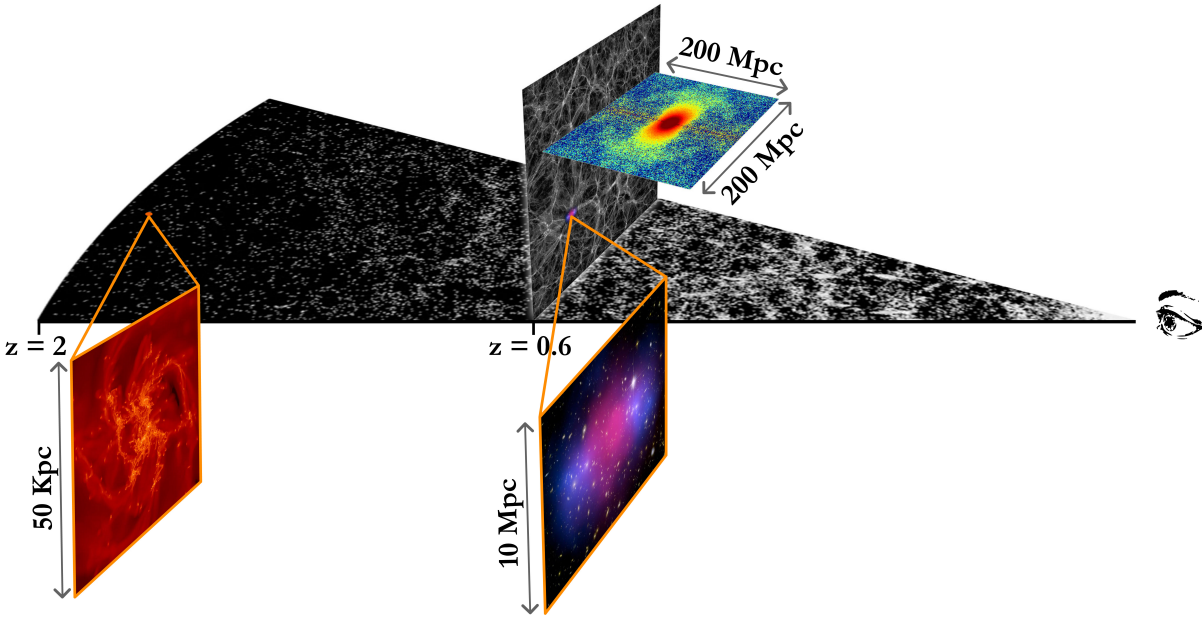
DE LA RECHERCHE À L'INDUSTRIE

www.cea.fr

Cosmology
@ IRFU



D. Elbaz

Friday 13 May 2016

COSMOLOGY AT IRFU

Cosmology at SAp – 14 staff

- Cosmology and Galaxy Evolution Laboratory (LCEG)
  12 staff, 10 postdocs, 6 PhD students
  → **Herschel, XMM**, *ALMA,* **SVOM**

- Cosmology & Statistics **SAp + SEDI** (COSMOSTAT)
  2+3 staff, 2+1 postdocs, 2+1 PhD students
  → **Planck, Euclid**

Cosmology at SPP – 15 staff

- Cosmological probes: Baryonic acoustic oscillations (BAO), galaxy clusters, CMB, SNIa + modified gravity
  → **BOSS, eBOSS, DESI + Planck**
  → 10 staff, 1 postdoc, 4 PhD students
- **HESS, CTA** / dark matter (5 staff)

Cosmology at SEDI – 11 staff

- *Cosmology & Statistics **SAp + SEDI***
- simulations & visualisation (COAST)
- SVOM
- Planck, Euclid

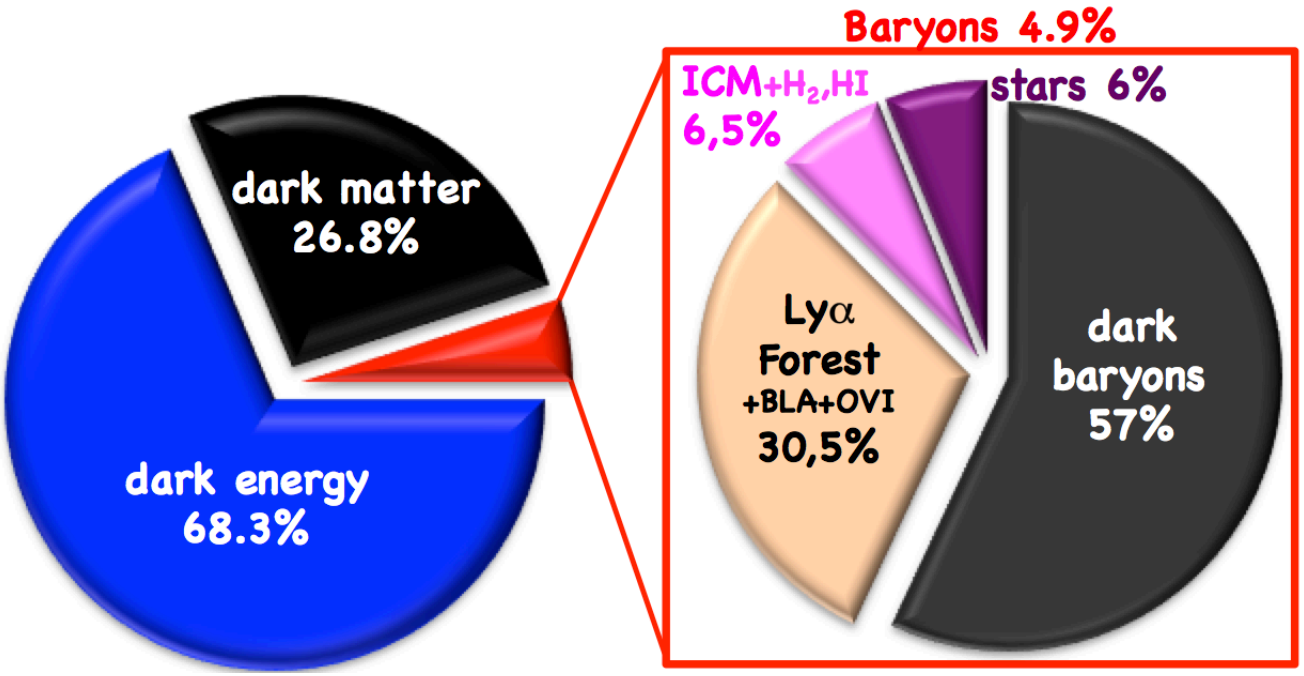
Cosmology at IPhT – 5 staff

- Alternatives to the standard ΛCDM model (modified gravity,…)
- Primordial cosmology (gravitational waves, inflation), dark energy

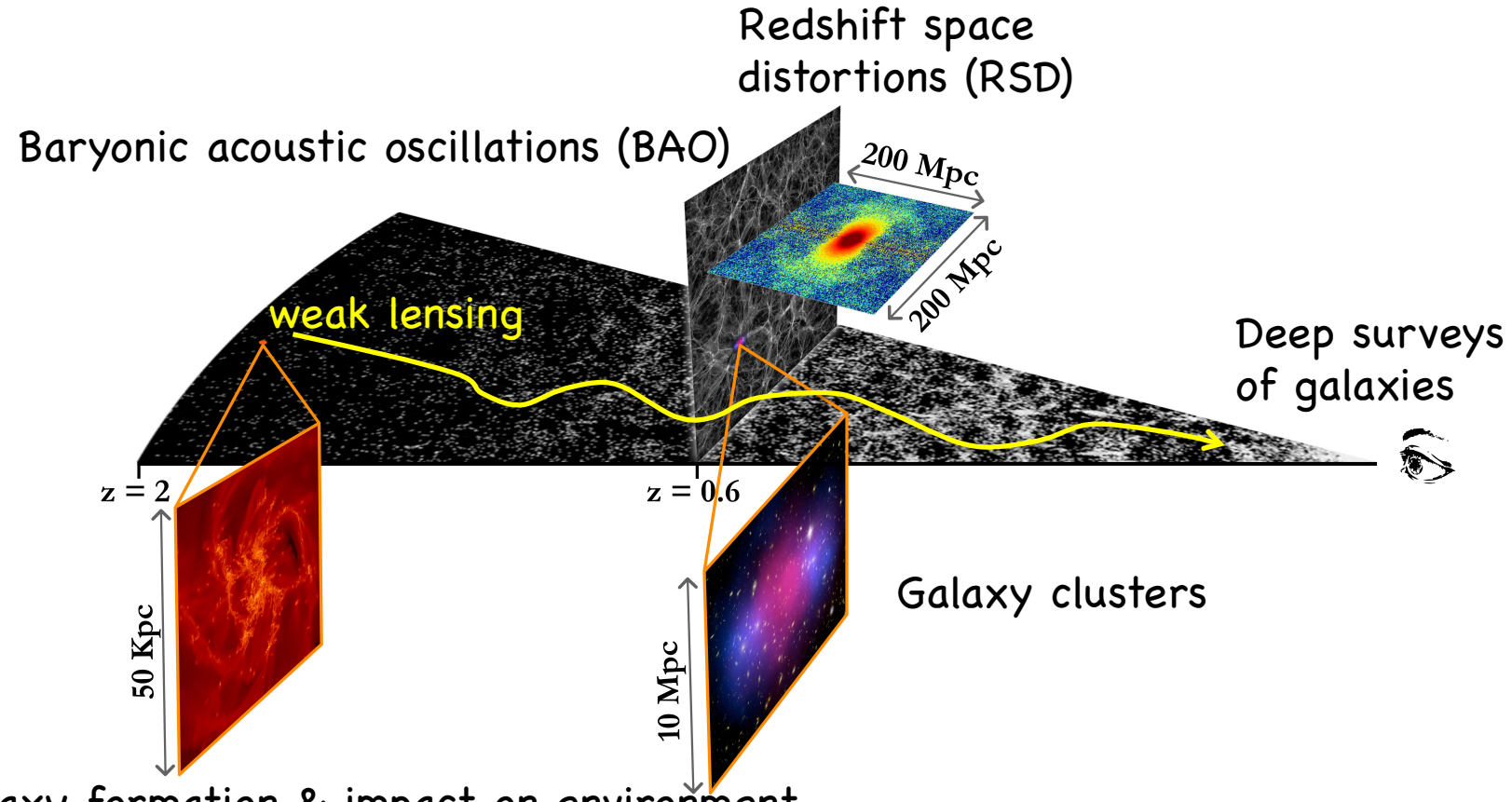
IPhT Saclay

COSMOLOGY AT IRFU
FROM THE SMALL TO THE LARGEST SCALES

1. What controls the growth of galaxies and galaxy clusters ?
2. What does it tell us on the nature of dark matter & dark energy ?
3. What is the respective impacts of baryons on dark matter and reversely ?
4. What is the nature of dark energy ? (eq. of state, cosmological parameters)
5. Do we see any evidence for alternative cosmologies ?

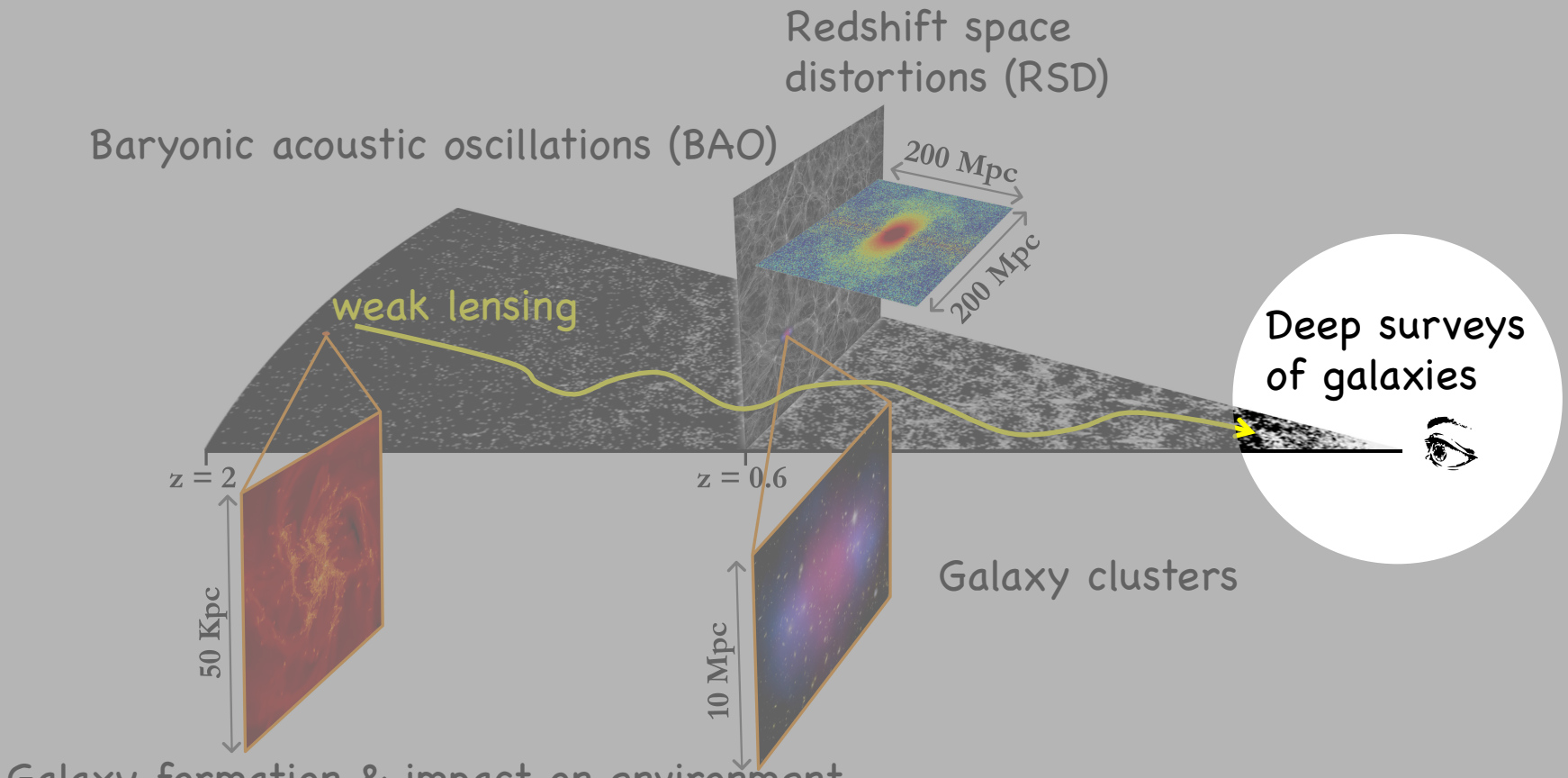


COSMOLOGY AT IRFU
FROM THE SMALL TO THE LARGEST SCALES

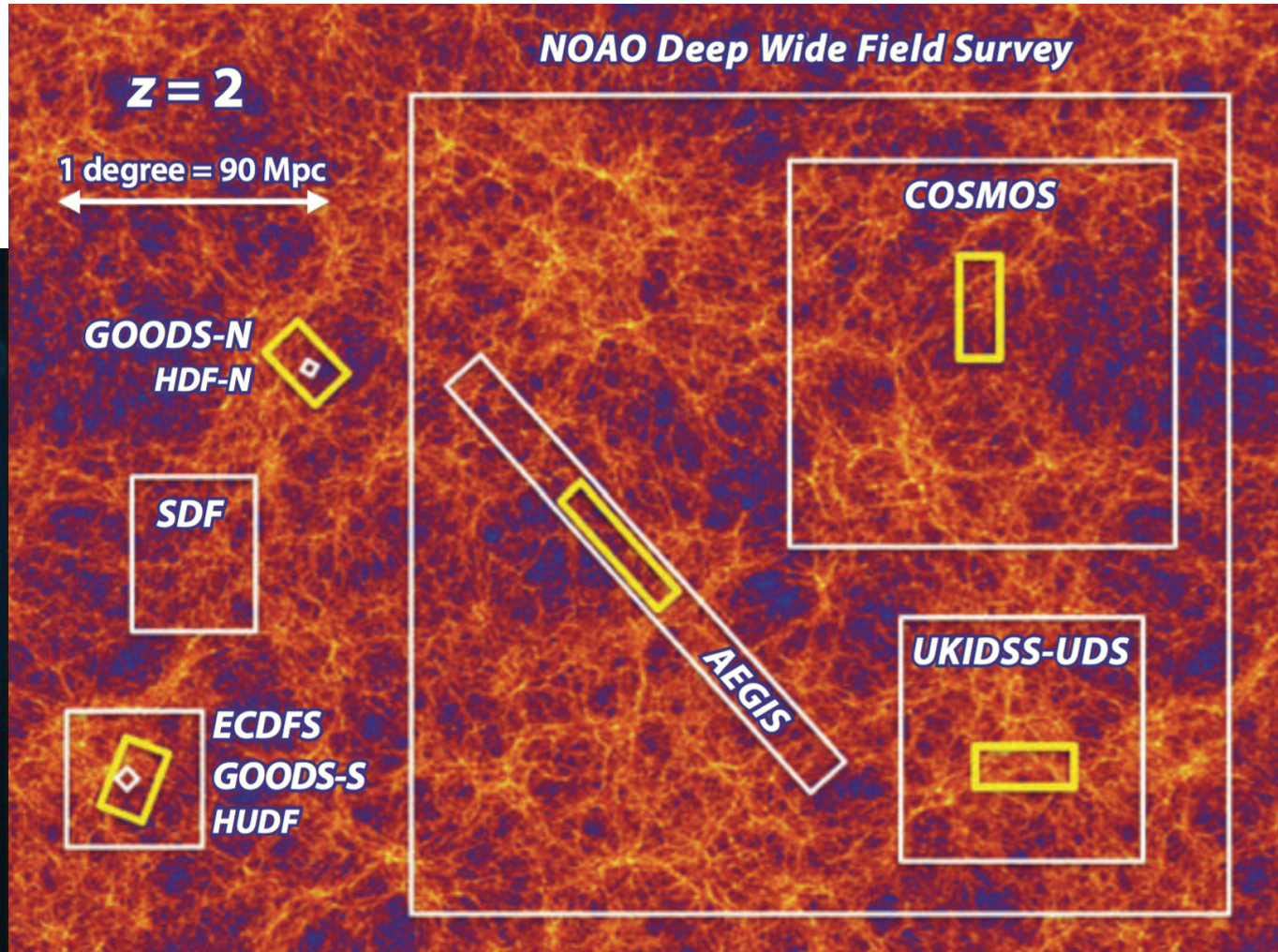


COSMOLOGY AT IRFU
FROM THE SMALL TO THE LARGEST SCALES

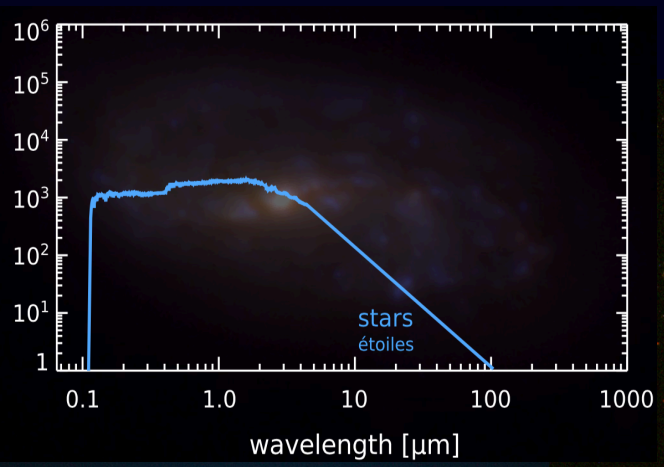
The astrophysical tools used at IRFU to address those issues…

