Testing gravity and the cosmological model with LSS

LSST & BAORadio (LAL / IJCLab)

Réza Ansari
Univ. Paris-Saclay & IJCLab / CNRS-IN2P3

IJCLab, Orsay

14 December 2020

- Large Scale Structure
  - ΛCDM model and cosmological probes
  - LSS & BAO's , RSD
  - Some recent results
- Vera Rubin Observatory (LSST)
  - Project overview, LSST@LAL
  - Photometric redshifts and BAO's
  - Holospec , AngPow , Fink …
- 21 cm Intensity mapping
  - Instrumental & data analysis challenges
  - PAON4 , Tianlai … IDROGEN
  - Future-Fiction

Large Scale Structure
BAO's

- We do have a fairly good model (Hot Big Bang model) describing the evolution of the universe, with rather well measured parameters
- The concordance ΛCDM model is based on General Relativity and the Standard Model of Particles (ElectroWeak+QCD), but needs some additional ingredients
  - *Inflation and the inflaton field ?*
  - *matter anti-matter asymmetry ?*
  - **Dark matter (?)** : the existence of an exotic form of matter (non baryonic) is required - Mean Dark Matter density is 5-6 times larger that ordinary matter density
  - **Dark Energy (?)** : A cosmological constant or another form of energy density is also required. Today's universe energy density is dominated by DE, which has repulsive gravitational effects at very large (cosmological scales) and is responsible for the observed accelerated expansion of the universe

ΛCDM model with 6 parameters

3 parameters to set (though General Relativity) the dynamics of the Universe,
1 parameter to capture the effect of reionisation (end of the dark ages),
2 parameters to describe the characteristics of primordial fluctuations.
Flat spatial geometry assumed.

$\Omega_b h^2$ Baryon density today - The amount of ordinary matter
$\Omega_c h^2$ Cold dark matter density today – only weakly interacting
Θ Sound horizon size when optical depth τ reaches unity
(Distance traveled by a sound wave since inflation, when universe became transparent at recombination at t ~380 000 years)

τ Optical depth at reionisation (due to Thomson scattering of photons on e^-), fraction of the CMB photons re-scattered during that process

A_s Amplitude of the curvature power spectrum (Overall contrast of primordial fluctuations)
n_s Scalar power spectrum power law index (n_s-1 measures departure from scale invariance)

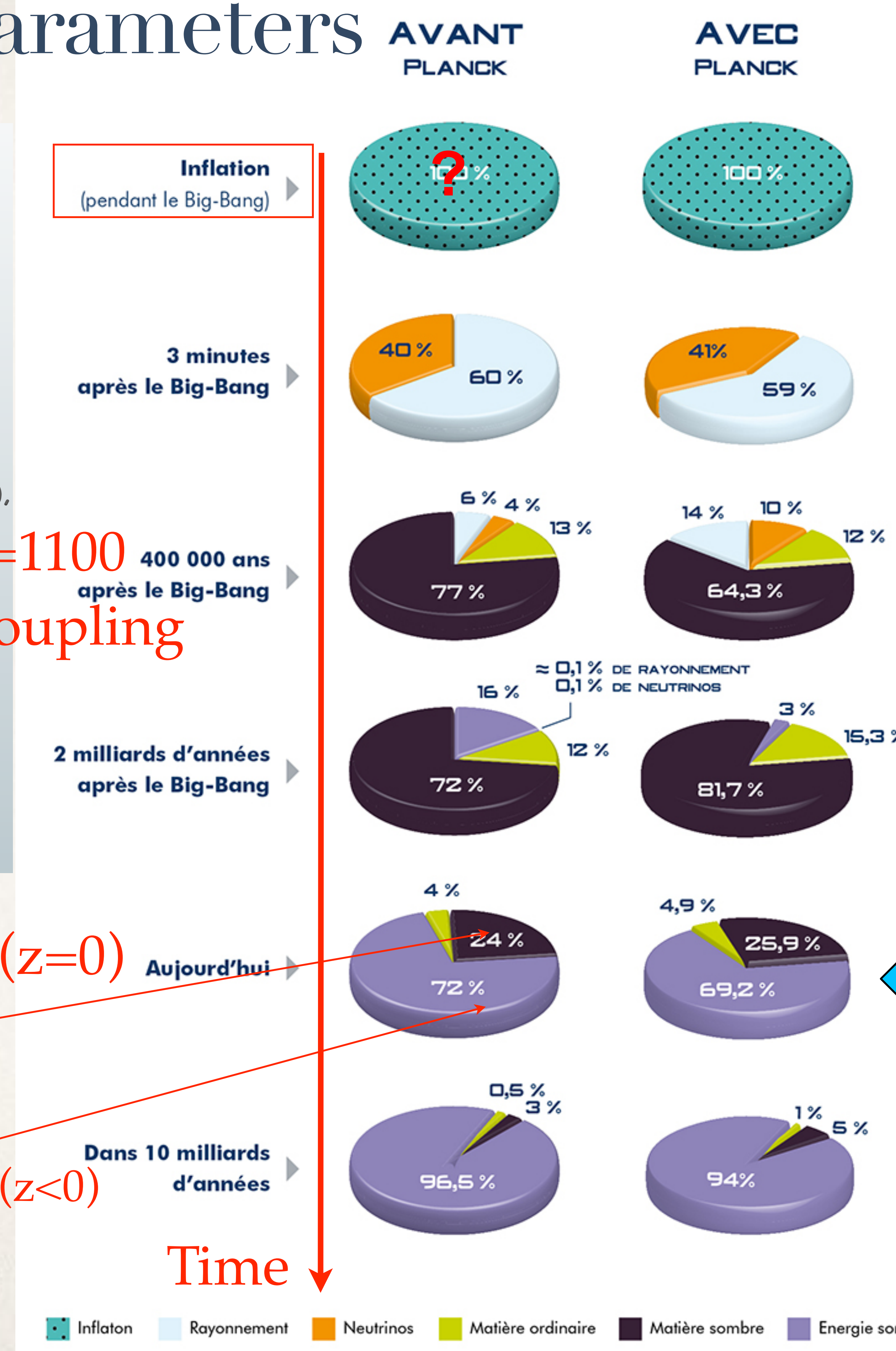
Others are *derived* parameters within the model, in particular

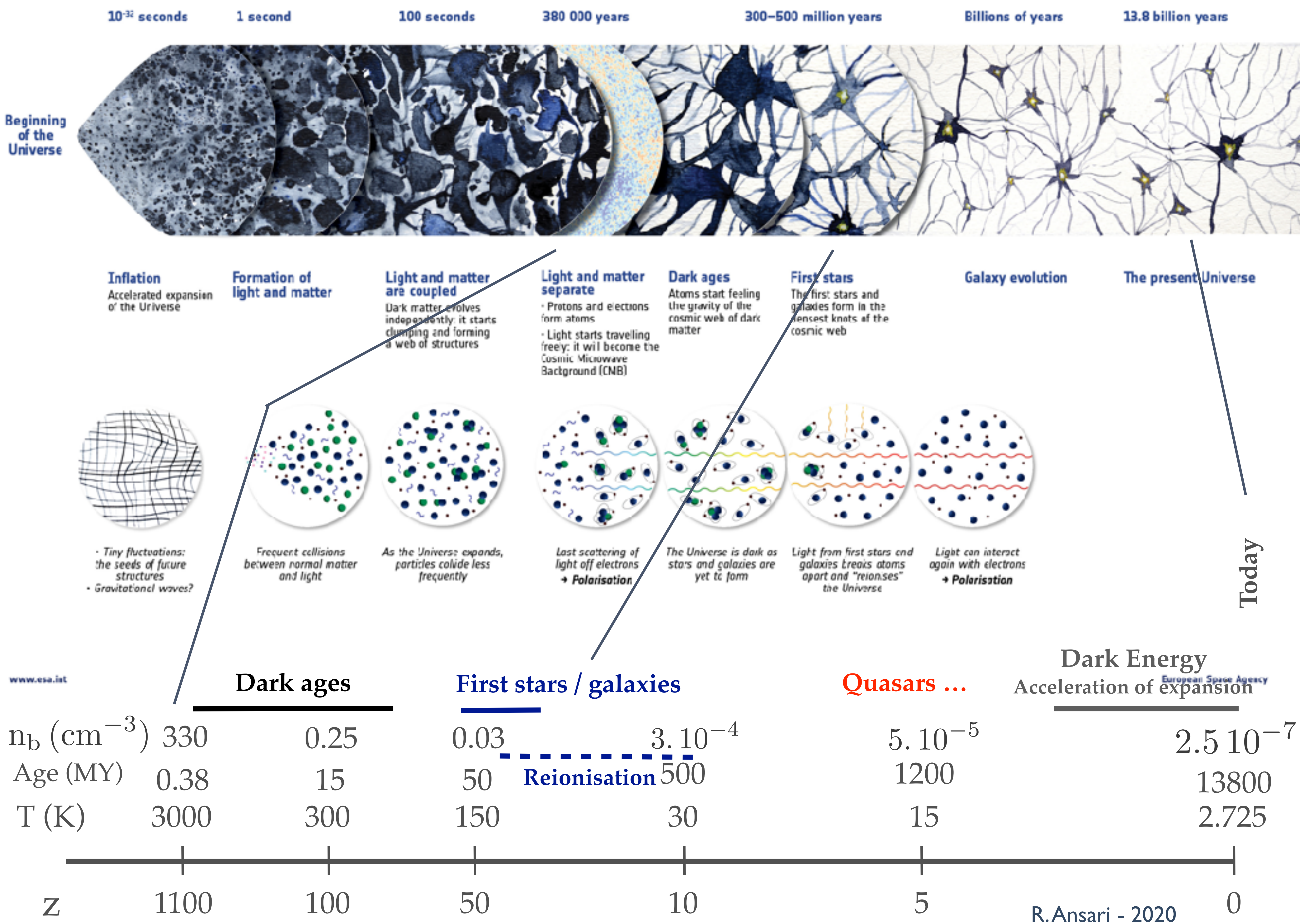
- *Ω "Dark Energy" fraction of the critical density (derived only if assumed flat)*
- *H_0 the expansion rate today (in km/s per Mpc of separation)*
- *t_0 the age of the universe (in Gy)*

