Gravitational Lensing - How to make dark matter visible

and what we learn about cosmology with this tool

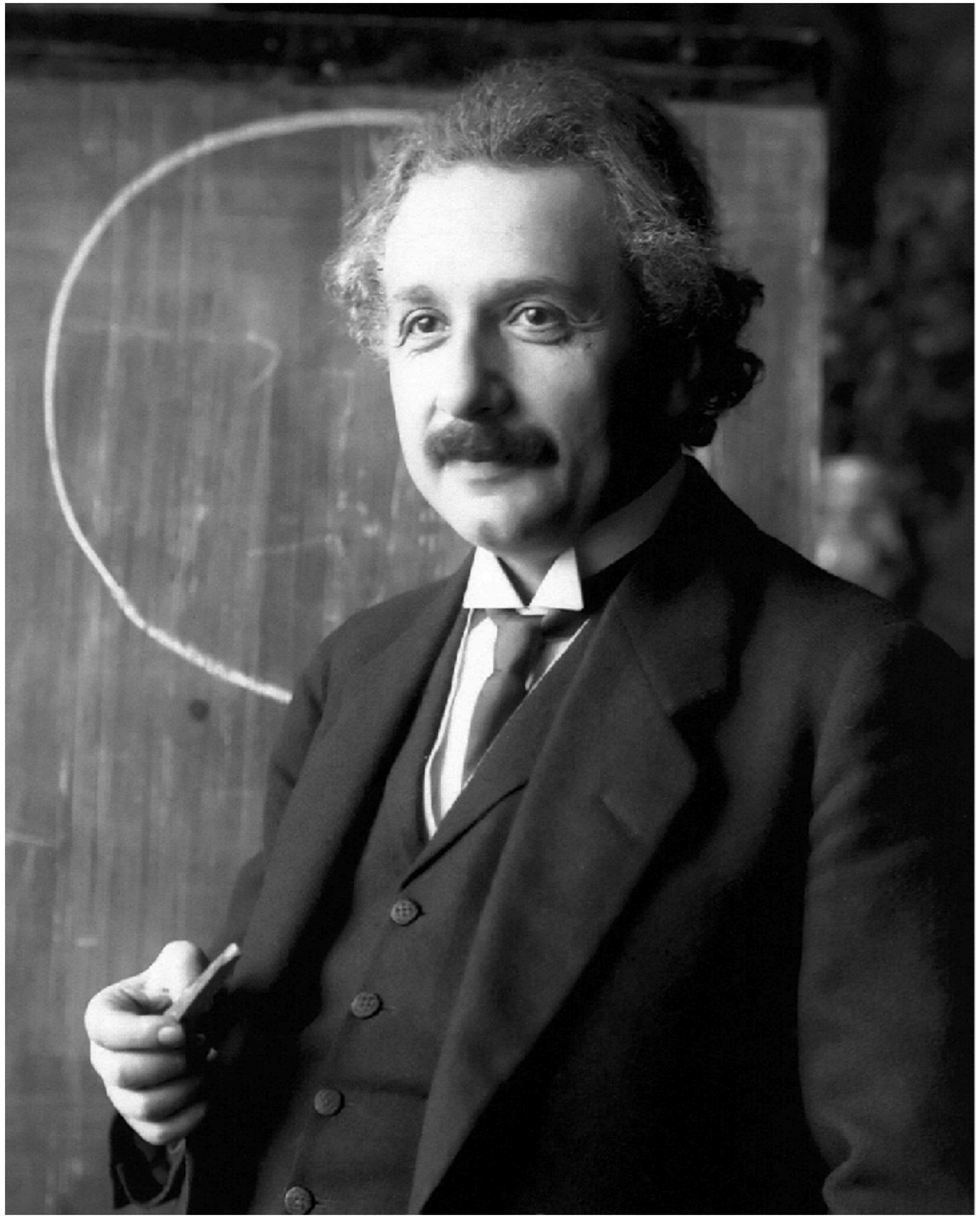
Hendrik Hildebrandt, Ruhr University Bochum
“Crossing the Desert”, 21st May 2021

RUB

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)

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

$$v = H_0 D$$

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

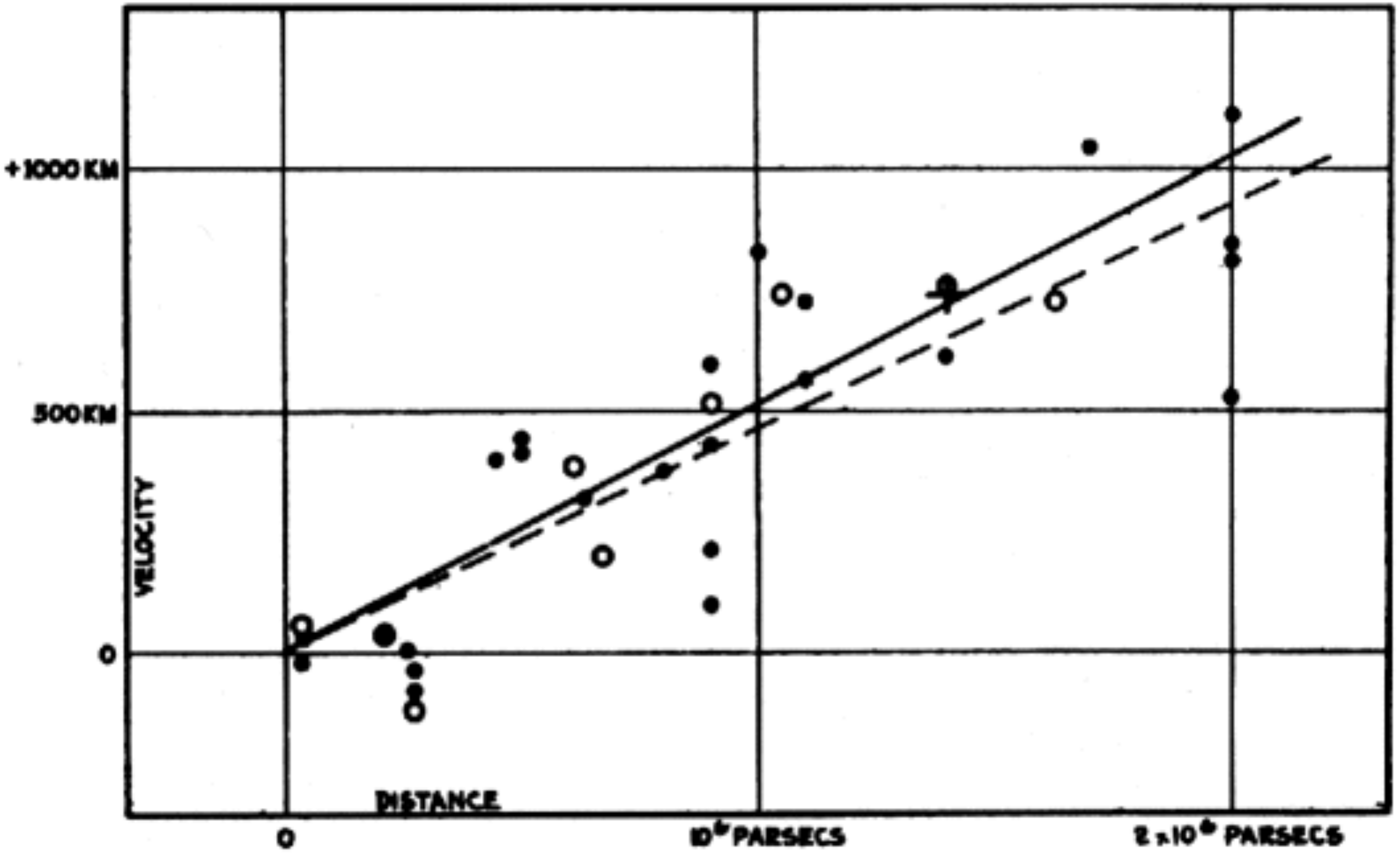


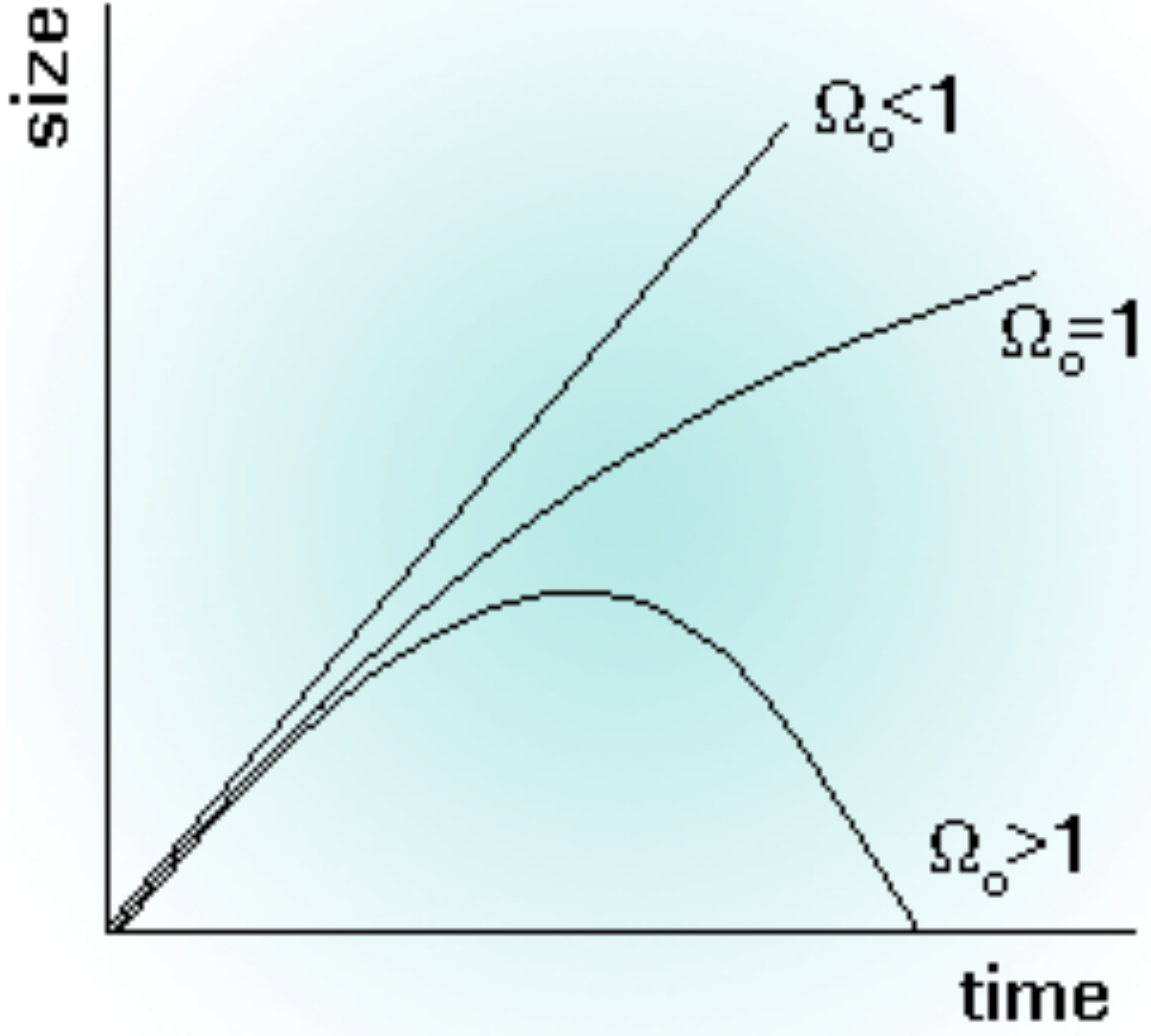
FIGURE 1
Velocity-Distance Relation among Extra-Galactic Nebulae.

Cosmological redshift z

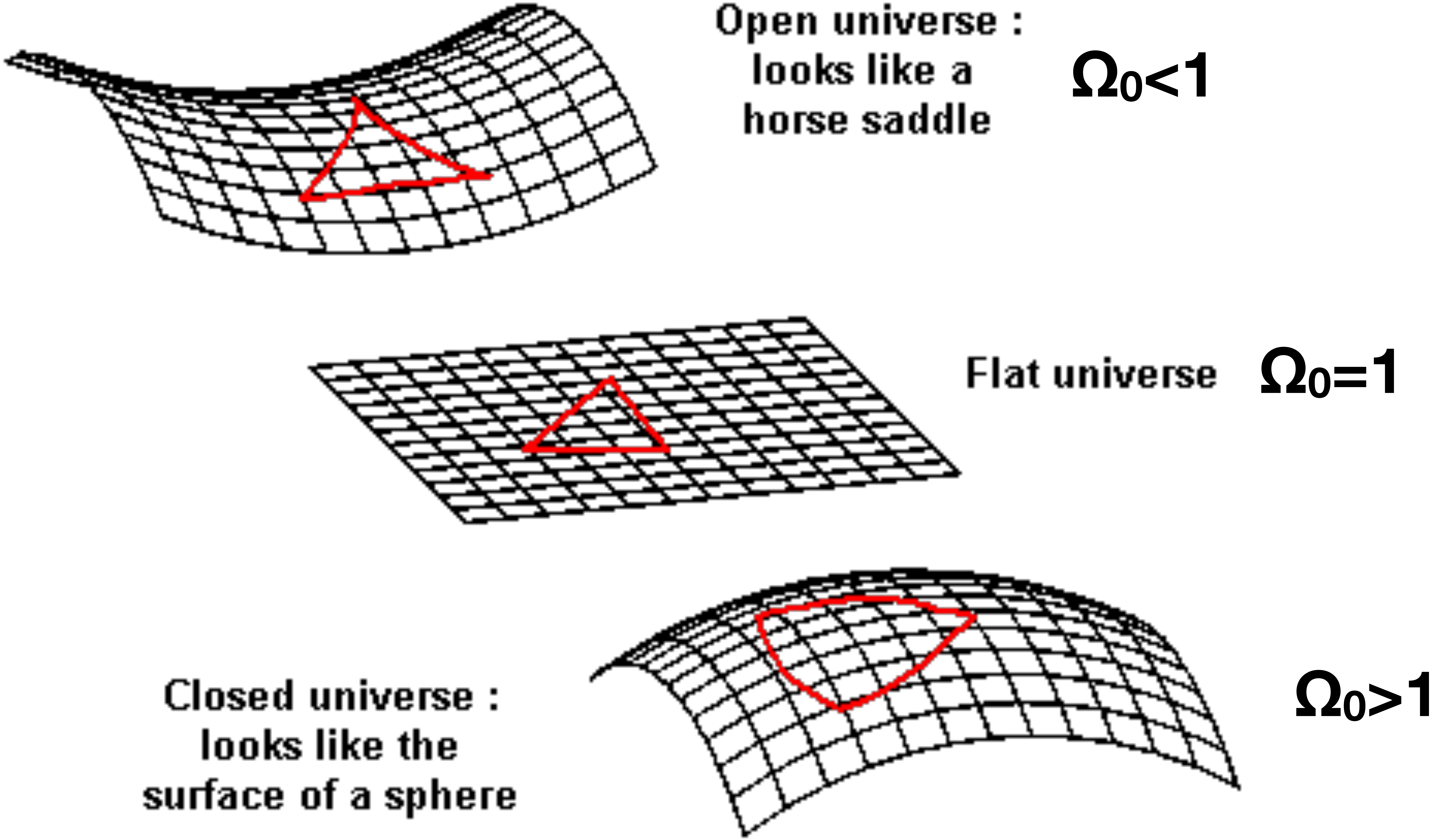
$$\frac{\lambda_{\text{obs}}}{\lambda_{\text{em}}} = (1 + z) = \frac{1}{a}$$

Expansion depends on contents

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



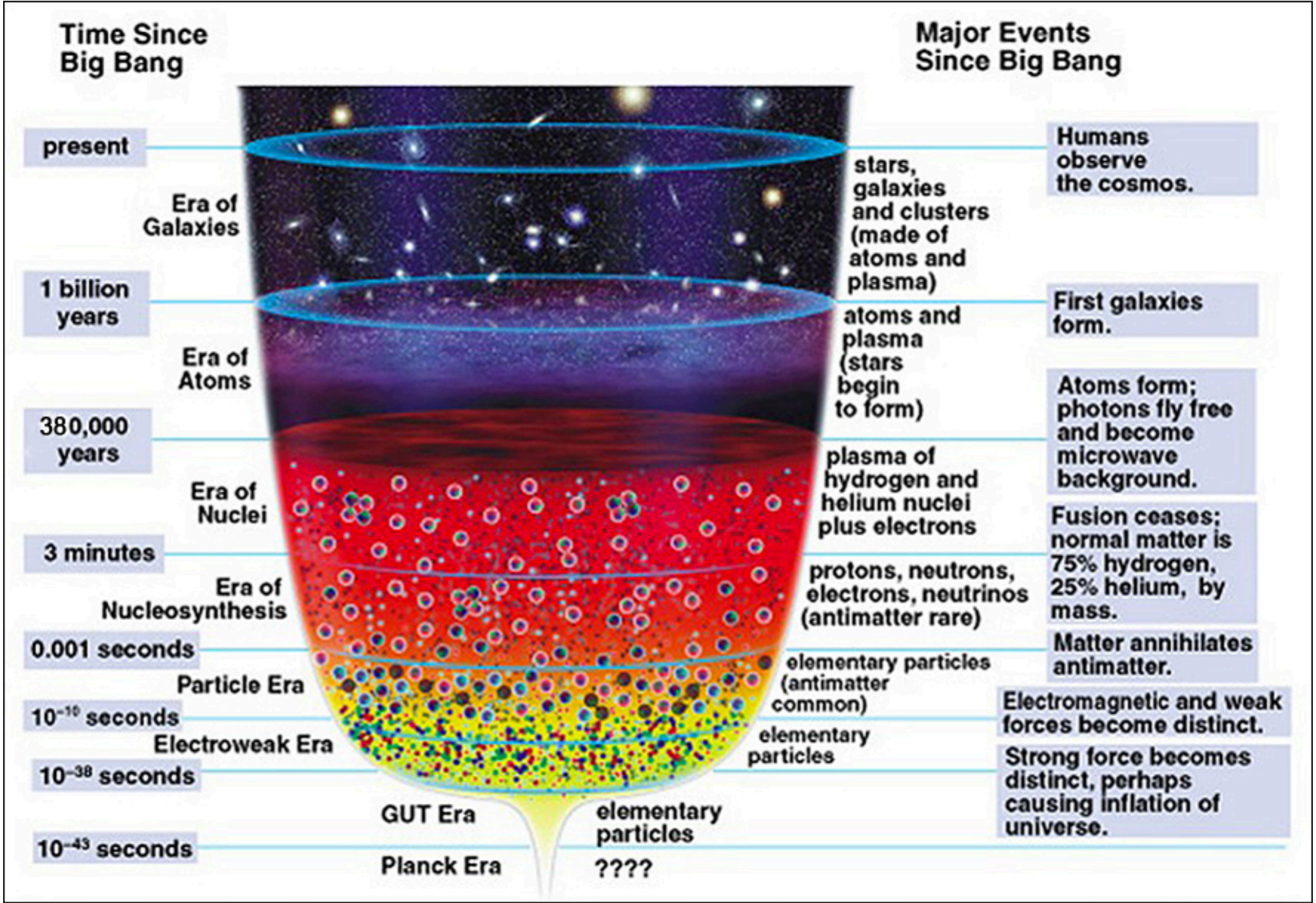
Ω_0 = 1
critical density
~ 10 atoms per m^3



Open universe : looks like a horse saddle
$\Omega_0<1$
Flat universe
$\Omega_0=1$
Closed universe : looks like the surface of a sphere
$\Omega_0>1$

Hot big bang

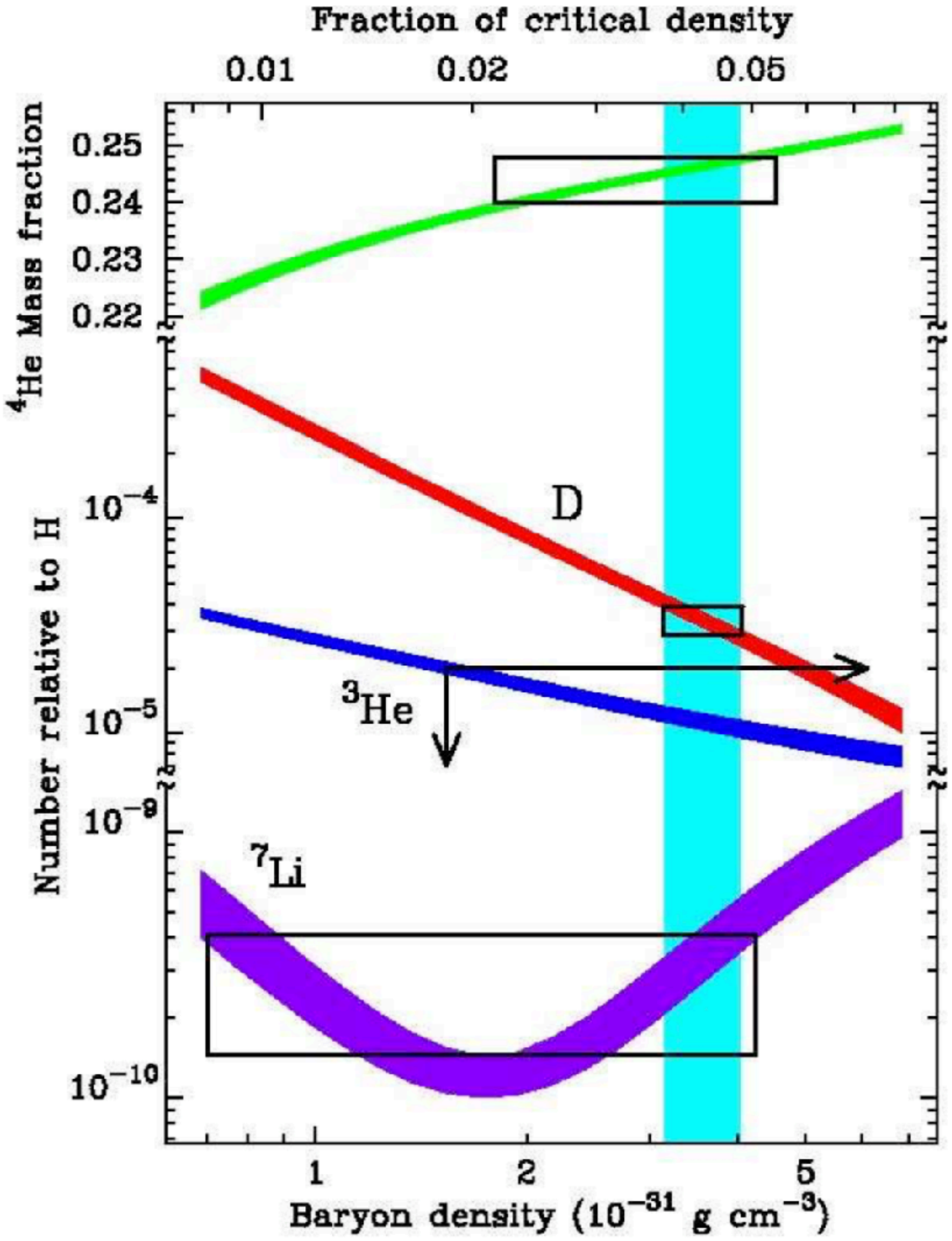
$$T \propto a^{-1} = (1 + z)$$



Time Since Big Bang
Major Events Since Big Bang
present
Humans observe the cosmos.
stars, galaxies and clusters (made of atoms and plasma)
Era of Galaxies
1 billion years
First galaxies form.
atoms and plasma (stars begin to form)
Era of Atoms
380,000 years
Atoms form; photons fly free and become microwave background.
plasma of hydrogen and helium nuclei plus electrons
Era of Nuclei
3 minutes
Fusion ceases; normal matter is 75% hydrogen, 25% helium, by mass.
protons, neutrons, electrons, neutrinos (antimatter rare)
Era of Nucleosynthesis
0.001 seconds
Matter annihilates antimatter.
elementary particles (antimatter common)
Particle Era
10^{-10} seconds
Electromagnetic and weak forces become distinct.
elementary particles
Electroweak Era
10^{-38} seconds
Strong force becomes distinct, perhaps causing inflation of universe.
GUT Era
elementary particles
10^{-43} seconds
Planck Era
????

