Testing gravity on cosmological scales with weak lensing

JPL Postdoc Seminar Series

August 13, 2009

Ali Vanderveld (JPL, Caltech)

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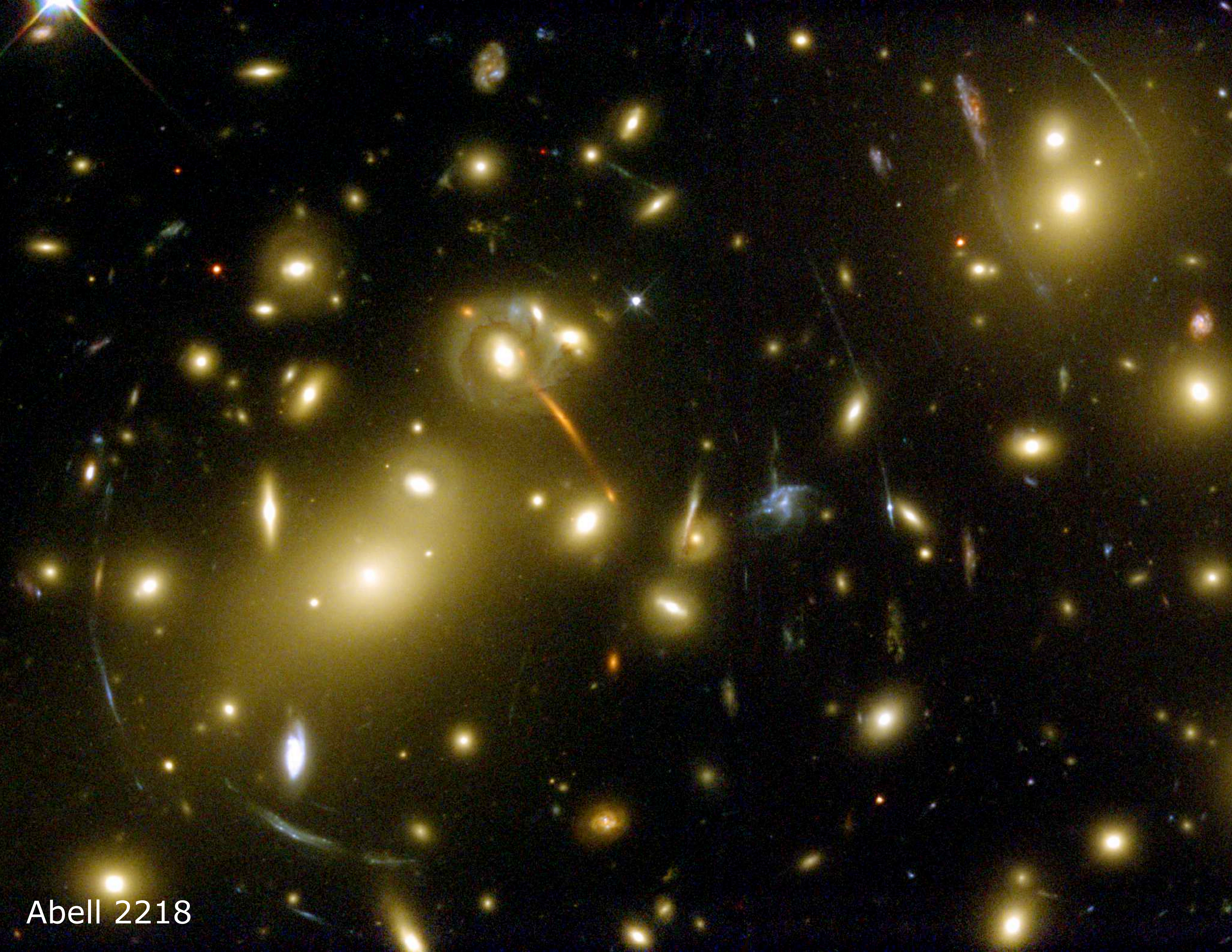
Abell 2218

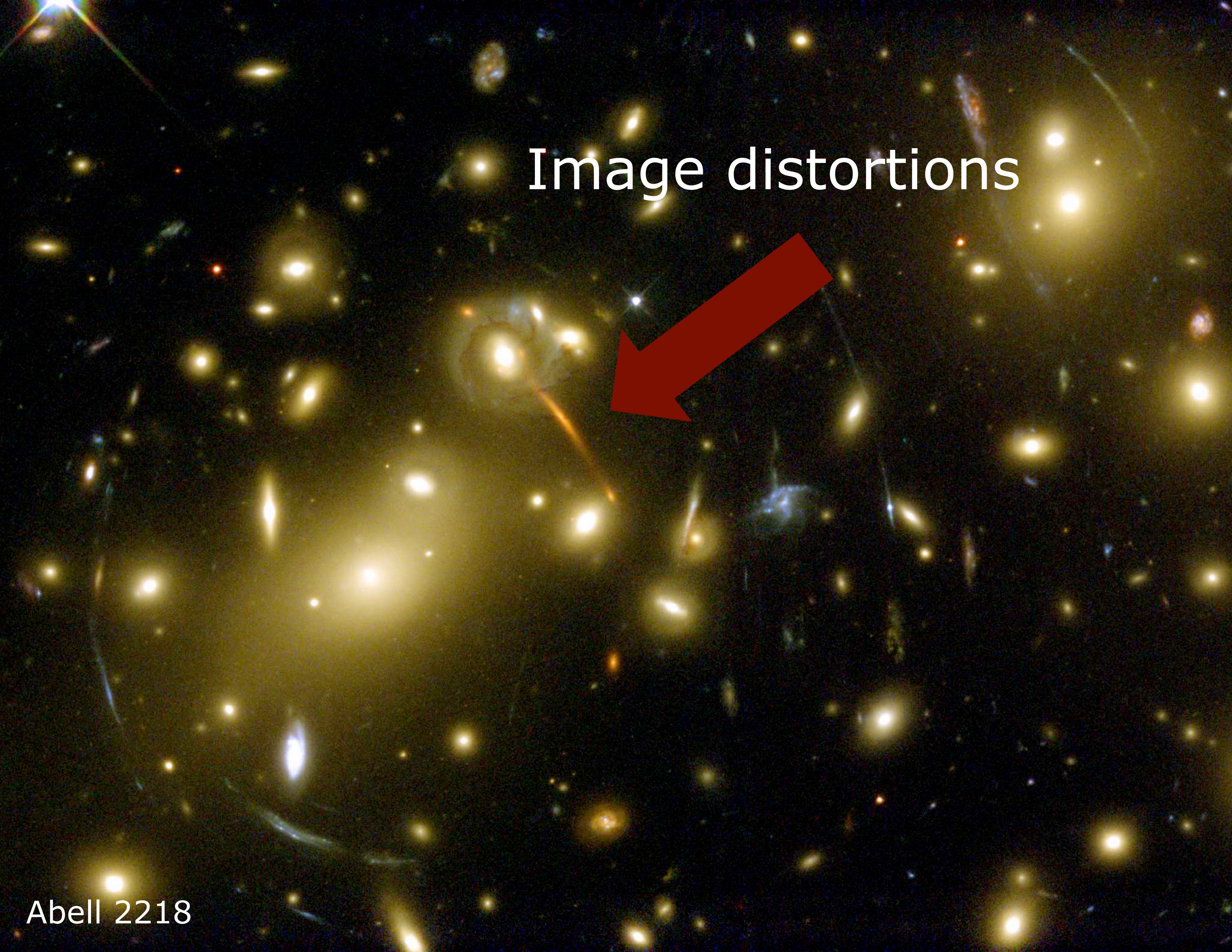
Image distortions
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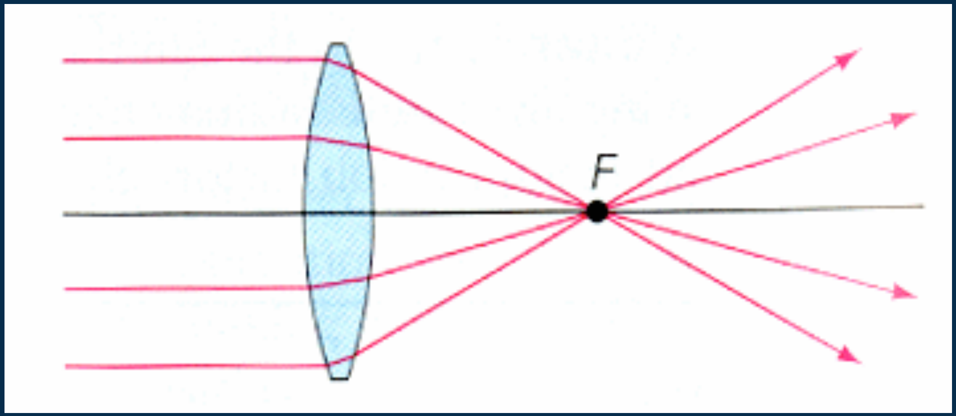
Two kinds of lenses

(1) Lensing via refraction



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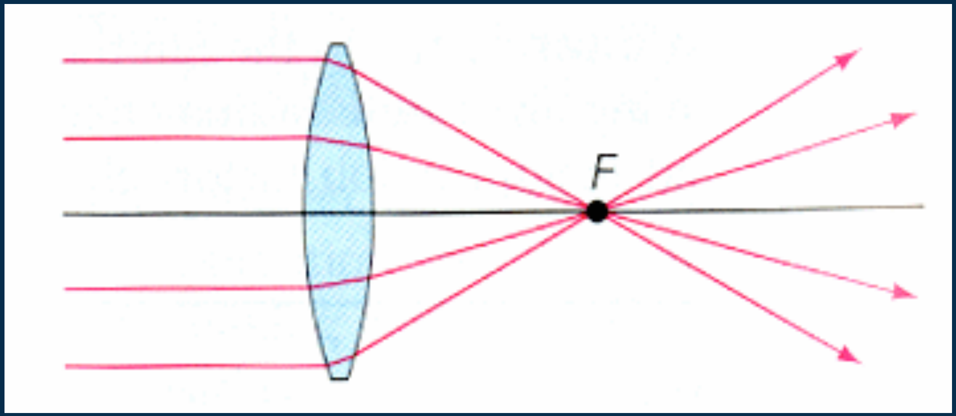

Light rays move at a different speed in the lens medium

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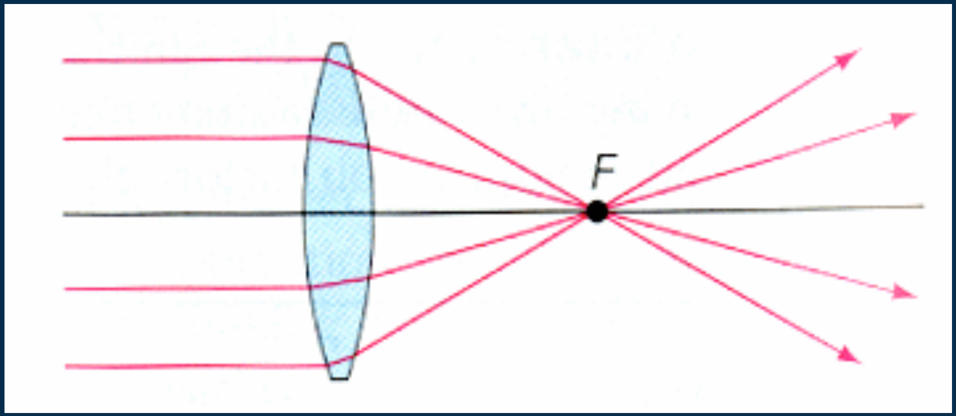

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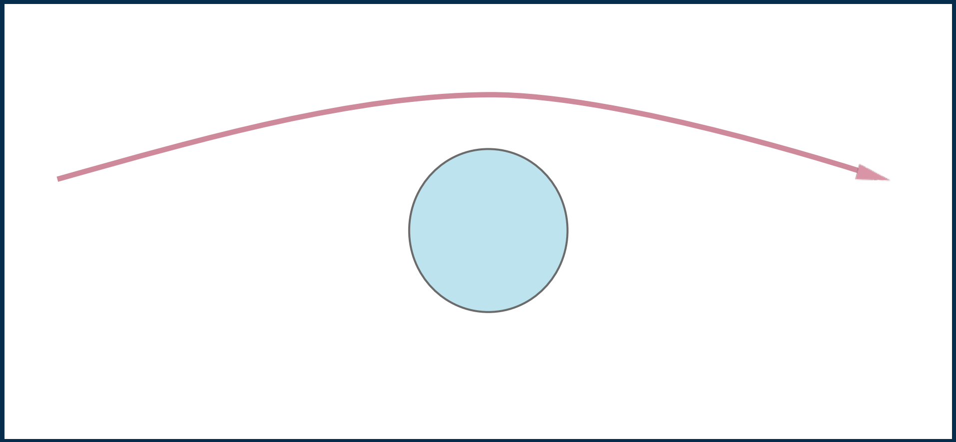

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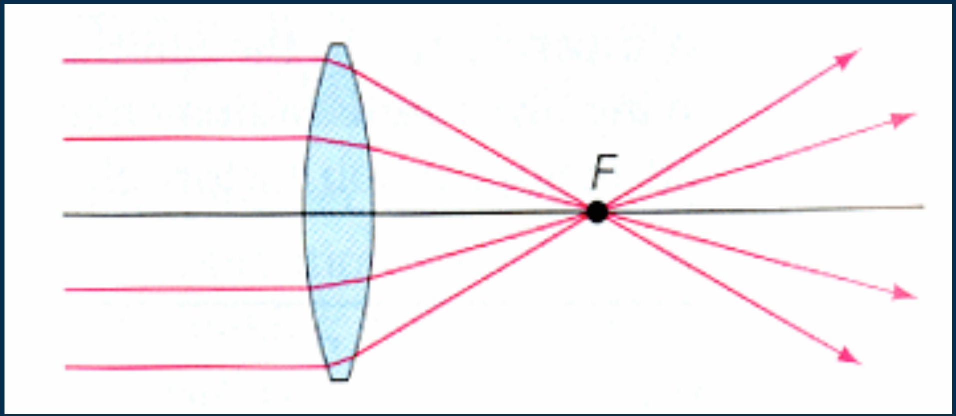

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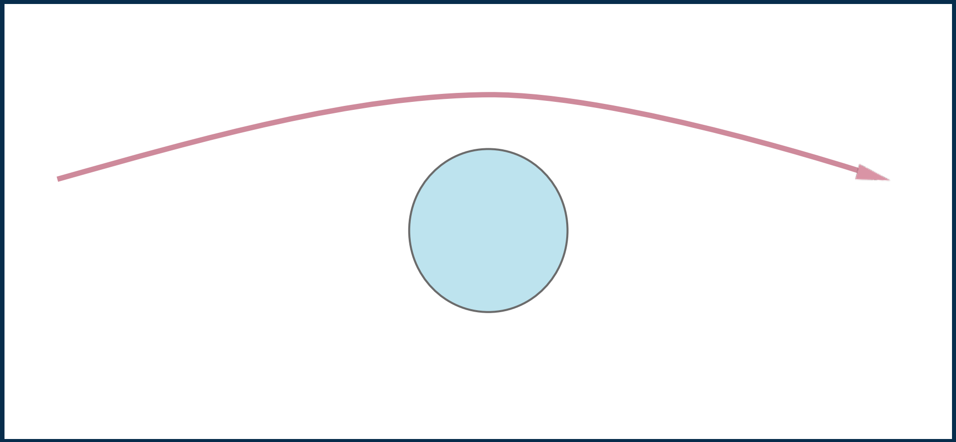

