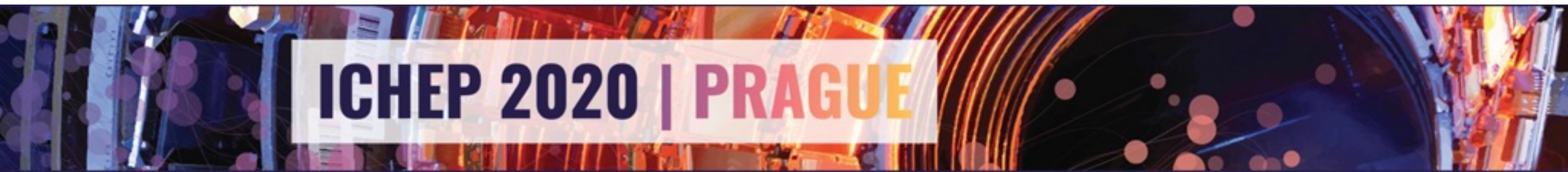
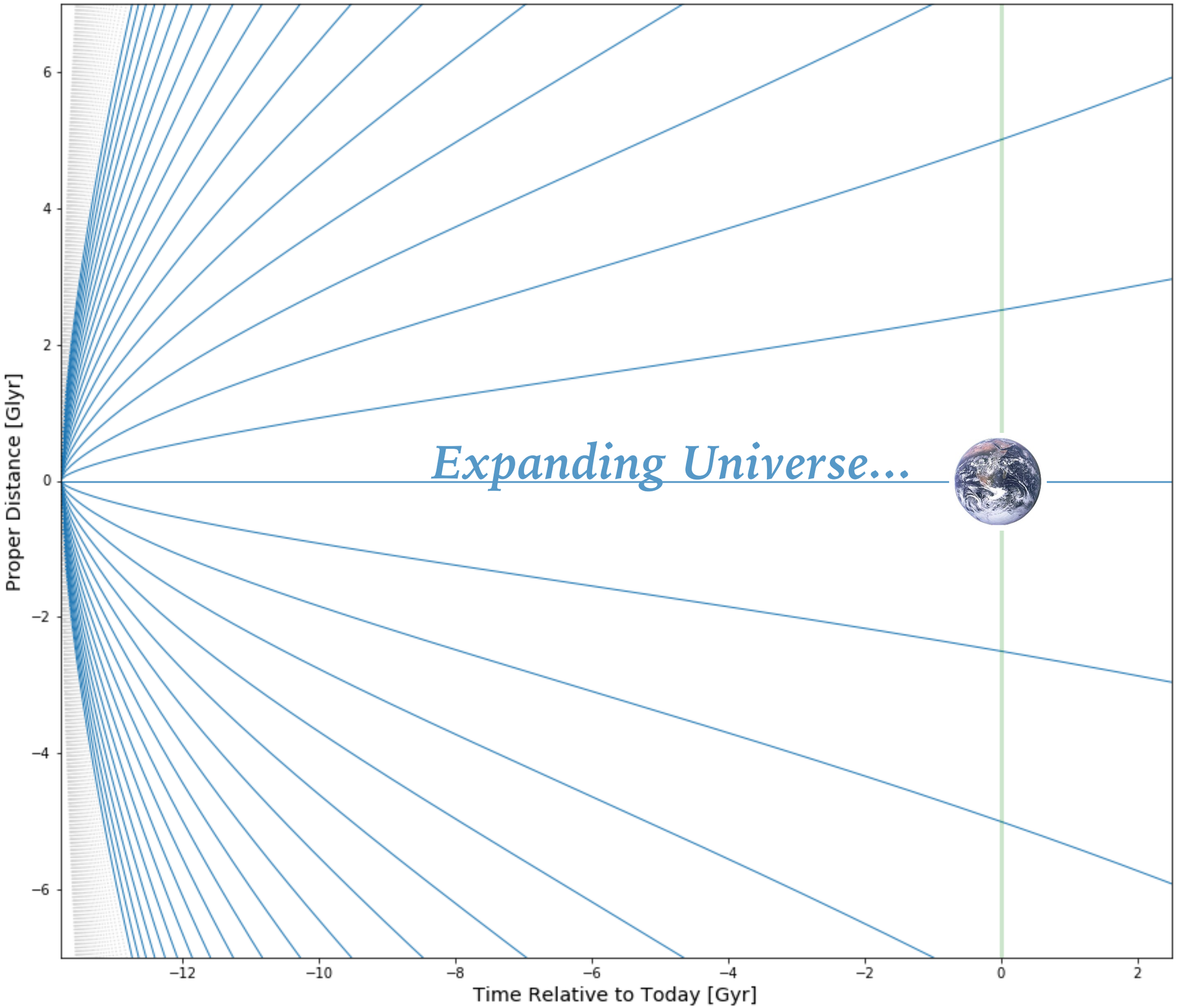
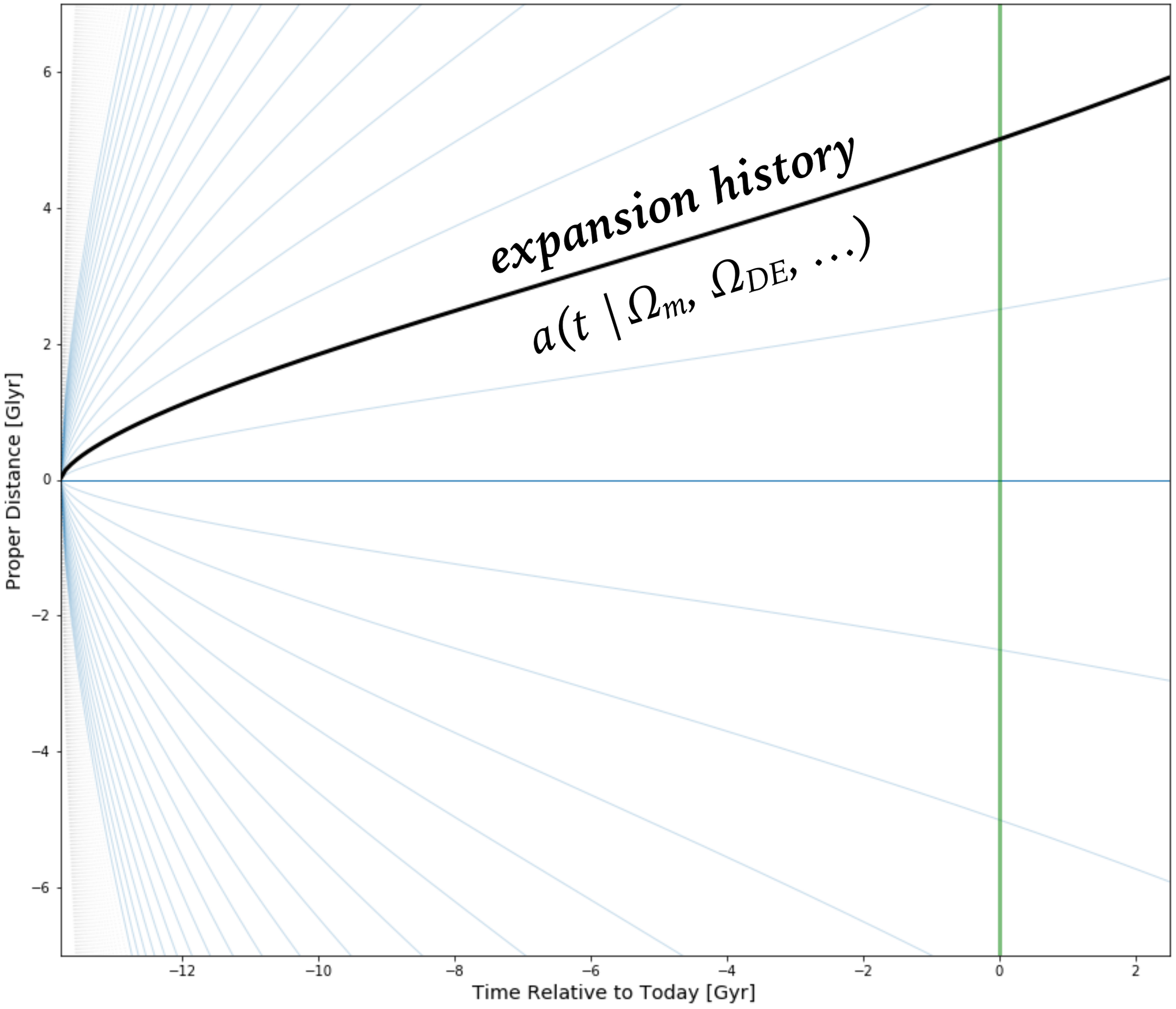
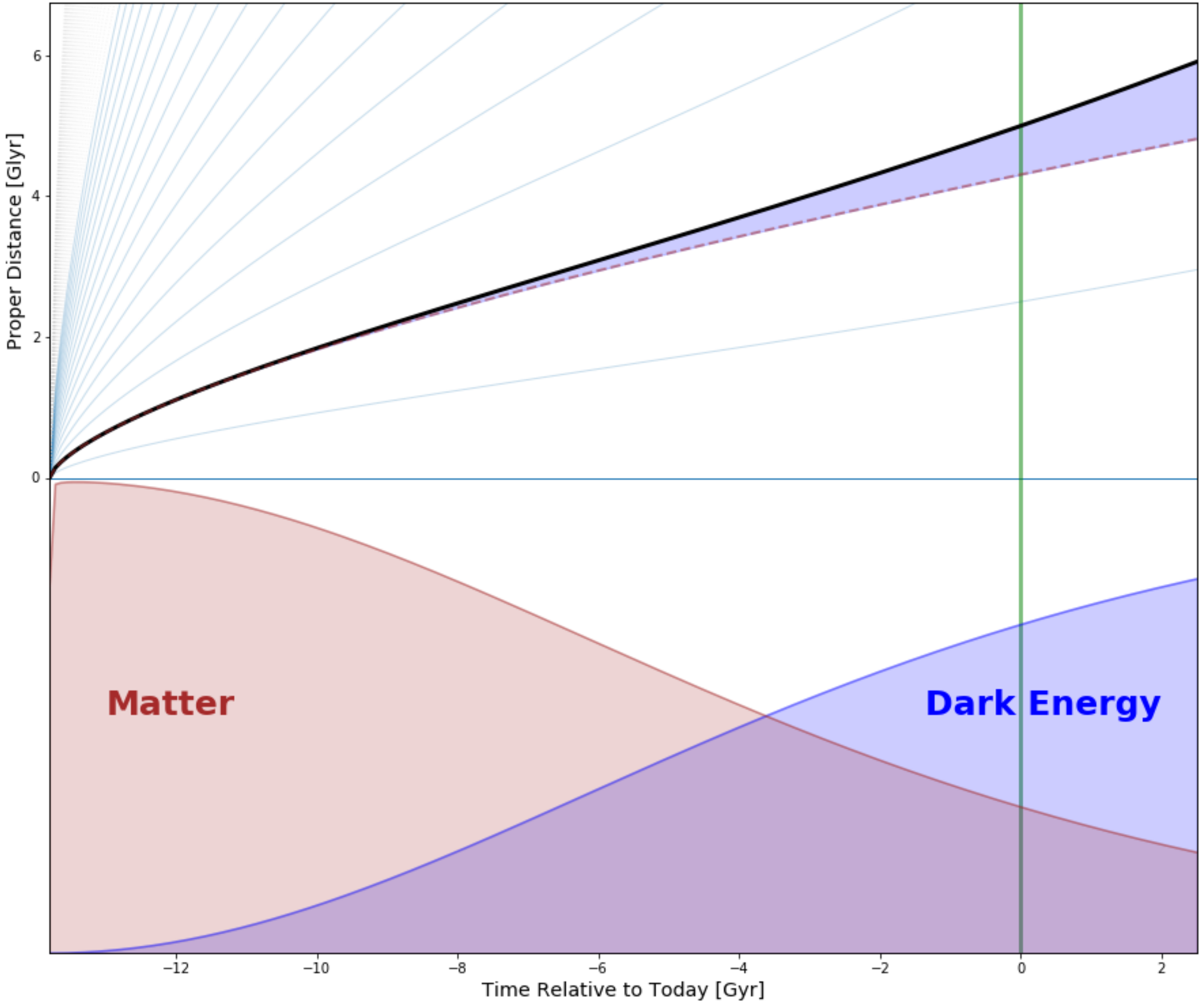
COSMOLOGY IN THE 2020s

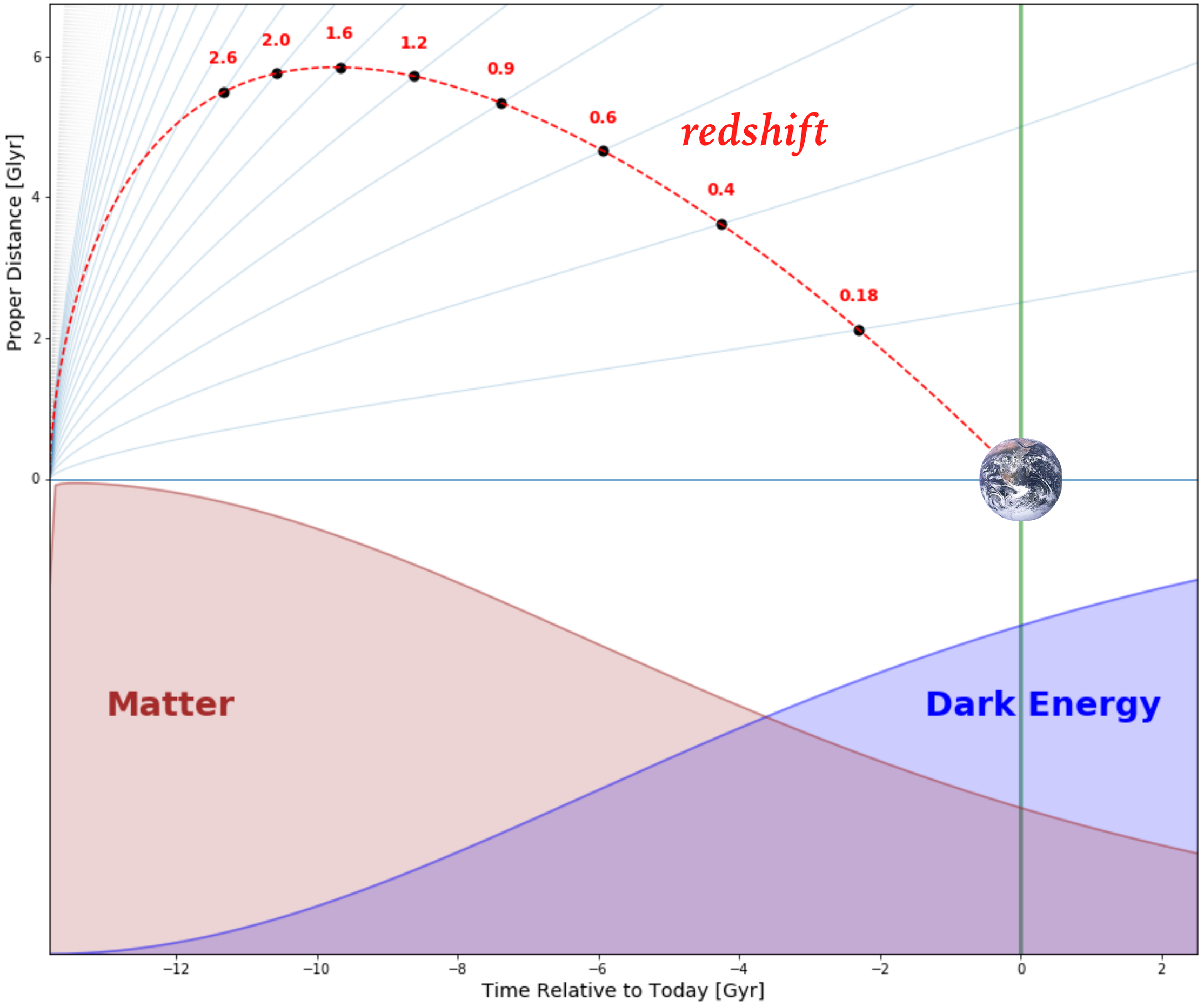
David Kirkby
University of California, Irvine, USA
4 August 2020

