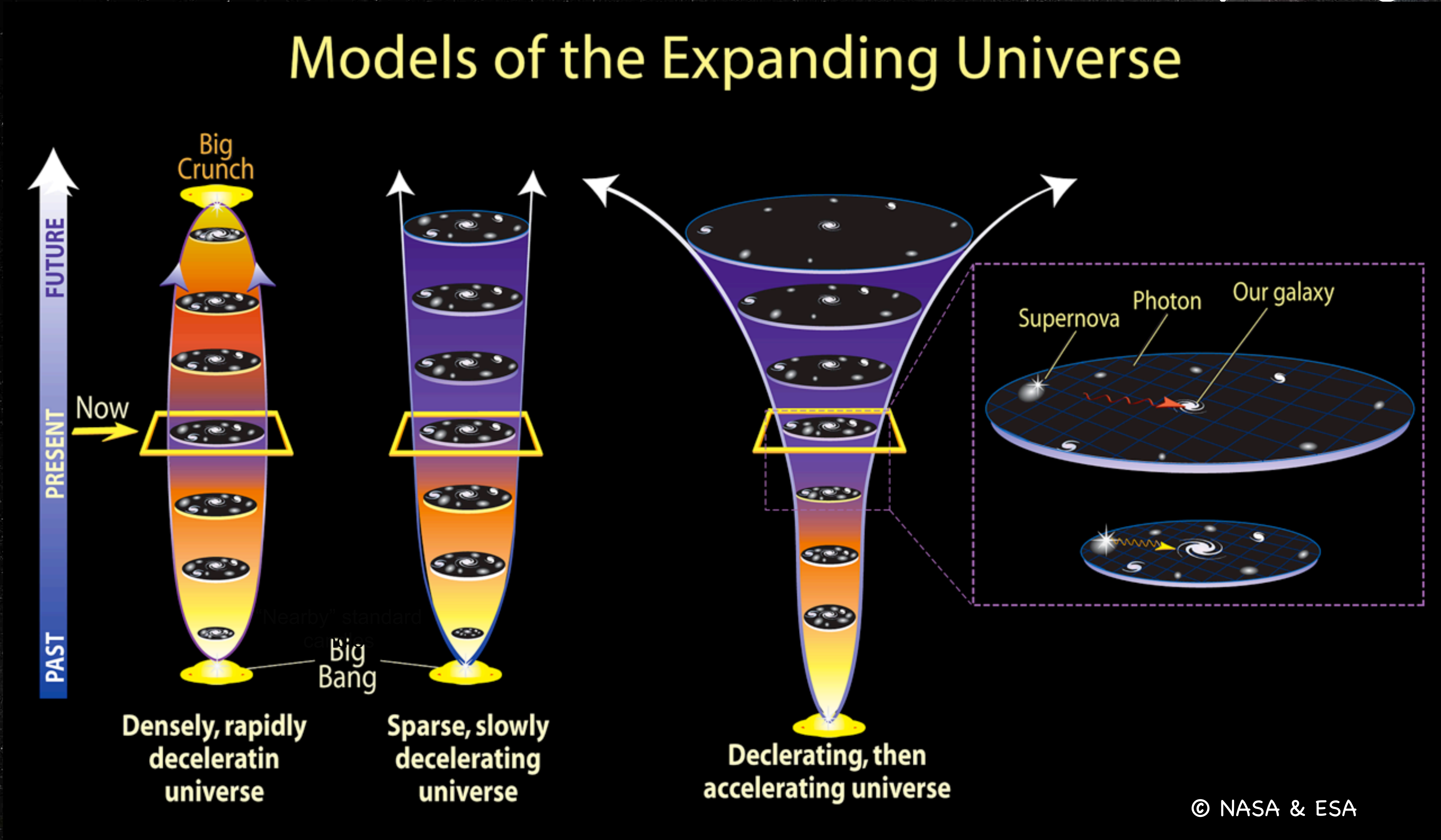
New light on dark energy

Raul Abramo
Physics Institute
USP

We know since 1929 (Hubble) that the Universe is **expanding...**



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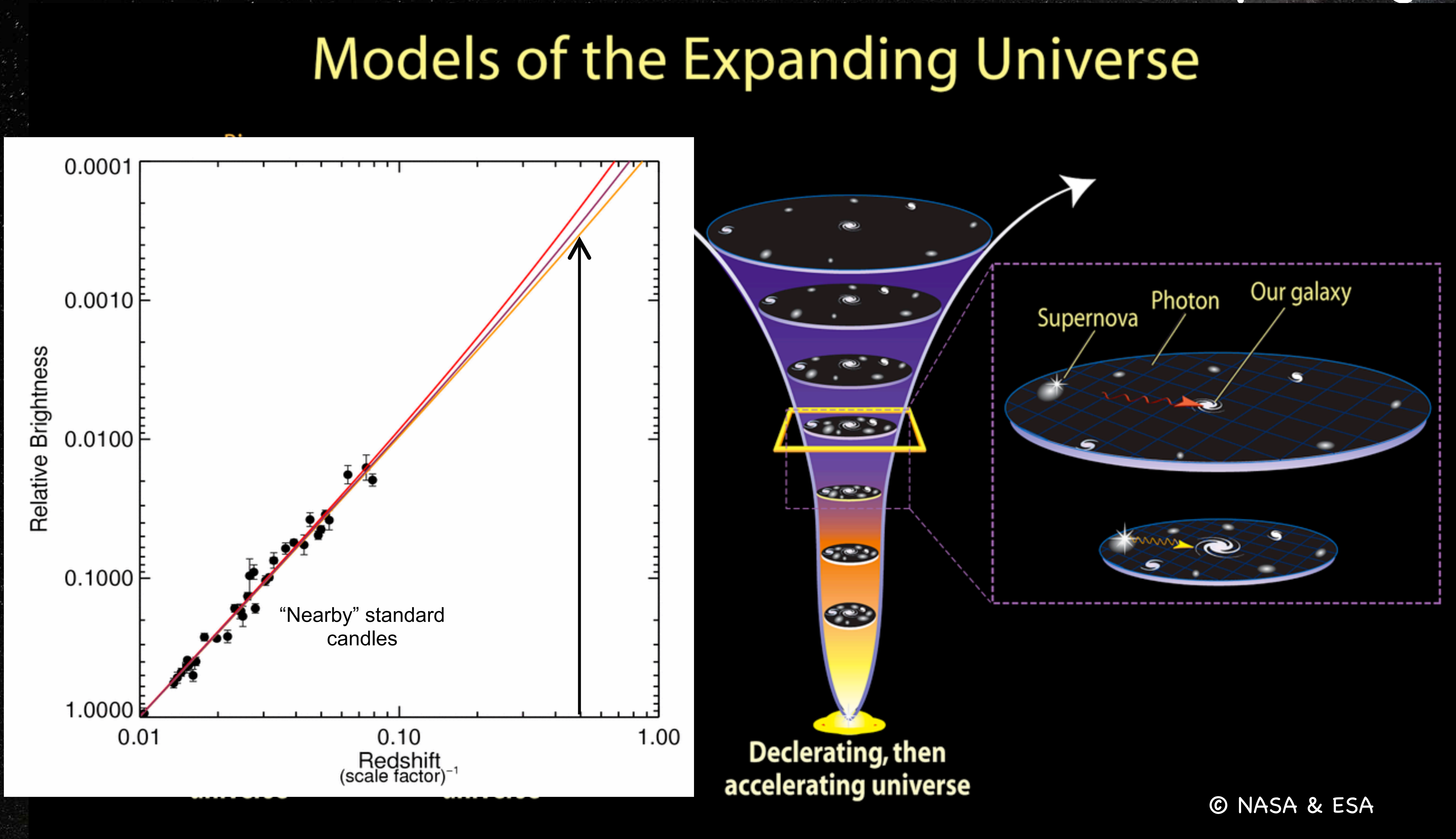

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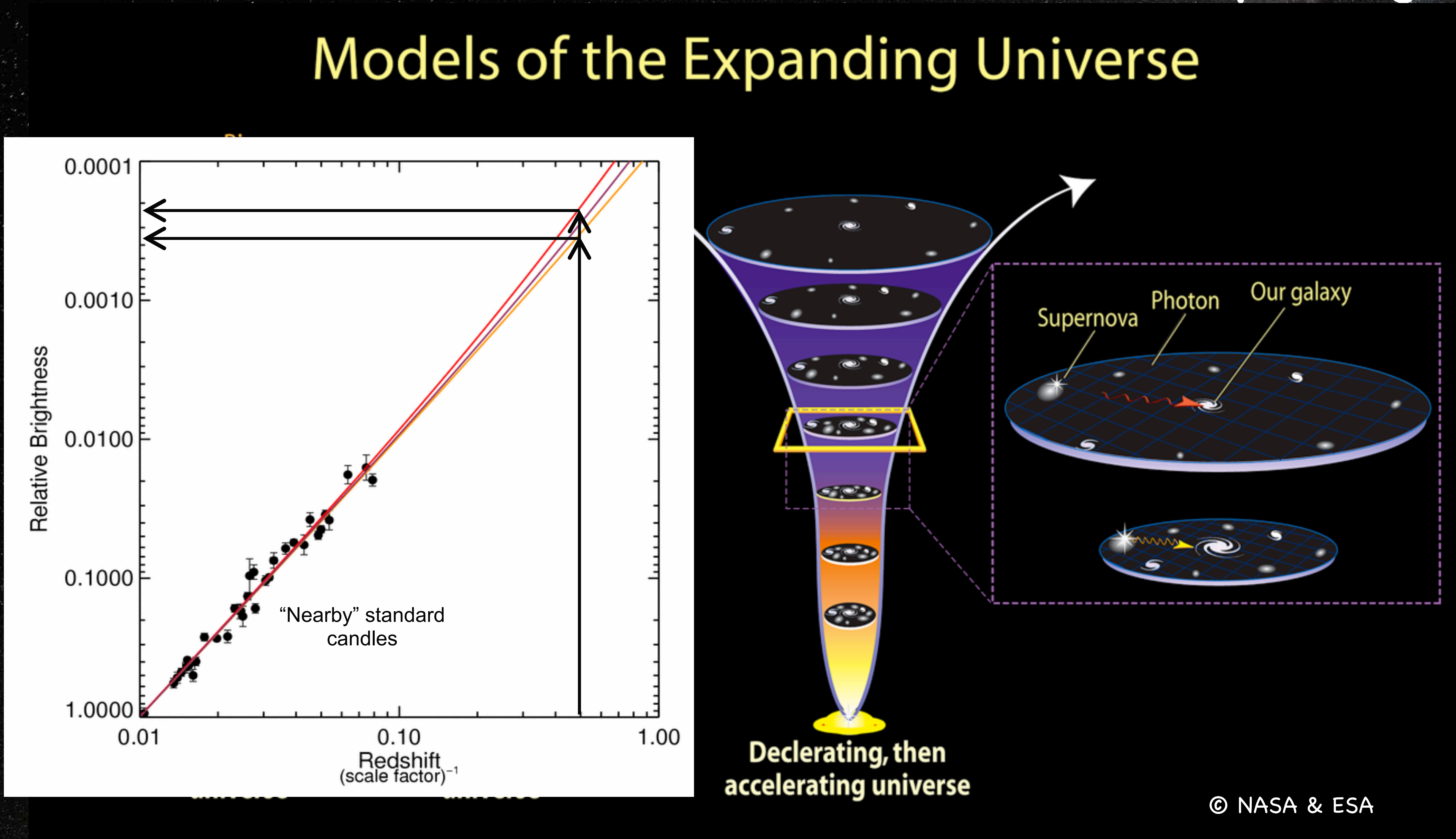

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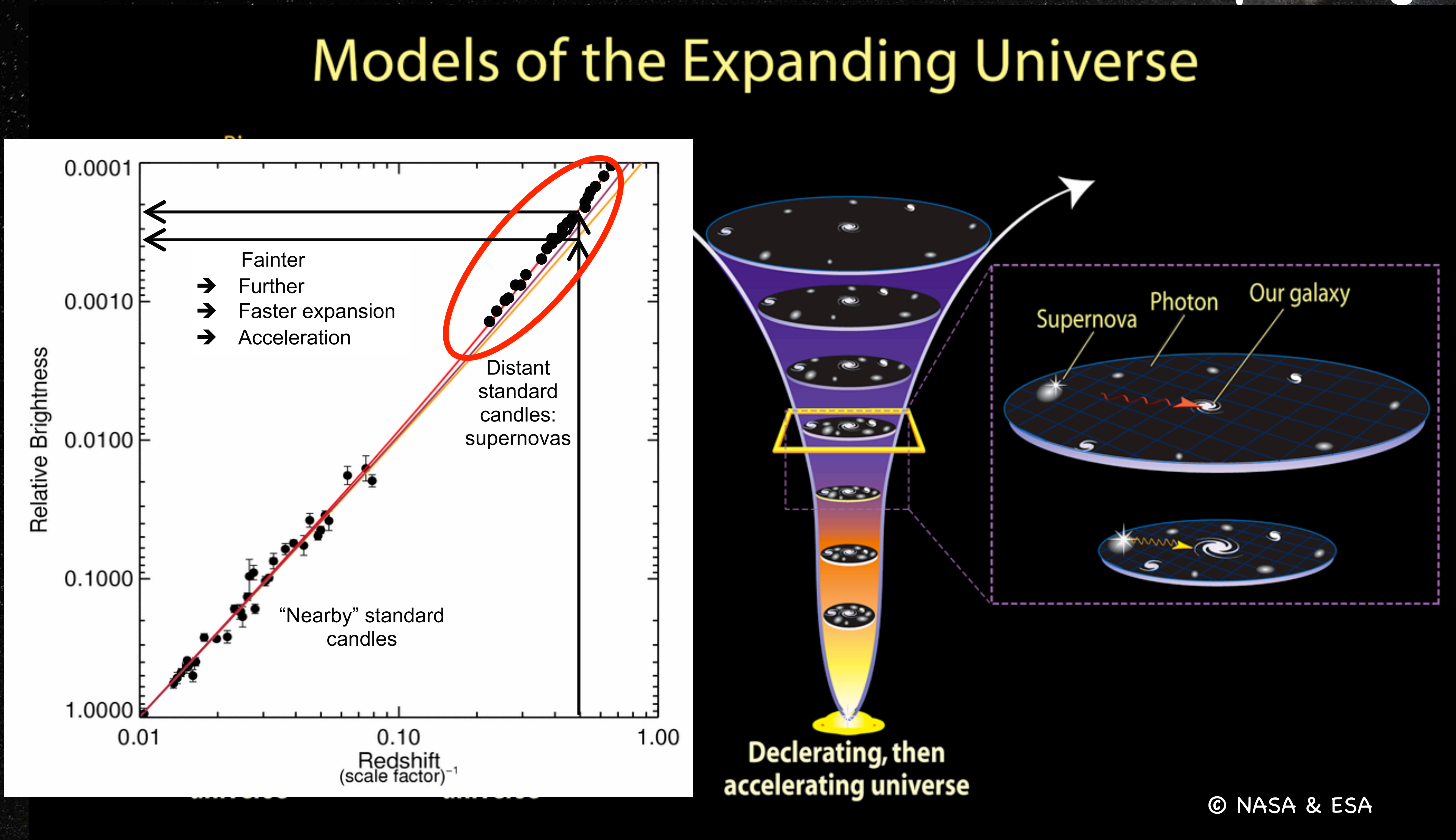
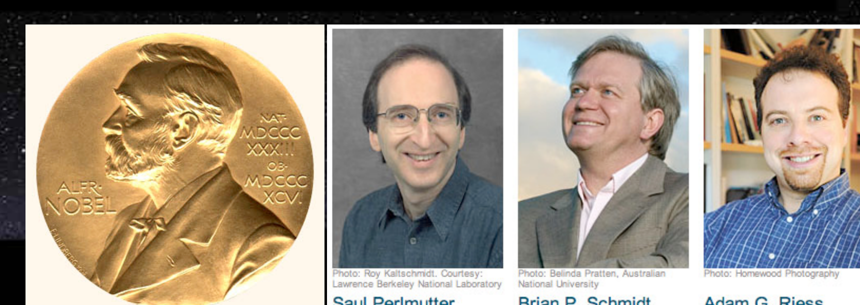


... but we only learned in **1998** that this expansion is now **accelerating**



WHY? WHAT? HOW?

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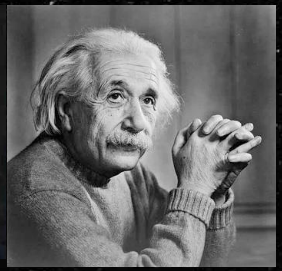

Gravity is **attractive** - it should **pull things together,** acting as a **break** on expansion

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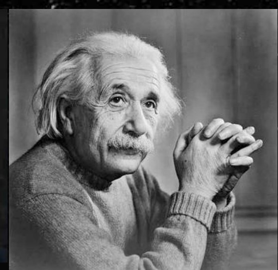

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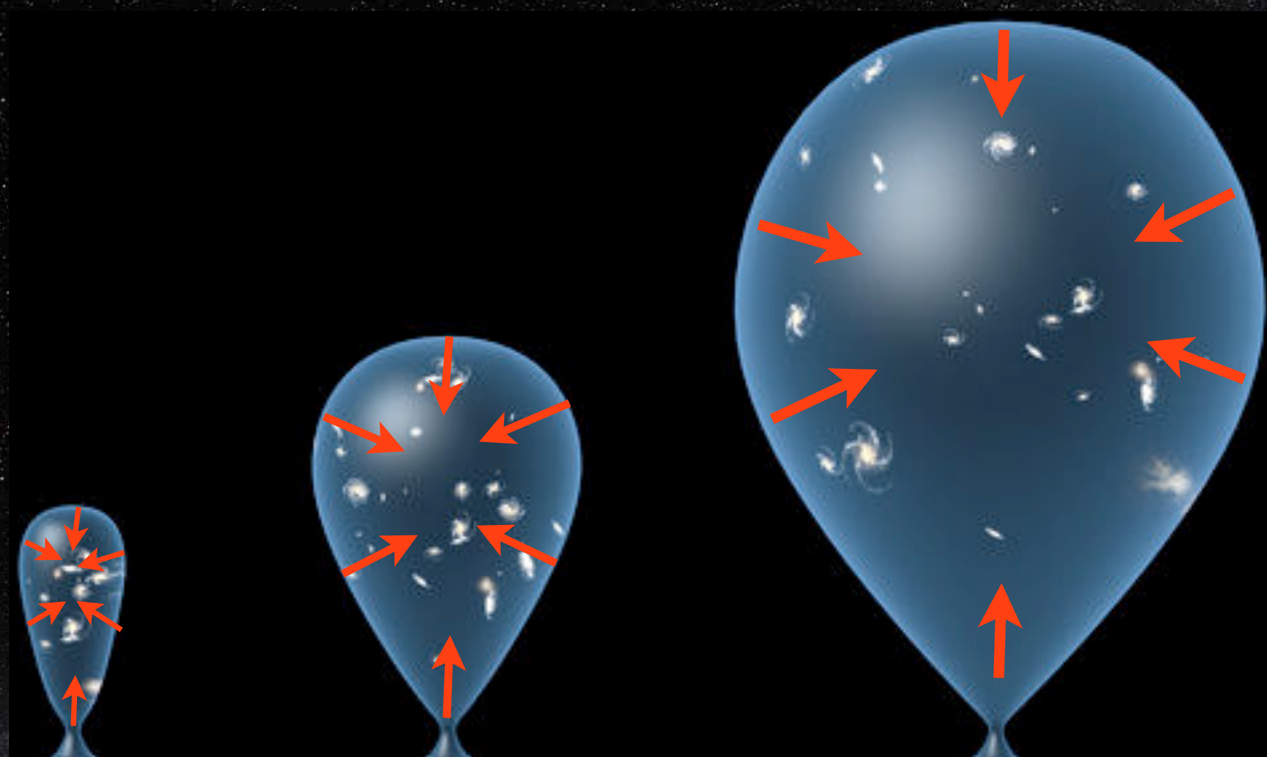

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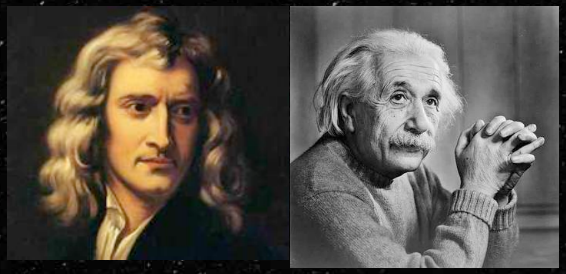

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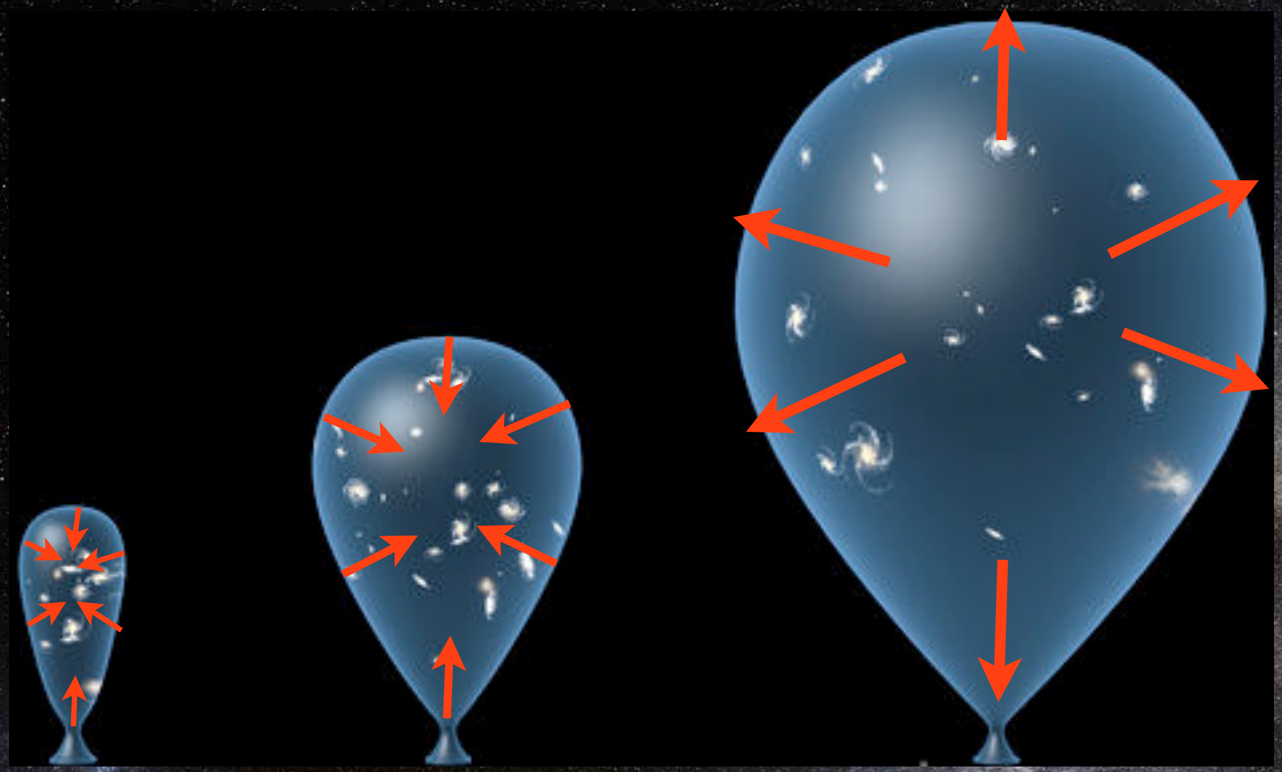
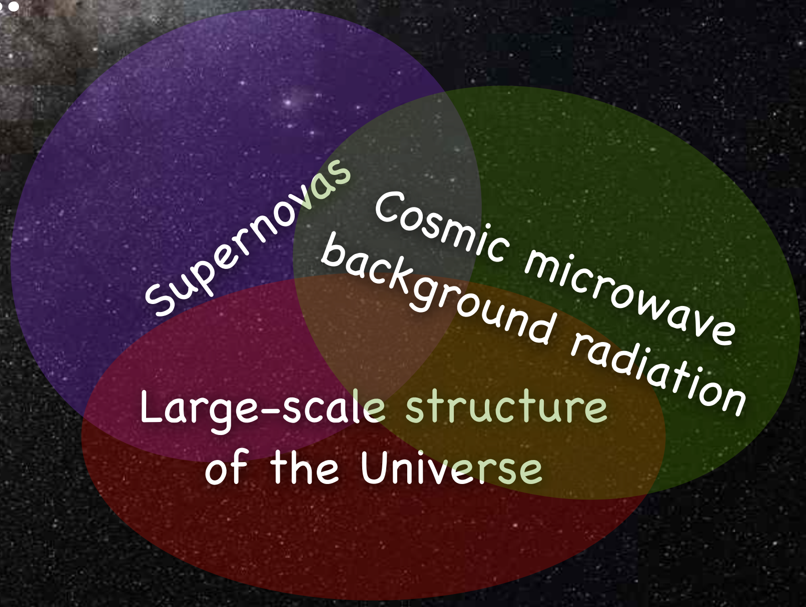


But observations show that, recently, the expansion started to **speed up...**



So, either:

1) some strange new form of energy took over the Universe at ~1/2 its present age, **or**

2) for some reason, gravity itself behaves in a very surprising way

Einstein's Cosmological Constant (Λ) is the **simplest explanation** - and it's consistent with all the data, so far

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But in terms of any of the known symmetry-breaking mass scales, such a **vacuum energy Λ/M^4** should be **incredibly small:**

$$\Lambda \approx 10^{-29}\ \mathrm{g/cm^3}$$

$$\Lambda \approx 10^{-43}\ \mathrm{GeV^4}$$

➩ 9 out of 10 physicists reject it outright!