Planck 2015 , arXiv:
Planck 2018, arXiv:1807.06209

Dark Matter (25%)

Dark Energy / Λ (70%)





10⁻³² seconds
1 second
100 seconds
380 000 years
300–500 million years
Billions of years
13.8 billion years
Beginning of the Universe
Inflation
Accelerated expansion of the Universe
Formation of light and matter
Light and matter are coupled
Dark matter evolves independently: it starts clumping and forming a web of structures
Light and matter separate
· Protons and electrons form atoms
· Light starts travelling freely: it will become the Cosmic Microwave Background (CMB)
Dark ages
Atoms start feeling the gravity of the cosmic web of dark matter
First stars
The first stars and galaxies form in the densest knots of the cosmic web
Galaxy evolution
The present Universe
· Tiny fluctuations: the seeds of future structures
· Gravitational waves?
Frequent collisions between normal matter and light
As the Universe expands, particles collide less frequently
Last scattering of light off electrons
→ Polarisation
The Universe is dark as stars and galaxies are yet to form
Light from first stars and galaxies breaks atoms apart and "reionises" the Universe
Light can interact again with electrons
→ Polarisation
Today
www.esa.int
European Space Agency
Dark ages
First stars / galaxies
Quasars …
Dark Energy
Acceleration of expansion
n_b (cm^{-3}) 330 0.25 0.03 3. 10^{-4} 5. 10^{-5} 2.5 10^{-7}
Reionisation
Age (MY) 0.38 15 50 500 1200 13800
T (K) 3000 300 150 30 15 2.725
z 1100 100 50 10 5 0
R.Ansari - 2020

Cosmological probes and Dark energy (I)

- Large Scale Structure (**LSS**) : shape (power spectrum or correlation function) and its evolution with redshift is a powerful cosmological probe - in particular the BAO feature in the LSS
- Baryon Acoustic Oscillations (**BAO**) : Measurement of characteristic scales → $d_A(z)$, $H(z)$
- Supernovae (**SN**) : Measure of apparent SNIa luminosity as a function of → $d_L(z)$
- Weak lensing (**WL**) : Measure of preferred orientation of galaxies → $d_A(z)$, growth of inhomogeneities (structures / LSS)
- Galaxy Clusters (**CL**) : number count and distribution of clusters → $d_A(z)$, $H(z)$, Structure formation (LSS)
- Integrated Sachs Wolf (**ISW**) effect : effect of evolving gravitational potential in large scale structures (with redshift)

Cosmological probes (II)

- 1- Study the geometry of the universe (FLRW metric) - with a distance-redshift relation depending on the cosmological parameters (energy-matter densities)
  - Standard candles : SNIa , gravitational sirenes (GW)…
  - Standard ruler probes : BAO
- 2- Study the dynamics of structure formation : observe the LSS form and evolve through cosmic time (redshift)
  - Matter distribution using tracers (LSS) or the gravitational potential through lensing
- Statistical properties of matter distribution in the universe and its evolution with time (redshift) is one of the major tools/probes to test the cosmological model, determine its parameters: Dark matter and dark energy properties, neutrinos masses …
- The analysis is often carried out using the correlation function (or the spatial or angular power spectrum P(k) , C(l) …

ELSEVIER

Physics Reports

Volume 530, Issue 2, 10 September 2013, Pages 87-255

Observational probes of cosmic acceleration

David H. Weinberg [a, b], Michael J. Mortonson [b], Daniel J. Eisenstein [c, d], Christopher Hirata [e], Adam G. Riess [f], Eduardo Rozo [g]

Show more

Share Cite

https://doi.org/10.1016/j.physrep.2013.05.001

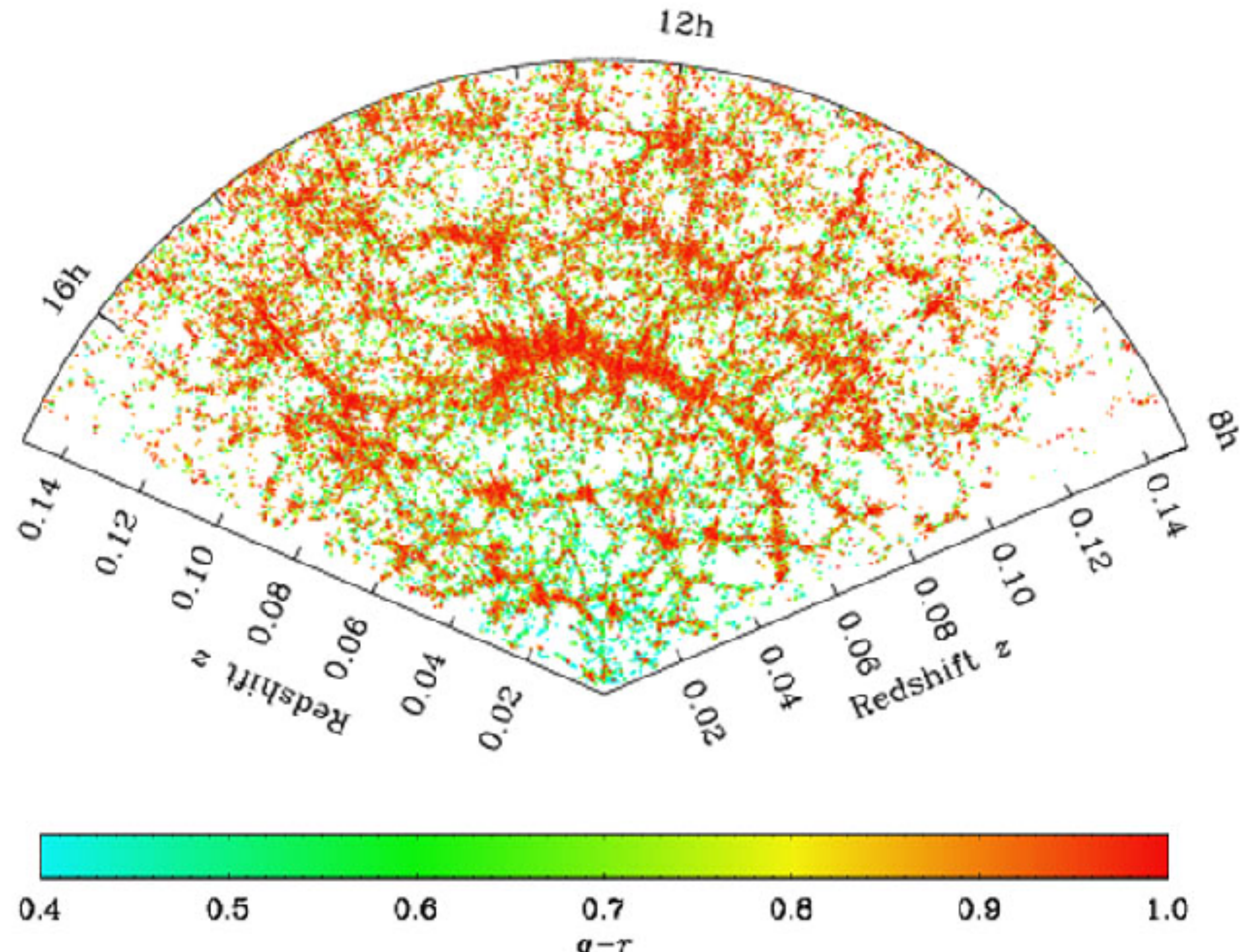
D. Weinberg et al. Phys.Rep. 2013, arXiv:1201.2434

L. Amendola et al. Phys.Rev. D . 2013, arXiv:1210.0439

L. Amendola et al. , Living Reviews in Relativity . 2018, arXiv:1606.00180

Nearly homogeneous and isotropic universe at large scales (>Gpc), but structured at smaller scales, from few hundred Mpc (BAO ~100 Mpc), then galaxy clusters (1-10 Mpc), to galaxies (10-100 kpc) et of course stars and planetary systems.

