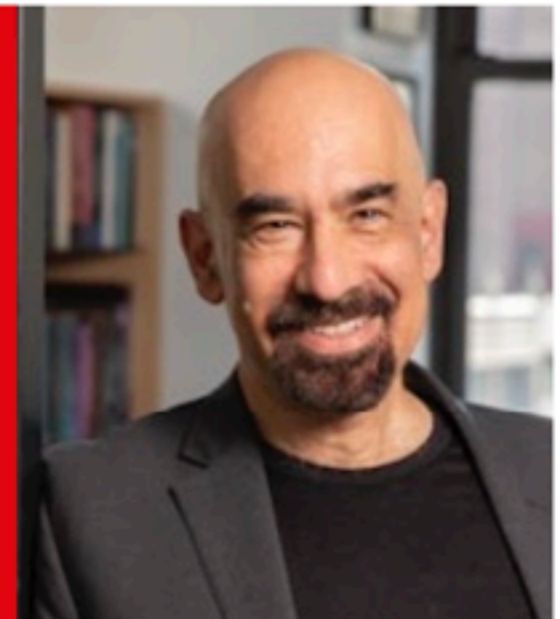
Contents and Properties of the Observable Universe - 2

Jean-Paul Kneib

Quiz

- What is the galaxy correlation function?
- If galaxies were randomly distributed, what would the correlation function be?
- What does the "CMB" stand for?
- What was the age of the Universe when the CMB was emitted?
- What is the CMB temperature today? How many CMB photons per cm^{-3}?
- What are the 4 main ways to study clusters of galaxies?
- What have we learn from the study of the Bullet Cluster?

Recent Results from the Atacama Cosmology Telescope



Prof. David Spergel
Princeton Univ.

President, Simons Foundation

APERO after the colloquium

Thursday
March 20th
12:15
CE1 4

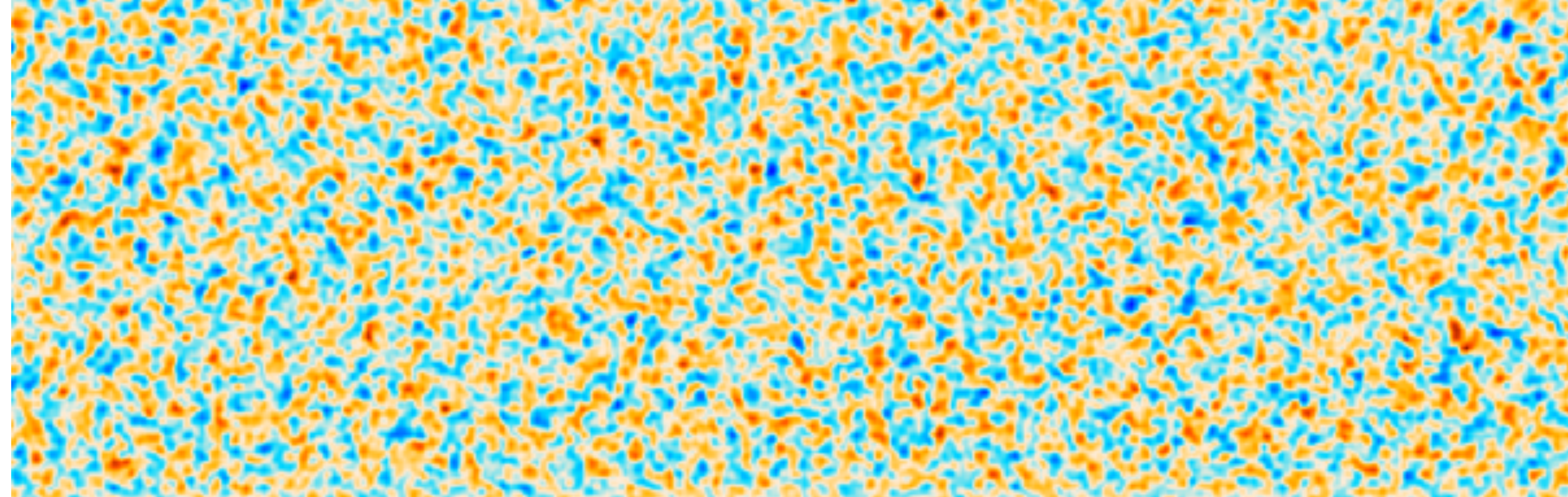
or on zoom :
https://epfl.zoom.us/j/64905394203

The Atacama Cosmology Telescope has recently reported the most accurate measurements of temperature and polarization of the cosmic microwave background. I will highlight these results and their implications for our understanding of cosmology.

The new measurements constrain the number and mass of neutrinos, the presence of new light particles, the properties of dark matter and dark energy, and the physics of inflation.

Host: Prof. Jean-Paul Kneib

Atacama Cosmology Telescope (ACT) and CMB observation

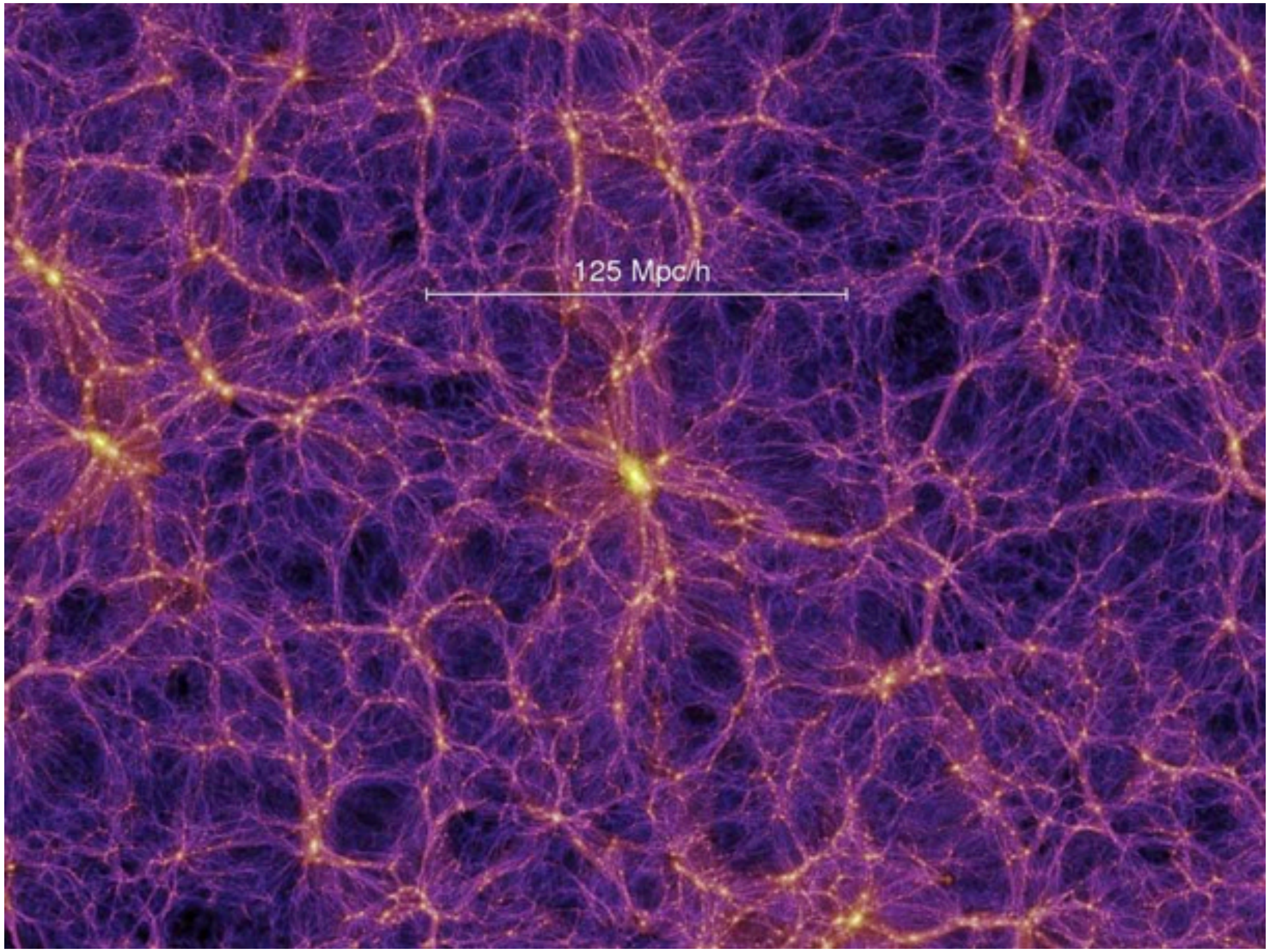


Content of the Universe

- Tracers from a Cosmology standpoints:
  - Distribution of Galaxies
  - Background Radiation (e.g. Cosmic Microwave Background)
  - Cluster of Galaxies
  - Large Scale structures: Cosmic Web: Filaments & Voids
  - Quasars
  - Inter-Galactic Medium (gas)

Large Scale Structures

- Cosmic Web
- Filaments
- Voids



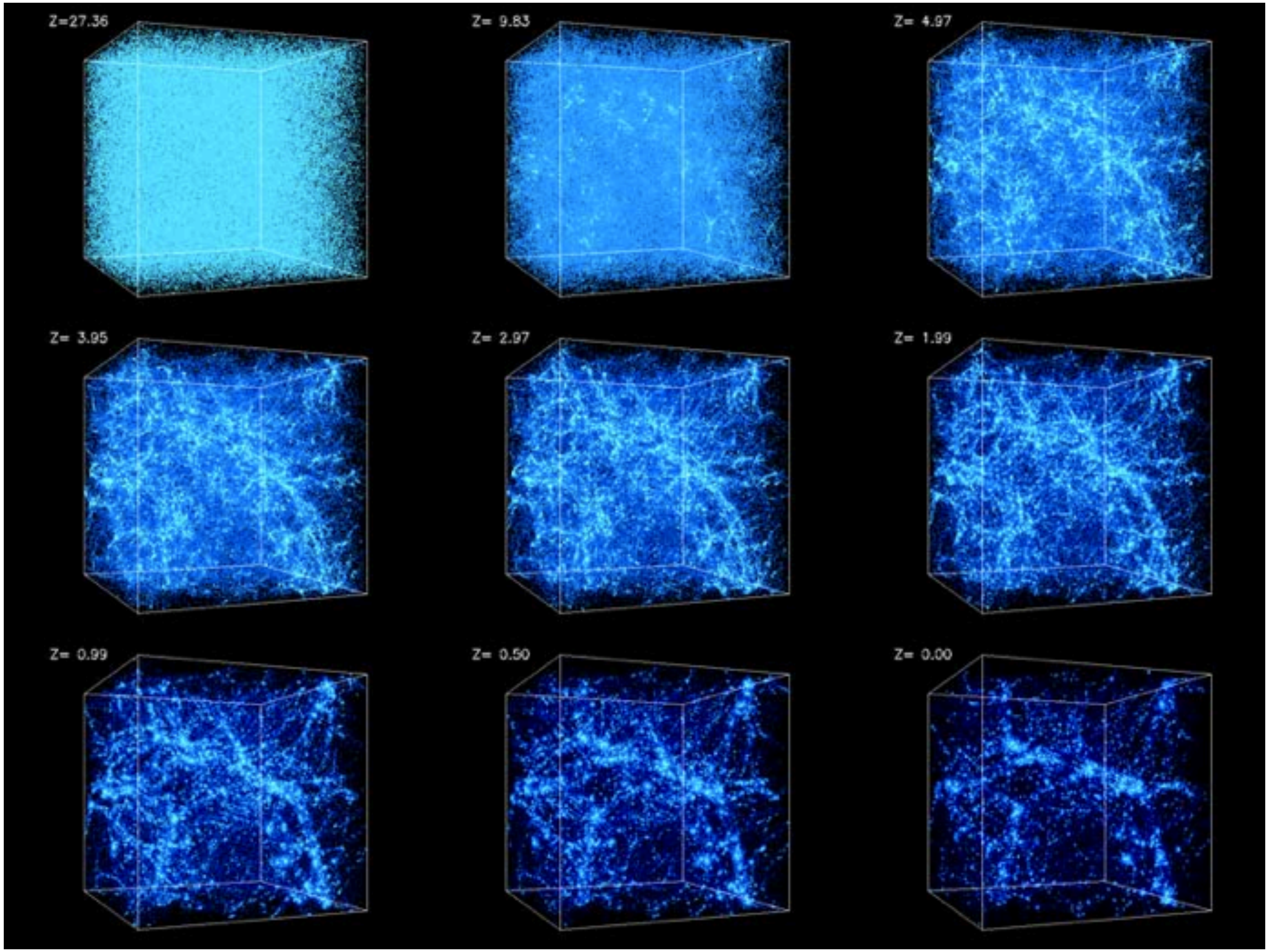
The dark matter distribution of the universe on extremely large scales. At the intersection of the filaments are the largest luminous structures in the universe: galaxy clusters. From Springel et al, **Millennium Simulation**.

https://youtu.be/74IsySs3RGU

http://wwwmpa.mpa-garching.mpg.de/galform/virgo/millennium/

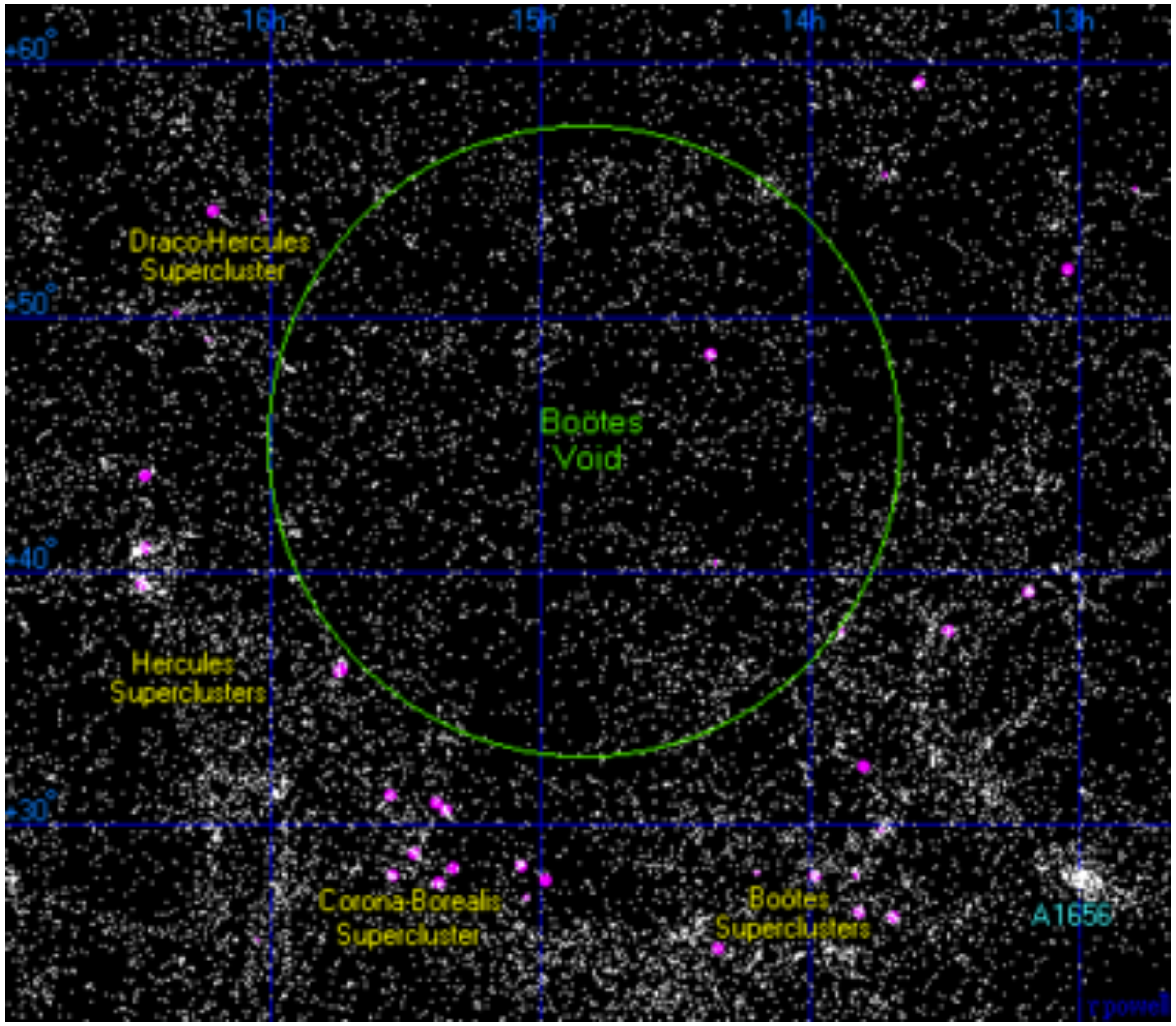
Large Scale Structures

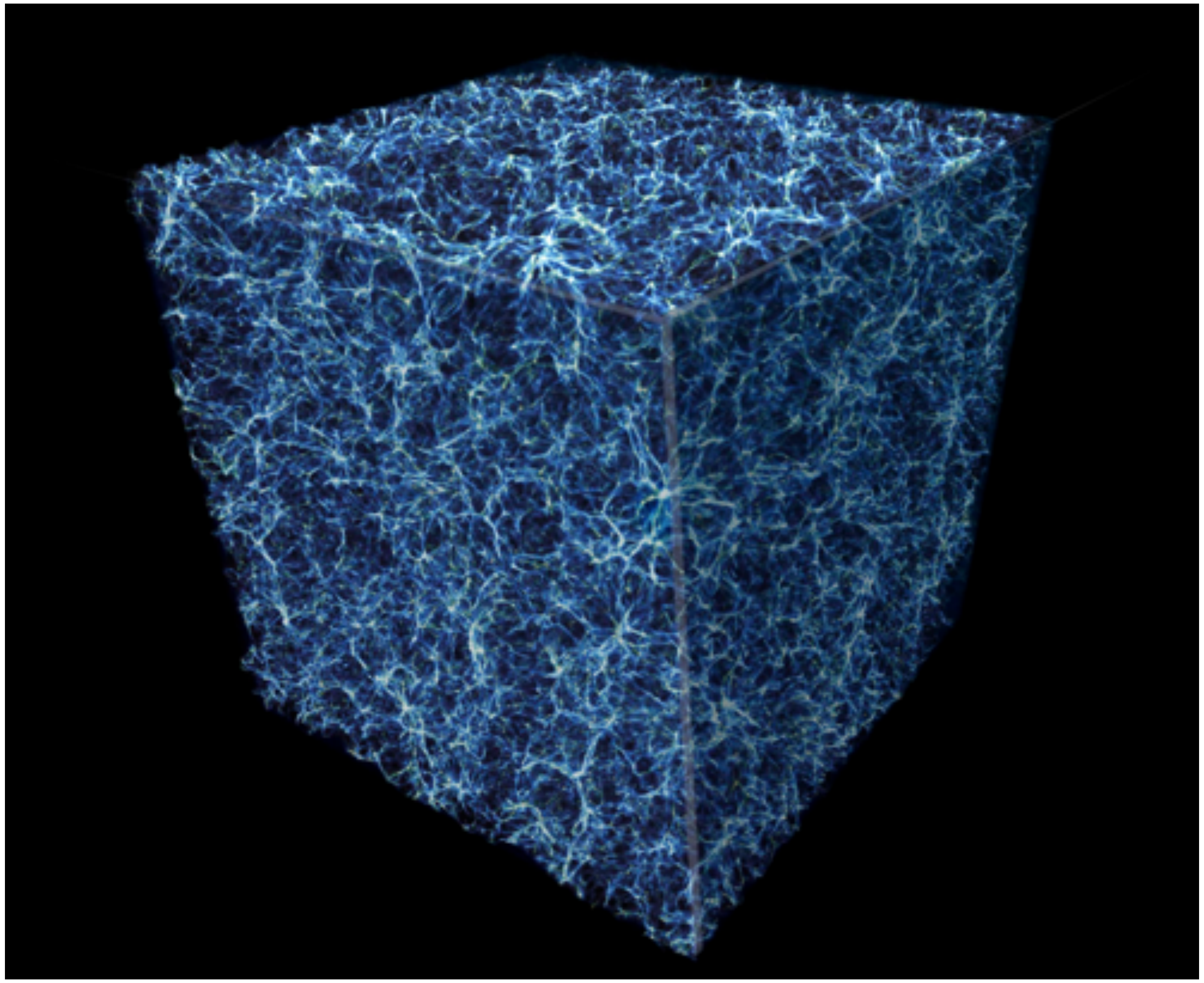
- Filaments are evolving with time
- They are feeding massive clusters
- Becoming thicker with time



