Gravitational Lensing - How to make dark matter visible

and what we learn about cosmology with this tool

Hendrik Hildebrandt, Ruhr University Bochum
“Crossing the Desert”, 15th October 2021

RUB

erc

European Research Council

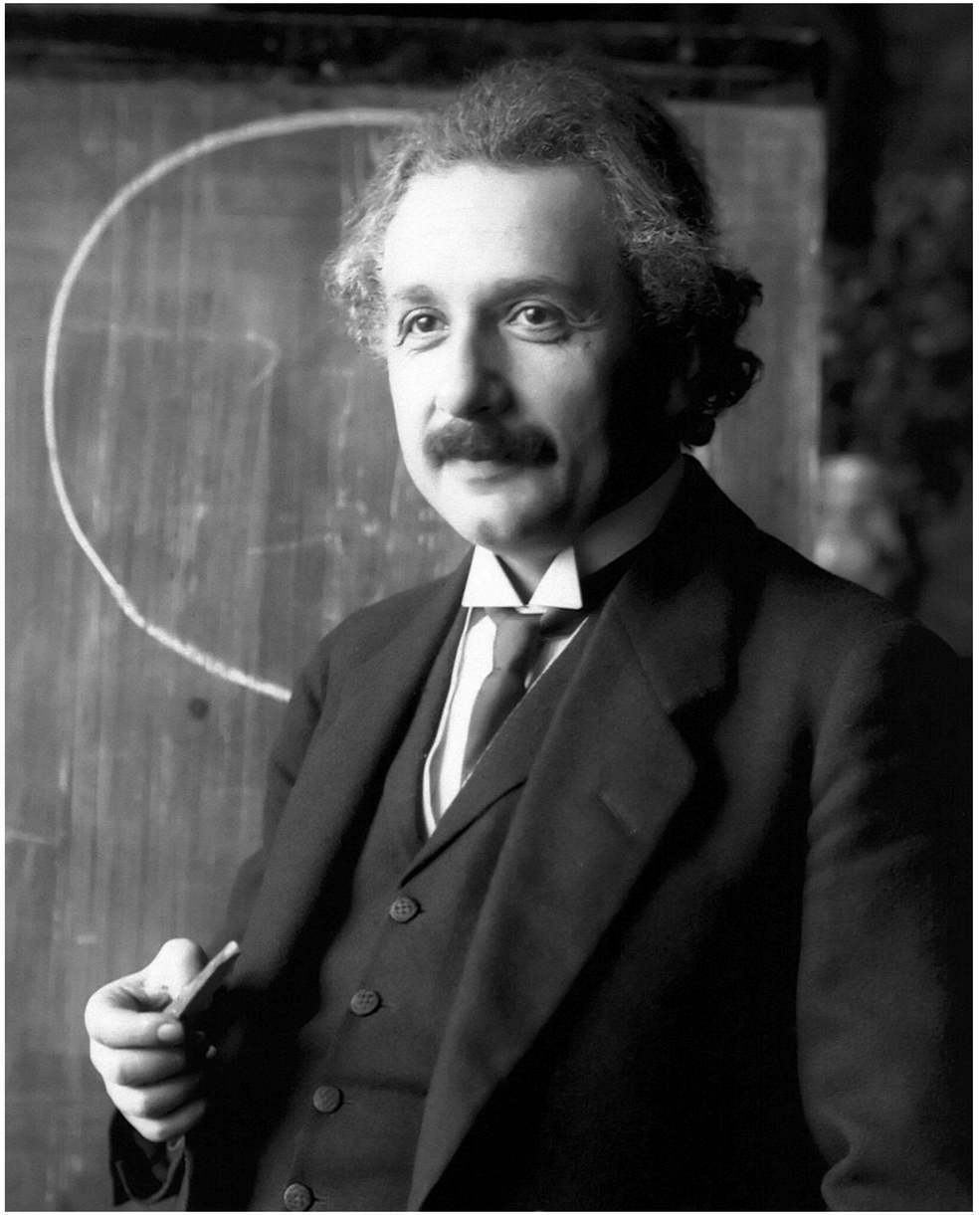
Established by the European Commission

GCCL

GERMAN CENTRE FOR COSMOLOGICAL LENSING

Heisenberg-Programm

DFG Deutsche Forschungsgemeinschaft



1916. № 7.

ANNALEN DER PHYSIK.

VIERTE FOLGE. BAND 49.

1. *Die Grundlage der allgemeinen Relativitätstheorie;* *von A. Einstein.*

Die im nachfolgenden dargelegte Theorie bildet die denkbar weitgehendste Verallgemeinerung der heute allgemein als „Relativitätstheorie" bezeichneten Theorie; die letztere nenne ich im folgenden zur Unterscheidung von der ersteren „spezielle Relativitätstheorie" und setze sie als bekannt voraus. Die Verallgemeinerung der Relativitätstheorie wurde sehr erleichtert durch die Gestalt, welche der speziellen Relativitätstheorie durch Minkowski gegeben wurde, welcher Mathematiker zuerst die formale Gleichwertigkeit der räumlichen Koordinaten und der Zeitkoordinate klar erkannte und für den Aufbau der Theorie nutzbar machte. Die für die allgemeine Relativitätstheorie nötigen mathematischen Hilfsmittel lagen fertig bereit in dem „absoluten Differentialkalkül", welcher auf den Forschungen von Gauss, Riemann und Christoffel über nichteuklidische Mannigfaltigkeiten ruht und von Ricci und Levi-Civita in ein System gebracht und bereits auf Probleme der theoretischen Physik angewendet wurde. Ich habe im Abschnitt B der vorliegenden Abhandlung alle für uns nötigen, bei dem Physiker nicht als bekannt vorauszusetzenden mathematischen Hilfsmittel in möglichst einfacher und durchsichtiger Weise entwickelt, so daß ein Studium mathematischer Literatur für das Verständnis der vorliegenden Abhandlung nicht erforderlich ist. Endlich sei an dieser Stelle dankbar meines Freundes, des Mathematikers Grossmann, gedacht, der mir durch seine Hilfe nicht nur das Studium der einschlägigen mathematischen Literatur ersparte, sondern mich auch beim Suchen nach den Feldgleichungen der Gravitation unterstützte.

$$G_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

+ Robertson-Walker metric

=> evolving Universe (FLRW)

$$G_{\mu\nu} + \Lambda g_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

$$v = H_0 D$$

$$H_0 \approx 70 \frac{\text{km}}{\text{s Mpc}}$$

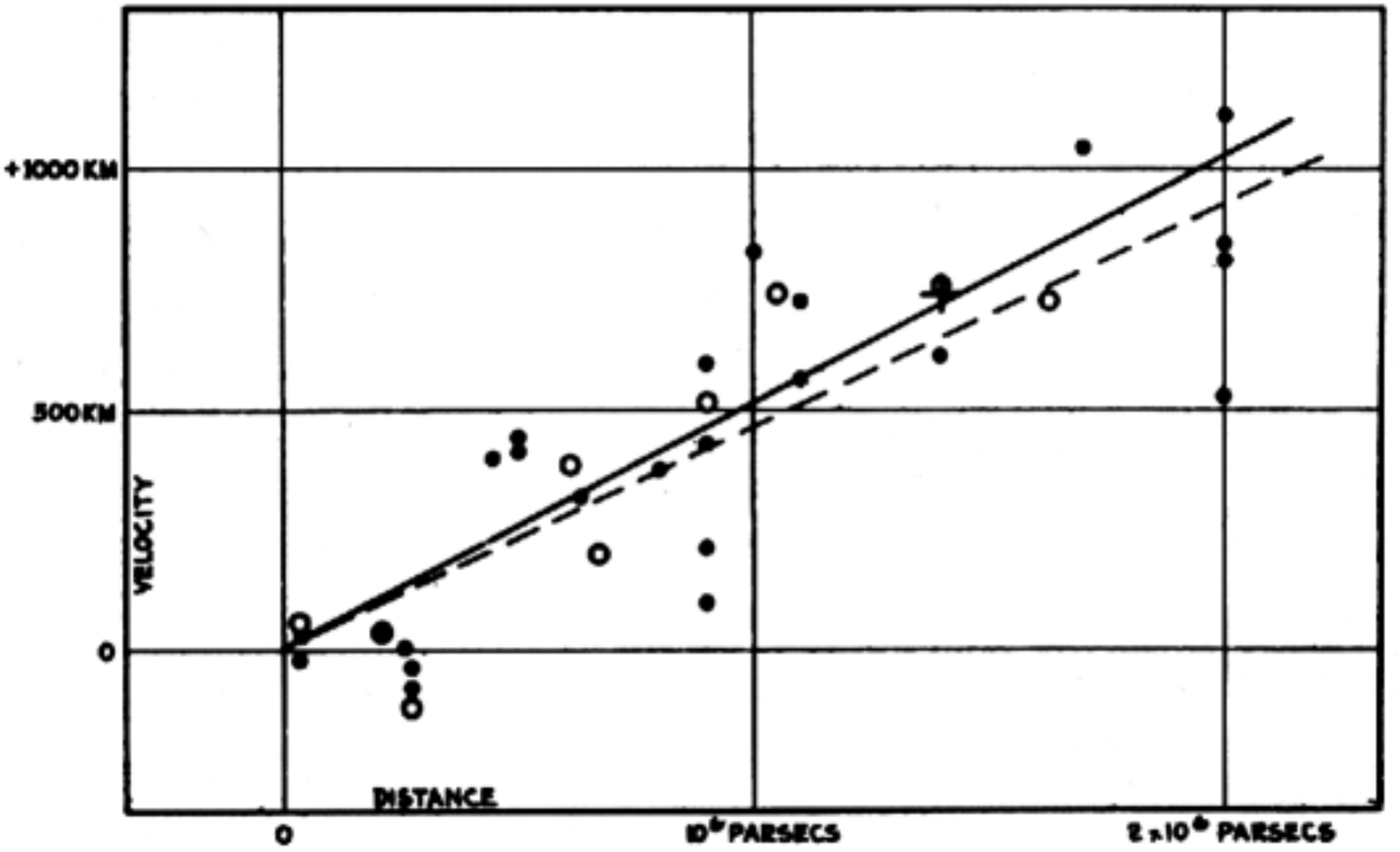


FIGURE 1

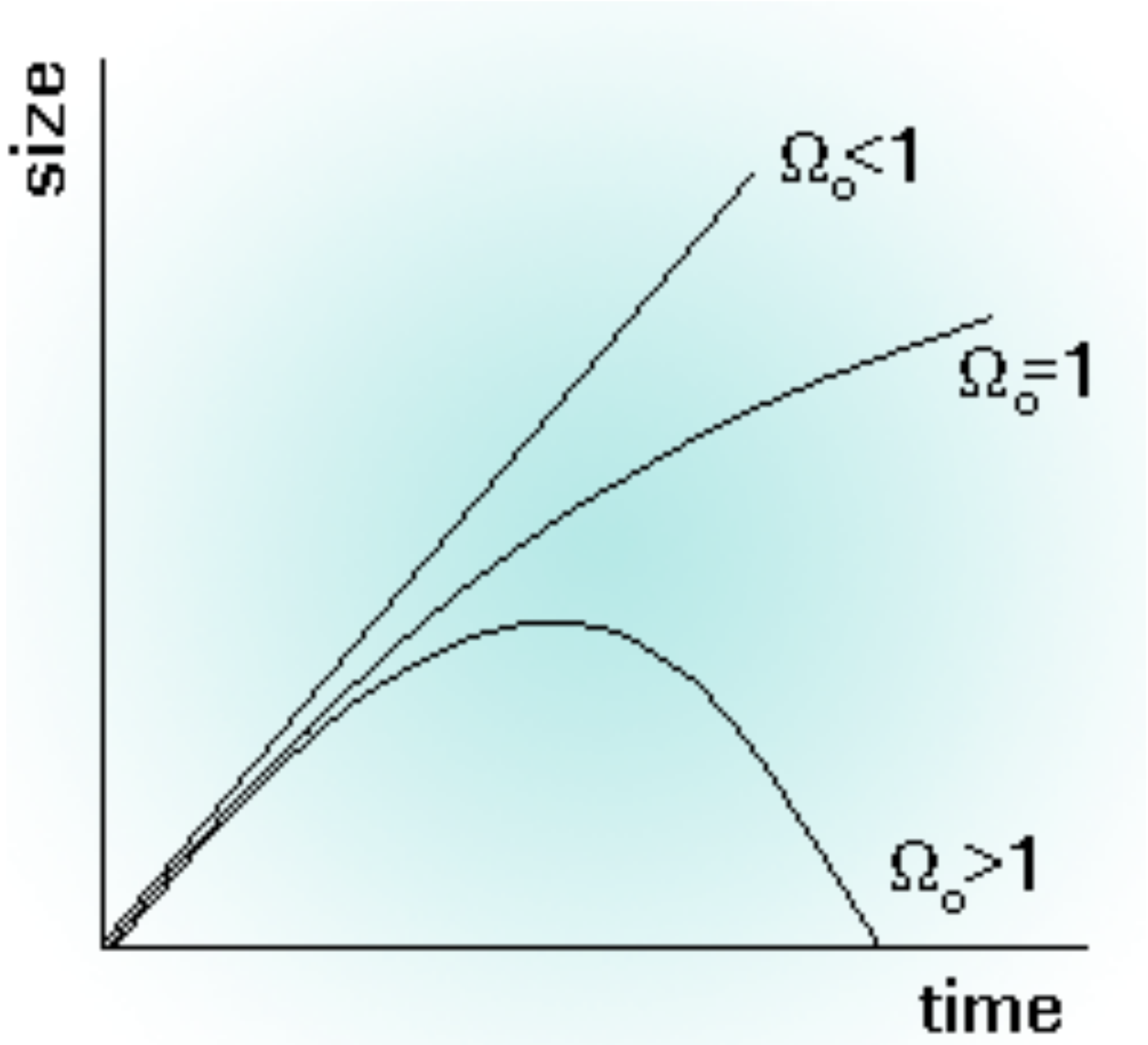
Velocity-Distance Relation among Extra-Galactic Nebulae.

Cosmological redshift z

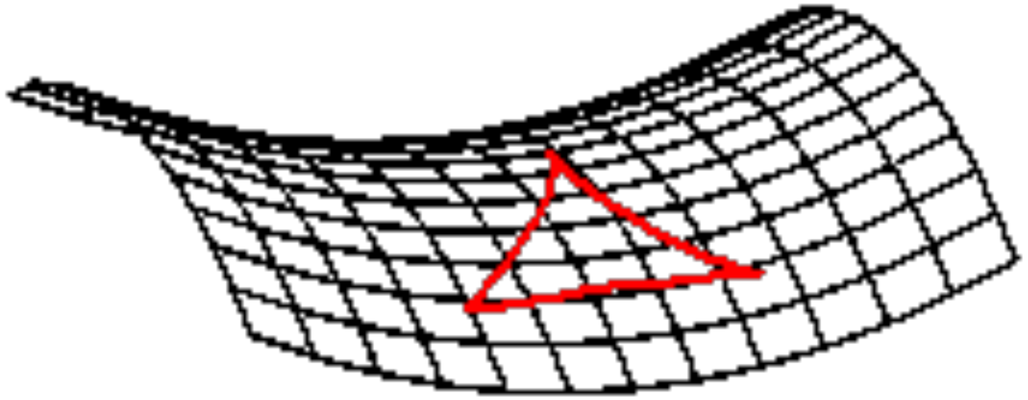
$$\frac{\lambda_{\mathrm{obs}}}{\lambda_{\mathrm{em}}} = (1+z) = \frac{1}{a}$$

Expansion depends on contents

- Normal matter
- Electromagnetic radiation (only important in the early universe)

