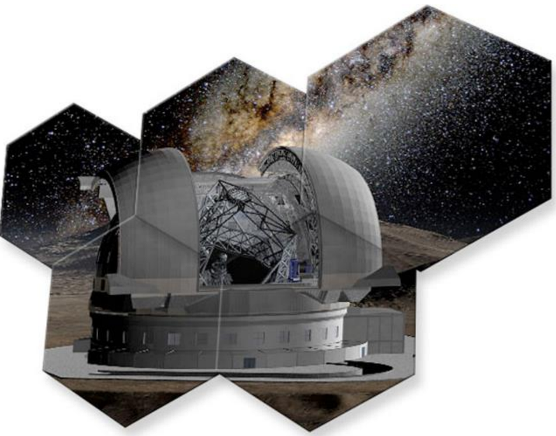
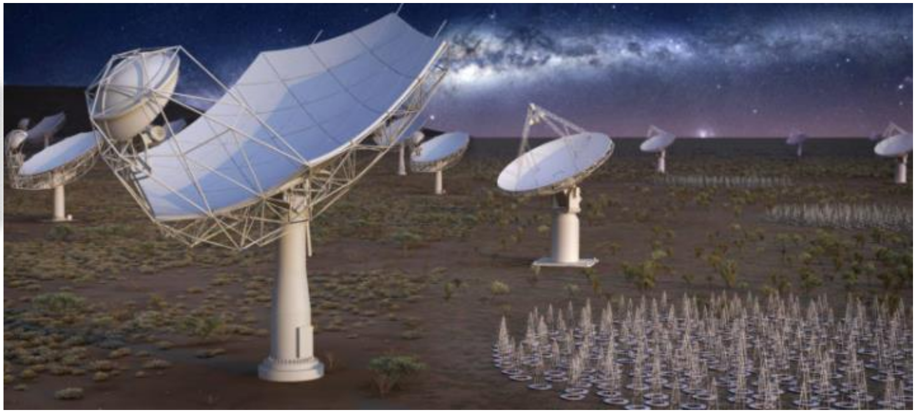
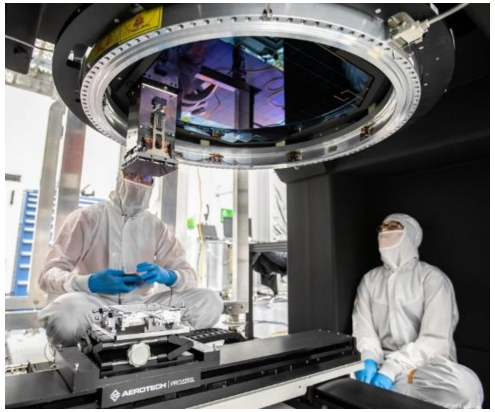
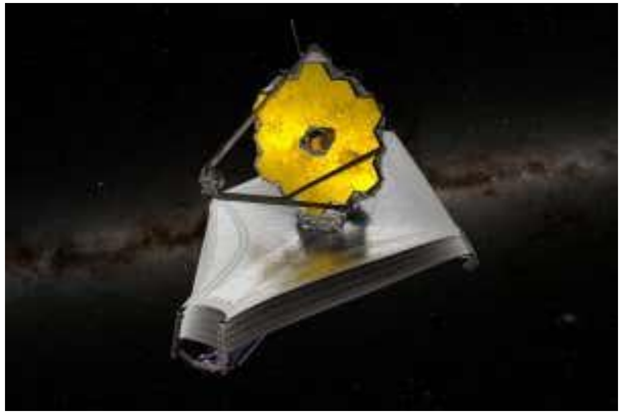
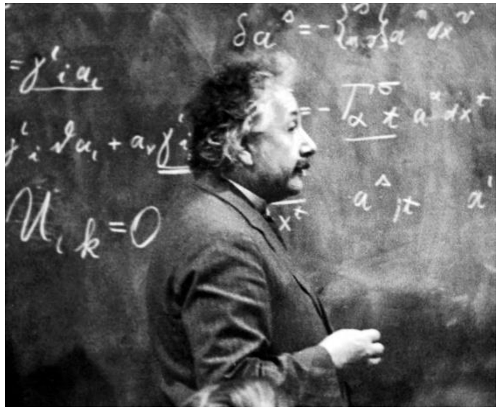
Large scale structure and physics of matter

Stefano Cristiani


INAF

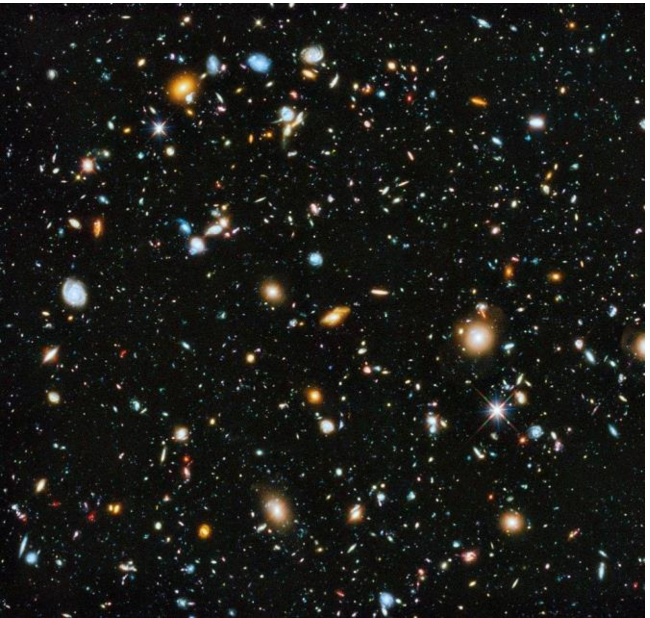
8. Formation and Evolution of Galaxies and Cosmic Structures

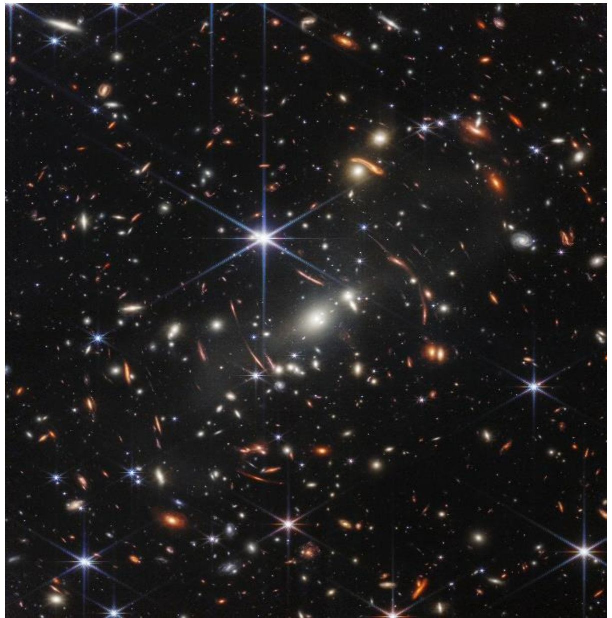
Keywords: Galaxies and AGN, Clusters of Galaxies, IGM and reionization

Key Question:

What are the physical processes driving the assembly and the evolution of structures on scales of galaxies up to clusters of galaxies?

- **Properties of first galaxies and black holes. Sources responsible for the reionization(s)**
- **Origin and fate of galaxies, the galaxy stellar mass function and morphological differentiation.**
- **Feedback processes among the different components of galaxies (stars, gas, dust) and AGN. Role of DM halos.**
- **External and internal mechanisms (environment and relationship with the Cosmic Web) regulating the efficiency of star formation and the structural parameters of galaxies.**
- **Census and distribution of mass/energy in large-scale structures (hot baryons, AGN-ICM connection, turbulence, non-thermal phenomena and their relationship with the thermal phenomena mapped in X-ray and with the Sunyaev-Zeldovich effect).**



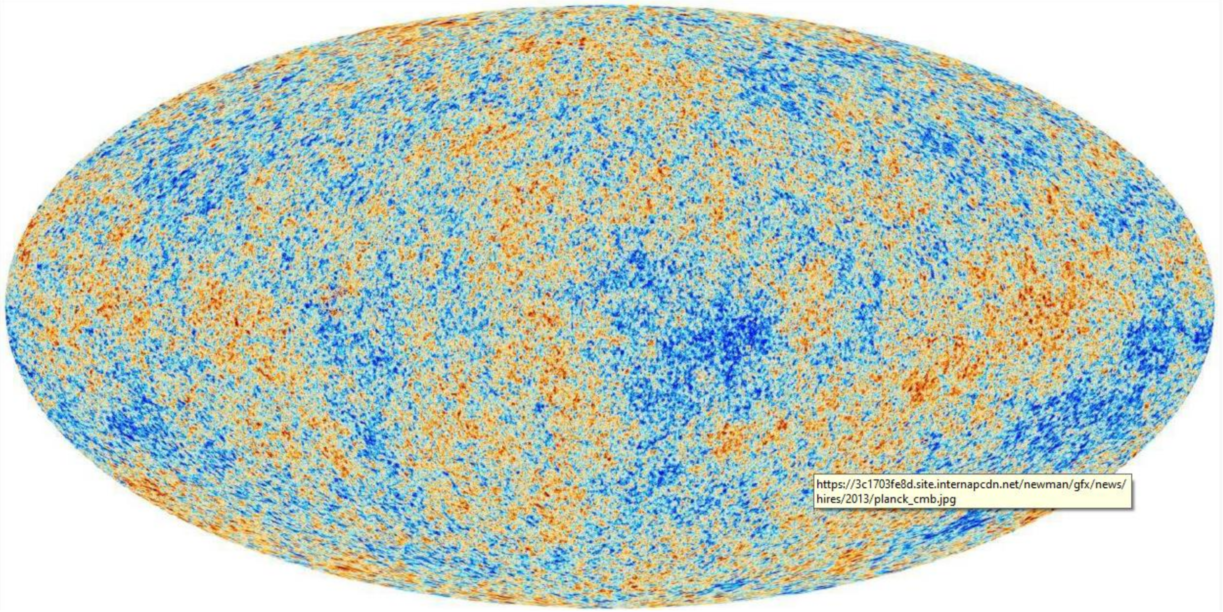


9 Cosmology and Fundamental Physics

Keywords: Geometry of the Universe, Cosmological parameters, Dark Matter, Dark Energy, Fundamental Physics.

Key questions:

- **The nature of Dark Matter**
- **The nature of Dark Energy**
- **Understanding gravity on large cosmological scales**
- **Initial conditions of Cosmology**
- **Fundamental interactions and constants of Physics**
- **The cosmic distance ladder and the Hubble constant debate**



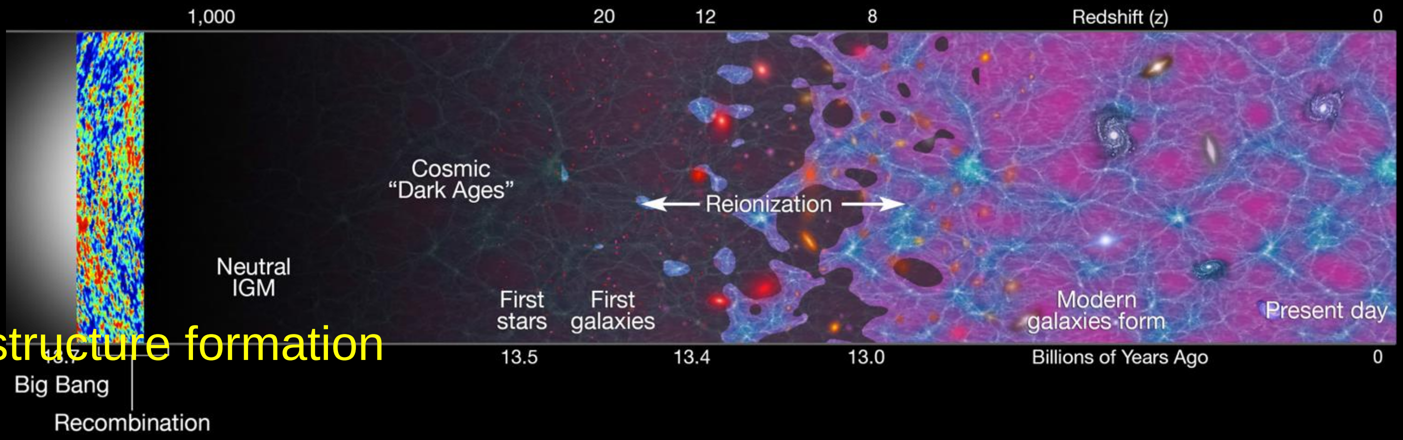
https://3c1703fe8d.site.internapcdn.net/newman/gfx/news/hires/2013/planck_cmb.jpg

The structures populating the Universe are the result of the growth of fluctuations of the primordial density distribution: while the backbone of the large scale structure of the Universe is determined by its cosmological parameters and by the gravitational interaction of the dominant dark matter, **the assembly and the evolution of structures on scales of galaxies and up to cluster of galaxies** are mainly **driven and strongly affected by the complex physics of baryons**. The challenge of the next decade will be **understanding these processes through the comparison of multi-wavelength observations with theoretical models and simulations**…

DVS 2019

How did the intergalactic medium and the first sources of radiation evolve from cosmic dawn through the epoch of reionization?

