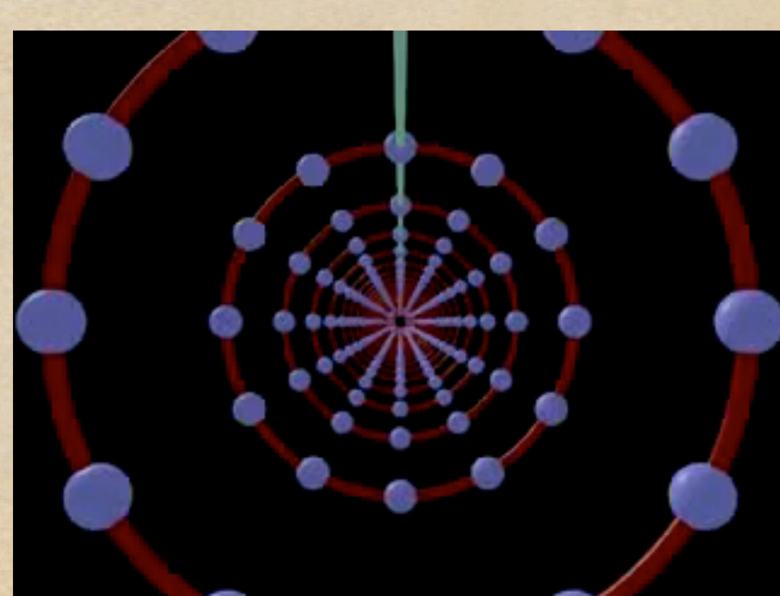

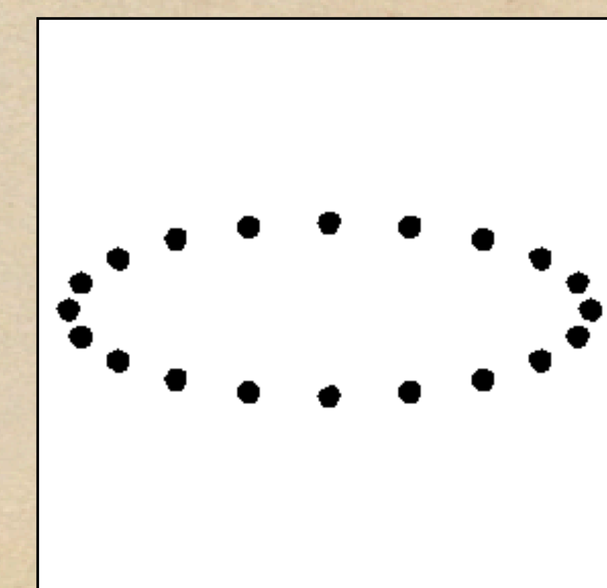

ABC's of Gravitational Waves

Case (II) $C_+ = 0$

$$S^1 = S^1(0) + \frac{1}{2} C_\times e^{ik_\sigma x^\sigma} S^2(0)$$

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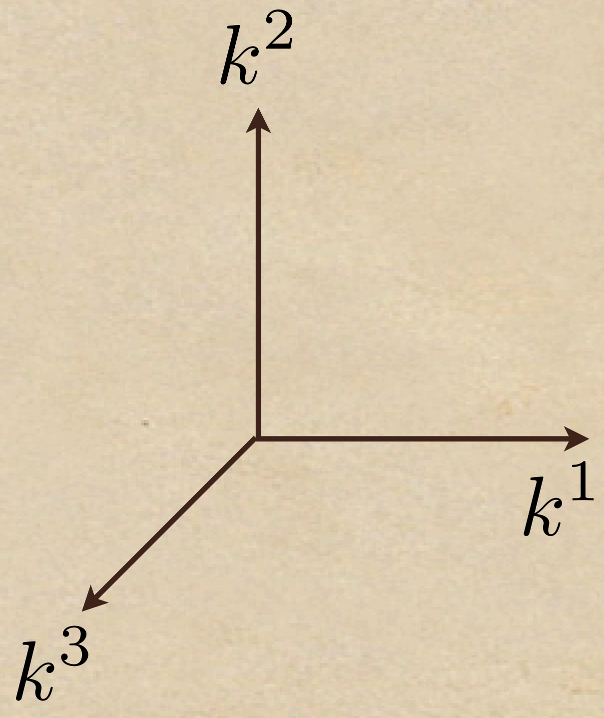

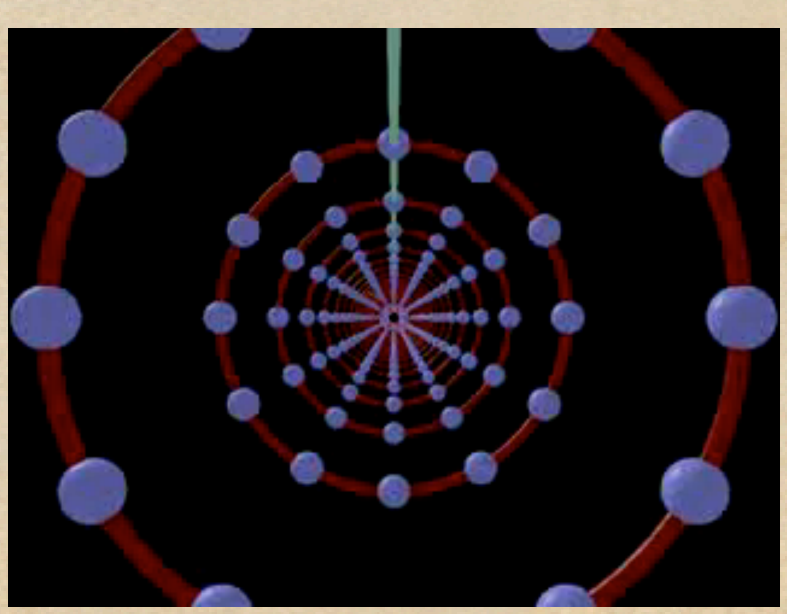

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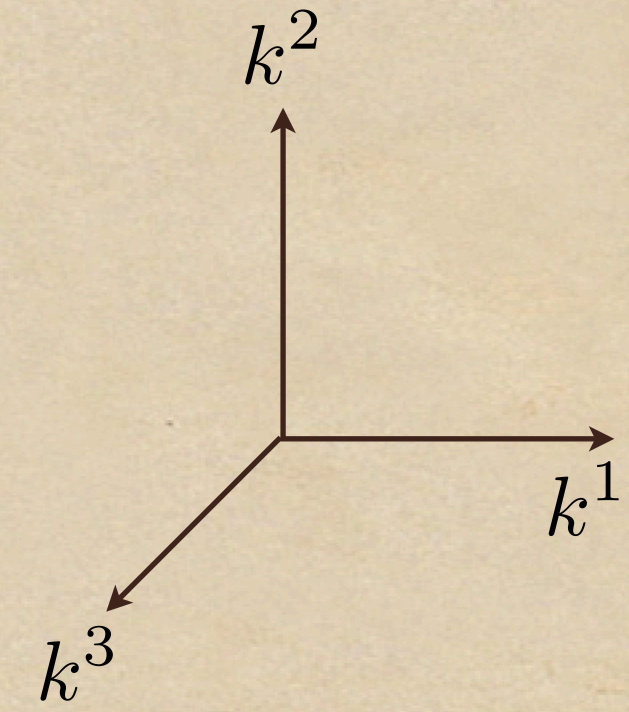

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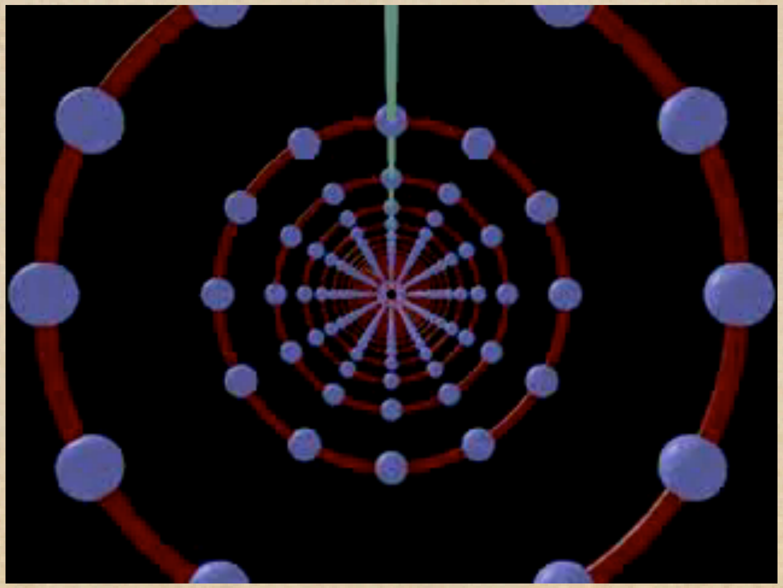

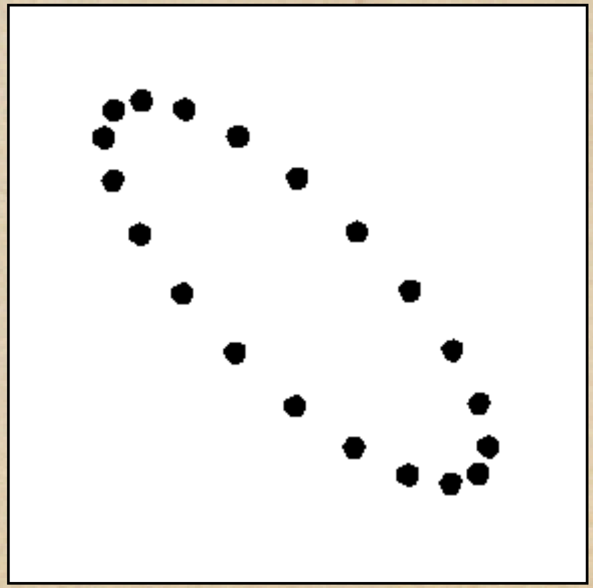

Astrophysical Sources of GW

Artist's concept depicts two white dwarfs
RXJ0806.3+1527 or J0806, swirling close together...

Credit: GSFC/D. Berry

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Primordial Gravity Wave Background

- Waves stemming from the inflationary expansion of space itself
- Waves from the collision of bubble-like clumps of new matter at reheating after inflation
- Waves from the turbulent fluid mixing of the early pools of matter and radiation

2nd order Tensors from 1st order Scalars

Metric Decomposition

$$\bar{g}_{\mu\nu} = g_{\mu\nu} + \underline{\delta g_{\mu\nu}} + \underline{\delta^2 g_{\mu\nu}}$$

purely scalar d.o.f — purely tensor d.o.f

S. Matarrese, O. Pantano, and D. Saez, PRD, 47, 1311 (1993)

K. N. Ananda, C. Clarkson, and D. Wands, PRD, 75, 123518 (2007)

D. Baumann, P. Steinhardt, K. Takahashi, and K. Ichiki, PRD, 76, 084019 (2007)

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$$\Phi^{''} + 3aH(1+c_s^2)\Phi^{'} + c_s^2 k^2 \Phi = 0$$

SCALAR

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SCALAR

TENSOR

$$h_{ij}^{''} + 2aHh_{ij}^{'} - \nabla^2 h_{ij} = -4\hat{T}_{ij}^{lm} S_{lm}$$

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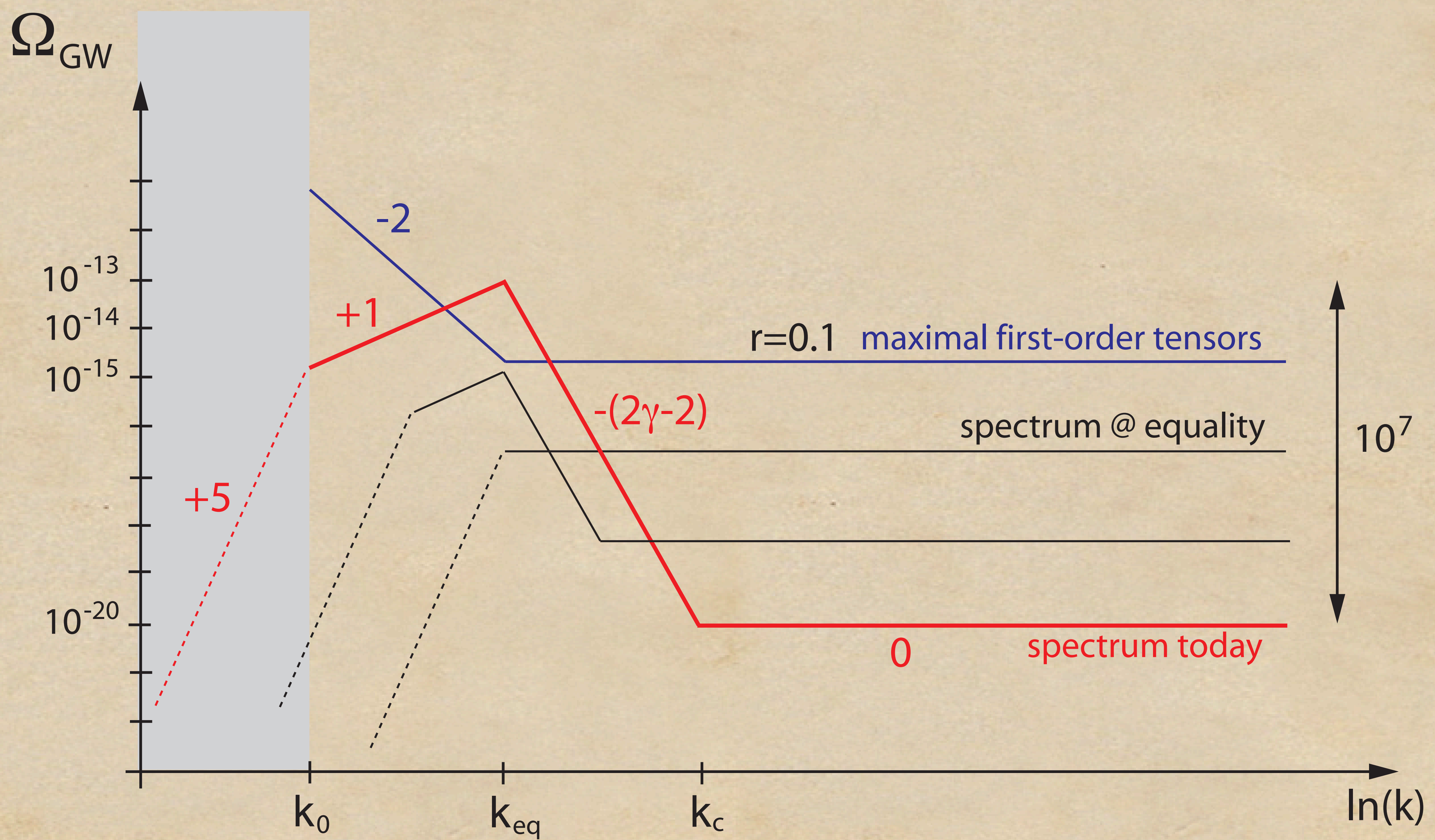
Relative Strengths



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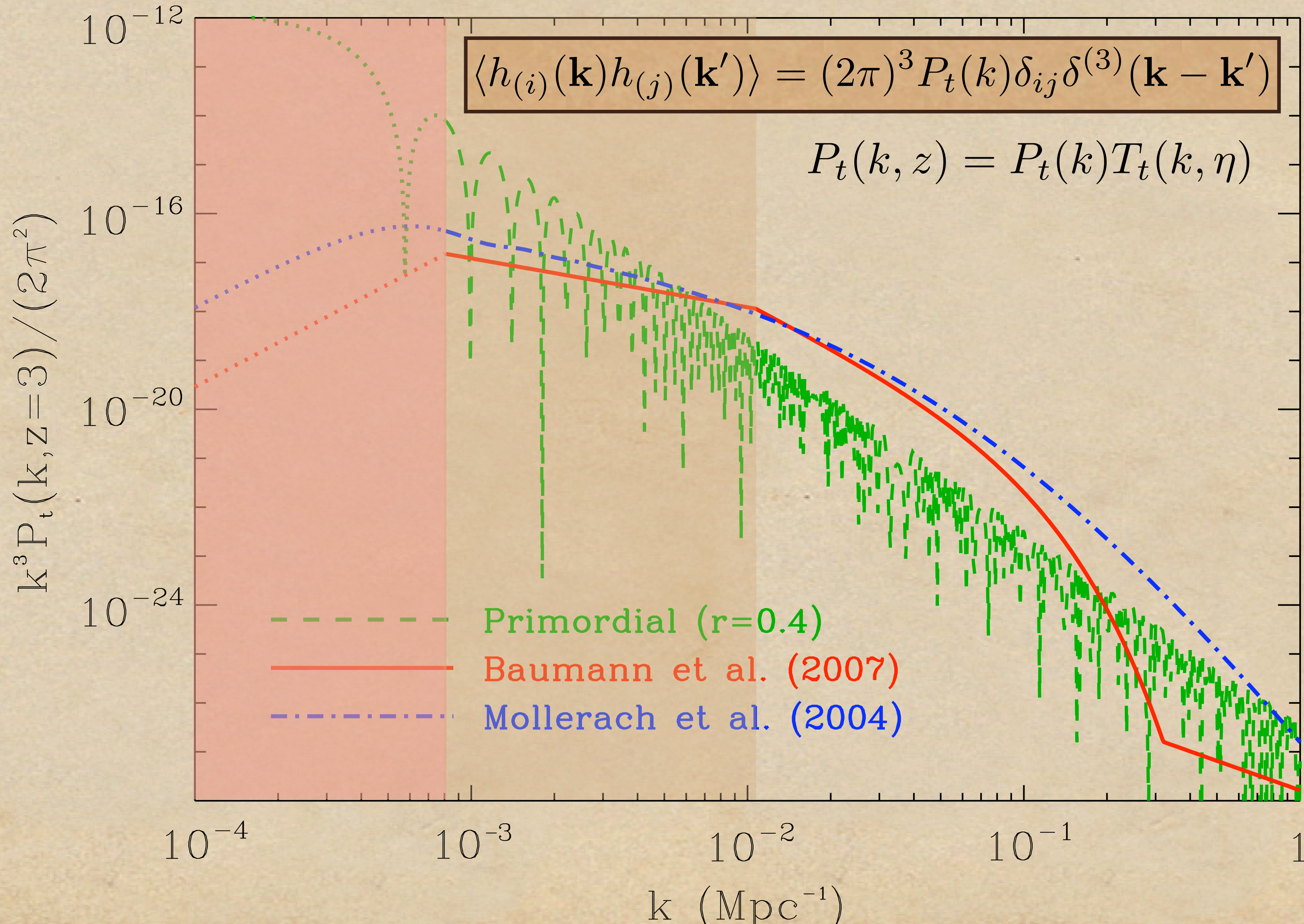
How Do the Power Spectra Look Like?