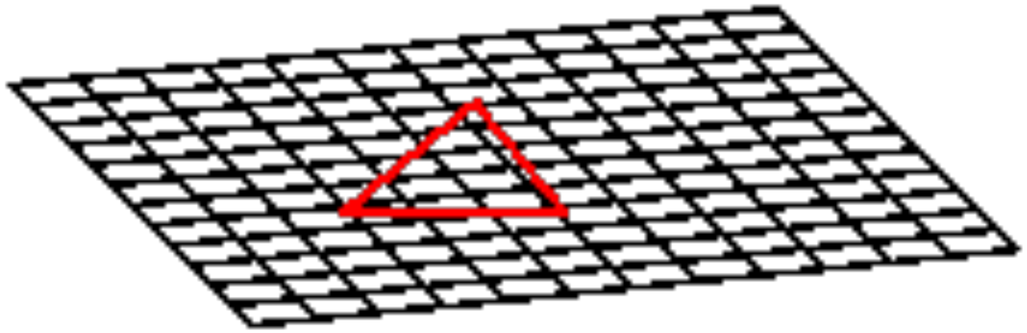


$\Omega_0 = 1$
critical density
~ 10 atoms per m^3

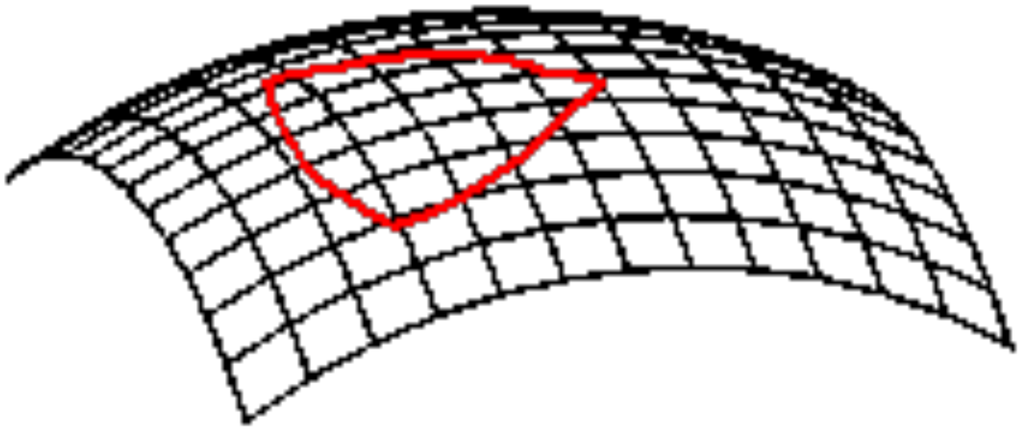


Open universe :
looks like a
horse saddle

$\Omega_0<1$



Flat universe $\Omega_0=1$



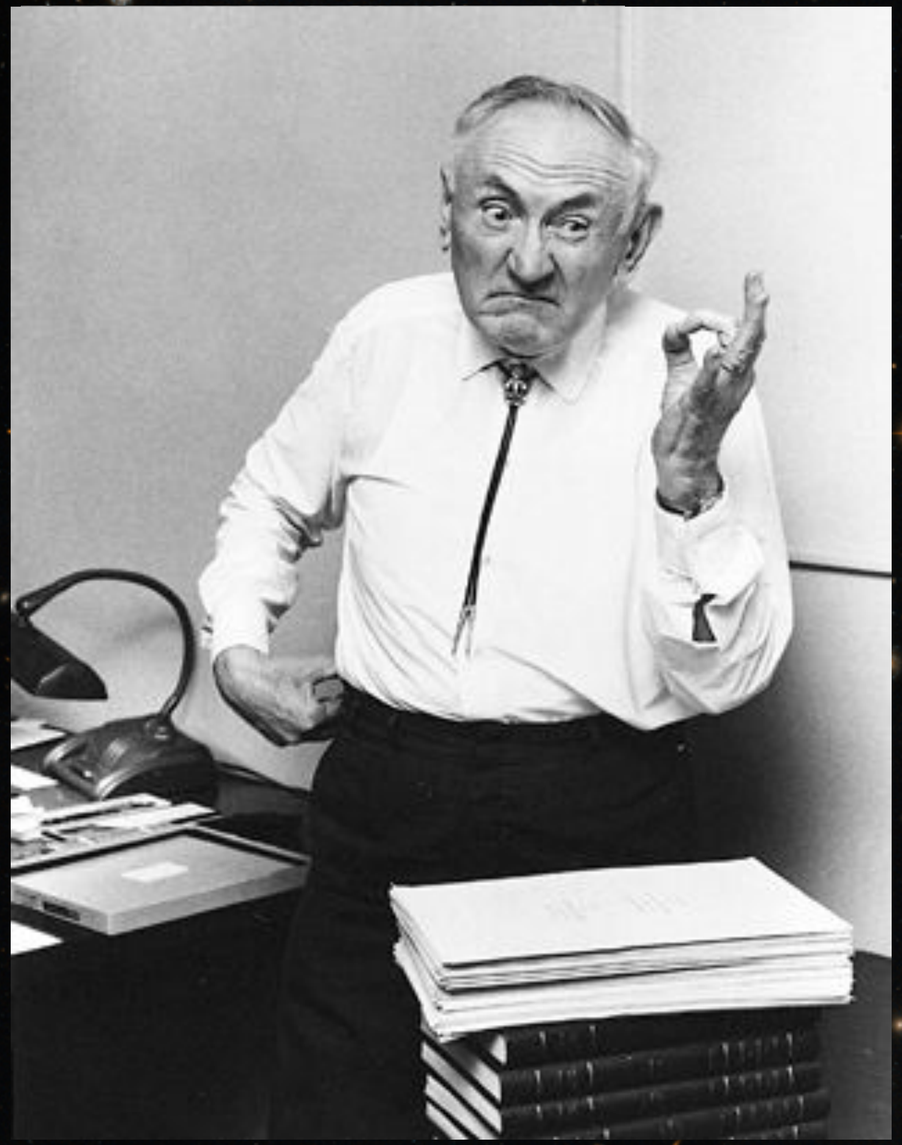
Closed universe :
looks like the
surface of a sphere

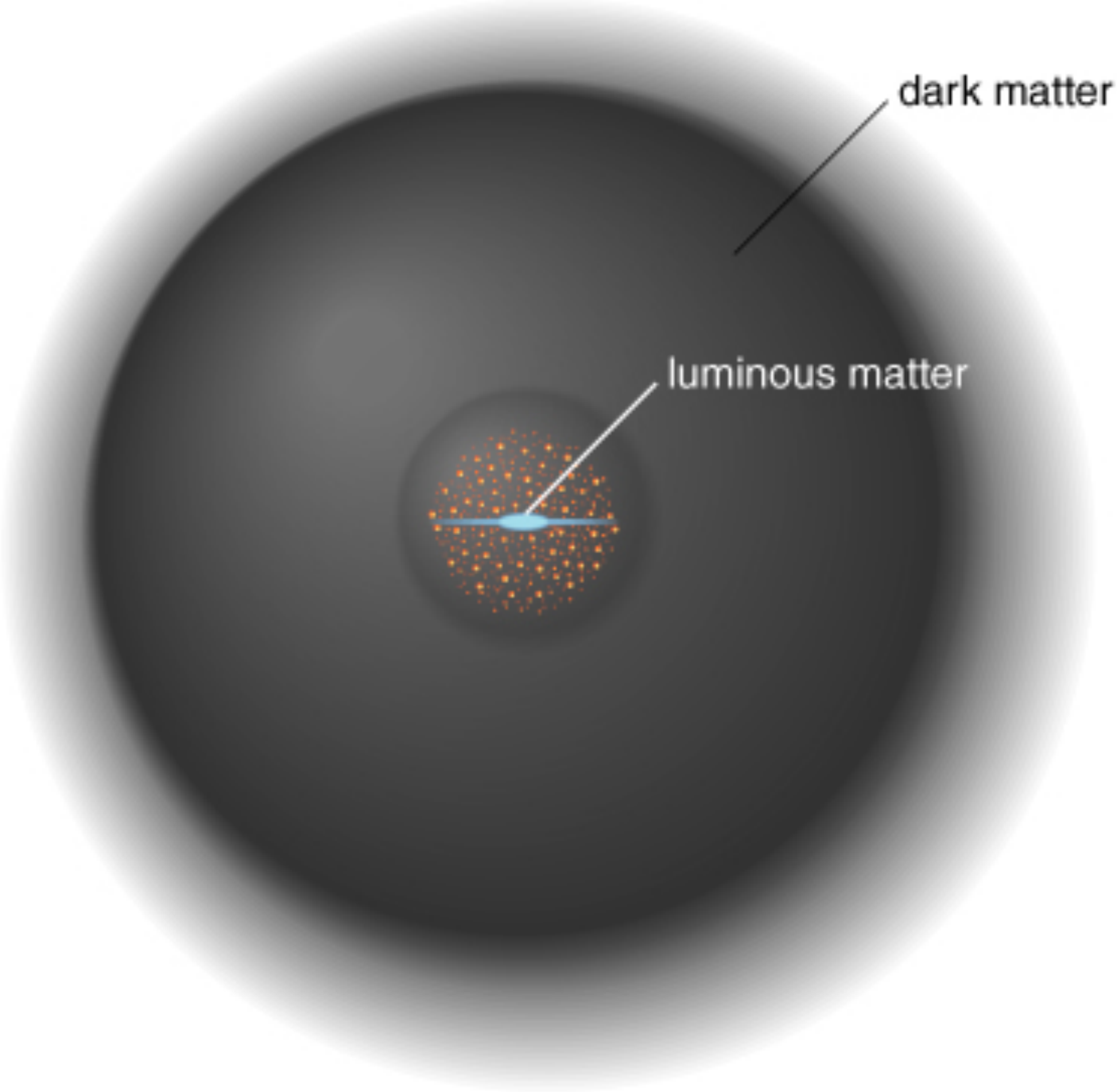
$\Omega_0>1$

Normal (baryonic) matter

$$\Omega_b = 0.05$$

Open Universe?




dark matter
luminous matter

Expansion depends on contents

- Normal matter
- Electromagnetic radiation
- Dark matter

Dark Matter

$$\Omega_{dm} = 0.25$$

Dark Matter

- Collisionless
- Dissipationless
- Cold
- Just weak interaction and gravity
- WIMPs? Axions? Sterile Neutrinos? Primordial black holes?

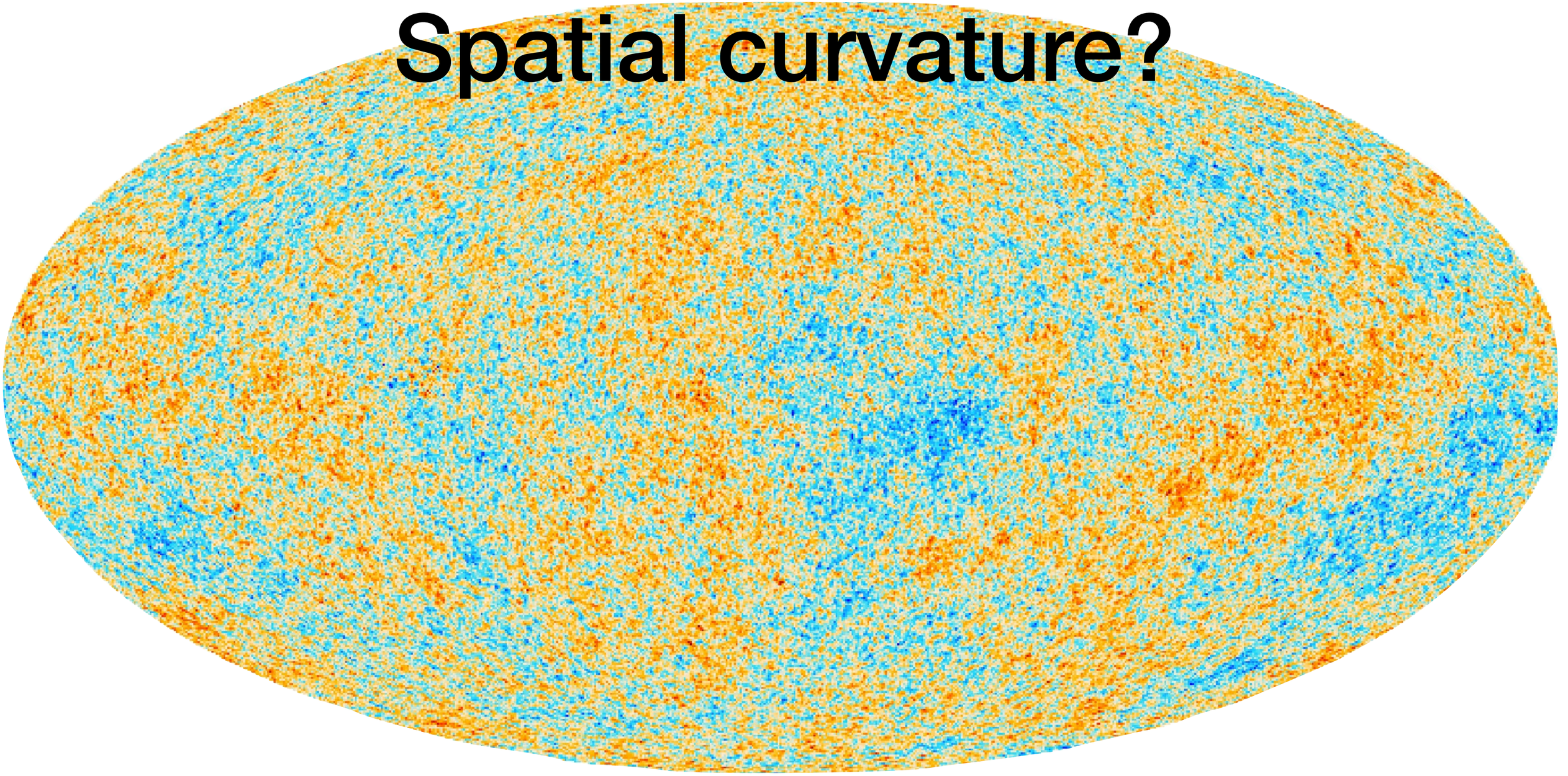
- Alternative: Modification of general relativity

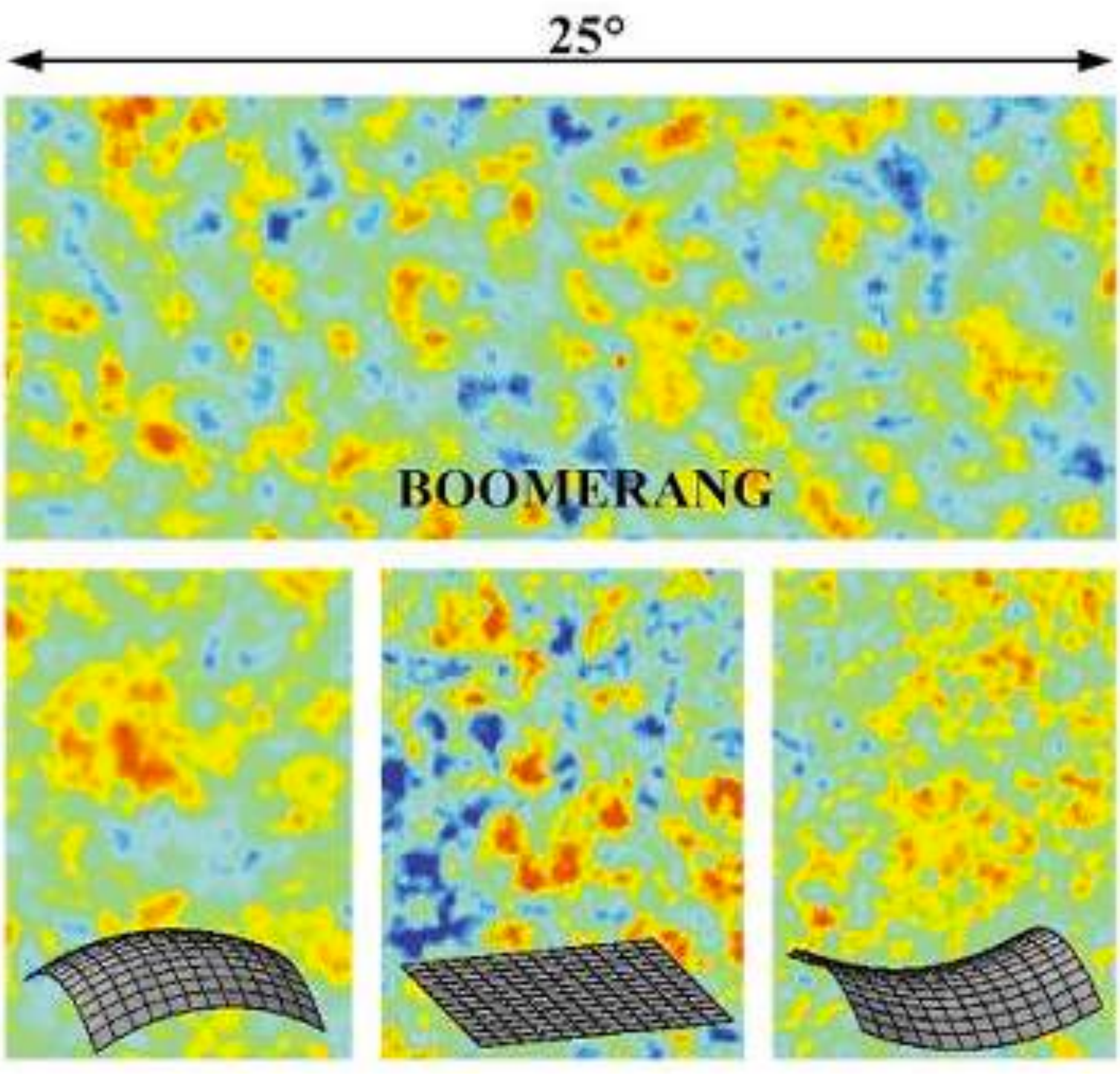
Total matter density

$$\Omega_m = \Omega_b + \Omega_{dm} = 0.3$$

Open Universe?

Spatial curvature?