Cosmic Reionization



The last phase transition

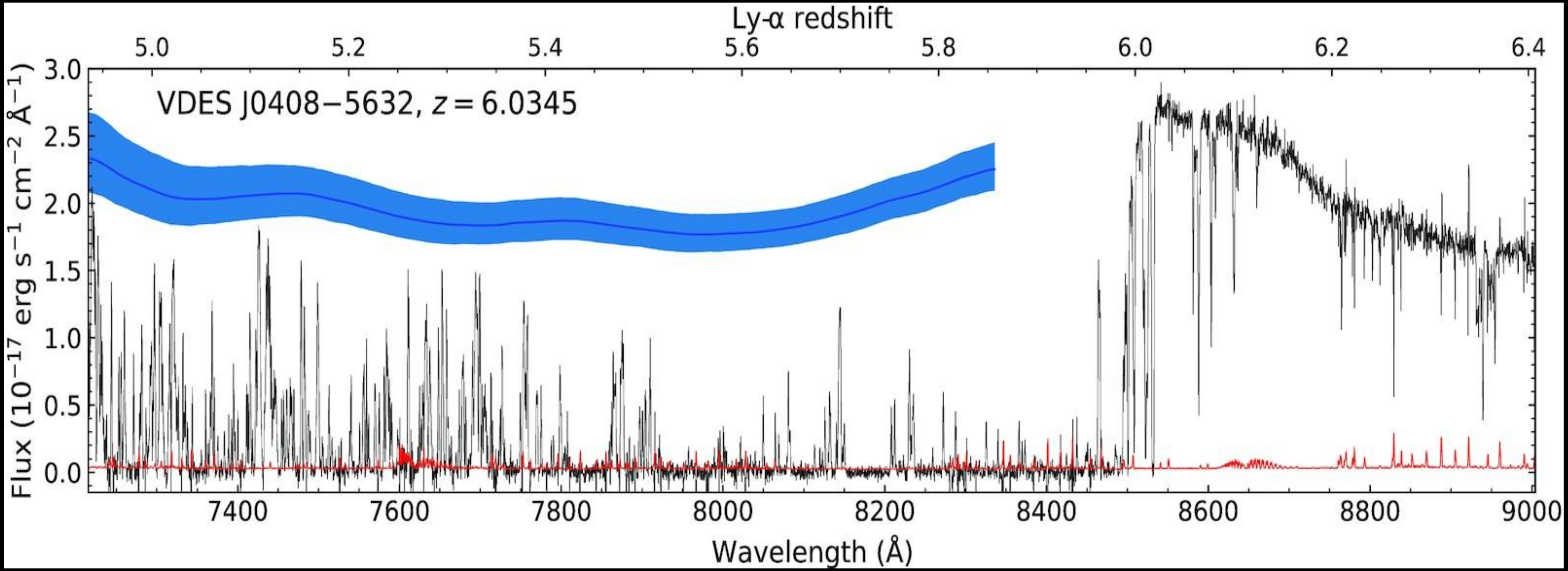
Result of structure formation AND feedback on structure formation

After > 50 yr still not settled

nature of the first sources of UV radiation, how they interacted with their environment,

back-reaction of reionization on infant galaxies, imprint on their luminosity function, gas content

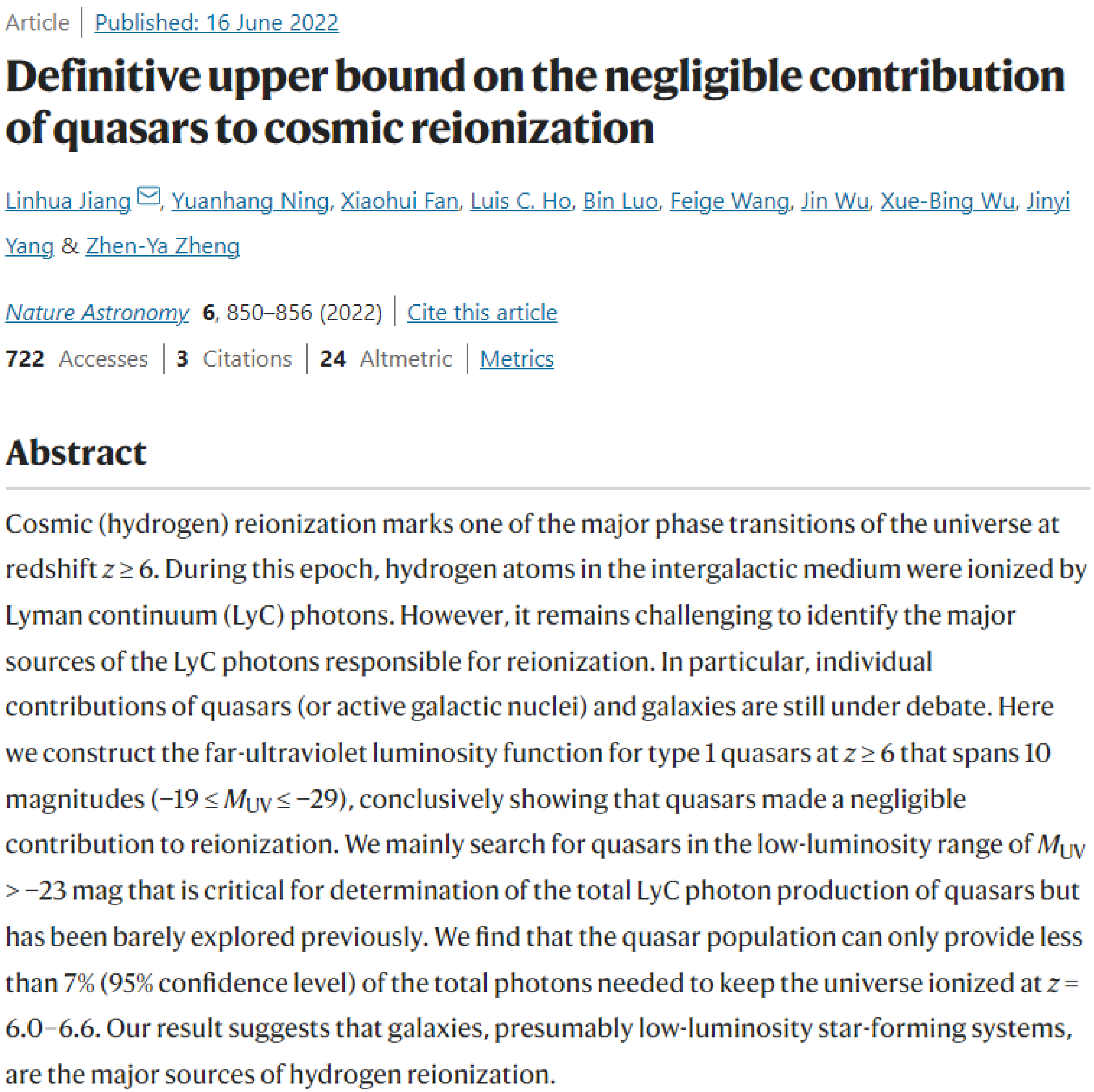
impact of patchy reionization on observables, thermodynamics of primordial baryonic gas, **all highly uncertain**



Bosman+2022

XQR-30

D'Ododorico+



Article | Published: 16 June 2022

Definitive upper bound on the negligible contribution of quasars to cosmic reionization

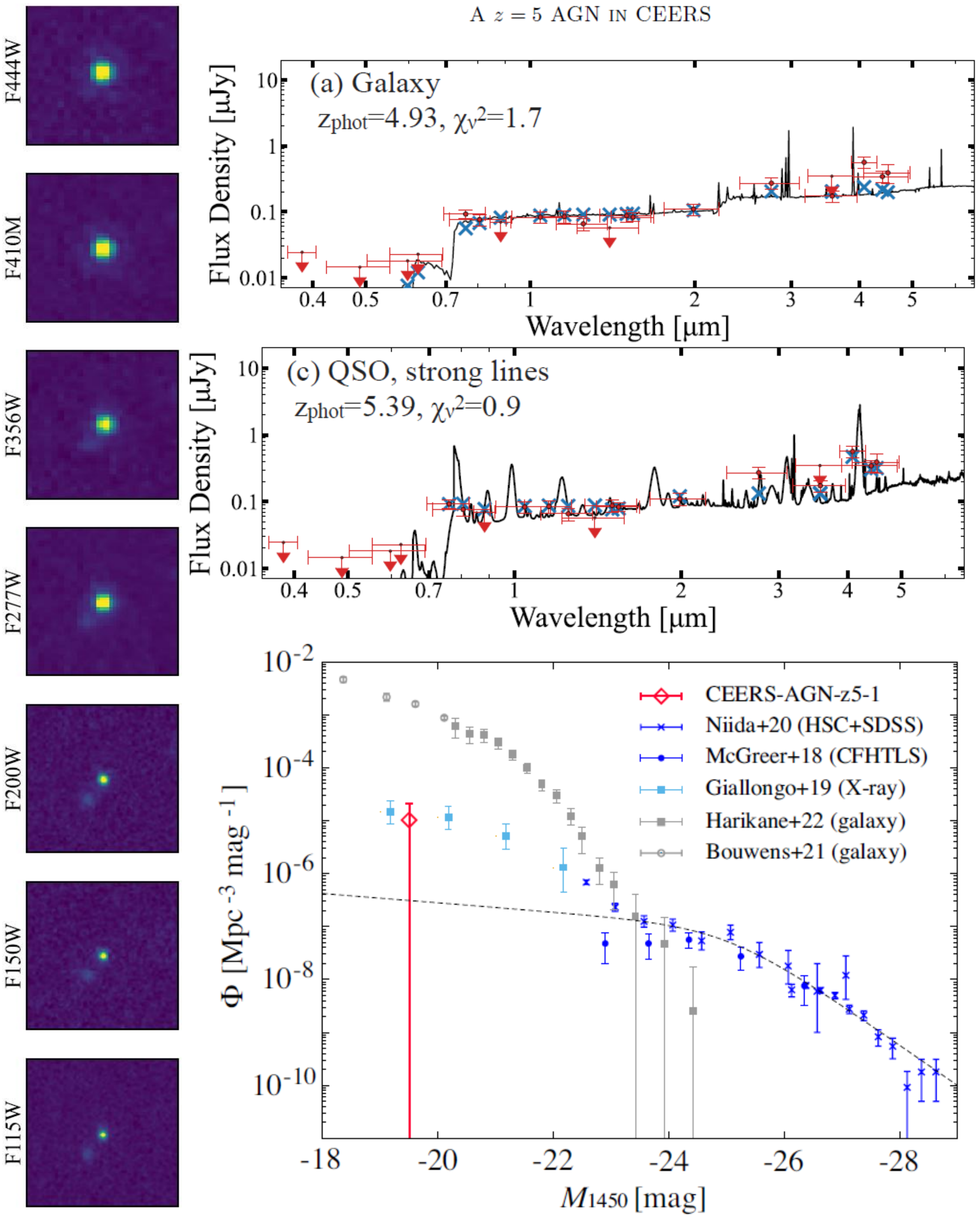
Linhua Jiang, Yuanhang Ning, Xiaohui Fan, Luis C. Ho, Bin Luo, Feige Wang, Jin Wu, Xue-Bing Wu, Jinyi Yang & Zhen-Ya Zheng

Nature Astronomy **6**, 850–856 (2022) | Cite this article

722 Accesses | **3** Citations | **24** Altmetric | Metrics

Abstract

Cosmic (hydrogen) reionization marks one of the major phase transitions of the universe at redshift $z \geq 6$. During this epoch, hydrogen atoms in the intergalactic medium were ionized by Lyman continuum (LyC) photons. However, it remains challenging to identify the major sources of the LyC photons responsible for reionization. In particular, individual contributions of quasars (or active galactic nuclei) and galaxies are still under debate. Here we construct the far-ultraviolet luminosity function for type 1 quasars at $z \geq 6$ that spans 10 magnitudes ($-19 \leq M_{\mathrm{UV}} \leq -29$), conclusively showing that quasars made a negligible contribution to reionization. We mainly search for quasars in the low-luminosity range of $M_{\mathrm{UV}} > -23$ mag that is critical for determination of the total LyC photon production of quasars but has been barely explored previously. We find that the quasar population can only provide less than 7% (95% confidence level) of the total photons needed to keep the universe ionized at $z = 6.0$–6.6. Our result suggests that galaxies, presumably low-luminosity star-forming systems, are the major sources of hydrogen reionization.



Onoue+2209.07325

Cosmic reionization as a show case

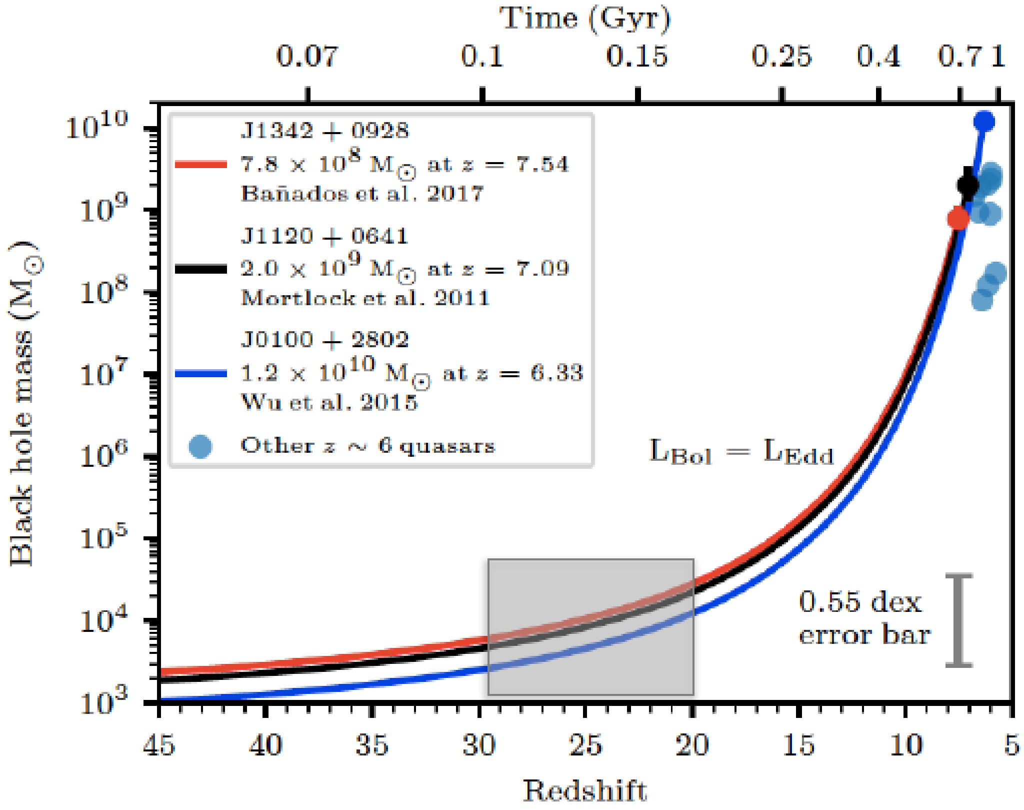
Despite a considerable community effort, many key aspects of this process, such as the very nature of the first sources of UV radiation, how they interacted with their environment, the back-reaction of reionization on infant galaxies and its imprint on their luminosity function and gas content, the impact of patchy reionization on observables, and the thermodynamics of primordial baryonic gas, all remain highly uncertain.

