

Data handling in Cosmology

The background features a complex visualization of cosmological data. It includes a network of blue and yellow nodes connected by thin lines, representing a galaxy cluster or a web of galaxies. There are also several spiral galaxies, some in the foreground and some in the distance. A prominent feature is a series of vertical lines of varying heights, resembling a histogram or a data plot, overlaid on the network. The overall color palette is dark blue and black, with highlights in yellow and white.

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The questions Cosmology tries to answer

- **What is the Universe made of?**

Ordinary matter, dark matter, radiation, neutrinos, dark energy all contribute to the cosmic energy budget.

- **How did the Universe begin and evolve?**

Cosmology studies the history from Big Bang to our current Universe.

- **How did the structures in the Universe form?**

The growth of structure from primordial density fluctuations to Galaxies, clusters, filaments, voids.

- **What is the fate of the Universe?**

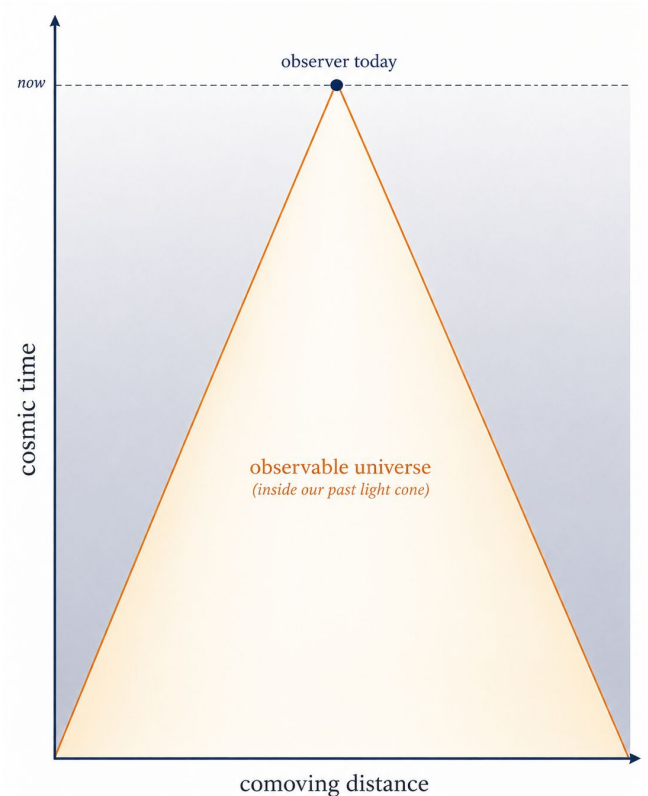
Depends on the expansion history, spatial curvature and nature of dark energy.

In practice, many of these physical questions are encoded in a set of cosmological parameters that describe the contents, expansion history, and growth of structure in the Universe.

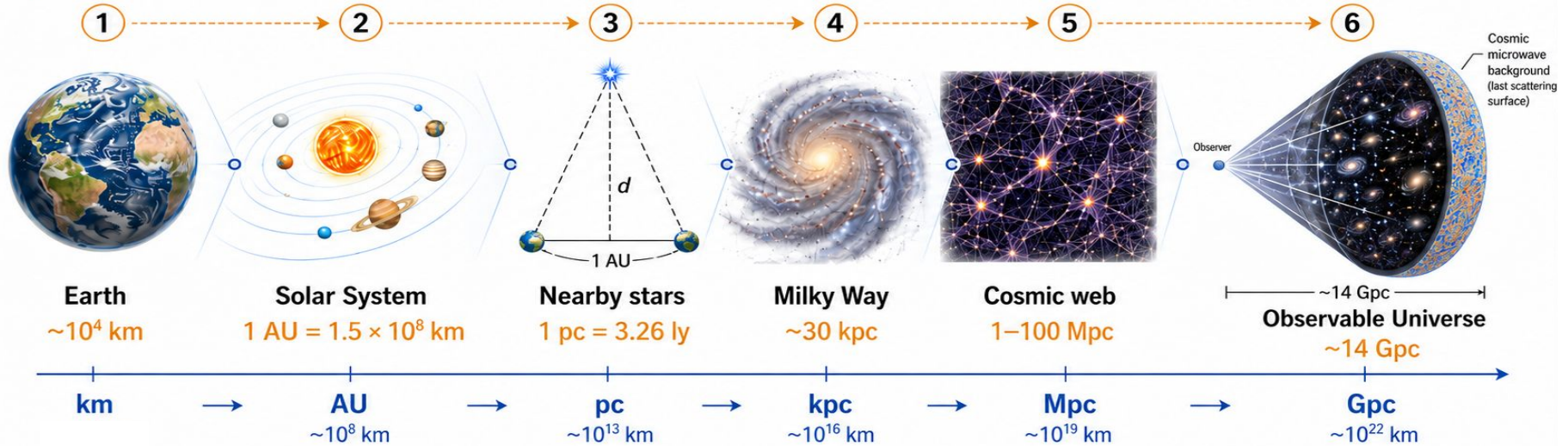
The Observable Universe: What Can We Actually see?

In this lecture, the **Universe** refers to the **Observable Universe**.

- **Observable universe** is the region from which light has had time to reach us. Limited by finite light speed and age of Universe.
- **Whole universe** may be larger than what we can observe directly.
- **Looking farther away also means looking further back in cosmic time.** Distance and **lookback time** are therefore entangled in cosmological data. The collection of all light reaching us today forms our **past light cone**.



Cosmological Distance scales



Why is cosmology different from a laboratory experiment?

Cosmology deals with extremely large scales. Distance, time and evolution are tied together.

Cosmology studies the Universe as a single physical system that can be measured through observations and described with mathematical models.

- Unlike laboratory experiments, we cannot rerun the Universe under different conditions. Instead, we infer its history by comparing observations with physical models.
- The aim is not simply to catalogue astronomical objects, but to understand how different observations constrain the origin, composition, evolution, and structure of the Universe.

We observe limited pieces of the Universe and use them to infer the larger physical story that connects them.

Cosmology is a historical science; we reconstruct the Universe's past using light, matter tracers, and statistical patterns observed today.

Cosmological data: What does a telescope measure?

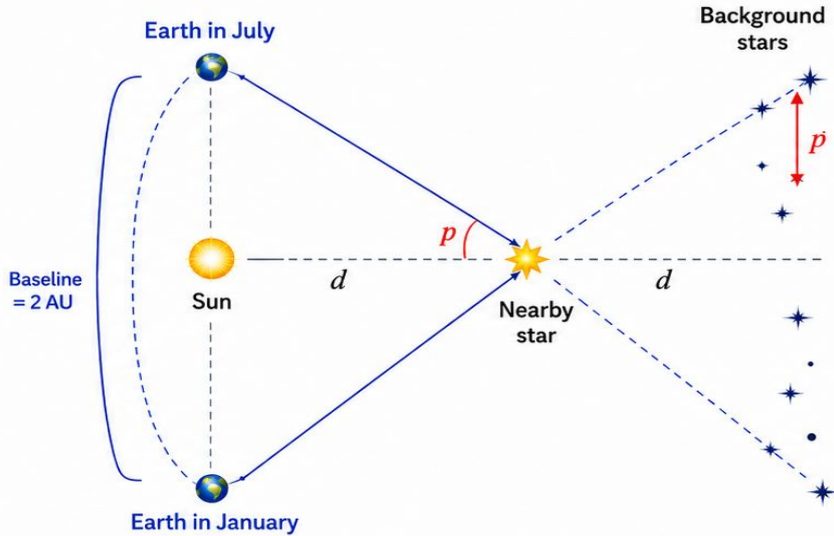
Cosmological data do not give us the Universe directly. They give us light, positions, spectra, fluxes, images, and counts, which we interpret through physical models.

- Each photon carries information about where, when, and how it was emitted or absorbed.
- A telescope measures photons arriving here and now.
- Cosmological observables begin as the following properties of photons, not as parameters of model.
 - ❖ **Direction** on the sky: angular position
 - ❖ **Wavelength/frequency**: spectral information and redshift
 - ❖ **Flux/counts**: brightness after calibration
 - ❖ **Image shape/polarization/time variation**: probe-dependent information
 - ❖ **Noise, masks, resolution, selection**: part of the measurement

How do astronomers measure distances?

Parallax Method

Measuring stellar distances by annual parallax

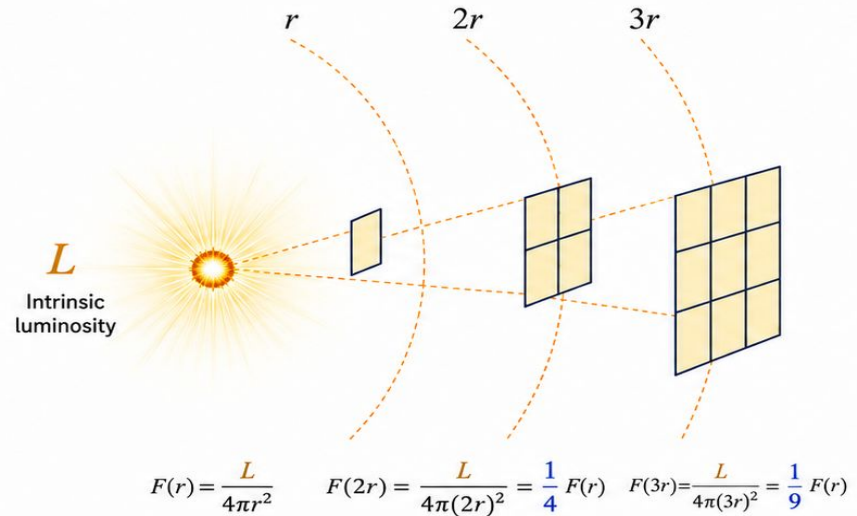


$$d \text{ (pc)} = \frac{1}{p \text{ (arcsec)}}$$

p = annual parallax angle (arcseconds)

Standard Candle

Inferring distance from the inverse-square law



$$F = \frac{L}{4\pi d^2}$$

F = observed flux (energy per unit area per unit time)

L = intrinsic luminosity (total energy per unit time)

d = distance to the source

Hubble's Law: The First Evidence for an Expanding Universe

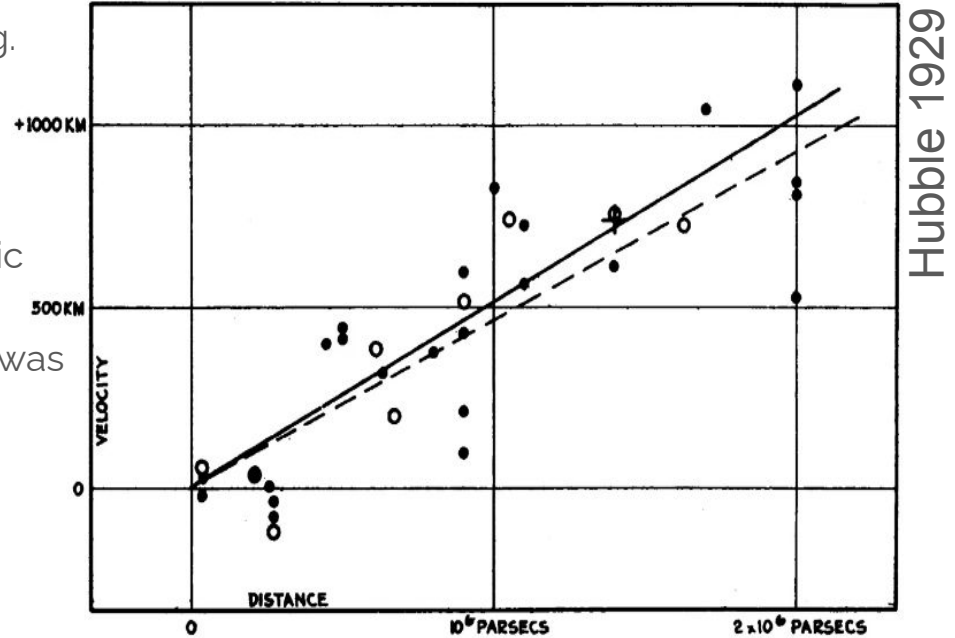
- The distance to the standard candles (eg. Cepheid Variables) were estimated.

$$d = \sqrt{\frac{L}{4\pi F}}$$

- Galaxy spectra contain identifiable atomic lines. Many were observed at longer wavelengths than in the laboratory. This was interpreted as a recession speed:

$$\frac{\Delta\lambda}{\lambda_{\text{lab}}} \simeq \frac{v}{c}$$

- Hubble found a linear trend $v \simeq H_0 d$
(Hubble's Law)



The Universe is not static. On large scales, distances between galaxies grow with time.
The Universe is expanding.

Expansion means the cosmic distance scale changes

On large scales, the physical distance between objects changes because the scale of the Universe changes with time.

$$r(t) = a(t)\chi$$

where:

- χ : **comoving** distance
- $a(t)$: scale factor
- $r(t)$: **physical** distance

If $a(t)$ grows with time, distances between objects grows. This naturally gives:

$$v = \dot{r} = \frac{\dot{a}}{a}r = H(t)r.$$

At present time, $v \simeq H_0d$

From expansion to redshift, an observational coordinate

Light travelling through expanding space is stretched. Therefore, a photon emitted with wavelength λ_{em} is observed with a longer wavelength λ_{obs} .

$$\lambda_{\text{obs}} > \lambda_{\text{em}}$$

emitted: λ_{emit}

observed: λ_{obs}

This is called **redshift**

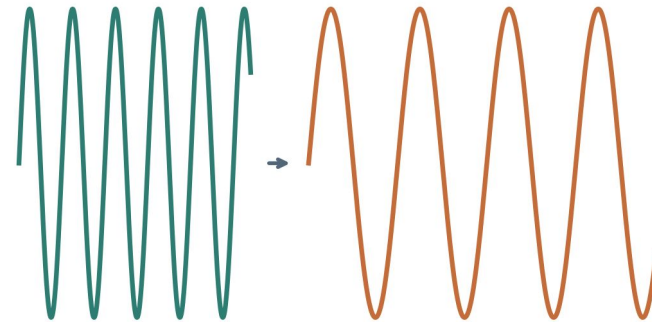
$$1 + z = \frac{\lambda_{\text{obs}}}{\lambda_{\text{em}}}$$

In an expanding Universe

$$1 + z = \frac{a(t_0)}{a(t_{\text{em}})}$$

With $a(t_0) = 1$,

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



expansion
stretches light

Redshift tells us how much the Universe has expanded since the light was emitted.