Structure formation driven mostly by the gravitational forces and collapse



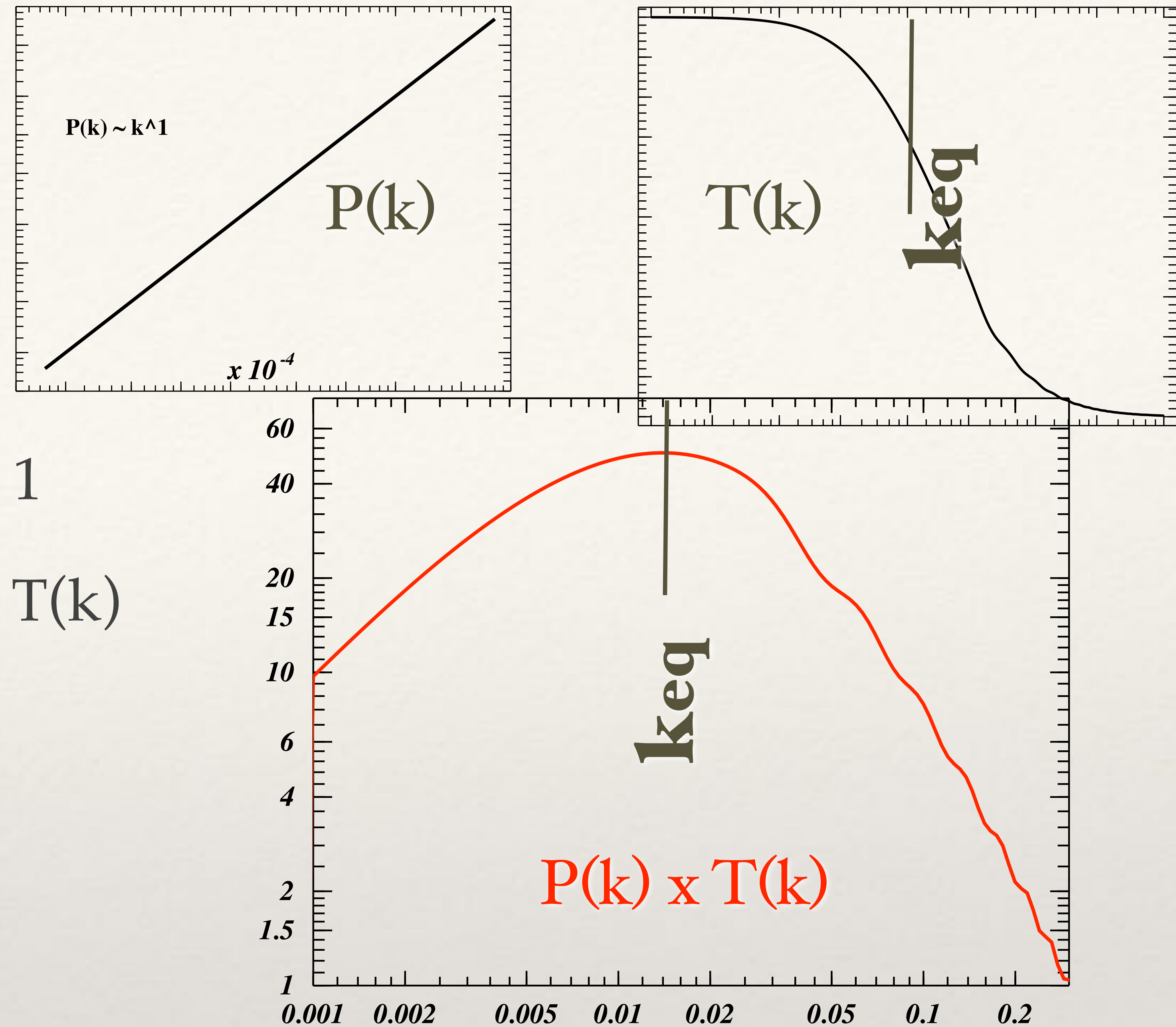
A slice through the SDSS galaxy 3D distribution

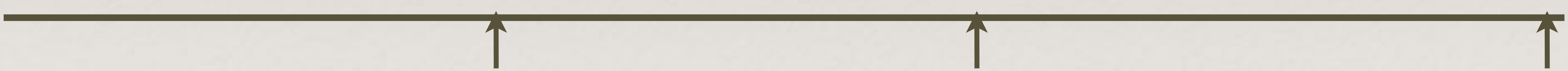
Zehavi et al. ApJ 2011, arXiv:1005.2413

Structure formation : LSS

- Initial spectrum : P(k) = k^n , n ~ 1
- Transfer function (linear regime): T(k)
- Growth factor
- Characteristic scale

$$k_{eq}.k_{dec}, k_{silk}$$





z_{eq} z_{dec} $z = 0$

Radiation dominated universe

No growth for pour $k > k_{eq}$,
(for length scales smaller than $1/k_{eq}$)

Photons-baryons coupling
Acoustic Oscillations

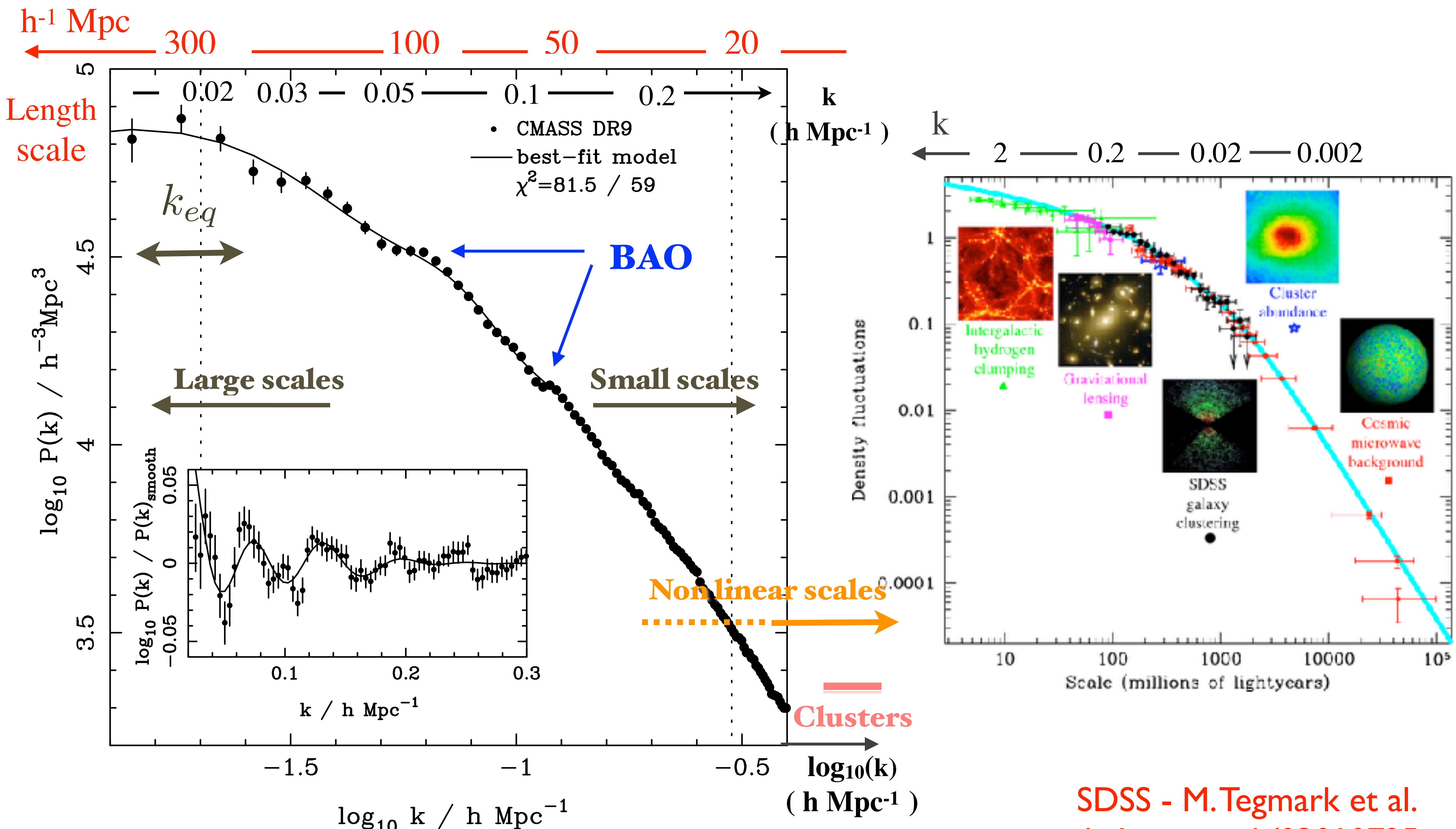
Growth of dark matter density fluctuations