Even a complete knowledge of the sources and sinks of UV and X-ray light in the early Universe, which astrophysicists by no means possess, would not automatically translate into a detailed understanding of the reionization process as a whole, as this ultimately requires extremely challenging cosmological numerical simulations that self-consistently couple all the relevant physical processes dark matter dynamics, gas dynamics, self-gravity, star formation/feedback, radiative transfer, non-equilibrium ionizations and recombinations, chemical enrichment, heating and cooling over a huge range of scales.

Gnedin & Madau 2208.02260

how do supermassive black holes grow in less than 1 Gyr?

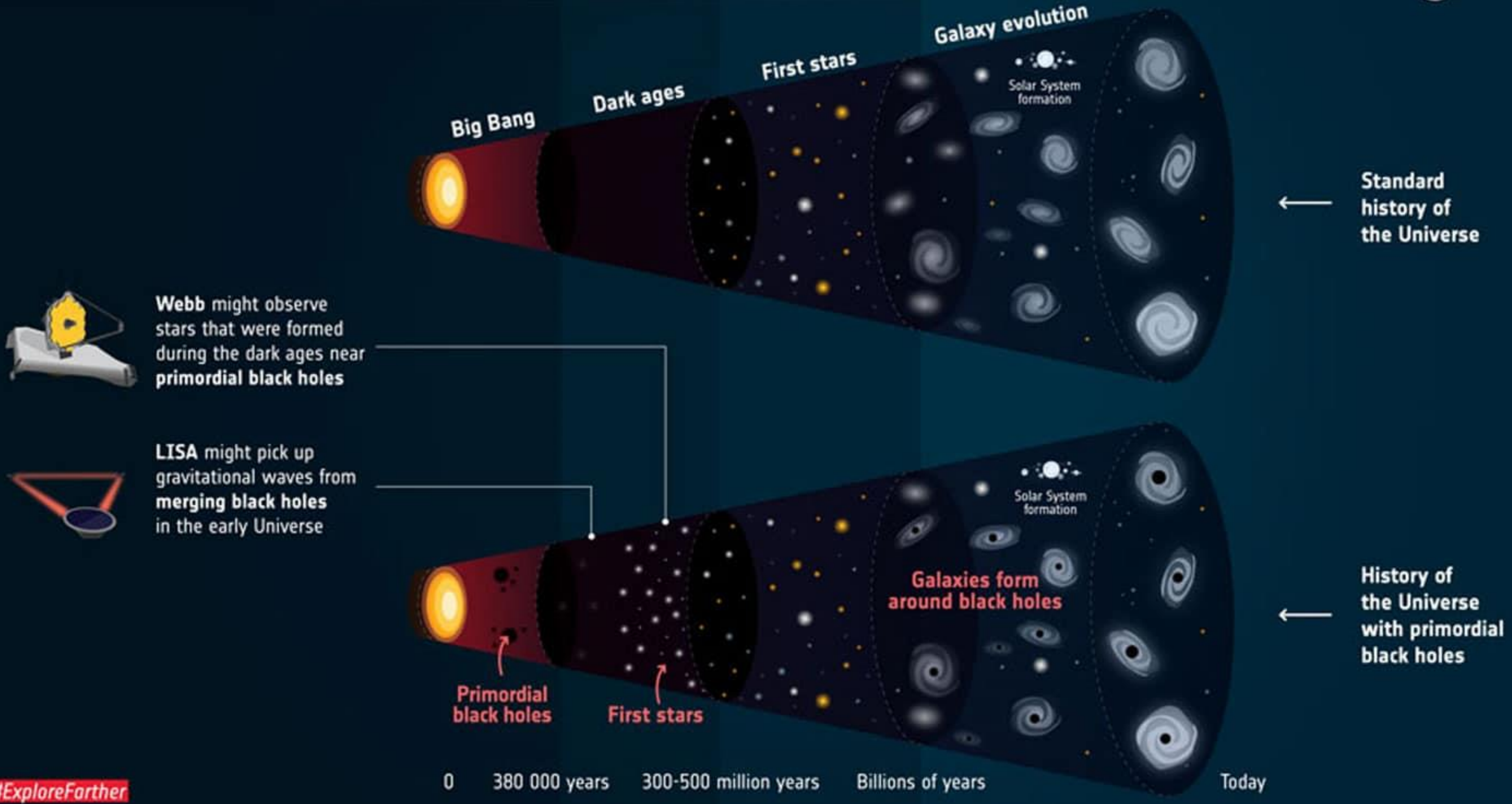
$M_{SMBH}(t) = M_{seed}(t_{form})\ e^{[(1-\varepsilon)/\varepsilon]\Delta t/tEdd}$ $\varepsilon = 0.1$ $t_{Edd} = 0.45$ Gyr



Banados et al. 2018

models of SMBH growth require massive seeds (> 10^3 - 10^5 M_{sun}) and/or episodes of super-Eddington accretion

DID BLACK HOLES FORM IMMEDIATELY AFTER THE BIG BANG?

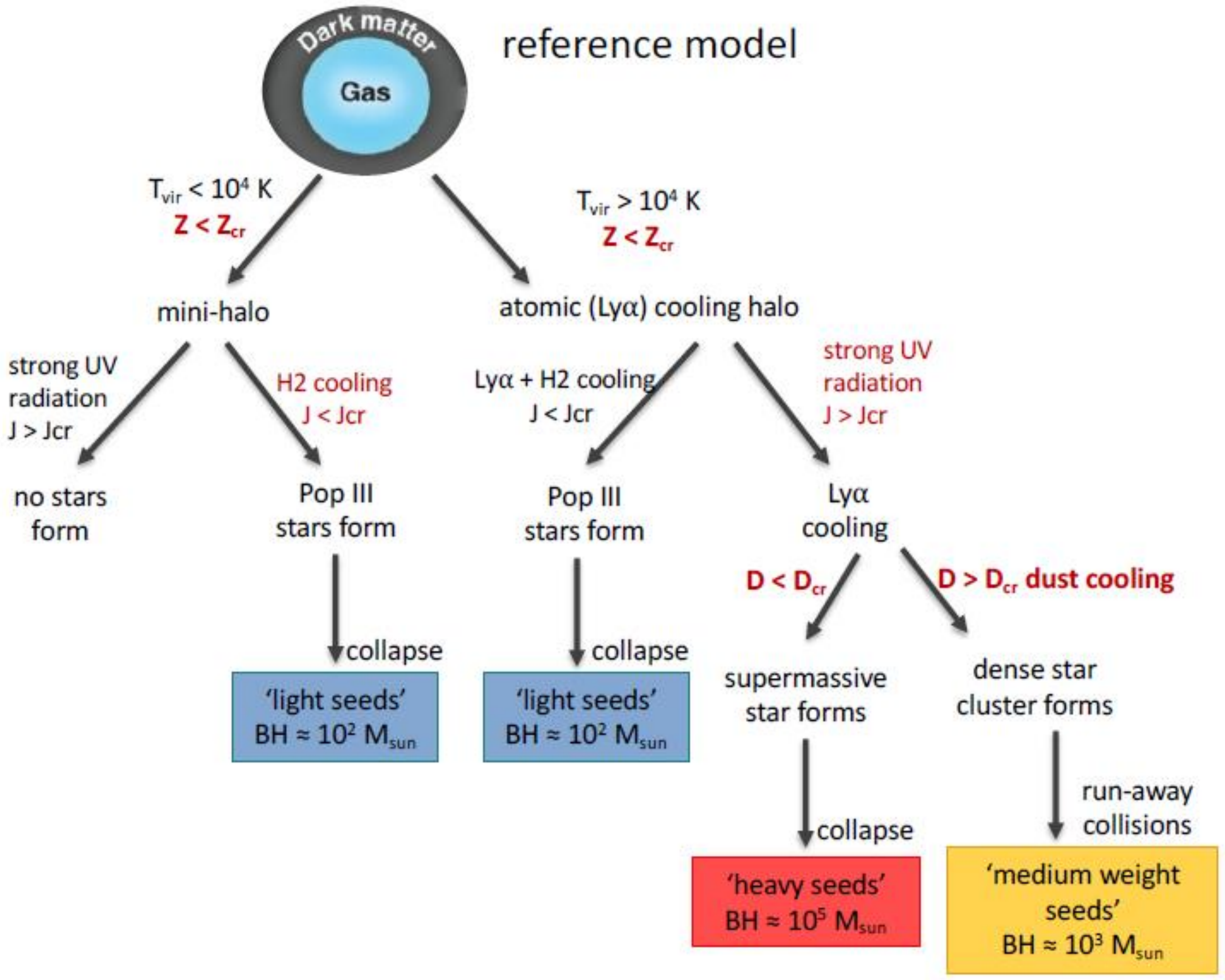


Webb might observe stars that were formed during the dark ages near **primordial black holes**

LISA might pick up gravitational waves from **merging black holes** in the early Universe

#ExploreFarther

conditions to form massive objects: **inefficient gas cooling (fragmentation)** and efficient gas accretion



reference model

$T_{vir} < 10^4$ K
$Z < Z_{cr}$

mini-halo

strong UV radiation $J > J_{cr}$

no stars form

H2 cooling $J < J_{cr}$

Pop III stars form

collapse

'light seeds'
BH ≈ 10^2 M_{sun}

$T_{vir} > 10^4$ K
$Z < Z_{cr}$

atomic (Lyα) cooling halo

Lyα + H2 cooling $J < J_{cr}$

Pop III stars form

collapse

'light seeds'
BH ≈ 10^2 M_{sun}

strong UV radiation $J > J_{cr}$

Lyα cooling

$D < D_{cr}$

supermassive star forms

collapse

'heavy seeds'
BH ≈ 10^5 M_{sun}

$D > D_{cr}$ dust cooling

dense star cluster forms

run-away collisions

'medium weight seeds'
BH ≈ 10^3 M_{sun}

Lynx

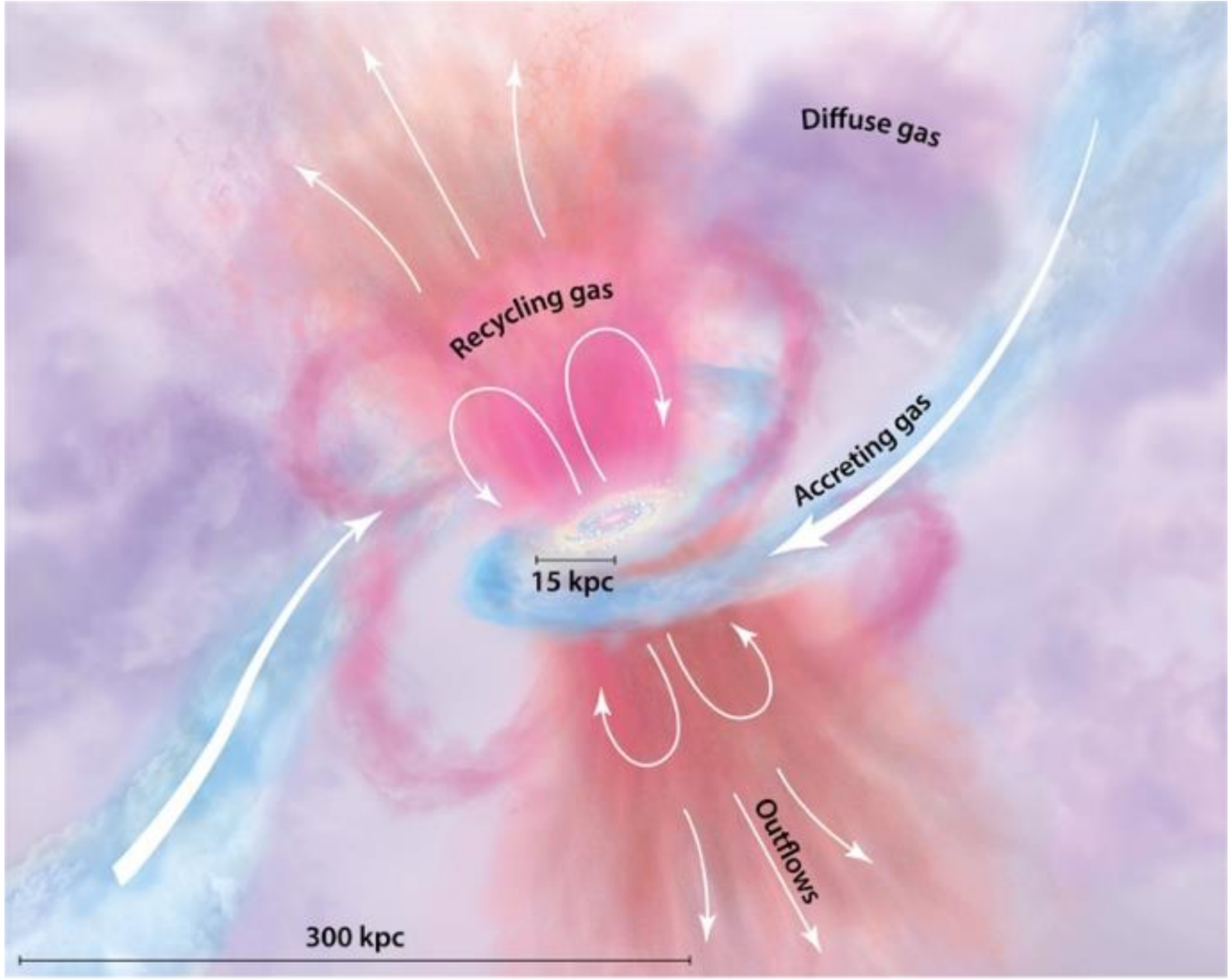
Athena ?

Sassano, RS+2021

Courtesy of R.Schneider

How do supermassive black holes form and how is their growth coupled to the evolution of their host galaxies?