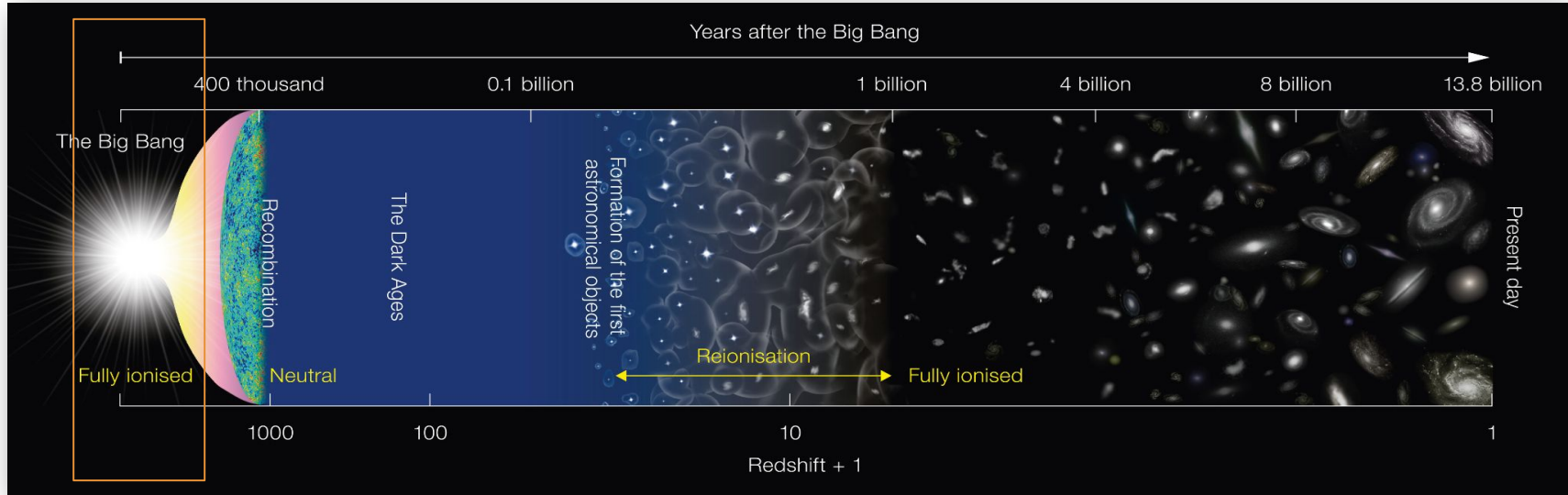
From expansion to redshift, an observational coordinate

- A telescope directly measures angular position on the sky and spectral information.
- For a galaxy survey, the basic observed coordinates are (θ, ϕ, z)
- The angles (θ, ϕ) locate the object on the sky.
The redshift z tells us where it lies along the line of sight.
- With a cosmological model, redshift can be converted into distance.

$$\chi(z) = c \int_0^z \frac{dz'}{H(z')}$$

Redshift acts both as a coordinate along the cosmic light cone and as a marker of cosmic time. Higher redshift means we are observing an earlier epoch of the Universe.

A brief history of Cosmic Timeline



Big Bang (t=0) :

- Hot dense Universe
- Smooth Initial state
- Beginning of Cosmic History

Inflation

($t \sim 10^{-36} \text{s} - 10^{-32} \text{s}$) :

- Extremely rapid expansion
- Quantum fluctuations
- Seeds of structure

Particle Plasma

($t \sim 1 \text{s}$) :

- Hot particle soup
- Radiation domination
- Cooling with expansion

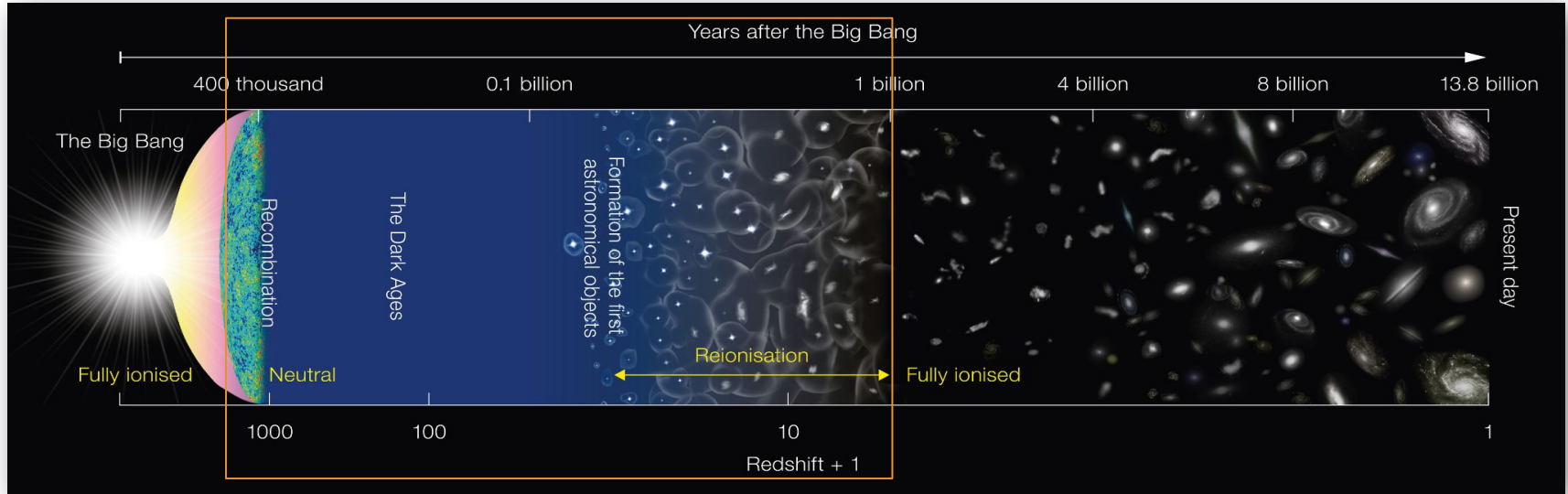
Big Bang

Nucleosynthesis

($t \sim 3 - 20 \text{min}$) :

- First nuclei, Hydrogen, Helium, trace Lithium.
- No neutral atoms yet.

A brief history of Cosmic Timeline



Recombination ($t=380,000$ yr) :

- Neutral atoms,
- Photon decoupling
- Transparent Universe
- Cosmic Microwave Background

Dark Ages ($t=0.4-100$ Myr) :

- Neutral hydrogen.
- No luminous source
- Gravitational collapse, cosmic structure growth.

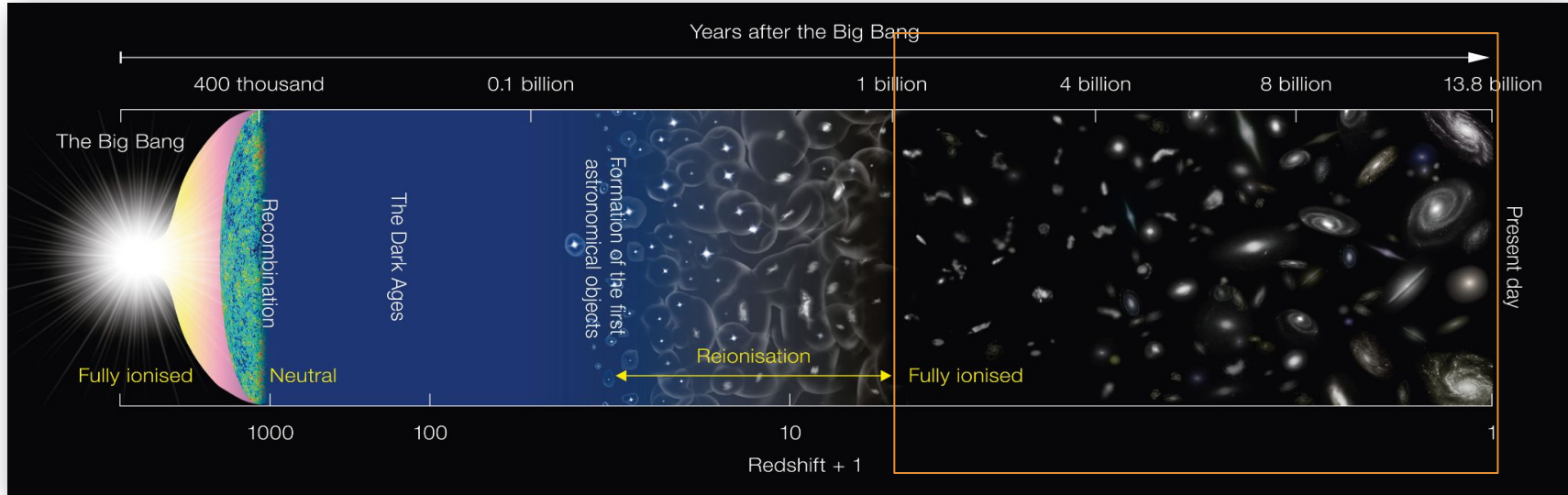
Cosmic Dawn ($t\sim 100$ Myr) :

- Dark matter halos, gas cooling.
- First stars and galaxies.
- UV radiation begins

Reionization ($t\sim 0.1-1$ Gyr) :

- UV photons from galaxies ionizes the Universe.
- Formation of ionized bubbles in IGM.

A brief history of Cosmic Timeline



Cosmic Web (t > 1Gyr) :

- Large scale structures, Gravity-driven growth.
- Formation of voids, filaments, sheets, nodes.

Cosmic Noon (t = 2-4 Gyr) :

- Peak star formation
- Rapid galaxy growth
- Active black holes
- Bright quasars
- Metal enrichment

Accelerated Expansion (z < 0.7) :

- Dark energy domination.
- Accelerating expansion.
- Slower structure growth
- Expanding cosmic distances
- Late-time cosmology

Universe is homogeneous and isotropic at large scales

- At sufficiently large scales (>100Mpc), the Universe is:
 - Homogenous (no preferred position).
 - Isotropic (no preferred direction)
- Cosmic evolution is determined by scale factor $a(t)$.
- Local structures exist, but are smoothed over large scales.
- Under these symmetry conditions, Friedmann–Lemaître–Robertson–Walker (**FLRW**) metric describes the expanding Universe.

$$ds^2 = -c^2 dt^2 + a^2(t) \left[\frac{dr^2}{1 - kr^2} + r^2 d\Omega^2 \right]$$

- $a(t)$: scale factor
- $k = 0, +1, -1$: spatial curvature
- t : cosmic time
- r, θ, ϕ : comoving coordinates

What controls Universe's expansion?

- The Universe contains different components:

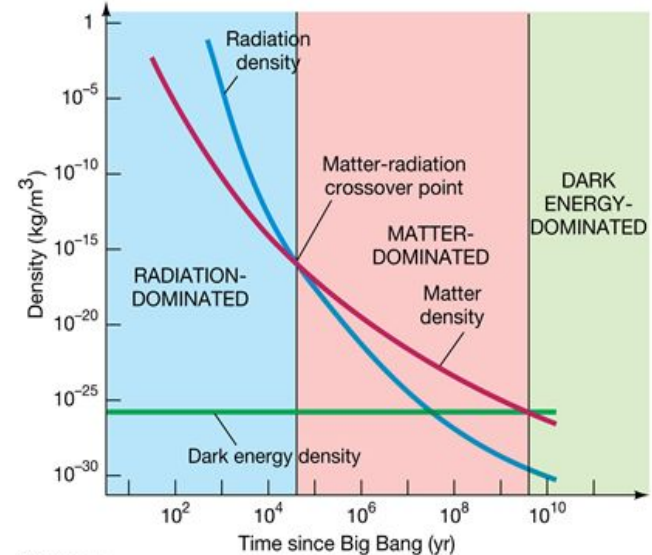
$$\rho_{\text{tot}} = \rho_m + \rho_r + \rho_\Lambda + \rho_k$$

- Matter: Baryonic Matter (~15%), Dark matter (~85%)**
 - Radiation:** photons, relativistic species
 - Dark energy:** accelerated expansion
 - Curvature:** spatial geometry
-
- Different components evolve differently with time.

$$\rho_m \propto a^{-3}$$

$$\rho_r \propto a^{-4}$$

$$\rho_\Lambda = \text{constant}$$



The Friedmann equation

$$H^2(t) = \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3}\rho - \frac{kc^2}{a^2} + \frac{\Lambda c^2}{3}$$

$$H^2(a) = H_0^2 [\Omega_r a^{-4} + \Omega_m a^{-3} + \Omega_k a^{-2} + \Omega_\Lambda]$$

$$H^2(z) = H_0^2 [\Omega_r (1+z)^4 + \Omega_m (1+z)^3 + \Omega_k (1+z)^2 + \Omega_\Lambda]$$

Main cosmological parameters:

- H_0 : expansion rate today
- Ω_m : matter density
- Ω_b : baryon density
- Ω_Λ : dark energy density
- Ω_k : curvature

Structure formation in the background smooth Universe

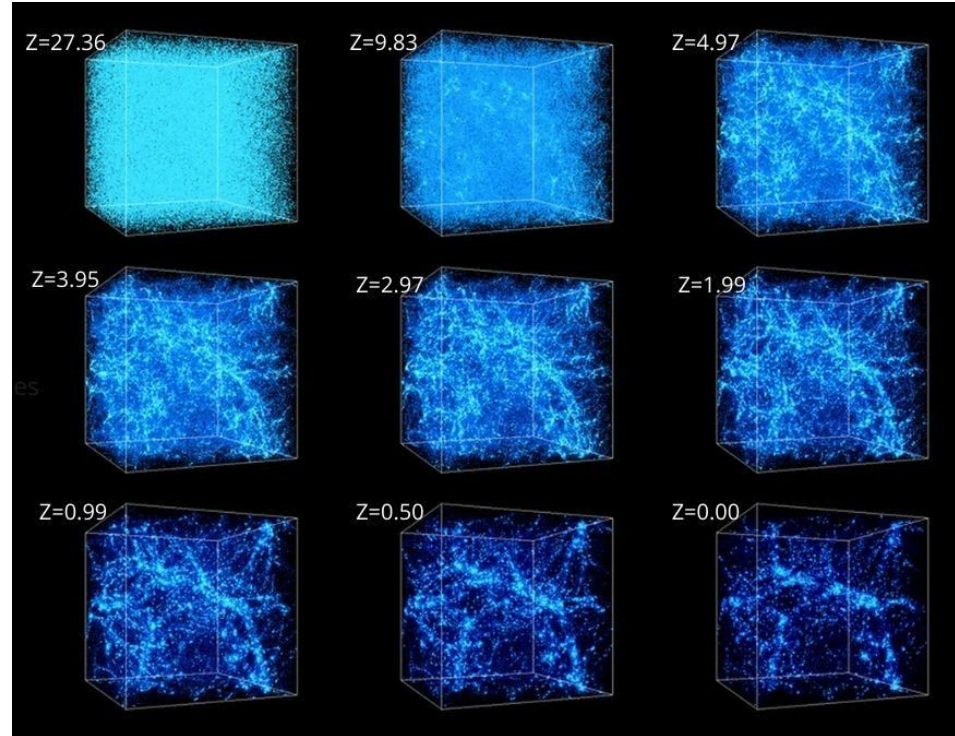
- FLRW describes the homogeneous and isotropic expanding Universe.
- Real universe: small departures from the mean density.
- These perturbations grow under gravity.

$$\rho_m(\mathbf{x}, t) = \bar{\rho}_m(t) [1 + \delta_m(\mathbf{x}, t)]$$

$$\delta_m(\mathbf{x}, t) = \frac{\rho_m(\mathbf{x}, t) - \bar{\rho}_m(t)}{\bar{\rho}_m(t)}$$

- $\bar{\rho}_m(t)$: homogeneous background density.
- $\delta_m > 0$: overdense regions.
- $\delta_m < 0$: underdense regions.
- Structure formation is the evolution of $\delta_m(\mathbf{x}, t)$.

The background tells us how the universe expands; δ_m tells us how matter clusters.



Artist's impression of the cosmic web, showing diffuse intergalactic matter distributed along filaments between galaxies. Image credit: Mark Garlick / Science Photo Library / Getty Images.