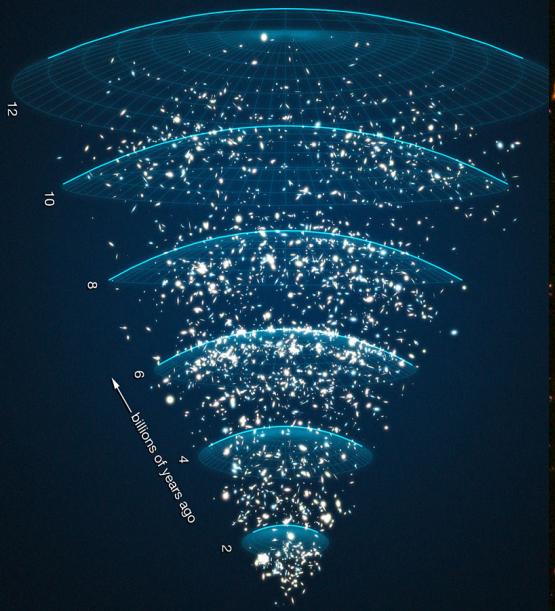


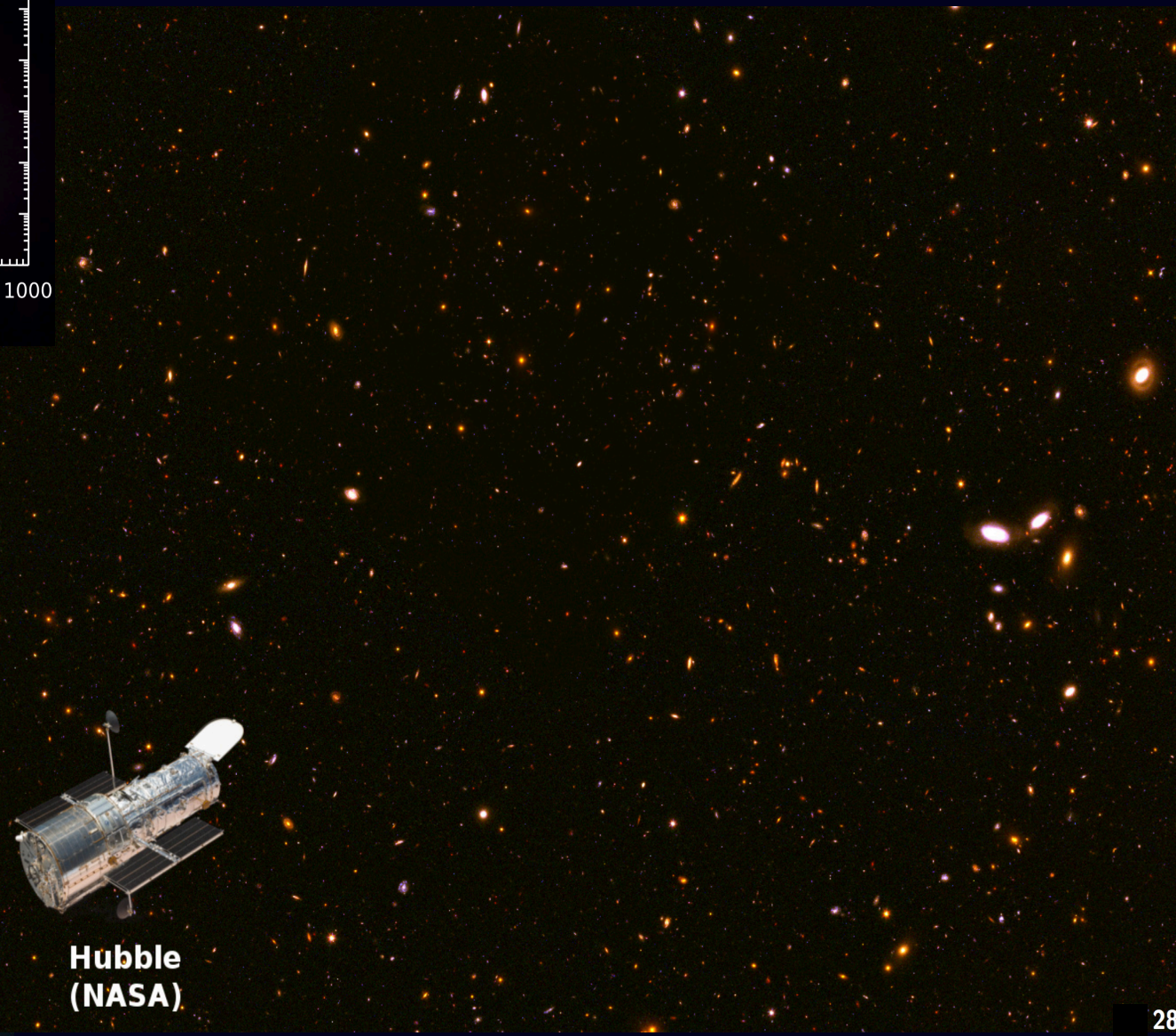
Tracing back the history of galaxy formation with deep surveys



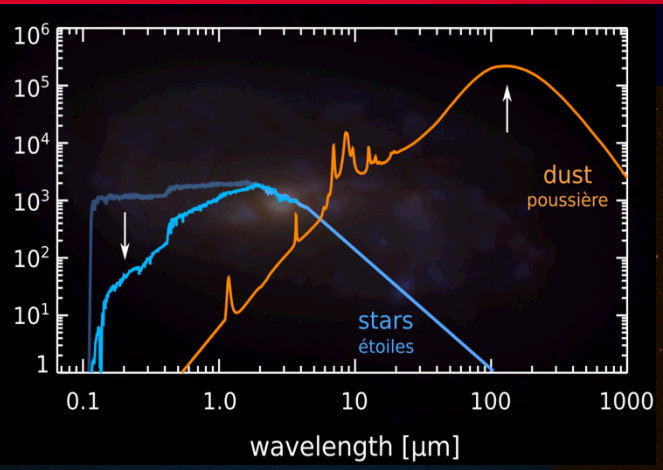
TRACING BACK THE HISTORY OF GALAXY FORMATION WITH DEEP SURVEYS

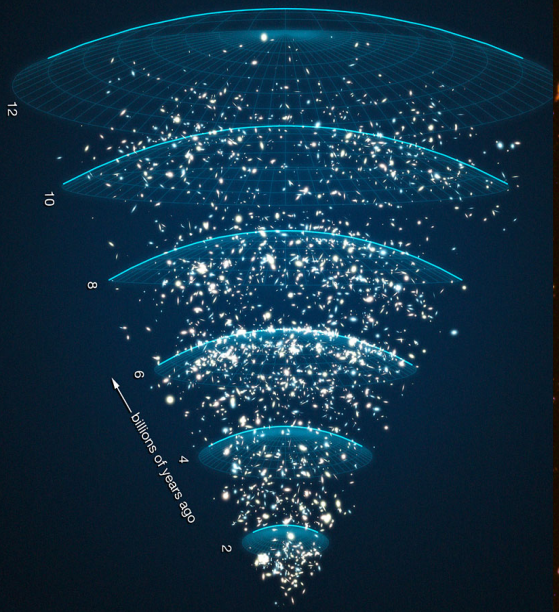


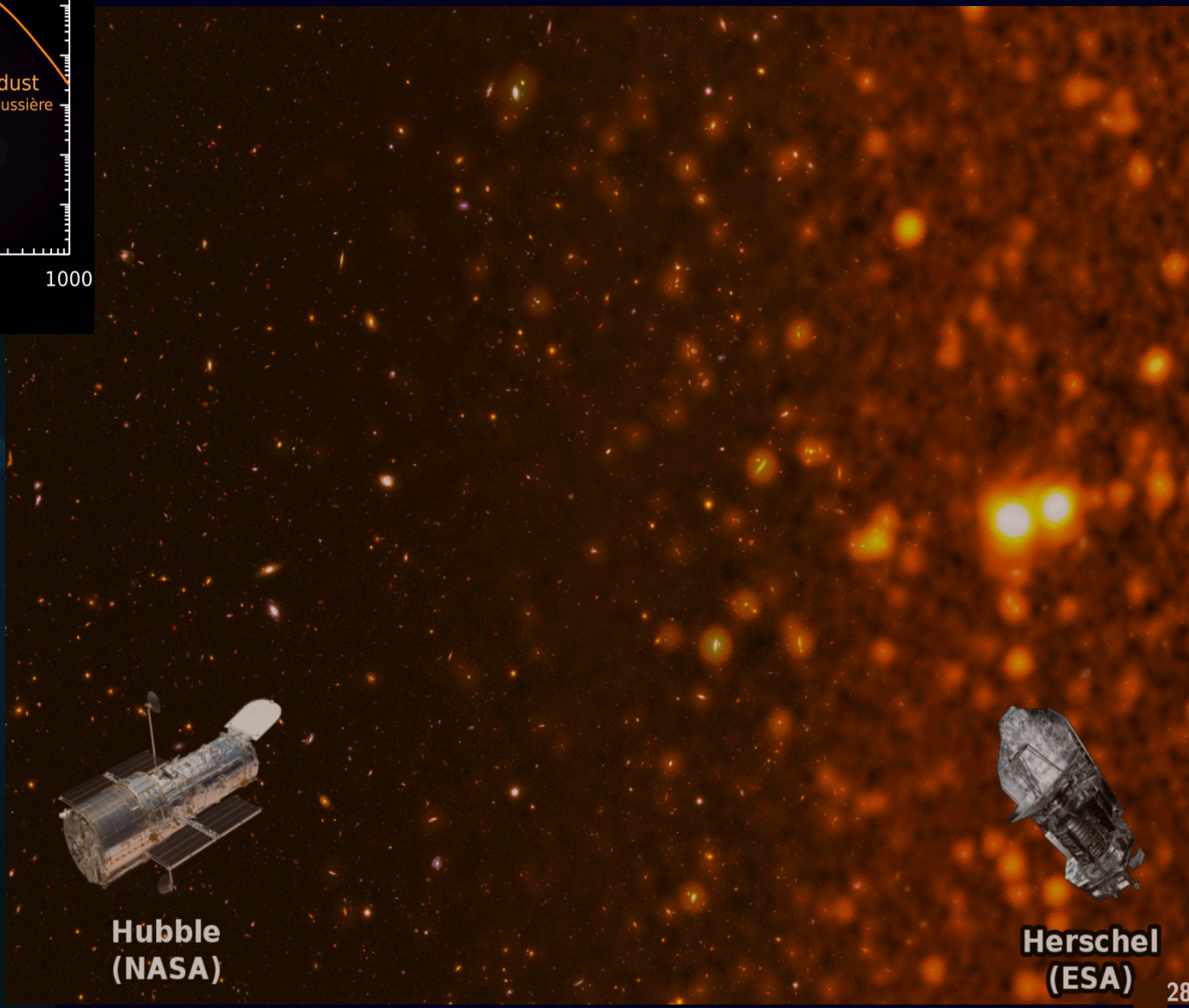




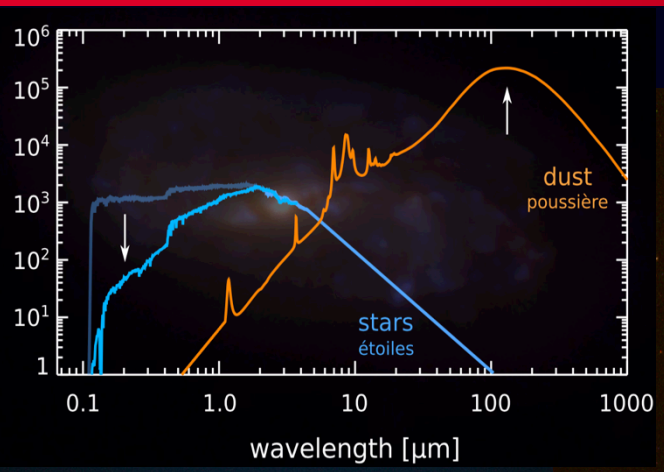
TRACING BACK THE HISTORY OF GALAXY FORMATION WITH DEEP SURVEYS

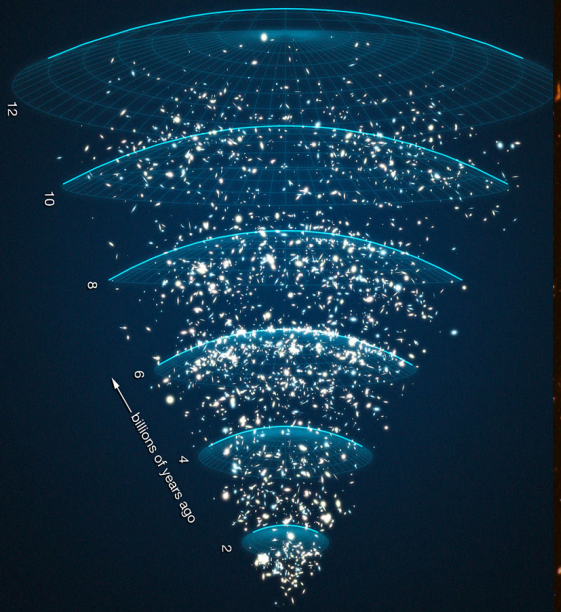


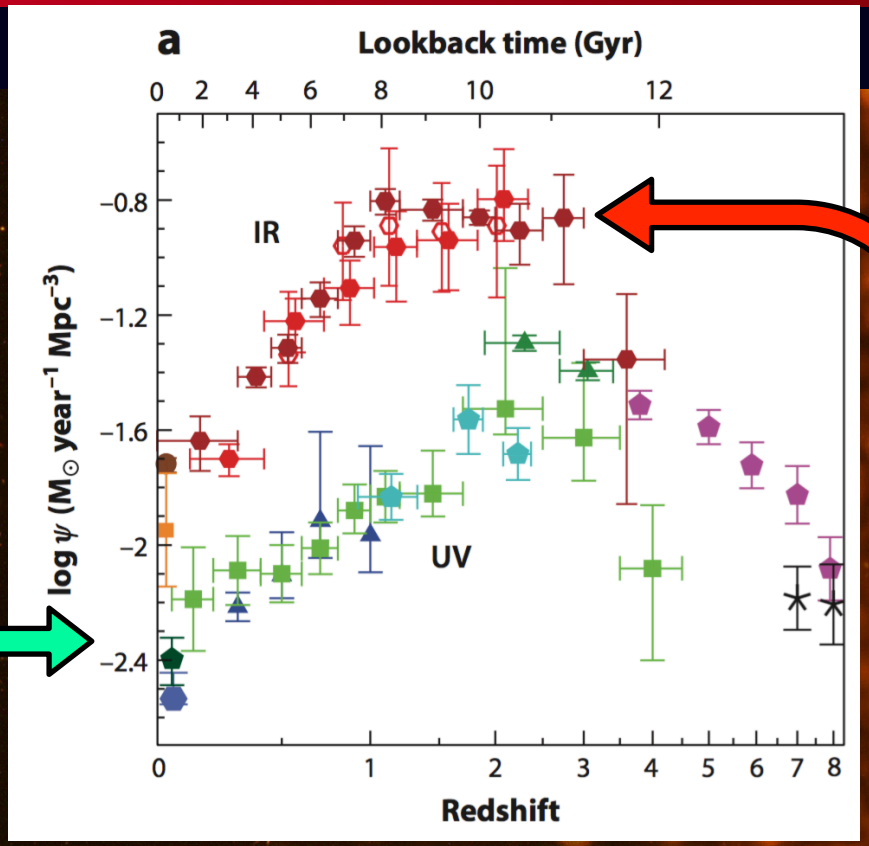




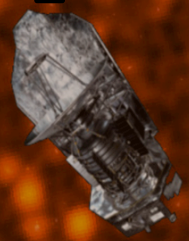
TRACING BACK THE HISTORY OF GALAXY FORMATION WITH DEEP SURVEYS







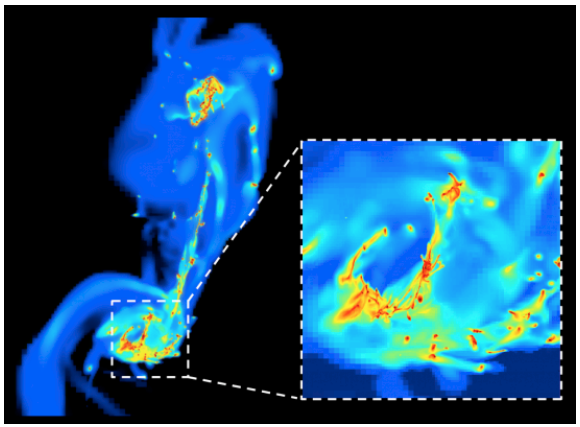

Hubble (NASA)

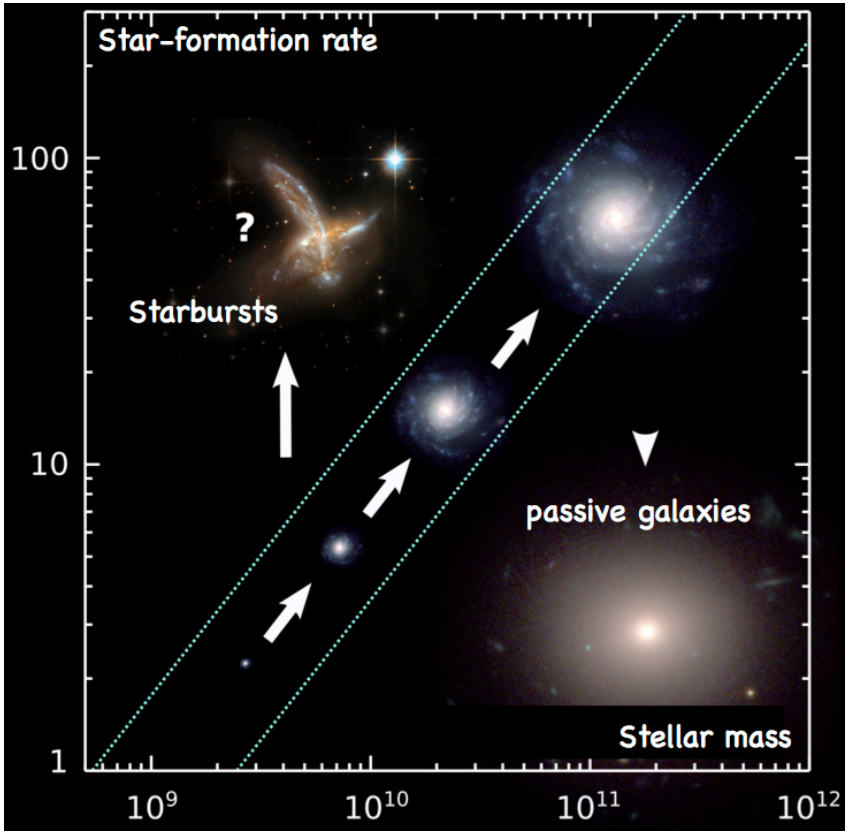

Herschel (ESA)

A PARADIGM SHIFT ON GALAXY FORMATION: THE GALAXY MAIN SEQUENCE

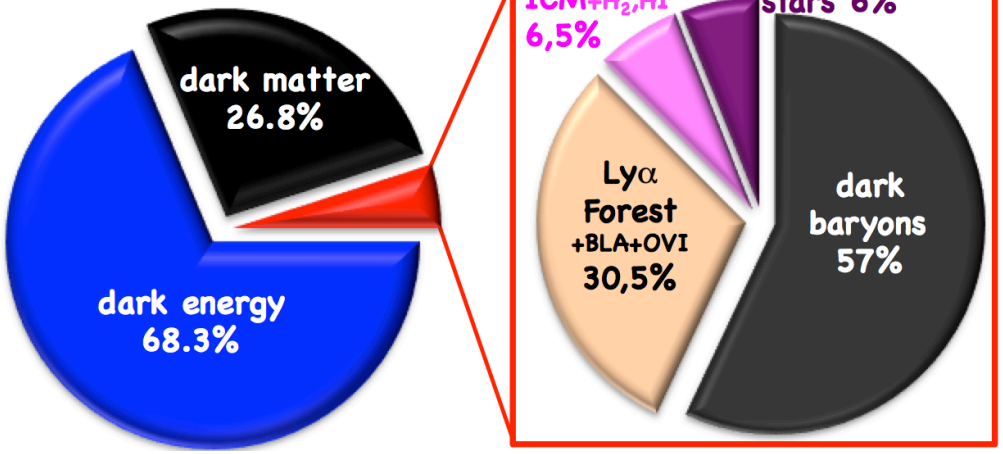
Daddi et al. 2007: 770 citations
Daddi, Elbaz et al. 2010a,b: 424, 331 citations
Elbaz et al. 2007, 2011: 676 & 460 citations
Magnelli, Elbaz et al. 2009: 257 citations

Bournaud, Renaud et al.