Photons gravitate towards the massive object

How matter bends light

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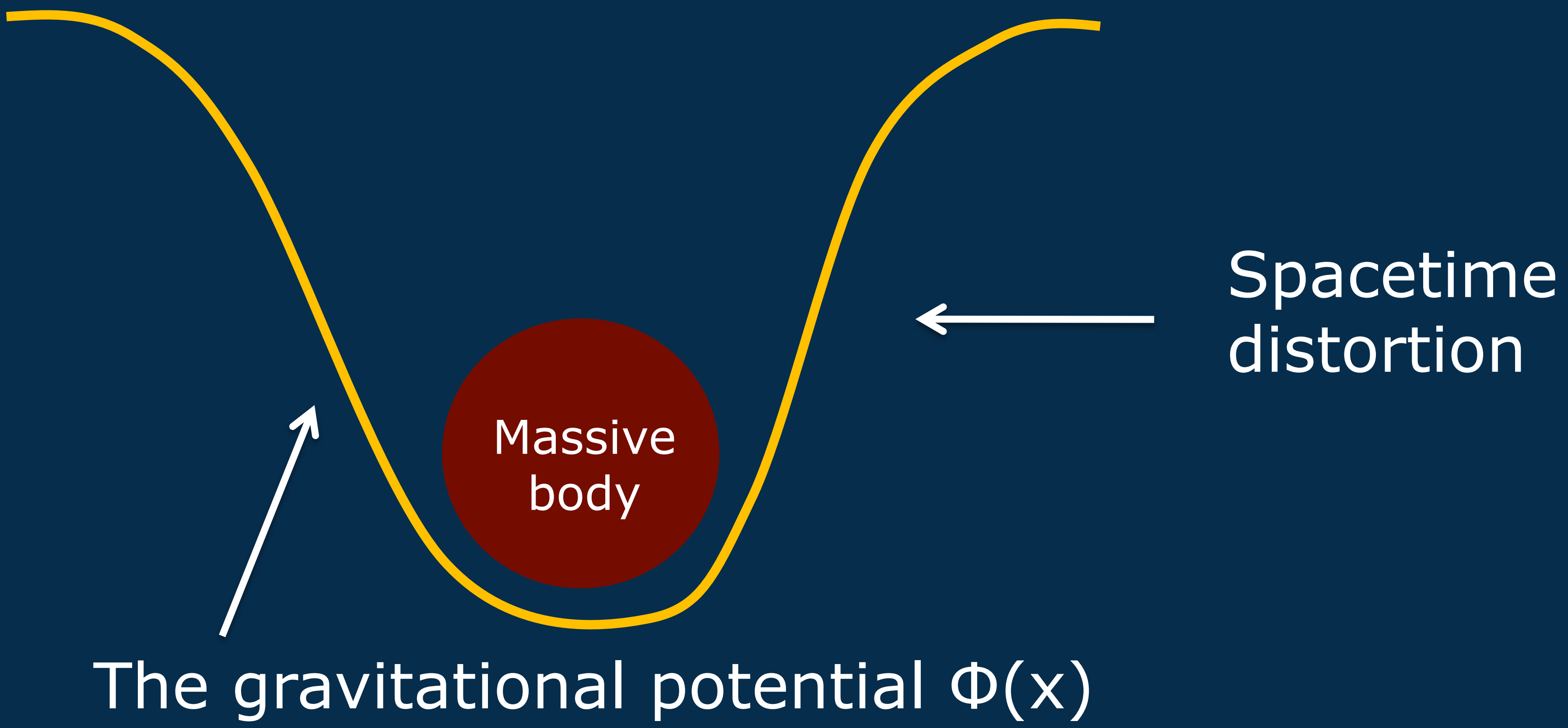

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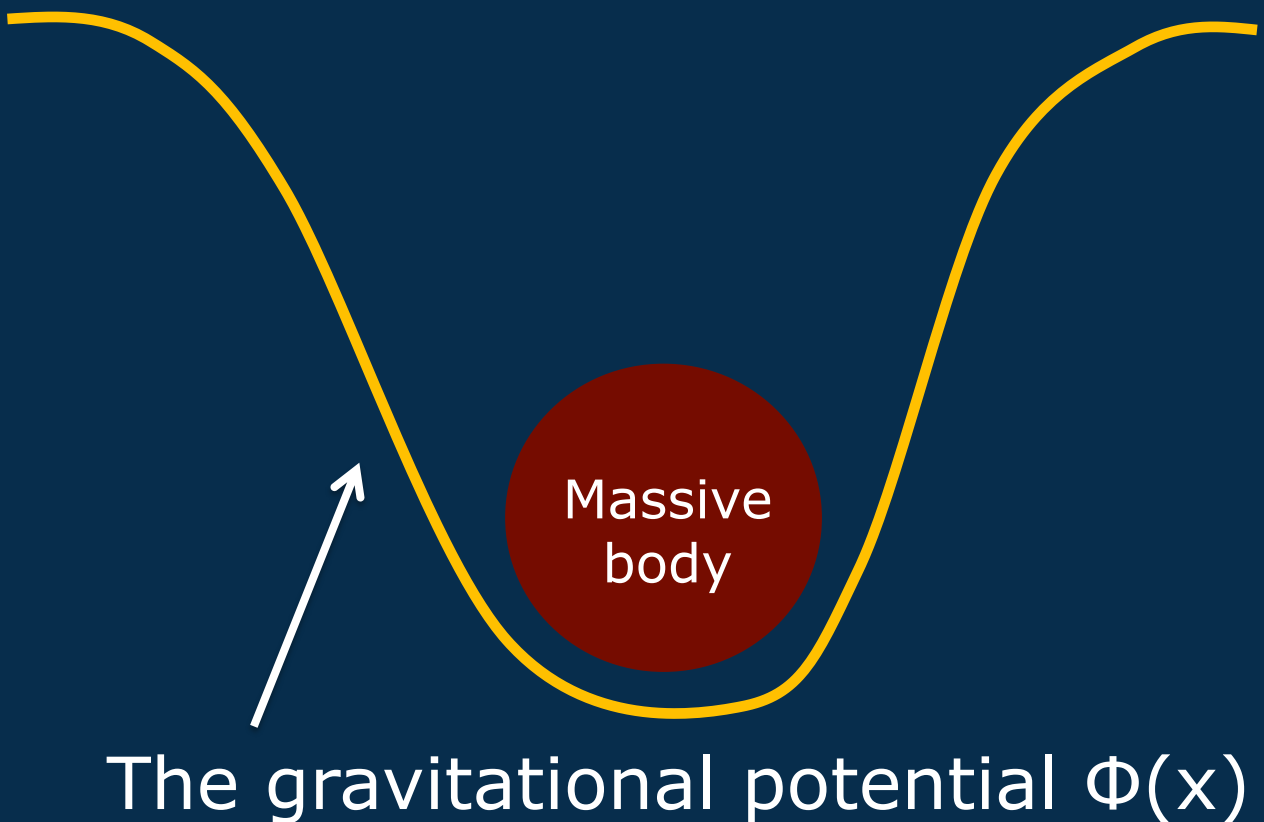

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$$\Phi = F(\rho)$$

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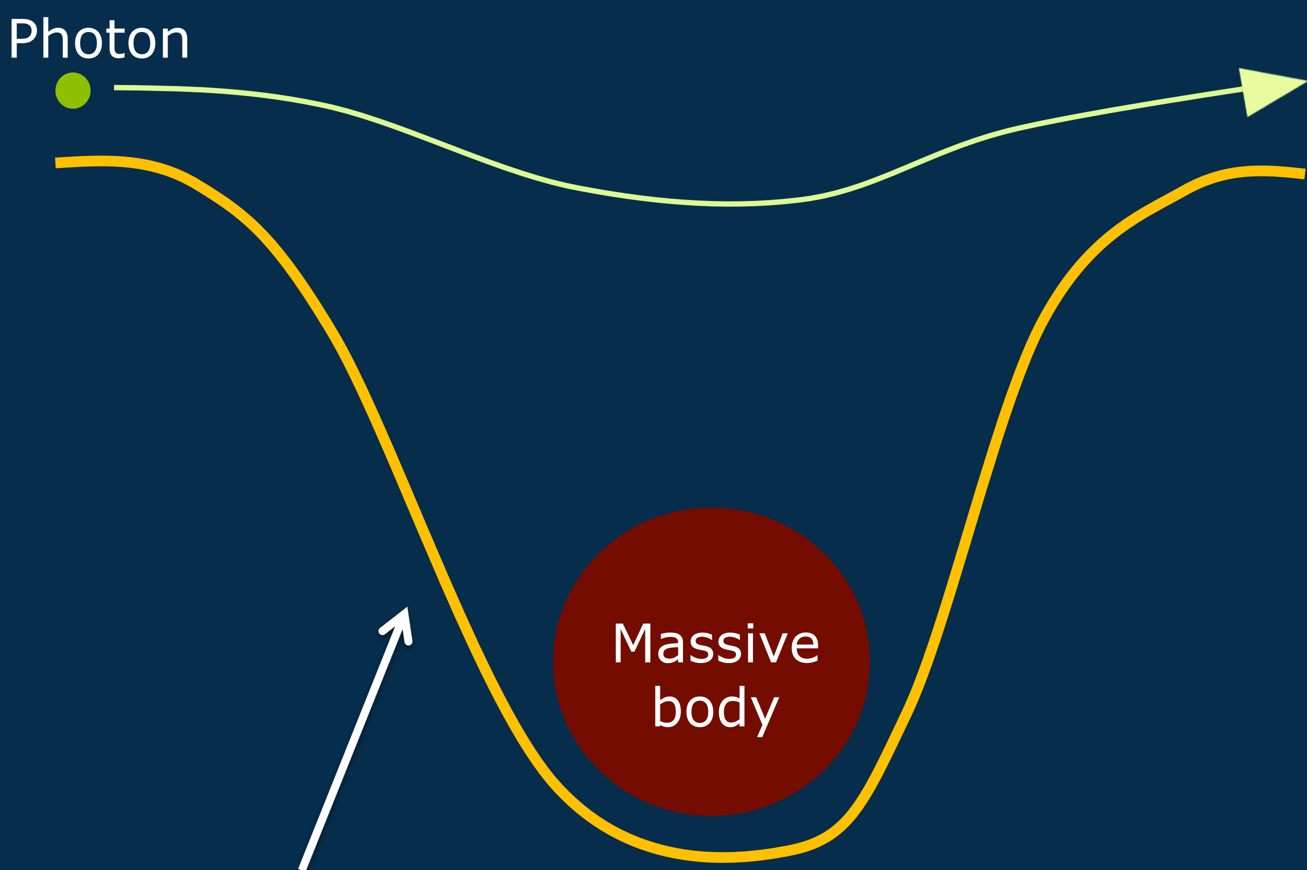

The gravitational potential $\Phi(x)$

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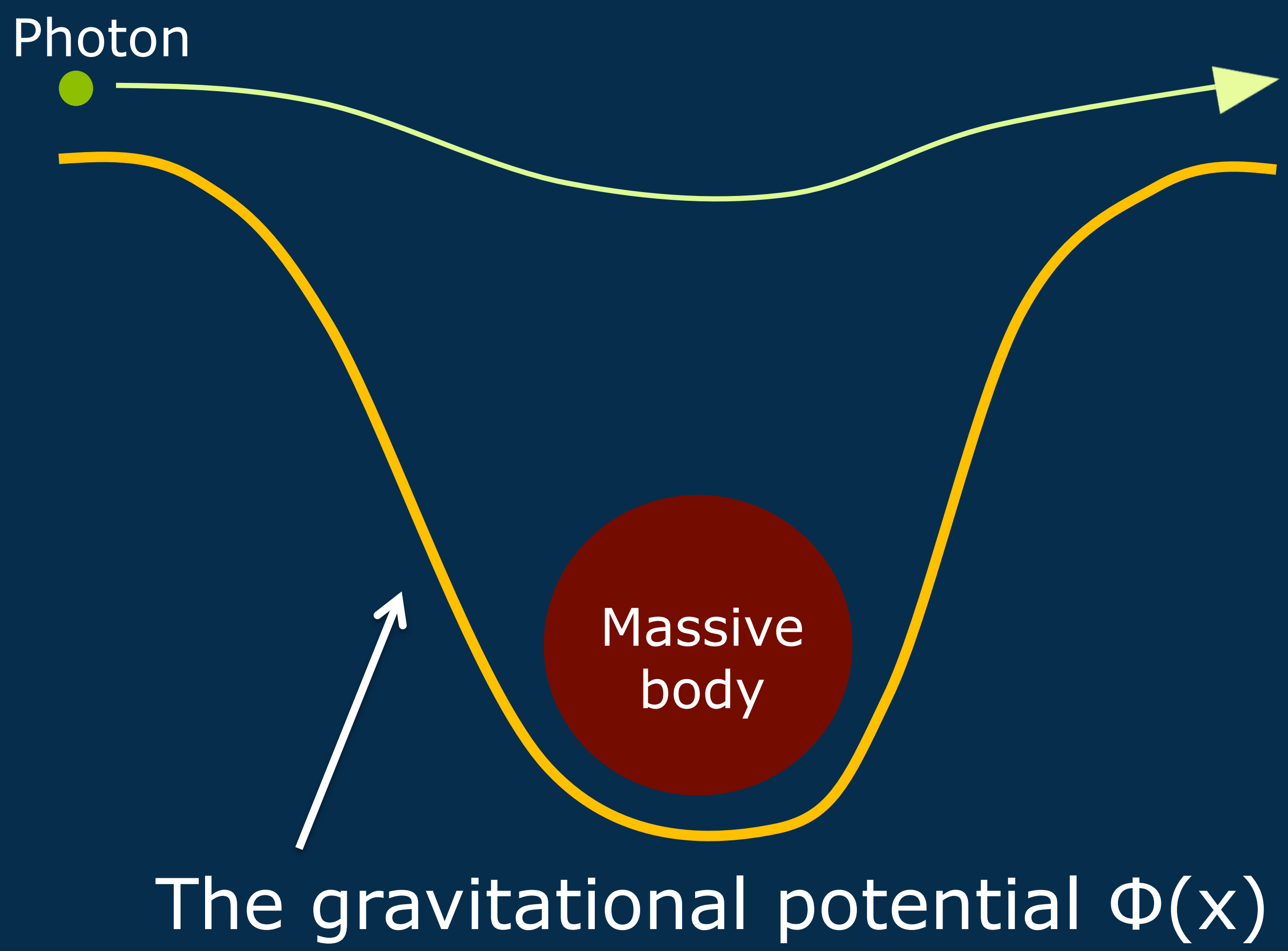

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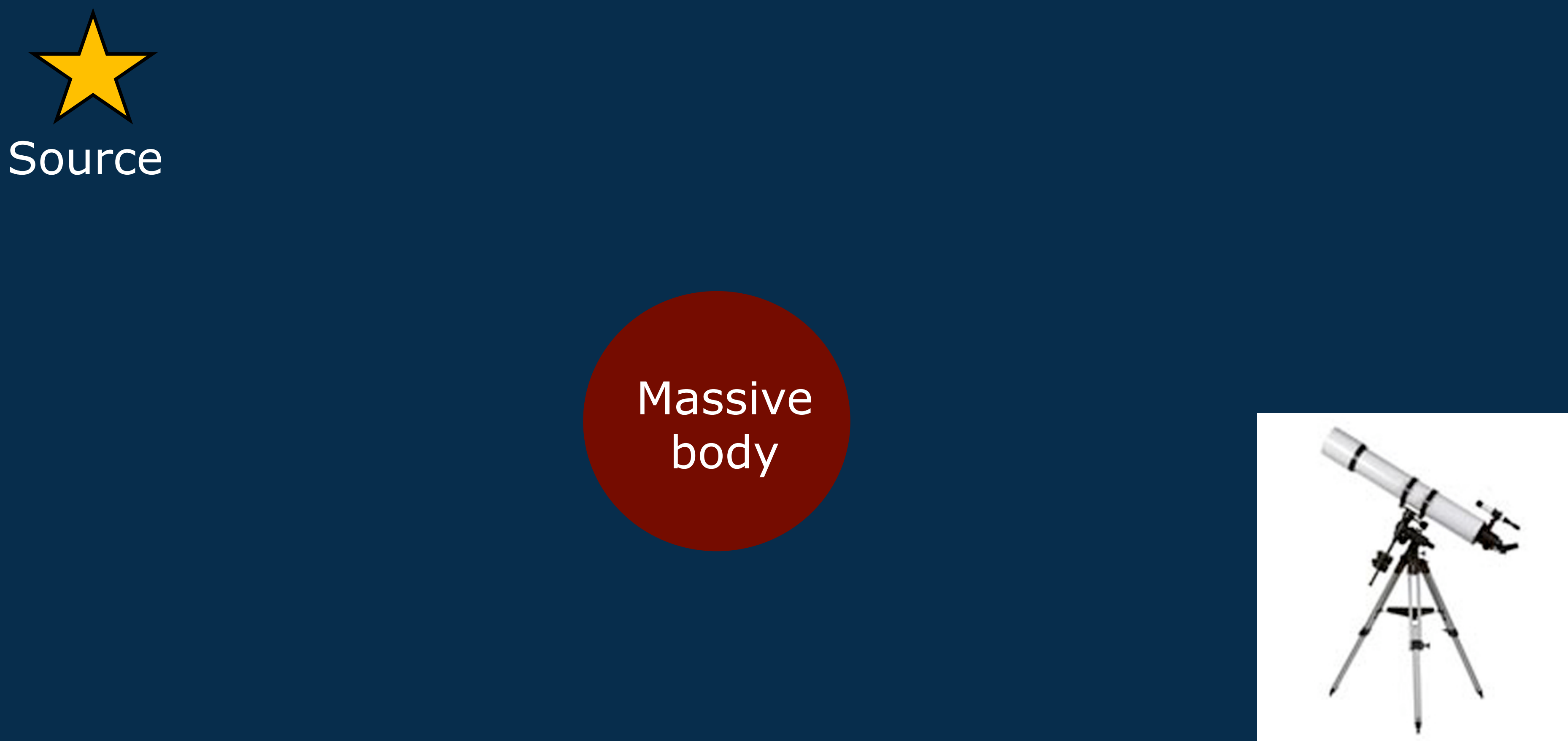