25°
BOOMERANG

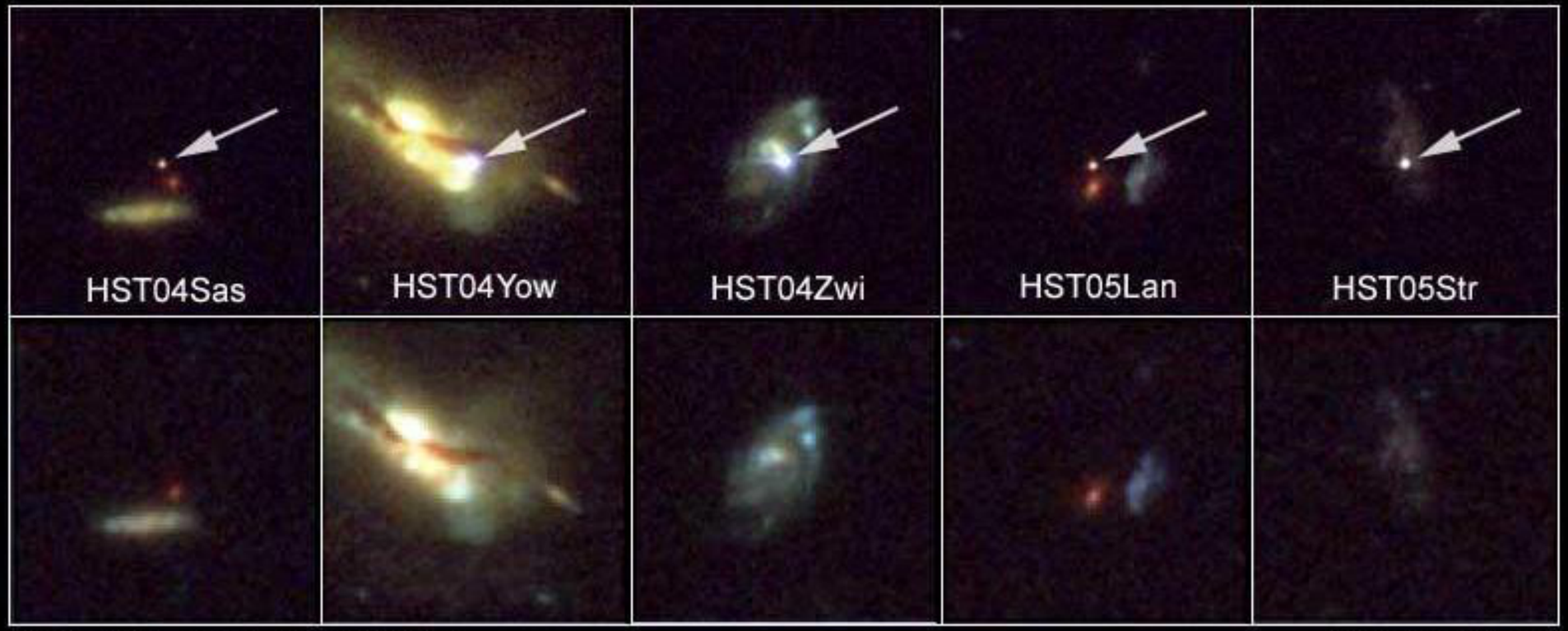
$$\Omega_0 = 1 \text{ +/- } 0.01$$

Expansion depends on contents

- Normal matter
- Electromagnetic radiation
- Dark matter
- …

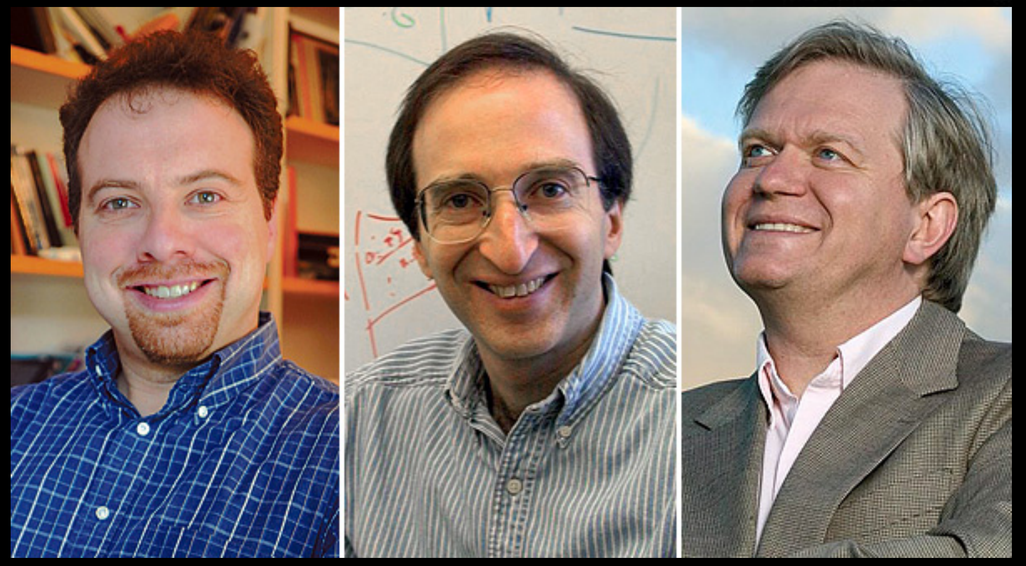
Host Galaxies of Distant Supernovae

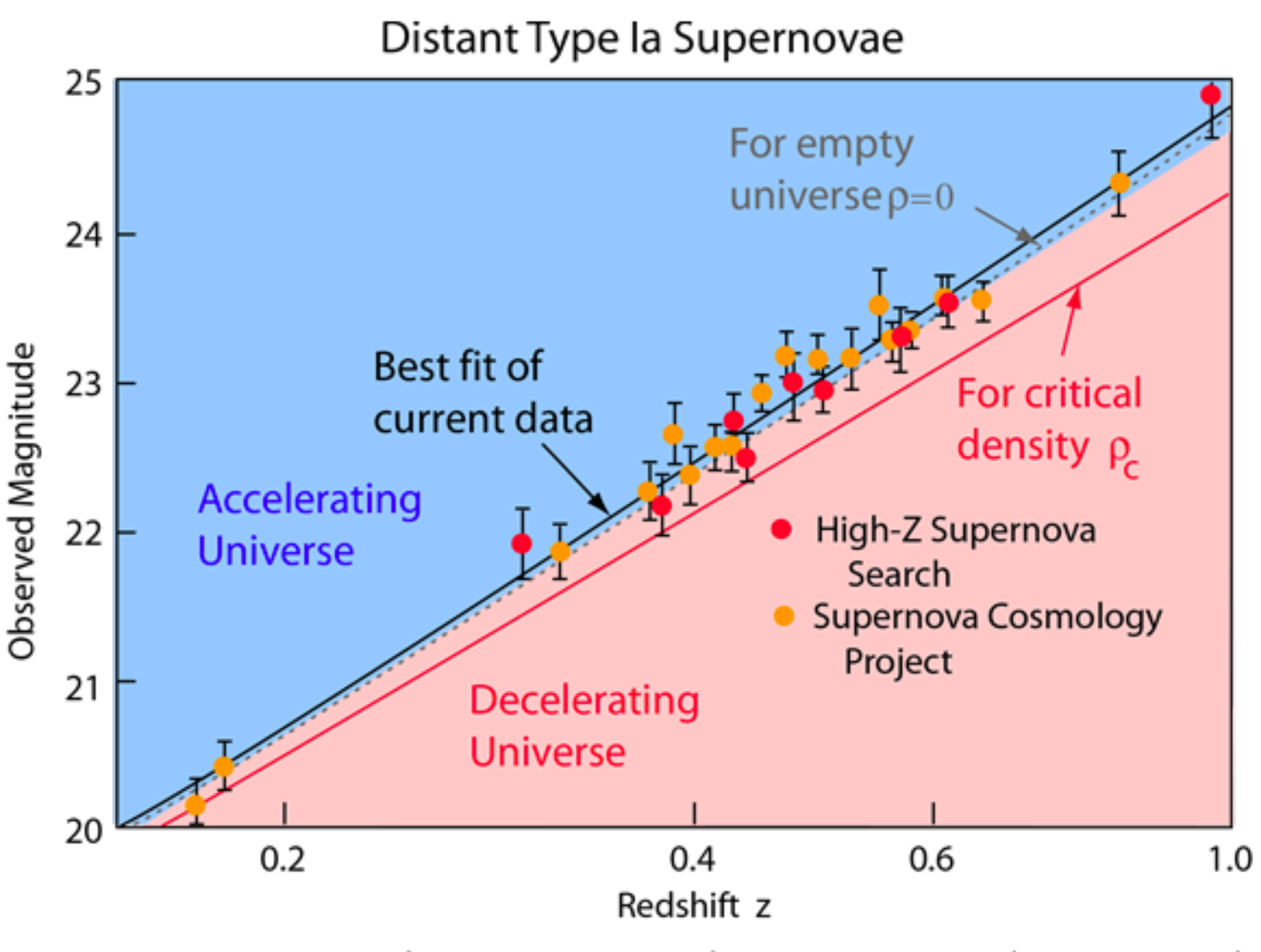
HST ▪ ACS/WFC

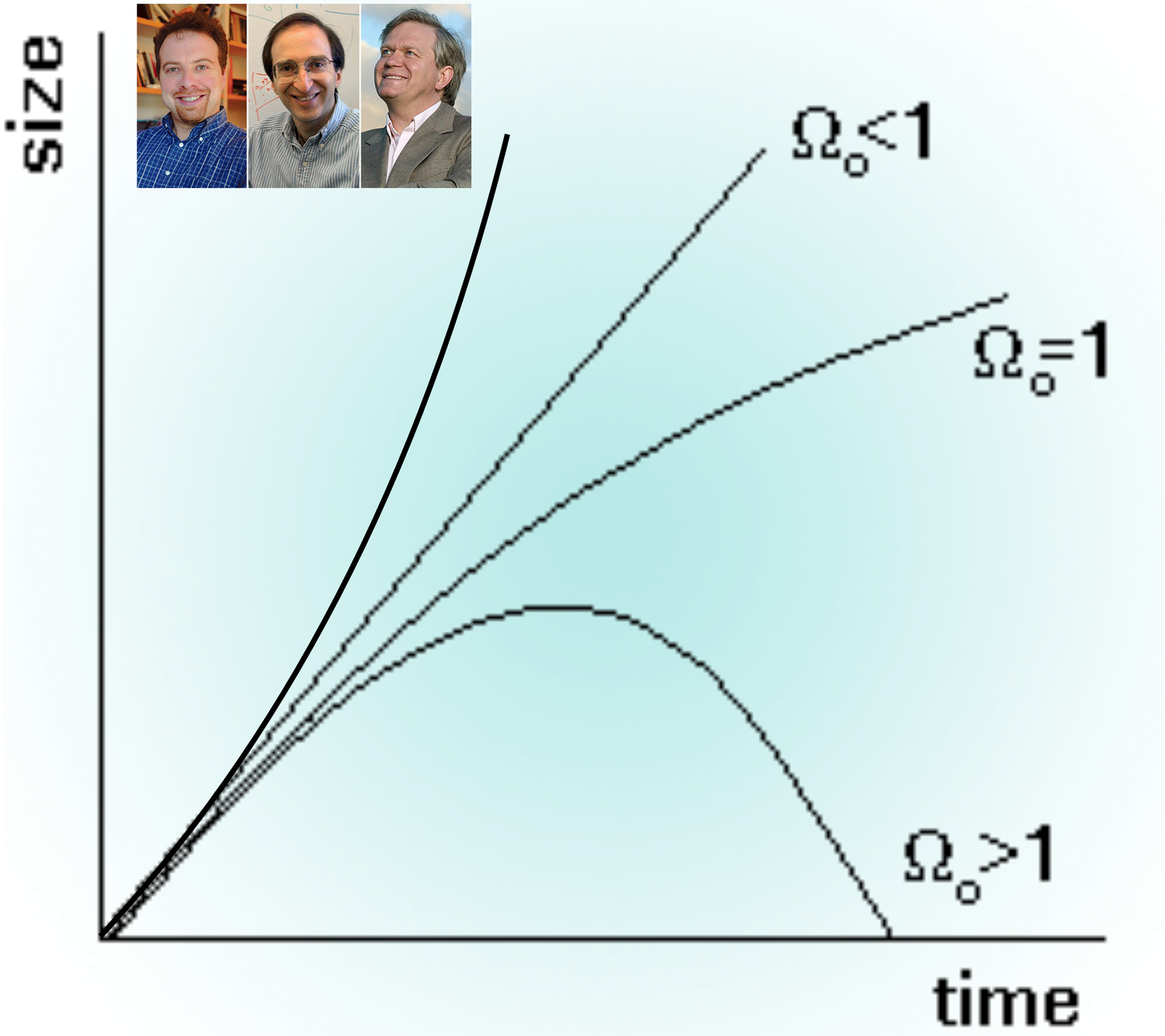


NASA, ESA, and A. Riess (STScI)

STScI-PRC06-52




Distant Type Ia Supernovae
Observed Magnitude
25
24
23
22
21
20
0.2
0.4
0.6
1.0
Redshift z
For empty universe ρ=0
Best fit of current data
For critical density ρc
Accelerating Universe
Decelerating Universe
High-Z Supernova Search
Supernova Cosmology Project


size
Ω_o<1
Ω_o=1
Ω_o>1
time

Expansion depends on contents

- Normal matter
- Electromagnetic radiation
- Dark matter
- Cosmological constant / dark energy

Energy density of dark energy

$$\Omega_{de} = 0.7$$

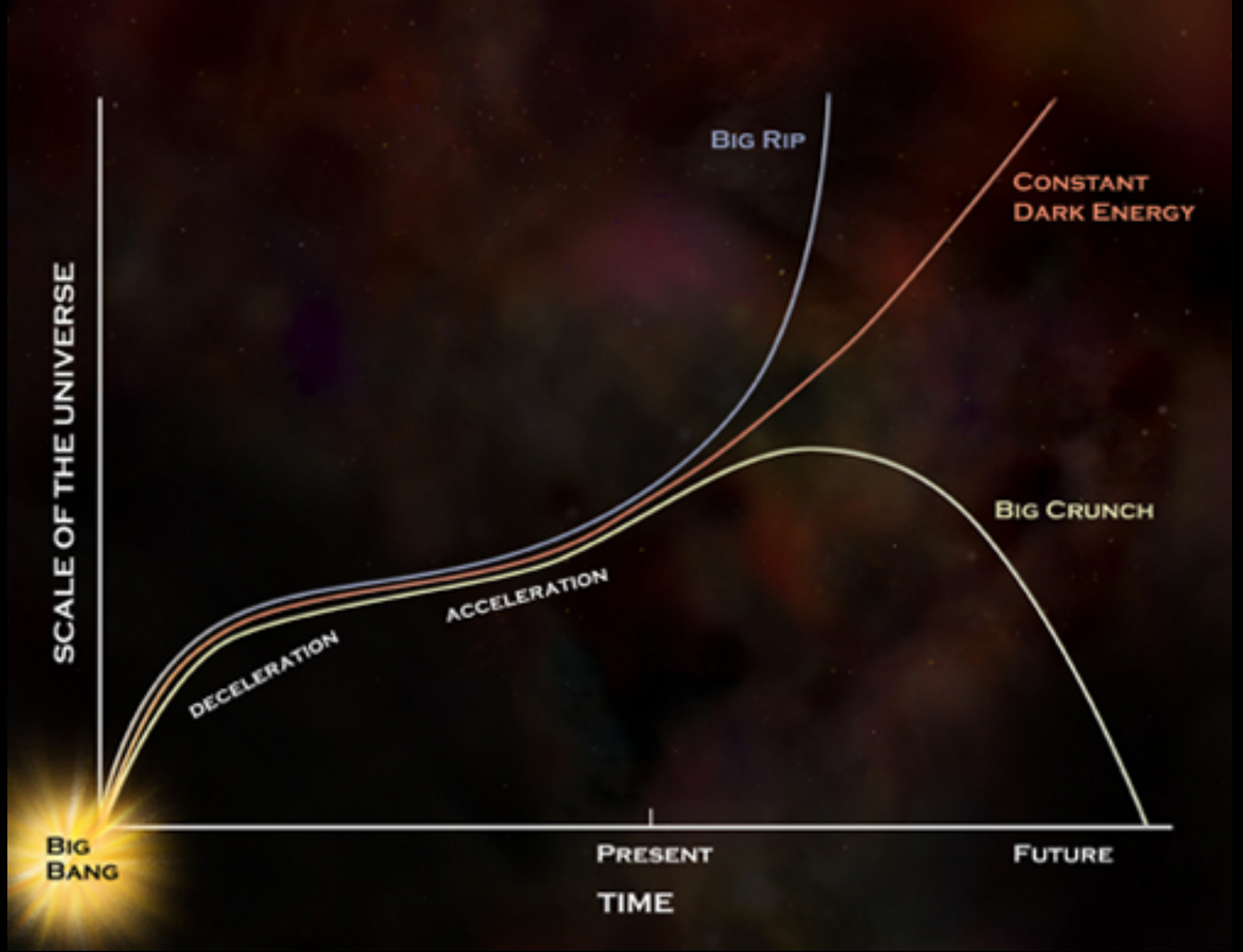
$$\Omega_0 = \Omega_m + \Omega_{de} = 1$$

Cosmological Constant?

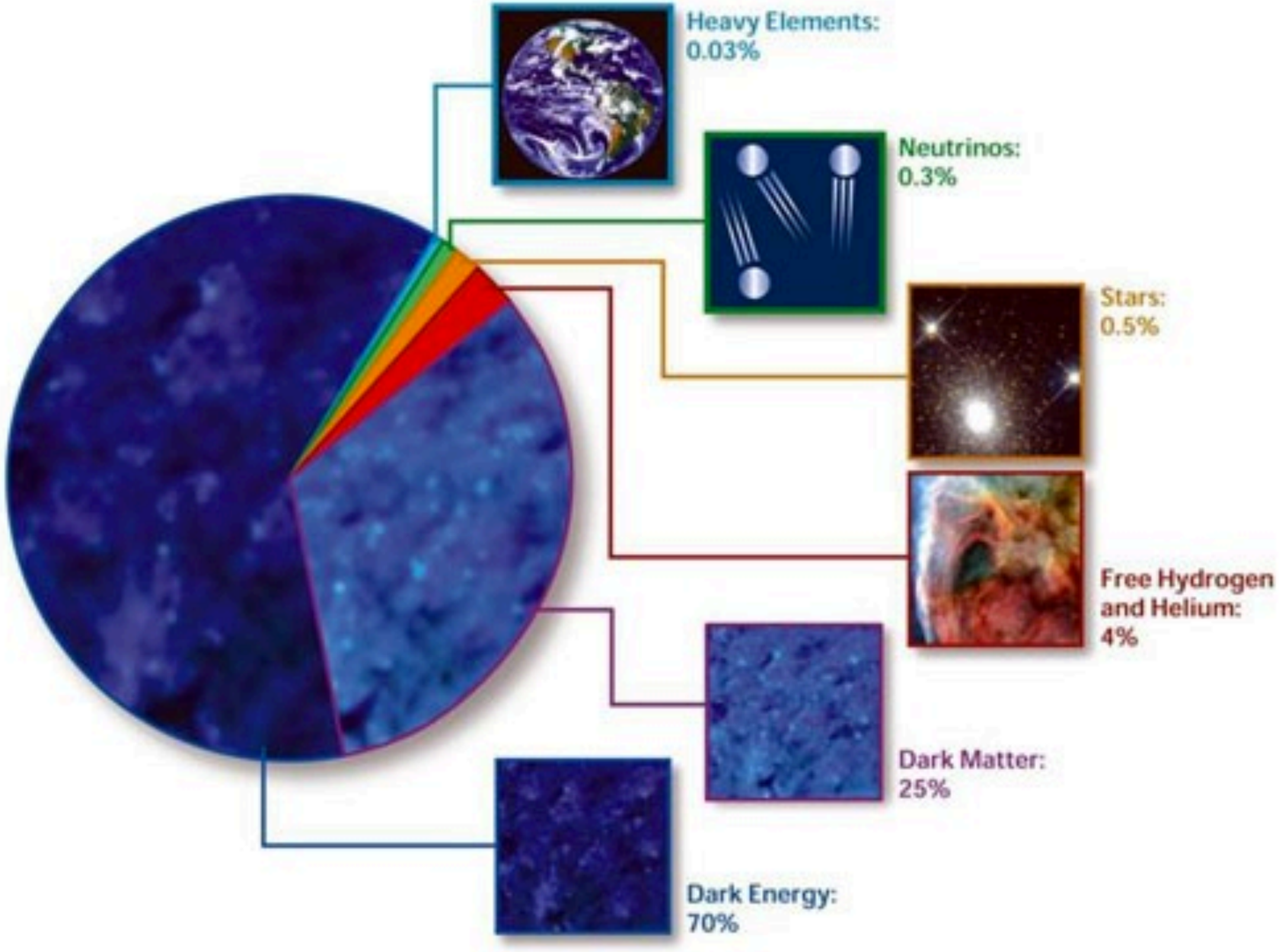
Vacuum energy?

Exotic particles?

Modification of general relativity?