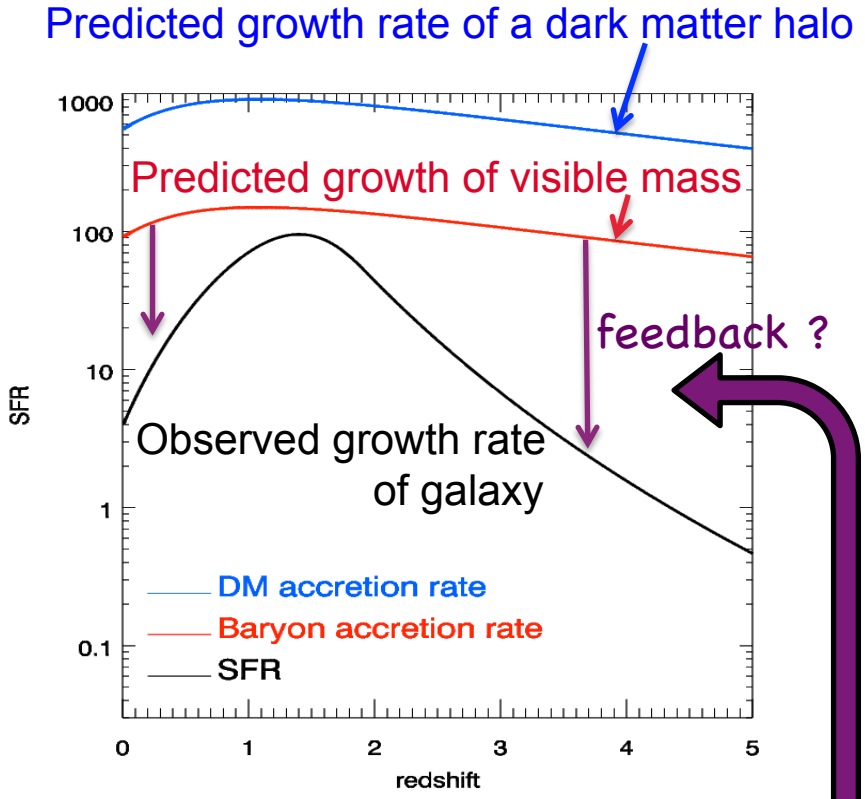


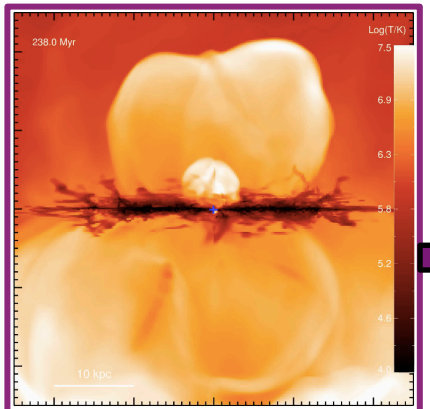


THE OVERCOOLING PROBLEM:
a cosmological issue or evidence for a strong impact of baryonic physics on mass distribution ?



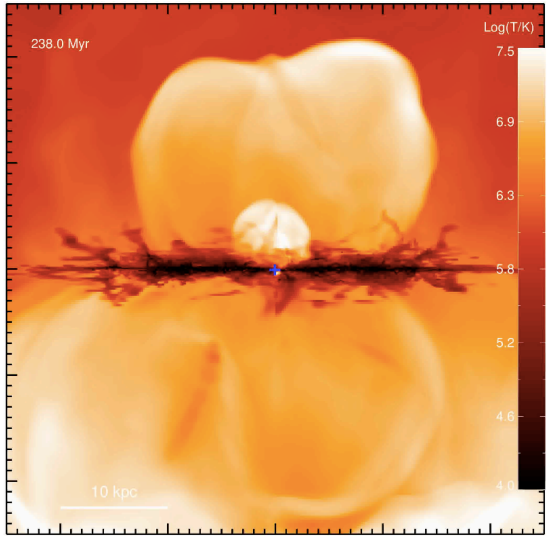
most baryons are dark:
only 6% of stars...



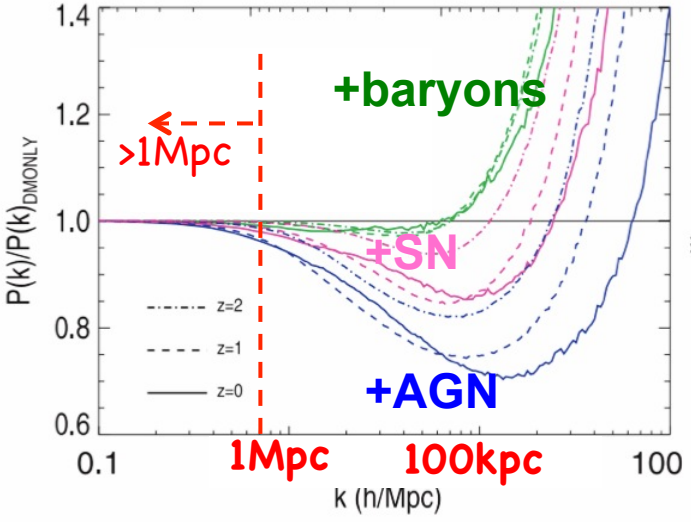


hydrodynamical simulation
of feedback (Bournaud et al.)

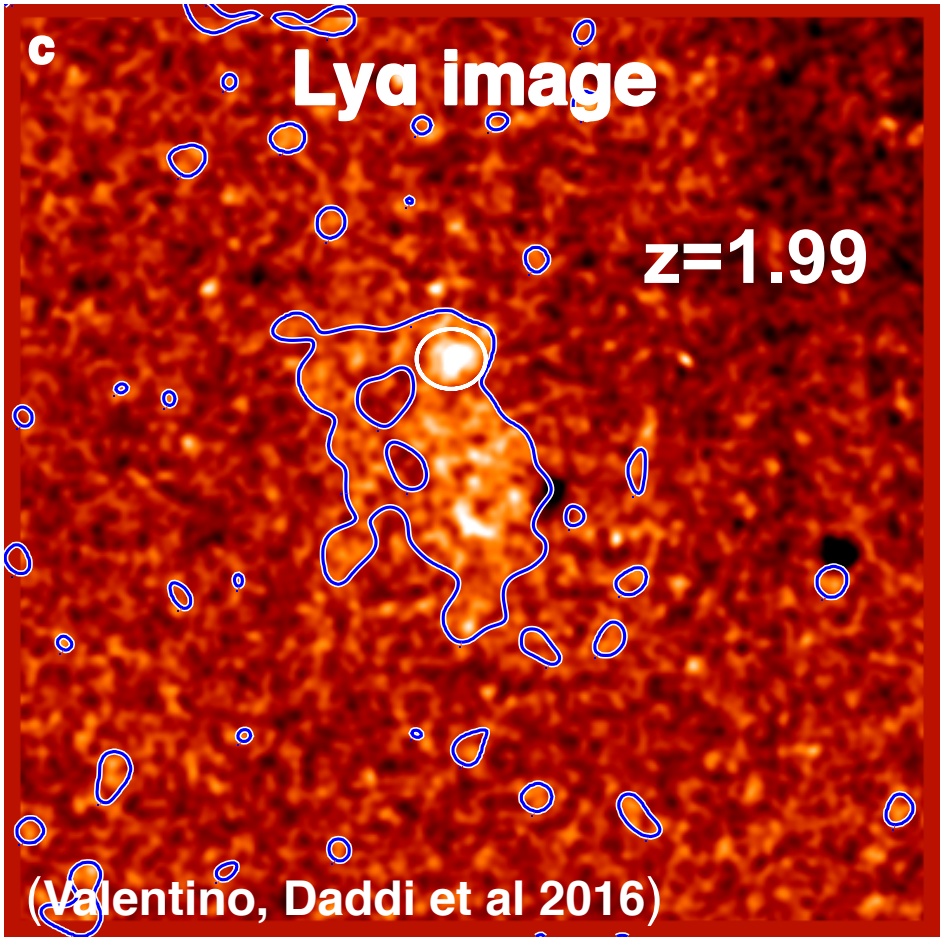
THE REDISTRIBUTION OF BARYONS BY FEEDBACK HAS STRONG IMPLICATIONS ON EUCLID & ON NEUTRINOS MASS LIMIT FROM LYMAN ALPHA FOREST.

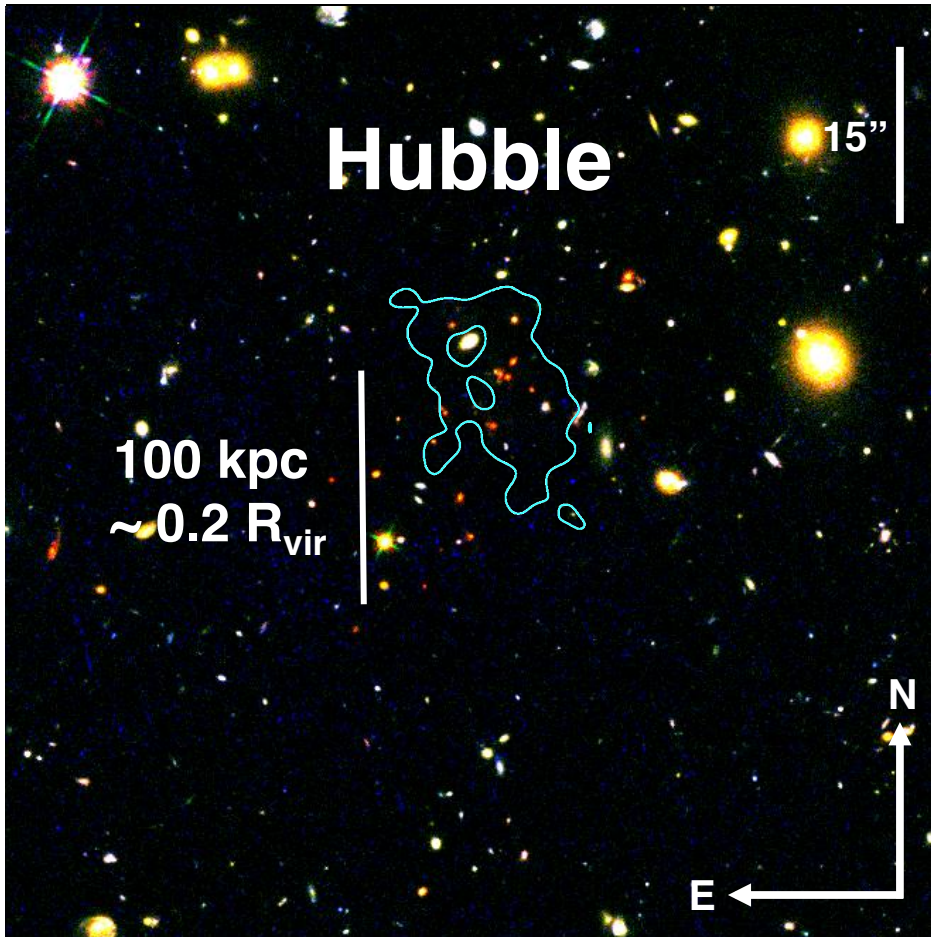


Dark Matter power spectrum normalized to a dark matter-pure universe



First time: Lyα nebula on high-z cluster-sized halo

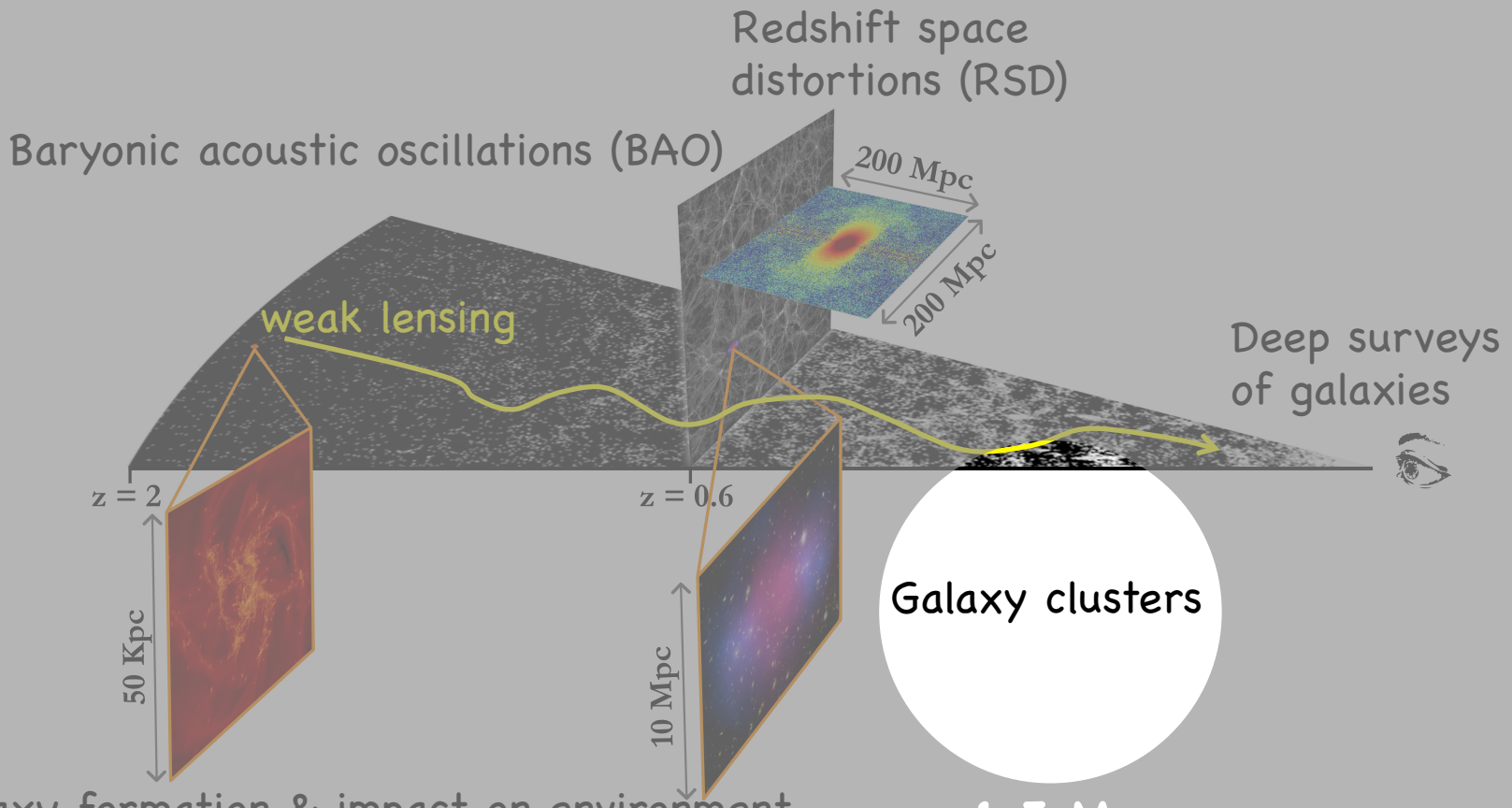




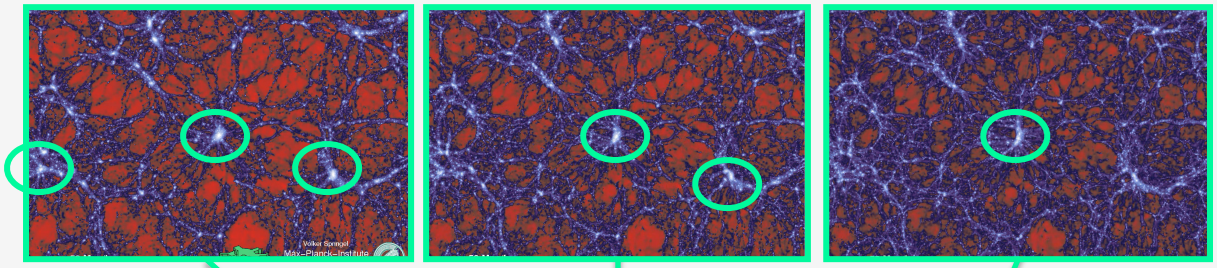
First constraints on energy injection processes on cluster atmosphere at high-z
Prospects for understanding ICM evolution, crucial preparation for Athena and Euclid

COSMOLOGY AND STRUCTURE FORMATION AT IRFU FROM THE SMALL TO THE LARGEST SCALES

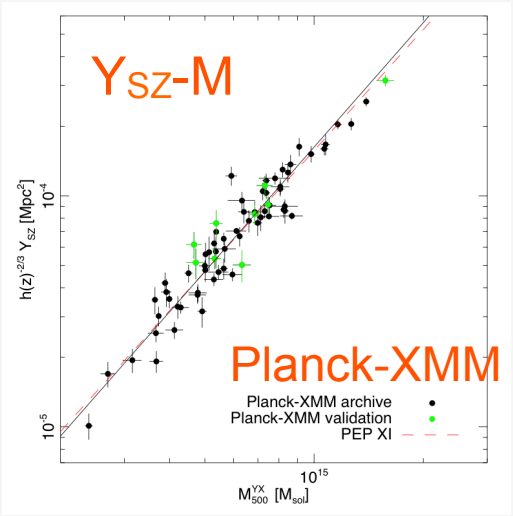
The astrophysical tools used at IRFU to address those issues…



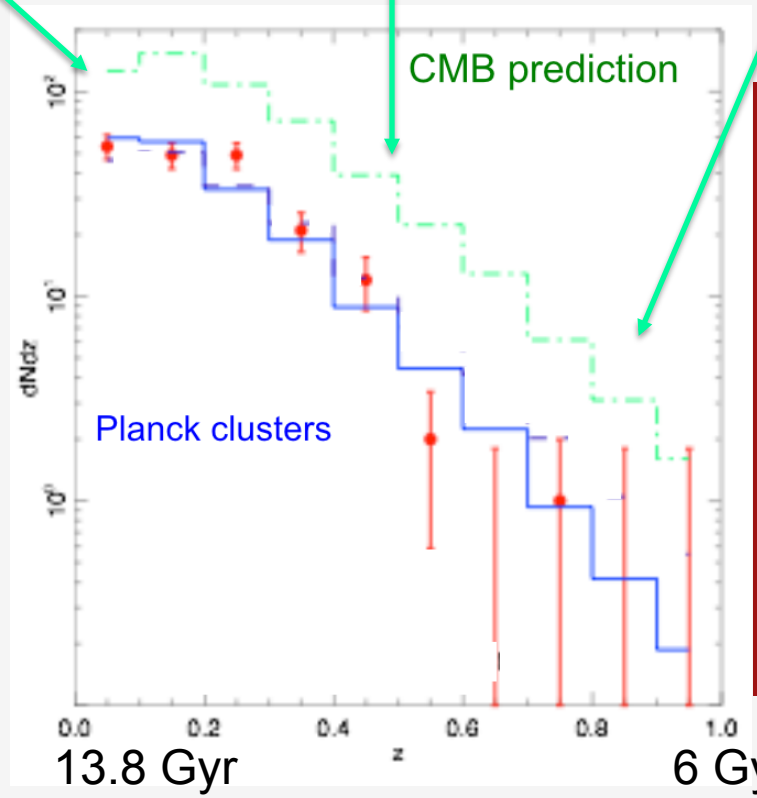
THE « MISSING CLUSTERS » PROBLEM: PLANCK FOUND TWICE LESS CLUSTERS



SZ- Mass



Planck 2013 results XX
Planck 2015 results XXIV



What causes the tension ?