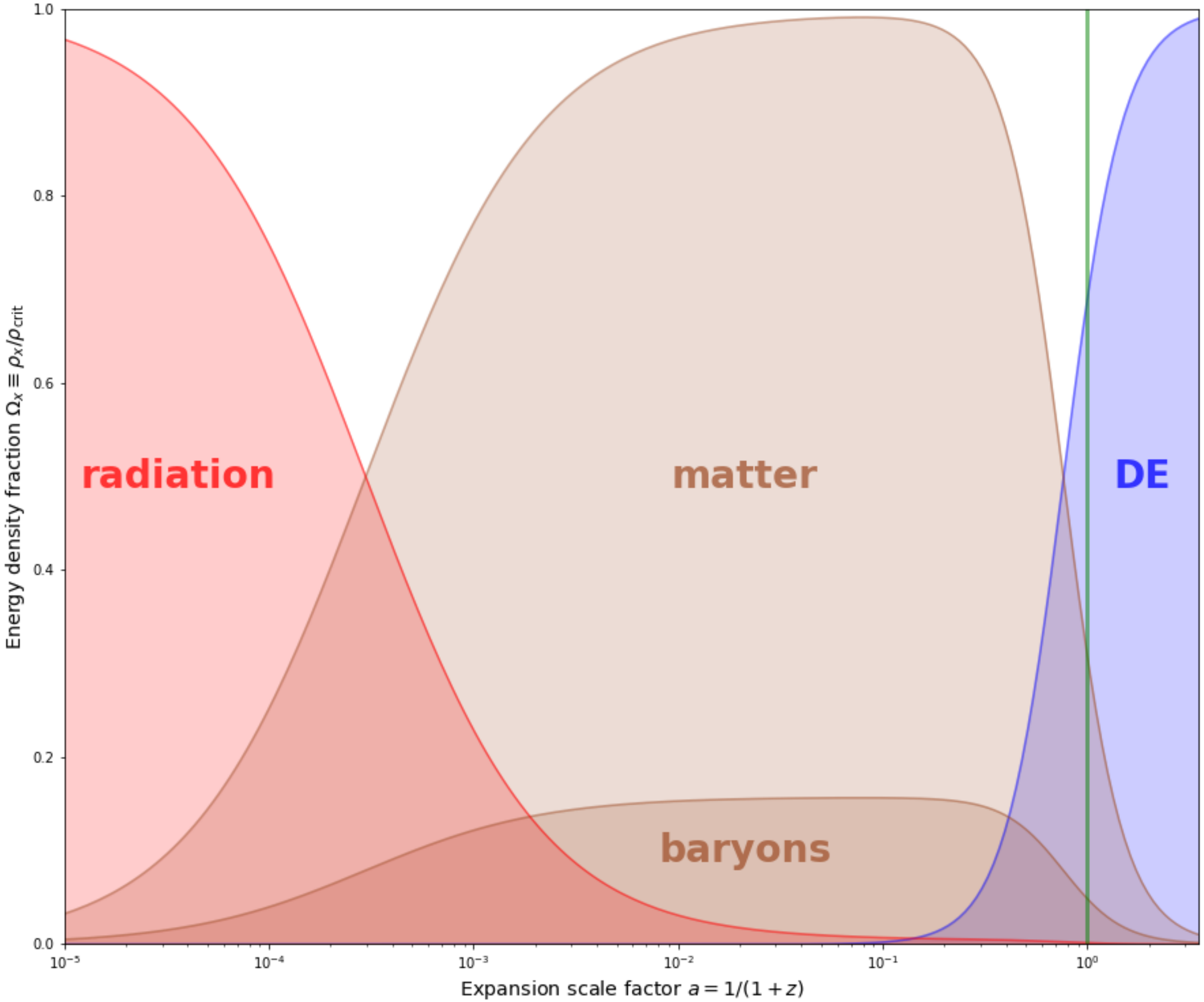


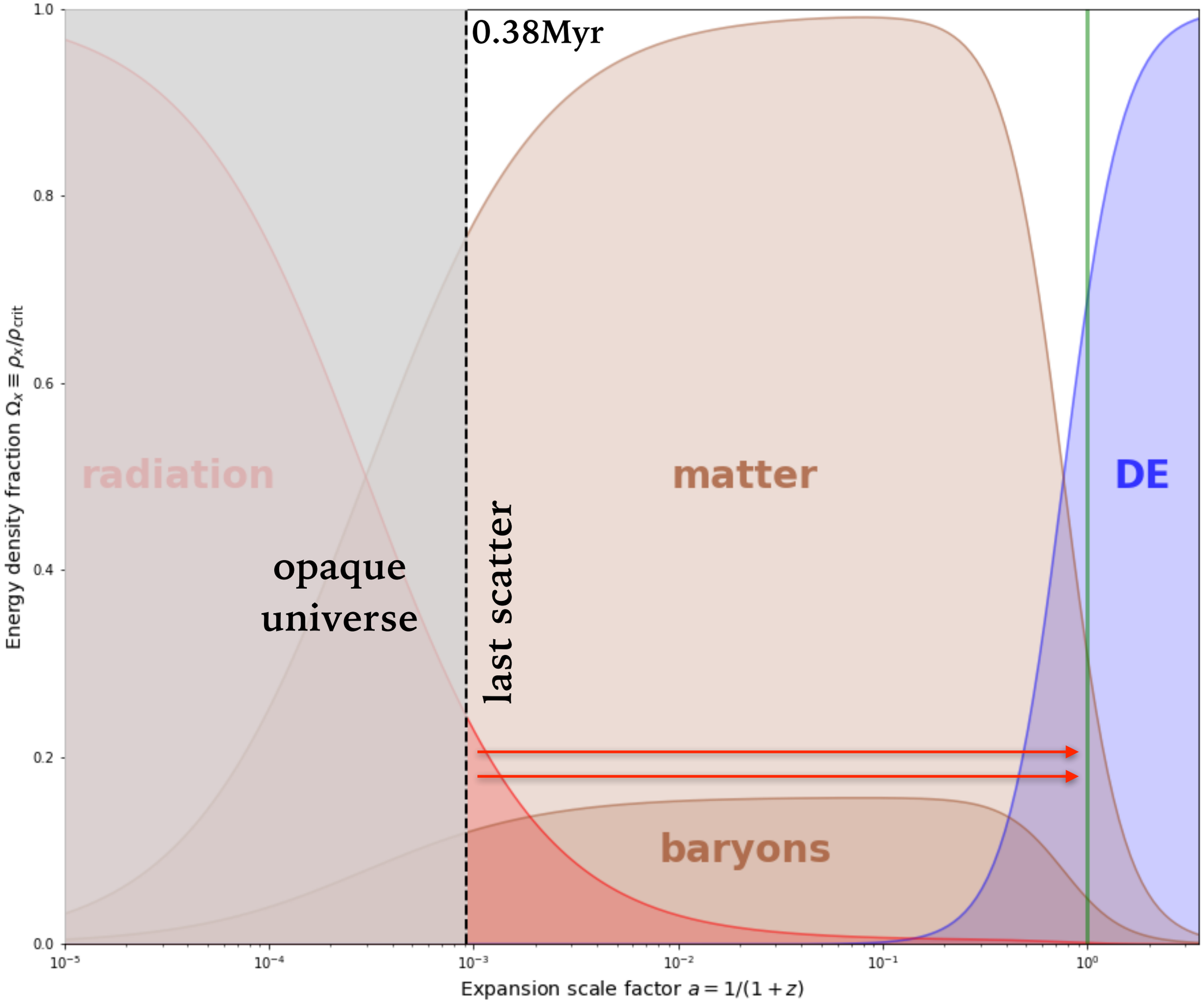

Expanding Universe...
Proper Distance [Glyr]
Time Relative to Today [Gyr]
6
4
2
0
−2
−4
−6
−12
−10
−8
−6
−4
−2
0
2

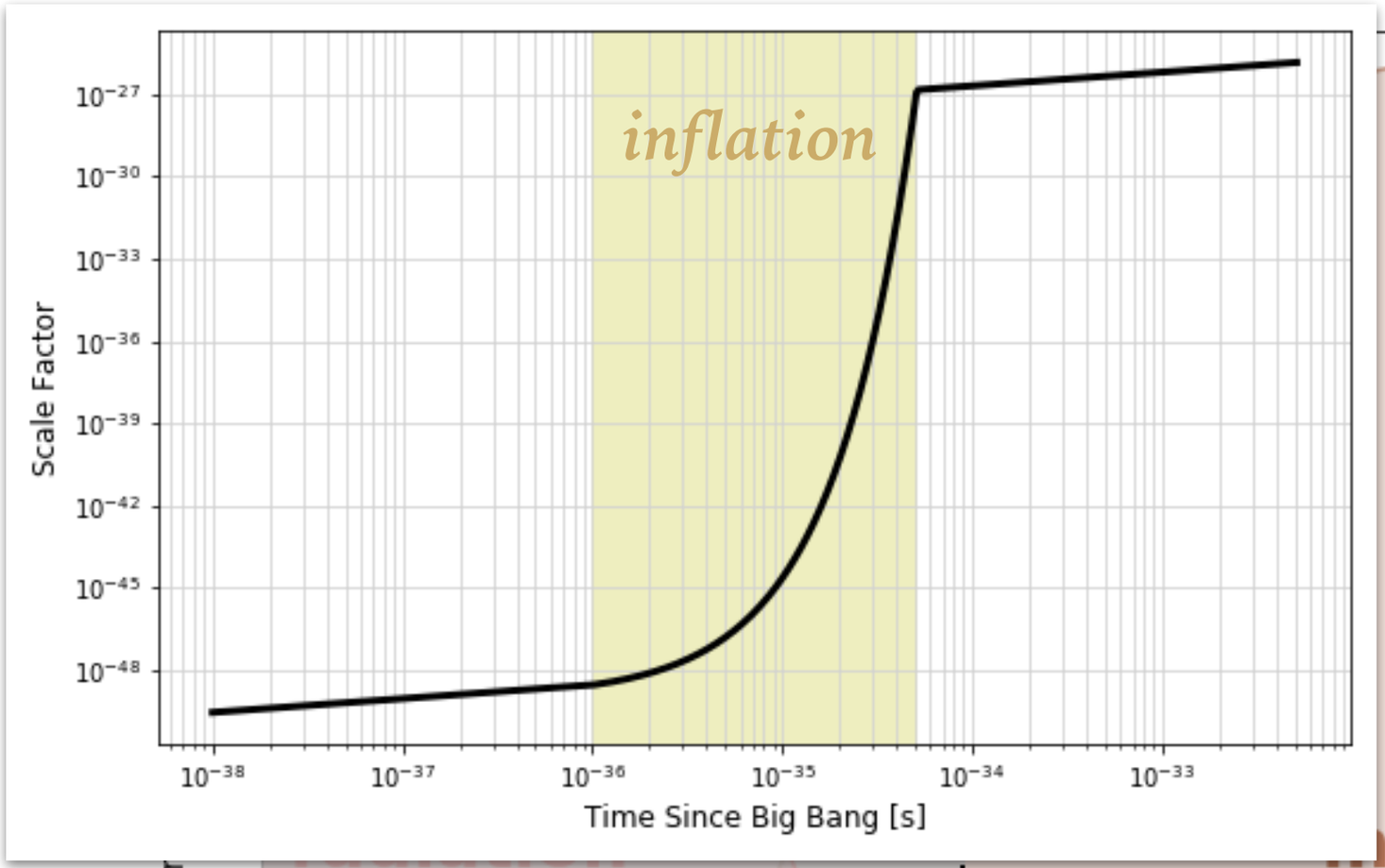

expansion history
$a(t \mid \Omega_m, \Omega_{DE}, \ldots)$
Proper Distance [Glyr]
Time Relative to Today [Gyr]
6
4
2
0
−2
−4
−6
−12
−10
−8
−6
−4
−2
0
2


Proper Distance [Glyr]
6
4
2
0
Matter
Dark Energy
−12
−10
−8
−6
−4
−2
0
2
Time Relative to Today [Gyr]


redshift
2.6
2.0
1.6
1.2
0.9
0.6
0.4
0.18
Matter
Dark Energy
Proper Distance [Glyr]
Time Relative to Today [Gyr]
6
4
2
0
−12
−10
−8
−6
−4
−2
0
2

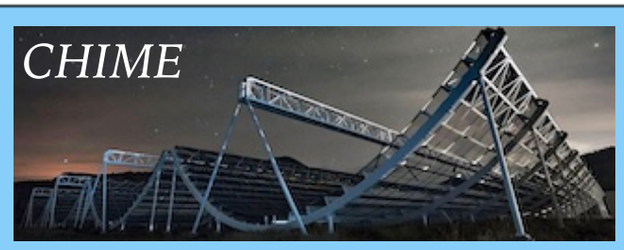

radiation
matter
DE
baryons
Energy density fraction $\Omega_X \equiv \rho_X/\rho_{\rm crit}$
Expansion scale factor $a = 1/(1+z)$
1.0
0.8
0.6
0.4
0.2
0.0
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
10^{0}


0.38Myr
radiation
matter
DE
opaque
universe
last scatter
baryons
Energy density fraction $\Omega_X \equiv \rho_X/\rho_{crit}$
Expansion scale factor $a = 1/(1+z)$
1.0
0.8
0.6
0.4
0.2
0.0
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
10^{0}


inflation
Scale Factor
10^{-27}
10^{-30}
10^{-33}
10^{-36}
10^{-39}
10^{-42}
10^{-45}
10^{-48}
10^{-38}
10^{-37}
10^{-36}
10^{-35}
10^{-34}
10^{-33}
Time Since Big Bang [s]

matter
DE
opaque
universe
last scatter
gravity waves?
baryons
Energy density fr
0.4
0.2
0.0
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
10^{0}
Expansion scale factor $a = 1/(1+z)$

Radio



1m

Hydrogen 21cm

Microwave

1cm

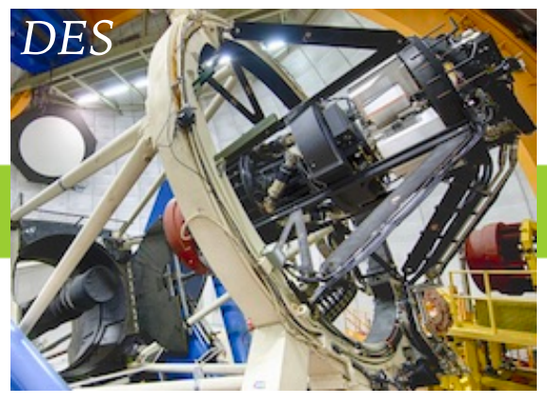
Wavelength

1μm

Optical-NIR

4000A break

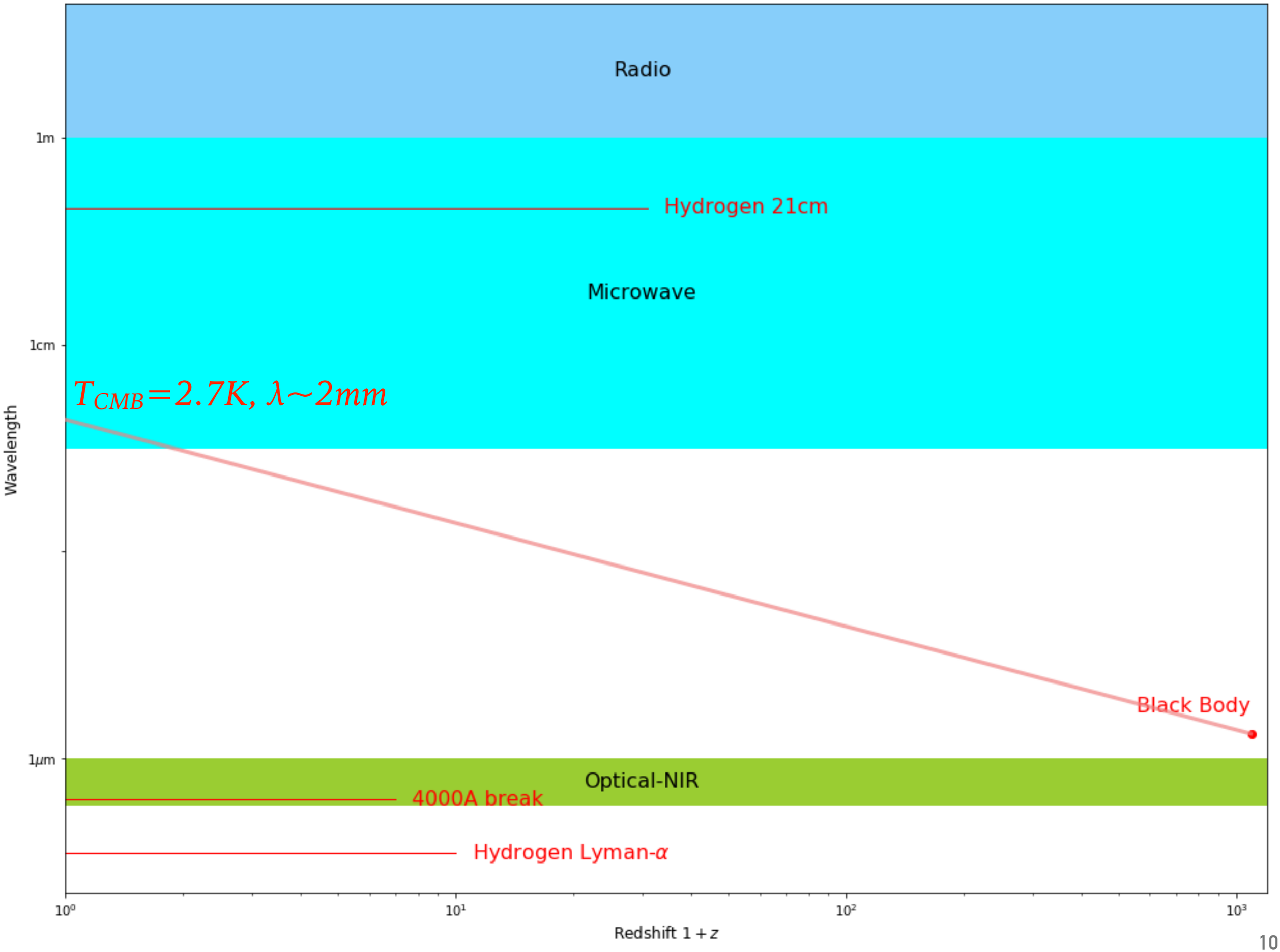
Hydrogen Lyman-α



Black Body

10^0 10^1 10^2 10^3

Redshift $1+z$


Radio
1m
Hydrogen 21cm
Microwave
1cm
$T_{CMB}=2.7K,\ \lambda\sim 2mm$
Wavelength
Black Body
1μm
Optical-NIR
4000A break
Hydrogen Lyman-α
10^0
10^1
10^2
10^3
Redshift $1+z$

Radio

1m

Hydrogen 21cm

Microwave

CMB

1cm

$T_{CMB}=2.7K,\ \lambda\sim 2mm$

Wavelength

Black Body

Galaxies

1μm

Optical-NIR

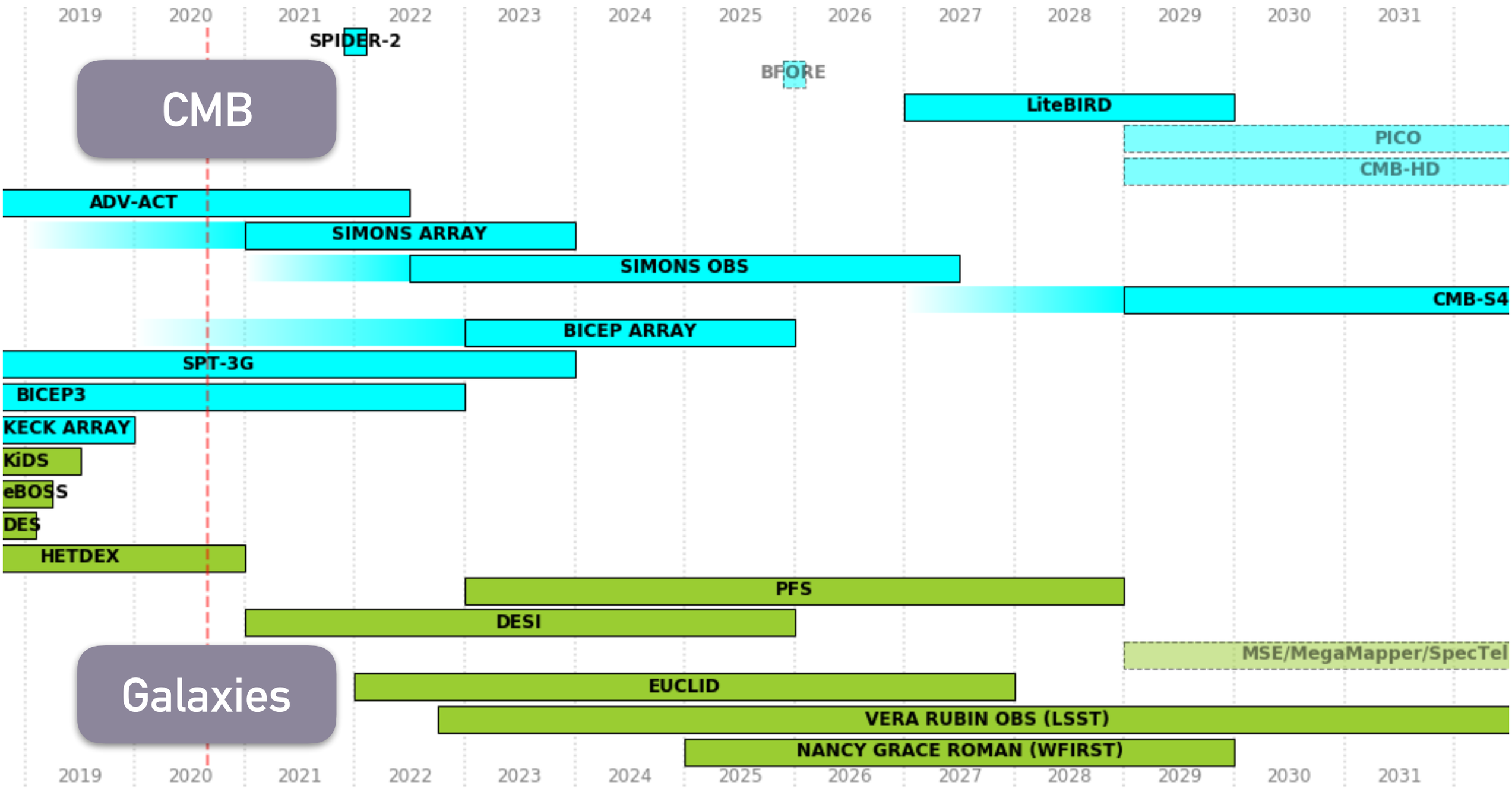
4000A break

Hydrogen Lyman-α

10^0 10^1 10^2 10^3

Redshift $1+z$

microwave projects: cosmic microwave background (primordial gravity waves, neutrinos, ...)



optical & NIR projects: galaxy surveys (dark energy, neutrinos, ...)