Structure formation in the background smooth Universe

- Linear perturbation equation:

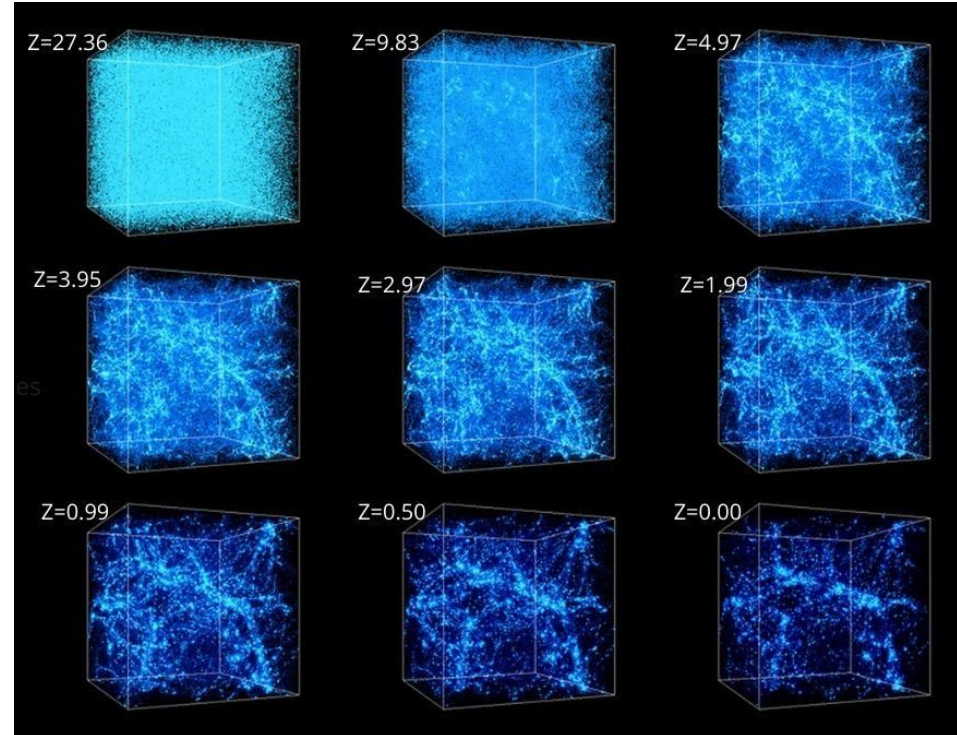
$$\ddot{\delta} + 2H\dot{\delta} - 4\pi G\bar{\rho}_m\delta = 0$$

$$\delta(\mathbf{x}, a) = D(a) \delta(\mathbf{x}, a_{\text{ini}})$$

where $D(a)$ is the **linear growth factor**.

- Gravity makes overdensities grow. Dark matter dominates the contribution.
- Expansion acts as a friction term through $2H\dot{\delta}$.
- The growth history depends on cosmological parameters like Ω_m , Ω_Λ , σ_8 , and initial conditions.

The background tells us how the universe expands; δ_m tells us how matter clusters.



Artist's impression of the cosmic web, showing diffuse intergalactic matter distributed along filaments between galaxies. Image credit: Mark Garlick / Science Photo Library / Getty Images.

Matter power spectrum: Structure as a function of scale

Fourier transform:

$$\delta_m(\mathbf{x}) \rightarrow \delta_m(\mathbf{k})$$

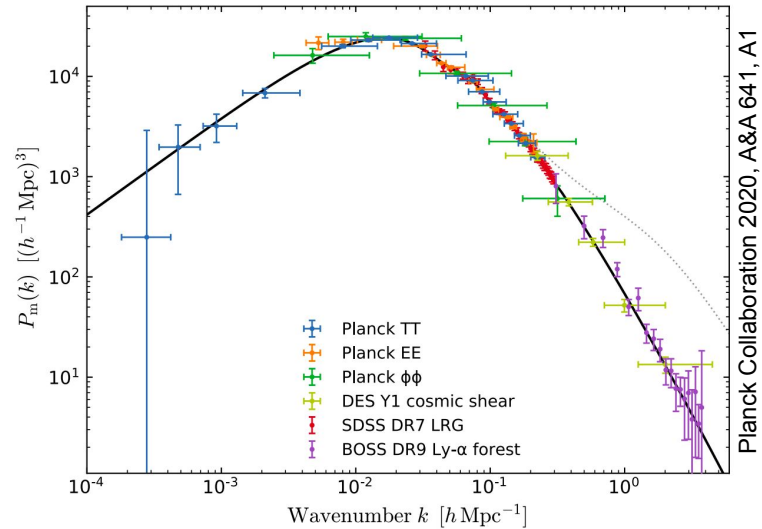
Power spectrum:

$$\langle \delta_m(\mathbf{k}) \delta_m^*(\mathbf{k}') \rangle = (2\pi)^3 \delta_D(\mathbf{k} - \mathbf{k}') P_{mm}(k)$$

Dimensionless power:

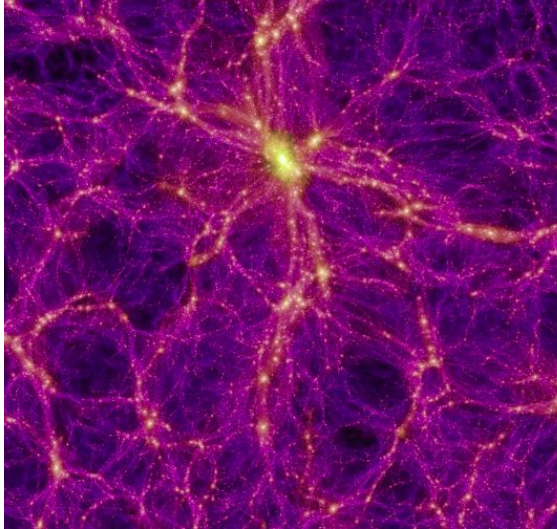
$$\Delta^2(k) = \frac{k^3 P(k)}{2\pi^2}$$

- Small k : large physical scales.
- Large k : small physical scales.
- $P(k)$ measures variance per Fourier mode.
- Shape of $P(k)$ contains crucial cosmological information.
- Cosmology usually predicts statistics, not the exact position of every galaxy.



The power spectrum compresses the density field into fluctuation amplitude versus scale.

Tracers: What we actually observe



Millennium Simulation



Credit: ESA/Webb, NASA & CSA, G. Gozaliasl, A. Koekemoer, M. Franco, and the COSMOS-Web team

We want the matter field, but we observe tracers of it.

Tracers: What we actually observe

Underlying field:

$$\delta_m(\mathbf{x})$$

Observed tracer fields:

$$\delta_g(\mathbf{x}), \delta_q(\mathbf{x}), \delta_{\text{Ly}\alpha}(\mathbf{x}), \kappa(\mathbf{x}), T_{21}(\mathbf{x}), T_{\text{CMB}}(\hat{\mathbf{n}}), \mu_{\text{SN}}(z)$$

Examples:

Tracer	What it roughly traces	Data product
Galaxies	biased matter peaks	catalog
Quasars	rare massive environments	sparse catalog
Ly α forest	neutral hydrogen / IGM density	spectra
Weak lensing	projected matter field	shear map
21 cm	neutral hydrogen field	intensity map/cube
Clusters	massive halo population	catalog
CMB	primordial fluctuations / projected early-Universe field	temperature / polarization maps
Supernovae	expansion history / distance indicator	light-curve / distance catalog

Tracers: What we actually observe

Galaxies: Luminous tracers of cosmic structures

- Massive systems of stars, gas, and dust held together by gravity.
- Observed as positions, redshifts, luminosities, colours.
- Discrete tracers of high-density peaks.
- Data product: galaxy catalogue

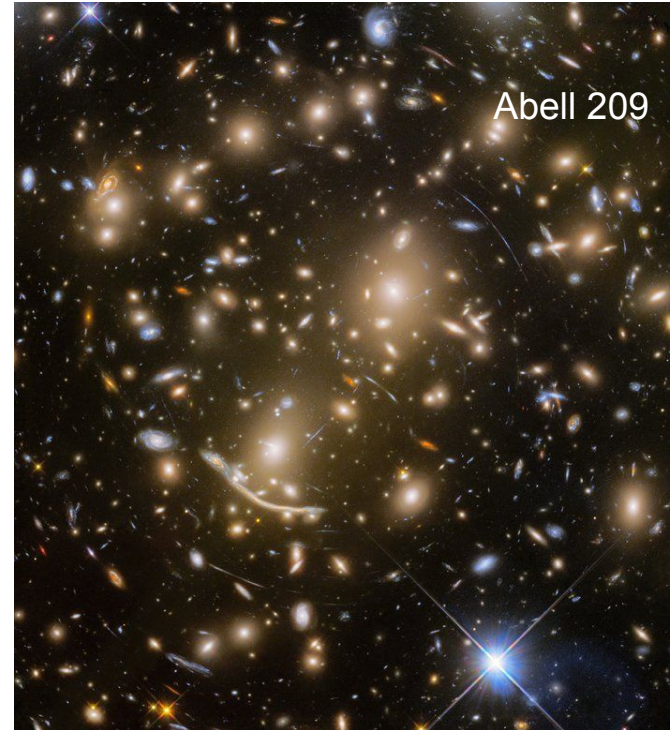


Credit: ESA/Webb, NASA & CSA, G. Gozaliasl, A. Koekemoer, M. Franco, and the COSMOS-Web team

Tracers: What we actually observe

Galaxy clusters: Rare high-mass peaks

- Largest gravitationally bound structures.
- Trace rare peaks of δ_m .
- Data product: cluster catalogue

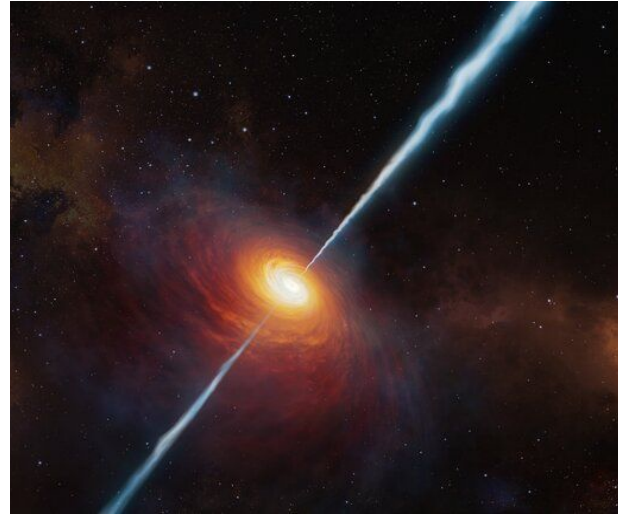


Credit: NASA, ESA/Hubble, HST Frontier Fields

Tracers: What we actually observe

Quasars: Rare, bright beacons in massive environments

- Galaxies powered by accretion onto supermassive black holes
- Very luminous, visible to high redshifts.
- Rare objects → sparse catalogue.
- Strongly biased environments.
- Also act as background lamps to spectroscopically probe the foreground intergalactic gas.

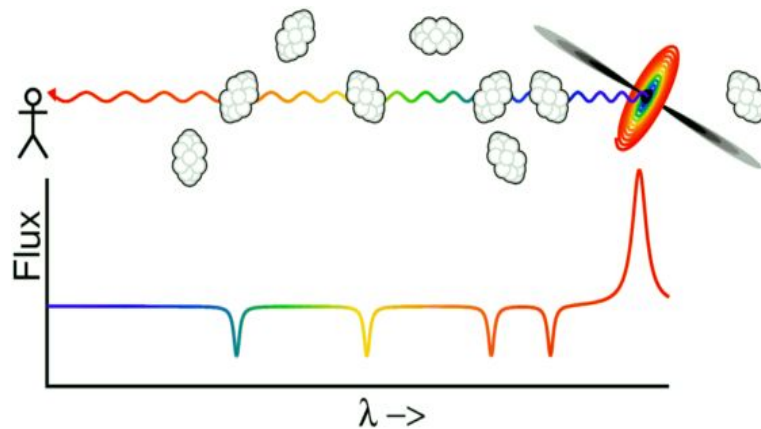


Artist's impression of quasar P172+18

Tracers: What we actually observe

Ly α forest: 1D sightlines through the cosmic web

- Background quasar provides the light.
- Intervening neutral hydrogen (H I) absorbs at Ly α .
- Each spectrum gives a 1D line-of-sight skewer.
- Sensitive to cosmic mean densities.
- Data product: quasar spectra / transmitted-flux field.

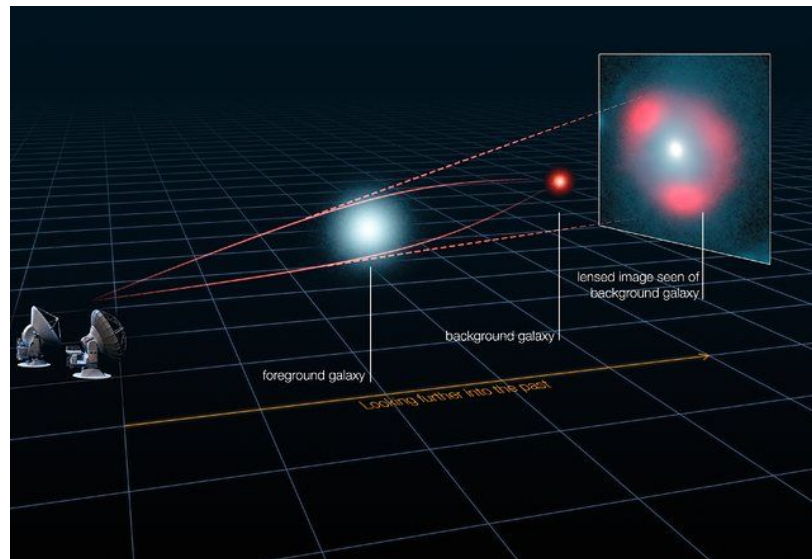


<https://www.astro.ucla.edu/~wright/Lyman-alpha-forest.html>

Tracers: What we actually observe

Weak lensing: Seeing matter through distorted light

- Gravity distorts background galaxy images.
- Sensitive to total matter, not just luminous matter.
- Measures projected mass along the line of sight.
- Data product: shear catalogue / convergence map.

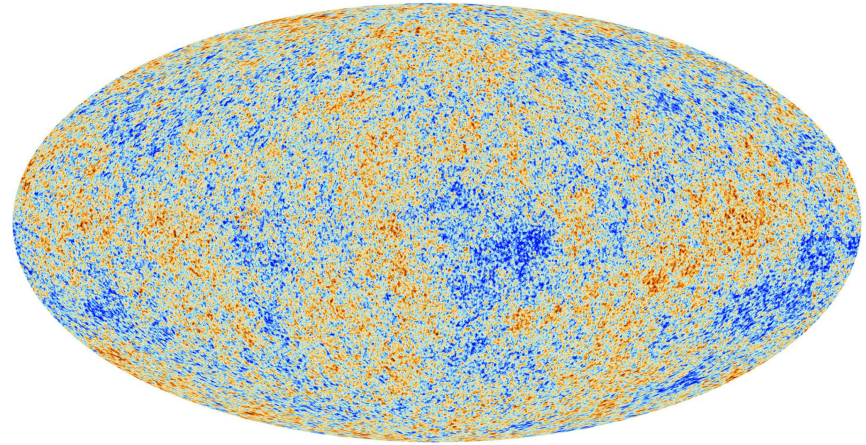


Credit: ALMA (ESO/NRAO/NAOJ), L. Calçada (ESO), Y. Hezaveh et al.