A large neutrino mass ?
Σm_ν = (0,22 ± 0,09) eV

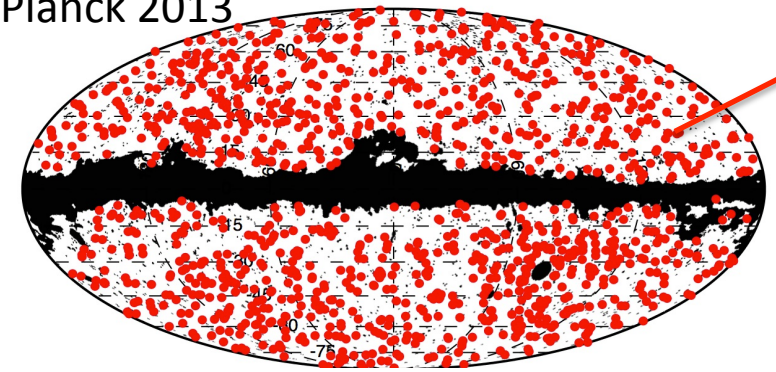
or / and

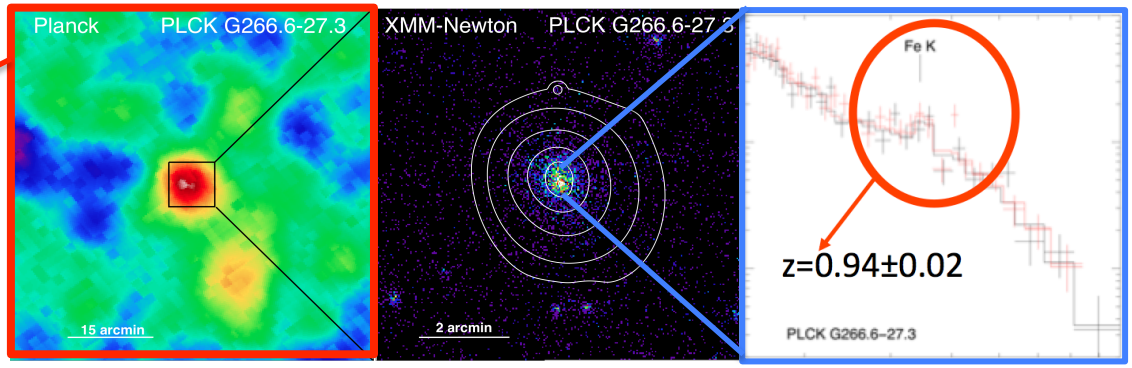
Cluster physics ?
e.g. departure from hydrostatic equilibrium → but would imply mass underestimated by 40% !

Planck clusters detected by Sunyaev-Zeldovich effect: inverse Compton on the CMB photons
Mass estimated by XMM X-ray follow-up (hydrostatic equilibrium, Virial)

THE MOST MASSIVE GALAXY CLUSTERS ACROSS COSMIC TIME PROBE DARK MATTER → ERC M.ARNAUD

Planck 2013

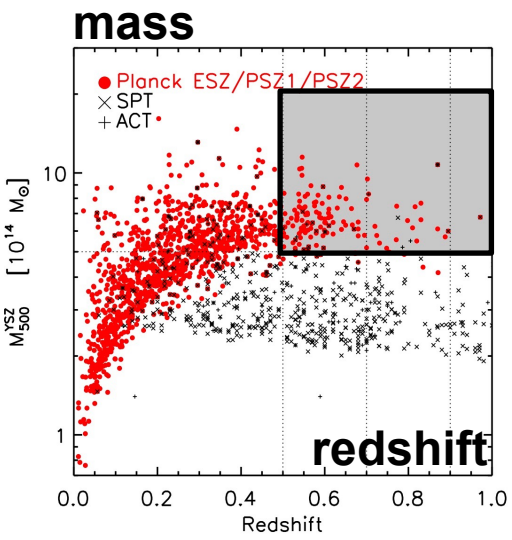


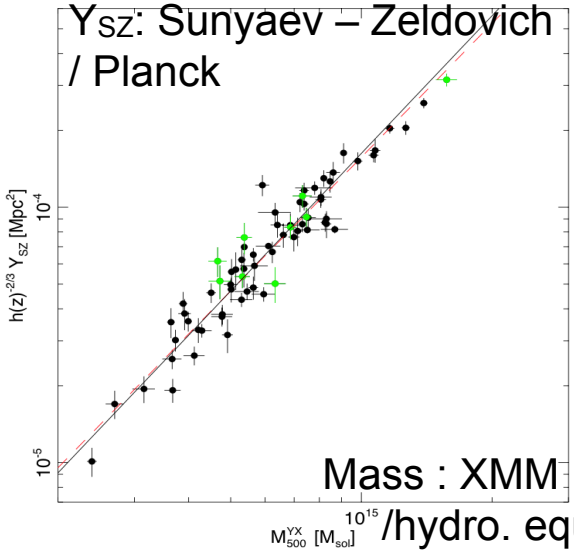


- Detection (new method J.B.Melin – SPP) using XMM pressure profile (Arnaud, Pratt – SAp)
- DDT XMM validation campaign (*lead by Sap*) → *z (iron line), mass of DM & baryons*

71 clusters 2012 → 189 in 2013 → 439 in 2015 : Nb clusters x6

- Comparison to cosmology → require very large simulations to include very massive clusters

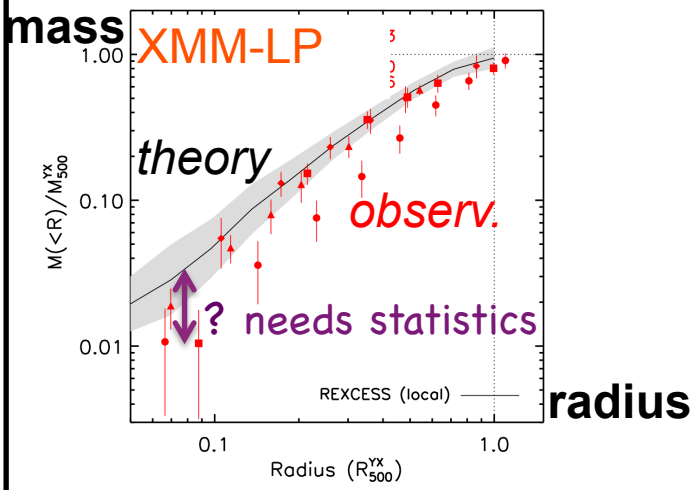




Planck 2013 results XX
Planck 2015 results XXIV

THE MOST MASSIVE GALAXY CLUSTERS ACROSS COSMIC TIME PROBE DARK MATTER → ERC M.ARNAUD

Dark matter profiles as a test of ΛCDM



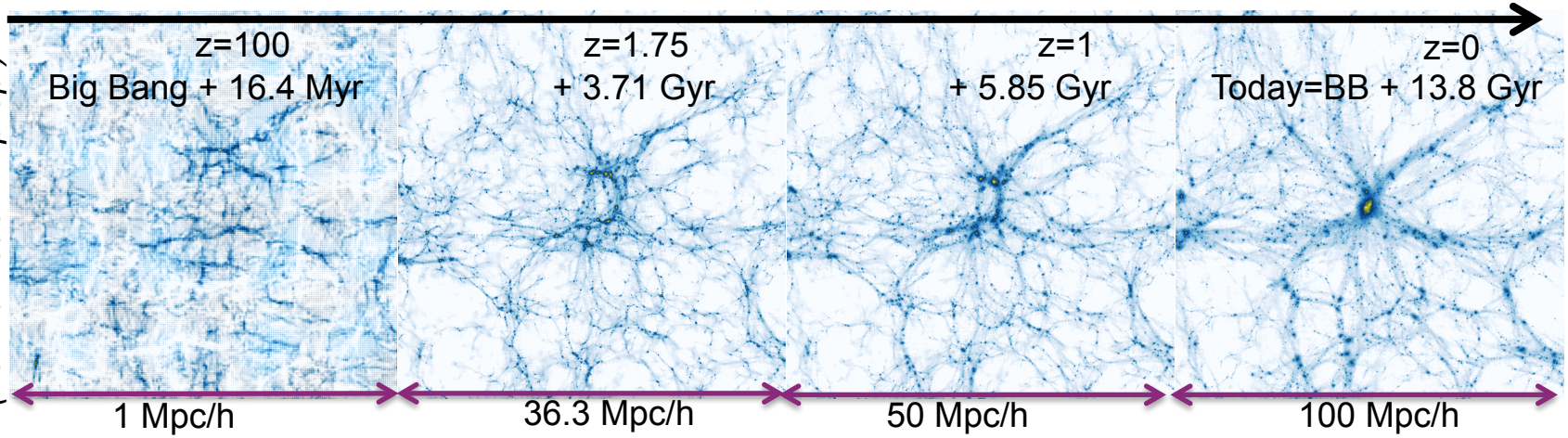
M. Arnaud G.Pratt I.Bartalucci J.Democles

Mass profiles less peaked than predicted by theory but only 5 clusters :

to quantify the dispersion: 30 clusters/redshift bin

→ improve Planck cluster detection : JB Melin, SPP
→ optical follow-up to validate them (SAp)
→ everal XMM large programs → mass, profil : hydro. equilibrium ?
→ simulations:
cosmological + zoom on massive clusters

RAMSES (Teyssier 2002) simulations run at GENCI (Le Brun et al. in prep.)



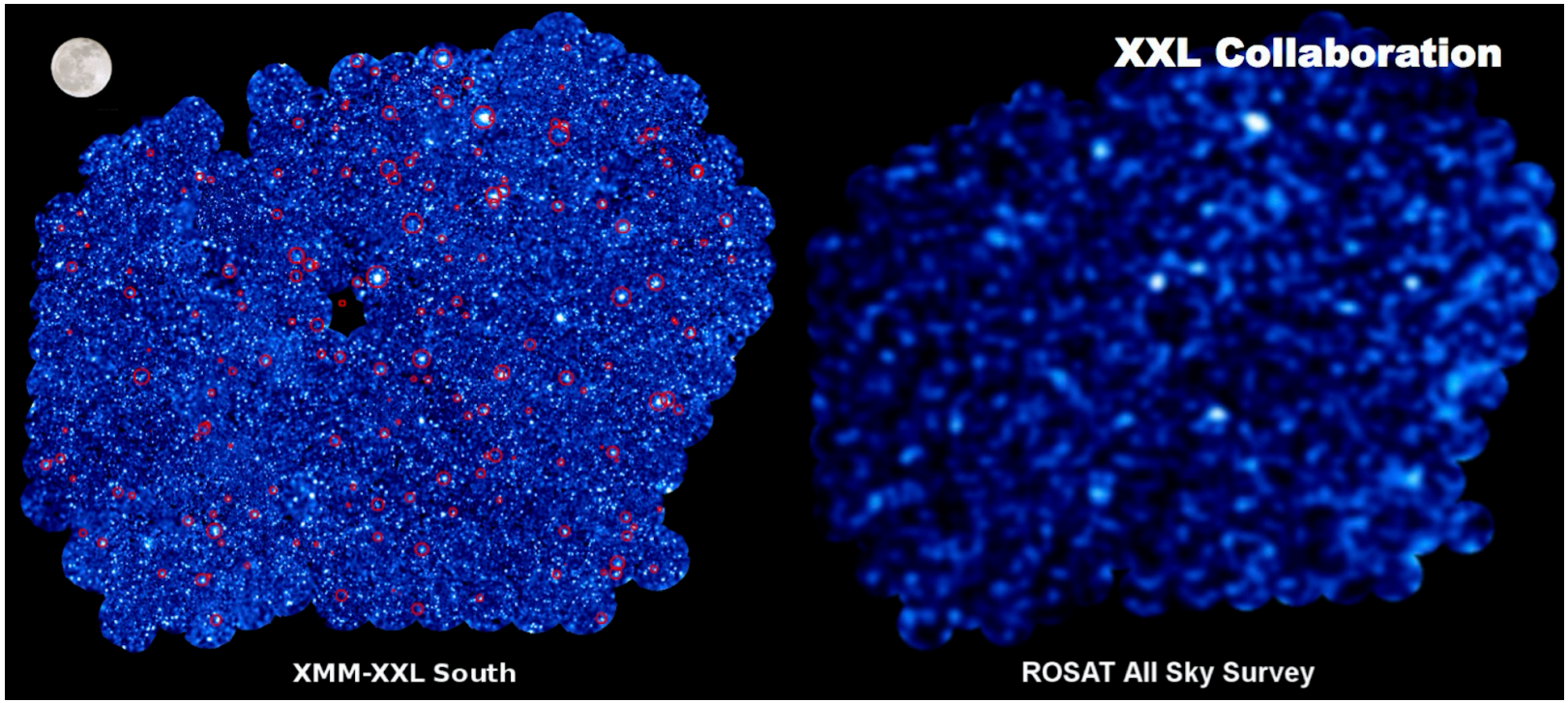
GALAXY CLUSTERS AS COSMOLOGICAL PROBES: XXL

50 deg^2 , largest XMM program (6.9Msec), ~100 scientists (13 IRFU, PI M.Pierre)

→ **22 000 AGN & 450 amas de galaxies**

→ cosmological parameters + physics & evolution of AGNs and clusters

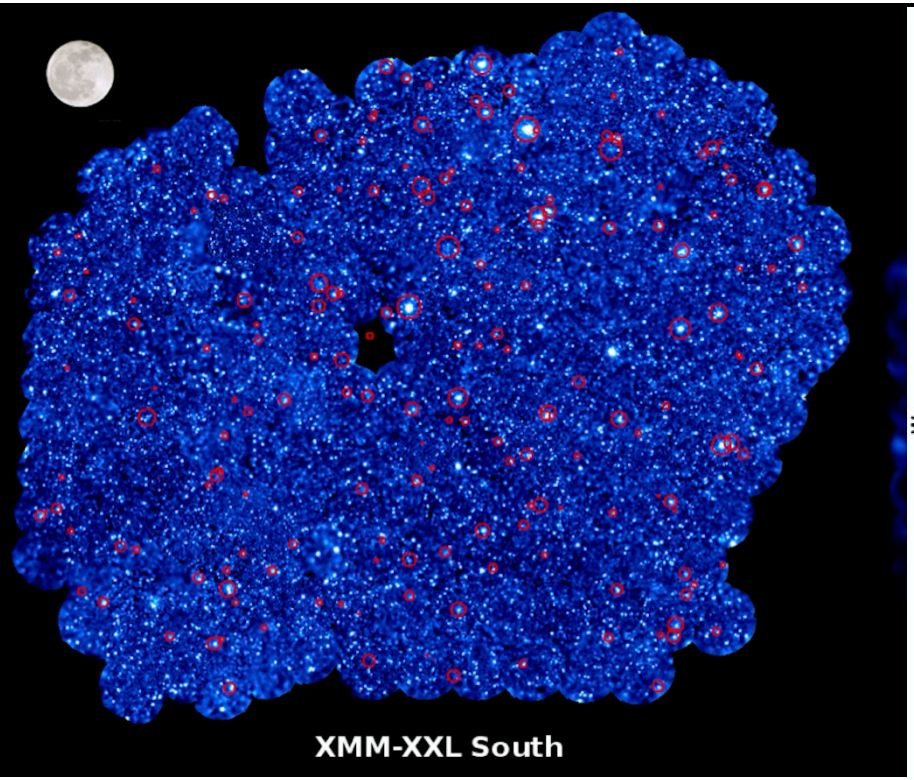
- 14 papers in decembre 2015 + 4 PR

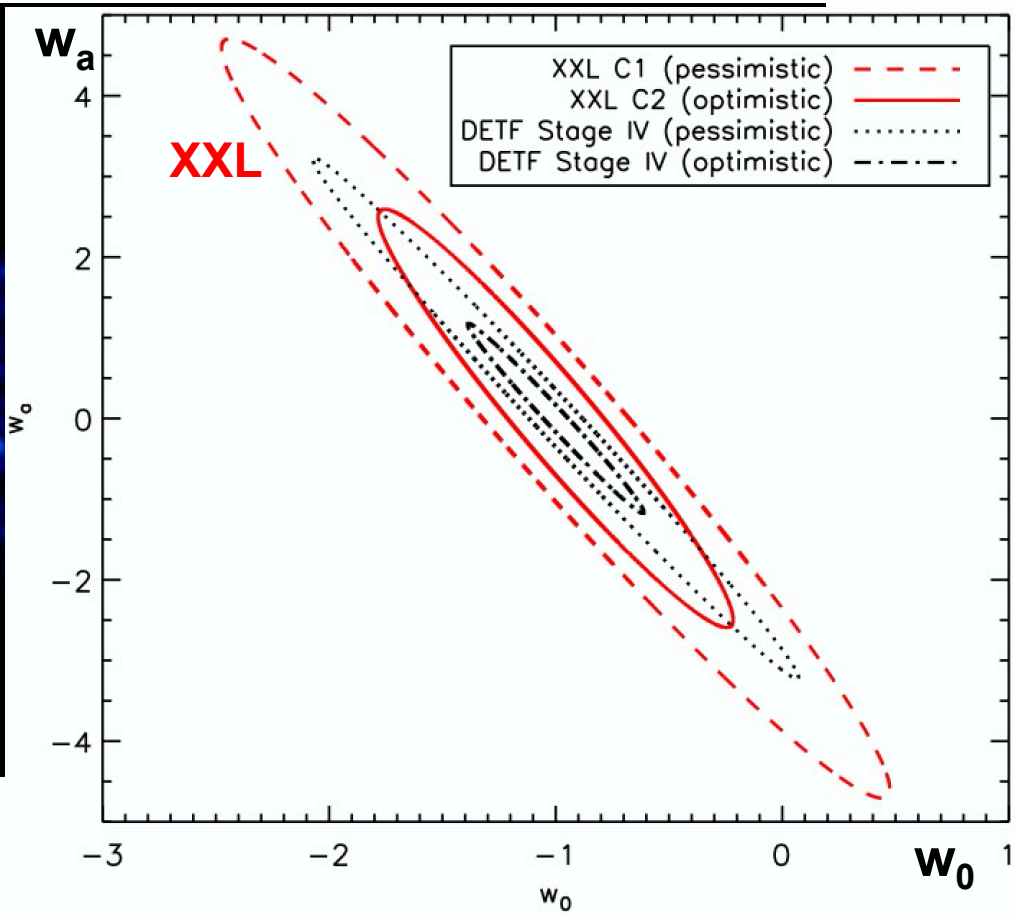


25 deg^2 XMM field → >12,000 AGNs + ~200 clusters (red circles)
= largest view of the deep X-ray sky obtained to date.
ROSAT All-Sky-Survey → only 45 sources in the same field size