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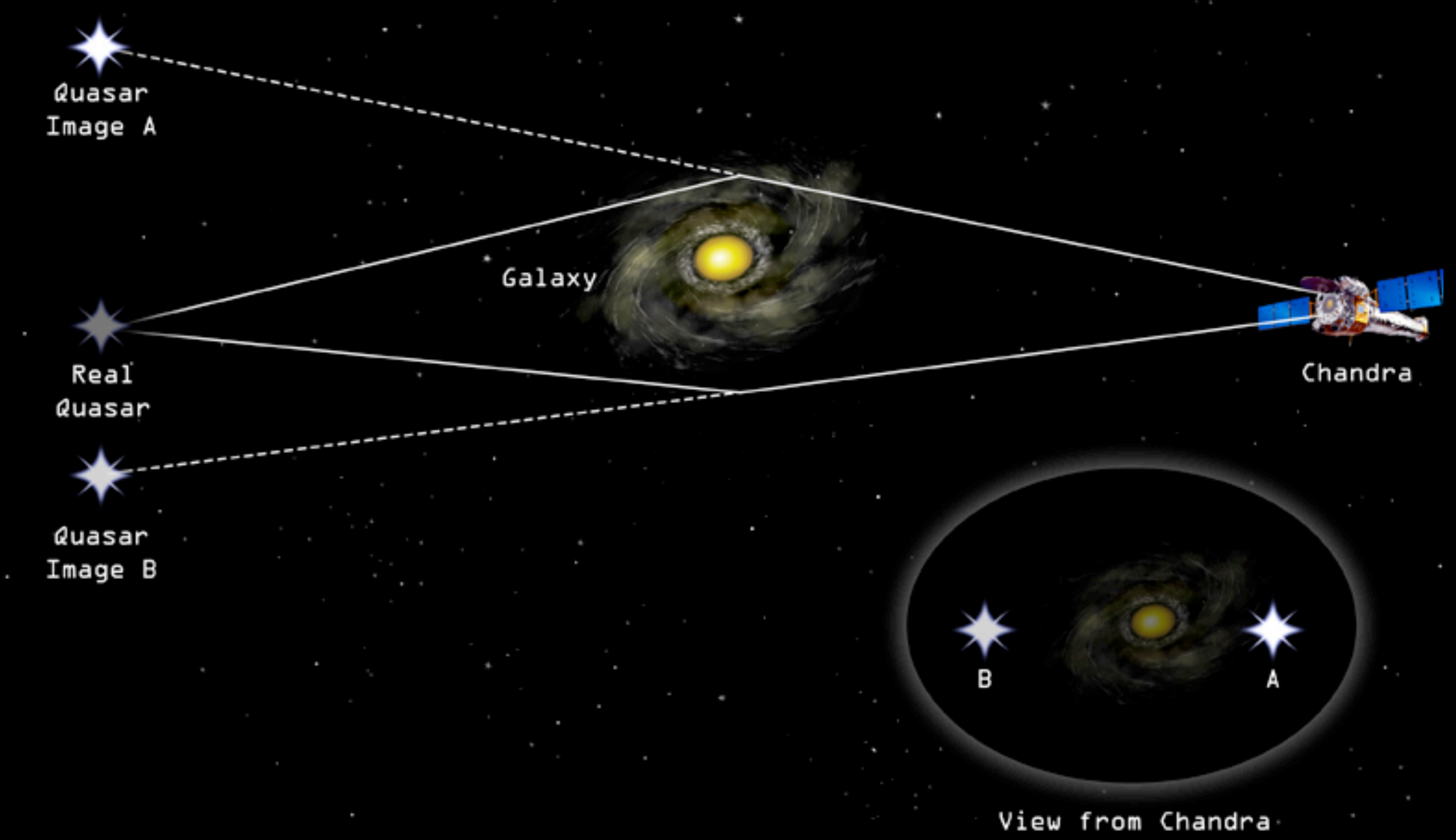
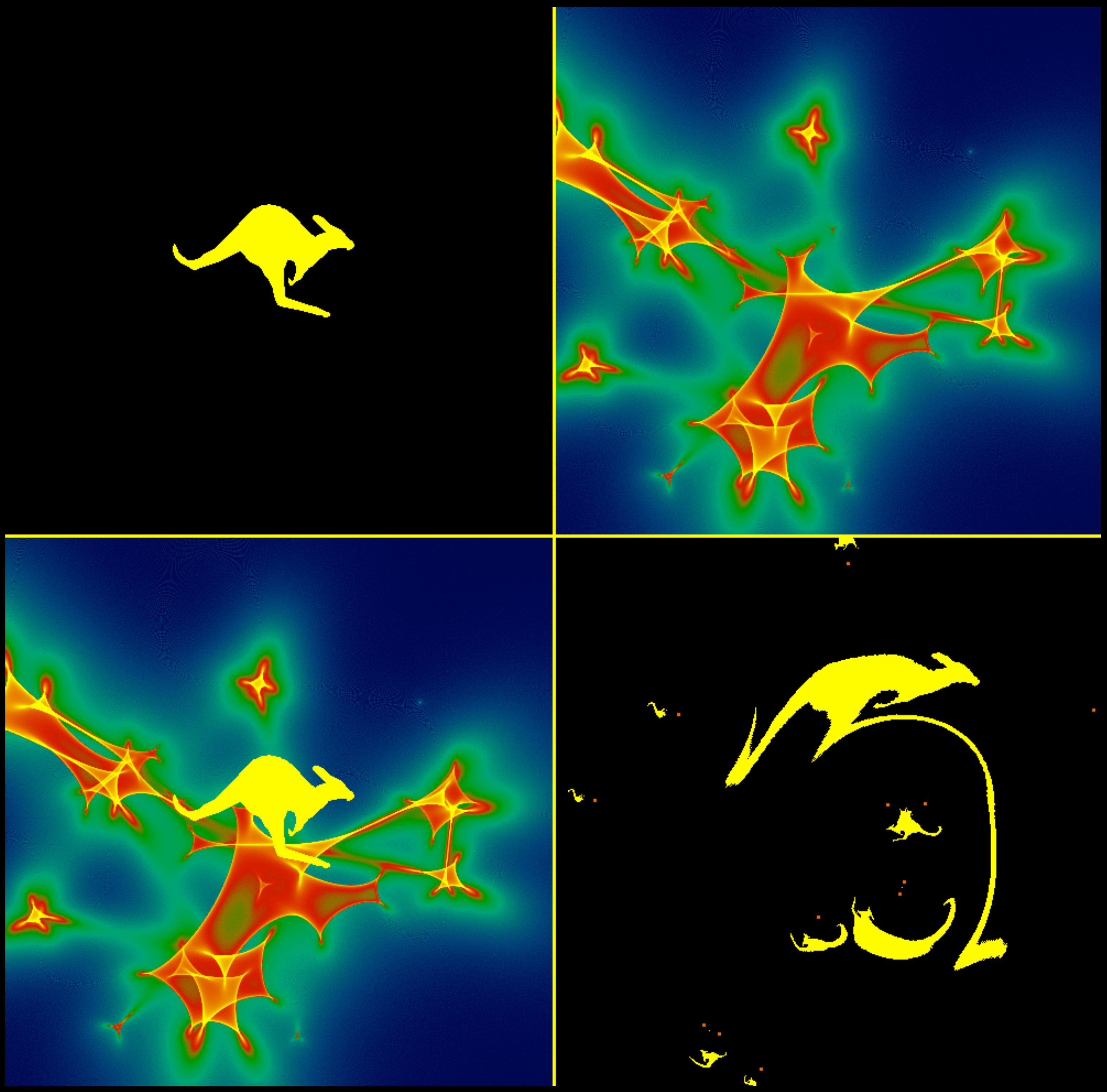
Gravitational Lensing



Gravitational Lensing

Lensing Galaxy

Gravitational Lensing



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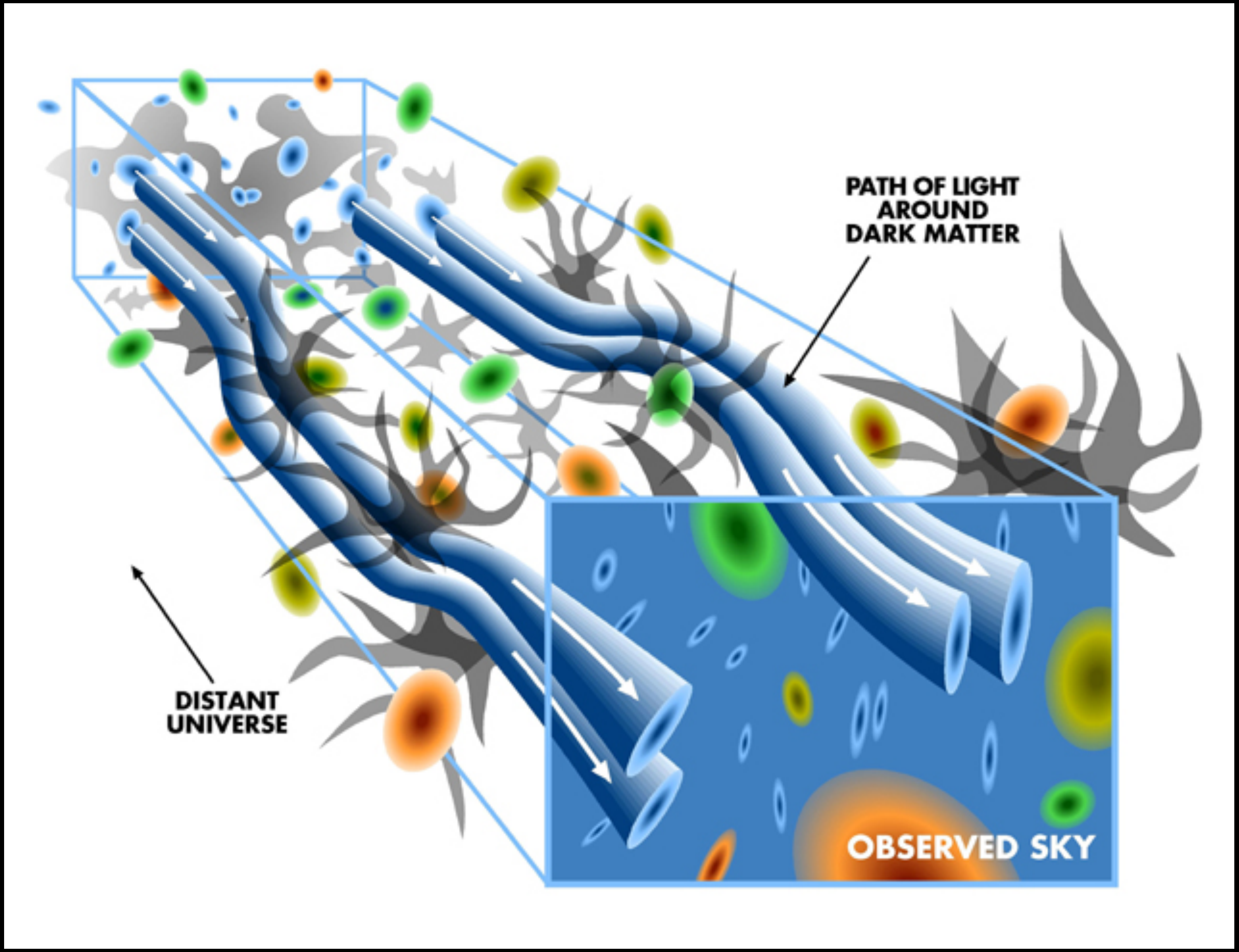
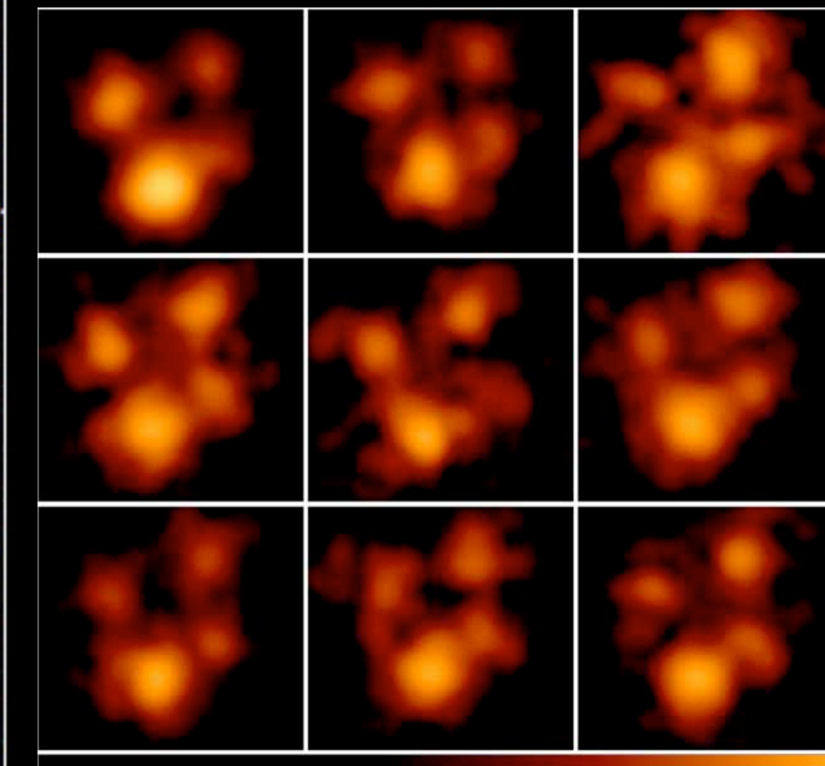


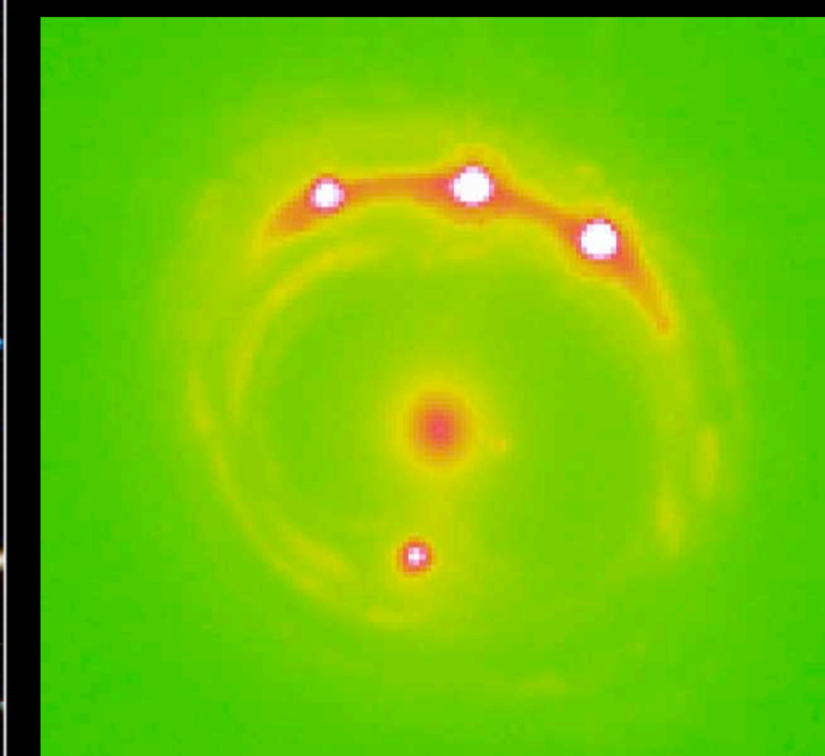
Reconstruction of Dark Matter Distribution from Observation