Tracers: What we actually observe

Cosmic Microwave Background: The oldest light and initial condition map

- Relic radiation from the early Universe.
- Emitted when the Universe became neutral and transparent.
- Maps tiny temperature anisotropies on the sky.
- Traces primordial density perturbations.
- Data product: full-sky temperature / polarization maps

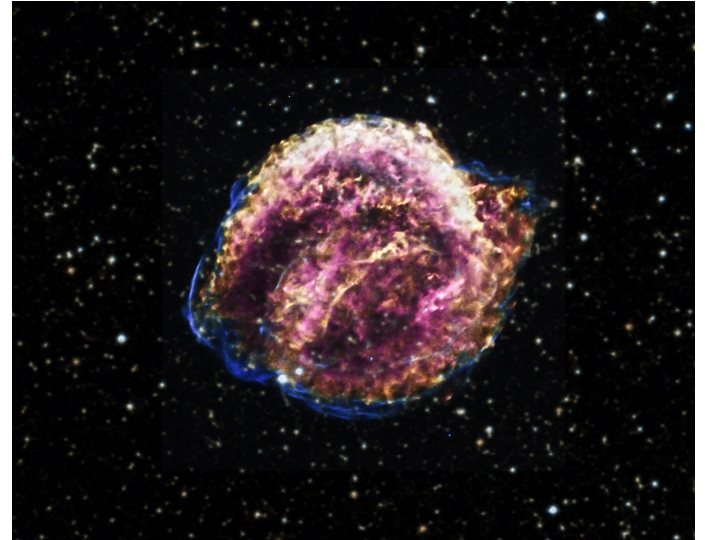


Credit: ESA and the Planck Collaboration

Tracers: What we actually observe

Supernovae: Distance tracers of cosmic expansion

- Standardized candles: Type Ia supernovae have standardizable luminosities
- Observed brightness gives luminosity distance.
- Redshift gives position on cosmic timeline.
- Distance–redshift relation probes expansion history.
- Data product: supernova light curves + redshifts

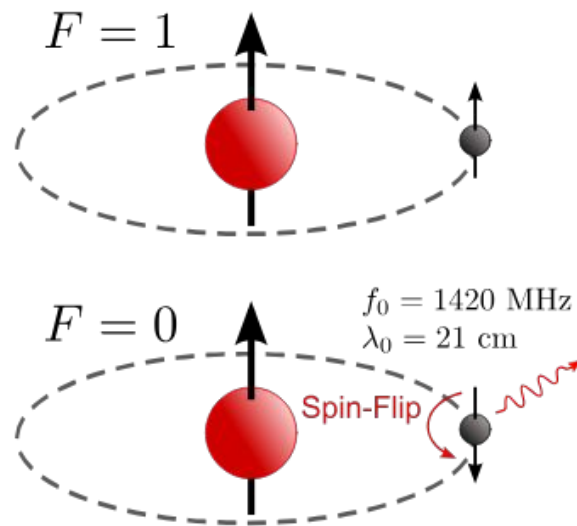


Kepler's supernova remnant, shown here in a combination of X-ray and optical wavelengths
[X-ray: NASA/CXC/SAO/D.Patnaude, Optical: DSS]































Tracers: What we actually observe

21 cm: Mapping neutral hydrogen directly

- Hyperfine transition of neutral hydrogen.
- Traces H I rather than starlight.
- During reionization: sensitive to ionized bubbles.
- Post-reionization: H I intensity mapping traces large-scale structure.
- Data product: radio intensity map / cube.



Cosmological Tracers and Major surveys/telescopes

Tracer (What we observe)	Major Surveys / Telescopes (examples)						Other / Emerging Tracers
1 Galaxies (Positions, spectra, shapes)	 SDSS (I–V)	 DESI (Dark Energy Spectroscopic Instrument)	 Euclid (ESA)	 LSST (Vera C. Rubin Observatory)	 HSC (Subaru)		<ul style="list-style-type: none"> • Strong Lensing Mass maps, substructure, cosmography Surveys: HSC, LSST, Euclid • 21-cm Intensity Mapping HI distribution over cosmic time Surveys: HERA, CHIME, IMPACT, SKA (future) • Gravitational Waves (standard sirens) Independent distance measurements Surveys: LIGO–Virgo–KAGRA, Einstein Telescope (future) • Gamma-ray Bursts High-z standardizable candles Surveys: Fermi, Swift, SVOM (future)
2 Weak Gravitational Lensing (Galaxy shapes)	 KIDS (VLT)	 DESY (Dark Energy Survey)	 HSC (Subaru)	 LSST (Vera C. Rubin)	 Euclid (ESA)		
3 Cosmic Microwave Background (CMB temperature & polarization)	 Planck (ESA)	 ACT (Atacama)	 SPT-3G (South Pole)	 Simons Observatory	 CMB-S4 (Future)		
4 Type Ia Supernovae (Standard candles)	 Pantheon+	 DES (SN program)	 OZTF (Transient Factory)	 LSST (Vera C. Rubin)	 Roman (ESA)		
5 Quasars & Lyα Forest (Spectra)	 eBOSS (SDSS)	 BOSS (SDSS)	 DESI (DESI)	 KODIAQ (Keck)	 SQUAD (VLT)		
6 Galaxy Clusters (Positions, masses, X-ray/SZ)	 eROSITA (All-sky X-ray)	 ACT (SZ clusters)	 SPT (SZ clusters)	 DES (Optical clusters)	 LSST (Future clusters)		

Different tracers probe different physics and epoch of the Universe. Together, they can break degeneracies and provide a consistent picture of the Universe.

Tracer statistics: Auto, Cross and Higher-order

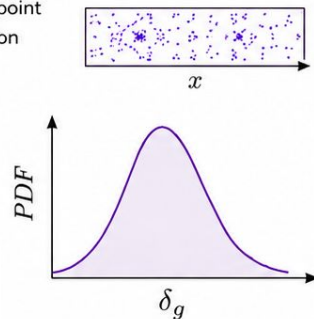
1D statistics

1D statistics compress the field into one-point information and summarize the distribution of tracer values.

Example: PDF of galaxy overdensity / transmitted flux

$P(\delta_g)$ or PDF(δ_g)

- mean: $\langle \delta_g \rangle$

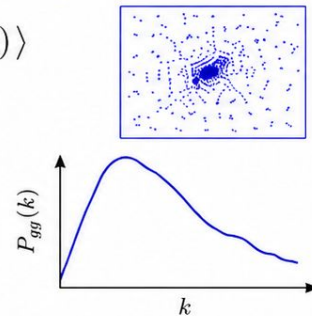


Auto-correlation / auto-power

$$P_{gg}(k) = \langle \delta_g(\mathbf{k}) \delta_g^*(\mathbf{k}) \rangle$$

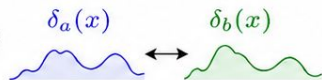
Measures how strongly the tracer clusters with itself.

Example: galaxy \times galaxy



Cross-correlation / cross-power

$$P_{ab}(k) = \langle \delta_a(\mathbf{k}) \delta_b^*(\mathbf{k}) \rangle$$



Examples:

- galaxy \times weak lensing
- Ly α forest \times quasars
- LAEs \times 21 cm

$$r_{ab}(k) = \frac{P_{ab}(k)}{\sqrt{P_{aa}(k)P_{bb}(k)}}$$

- $r = 1$: perfectly correlated fields.
- $r < 1$: stochasticity, noise, nonlinear physics, or different astrophysical response.

Higher-order tracer statistics

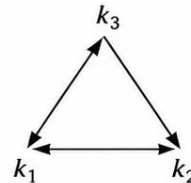
Two-point statistics measure variance, but nonlinear structure contains more information.

$$\langle \delta(\mathbf{k}_1) \delta(\mathbf{k}_2) \delta(\mathbf{k}_3) \rangle = (2\pi)^3 \delta_D(k_1 + k_2 + k_3) B(k_1, k_2, k_3)$$

$$k_1 + k_2 + k_3 = 0$$

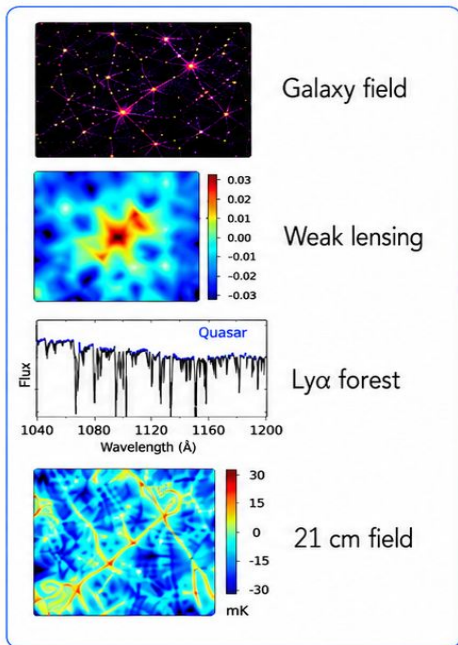
Higher-order statistics capture:

- nonlinear gravitational evolution
- nonlinear bias
- phase correlations
- filamentarity
- bubble morphology
- reionization topology
- feedback-induced non-Gaussianity

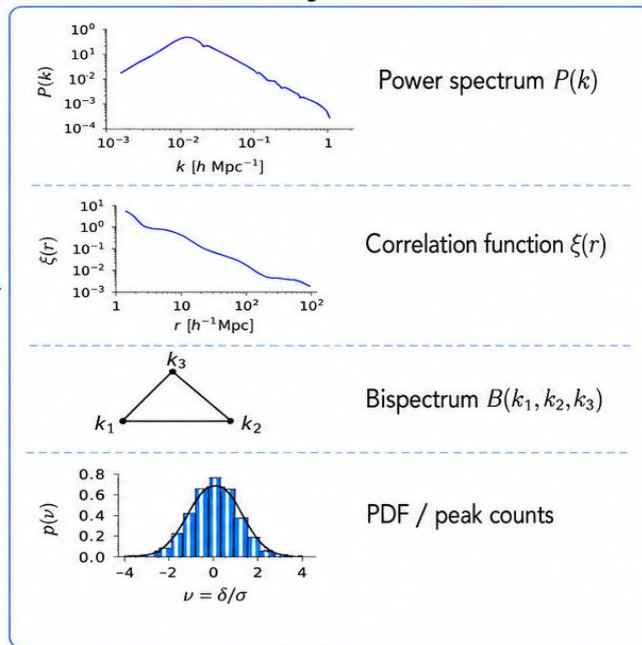


Inferring cosmological parameters from tracers

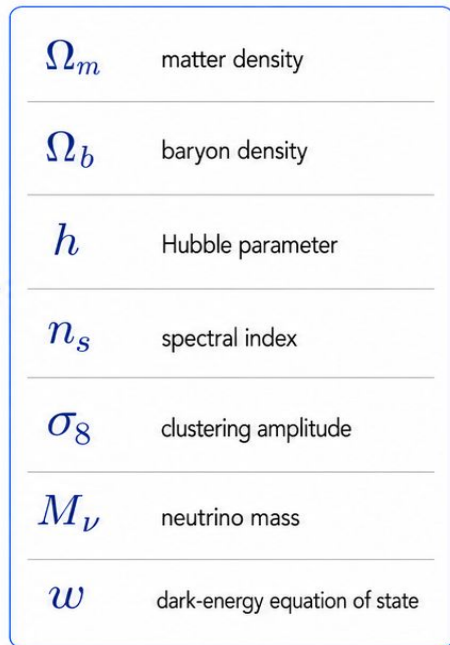
Observables



Compression into summary statistics



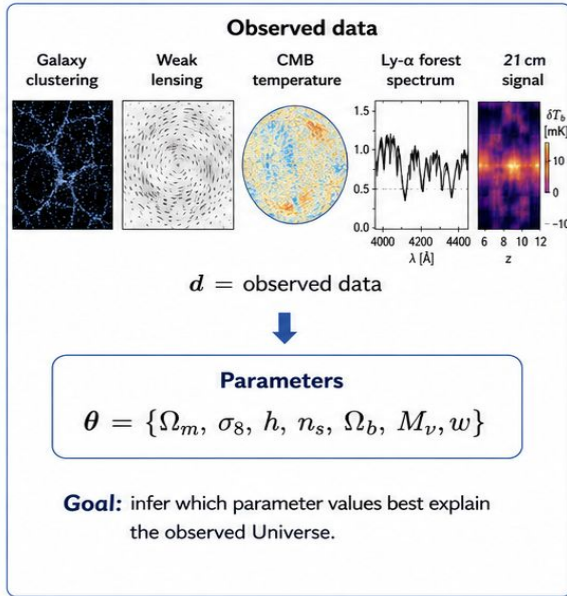
Cosmological parameters



We compress the tracer data into summary statistics and ask which cosmological model most likely produced them.

Bayesian Parameter Inference in Cosmology

1. The inference problem



2. Bayes' theorem

$$P(\theta|d) = \frac{P(d|\theta) P(\theta)}{P(d)}$$

Posterior = Likelihood \times Prior / Evidence

1) Posterior

$P(\theta|d)$: updated knowledge of parameters after seeing the data

2) Likelihood

$P(d|\theta)$: probability of the observed data for a chosen model

3) Prior

$P(\theta)$: information or assumptions before seeing the data

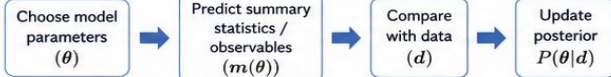
4) Evidence

$P(d)$: normalization; useful for model comparison



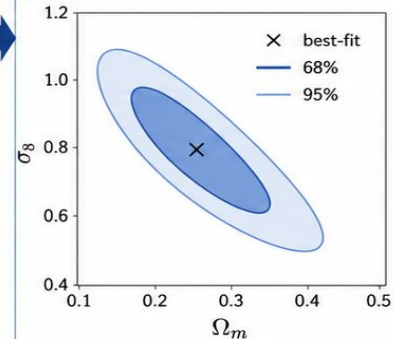
Important: $P(\theta|d)$ is not the same as $P(d|\theta)$.

3. From model comparison to parameter constraints



$$\mathcal{L}(d|\theta) \propto \exp \left[-\frac{1}{2} (d - m(\theta))^T C^{-1} (d - m(\theta)) \right]$$

$m(\theta)$: model prediction (mean) C : covariance matrix of the data



- The result of inference is a probability distribution, not just one number.
- Broad contours mean weak constraints; narrow contours mean strong constraints.
- Tilted contours indicate parameter degeneracy.

Bayesian inference turns cosmological observations into probabilistic constraints on physical models.