Growth of matter density inhomogeneities
Gravitational collapse

Structure formation → LSS

http://www.virgo.dur.ac.uk/2014/11/11/EAGLE/index.html

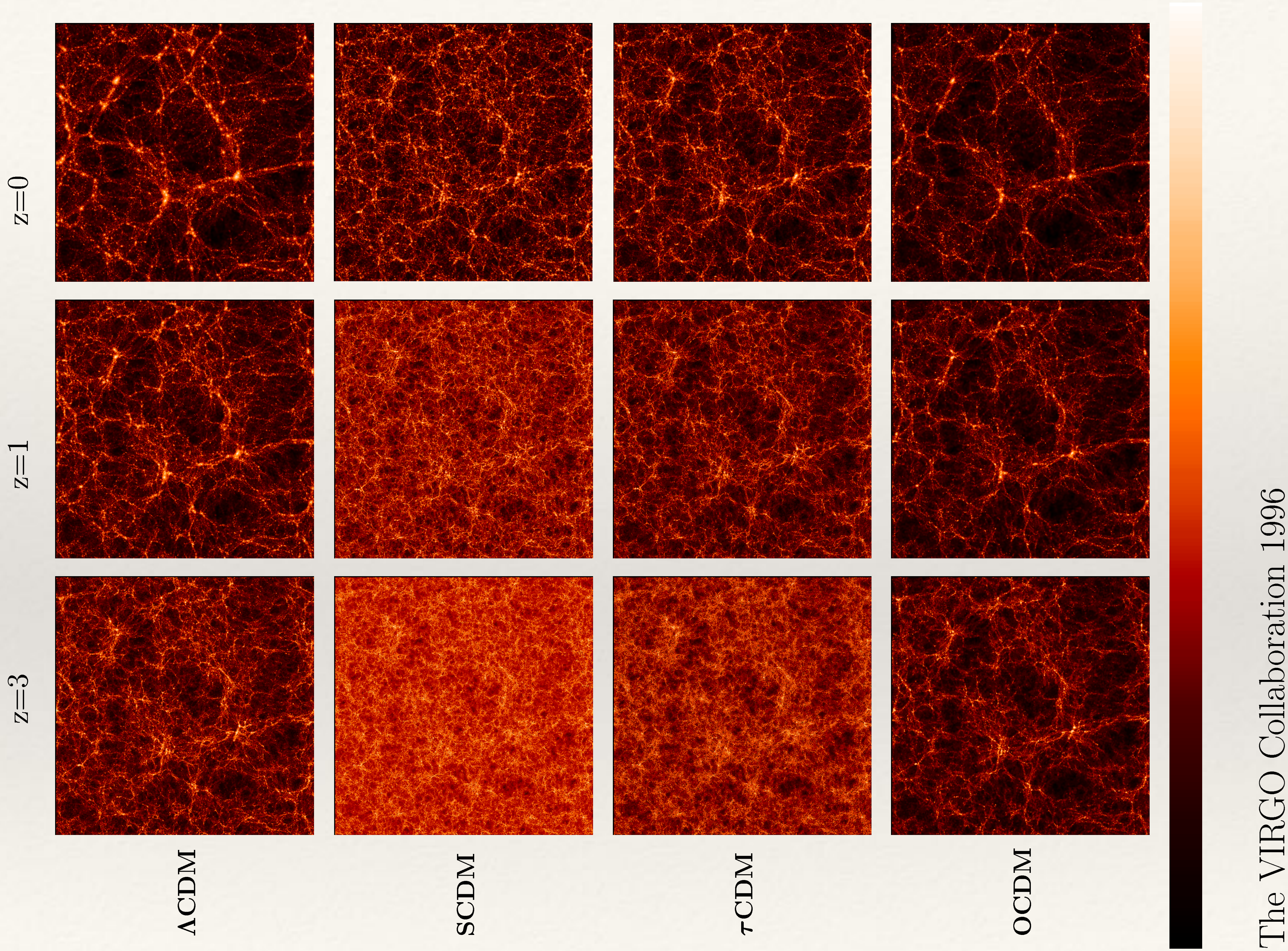
LSS : Power spectrum and different scales