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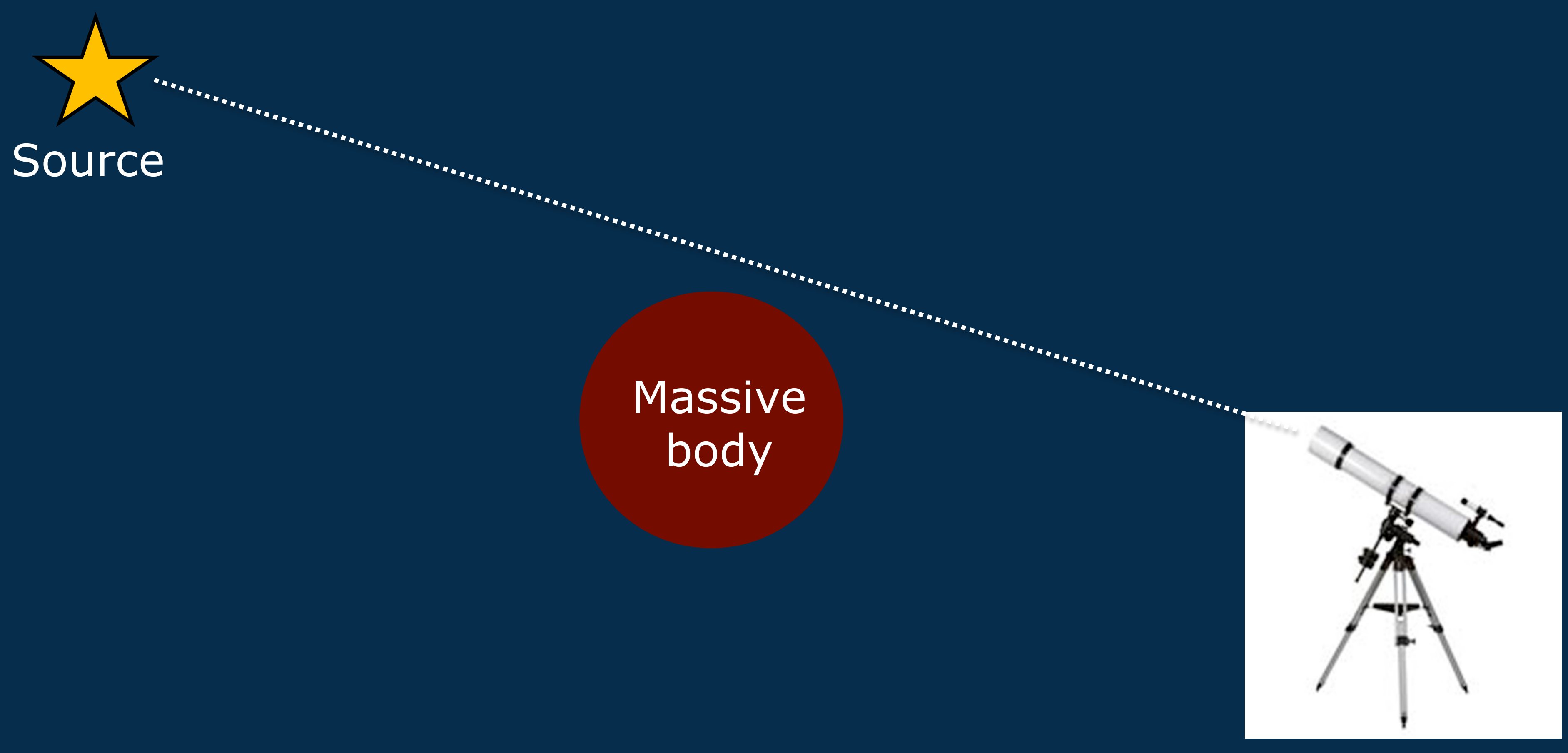

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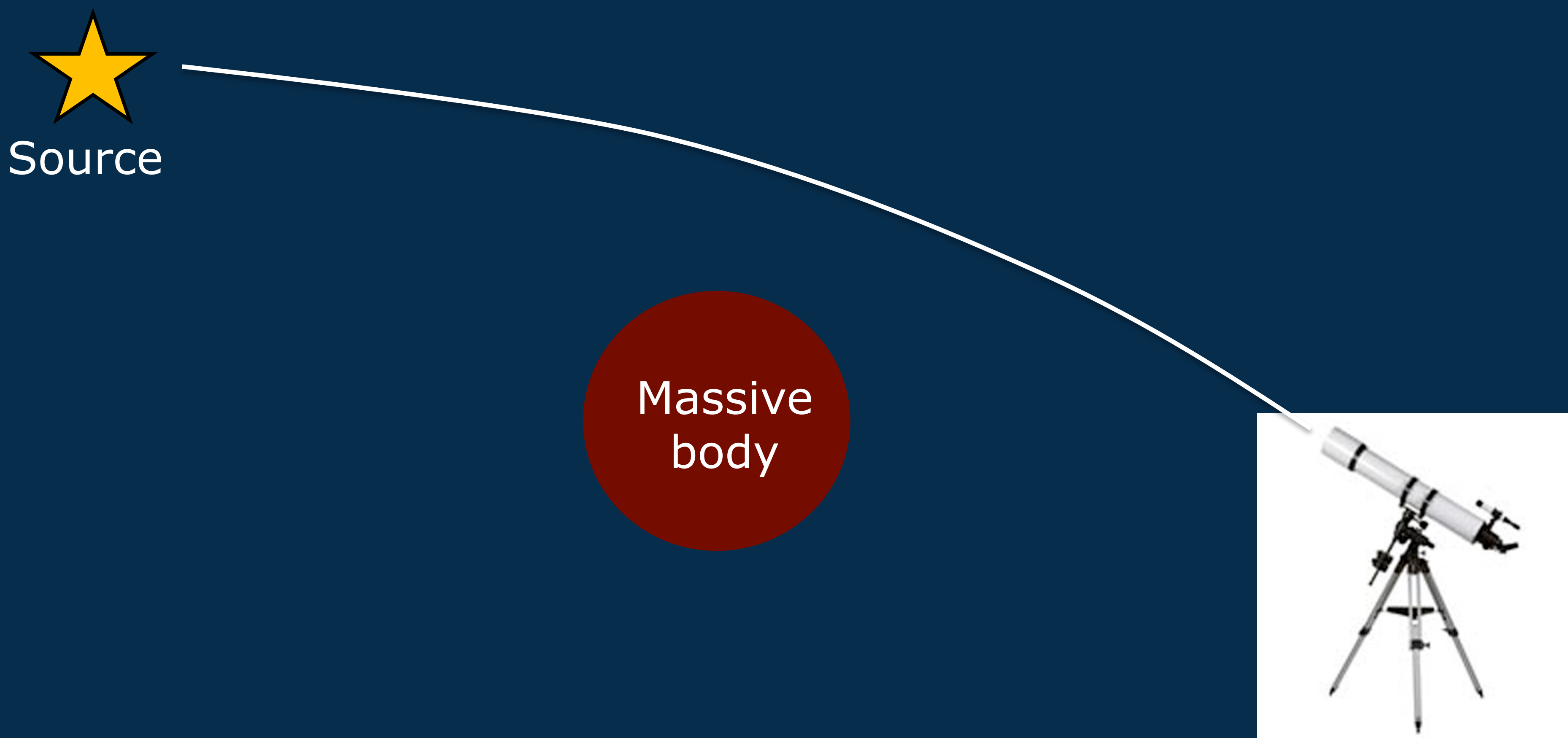

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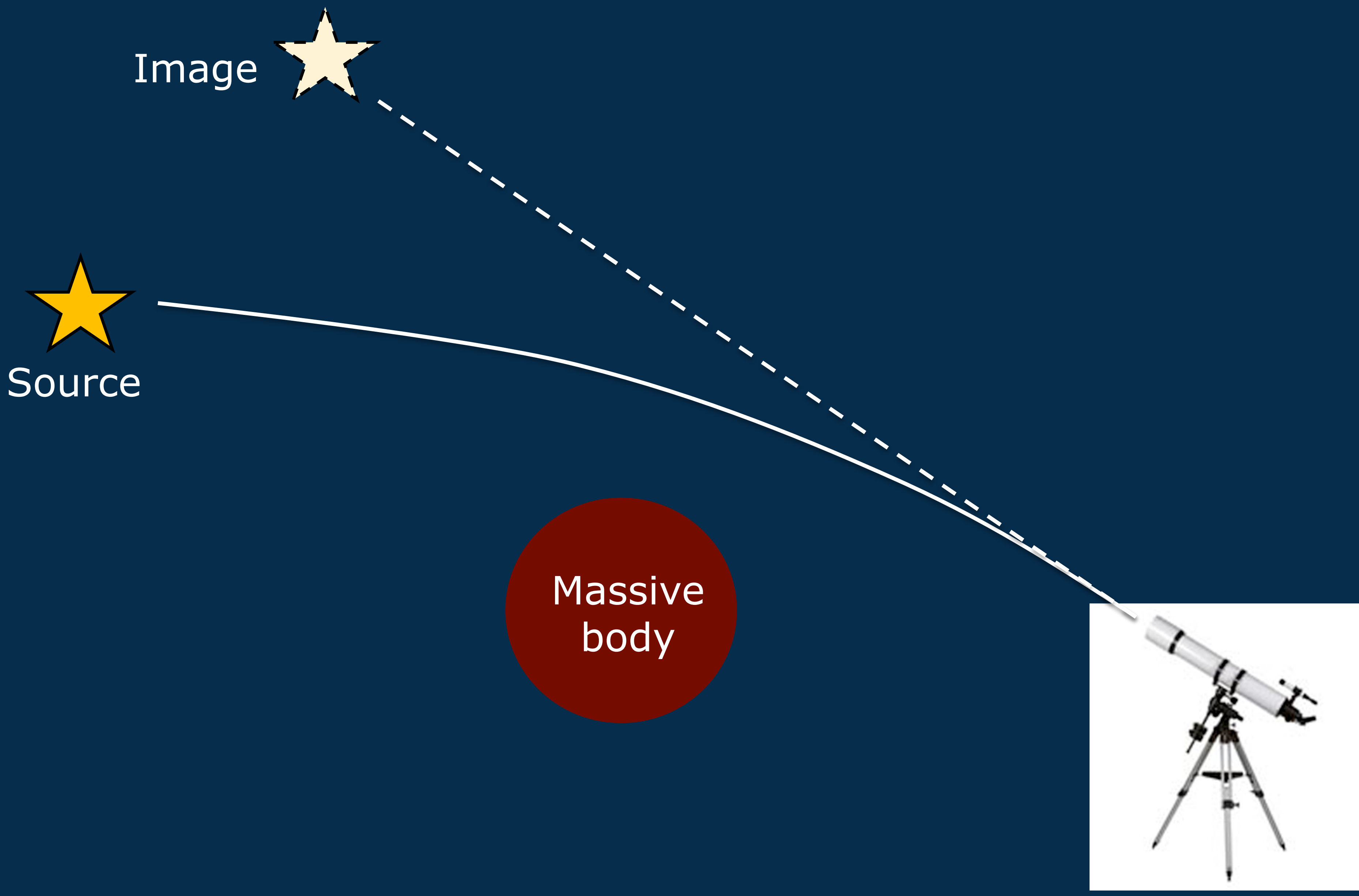

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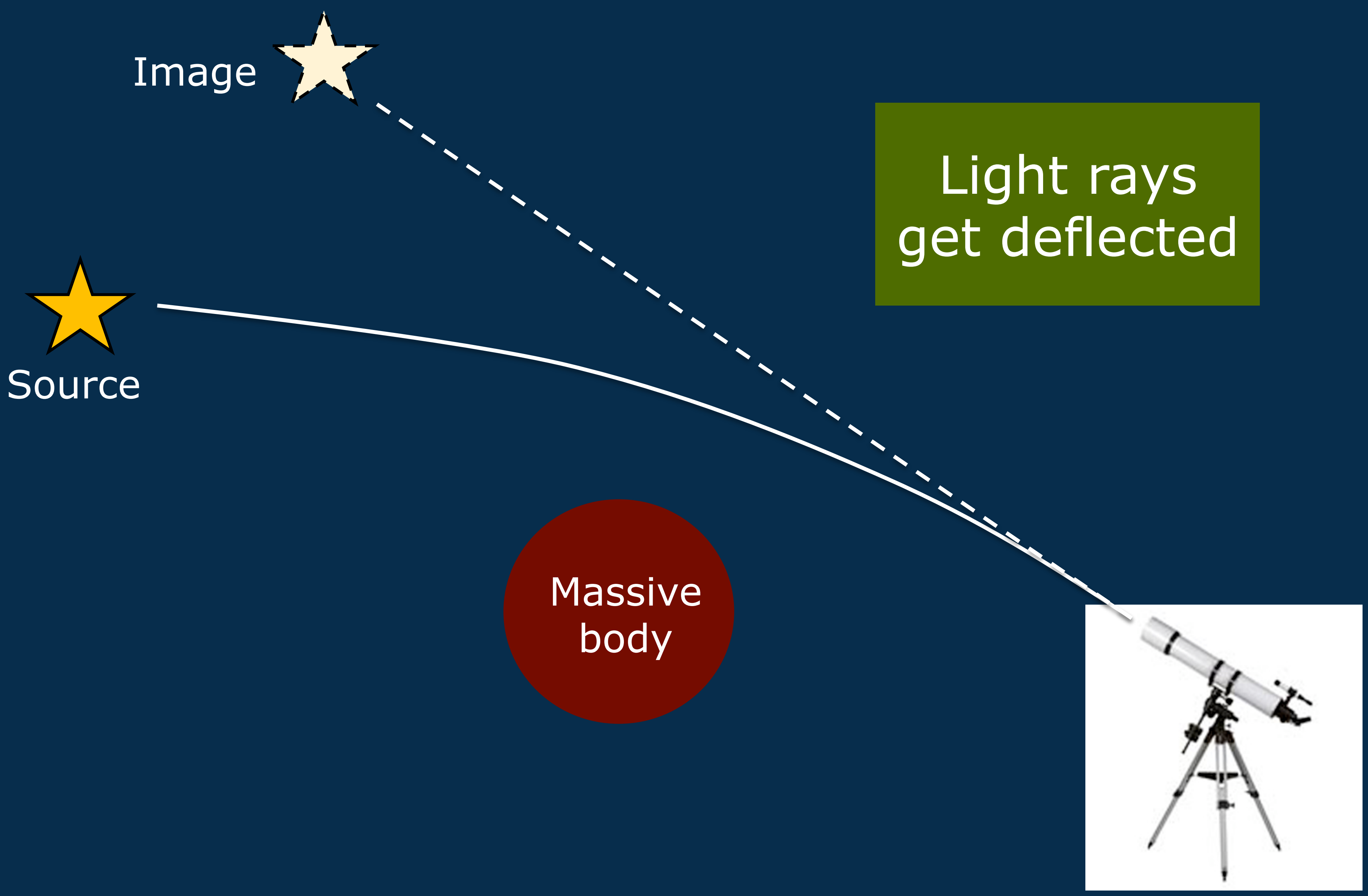
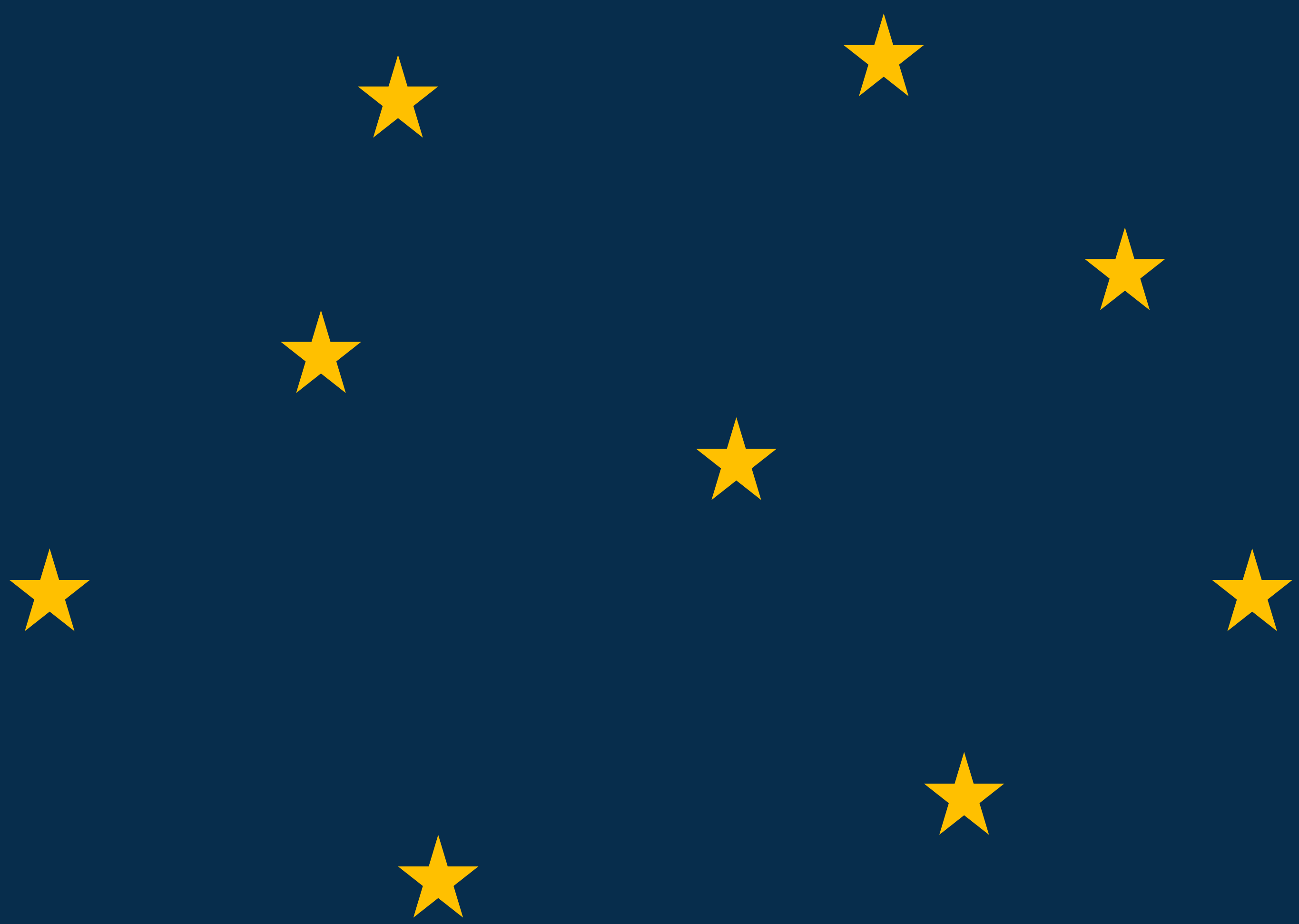