Large Scale Structures

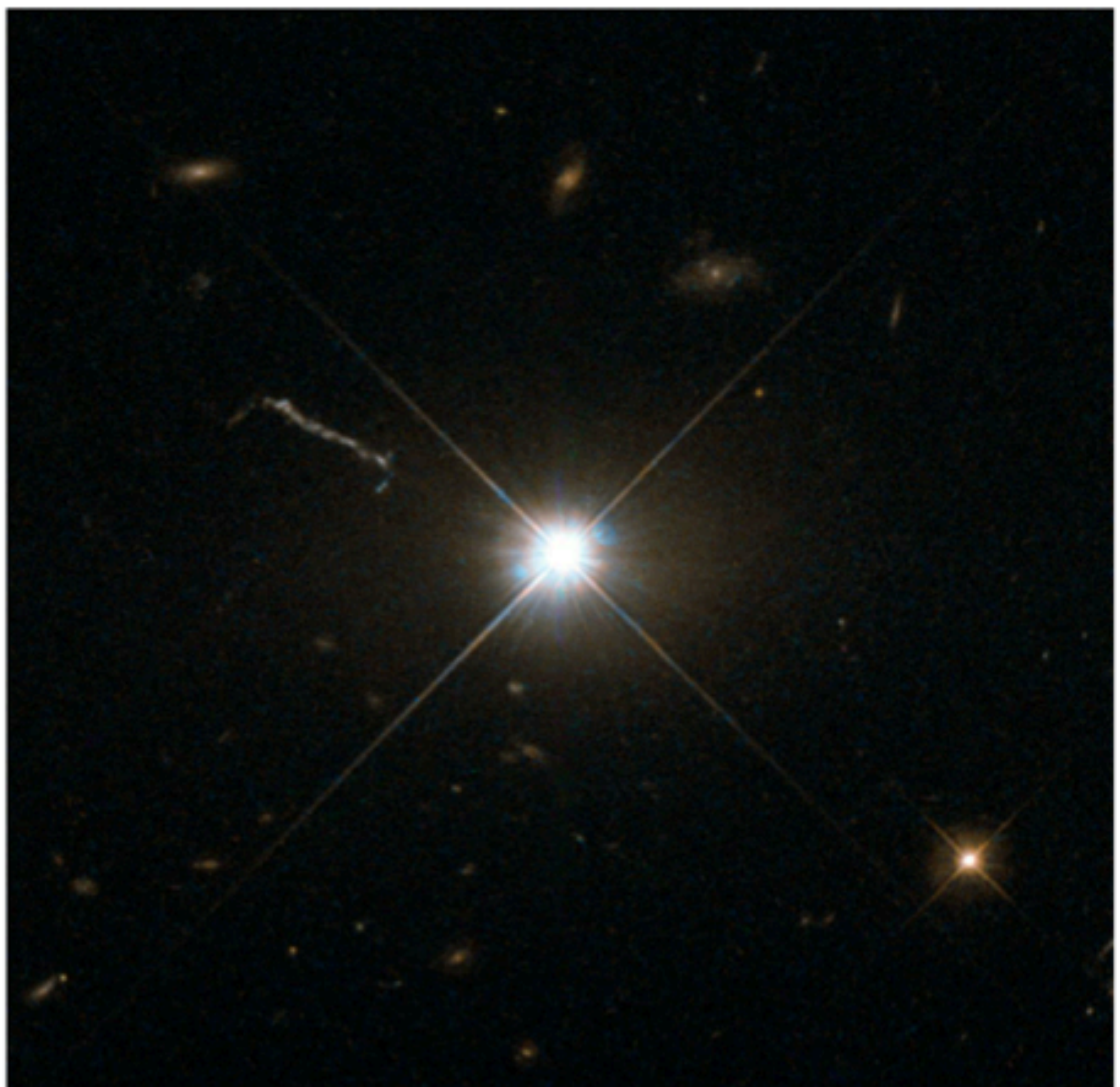
- Voids are the empty space between the filaments, they contain few or no galaxies



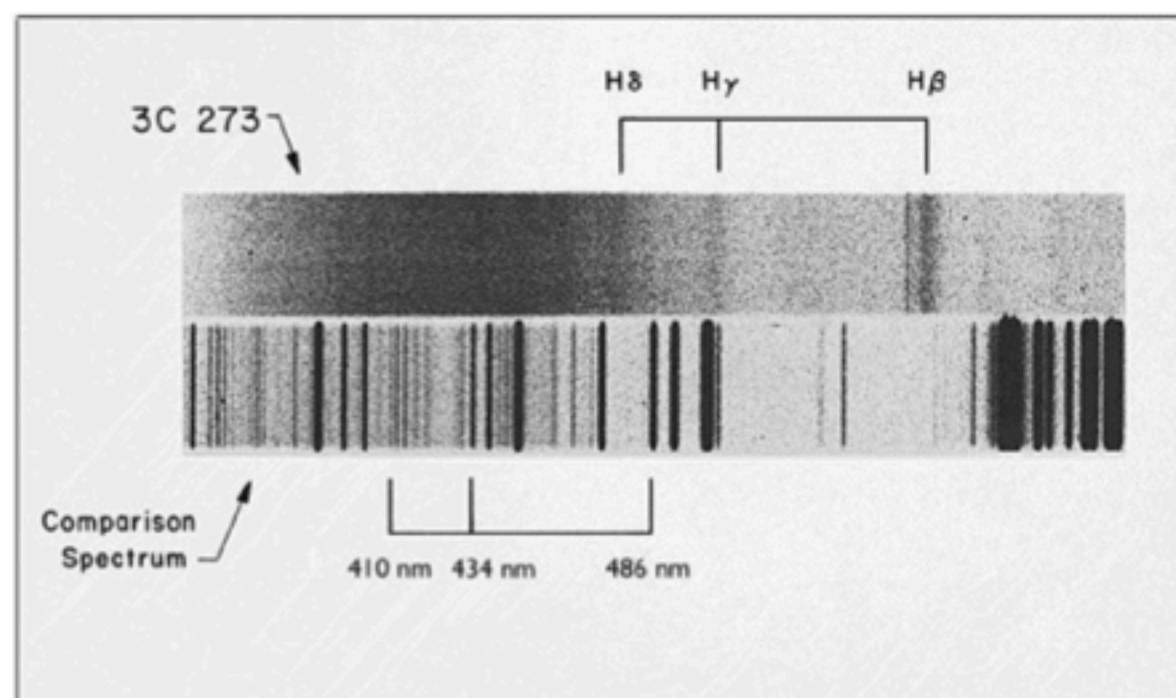


Quasar

- 1963: Discovery of the first quasar
- today: ~1 million quasars identified

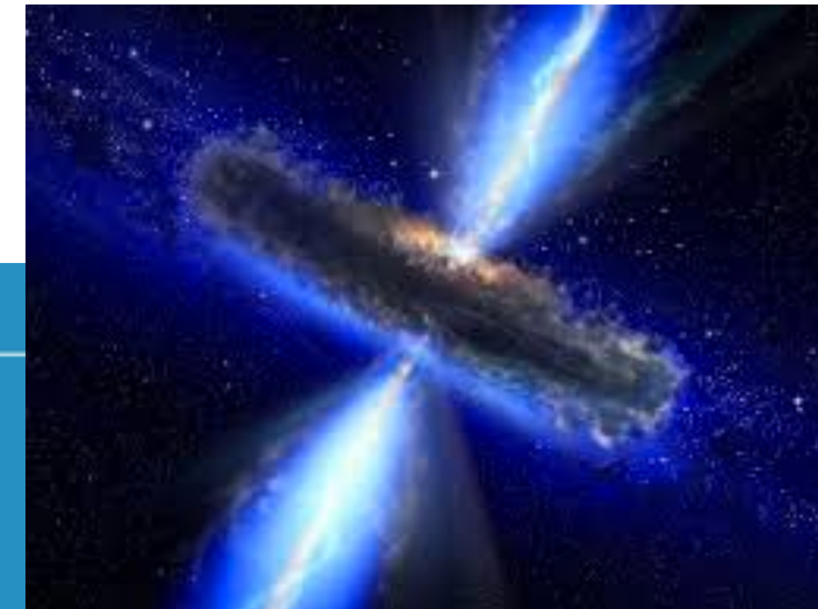


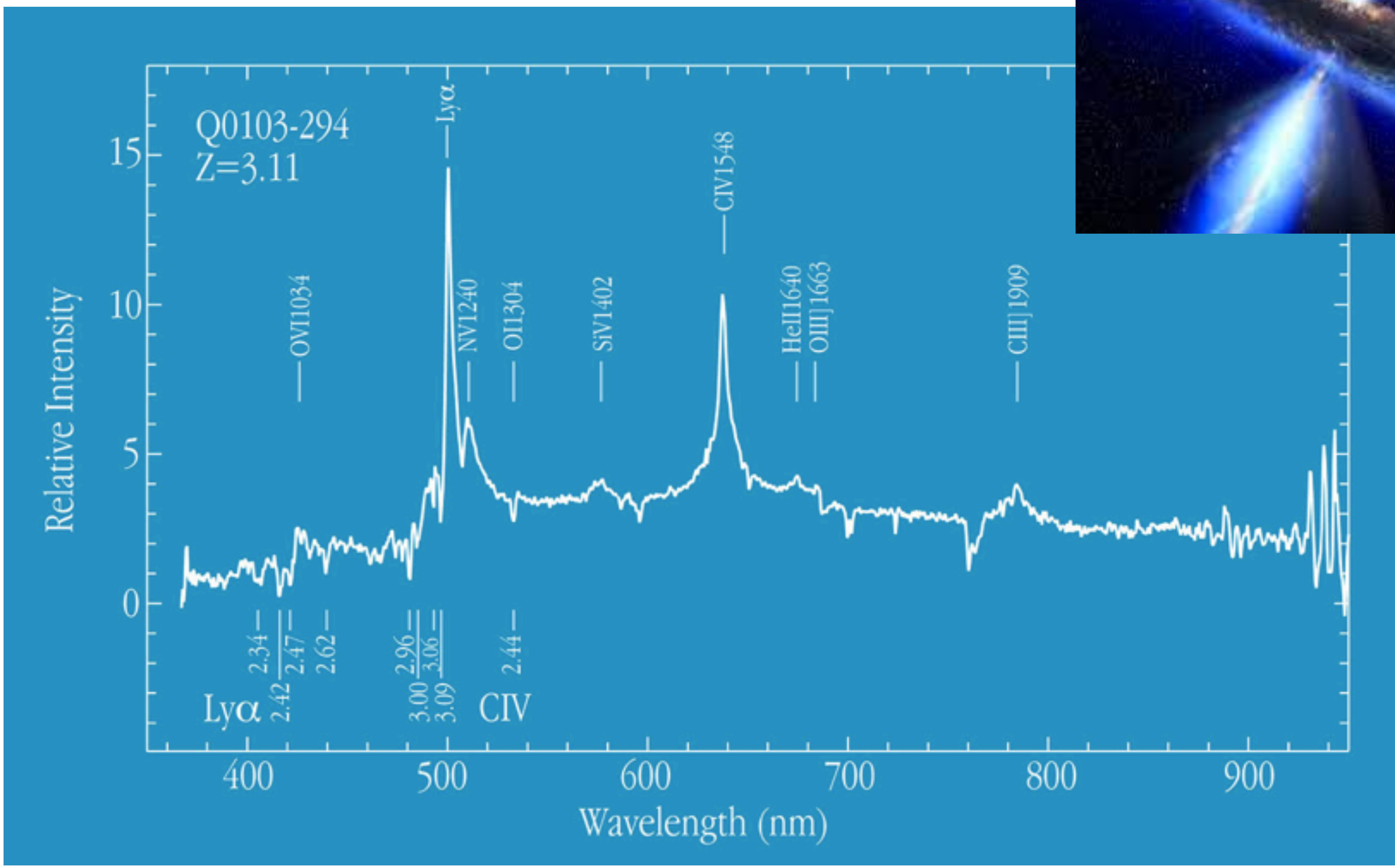
- 3C 273 was discovered in 1963 (Schmidt, 1963)
- Optical point-source with radio emission