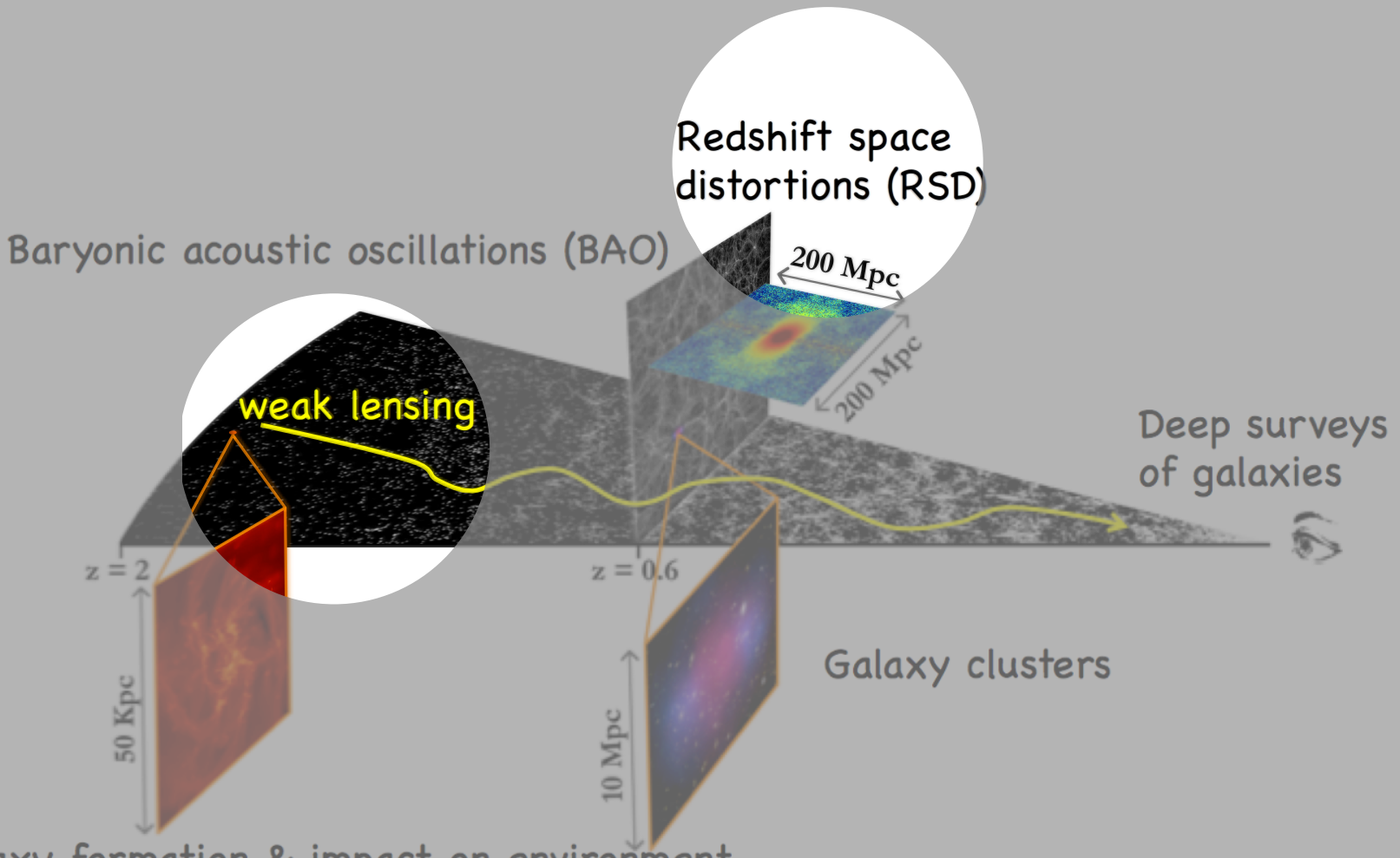
GALAXY CLUSTERS AS COSMOLOGICAL PROBES: XXL

Goal for 2018: **XXL constraints** (red lines) on the equation of state of dark energy: $w=P_{DE}/\rho_{DE}=w_0+w_a z/(1+z)$ compared to **level 4 DETF** (dark energy task force) (black lines) such as Euclid, eRosita, …



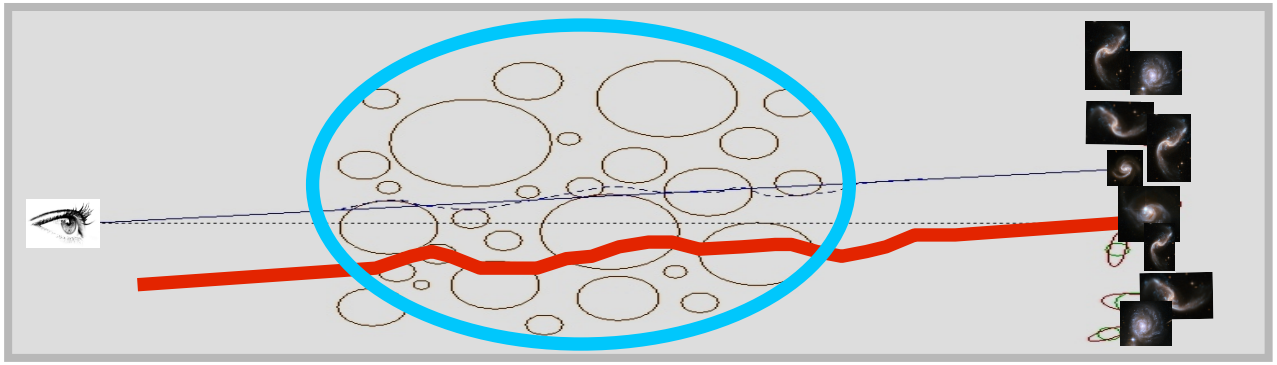


Cosmology and structure formation at IRFU
from the small to the largest scales



The transition between the non linear (gravity) and non linear regimes and its implications on cosmological parameters

weak lensing (Euclid)



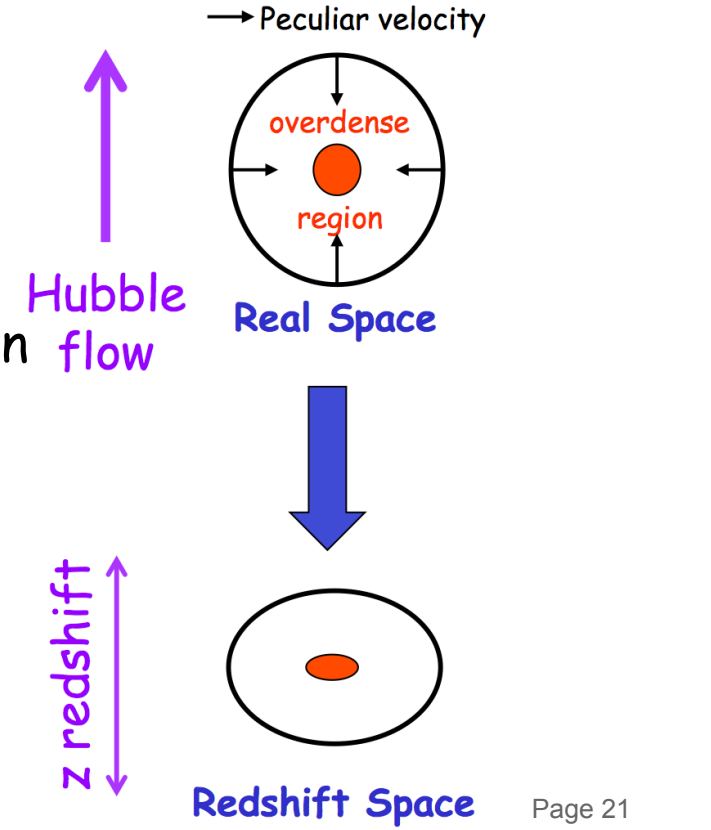
redshift space distortion (Euclid, DESI)

Acceleration toward overdense regions
→ flattening in redshift space (over tens Mpc)
→ action of gravitation (5-40 Mpc) Gpc away
Distortions measured by multipole decomposition

$$\xi(r,\cos(\theta)) = \sum_{\ell=0,2,4...} b^2 C_\ell \xi(r) P_\ell(\cos(\theta))$$

N. Kaiser, MNRAS 227, 1 (1987)

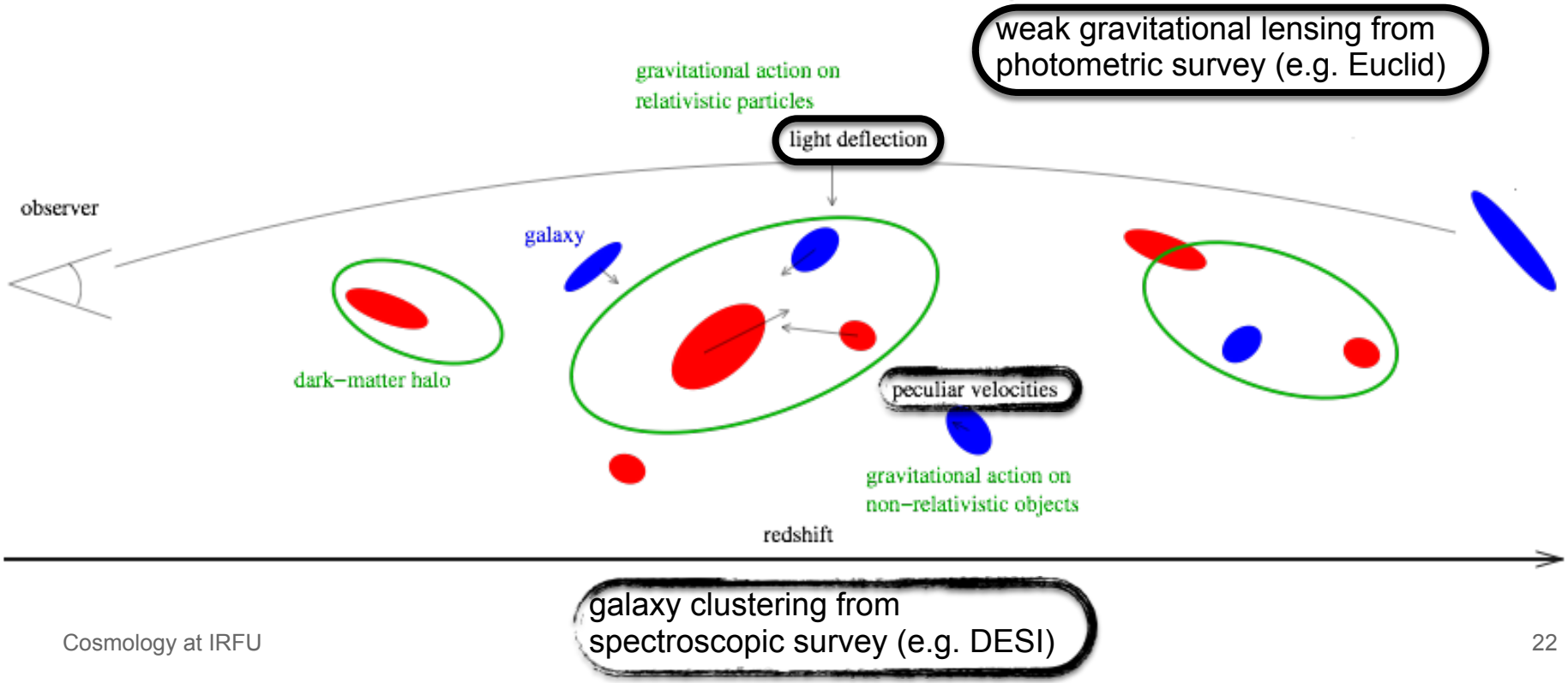
P_l Legendre polynomials, θ angle between pair vector and LoS, b linear galaxy bias



Testing general relativity on cosmological scales

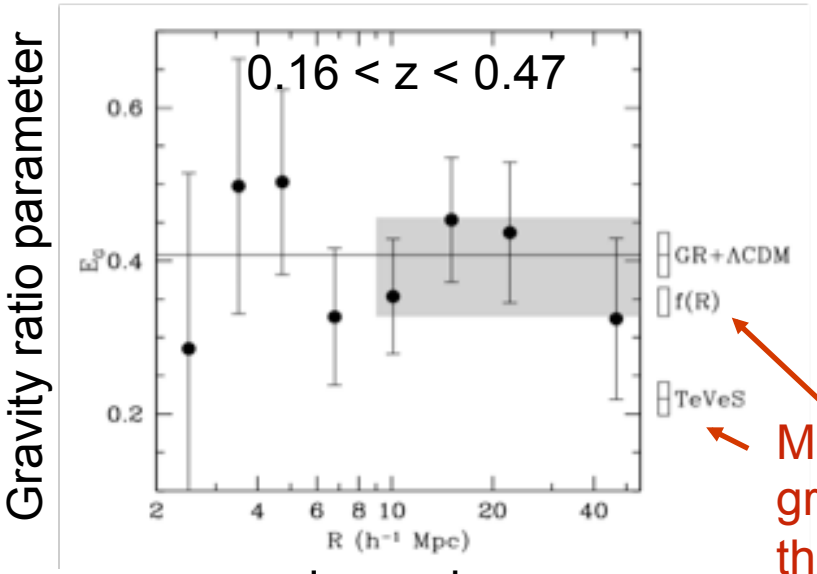
Measuring gravitational action on light and galaxies:
Equal in General Relativity, **different** in modified gravity theories.

Modified gravity affects differently mass (galaxy clustering, non relativistic) and light(weak lensing, relativistic), measuring the difference with both probes will test GR.



Testing modified gravity as cause of accelerated expansion by combining weak lensing and redshift space distortion

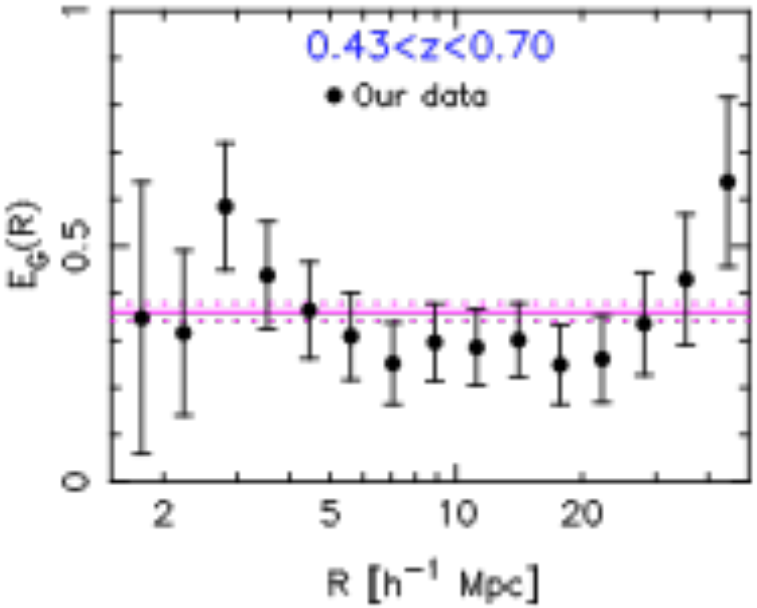
Reyes et al. (2010; Nature), SDSS



angular scale

Modified gravity theories

Blake et al. (2015), CFHTLenS+RCSLens, WiggleZ+BOSS



Gravity ratio = **weak lensing / (anisotropic * isotropic) galaxy clustering**

Upcoming surveys:

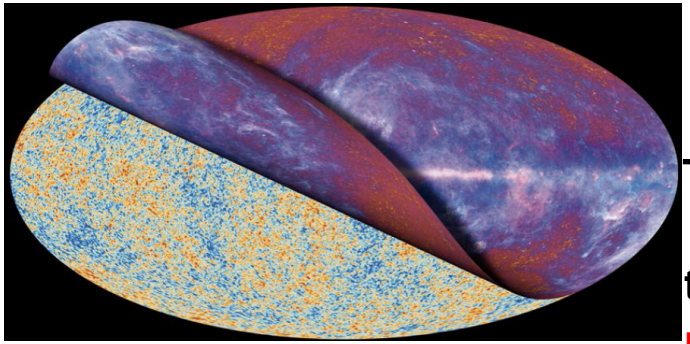
DESI + CFIS (Canada-France-Hawai'i imaging survey), 4000 deg^2 overlapping area.

DESI + Euclid 9,000 deg^2.

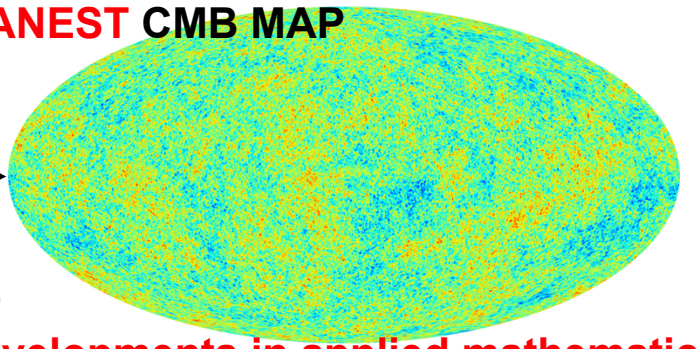
Improvement on accuracy of gravity ratio parameter of ~ 3-10!
Subject of proposed **ERC Consolidator "MONGOOSE"**,
PI: M. Kilbinger (SAp), with C. Yèche (SPP).

The impact of a better control of systematics and sparse signal extraction on Cosmology

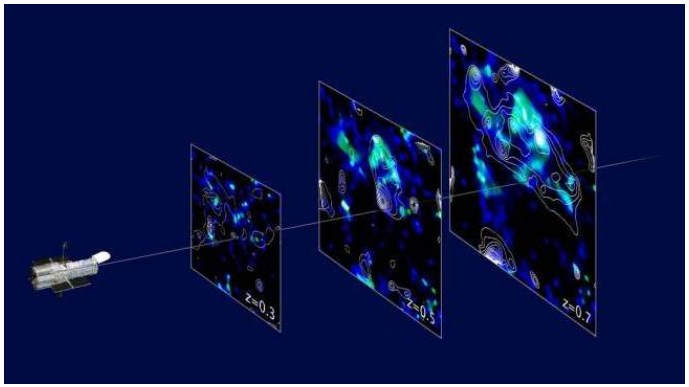
COSMOSTAT laboratory common between SAp & SEDI (5 staff + 6 post/PhD)
2+3 staff, 2+1 postdocs, 2+1 PhD students
2 ERC *(Starck SAp, Bobin SEDI)* + 2 H2020 contracts with industrial partners



The CLEANEST CMB MAP



thanks to
recent developments in applied mathematics



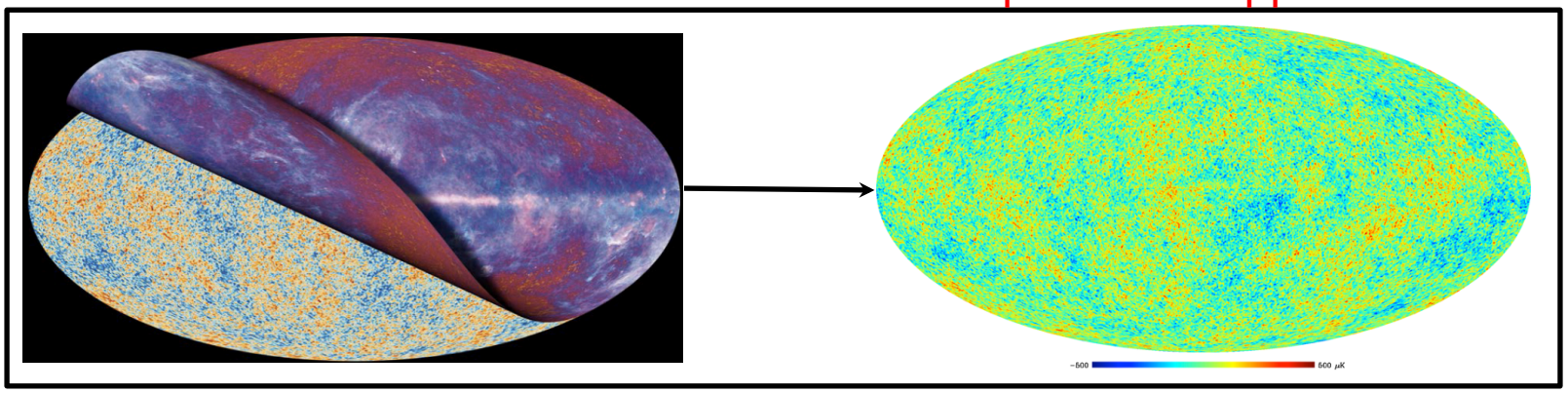
Cosmology in the era of big data :Euclid
150 petabytes, ten's of billion sources

new methods for mass maps with Euclid
"peak counting » → direct constraints on cosmology from number of mass peaks

The impact of a better control of systematics and sparse signal extraction on Cosmology

COSMOSTAT laboratory common between SAp & SEDI (5 staff + 6 post/PhD)
2+3 staff, 2+1 postdocs, 2+1 PhD students

The CLEANEST CMB MAP: thanks to recent developments in applied mathematics



Using harmonic analysis techniques (sparsity) + proximal theory (optim)

Taking into account systematics (foreground, ISW effect, etc), we do not confirm the high detection anomalies (> 4sigma, cold spot, alignements, etc) claimed by other groups.