The Eddington experiment



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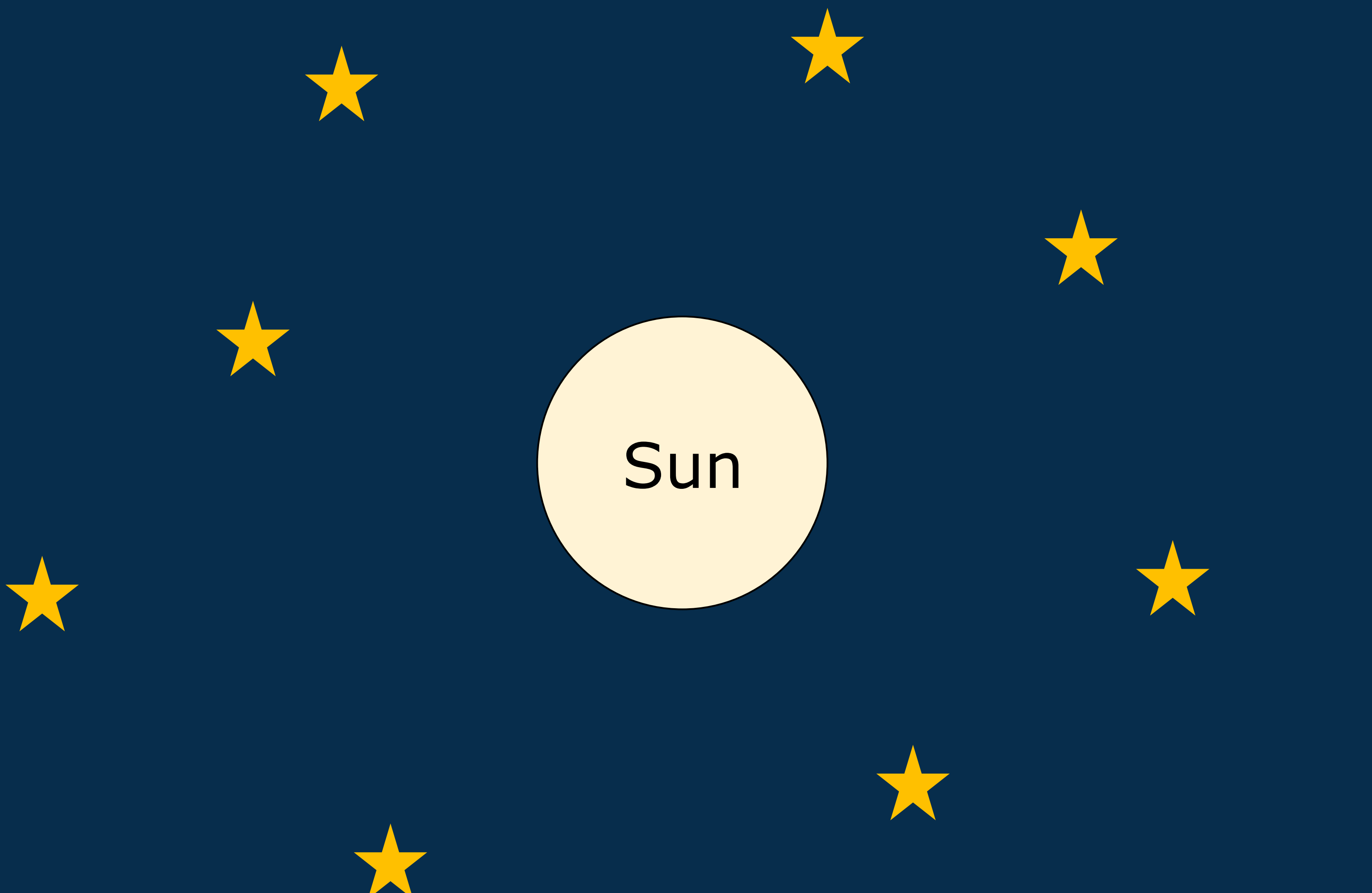

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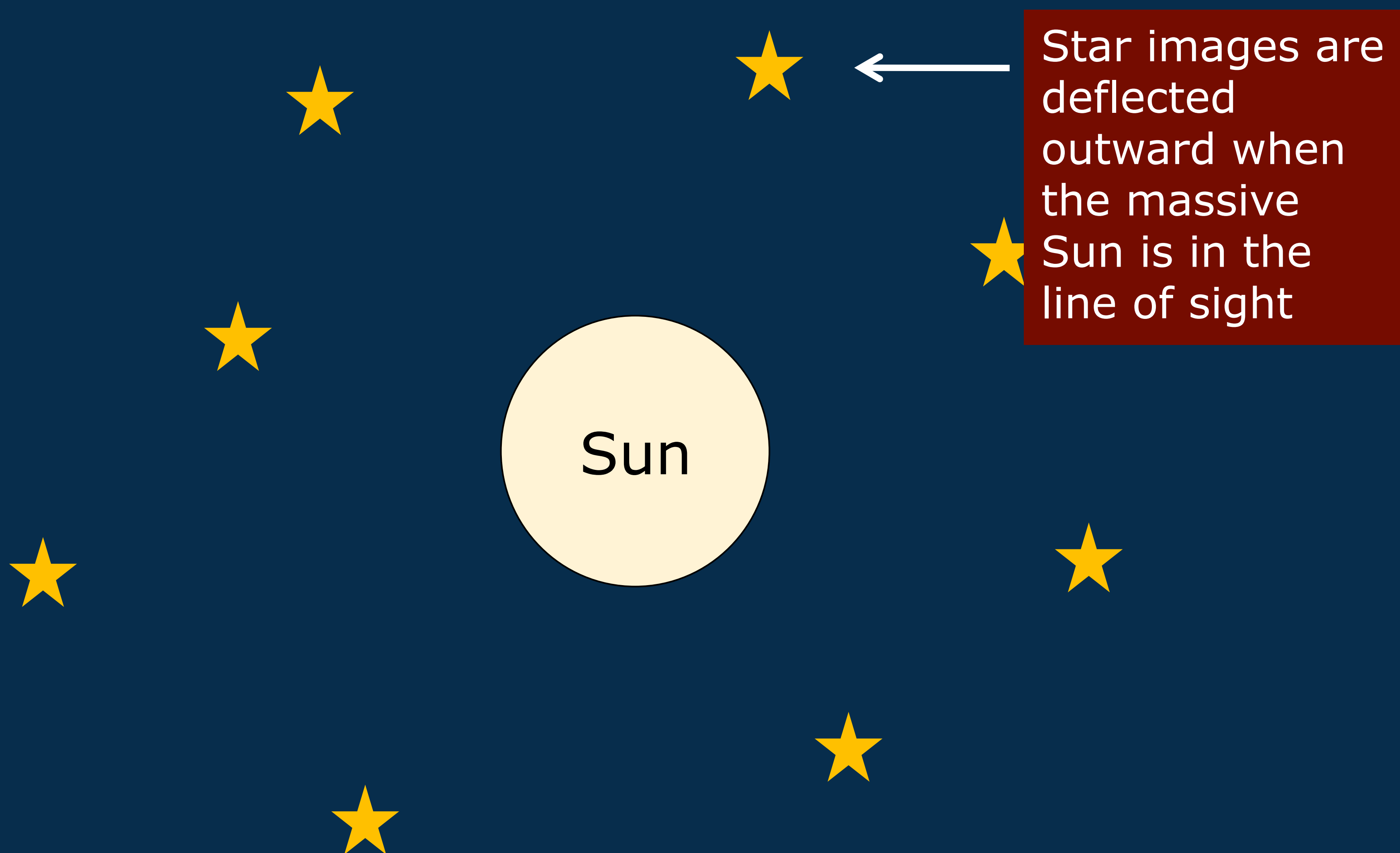
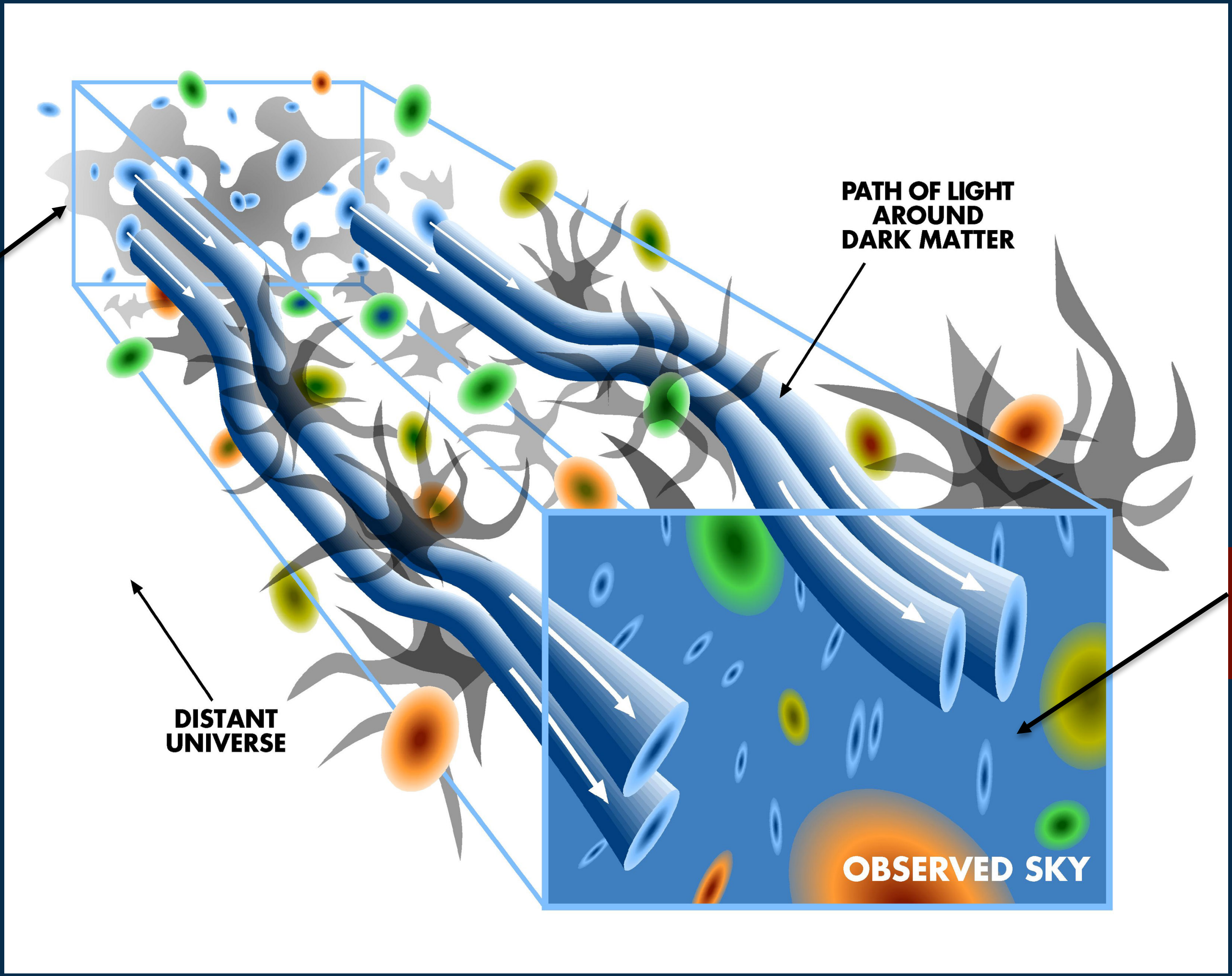


Lensing changes image shapes



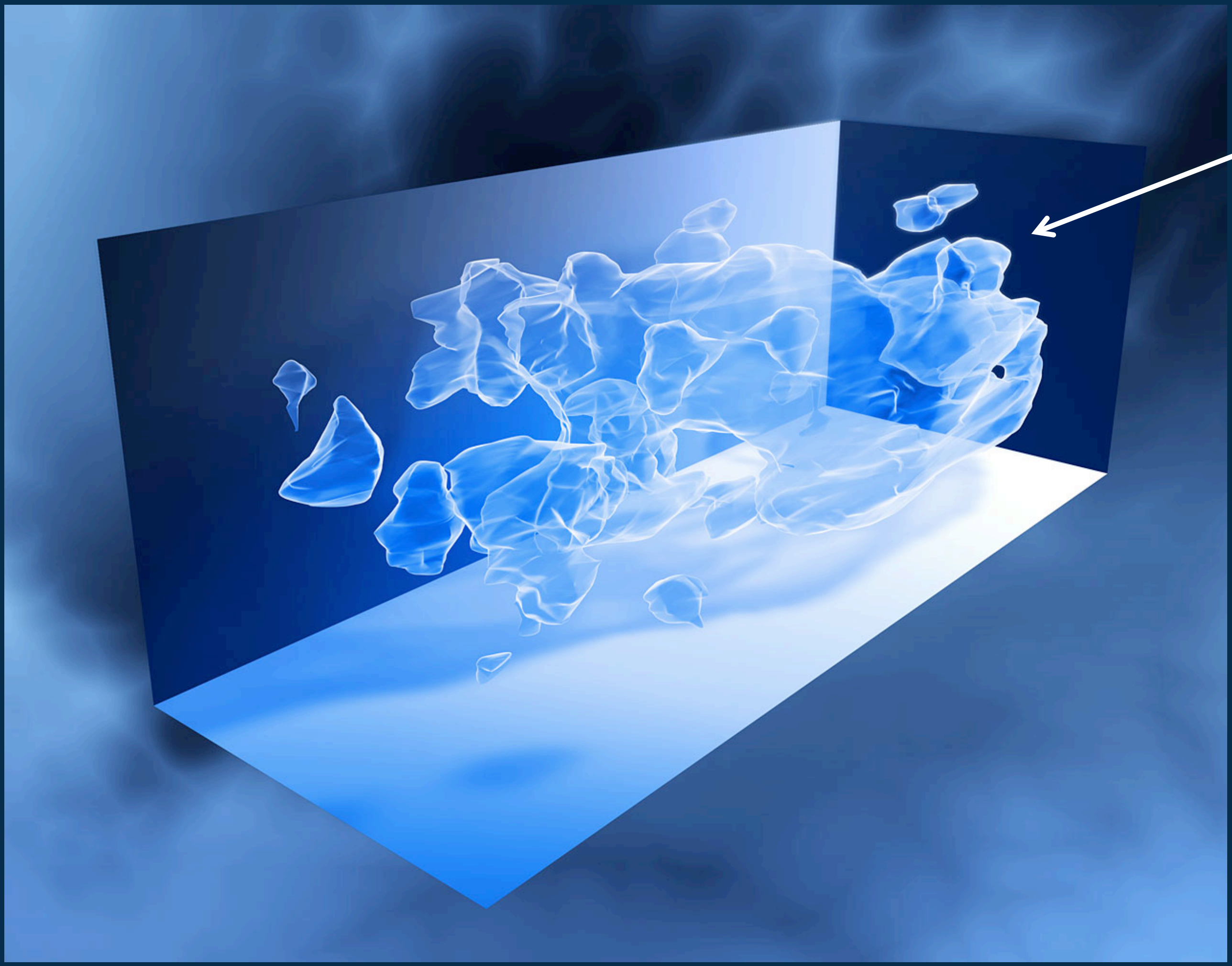
Intrinsic shapes

Distorted shapes

http://www.lsst.org

Why is this useful?