Galaxy Cluster Cl 0024+17 (ZwCl 0024+1652) *HST* • ACS/WFC

NASA, ESA, and M.J. Jee (Johns Hopkins University) STScI-PRC07-17b



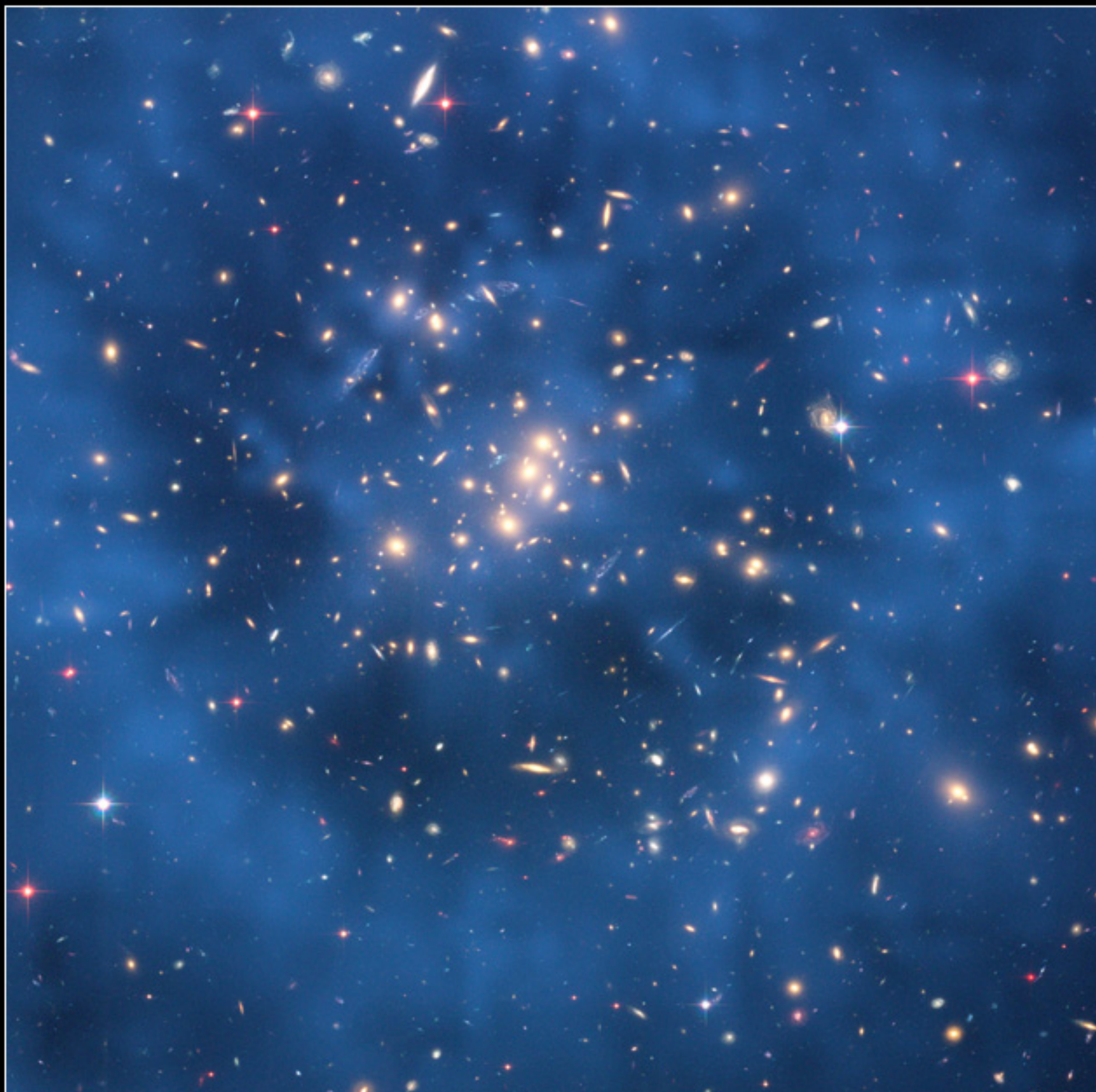
X-Ray images of Quasar Q2237+0305
(Mosaic courtesy: Ohio State University)



Optical images of Quasar RXJ1131-1231
(courtesy: Ohio State University)

Reconstruction of Dark Matter Distribution from Observation

Dark Matter Ring in Cl 0024+17 (ZwCl 0024+1652) *HST* • ACS/WFC



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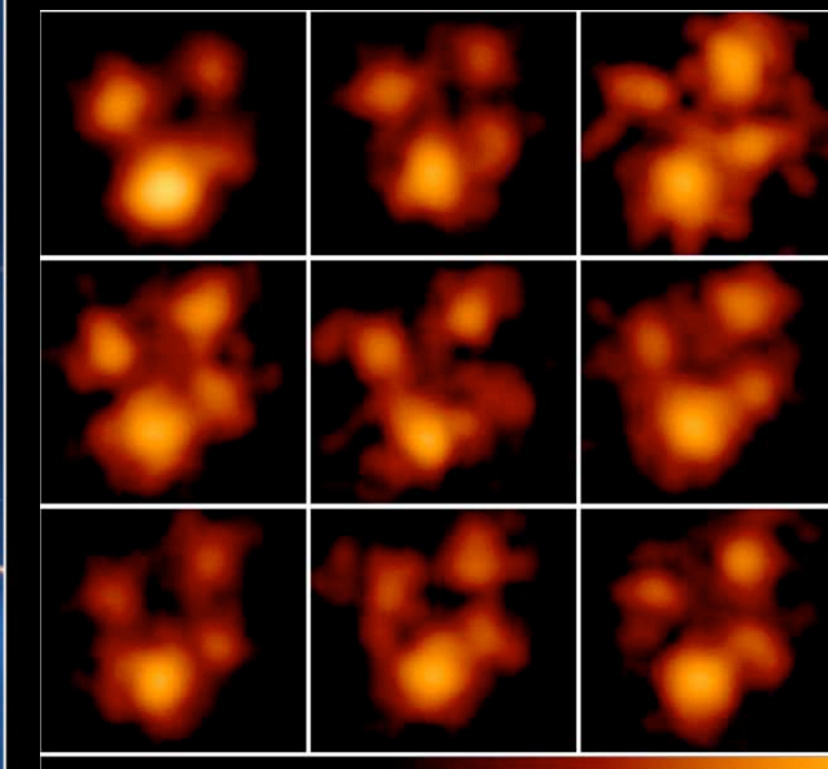

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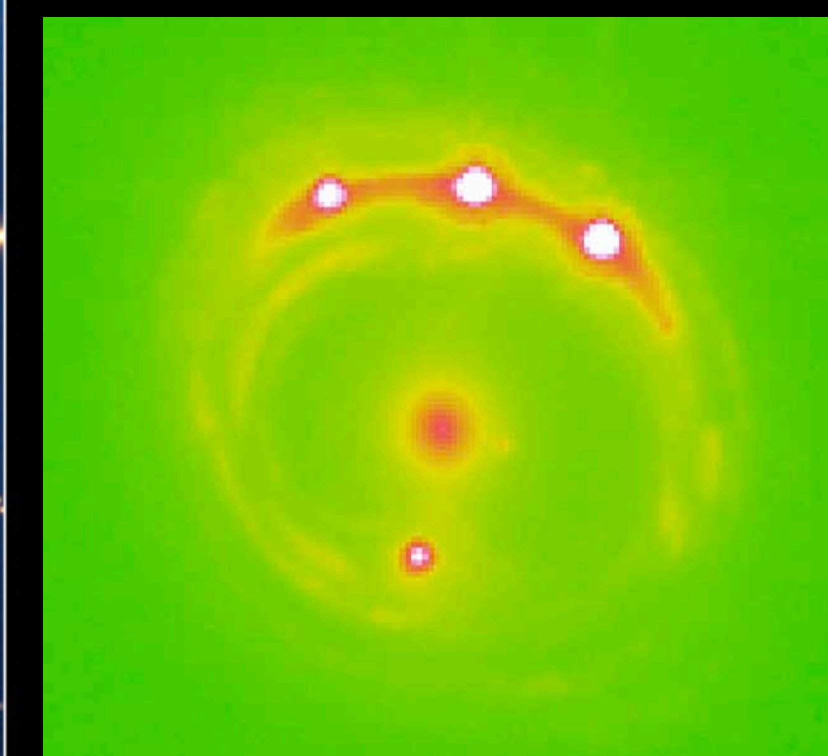

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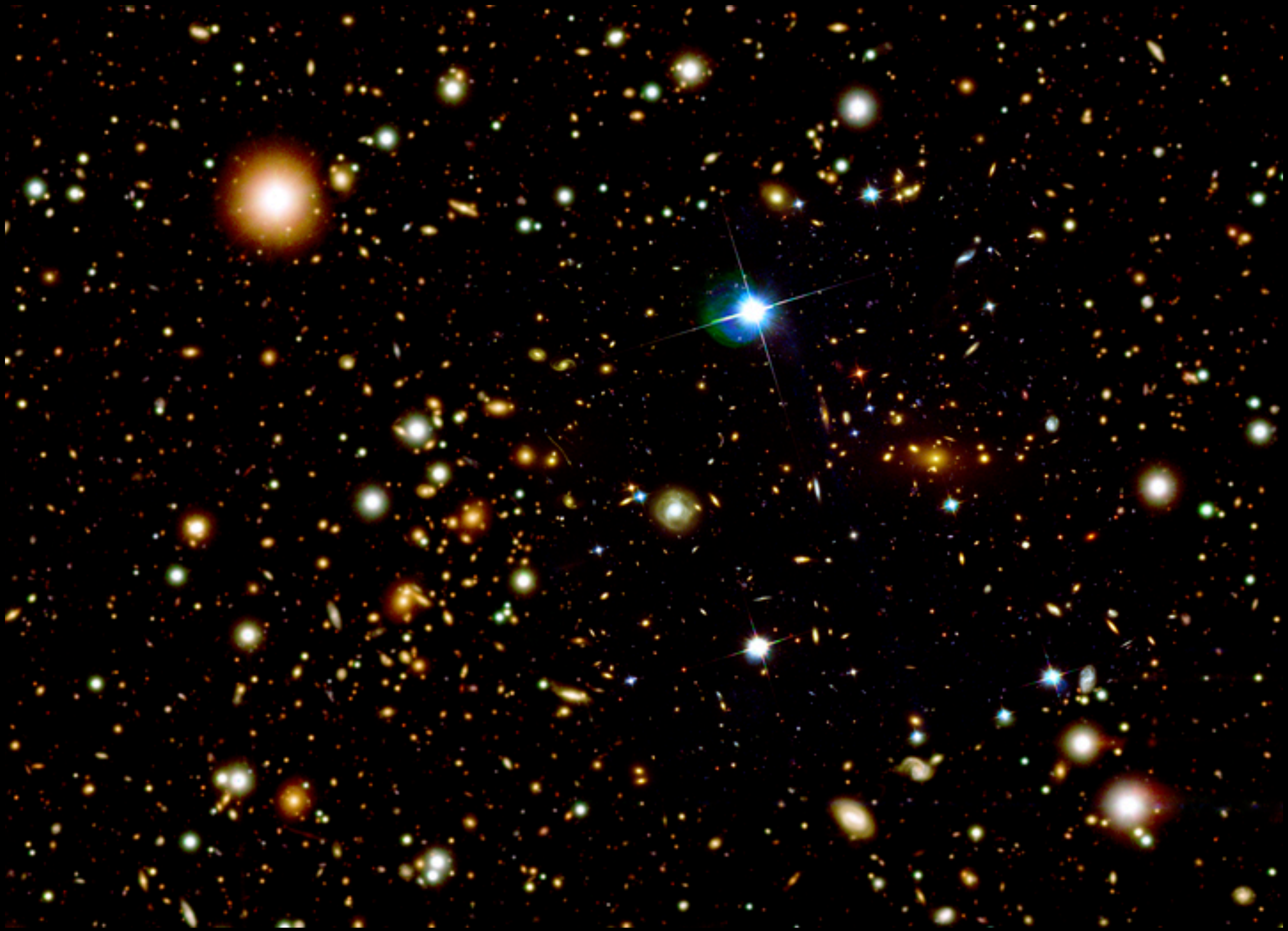
Dark Matter Expose: Bullet Cluster

OPTICAL



X-ray: NASA/CXC/CfA/M.Markevitch et al.; Optical: NASA/STScI; Magellan/U.Arizona/
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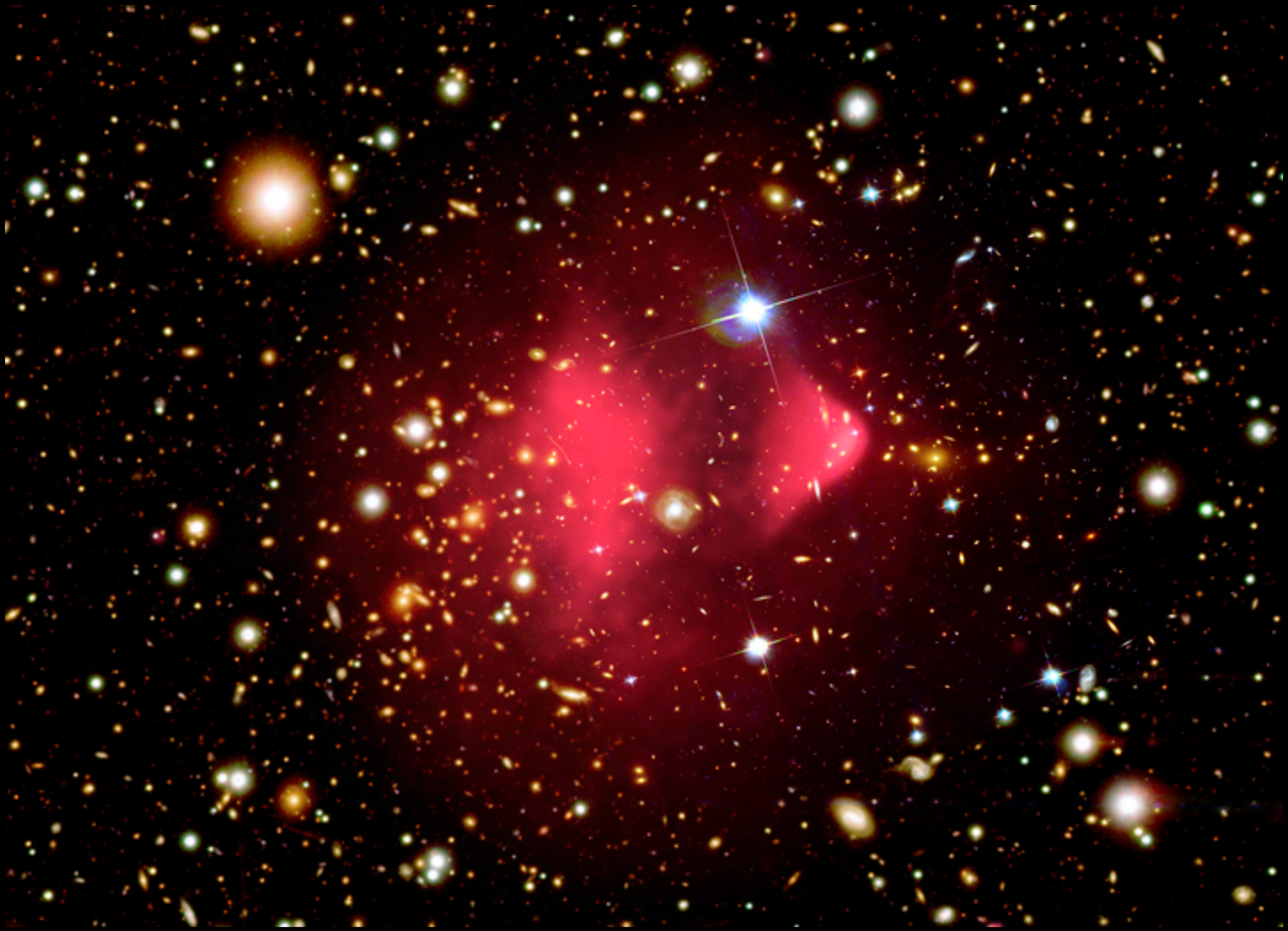