"The most profound mystery in basic science"
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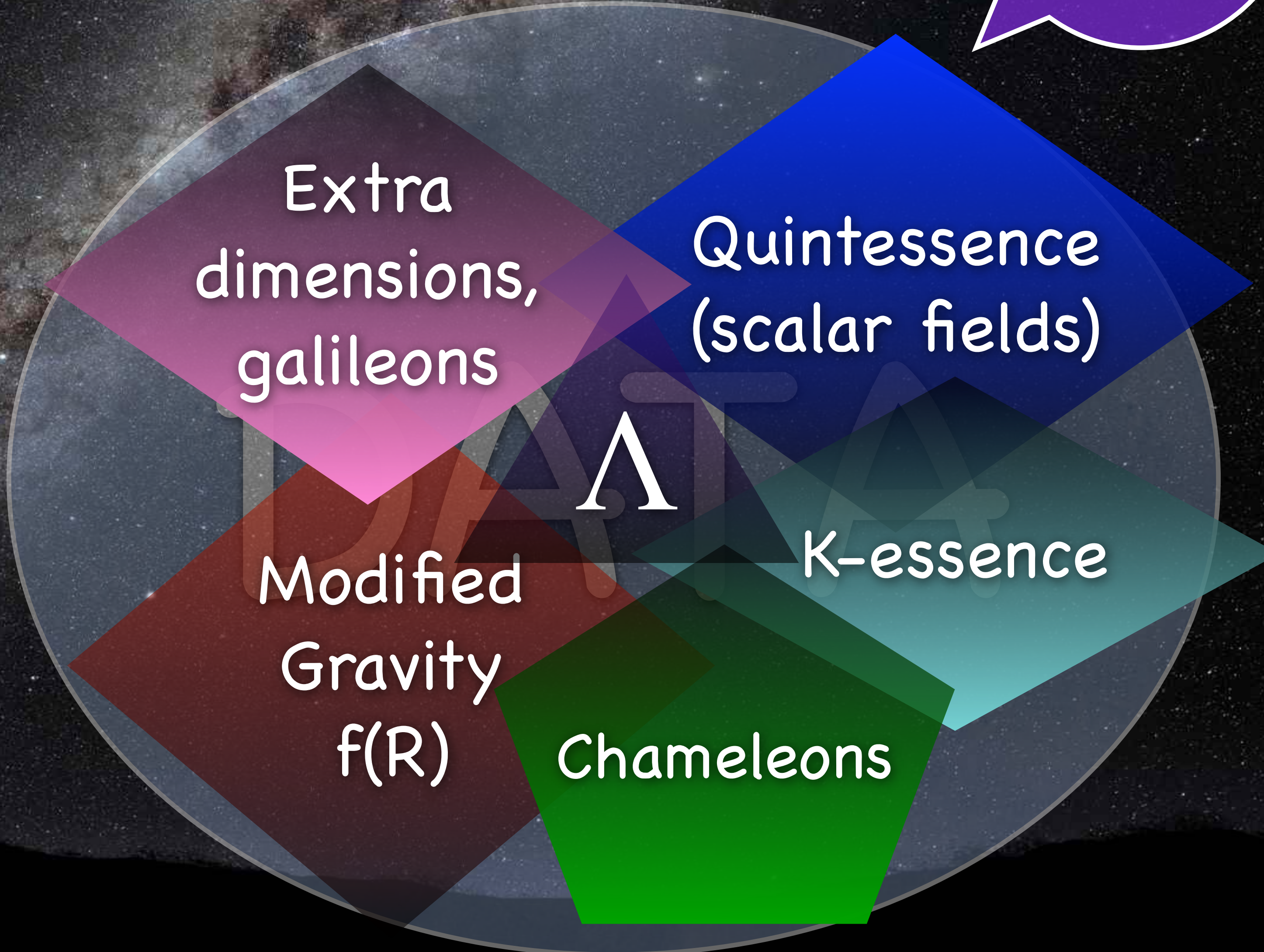
➯ Theoretical efforts have not yet produced a clear-cut "standard model" for the cosmic acceleration



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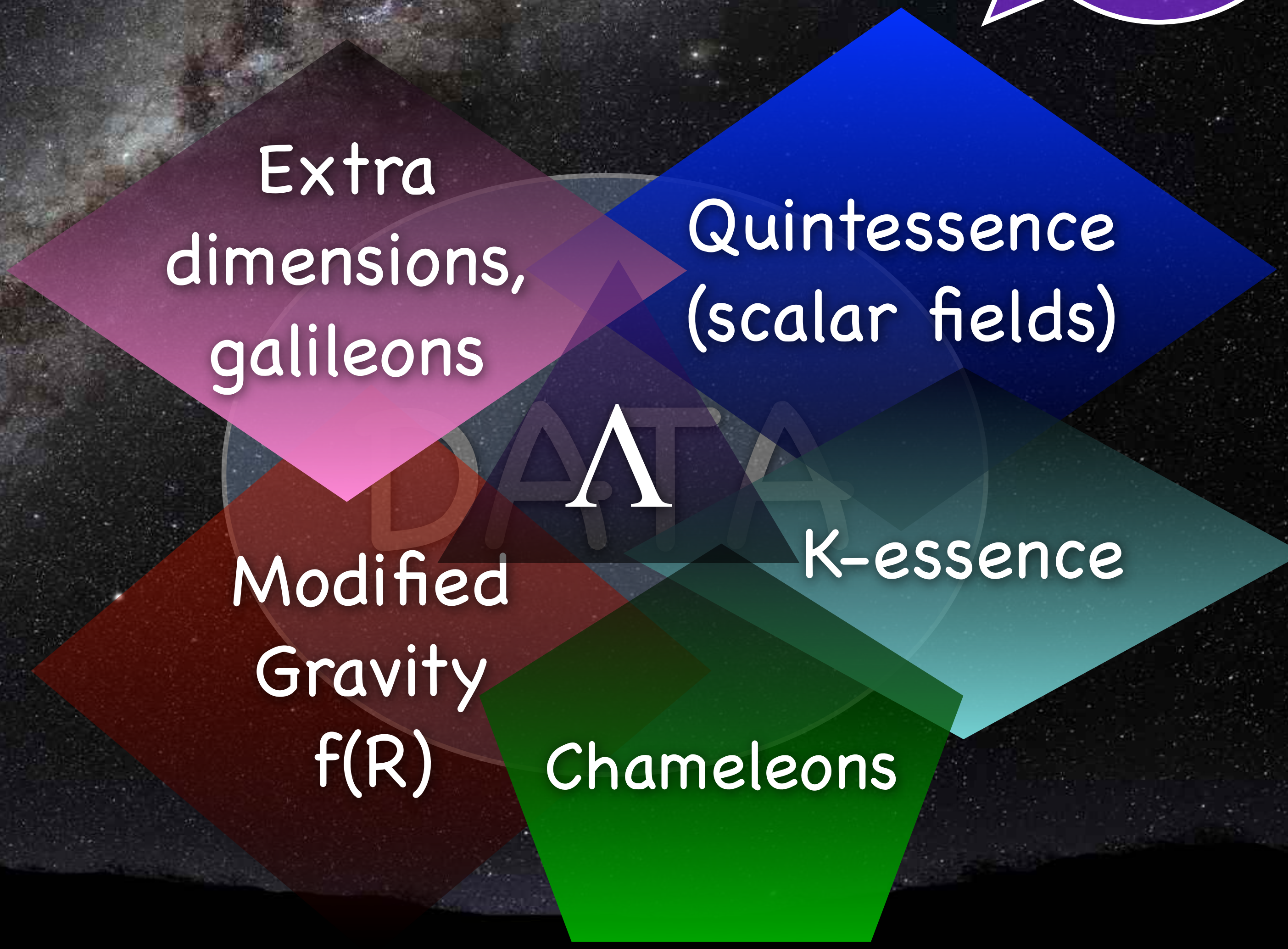

➯ Meanwhile, data keeps getting better and better...

Dark energy or modified gravity?

$$G_{\mu\nu} = 8\pi G T_{\mu\nu} + 8\pi G T^{E}_{\mu\nu}$$

$$\Delta G \mu\nu + G_{\mu\nu} = 8\pi G T_{\mu\nu}$$

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⇒ Acceleration

Degenerate w/
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Degenerate w/ dark energy

⇒ Acceleration

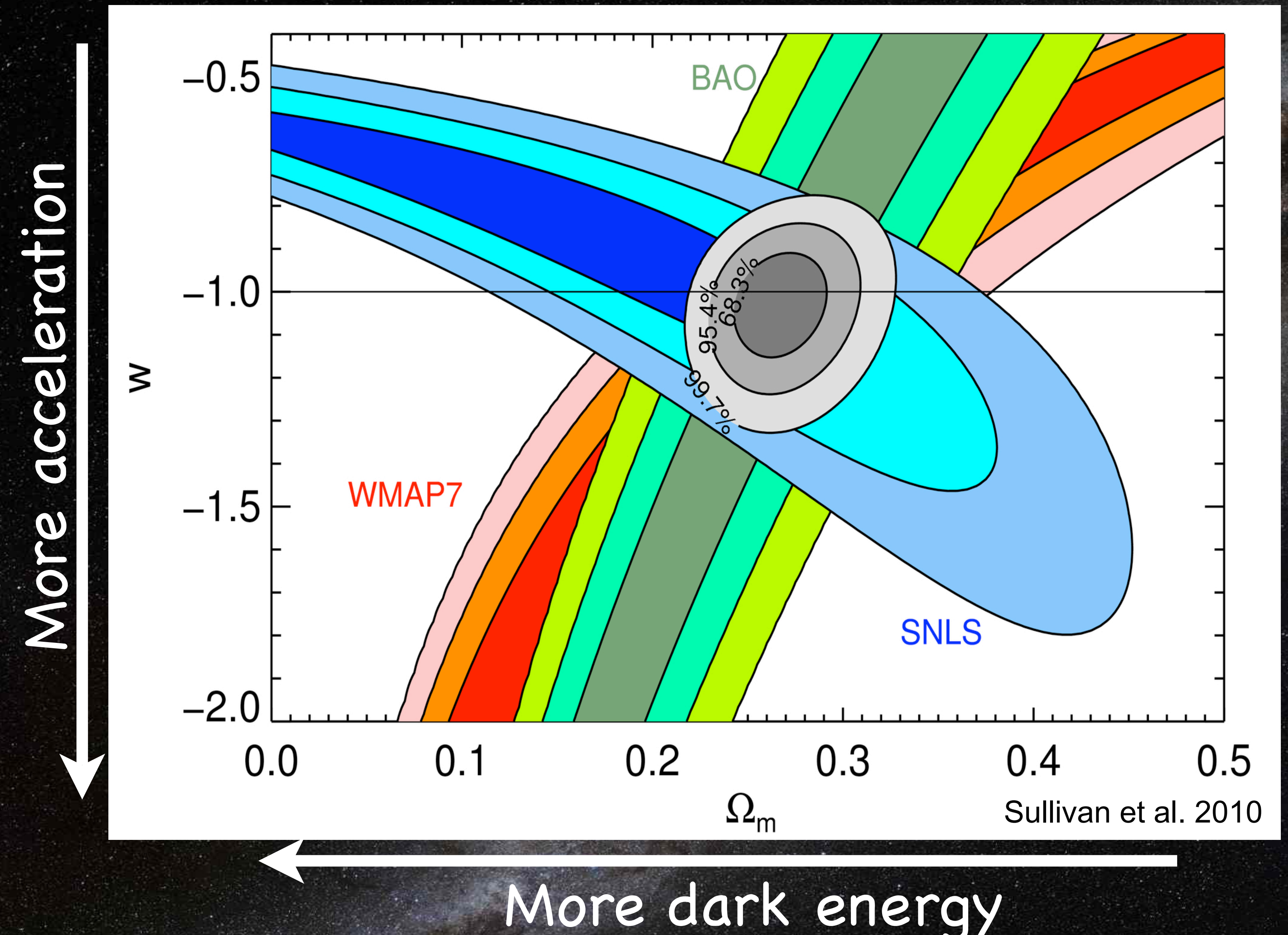
However, modified gravity also changes the Poisson equation! In f(R) theories:

Same matter, diff. gravit. force

$$\nabla^2\Phi = \frac{16\pi G}{3}\delta\rho - \frac{1}{6}\delta R(f_R)$$

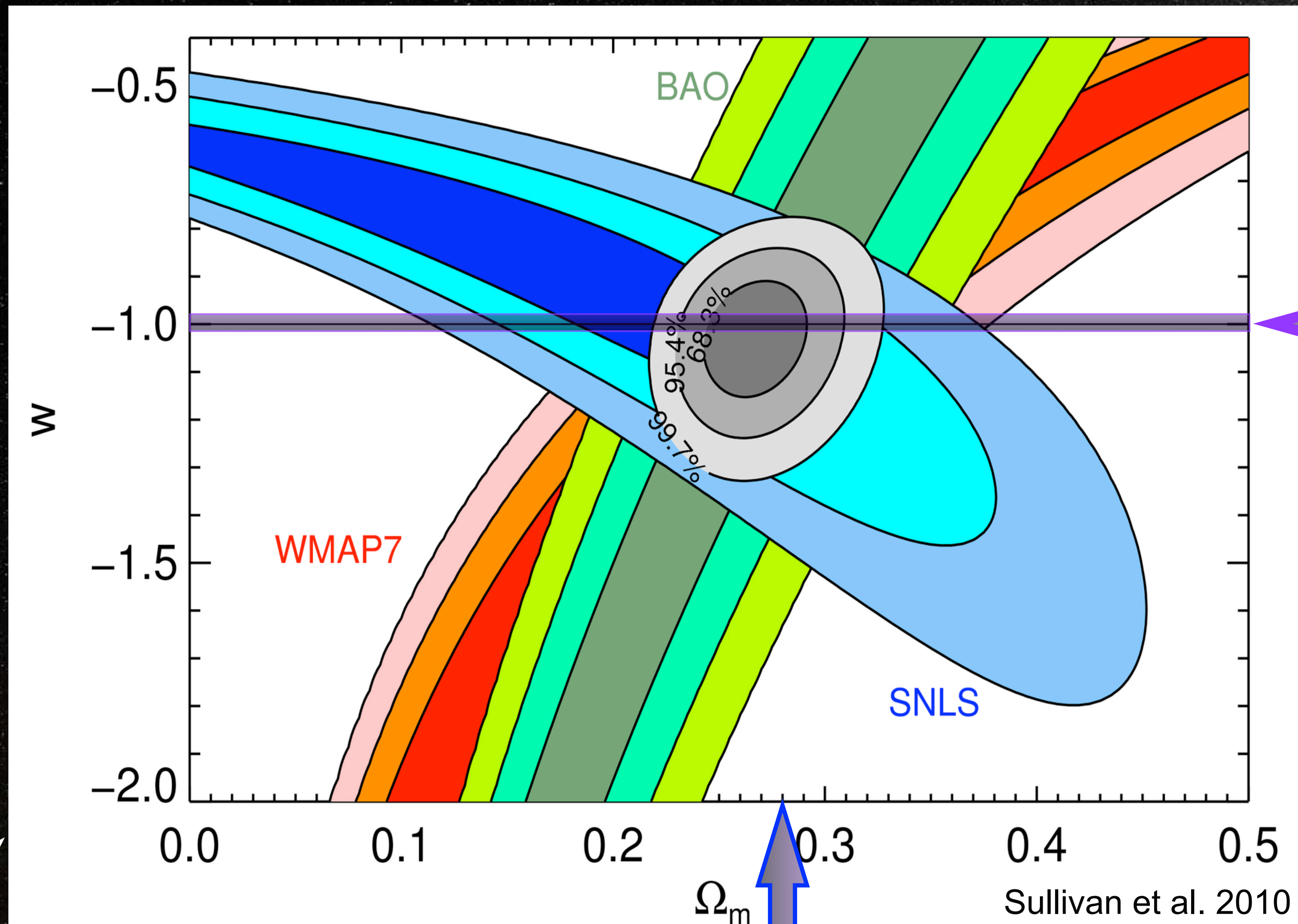
The **growth of structures** is modified!

Zooming into the nature of dark energy



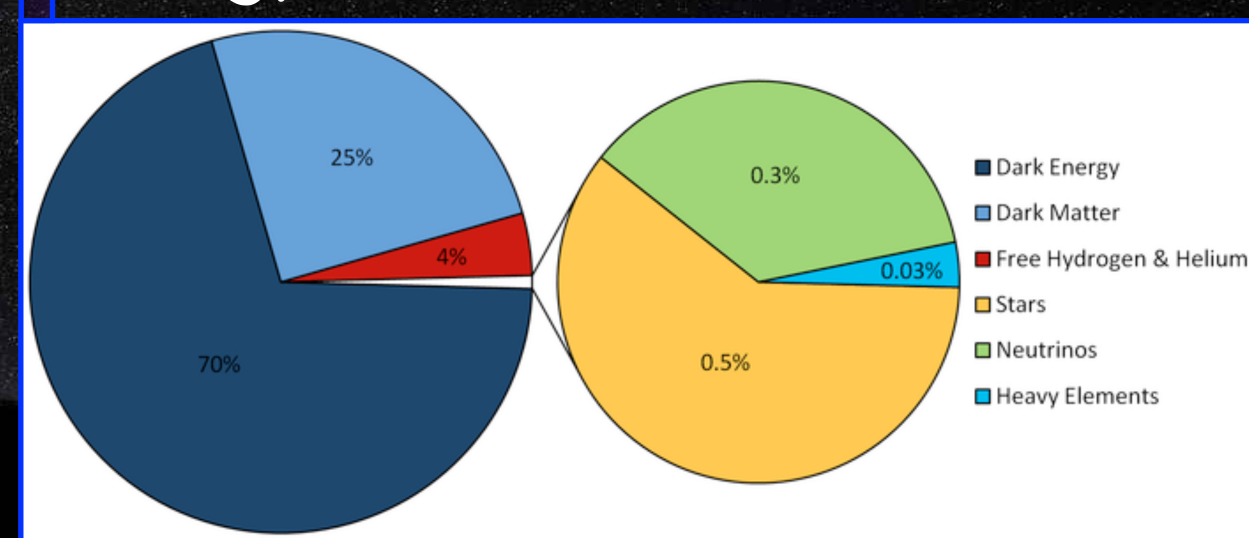
Zooming into the nature of dark energy

More acceleration



Λ

More dark energy



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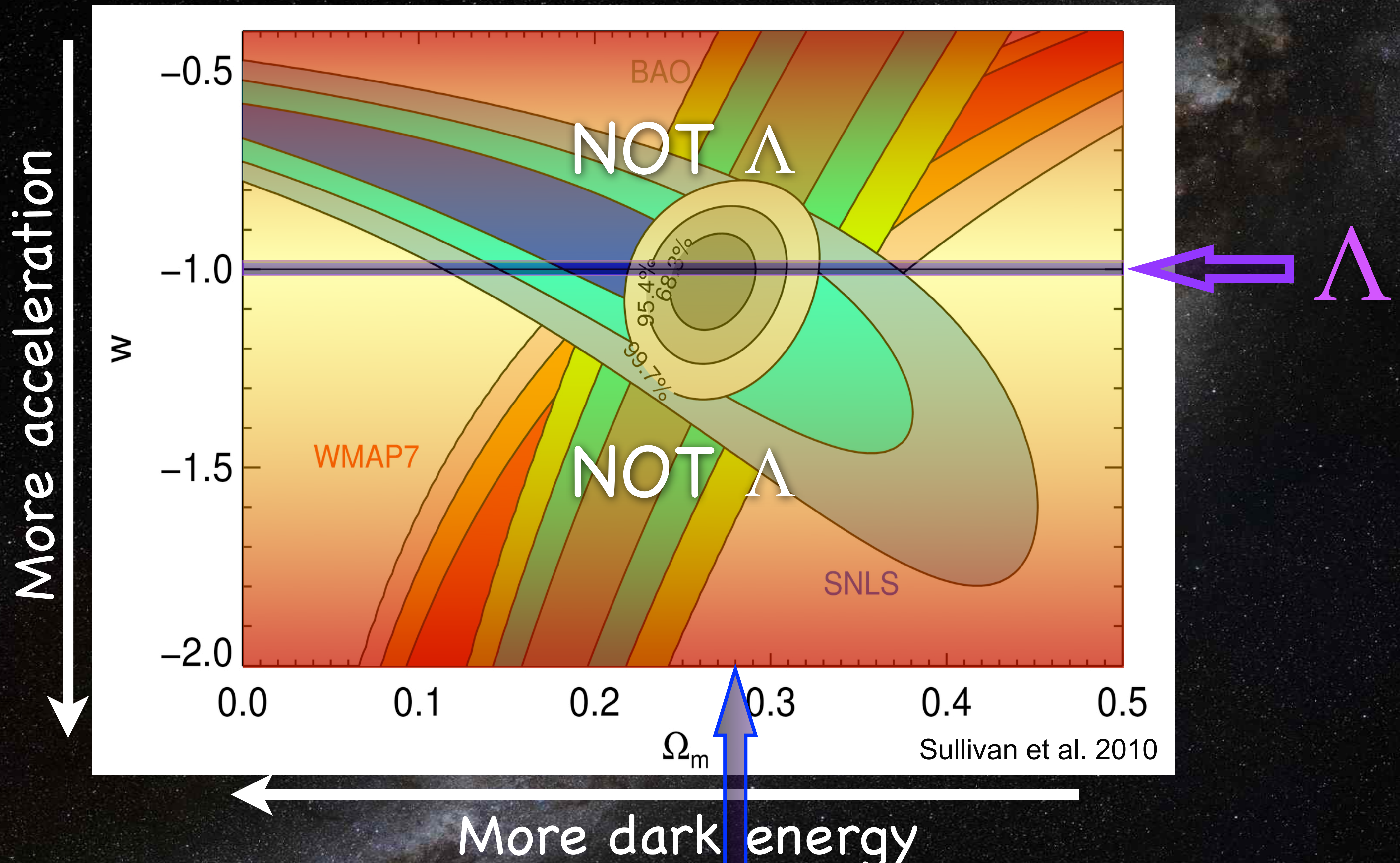
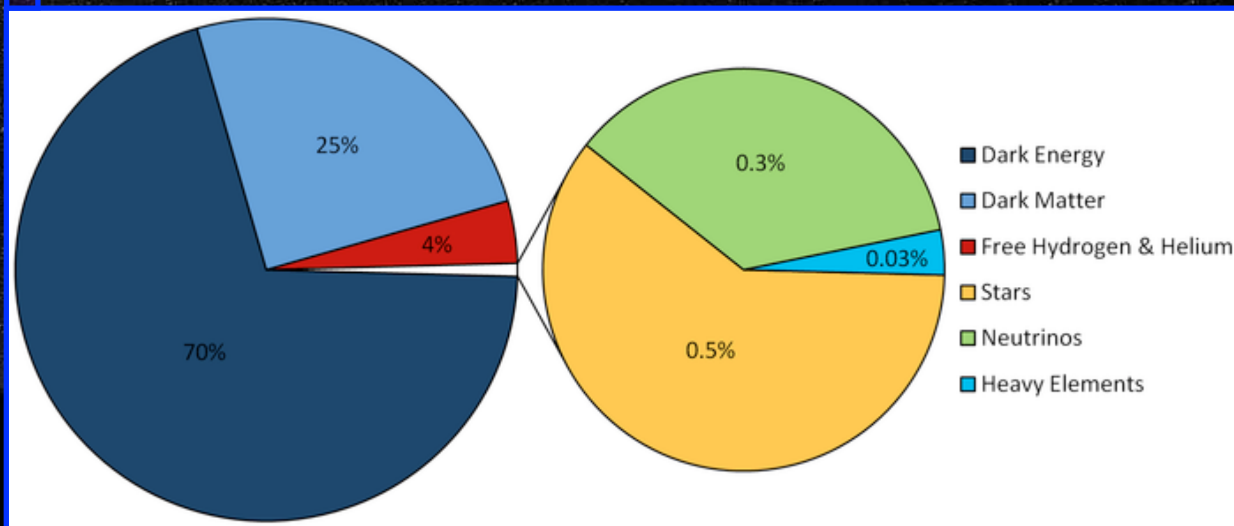
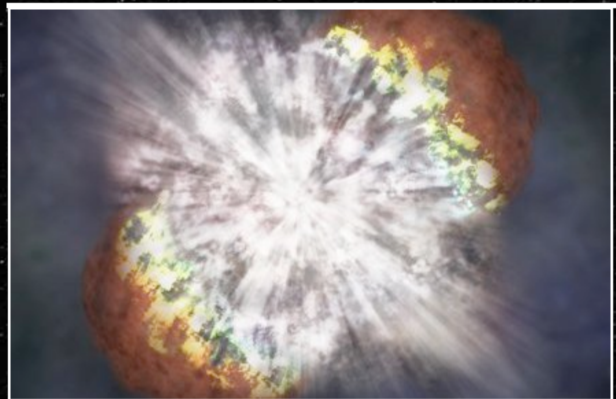
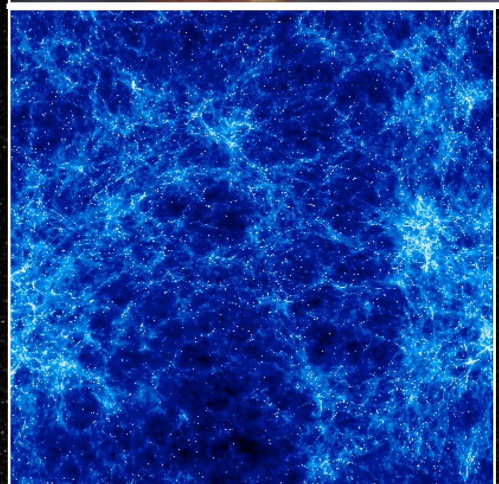




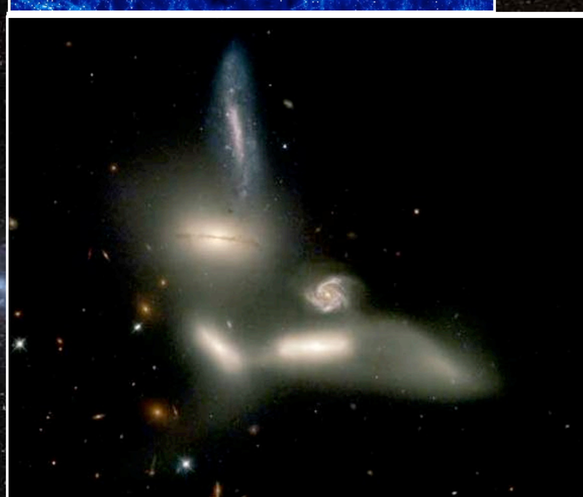
Astronomers are now looking everywhere for clues of dark energy:



- Type-Ia supernovas (most distant standard candles)