SCALE OF THE UNIVERSE
BIG RIP
CONSTANT
DARK ENERGY
BIG CRUNCH
DECELERATION
ACCELERATION
BIG
BANG
PRESENT
FUTURE
TIME

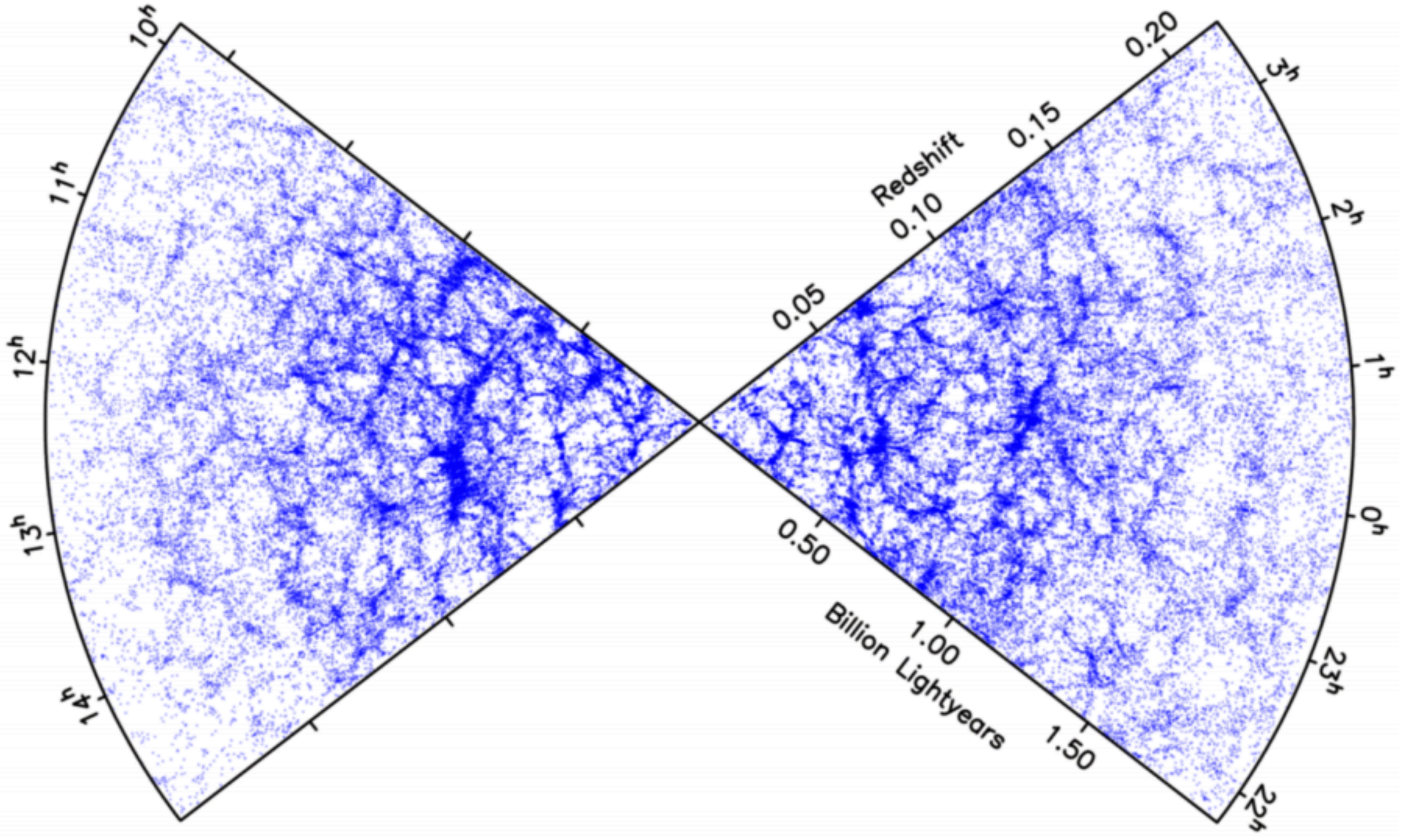
COMPOSITION OF THE COSMOS

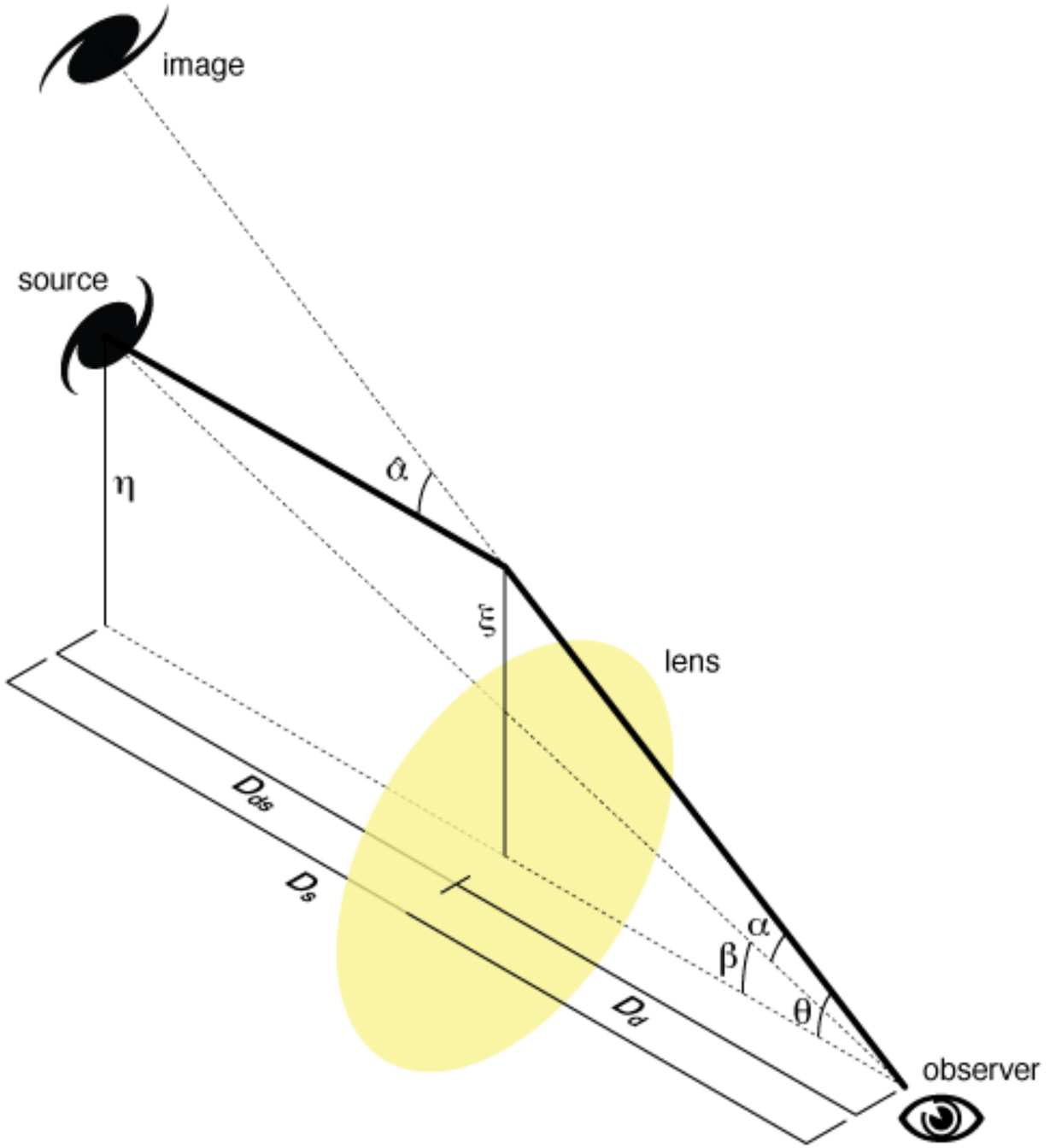


Observing dark energy

- Distance-redshift relation:
    1. Supernovae type Ia
    2. Baryon acoustic oscillations
- + Growth of structures:
    3. Galaxy cluster mass function
    4. **Weak gravitational lensing**

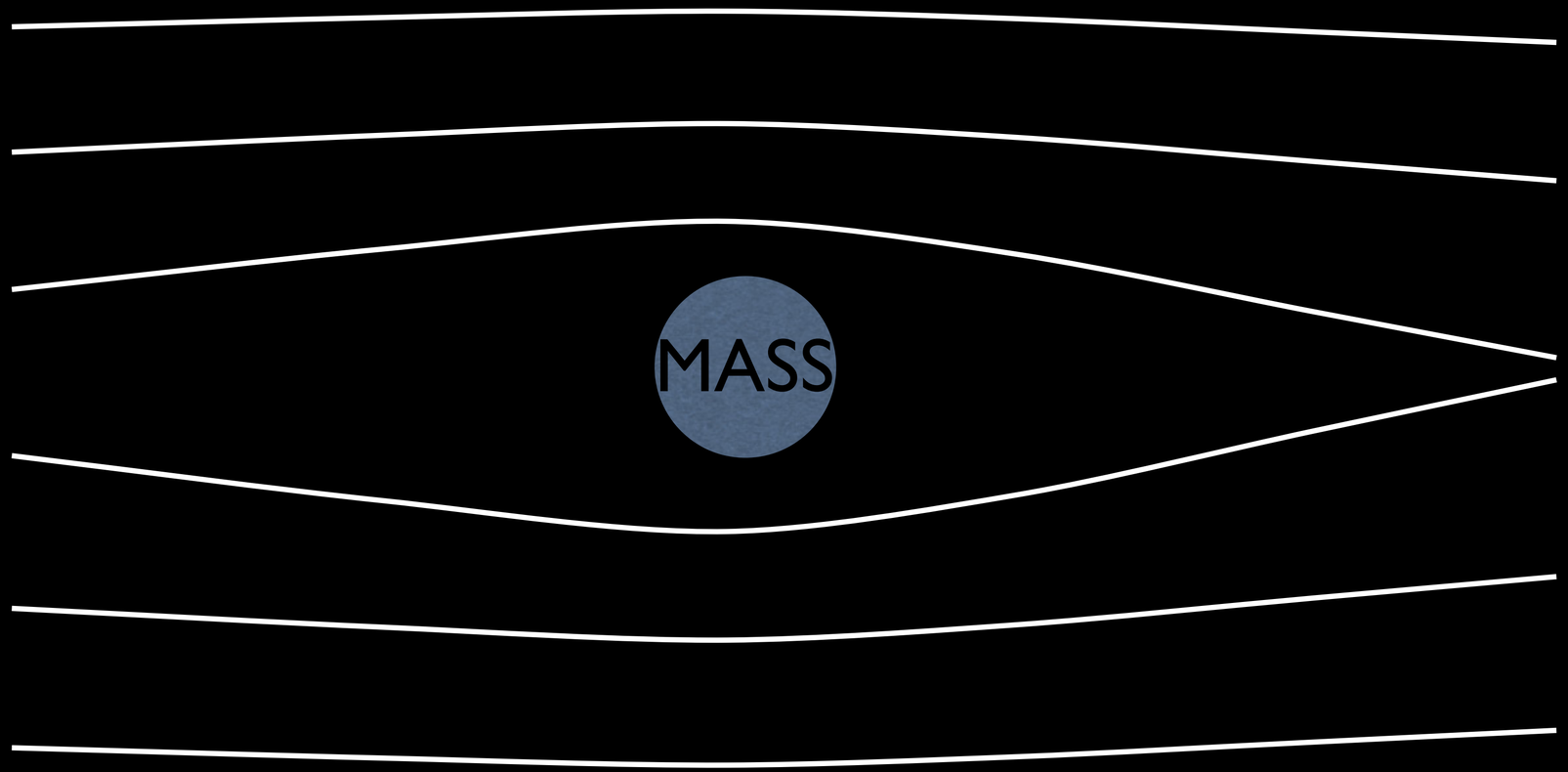
Gravitational Lensing


10h
11h
12h
13h
14h
Redshift
0.05
0.10
0.15
0.20
0.50
1.00
1.50
Billion Lightyears
3h
2h
1h
0h
23h
22h