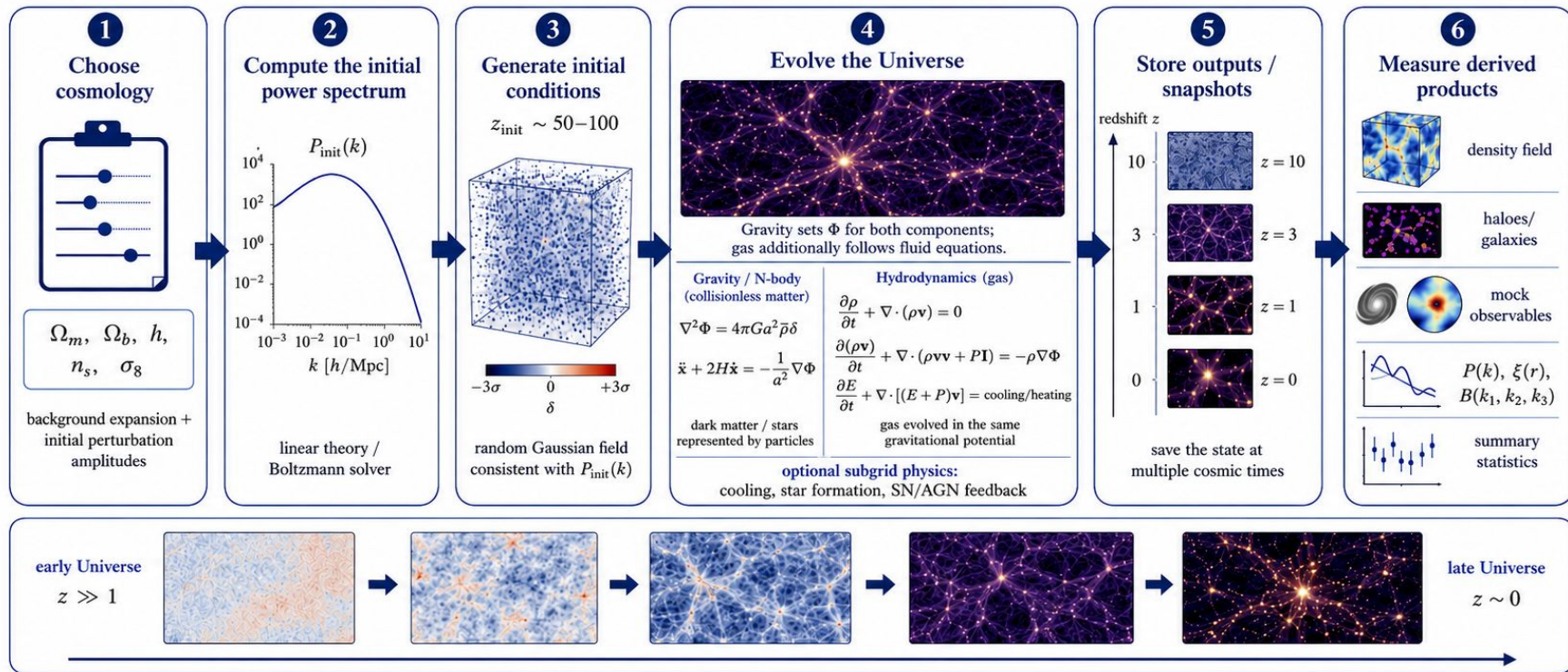
Inference requires a family of models

- To infer parameters, we need predictions for many possible choices of cosmology and astrophysics. The observed Universe is then compared against this ensemble.
- In cosmology, the models usually come from simulations.
- A simulation takes model parameters and forward models a mock instance of the Universe.

$\theta \rightarrow \text{simulation} \rightarrow \text{mock Universe} \rightarrow \text{summary statistics}$

Simulation type	What it models	Used for
N-body	collisionless dark matter	matter clustering, halo formation
hydrodynamical	dark matter + gas + stars + black holes	galaxies, baryons, feedback
radiative transfer	propagation of radiation	reionization, Ly α , 21 cm
mock survey pipelines	observational selection/noise	realistic comparison to data

How cosmological simulations are run



CAMELS: A public Simulation Suite for inference

CAMELS

Science

Publications

Documentation

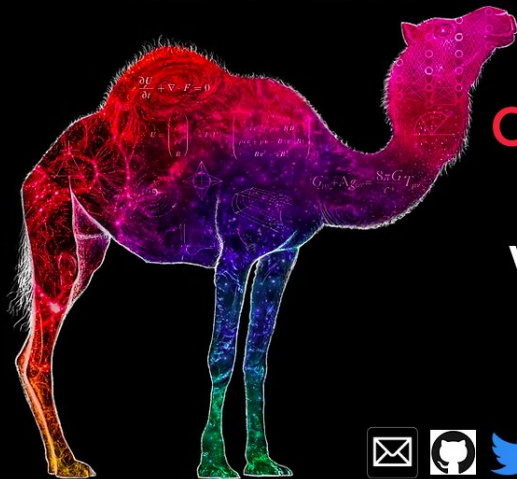
Multimedia

Videos

Blog

Team

CAMELS



Cosmology and
Astrophysics
with Machine
Learning
Simulations



<https://www.camel-simulations.org/>

CAMELS: A public Simulation Suite for inference

News

Scientific goals

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Data Access

CAMELS Agents

Citation

SIMULATIONS

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Subfind catalogs

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Rockstar catalogs

AHF catalogs

CAESAR catalogs

Photometry catalogs

Power spectra

Bispectra

Probability distribution functions

VIDE Voids

Lyman-alpha spectra

X-Rays

CAMELS CGM Profiles

CAMELS Multifield Dataset

CAMELS-SAM

CAMELS-zoomGZ

USEFUL

Tutorials

General description

As of March 2025, CAMELS host more than 2 petabytes of data from 16,960 cosmological simulations: 7,208 N-body and 9,752 hydrodynamic simulations. This project is the result of a large, collaborative effort and represents the most extensive suite of cosmological hydrodynamic simulations ever conducted.

The simulations are run with different codes (suites), cover different volumes and number of particles (generations), and sample different points in parameter space (sets), defined as the space formed from cosmological and astrophysical parameters and different initial conditions.

All CAMELS simulations share a few characteristics:

- All simulations start at redshift $z = 127$ and finish at $z = 0$.
- All simulations have the same mass and spatial resolution.
- For each simulation we store multiple snapshots, halo/subhalo catalogs, and summary statistics (e.g. power spectra) see [Data organization](#).
- The N-body simulations only model the spatial phase-space distribution of total matter under the influence of gravity.
- The hydrodynamic simulations account for gravity + (magenta-)hydrodynamics + astrophysical processes (e.g. supernova and AGN feedback).

Organization

The simulations can be classified into:

- **Suites:** depending on the code and subgrid physics model used to run them. CAMELS has 9 suites:

Suite	Code	Subgrid Physics Model
IllustrisTNG	AREPO	IllustrisTNG
SIMBA	GIZMO	SIMBA
Astrid	MP-Gadget	Astrid
Magneticum	OpenGadget	Magneticum-like
Swift-EAGLE	Swift	EAGLE
Ramses	Ramses	—
Enzo	Enzo	—
CROCODILE	Gadget4-Osaka	CROCODILE
Obsidian	GIZMO	Obsidian

CAMELS: A public Simulation Suite for inference

Cosmological parameters

All simulations share the value of these cosmological parameters:

w	M_ν	Ω_k
-1	0.0 eV	0.0

For the other cosmological parameters, the different sets vary them differently:

	Ω_m	σ_8	Ω_b	h	n_s
CV	0.3	0.8	0.049	0.6711	0.9624
BE	0.3	0.8	0.049	0.6711	0.9624
EX	0.3	0.8	0.049	0.6711	0.9624
LH	0.1 - 0.5	0.6 - 1.0	0.049	0.6711	0.9624
1P	0.1 - 0.5	0.6 - 1.0	0.029 - 0.069	0.4711 - 0.8711	0.7624 - 1.1624
SB	0.1 - 0.5	0.6 - 1.0	0.029 - 0.069	0.4711 - 0.8711	0.7624 - 1.1624

Astrophysical parameters

We emphasize that every subgrid physics model is different, and the parameters of one model does not mean anything in another one. Thus, we will describe these parameters for each suite and what is varied.

IllustrisTNG

The IllustrisTNG suite contains all sets: 1P, CV, LH, EX, BE, and SB. This table shows which parameters are varied in each set:

	Astrophysical parameters	
	First generation	Second generation
CV	fiducial IllustrisTNG	
BE	fiducial IllustrisTNG	
LH	standard 4 astrophysical parameters	—
EX	standard 4 astrophysical parameters	
1P	23 astrophysical parameters	30 astrophysical parameters
SB	SB28: 23 astrophysical parameters	SB35: 30 astrophysical parameters

The meaning and range of variation of the 4 *standard* IllustrisTNG parameters are these:

- $A_{\text{SN}1}$: it represents the energy per unit SFR of the galactic winds. It can vary from 0.25 to 4. Fiducial value is 1.
- $A_{\text{SN}2}$: it represents the wind speed of the galactic winds. It can vary from 0.5 to 2. Fiducial value is 1.
- $A_{\text{AGN}1}$: it represents the energy per unit black-hole accretion rate. It can vary from 0.25 to 4. Fiducial value is 1.
- $A_{\text{AGN}2}$: it represents the ejection speed/burstiness of the kinetic mode of the black-hole feedback. It can vary from 0.5 to 2. Fiducial value is 1.

CAMELS: A public Simulation Suite for inference

Data Access

Binder	Globus	URL	FlatHUB	Rusty
Binder link	Globus link	URL link	FlatHUB link	<code>/mnt/ceph/users/camels/PUBLIC_RELEASE</code>

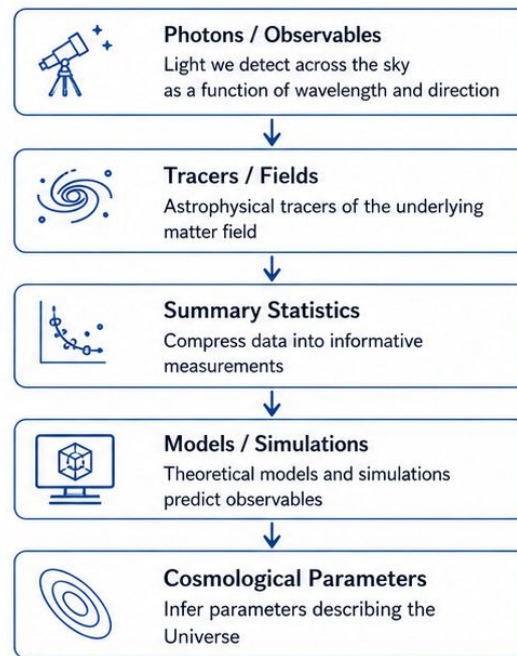
This table shows the availability of the different simulations:

	First generation	Second generation	Third generation
IllustrisTNG	Public	Private	
SIMBA	Public		
Astrid	Public	Private (running)	
Swift-EAGLE	Public		
Magneticum	Private		
Ramses	Private	Private (running)	
CROCODILE	Private	Private (running)	
Obsidian	Private		
Enzo	Private		
N-body	Public	Public	

Take-home messages: From light to cosmology

Cosmology as data-driven inference

- 1 We observe the Universe on our past light cone, not as a single snapshot in time.
- 2 Redshift is both an observational coordinate and a marker of cosmic time.
- 3 The expanding background Universe is described by $a(t)$, $H(z)$, and parameters such as Ω_m , Ω_Λ , H_0 , σ_8 , n_s .
- 4 Structure formation is described by the growth of density perturbations:
$$\delta_m(\mathbf{x}, t) = [\rho_m(\mathbf{x}, t) - \bar{\rho}_m(t)] / \bar{\rho}_m(t).$$
- 5 We do not observe the matter field directly; we observe tracers: galaxies, quasars, Ly α forest, weak lensing, CMB, supernovae, and 21 cm.
- 6 Cosmological information is extracted using summary statistics such as $P(k)$, $\xi(r)$, $B(k_1, k_2, k_3)$, PDFs, and cross-correlations.



Cosmological data handling turns observed photons into quantitative statements about the composition, expansion history, and structure of the Universe.

References:

- **T. Padmanabhan** — *Structure Formation in the Universe*
- **Scott Dodelson & Fabian Schmidt** — *Modern Cosmology*
- **P. J. E. Peebles** — *Principles of Physical Cosmology* or *The Large-Scale Structure of the Universe*

Lyman- α Forest as a 1D Probe of the Cosmic Structures

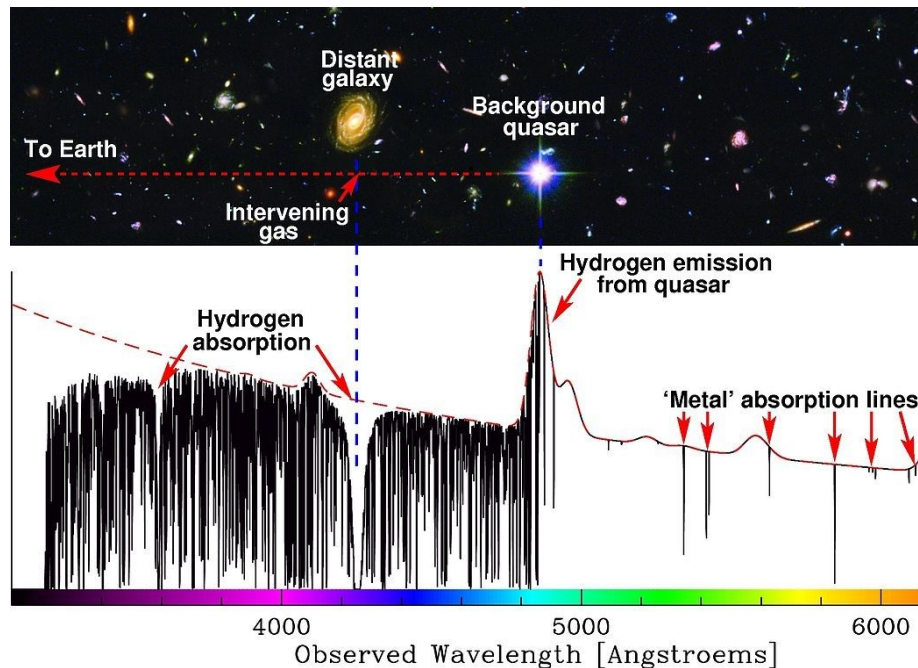
- Ly α forest is a series of absorption produced by neutral hydrogen (HI) due to the $1s \rightarrow 2p$ transition in the Quasar spectra.
- These absorptions get redshifted due to the expansion of the Universe.

$$E_{\alpha} = 10.2 \text{ eV}, \lambda_{\alpha} = 1215.67 \text{ \AA}$$

$$\lambda_{\text{obs}} = \lambda_{\alpha}(1 + z_{\text{abs}})$$

- This makes them a 1D map of the intervening HI gas present in the sightline of the distant Quasar.
- Lyman- α forest probes matter in a quasi-linear regime.
- $F_{\text{obs}} = F_{\text{cont}} e^{-\tau_{\text{HI}}}$ [Transmitted Flux: $F_{\text{obs}}/F_{\text{cont}}$]

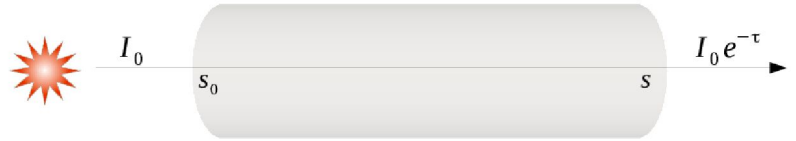
where F_{obs} is the observed Flux and F_{cont} is the continuum flux emitted by the quasar before absorption.