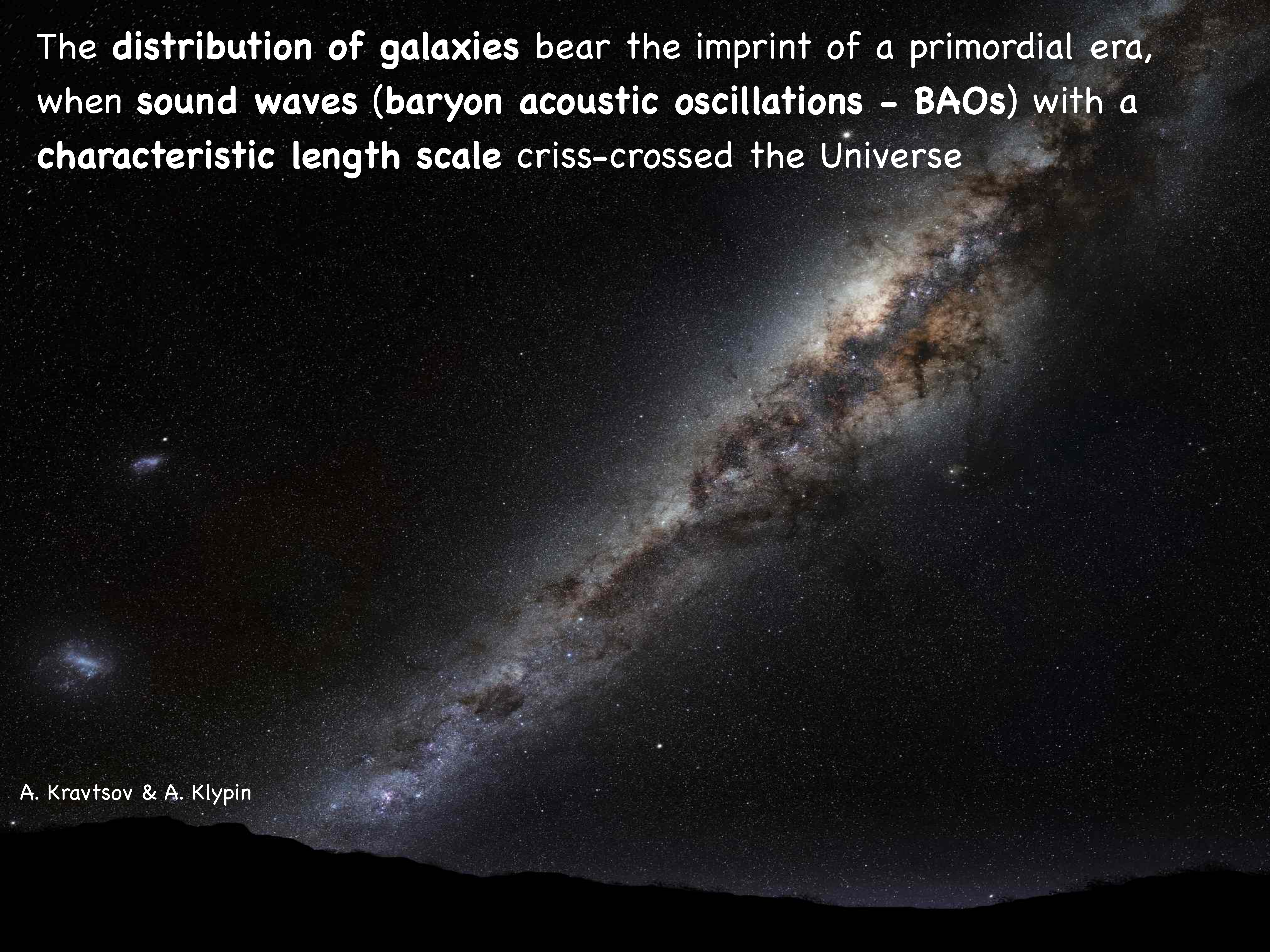
- Distribution of galaxies (statistical standard rulers - BAOs)



- Clusters and groups of galaxies (growth of large-scale structure)

- Gravitational lensing (direct probe of dark matter)

The **distribution of galaxies** bear the imprint of a primordial era, when **sound waves (baryon acoustic oscillations - BAOs)** with a **characteristic length scale** criss-crossed the Universe



A. Kravtsov & A. Klypin

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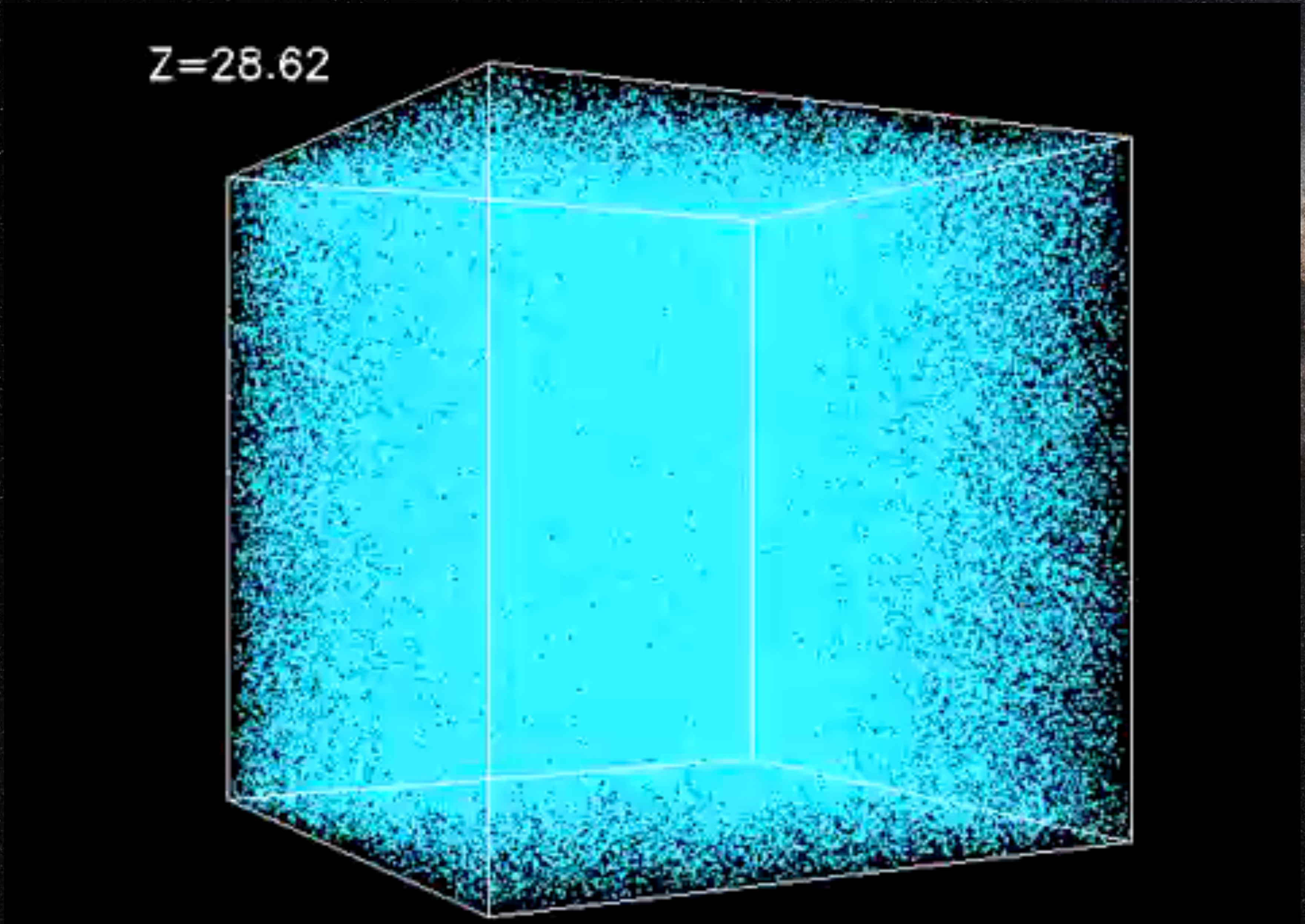

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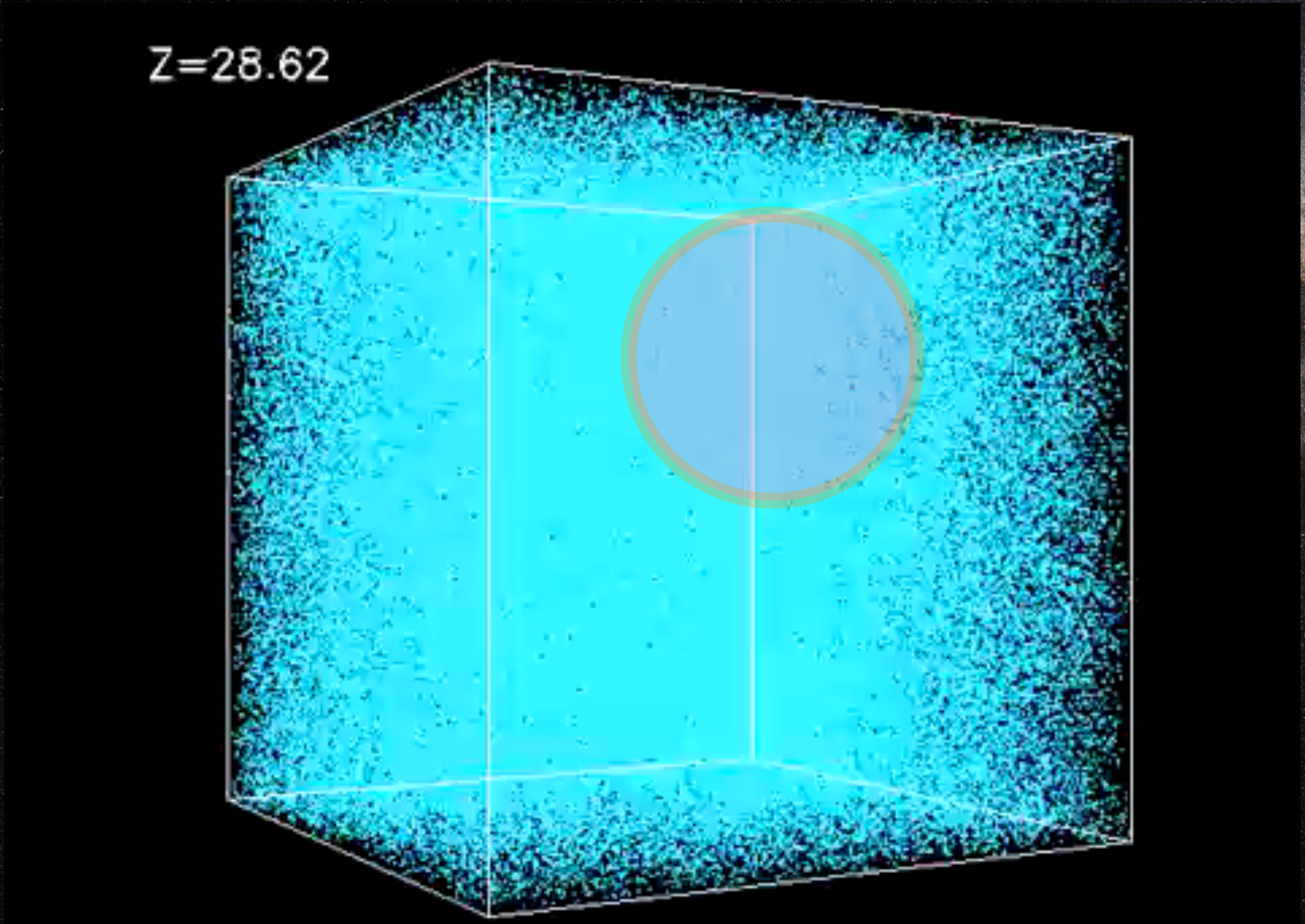

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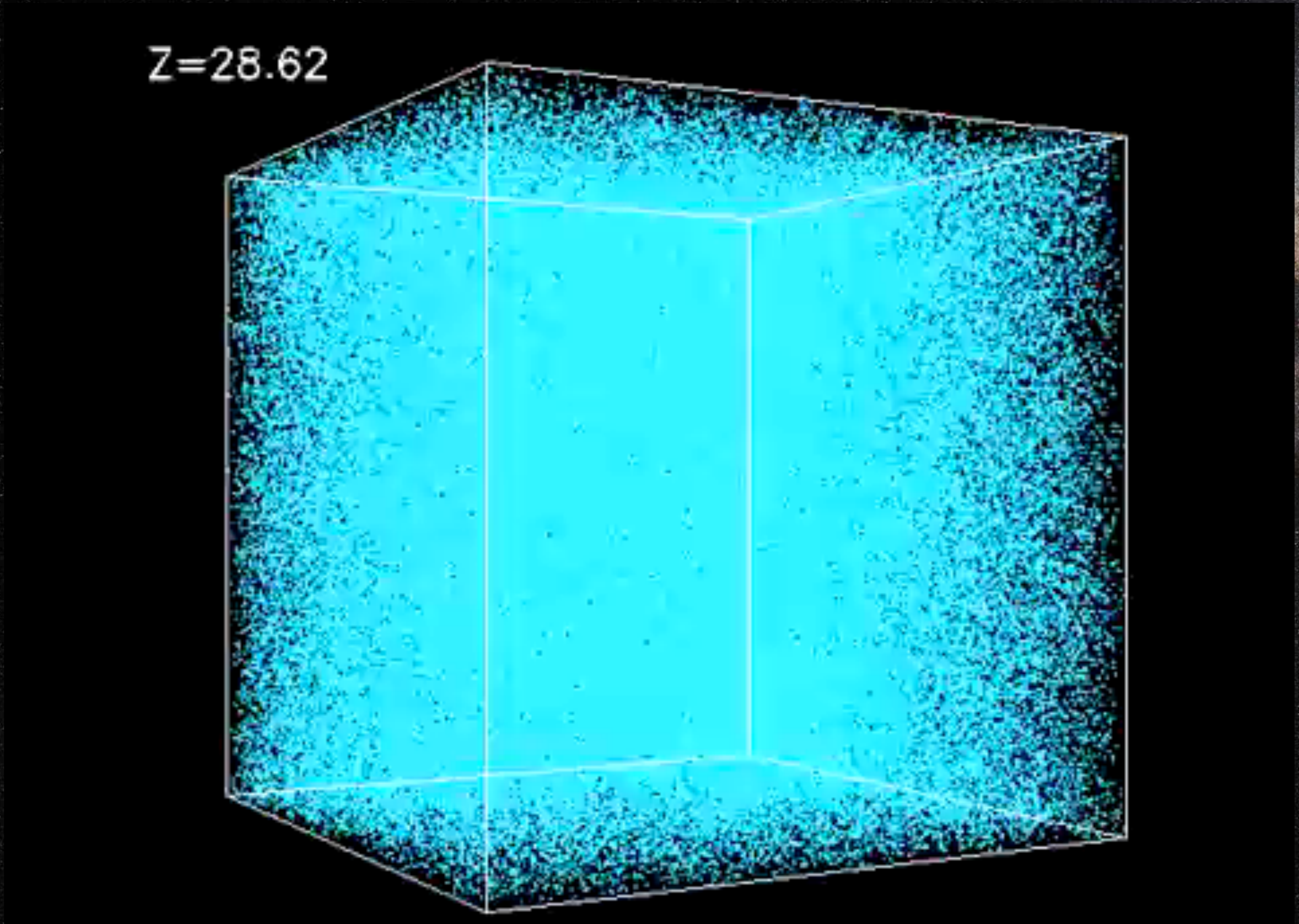

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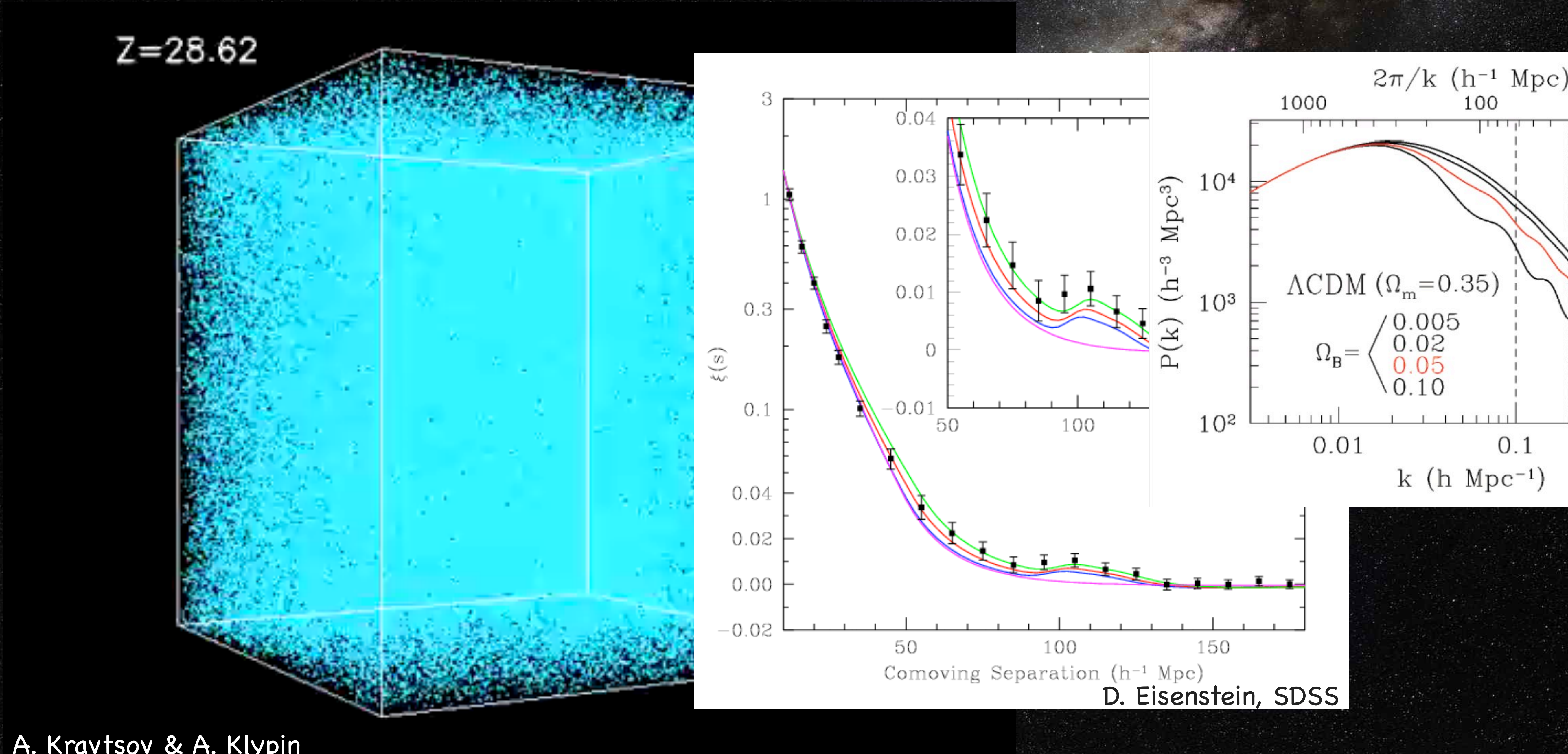
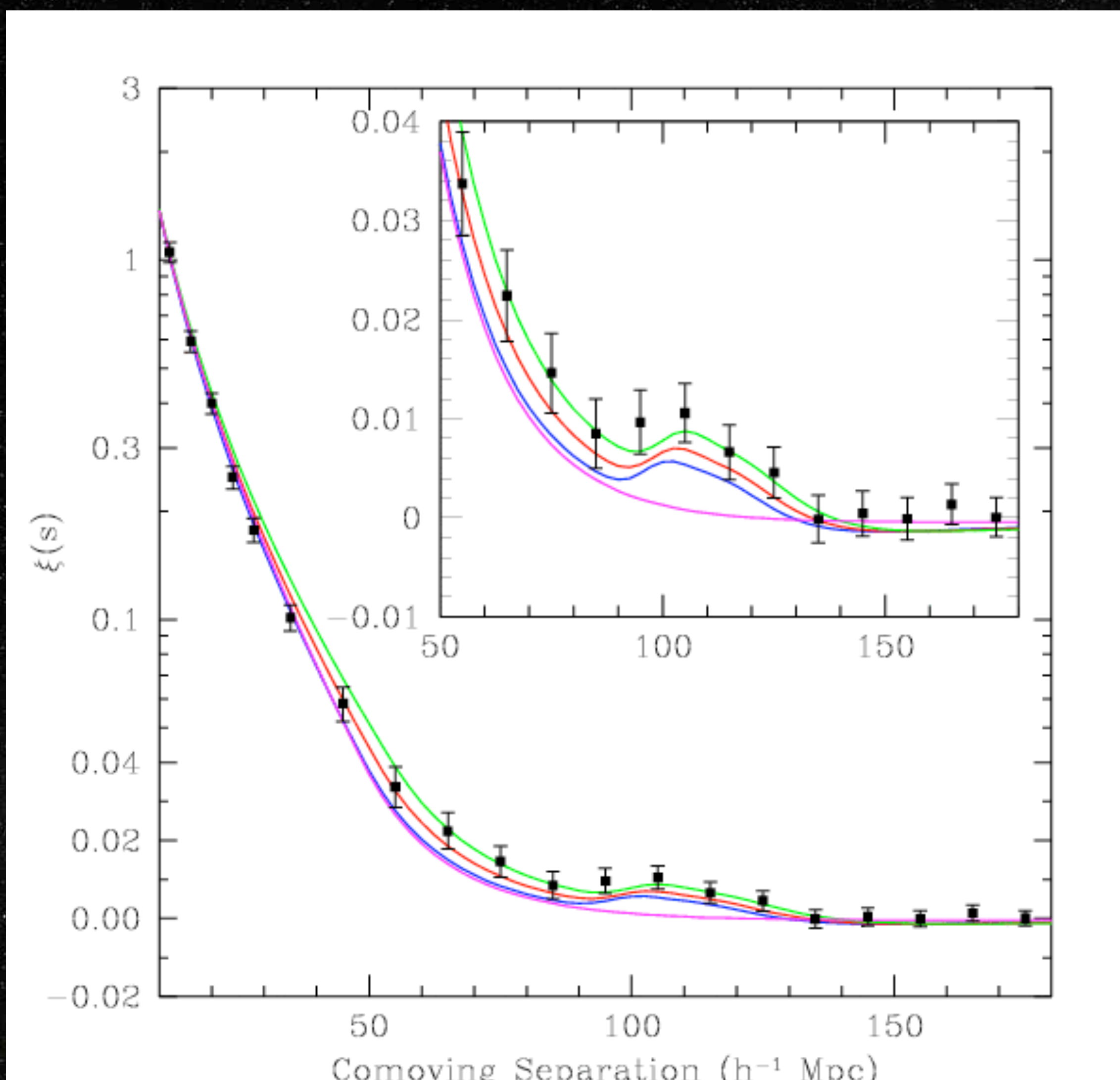


A. Kravtsov & A. Klypin

D. Eisenstein, SDSS

➯ **Statistical** measurement - must **map millions of galaxies in 3D**, over distances of **billions of light-years**

The **2pt galaxy correlation function,** $\xi(r)$, shows the BAOs as a slightly larger (~10%) probability of detecting galaxies ~150 Mpc from each other