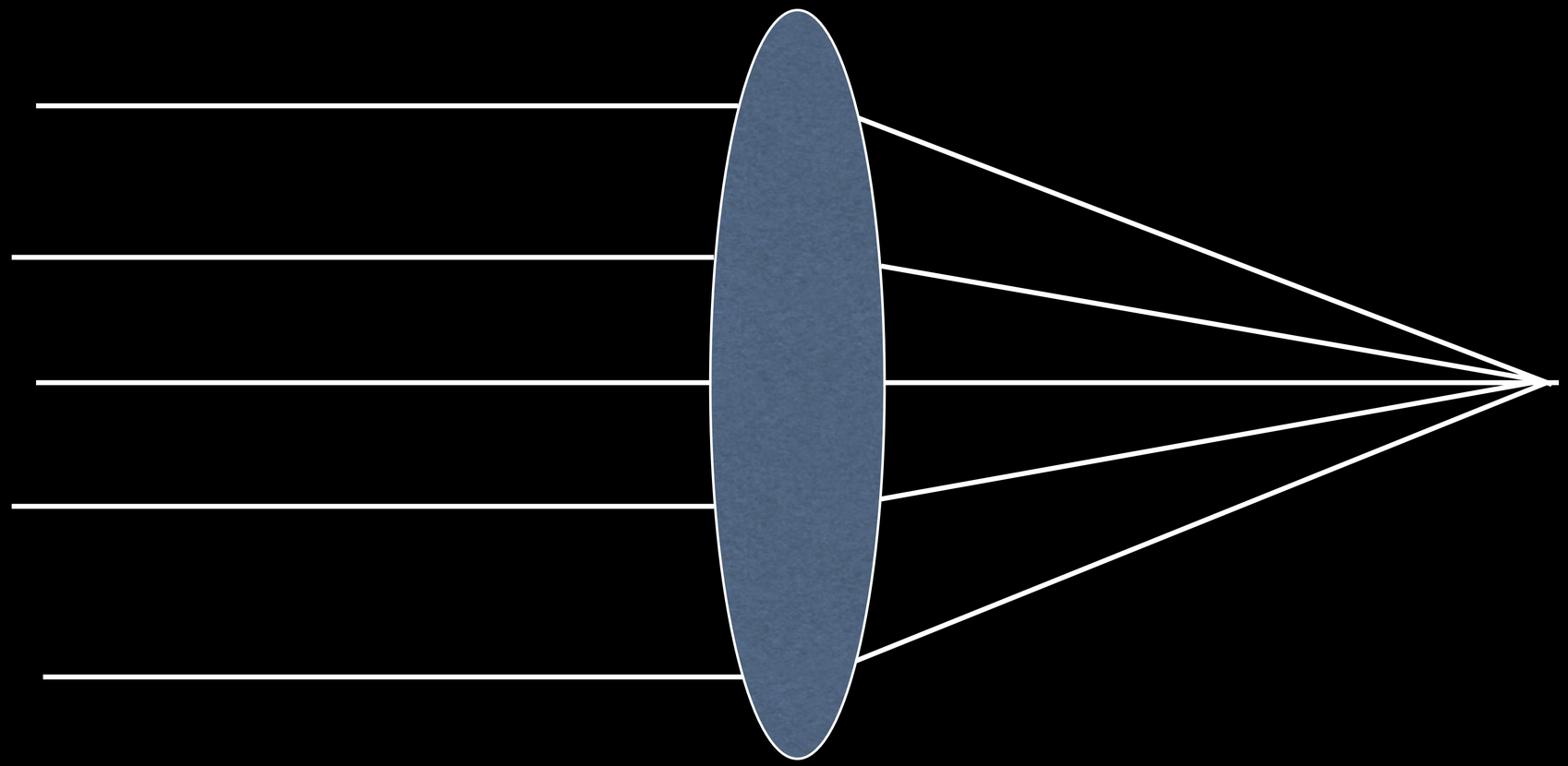


Credit: Michael Sachs

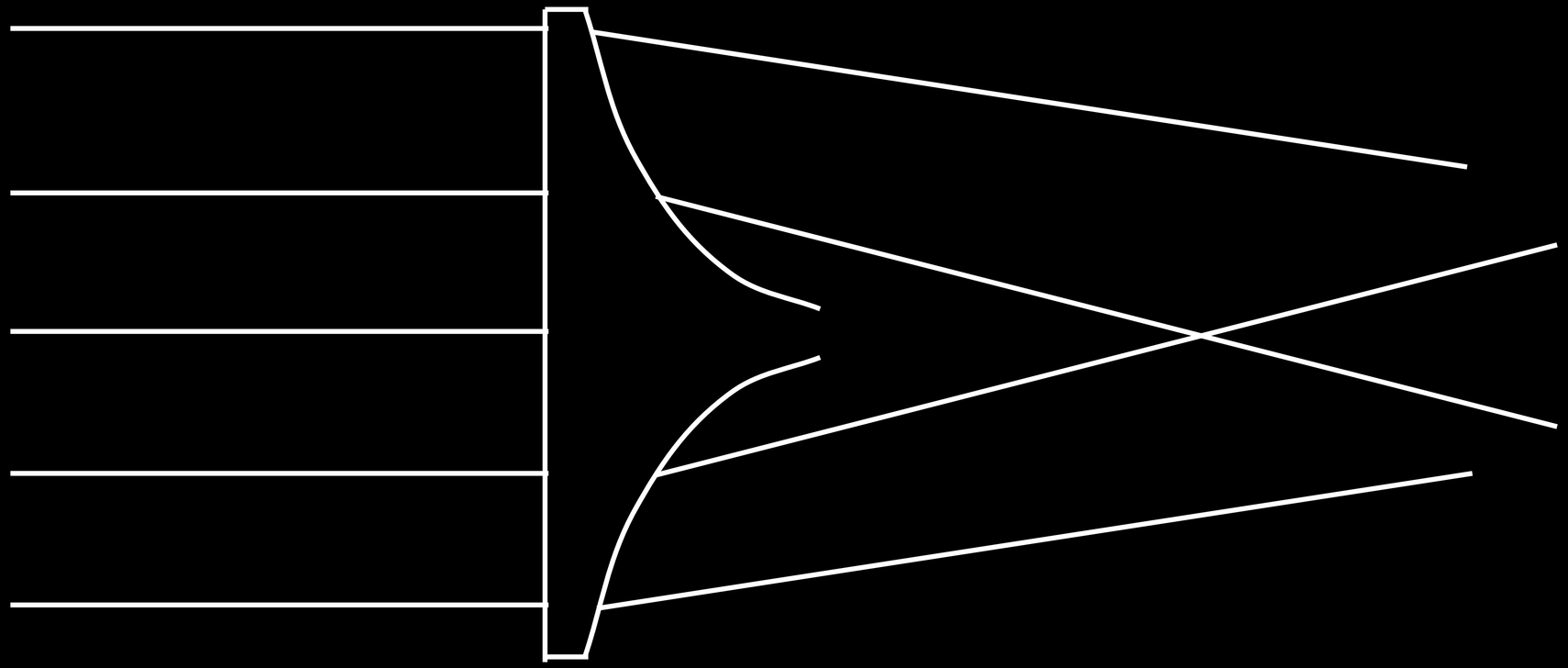
Gravitational lens



Optical lens

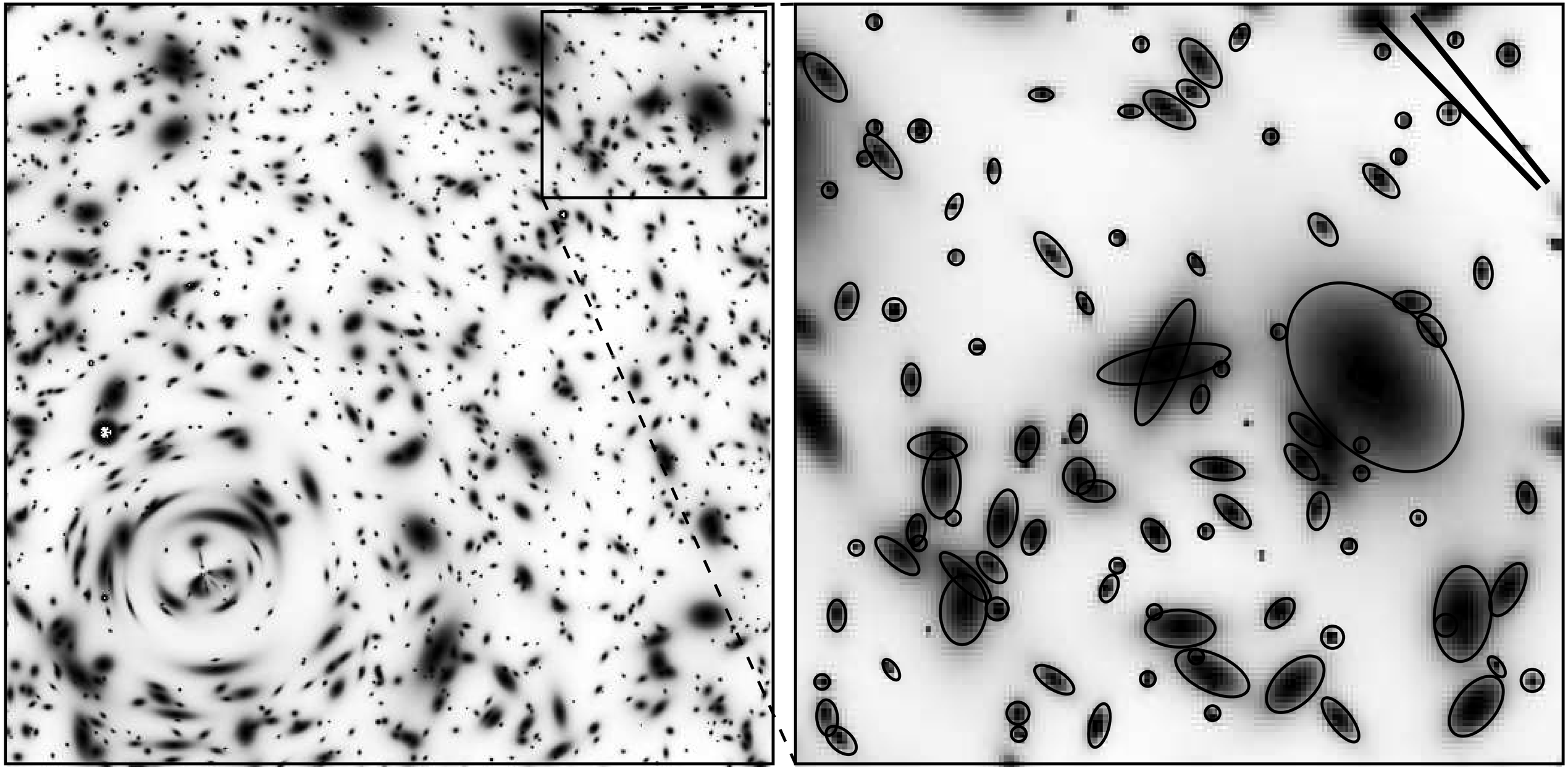


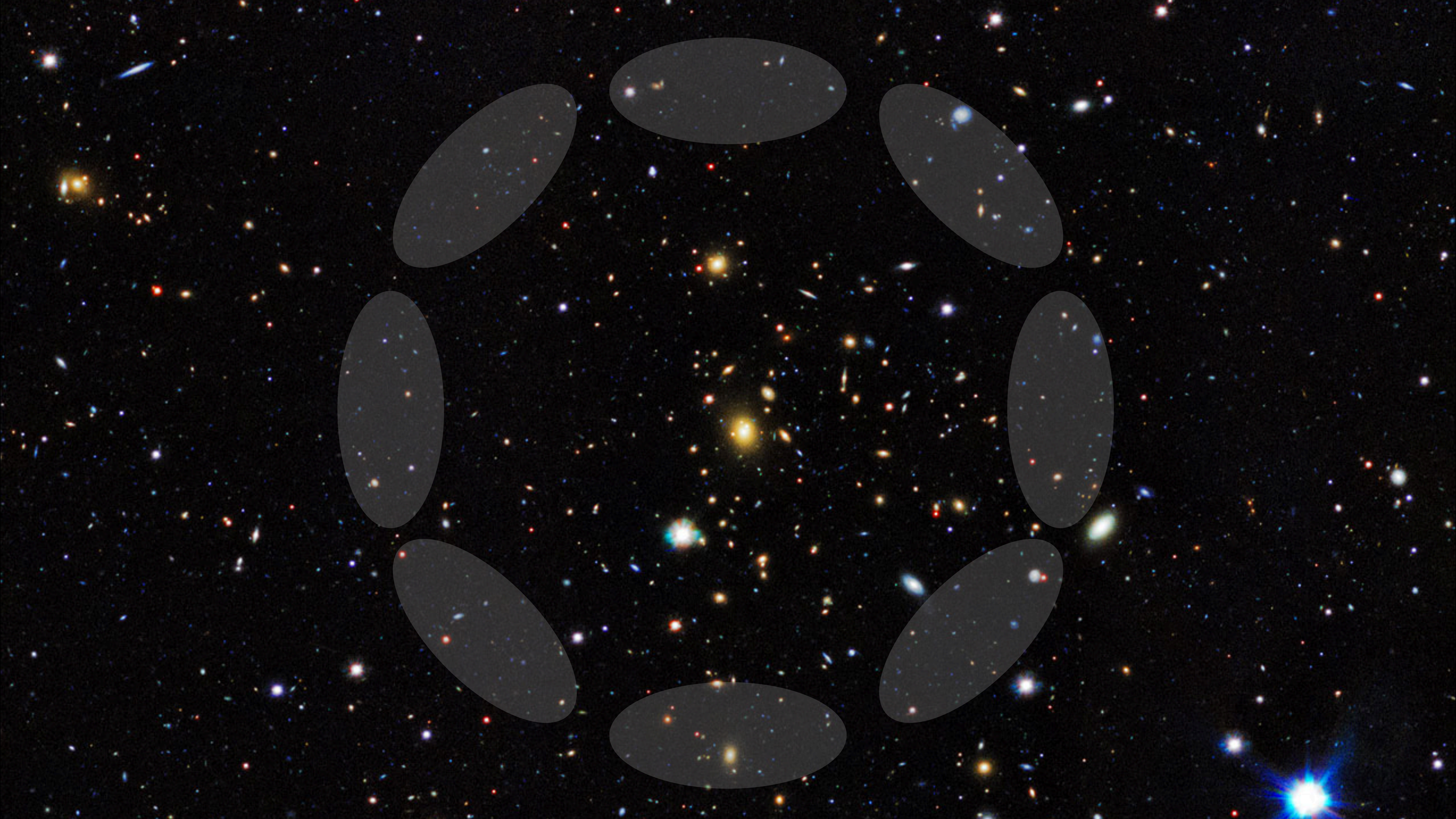
Gravitational lens analogue

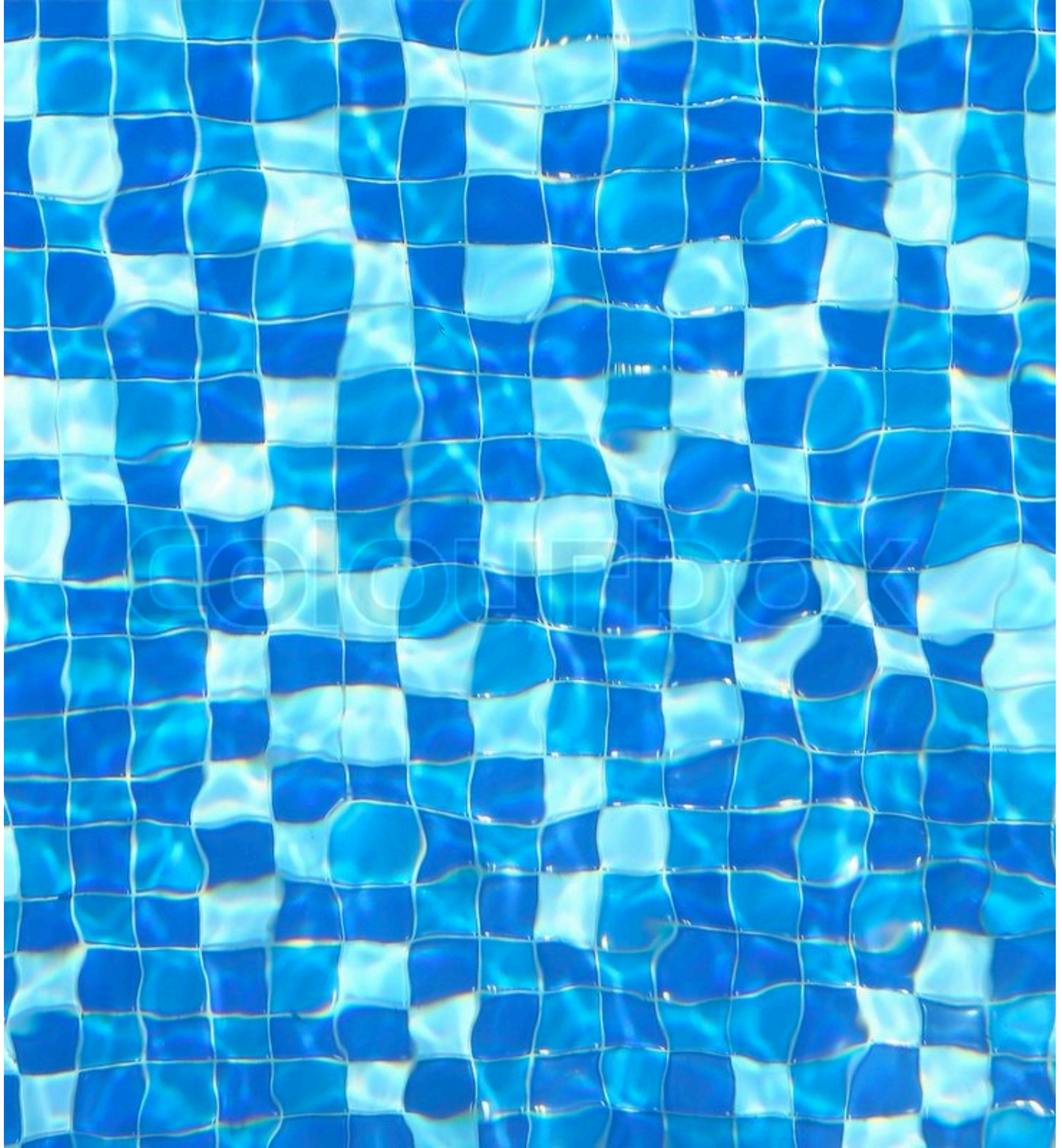


Spherical abberation!

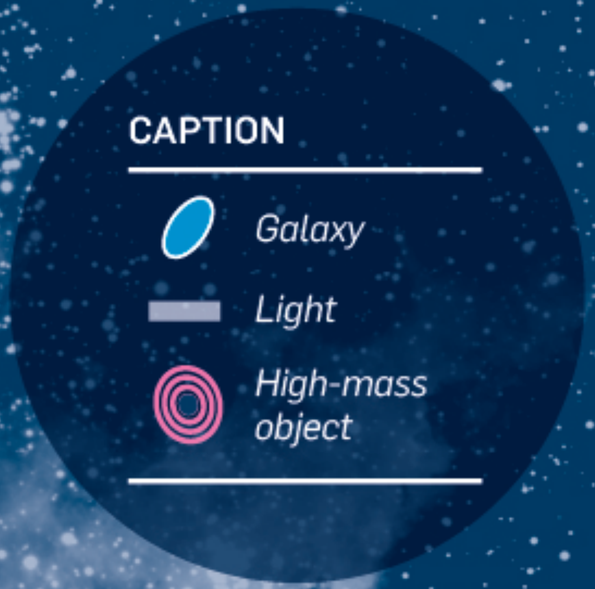

Credit: R. Schirdewahn

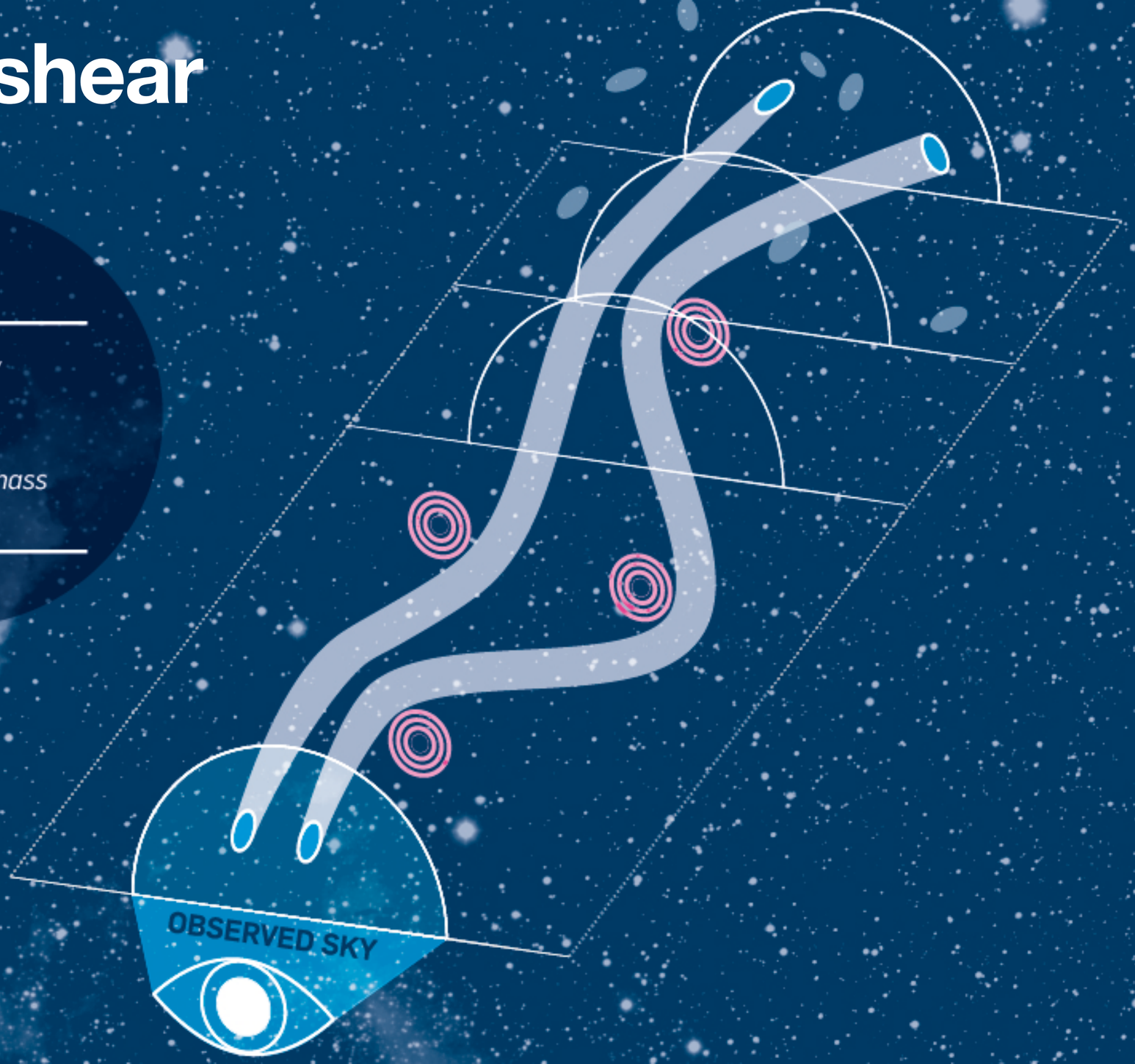






Cosmic shear





Sensitive to:

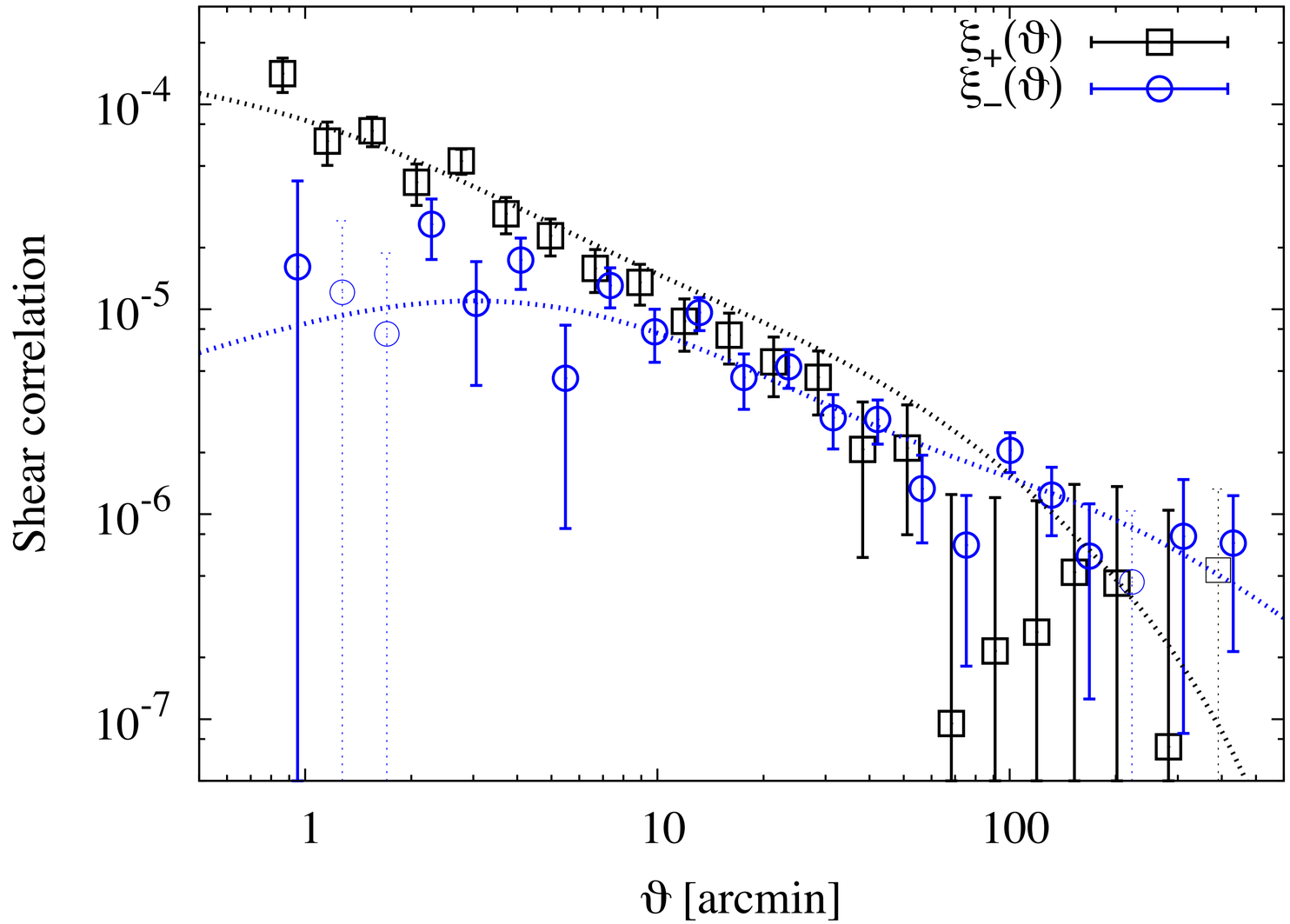
- Matter distribution
- Geometry

Observables:

- Ellipticities
- Photo-z

Statistical measurement of many galaxies

2pt shear correlation functions



Very directly related to the matter power spectrum P_δ.