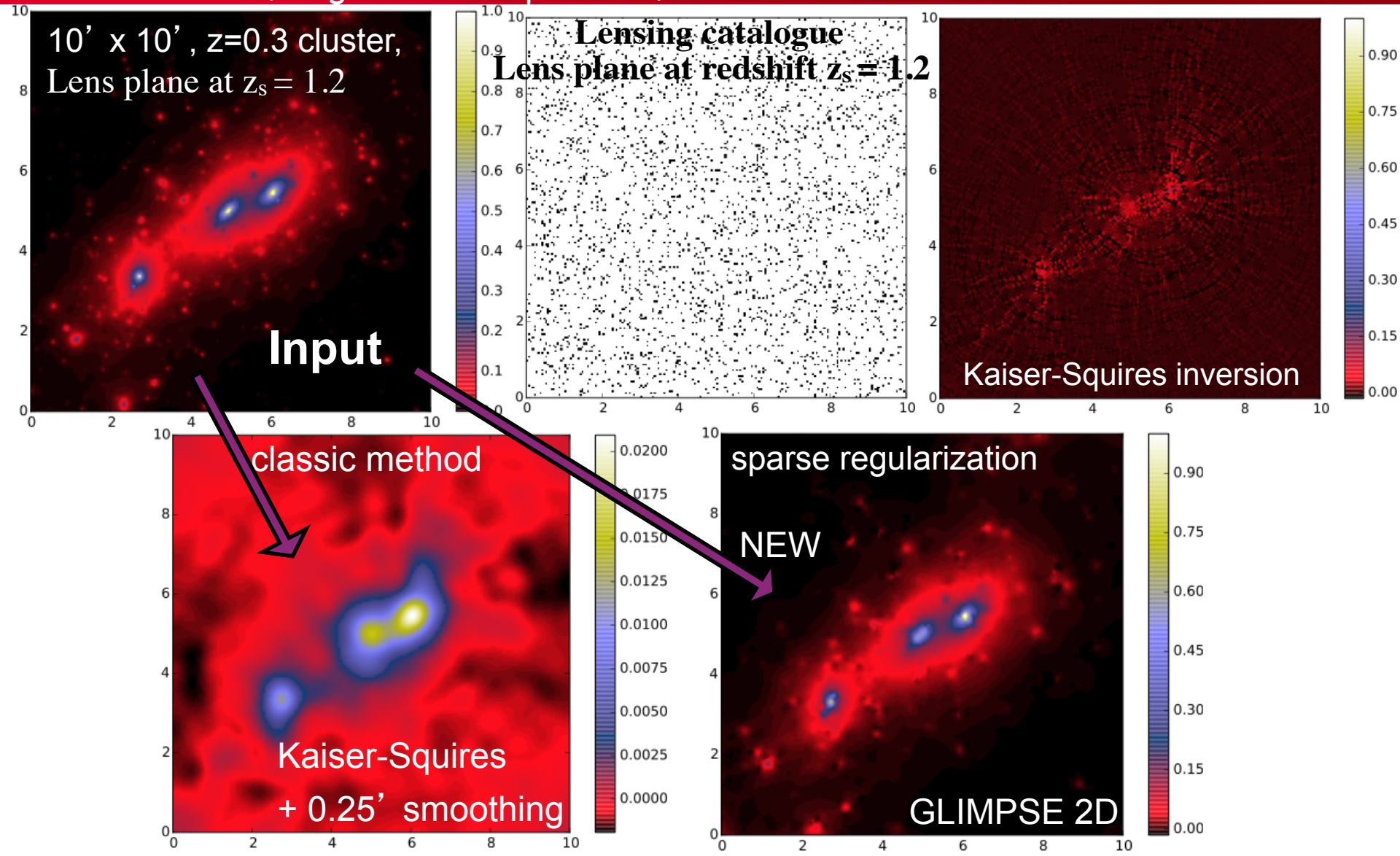
⇒ **CMB large scales are compatible with the standard ΛCDM cosmological model**

⇒ **no significant departure from theoretical prediction => no exotic inflation model.**

Joint Planck and WMAP CMB map reconstruction, A&A, 563, 2014, Bobin J., Sureau F., Starck J-L, et al
CMB reconstruction from the WMAP and Planck PR2 data, A&A, in press, 2016, Bobin J., Sureau F., Starck
PRISM: Sparse Recovery of the Primordial Power Spectrum (arXiv:1406.7725), A&A, 566, id.A77, 2014.
PRISM: Sparse recovery of the primordial spectrum from WMAP9 and Planck datasets, 571, id. L1, 4, A&A,2014.

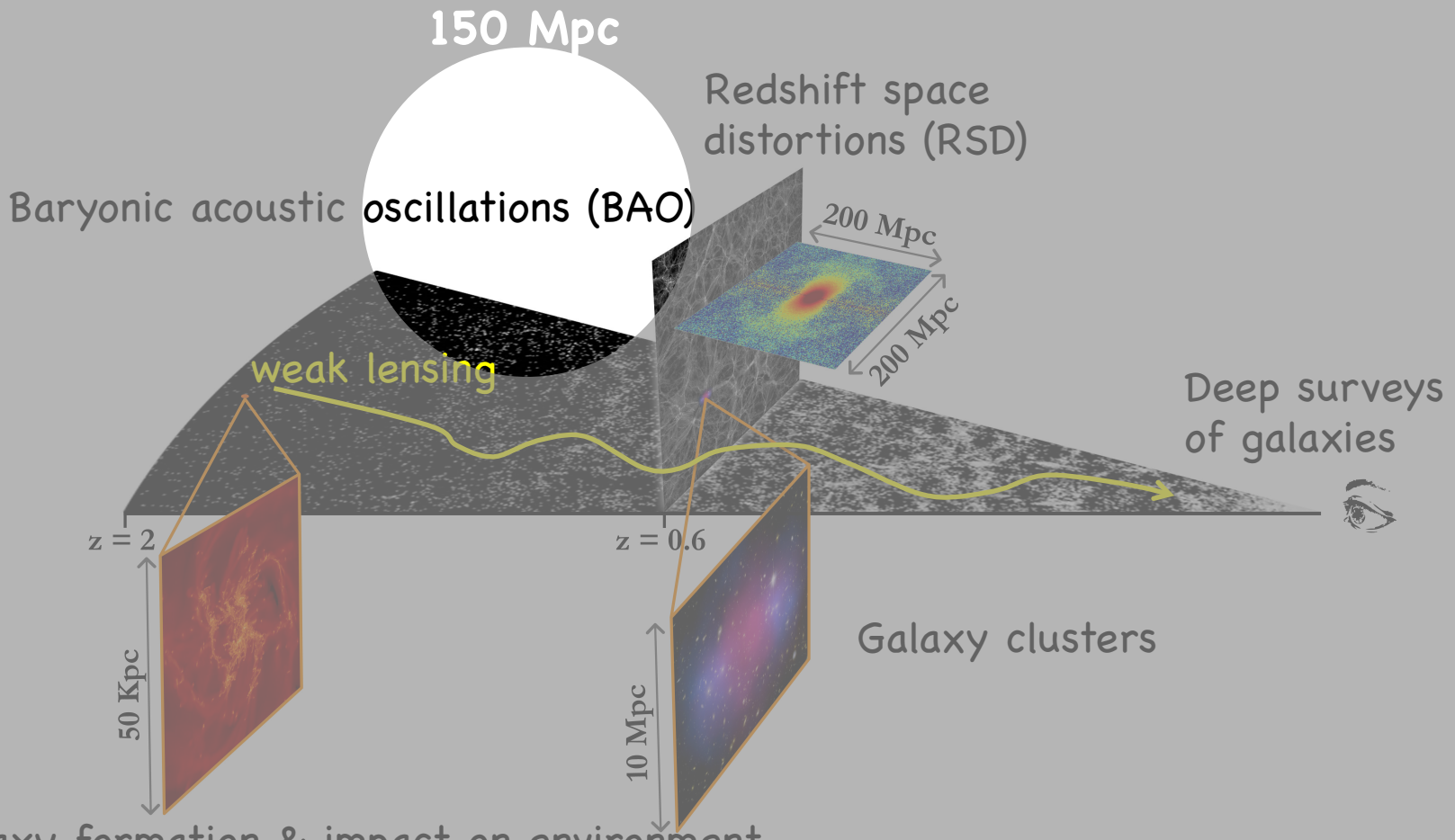
Example of sparse analysis for Euclid

Galaxy shapes for limited nb of galaxies ~ 93% of missing pixels
(30 galaxies / sq. arcmin)



COSMOLOGY AND STRUCTURE FORMATION AT IRFU FROM THE SMALL TO THE LARGEST SCALES

The astrophysical tools used at IRFU to address those issues…

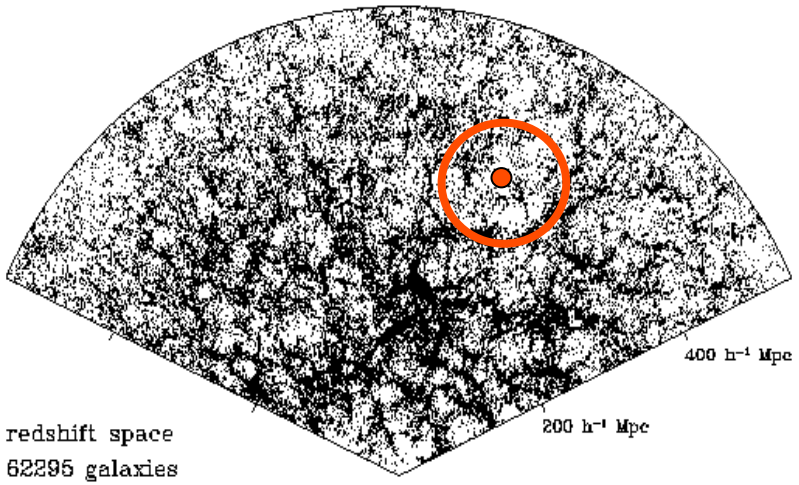


BARYONIC ACOUSTIC OSCILLATIONS (BAO)

A special distance:

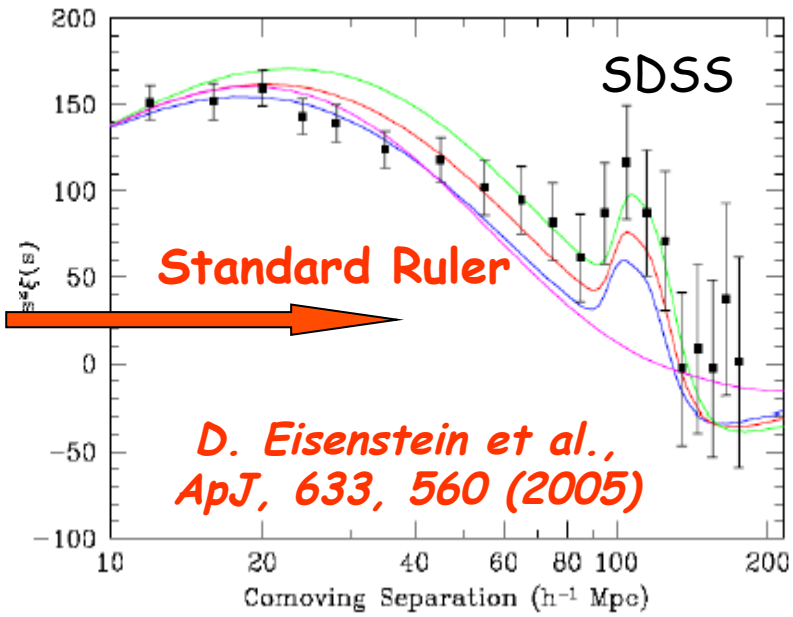
- Galaxies form in the overdense shells about 150 Mpc in radius.
- For all z, small excess of galaxies 150 Mpc (in comobile coordinates) away from other galaxies.

⇒ **Standard Ruler**



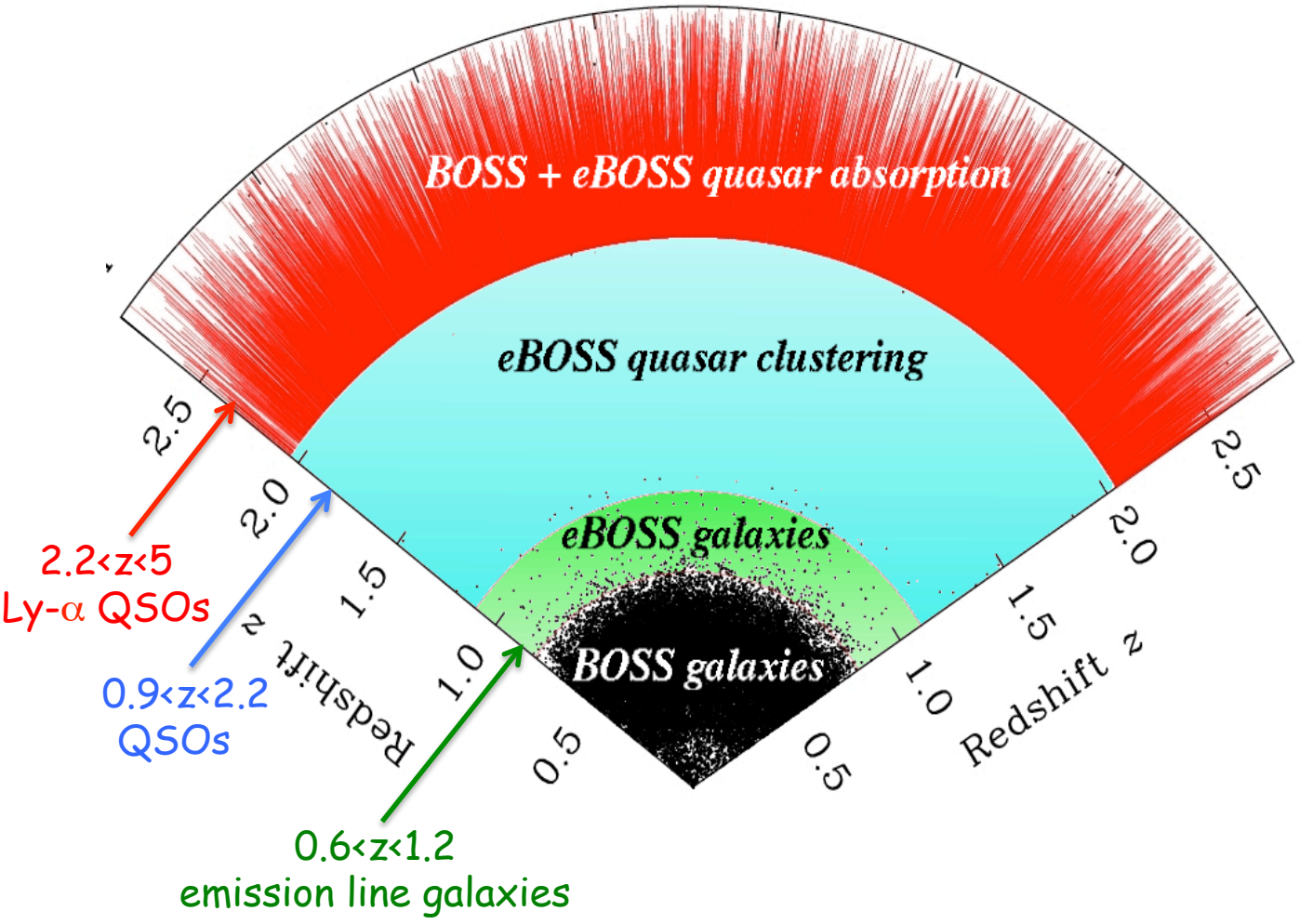
First observation:

- In 2005: First observations of baryonic oscillations by 2 teams (2dFGRS and SDSS)
- SDSS observe a peak at ~150 Mpc
- SDSS: ~50 000 LRGs
  "Luminous Red Galaxies"
  <z> ~ 0.35



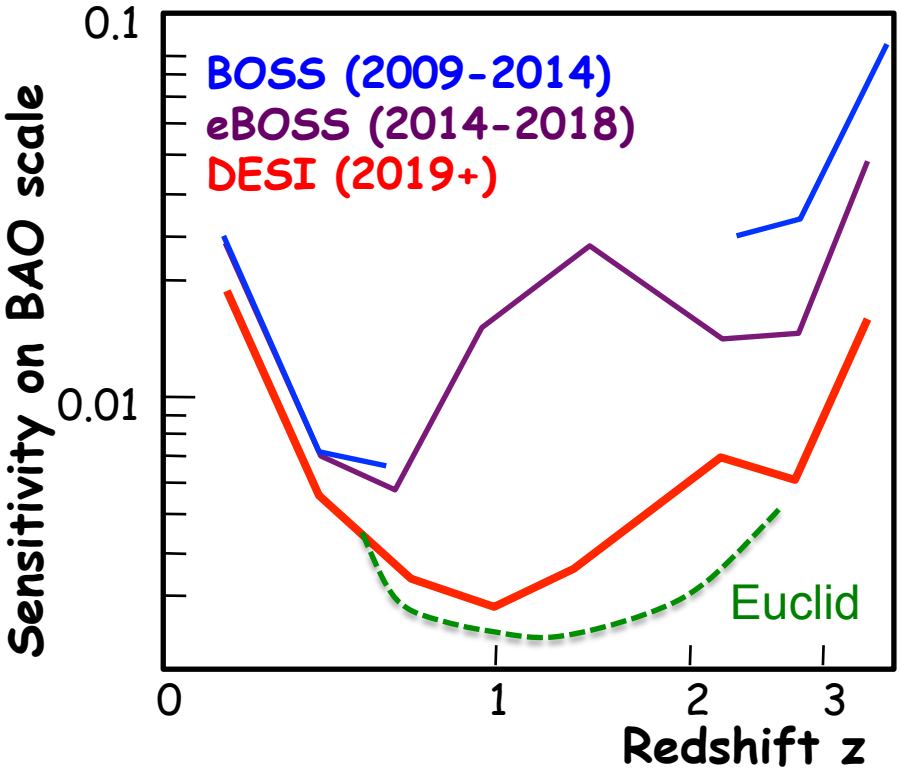
BARYONIC ACOUSTIC OSCILLATIONS (BAO)