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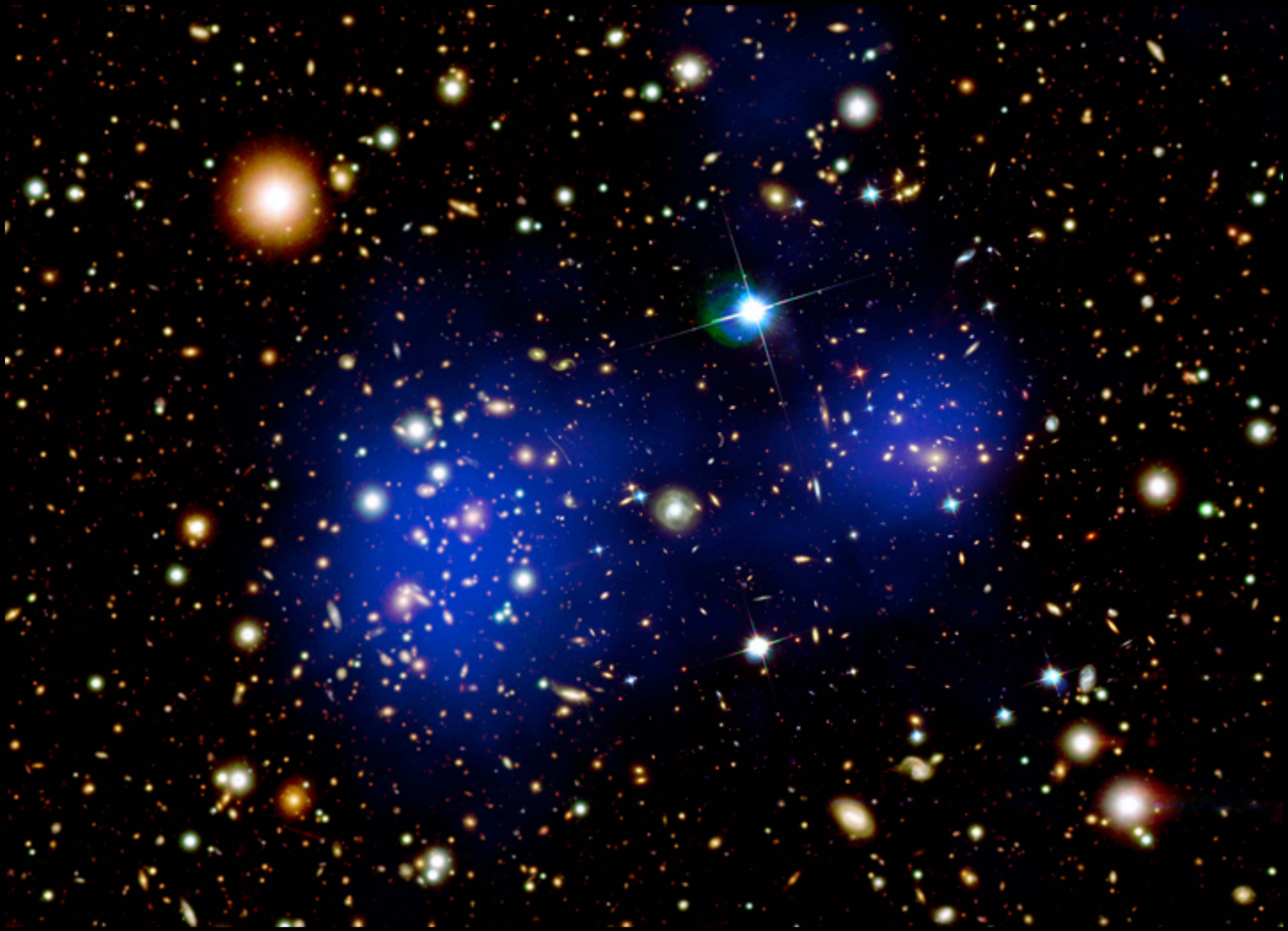

OPTICAL

Lensing

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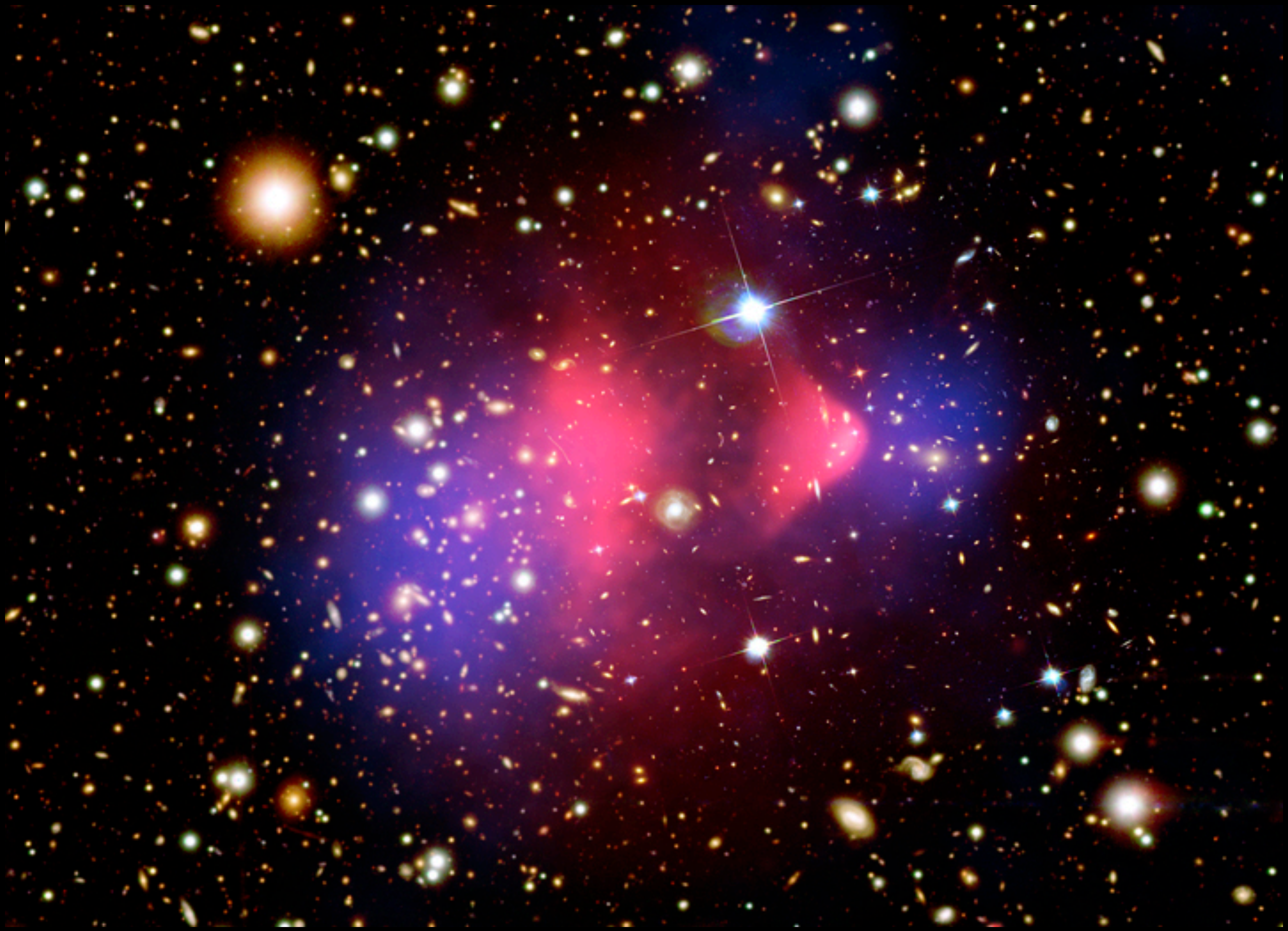

X-Ray

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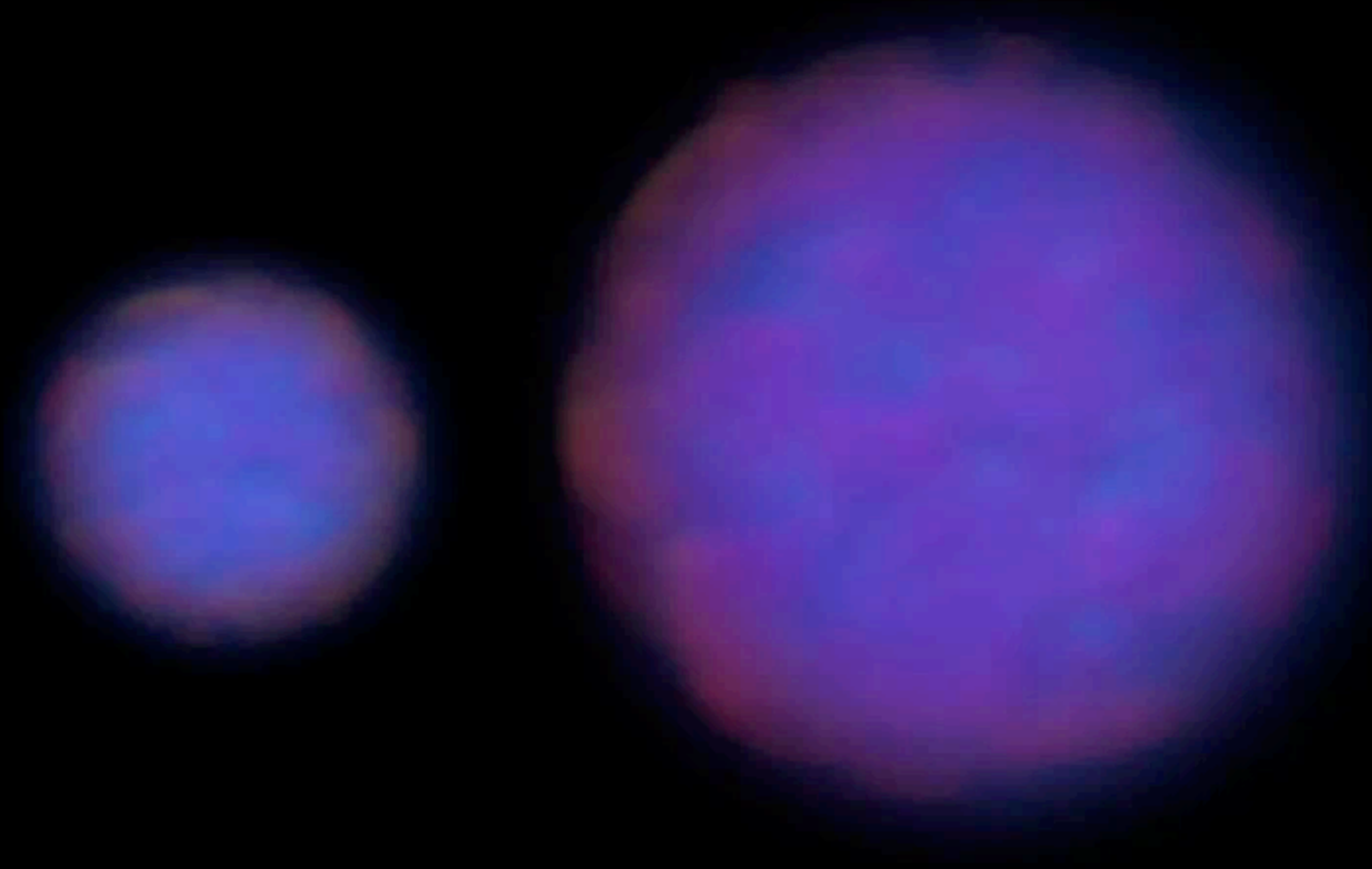

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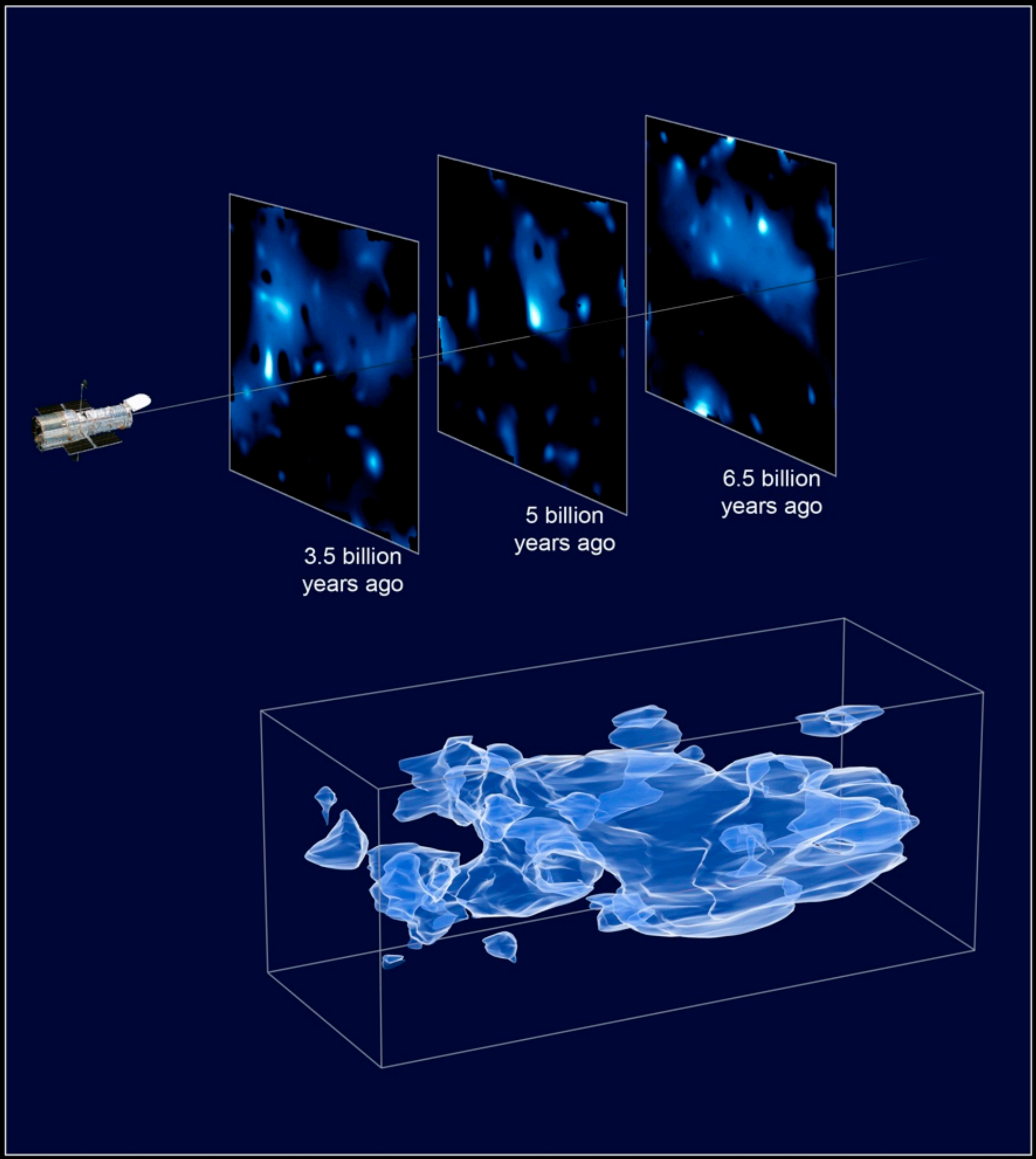
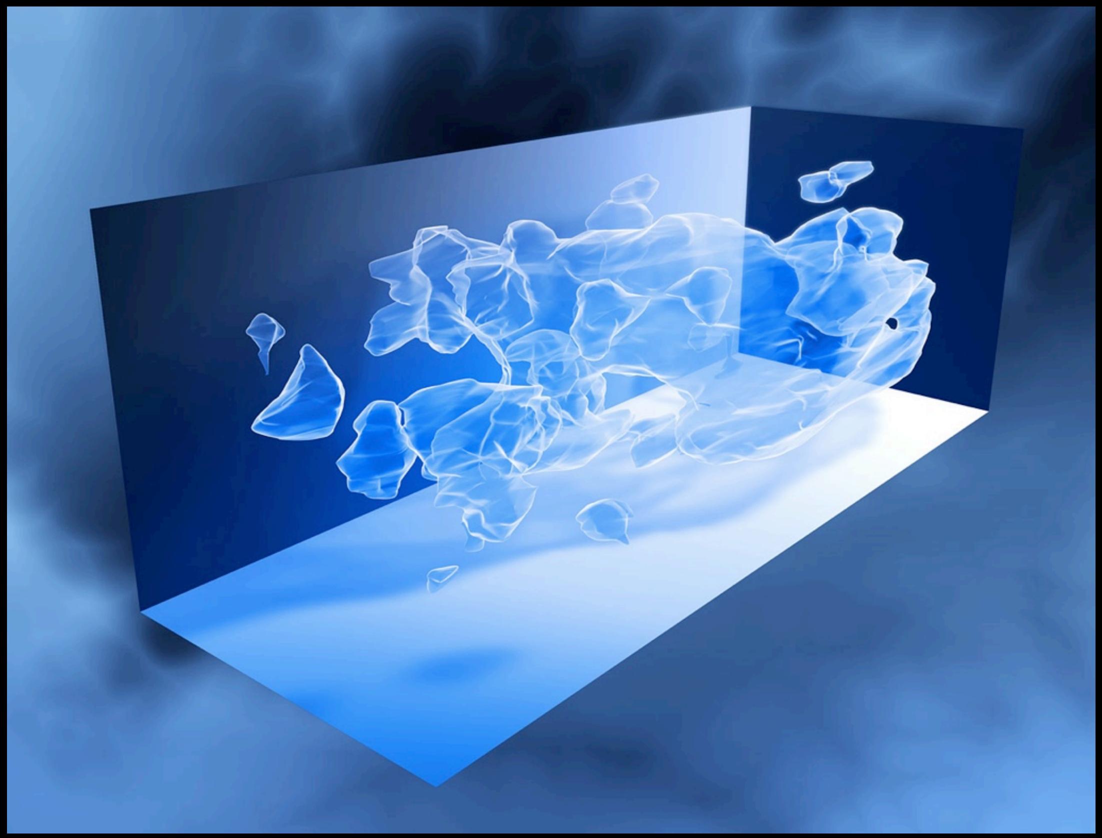
Distribution of Dark Matter