Dark matter mapping:



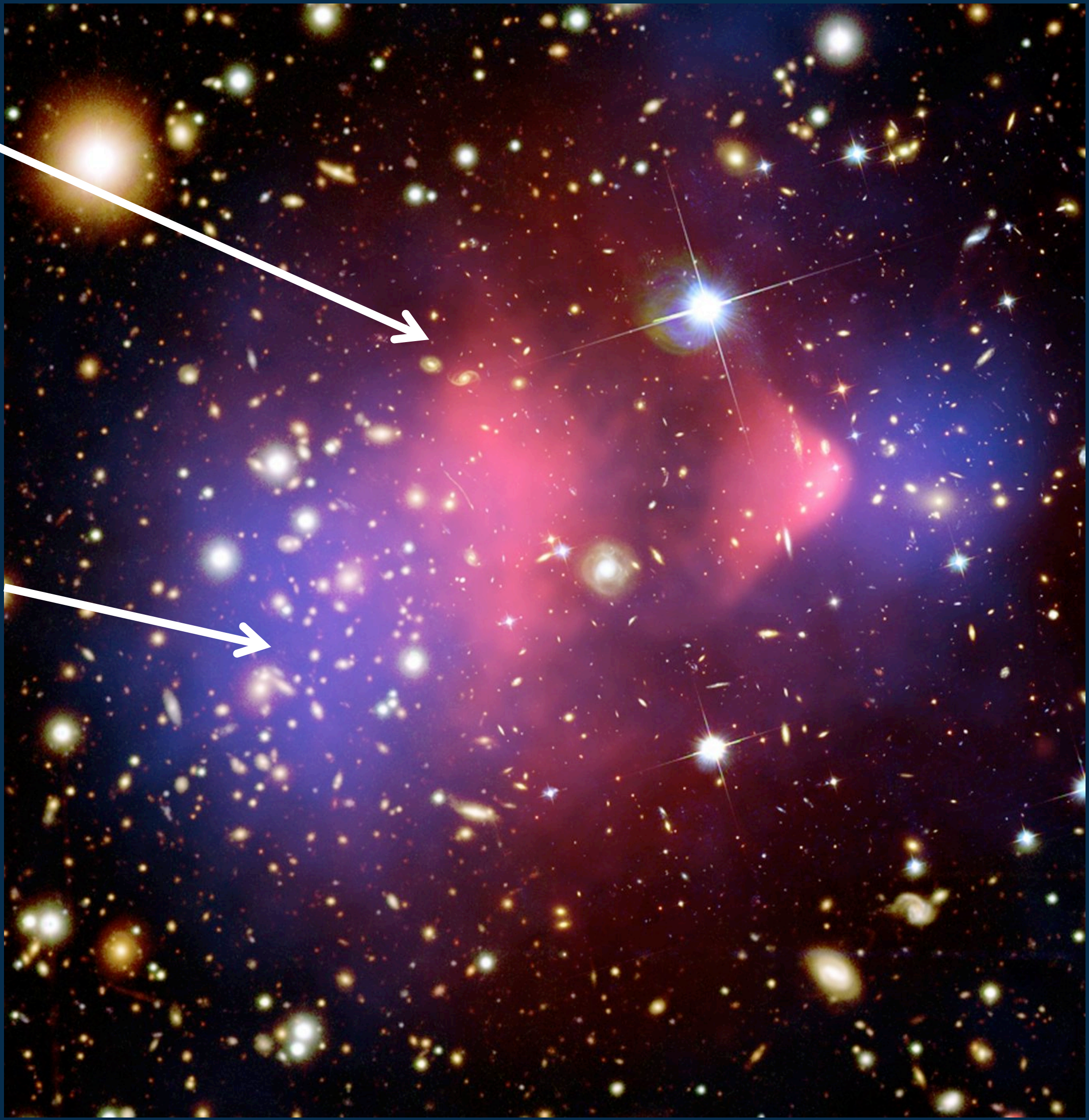
Massey et al. 2004

We think that about 85% of the matter in the Universe is dark

The bullet cluster – evidence for dark matter

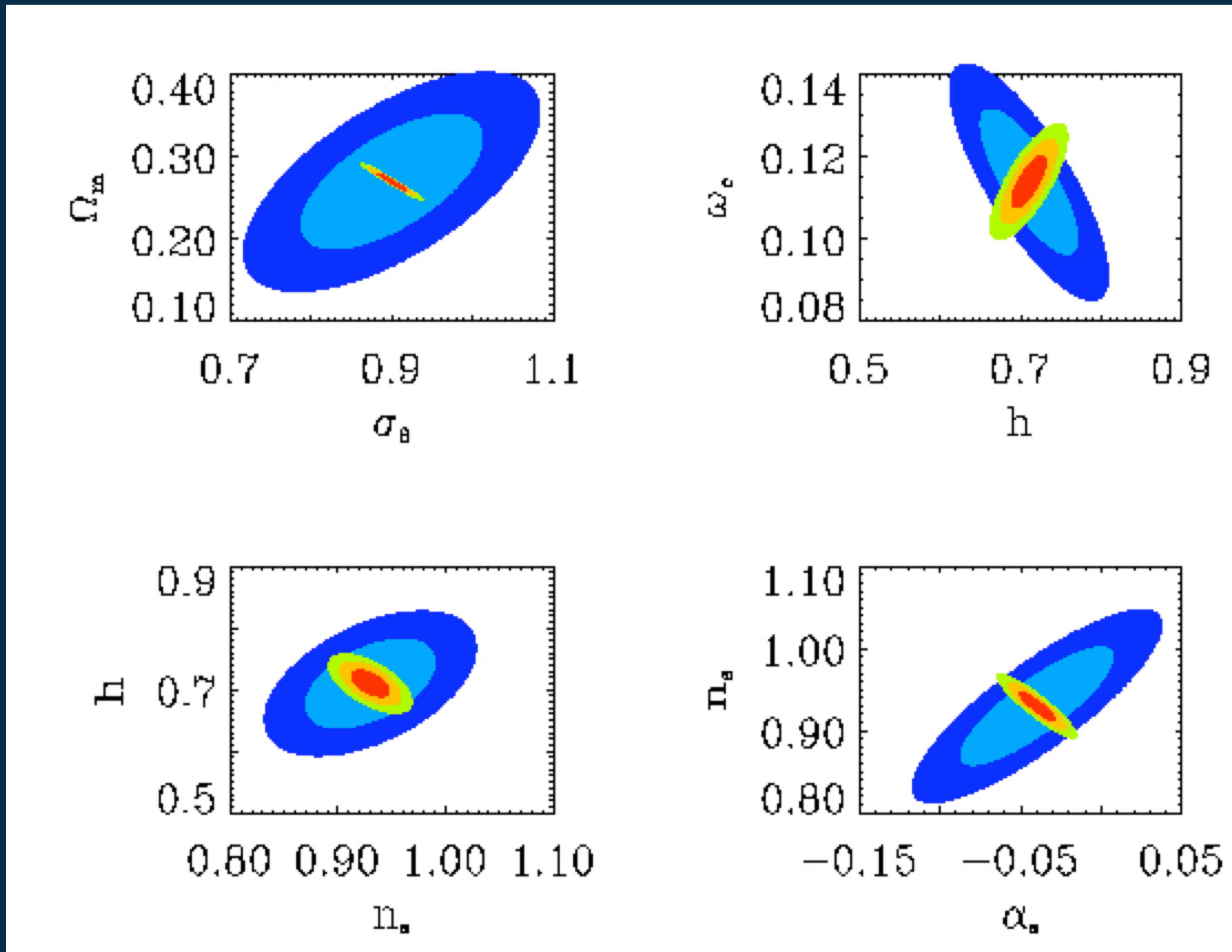
Pink: hot gas

Blue: total matter



http://ccapp.osu.edu

Lensing constrains other cosmological parameters



Tereno et al. 2005

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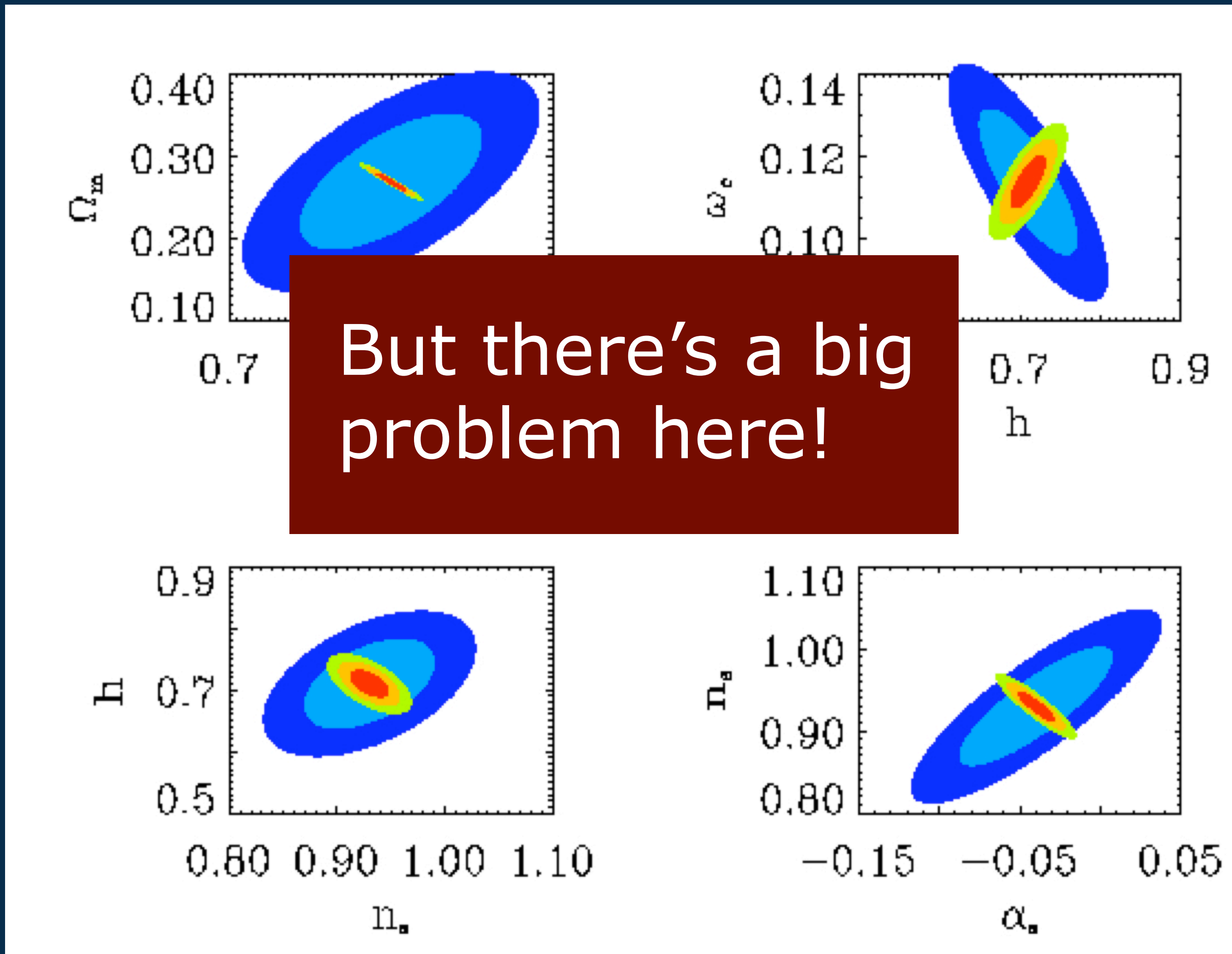

But there's a big problem here!

Tereno et al. 2005

The dark energy problem

Supernovae look dimmer than expected in a “normal” universe

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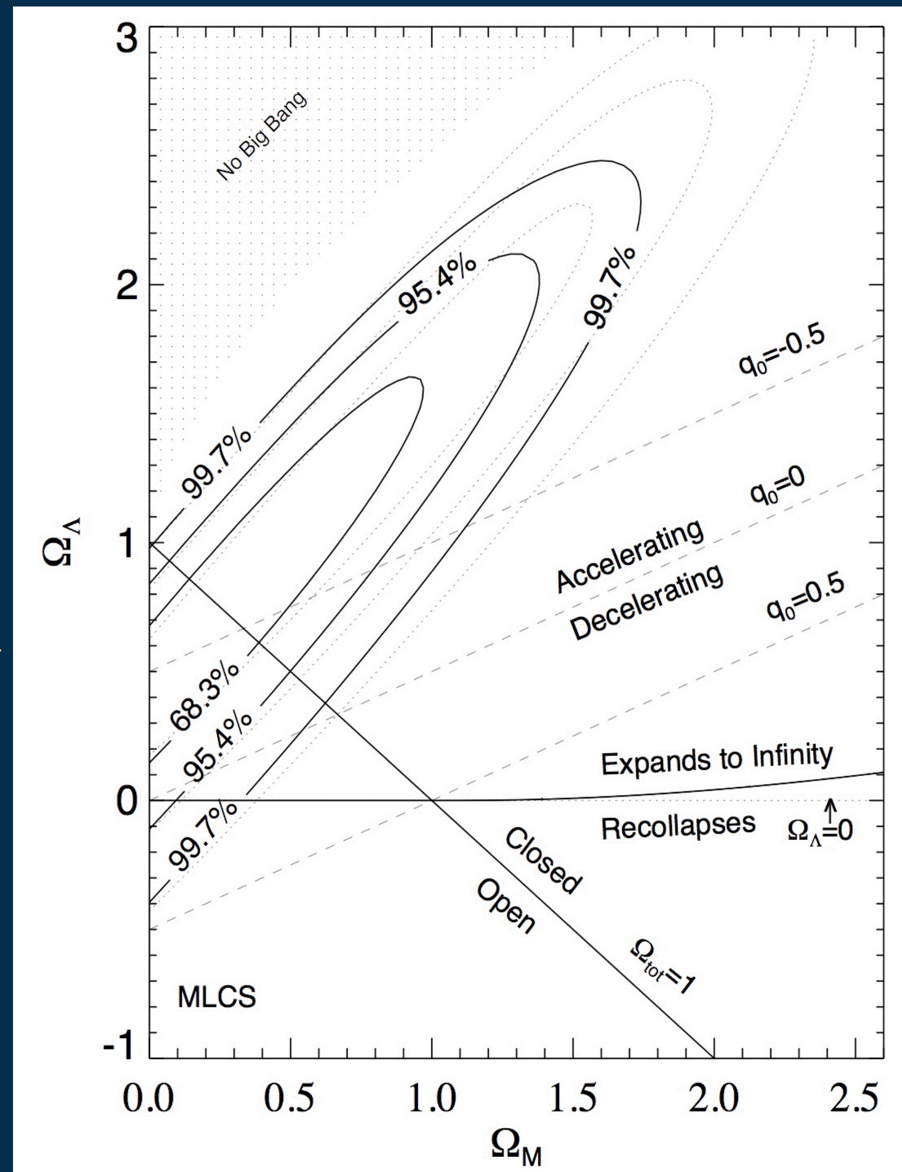
But we can fit the data if we add in some “dark energy”