Kilbinger et al. (2013)

Observation → theory

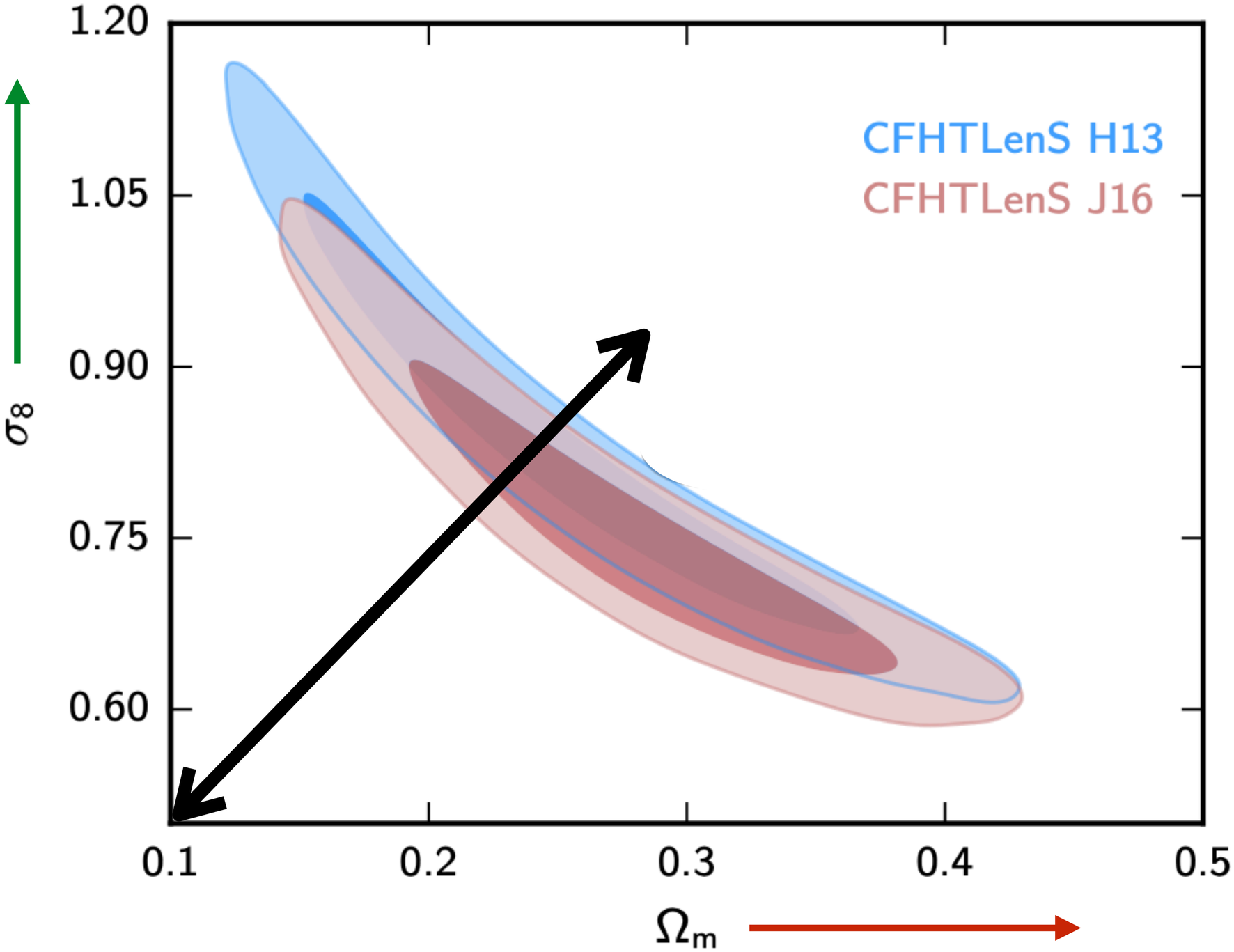
$$\xi_{\pm}(\theta) = \langle \gamma_{\rm t}\gamma_{\rm t} \rangle (\theta) \pm \langle \gamma_{\times}\gamma_{\times} \rangle (\theta)$$

$$\xi_{+}(\theta) = \int_0^{\infty} \frac{{\rm d}\ell\,\ell}{2\pi}\, {\rm J}_0(\ell\theta)\, P_{\kappa}(\ell)\,; \quad \xi_{-}(\theta) = \int_0^{\infty} \frac{{\rm d}\ell\,\ell}{2\pi}\, {\rm J}_4(\ell\theta)\, P_{\kappa}(\ell)$$

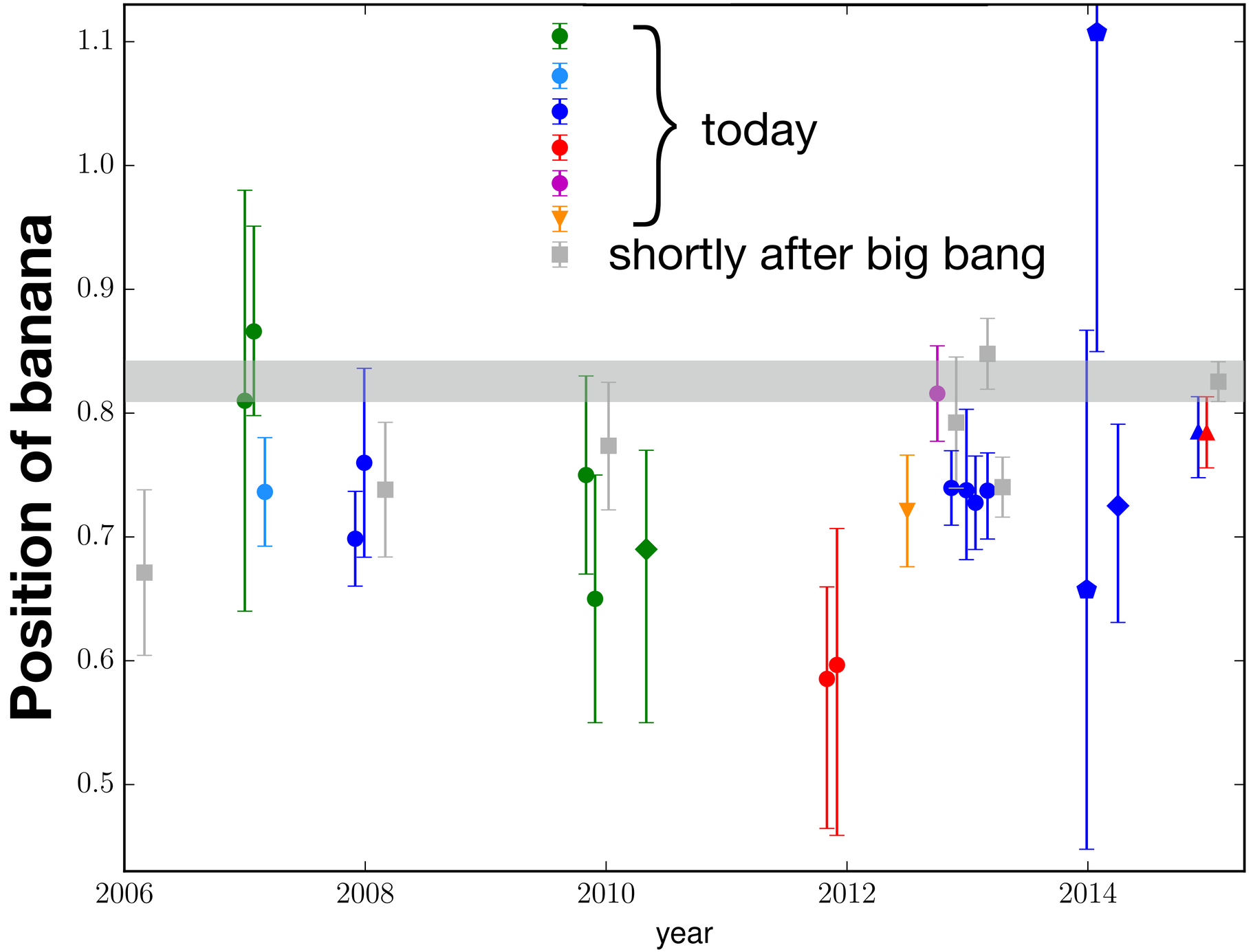
$$P_{\kappa}(\ell) = \frac{9H_0^4\Omega_{\rm m}^2}{4c^4} \int_0^{\chi_{\rm h}} {\rm d}\chi\, \frac{g^2(\chi)}{a^2(\chi)} P_{\delta}\left(\frac{\ell}{f_K(\chi)}, \chi\right)$$

$$g(\chi) = \int_{\chi}^{\chi_{\rm h}} {\rm d}\chi'\, p_{\chi}(\chi')\, \frac{f_K(\chi'-\chi)}{f_K(\chi')}$$

No galaxy biasing on this slide! Cosmic shear typically goes to **small scales**.



- Measures the **amount** of **clustered** matter
- Also: Dark energy


today
shortly after big bang
Position of banana
year
1.1
1.0
0.9
0.8
0.7
0.6
0.5
2006
2008
2010
2012
2014

Systematic challenges

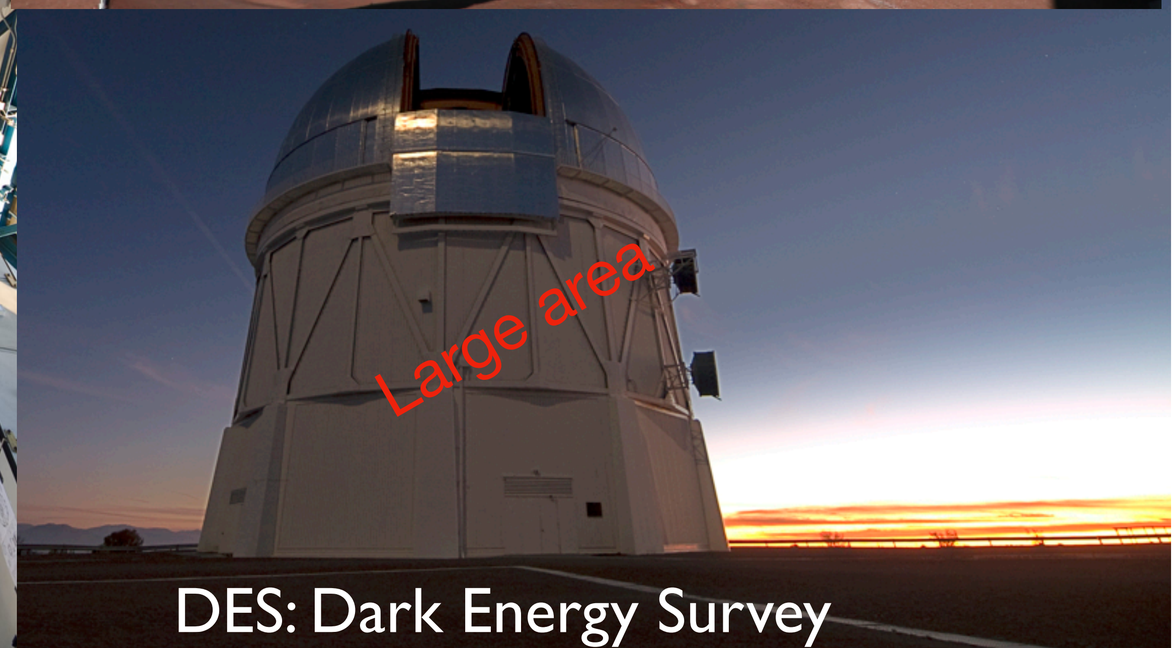
- Observational
  - Shape measurements
  - Redshift distributions
- Theoretical
  - Intrinsic alignments
  - Baryon feedback
- Psychological

Stage III Surveys

HSC: Hyper-Suprime Cam Survey

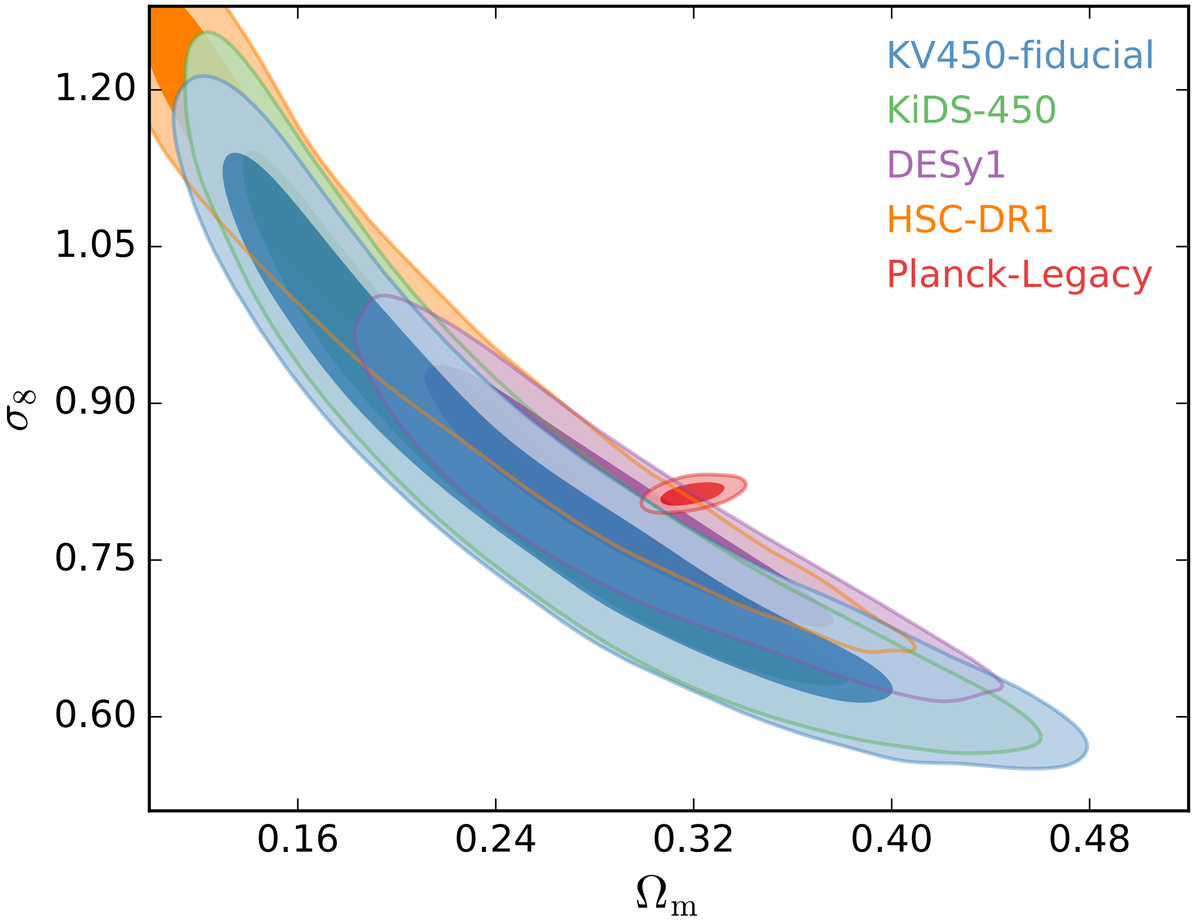
100s of millions of galaxies each!