Cosmic Ecosystem - circumgalactic medium



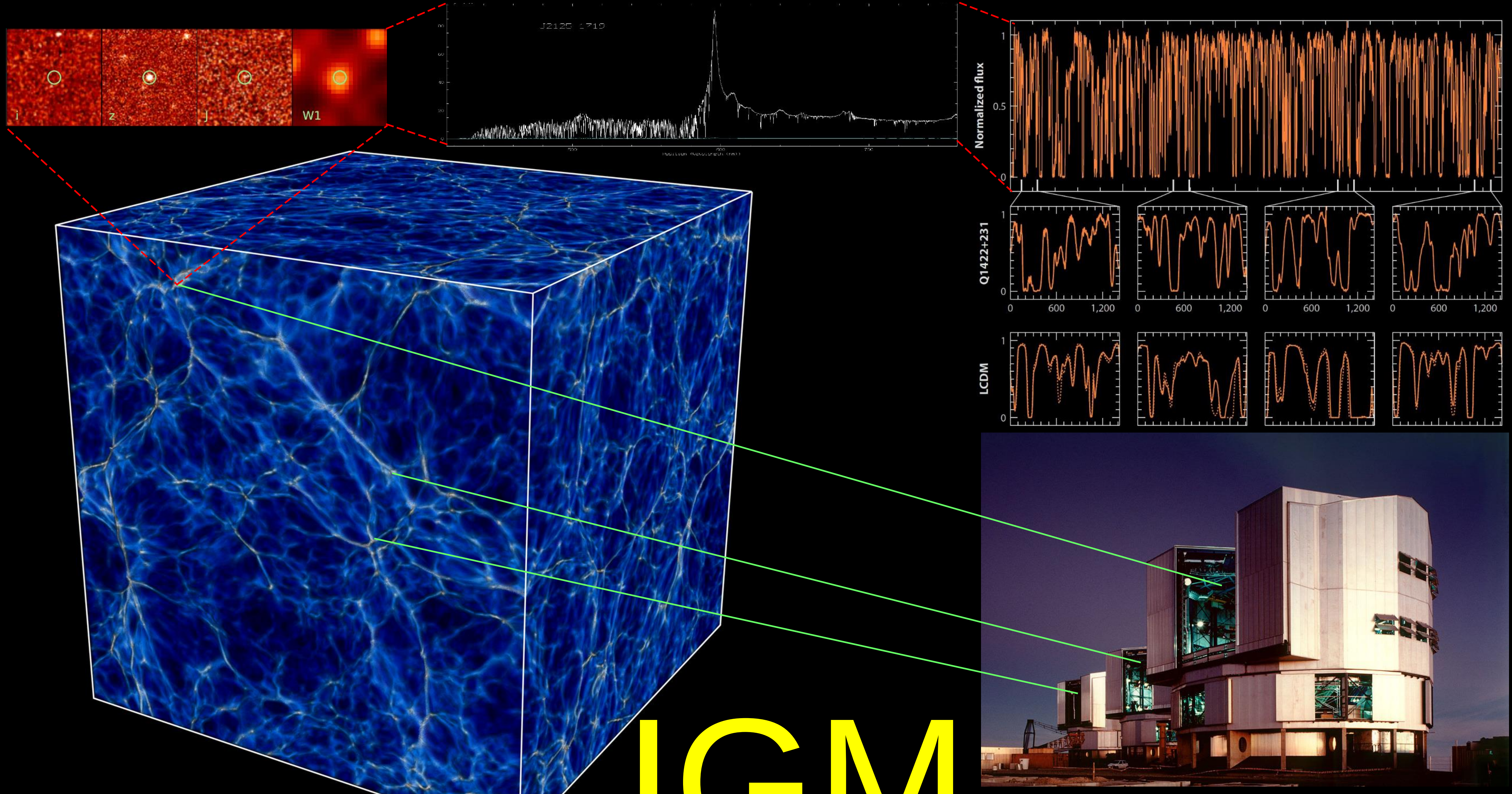
Tumlinson J, et al. 2017.
Annu. Rev. Astron. Astrophys. 55:389-432

Link to the IGM

Measure the properties of the diffuse gas within, surrounding, and between galaxies. Sites where baryons accrete on to galaxies, star formation is triggered, central black holes accrete and grow, and the feedback processes regulating galaxy growth are manifested. The key observational probes of all of these processes are emission and absorption-line **spectroscopy** of the diffuse gas, which contain a wealth of diagnostic information on the physical conditions, compositions, and dynamics of the gas. Current telescopes are only capable of probing the densest regions in emission and occasional single sightlines through rare galaxies which happen to be superimposed in front of a bright quasar.

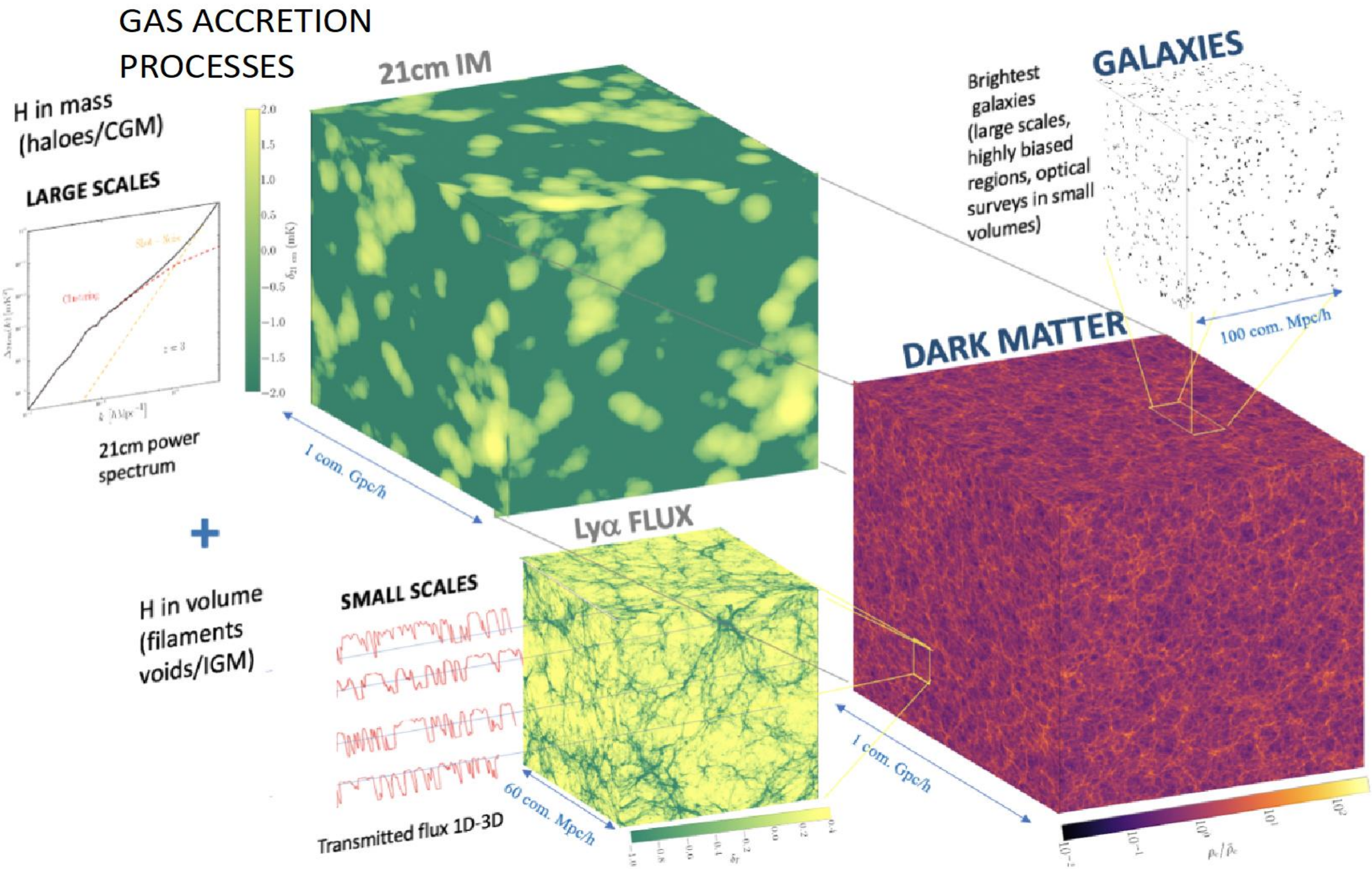
JWST, ALMA, NOEMA, ELT, Euclid…
VRO, Roman, SKA, ATHENA?

How do gas, metals, and dust flow into, through, and out of galaxies?


i
z
J
W1
J2125 1719
Normalized flux
1
0.5
0
Q1422+231
0
600
1,200
LCDM

IGM

A comprehensive view of the Universe



The (simple) physics of the Cosmic Web

~90 % of the baryons at z=3 are in the IGM (Lyman-α forest)

neutral hydrogen (HI) is determined by ionization balance between recombination of e and p and HI ionization from UV photons

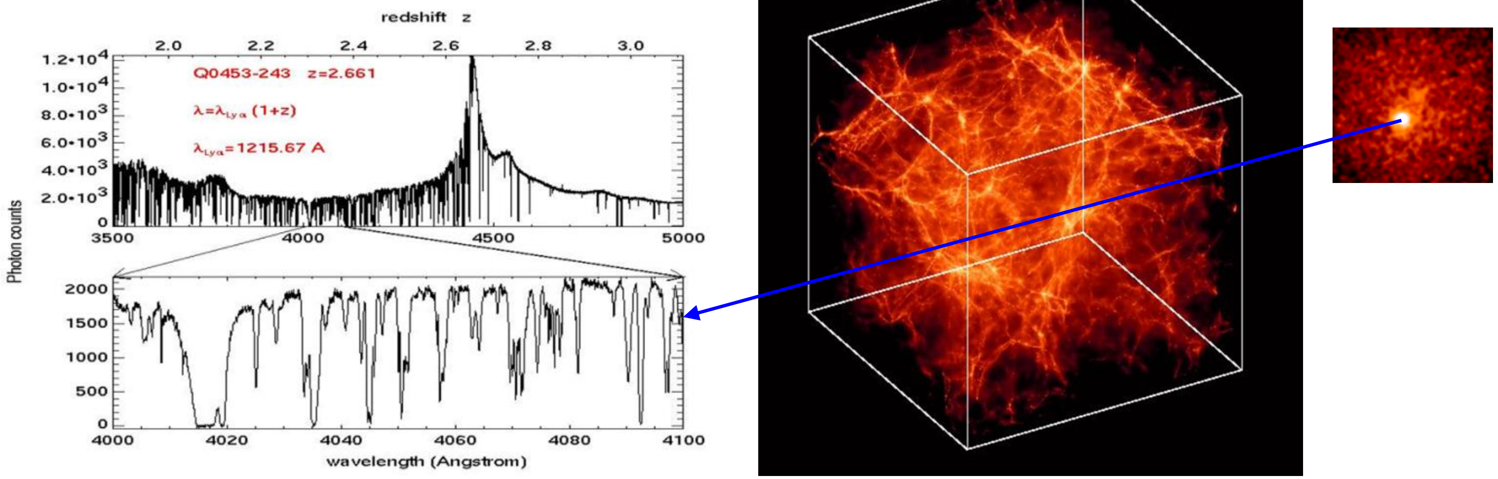
Recombination coefficient depends on T(gas)

$$\rho_{HI} \propto \rho_{gas}^{2}$$

Neutral hydrogen traces overall gas distribution, which traces dark matter on large scales, with additional pressure effects on small scales

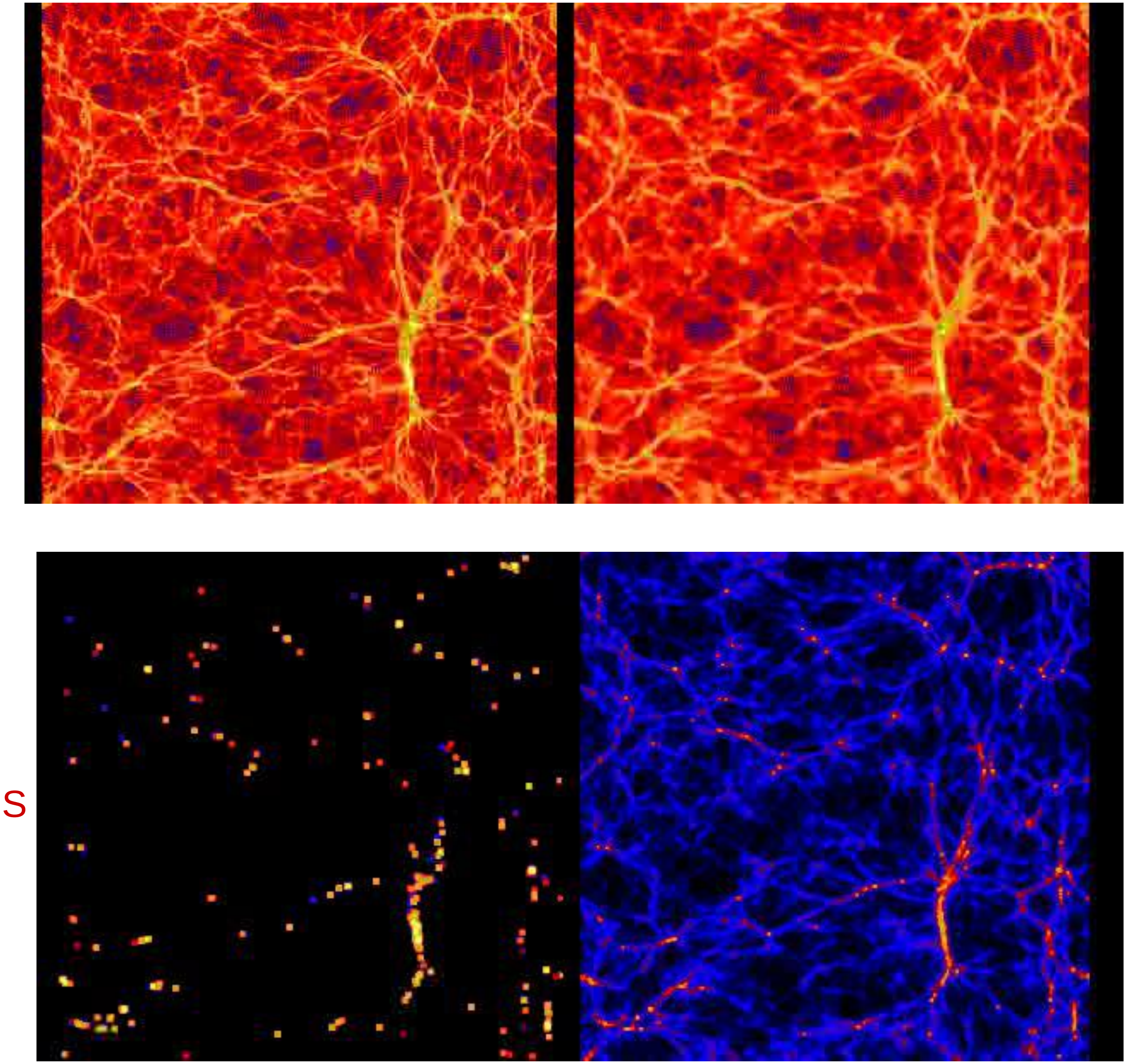
Density and temperature are correlated, modeled as a power law with slope γ and amplitude To

$$T = T_0 (1+\delta)^{\gamma}$$



$\Omega_m = 0.26$ $\Omega_\Lambda = 0.74$ $\Omega_b = 0.0463$ H = 72 km/sec/Mpc - 60 Mpc/h