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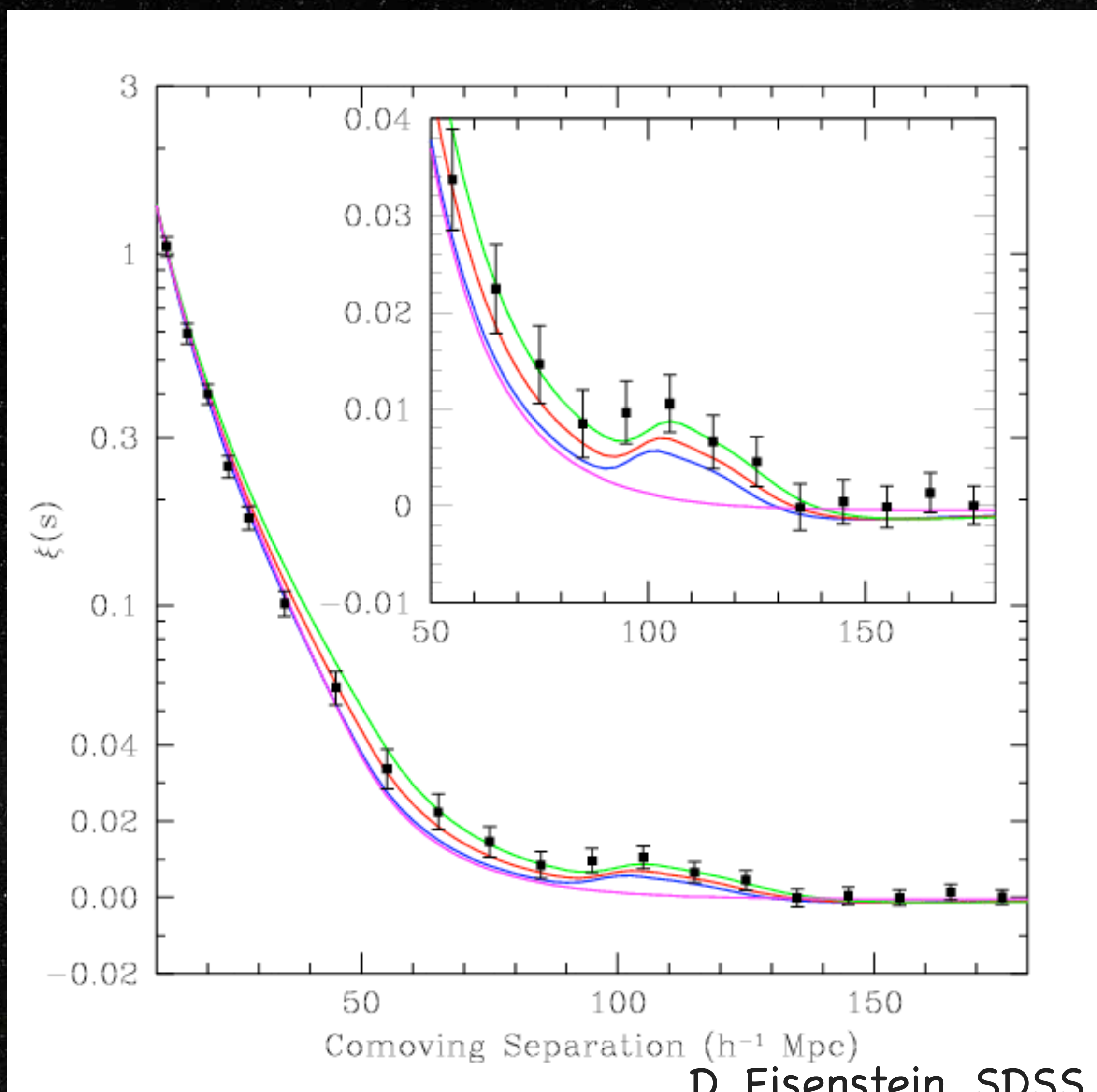
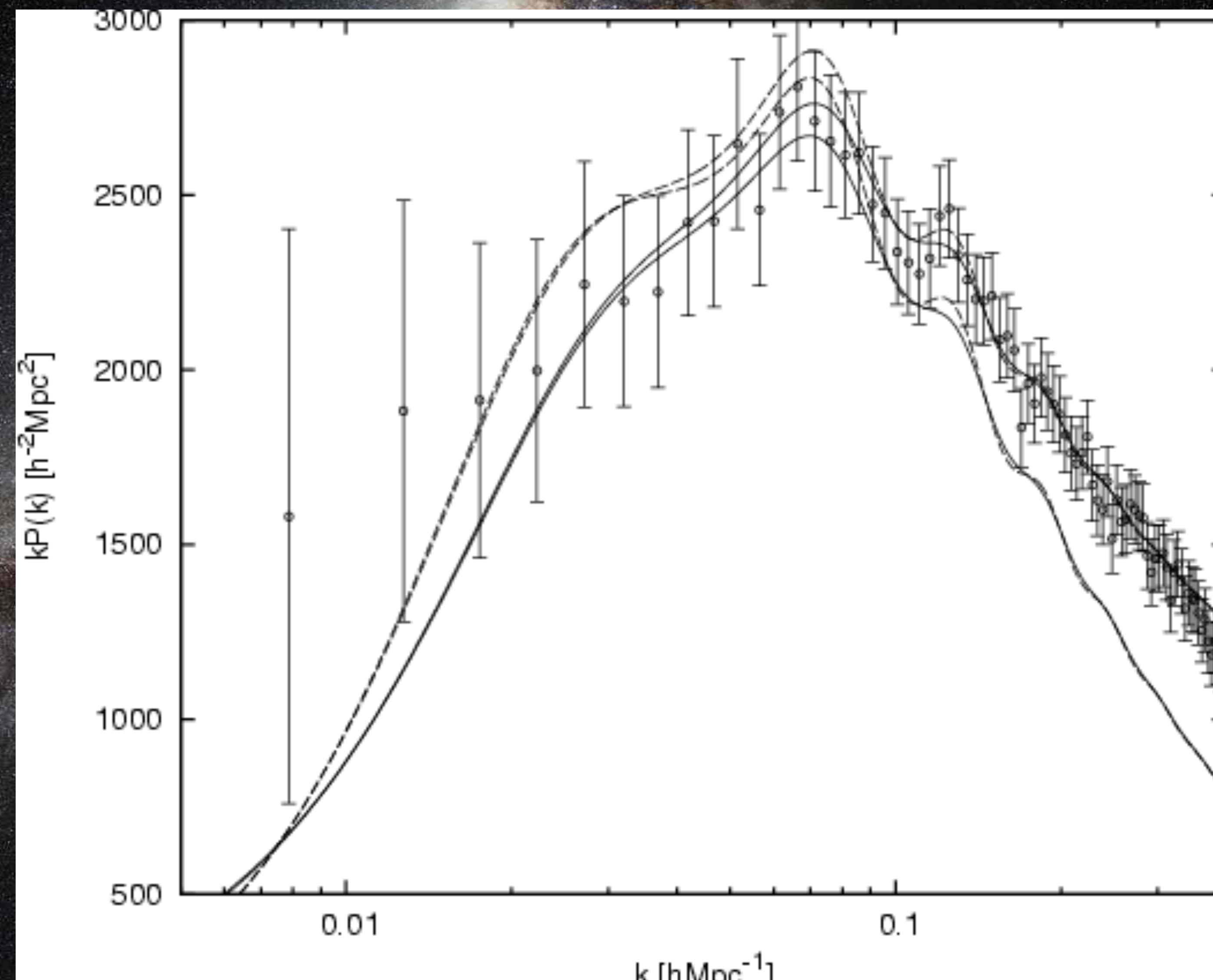
The Fourier transform of the correlation function, the **matter spectrum P(k),** shows this feature as oscillations



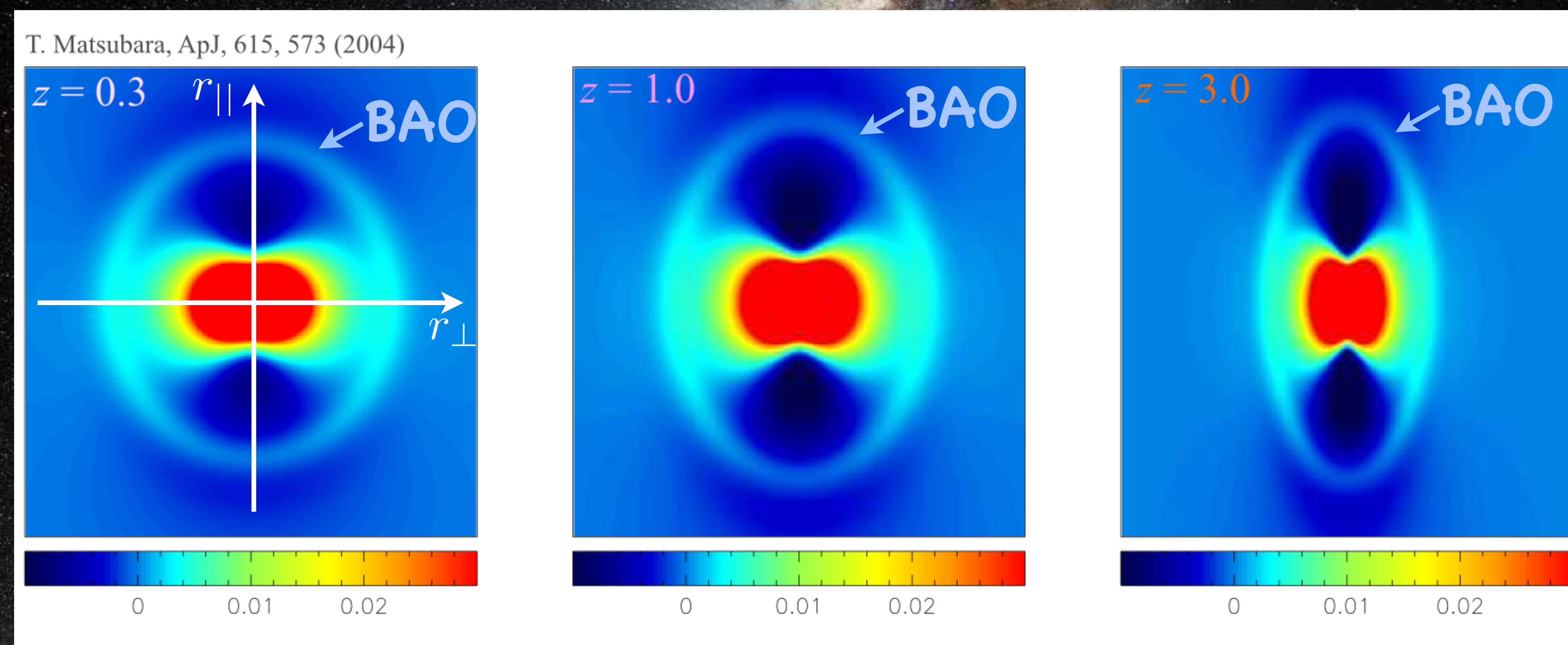


The **positions of galaxies in the radial direction are inferred from their redshifts** - and they are affected by their peculiar velocities!

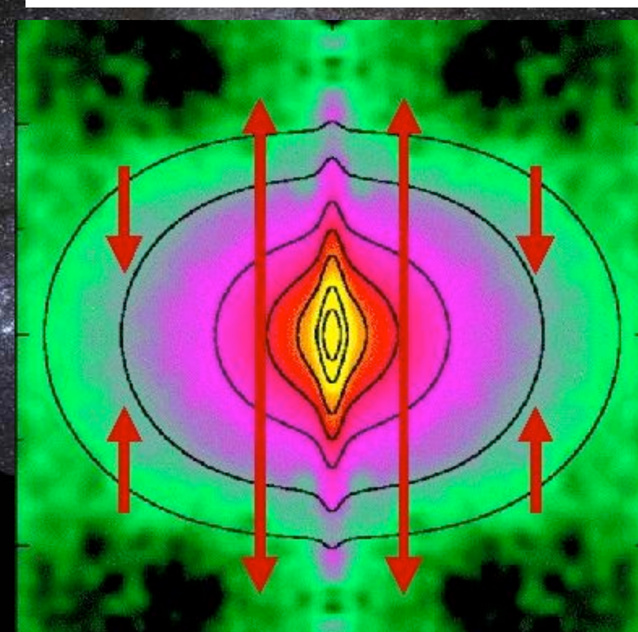
➯ The **observed** (z-space) 2pt correlation function is **anisotropic:**

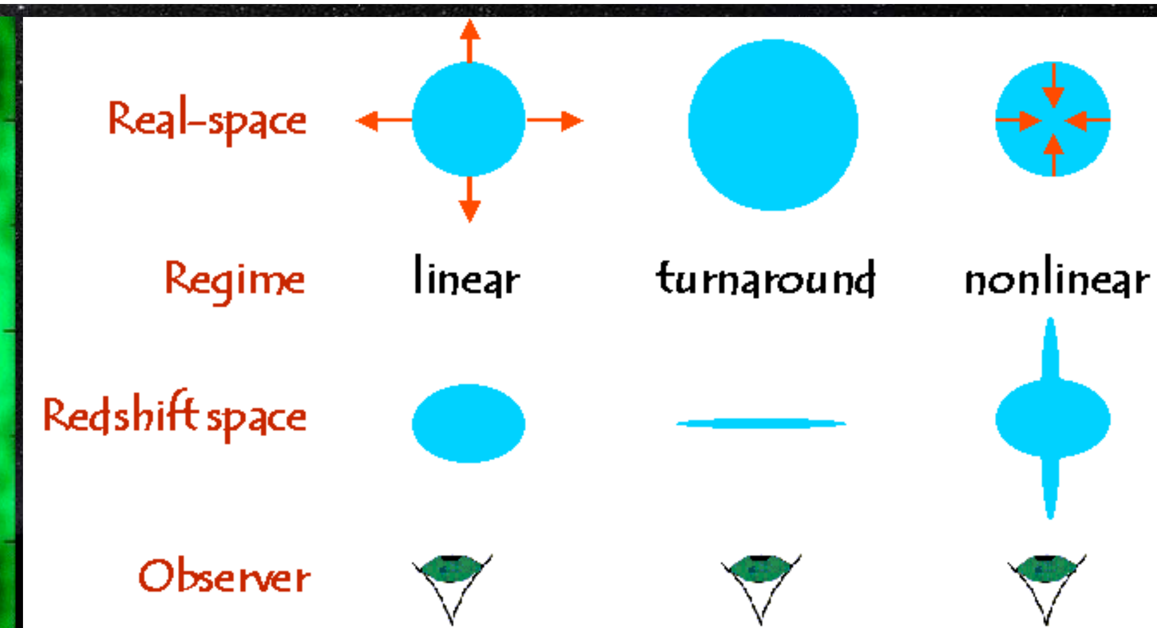
$$\xi(r) \rightarrow \xi_{obs}(r_{\perp}, r_{||})$$

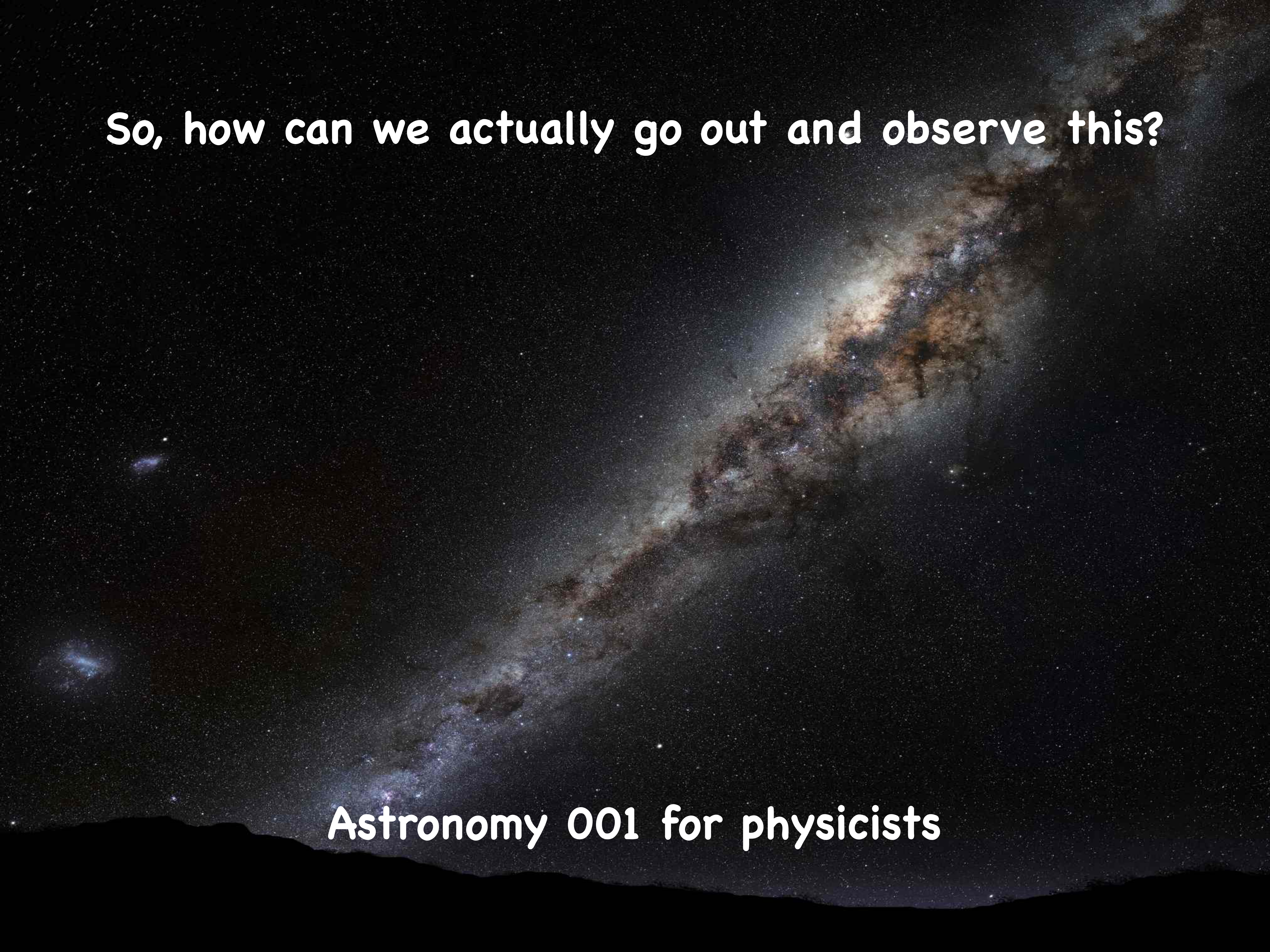
Redshift distortions in the linear regime of structure formation

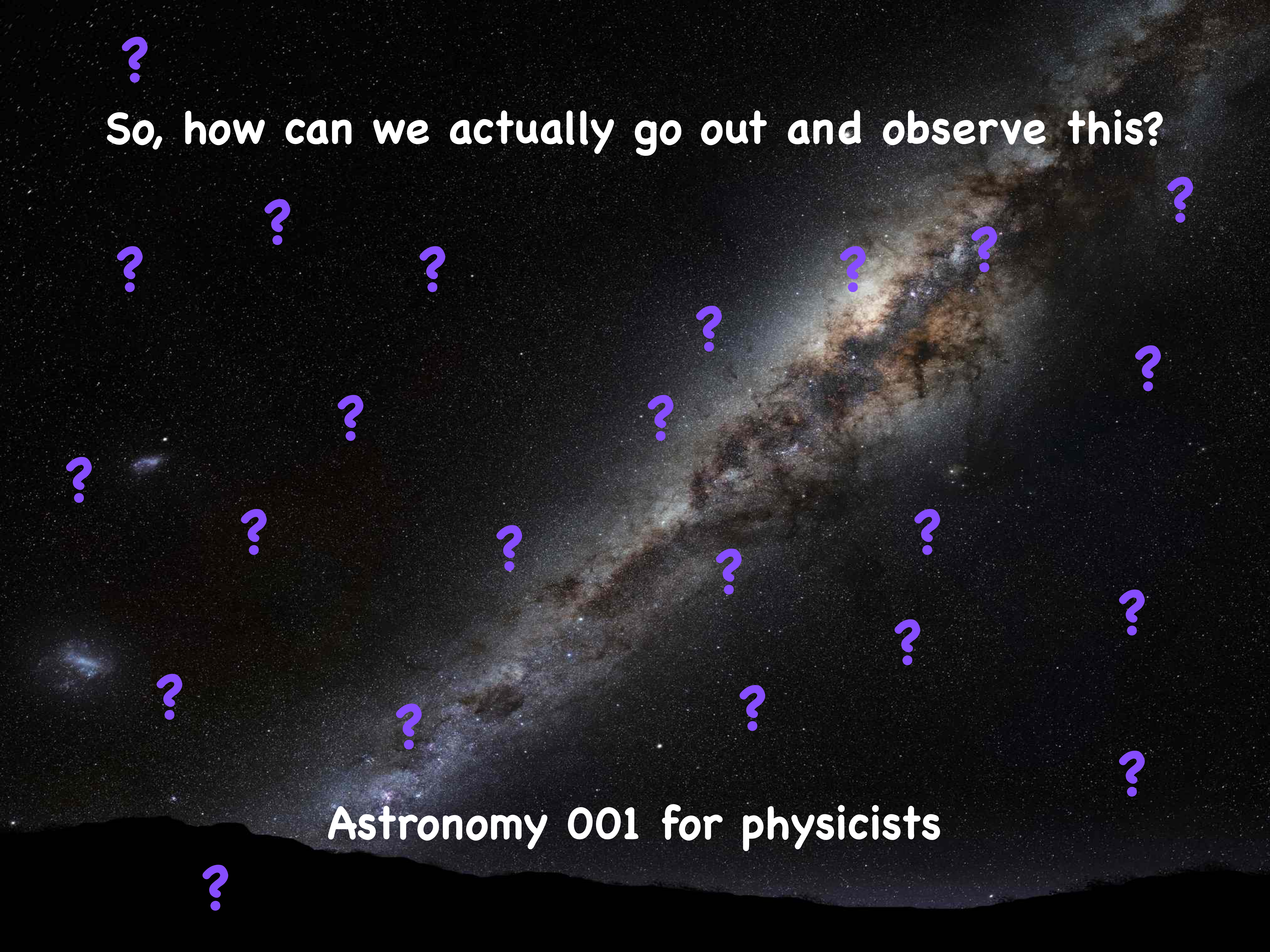


... and in the non-linear regime






So, how can we actually go out and observe this?
Astronomy 001 for physicists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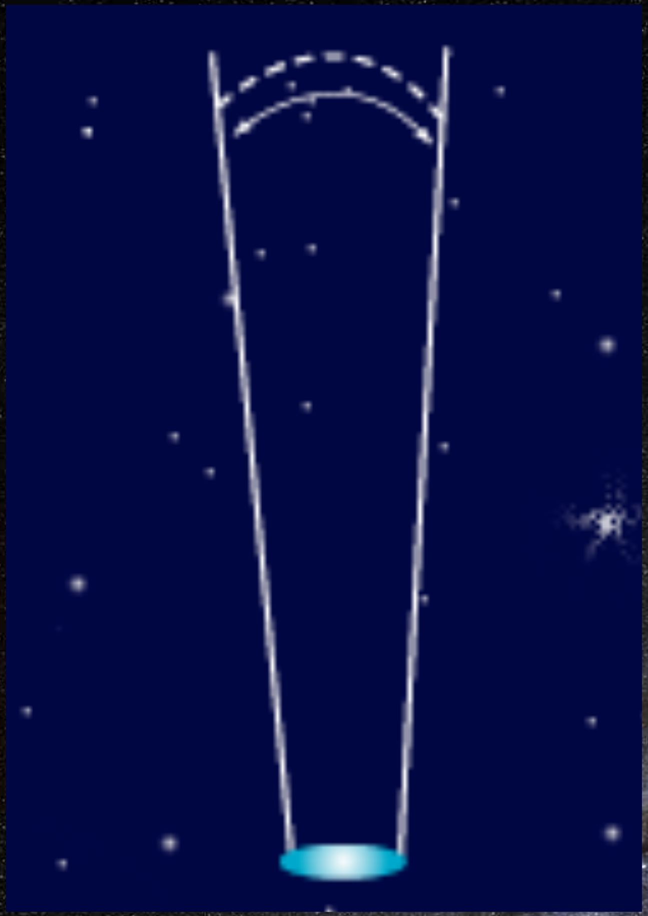
Lesson #1: Telescopes are not all the same!



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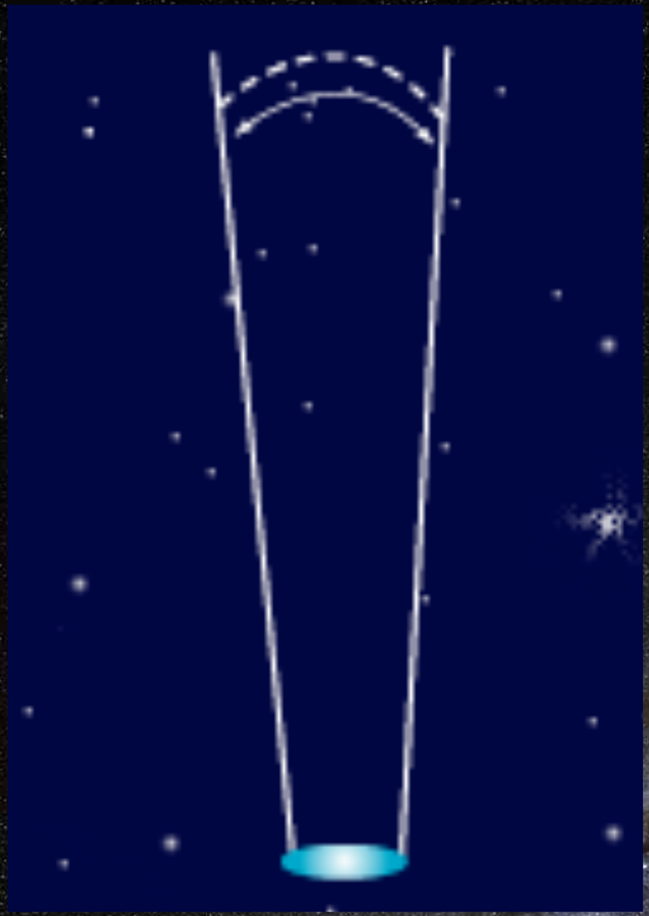
Telescopes with mirrors of the **same size** can have **different fields of view**!



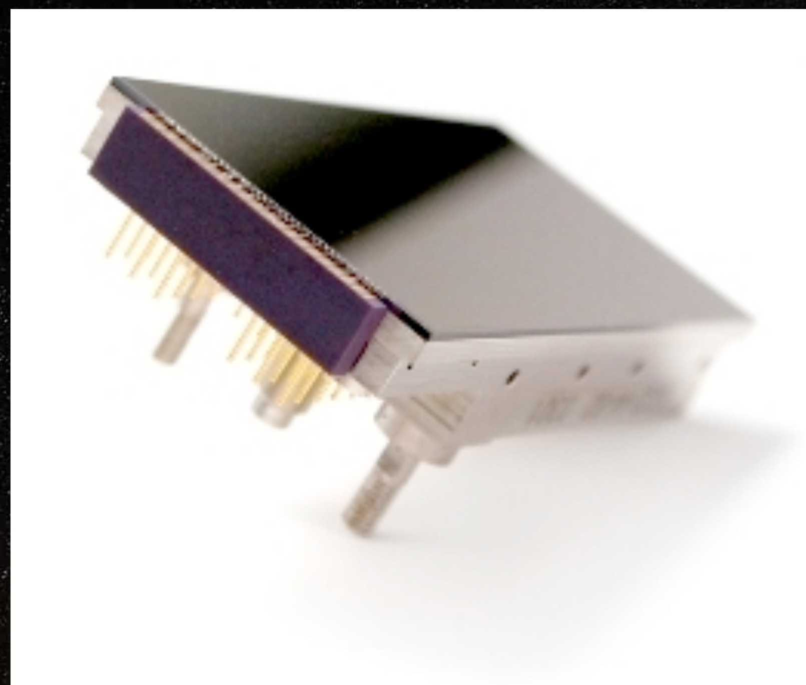
Small field of view
("classical" Astronomy)
➩ Good spatial resolution f/ objects

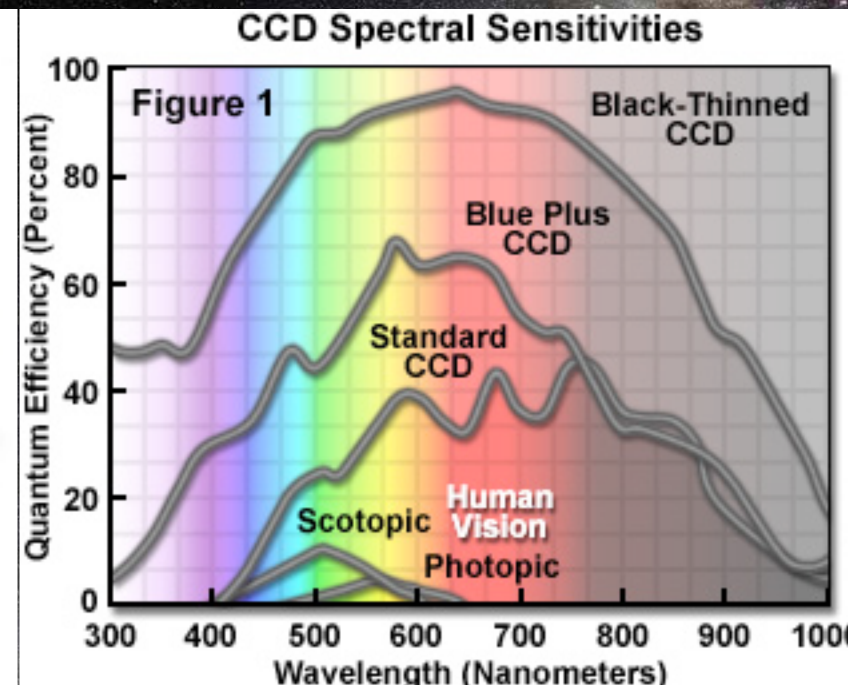
Large field of view
(ideal f/ Cosmology)
➩ Large areas

Lesson #2: Difference methods, different instruments!