2019 2020 2021 2022 2023 2024 2025 2026 2027 2028 2029 2030 2031

SPIDER-2

BFORE

CMB

LiteBIRD

PICO

CMB-HD

ADV-ACT

SIMONS ARRAY

SIMONS OBS

CMB-S4

BICEP ARRAY

SPT-3G

BICEP3

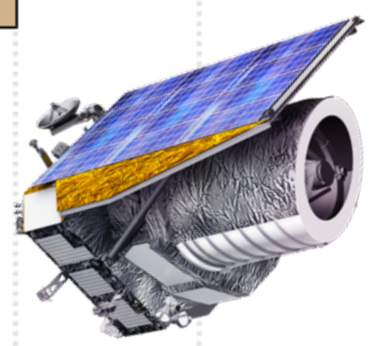
KECK ARRAY

KiDS

eBOSS

DES

HETDEX



PFS

DESI

MSE/MegaMapper/SpecTel

Galaxies

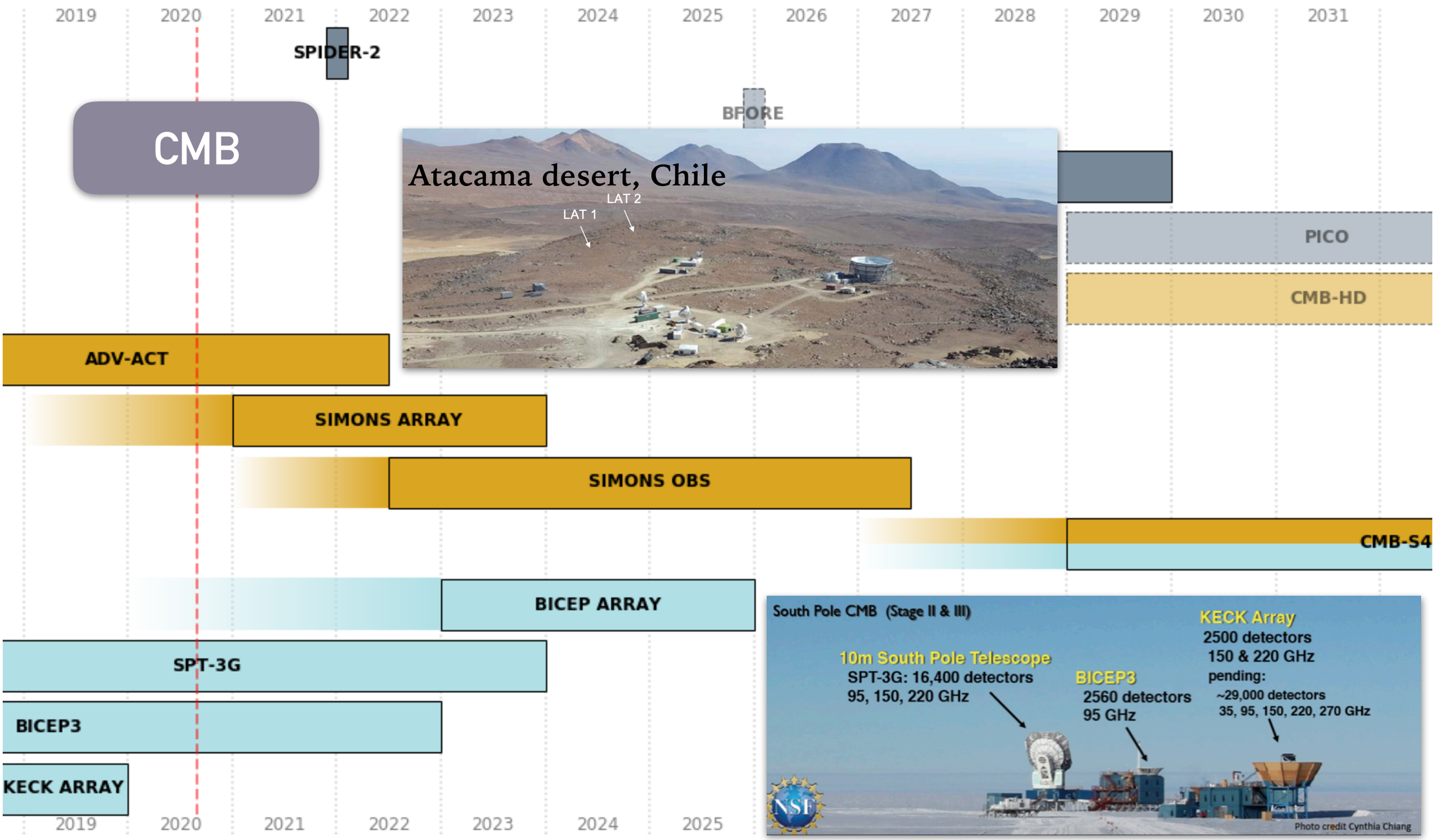
EUCLID

VERA RUBIN OBS (LSST)

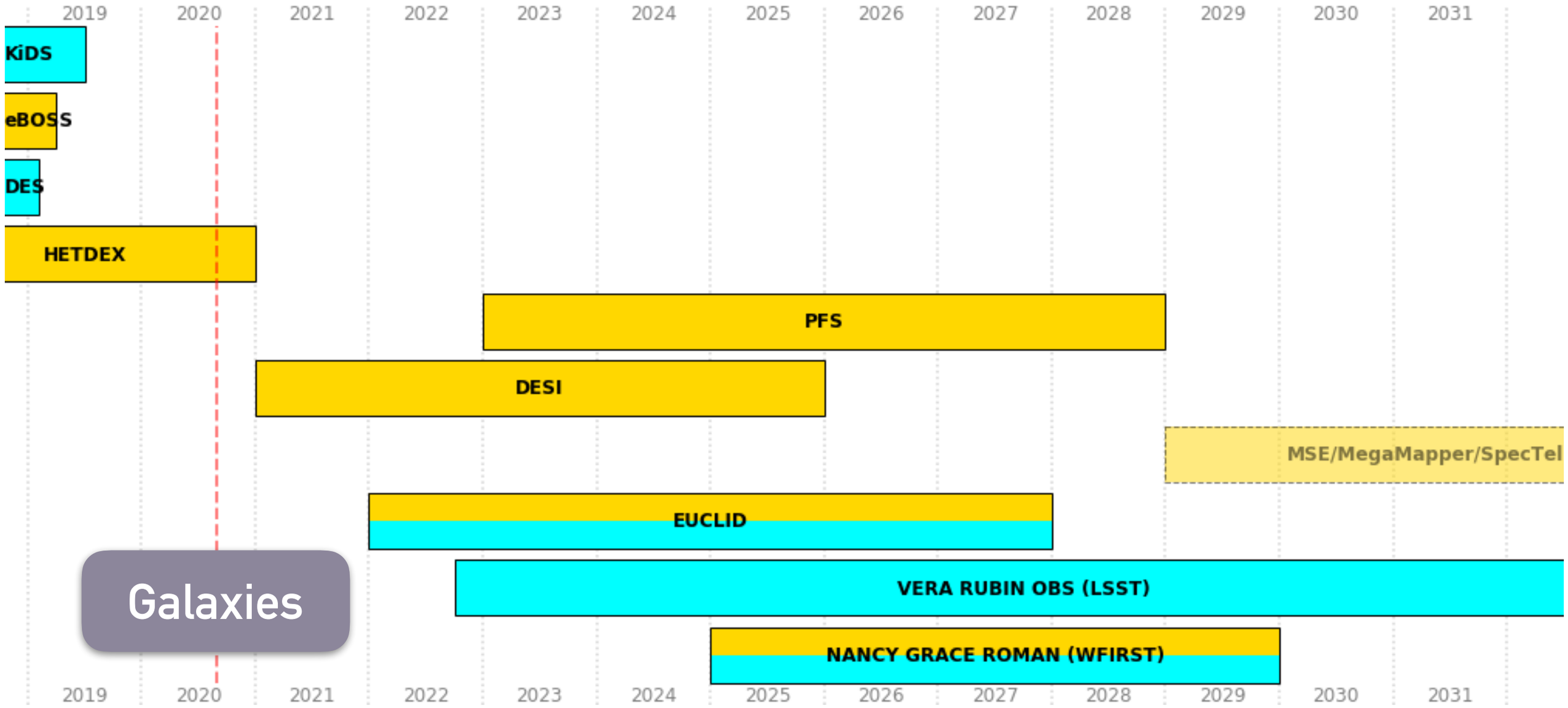
NANCY GRACE ROMAN (WFIRST)

2019 2020 2021 2022 2023 2024 2025 2026 2027 2028 2029 2030 2031

telescope location: ground / above atmosphere



CMB ground telescope location: Atacama desert / South Pole

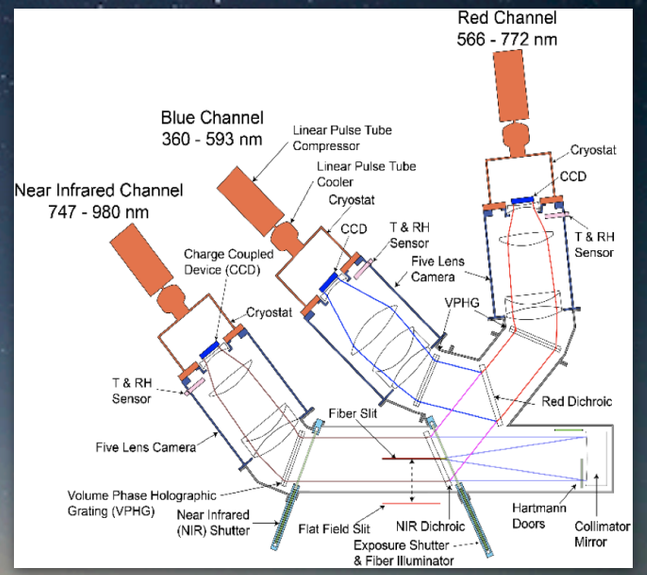


Galaxy survey instrument: spectrograph / imager

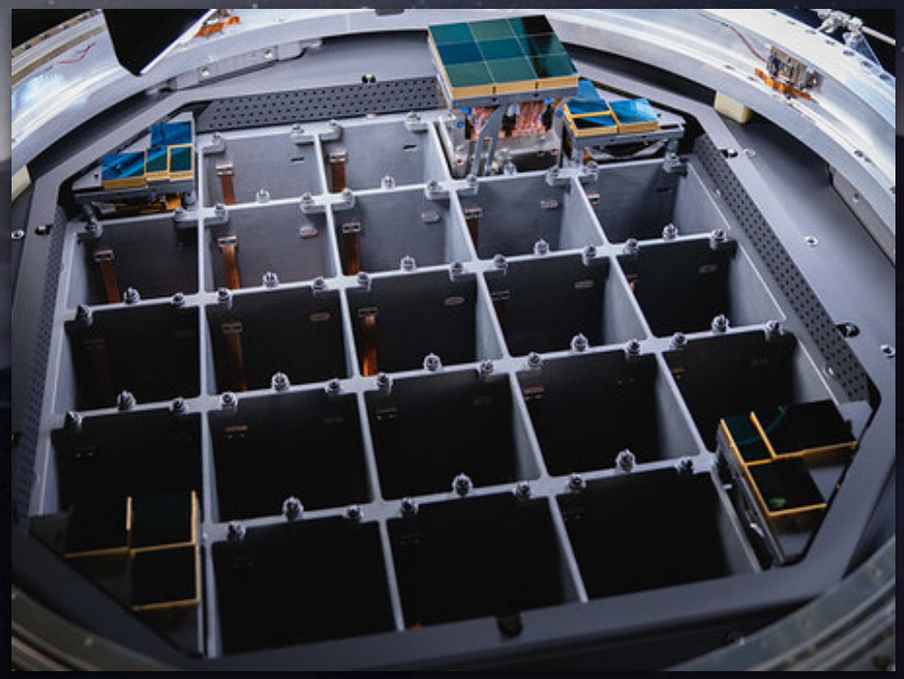
Dark Energy Spectroscopic Instrument (DESI)

Vera Rubin Observatory

Dark Energy Spectroscopic Instrument (DESI)

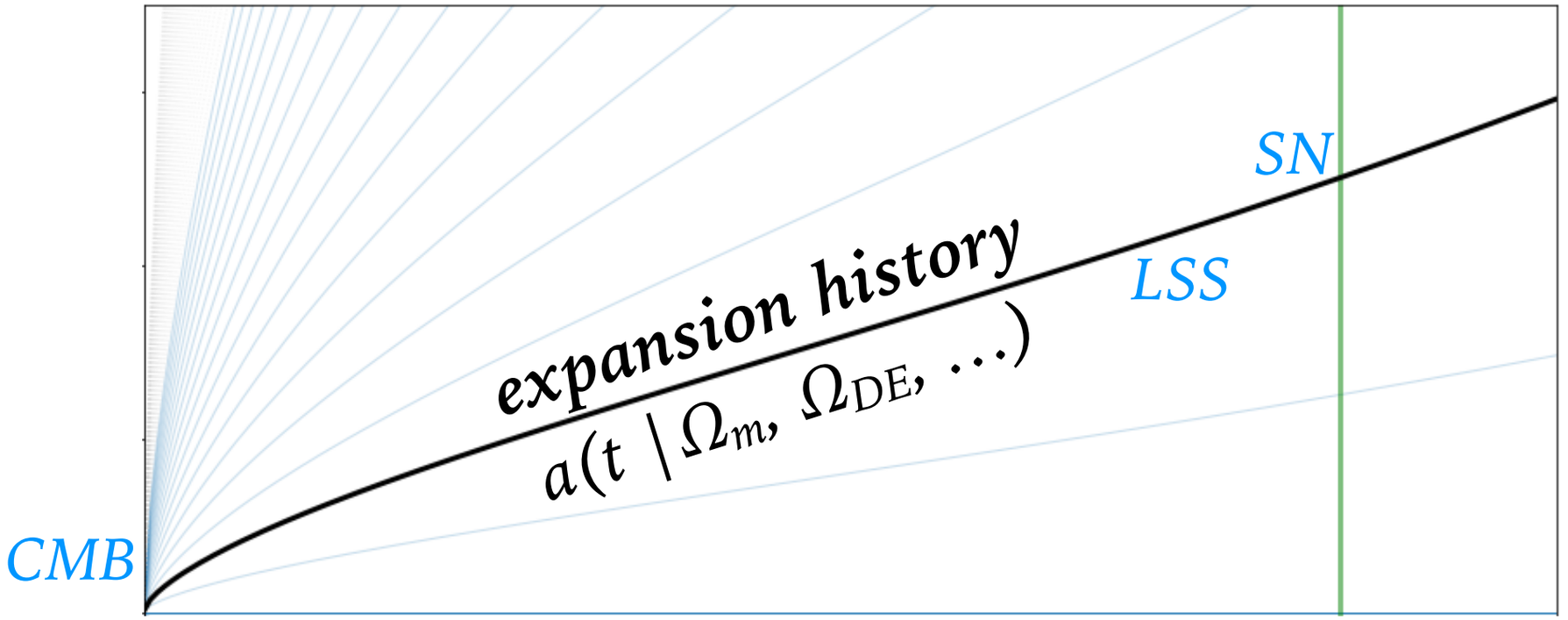


Vera Rubin Observatory



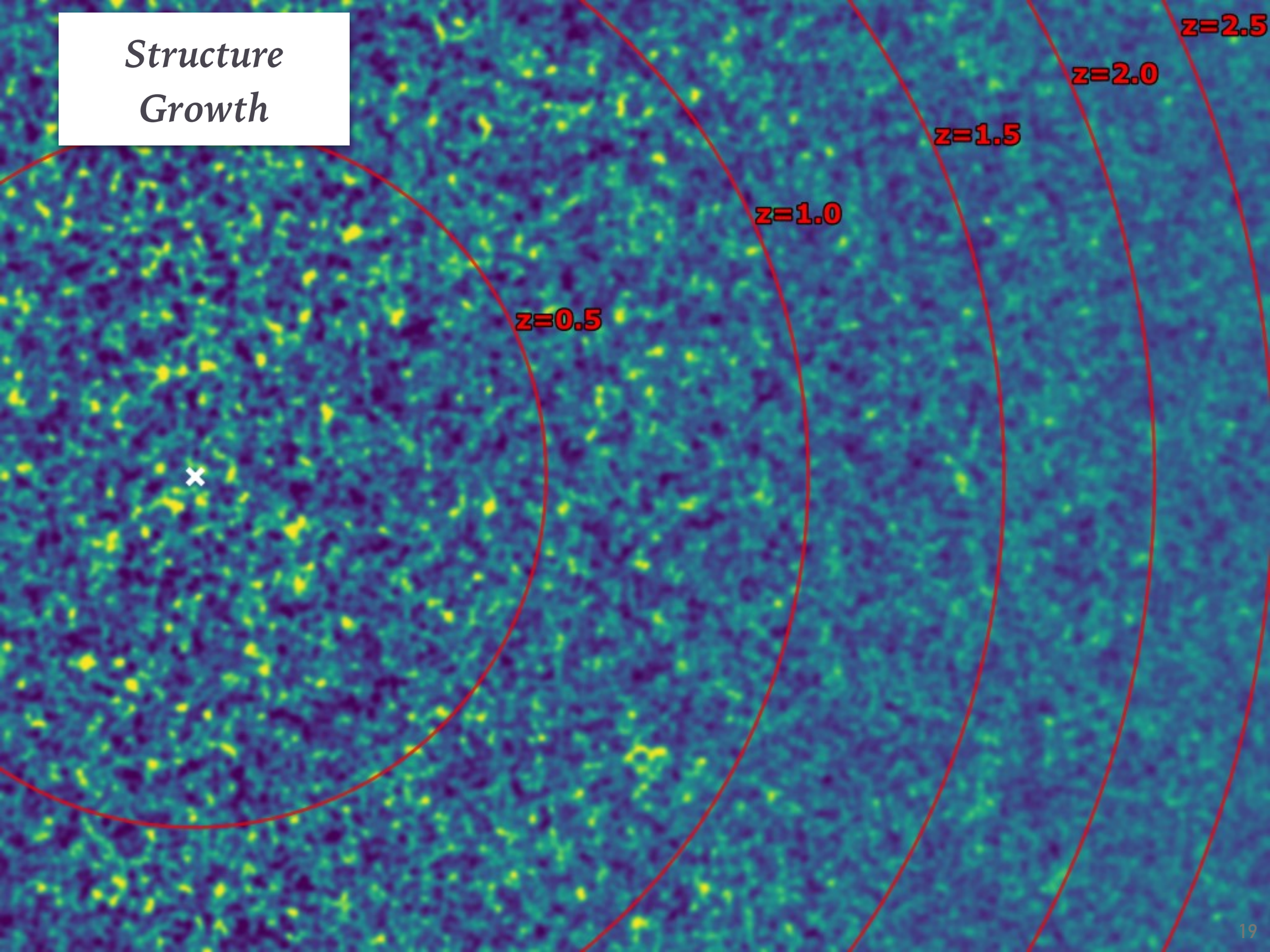
EXPANSION HISTORY VS STRUCTURE GROWTH

Measurements of our cosmic expansion history constrain the parameters of an expanding homogenous universe:

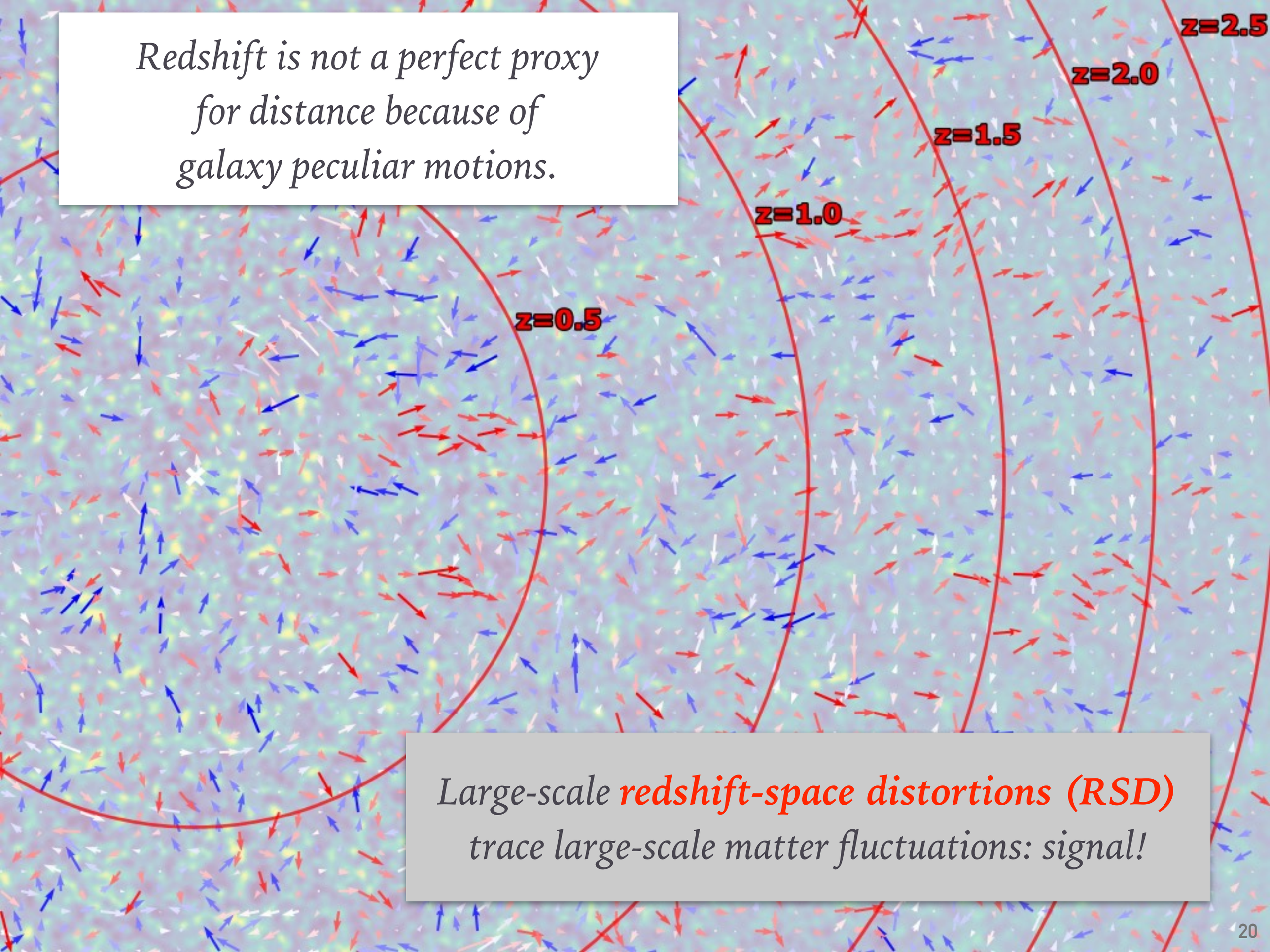


Small inhomogeneities are growing against this backdrop. Measurements of this structure growth provide complementary constraints.

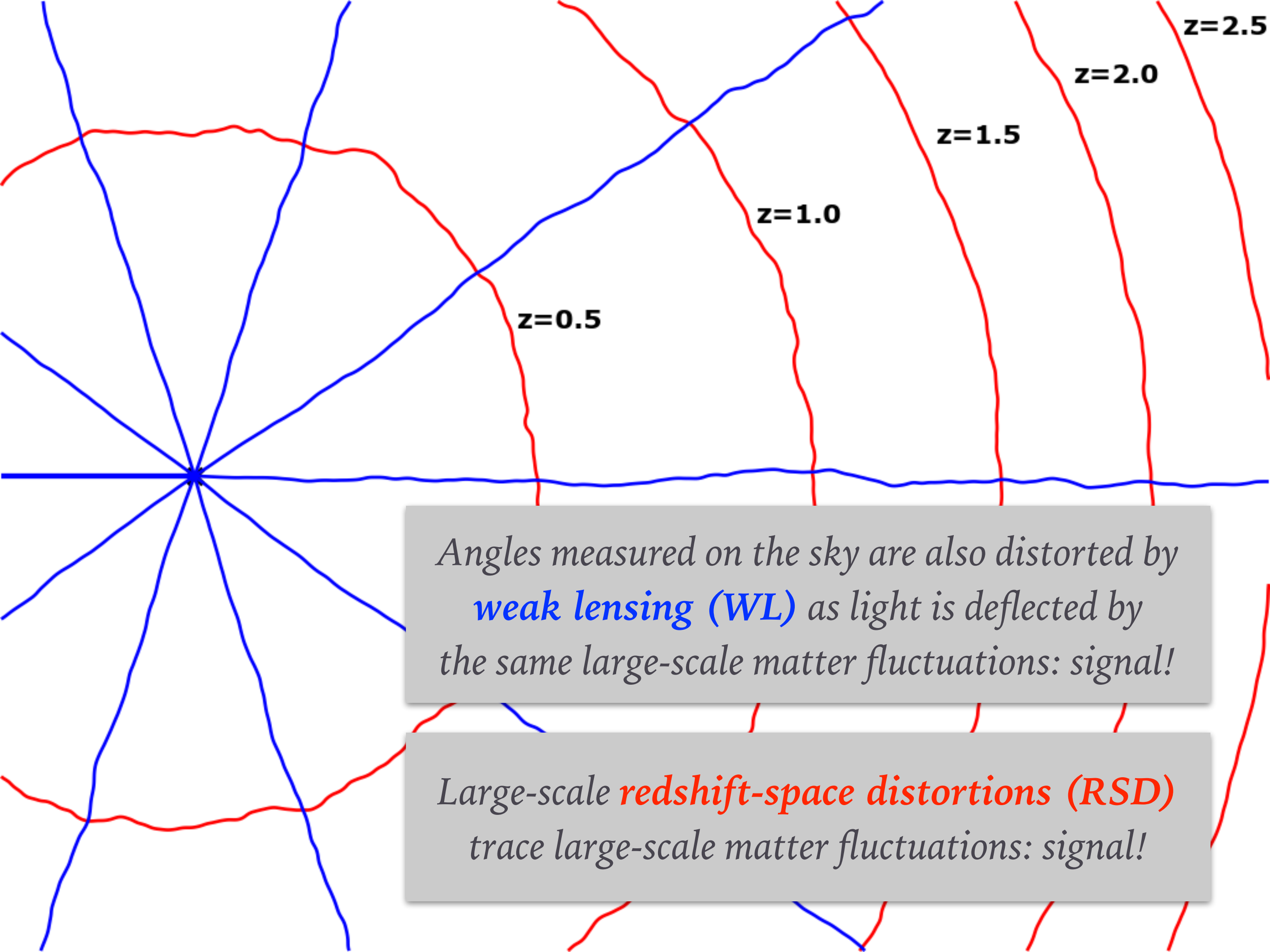
Structure Growth



Redshift is not a perfect proxy for distance because of galaxy peculiar motions.



*Large-scale **redshift-space distortions (RSD)** trace large-scale matter fluctuations: signal!*

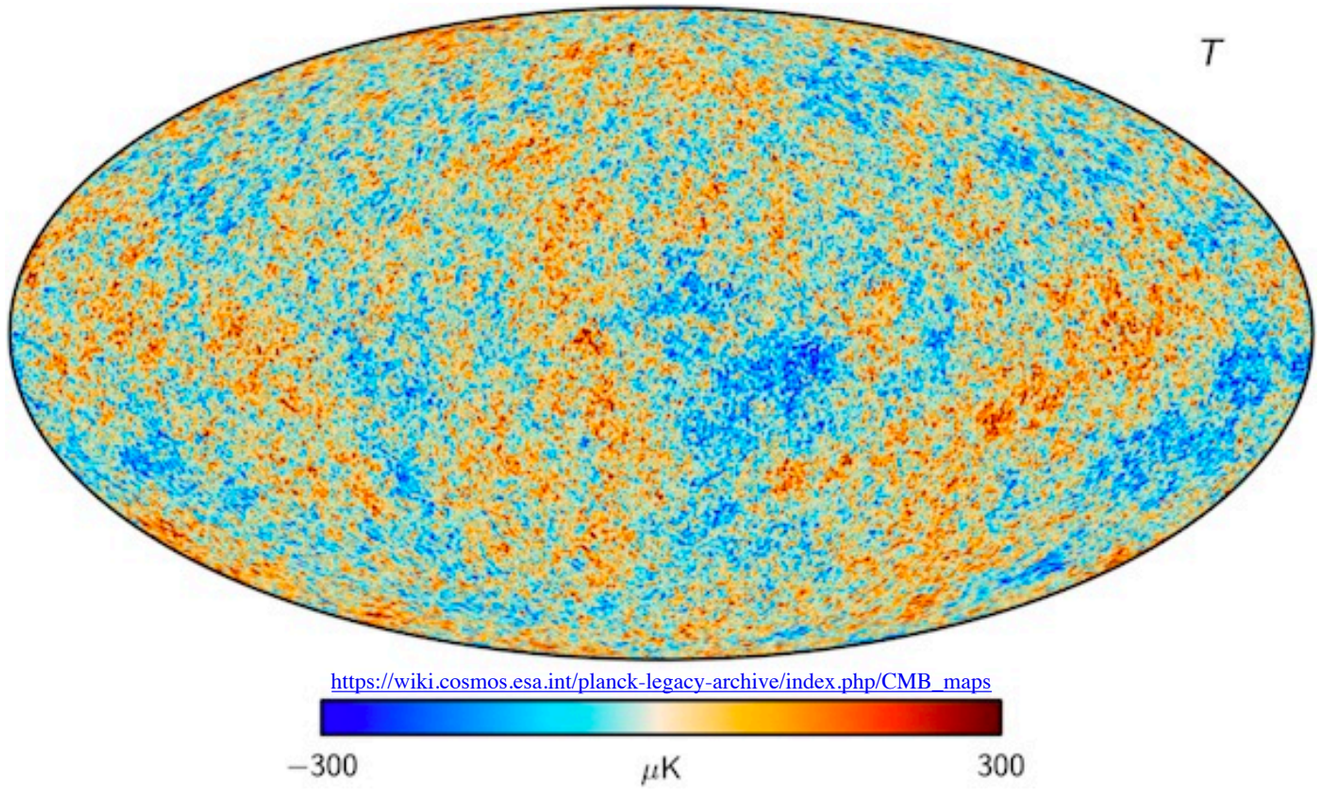


Angles measured on the sky are also distorted by ***weak lensing (WL)*** *as light is deflected by the same large-scale matter fluctuations: signal!*

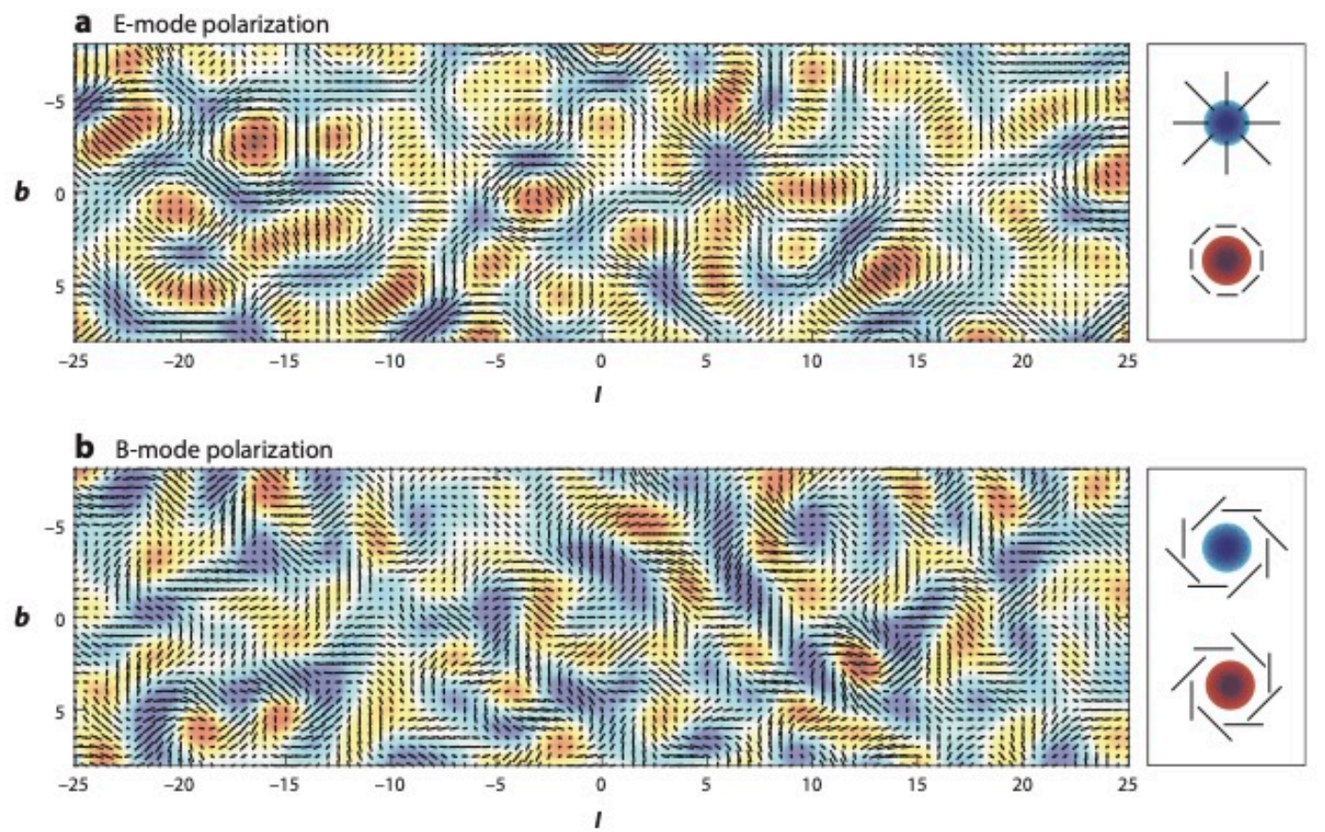
Large-scale ***redshift-space distortions (RSD)*** *trace large-scale matter fluctuations: signal!*

CMB measures initial conditions of structure growth at z~1090:

CMB photons also experience weak lensing!