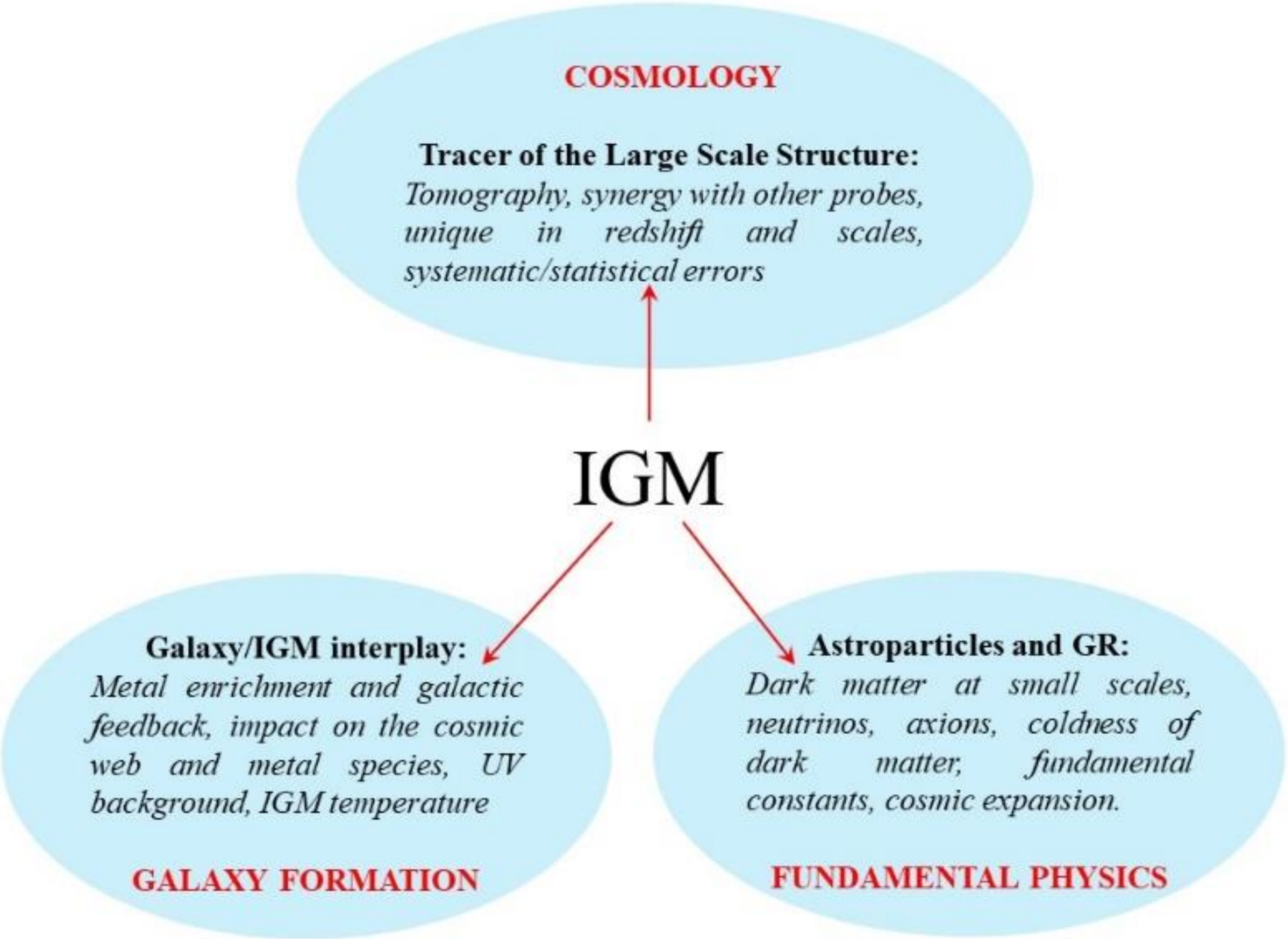
COSMOS computer – DAMTP (Cambridge)



$\delta_{IGM} \sim \delta_{DM}$ at scales larger than the Jeans length ~ 1 com Mpc

flux = $\exp(-\tau) \sim \exp[-(\delta_{IGM})^{1.6}\, T^{-0.7}]$

Courtesy M.Viel



COSMOLOGY

Tracer of the Large Scale Structure:
Tomography, synergy with other probes, unique in redshift and scales, systematic/statistical errors

IGM

Galaxy/IGM interplay:
Metal enrichment and galactic feedback, impact on the cosmic web and metal species, UV background, IGM temperature

GALAXY FORMATION

Astroparticles and GR:
Dark matter at small scales, neutrinos, axions, coldness of dark matter, fundamental constants, cosmic expansion.

FUNDAMENTAL PHYSICS

IGM - Absorption Lines – Why?

What were the physical conditions of the primordial Universe?

What fraction of the matter was in a diffuse medium and how early did it condense in clouds?

Where are most of the baryons at the various redshifts?

How early and in what amount have metals been produced?

Which constraints on cosmology & types of DM (e.g. ν) are derived from the IGM LSS?

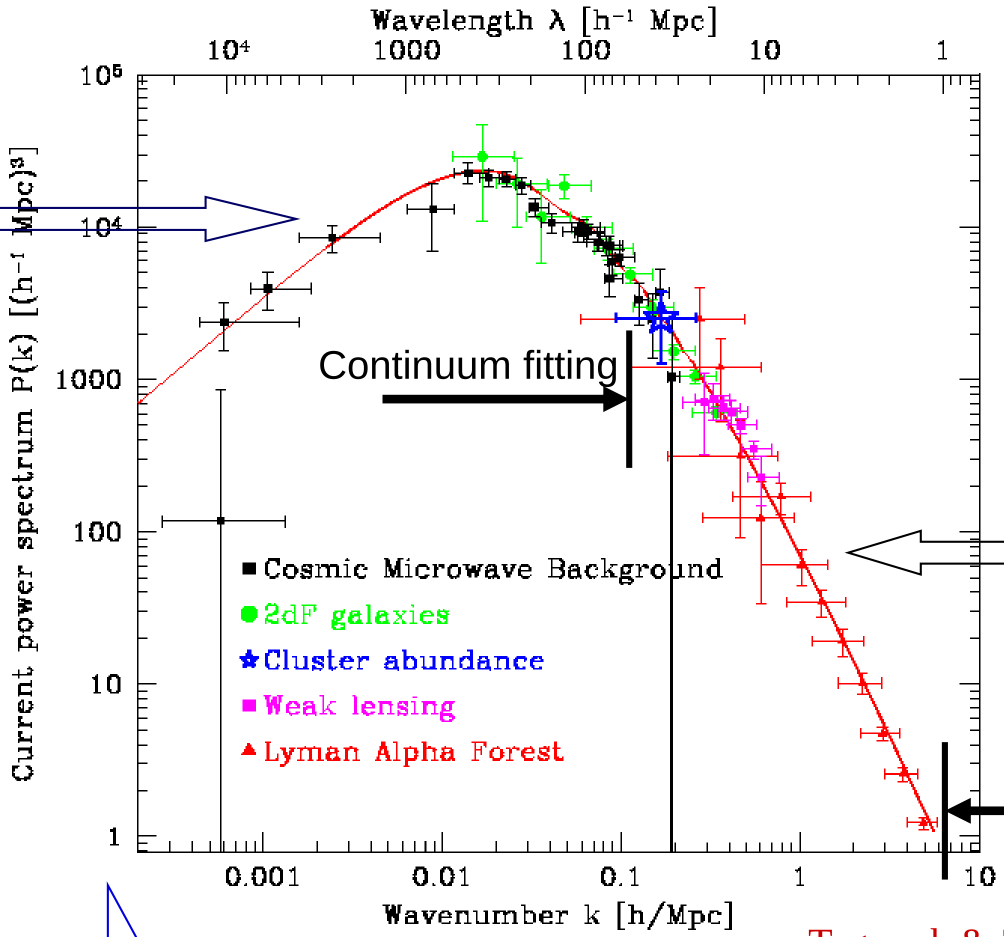
What was the typical radiation field, how homogenous, and what was producing it?

When and how, after the Dark Ages following recombination, did the Universe get reionized?

Does the SBBN correctly predict primordial element abundances and CMB T evolution?

Do fundamental constants of physics (e.g. α, μ) vary with time?

The primordial dark matter power spectrum



CMB physics
z = 1100
dynamics

Continuum fitting

Lyα physics
z < 6
dynamics
+
termodynamics

Temperature, metals, noise

Tegmark & Zaldarriaga 2002

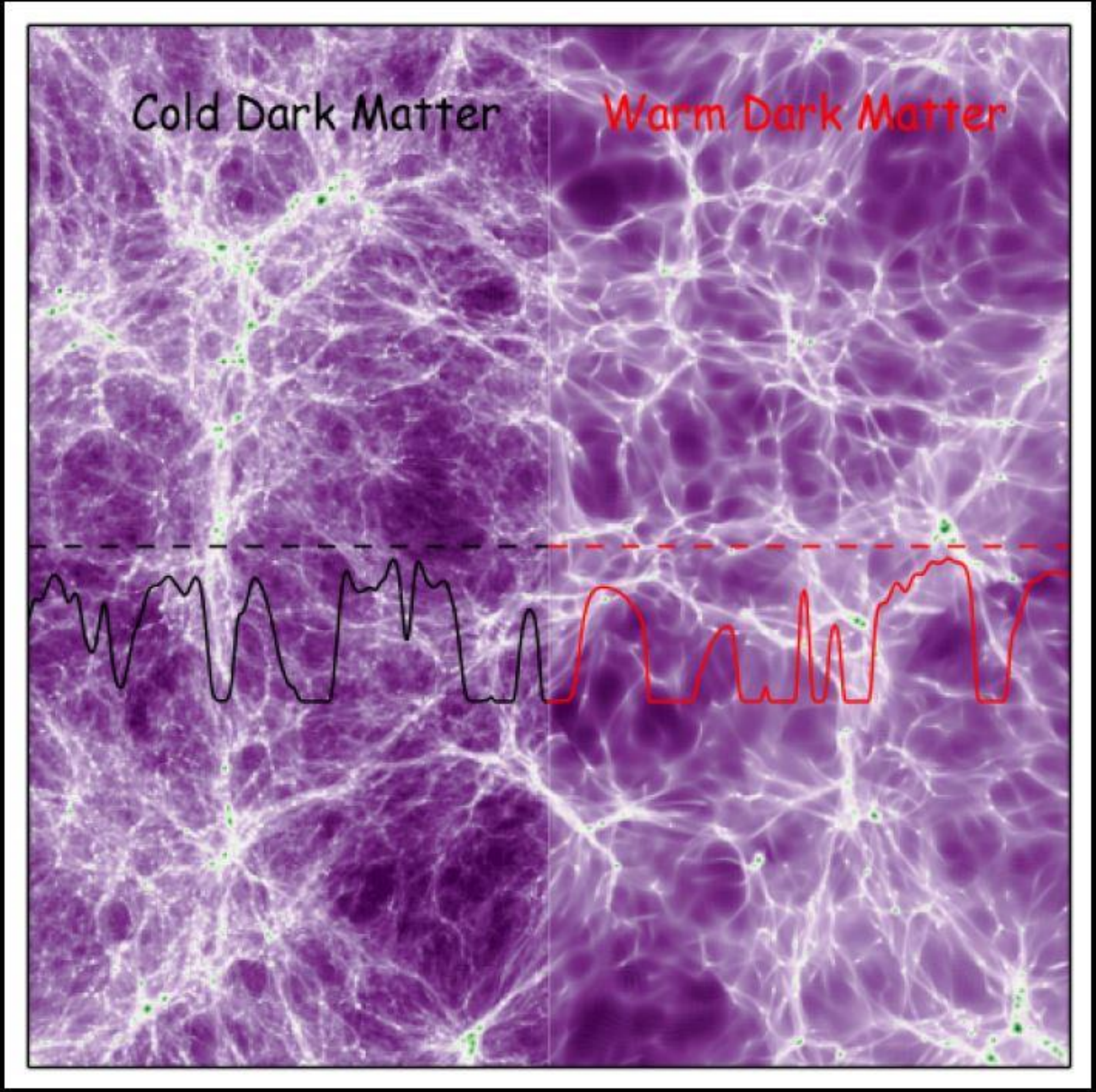
CMB + Lyman α

Long lever arm

Constrain spectral index and shape

Relation: P_{FLUX} (k) - P_{MATTER} (k)?