Imaging v. Spectroscopy

Modern CCDs: cheap, high **quantum efficiency** (> 80% of photons)...





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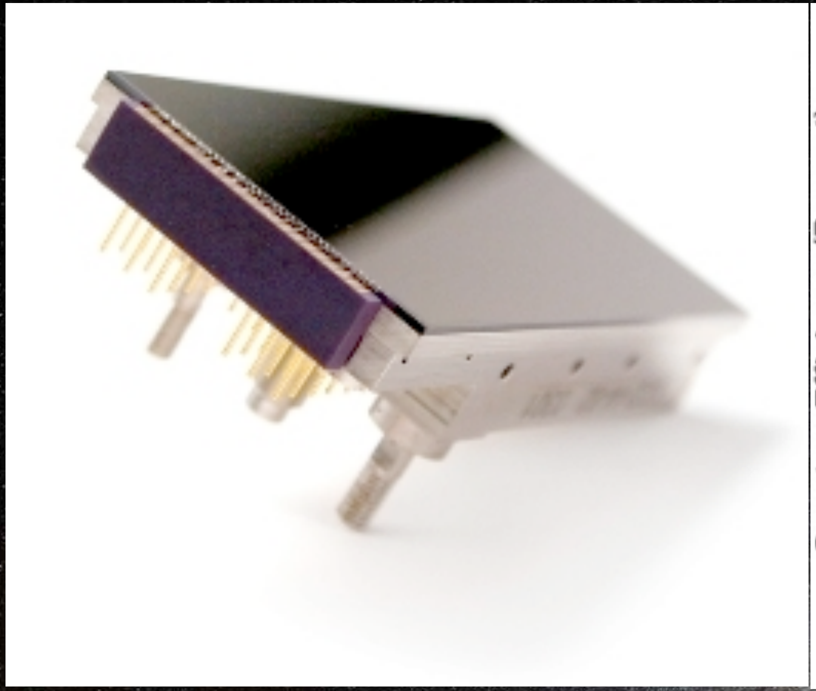
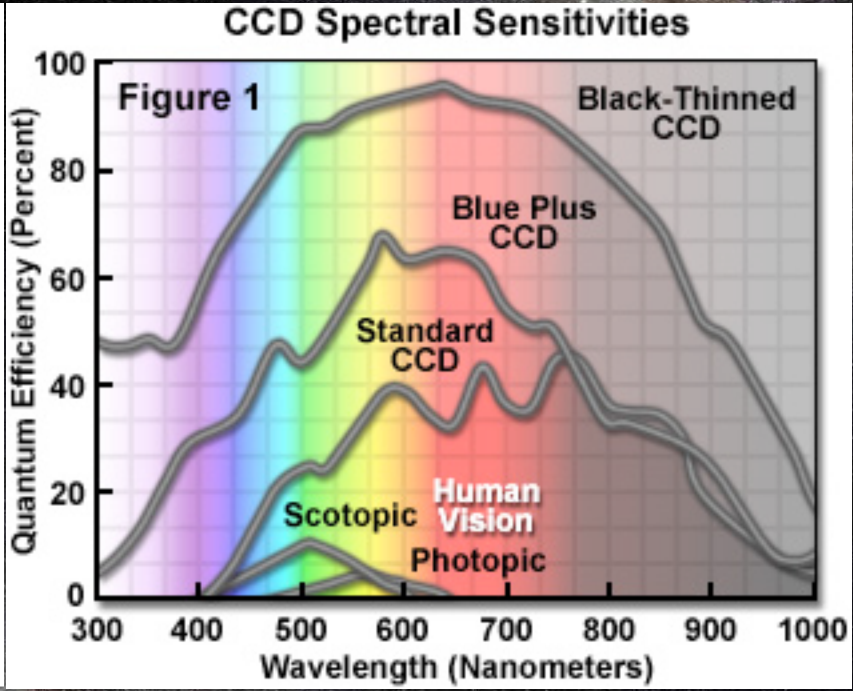


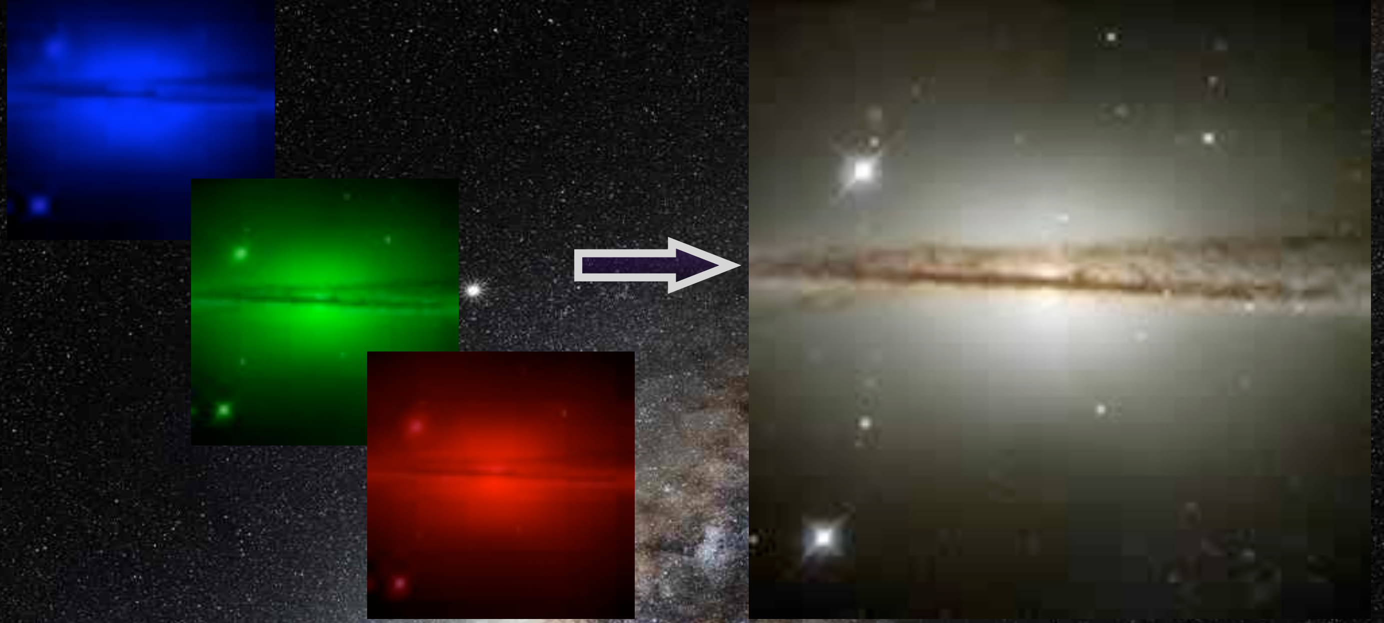


However, they **cannot measure the wavelengths**!

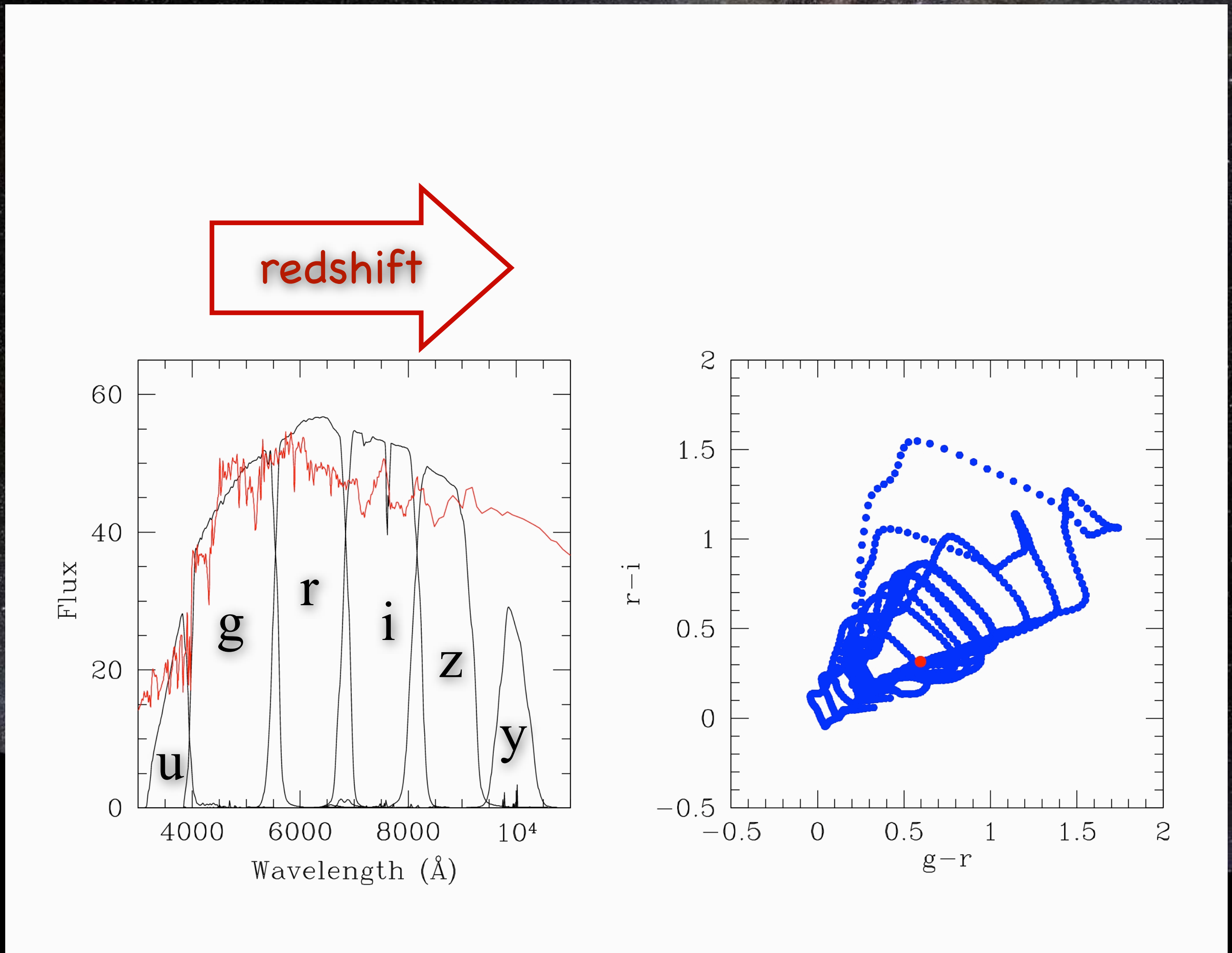
$$\lambda_{obs} = (1+z)\,\lambda_{em}$$

No colors, no redshifts!

Strategy #1: imaging with filters



- ✱ Gets every object in a given field/pointing ⇨ very **complete**
- ✱ poor measure of redshifts ⇨ dimension along line-of-sight **blurred**



Strategy #2: spectroscopy

Requires:
1. Previous imaging (targets)
2. Multiplexing (to obtain many spectra per pointing)

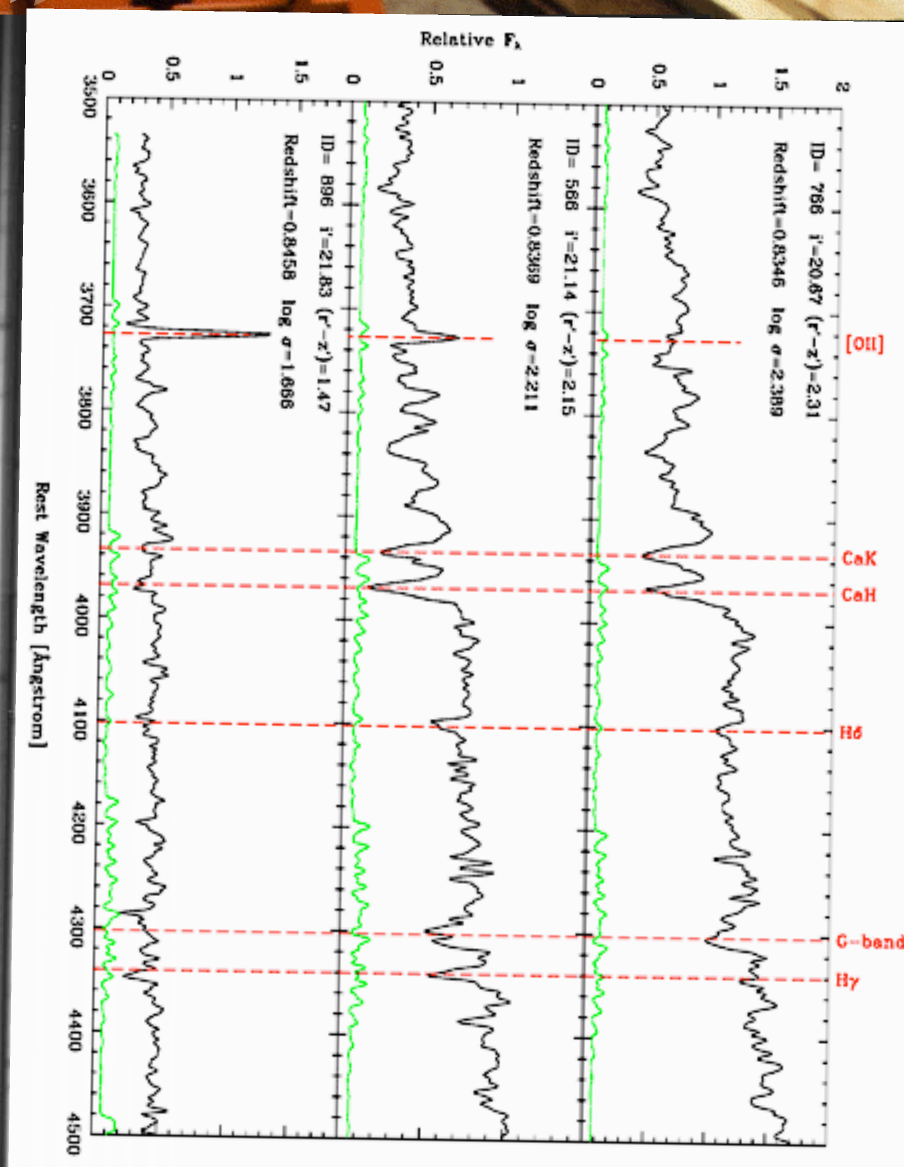
* Excellent redshifts

* Limited # of objects per field

SDSS: 650 / 6 deg^2

BOSS: 1000 / 6 deg^2

PFS: 2400 / 1.8 deg^2



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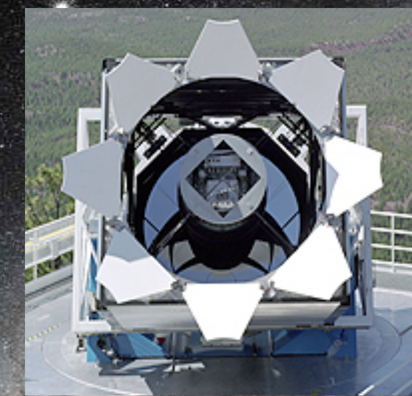
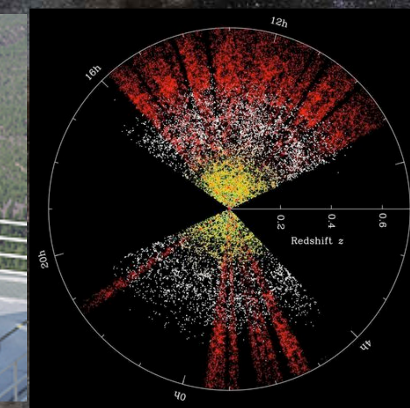
Brazil (since 2010): science/IT

SDSS: highest-impact project in the history of Astronomy





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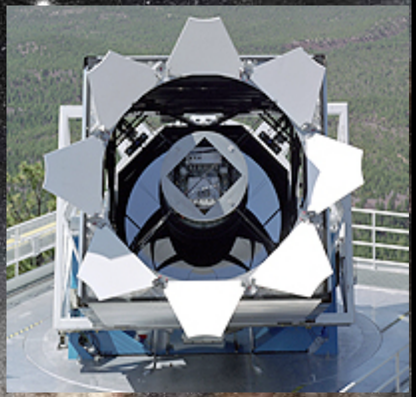
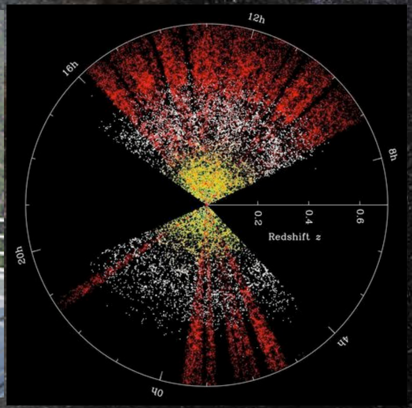
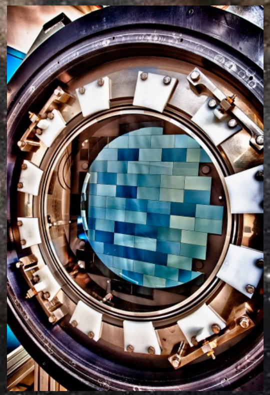
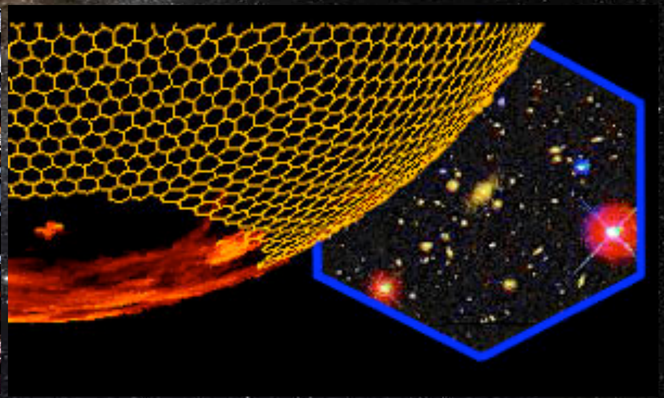




- **DES** - **D**ark **E**nergy **S**urvey: ~2012~2016 ~ U$ 45M total

  Brazil: ~2M - science/IT





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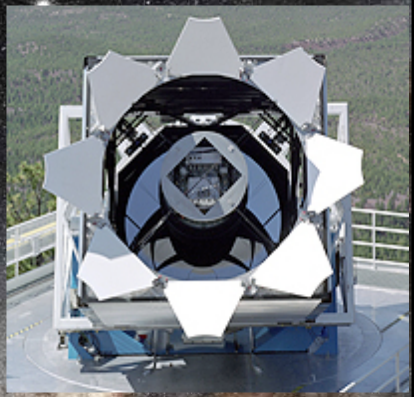
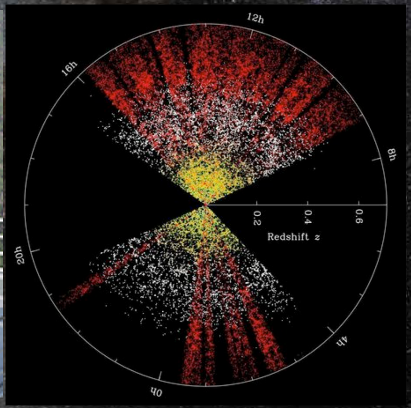

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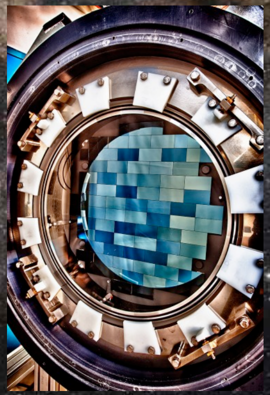
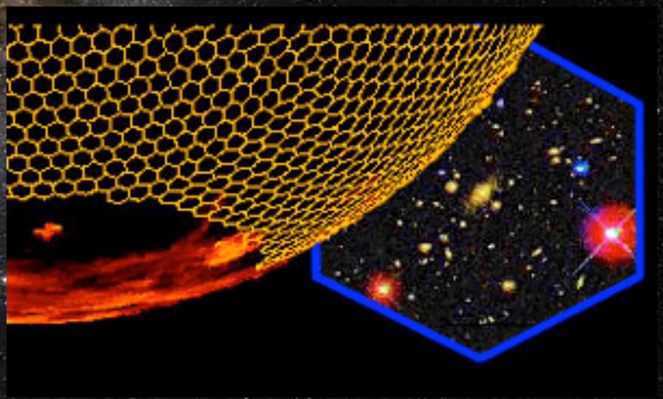
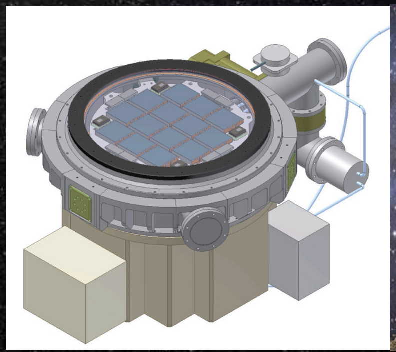



- **J-PAS** - **J**avalambre **P**hysics of **A**cceleration **S**urvey: ~2013~2018
  ~U$ 35M total

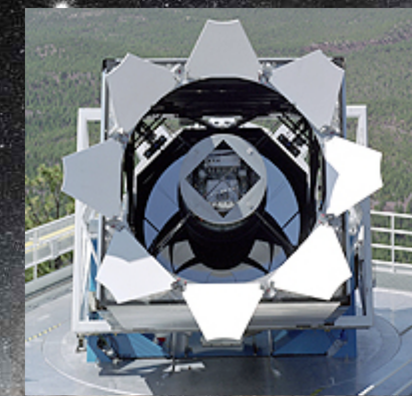
  Brazil: U$ 5M - instrumentation, science, IT

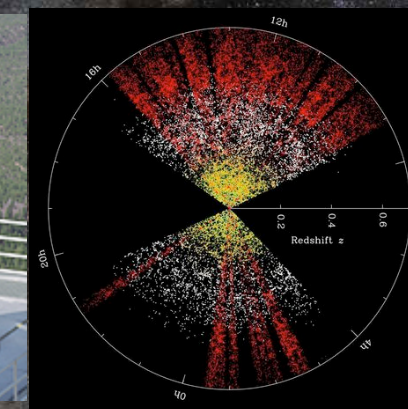



A new generation of **smart telescopes and instruments** is being designed to **map the 3D distribution of matter in the Universe**

- **BOSS** - **B**aryon **O**scillations **S**pectroscopic **S**urvey (**SDSS**-III): 2010~2014

  Brazil (since 2010): science/IT

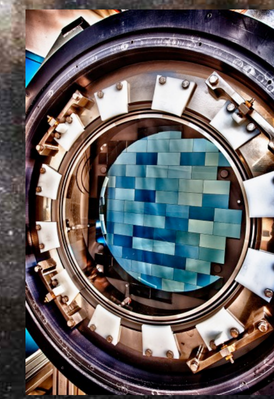


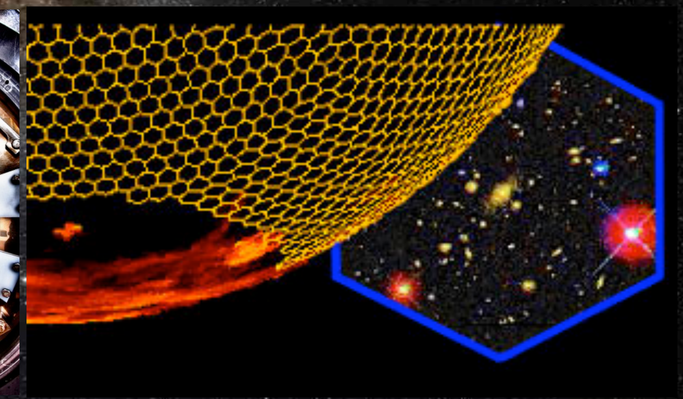


- **DES** - **D**ark **E**nergy **S**urvey: ~2012~2016

  ~ U$ 45M total

  Brazil: ~2M - science/IT

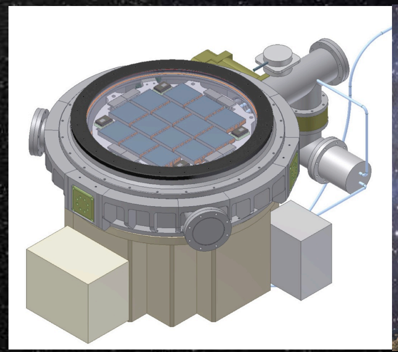




- **J-PAS** - **J**avalambre **P**hysics of **A**cceleration **S**urvey: ~2013~2018

  ~U$ 35M total

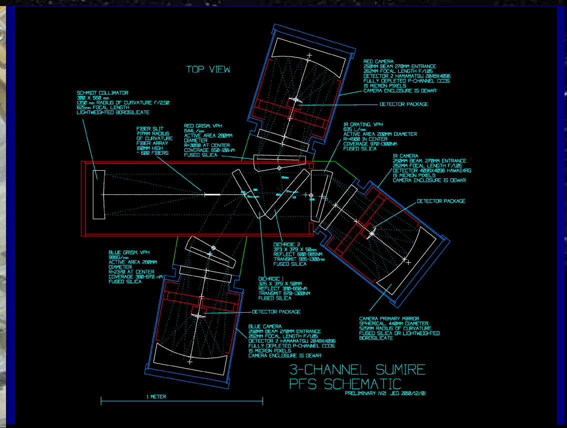
  Brazil: U$ 5M - instrumentation, science, IT



- **HSC & PFS (SuMIRe)** - **S**ubaru **M**easurement of **I**mages & **R**edshifts: ~2017~2020