Normal (baryonic) matter

$$\Omega_b = ?$$



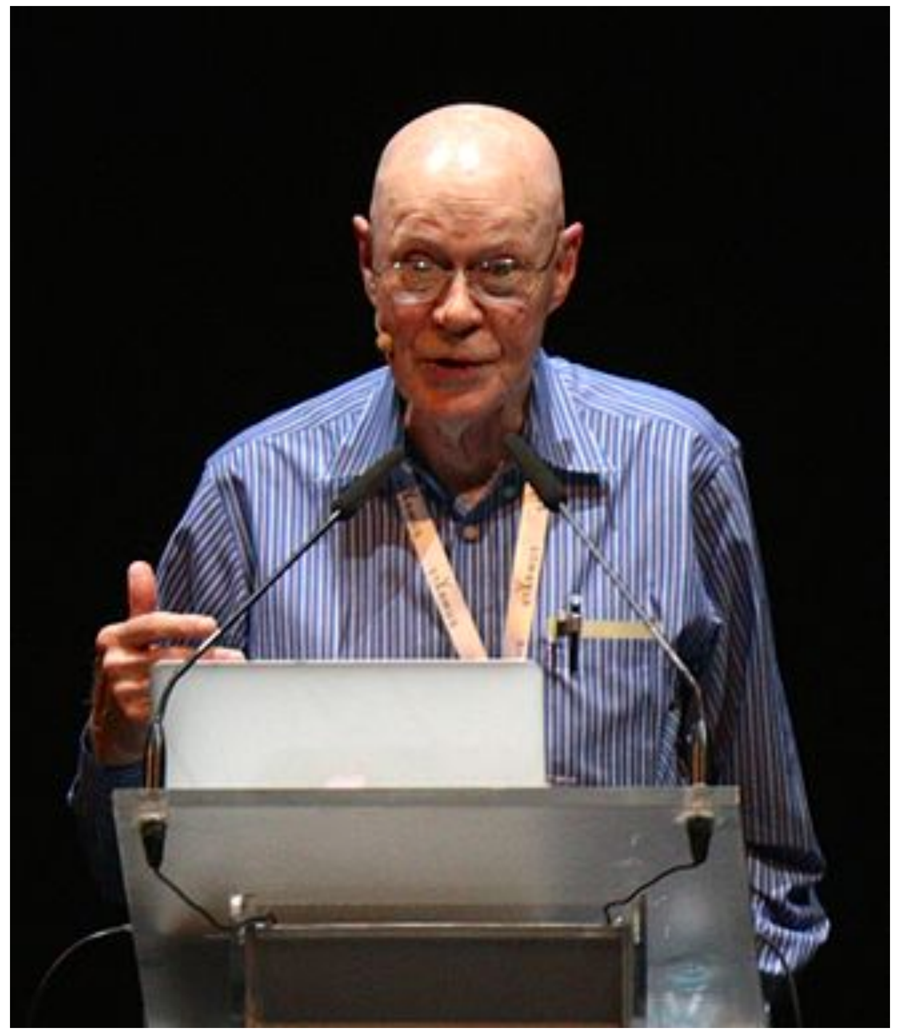
Fraction of critical density
0.01
0.02
0.05
^{4}He Mass fraction
0.25
0.24
0.23
0.22
Number relative to H
10^{-4}
10^{-5}
10^{-9}
10^{-10}
D
^{3}He
^{7}Li
1
2
5
Baryon density (10^{-31} g cm^{-3})

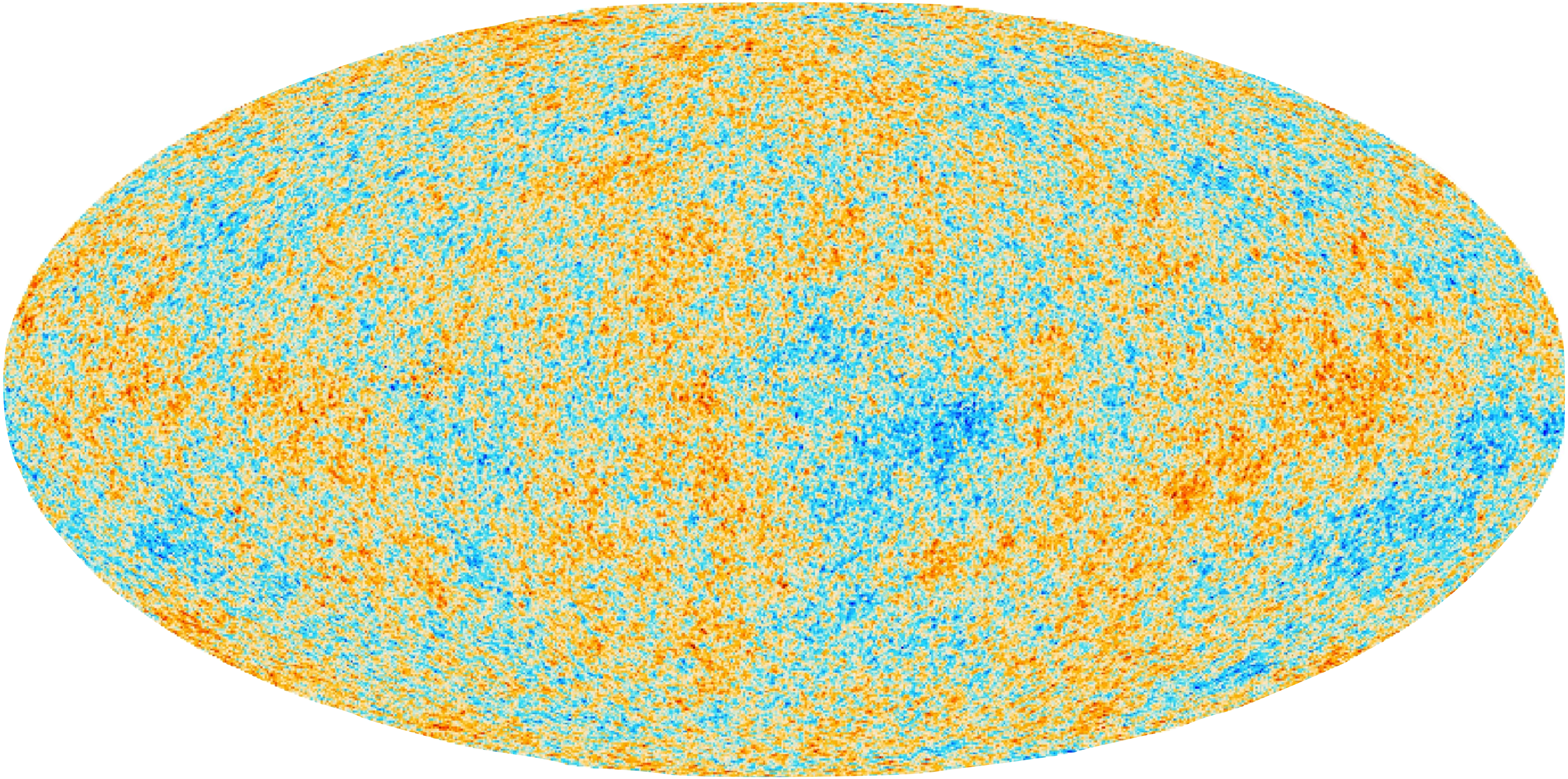
Normal (baryonic) matter

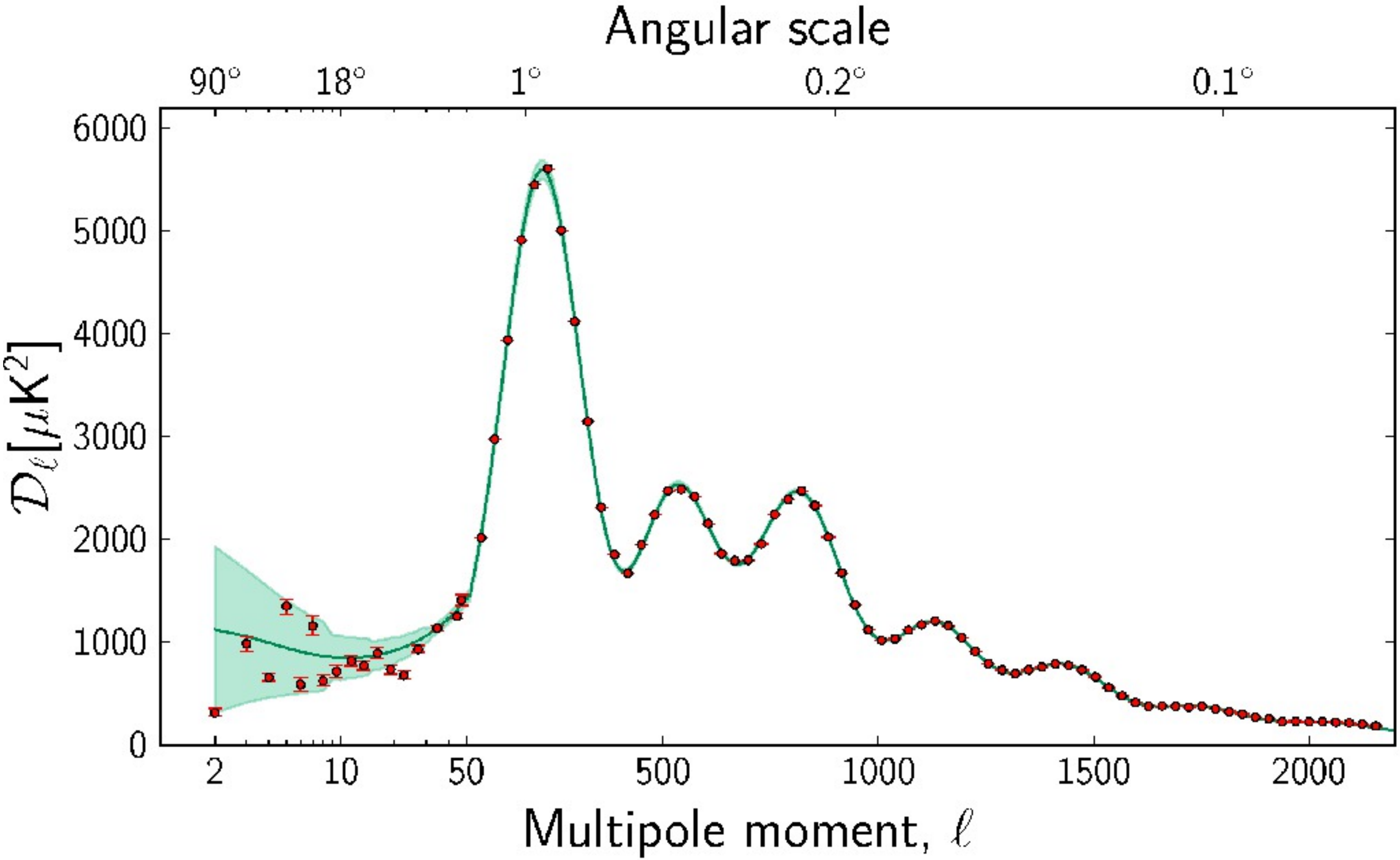
$$\Omega_b = 0.05$$

Recombination / CMB

- 400,000 years after big bang temperature low enough for atoms to form
- Before: opaque plasma
- After: transparent neutral gas
- Light emitted from this time (z~1100) can still be seen today
- Black body radiation with temperature of 2.7K
- Tiny fluctuations in the temperature -> seeds of structure formation



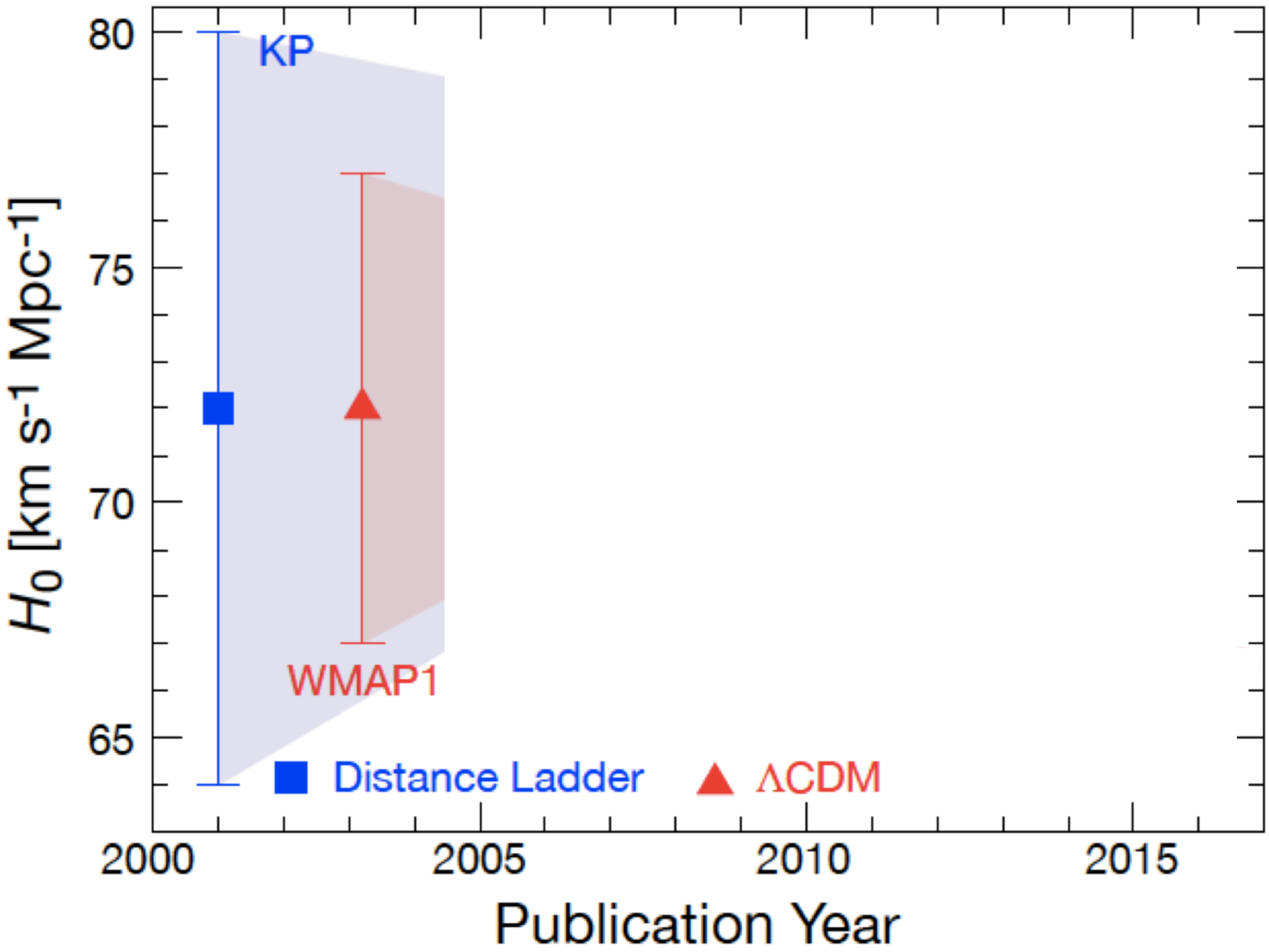




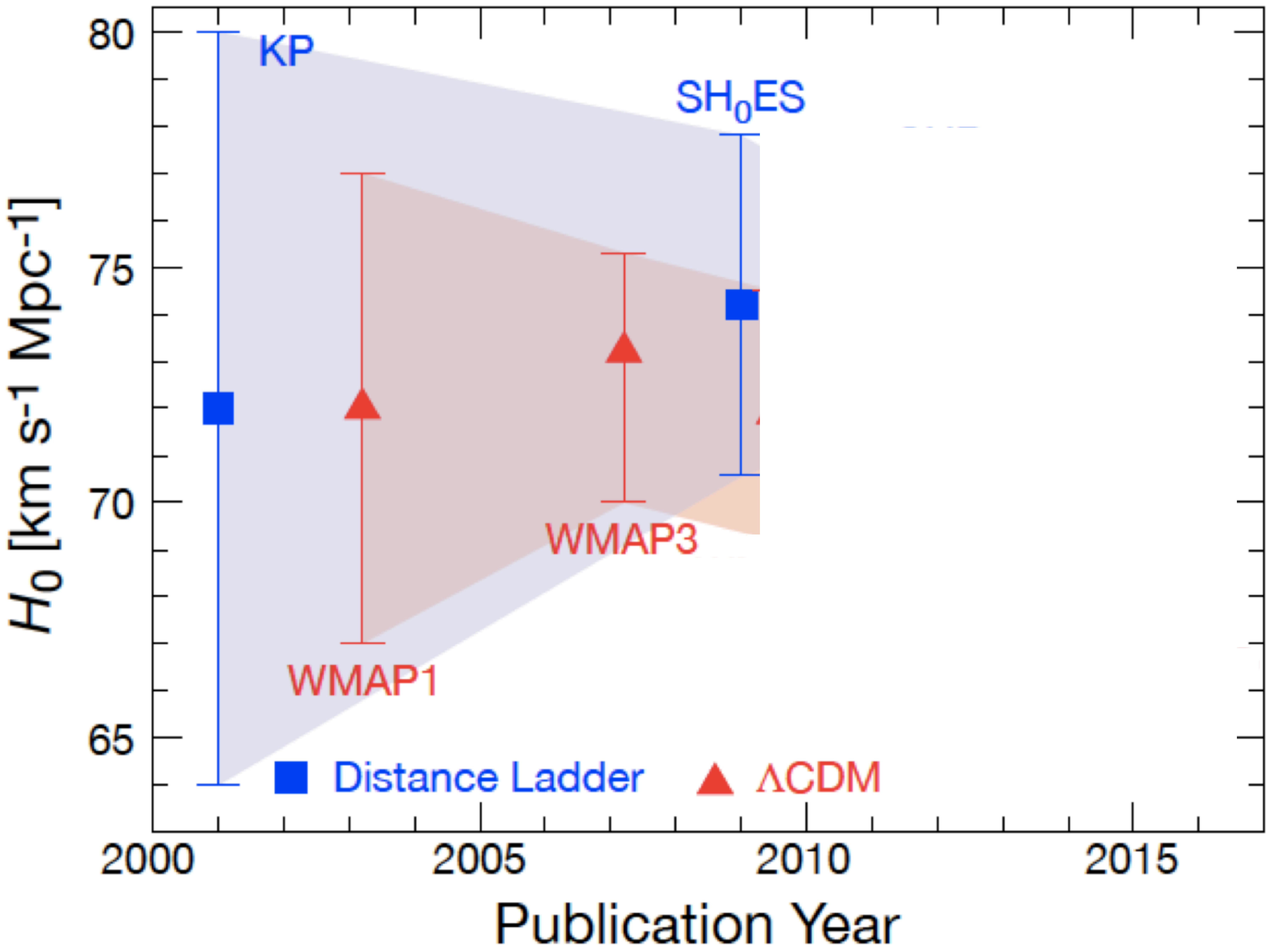
Angular scale
90°
18°
1°
0.2°
0.1°
6000
5000
4000
3000
2000
1000
0
$\mathcal{D}_\ell\,[\mu\mathrm{K}^2]$
2
10
50
500
1000
1500
2000
Multipole moment, ℓ

Parameter	TT+lowP 68 % limits	TT+lowP+lensing 68 % limits	TT+lowP+lensing+ext 68 % limits	TT,TE,EE+lowP 68 % limits	TT,TE,EE+lowP+lensing 68 % limits	TT,TE,EE+lowP+lensing+ext 68 % limits
$\Omega_b h^2$	0.02222 ± 0.00023	0.02226 ± 0.00023	0.02227 ± 0.00020	0.02225 ± 0.00016	0.02226 ± 0.00016	0.02230 ± 0.00014
$\Omega_c h^2$	0.1197 ± 0.0022	0.1186 ± 0.0020	0.1184 ± 0.0012	0.1198 ± 0.0015	0.1193 ± 0.0014	0.1188 ± 0.0010
$100\theta_{MC}$	1.04085 ± 0.00047	1.04103 ± 0.00046	1.04106 ± 0.00041	1.04077 ± 0.00032	1.04087 ± 0.00032	1.04093 ± 0.00030
τ	0.078 ± 0.019	0.066 ± 0.016	0.067 ± 0.013	0.079 ± 0.017	0.063 ± 0.014	0.066 ± 0.012
$\ln(10^{10} A_s)$	3.089 ± 0.036	3.062 ± 0.029	3.064 ± 0.024	3.094 ± 0.034	3.059 ± 0.025	3.064 ± 0.023
n_s	0.9655 ± 0.0062	0.9677 ± 0.0060	0.9681 ± 0.0044	0.9645 ± 0.0049	0.9653 ± 0.0048	0.9667 ± 0.0040
H_0	67.31 ± 0.96	67.81 ± 0.92	67.90 ± 0.55	67.27 ± 0.66	67.51 ± 0.64	67.74 ± 0.46
Ω_Λ	0.685 ± 0.013	0.692 ± 0.012	0.6935 ± 0.0072	0.6844 ± 0.0091	0.6879 ± 0.0087	0.6911 ± 0.0062
Ω_m	0.315 ± 0.013	0.308 ± 0.012	0.3065 ± 0.0072	0.3156 ± 0.0091	0.3121 ± 0.0087	0.3089 ± 0.0062
$\Omega_m h^2$	0.1426 ± 0.0020	0.1415 ± 0.0019	0.1413 ± 0.0011	0.1427 ± 0.0014	0.1422 ± 0.0013	0.14170 ± 0.00097
$\Omega_m h^3$	0.09597 ± 0.00045	0.09591 ± 0.00045	0.09593 ± 0.00045	0.09601 ± 0.00029	0.09596 ± 0.00030	0.09598 ± 0.00029
σ_8	0.829 ± 0.014	0.8149 ± 0.0093	0.8154 ± 0.0090	0.831 ± 0.013	0.8150 ± 0.0087	0.8159 ± 0.0086
$\sigma_8 \Omega_m^{0.5}$	0.466 ± 0.013	0.4521 ± 0.0088	0.4514 ± 0.0066	0.4668 ± 0.0098	0.4553 ± 0.0068	0.4535 ± 0.0059
$\sigma_8 \Omega_m^{0.25}$	0.621 ± 0.013	0.6069 ± 0.0076	0.6066 ± 0.0070	0.623 ± 0.011	0.6091 ± 0.0067	0.6083 ± 0.0066
z_{re}	$9.9^{+1.8}_{-1.6}$	$8.8^{+1.7}_{-1.4}$	$8.9^{+1.3}_{-1.2}$	$10.0^{+1.7}_{-1.5}$	$8.5^{+1.4}_{-1.2}$	$8.8^{+1.2}_{-1.1}$
$10^9 A_s$	$2.198^{+0.076}_{-0.085}$	2.139 ± 0.063	2.143 ± 0.051	2.207 ± 0.074	2.130 ± 0.053	2.142 ± 0.049
$10^9 A_s e^{-2\tau}$	1.880 ± 0.014	1.874 ± 0.013	1.873 ± 0.011	1.882 ± 0.012	1.878 ± 0.011	1.876 ± 0.011
Age/Gyr	13.813 ± 0.038	13.799 ± 0.038	13.796 ± 0.029	13.813 ± 0.026	13.807 ± 0.026	13.799 ± 0.021
z_*	1090.09 ± 0.42	1089.94 ± 0.42	1089.90 ± 0.30	1090.06 ± 0.30	1090.00 ± 0.29	1089.90 ± 0.23
r_*	144.61 ± 0.49	144.89 ± 0.44	144.93 ± 0.30	144.57 ± 0.32	144.71 ± 0.31	144.81 ± 0.24
$100\theta_*$	1.04105 ± 0.00046	1.04122 ± 0.00045	1.04126 ± 0.00041	1.04096 ± 0.00032	1.04106 ± 0.00031	1.04112 ± 0.00029
z_{drag}	1059.57 ± 0.46	1059.57 ± 0.47	1059.60 ± 0.44	1059.65 ± 0.31	1059.62 ± 0.31	1059.68 ± 0.29
r_{drag}	147.33 ± 0.49	147.60 ± 0.43	147.63 ± 0.32	147.27 ± 0.31	147.41 ± 0.30	147.50 ± 0.24
k_D	0.14050 ± 0.00052	0.14024 ± 0.00047	0.14022 ± 0.00042	0.14059 ± 0.00032	0.14044 ± 0.00032	0.14038 ± 0.00029
z_{eq}	3393 ± 49	3365 ± 44	3361 ± 27	3395 ± 33	3382 ± 32	3371 ± 23
k_{eq}	0.01035 ± 0.00015	0.01027 ± 0.00014	0.010258 ± 0.000083	0.01036 ± 0.00010	0.010322 ± 0.000096	0.010288 ± 0.000071
$100\theta_{s,eq}$	0.4502 ± 0.0047	0.4529 ± 0.0044	0.4533 ± 0.0026	0.4499 ± 0.0032	0.4512 ± 0.0031	0.4523 ± 0.0023

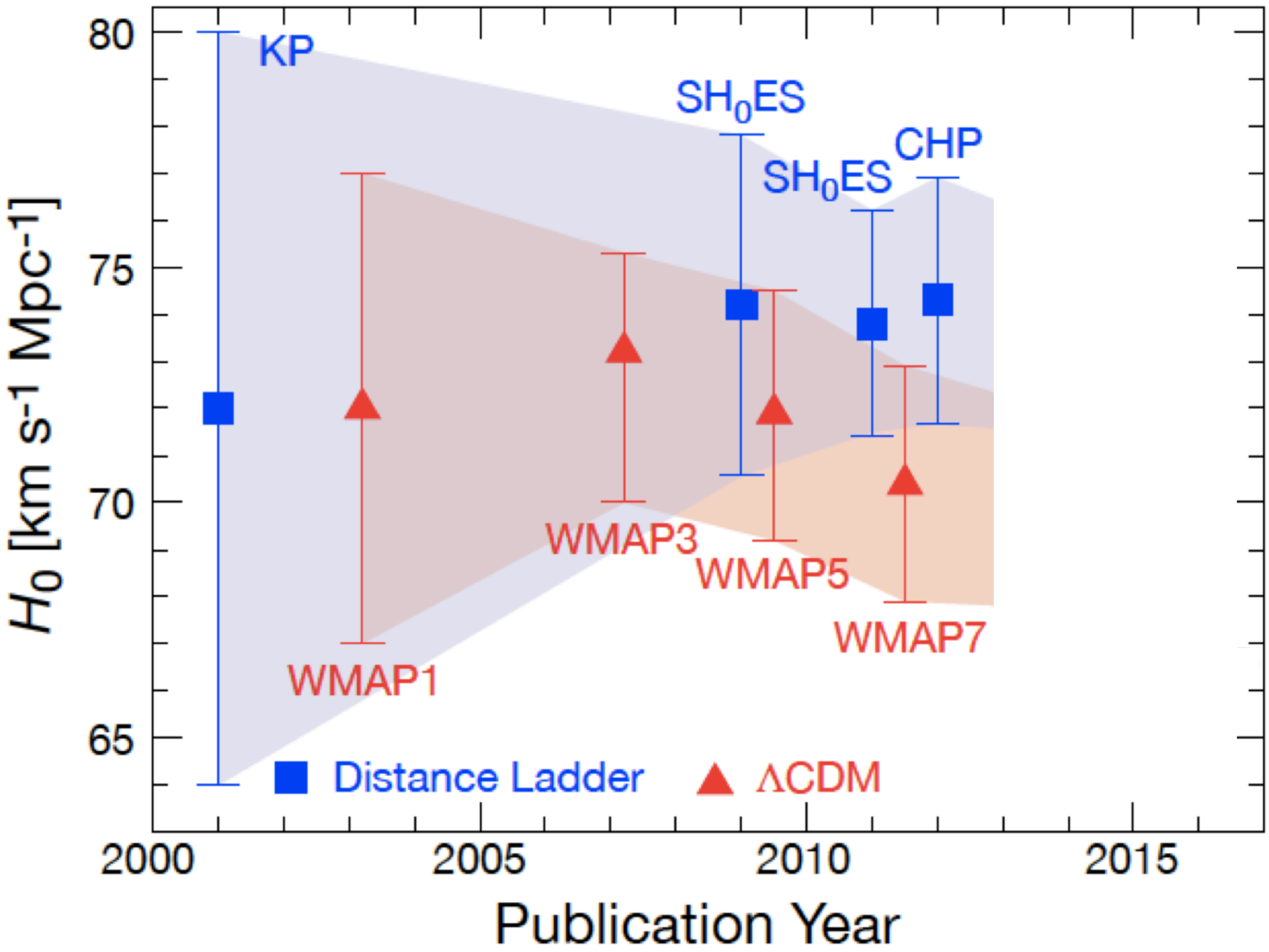
Planck 2015 results XIII.