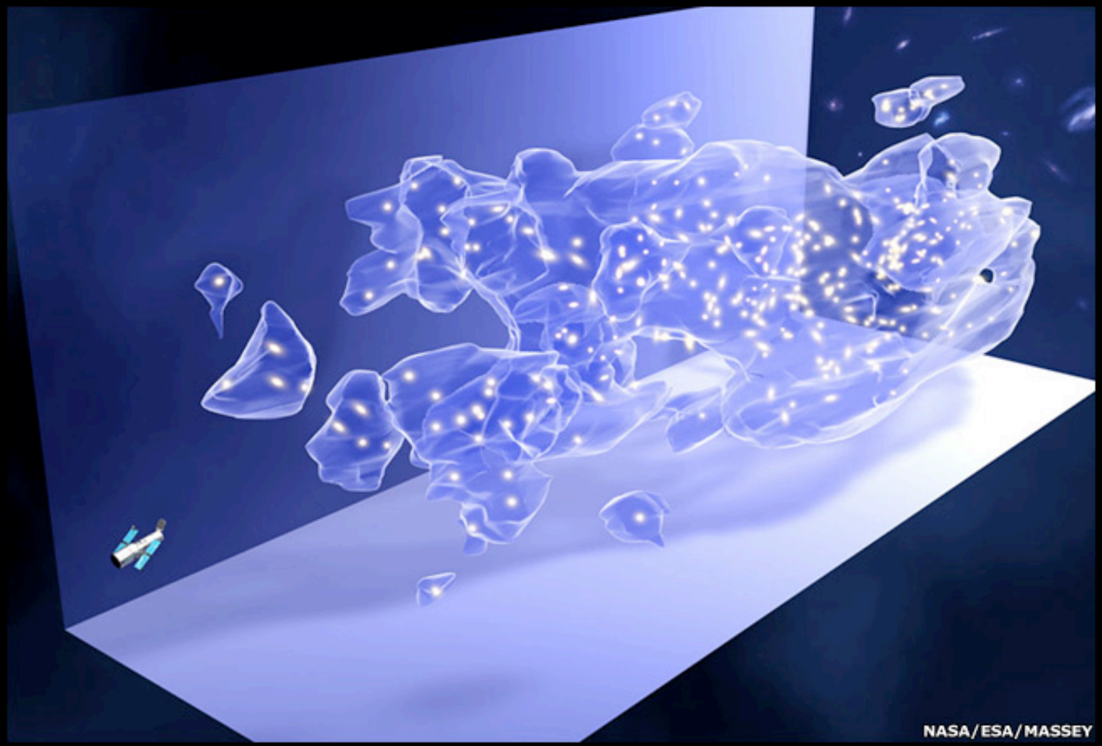
HST ▪ ACS/WFC



NASA, ESA, and R. Massey (California Institute of Technology)

STScI-PRC07-01a



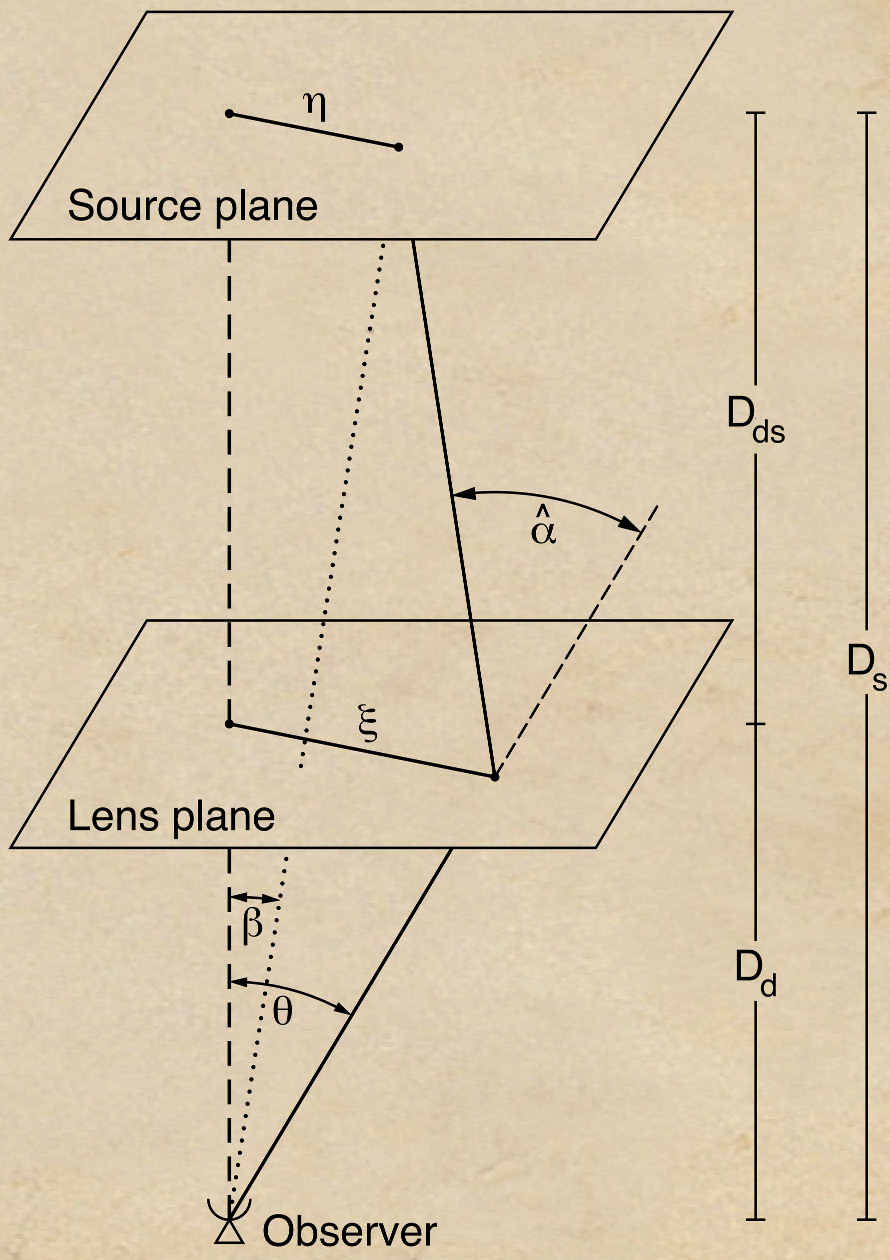


Gravitational Lensing 201

The Lens Equation:

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

$$\alpha(\vec{\theta}) = \frac{D_{ds}}{D_s}\hat{\alpha}(D_d\vec{\theta})$$



Credit: Bartelmann and Schneider 2001

Gravitational Lensing 201

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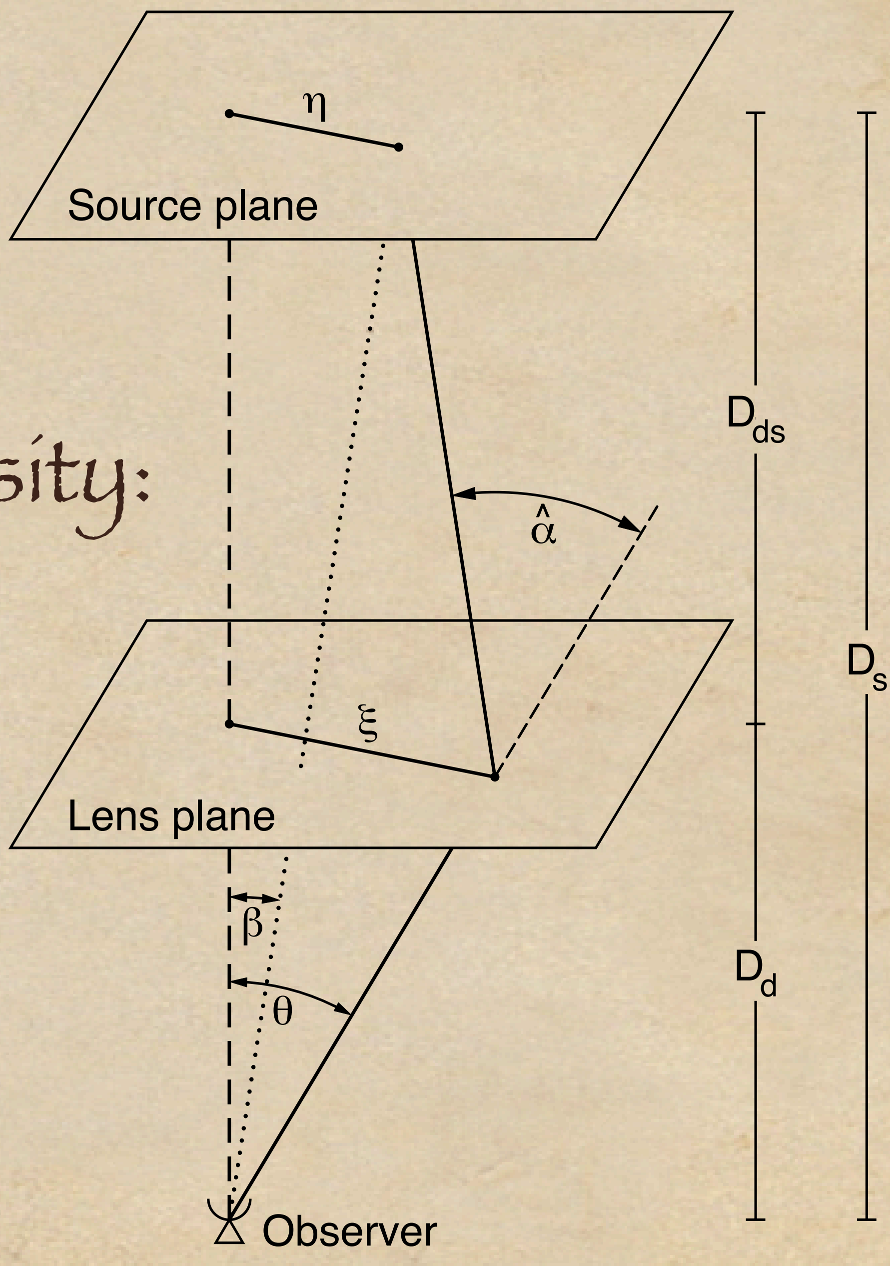

Dimensionless Surface Mass Density:

$$\kappa(\vec{\theta}) = \frac{\Sigma(D_d\theta)}{\Sigma_{cr}}$$

Credit: Bartelmann and Schneider 2001

Gravitational Lensing 201

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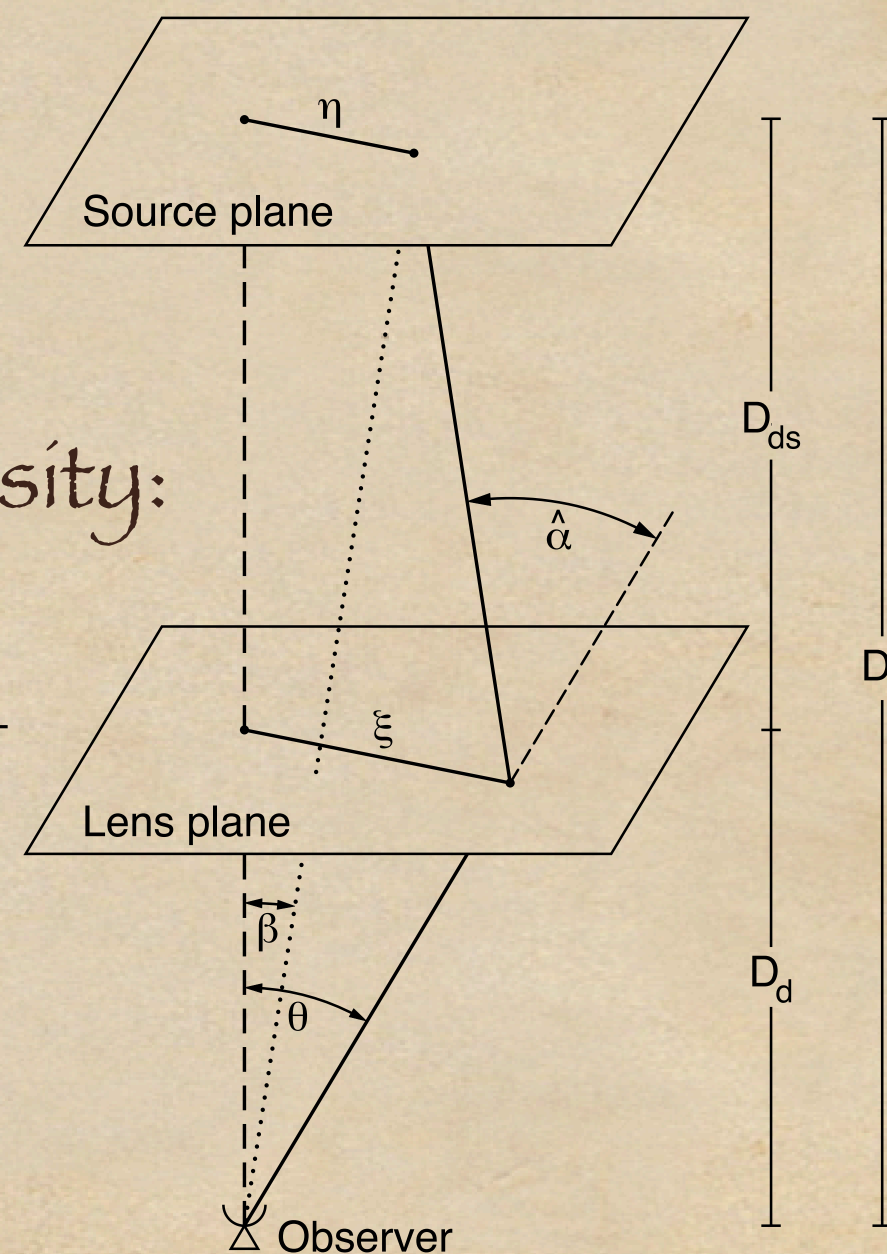

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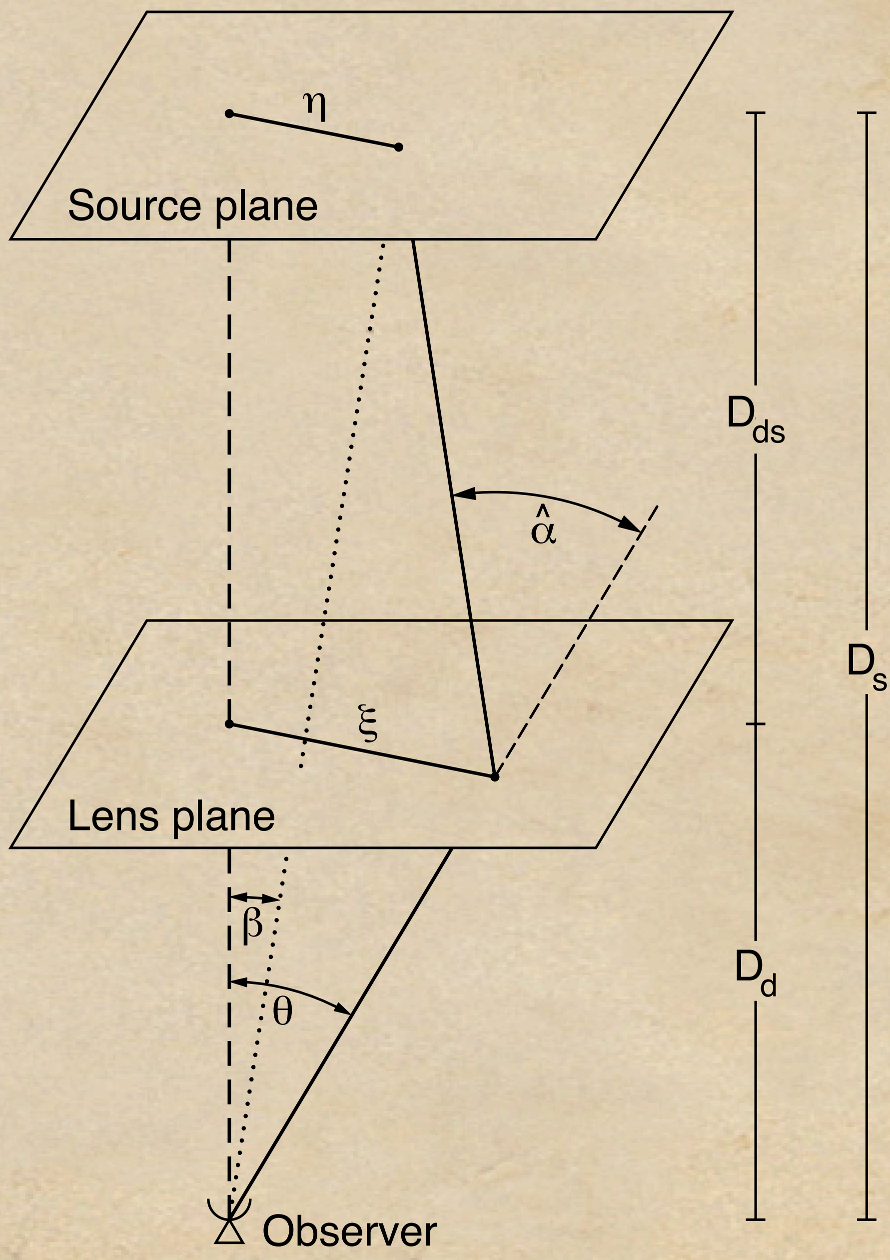