Non-CDM erases small scale structure



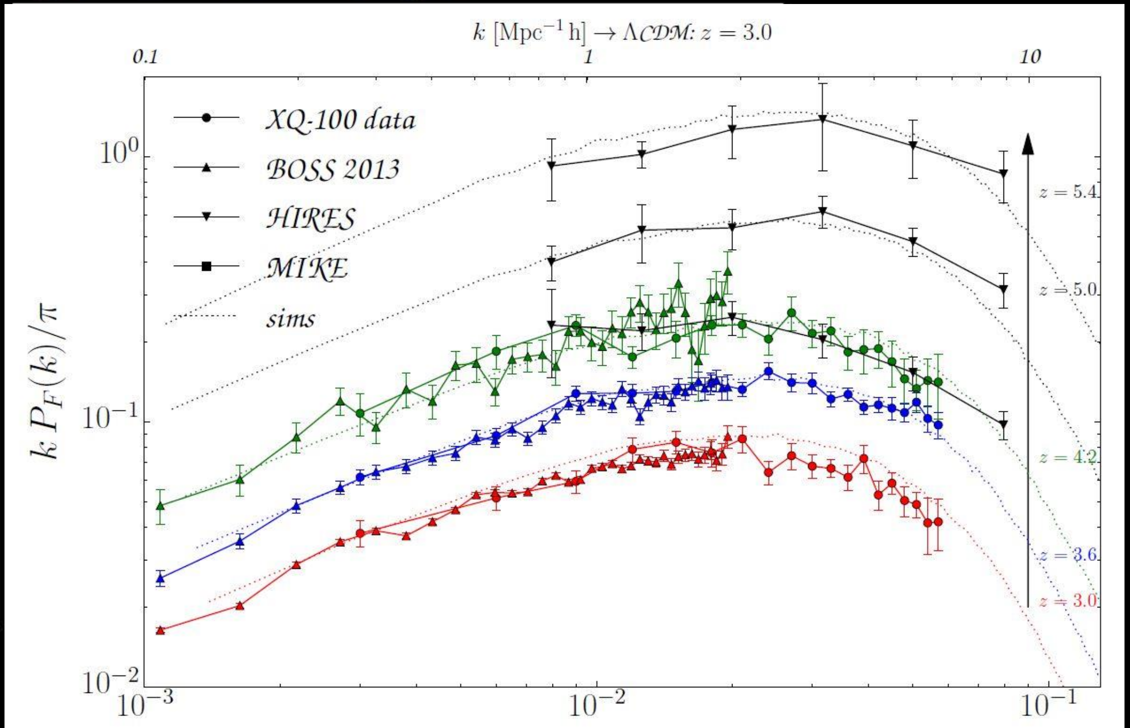
Credit: Vid Iršič

Warm Dark Matter (WDM):

Free-streaming of DM particles
(From the time they decouple
until they become non-relativistic)

$\Longrightarrow$ erases small scale structure

Typical $\lambda_{\mathrm{FS}} \sim \mathrm{Mpc/h}$



Lya forest robust cosmological probe to probe dynamics and geometry of the Universe

Parameter contraints on several non-CDM scenarios: thermal warm dark matter, ultra-light axions, DM-interacting with radiation etc.

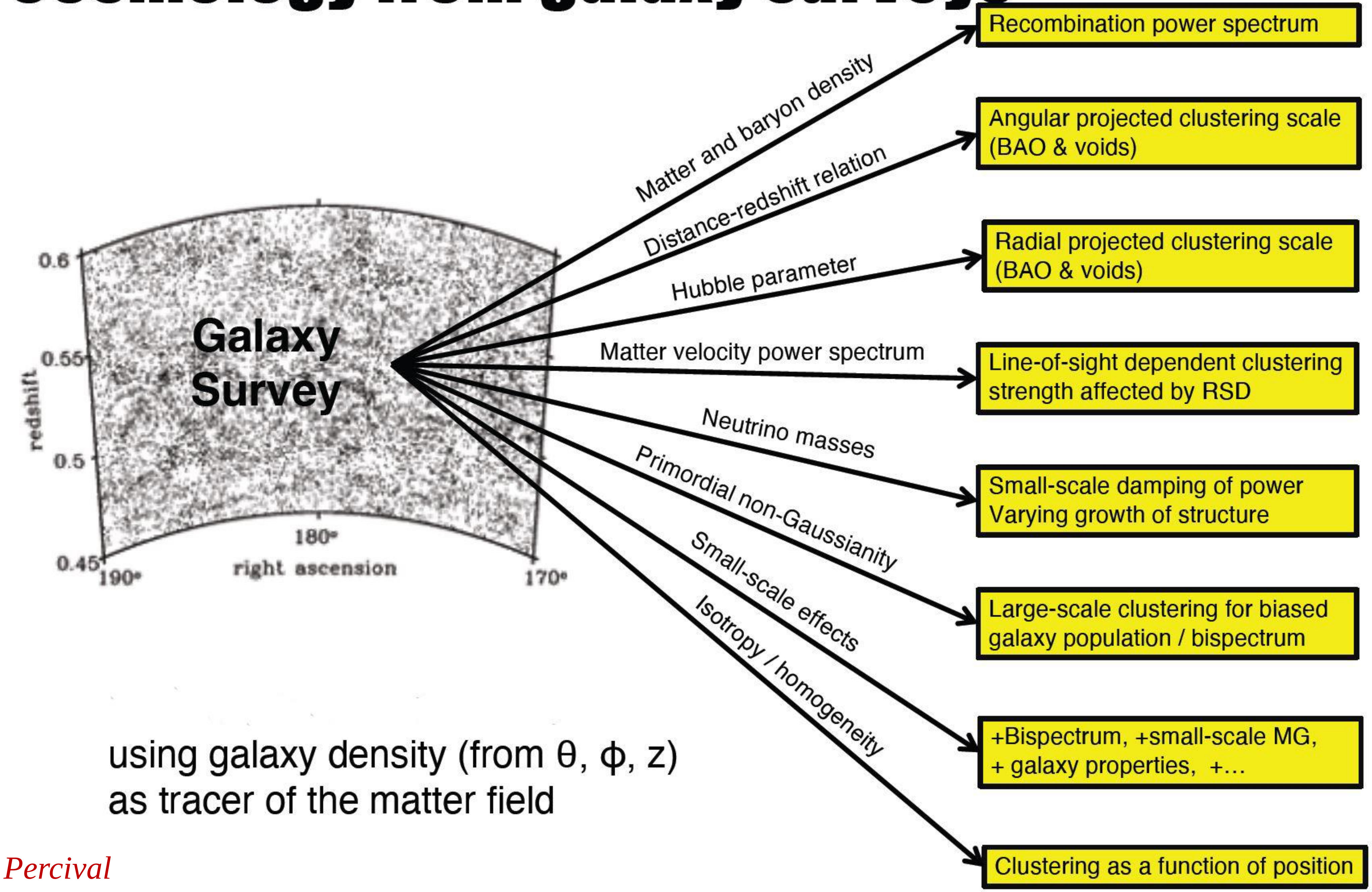
Mainly a small/medium scale physics probe, best exploited with ”anchors” at larger scales (e.g. CMB).

In plain LCDM models, constraints on neutrinos, shape/curvature of matter power spectrum, inflation, etc.

Ly-forest as a calorimeter, thermal history of the IGM as a dark matter detector (e.g. constraints on the dark photon models).

cf. M.Viel

Cosmology from galaxy surveys



Matter and baryon density → **Recombination power spectrum**

Distance-redshift relation → **Angular projected clustering scale (BAO & voids)**

Hubble parameter → **Radial projected clustering scale (BAO & voids)**

Matter velocity power spectrum → **Line-of-sight dependent clustering strength affected by RSD**

Neutrino masses → **Small-scale damping of power**
Varying growth of structure

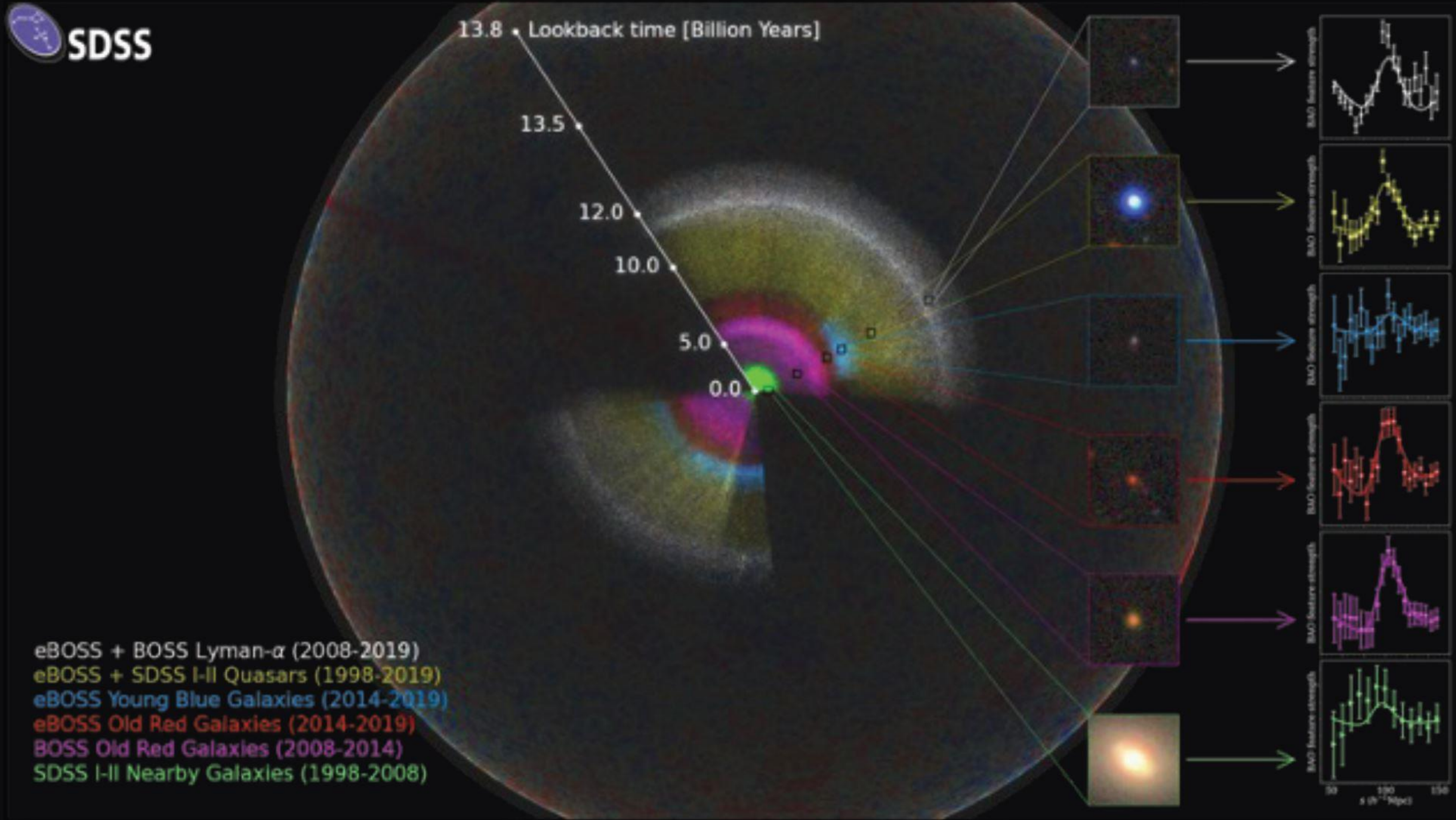
Primordial non-Gaussianity → **Large-scale clustering for biased galaxy population / bispectrum**

Small-scale effects → **+Bispectrum, +small-scale MG, + galaxy properties, +…**

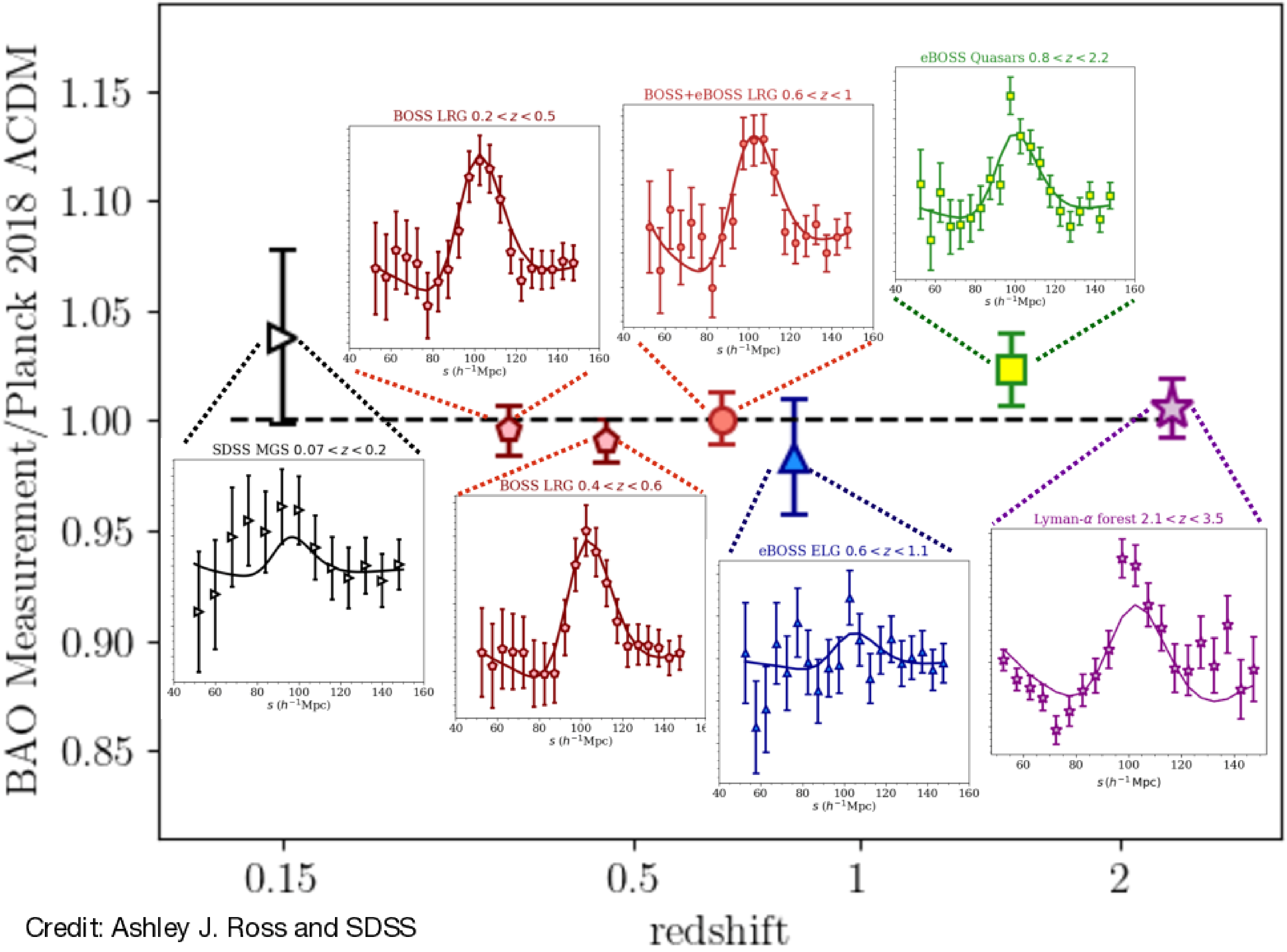
Isotropy / homogeneity → **Clustering as a function of position**