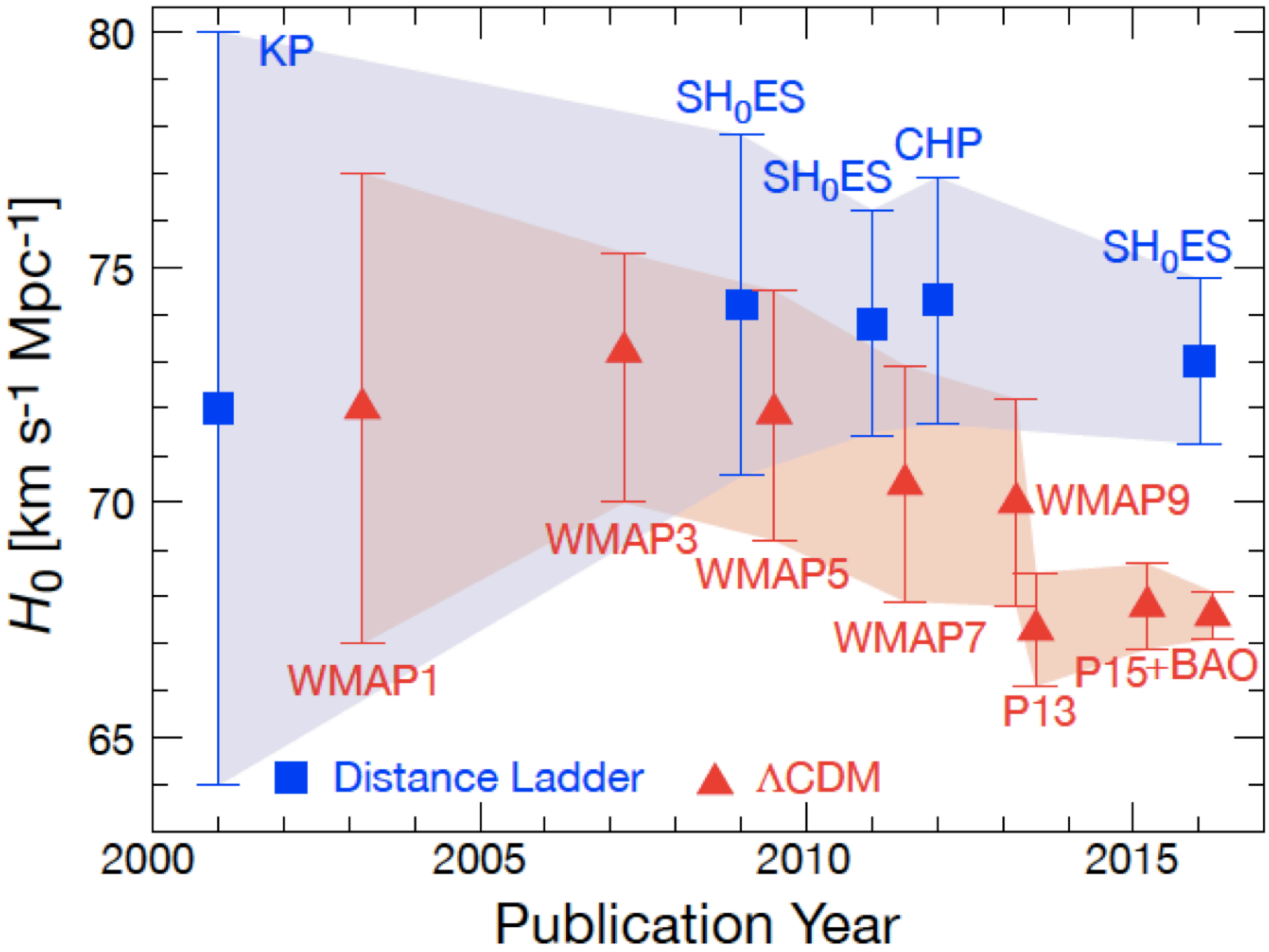
Freedman (2017)



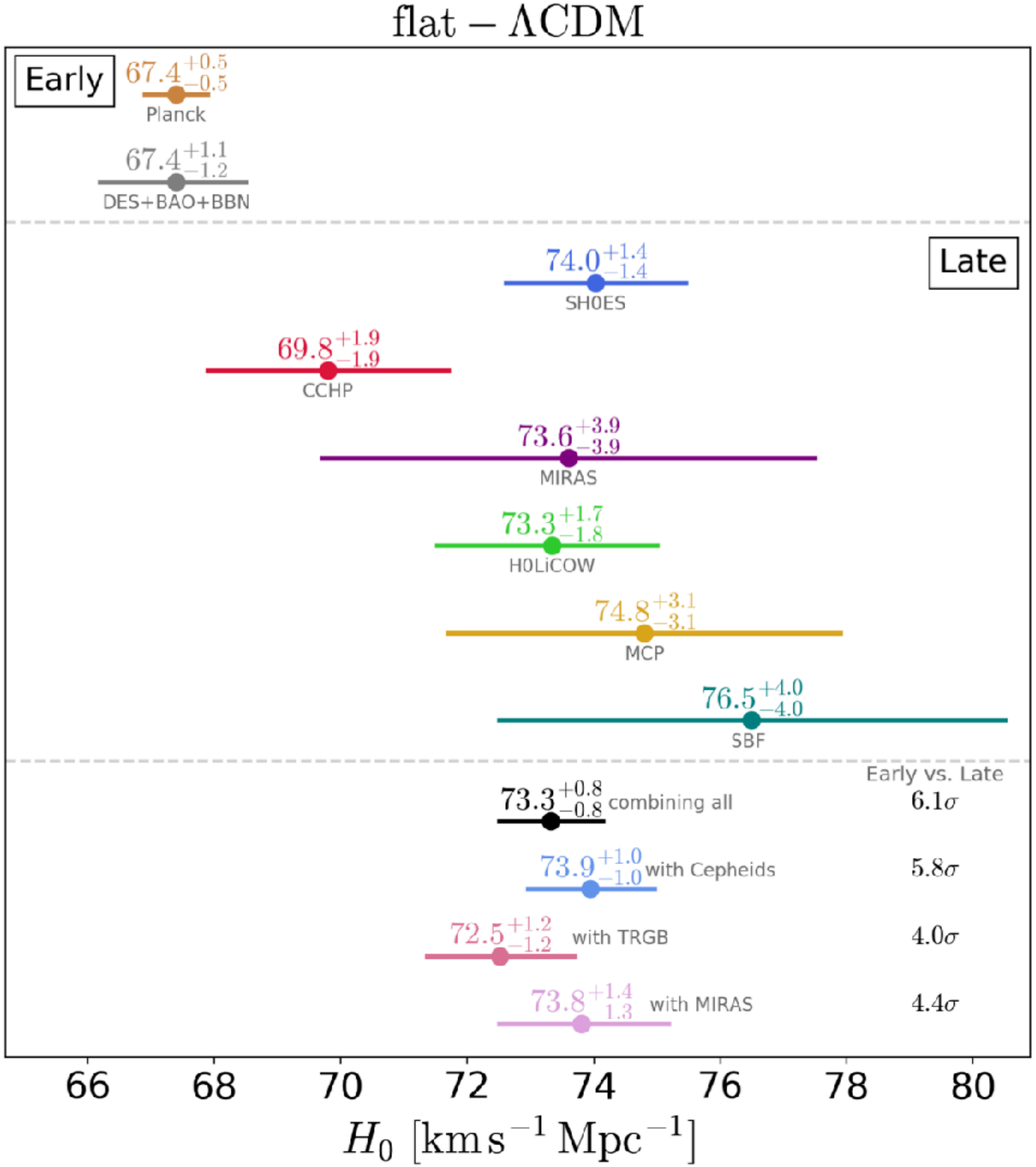
Freedman (2017)



Freedman (2017)



Freedman (2017)

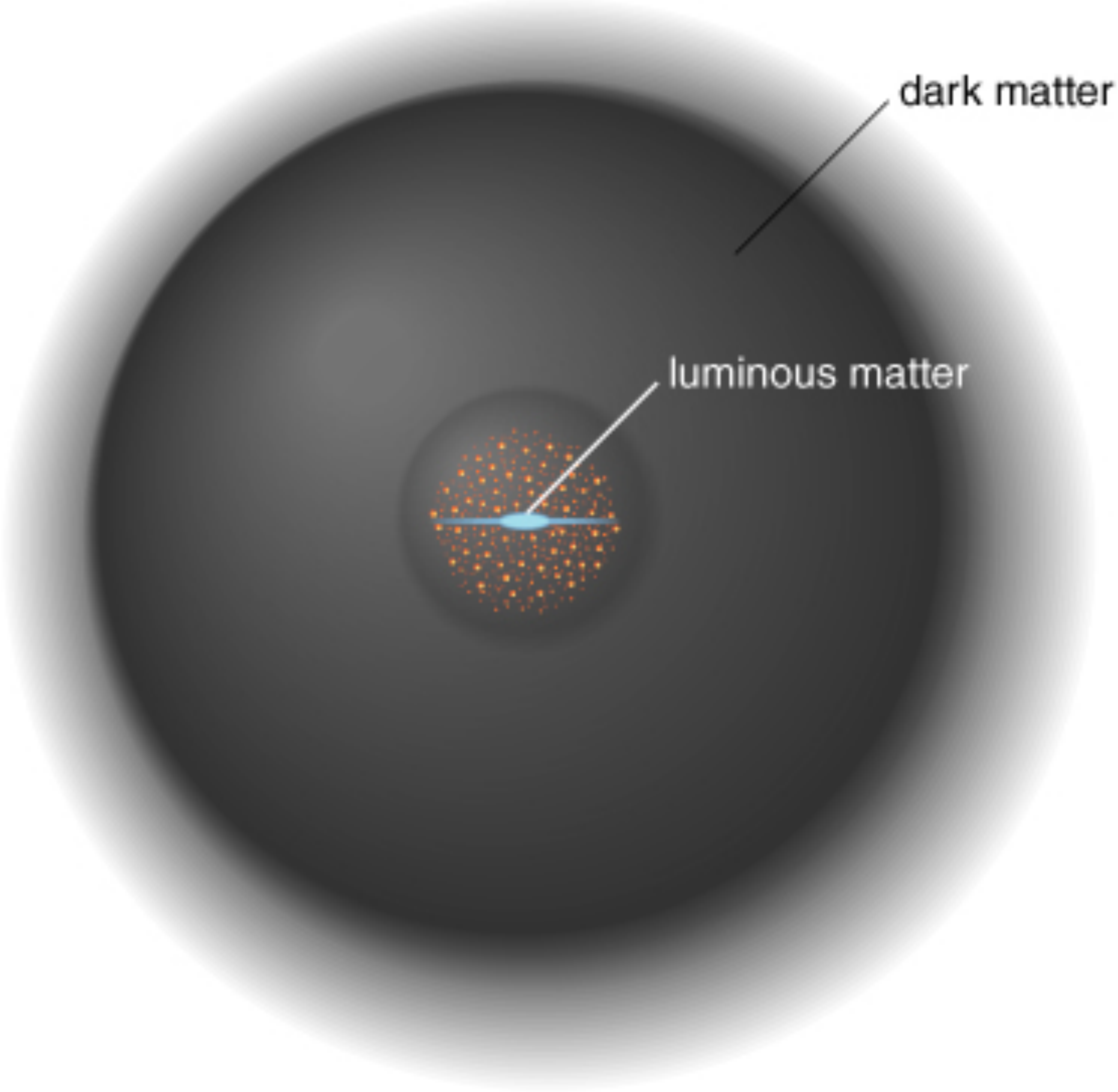


Verde et al. (2019)

Normal (baryonic) matter

$$\Omega_b = 0.05$$

Open Universe?


dark matter
luminous matter

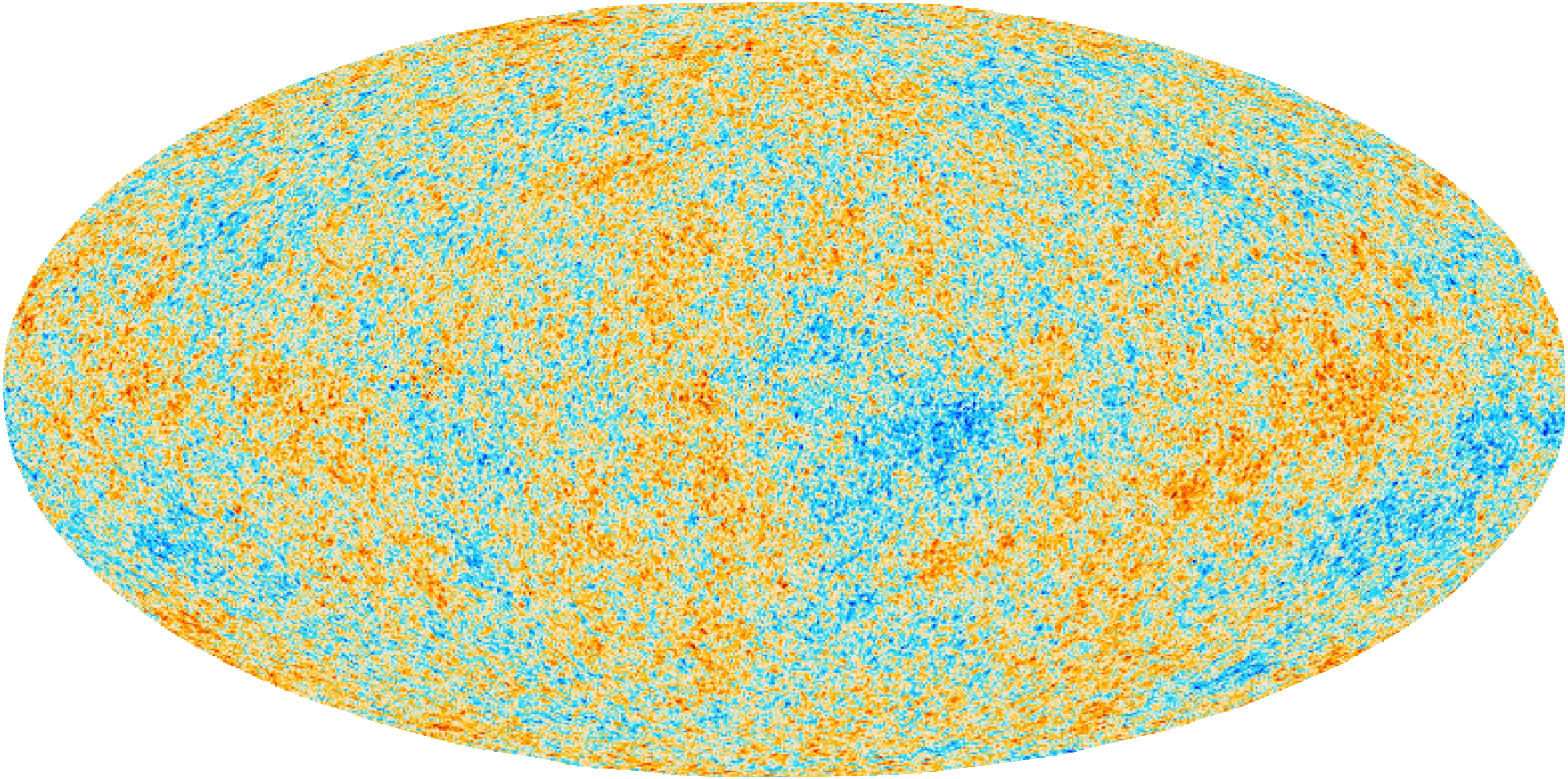
Expansion depends on contents

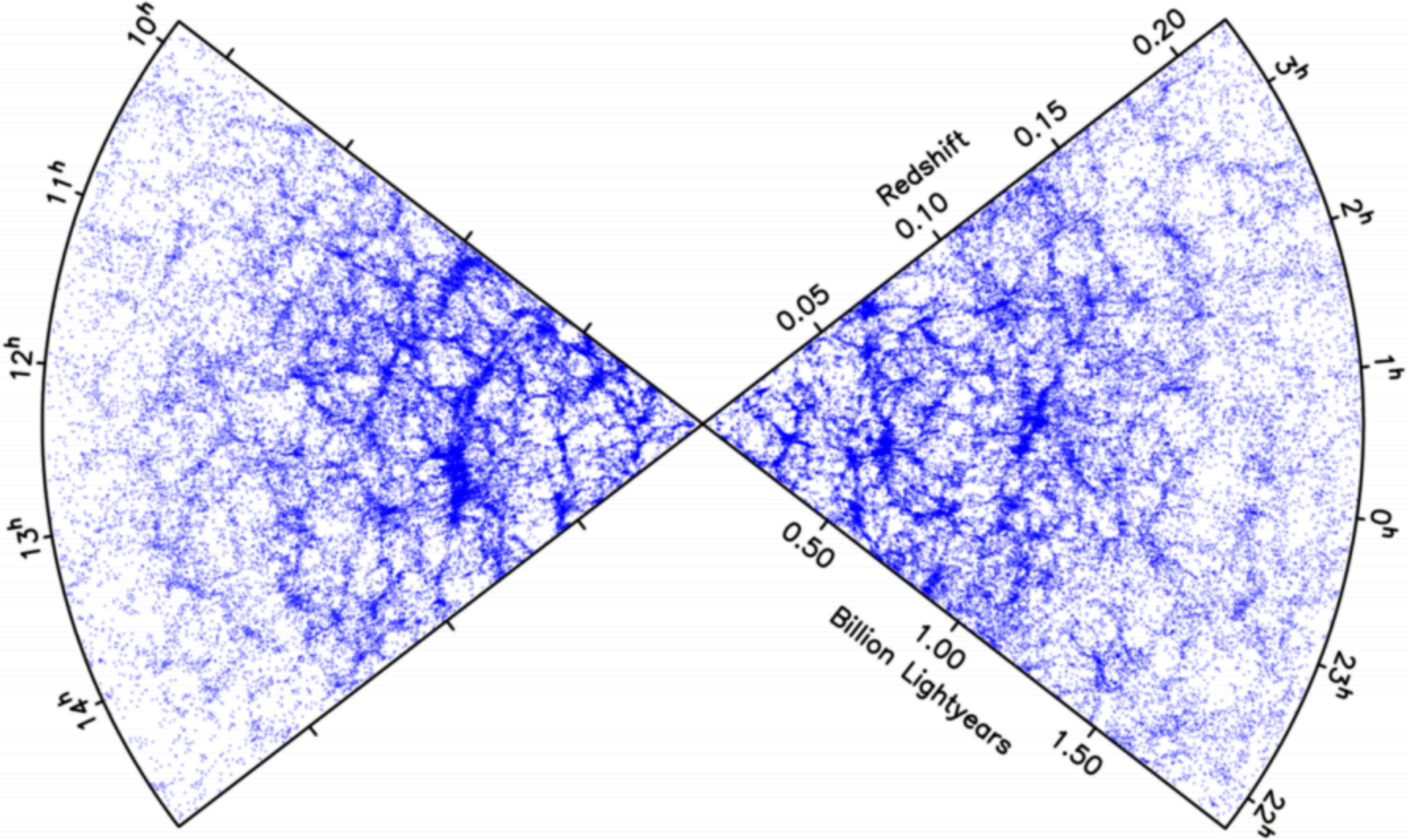
- Normal matter
- Electromagnetic radiation
- Dark matter

Dark Matter

$$\Omega_{dm} = ?$$

Cosmic structure formation





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

Structure formation

- Small fluctuations around the mean cosmic density present at early times
- Overdensities/underdensities grow over time due to gravitational instability
- Can be described mathematically with perturbation theory
- Growth depends on cosmological parameters
- High-density regions need to be simulated
- Structure growth is a very rich resource of cosmological information

Dark Matter

$$\Omega_{dm} = 0.25$$

Dark Matter

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

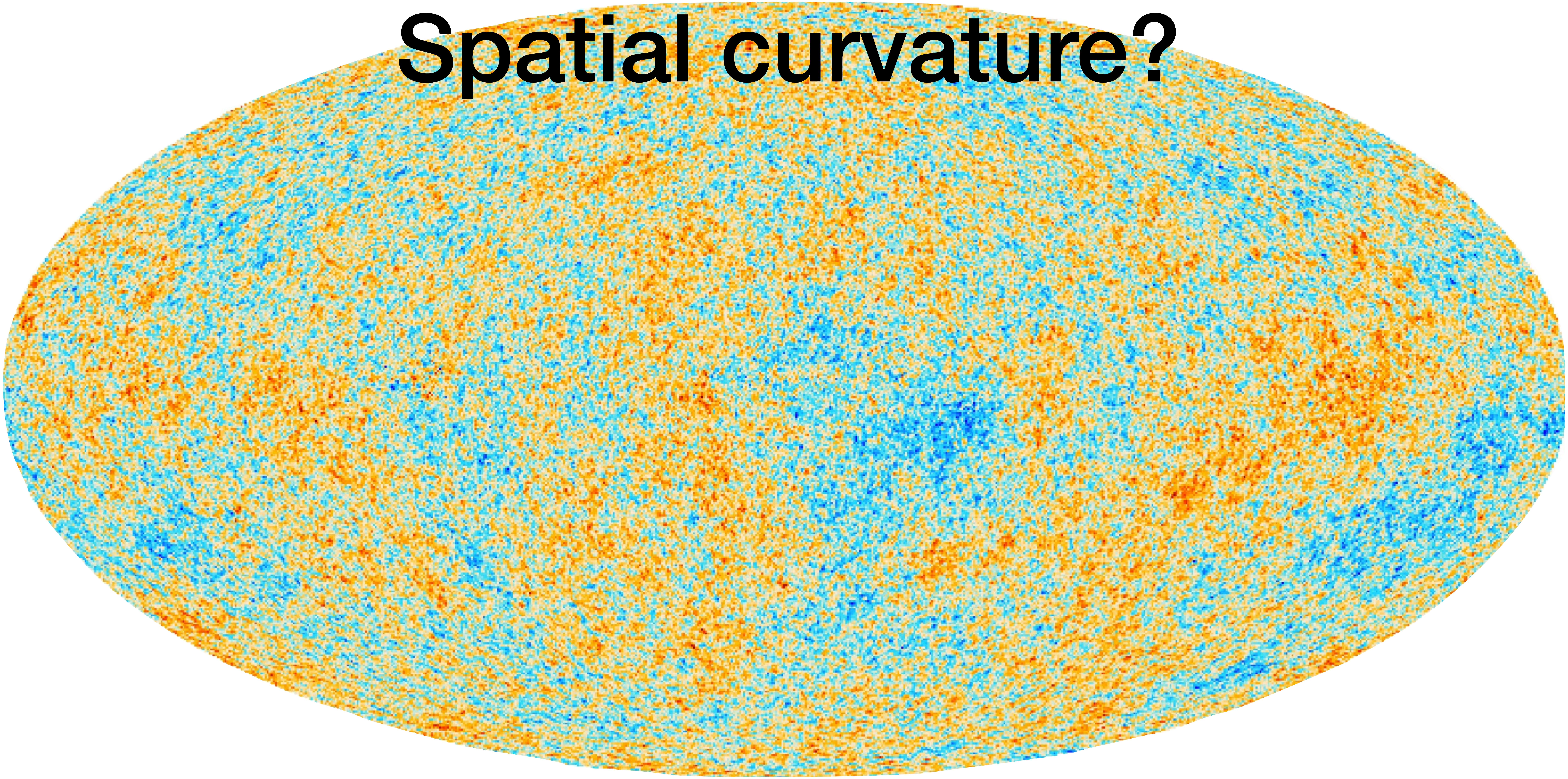
- Alternative: Modification of general relativity

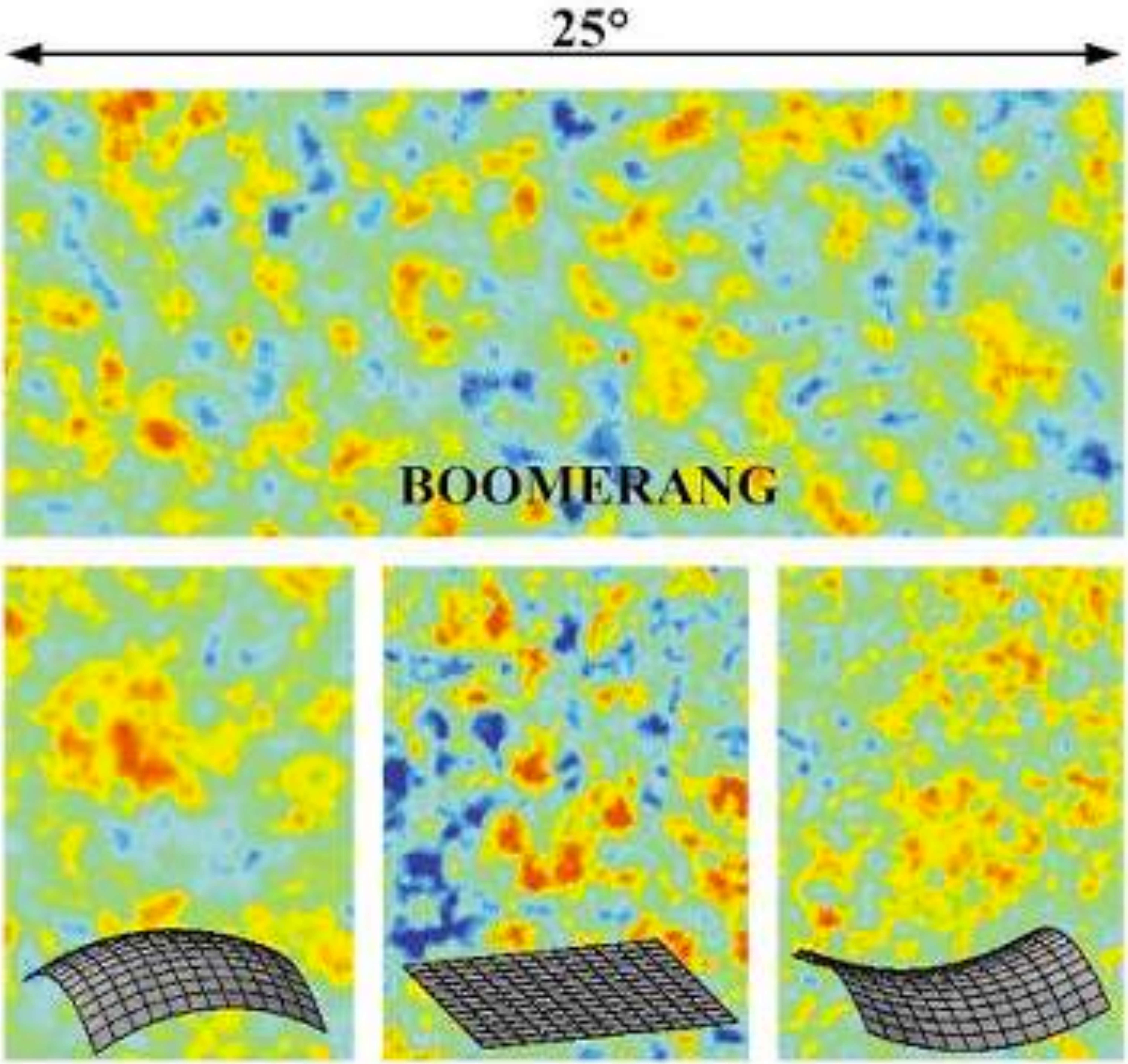
Total matter density

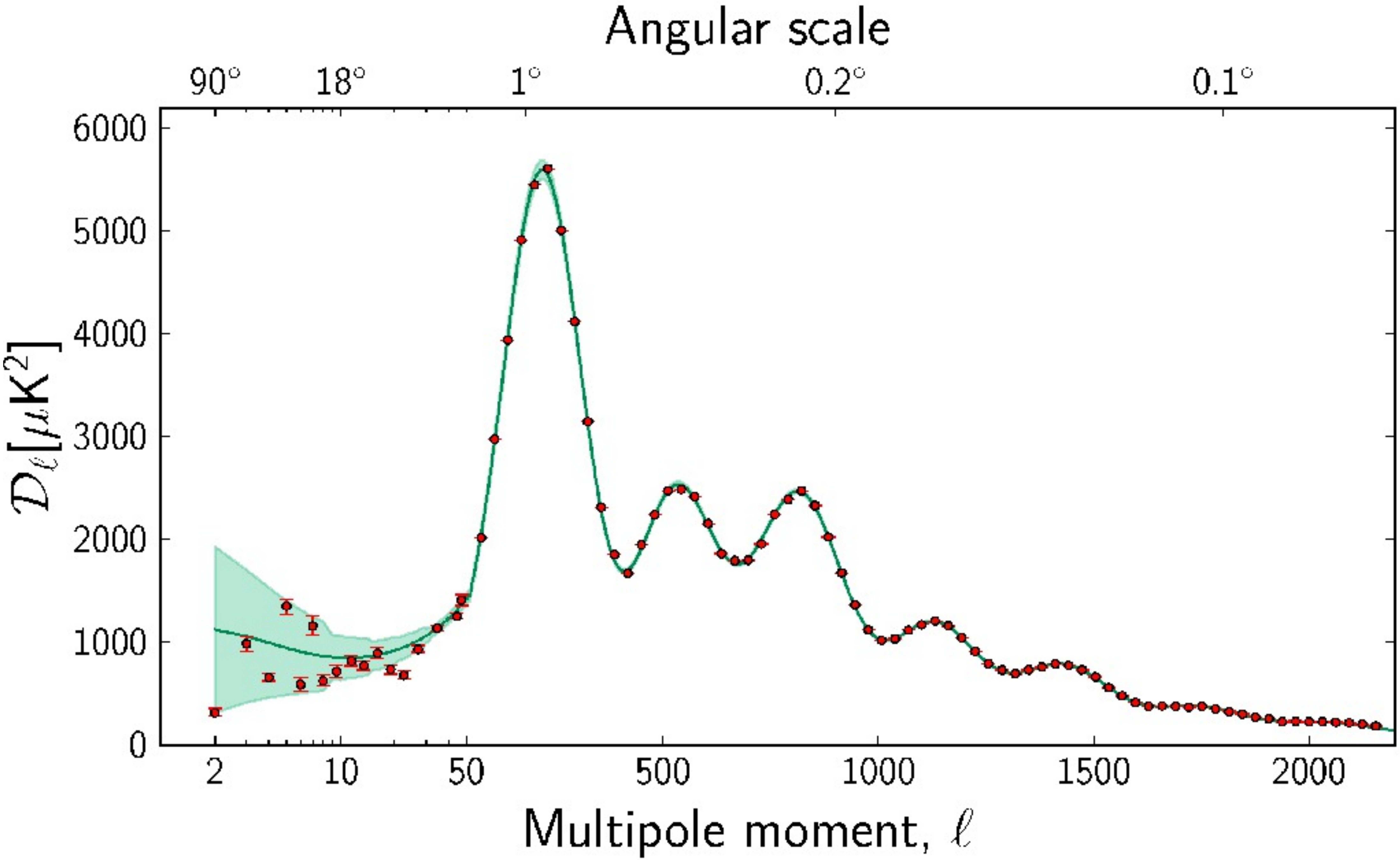
$$\Omega_m = \Omega_b + \Omega_{dm} = 0.3$$

Open Universe?

Spatial curvature?