Quasar

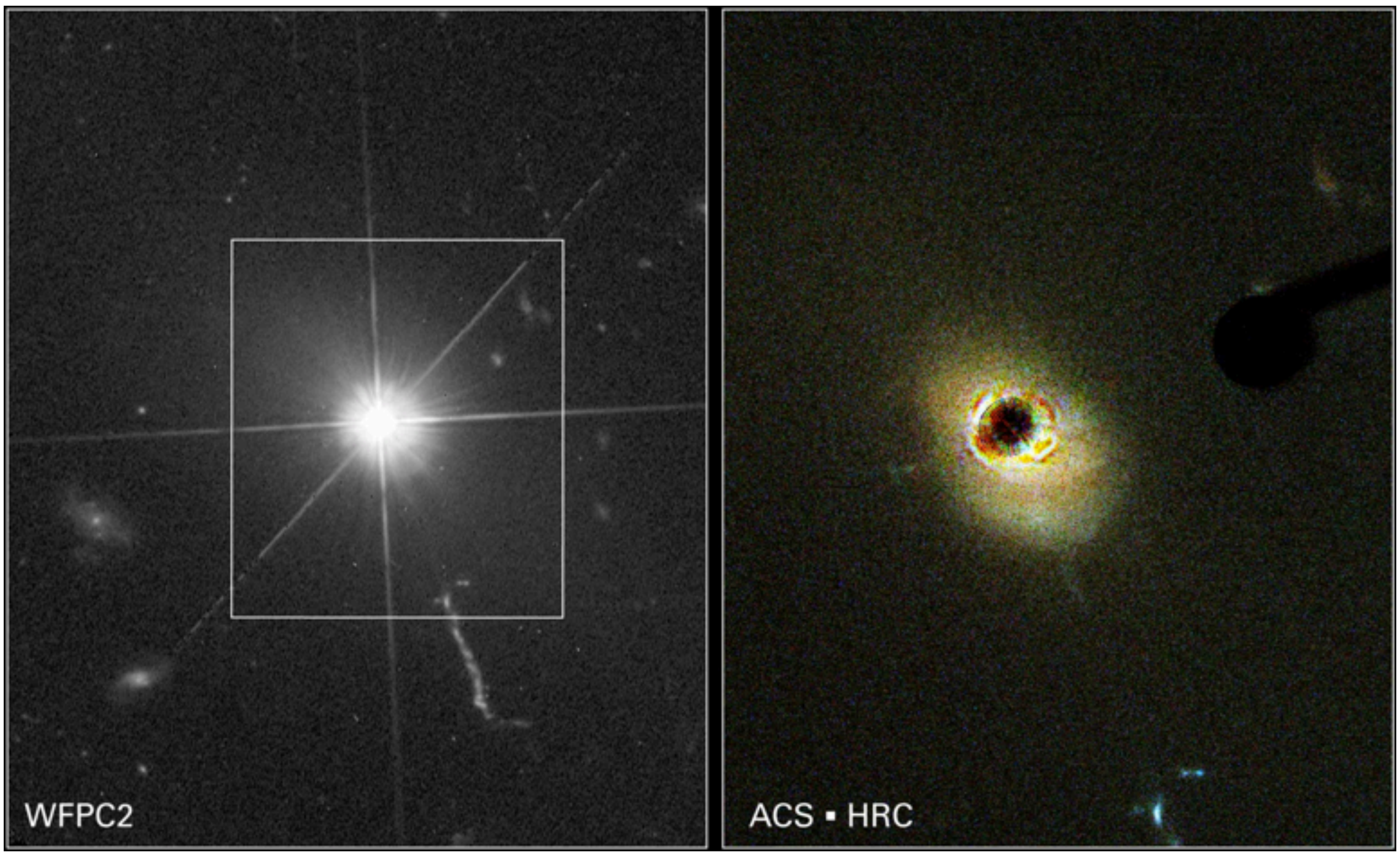
- typical quasar spectrum





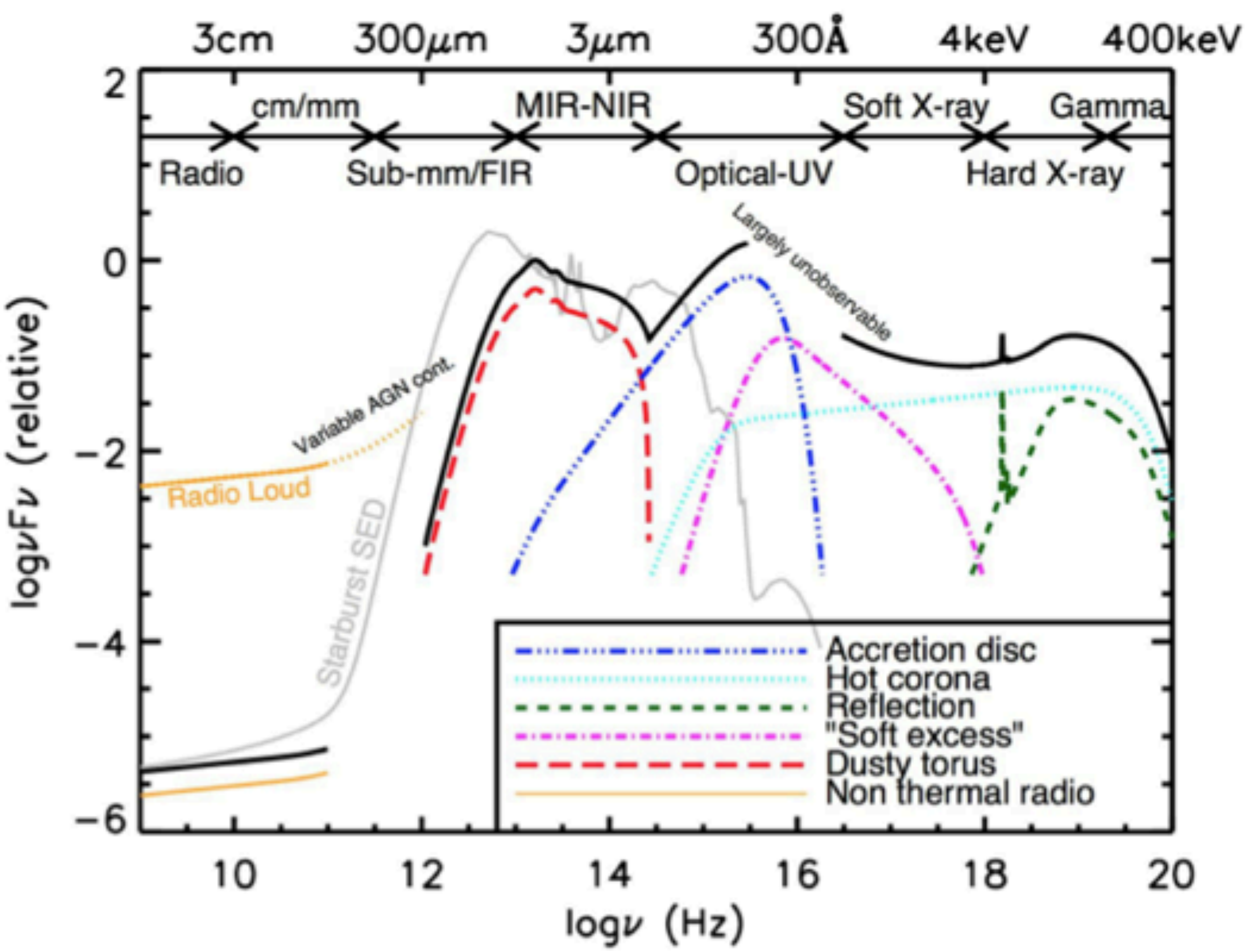
Quasar

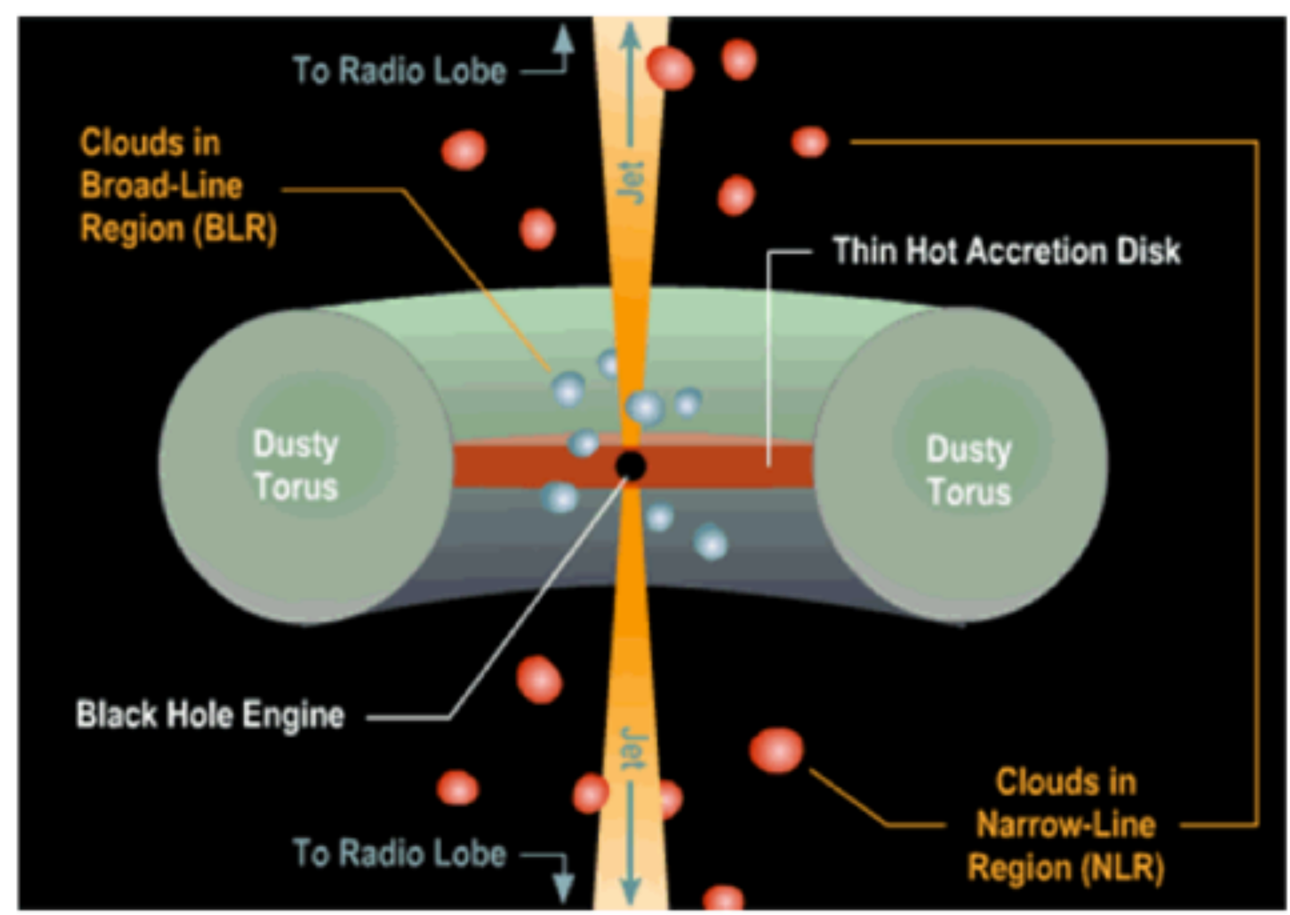
- The existence of a super massive black hole ($\sim 10^6$ solar mass) at the center of a galaxy explain the observation of quasars



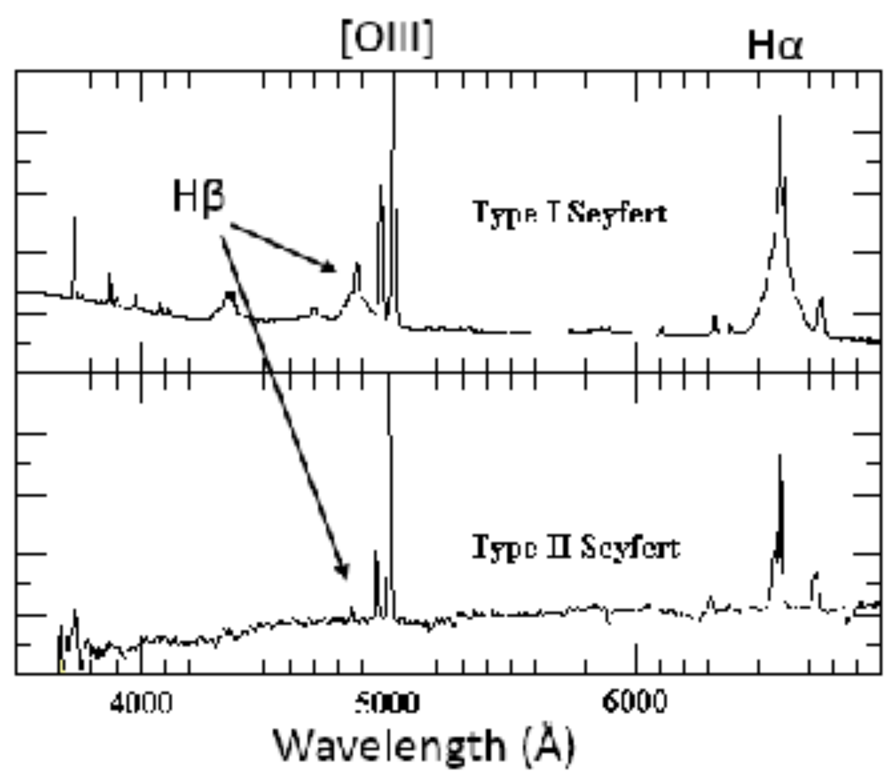
Quasar

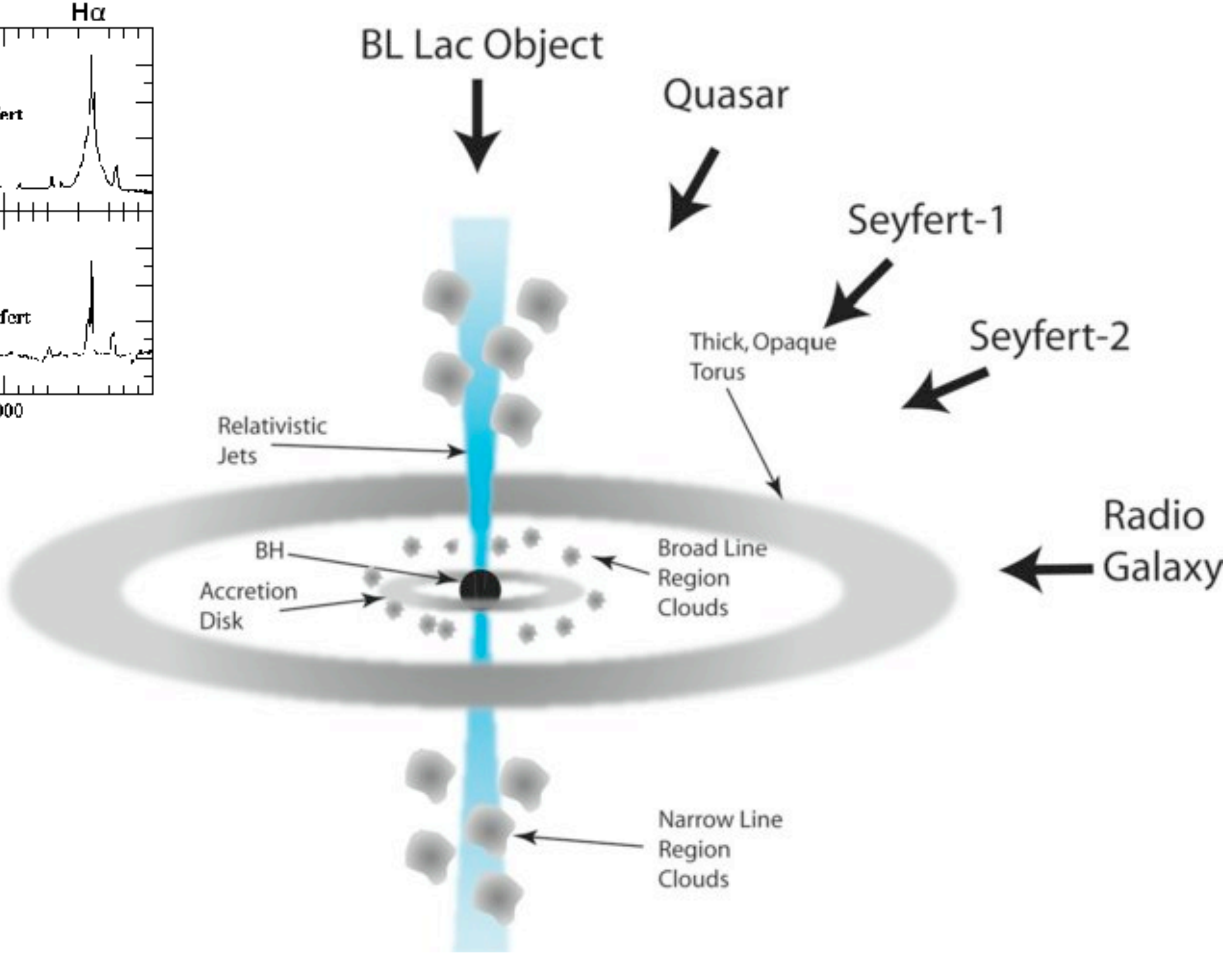
- Quasar across the electromagnetic spectrum
- 10% of quasar are radio-loud (synchrotron emission)
- infrared emission: thermal radiation





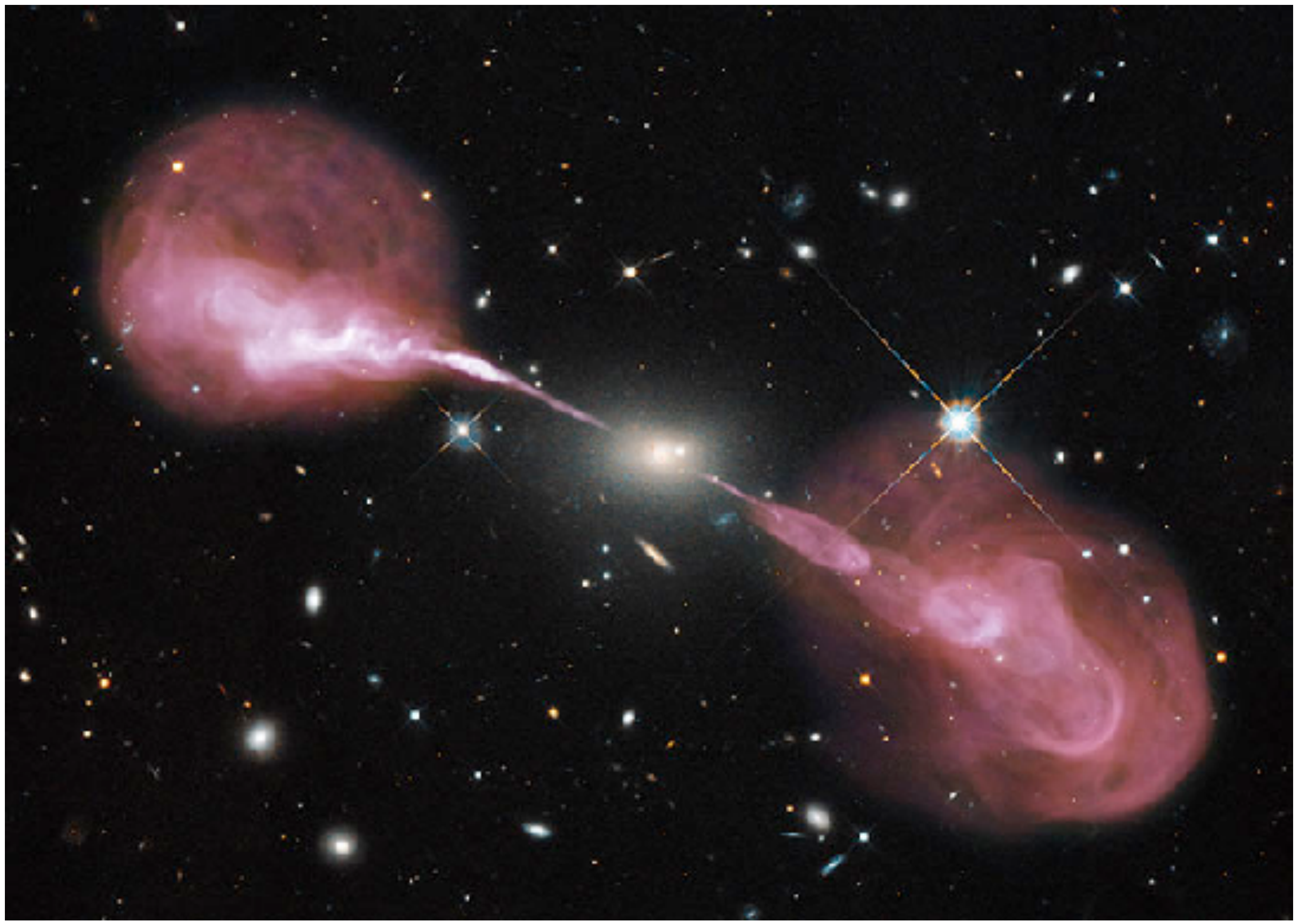
Quasar Engine and Object naming



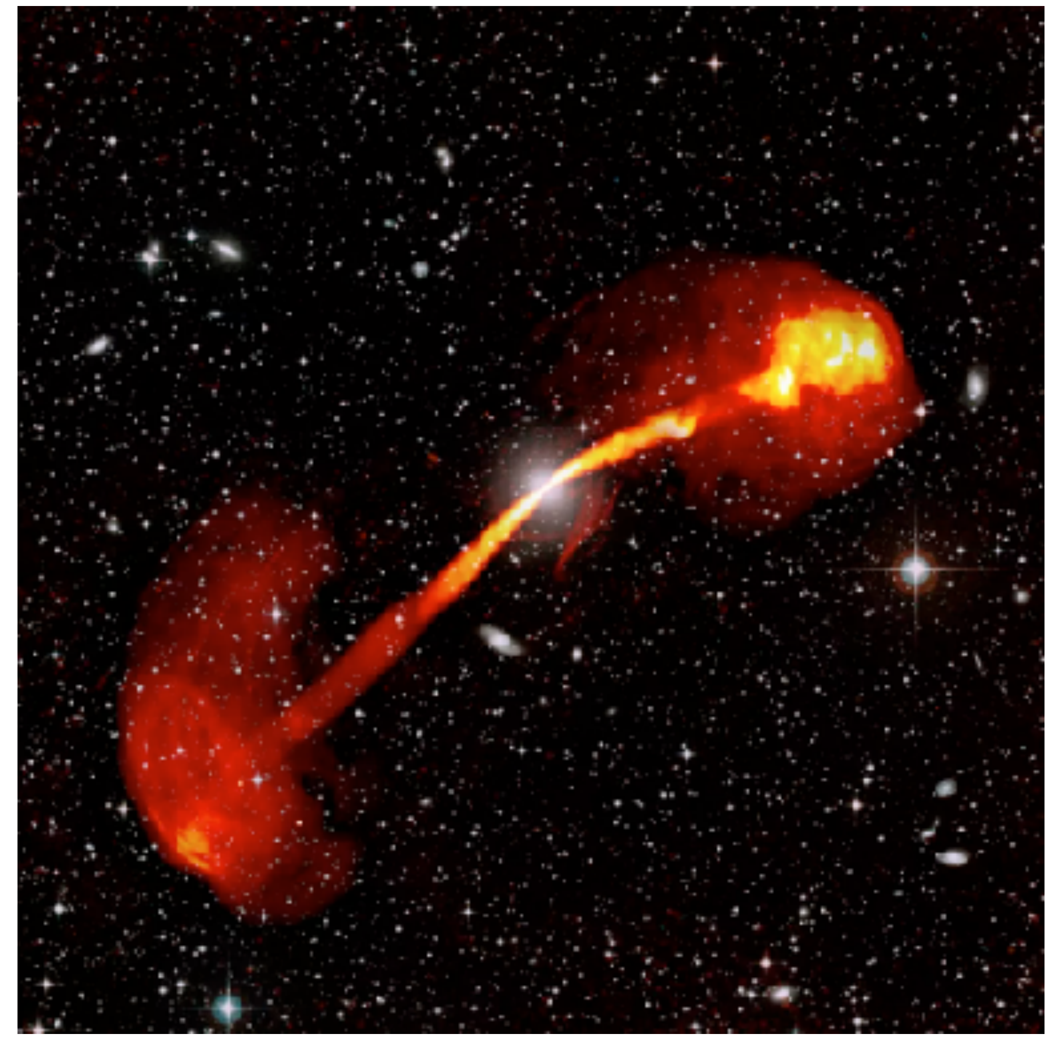


Radio-Loud Quasar

- 10% of quasar are radio-loud (synchrotron emission)