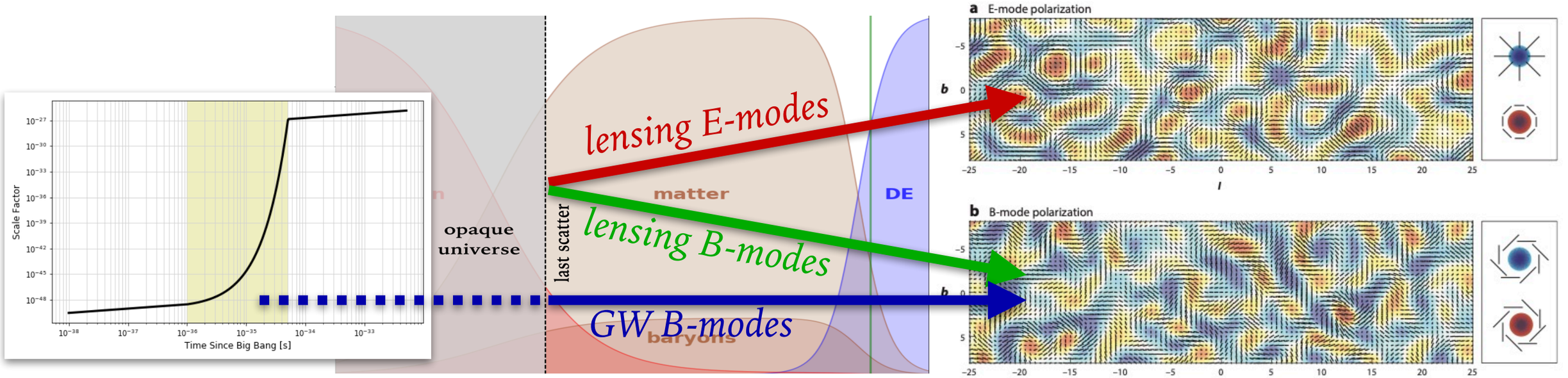
Temperature



Polarization

CMB: INFLATION ERA SIGNATURES

https://www.annualreviews.org/doi/abs/10.1146/annurev-astro-081915-023433



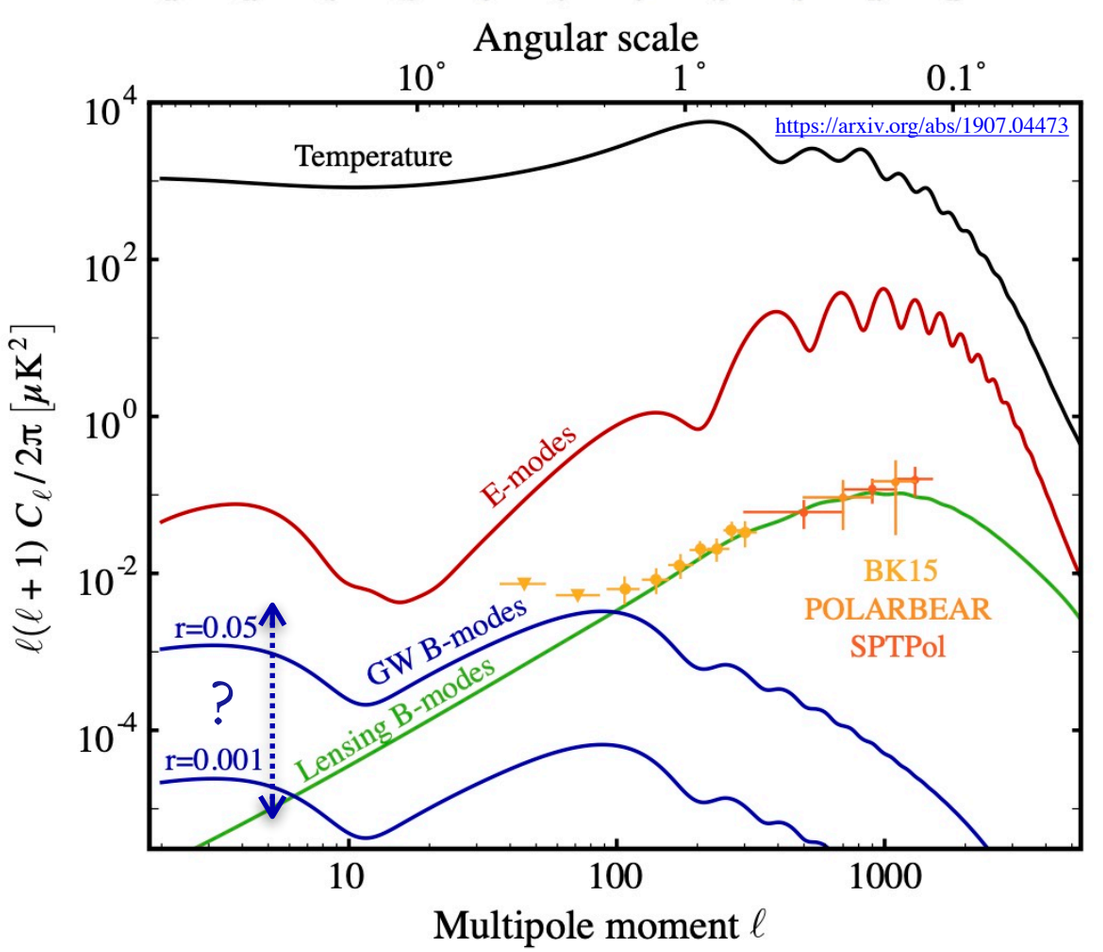
Lensing B modes already observed.

Next target:

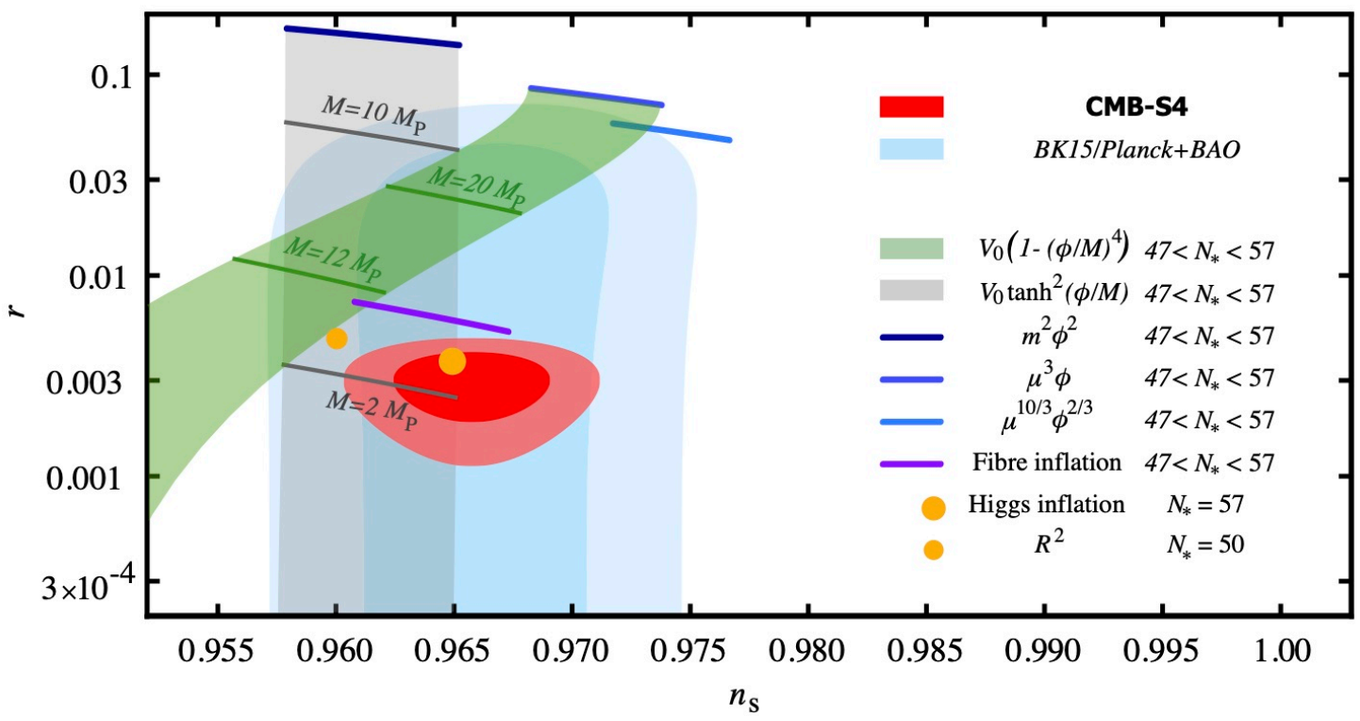
B modes from primordial gravity waves.

Key parameter:

r = tensor / scalar fluctuations



CMB: INFLATION ERA SIGNATURES



Forecast sensitivity to *r*

https://arxiv.org/abs/1907.04473

Lensing B modes already observed.

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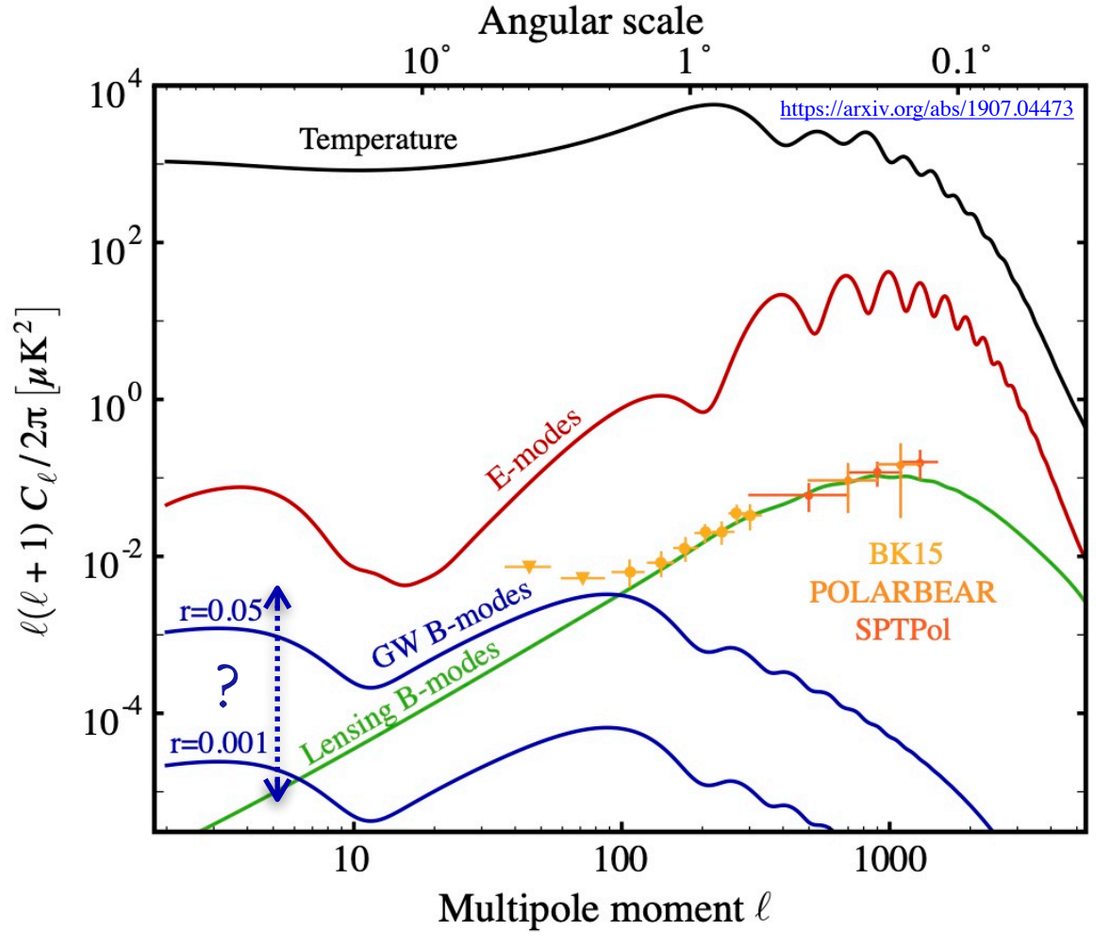


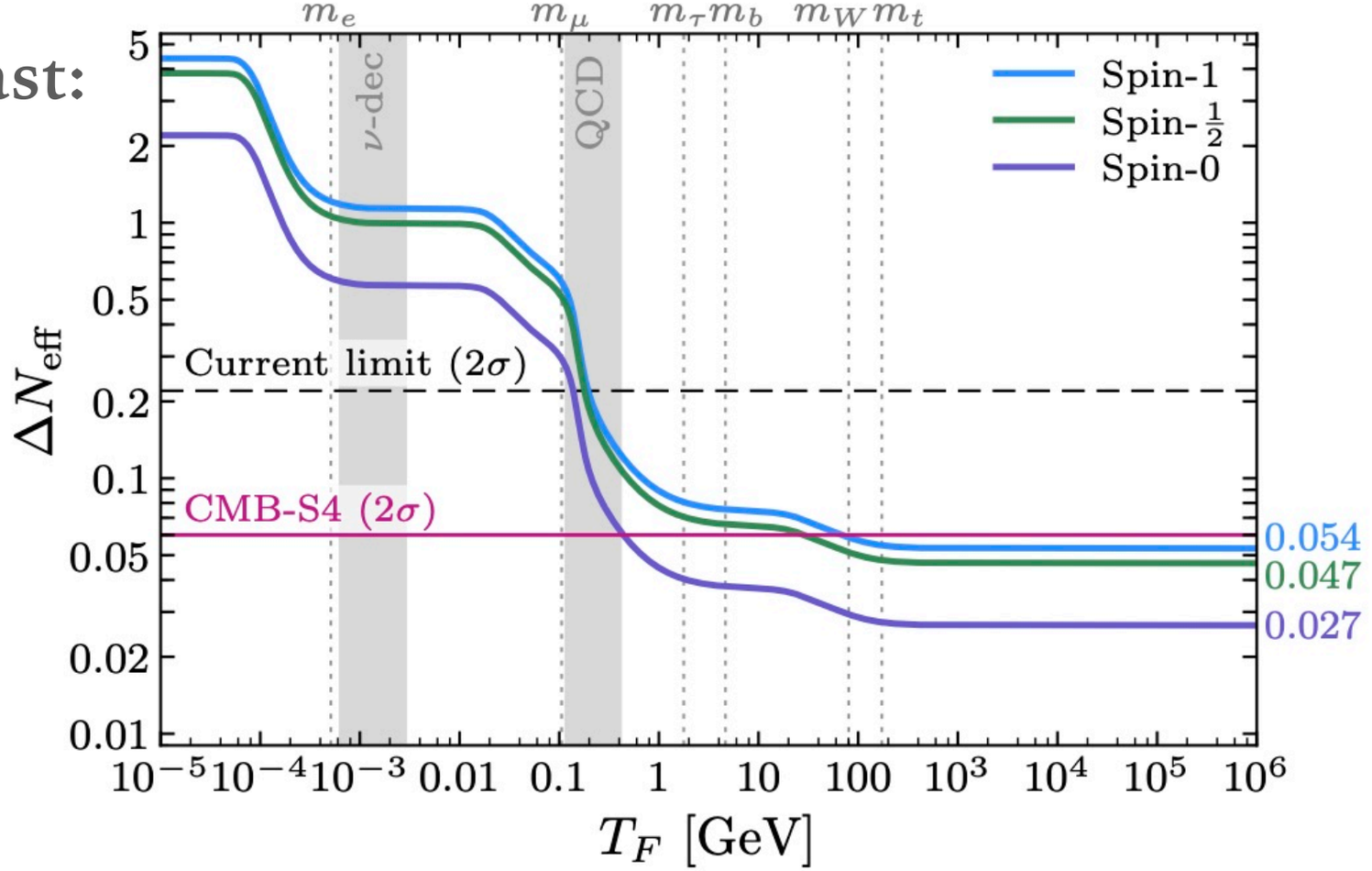
CMB: SEARCH FOR LIGHT RELIC PARTICLES

Measure gravitational effects of radiation fluid, including relativistic particles produced in thermal equilibrium.

Expect $N_{\rm eff} \sim 3$ from SM neutrinos.
Deviations $\Delta N_{\rm eff}$ are signature of new light particles.

CMB-S4 forecast:

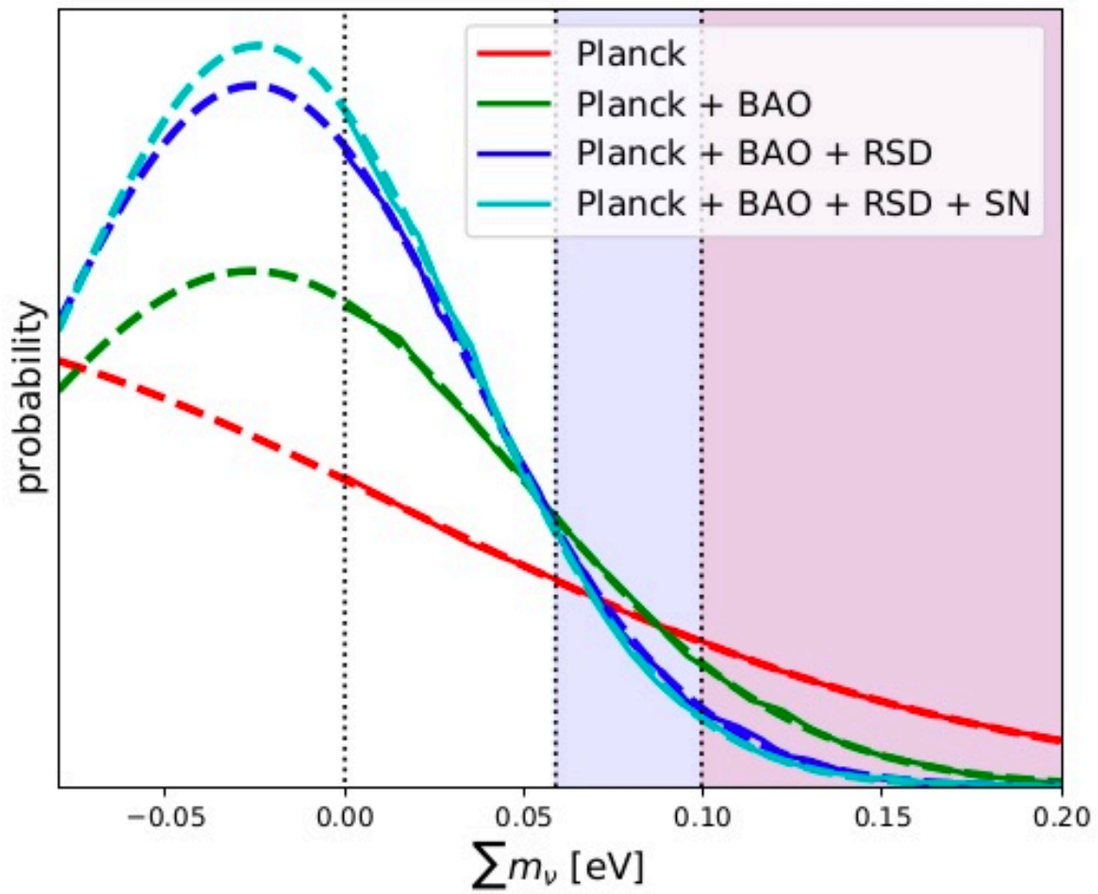
$$\Delta N_{\rm eff} = g_{\rm s} \left[\frac{43/4}{g_*(T_F)} \right]^{4/3}$$