25°
BOOMERANG



Angular scale
90°
18°
1°
0.2°
0.1°
6000
5000
4000
3000
2000
1000
0
$\mathcal{D}_\ell\,[\mu K^2]$
2
10
50
500
1000
1500
2000
Multipole moment, ℓ

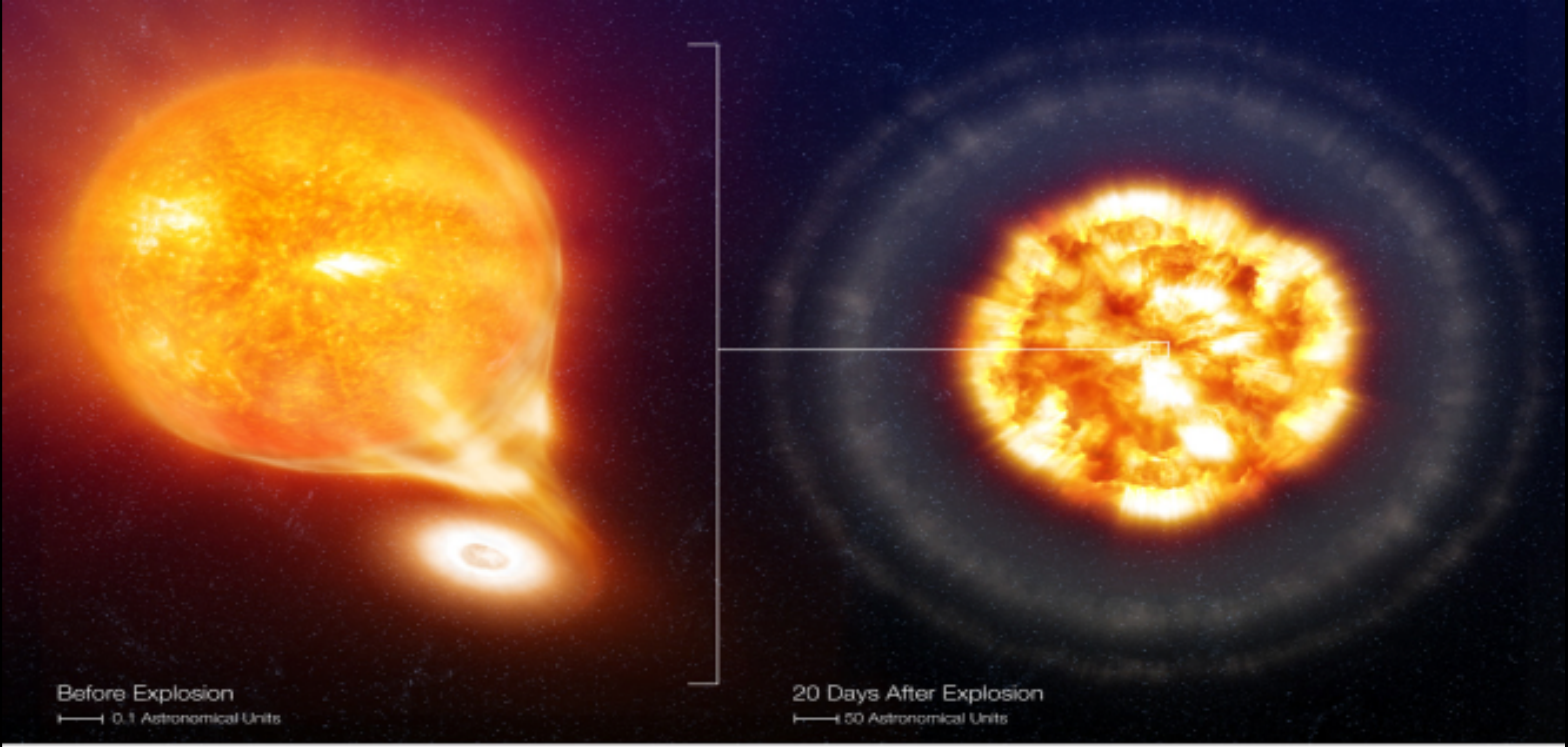
Parameter	TT+lowP 68 % limits	TT+lowP+lensing 68 % limits	TT+lowP+lensing+ext 68 % limits	TT,TE,EE+lowP 68 % limits	TT,TE,EE+lowP+lensing 68 % limits	TT,TE,EE+lowP+lensing+ext 68 % limits
$\Omega_b h^2$	0.02222 ± 0.00023	0.02226 ± 0.00023	0.02227 ± 0.00020	0.02225 ± 0.00016	0.02226 ± 0.00016	0.02230 ± 0.00014
$\Omega_c h^2$	0.1197 ± 0.0022	0.1186 ± 0.0020	0.1184 ± 0.0012	0.1198 ± 0.0015	0.1193 ± 0.0014	0.1188 ± 0.0010
$100\theta_{MC}$	1.04085 ± 0.00047	1.04103 ± 0.00046	1.04106 ± 0.00041	1.04077 ± 0.00032	1.04087 ± 0.00032	1.04093 ± 0.00030
τ	0.078 ± 0.019	0.066 ± 0.016	0.067 ± 0.013	0.079 ± 0.017	0.063 ± 0.014	0.066 ± 0.012
$\ln(10^{10} A_s)$	3.089 ± 0.036	3.062 ± 0.029	3.064 ± 0.024	3.094 ± 0.034	3.059 ± 0.025	3.064 ± 0.023
n_s	0.9655 ± 0.0062	0.9677 ± 0.0060	0.9681 ± 0.0044	0.9645 ± 0.0049	0.9653 ± 0.0048	0.9667 ± 0.0040
H_0	67.31 ± 0.96	67.81 ± 0.92	67.90 ± 0.55	67.27 ± 0.66	67.51 ± 0.64	67.74 ± 0.46
Ω_Λ	0.685 ± 0.013	0.692 ± 0.012	0.6935 ± 0.0072	0.6844 ± 0.0091	0.6879 ± 0.0087	0.6911 ± 0.0062
Ω_m	0.315 ± 0.013	0.308 ± 0.012	0.3065 ± 0.0072	0.3156 ± 0.0091	0.3121 ± 0.0087	0.3089 ± 0.0062
$\Omega_m h^2$	0.1426 ± 0.0020	0.1415 ± 0.0019	0.1413 ± 0.0011	0.1427 ± 0.0014	0.1422 ± 0.0013	0.14170 ± 0.00097
$\Omega_m h^3$	0.09597 ± 0.00045	0.09591 ± 0.00045	0.09593 ± 0.00045	0.09601 ± 0.00029	0.09596 ± 0.00030	0.09598 ± 0.00029
σ_8	0.829 ± 0.014	0.8149 ± 0.0093	0.8154 ± 0.0090	0.831 ± 0.013	0.8150 ± 0.0087	0.8159 ± 0.0086
$\sigma_8 \Omega_m^{0.5}$	0.466 ± 0.013	0.4521 ± 0.0088	0.4514 ± 0.0066	0.4668 ± 0.0098	0.4553 ± 0.0068	0.4535 ± 0.0059
$\sigma_8 \Omega_m^{0.25}$	0.621 ± 0.013	0.6069 ± 0.0076	0.6066 ± 0.0070	0.623 ± 0.011	0.6091 ± 0.0067	0.6083 ± 0.0066
z_{re}	$9.9^{+1.8}_{-1.6}$	$8.8^{+1.7}_{-1.4}$	$8.9^{+1.3}_{-1.2}$	$10.0^{+1.7}_{-1.5}$	$8.5^{+1.4}_{-1.2}$	$8.8^{+1.2}_{-1.1}$
$10^9 A_s$	$2.198^{+0.076}_{-0.085}$	2.139 ± 0.063	2.143 ± 0.051	2.207 ± 0.074	2.130 ± 0.053	2.142 ± 0.049
$10^9 A_s e^{-2\tau}$	1.880 ± 0.014	1.874 ± 0.013	1.873 ± 0.011	1.882 ± 0.012	1.878 ± 0.011	1.876 ± 0.011
Age/Gyr	13.813 ± 0.038	13.799 ± 0.038	13.796 ± 0.029	13.813 ± 0.026	13.807 ± 0.026	13.799 ± 0.021
z_*	1090.09 ± 0.42	1089.94 ± 0.42	1089.90 ± 0.30	1090.06 ± 0.30	1090.00 ± 0.29	1089.90 ± 0.23
r_*	144.61 ± 0.49	144.89 ± 0.44	144.93 ± 0.30	144.57 ± 0.32	144.71 ± 0.31	144.81 ± 0.24
$100\theta_*$	1.04105 ± 0.00046	1.04122 ± 0.00045	1.04126 ± 0.00041	1.04096 ± 0.00032	1.04106 ± 0.00031	1.04112 ± 0.00029
z_{drag}	1059.57 ± 0.46	1059.57 ± 0.47	1059.60 ± 0.44	1059.65 ± 0.31	1059.62 ± 0.31	1059.68 ± 0.29
r_{drag}	147.33 ± 0.49	147.60 ± 0.43	147.63 ± 0.32	147.27 ± 0.31	147.41 ± 0.30	147.50 ± 0.24
k_D	0.14050 ± 0.00052	0.14024 ± 0.00047	0.14022 ± 0.00042	0.14059 ± 0.00032	0.14044 ± 0.00032	0.14038 ± 0.00029
z_{eq}	3393 ± 49	3365 ± 44	3361 ± 27	3395 ± 33	3382 ± 32	3371 ± 23
k_{eq}	0.01035 ± 0.00015	0.01027 ± 0.00014	0.010258 ± 0.000083	0.01036 ± 0.00010	0.010322 ± 0.000096	0.010288 ± 0.000071
$100\theta_{s,eq}$	0.4502 ± 0.0047	0.4529 ± 0.0044	0.4533 ± 0.0026	0.4499 ± 0.0032	0.4512 ± 0.0031	0.4523 ± 0.0023

Planck 2015 results XIII.

$$\Omega_0 = 1 \pm 0.01$$

Expansion depends on contents

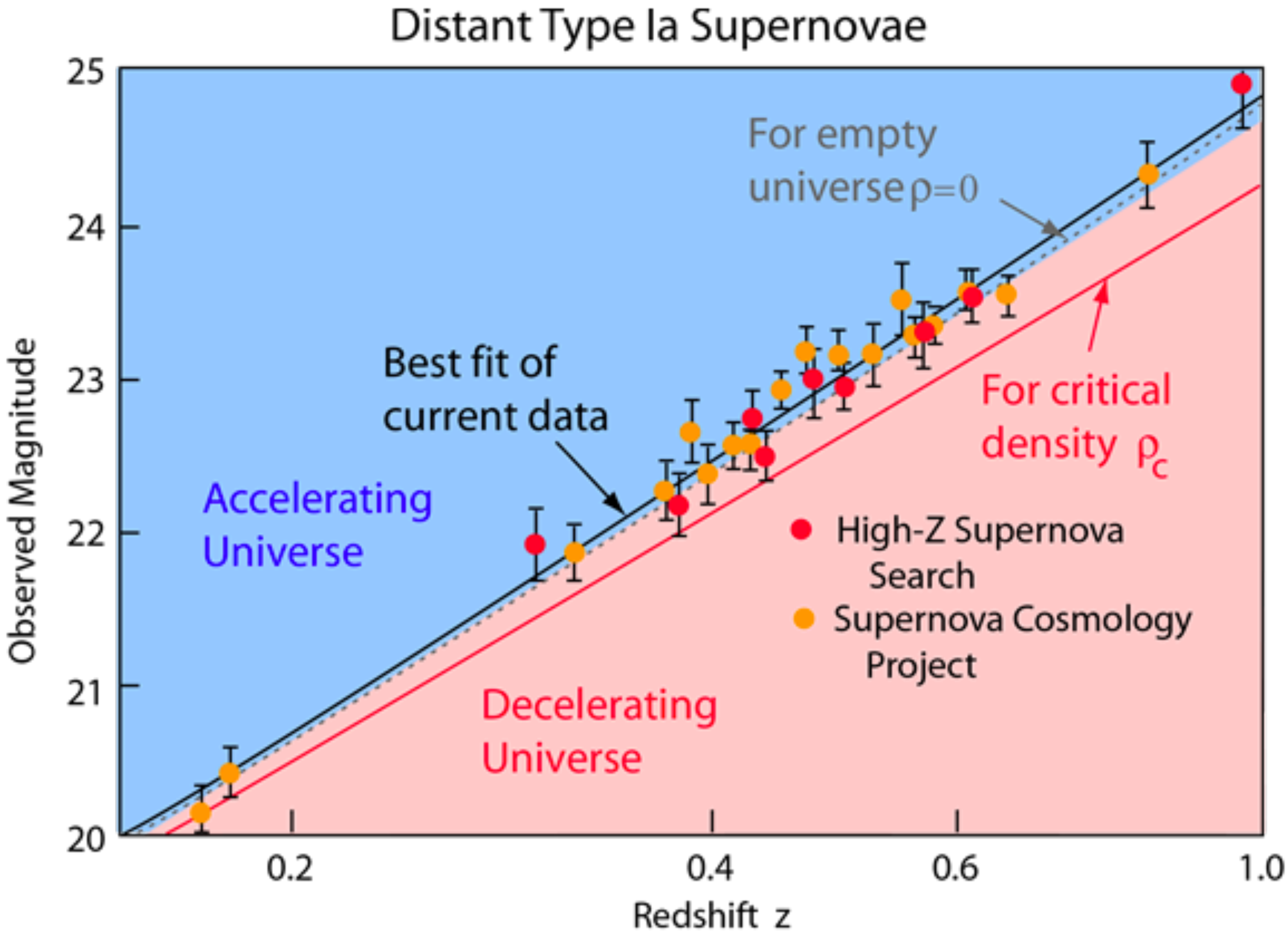
- Normal matter
- Electromagnetic radiation
- Dark matter
- …



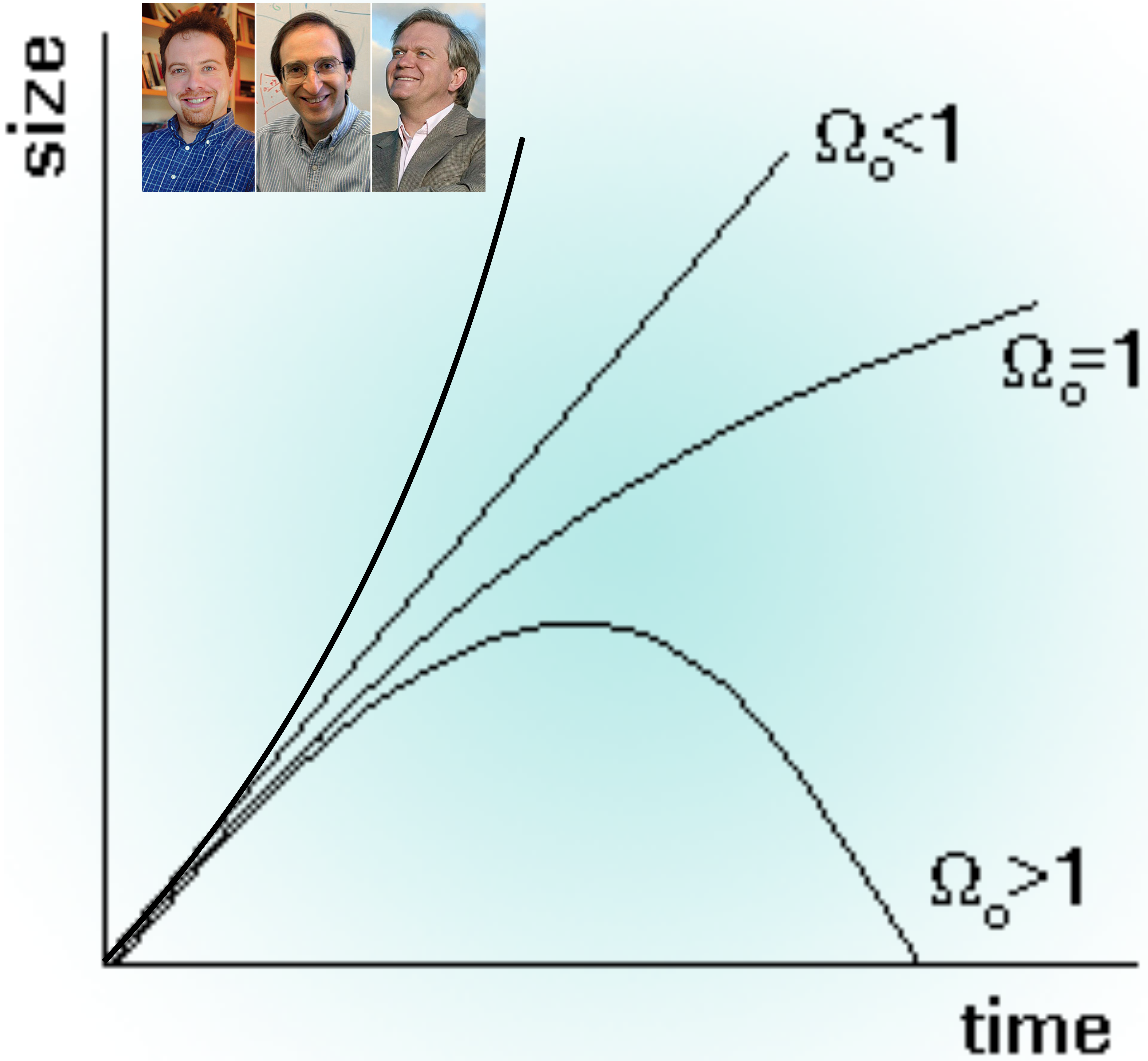
SN 2006X, before and after the Type Ia Supernova Explosion
(Artist Impression)

ESO Press Photo 31b/07 (12 July 2007)


Host Galaxies of Distant Supernovae
HST ▪ ACS/WFC
HST04Sas
HST04Yow
HST04Zwi
HST05Lan
HST05Str
NASA, ESA, and A. Riess (STScI)
STScI-PRC06-52



Distant Type Ia Supernovae
Observed Magnitude
25
24
23
22
21
20
Redshift z
0.2
0.4
0.6
1.0
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
$\Omega_o<1$
$\Omega_o=1$
$\Omega_o>1$
time

Expansion depends on contents

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

Energy density of dark energy

$$\Omega_{de} = ?$$

Energy density of dark energy

$$\Omega_{de} = 0.7$$

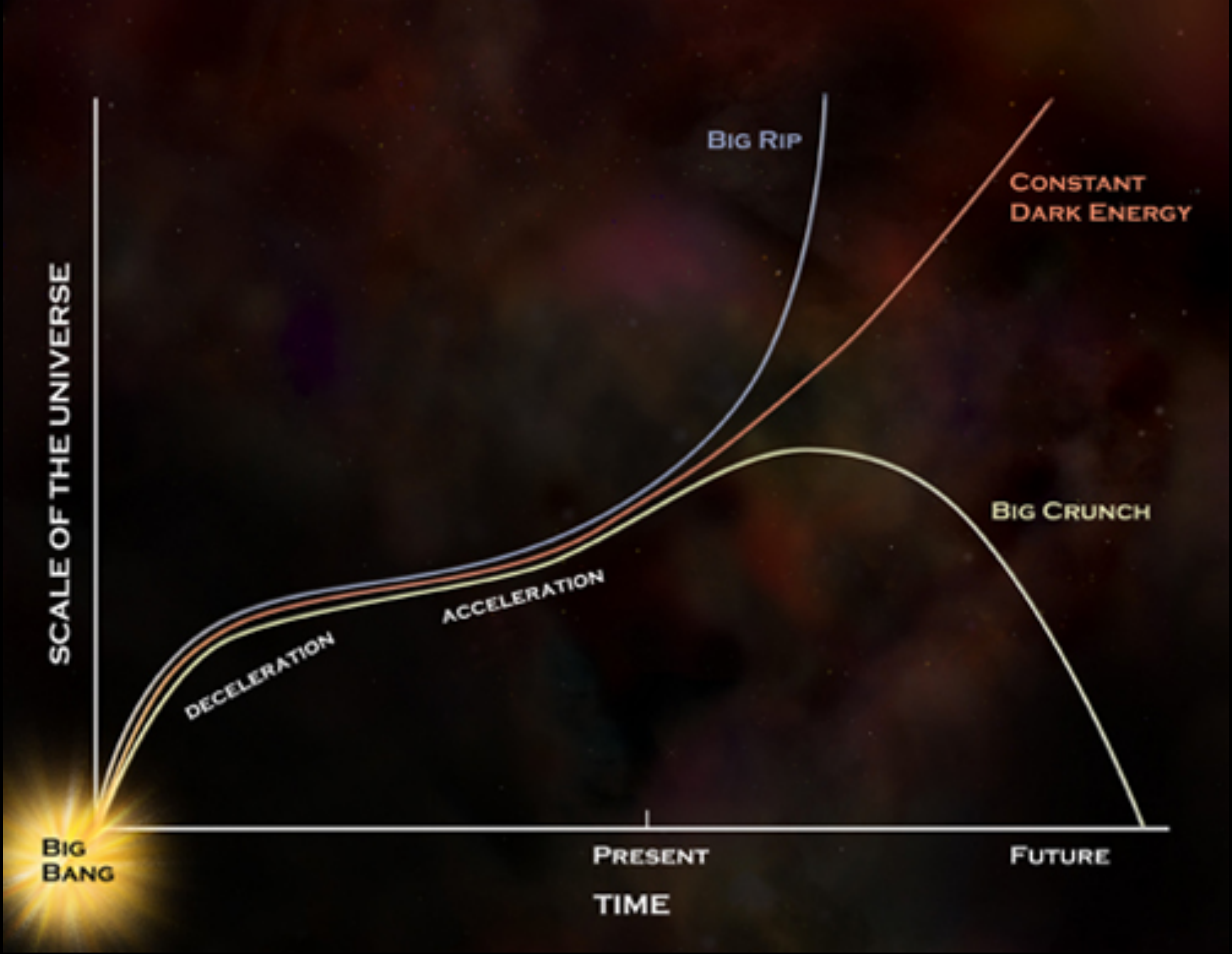
$$\Omega_0 = \Omega_m + \Omega_{de} = 1$$

Cosmological Constant?

Vacuum energy?

Exotic particles?

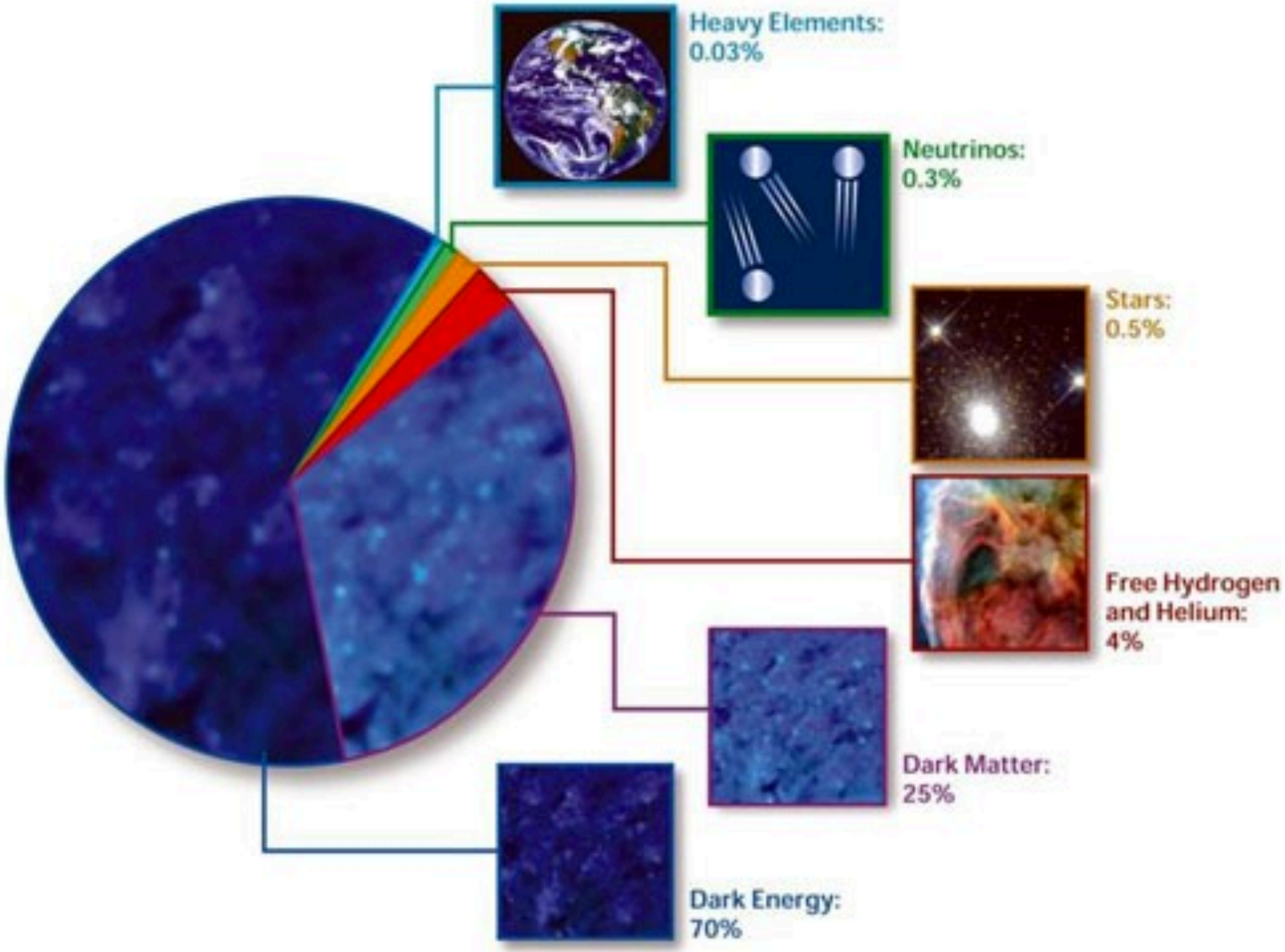
Modification of general relativity?