Lyman- α Radiative transfer

- The basic radiative transfer equation for absorption is $I_\nu = I_{\nu,0}e^{-\tau_\nu}$.
- For a particular frequency ν , the optical depth over a distance s_0 to s is given by

$$\tau_\nu = \int_{s_0}^s ds' n(s', t') \sigma_\nu$$



where, n : Number density of the absorbers

σ_ν : Frequency dependent absorption cross-section.

- σ_ν for the absorbers at rest is given by a Lorentzian profile as

$$\sigma_\nu = \left(\frac{\pi e^2}{m_e c} \right) \left(\frac{f_{lu}}{4\pi\epsilon_0} \right) \frac{\Gamma_{ul}/4\pi^2}{(\nu - \nu_{lu})^2 + (\Gamma_{ul}/4\pi)^2}$$

- Here, f_{lu} is the upward oscillator strength, Γ_{ul} is the damping width of the upper level and ν_{lu} is the resonance line frequency.
- For hydrogen Lyman- α , $f_{lu} = 0.4162$, $\lambda_{lu} = 1215.67 \text{ \AA}$, and $\Gamma_{ul} = 6.262 \times 10^8 \text{ s}^{-1}$.

Lyman- α Radiative transfer

- The absorbers are rarely at rest.
Ignoring non-thermal velocities, the actual absorption cross-section is obtained by convolving the Lorentzian with a Maxwellian profile.

$$\sigma_\nu = \left(\frac{\pi e^2}{m_e c} \right) \left(\frac{f_{lu}}{4\pi\epsilon_0} \right) \boxed{\varphi_V(\alpha, \nu)}, \text{ Voigt Profile}$$

$$\varphi_V(a, x) = \frac{1}{\pi^{1/2} \Delta\nu_D} V(a, x) = \frac{a}{\pi^{3/2} \Delta\nu_D} \int_{-\infty}^{\infty} \frac{e^{-y^2}}{(x-y)^2 + a^2}$$

where, $\Delta\nu_D = v_{lu} b/c$, with b being the doppler parameter ($b = \sqrt{2k_B T/m}$), $a = \Gamma_{ul}/(4\pi\Delta\nu_D)$ and $x = (\nu - \nu_{lu})/\Delta\nu_D$.

- The Lyman- α absorption optical depth at redshift z_0 will then be given as

$$\tau(z_0) = \frac{cI_\alpha}{\pi^{1/2}} \int ds \left(\frac{n_{HI}[s, z(s)]}{b[s, z(s)][1 + z(s)]} \right) V \left[a, \frac{cz(s) - z_0}{b[s, z(s)][1 + z_0]} + \frac{v[s, z(s)]}{b[s, z(s)]} \right]$$

where n_{HI} is the neutral hydrogen density and $I_\alpha = 4.45 \times 10^{-18} \text{cm}^2$.

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where n_{HI} is the neutral hydrogen density and $I_\alpha = 4.45 \times 10^{-18} \text{cm}^2$.

Understanding the Voigt profile

Important parameters:

- n_{HI} : Neutral hydrogen density
- T : IGM temperature
- v : peculiar velocity, i.e, velocity on top of the Hubble expansion.

Under Photoionization equilibrium assumption, $n_{\text{HI}} \Gamma_{\text{HI}} = n_e n_p \alpha_A(T)$
Ionization Recombination

For highly ionized hydrogen ($n_e \approx n_p \approx n_H$), $n_{\text{HI}} \simeq \frac{\alpha_A(T) n_H^2}{\Gamma_{\text{HI}}}$

Recombination coefficient roughly scales as $\alpha_A(T) \propto T^{-0.7}$.

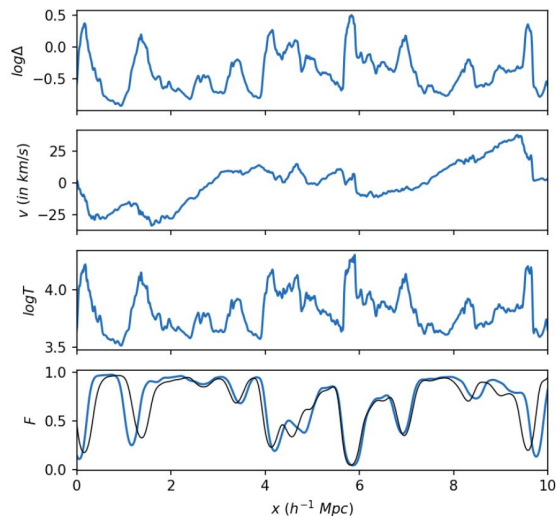
Hence, $n_{\text{HI}} \propto \frac{n_H^2 T^{-0.7}}{\Gamma_{\text{HI}}}$, where n_H is the hydrogen density that is proportional to the matter density $\Delta = \rho / \langle \rho \rangle$ and

Γ_{HI} is the hydrogen photoionization rate.

So the final important parameters governing Lyman-alpha forest Voigt profile are Δ (Density), Γ_{HI} (photoionization rate), T (IGM temperature) and v (peculiar velocity)

Understanding the Voigt profile

- Effect of Δ (Density): Increases n_{HI} , stronger absorption.
- Effect of Γ_{HI} (photoionization rate): Higher Γ_{HI} decreases n_{HI} , weaker absorption.
- Effect of T (IGM temperature):
 - Higher temperature decreases recombination rate, lower n_{HI} .
 - Higher temperature increase b -parameter, wider absorption lines (**Thermal broadening**)
- Effect of peculiar velocity:



Fluctuating Gunn Peterson Approximation:

Approximate dependence on cosmological and astrophysical parameters

Main approximations:

- Highly ionized IGM: $n_e \approx n_p \approx n_H$
- Photoionization equilibrium, temperature dependent recombination (previous slide)
- Power law temperature-density relation: $T = T_0(1 + \delta_b)^{\gamma-1}$
- Local optical depth approximation: $\tau(\mathbf{x}) \propto n_{\text{HI}}(\mathbf{x})$

$$\tau(\Delta, z) \propto \frac{(\Omega_b h^2)^2 (1+z)^{4.5}}{h \Omega_m^{1/2} \Gamma_{\text{HI}}} T_0^{-0.7} \Delta^{2-0.7(\gamma-1)}$$

$$F(\Delta, z) = \exp[-\tau(\Delta, z)]$$

Fluctuating Gunn Peterson Approximation:

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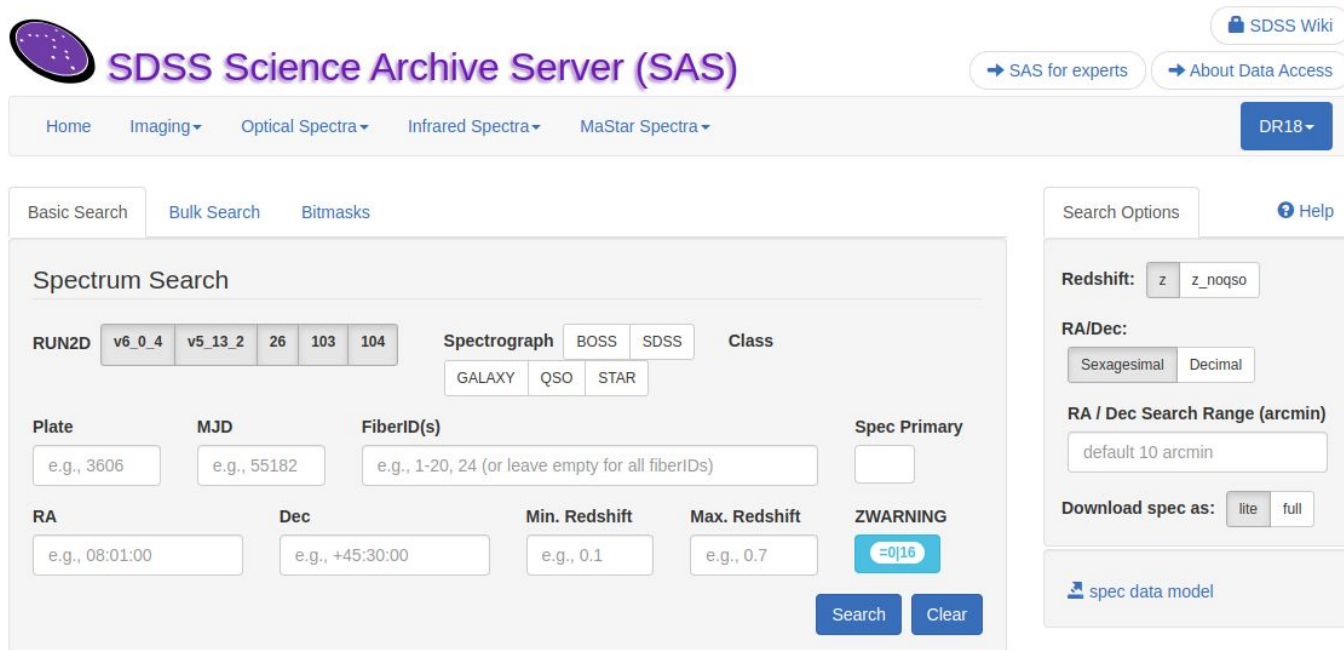
$$F(\Delta, z) = \exp[-\tau(\Delta, z)]$$

References:

- **Avery A. Meiksin**, “The physics of the intergalactic medium,” *Reviews of Modern Physics*, 81, 1405–1469, 2009.
- **Matthew McQuinn**, “The Evolution of the Intergalactic Medium,” *Annual Review of Astronomy and Astrophysics*, 54, 313–362, 2016.

Now let's look at some realistic Lyman- α forest spectra

SDSS: Low resolution spectra ($R \sim 2000$), large in number



The screenshot shows the SDSS Science Archive Server (SAS) search interface. At the top, there is a navigation bar with links for Home, Imaging, Optical Spectra, Infrared Spectra, and MaStar Spectra. A blue button labeled 'DR18' is on the right. Below the navigation bar, there are tabs for 'Basic Search', 'Bulk Search', and 'Bitmasks'. The main search area is titled 'Spectrum Search' and contains several input fields and buttons. The 'RUN2D' field has buttons for 'v6_0_4', 'v5_13_2', '26', '103', and '104'. The 'Spectrograph' field has buttons for 'BOSS', 'SDSS', 'GALAXY', 'QSO', and 'STAR'. The 'Class' field is empty. The 'Plate' field has a text input with 'e.g., 3606'. The 'MJD' field has a text input with 'e.g., 55182'. The 'FiberID(s)' field has a text input with 'e.g., 1-20, 24 (or leave empty for all fiberIDs)'. The 'Spec Primary' field is empty. The 'RA' field has a text input with 'e.g., 08:01:00'. The 'Dec' field has a text input with 'e.g., +45:30:00'. The 'Min. Redshift' field has a text input with 'e.g., 0.1'. The 'Max. Redshift' field has a text input with 'e.g., 0.7'. The 'ZWARNING' field has a button with '=0|16'. There are 'Search' and 'Clear' buttons at the bottom right of the search area. On the right side, there is a 'Search Options' panel with a 'Help' icon. It contains a 'Redshift' field with buttons for 'z' and 'z_nogso'. The 'RA/Dec:' field has buttons for 'Sexagesimal' and 'Decimal'. The 'RA / Dec Search Range (arcmin)' field has a text input with 'default 10 arcmin'. The 'Download spec as:' field has buttons for 'lite' and 'full'. At the bottom of the search options panel, there is a link for 'spec data model'.

SDSS Science Archive Server (SAS)

Home Imaging Optical Spectra Infrared Spectra MaStar Spectra DR18

Basic Search Bulk Search Bitmasks

Spectrum Search

RUN2D v6_0_4 v5_13_2 26 103 104 Spectrograph BOSS SDSS Class GALAXY QSO STAR

Plate MJD FiberID(s) Spec Primary

e.g., 3606 e.g., 55182 e.g., 1-20, 24 (or leave empty for all fiberIDs)

RA Dec Min. Redshift Max. Redshift ZWARNING

e.g., 08:01:00 e.g., +45:30:00 e.g., 0.1 e.g., 0.7 =0|16

Search Clear

Search Options Help

Redshift: z z_nogso

RA/Dec: Sexagesimal Decimal

RA / Dec Search Range (arcmin) default 10 arcmin

Download spec as: lite full

spec data model

<https://dr18.sdss.org/optical/spectrum/search>

Now let's look at some realistic Lyman- α forest spectra

The screenshot shows the SDSS Science Archive Server (SAS) interface. At the top, there is a logo for the SDSS Science Archive Server (SAS) and navigation links for "SAS for experts" and "About Data Access". Below the logo, there are tabs for "Home", "Imaging", "Optical Spectra", "Infrared Spectra", and "MaStar Spectra". A "DR18" dropdown menu is visible on the right. The main search area is titled "Spectrum Search" and includes a search bar with the text "Matched 18923 rows for this search". Below the search bar, there are several input fields and buttons for refining the search. The "RUN2D" section has buttons for "v6_0_4", "v5_13_2", "26", "103", and "104". The "Spectrograph" section has buttons for "BOSS", "SDSS", "GALAXY", "QSO", and "STAR". The "Class" section has a dropdown menu. The "Plate" field has a text input with "e.g., 3606". The "MJD" field has a text input with "e.g., 55182". The "FiberID(s)" field has a text input with "e.g., 1-20, 24 (or leave empty for all fiberIDs)". The "Spec Primary" field has a text input. The "RA" field has a text input with "e.g., 08:01:00". The "Dec" field has a text input with "e.g., +45:30:00". The "Min. Redshift" field has a text input with "2.7". The "Max. Redshift" field has a text input with "2.8". The "ZWARNING" field has a text input with "=0|16". There are "Search" and "Clear" buttons. A "Permalink for this search" button is also present. On the right side, there is a "Search Options" panel with a "Help" icon. It includes a "Redshift" section with a dropdown menu for "z" and a text input for "z_noqso". There is a "RA/Dec:" section with "Sexagesimal" and "Decimal" radio buttons. The "RA / Dec Search Range (arcmin)" section has a text input with "default 10 arcmin". The "Download spec as:" section has "lite" and "full" radio buttons. There is an "Update" button. At the bottom of the search panel, there is a link for "spec data model".