Riess et al. 1998

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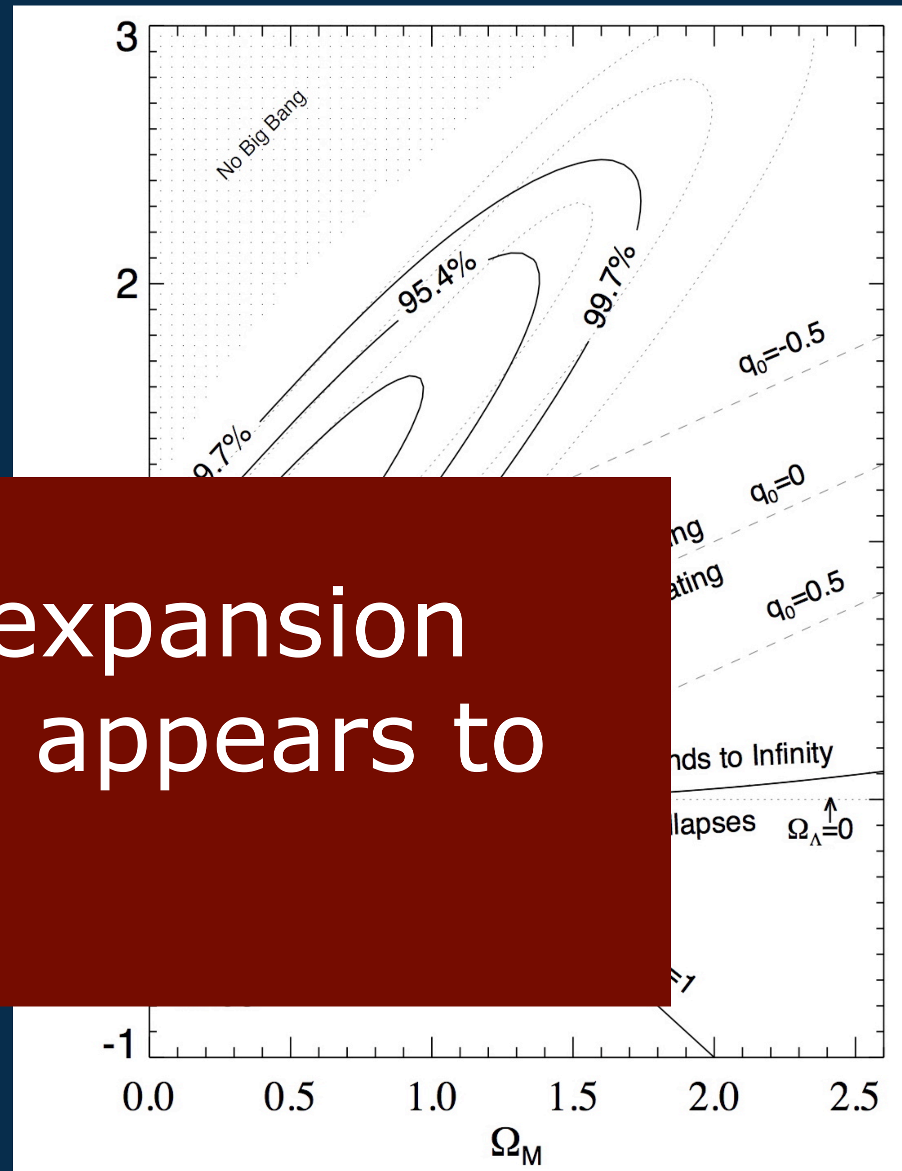

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Problem: the expansion of the Universe appears to be accelerating

Potential explanations

- **Measurement error** – maybe we did the measurements or data analysis wrong? (Unlikely)

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Modifying gravity

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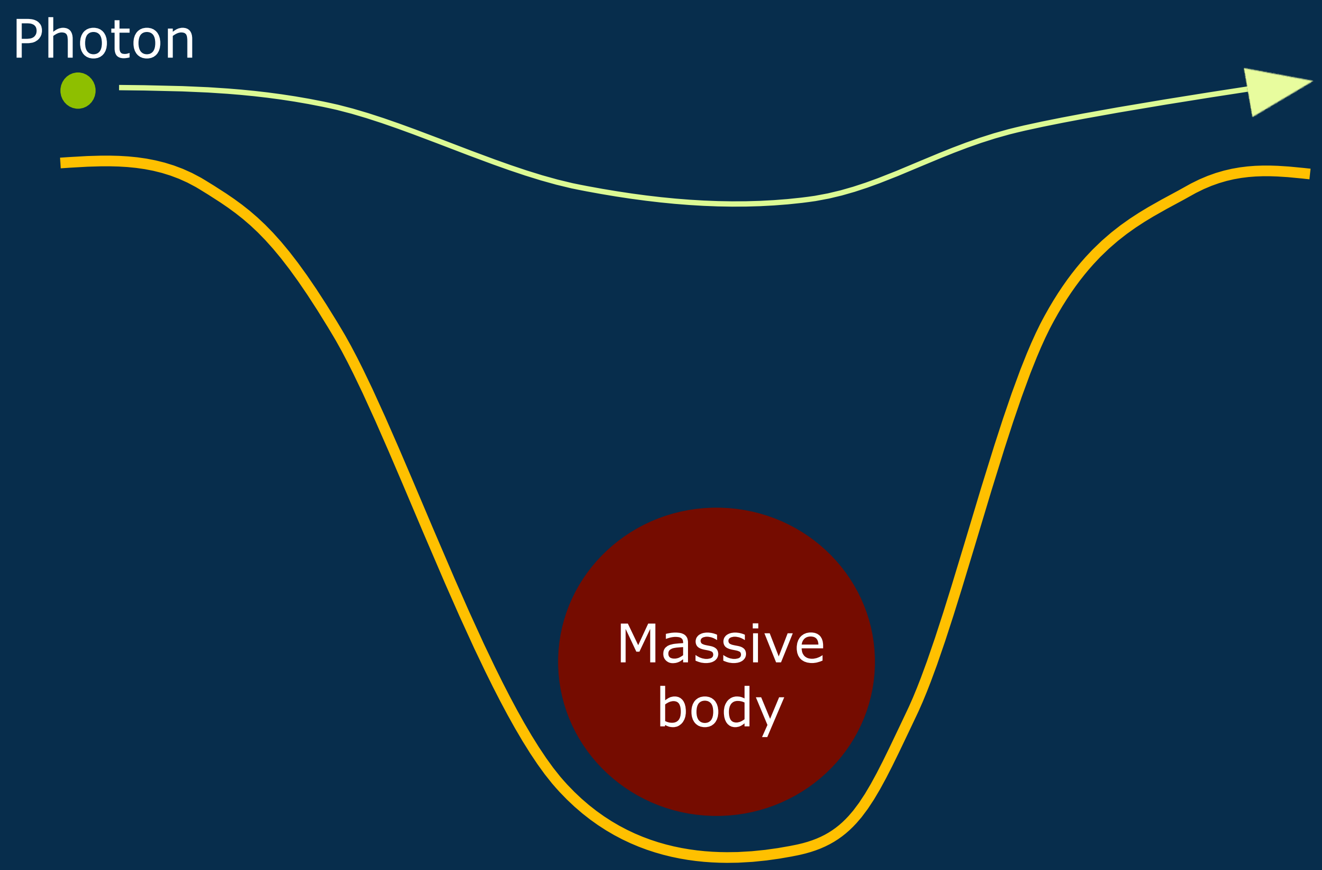
How do we measure these modifications?
One way:
Gravitational lensing

Lensing in GR



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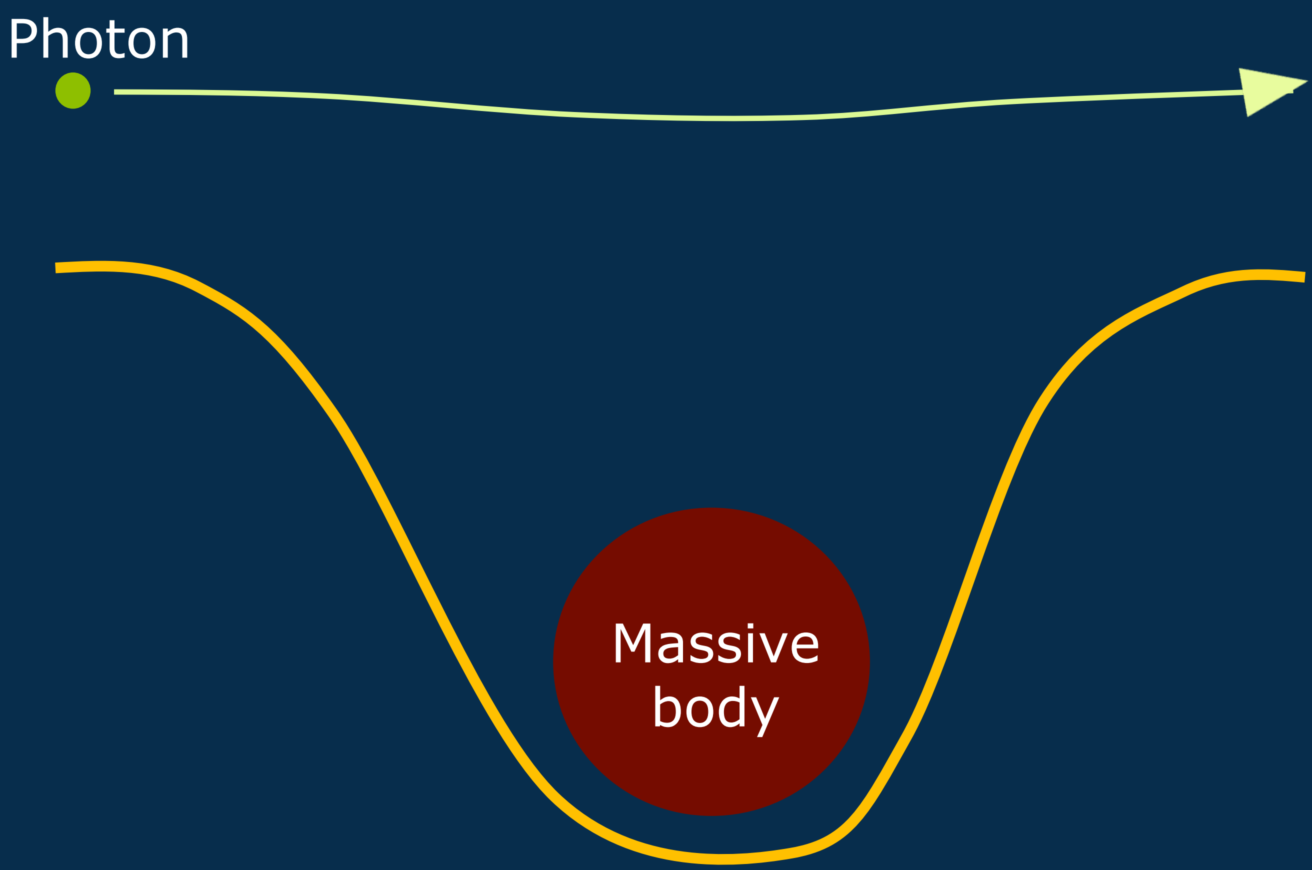
Lensing in modified gravity



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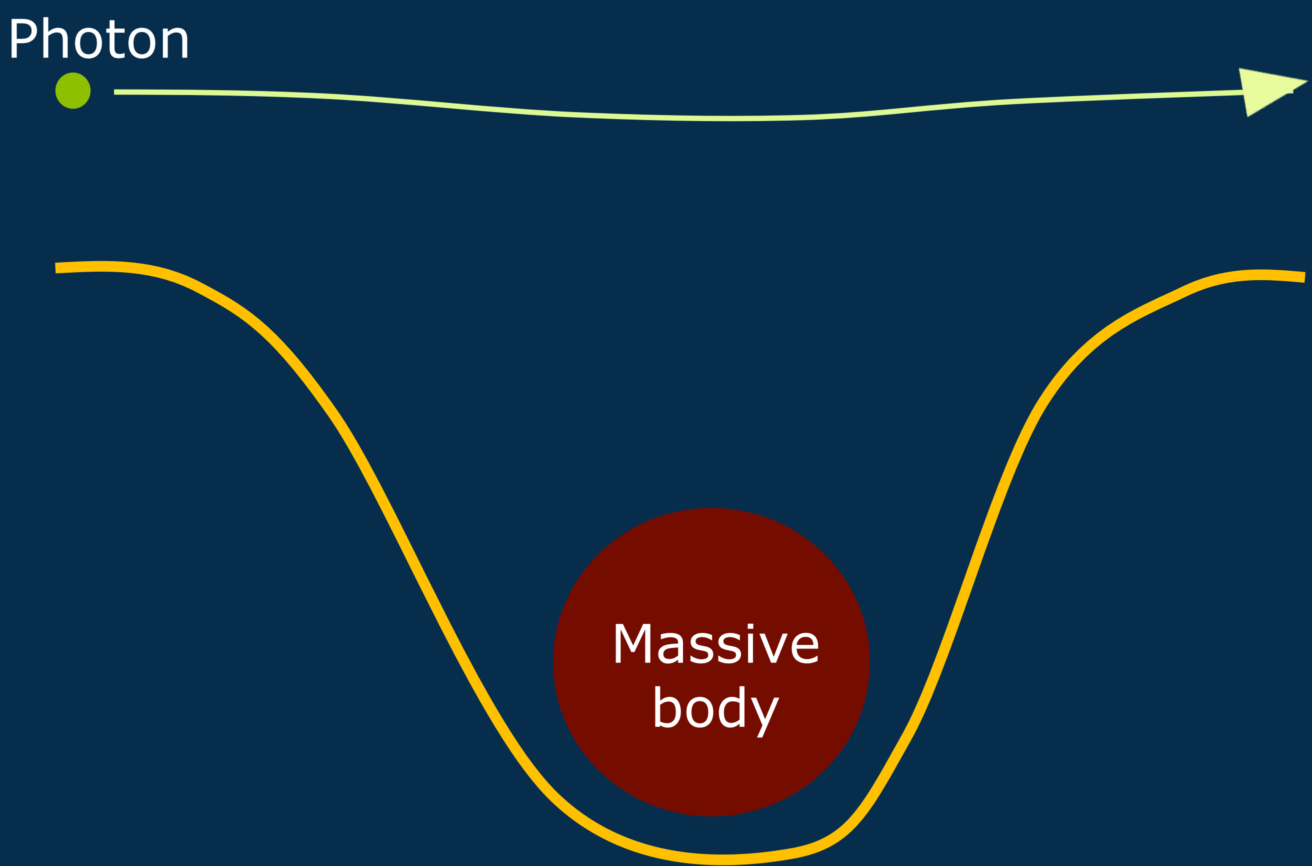

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Changes how matter produces potentials
Changes how photons move in those potentials

Big question: How do we best use gravitational lensing observations to constrain modifications of GR on very large scales?