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Gravitational Lensing 201

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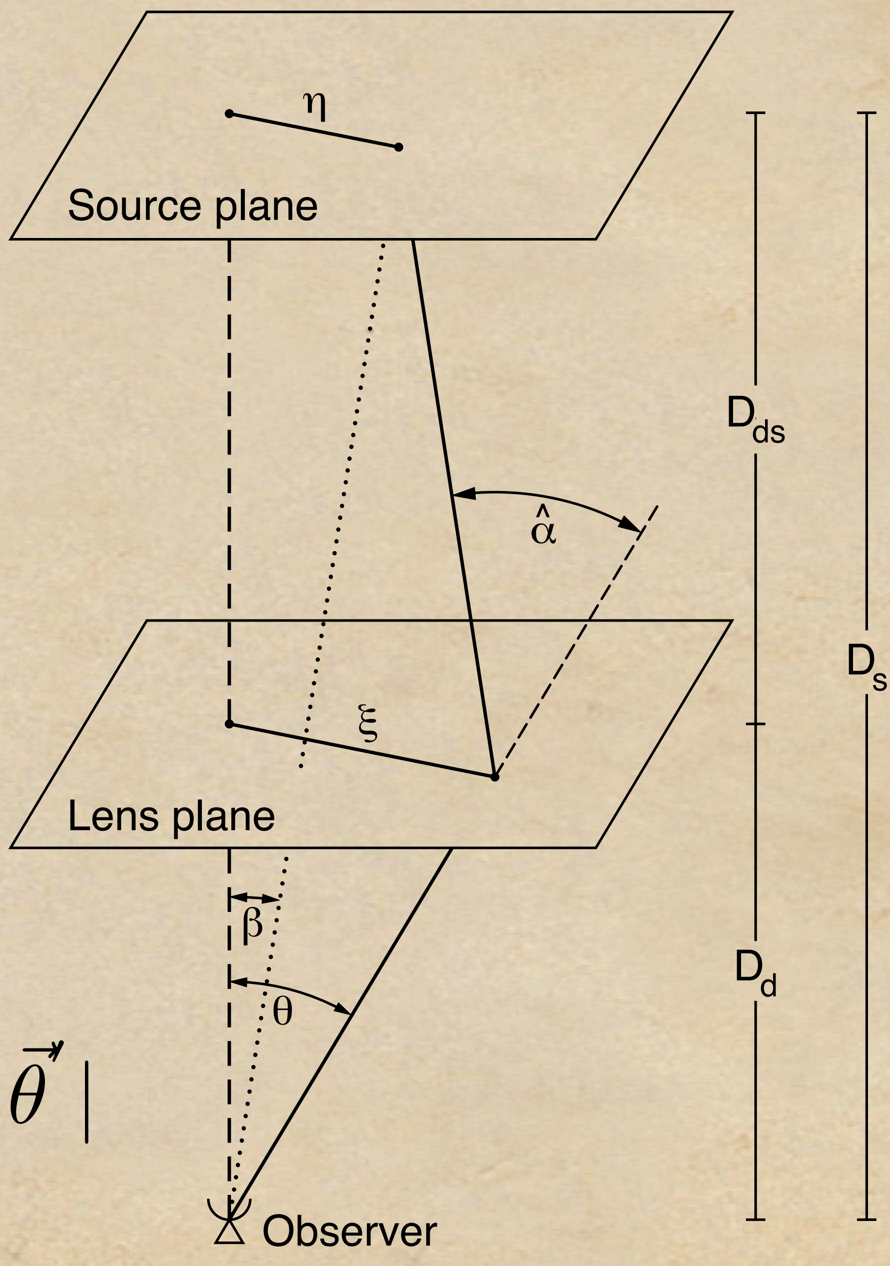
$$\alpha(\vec{\theta}) = \nabla\phi$$

$$\phi(\vec{\theta}) = \frac{1}{\pi}\int_{R^2} d^2\theta' \kappa(\vec{\theta}') \ln|\vec{\theta} - \vec{\theta}'|$$



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Gravitational Lensing 201

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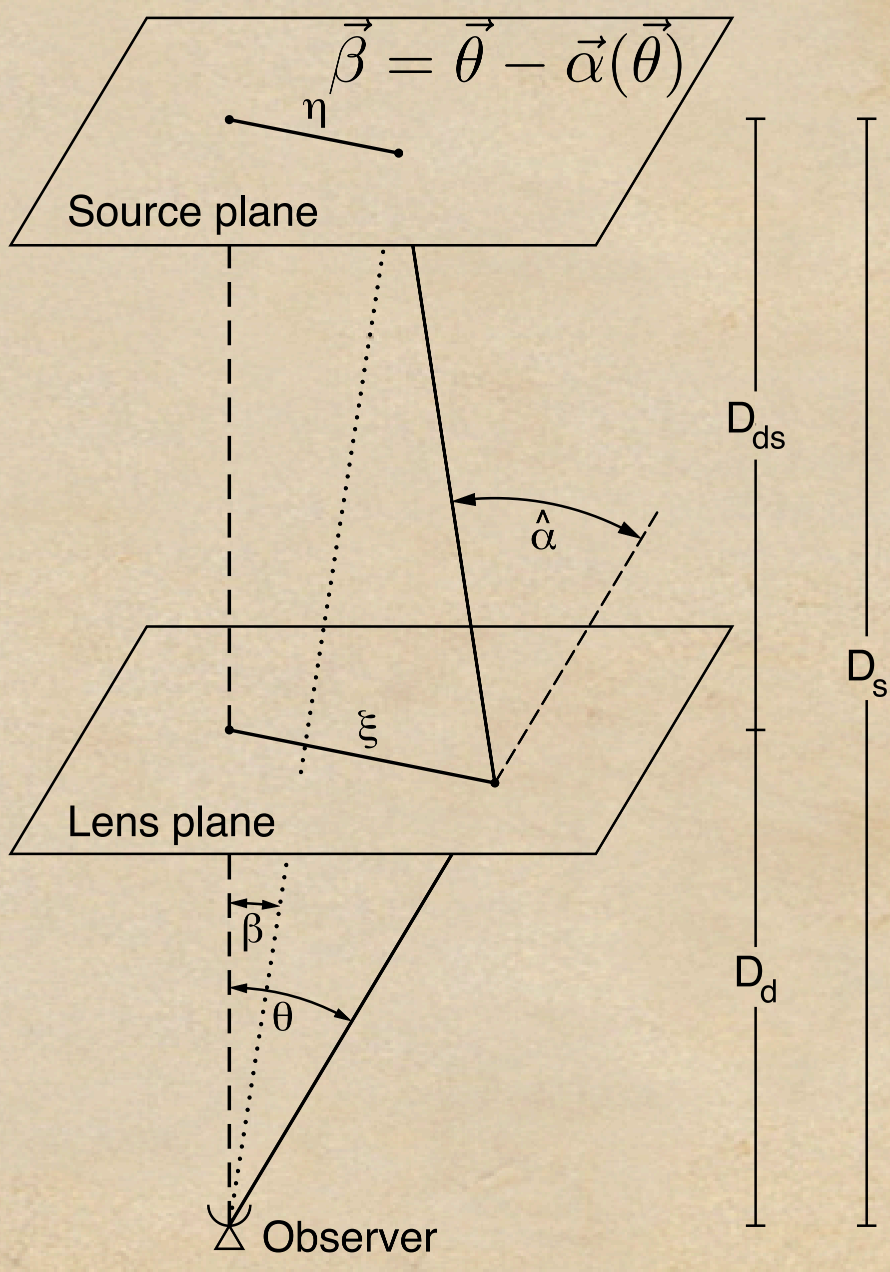


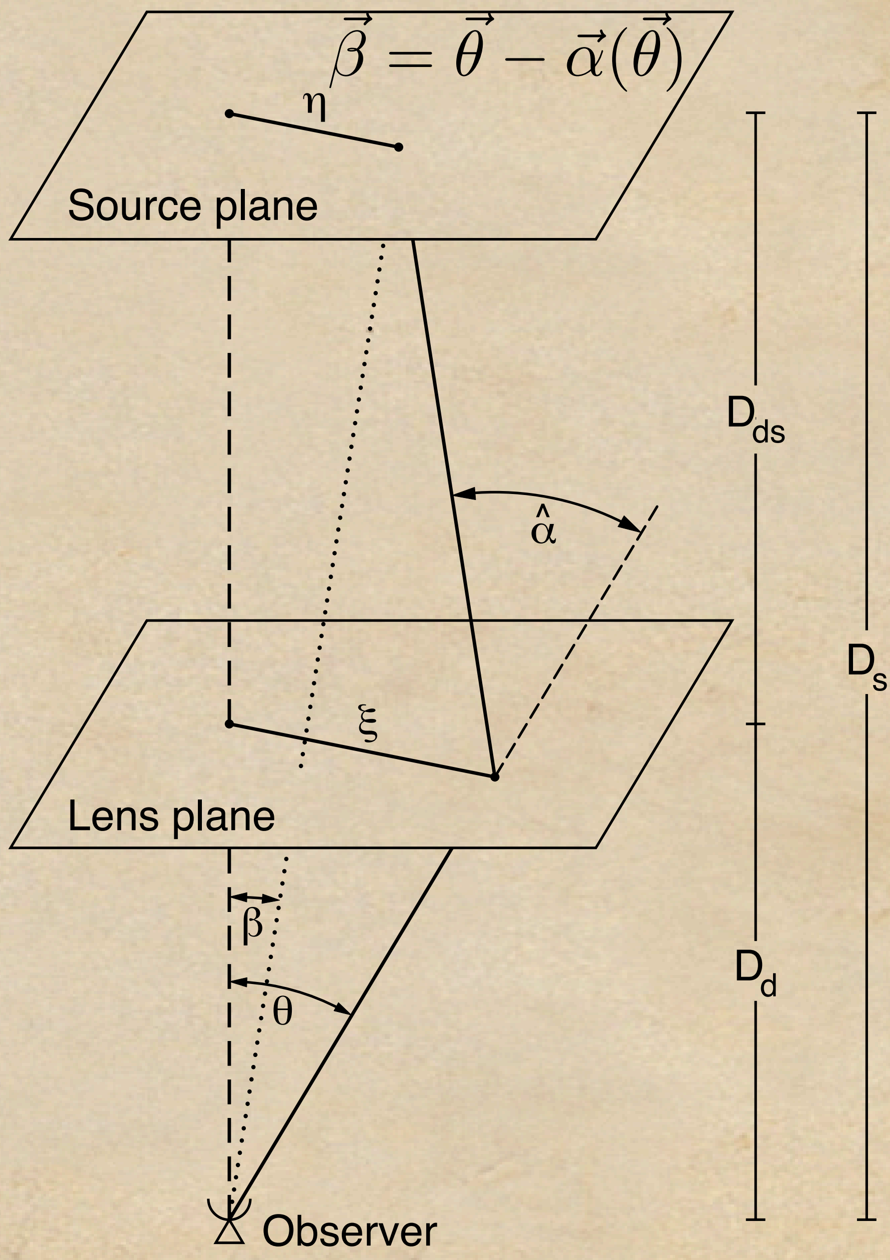
Credit: Bartelmann and Schneider 2001

Gravitational Lensing 201

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

Distortion of images by Jacobian:

$$\mathcal{A}(\vec{\theta}) = \frac{\partial \vec{\beta}}{\partial \vec{\theta}} = \left(\delta_{ij} - \frac{\partial^2 \phi(\vec{\theta})}{\partial \theta_i \partial \theta_i} \right)$$



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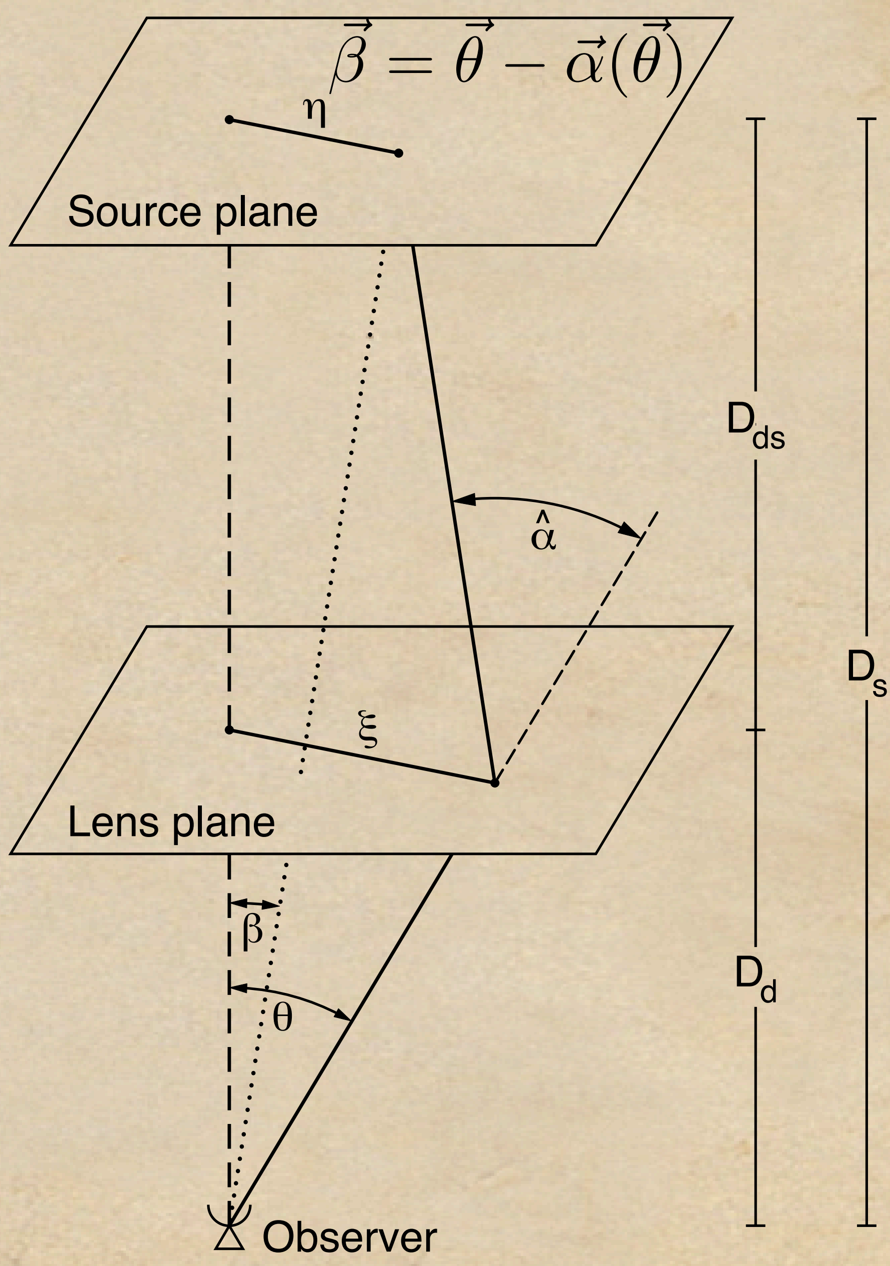

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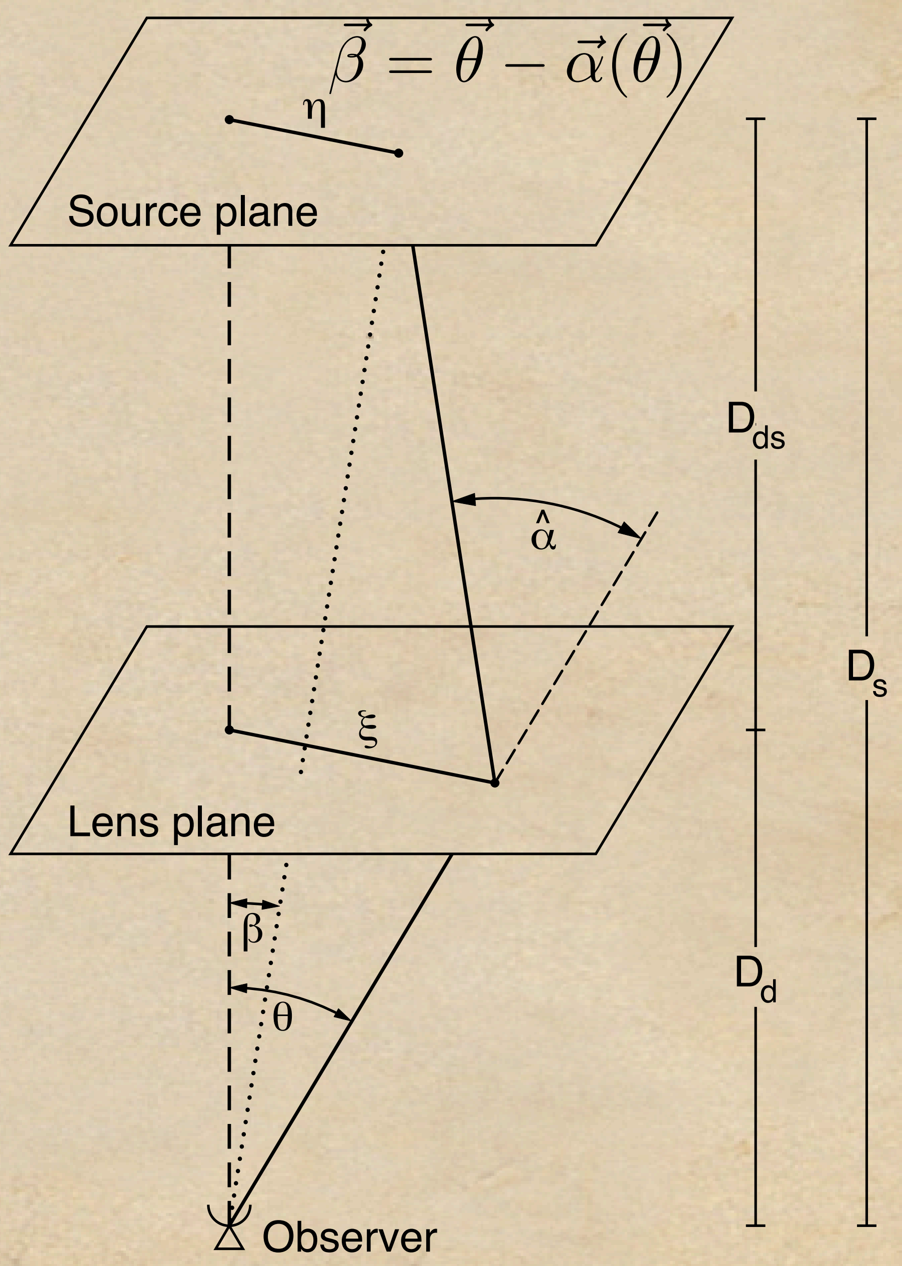
$$\mathcal{A}(\vec{\theta}) = \begin{pmatrix} 1-\kappa-\gamma_1 & -\gamma_2 \\ -\gamma_2 & 1-\kappa+\gamma_1 \end{pmatrix}$$