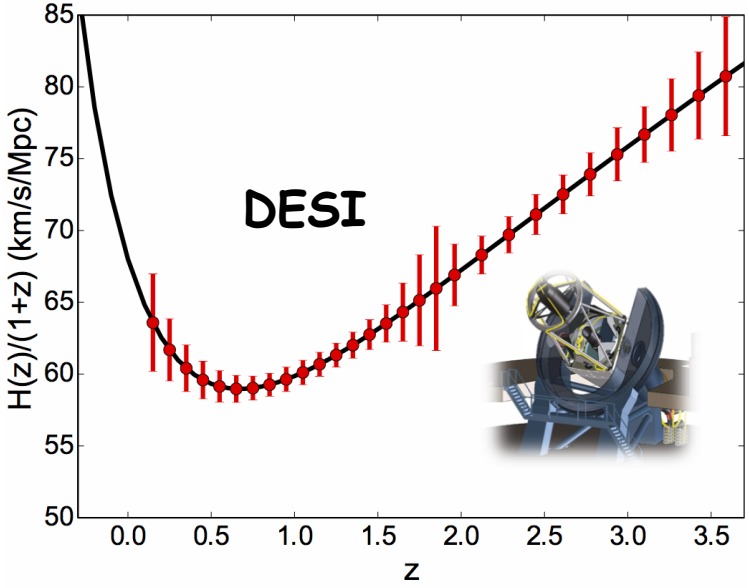
eBOSS 2014-2020



BARYONIC ACOUSTIC OSCILLATIONS (BAO)

from BOSS to eBOSS to DESI to Euclid





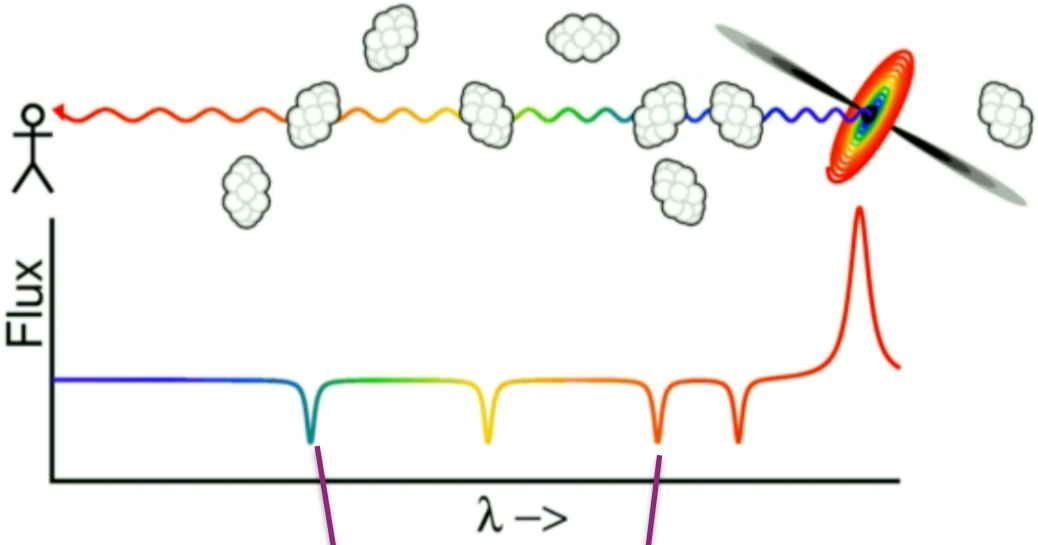
eBOSS= precuror of DESI, Euclid → continuous measurement of BAO for 0.3<z<4.0

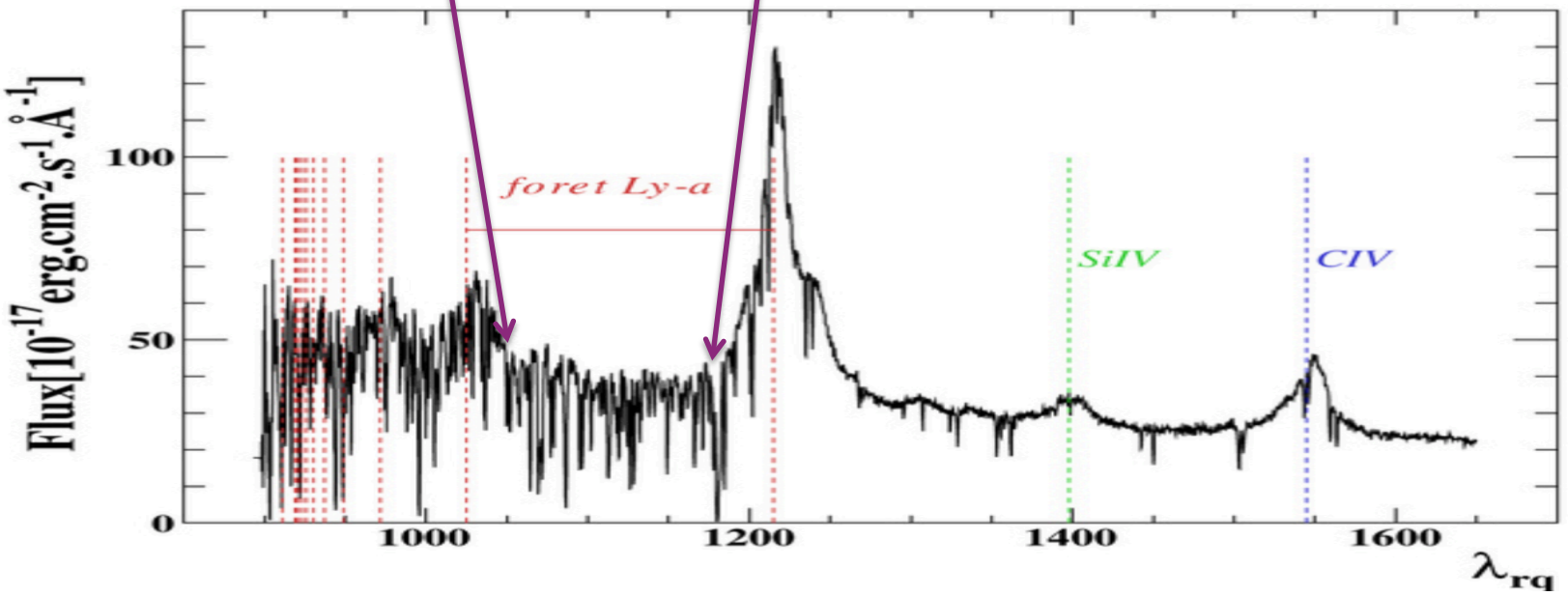
DESI & Euclid : sub-% level measurements within $\delta z = 0.1$ over $0.6 < z < 2.0$!

Neutrino mass accuracy ~20-25 meV on Σm_ν

➢ **Important role of IRFU**

Lya forest in QSO line of sight traces the distribution of mass in the Universe → best constraint on the smallest structures → sensitive to neutrino mass



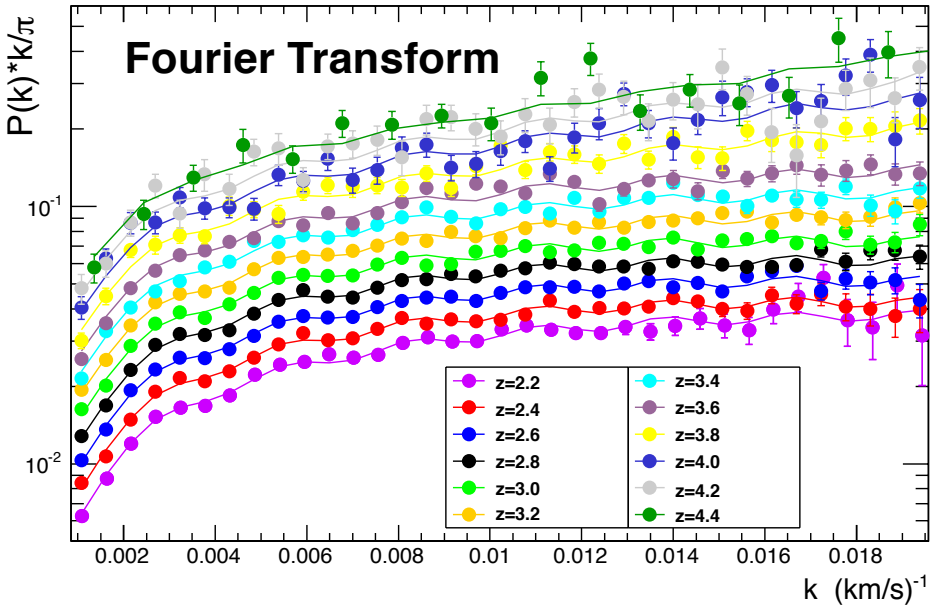


Cosmological simulations (SPP): impact of neutrino mass Σmν and sterile neutrino mass m_s on structure formation

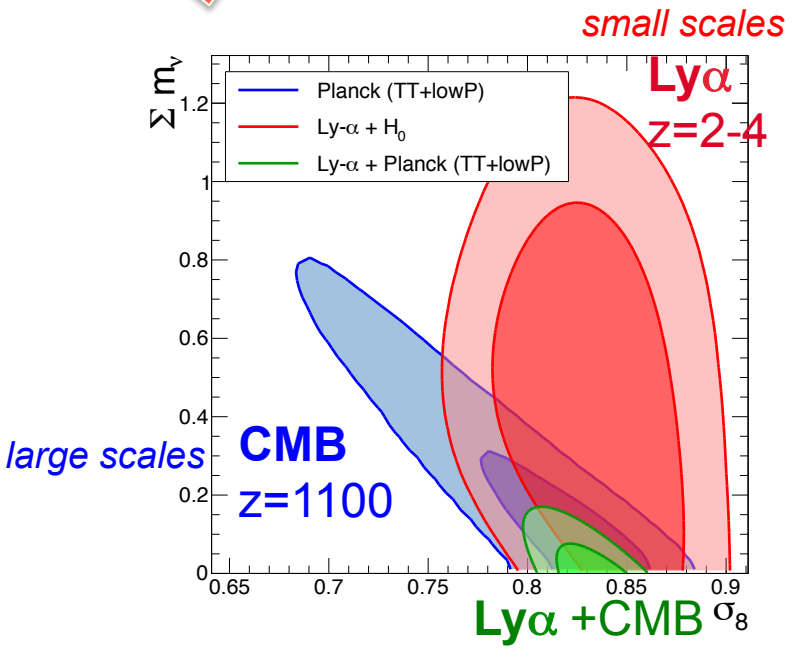
$$P_{Raw}(k) = [\underbrace{P_{Ly\alpha}(k)}_{\text{Cosmology (BAO)}} + \underbrace{P_{Ly\alpha\text{-SiIII}}(k) + P_{metals}(k)}_{\text{systematics}}] \times \underbrace{W^2(k) + P_{Noise}(k)}_{\text{Instrumental noise + res°}}$$

P Lyα : data (corrected for instrument) vs model (including modeling of syst.)

Constraints on cosmolgy



(Palanque-Delabrouille+ 2013)



(Borde+ 2014, Palanque-Delabrouille+ 2015)

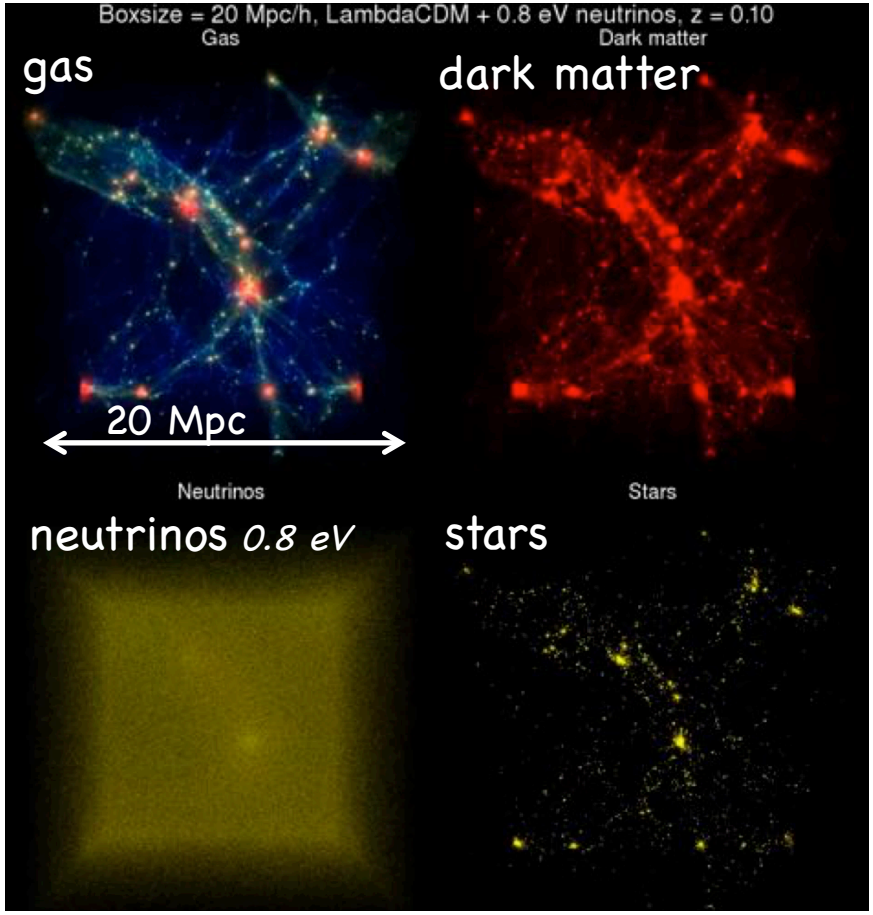
Cosmological simulations (SPP): impact of neutrino mass Σmν and sterile neutrino mass m_s on structure formation

15 million hours on Curie at TGCC, mostly through PRACE calls
→ Gadget-3 code (a massively parallel tree-SPH code widely used in cosmology)

Grid of ~100 simulations: Large volume (100 Mpc^3) , 3072^3 particles per species: Baryons → stars when $T<10^5 K$ & $\delta>10^3$, dark matter, neutrinos (Borde+ 2014, Rossi+ 2014)

Σmν < 0.12 eV, Neff = 2.9 ± 0.2
(Palanque-Delabrouille+ 2015a, 2015b, Rossi+ 2014)

Dedicated simulation with
DM= sterile neutrinos only
→ m_s > 26 keV (Baur+ 2016)



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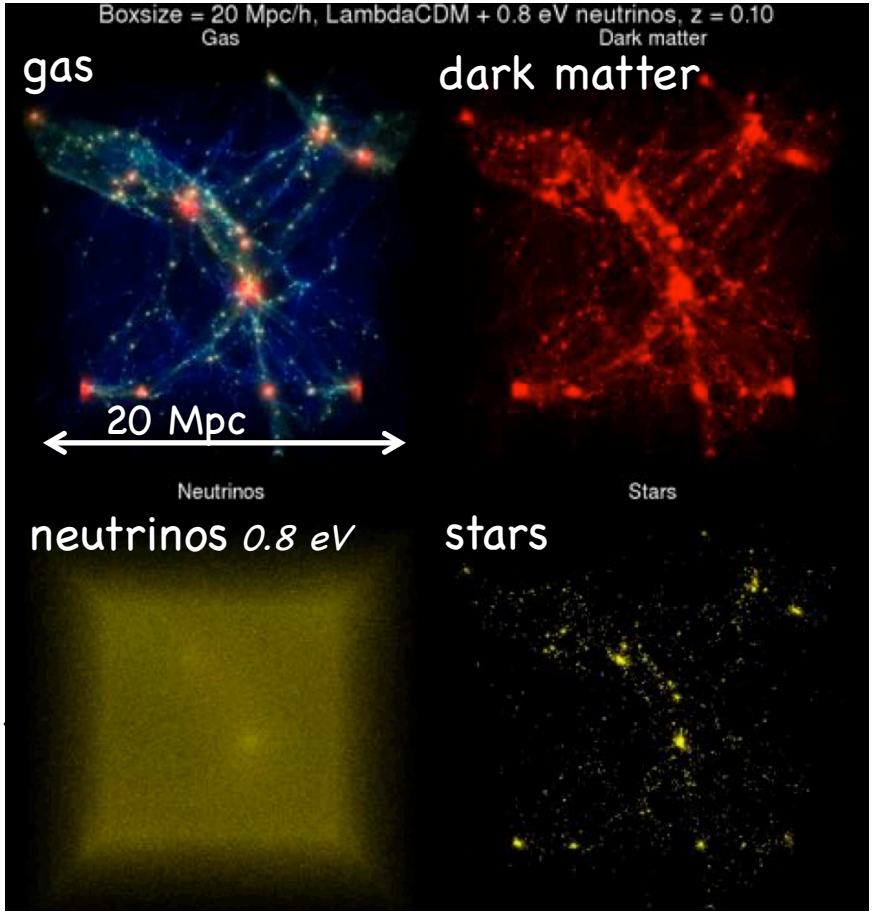
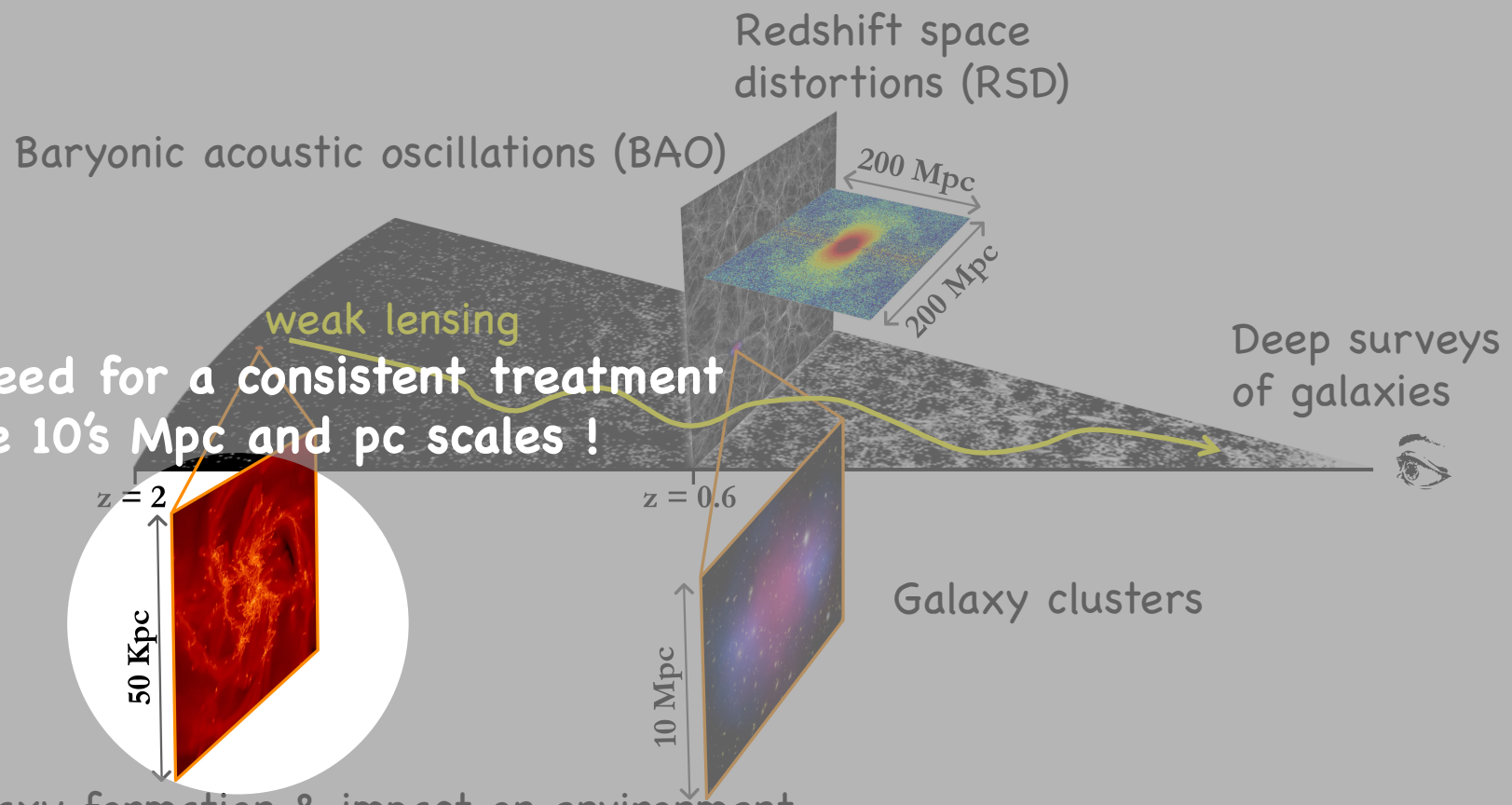


But:
feedback(SN, AGN,...) redistributes baryons
→ mimicks increase of neutrino mass effec

Cosmology and structure formation at IRFU from the small to the largest scales

The astrophysical tools used at IRFU to address those issues…



the need for a consistent treatment of the 10's Mpc and pc scales !