SDSS - M.Tegmark et al.
ApJ , astro-ph/03010725

SDSS-DR9 , Anderson et al et al. 2012, arXiv:1203.6594

LSS sensitivity to cosmological parameters



VIRGO simulations arXiv: 9709010

, https://wwwmpa.mpa-garching.mpg.de/Virgo/virgopics.html

See also DEUS consortium : http://www.deus-consortium.org

LSS and neutrinos

PDG review 2019

https://pdg.lbl.gov/2019/reviews/rpp2019-rev-neutrinos-in-cosmology.pdf

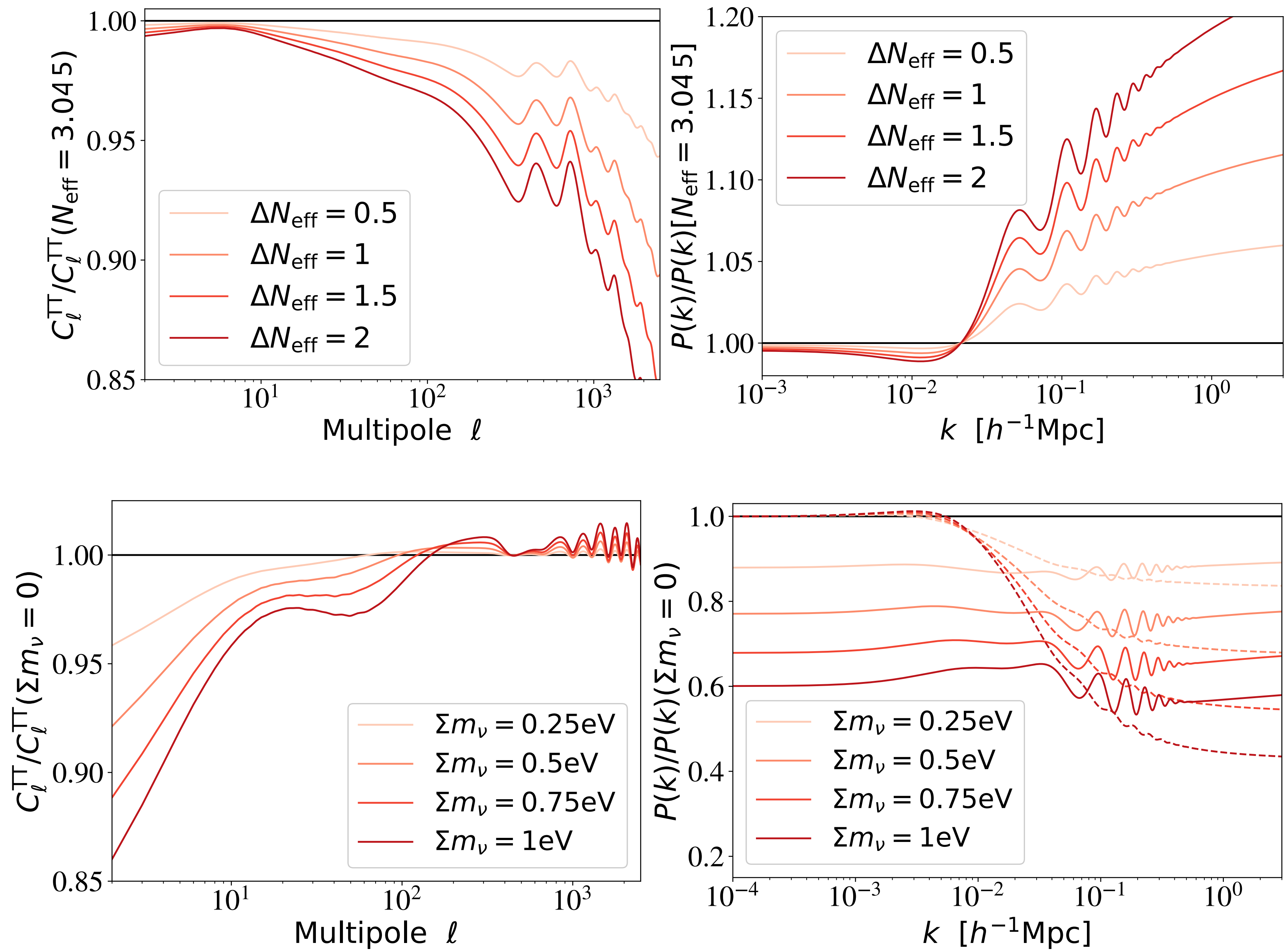
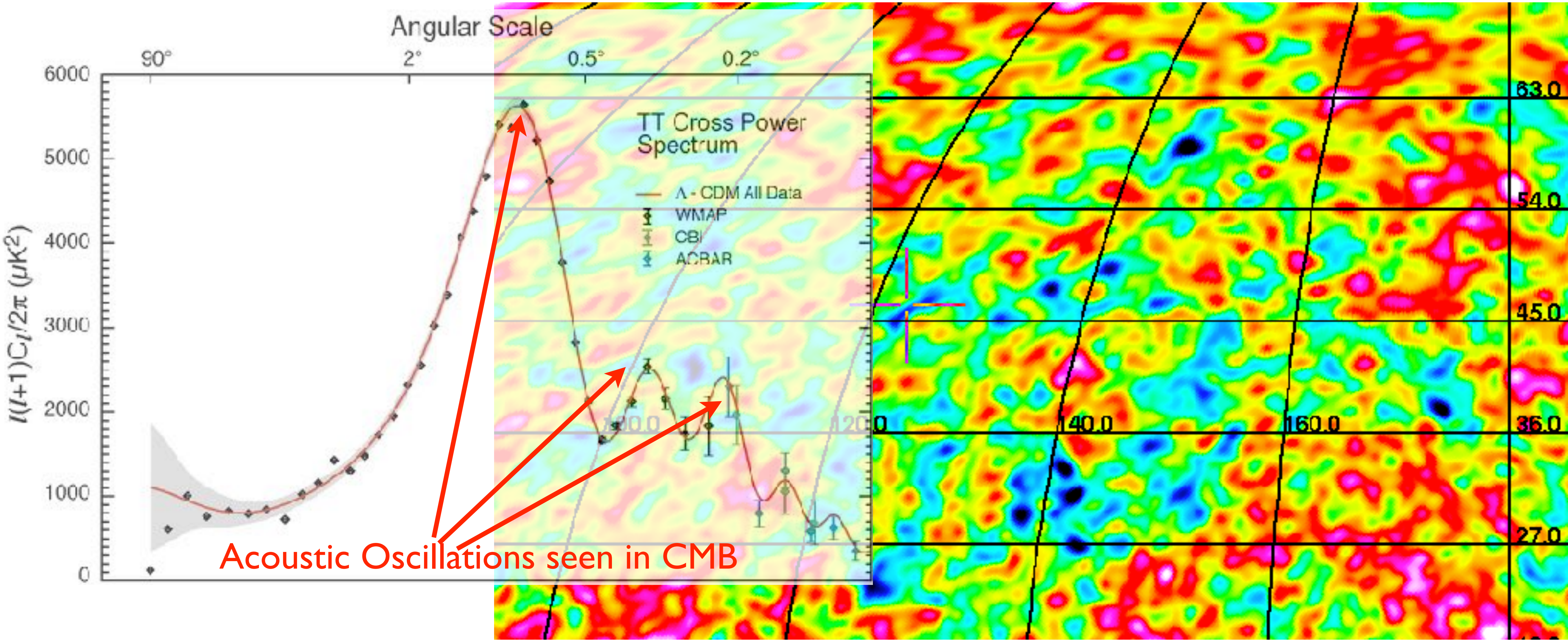
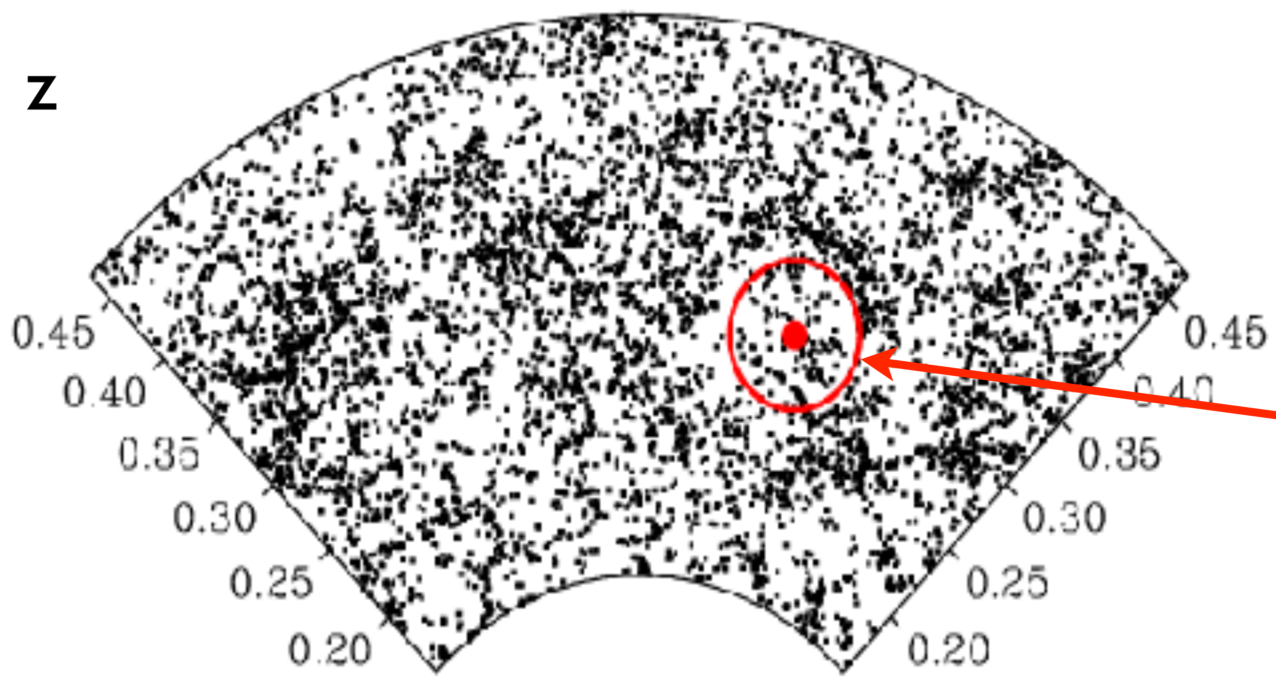
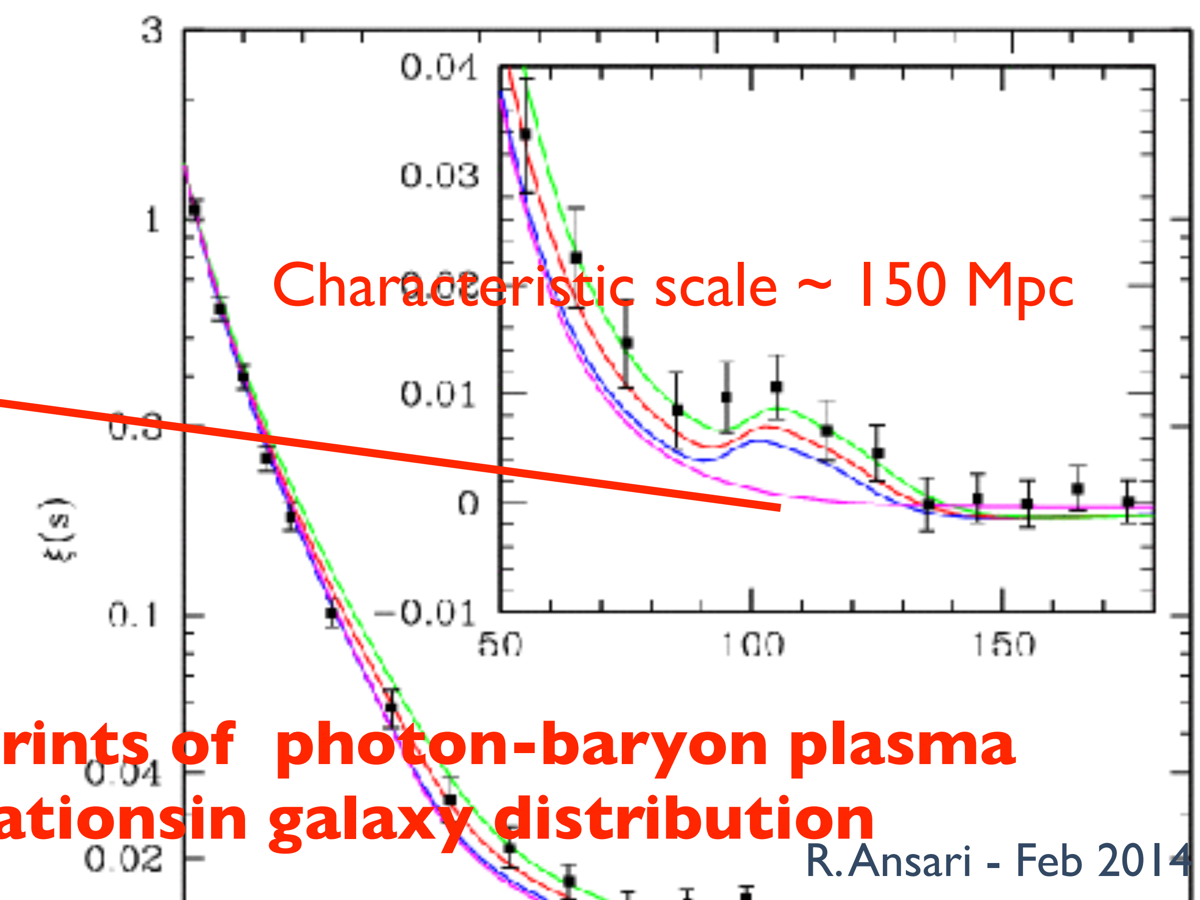


Figure 25.2: Ratio of the CMB C_ℓ^{TT} and matter power spectrum $P(k)$ (computed for each model in units of $(h^{-1}\mathrm{Mpc})^3$) for different values of $\sum m_\nu$ over those of a reference model with massless neutrinos. In order to minimize and better characterise the effect of $\sum m_\nu$ on the CMB, the parameters that are kept fixed are ω_b, ω_c, τ, the angular scale of the sound horizon θ_s and the primordial spectrum parameters (solid lines). This implies that we are increasing the Hubble parameter h as a function of $\sum m_\nu$. For the matter power spectrum, in order to single out the effect of neutrino free-streaming on $P(k)$, the dashed lines show the spectrum ratio when $\{\omega_\mathrm{m}, \omega_\mathrm{b}, \Omega_\Lambda\}$ are kept fixed. For comparison, the error on $P(k)$ is of the order of 5% with current observations, and the fractional C_ℓ errors are of the order of $1/\sqrt{\ell}$ at low ℓ.