Big Rip
Constant
Dark Energy
Big Crunch
Scale of the Universe
Deceleration
Acceleration
Big
Bang
Present
Future
Time

Dark energy equation of state

- Equation of state: $P = w \rho c^2$
- Accelerating expansion for $w < -1/3$
- Cosmological constant: $w = -1$
- Parametrisation of time dependence:
  $w(a) = w_0 + w_a(1+a)$ mit $a=1/(1+z)$

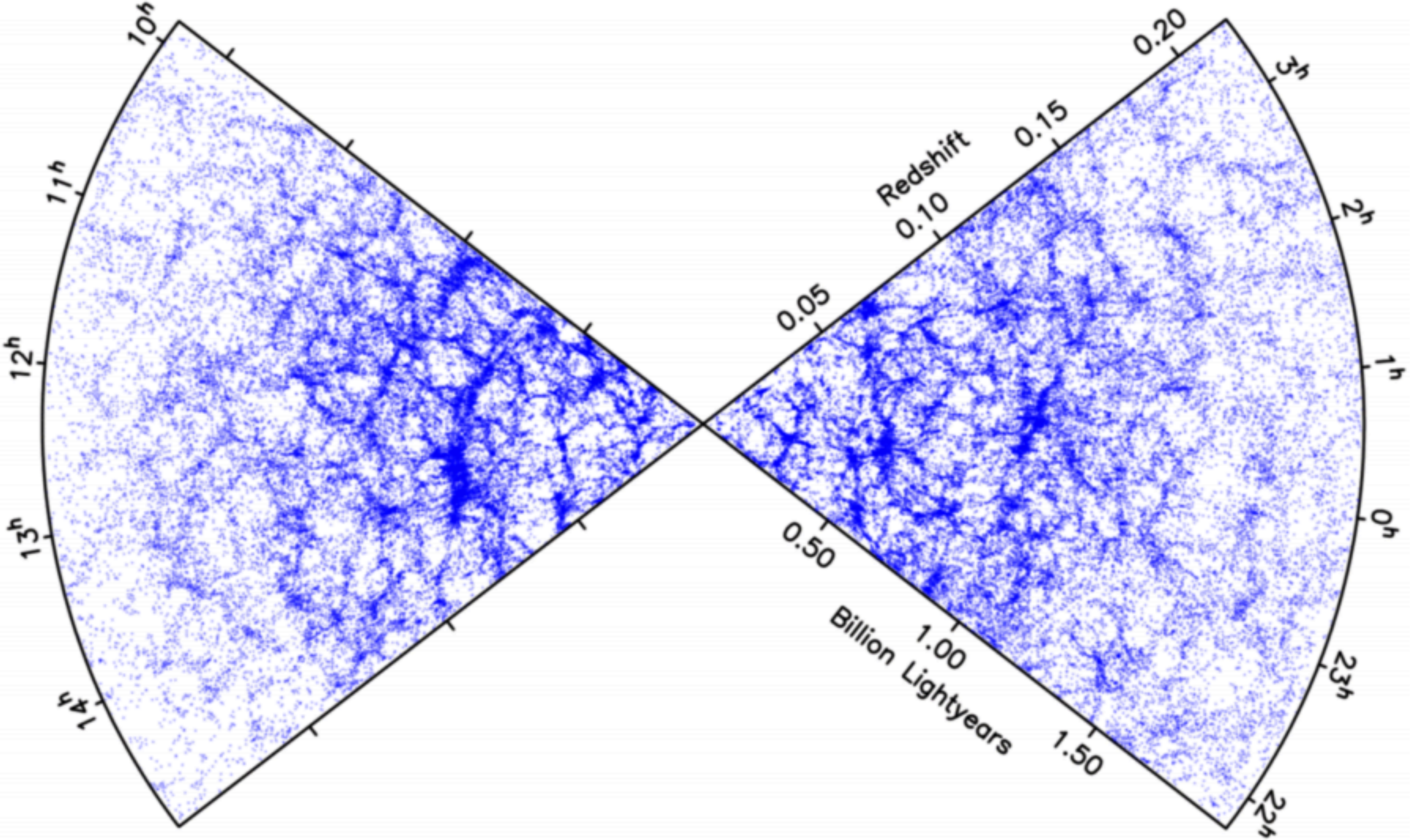
COMPOSITION OF THE COSMOS



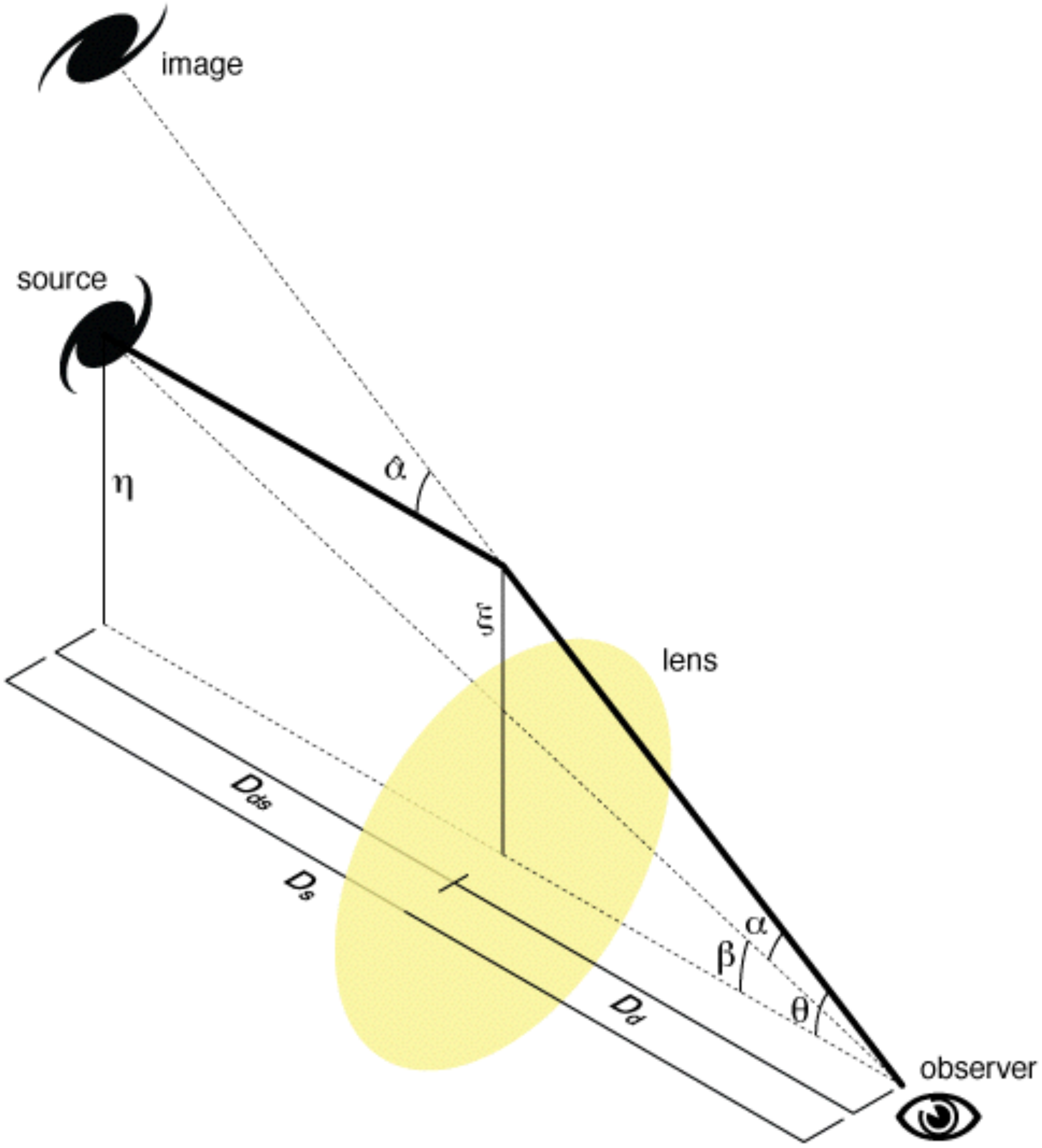
Observing dark energy

- 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

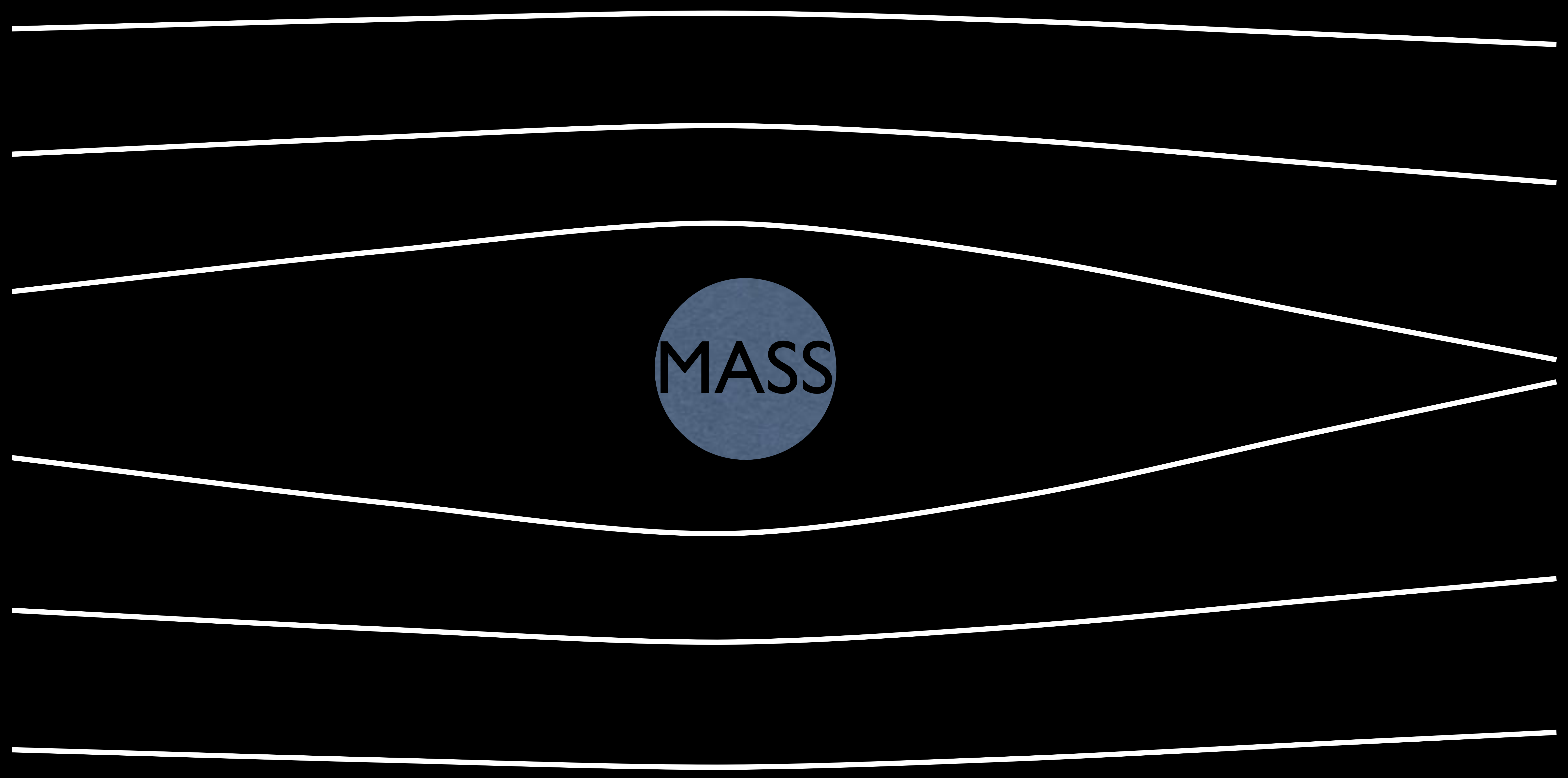


Redshift
0.05
0.10
0.15
0.20
Billion Lightyears
0.50
1.00
1.50
10h
11h
12h
13h
14h
3h
2h
1h
0h
23h
22h

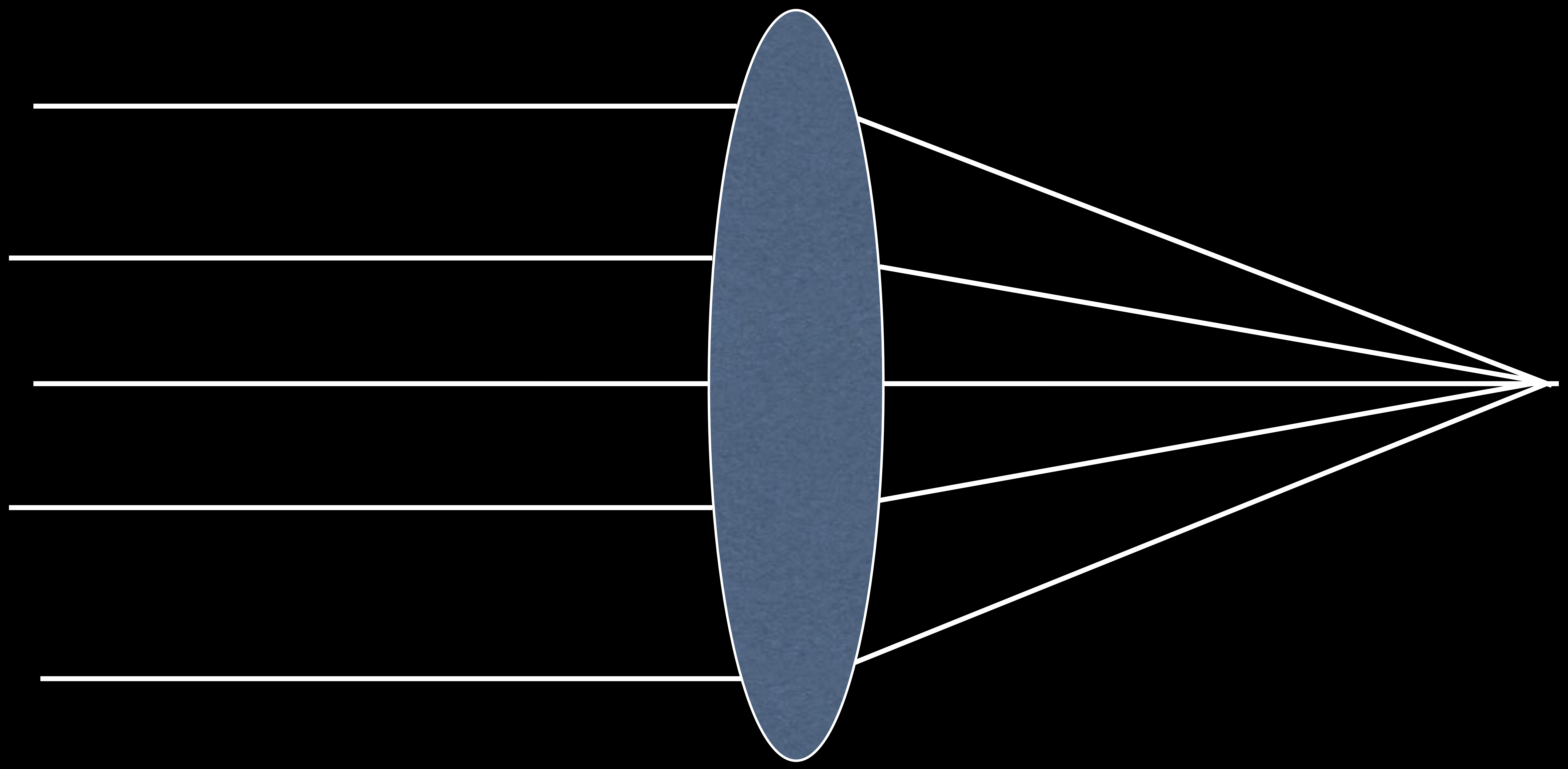


Credit: Michael Sachs

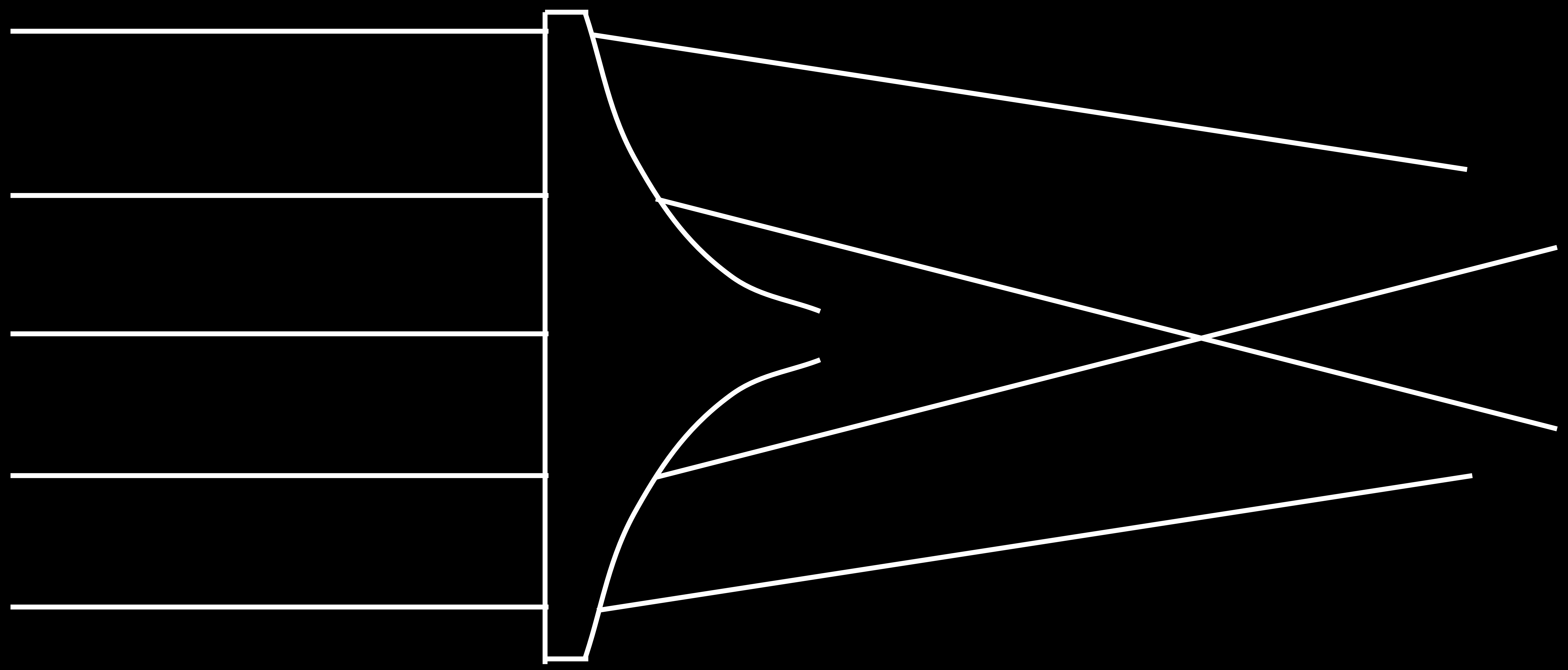
Gravitational lens



Optical lens

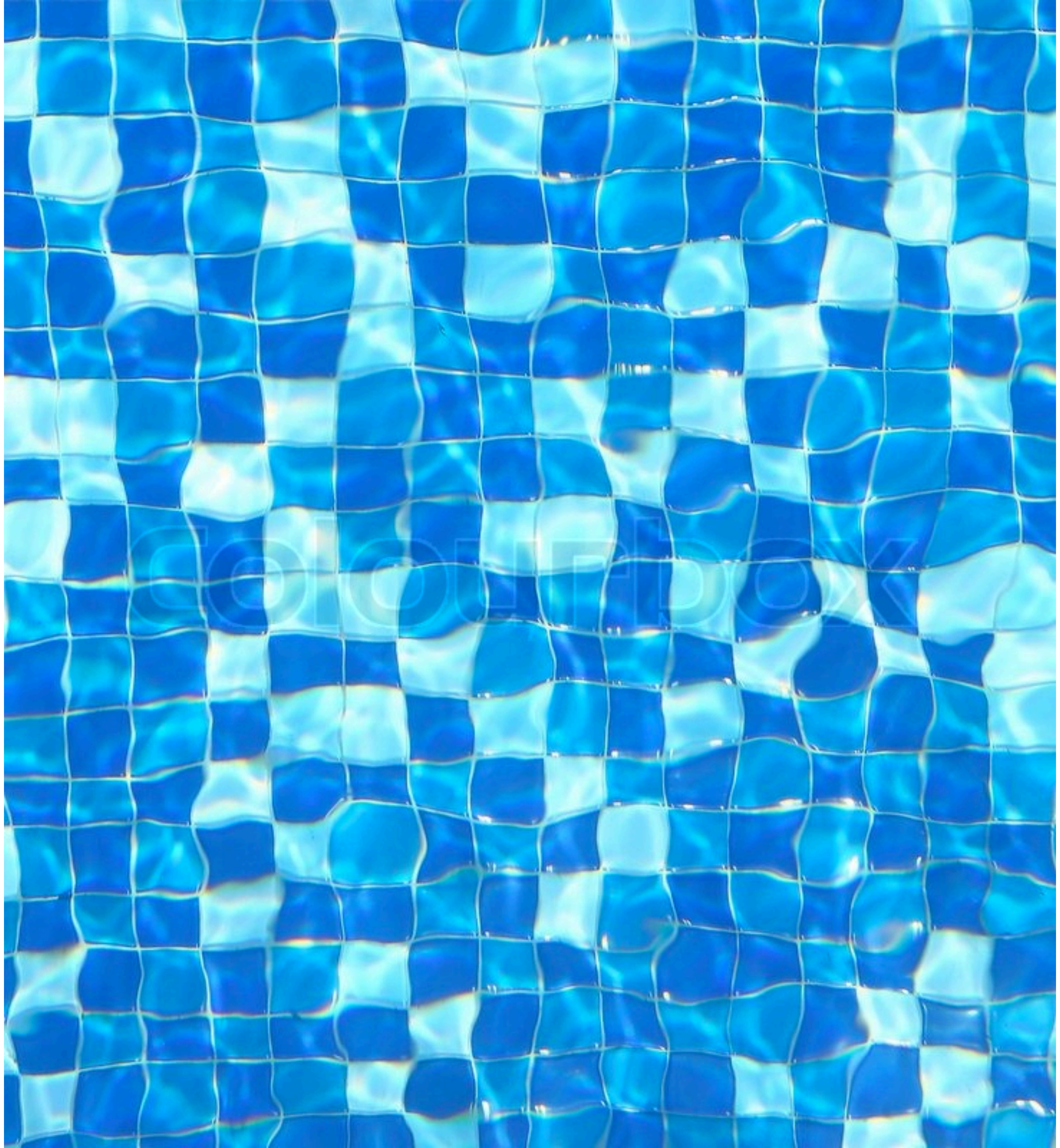


Gravitational lens analogue

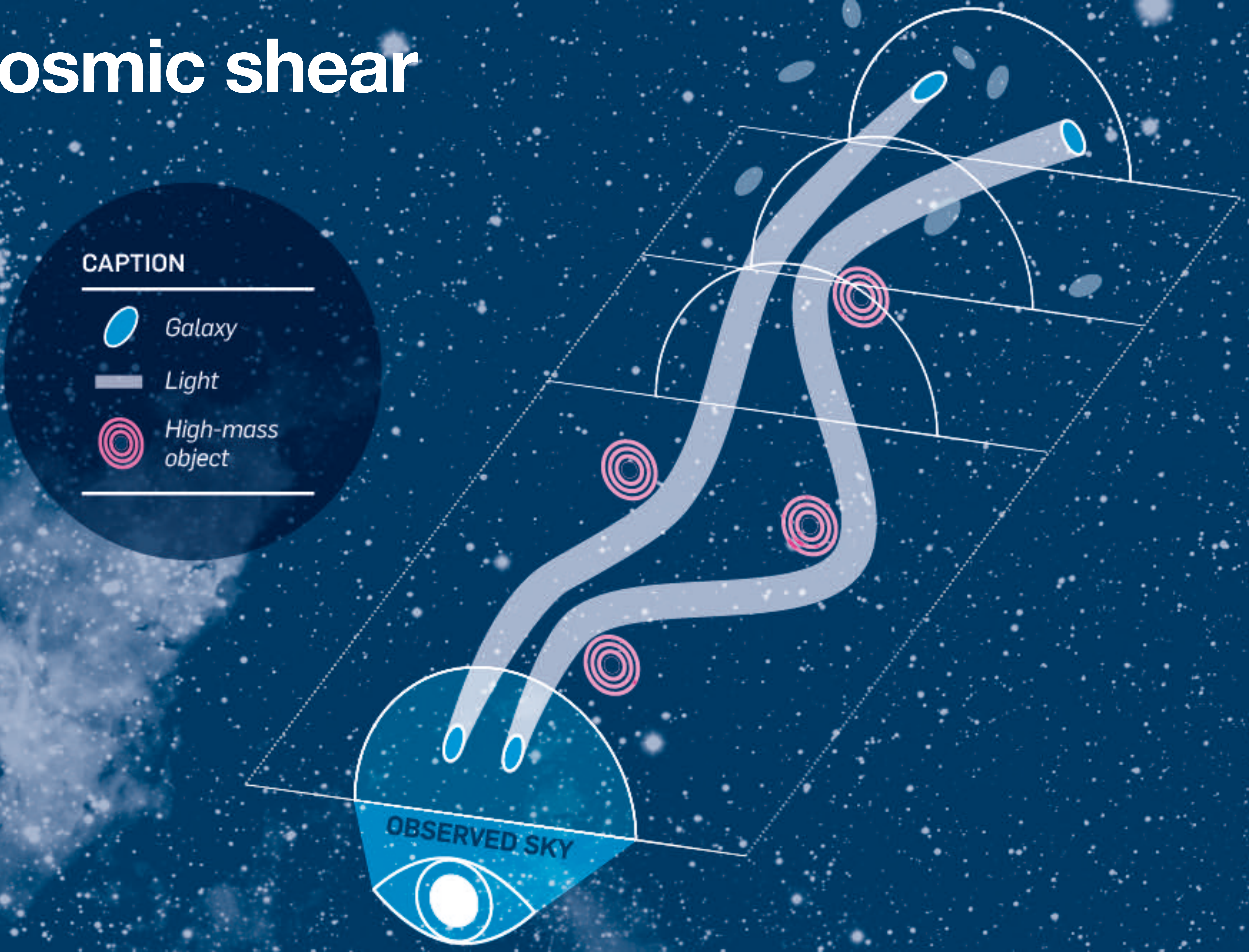


Spherical abberation!