CMB+GALAXIES: SUM OF NEUTRINO MASSES

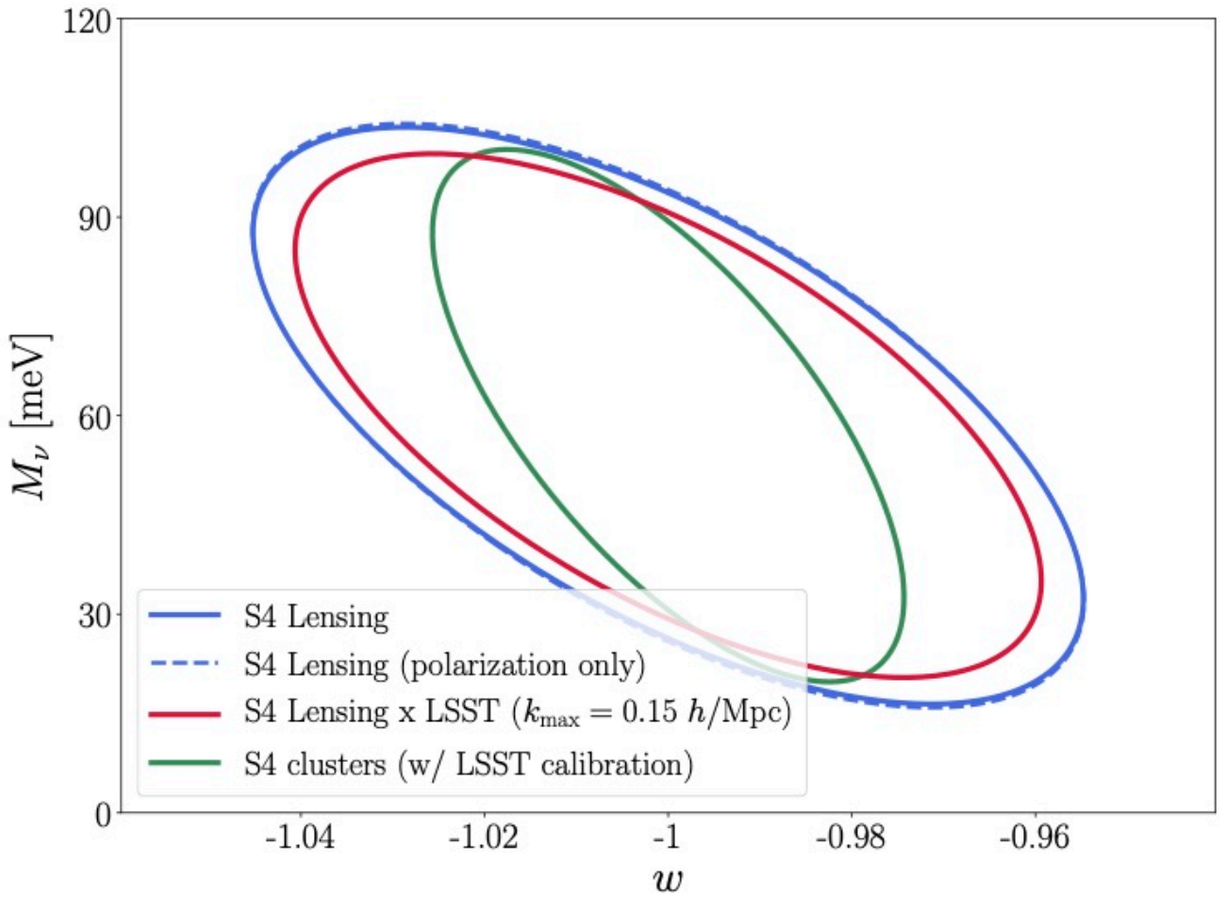
SM neutrinos are relativistic in early universe (CMB),
then non-relativistic (matter like) in the late universe (DE).

The transition between these regimes is sensitive to $M_\nu = \Sigma\, m_\nu$



eBOSS: Alam et al (July 2020)

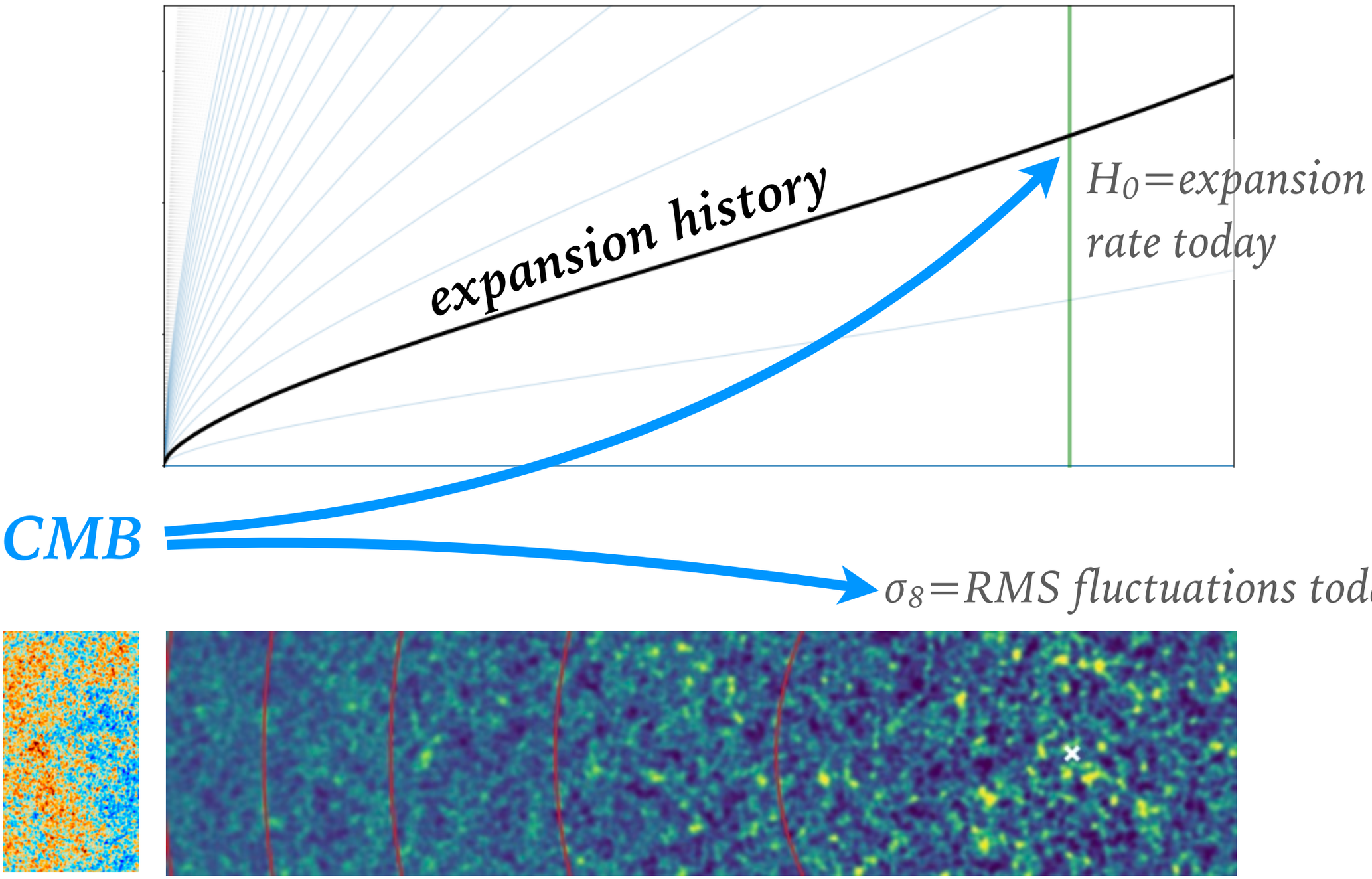
https://arxiv.org/abs/2007.08991



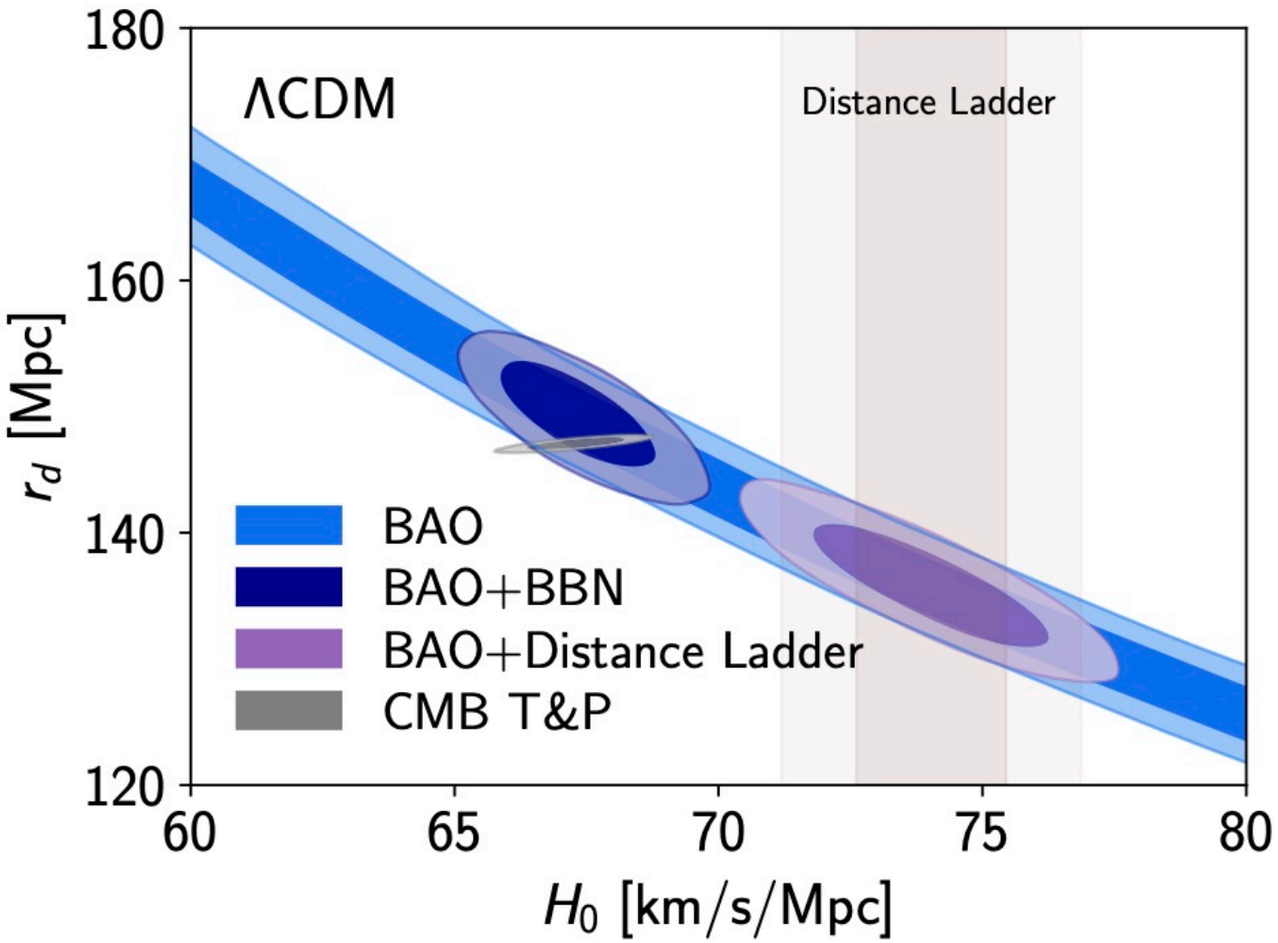
Forecast: CMB-S4 + Rubin Obs

https://arxiv.org/abs/1907.04473

SOME (MILD) TENSIONS WHEN EXTRAPOLATING FROM CMB



NEW RESULTS ON H_0 TENSION

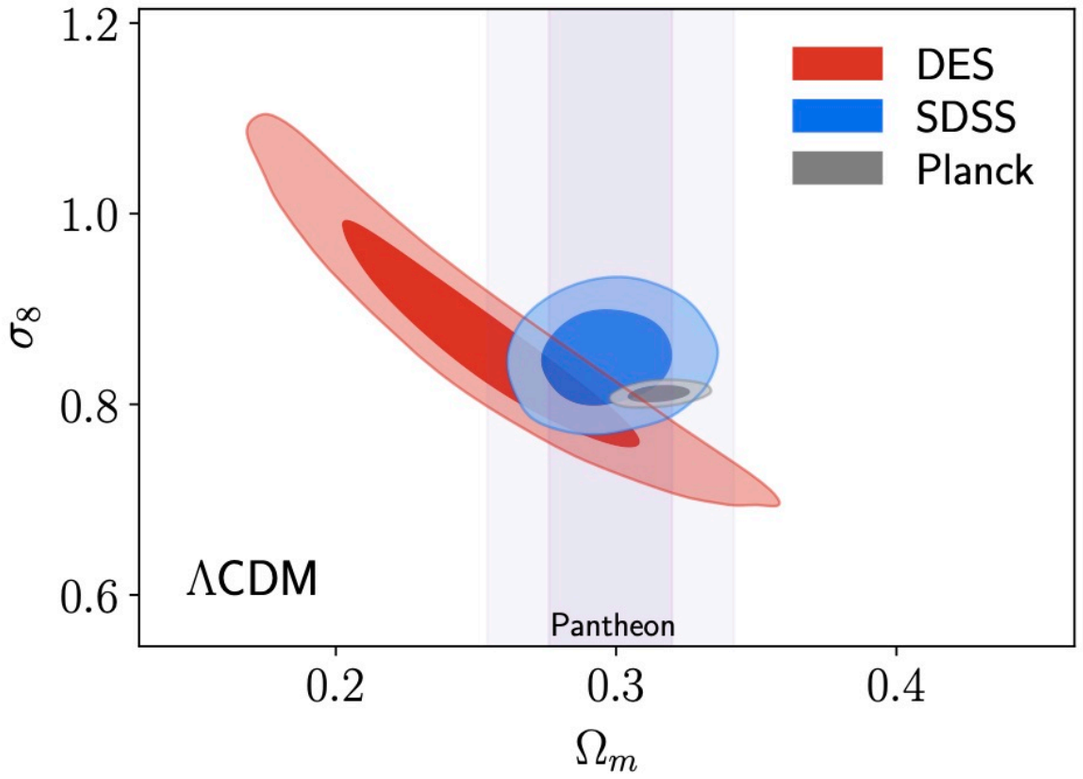


eBOSS(BAO): Alam et al (July 2020)

https://arxiv.org/abs/2007.08991

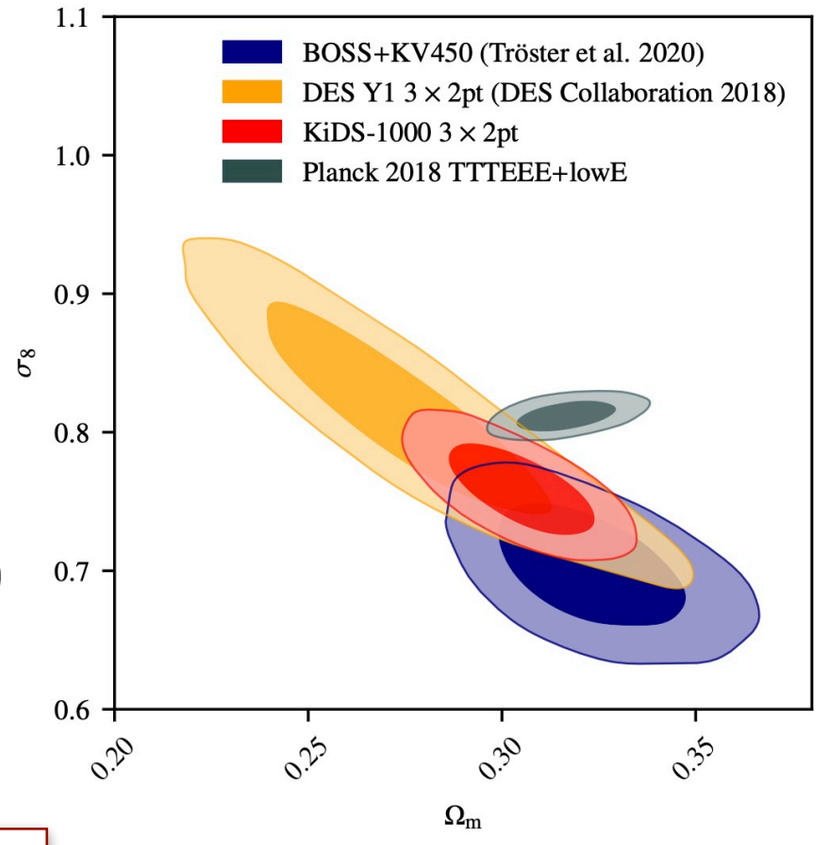
tension is 2-3 σ

NEW RESULTS ON THE S_8 TENSION



eBOSS(SDSS): Alam et al (July 2020)

https://arxiv.org/abs/2007.08991

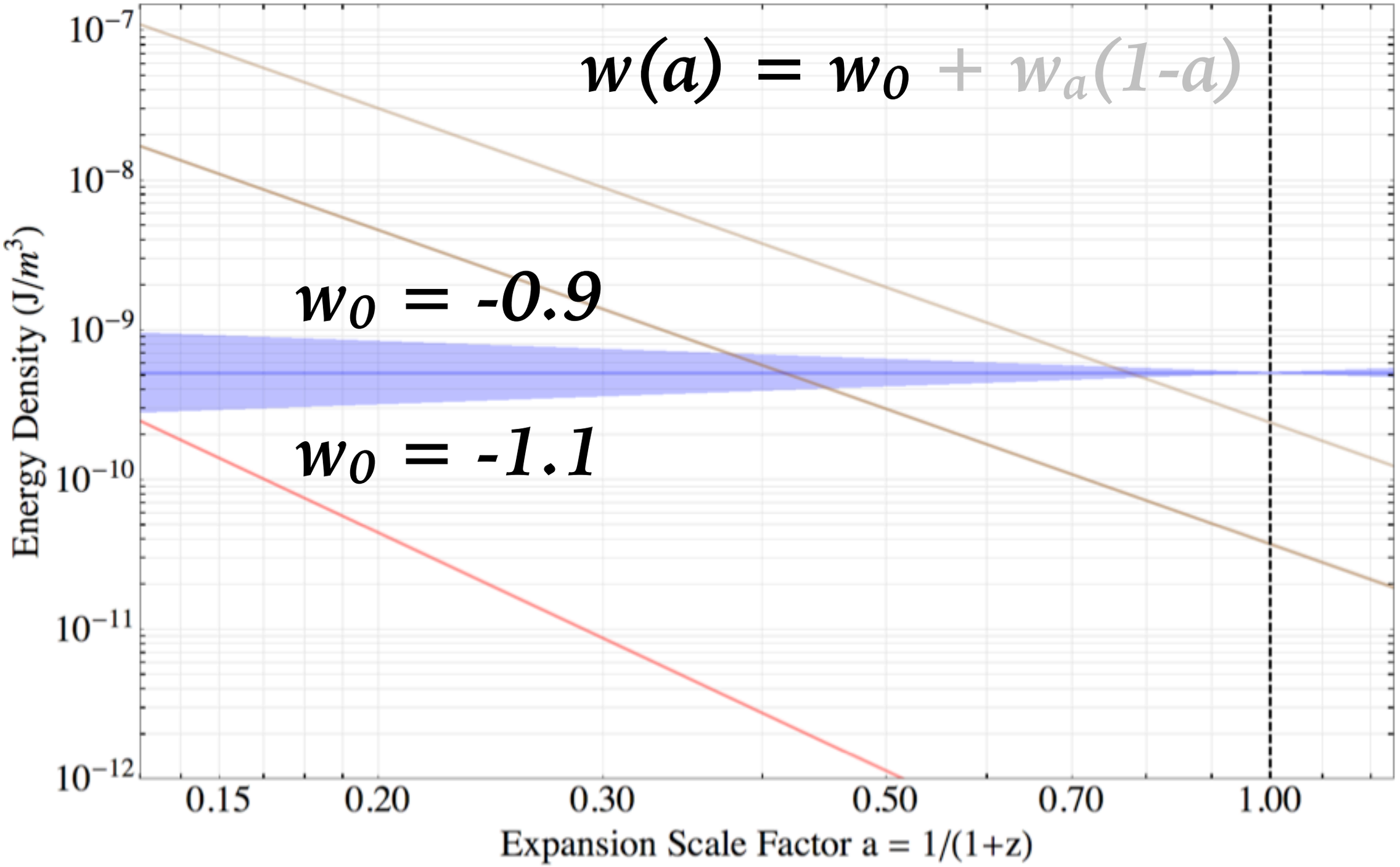


KiDS-1000: Heymans et al (July 2020)