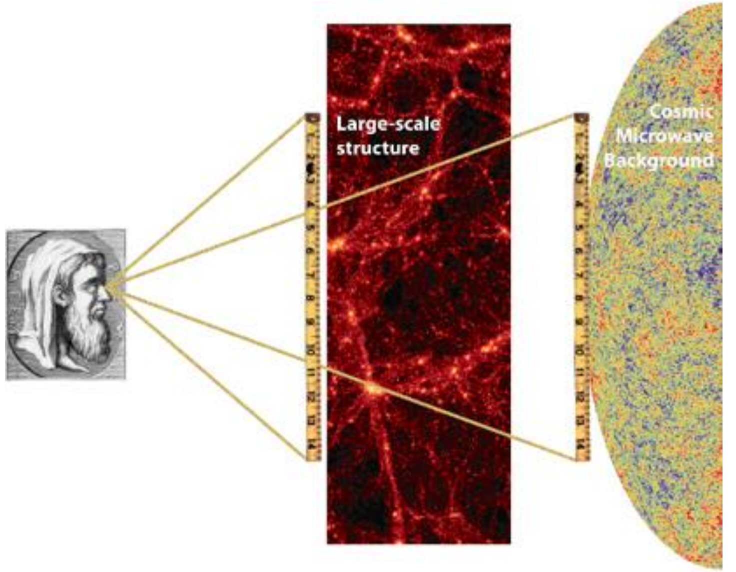
using galaxy density (from θ, ϕ, z)
as tracer of the matter field

Credit: Will Percival


SDSS
13.8 Lookback time [Billion Years]
13.5
12.0
10.0
5.0
0.0
eBOSS + BOSS Lyman-α (2008-2019)
eBOSS + SDSS I-II Quasars (1998-2019)
eBOSS Young Blue Galaxies (2014-2019)
eBOSS Old Red Galaxies (2014-2019)
BOSS Old Red Galaxies (2008-2014)
SDSS I-II Nearby Galaxies (1998-2008)
BAO feature strength
50
100
150
s (h⁻¹ Mpc)

SDSS BAO Distance Ladder

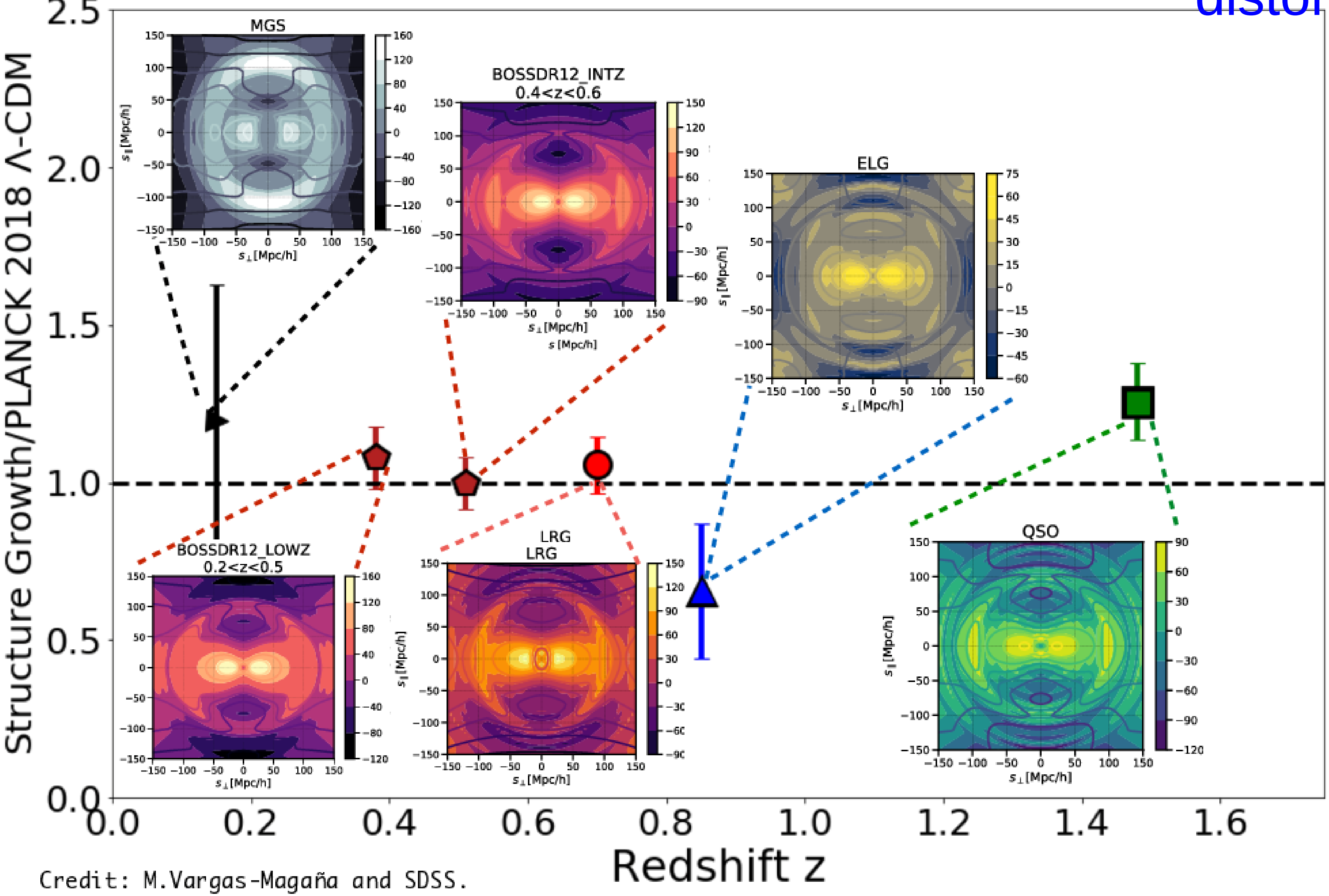




Credit: Ashley J. Ross and SDSS

Redshift space distortions

Growth of structure



Credit: M.Vargas-Magaña and SDSS.

Redshift space power-spectrum

$$P^s(k) = (b + f\mu)^2 \; P(k)$$

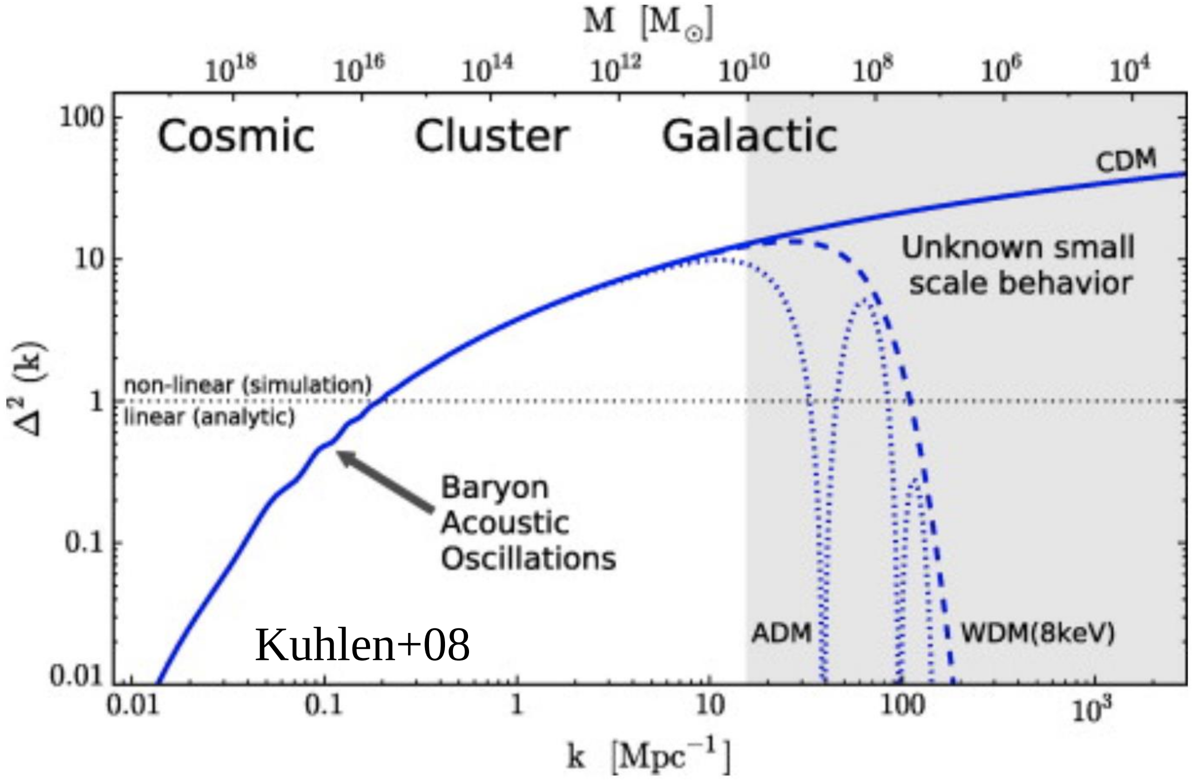
Local bias (deterministic)

RSD (depends on σ_8)

Kaiser 1987

The matter power spectrum

LARGE SCALES **SMALL SCALES**



Kuhlen+08

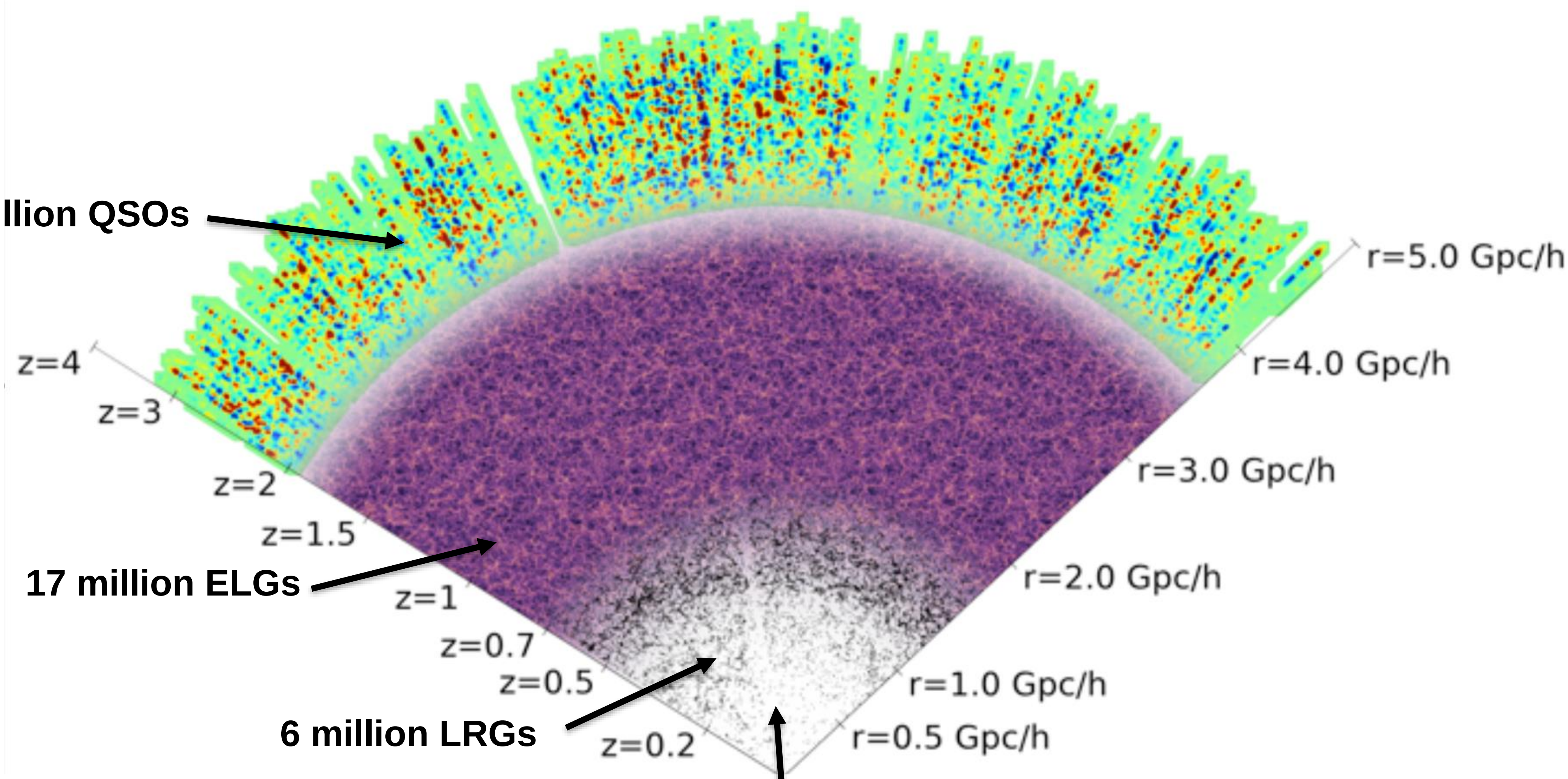
$$P_{matter} \rightarrow P^{1D,3D}_{Ly\alpha-flux}$$

- *Dynamical growth of perturbations - but also geometry via BAOs*
- *P(k) it is a physical quantity linked to parameters of the models*
- *Different scales probed by different observables, beat down systematics*

What are the properties of dark matter and the dark sector?