Spectra Individual Spectrum Plot Combined eFEDS Spectrum Plot

Table (csv) Spectra (rsync) Spectra (wget)

Plate	MJD	FiberID	specobj_id	RA	Dec	z	zerr	S/N	class	Plot	File	CAS
269	51581	199	302921802168952832	10:04:23.27	-00:40:42.84	2.73165	0.000535	10.94	QSO			
269	51910	189	302919058909587456	10:04:23.27	-00:40:42.84	2.7313	0.000446	11.94	QSO			
286	51999	585	322168210470234112	12:08:47.64	+00:43:21.69	2.71383	0.0003	10.91	QSO			
286	51999	598	322171783883024384	12:08:34.85	+00:20:47.85	2.70908	0.000479	11.54	QSO			
288	52000	266	324332324248381440	12:15:49.81	-00:34:32.10	2.70732	0.000386	31.76	QSO			
291	51660	607	327803751630923776	12:45:51.45	+01:05:05.04	2.79783	0.000163	18.6	QSO			
291	51928	612	327805130516752384	12:45:51.45	+01:05:05.04	2.79776	0.00015	19.67	QSO			
293	51689	65	329906568105584640	13:01:47.88	-00:38:17.31	2.70741	0.000348	9.01	QSO			
293	51994	66	329906848100542464	13:01:47.88	-00:38:17.31	2.70712	0.000404	7.43	QSO			

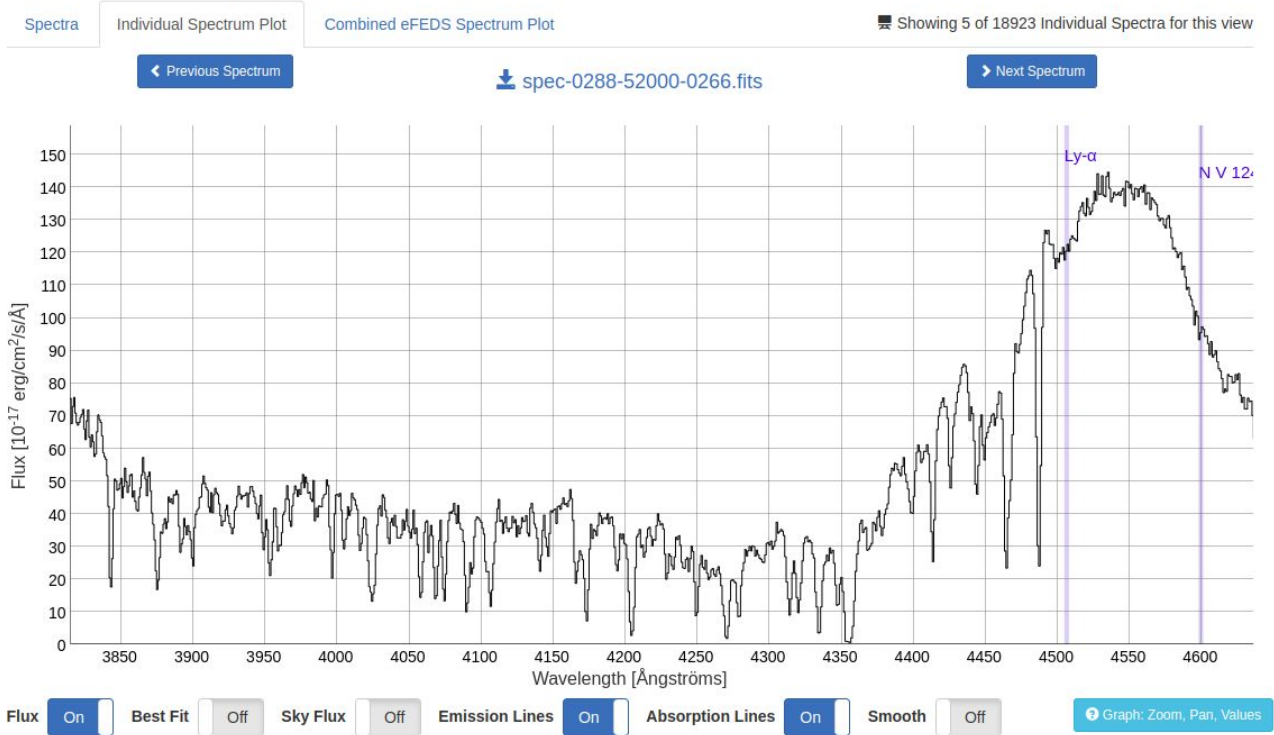
Showing 1 to 10 of 18923 rows 10 rows per page

1 2 3 4 5 ... 1893

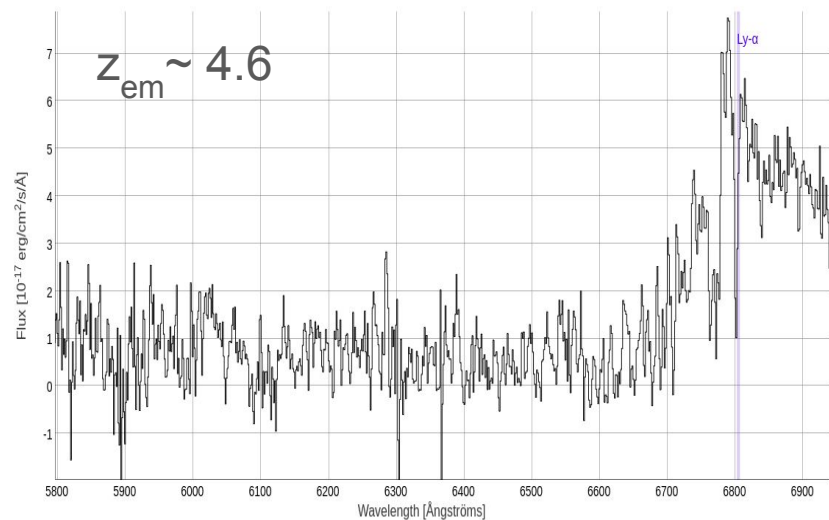
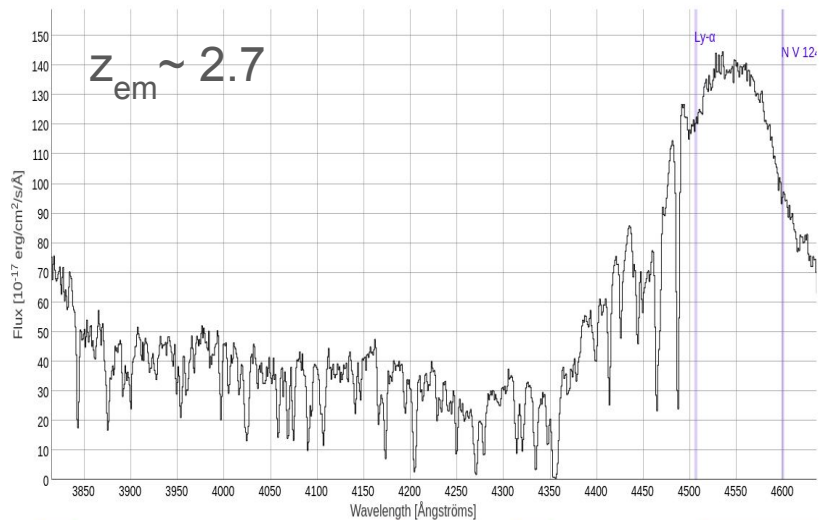
Now let's look at some realistic Lyman- α forest spectra



Now let's look at some realistic Lyman- α forest spectra

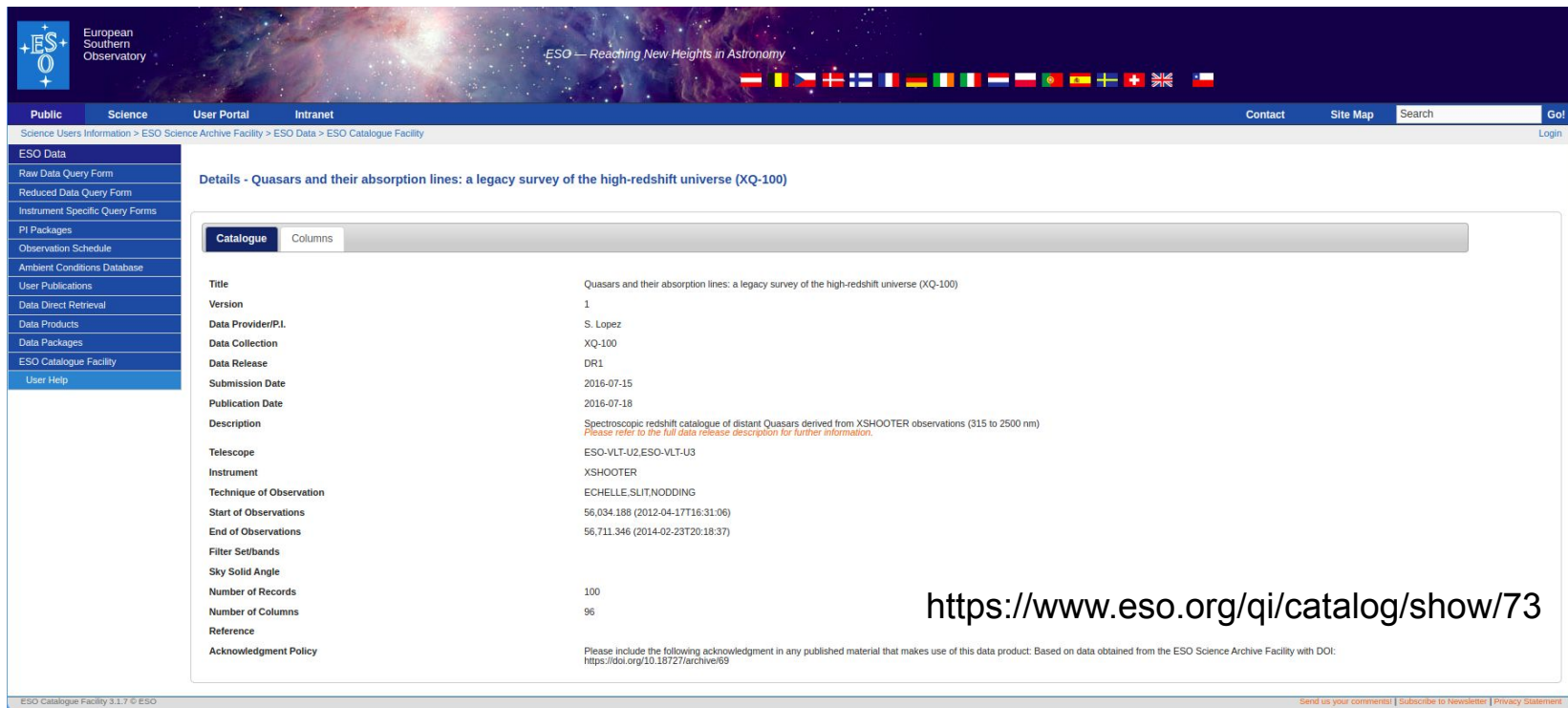


Now let's look at some realistic Lyman- α forest spectra



Now let's look at some realistic Lyman- α forest spectra

XQ100: Medium resolution ($R=6000-9000$), VLT/X-shooter spectrograph



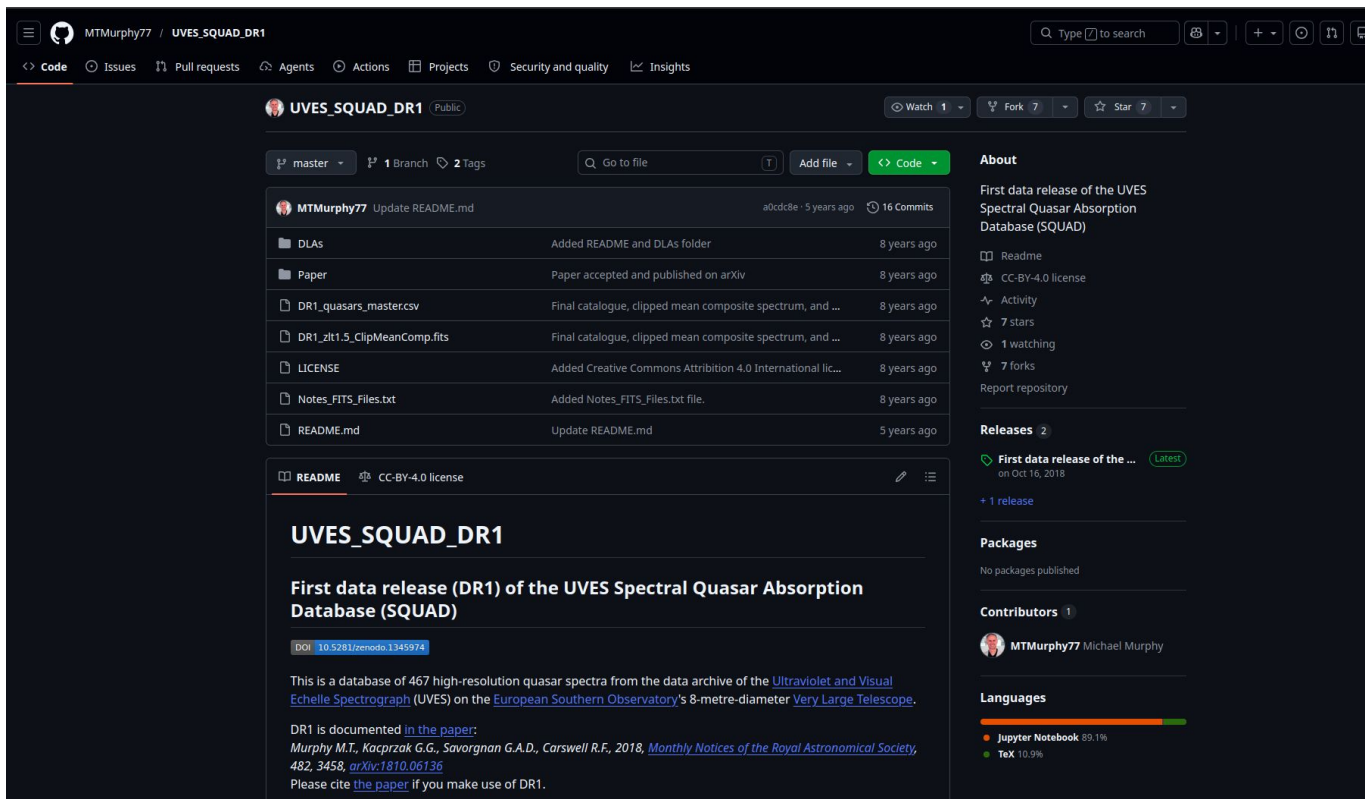
The screenshot shows the ESO Science Archive Facility website. The header includes the ESO logo and the tagline "ESO — Reaching New Heights in Astronomy". The navigation bar has tabs for "Public", "Science", "User Portal", and "Intranet". The main content area displays the title "Details - Quasars and their absorption lines: a legacy survey of the high-redshift universe (XQ-100)". Below the title, there are two tabs: "Catalogue" (selected) and "Columns". The "Catalogue" tab shows a table with the following details:

Title	Quasars and their absorption lines: a legacy survey of the high-redshift universe (XQ-100)
Version	1
Data Provider/PI	S. Lopez
Data Collection	XQ-100
Data Release	DR1
Submission Date	2016-07-15
Publication Date	2016-07-18
Description	Spectroscopic redshift catalogue of distant Quasars derived from XSHOOTER observations (315 to 2500 nm) <i>Please refer to the full data release description for further information.</i>
Telescope	ESO-VLT-U2,ESO-VLT-U3
Instrument	XSHOOTER
Technique of Observation	ECHELLE.SLIT.NODDING
Start of Observations	56,034.188 (2012-04-17T16:31:06)
End of Observations	56,711.346 (2014-02-23T20:18:37)
Filter Setbands	
Sky Solid Angle	
Number of Records	100
Number of Columns	96
Reference	
Acknowledgment Policy	Please include the following acknowledgment in any published material that makes use of this data product: Based on data obtained from the ESO Science Archive Facility with DOI: https://doi.org/10.18727/archive/69

At the bottom right of the page, the URL <https://www.eso.org/qi/catalog/show/73> is displayed. The footer contains the text "ESO Catalogue Facility 3.1.7 © ESO" and links for "Send us your comments", "Subscribe to Newsletter", and "Privacy Statement".