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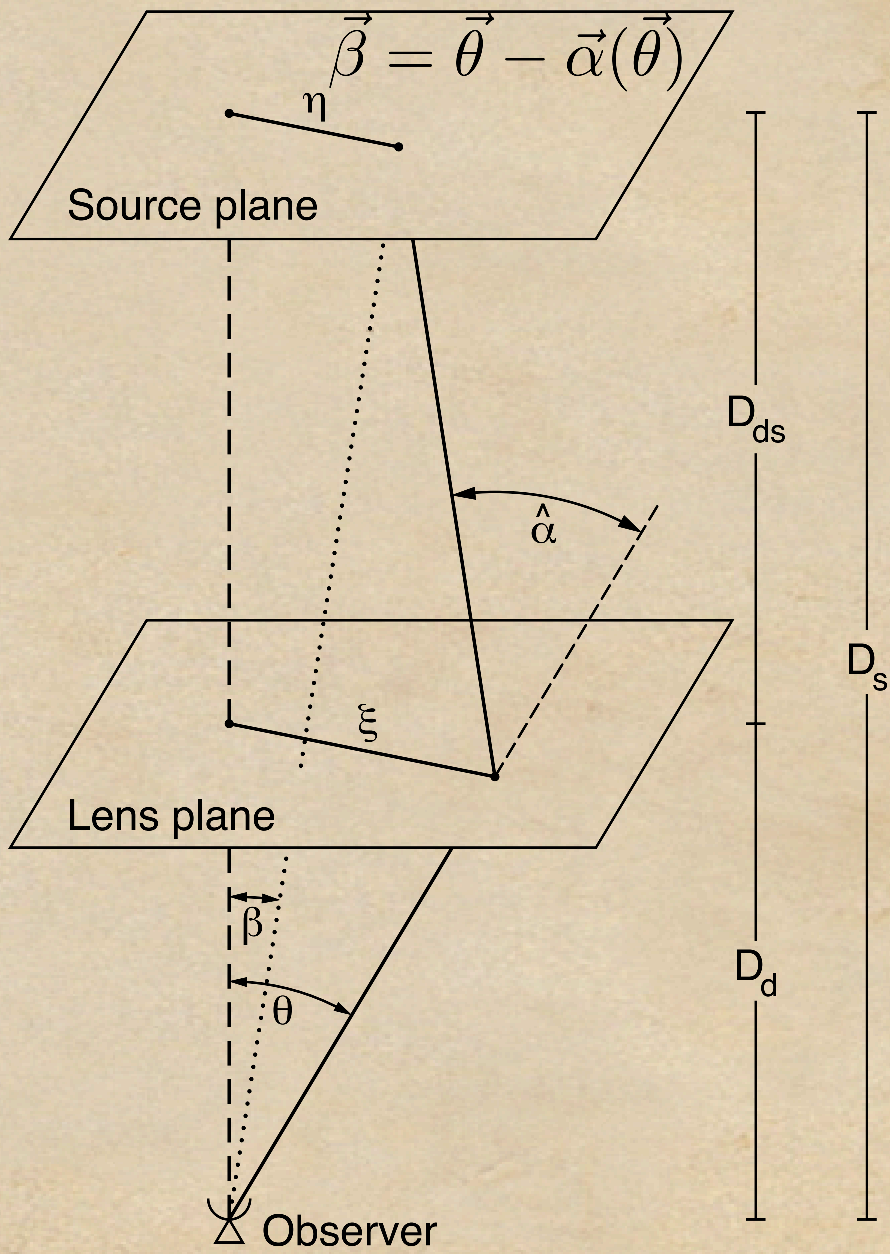
$$\gamma \equiv \gamma_1 + \mathrm{i}\gamma_2 = |\gamma| \mathrm{e}^{2\mathrm{i}\varphi}$$

$$\gamma_1 = \frac{1}{2}(\psi_{,11} - \psi_{,22}) \,, \quad \gamma_2 = \psi_{,12}$$

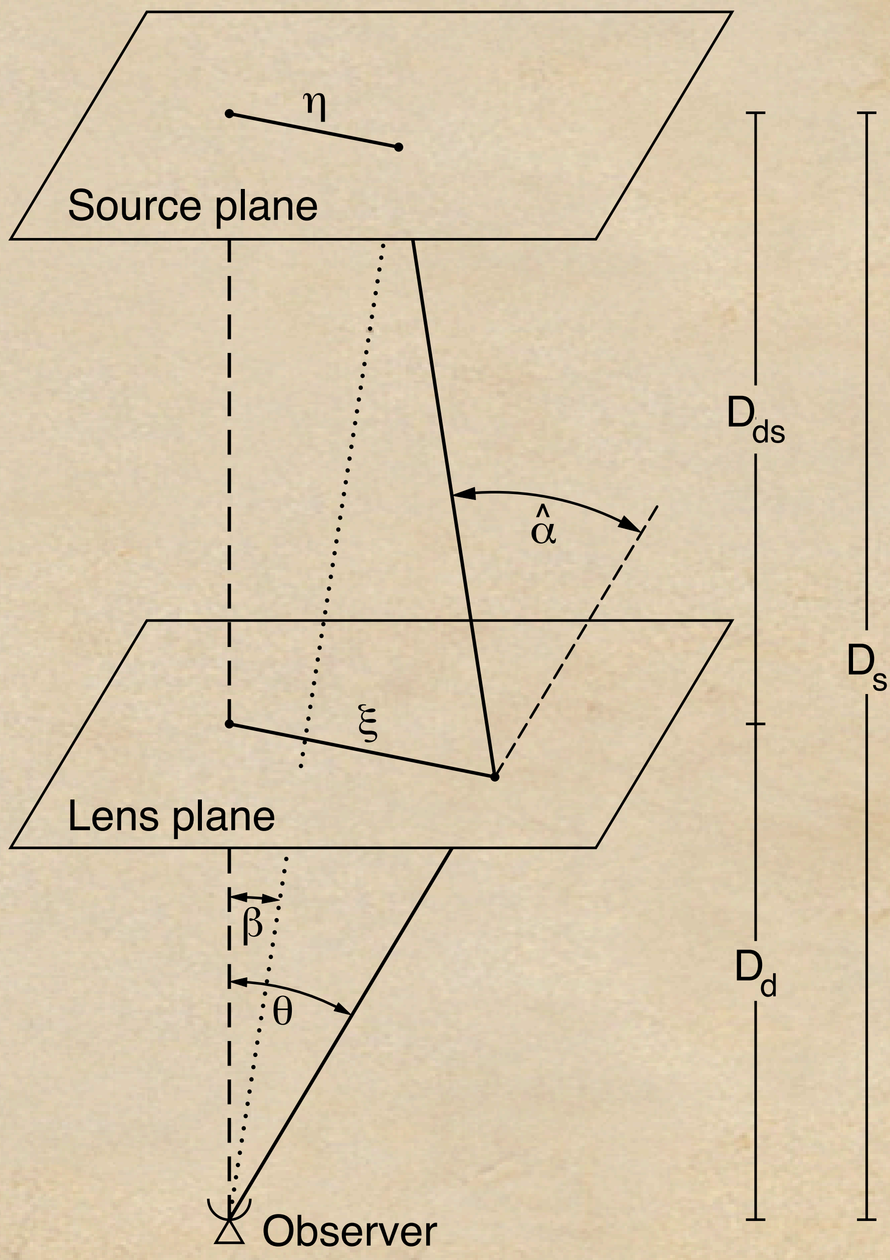


Credit: Bartelmann and Schneider 2001

Gravitational Lensing 201

But Did we Miss Anything???

$$\mathcal{A}_{ij} = \frac{\partial x_i^S}{\partial x_j^I}$$



Credit: Bartelmann and Schneider 2001

Gravitational Lensing 201

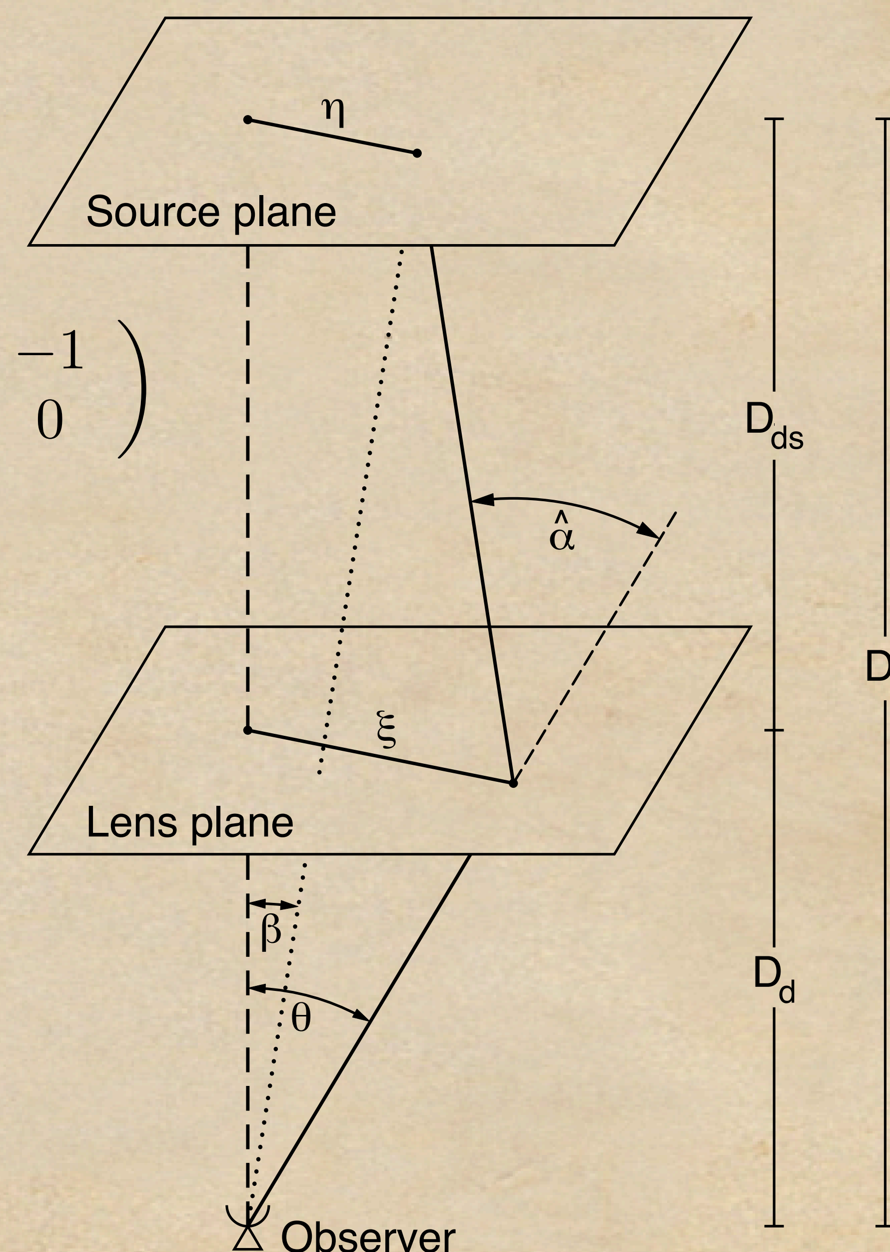
But Did we Miss Anything???

$$\mathcal{A}_{ij} = \frac{\partial x_i^S}{\partial x_j^I}$$

$$= (1-\kappa)\delta_{ij} - \gamma_{ij} + \omega\epsilon_{ij}$$

$$\epsilon_{ij} = \begin{pmatrix} 0 & -1 \\ 1 & 0 \end{pmatrix}$$

- $(1-\kappa)\delta_{ij}$ → trace
- γ_{ij} → symmetric traceless
- $\omega\epsilon_{ij}$ → antisymmetric rotation



Credit: Bartelmann and Schneider 2001

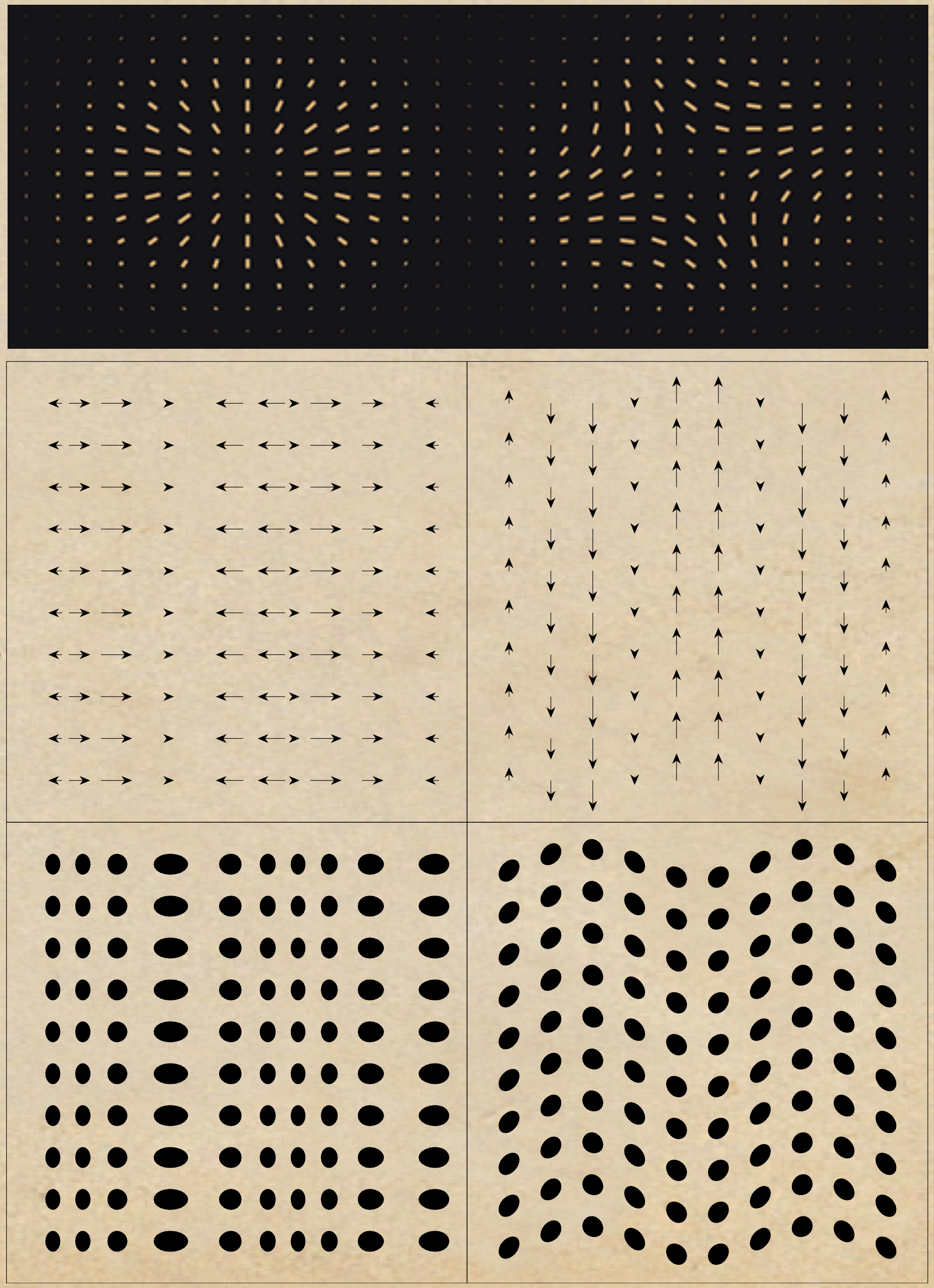
Gravitational Lensing 201

Cosmic Shear by Gravity Waves:

$$\mathcal{A} = \begin{pmatrix} 1-\kappa-\gamma_1 & -\gamma_2-\omega \\ -\gamma_2+\omega & 1-\kappa+\gamma_1 \end{pmatrix}$$