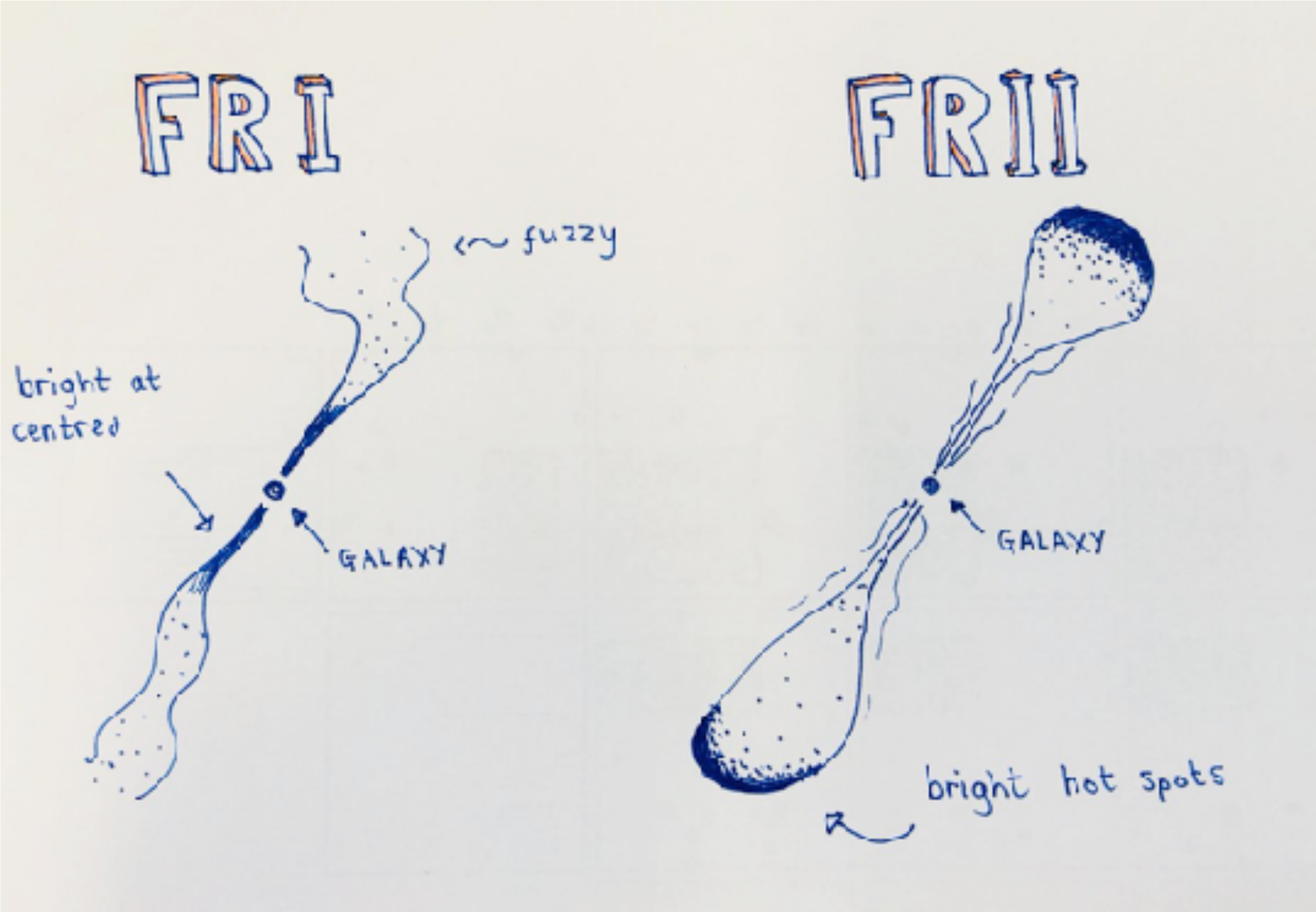
Spectacular jets powered by the gravitational energy of a super massive black hole in the core of the elliptical galaxy Hercules A seen by HST+VLA

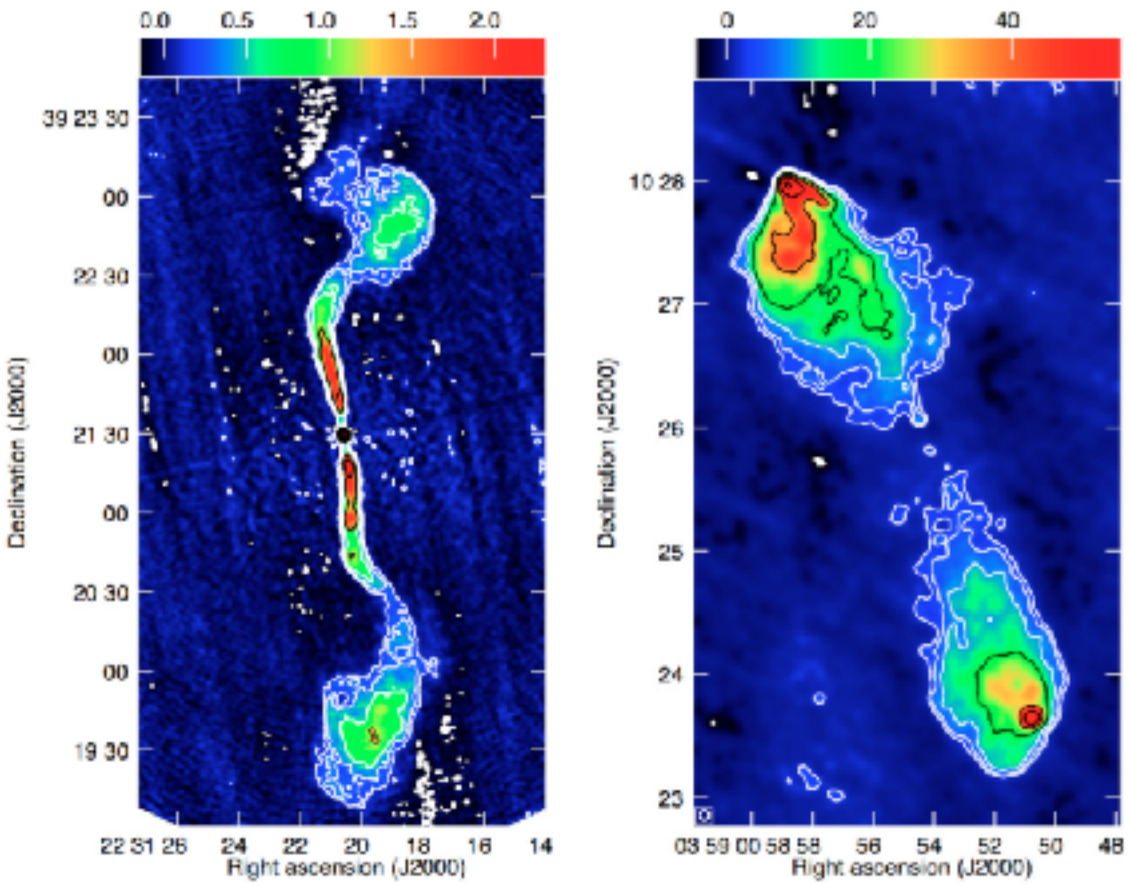


The Fanaroff-Riley Type I radio galaxy IC 4296, seen by MeerKat.

Radio-Loud Quasar

- Fanaroff-Riley classification

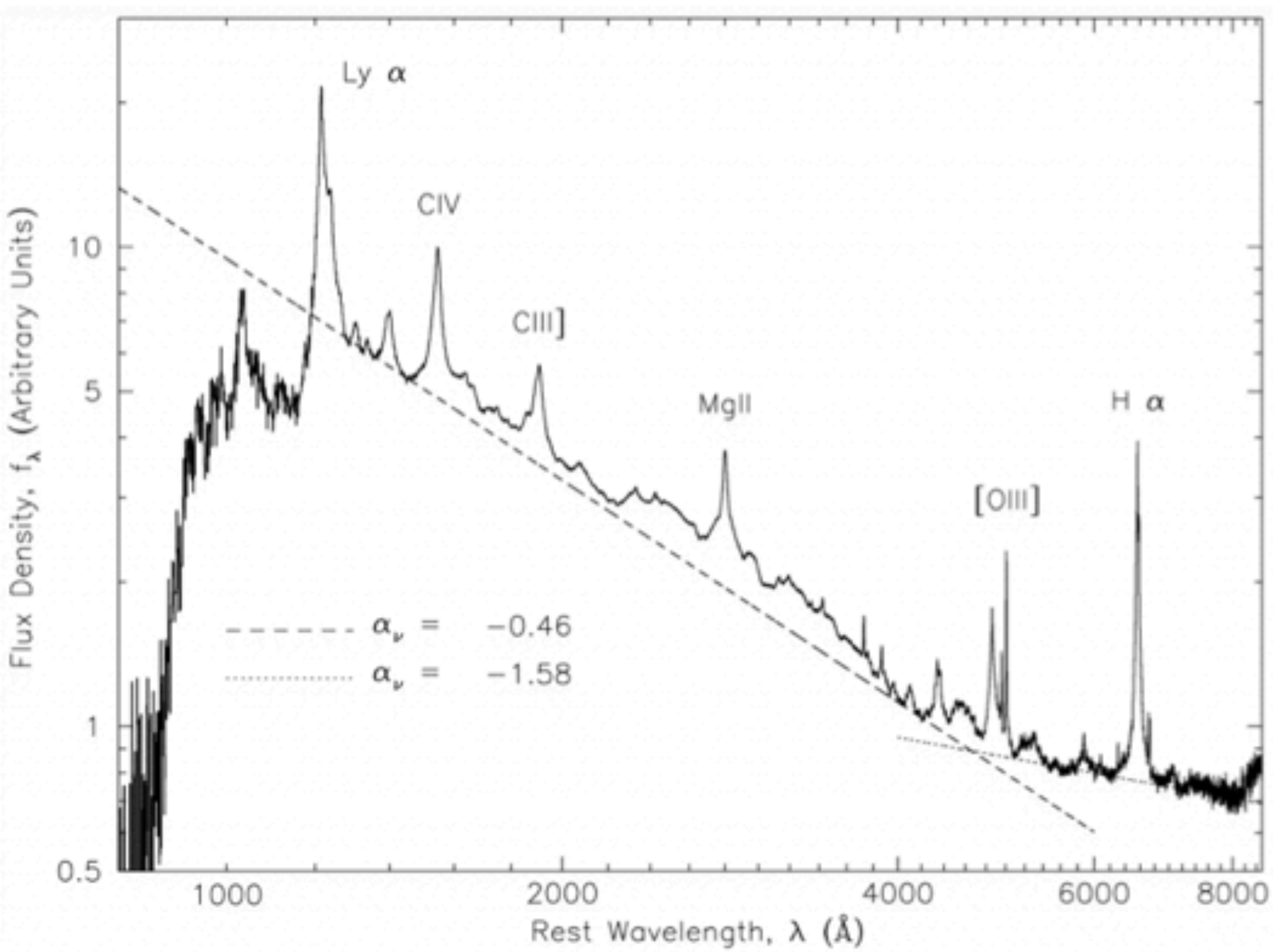




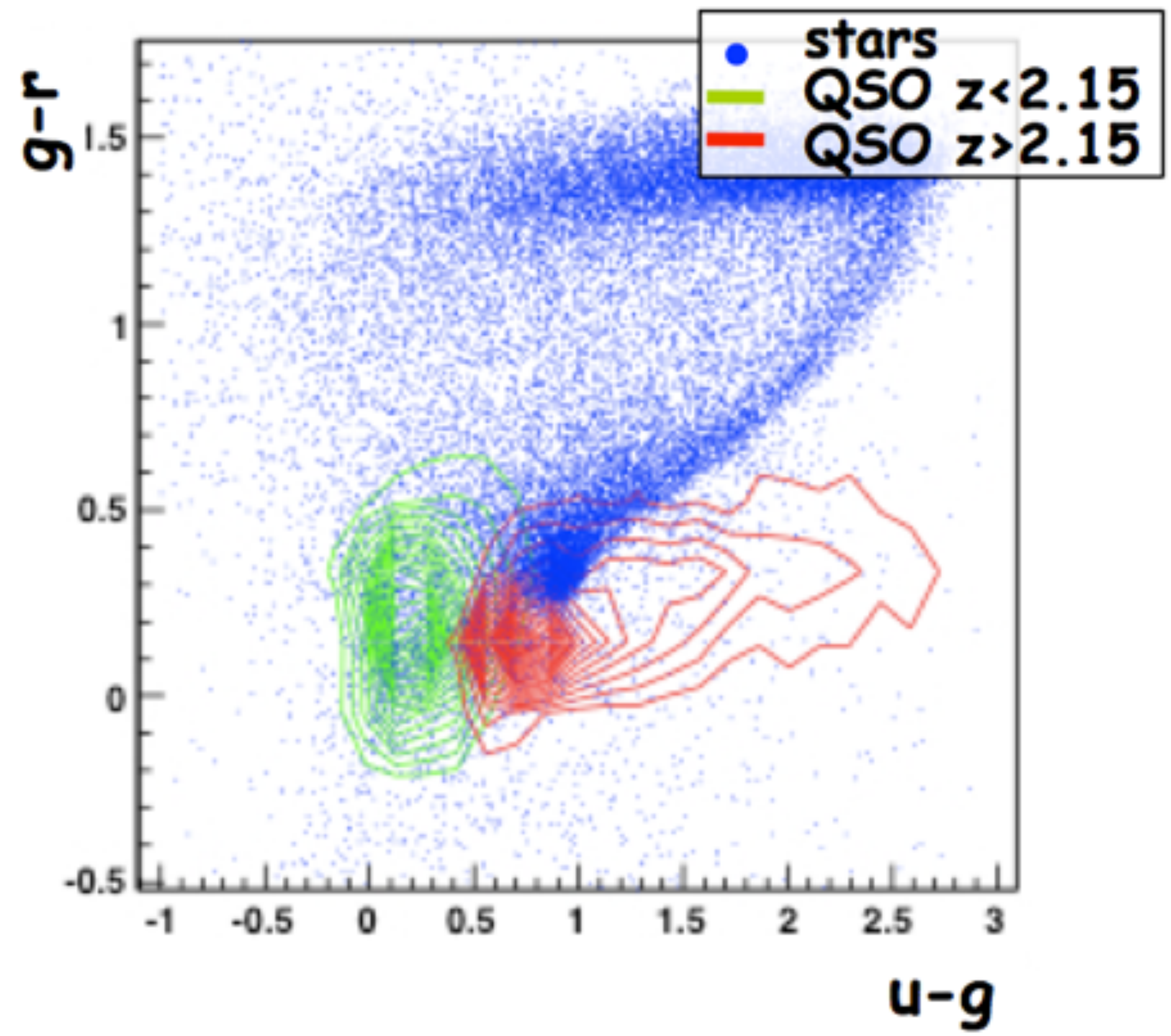
The FRI: 3C 449   and the FRII: 3C 98

Quasar

- particularly blue spectrum with broad emission lines
- can be detected through their UV excess