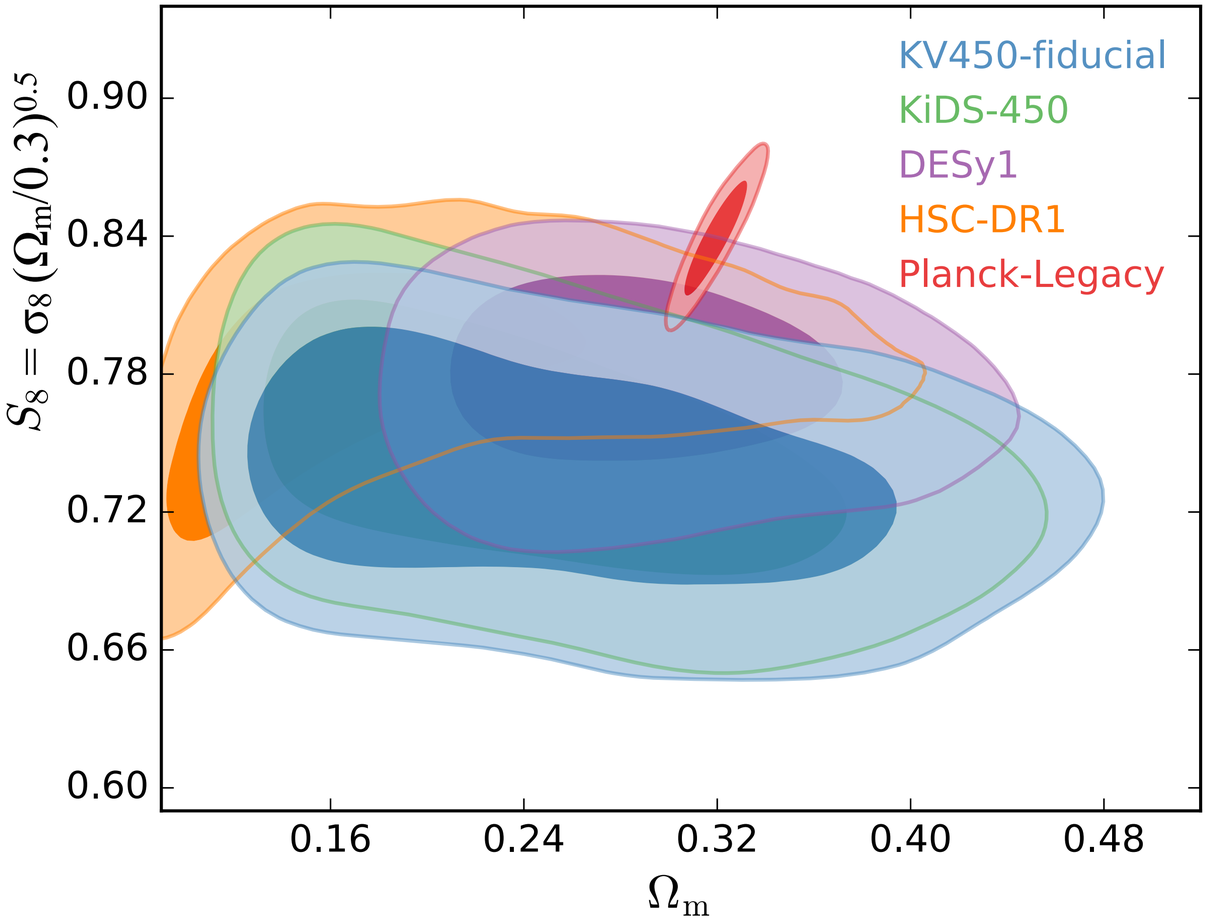
KiDS: Kilo Degree Survey



DES: Dark Energy Survey

Cosmic shear before Covid-19

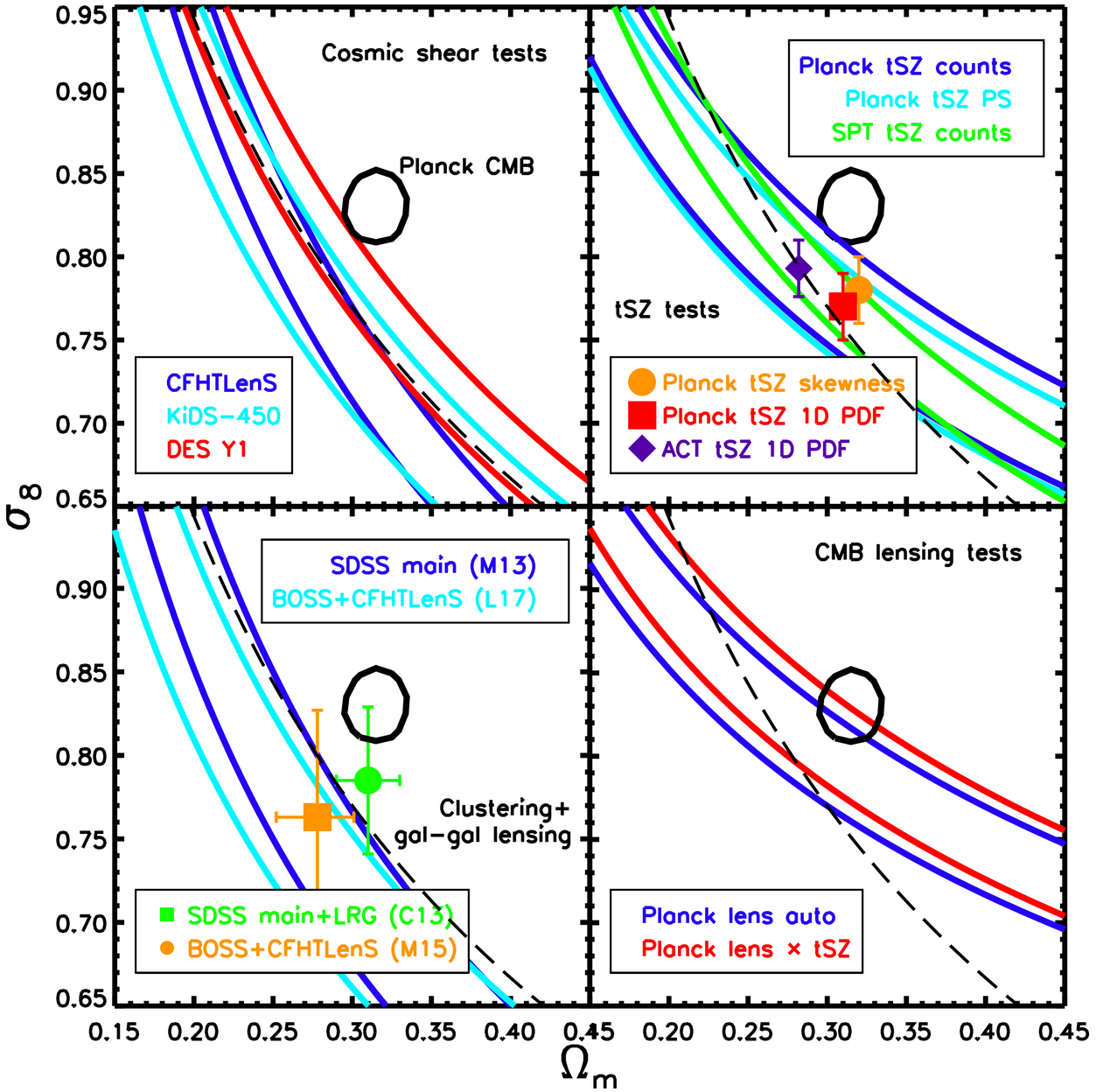




Agreement of WL measurements. All lower than Planck.

HSC-DR1: Hikage et al. (2019)
DES-Y1: Troxel et al. (2018a)
KiDS-VIKING-450: Hildebrandt et al. (2020)

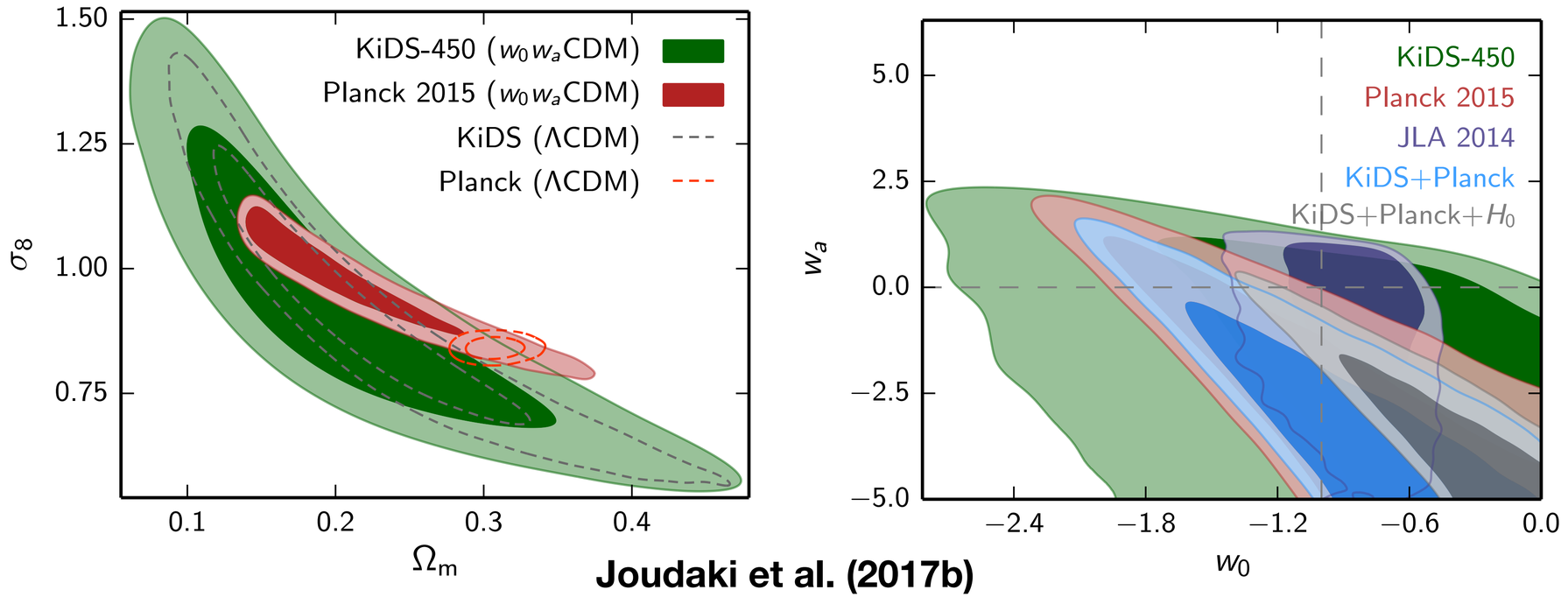
Other probes



Not a single late Universe LSS measurement yields an S_8 higher than Planck.

McCarthy et al. (2017)

Evolving dark energy

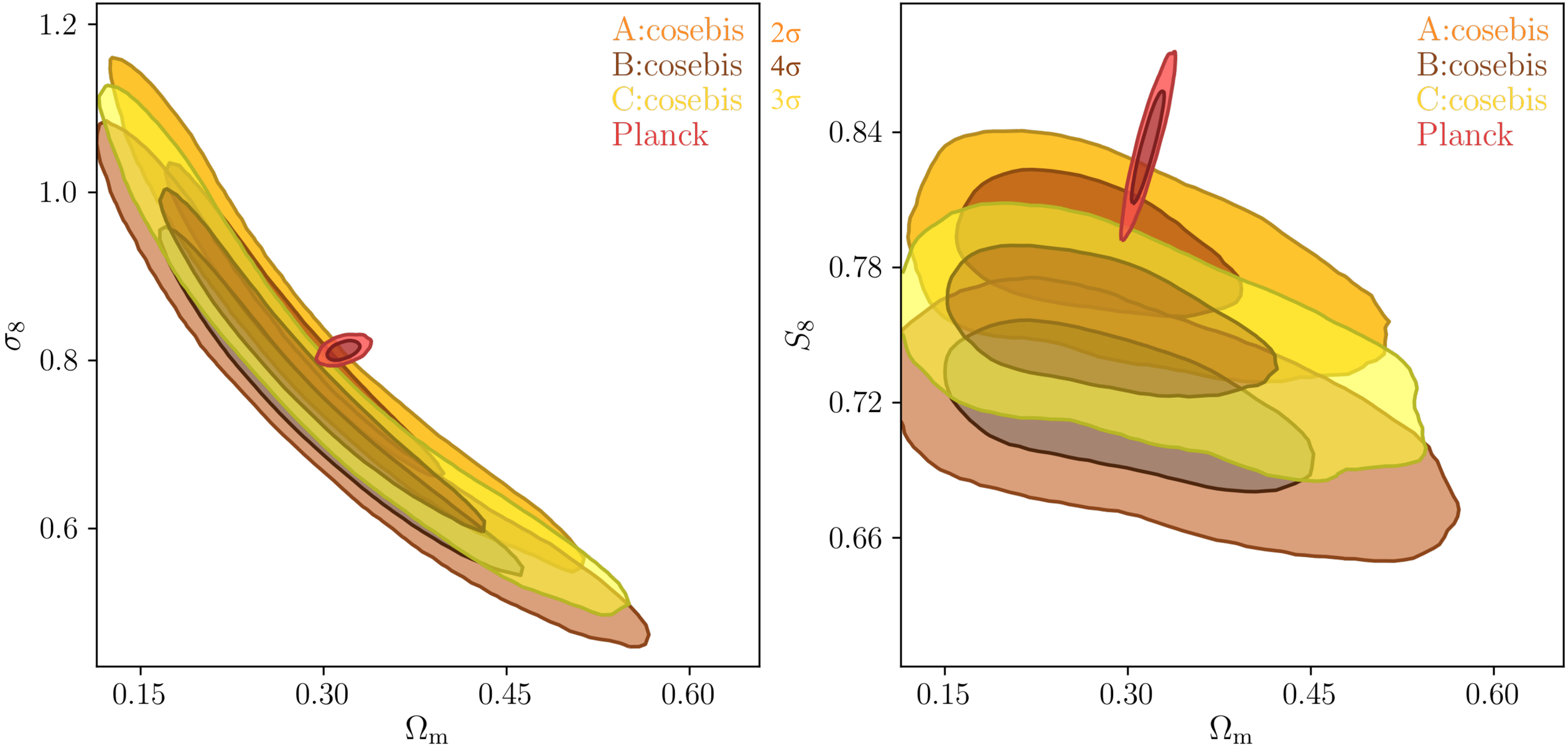


Joudaki et al. (2017b)

- Resolves tension between KiDS and Planck.
- Only extension that is moderately favoured by the data.
- Resolves H_0 tension between SH_0ES and Planck.