Ang. deflctn proj. on the sky:

$$\vec{\Delta} = \left[\vec{r} - (\hat{n}\cdot\hat{r})\hat{n}\right]/(\eta_0 - \eta)$$



Credit: BPol, Albert Stebbins

Gravitational Lensing 201

The angular power spectrum of the rotational component:

$$\omega(\hat{n}) \equiv -\frac{1}{2}\hat{n} \cdot [\nabla \times \hat{r}(\hat{n}, \eta_S)]$$

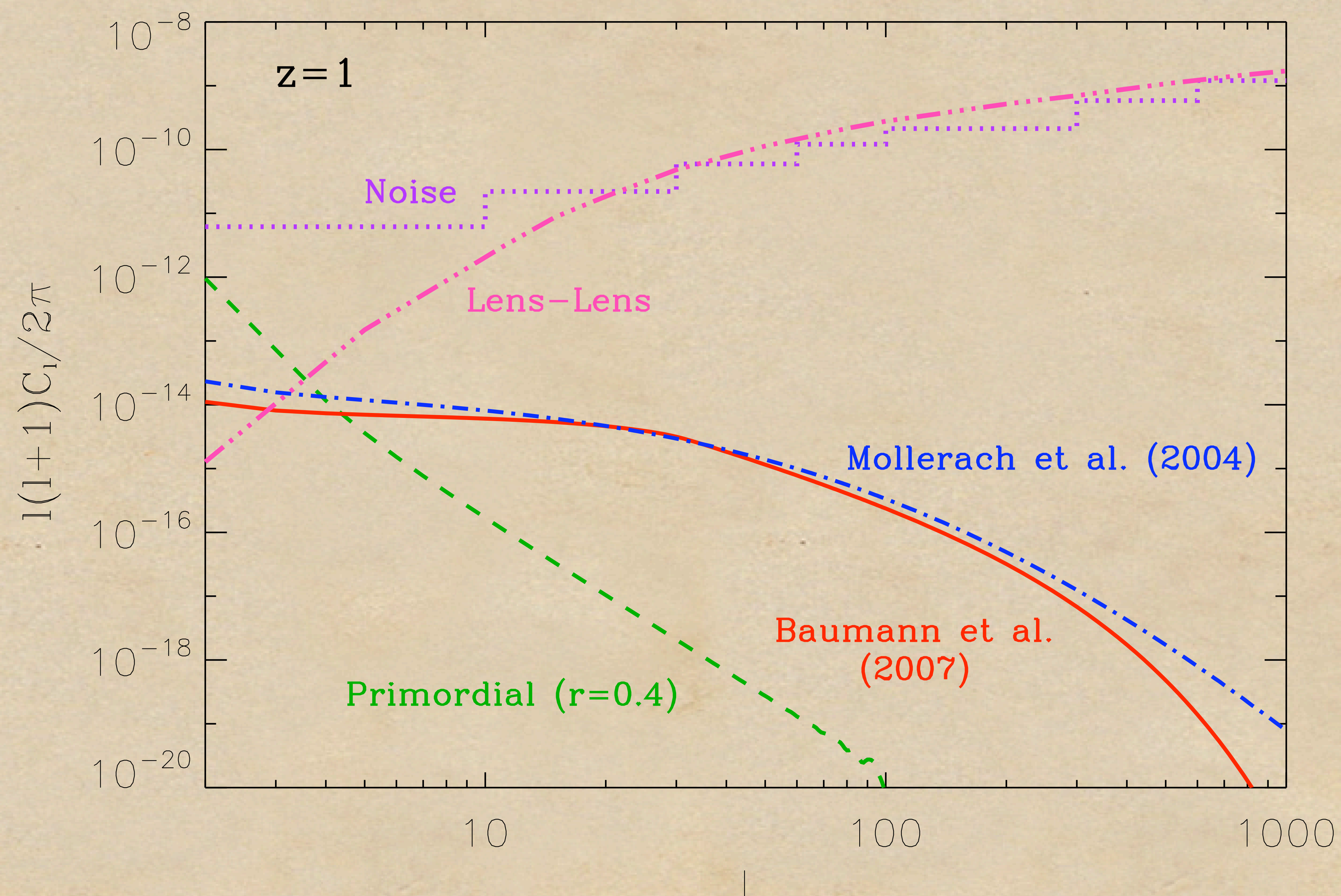
$$\begin{aligned} C_l^{\omega\omega} &= \frac{1}{2l+1} \sum_{m=-l}^{l} \langle |\omega_{lm}|^2 \rangle \\ &= \frac{2}{\pi} \int k^2 \, \mathrm{d}k \, P_t(k) \, |T_l^{\omega}(k, \eta_S)|^2 \end{aligned}$$

$$T_l^{\omega}(k, \eta_S) = \sqrt{\frac{(l+2)!}{(l-2)!}} \int_{\eta_S}^{\eta_0} k \, \mathrm{d}\eta' \, T_t(k, \eta') \left. \frac{j_l(x)}{x^2} \right|_{x = k(\eta_0 - \eta')}$$

Agenda

- [x] ABC's of Gravitational Waves
- [x] Primary GWB vs Scalar-Induced GW
- [x] Why Cosmic Shear?
- [x] Gravitational Lensing 201
- [ ] Method and Results
- [ ] Conclusion

Cosmic Shear Curl Mode Power Spectra



D.S., P. Serra, A. Cooray, K. Ichiki, D. Baumann, PRD, *77*, 103515 (2008)

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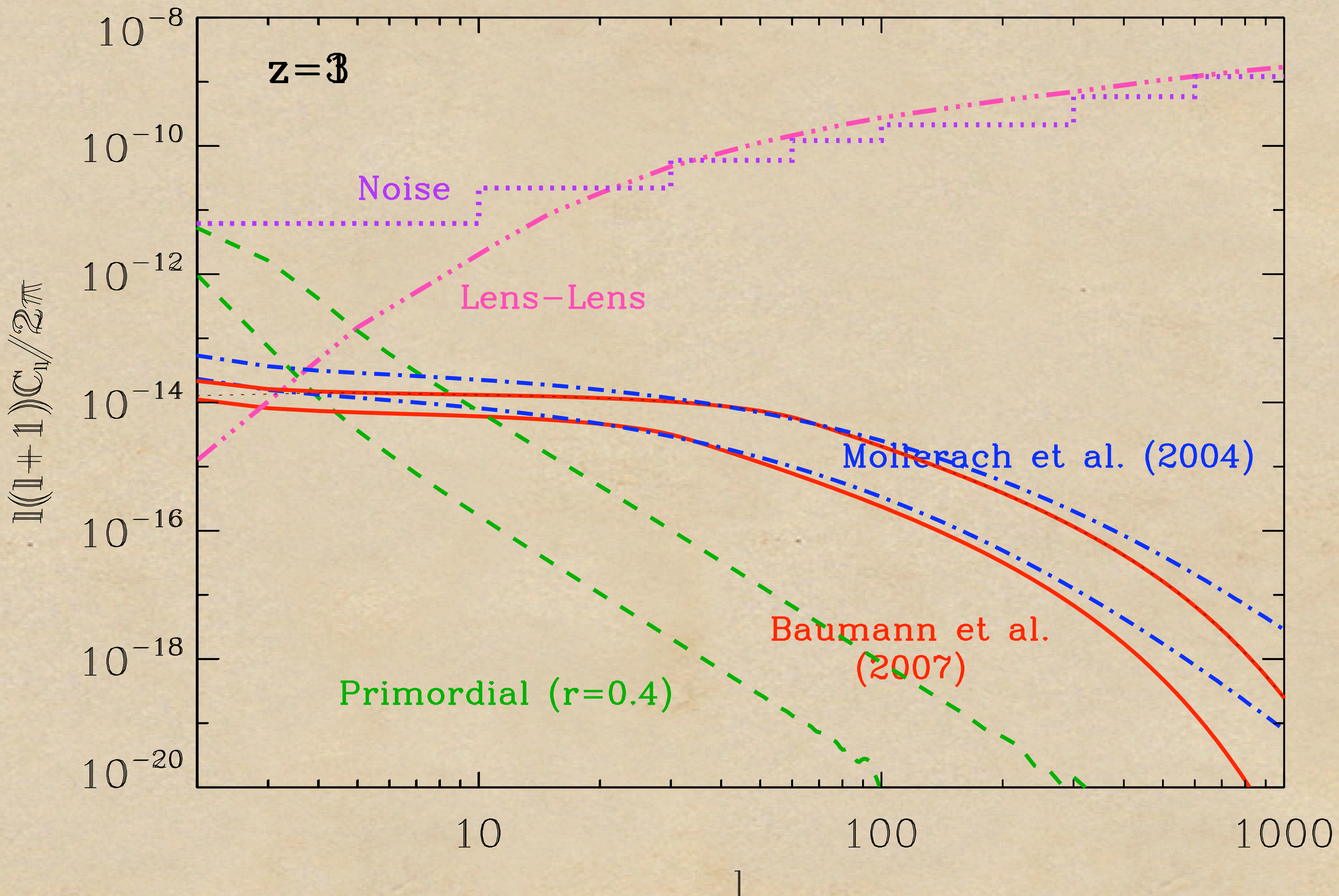

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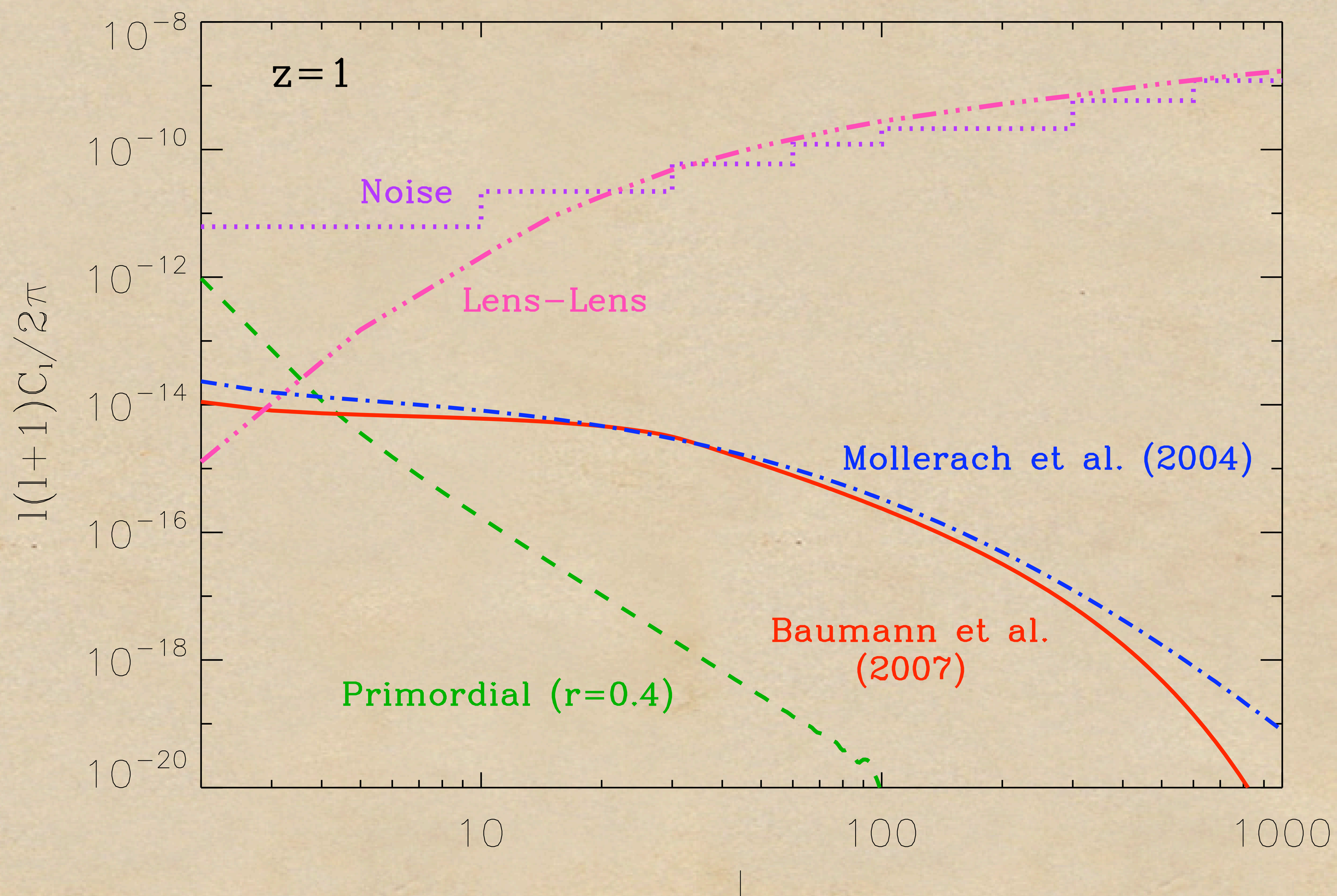

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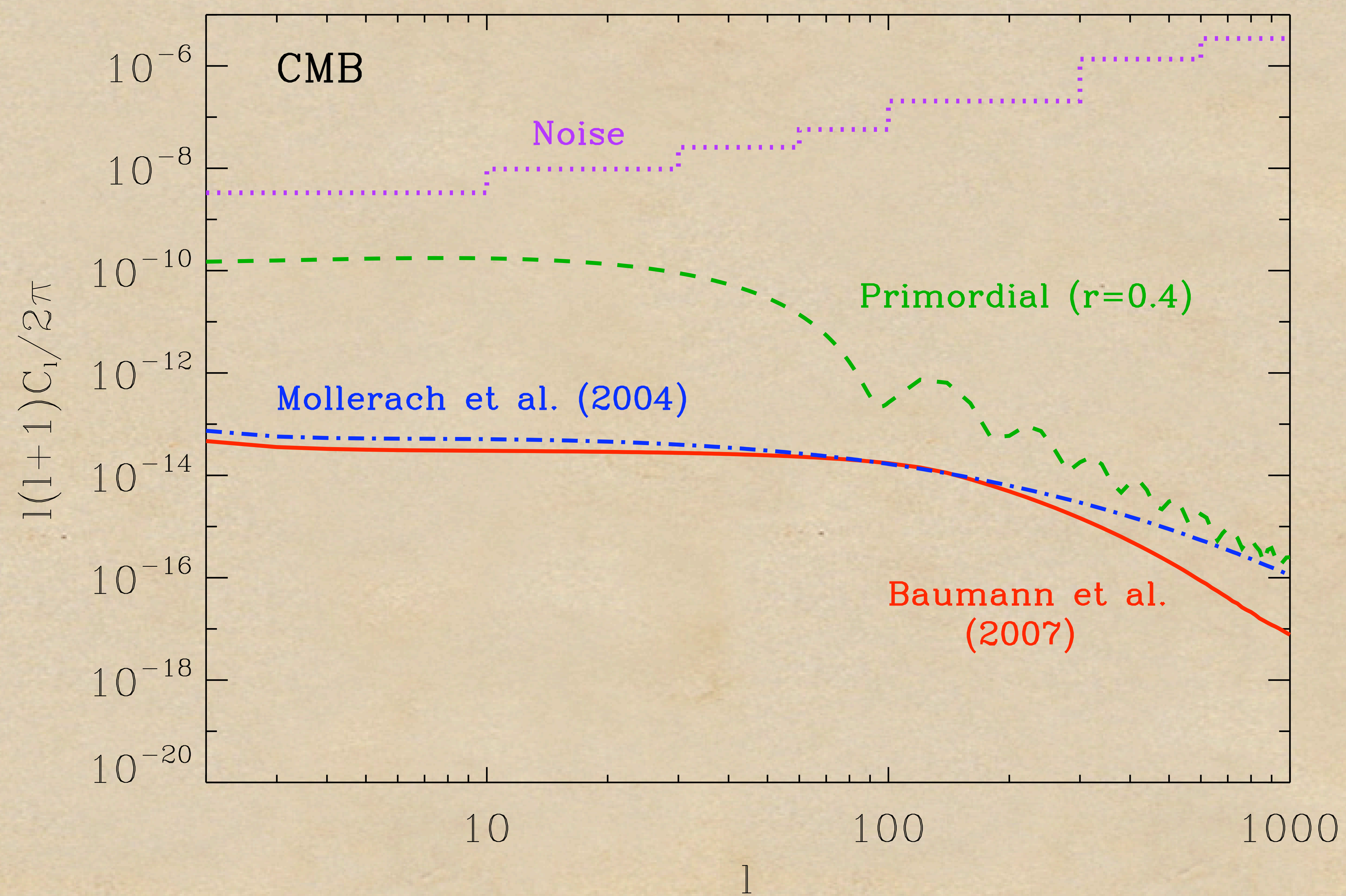
Lensing of CMB Anisotropies by GW



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