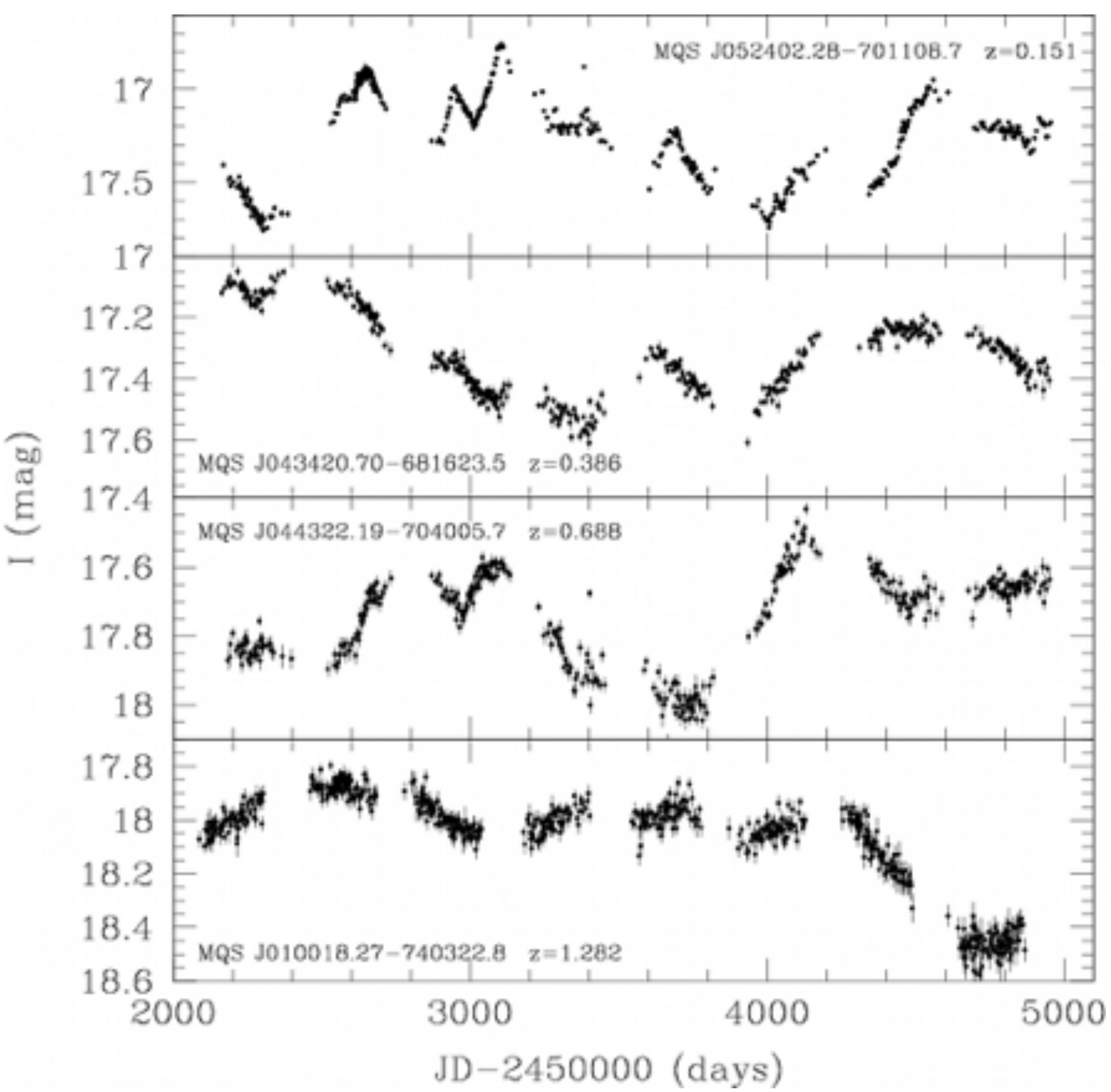


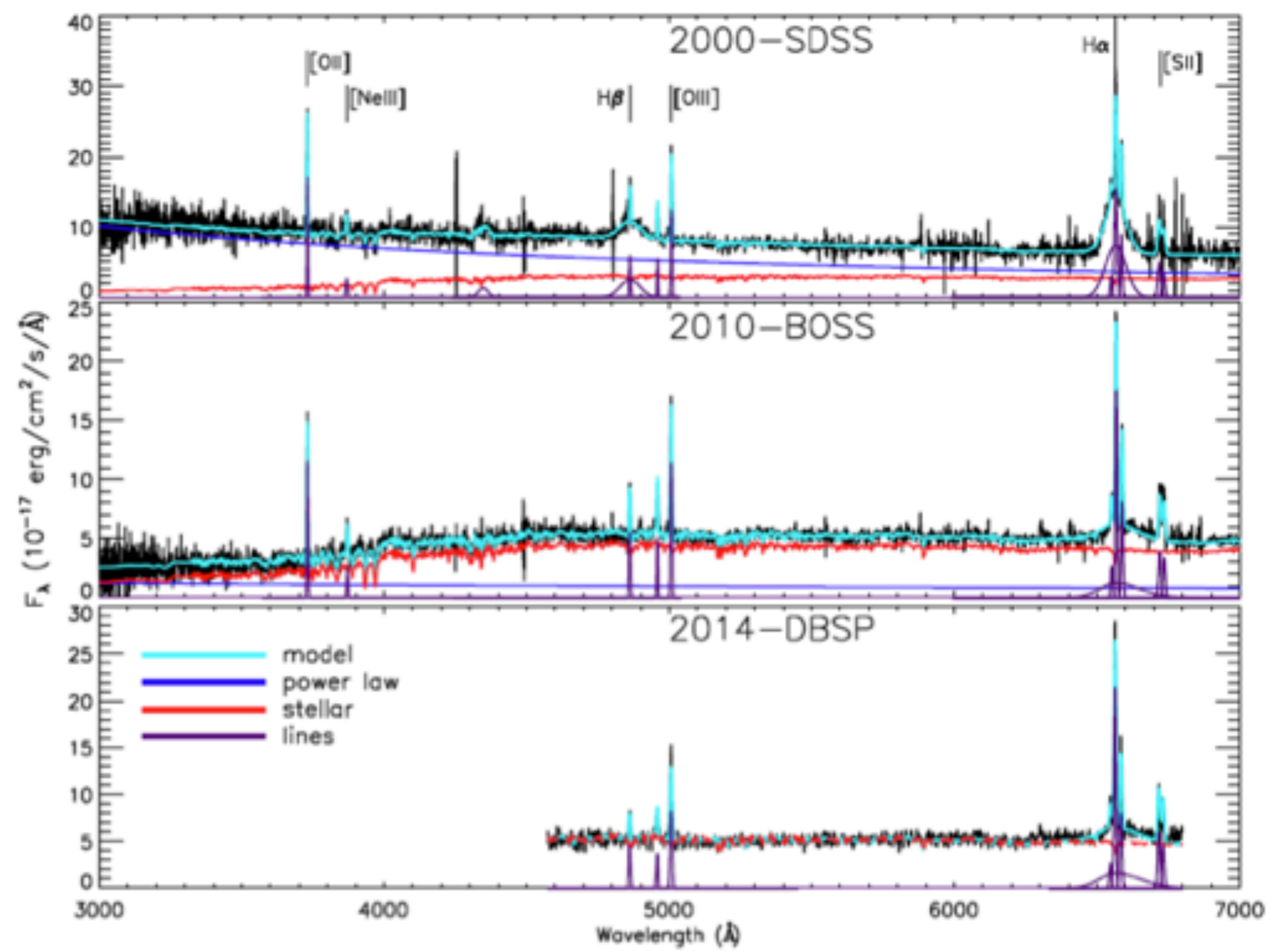
Vanden Berk et al. (2001)



Quasar

- Temporary state in the evolution of galaxies
- quasars show (random) variability (a good way to distinguish them from stars).

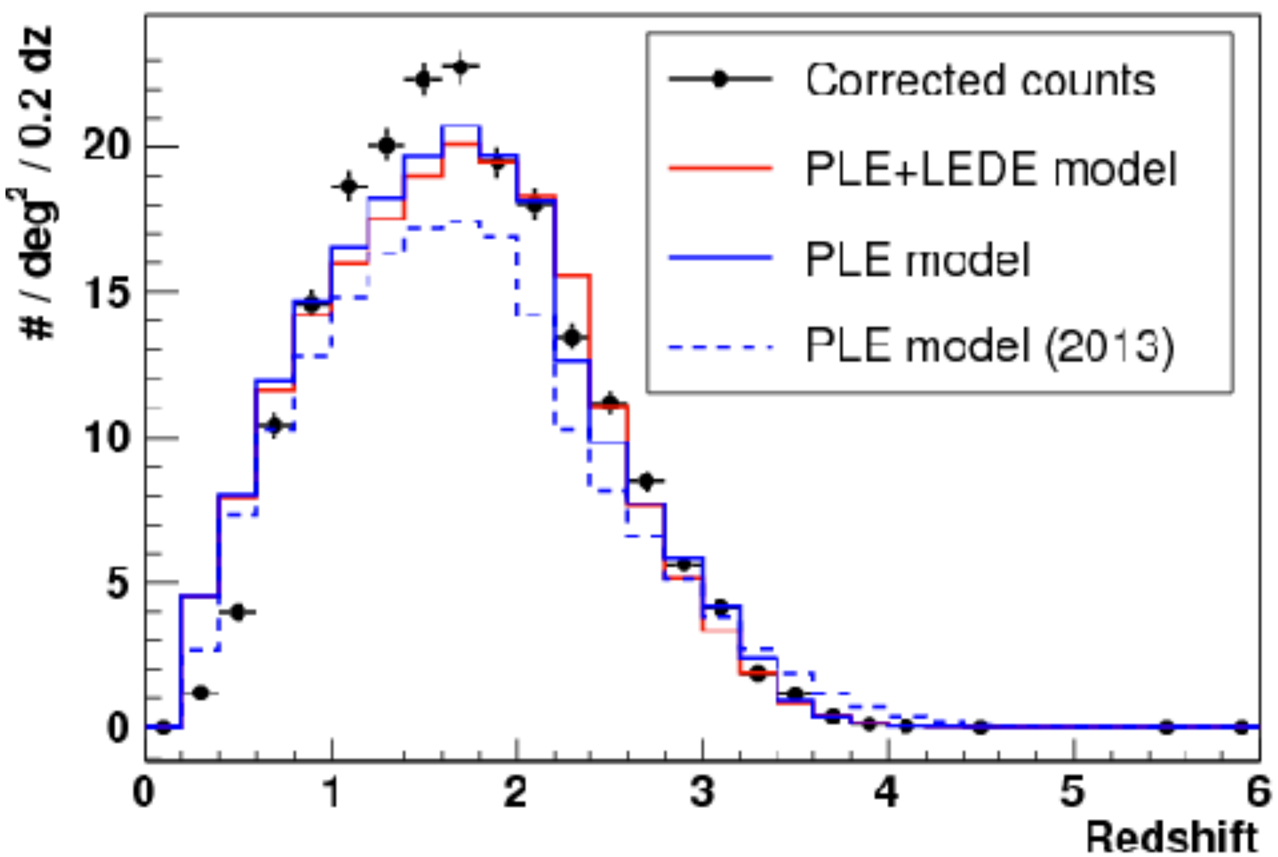




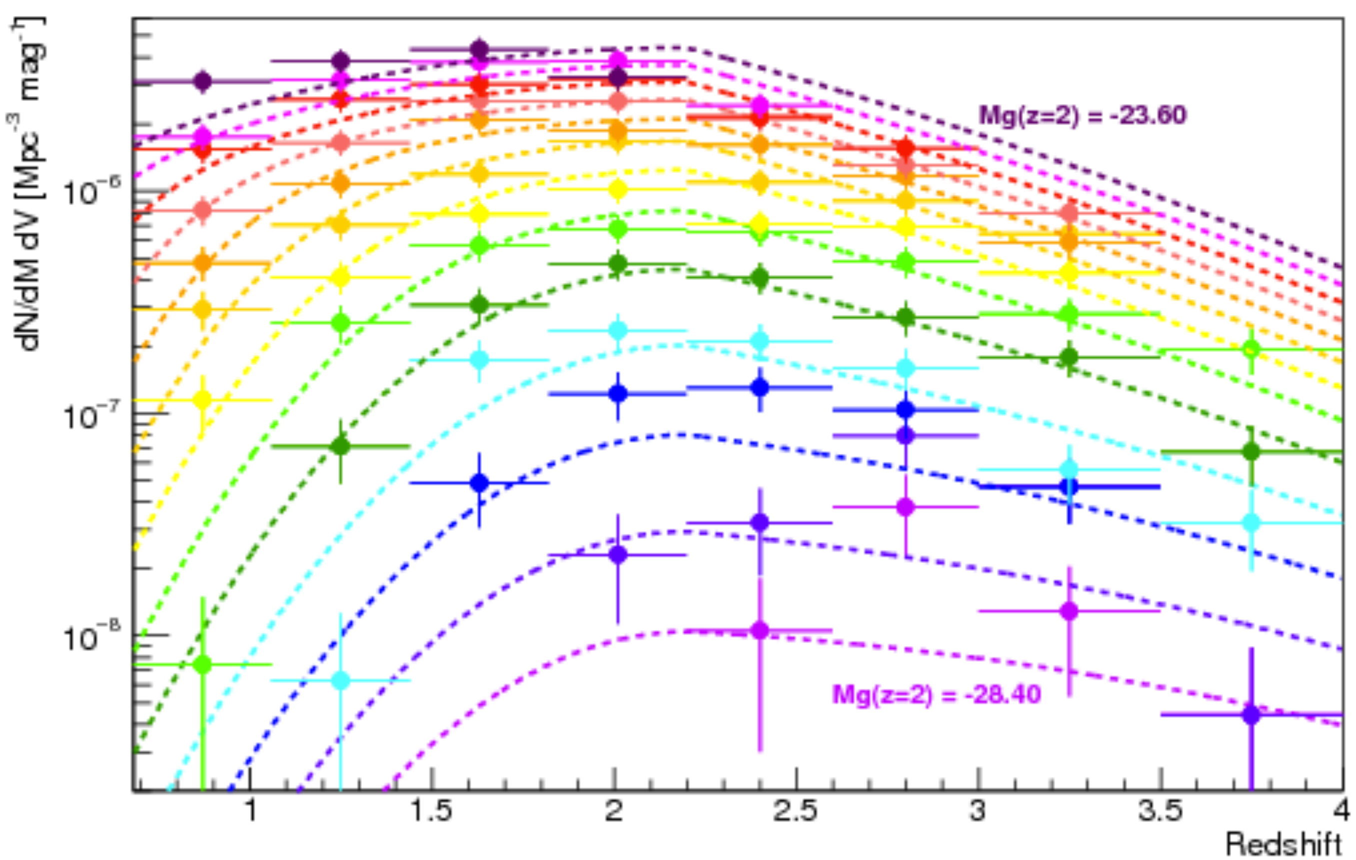
LaMassa et al. (2015)

Quasar

- Quasar luminosity function - peaks at z~1.5-2 (maximum of the star formation activity in the Universe)



Quasar redshift distribution for g<22.5
~100 quasar per sq..degree



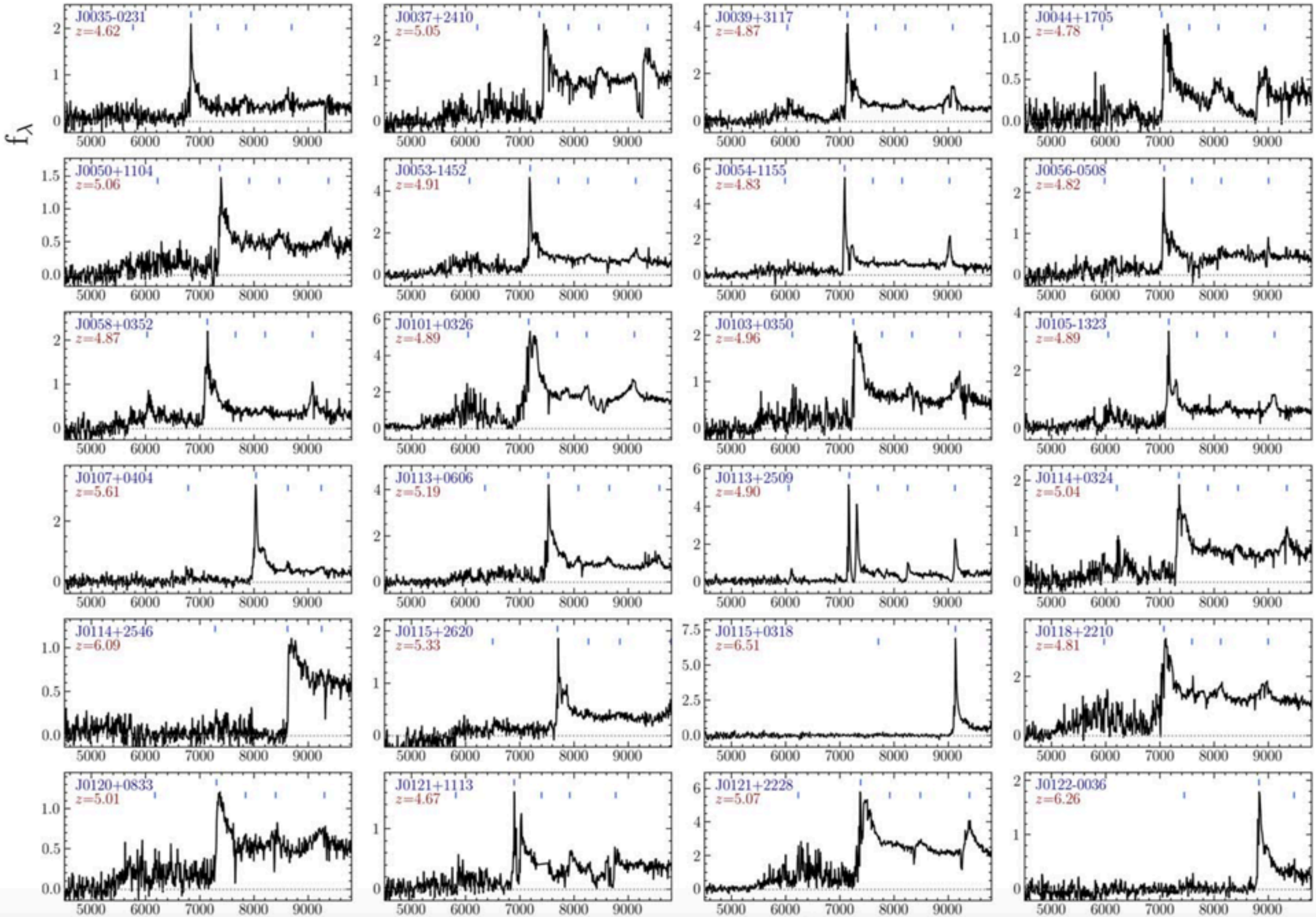
Quasar luminosity function: number counts of quasar as a function of absolute magnitude