Credit: R. Schirdewahn



Cosmic shear



Sensitive to:

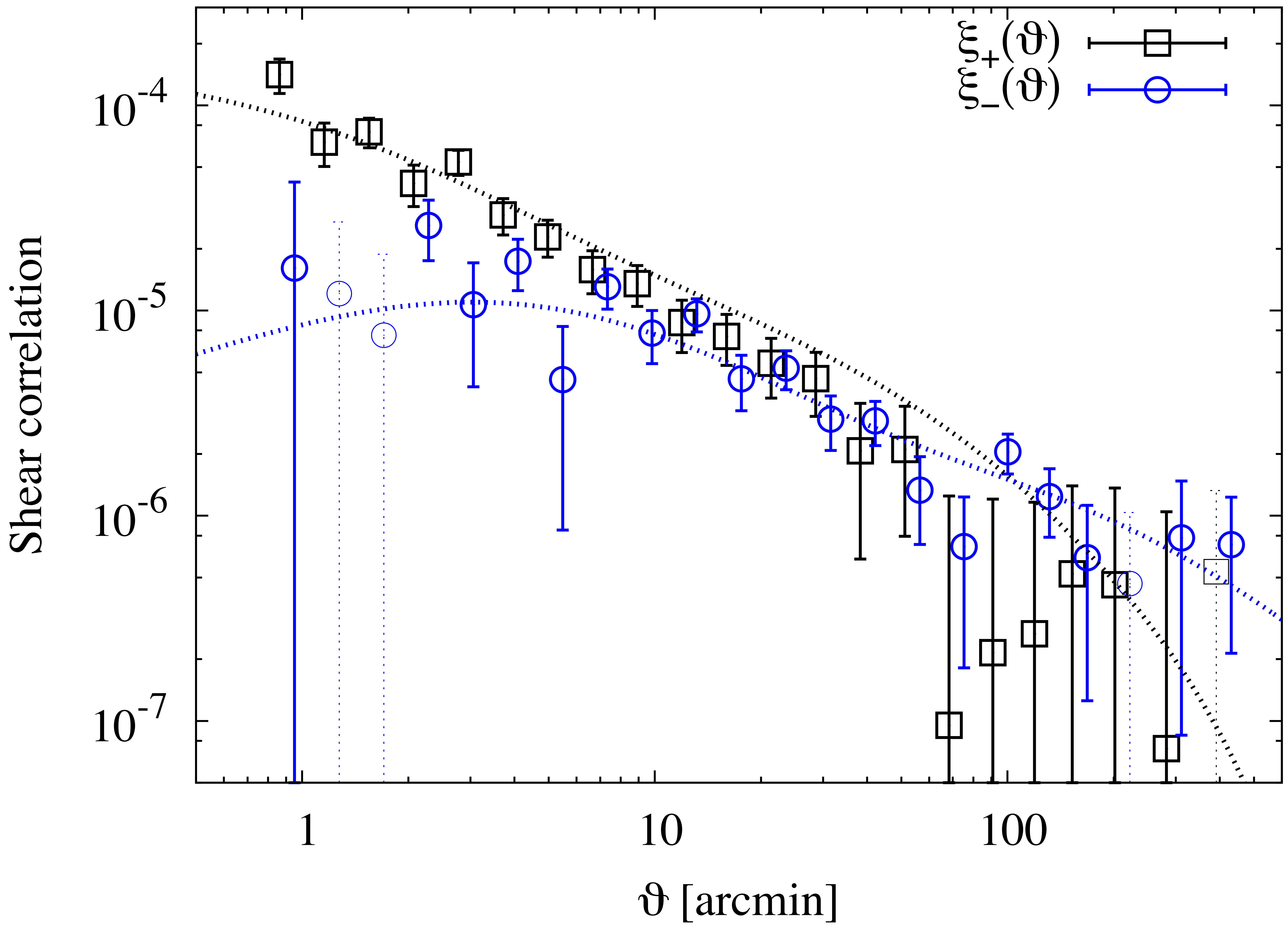
- Matter distribution
- Geometry

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

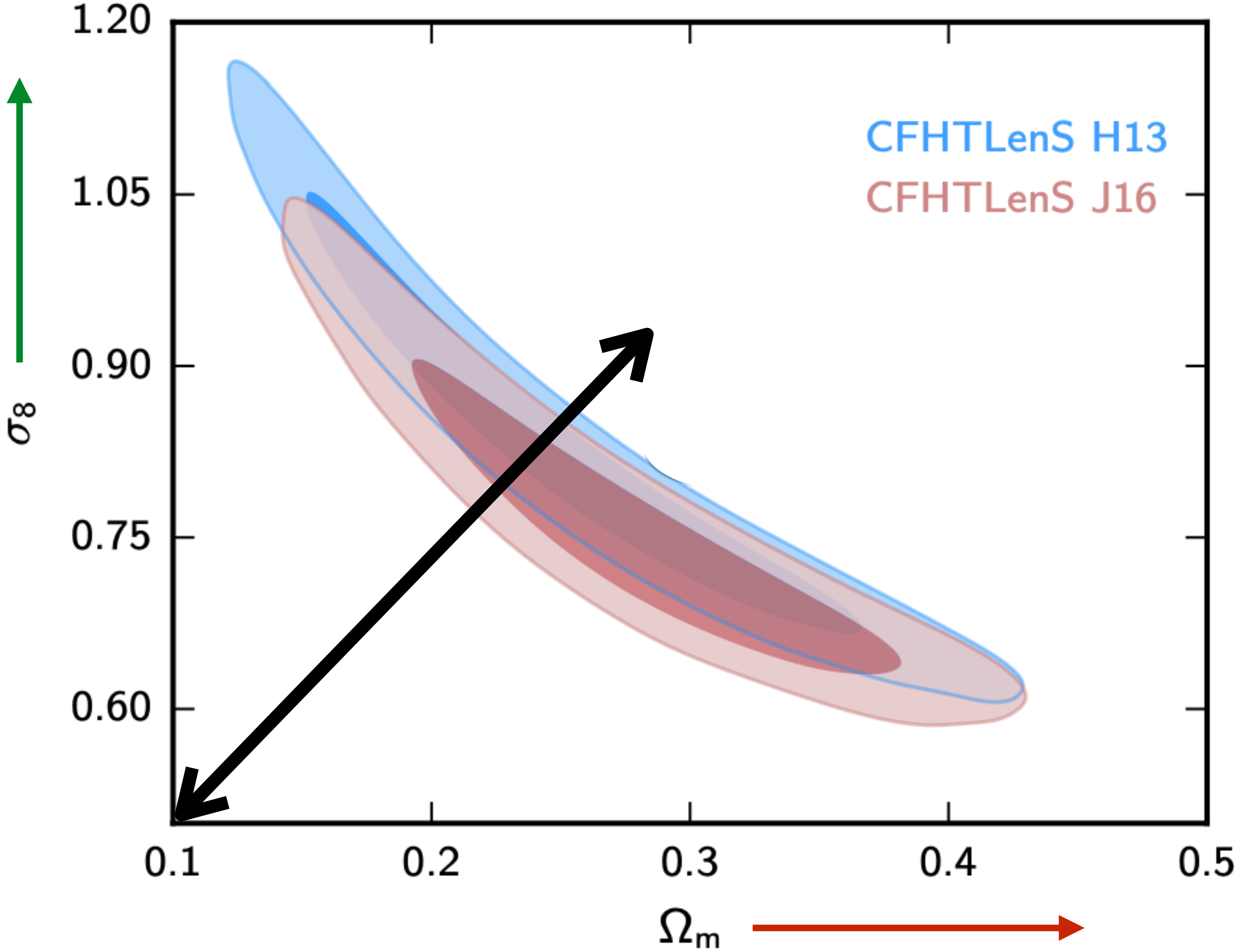
$$\xi_\pm(\theta) = \langle \gamma_\mathrm{t}\gamma_\mathrm{t}\rangle(\theta) \pm \langle \gamma_\times\gamma_\times\rangle(\theta)$$

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

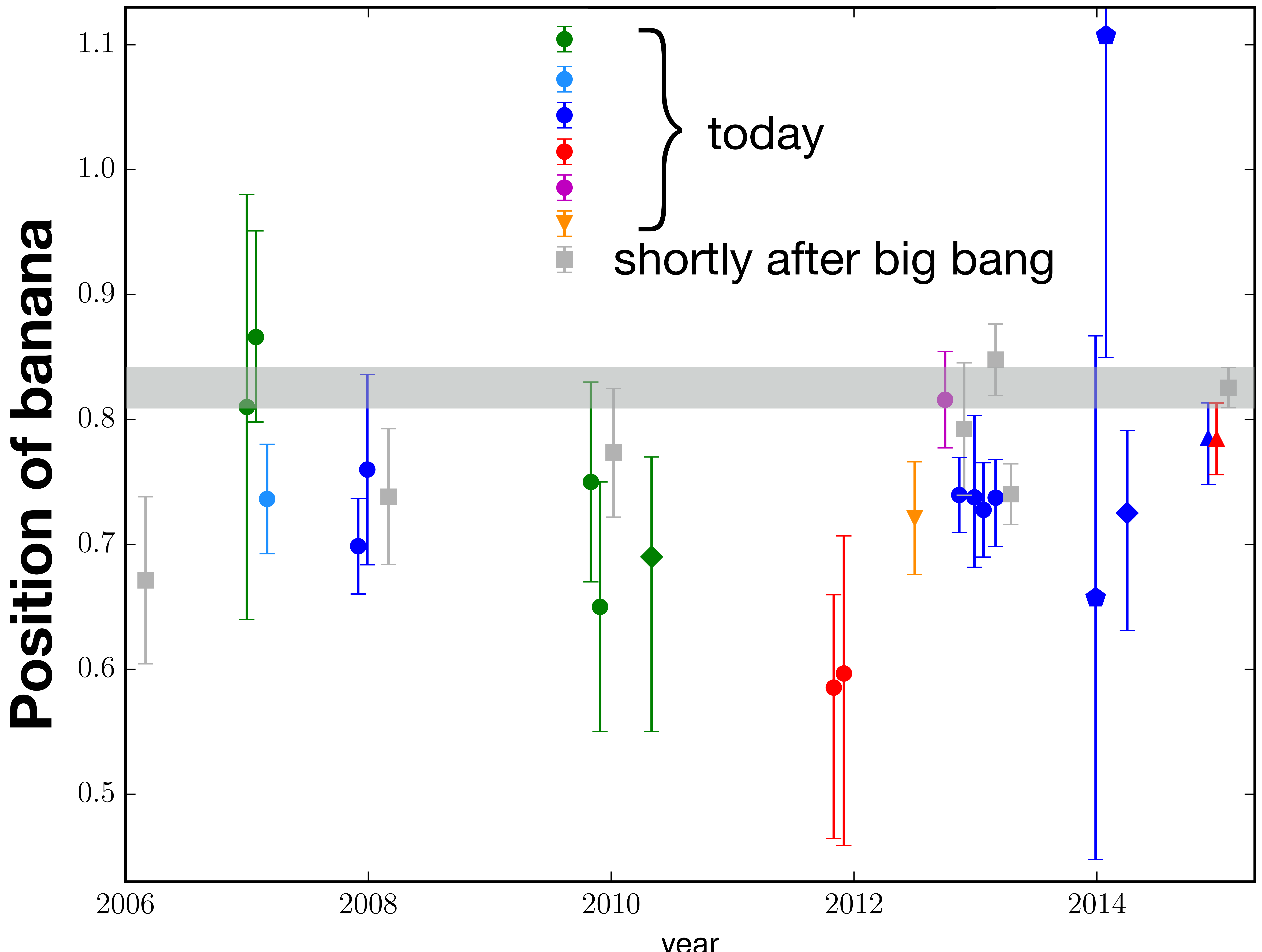
$$P_\kappa(\ell) = \frac{9H_0^4\Omega_\mathrm{m}^2}{4c^4}\int_0^{\chi_\mathrm{h}} \mathrm{d}\chi\,\frac{g^2(\chi)}{a^2(\chi)}\,P_\delta\left(\frac{\ell}{f_K(\chi)},\chi\right)$$

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

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



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

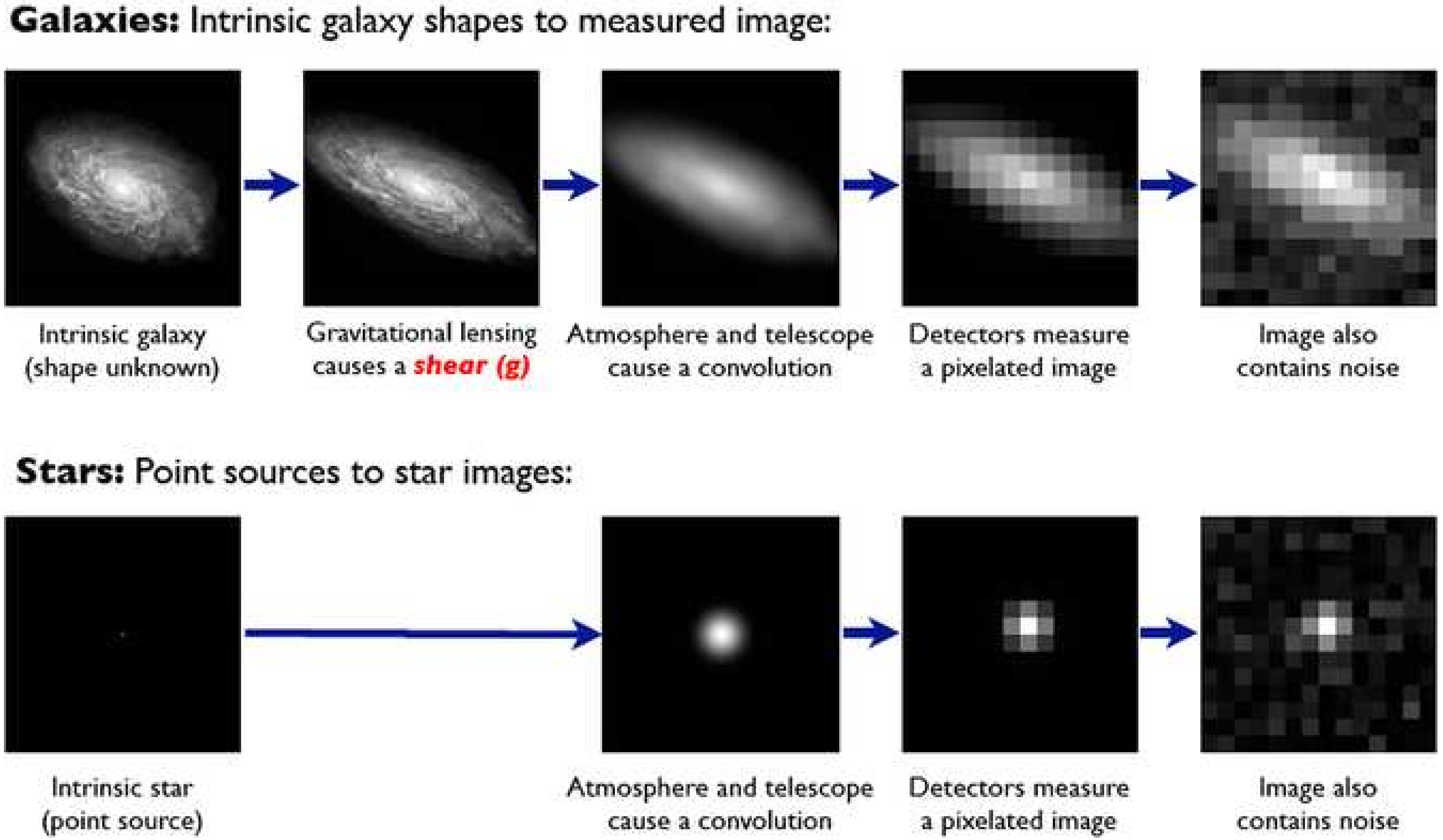


today
shortly after big bang
Position of banana
year
2006
2008
2010
2012
2014
0.5
0.6
0.7
0.8
0.9
1.0
1.1

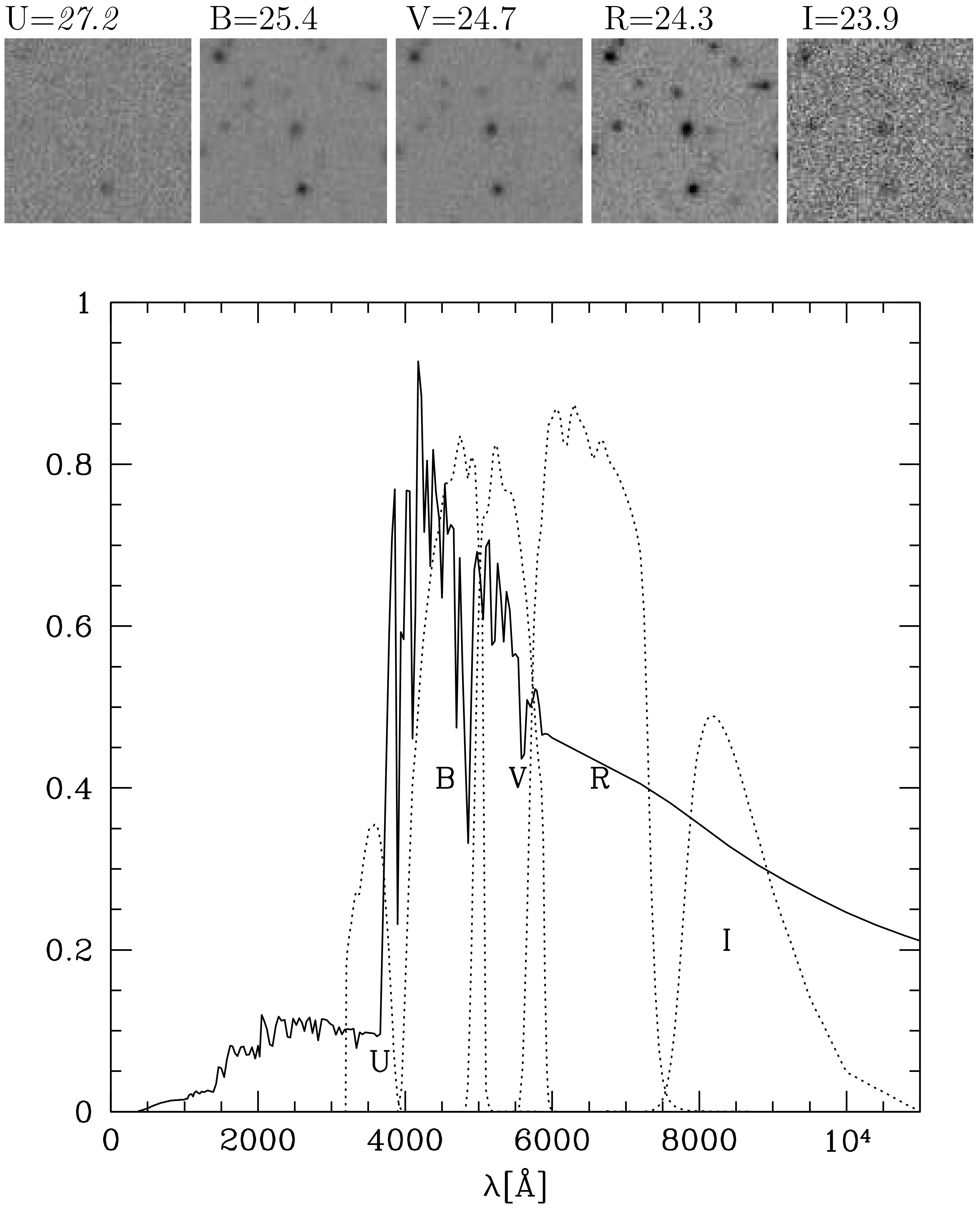
Systematic challenges

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

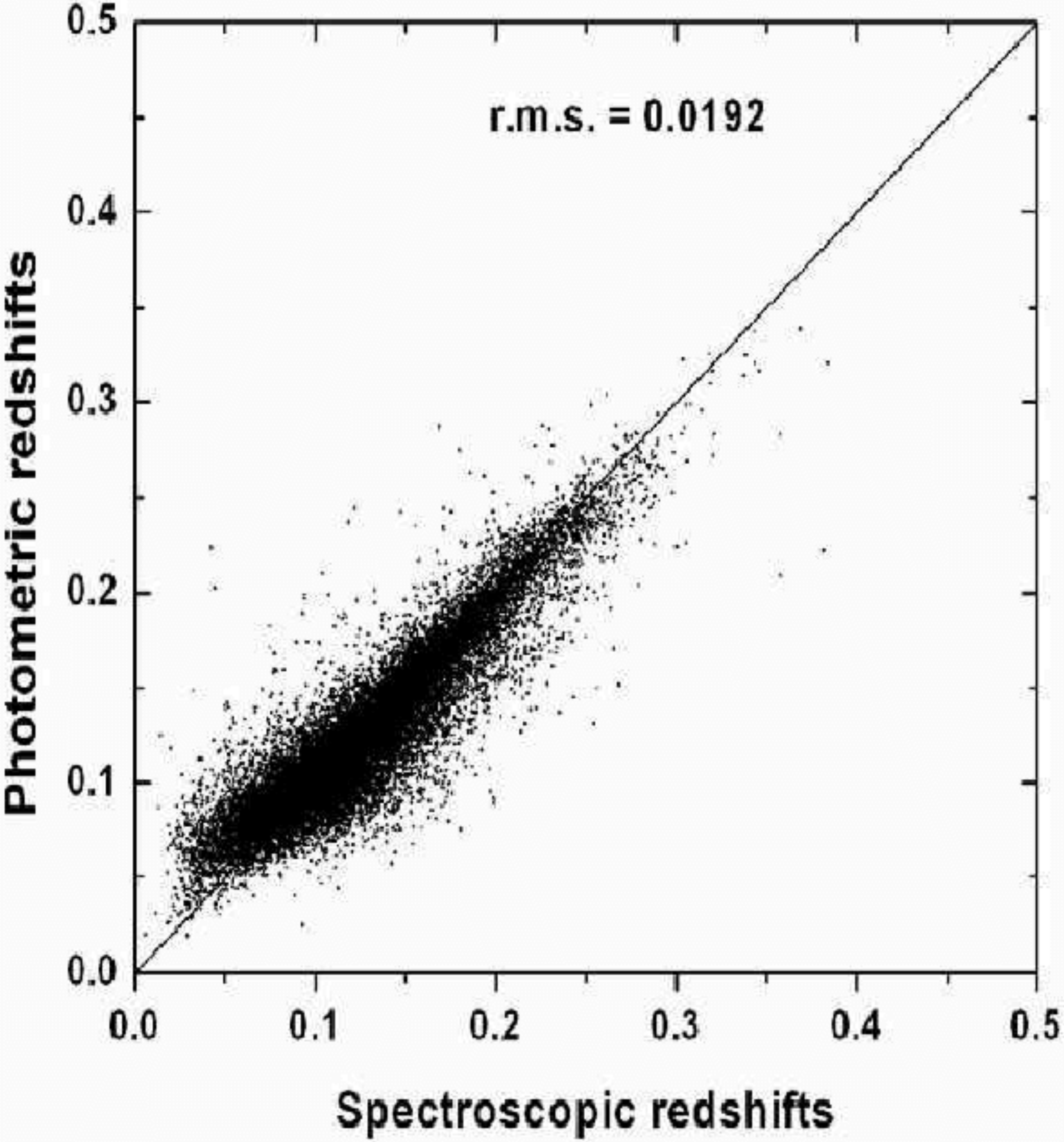
Shape measurements

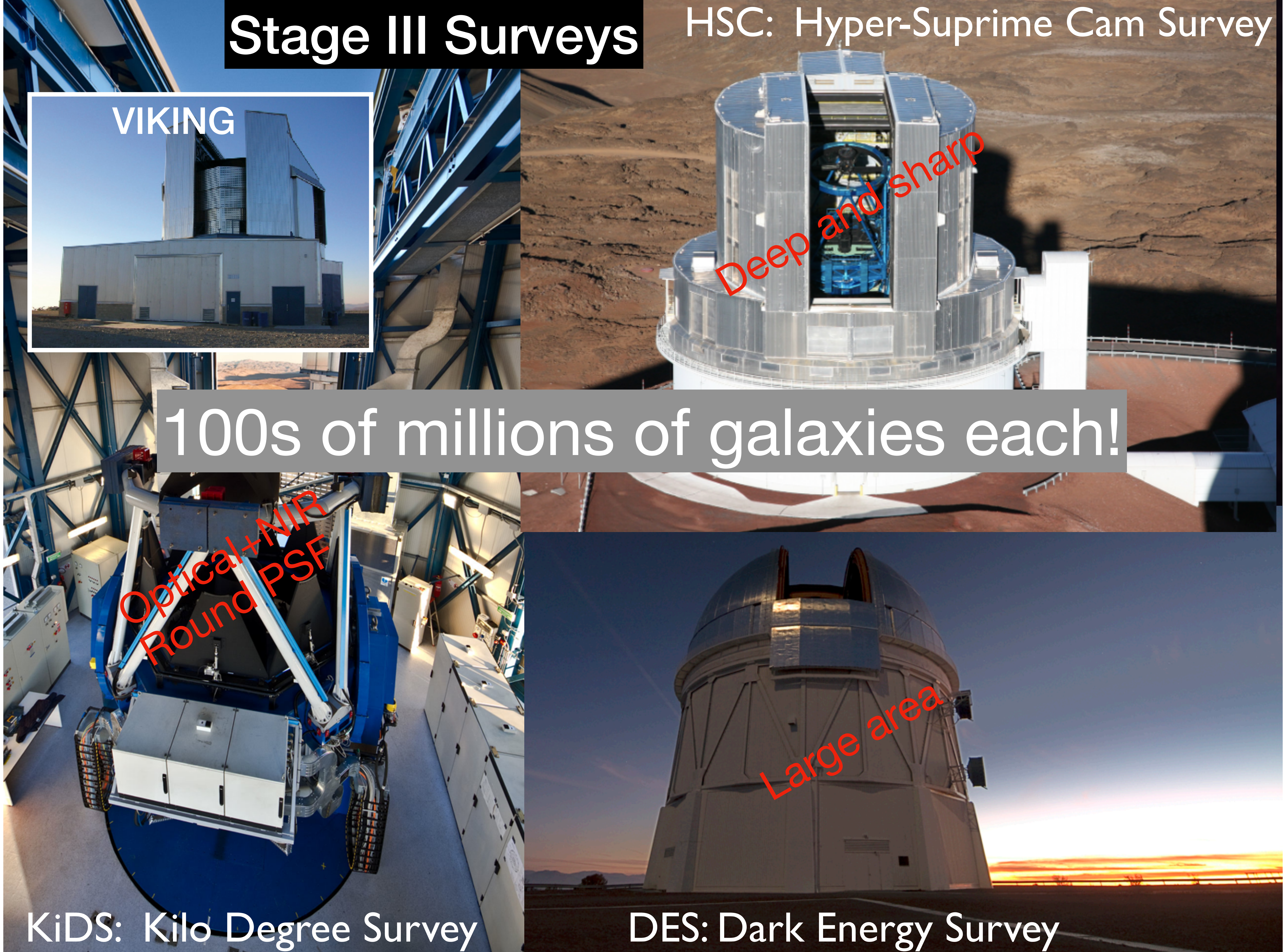


Bridle et al. (2009)

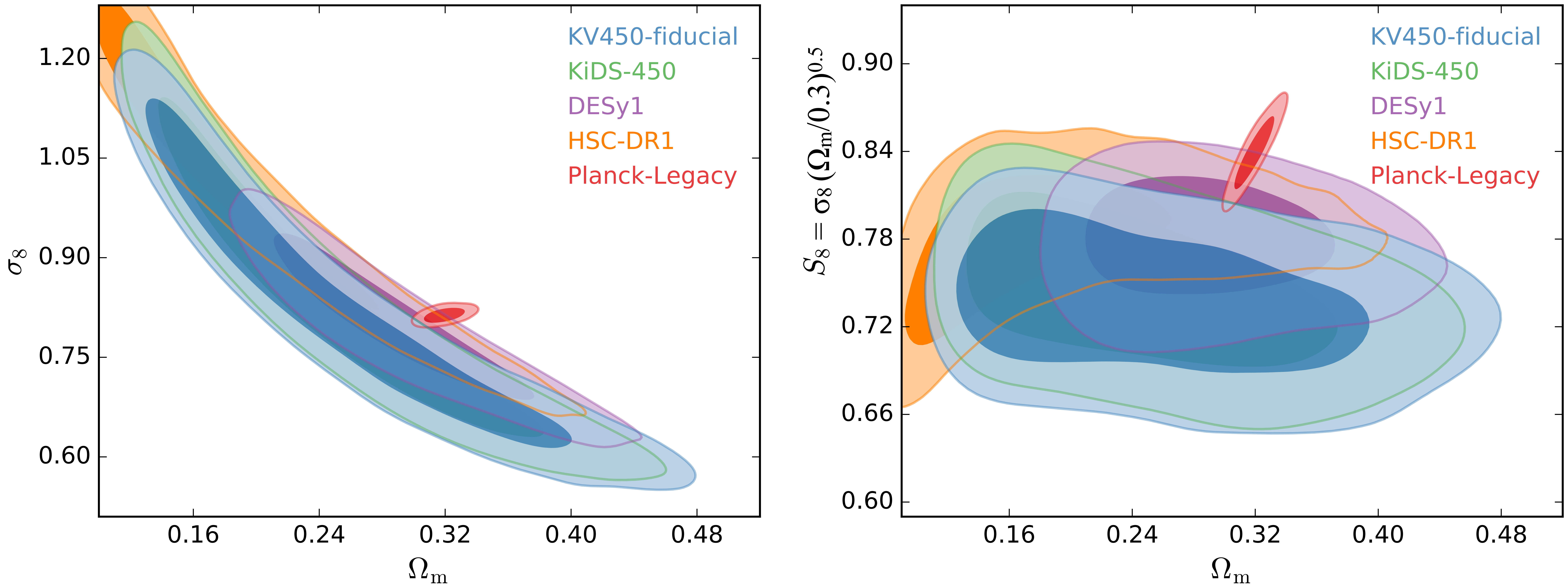


U=27.2
B=25.4
V=24.7
R=24.3
I=23.9
1
0.8
0.6
0.4
0.2
0
0
2000
4000
6000
8000
10⁴
λ[Å]
U
B
V
R
I


r.m.s. = 0.0192
Photometric redshifts
Spectroscopic redshifts
0.0
0.1
0.2
0.3
0.4
0.5


Stage III Surveys
HSC: Hyper-Suprime Cam Survey
VIKING
Deep and sharp
100s of millions of galaxies each!
Optical+NIR
Round PSF
Large area
KiDS: Kilo Degree Survey
DES: Dark Energy Survey

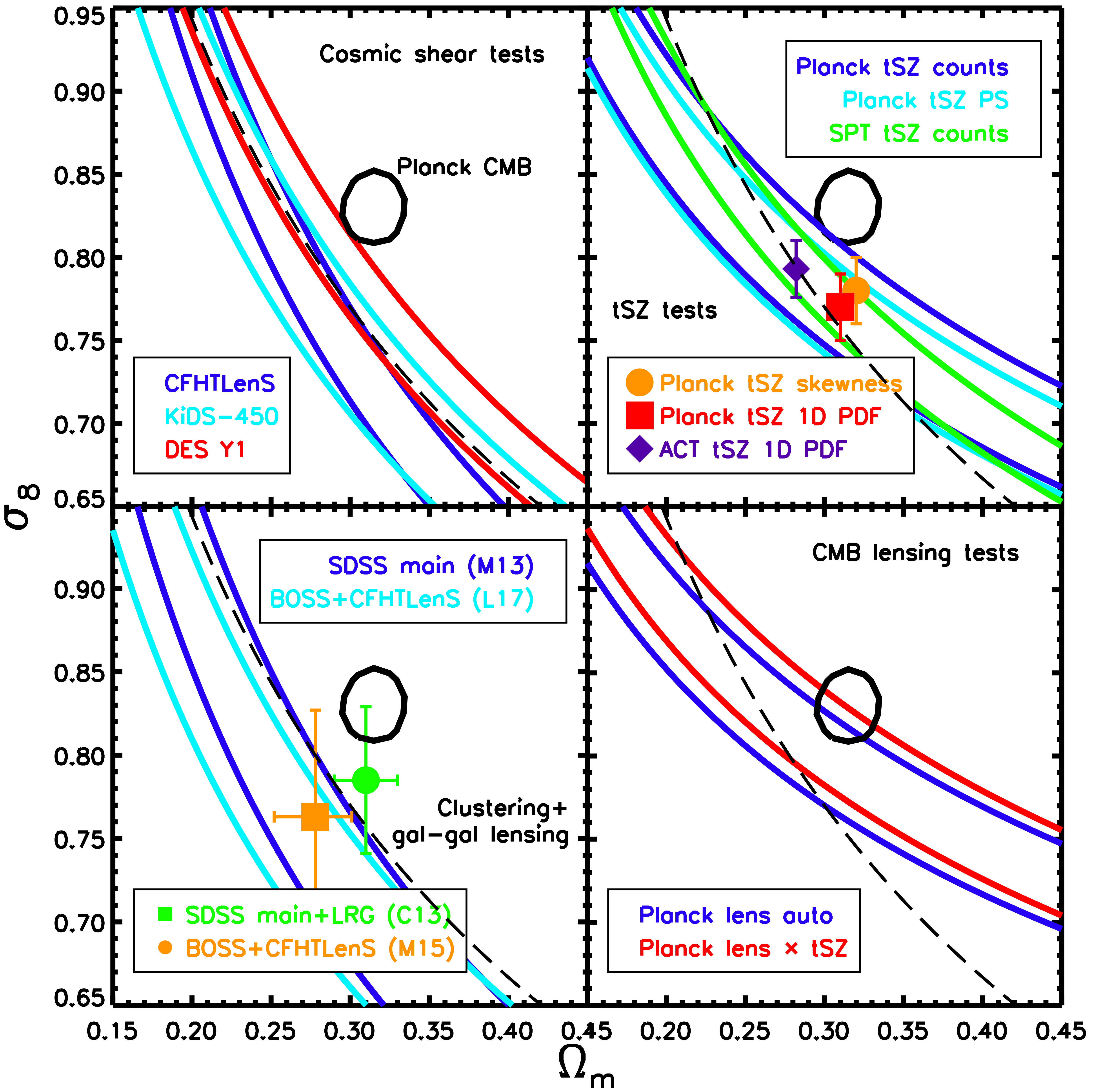
Cosmic shear before Covid-19



Agreement of WL measurements. All lower than Planck.