Now let's look at some realistic Lyman- α forest spectra

SQUAD: High resolution ($R \sim 45,000$), VLT/UVES spectrograph



The screenshot shows the GitHub repository page for `UVES_SQUAD_DR1` by user `MTMurphy77`. The repository is public and has 1 watch, 7 forks, and 7 stars. The main content area displays a list of files and folders, including `DLAs`, `Paper`, `DR1_quasars_master.csv`, `DR1_zlt1.5_ClipMeanComp.fits`, `LICENSE`, `Notes_FITS_Files.txt`, and `README.md`. The `README.md` file is selected and its content is visible below. The README describes the first data release (DR1) of the UVES Spectral Quasar Absorption Database (SQUAD), providing a DOI ([10.5281/zenodo.1345974](https://doi.org/10.5281/zenodo.1345974)) and a citation: *Murphy M.T., Kacprzak G.G., Savorgnan G.A.D., Carswell R.F., 2018, Monthly Notices of the Royal Astronomical Society, 482, 3458, arXiv:1810.06136*. The right sidebar contains an 'About' section, a 'Releases' section with the latest release on Oct 16, 2018, and a 'Languages' section showing `Jupyter Notebook` at 89.1% and `TeX` at 10.9%.

MTMurphy77 / UVES_SQUAD_DR1

Code Issues Pull requests Agents Actions Projects Security and quality Insights

UVES_SQUAD_DR1 Public

Watch 1 Fork 7 Star 7

master 1 Branch 2 Tags

Go to file Add file Code

File/Folder	Description	Time
MTMurphy77	Update README.md	a0cd9e · 5 years ago 16 Commits
DLAs	Added README and DLAs folder	8 years ago
Paper	Paper accepted and published on arXiv	8 years ago
DR1_quasars_master.csv	Final catalogue, clipped mean composite spectrum, and ...	8 years ago
DR1_zlt1.5_ClipMeanComp.fits	Final catalogue, clipped mean composite spectrum, and ...	8 years ago
LICENSE	Added Creative Commons Attribution 4.0 International lic...	8 years ago
Notes_FITS_Files.txt	Added Notes_FITS_Files.txt file.	8 years ago
README.md	Update README.md	5 years ago

README CC-BY-4.0 license

UVES_SQUAD_DR1

First data release (DR1) of the UVES Spectral Quasar Absorption Database (SQUAD)

DOI: [10.5281/zenodo.1345974](https://doi.org/10.5281/zenodo.1345974)

This is a database of 467 high-resolution quasar spectra from the data archive of the [Ultraviolet and Visual Echelle Spectrograph \(UVES\)](#) on the [European Southern Observatory's 8-metre-diameter Very Large Telescope](#).

DR1 is documented [in the paper](#):

Murphy M.T., Kacprzak G.G., Savorgnan G.A.D., Carswell R.F., 2018, Monthly Notices of the Royal Astronomical Society, 482, 3458, arXiv:1810.06136

Please cite [the paper](#) if you make use of DR1.

About

First data release of the UVES Spectral Quasar Absorption Database (SQUAD)

Readme

CC-BY-4.0 license

Activity

7 stars

1 watching

7 forks

Report repository

Releases 2

First data release of the ... Latest
on Oct 16, 2018

+ 1 release

Packages

No packages published

Contributors 1

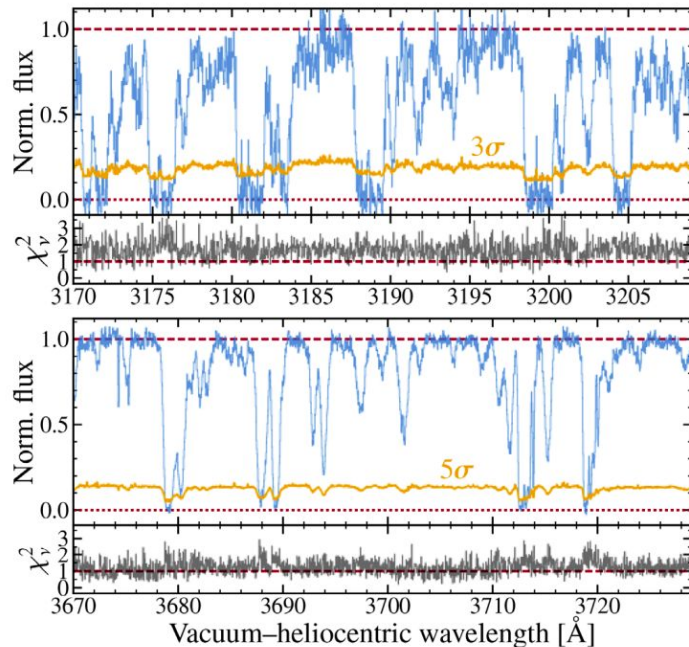
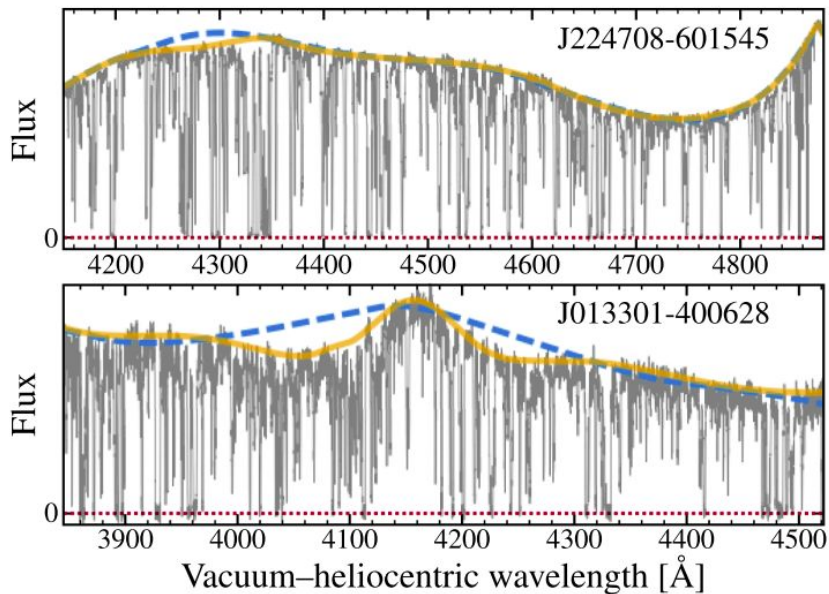
MTMurphy77 Michael Murphy

Languages

- Jupyter Notebook 89.1%
- TeX 10.9%

Now let's look at some realistic Lyman- α forest spectra

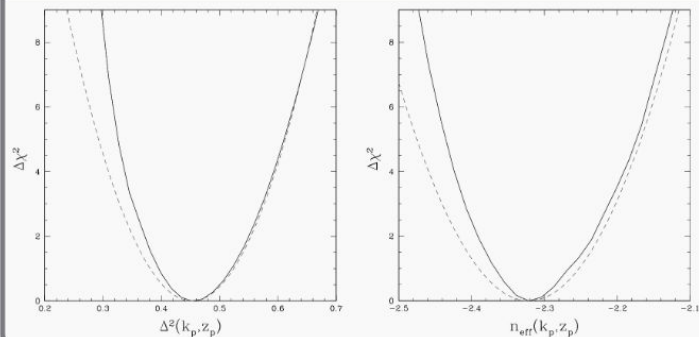
SQUAD: High resolution ($R \sim 45,000$), VLT/UVES spectrograph



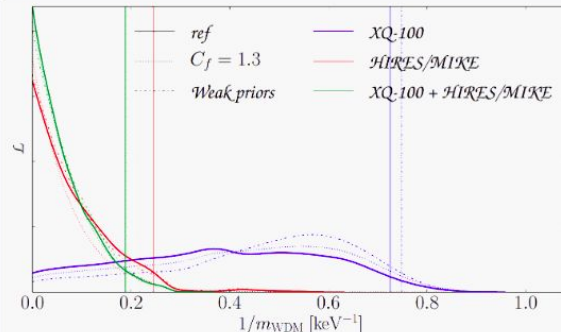
Murphy et al. 2018

Lyman- α forest: Cosmological Utility

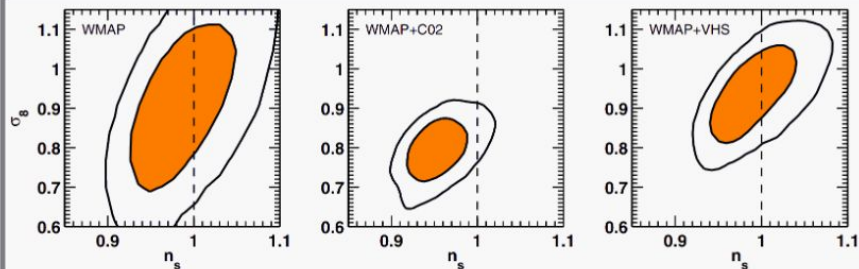
Linear Theory Power spectrum (McDonald+2005)



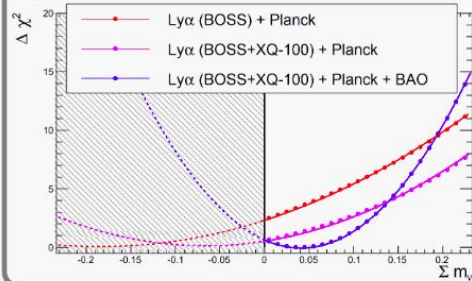
Warm Dark Matter model (Irsic+2017)



Primordial Power spectrum (Viel+2004)

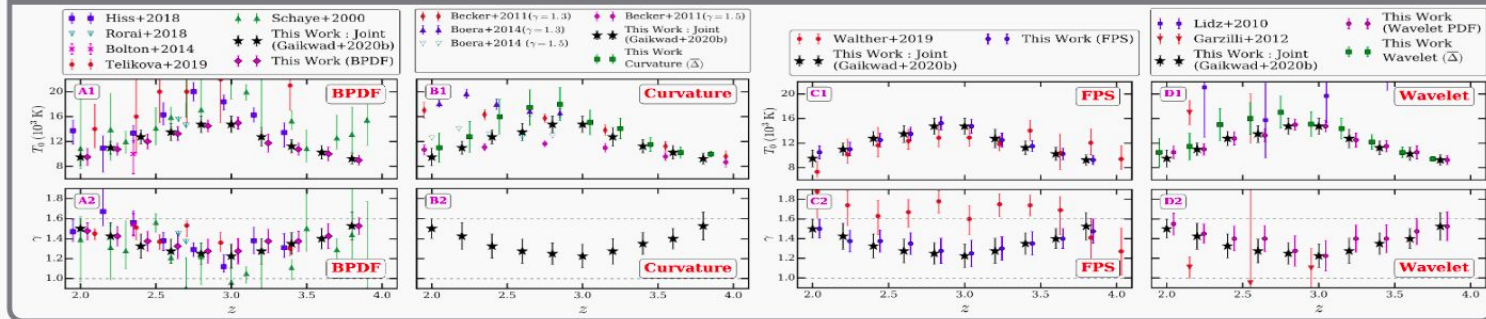


Neutrino Mass (Yeche+2017)

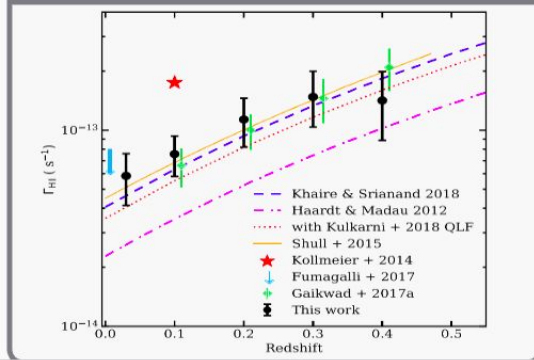


Lyman- α forest: Astrophysical Utility

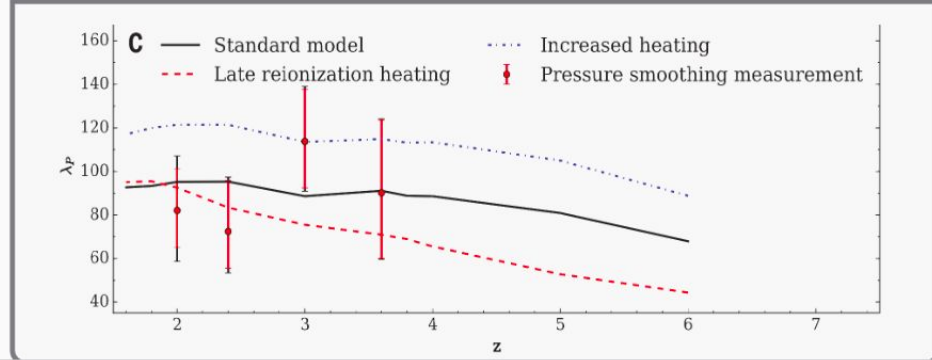
IGM Thermal Evolution (Gaikwad+2020)



UV Background (Khaire+2019)



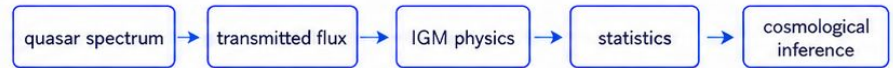
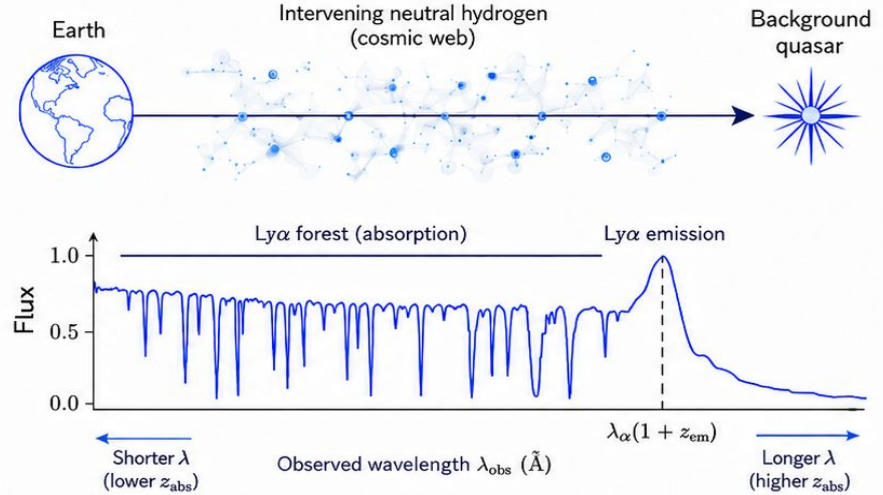
Pressure broadening scale: Sensitive to thermal history (Rorai+2017)



Take-home messages: Ly α forest in cosmology

A one-dimensional probe of the cosmic web

- 1 A background quasar provides bright light that passes through intervening neutral hydrogen.
- 2 Absorption at the Ly α transition ($\lambda = 1215.67 \text{ \AA}$) imprints a series of features blueward of the quasar's Ly α emission line.
- 3 Observed wavelength maps to absorber redshift:
 $\lambda_{\text{obs}} = \lambda_{\alpha}(1 + z_{\text{abs}})$.
- 4 The transmitted flux is $F = F_{\text{obs}}/F_{\text{cont}} = \exp(-\tau_{\text{HI}})$.
- 5 The optical depth depends on density Δ , temperature T , photoionization rate Γ_{HI} , and peculiar velocity v_{pec} .
- 6 Many quasar sightlines together provide flux statistics and constraints on the IGM, the cosmic web, and cosmology.



The Ly α forest is a sparse but powerful map of the cosmic web: each quasar spectrum is a 1D skewer through the intergalactic medium, and many such skewers become a statistical probe of structure formation.