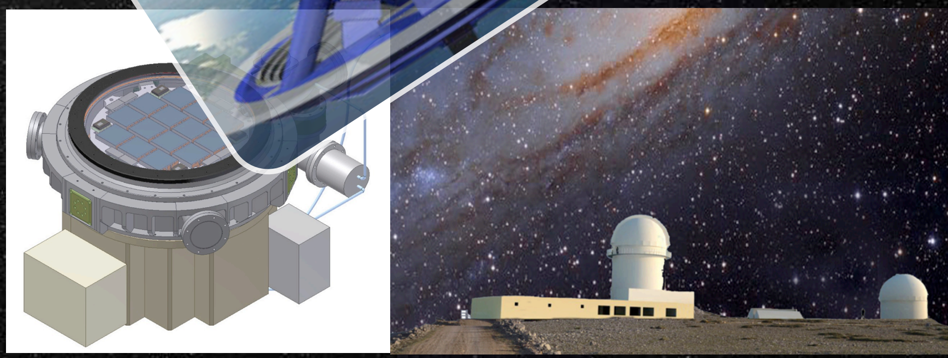
  ~ U$ 50M (PFS) + U$ 200M (HSC)

  Brazil: U$ 5M - instrument., science, IT f/PFS

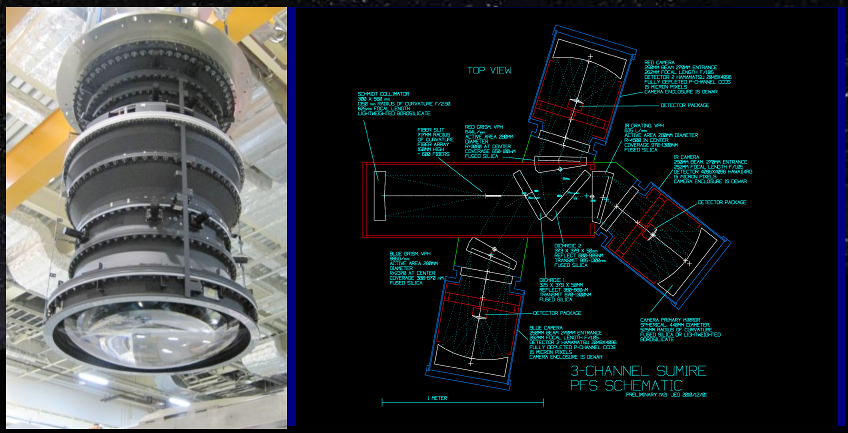


A new generation of **smart telescopes and instruments** is being designed to **map the 3D distribution of matter in the Universe**

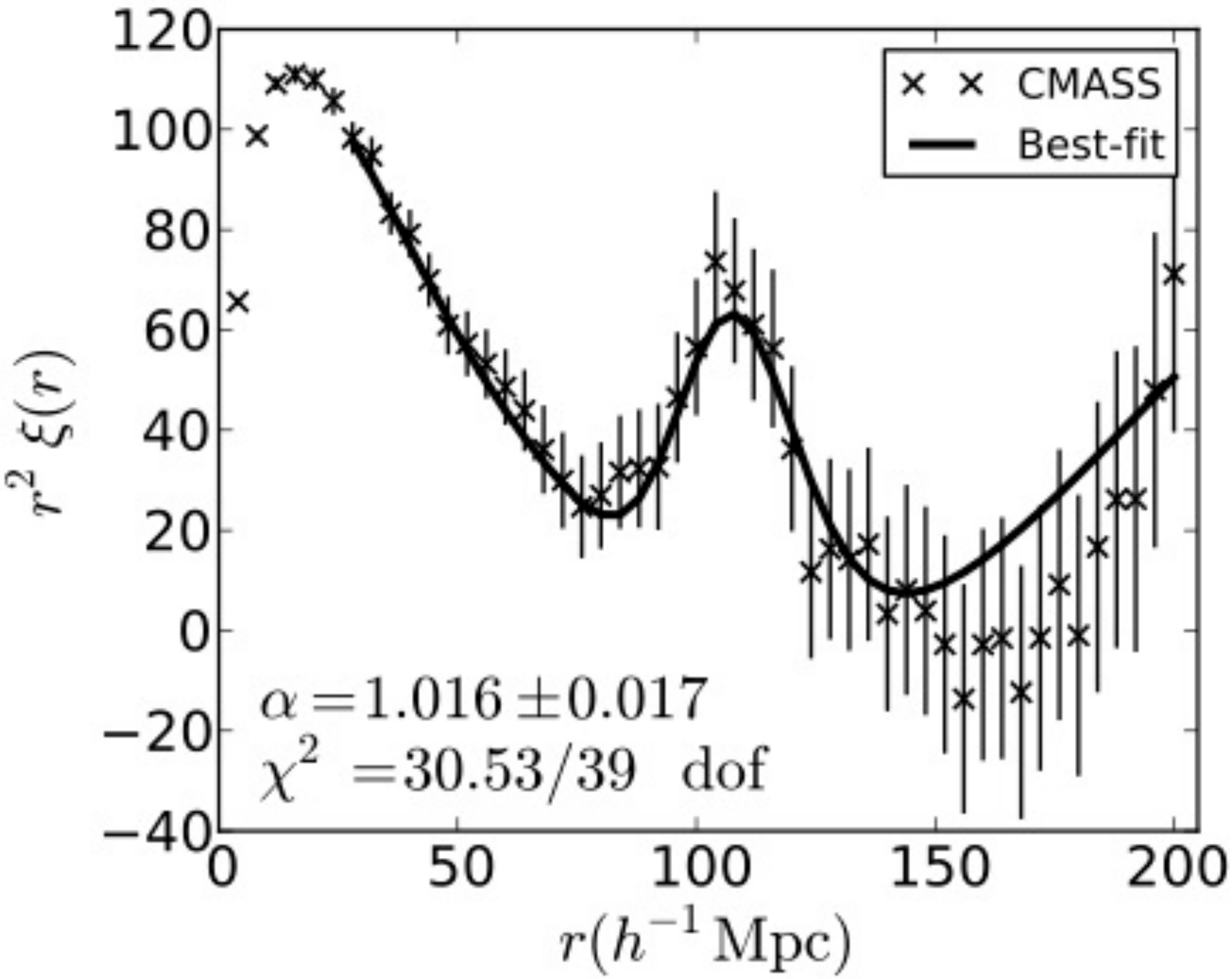
- **BOSS - Baryon Oscillations Spectroscopic Survey (SDSS-III)**: 2010~2014
  Brazil (since 2010): science/IT
- **DES - Dark Energy Survey**: ~2012~2016
  ~ U$ 45M total
  Brazil: ~2M - science/IT
- **J-PAS - Javalambre Physics of Acceleration Survey**: ~2013~2018
  ~U$ 35M total
  Brazil: U$ 5M - instrumentation, science, IT

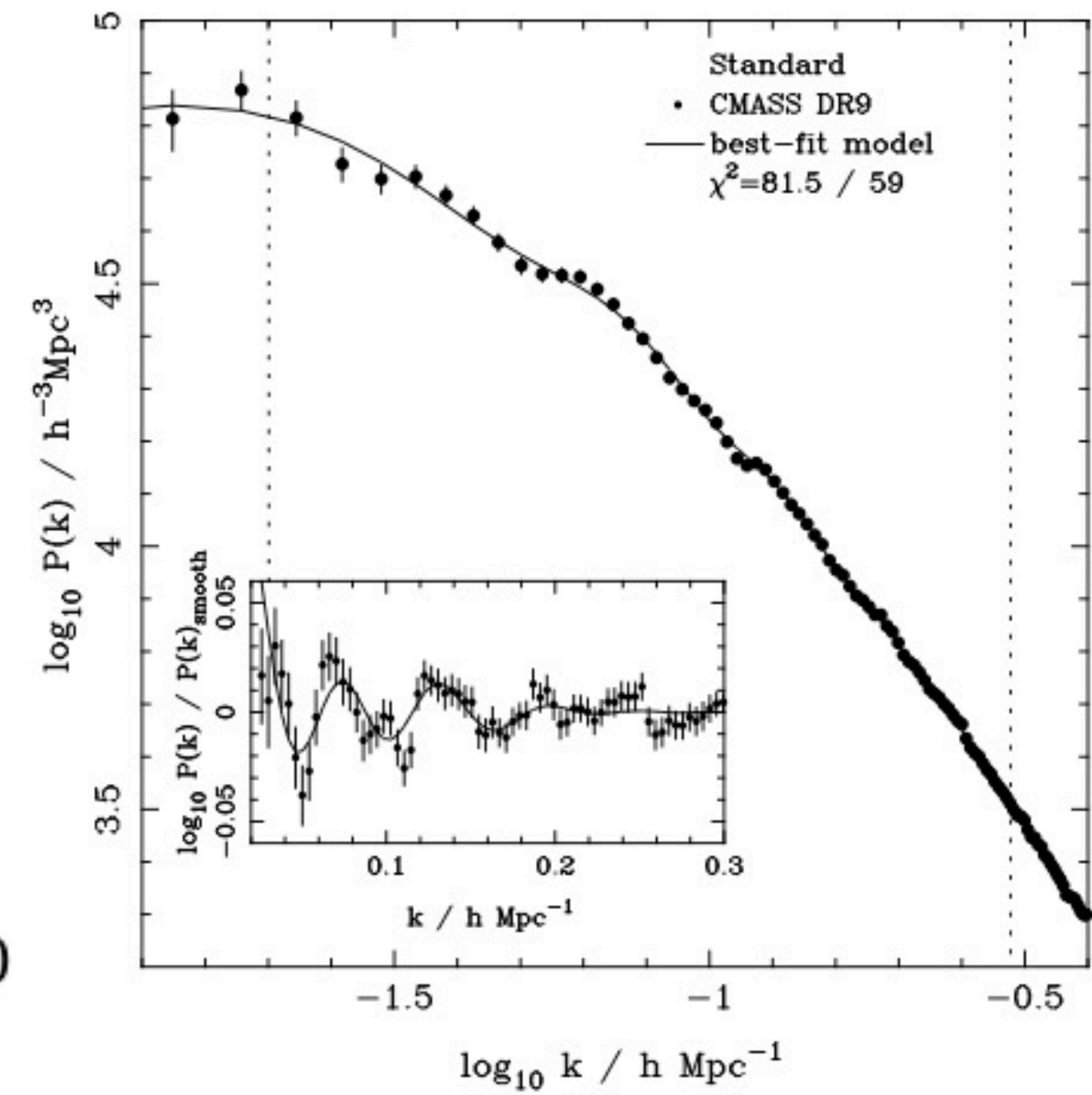


- **HSC & PFS (SuMIRe) - Subaru Measurement of Images & Redshifts**: ~2017~2020
  ~ U$ 50M (PFS) + U$ 200M (HSC)
  Brazil: U$ 5M - instrument., science, IT f/PFS



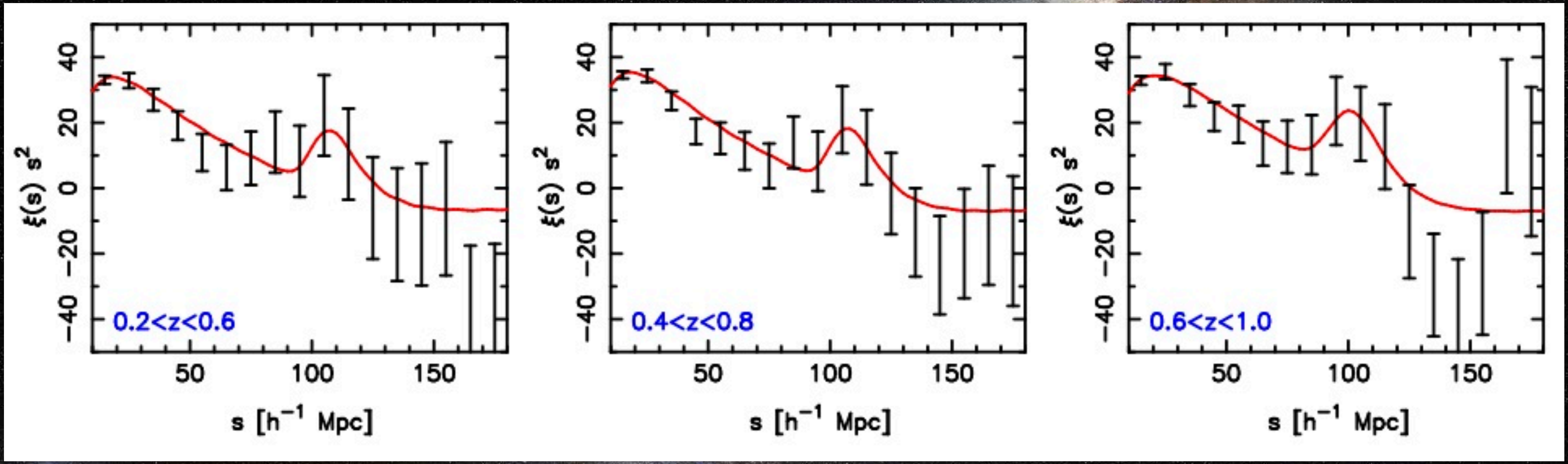
Latest observations: BOSS
(264k galaxies, 3275 deg^2, ~2.2 Gpc^3)



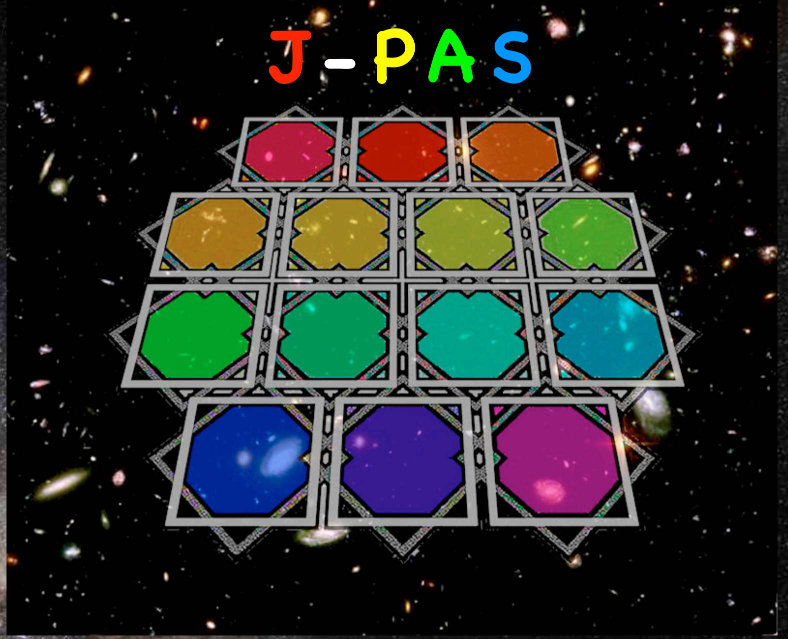


Wiggle-Z

(200k redshifts, 800 deg^2, ~2.2 Gpc^3)

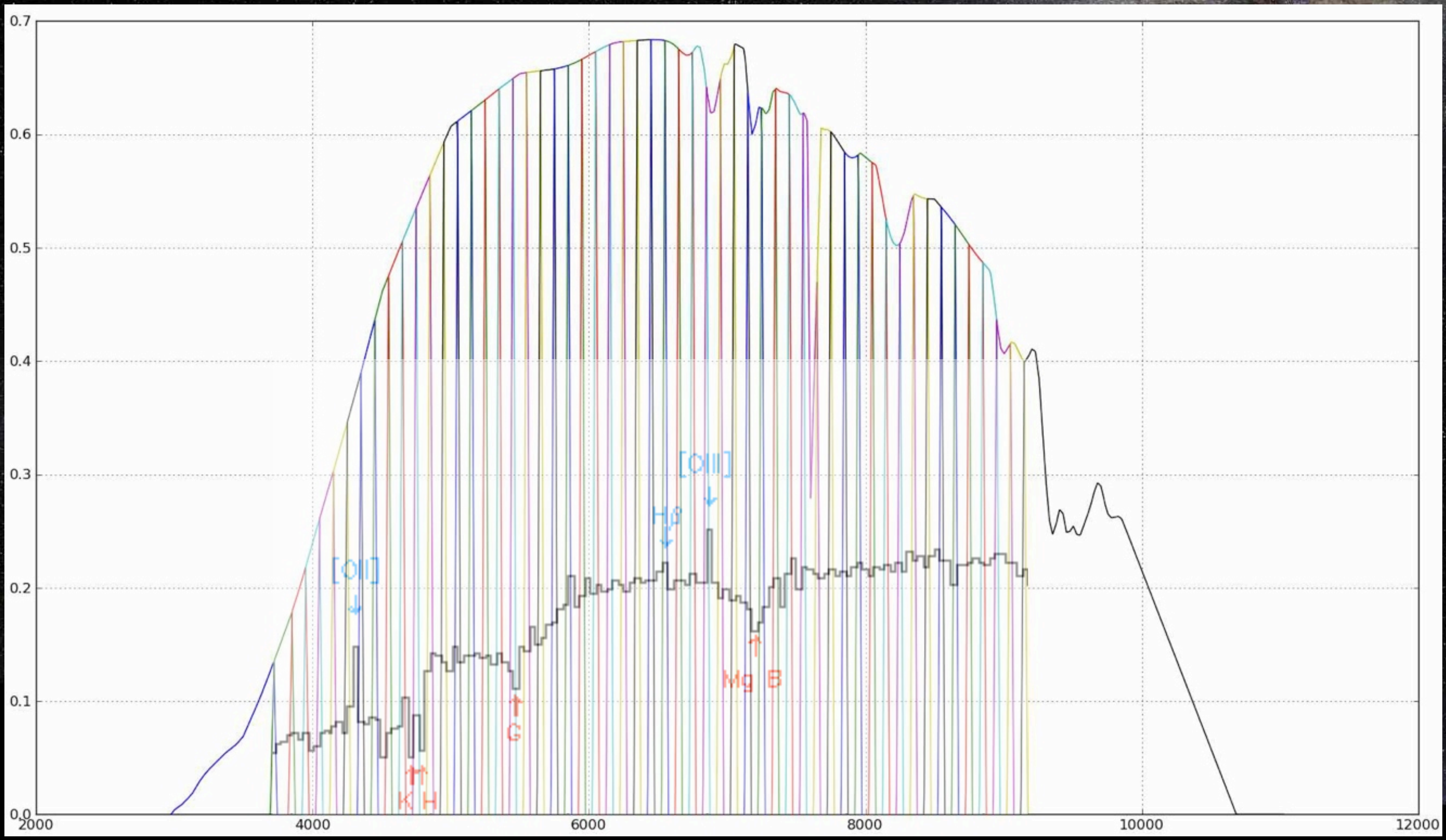


J-PAS - http://j-pas.org

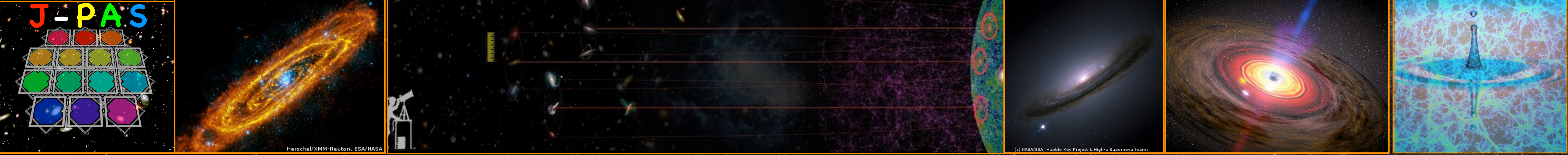


New telescope (Spain) & camera (Brazil), with an innovative approach: imaging in 54 **narrow-band filters**

➾ images & low-resolution spectra of **everything** in ~8500 deg^2

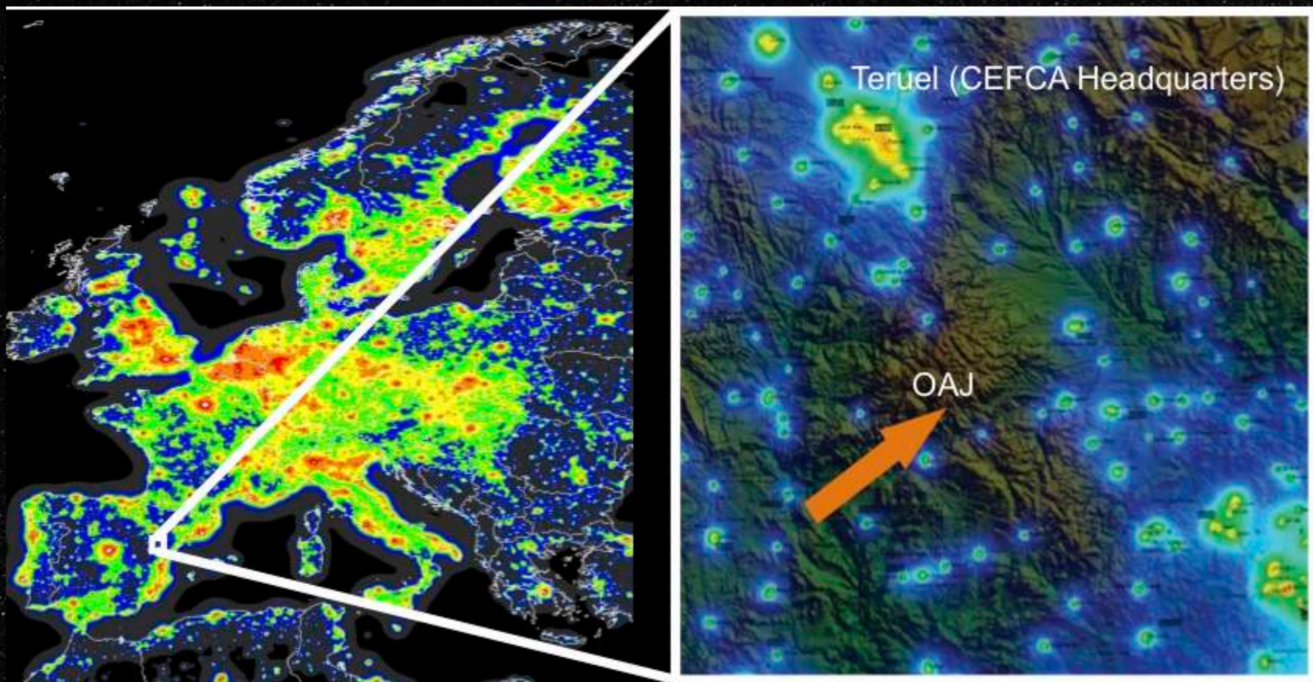


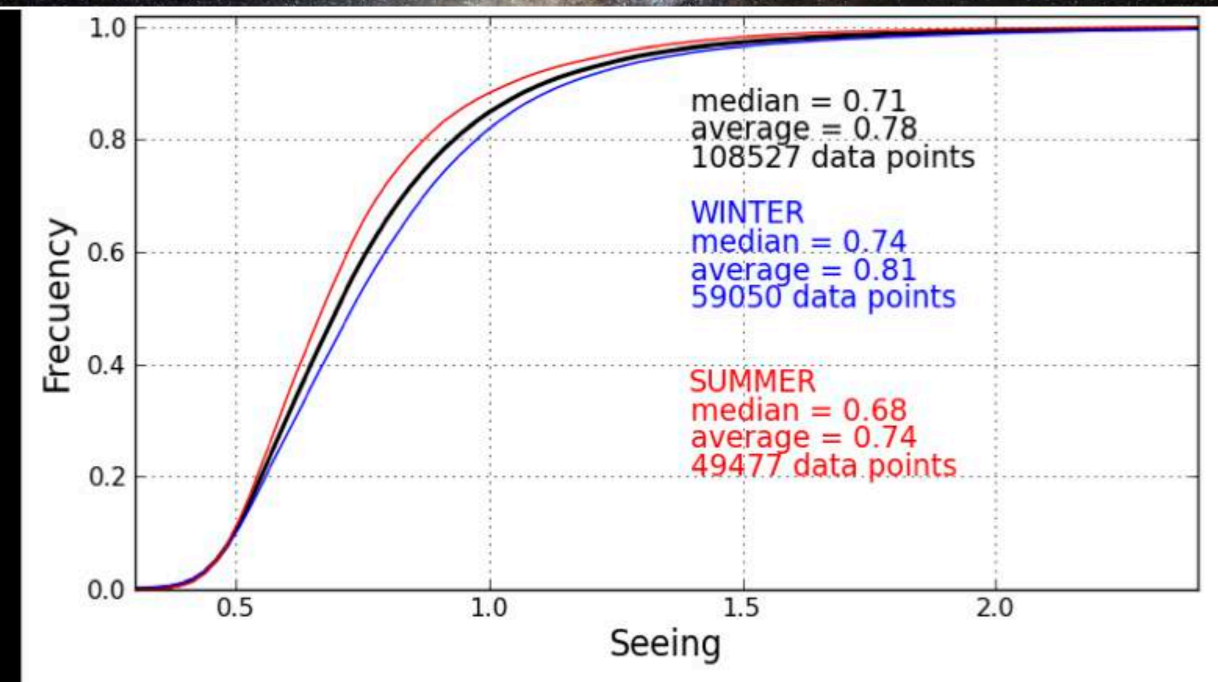
- ➾ BAOs
- ➾ Clusters
- ➾ Supernovas
- ➾ Lensing



New observatory (OAJ) and new Institute of Astrophysics & Cosmology (CEFCA)