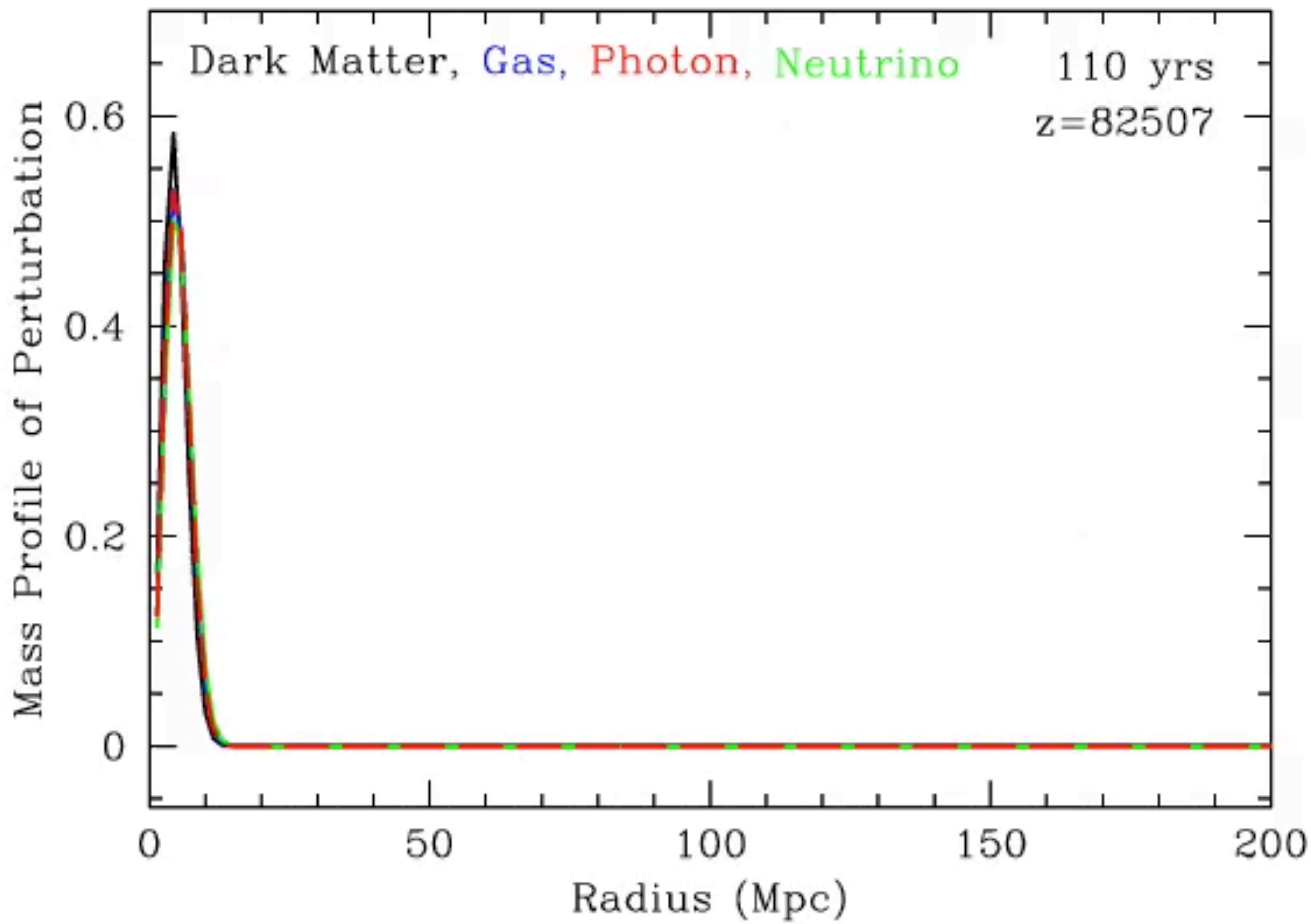


Galaxy distribution
(z, angle (α,δ)) plane



BAO: Imprints of photon-baryon plasma oscillationsin galaxy distribution

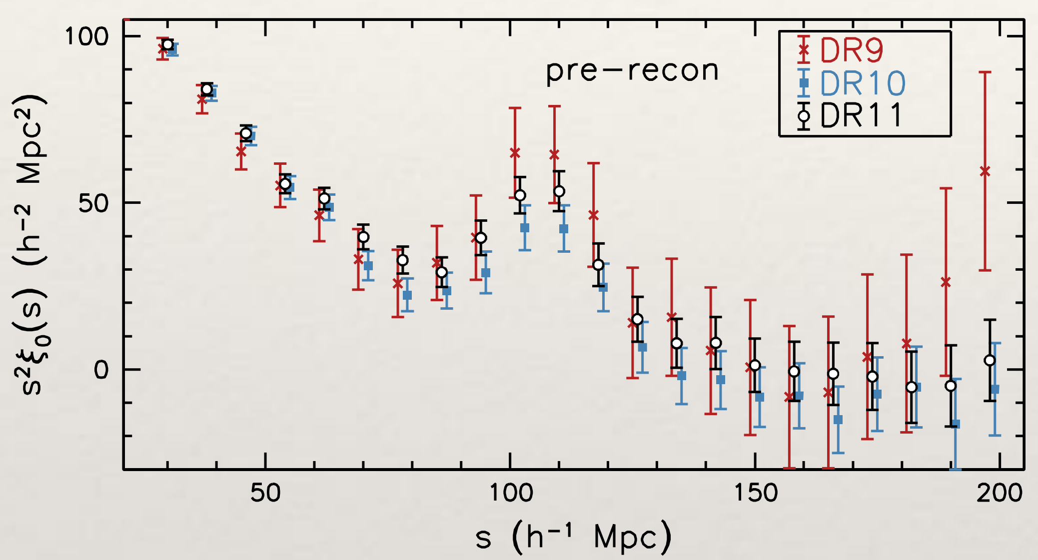
Matter clustering and Acoustic Oscillations

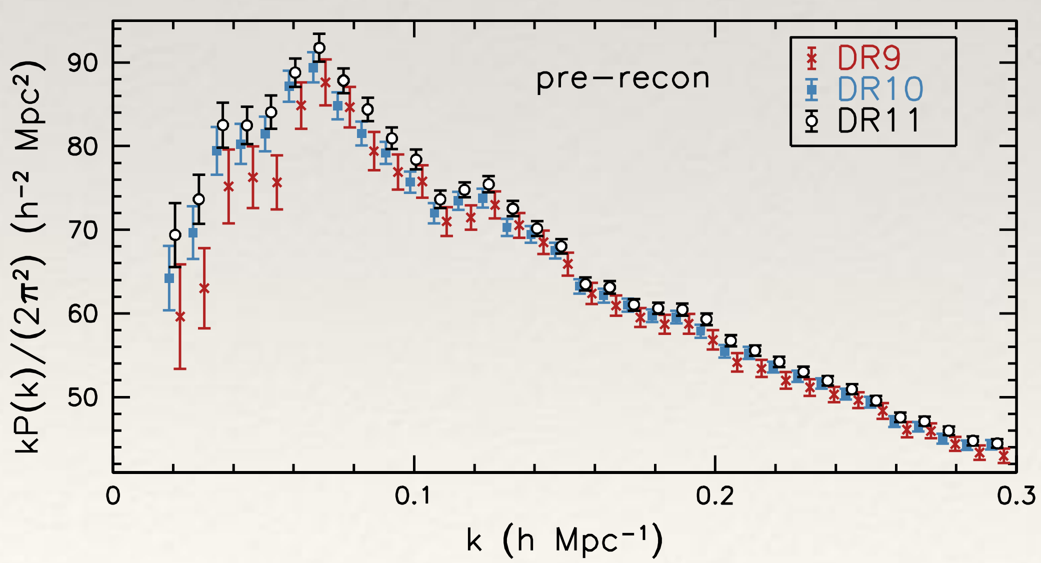


Animation : D. Eisenstein

BAO : Power spectrum and correlation function

- BAO's : Imprints left by the baryon-photon plasma oscillations prior to decoupling, on dark matter and visible matter (galaxies …) during structure formation after decoupling
- Wiggles in the distribution of matter, dominated by dark matter (and also visible matter / galaxies) : A preferential length scale (~ 150 Mpc) in the matter clustering → **Standard ruler type cosmological probe with a measurement @ z ~ 1100 (CMB anisotropies)**