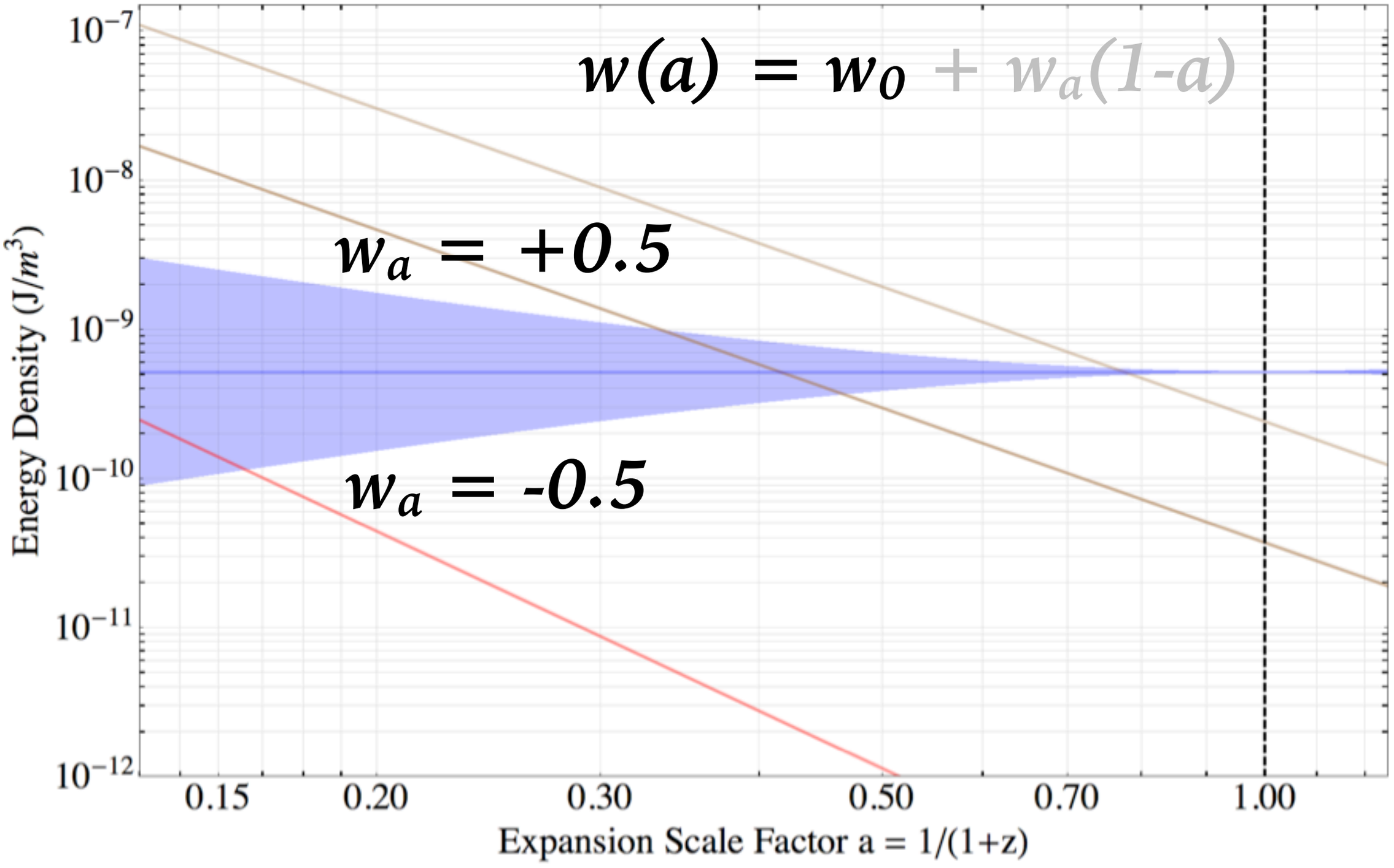
https://arxiv.org/abs/2007.15632

tension is 2-3 σ

GALAXIES: DARK ENERGY EVOLUTION

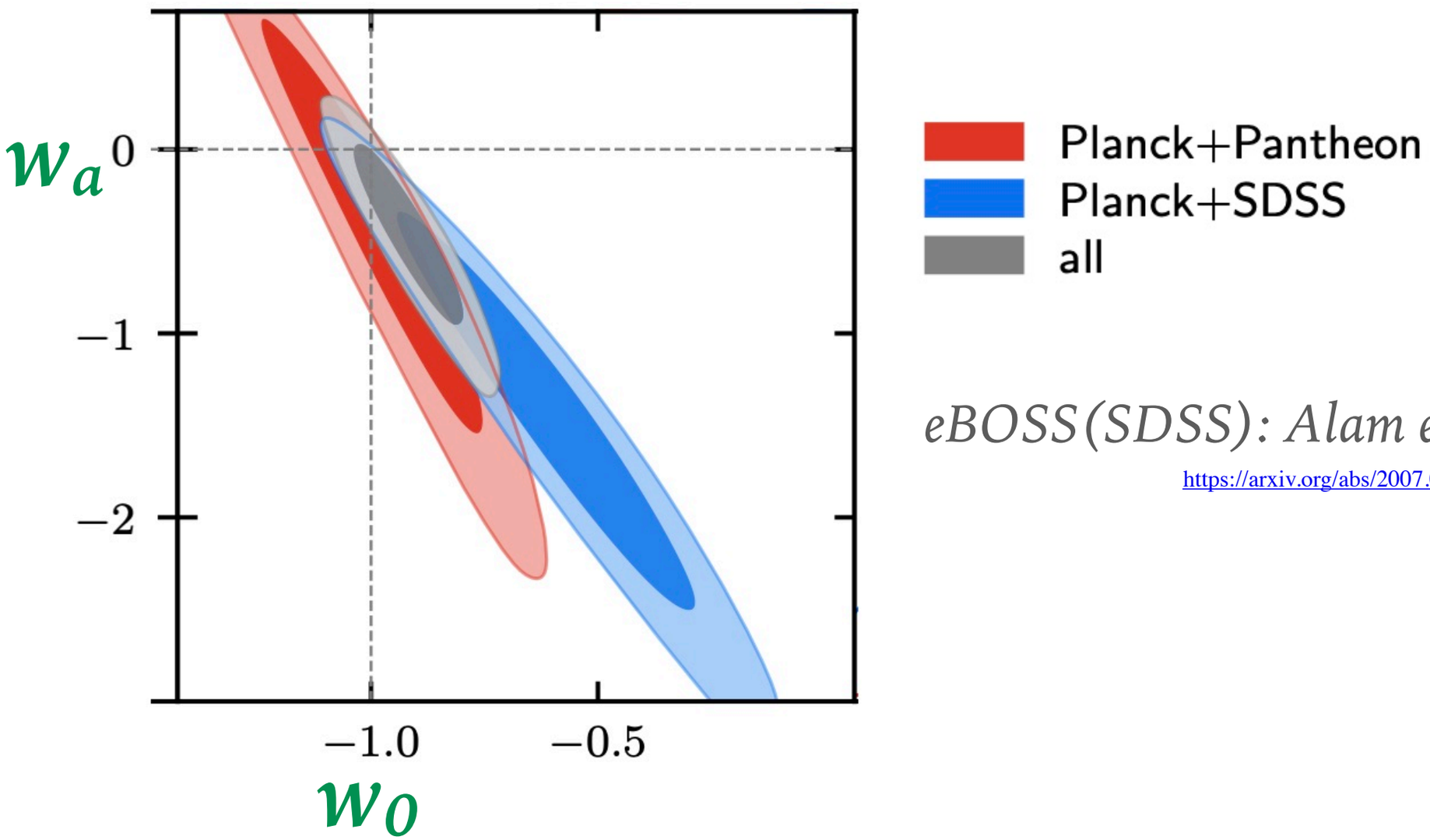


GALAXIES: DARK ENERGY EVOLUTION



GALAXIES: NEW RESULTS ON DARK ENERGY

$$w(a) = w_0 + w_a(1\text{-}a)$$



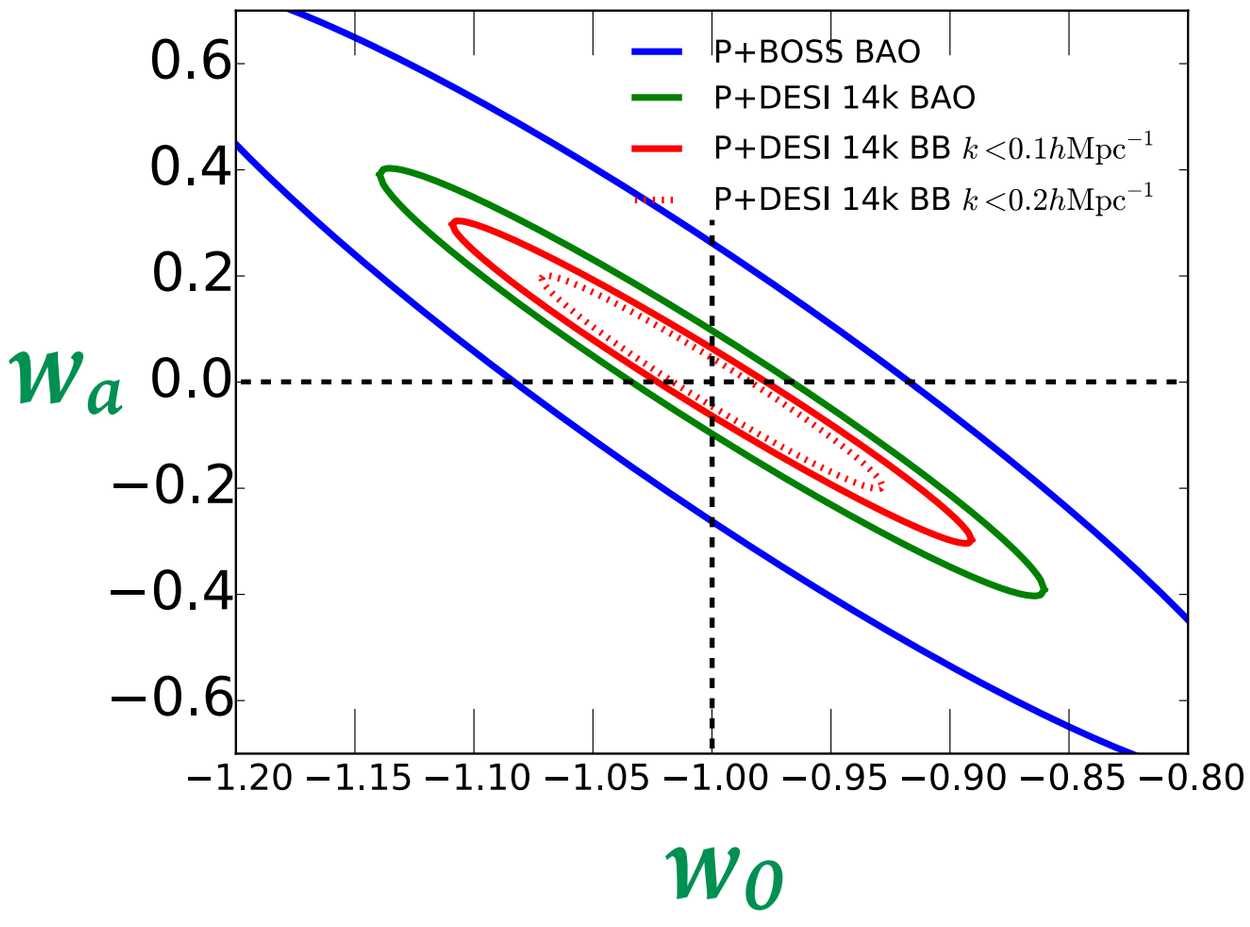
eBOSS(SDSS): Alam et al (July 2020)

https://arxiv.org/abs/2007.08991

GALAXIES: DARK ENERGY FORECASTS

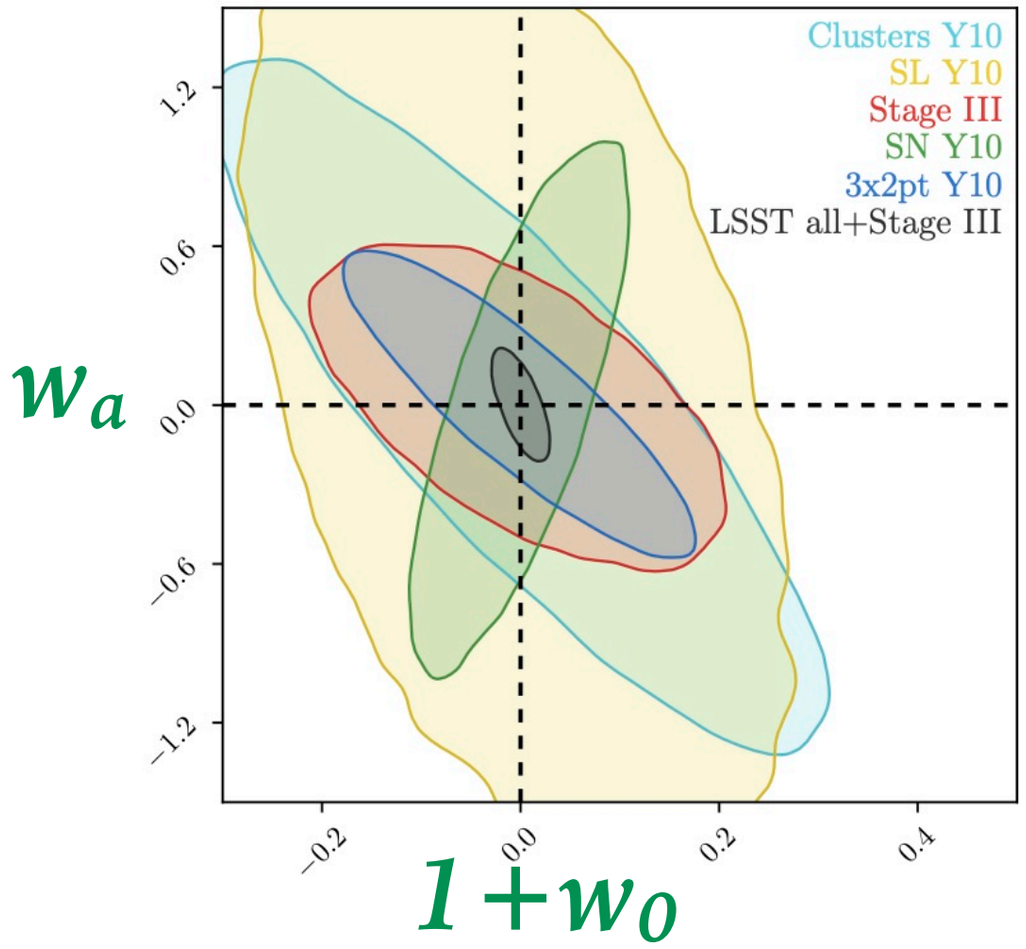
expect percent-level test of w_0=-1 during 2020s