Investment (Spain): approx. € 35 M



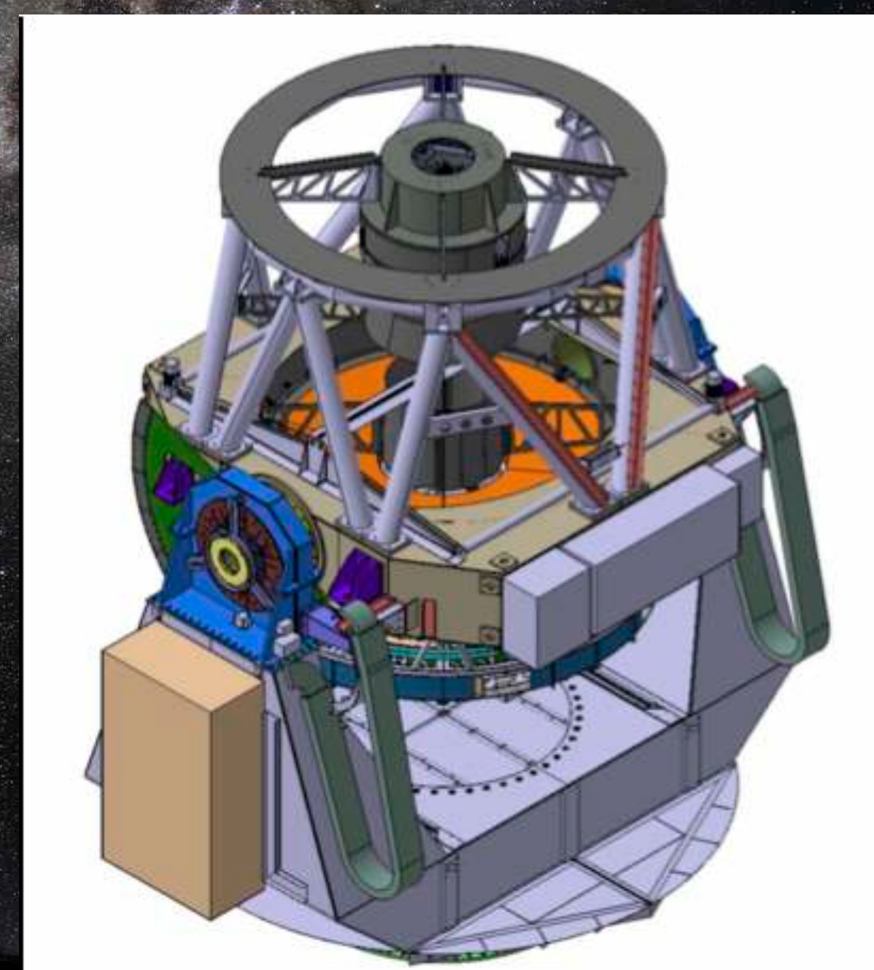


Main Telescope: T250 (2.5m)

M1 = 2.5m
FoV = 3 deg = 476 mm at FP
Effective coll. area = 3.89 m^2
Etendue = 27.5 m^2 deg^2
Plate scale = 22.67"/mm = 0.22"/pix
Focal length = 9098 mm (F#3.5)

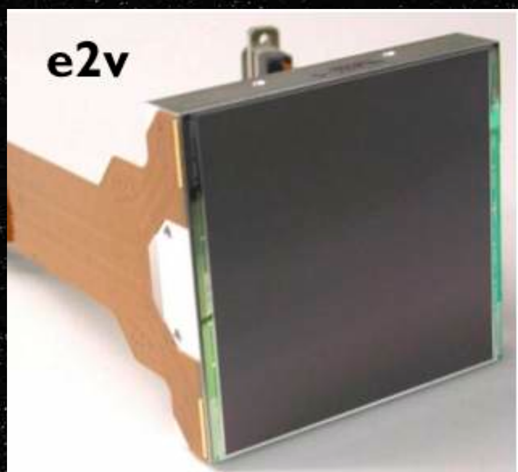
Type = Ritchey Chrétien-like
Mount = Alt-azimuthal
Focus = Cassegrain
Field corrector = 3 lenses
Mass = 45.000 Kg

Opto-mechanics by AMOS
FDR accepted; on site in Q3 2012



J-PAS

Camera: JPCam (Brazil; cost: approx. U$ 6 M)

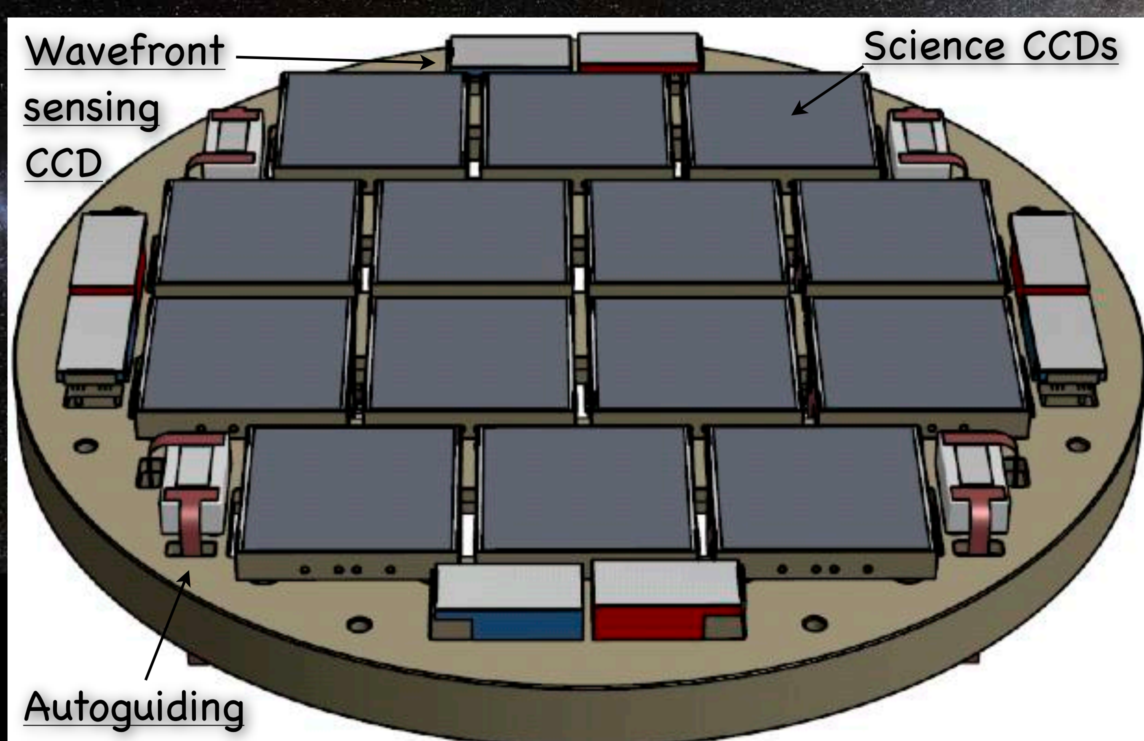


CCDs: 9,216k x 9,216k (e2V)

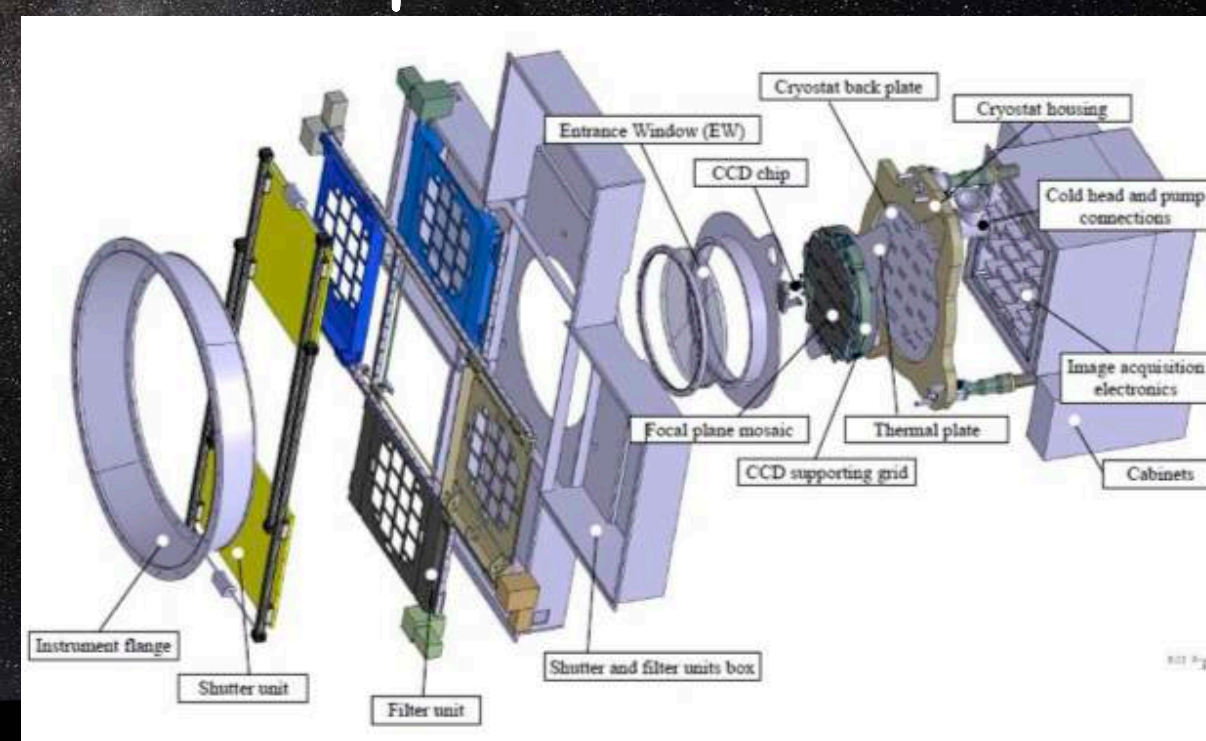
QE > 80% (400-880nm)

RoN @ 1MHz=5.0 e^-/pix

Mosaic of 14 CCDs



"exploded" view of camera



Ministério da Ciência e Tecnologia
BRASIL UM PAÍS DE TODOS
FAPESP
Observatório Nacional
Instituto de Física
Universidade Federal do Rio de Janeiro
Dep. de Física Matemática/IFUSP

J-PAS

Cosmology/Extragalactic goals

☛ ~ 13 million **red galaxies** to z<1.1 - $\sigma_z \sim 0.003(1+z)$

☛ ~ 100 million **ELGs** to z<1.3 - $\sigma_z \sim 0.0025(1+z)$

☛ ~ 200 million **galaxies** (gen) to z<1.4 - $\sigma_z \sim 0.01(1+z)$

☛ ~ 2-3 million **quasars** to z<5 - $\sigma_z \sim 0.0015(1+z)$

☛ Hundreds (thousands?) of **supernovas** (no need of spectr.!)

☛ Tens of thousands of galaxy **clusters and groups**

☛ Serendipitous discoveries

Science apps

☛ LSS, BAOs, P(k), non-gaussianities

☛ Dark energy, dark matter, cosmography

☛ > 10^5 clusters & groups

☛ Weak lensing

☛ Evolution of our galaxy

☛ Stellar population in the local Universe

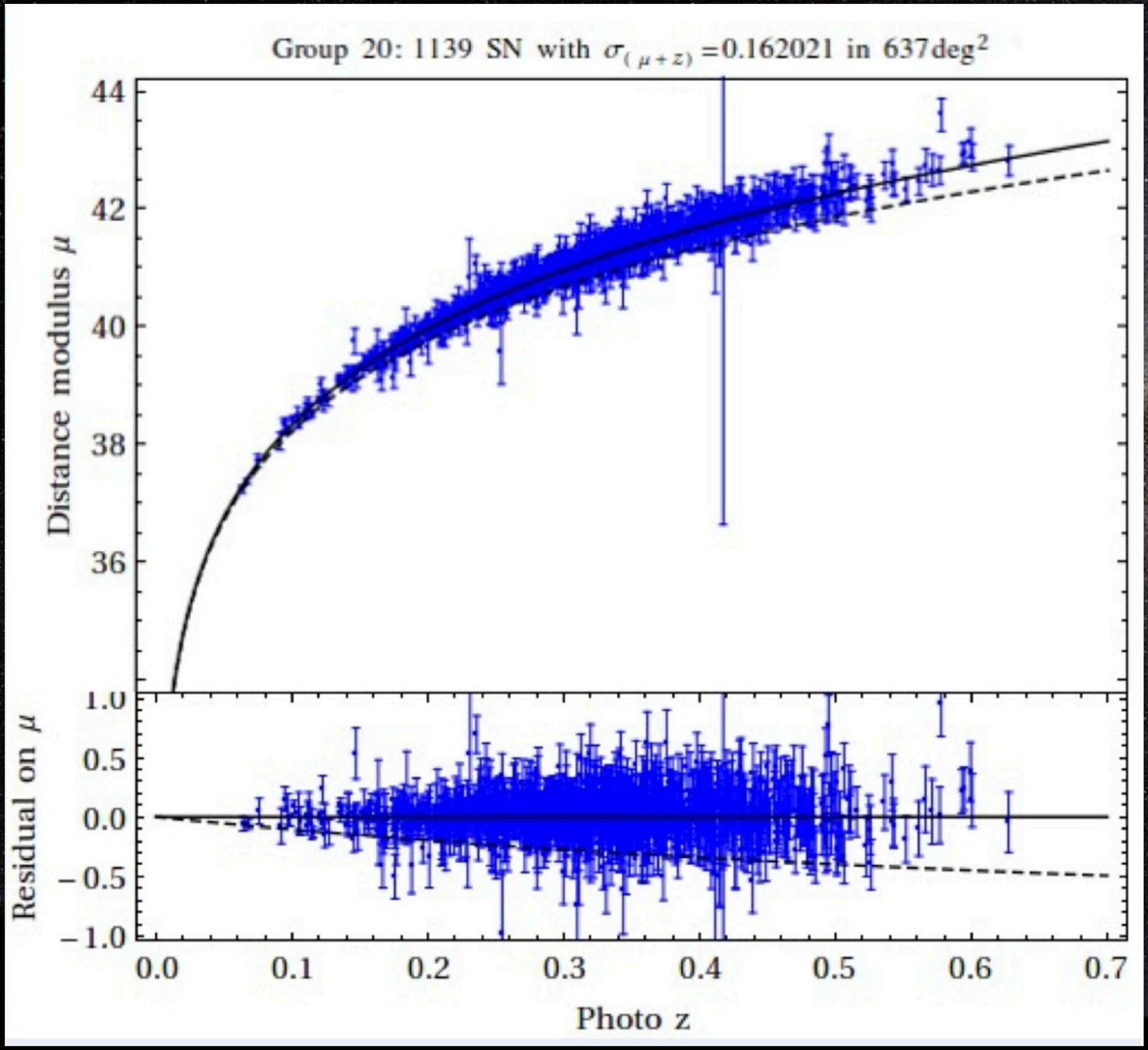
☛ ...

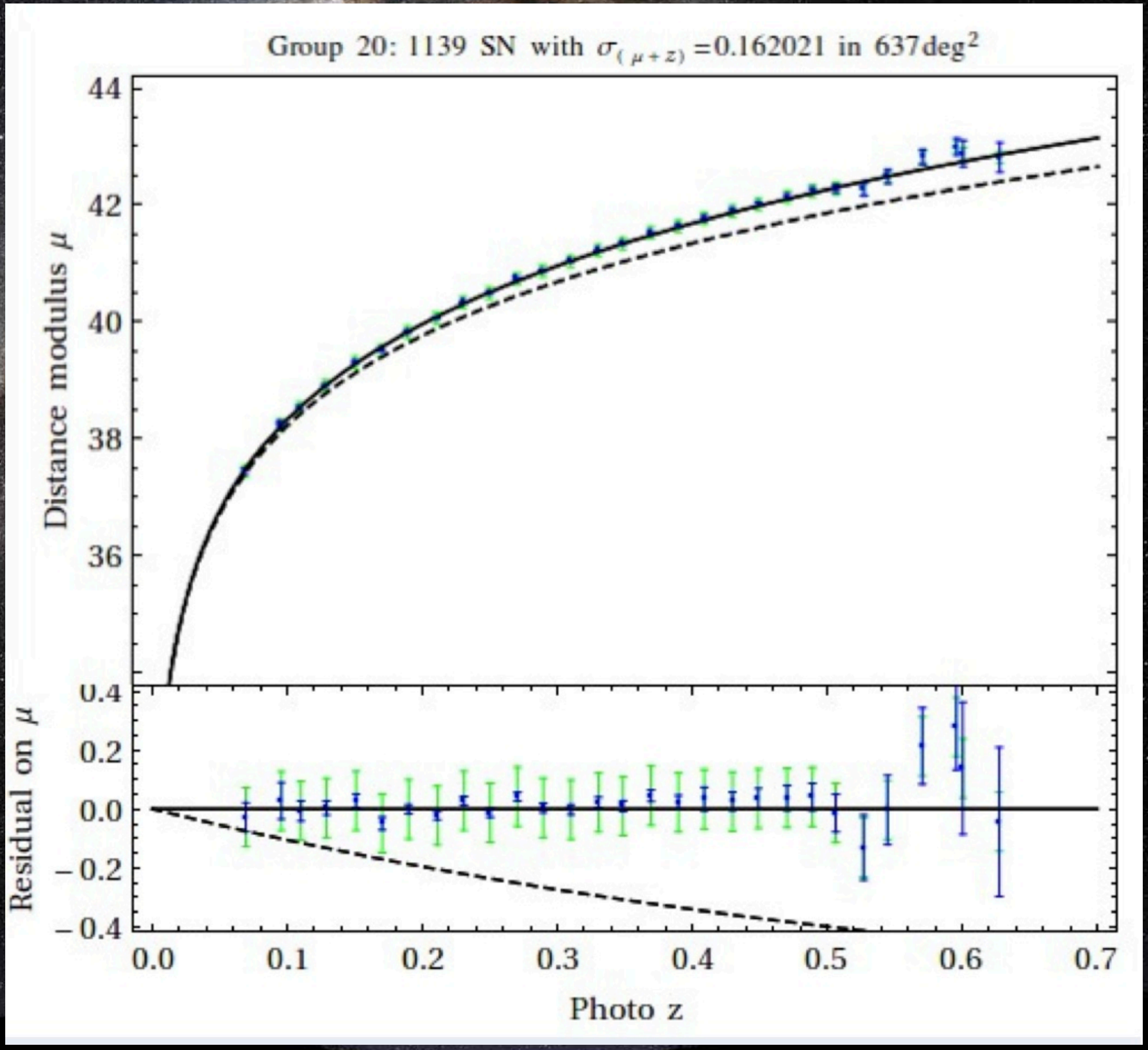
Type 1a Supernovas

Hundreds or thousands of objects may be detected

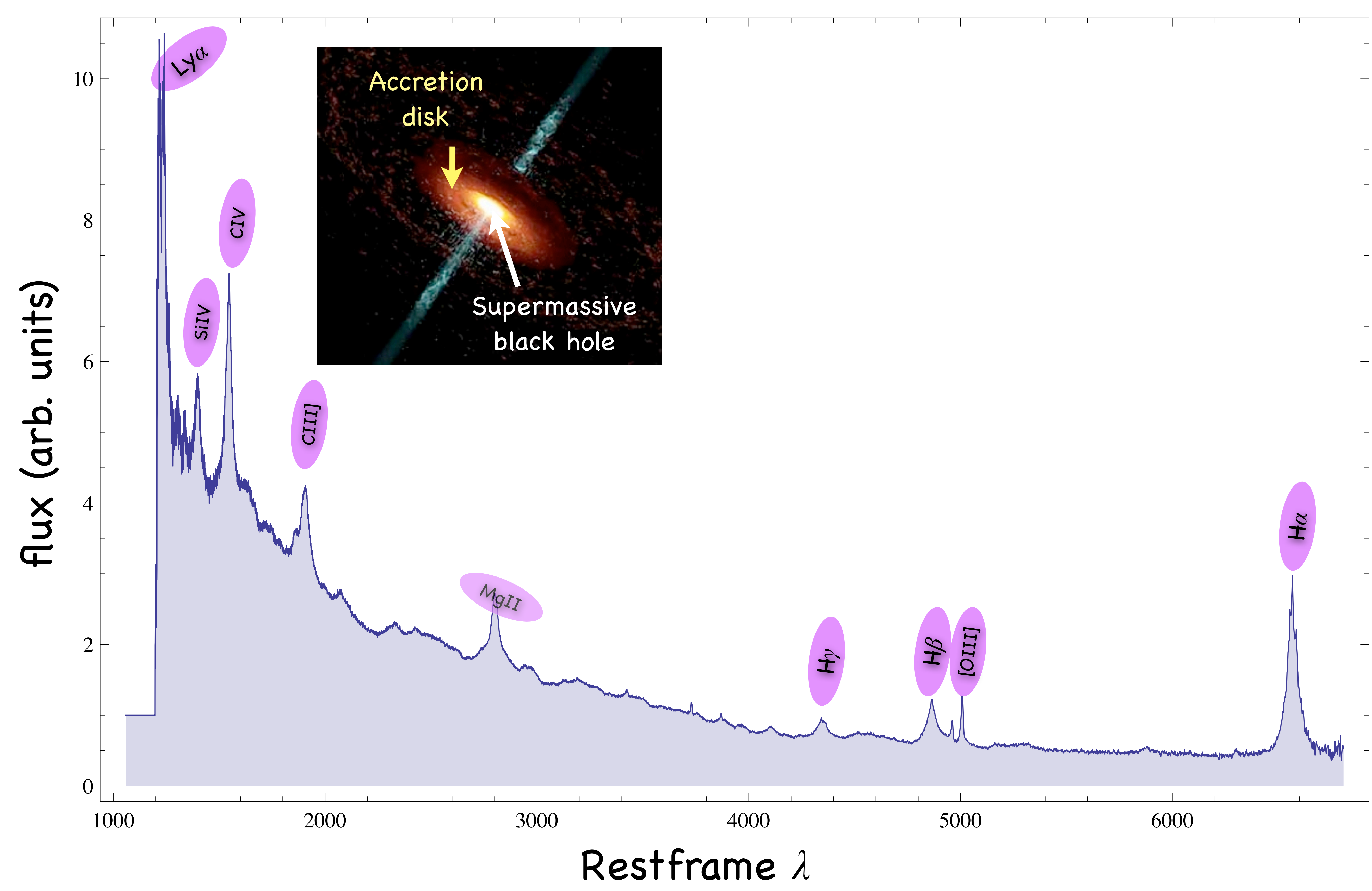
Even without spectroscopy, contamination will be minimal

H. Xavier, R.A., M. Sako, et al.





Black holes and dark energy: using quasars to map the Universe with J-PAS



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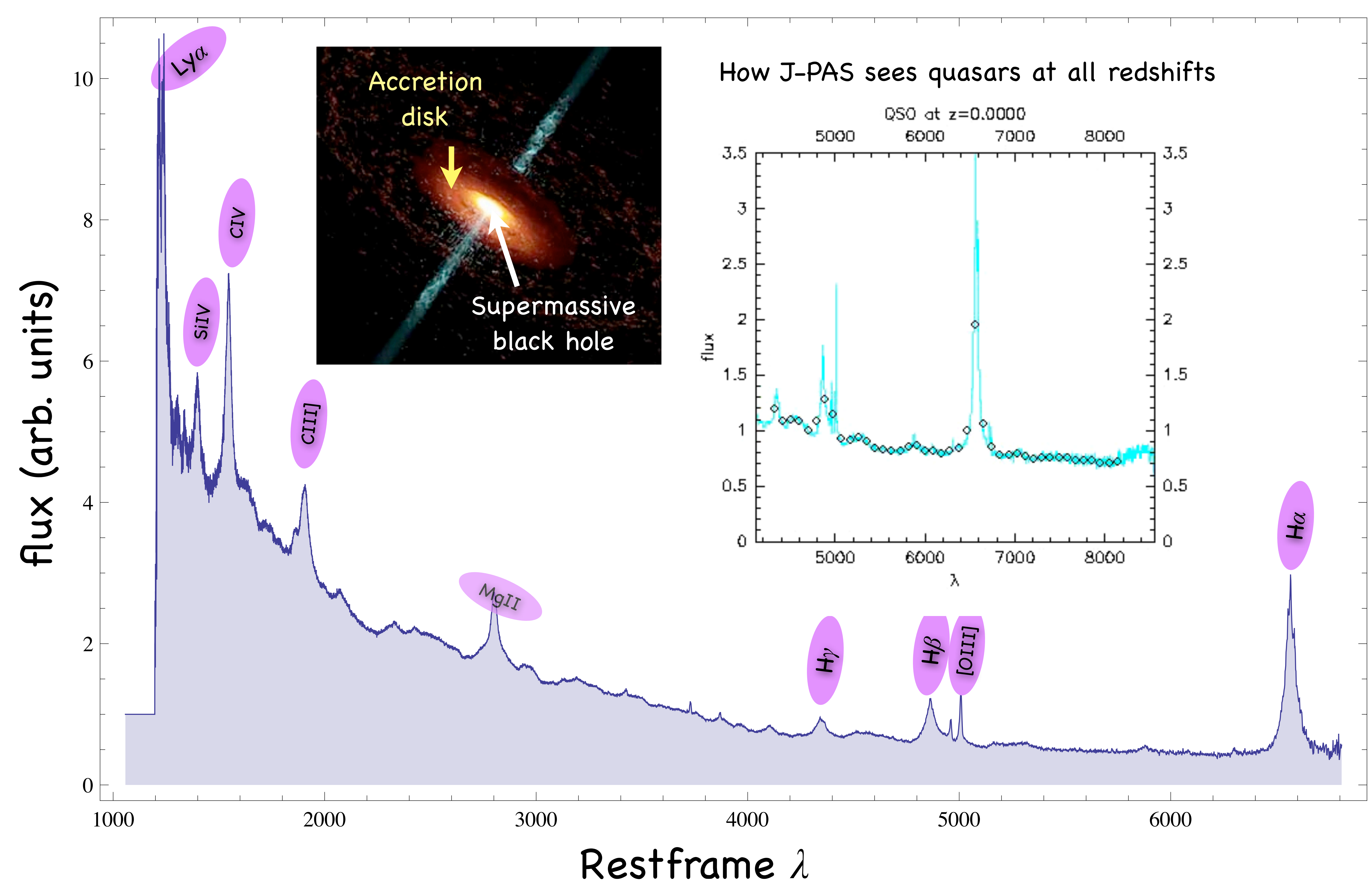
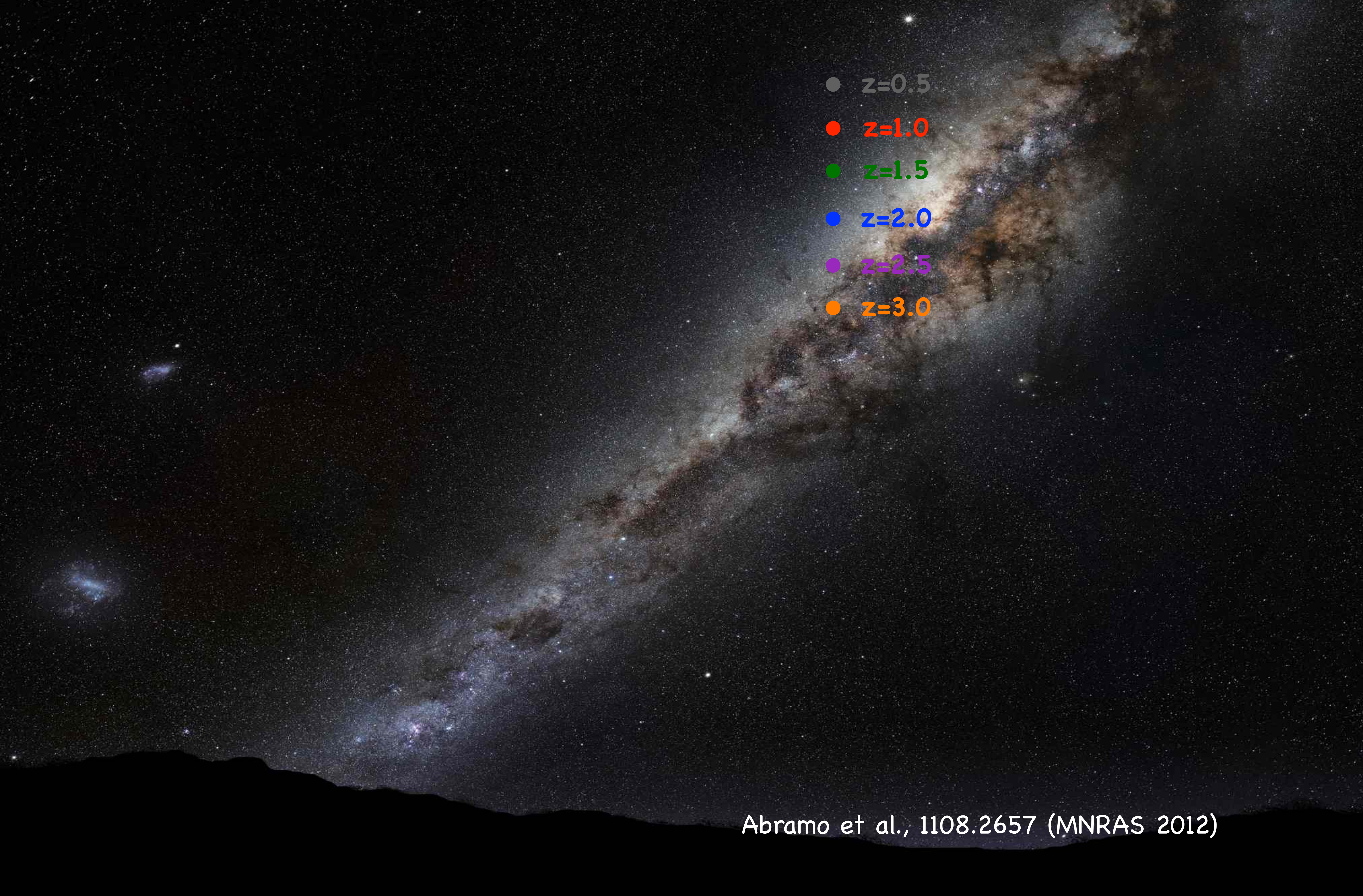