Lessons from “small” scales

The parameterized post-Newtonian formalism –

the gravitational potentials of GR are modified, for instance:

Matter distribution $\rho(x)$

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The parameterized post-Newtonian formalism –

the gravitational potentials of GR are modified, for instance:

Matter distribution $\rho(x)$ → Photons "feel" the gravitational potential $\gamma\Phi(x)$

→ Can constrain the parameter γ

PPN parameters

Parameter	What it measures relative to GR	Value in GR	Value in semi-conservative theories	Value in fully conservative theories
γ	How much space-curvature produced by unit rest mass?	1	γ	γ
β	How much "nonlinearity" in the superposition law for gravity?	1	β	β
ξ	Preferred-location effects?	0	ξ	ξ
α_1	Preferred-frame effects?	0	α_1	0
α_2		0	α_2	0
α_3		0	0	0
α_3	Violation of conservation of total momentum?	0	0	0
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Will, 2006

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Framework for parameterizing deviations from GR in "weak field" gravity:

(1) The Solar System

(2) Large scale cosmology

Will, 2006

The PPN formalism leads to model-independent constraints

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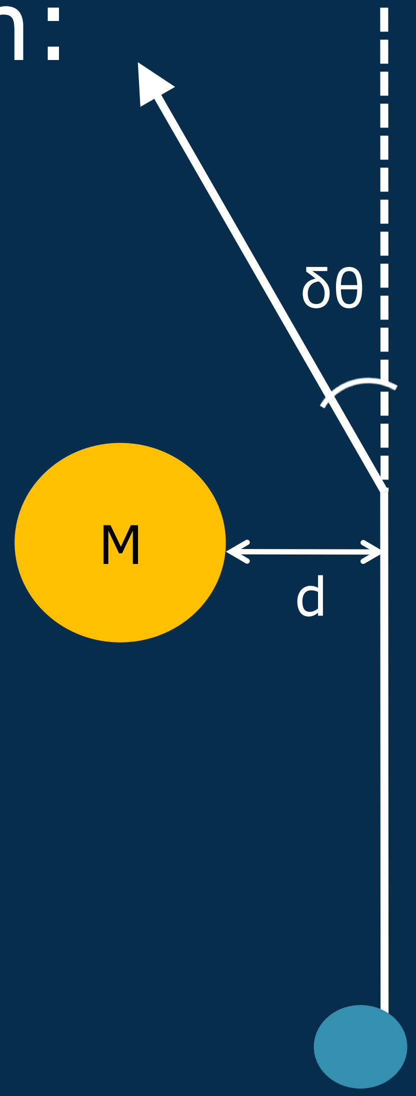
Solar system constraints

Light deflection due to the Sun:

$$\delta\theta = \frac{1}{2}(1+\gamma)\frac{4M}{d}$$



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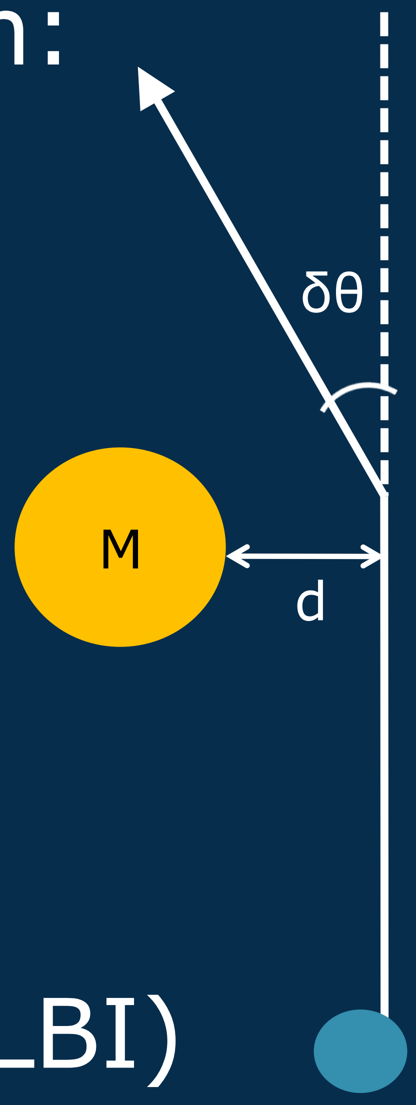
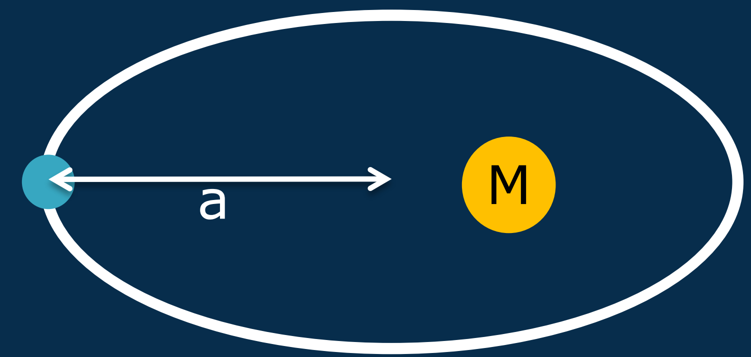


➡ $\gamma - 1 = (-1.7 \pm 4.5) \times 10^{-4}$ (VLBI)

Solar system constraints

Perihelion precession of Mercury:



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$$\Delta\phi = \frac{2\pi M}{a(1-e^2)}(2+2\gamma-\beta)+\ldots$$

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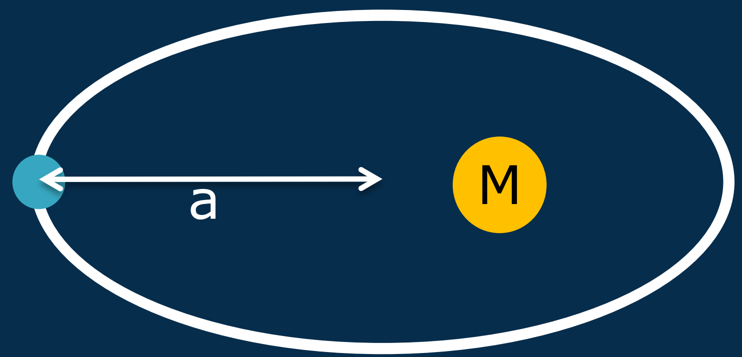

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→ $|2\gamma-\beta-1|<3\times10^{-3}$ (Shapiro, 1990)

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If not → **modified gravity**

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Weak lensing data → Constrain PPN parameters

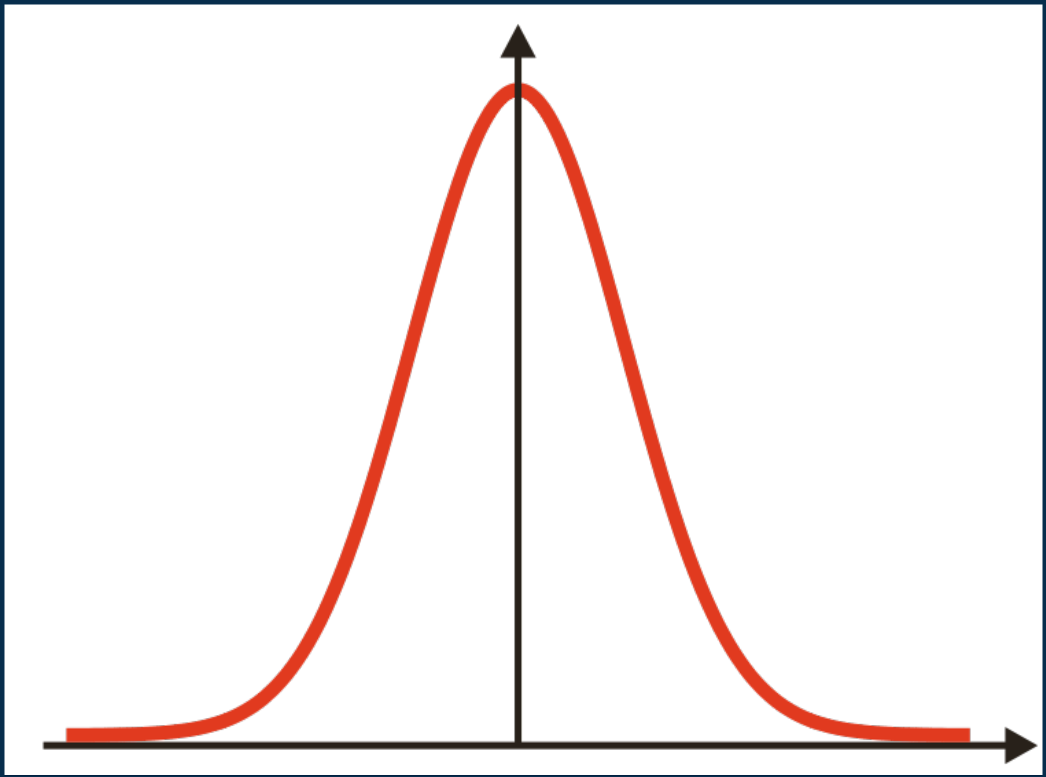
Weak lensing observables in modified gravity

Through the SURP program, we are working with Prof. Robert Caldwell at Dartmouth to compute:

- Light bending and image distortions
- Weak lensing power spectrum
- Higher-order statistics, such as the bispectrum

Example: Apparent non-Gaussianity

If density fluctuations are very small, they can be approximated as a random field with a Gaussian distribution:



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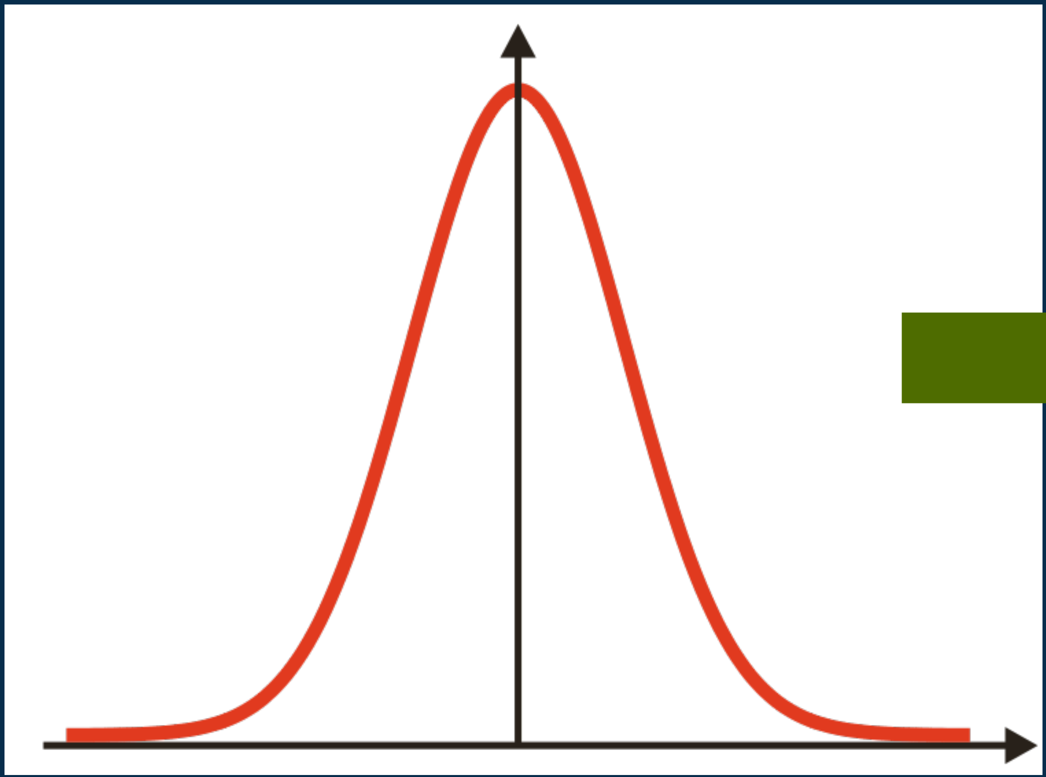

Weak lensing distortions will also be random

The search for non-Gaussianity

Ways for these distributions to the non-Gaussian:

- Exotic new physics

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→ Modified gravity theories have different levels of nonlinearity via the PPN parameter β

Non-Gaussianity from modified gravity

Gaussian distributions have zero skewness

$$S_3 \equiv \frac{\langle \kappa^3 \rangle}{\langle \kappa^2 \rangle^{3/2}}$$

= a measure of asymmetry of the distribution

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Measure the weak lensing skewness → Constrain β

Non-Gaussianity from modified gravity

Gaussian distr

skewness

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Get one step closer to finding the cause of cosmic acceleration

the distributi

Measure the weak lensing skewness → Constrain β ↑

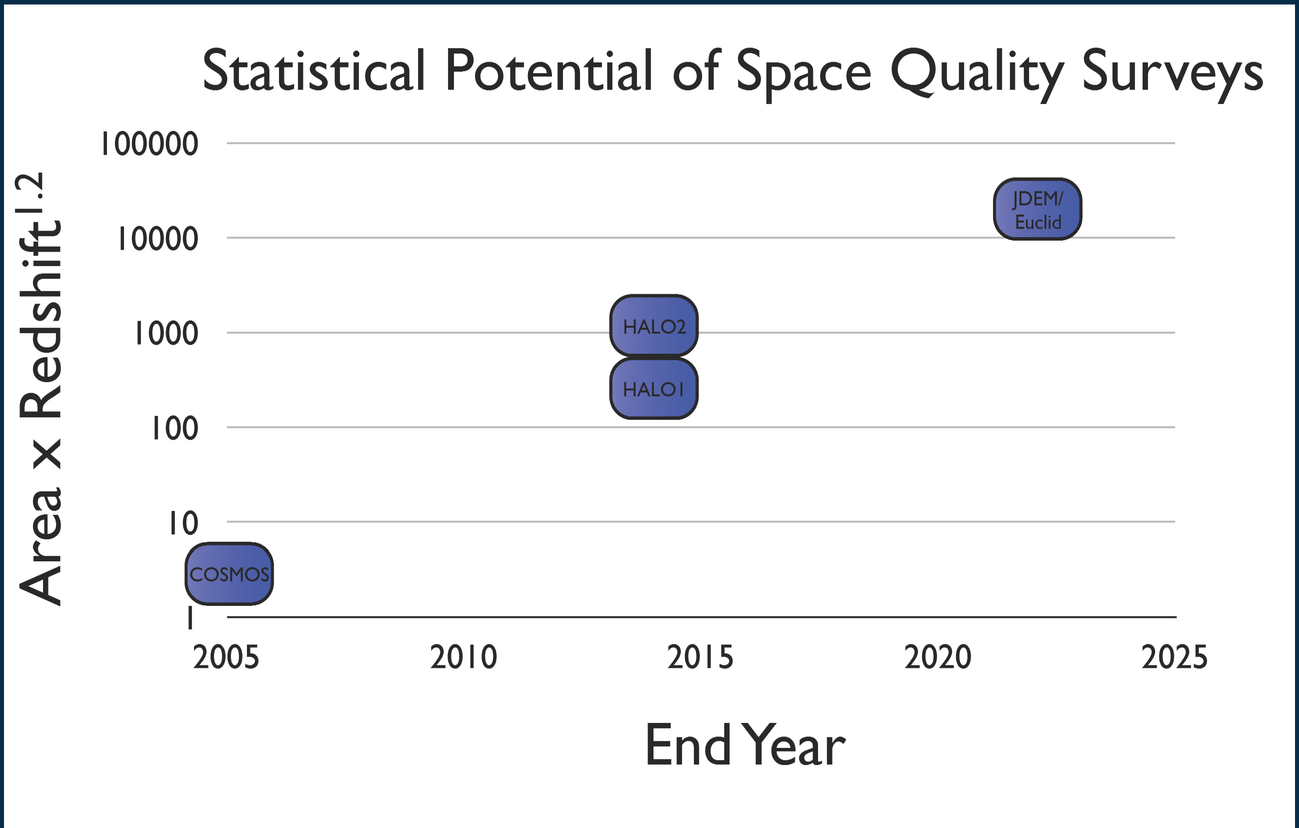
Another big question: How do we obtain these weak lensing observations?