Quasar

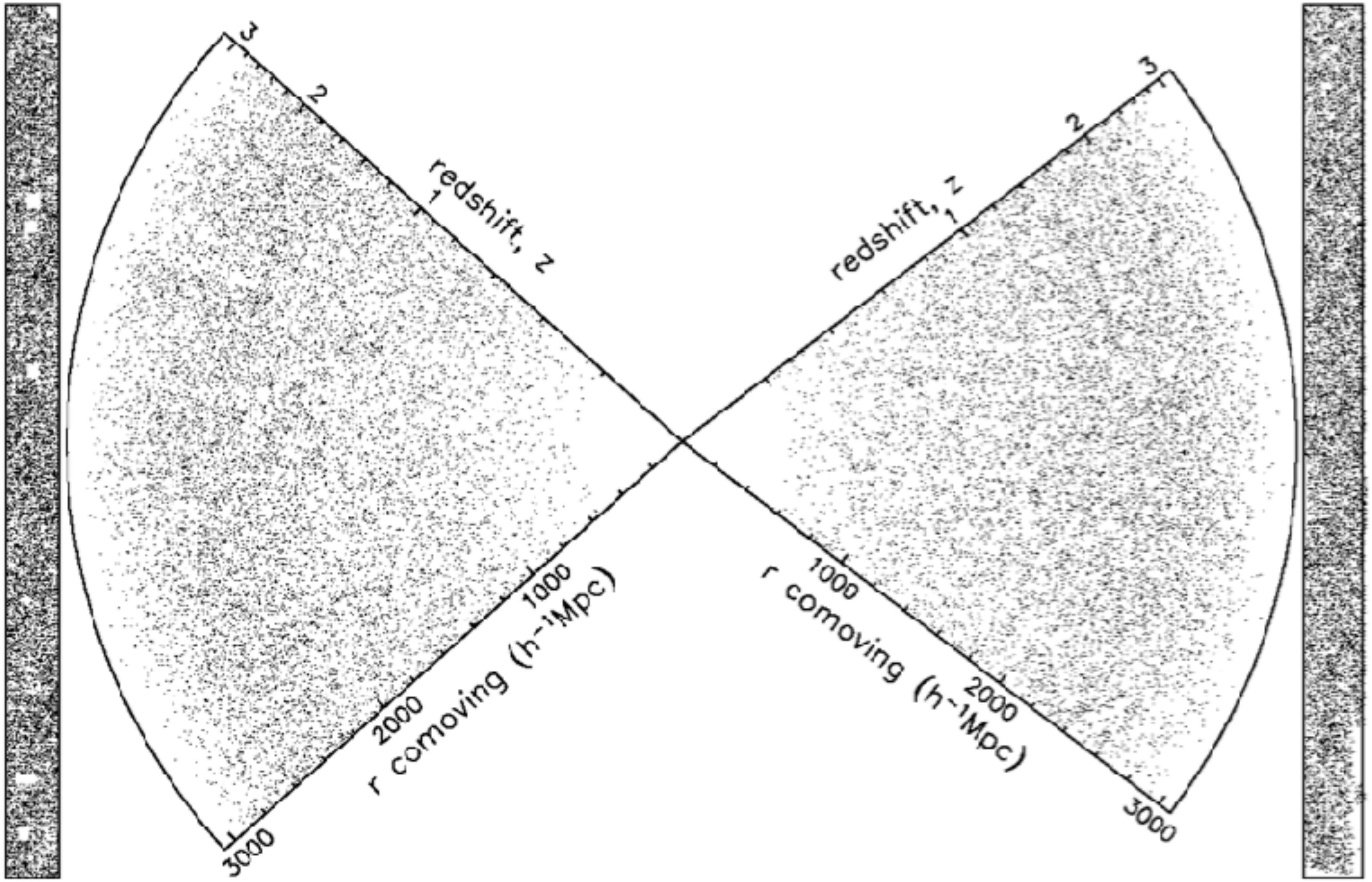
- **Quasar surveys:**
  - 2dF QSO survey (Croom et al 2004):
    - 23’338 quasars
  - SDSS-I and II survey (Schneider et al 2010):
    - 105’783 quasars, 1’248 quasars with $z>4$
  - SDSS-III survey (DR12):
    - 297’301 quasars
  - eBOSS (2014-2019): ~750’000 quasars
  - DESI (2019-2026): aiming to measure 3 million new quasars - 400 new at $z\sim5$

DESI z>~5 quasars

https://iopscience.iop.org/article/10.3847/1538-4365/acf99b



Quasar redshift distribution



- 2DF QSO Redshift survey extends to z~3
- Distribution is rather homogenous (density not enough to identify LSS)

Inter-Galactic Medium

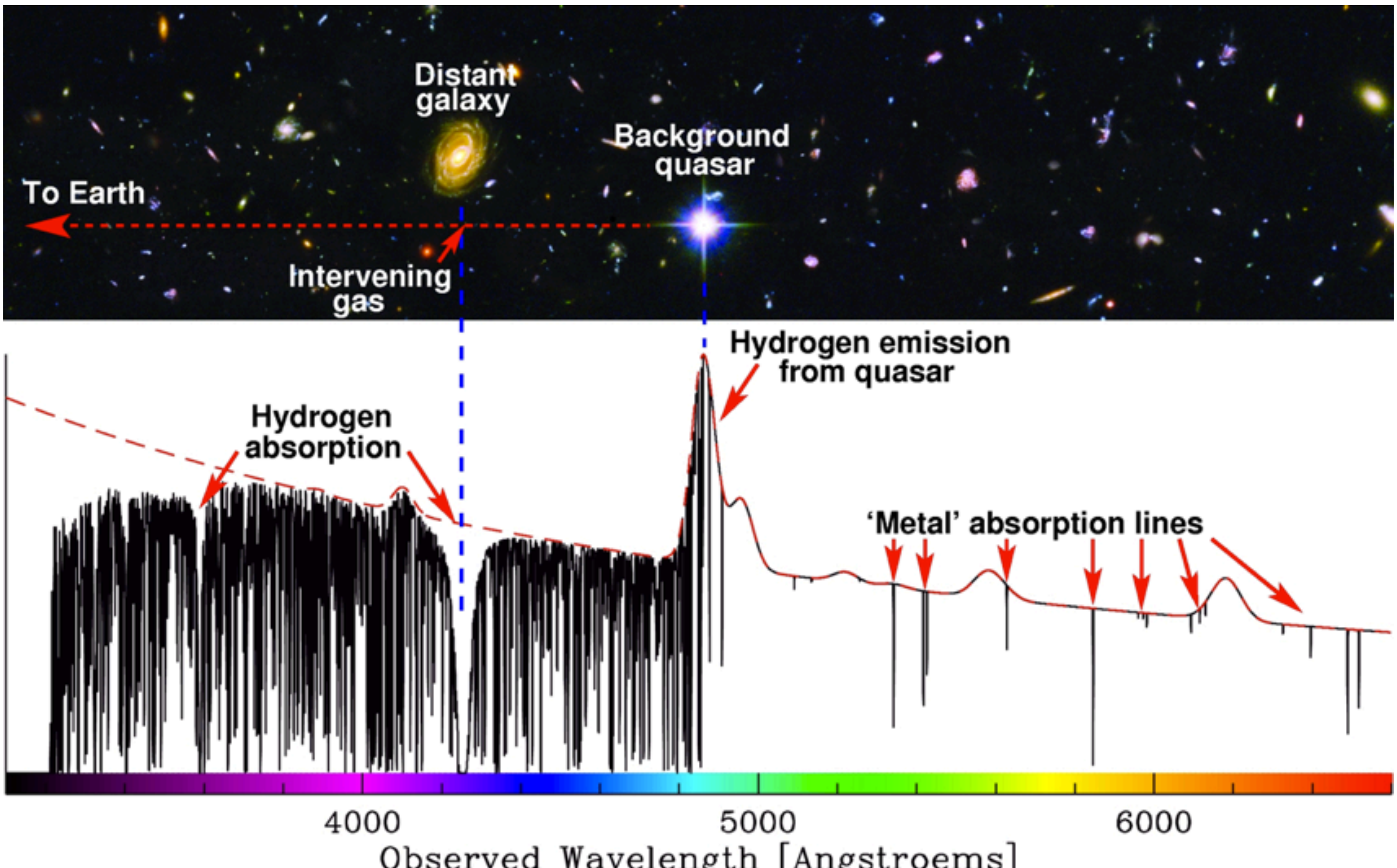
- Outer space is the closest known approximation to a perfect vacuum.
- There is (almost) no friction for bodies (planets, stars, galaxies) to move within the space.
- *However, even the deep vacuum of intergalactic space is not devoid of matter.* ***It contains a few hydrogen atoms per cubic meter.***
- By comparison, the air we breathe contains about *10^{25} molecules per cubic meter*.

Inter-Galactic Medium

- Sparse density of atoms means light can travel easily through the Universe without interaction, we are talking of mean free path of the order of 10 billions light years.
- Absorption and scattering of photons by dust and gas, is an important factor in galactic and intergalactic astronomy.
- How to probe the IGM ?

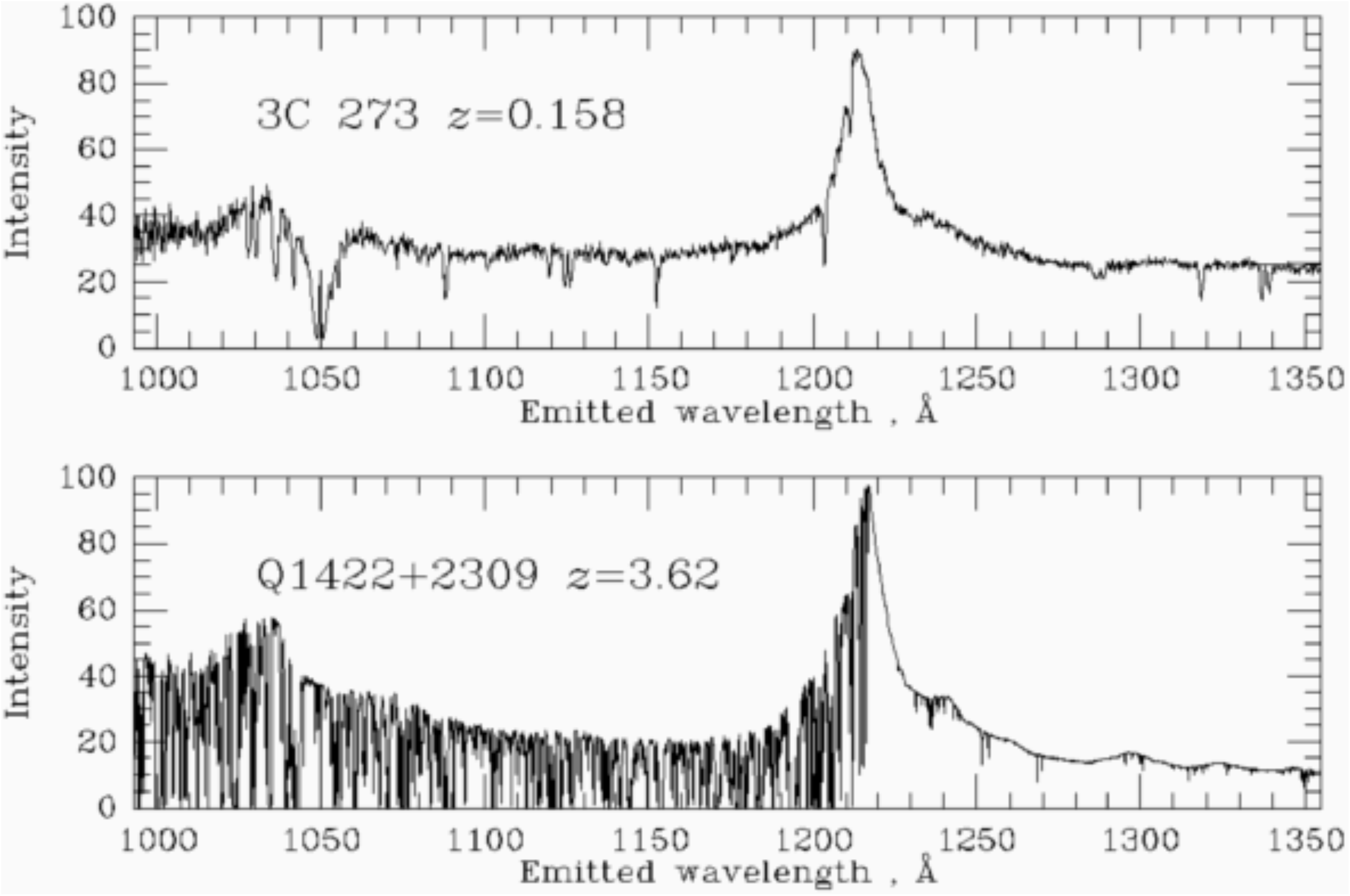
Inter-Galactic Medium

- Quasar light absorption

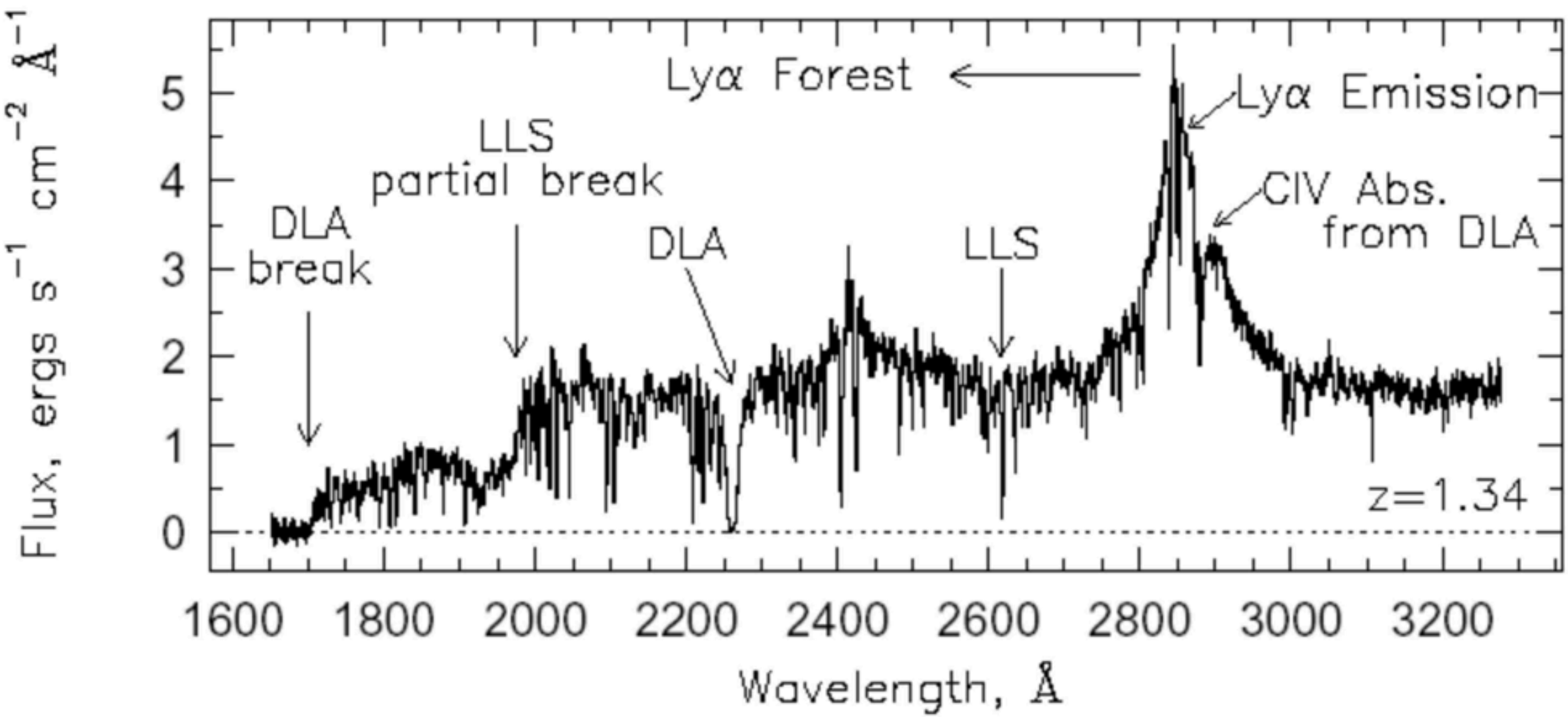


Inter-Galactic Medium

- Quasar light absorption (stronger absorption at higher redshift: more clouds)



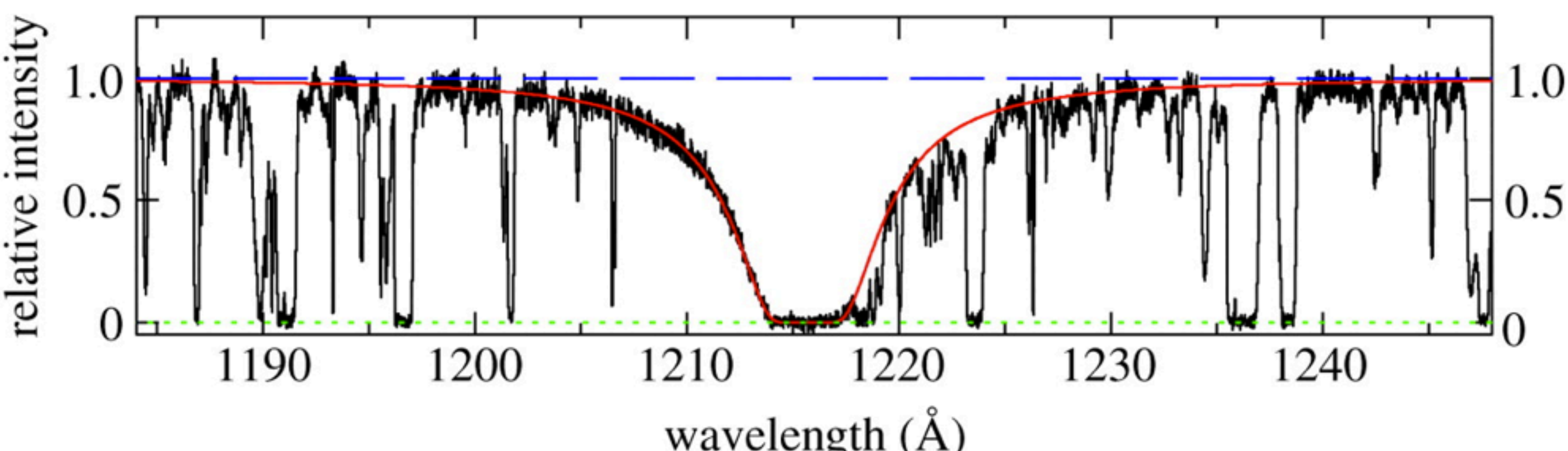
Quasar Spectrum and the Lyman-alpha forest



Quasars have a ~flat continuum and broad emission lines. The vast majority of absorption lines are produced by the IGM. The numerous absorption lines blueward the Ly α emission are mostly Ly α lines at different redshifts $z_{abs} < z_{QSO}$. The observed wavelengths are $\lambda_{obs} = \lambda_{rest}(1 + z_{abs})$, where λ_{rest} = 1215.67 Å. The region redward of the Ly α emission are populated only by absorption due to other chemical transitions with longer λ_{rest}.