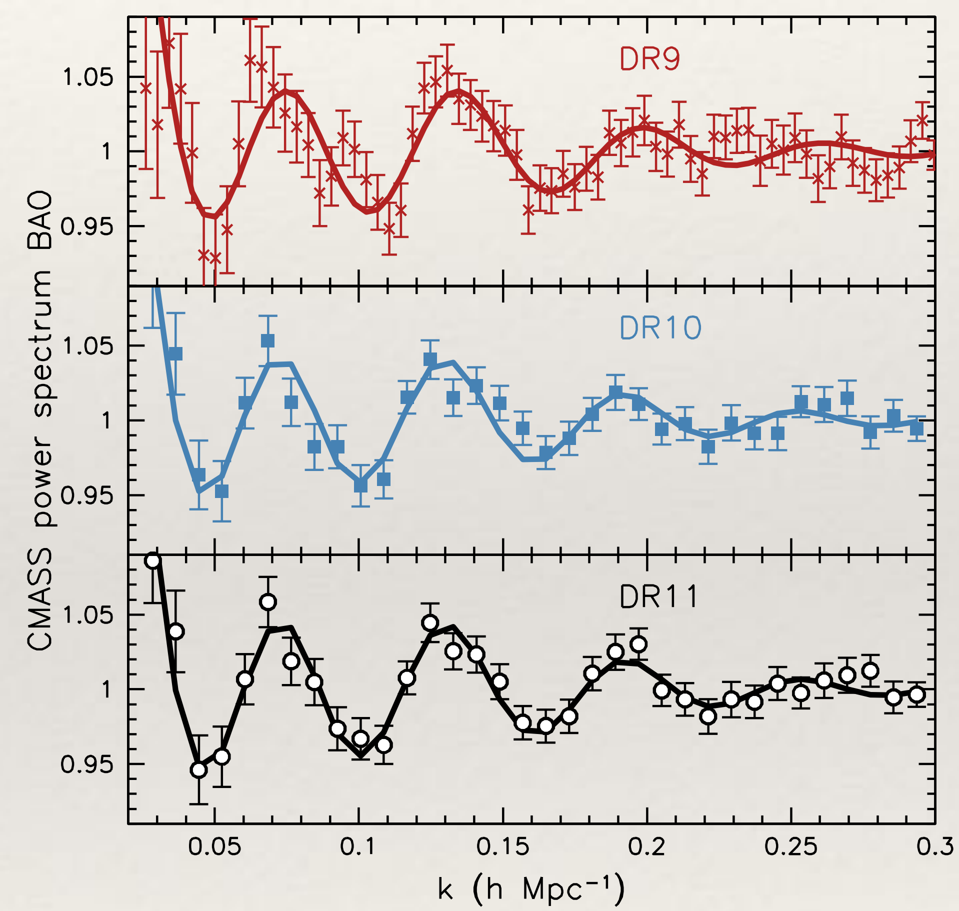


Figure 16. The CMASS BAO feature in the measured reconstructed power spectrum of each of the BOSS data releases, DR9, DR10, and DR11. The data are displayed with points and error-bars and the best-fit model is displayed with the curves. Both are divided by the best-fit smooth model. We note that a finer binning was used in the DR9 analysis.

SDSS-DR11 , Anderson et al et al. 2013, arXiv:1312.4877

RSD , AP, bias ...

- Galaxies falling in the potential : peculiar velocities with respect to the Hubble flow - which effects mainly the inhomogeneities along the radial direction. Peculiar velocities sensitive to the gravitational potential (total matter densities and not only the tracer density)
- Observations are carried in redshift space creates P(k) distortions, called **RSD** (Redshift Space Distortions)
- Alcock-Paczynski (**AP**) - compare radial and transverse size of an isotropic structure, due for example to mismatch between angular and radial distance scales
- LSS observed through ***biased*** tracers (galaxies, HI gas …) - bias could be scale and redshift dependent, which adds complexity and degeneracies to the analysis
- RSD can be used in conjunction with BAO to constrain structure growth , and tracer bias

$$P(\mathbf{k},z) = F_{\rm RSD}(\mathbf{k},z) P(k,z)$$

$$F_{\rm RSD}(\mathbf{k},z) = \left(b(z,k) + f(z,k)\mu^2 \right)^2 e^{-k^2\mu^2\sigma_{\rm NL}^2}$$

D. Weinberg et al. Phys.Rep. 2013, arXiv:1201.2434

$$\text{wave vector angle / los : } \mu = \cos\theta$$

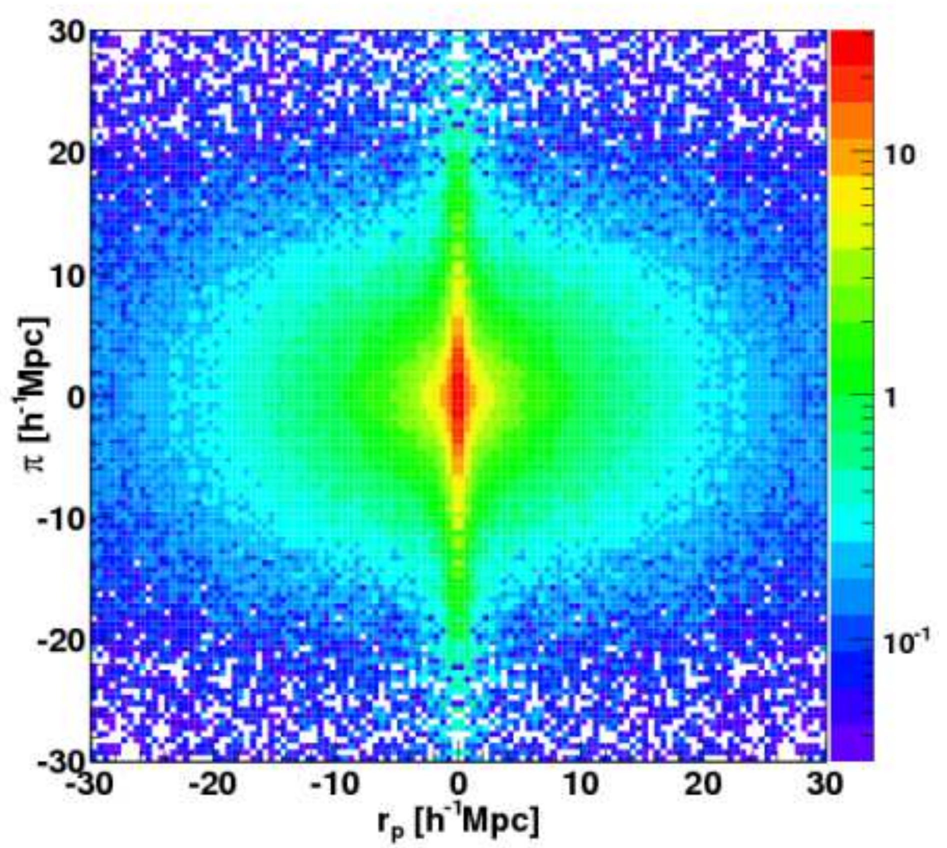
$$f \text{ : growth factor , } b \text{ : tracer bias}$$

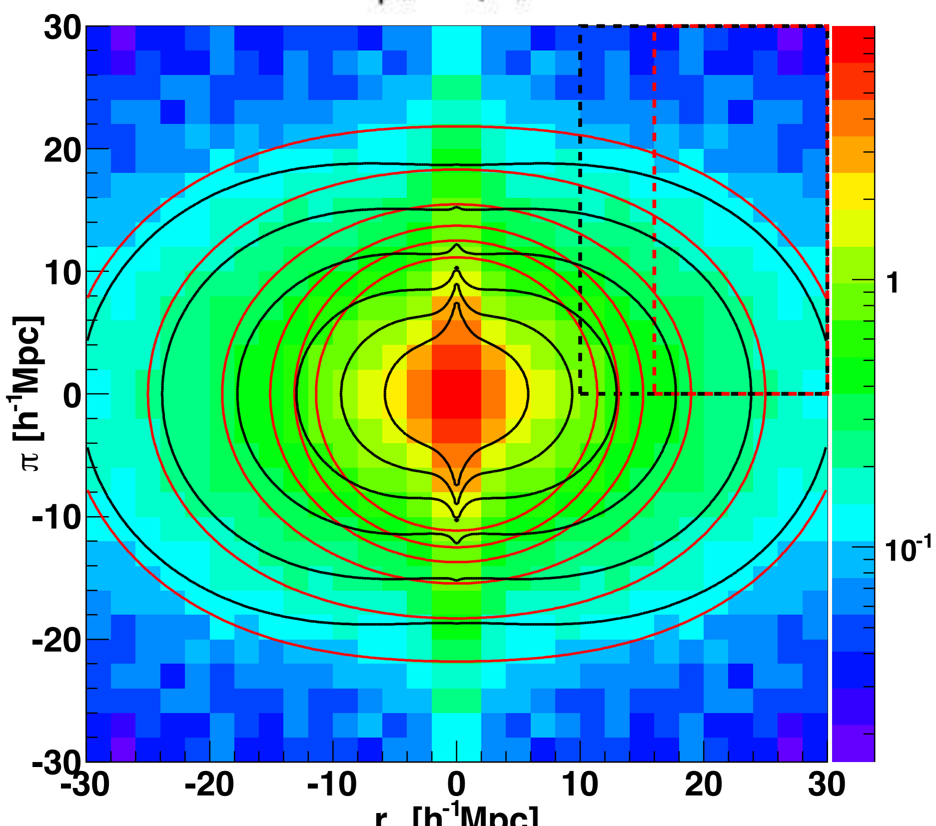
$$f = \frac{\partial \ln \sigma_8}{\partial \ln a},$$