$$w(a) = w_0 + w_a(1-a)$$



DESI forecast

https://arxiv.org/abs/1611.00036



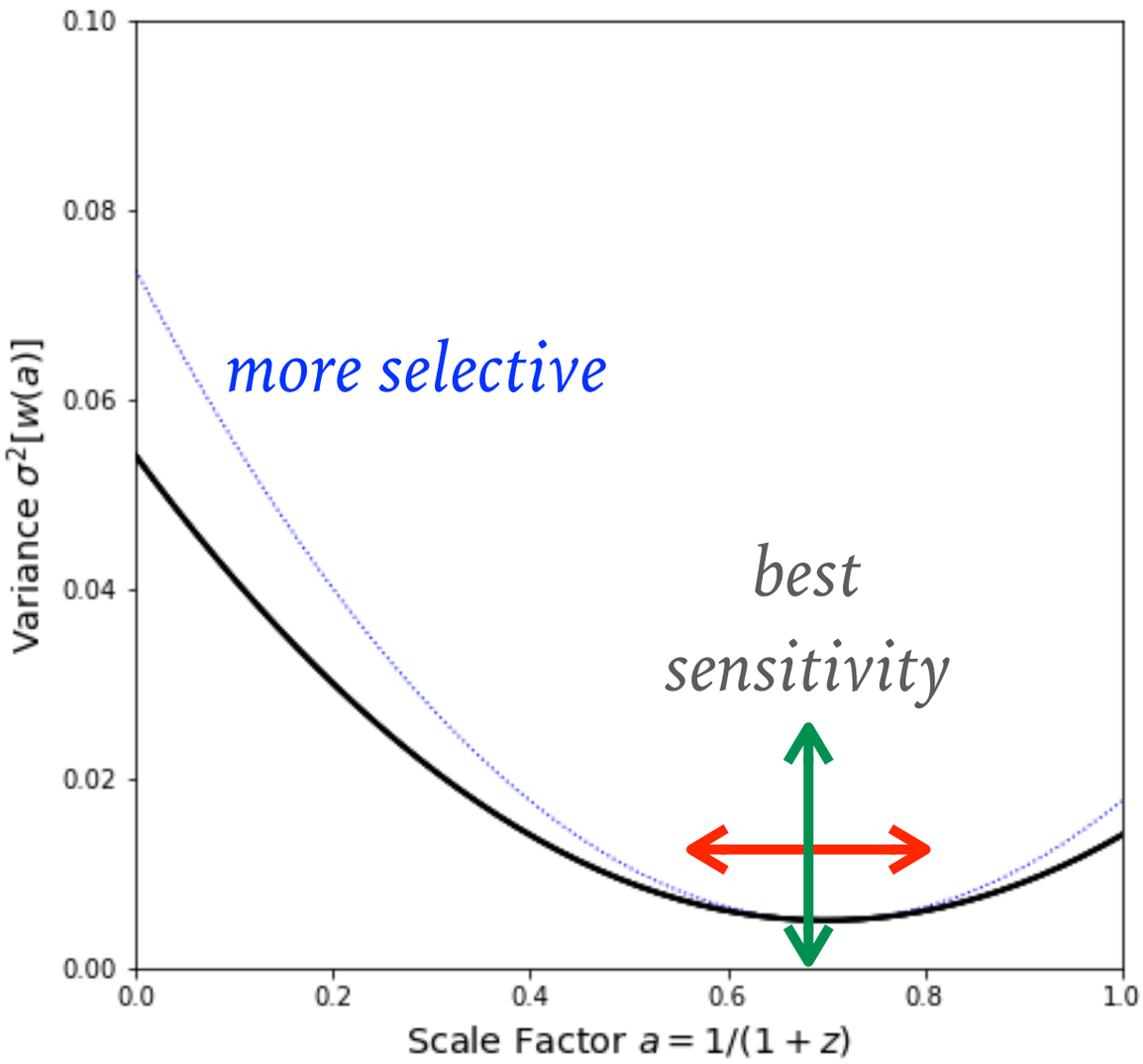
Vera Rubin Obs (DESC) forecast

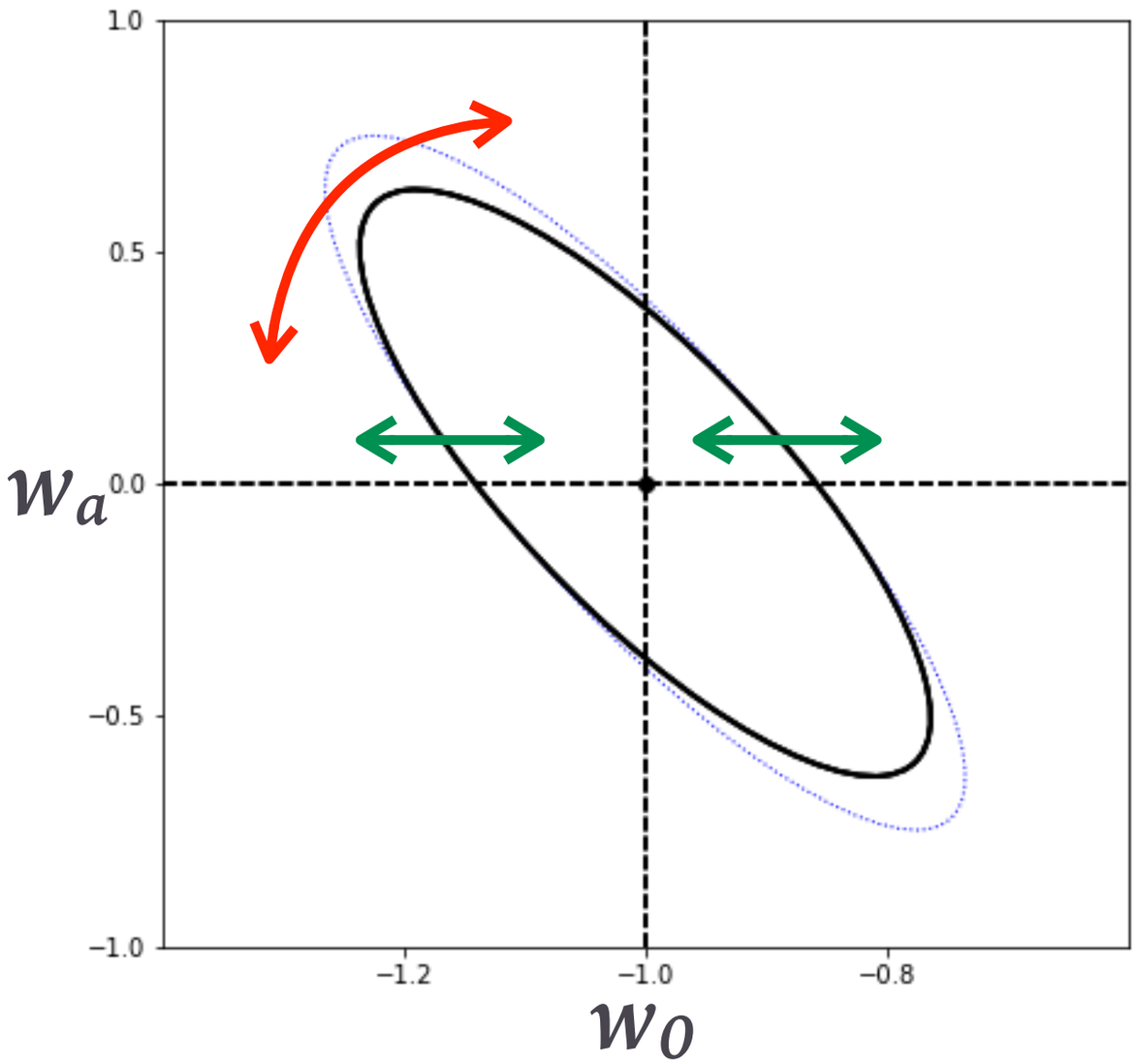
https://arxiv.org/abs/1809.01669

GALAXIES: DARK ENERGY FORECASTING GUIDE

$$w(a) = w_0 + w_a(1-a)$$

Contour in (w_0, w_a) translates to a sensitivity curve:





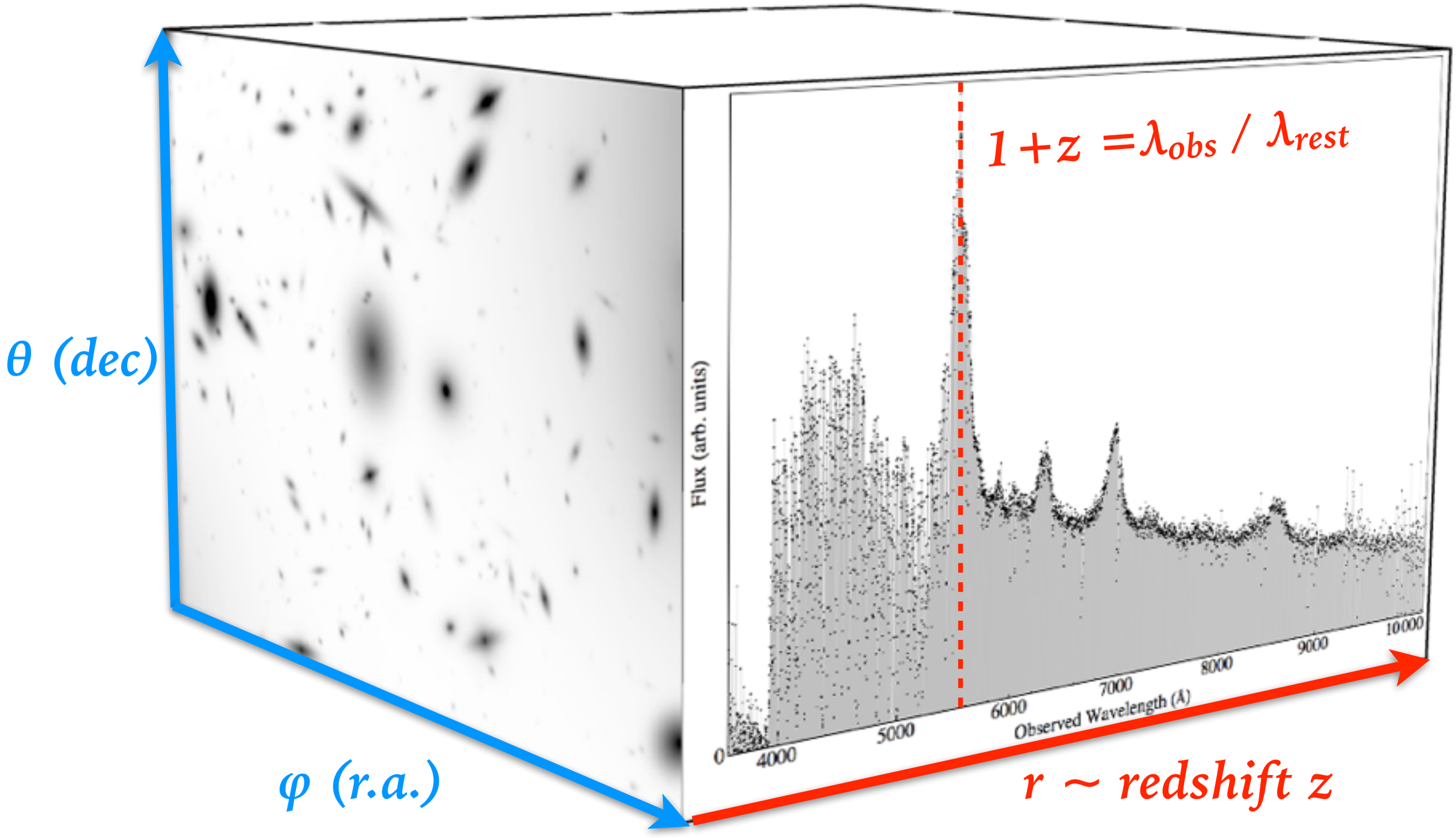
COSMOLOGY TRENDS FOR THE 2020S

Our ability to constrain cosmological parameters is increasingly limited by systematic uncertainties.

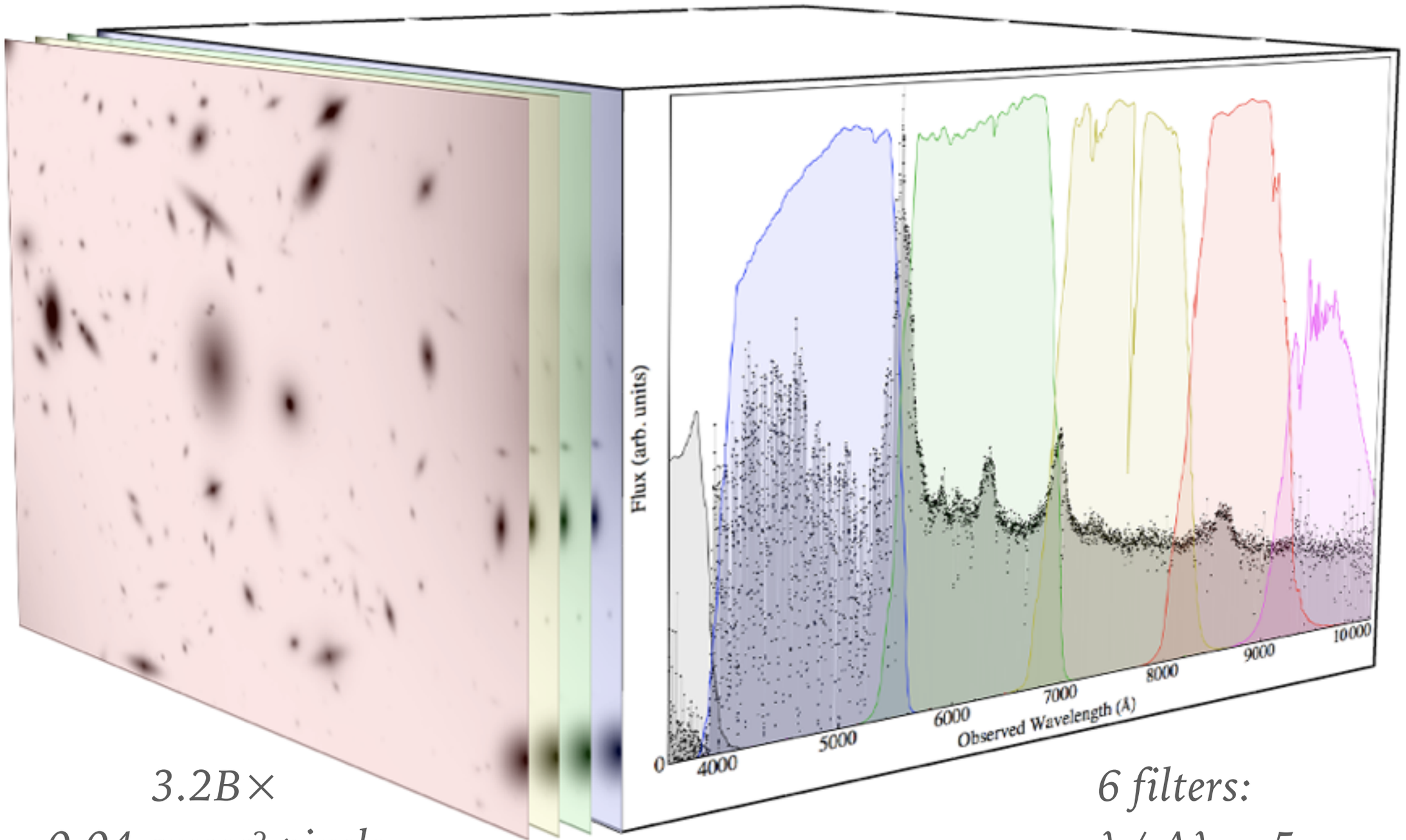
Our community is adopting many of the same mitigation strategies as HEP:

- fewer & larger collaborations
- joint analysis between experiments
  (cross correlations & joint pixel-level data processing)
- adoption of blind analysis methods
- exploration of machine-learning algorithms

BACKUP SLIDES



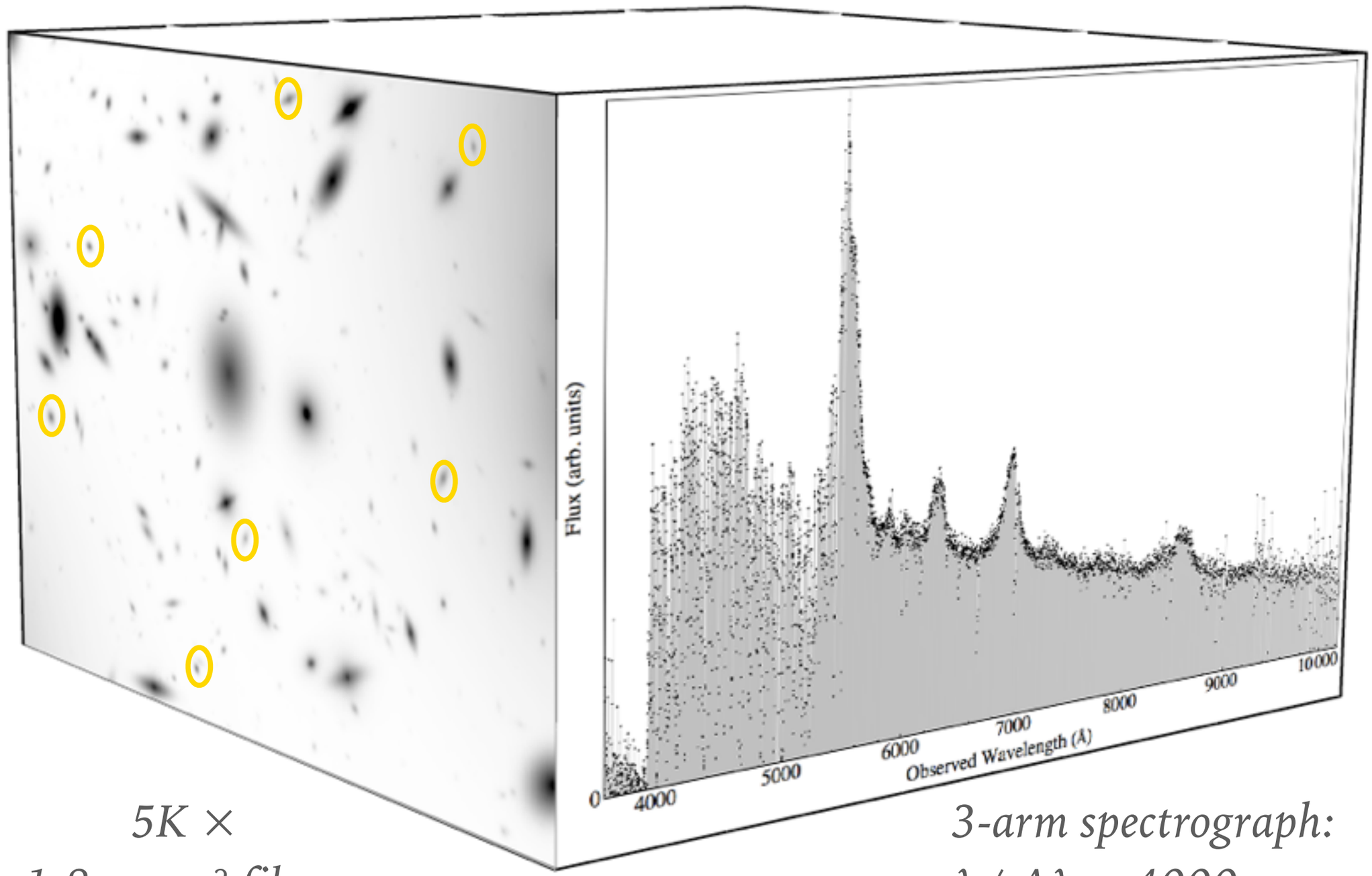
The optical sky is a data cube: $\theta \times \varphi \times r$



3.2B×
0.04 arcsec² pixels

6 filters:
$\lambda / \Delta\lambda \sim 5$

Galaxy survey imaging, e.g. Vera Rubin Observatory



5K ×
1.8 arcsec² fibers

3-arm spectrograph:
λ / Δλ ~ 4000

Galaxy survey spectroscopy, e.g. DESI