What physics drives the cosmic expansion and the large-scale evolution of the universe?

The DESI Survey



2.4 million QSOs

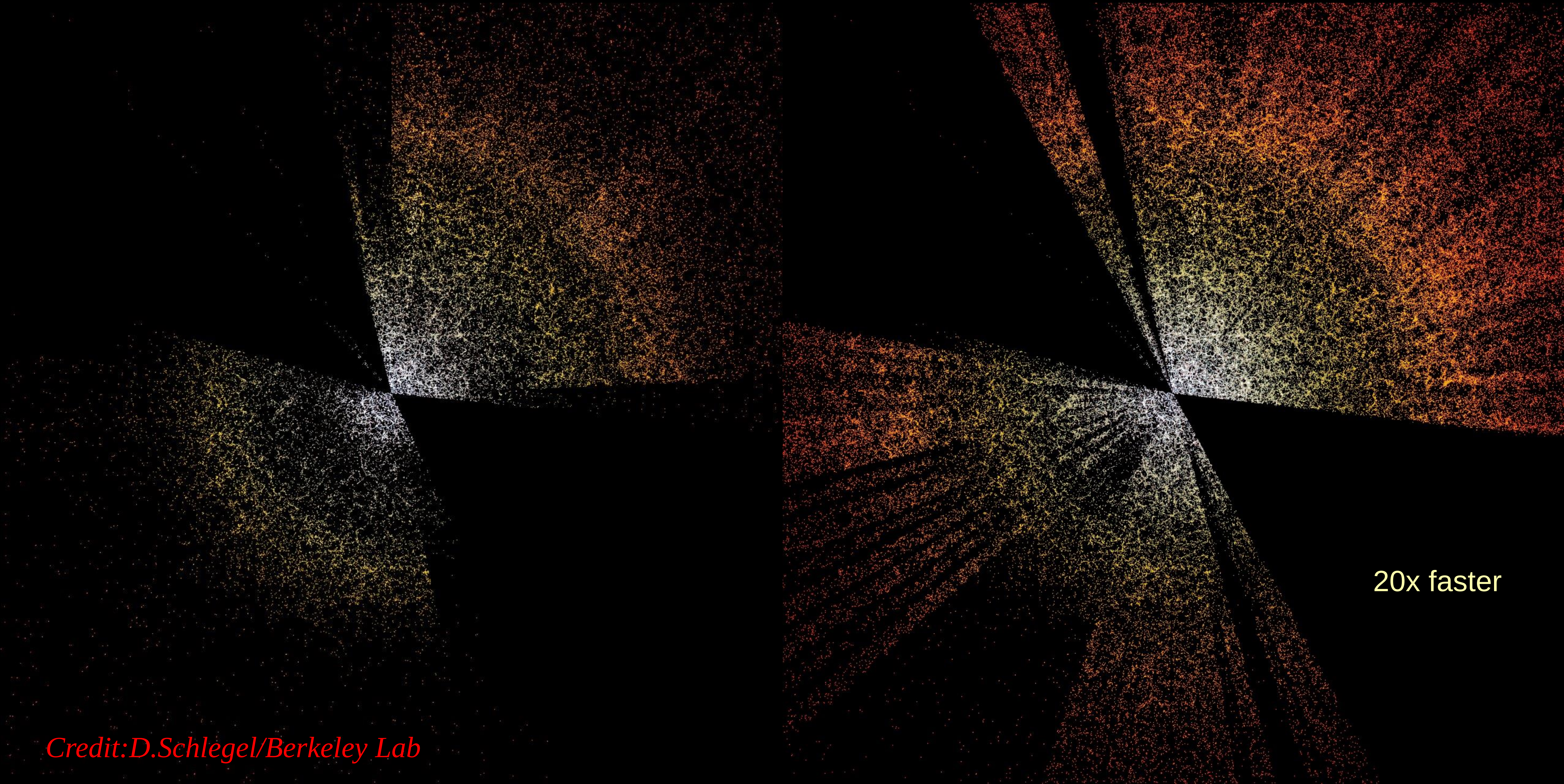
17 million ELGs

6 million LRGs

10 million brightest galaxies

https://www.desi.lbl.gov/

SDSS vs DESI (first 7 months)



20x faster

Credit:D.Schlegel/Berkeley Lab

Learning (many) lessons about ML

Beware of:

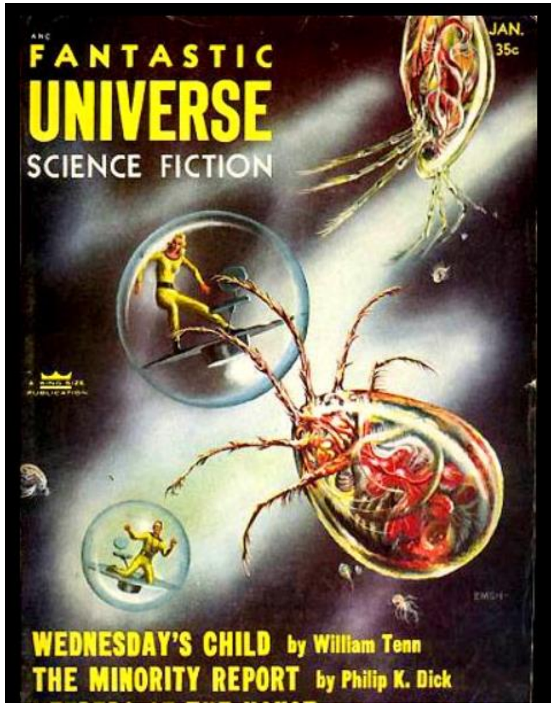
- Black box syndrome
- Overfitting (complementary methods)
- Fancy interpretation of unphysical features
- Amazing success rates and completeness

Consider that:

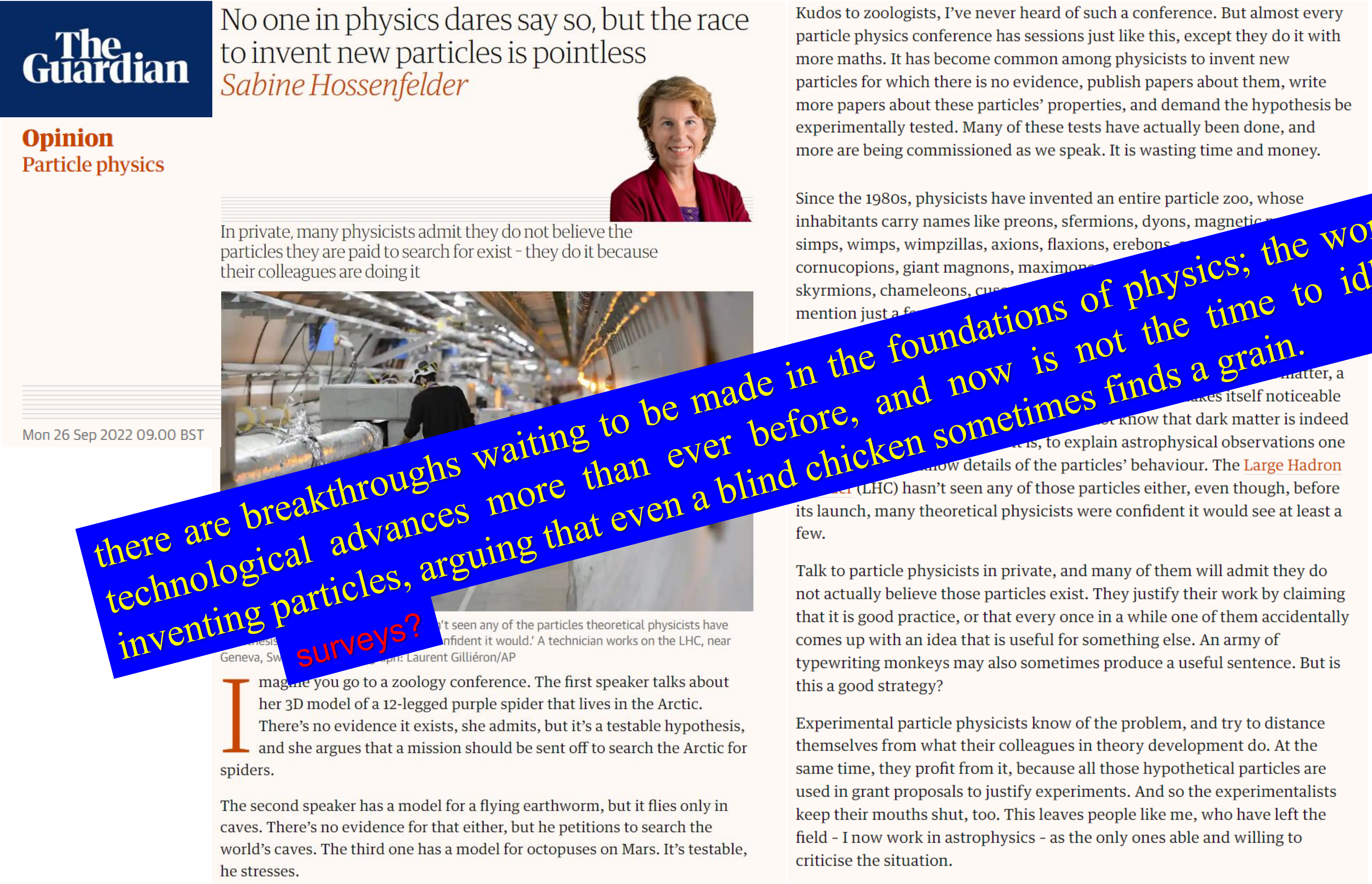
- Good for classification may be less good for regression
- On a well defined class, fitting a model may be fine

Need for:

- Large and balanced training sets (synthetic data)
- Proper error treatment
- Physical insight



Remember *Minority Report (Dick, 1956)*



The Guardian

Opinion
Particle physics

No one in physics dares say so, but the race to invent new particles is pointless

Sabine Hossenfelder

In private, many physicists admit they do not believe the particles they are paid to search for exist - they do it because their colleagues are doing it

Mon 26 Sep 2022 09.00 BST

…n't seen any of the particles theoretical physicists have … thesis … nfident it would.' A technician works on the LHC, near Geneva, Sw… …ph: Laurent Gilliéron/AP

Imagine you go to a zoology conference. The first speaker talks about her 3D model of a 12-legged purple spider that lives in the Arctic. There's no evidence it exists, she admits, but it's a testable hypothesis, and she argues that a mission should be sent off to search the Arctic for spiders.

The second speaker has a model for a flying earthworm, but it flies only in caves. There's no evidence for that either, but he petitions to search the world's caves. The third one has a model for octopuses on Mars. It's testable, he stresses.

Kudos to zoologists, I've never heard of such a conference. But almost every particle physics conference has sessions just like this, except they do it with more maths. It has become common among physicists to invent new particles for which there is no evidence, publish papers about them, write more papers about these particles' properties, and demand the hypothesis be experimentally tested. Many of these tests have actually been done, and more are being commissioned as we speak. It is wasting time and money.

Since the 1980s, physicists have invented an entire particle zoo, whose inhabitants carry names like preons, sfermions, dyons, magnetic … simps, wimps, wimpzillas, axions, flaxions, erebons, … cornucopions, giant magnons, maximons … skyrmions, chameleons, cus… mention just a f…

…matter, a …kes itself noticeable …t know that dark matter is indeed …t is, to explain astrophysical observations one …now details of the particles' behaviour. The Large Hadron …ider (LHC) hasn't seen any of those particles either, even though, before its launch, many theoretical physicists were confident it would see at least a few.

Talk to particle physicists in private, and many of them will admit they do not actually believe those particles exist. They justify their work by claiming that it is good practice, or that every once in a while one of them accidentally comes up with an idea that is useful for something else. An army of typewriting monkeys may also sometimes produce a useful sentence. But is this a good strategy?

Experimental particle physicists know of the problem, and try to distance themselves from what their colleagues in theory development do. At the same time, they profit from it, because all those hypothetical particles are used in grant proposals to justify experiments. And so the experimentalists keep their mouths shut, too. This leaves people like me, who have left the field - I now work in astrophysics - as the only ones able and willing to criticise the situation.

there are breakthroughs waiting to be made in the foundations of physics; the world needs technological advances more than ever before, and now is not the time to idle around inventing particles, arguing that even a blind chicken sometimes finds a grain.

surveys?

'big science' vs 'little science' ? (R. Ekers 2010)

- *Institutional Facilities are built to enable research on a scale which no individual can afford.*
- *National Facilities are built to enable research on a scale which no single institute can afford.*
- *International Facilities are built to enable research on a scale which no single nation can afford.*

Fundamentalist physics - Simon D.M. White (2007)

By uncritically adopting the values of an alien system, astronomers risk undermining the foundations of their own current success and endangering the future vitality of their field.

…. Large projects require large teams and long time-scales. The negative effects of this on young scientists' opportunities for creativity can be drastic and must be mitigated by promoting a diverse set of science goals for exploration by young team members.

big science facilities are expensive so they need to be common-user facilities to justify their cost.

DVS recommendation (2019)

1) A new program to **support specifically Theoretical Astrophysics**.
Every participation to a new project or facility should involve a commensurate number of theorists and interpretative astrophysicists to ensure an adequate scientific return for the Italian community.

A final thought

We need spectroscopy
wide, deep, ground-based and space born

SPACE was
not a bad idea!

e.g. PFS, MOONS…

Dedicated 10m class telescope:
MSE, DESI2, Post–LSST, WST, ESO Spec Tel
(Pasquini+2017, Ellis+2017)
See *Dark Energy and Cosmic Acceleration in the Modern Universe*, arxiv-2209.08049