The High Altitude Lensing Observatory

PI: Jason Rhodes

Jeff Booth (JPL), Kurt Liewer (JPL), Michael Seiffert (JPL),Wesley Traub (JPL), Richard Key (JPL), Adam Amara (ETH Zurich), Richard Ellis (Caltech), Richard Massey (University of Edinburgh), Satoshi Miyazaki (NOAJ Japan), Harry Teplitz (Spitzer Science Center, Caltech), Calvin Barth Netterfield (University of Toronto), Alexandre Refregier (CEA Saclay, Paris), Roger Smith (Caltech)

Space quality weak lensing past and future



Past: COSMOS survey

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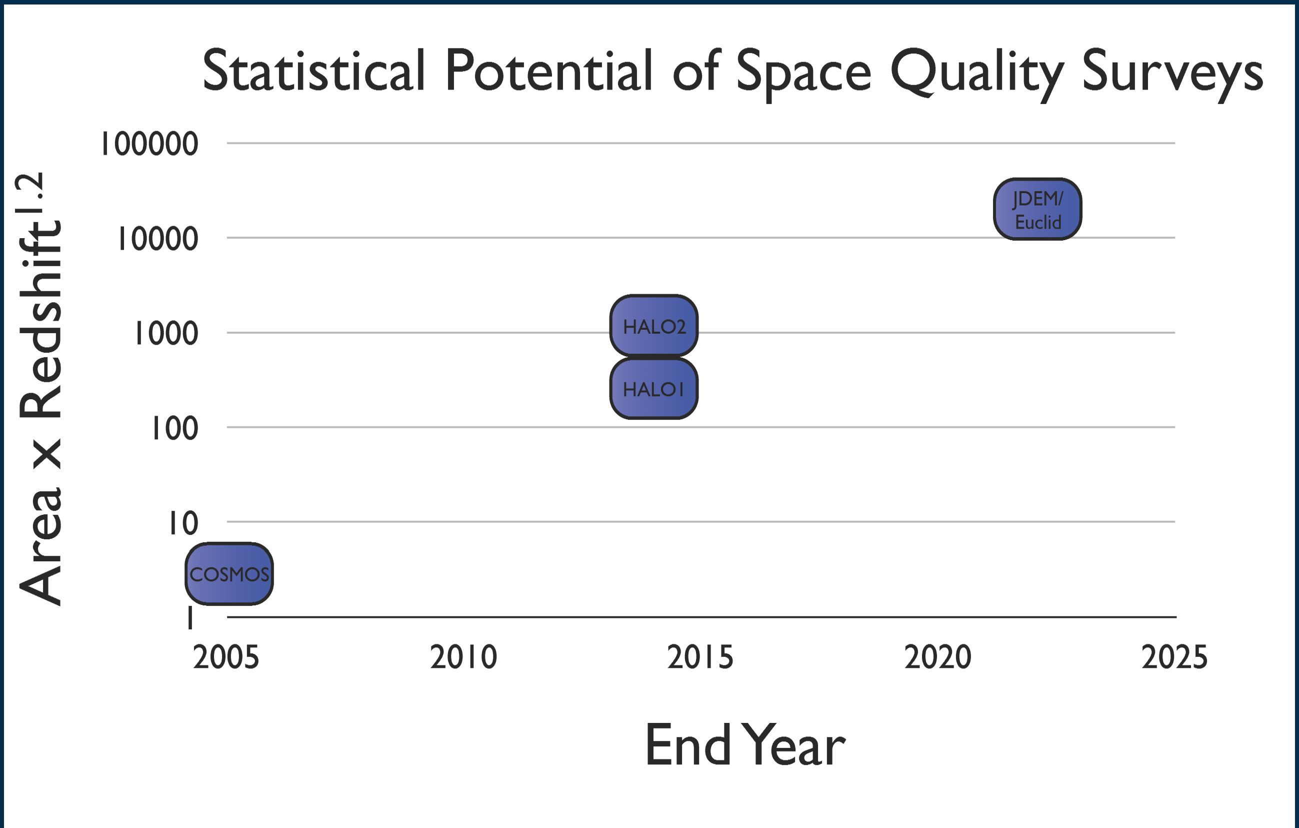

Past: COSMOS survey

Future: the Joint Dark Energy Mission (JDEM) and ESA's Euclid

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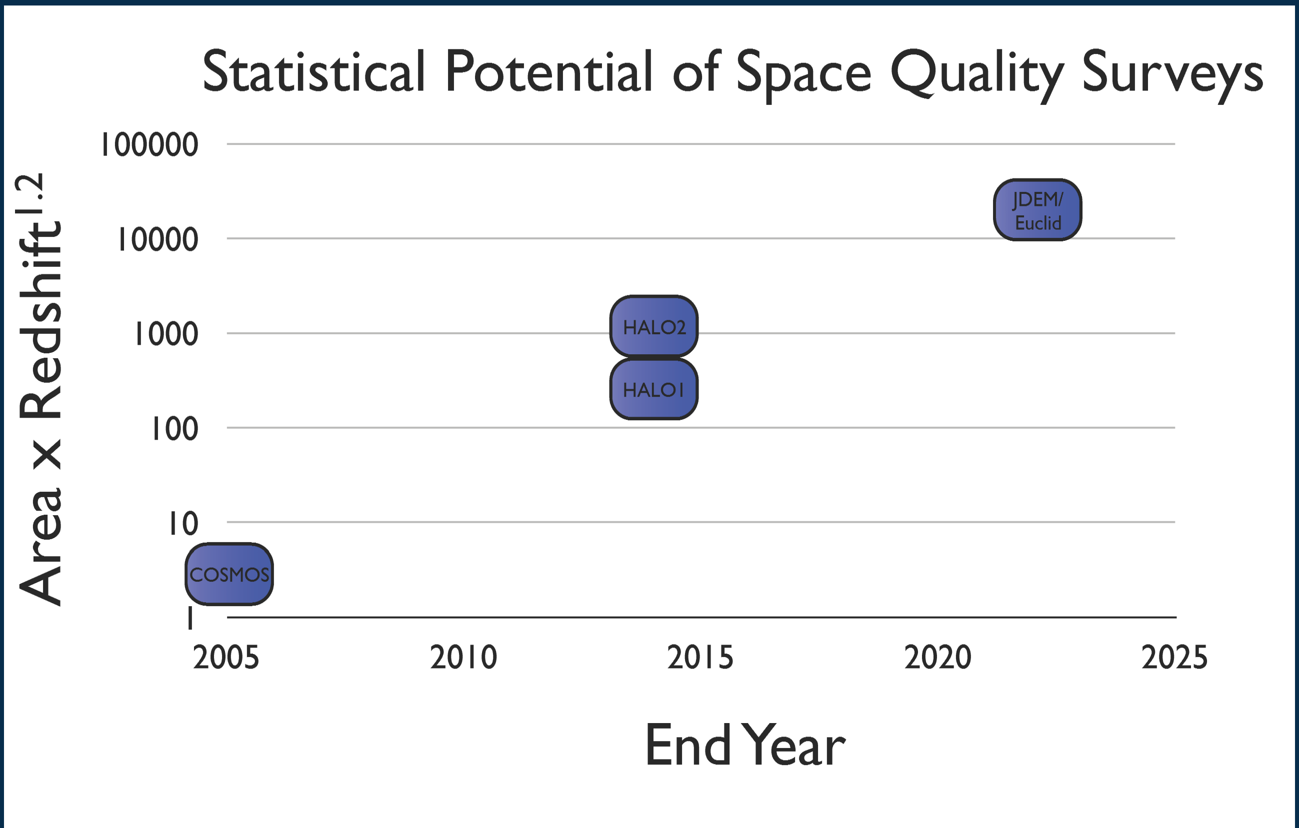

Past: COSMOS survey

Future: the Joint Dark Energy Mission (JDEM) and ESA's Euclid

Now: the balloon-based High Altitude Lensing Observatory (HALO) fills the gap

Why do weak lensing, and why from a balloon?

The Dark Energy Task Force (Albrecht et al. 2006)

Weak lensing is the best method for constraining dark energy and modified gravity, provided numerous systematic effects can be overcome

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But JDEM and Euclid are at least a decade away

Why do weak lensing, and why from a balloon?

The Dark Energy Task Force (Albrecht et al. 2006)

Weak lensing is the best method for constraining dark energy and modified gravity, provided numerous systematic effects can be overcome

Ground-based surveys are fundamentally limited by systematics

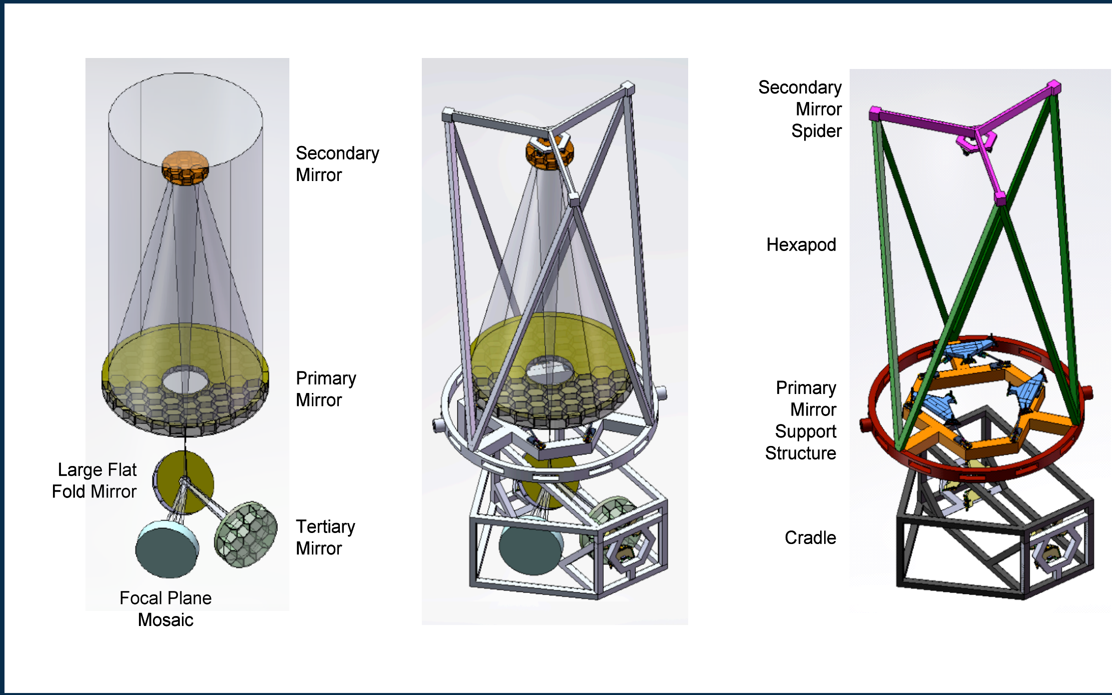
→ Need to get above the atmosphere

But JDEM and Euclid are at least a decade away

→ Use a balloon!

HALO

- 15-20 day flight Australia to Australia (can stop in South America if needed)
- 1.2m lightweight primary mirror
- 48 2k×4k Hamamatsu CCDs
- Single wide optical filter
- Solar panel to recharge batteries



- Need to pick up the disk drives (2 Tb) afterwards to do the science

Survey strategy

- 500-720 nm filter
- 1500 second integration time
- 13 square degrees per night
- 15-20 galaxies per square arcminute
- Redshifts from the ground

Science reach

Understand dark matter:

- Amount and distribution
- Weak and strong lensing

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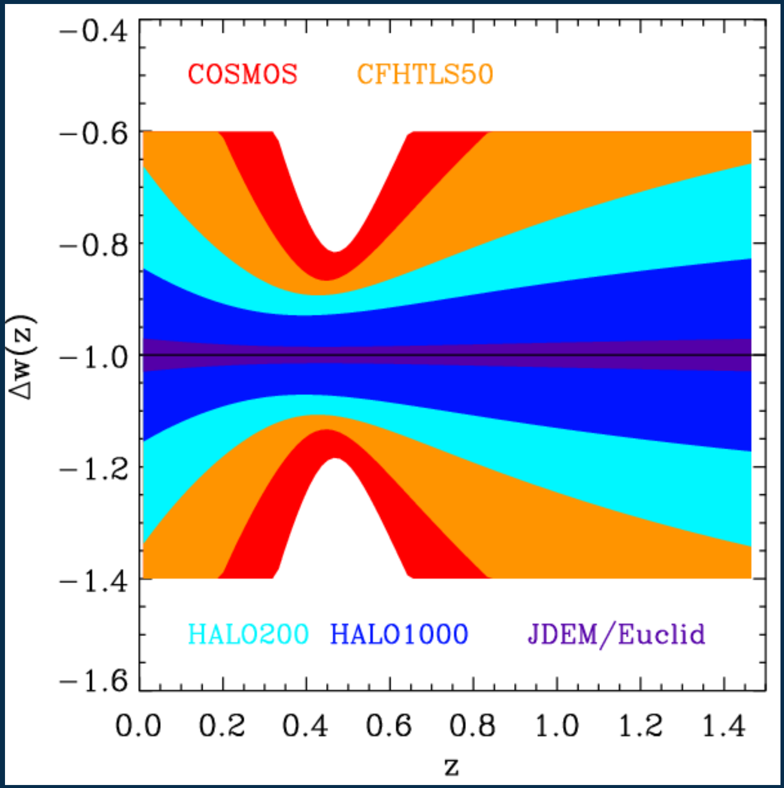
- Examine expansion history
- Growth of structure



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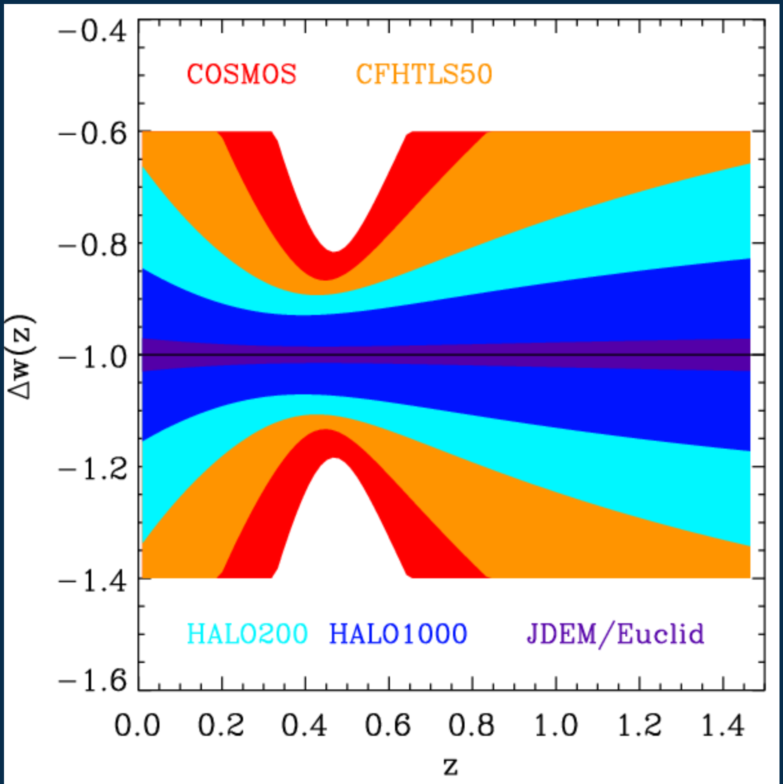

Ancillary science:

- Galaxy morphology and evolution
- Stellar counts
- Surface brightness fluctuations

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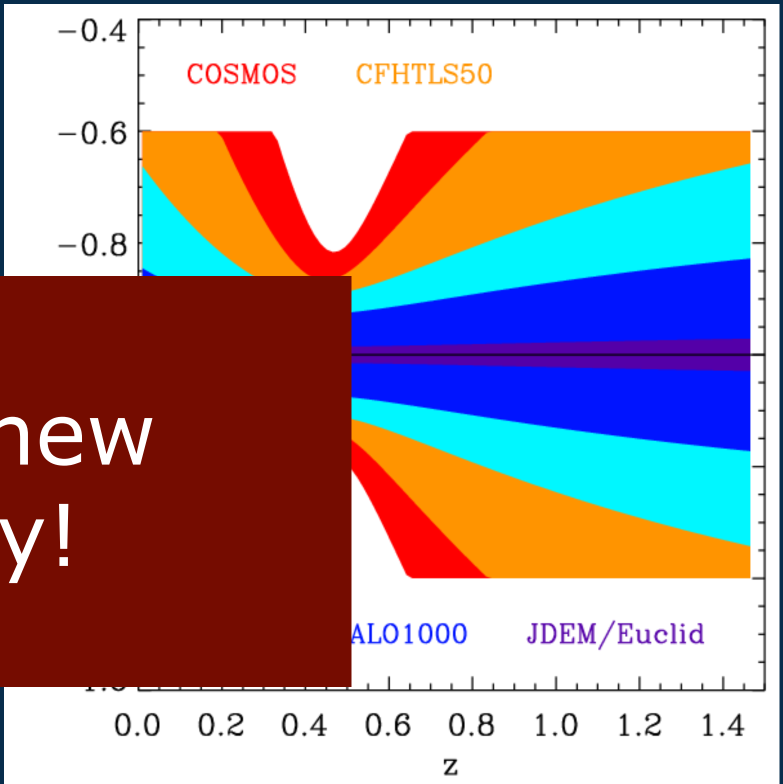

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An exciting new opportunity!

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Conclusions

- Modifications of GR on cosmological scales could explain cosmic acceleration
- Weak lensing is an excellent probe of modified gravity
- The High Altitude Lensing Observatory (HALO) will produce the high-quality weak lensing data needed to carry this out in the near term