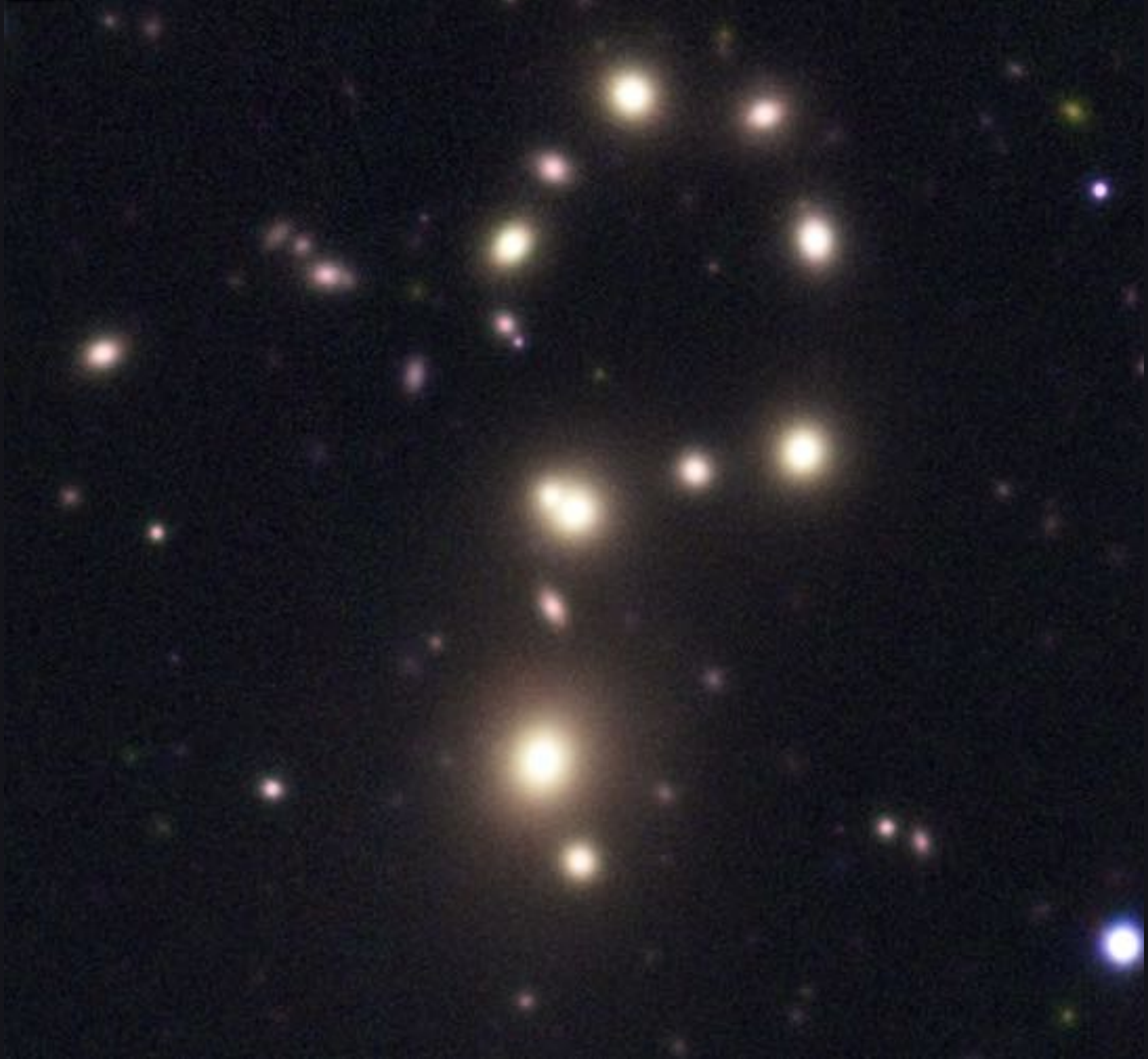
HSC-DR1: Hikage et al. (2019)
DES-Y1: Troxel et al. (2018a)
KiDS-VIKING-450: Hildebrandt et al. (2020)

Other probes

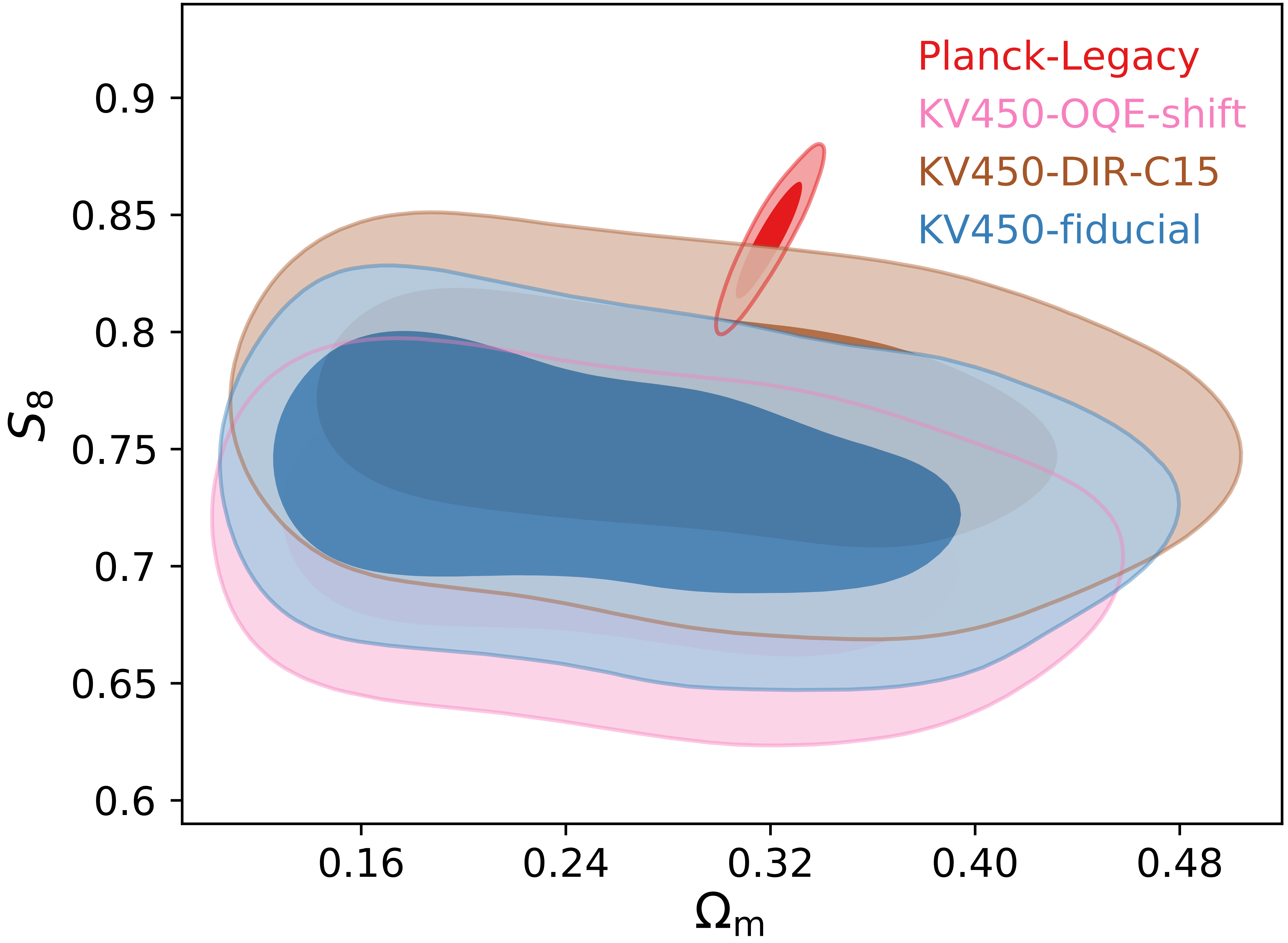


Not a single late Universe LSS measurement yields an S_8 higher than Planck.

McCarthy et al. (2017)

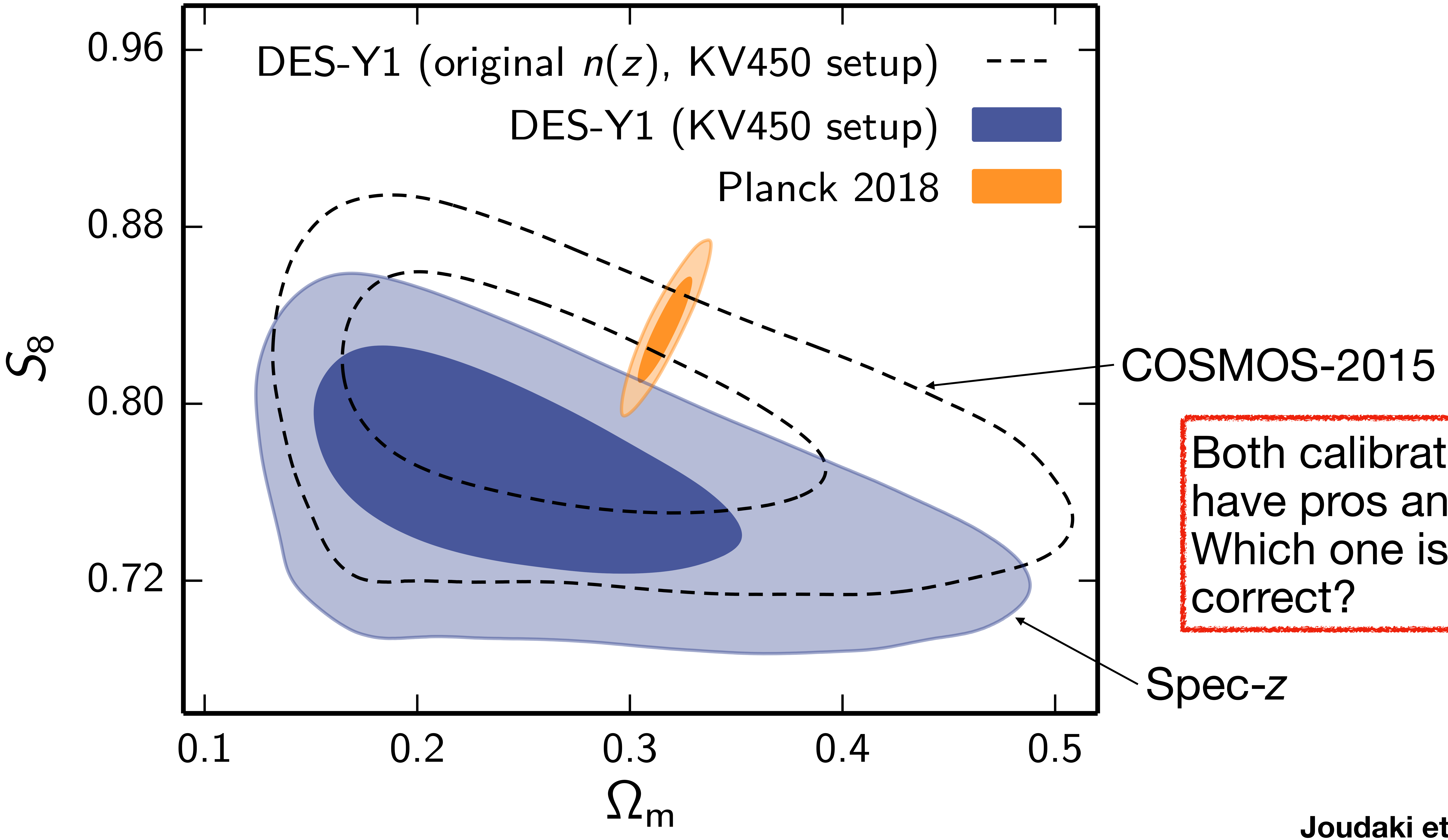


KiDS-VIKING-450 redshift calibration



Hildebrandt et al. (2020)

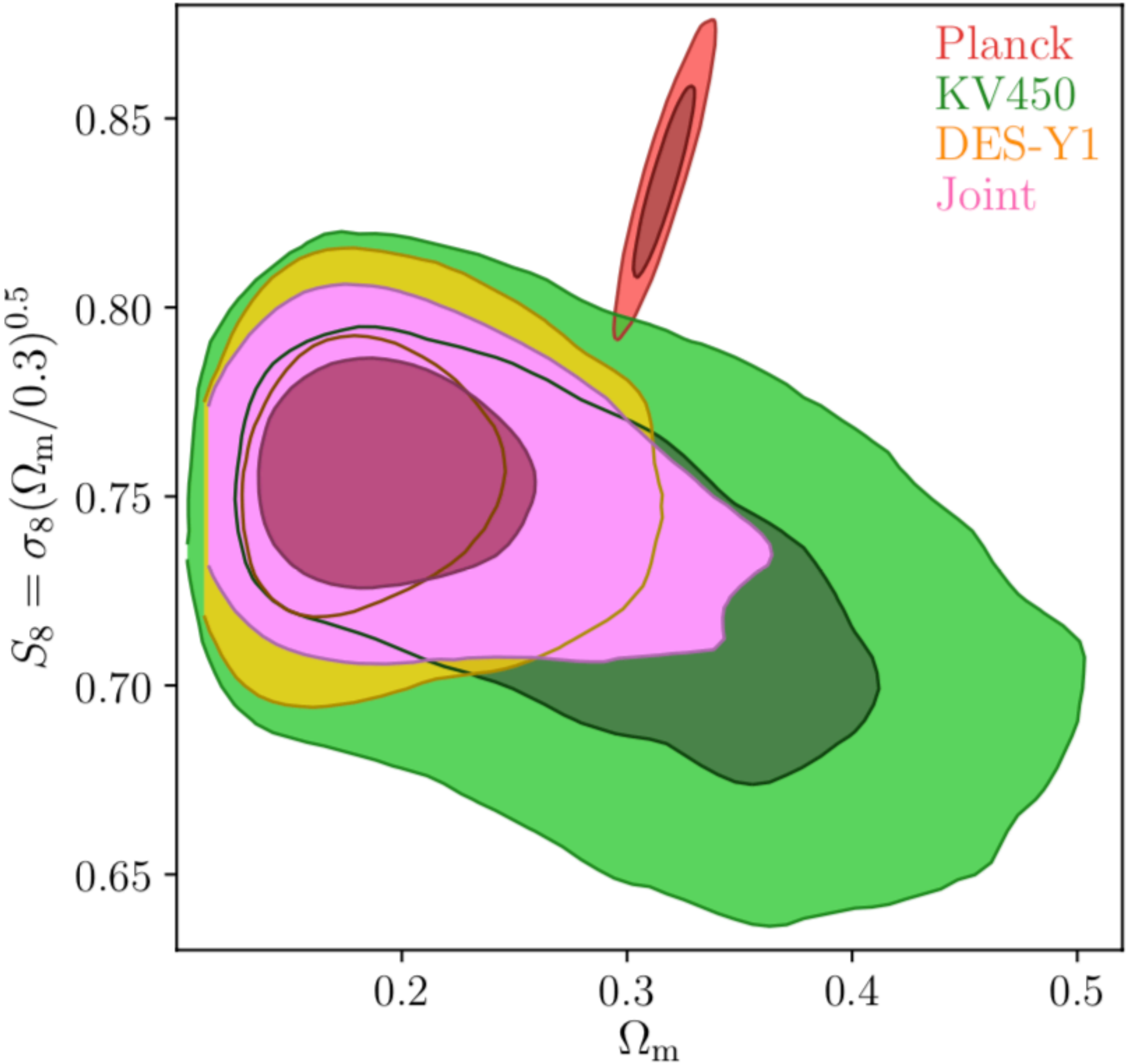
Recalibrating DES redshifts



Both calibrations have pros and cons. Which one is correct?

Joudaki et al. (2020)

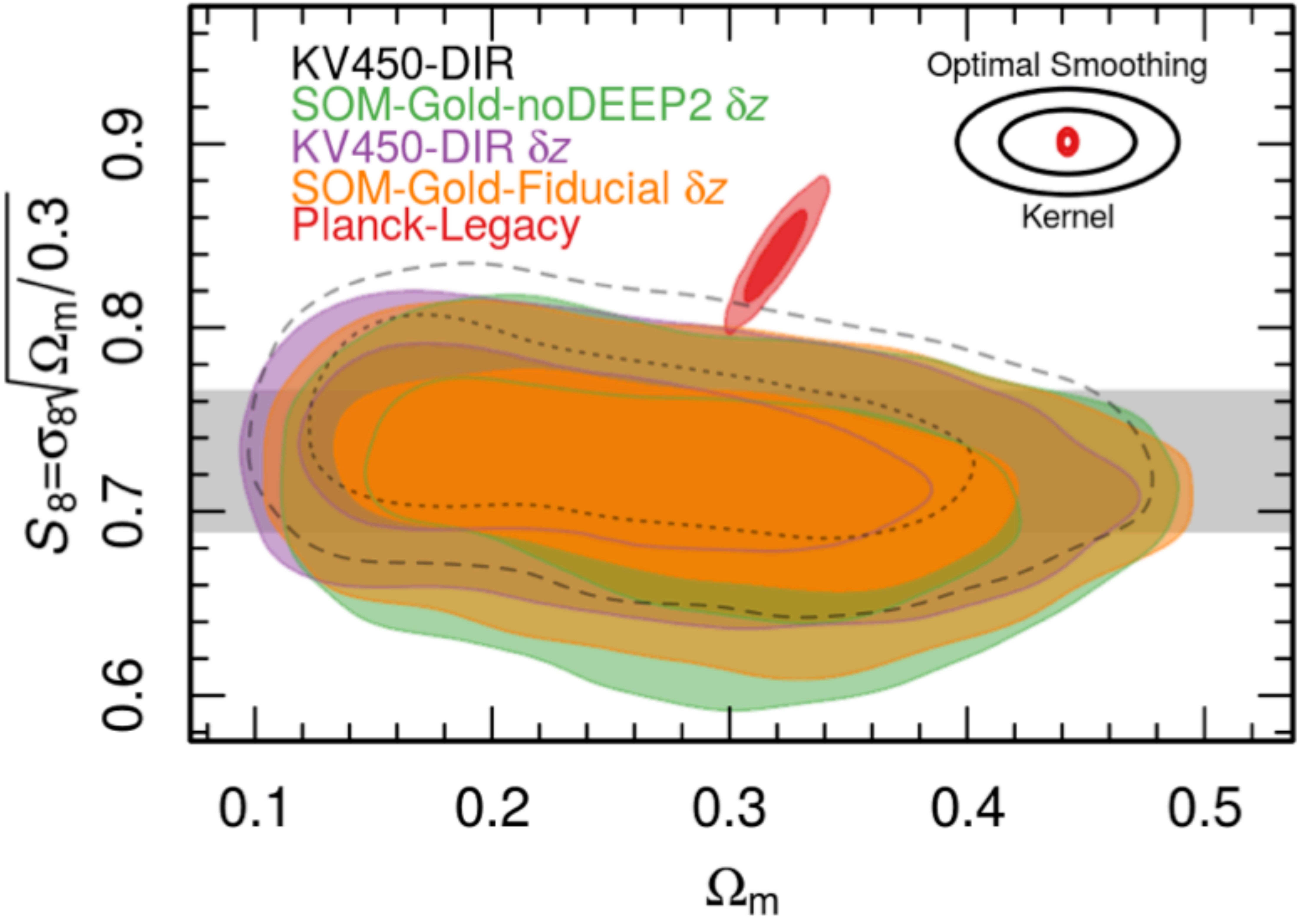
S_8 constraints

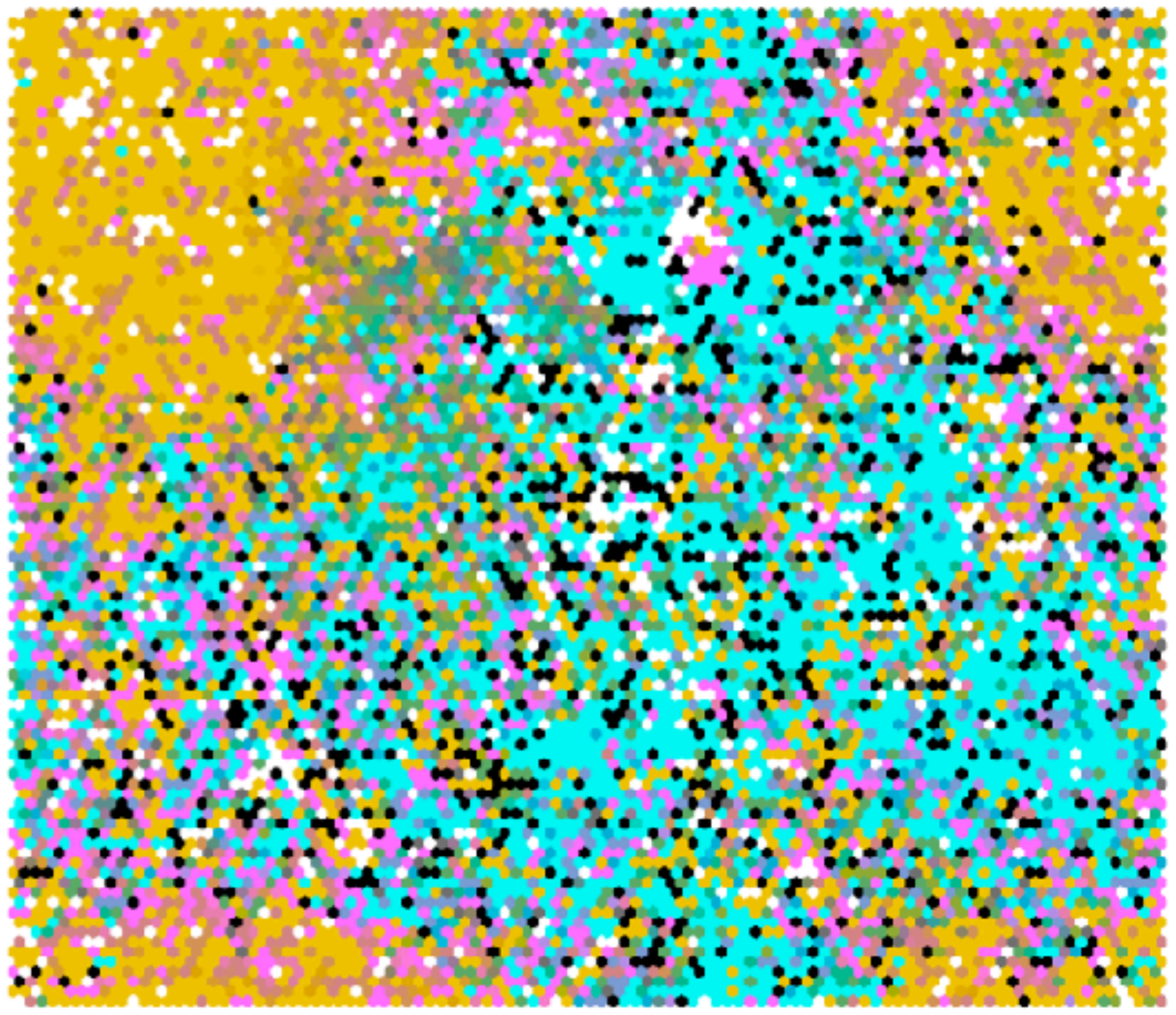


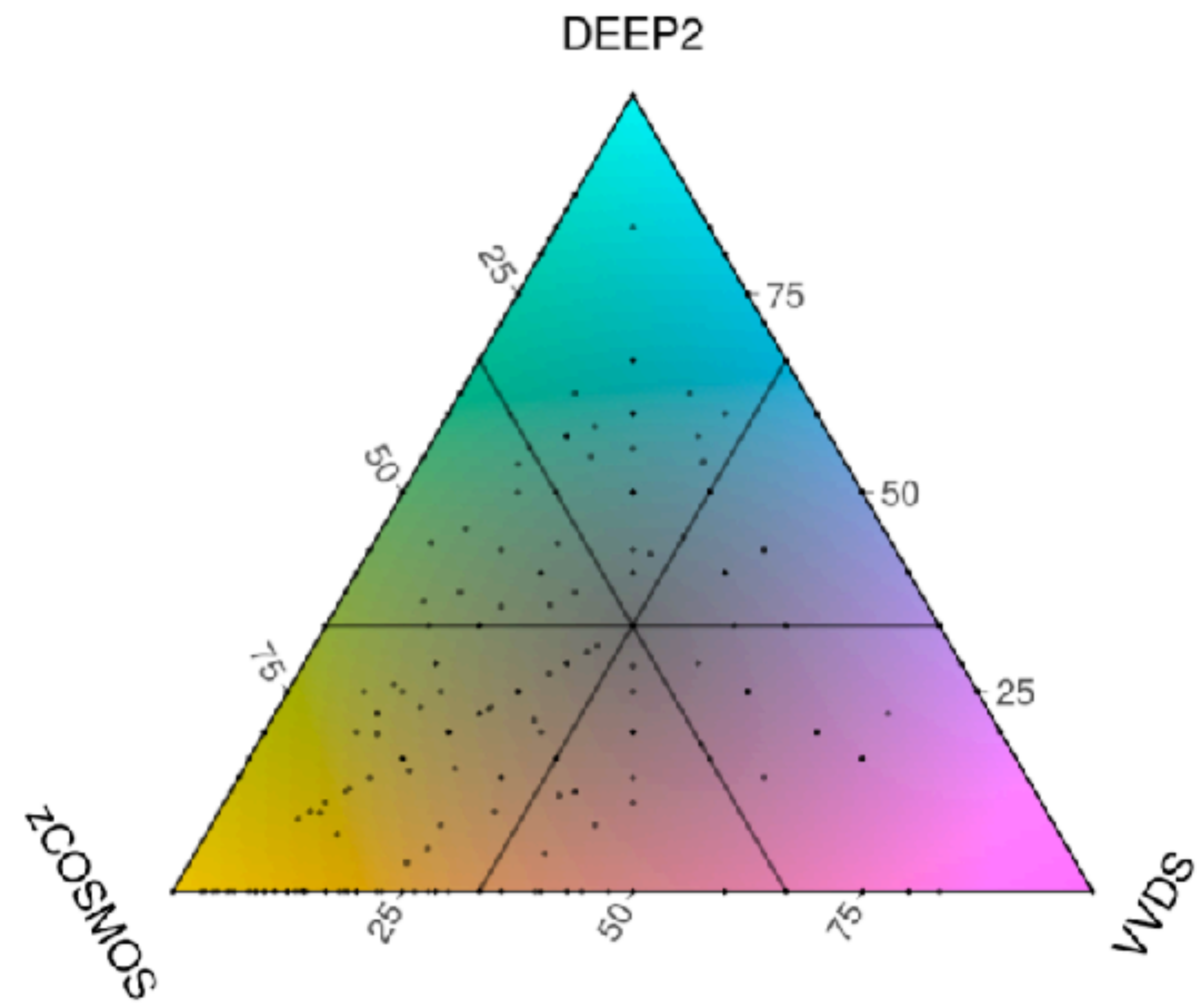
3.2σ tension between WL and Planck

Asgari et al. (2020)

KiDS-VIKING 450 “gold” sample







KiDS results robust against down-selection of sources.