Galaxy formation & impact on environment
observations & hydrodynamic simulations

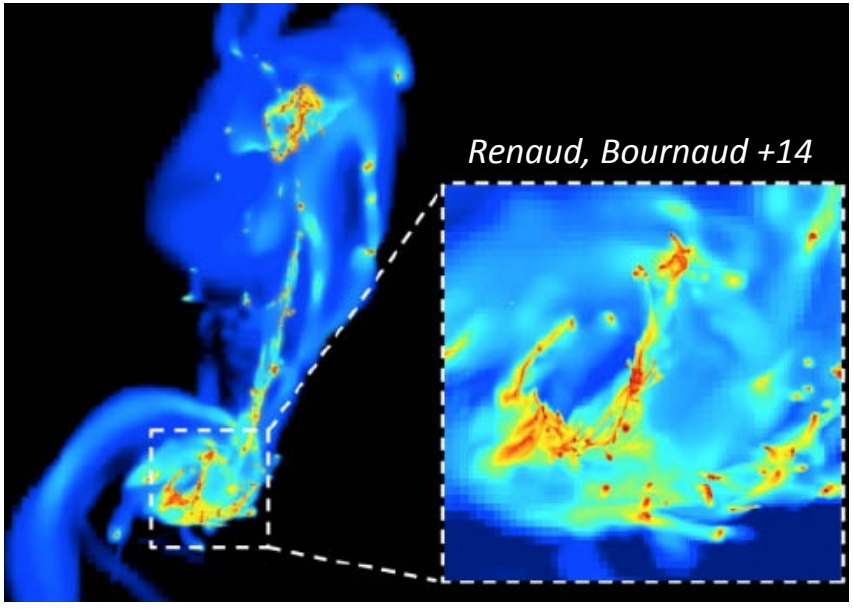
A multiscale approach (SAp/SPP) combining N-body and hydrodynamical simulations

"historic" view of feedback / supernovae and AGN :
± 0.01 systematic uncertainty on spectral index ns
± 0.02 eV systematic uncertainty on neutrino mass $\Sigma m\nu$
comparable to statistical uncertainty (Palanque-Delabrouille+ 15)

BUT:

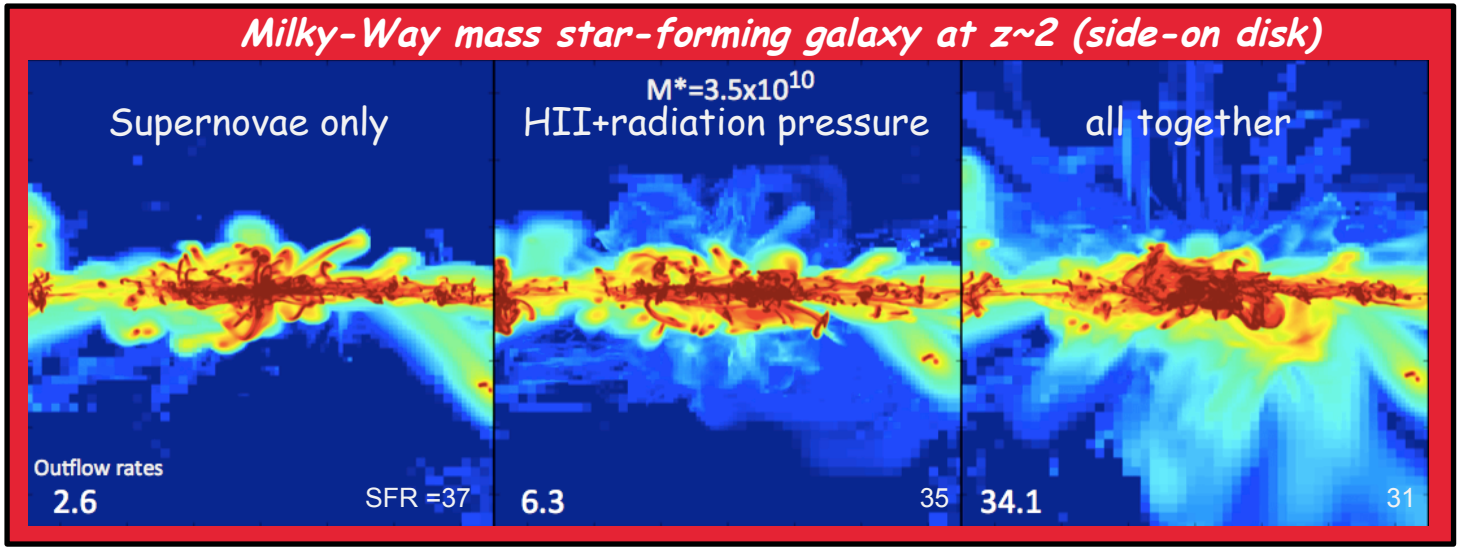
- Real stellar feedback involves radiation pressure and photo-ionization : much more efficient than supernovae (Murray et al. 2012, Bournaud et al. 2014)

- AGN in cosmological simulations dominate in very massive halos (>10^{13}), but detailed galactic models predict frequent AGN even at low mass (M_h~10^{11-12})
Predicted (Bournaud et al. 2012, De Graf et al. 2014) & observed (Daddi et al. 2012, Juneau et al. 2014, Trump et al. 2014)



- pc-scale resolution sim. of full galaxies & DM
- Resolution of ~100M_{sun} (high-dens. gas cores)
- ISM turbulence & fragmentation vs galaxy type and redshift

Accurate modeling of feedback (SAP)

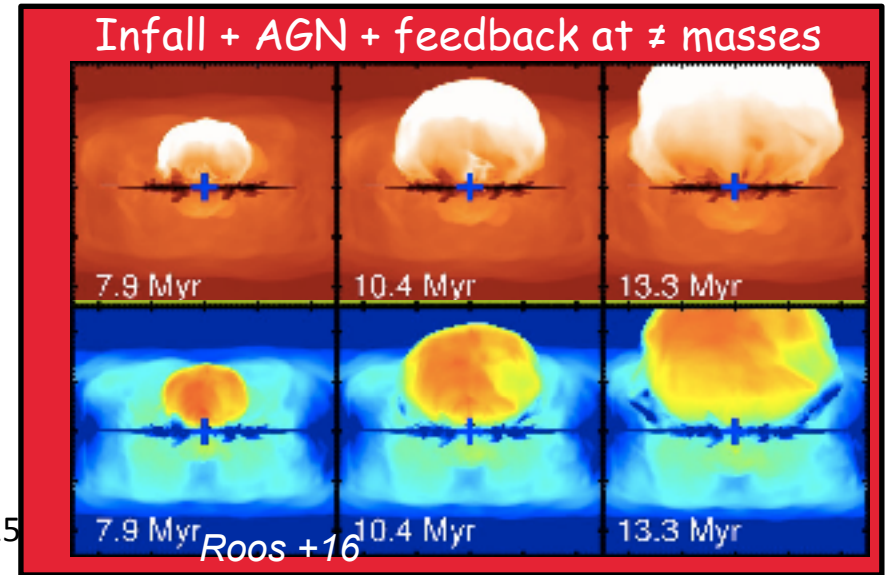


Outflow mass rate, velocity, temperature

as a function of

Galaxy (halo) mass, SFR, redshift

+ amplitude & timescale of variations



 Gabor & Bournaud 2014 ; Roos et al. 2015

CEA Highlights on BAO & feedback

CEA internal Press releases BAO

- November 2012: First measurement of the decelaration of the Universe
- April 2014 : Sloan Digital Sky Survey astronomers obtain the most precise measurement of the expansion rate of the Universe
- November 2014: Neutrinos are lighter than ever

Peer-reviewed publications

15 papers first-authored by Irfu/SPP on BAO in past 5 years
+ ~40 papers with major contribution by Irfu/SPP

Galactic feedback

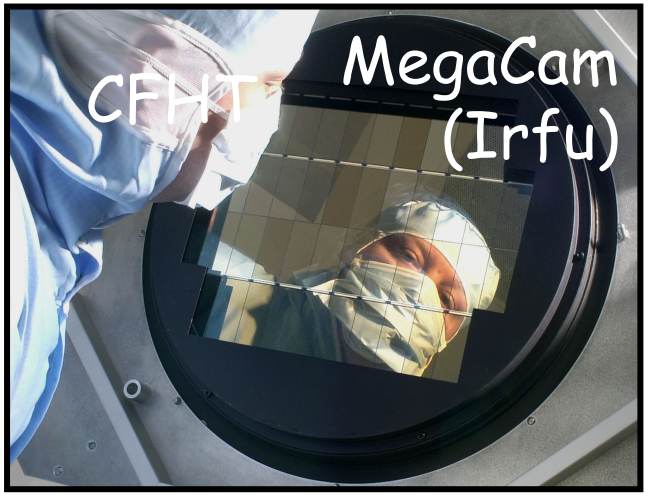
Several highlights in 2012-15 on galactic physics, star formation and feedback

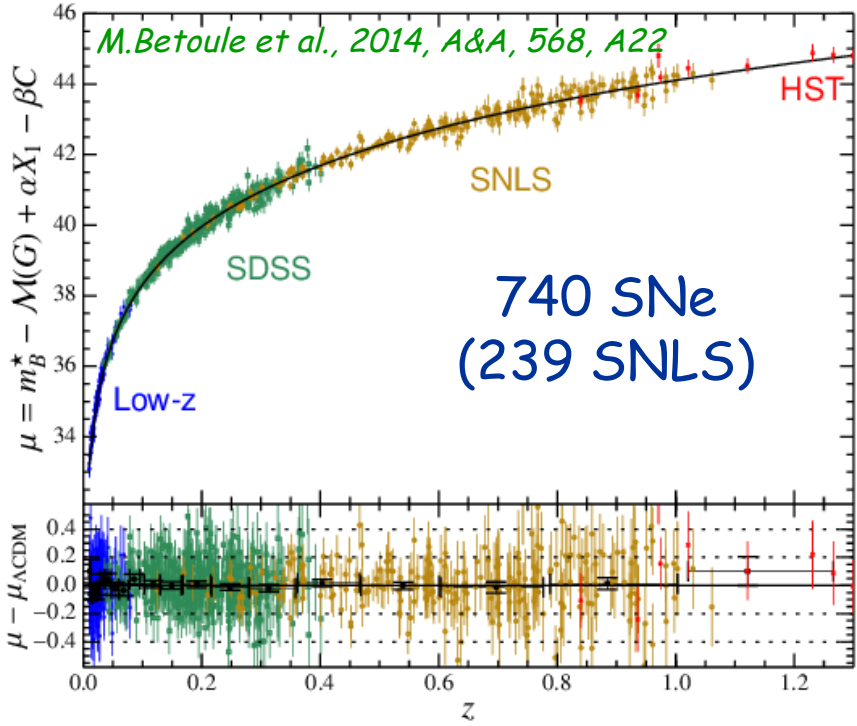
- three press releases
- 4 major PRACE projects led by IRFU/SAP on the topic
- "La Recherche" prize to the Renaud et al. publication in 2015.

Peer-reviewed publications

19 papers first-authored by Irfu/SAP on SF/AGN feeding/feedback in 4yr
And > 50 co-authored

SUPERNOVAE & COSMOLOGY AT SPP





- 3-year spectroscopic analysis complete
- final analysis (5-year) under way

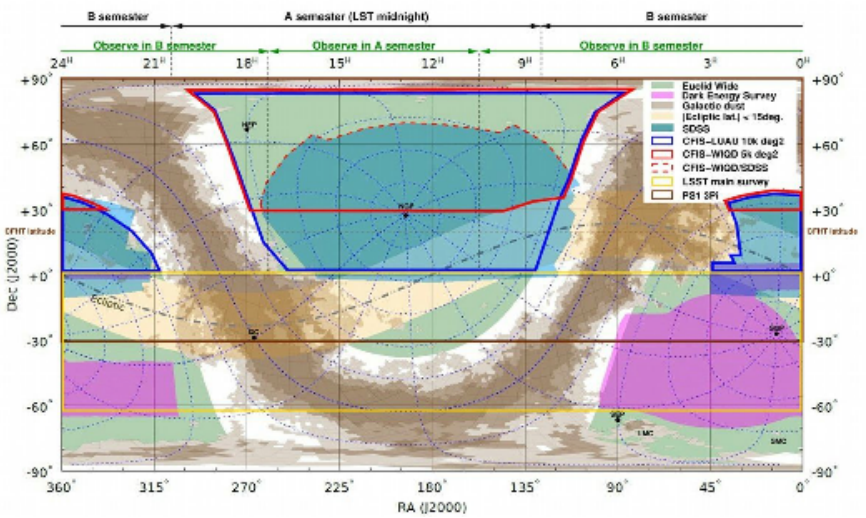
analysis of SNLS data based on new selection of SN in view of final 5-year analysis (paper in prep.) [3-year data: 3 PhD, 4 papers]

In parallel: work on alternative cosmology with modified gravity (Galileon) (SNe, CMB, BAO, $f\sigma_8$). [2 papers. 1 PhD, 1 student]

CFIS - Canada-France Hawai'i Imaging Survey

PIs: J.-C. Cuillandre (SAp), A. McConnachie (Canada); **co-Is from SAp, SPP, SEDI.**

Proposed **140 nights at CFHT**:
to u=24.3 and r=24.1.



Science cases:

- Dark-matter halos: filaments between groups, tidal stripping of satellite galaxies, halo shapes.
- Testing GR
- Photometric redshifts for Euclid
- Target selection for DESI (corresponding work package led by SPP)

Further joint SAp - SPP cosmology projects

A. Raichoor (PhD at SPP) with C. Yèche, N. Palanque, M. Kilbinger.

- eBOSS galaxy clustering: SPP uses software developed by SAp/CosmoStat
- DECaLS (target selection survey for DESI): exploratory studies for weak lensing use of this data set.

Future

Observations

Short Term: SAp: Herschel, *ALMA*, Artemis / SPP: eBOSS / **SAp+SPP: Planck, XMM, *NIKA2***

Mid Term: SAp: JWST / SPP: DESI (+SAp on galaxies) / **SAp+SPP: Euclid**

Long Term: SAp: ELT-METIS (2025), ATHENA (2028)

ESA M5 projects: SPICA (SAp), **Core++ (SPP+SAp)**

Theory/modeling

- feedback vs cosmology → combining hydrodynamical + N-body simulations
- simulations of massive clusters
- simulations of isolated & interacting galaxies → origin of departure from scaling laws in galaxies (main sequence, Schmidt law)
- impact of alternative cosmologies (with IPhT, LAL)
- modeling of infrared emission of dust from galaxies → bias in dust mass, SFR ?

New synergies & funding context

- Extended perimeter: Paris-Saclay
- Astrophysics "segment" at CEA : 26 programs to define the mission of CEA

scientists from SAp, SPP, SEDI & IPhT altogether included → PMLT: mid and long term plan

The Paris-Saclay perimeter: an opportunity for new synergies

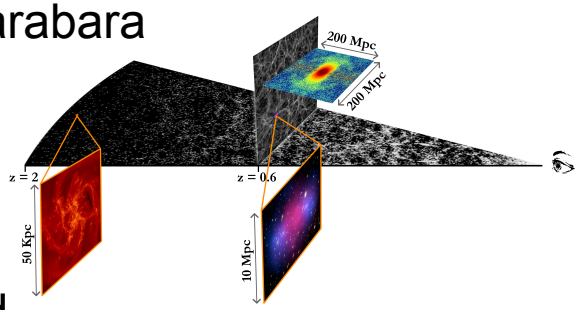
The Department SPU « Sciences de la Planète et de l'Univers »
Working group « Astrophysics & Cosmology » (includes members of SAp & SPP)

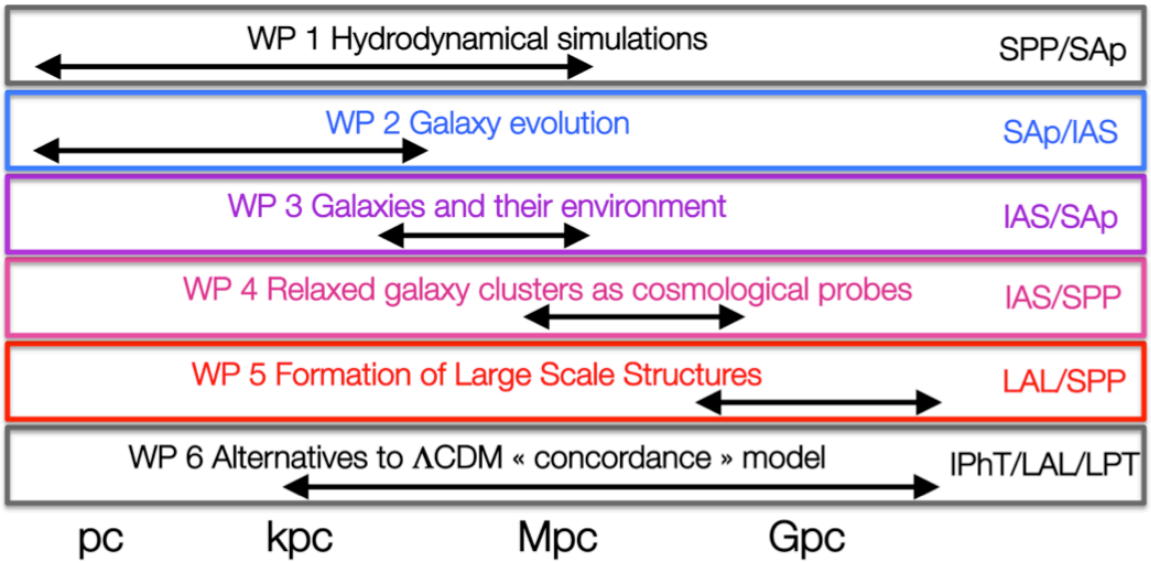
→ project submitted to Paris-Saclay, 1st phase successful : one or two 4-6 weeks collaborative meetings with several guests following the model of KITP, the Kavli Institute for Theoretical Physics, at UC Santa Barabara

The Labex P2IO, « physics of the two infinities »

→ Call for 900 k€ projects : COSMOS2STARS

not accepted but several meetings and synergies started





co-leads

Nathalie Palanque-Delabrouille (SPP)
Frédéric Bournaud (SAp)

David Elbaz (SAp)
Hervé Dole (IAS)

Hervé Dole (IAS)
Emanuele Daddi (SAp)

Nabila Aghanim (IAS)
Jean-Baptiste Melin (SPP)

Réza Ansari / Marc Moniez (LAL)
Christophe Yèche (SPP)

Jérémy Neveu (LAL)
Patrick Valageas (IPhT)
C. Charmousis/Y. Mambrini (LPT)