Quasar Spectrum and the Lyman-alpha forest

- Example of a Damped Ly-alpha system
- Most of these are Lyα lines produced by low-density gas in the IGM. The stronger damped Lyα line, is indicative of high surface densities of *neutral* gas, normally associated with the interstellar media of galaxies.



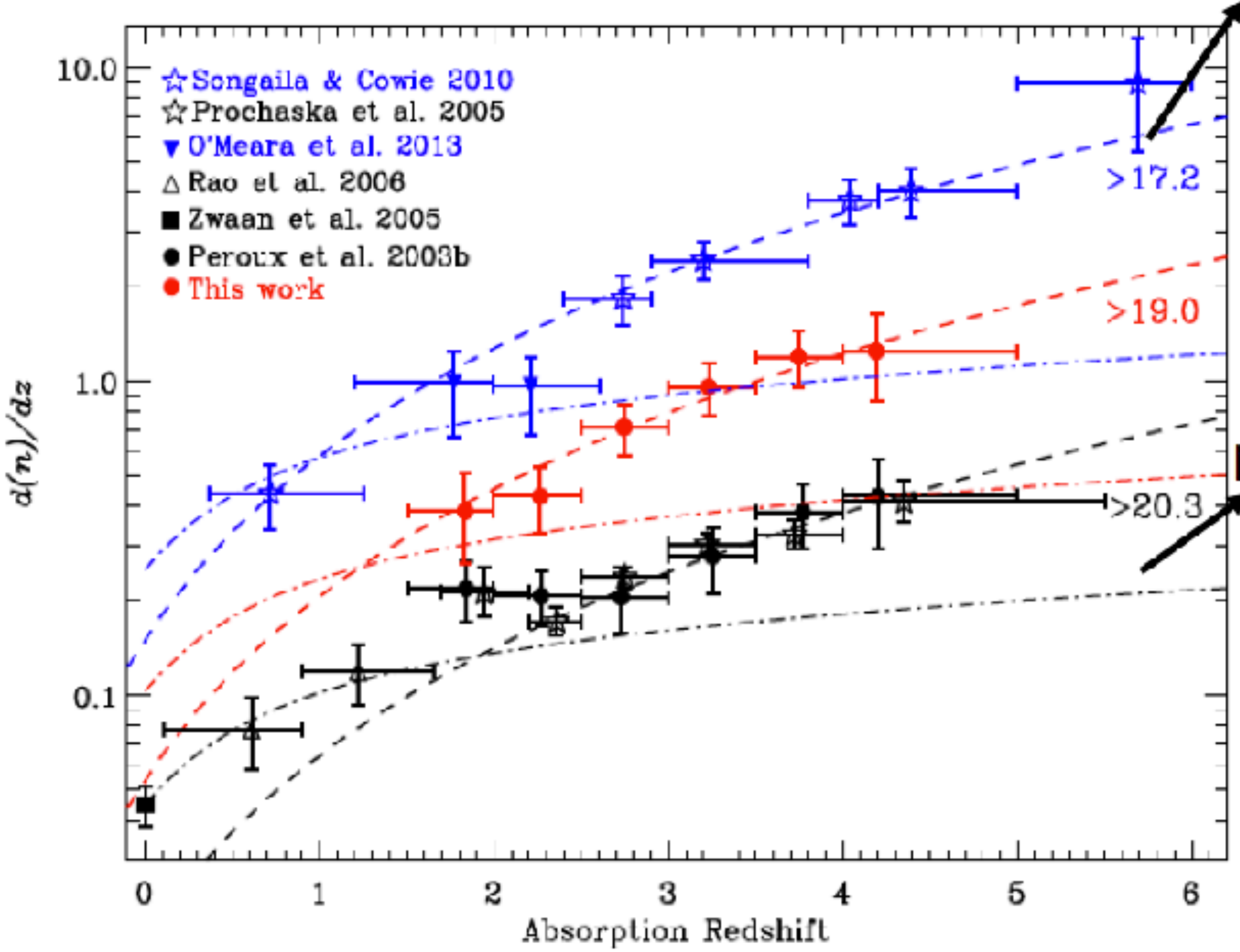
Quasar Spectrum and the Lyman-alpha forest

Number Density

LLS

Sub-DLA

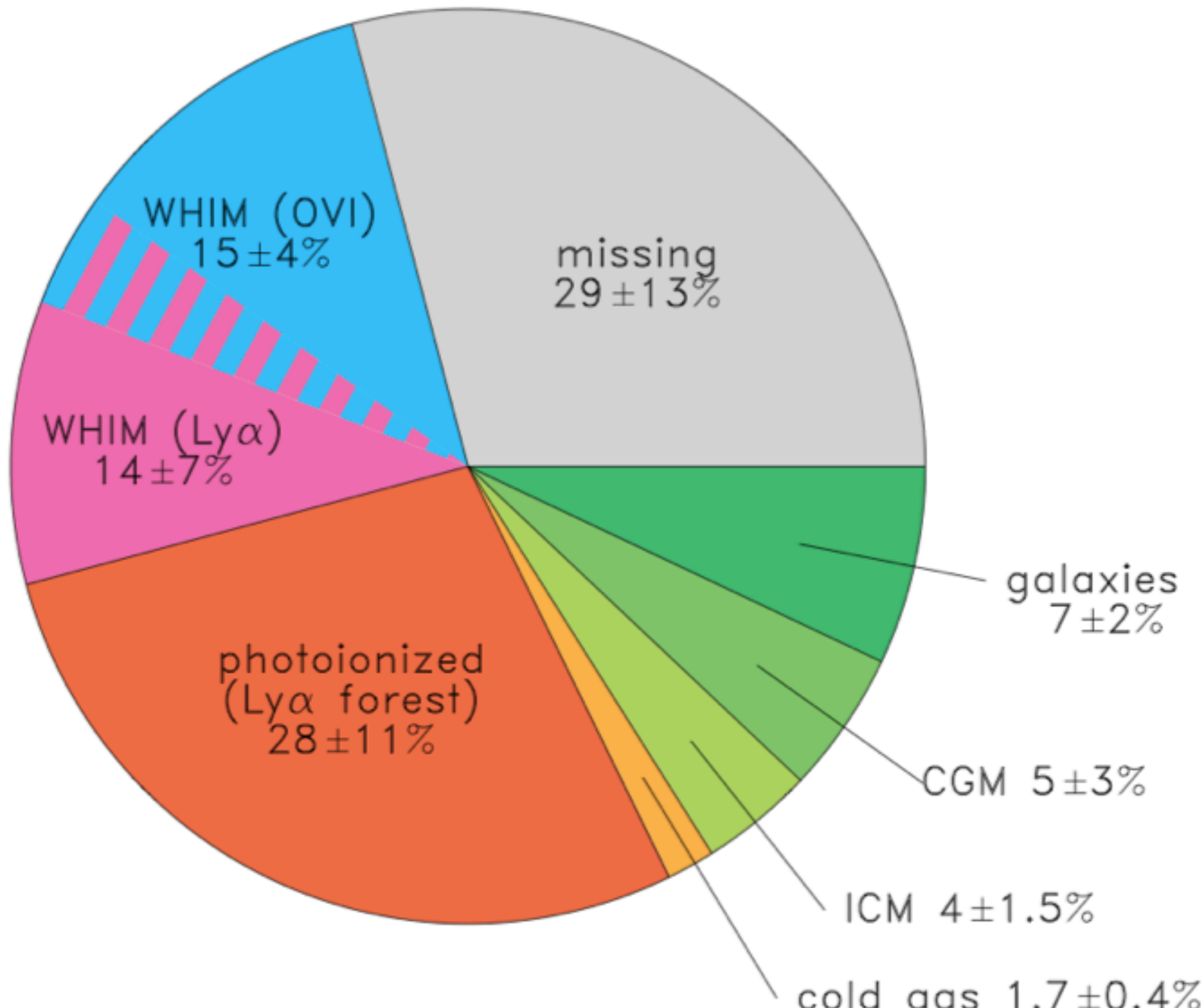
DLA



LLS maximum likelihood fit from Songaila & Cowie 2010

Non-evolution curves

Baryons in the Universe



z=0
Shull et al. 2011

Basics of Modern Cosmology - I

Jean-Paul KNEIB

Principles

- **Copernican Principle:**
    - We do not occupy a special place in the Universe
- **Cosmological Principle:**
    - Universe is homogeneous
    - Universe is isotropic
- **Weak Anthropic principle:**
    - The Universe is such that Life *is possible* (can fit with theism - God has enable Life)
- **Strong Anthropic principle:**
    - The Universe is such that Life *is inevitable* - **The purpose of the Universe is that we exist ...**

Assumptions of Modern Cosmology

- **General Relativity is the theory of Gravitation**
- **The Cosmological Principle:**
  - Universe is Homogeneous on large scale (>100 Mpc) - can be tested
  - and isotropic (we do not occupy a special place in the Universe) - can be tested
- The Einstein equations (linking mass-energy to space-time) - can be tested (hard)

Coordinate systems

From Special Relativity

$$ds^2 = c^2 dt^2 - (dx^2 + dy^2 + dz^2)$$

distance element in space-time

$$ds^2 = c^2 dt^2 - dl^2$$

$$\tau = \frac{s}{c}$$ is the proper time

Coordinate systems

From General Relativity

$$ds^2 = g_{\mu\nu} dx^\mu dx^\nu$$

$g_{\mu\nu}$ **is the metric tensor**

x^μ are the space-time coordinates

$x^0 = ct$ time coordinate

Coordinate system evolution

In a curved space-time, there is no coordinate system that can apply everywhere.
The coordinate system however can be approximated locally to a Lorentz manifold.
To do this we are using the **Christoffel Symbols**, which describe the evolution of the base vectors in the curved space-time:

$$\nabla_{\vec{e_i}} \vec{e_j} = \Gamma^k_{ij} \vec{e_k}$$

(covariant derivative=derivative along tangent vectors of a manifold.)

Coordinate system evolution

Because the metric is locally conserved, the derivative of the metric is zero:

$$\nabla_{\vec{e}_j} \overrightarrow{g_{ik}} = 0$$

Using the Christoffel symbol we can then show that:

$$\Gamma^{\lambda}_{\mu\nu} = \frac{1}{2} g^{\lambda\sigma} \left[\frac{\partial g_{\nu\sigma}}{\partial x^{\mu}} + \frac{\partial g_{\mu\sigma}}{\partial x^{\nu}} - \frac{\partial g_{\mu\nu}}{\partial x^{\sigma}} \right]$$

In other words, we are linking the change of the coordinate system to the variation of the metric tensor.

Path of a free particle

The equation of a geodesic (the straight line in general relativity) is defined by:

$$\frac{d^2x^\lambda}{ds^2} + \Gamma^\lambda_{\mu\nu}\frac{dx^\mu}{ds}\frac{dx^\nu}{ds} = 0$$

s is the scalar parameter of motion (*proper time*).

This equation is equivalent to the Newton's law of motion but in the context of General Relativity.

Einstein Field Equation

The Einstein field equation link mass-energy to the metric, it can be written as:

$$R_{\mu\nu} - \frac{1}{2} R g_{\mu\nu} + \Lambda g_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

$R_{\mu\nu}$ is the Ricci curvature tensor.

R is the Ricci scalar curvature.

$T_{\mu\nu}$ is the impulsion-energy tensor.

Λ is the cosmological constant.

Einstein Field Equation for beginners https://www.youtube.com/watch?v=foRPKAKZWx8

Cosmological Principle

- There is a universal time (proper time)

$$ds^2 = c^2 dt^2 - dl^2$$

- The universe is homogeneous and isotropic (no special position in space)

$$dl^2 = B(r,t)dx^2 = a^2(t)F(r)dx^2$$

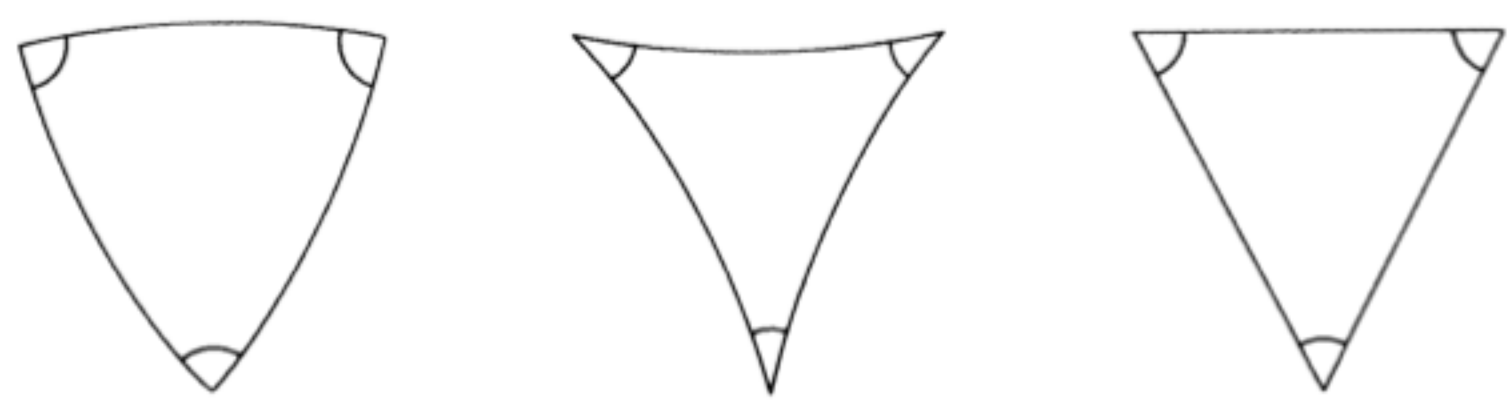
$a(t)$ is the scale factor $R(t)$ is also used

$F(r)$ defines the global curvature

Friedmann-Lemaitre-Robertson-Walker metric

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

- *the FLRW is the only general metric following the cosmological principle*
- k is the curvature:
  - -1: open hyperbolic
  - 0: flat
  - +1: closed spheric



k=1 k=-1 k=0

Redshift and scale factor

$t_e \;\; \lambda_e$  $t_0 \;\; \lambda_0$

$$\lambda \propto a(t)$$

$$1+z = \frac{\lambda_0}{\lambda_e}$$ Definition of redshift

$$1+z = \frac{a(t_0)}{a(t_e)}$$ Redshift is a measure of the change in the scale factor

often written with this simplified form: $1+z=\dfrac{1}{a(t)}$

Proper Distance

- The proper distance is time dependent, evaluated at a fixed time t. Because time is fixed, $dt=0$:

$$d_{pr}(t) = s(t) = \int_0^r ds = a(t) \int_0^r \frac{dr'}{\sqrt{1 - kr'^2}} = a(t) f(r)$$

- with

$$f(r) = \arcsin(r), \quad r, \quad \mathrm{argsh}(r)$$

- for $k=1, 0, -1$

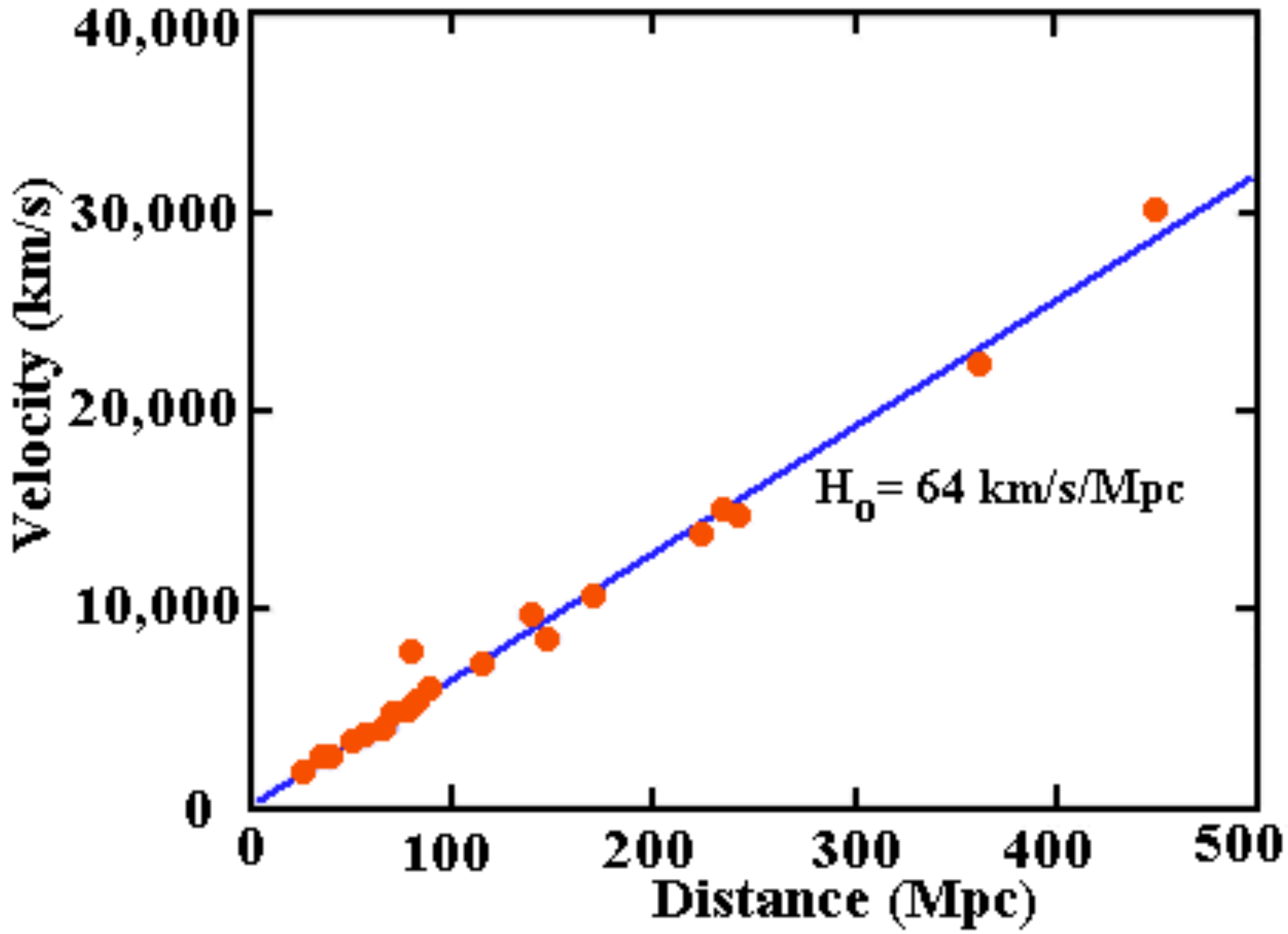
Hubble Law

- The relative velocity [due to the expansion of the Universe] (derivative of the proper distance):

$$v_r = \frac{d(d_{pr}(t))}{dt} = \dot{a}(t) f(r) = \frac{\dot{a}(t)}{a(t)} d_{pr} = H(t) d_{pr}$$

- is proportional to the proper distance times the Hubble parameter $H(t)$. **This is the Hubble Law.**
- When evaluated at present time: $t = t_0$,
- $H_0 = H(t_0)$ (Hubble constant).