Millions of quasars with J-PAS ⇨ BAOs & LSS



Abramo et al., 1108.2657 (MNRAS 2012)

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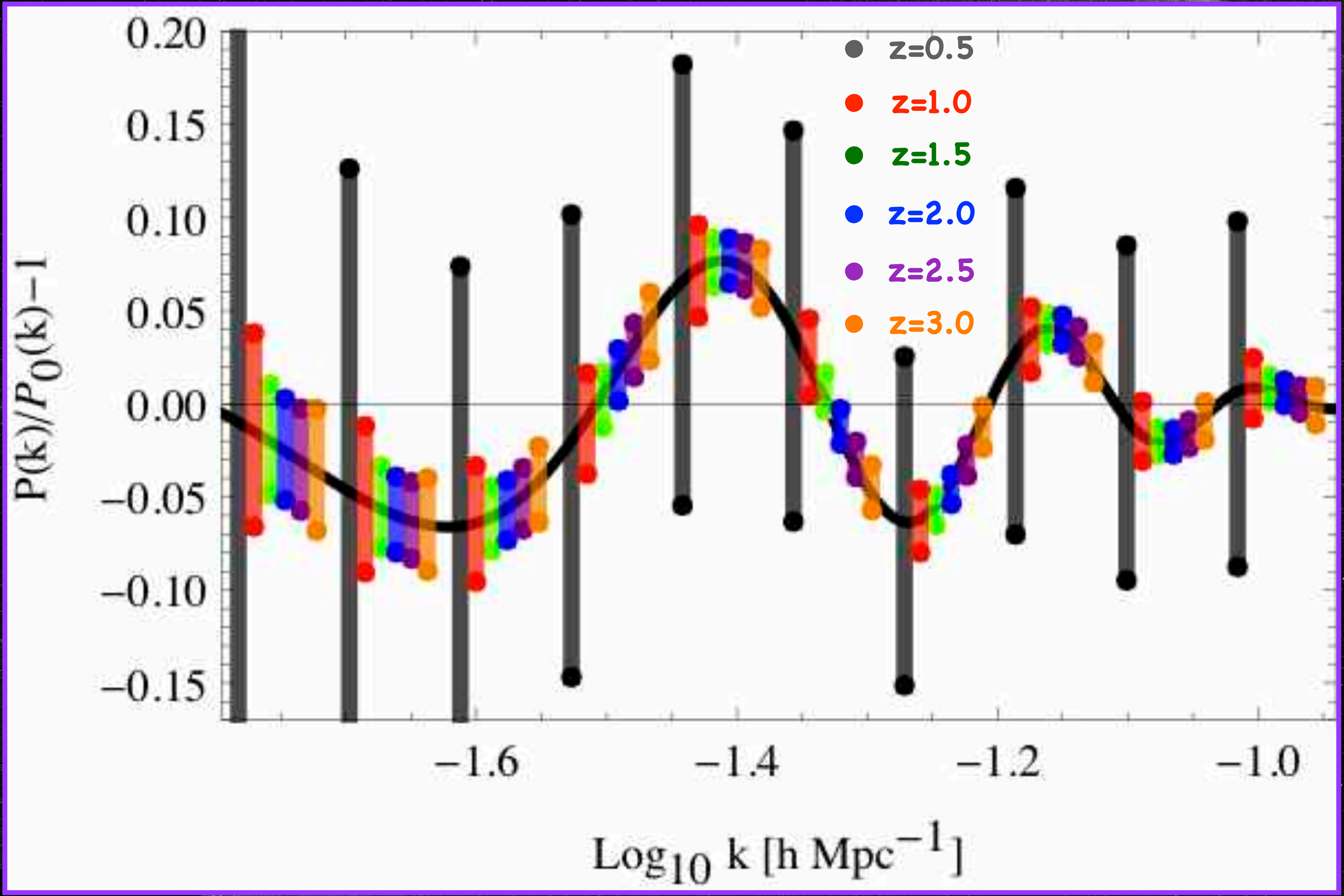
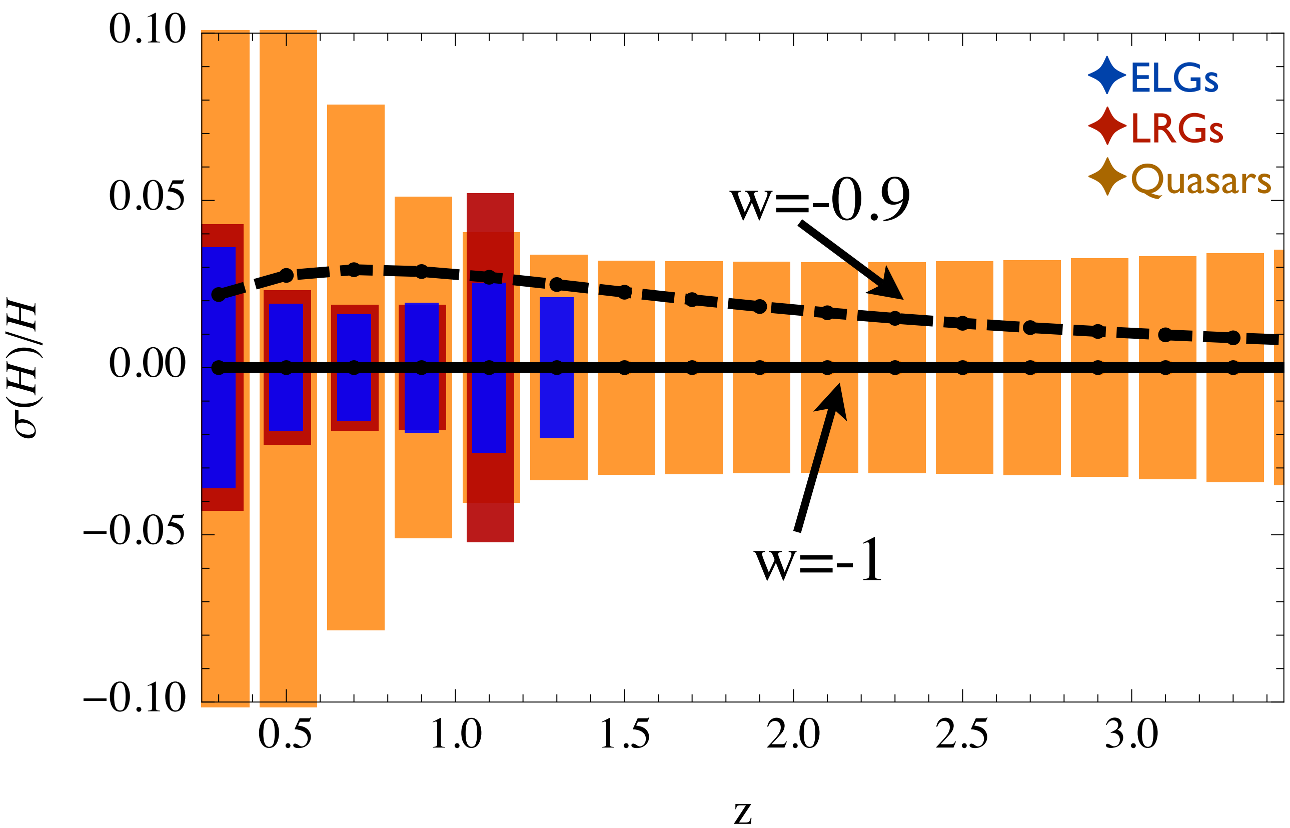
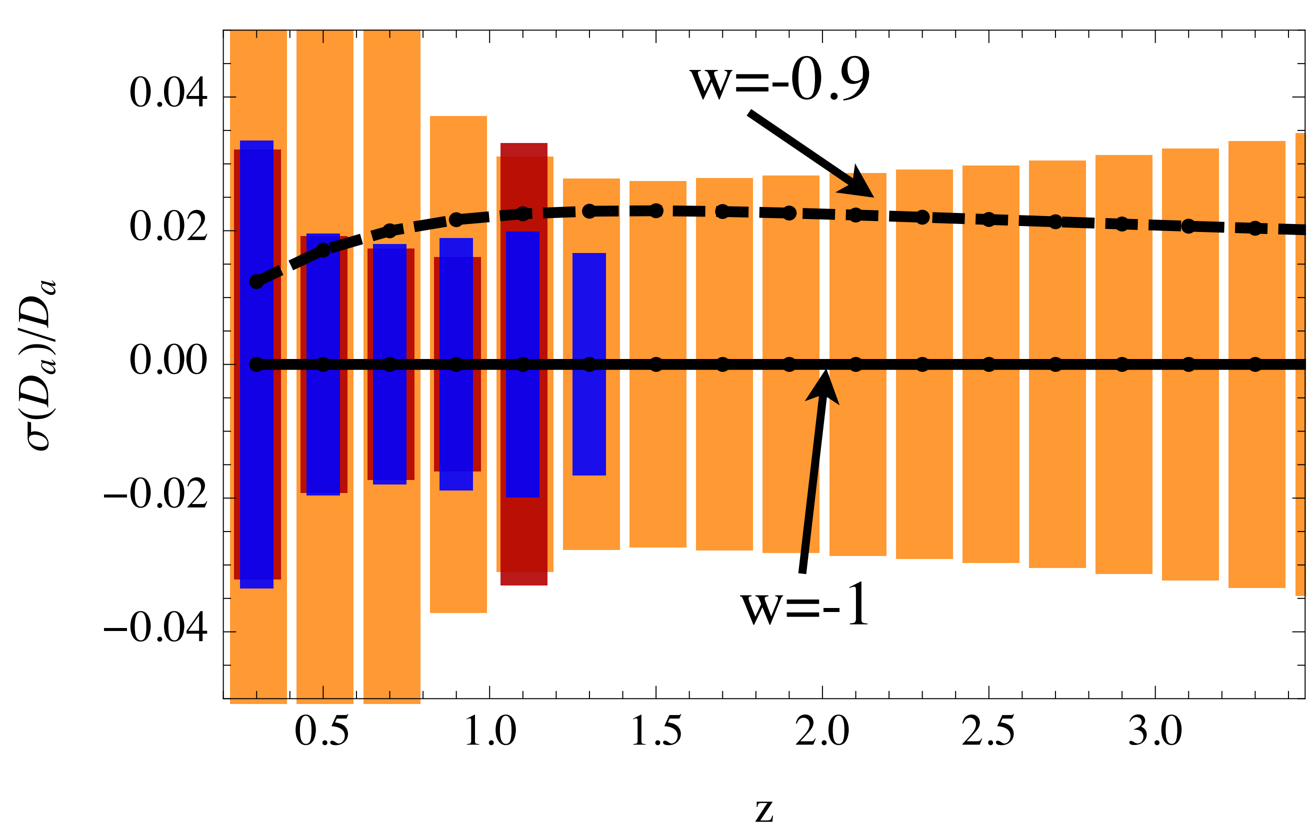


Abramo et al., 1108.2657 (MNRAS 2012)

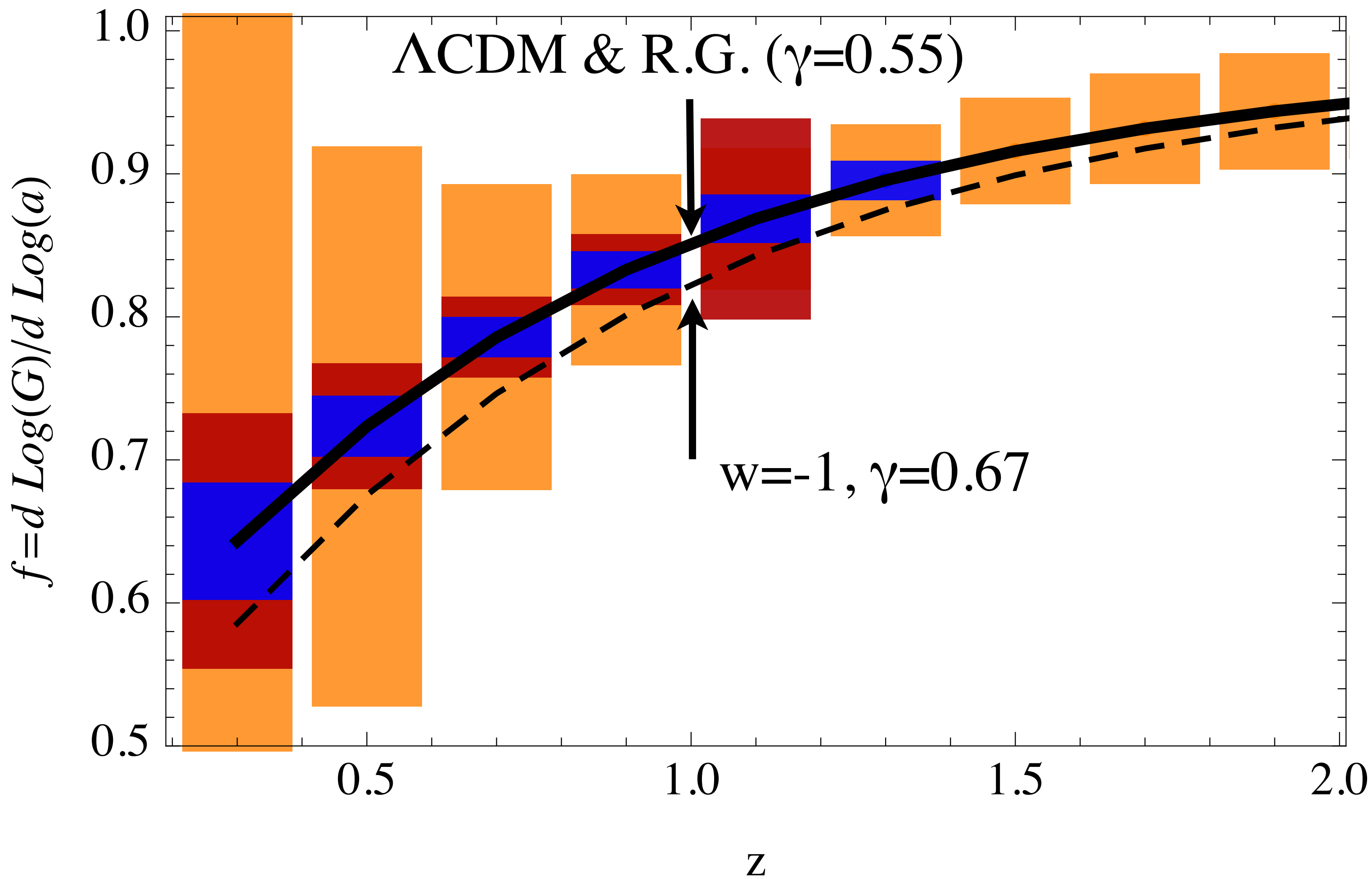
Measuring distances with BAOs on J-PAS





- The **excelent photometric redshifts of J-PAS** allow us to measure **radial distances (*H*)**, as well as **distances in the angular direction (D_a)** with high precision

Dark energy *v.* modified gravity with J-PAS



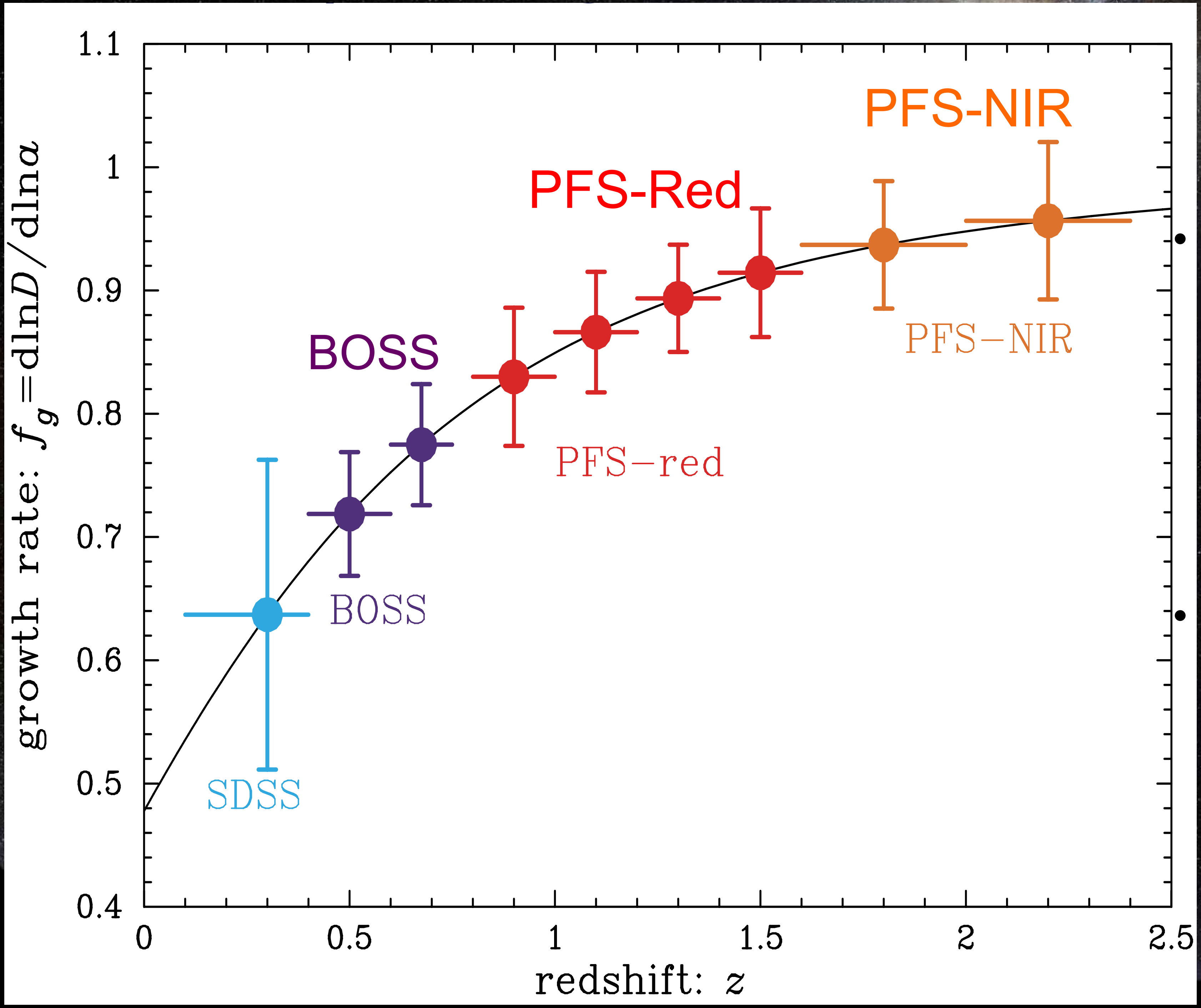
Growth of structures in the Universe:

$$\frac{\delta\rho}{\rho}(z) = G(z)\ \frac{\delta\rho}{\rho}\bigg|_{z=0}$$

$$f(z) = \frac{d\ln G}{d\ln a} = \Omega_m^\gamma(z)$$

- J-PAS will be able to measure the **matter growth function** using redshift-space distortions, **and test General Relativity**

➯ With PFS/HSC we will also measure the growth of structure - even better than J-PAS



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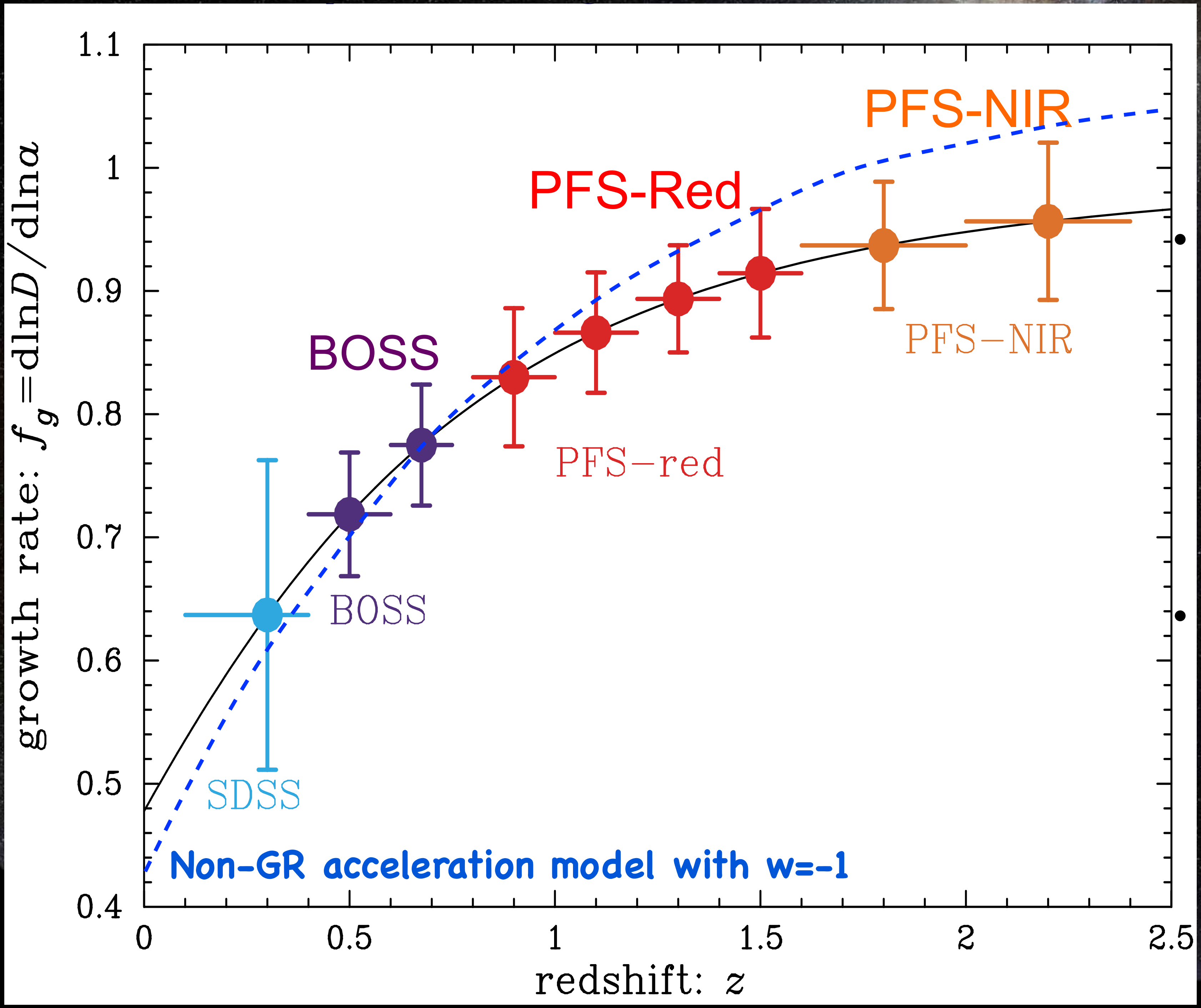


New light on dark energy

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- Right now, **technology & data**, more than theory, are driving research in Cosmology & Astrophysics

New light on dark energy

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- Amazing **new instruments** for next 10 years - potential for immense progress

New light on dark energy

- Right now, **technology & data**, more than theory, are driving research in Cosmology & Astrophysics
- Amazing **new instruments** for next 10 years - potential for immense progress
- **Great opportunities for students** that would like to make **real discoveries!**