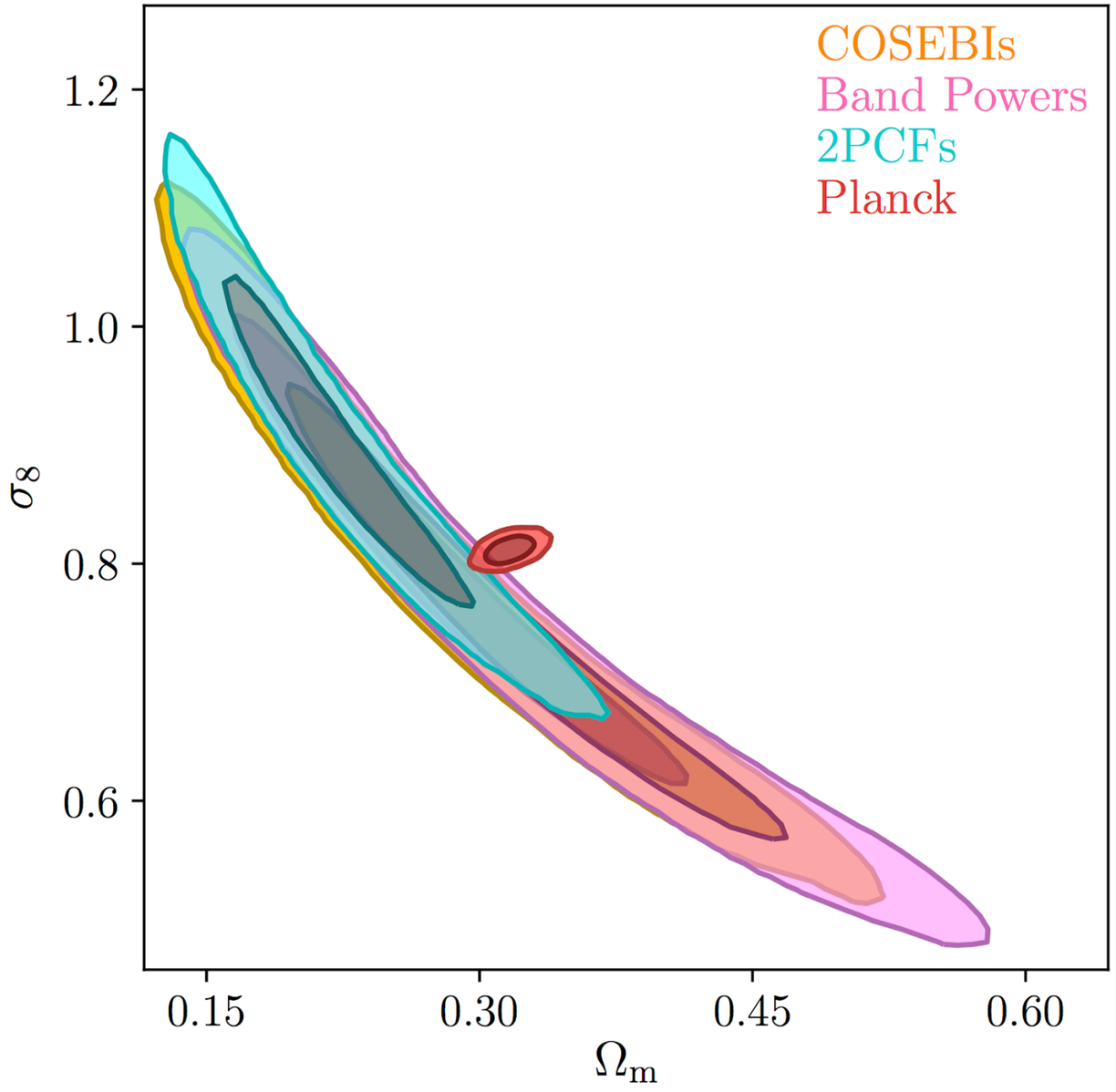
KiDS-1000

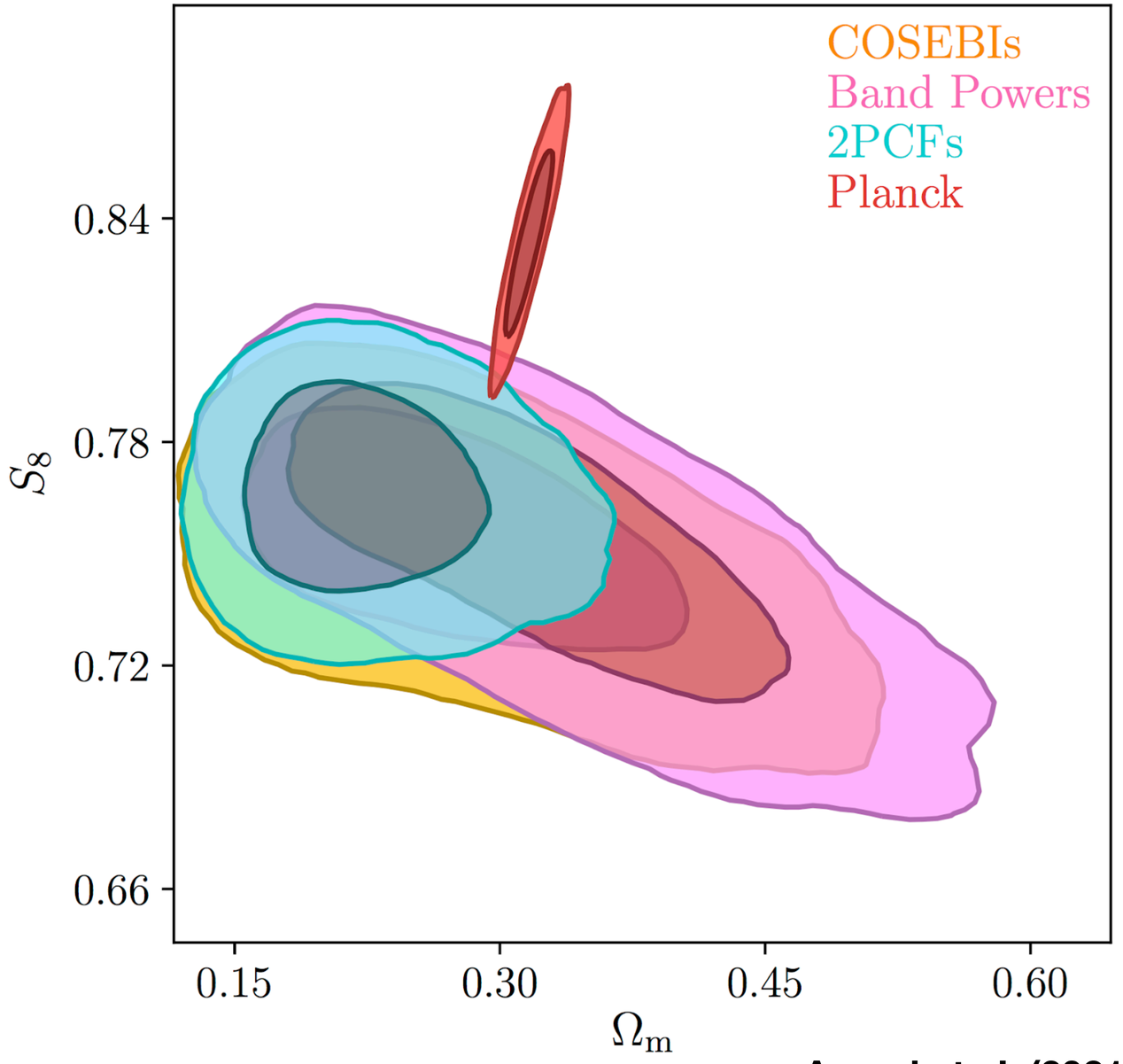
Blinding



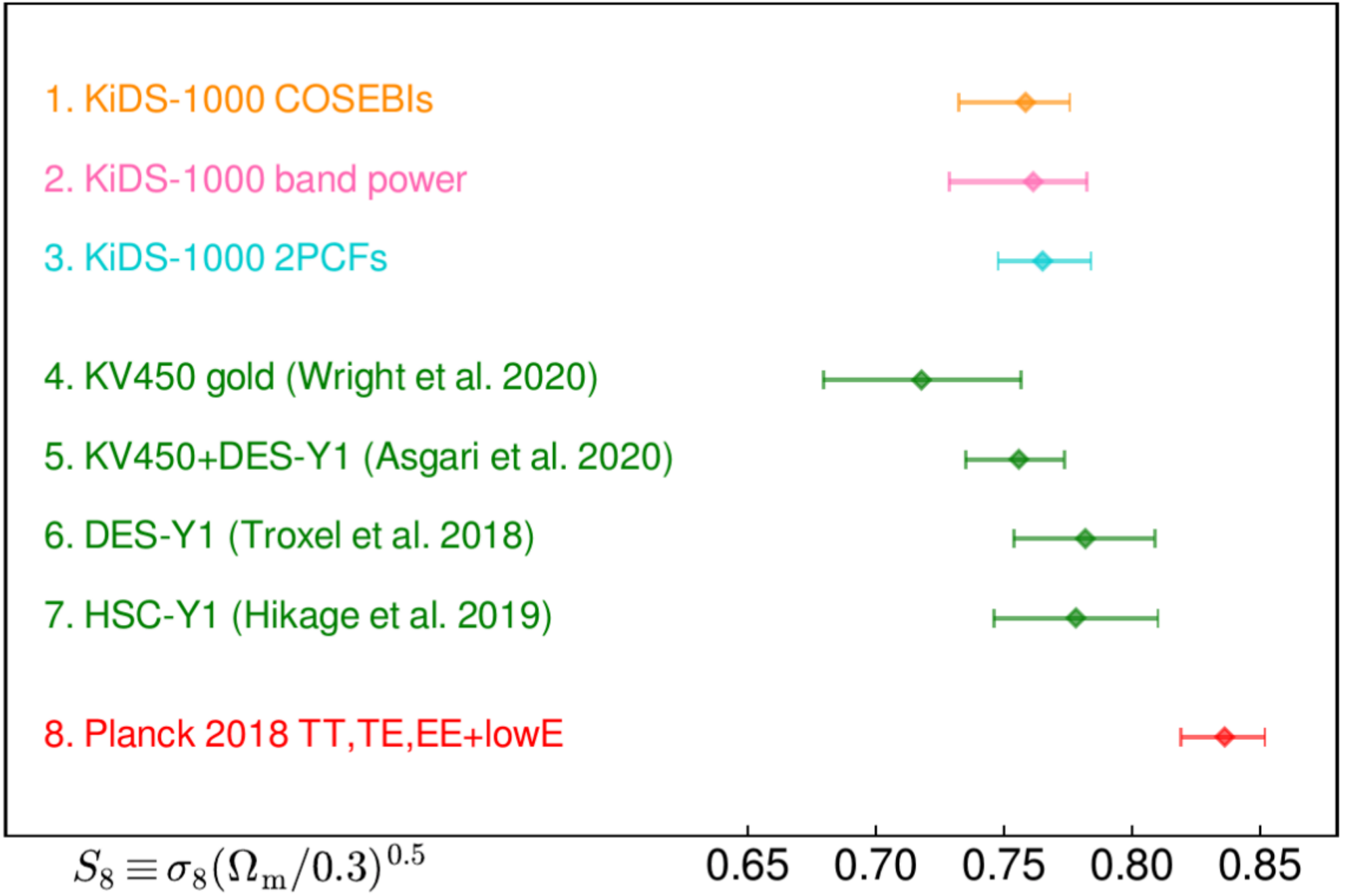
Asgari et al. (2021)

Cosmological constraints



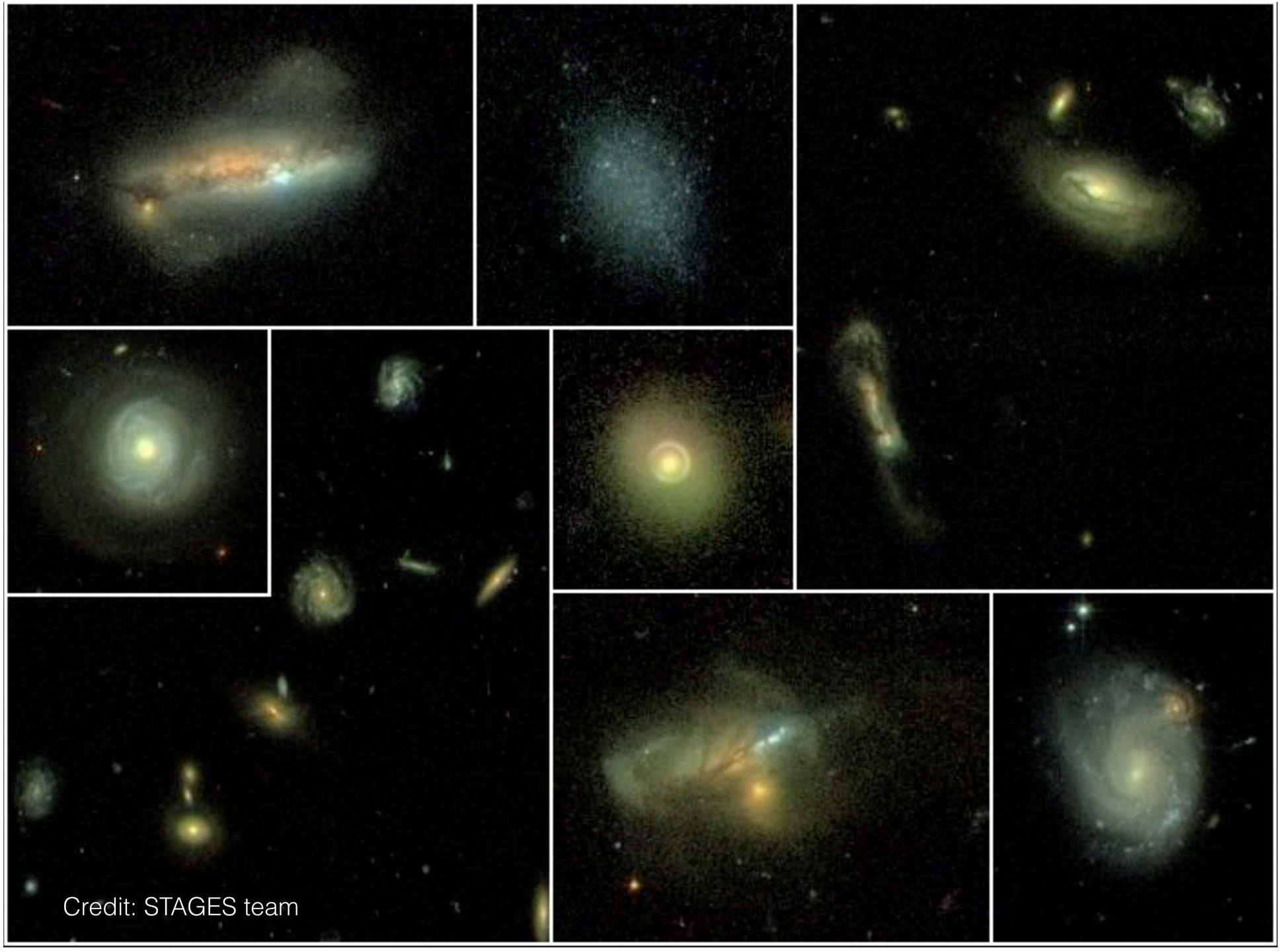


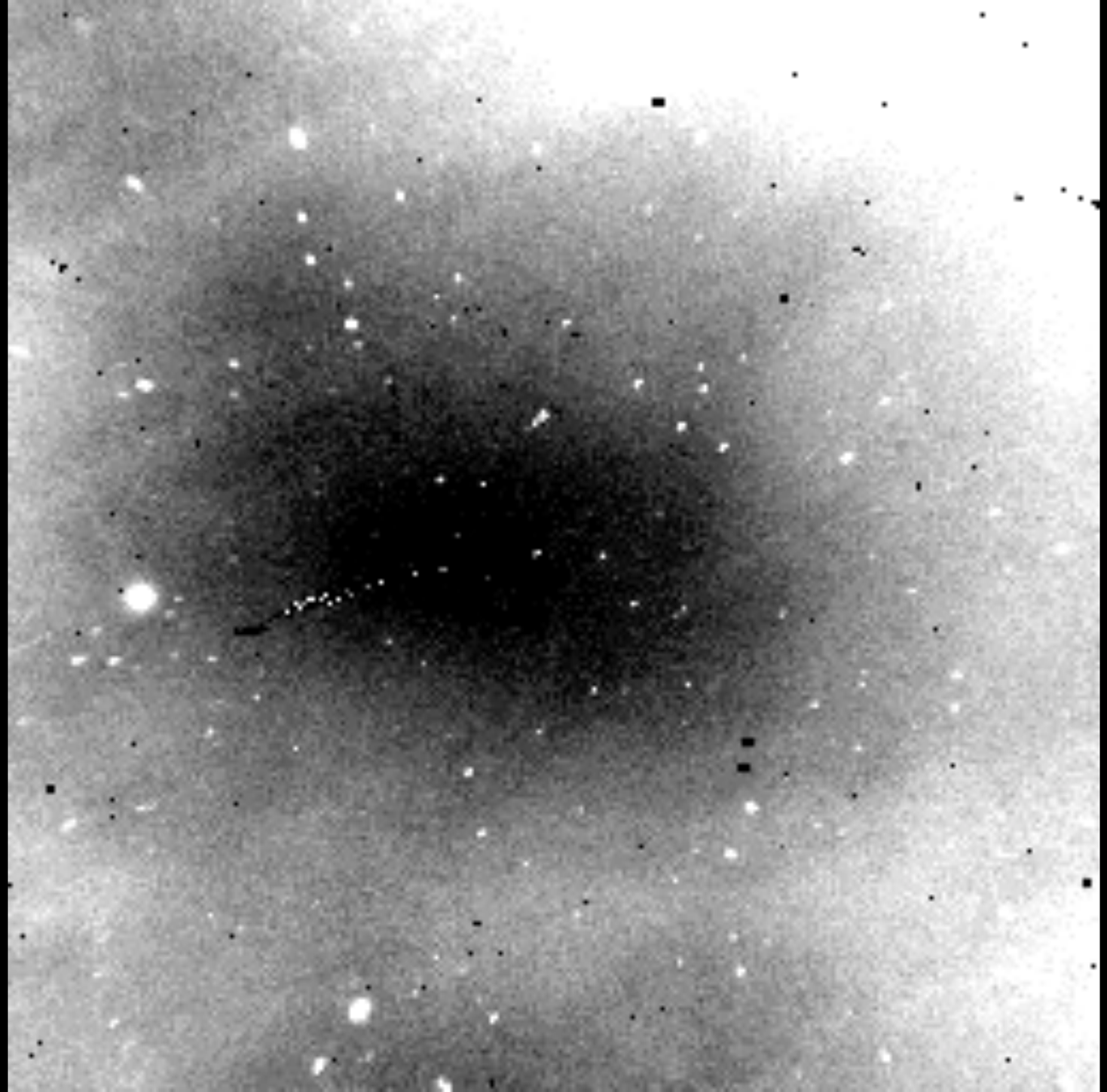
Asgari et al. (2021)



Asgari et al. (2021)


Credit: STAGES team


Credit: STAGES team

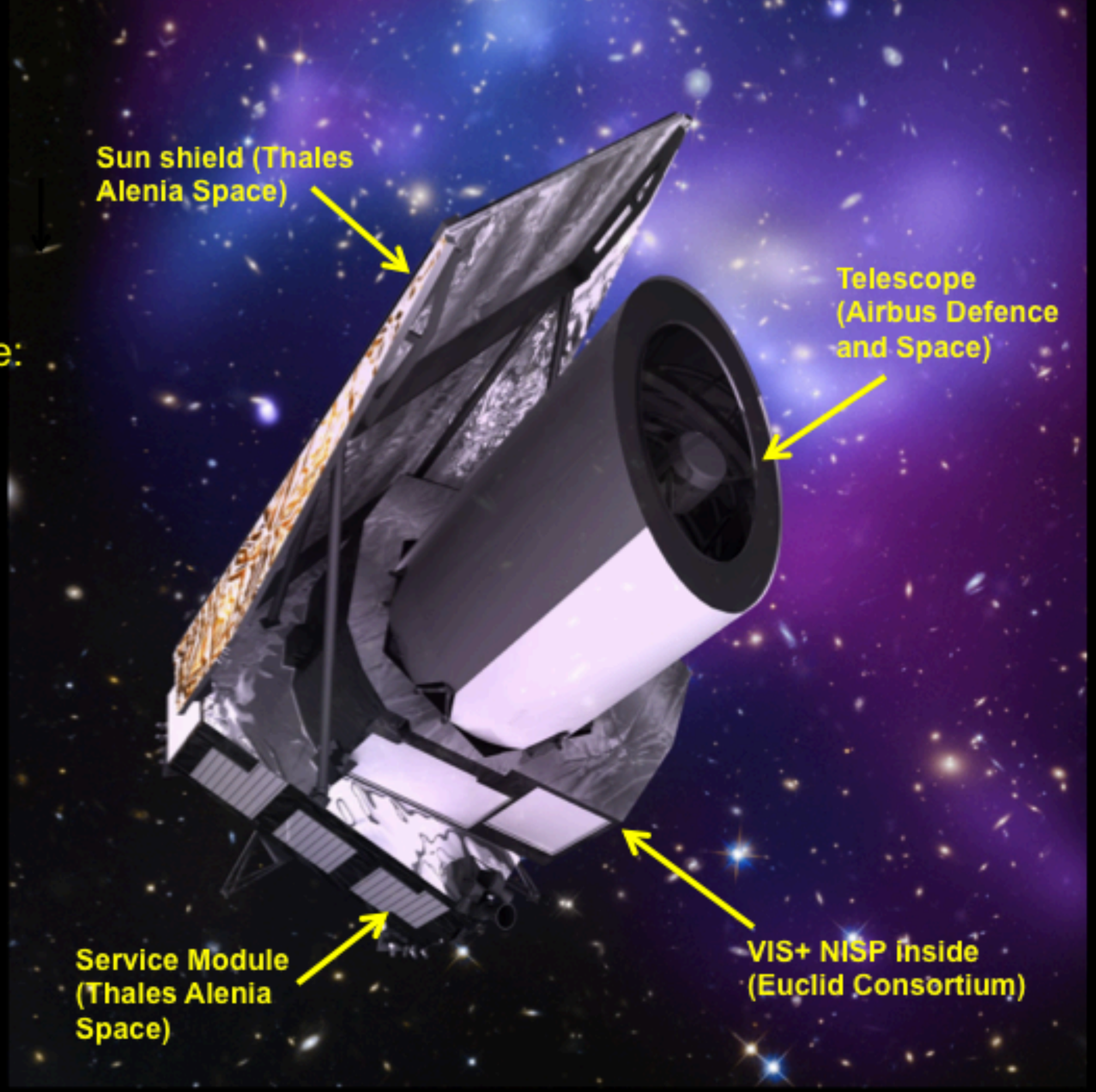


- Total mass satellite:

2200 kg

- Dimensions:

4,5 m x 3 m



Summary

- Normal matter makes up only 5% of the energy density of the Universe.
- Dark matter can be made visible with gravitational lensing.
- What is dark energy? Cosmological constant?
- Discrepancies in current data (H_0, S_8) might be hints to a solution.
- ESA’s Euclid satellite will launch in 2022 and solve this riddle.