Hubble Law



Notation:

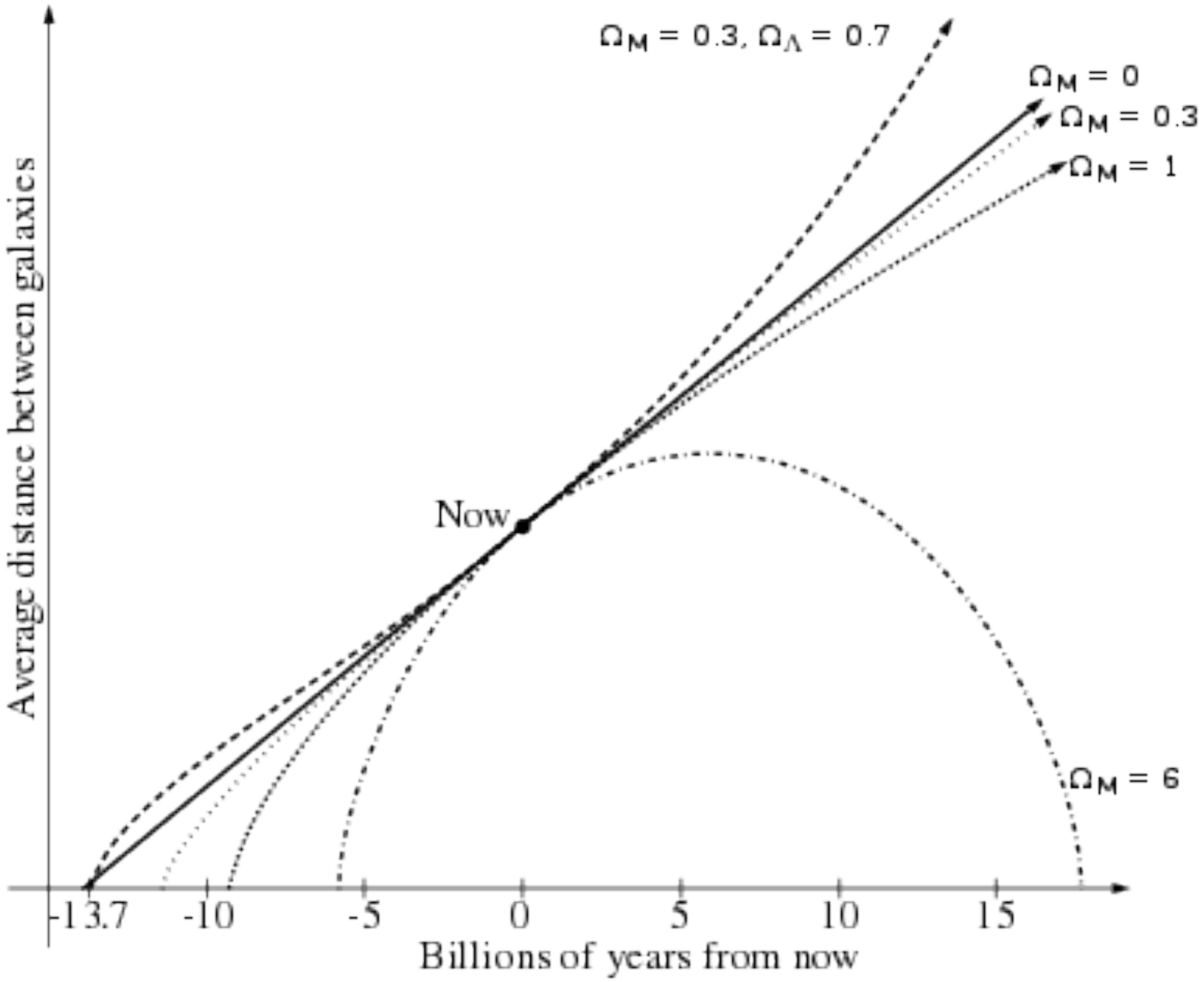
$H_0 = 100.h$ km/s/Mpc

h encapsulates our ignorance on the value of the Hubble constant.

(h_{50}, h_{100})

This diagram is based upon distances found using Supernovae. The slope of the line gives the value for the Hubble Constant, H_o. Data from Riess, Press and Kirshner (1996).

accelerating/decelerating Universe



Deceleration parameter

Let's expand the scale factor as a function of time

$$a(t)=a(t_0)+(t-t_0)\left(\frac{da(t)}{dt}\right)_{t=t_0}+\frac{1}{2}(t-t_0)^2\left(\frac{d^2a(t)}{dt^2}\right)_{t=t_0}+\ldots$$

introducing $H_0=H(t_0)=\frac{\dot{a}(t_0)}{a(t_0)}$ we have then:

$$a(t)=a_0\left[1+H_0(t-t_0)-\frac{1}{2}H_0^2q_0(t-t_0)^2+\ldots\right]$$

where $q_0=-\frac{\ddot{a}(t_0)a_0}{\dot{a}(t_0)^2}$ q_0 negative = acceleration

Look-back time as a function of redshift

$$1+z=\frac{a_0}{a(t)}=\frac{1}{\left[1+H_0(t-t_0)-\frac{1}{2}H_0^2q_0(t-t_0)^2+\ldots\right]}$$

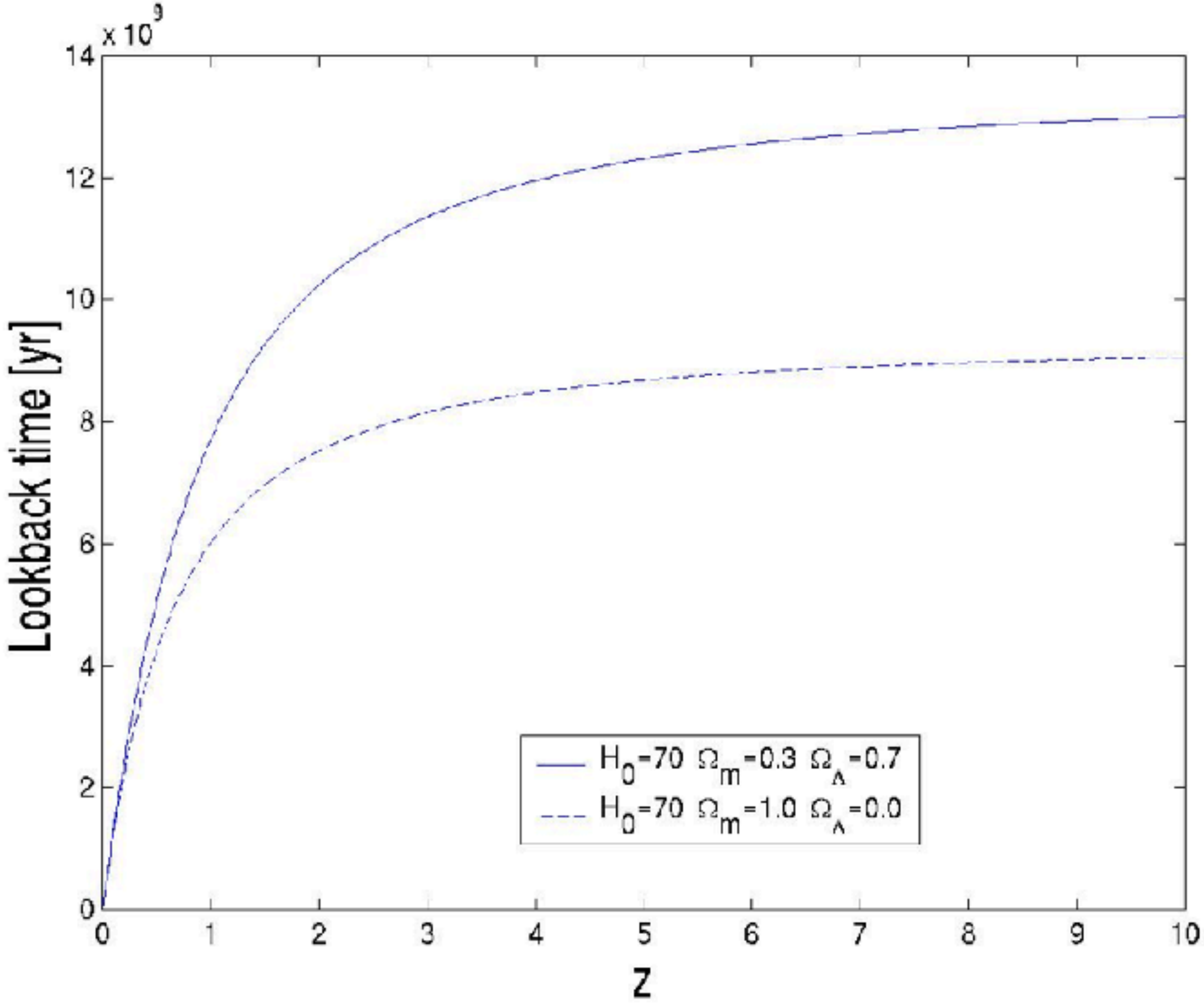
assuming $t-t_0$ small

$$1+z=1+H_0(t_0-t)+H_0^2(t_0-t)^2\left[1+\frac{q_0}{2}\right]+\ldots$$

and then inverting

$$t_0-t=\frac{1}{H_0}\left[z-z^2\left(1+\frac{q_0}{2}\right)+\ldots\right]$$

Look-back time



Volume calculation

- One can compute the volume for the 3 type of geometry:

$$V = a^3(t) \int_0^r \frac{r^2\,dr}{\sqrt{1-kr^2}} \int_0^\pi \sin\theta\,d\theta \int_0^{2\pi} d\phi$$

Depending on the curvature:

$$V_{k=0} = \frac{4\pi(a(t)r)^3}{3}$$

$$V_{k=1} = \frac{4\pi(a(t)r)^3}{2}\left[\frac{\arcsin(r)}{r^3} - \frac{\sqrt{1-r^2}}{r^2}\right]$$

$$V_{k=-1} = \frac{4\pi(a(t)r)^3}{2}\left[\frac{\sqrt{1+r^2}}{r^2} - \frac{\operatorname{argsh}(r)}{r^3}\right]$$

Distances

- **proper distance**: physical distance, at fixed time t:

$$d_{prop}=a(t)f(r)=\frac{f(r)}{1+z}$$

- **comoving distance**: distance between comoving coordinates (does not change with the expansion)

$$d_{comoving}=f(r)$$

- The comoving distance to an object with redshift z can be found by following a photon on a null geodesic ($ds=0$) from the emitted to the observed time (today):

$$d_{com}(z)=f(r(z))=\int_0^r \frac{dr'}{\sqrt{1-kr'^2}}=\int_{t_e}^{t_0}\frac{cdt'}{a(t')}=\int_0^z \frac{cdz'}{H(z')}$$

Note: comoving and physical distances are the same today ($a=1$)

Details of derivation

$$d_{com}(z) = f(r(z)) = \int_0^r \frac{dr'}{\sqrt{1 - kr'^2}} = \int_{t_e}^{t_0} \frac{cdt'}{a(t')} = \int_0^z \frac{cdz'}{H(z')}$$

By definition $$H = \frac{\dot{a}}{a} = \frac{da}{a.dt}$$

Link between scale factor an redshift $$a = \frac{1}{1+z}$$

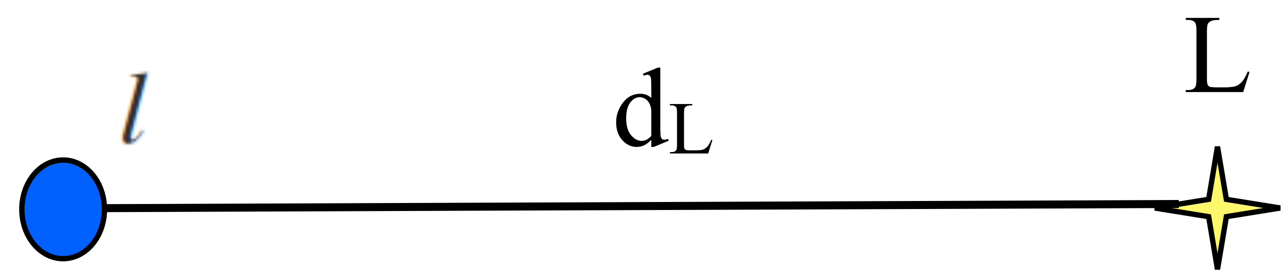
Taking the derivative: $$da = -\frac{dz}{(1+z)^2} = -a^2 dz$$

Then $$H = \frac{da}{a.dt} = -a\frac{dz}{dt} = -\frac{dz}{(1+z)dt}$$

Distances

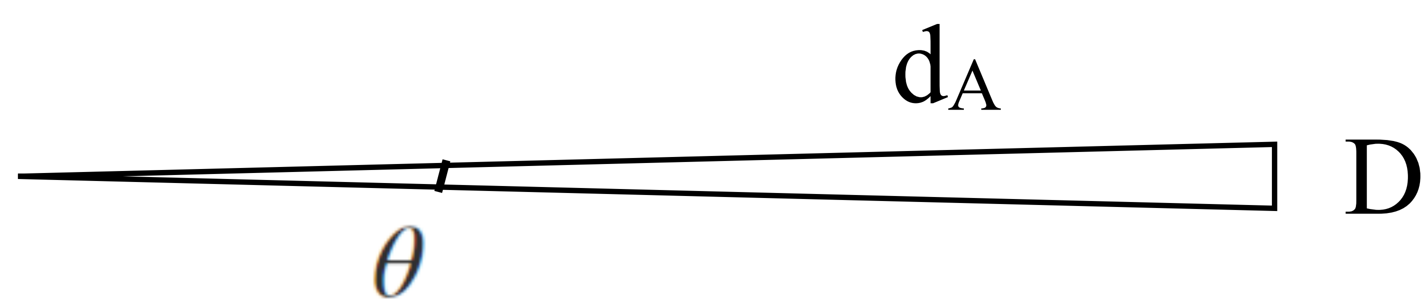
- **Luminosity distance** is defined using the standard relationship between observed and emitted flux:

$$d_L = \left(\frac{L}{4\pi l} \right)^{1/2}$$



- **Angular Diameter distance** is defined using the normal relationship between physical and angular sizes:

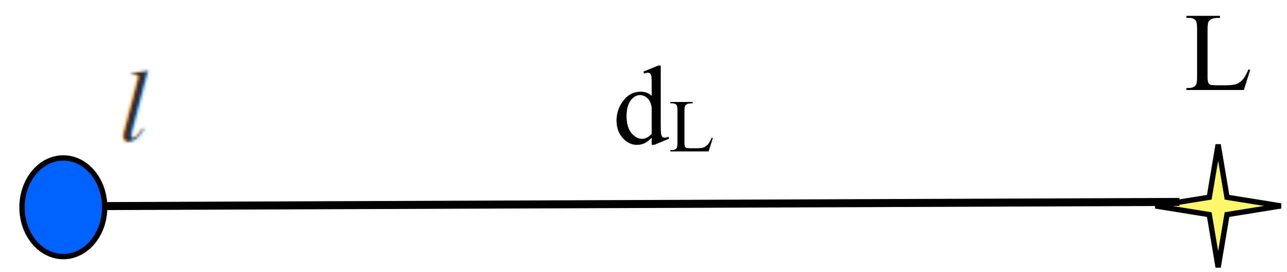
$$d_A = \frac{D}{\theta}$$



Distances

- **Luminosity distance**

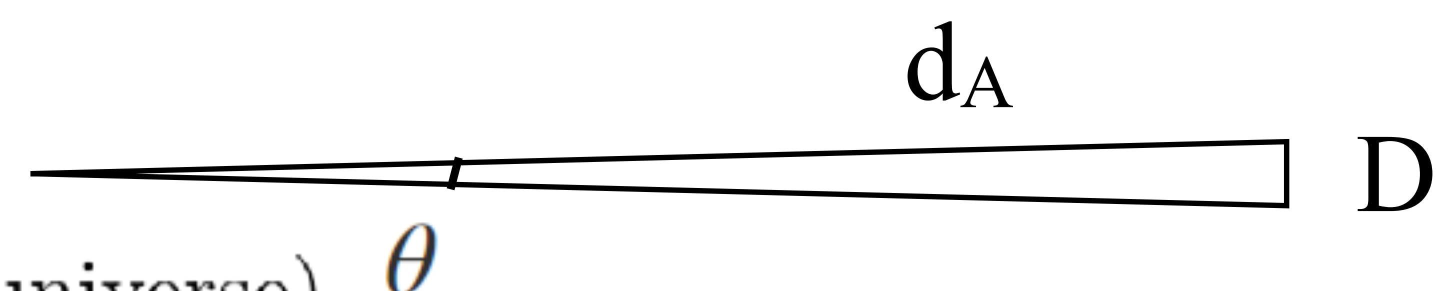
$$d_L = \left(\frac{L}{4\pi l} \right)^{1/2}$$



$$\begin{aligned} d_L(z) &= r(z)(1+z) \\ &= d_{com}(z)(1+z) \ \text{(flat universe)} \end{aligned}$$

- **Angular Diameter distance**

$$d_A = \frac{D}{\theta}$$



$$\begin{aligned} d_A(z) &= r(z)/(1+z) \\ &= d_{com}(z)/(1+z) \ \text{(flat universe)} \end{aligned}$$

In a flat Universe, the angular diameter distance equals the proper distance to an object *at the time the light was emitted.*