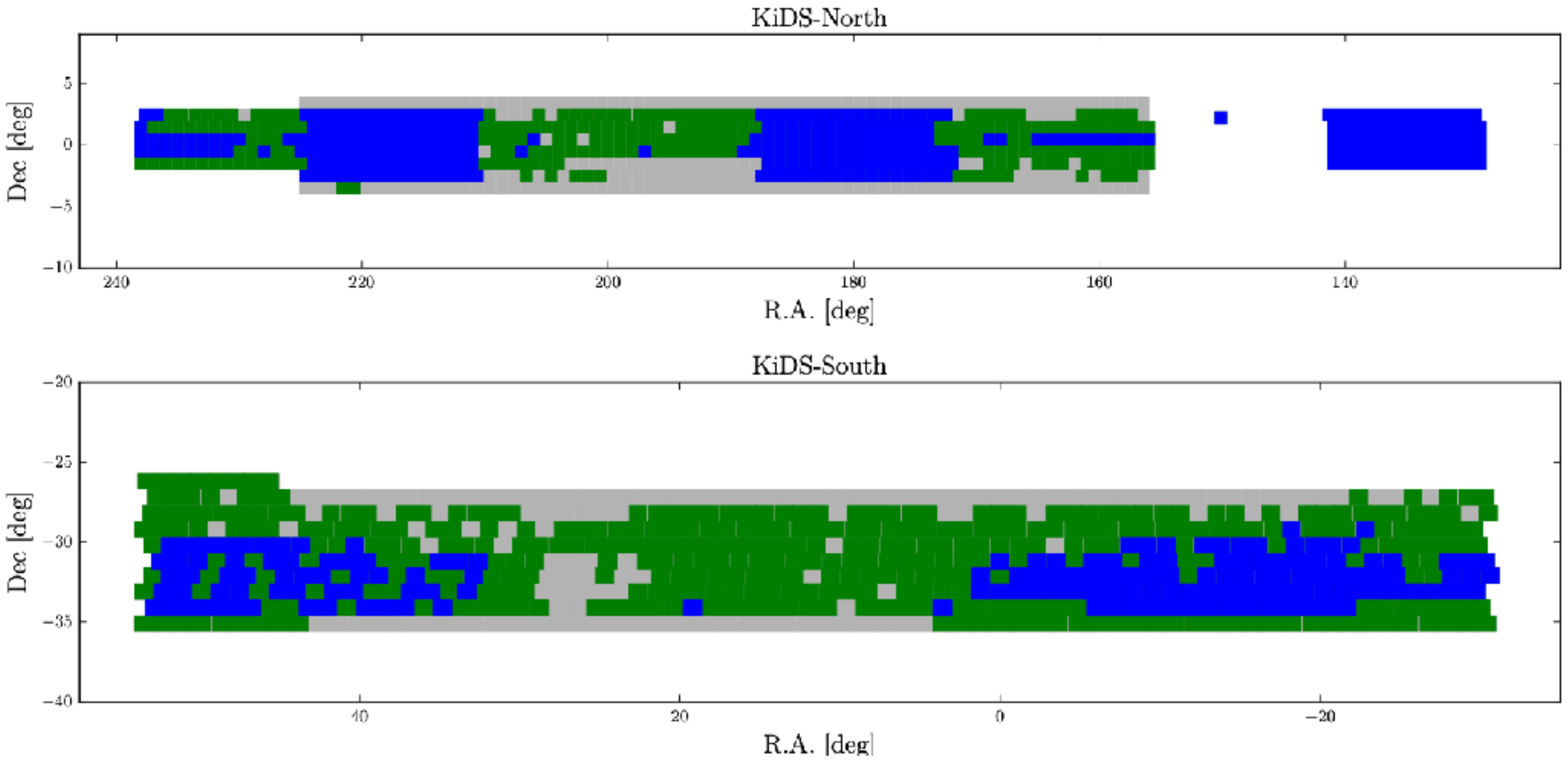
Wright et al. (2020a,2020b)

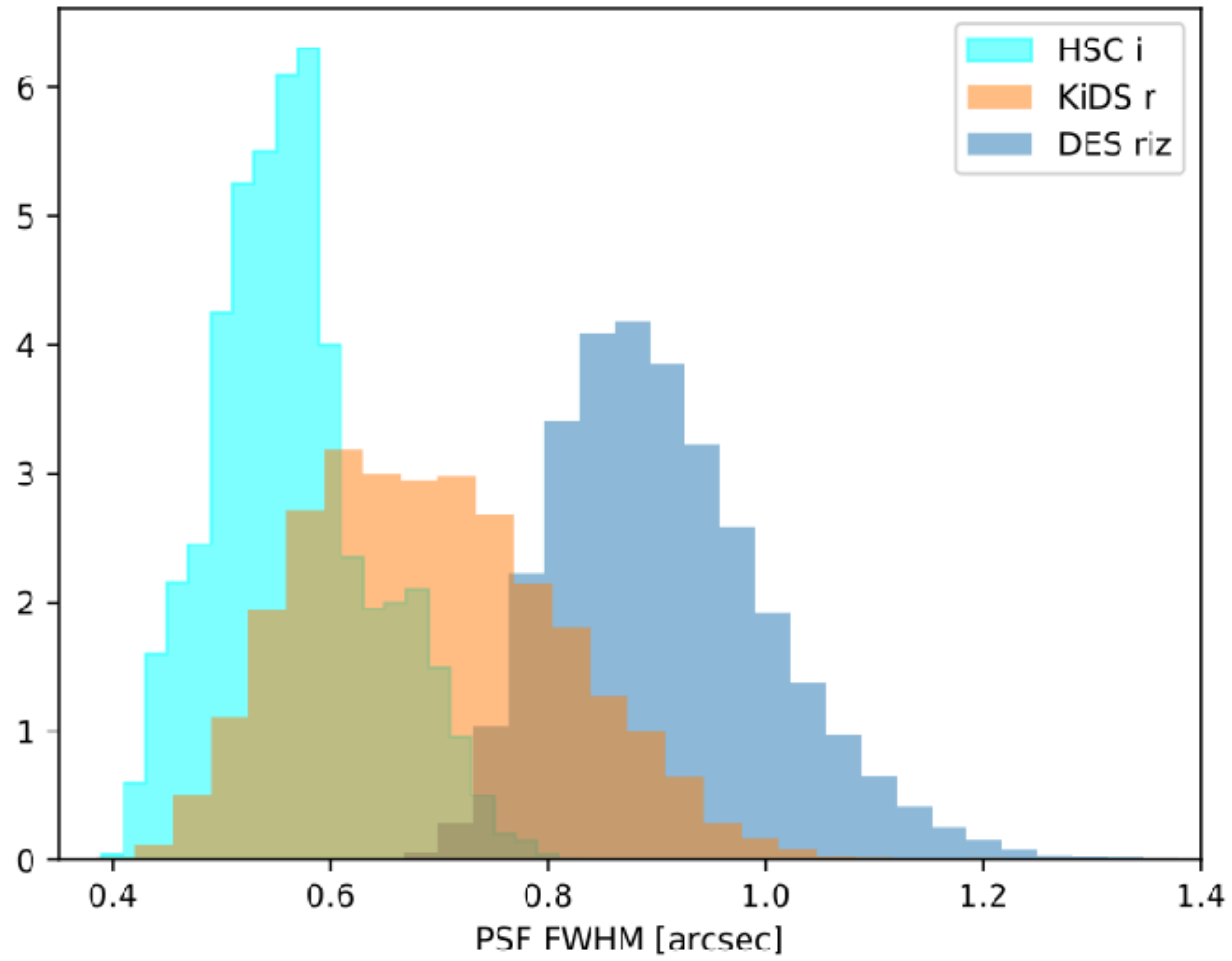
KiDS-1000

KiDS-1000 (DR4)

Key facts

- 1000deg^2 of *ugriZYJHK*s imaging
- 8.4gal/arcmin^{-2} with shapes
- Cosmic shear improvements:
    - Extensive mock tests
    - New covariance
    - SOM-based *n*(*z*) + gold selection
    - Three different 2pt statistics

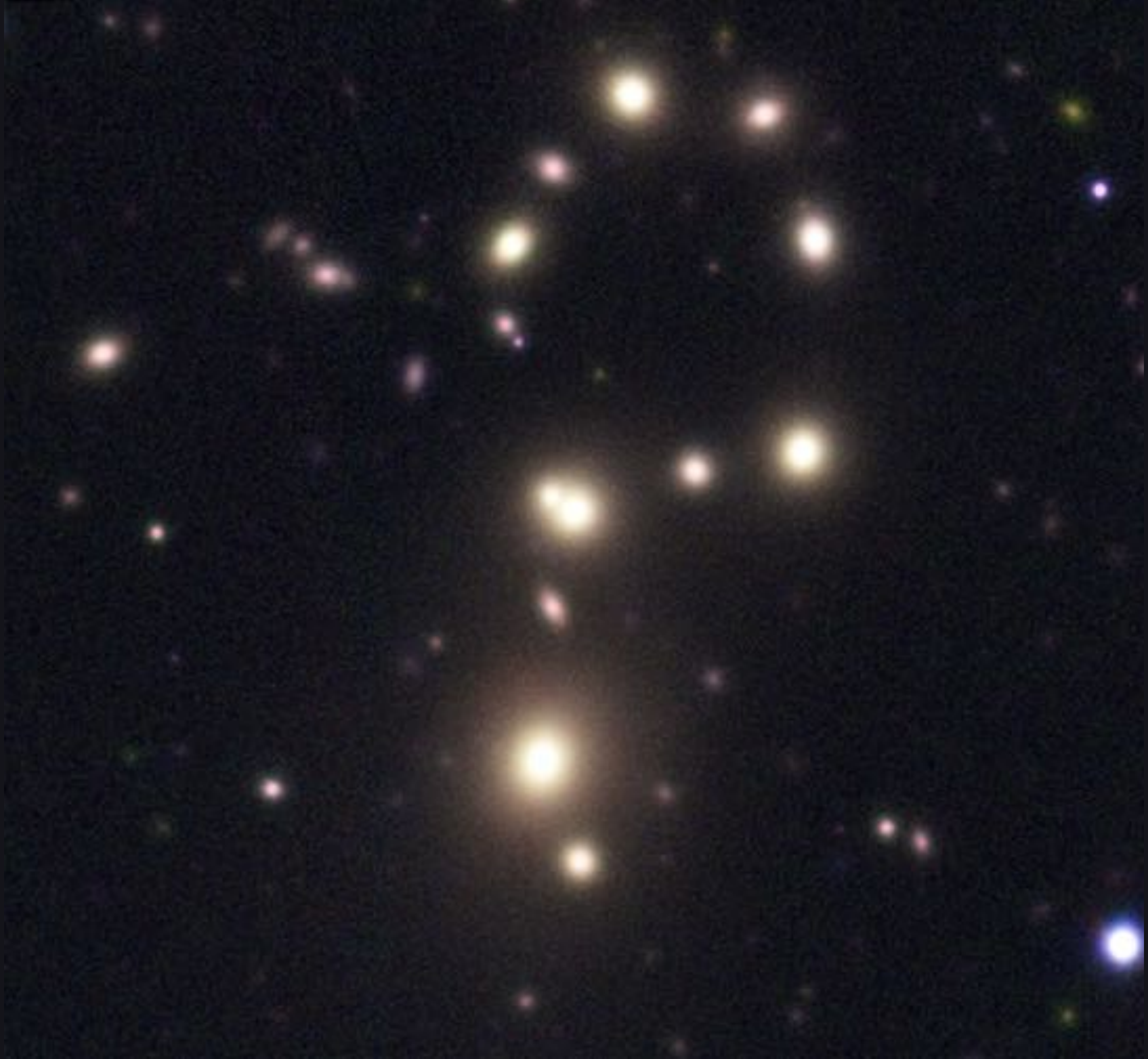




Kuijken et al. (2019)

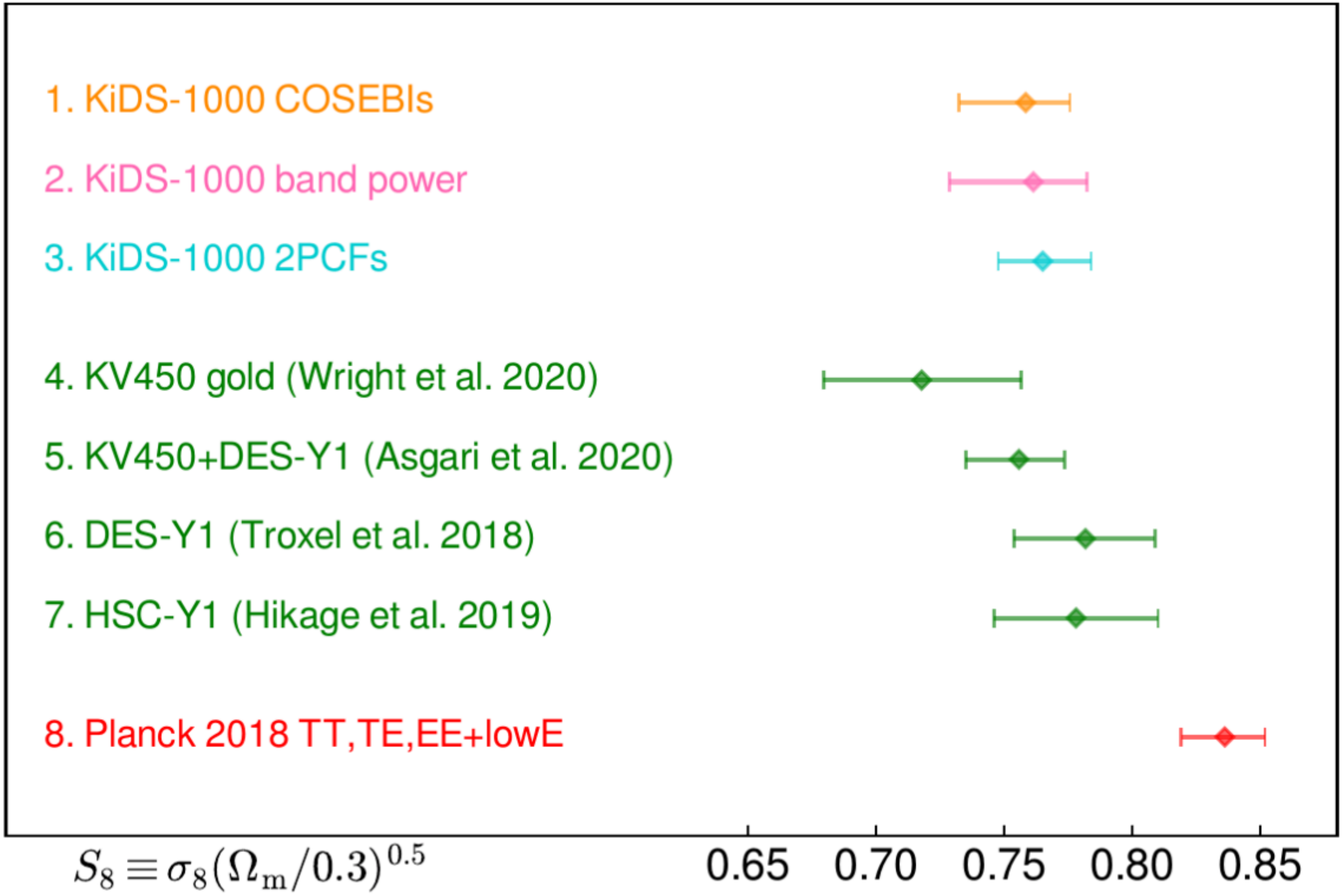
Blinding

Asgari et al. (2021)



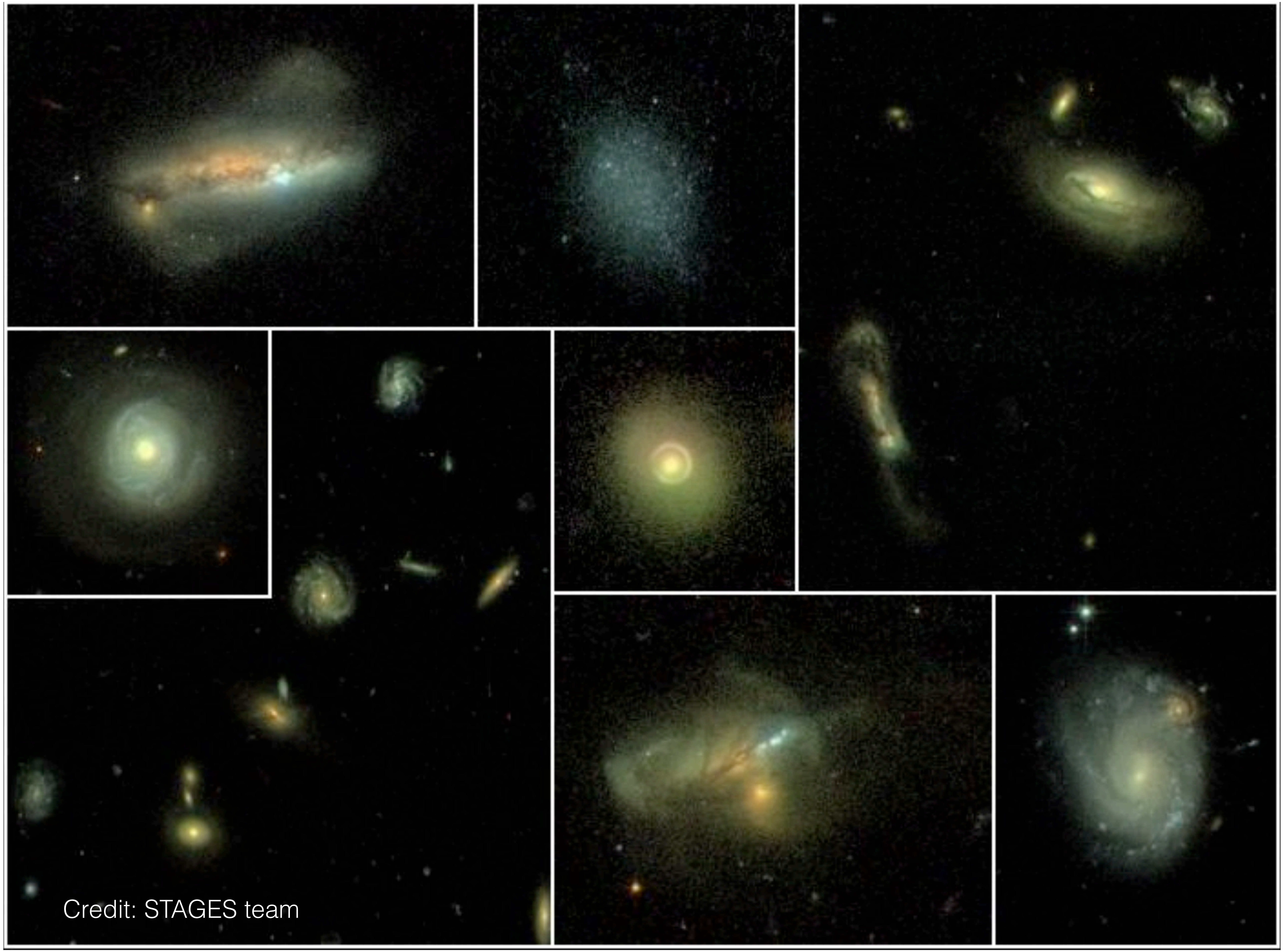
Cosmological constraints

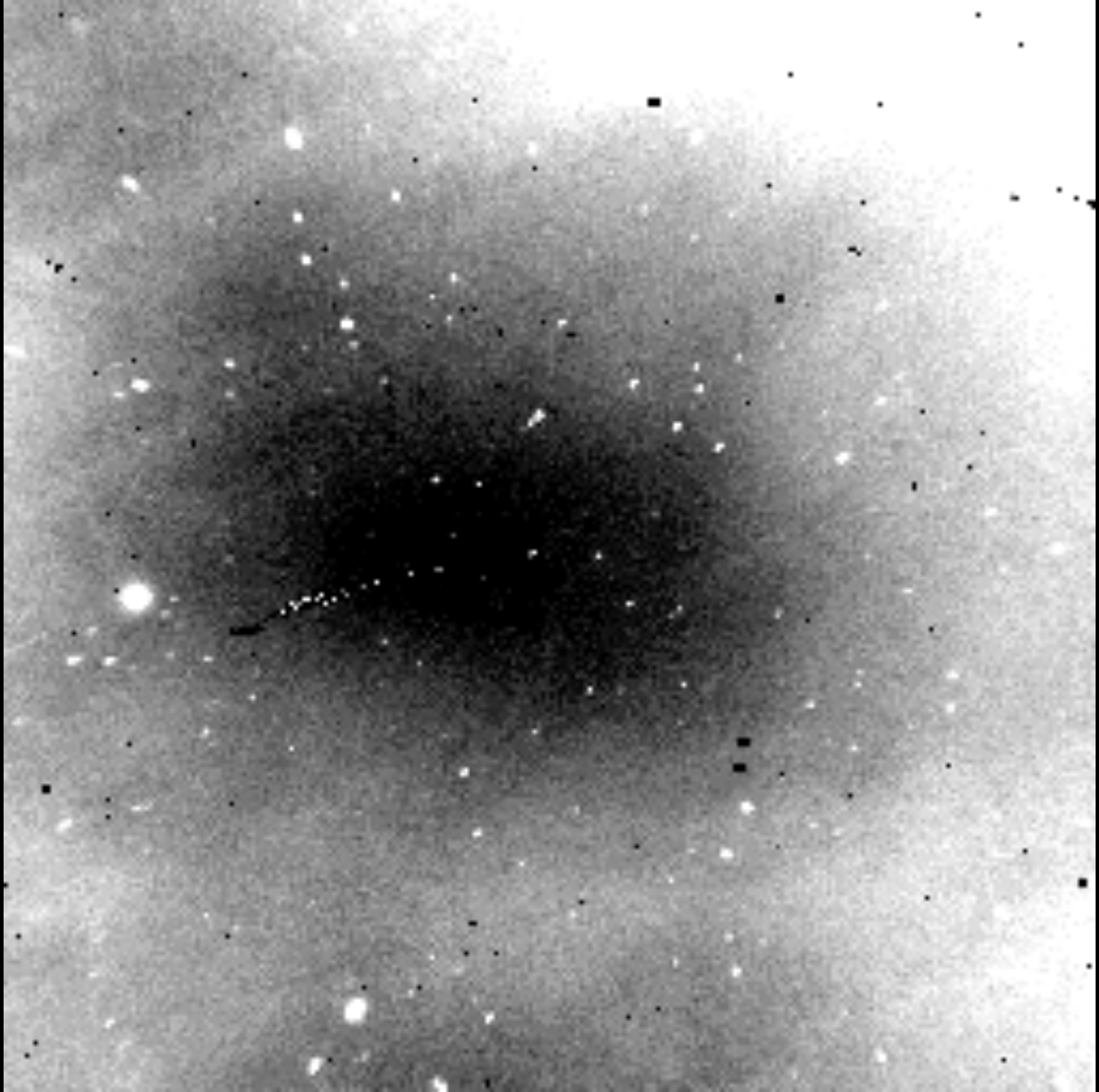
Asgari et al. (2021)



Asgari et al. (2021)


Credit: STAGES team


Credit: STAGES team

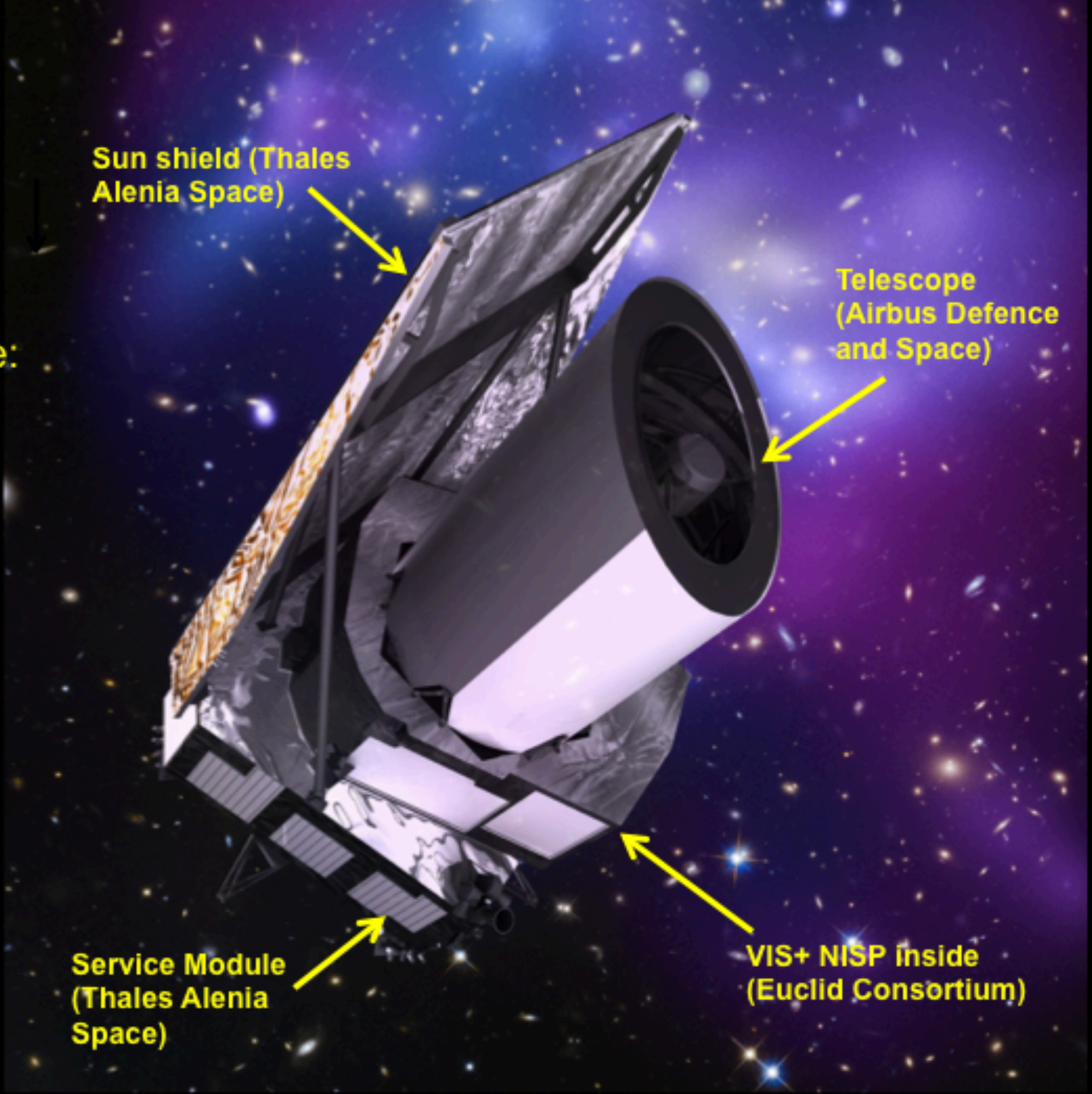


- Total mass satellite:

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 starten und solve this riddle.