Alcock & Paczynski, Nature, 1979

N. Kaiser, MNRAS , 1987

BAO/RSD , sensitivity to modified gravity





6dF Galaxy Survey , Beutler et al. ; MNRAS 2012

Correlation function , transverse and parallel to the line of sight (los)

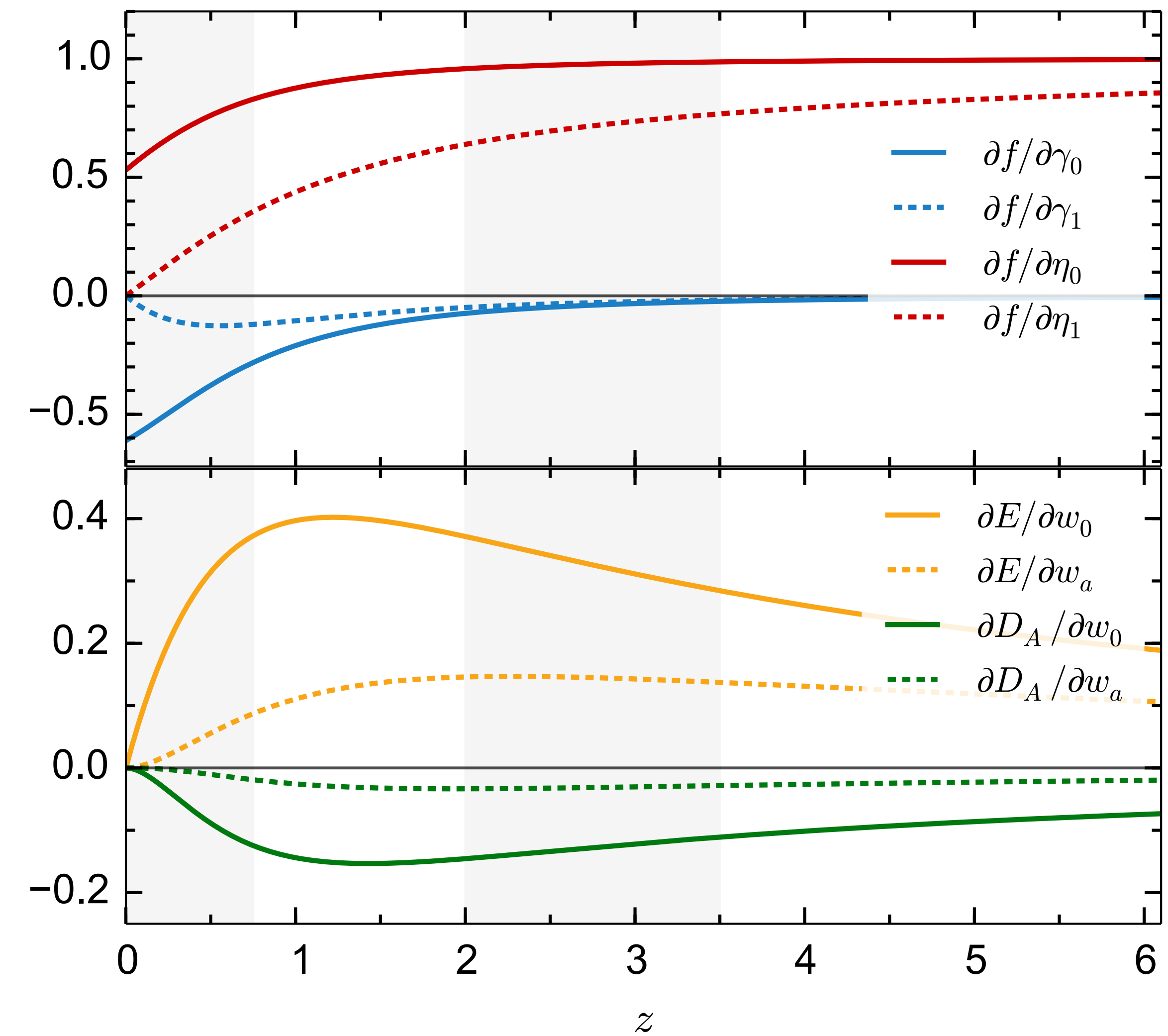
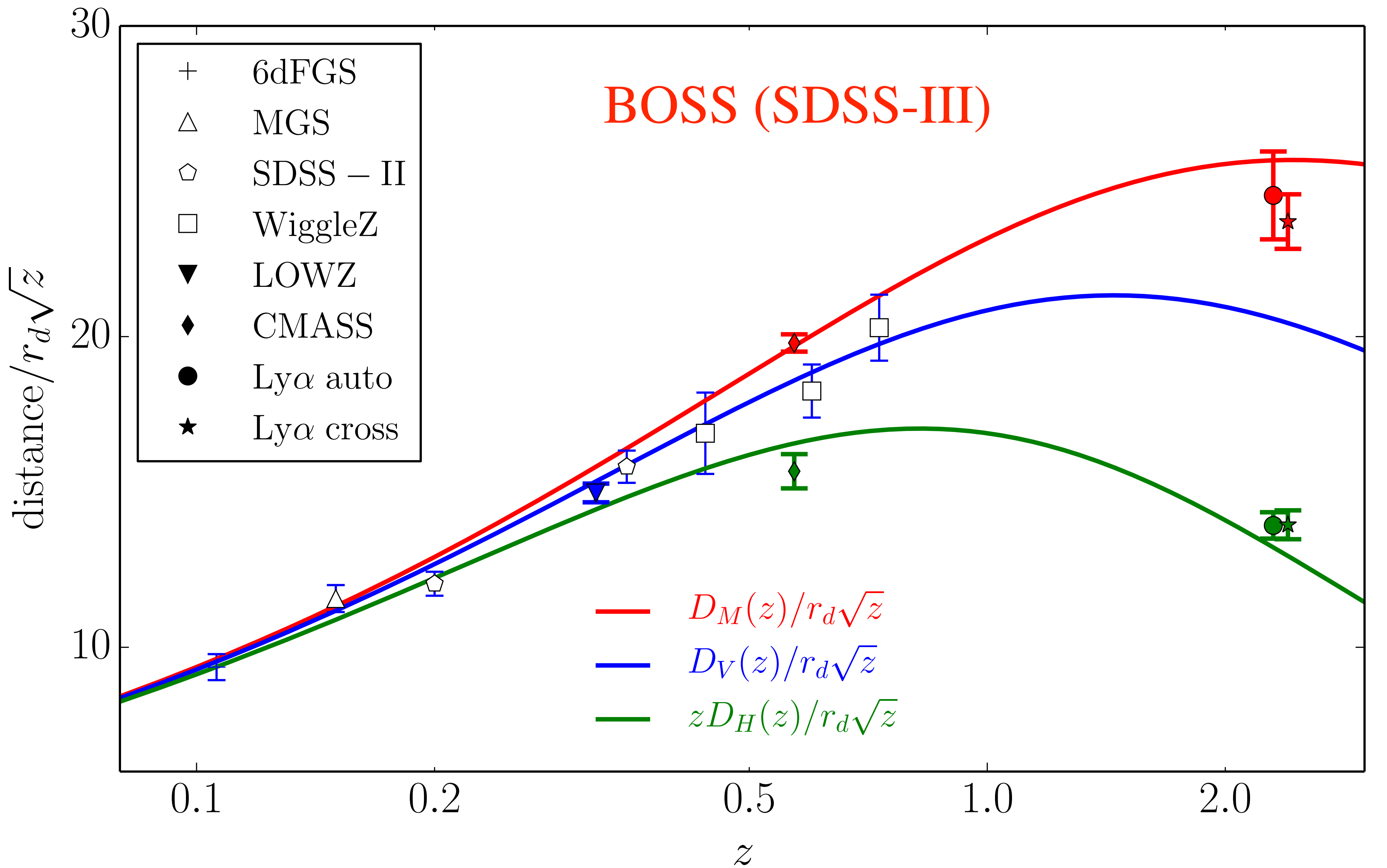


FIG. 3.— Derivatives of $f(z)$, $E = H(z)/H_0$, and $D_A(z)$ with respect to the modified growth and equation of state parameters. The D_A curves have been rescaled by a factor of $2H_0/c$.

From Extending Tests of General Relativity with SKA ,
P. Bull arXiv: 1509.07562

BAO Hubble diagram

Aubourg et al. arXiv:1411.1074



Transverse measurement $D_M(z)/r_d = \alpha_\perp D_{M,\mathrm{fid}}(z)/r_{d,\mathrm{fid}}$.

$D_H(z) = c/H(z)$,

Radial measurement

$D_H(z)/r_d = \alpha_\parallel D_{H,\mathrm{fid}}(z)/r_{d,\mathrm{fid}}$

$D_V(z) = \left[zD_H(z)D_M^2(z)\right]^{1/3}$,

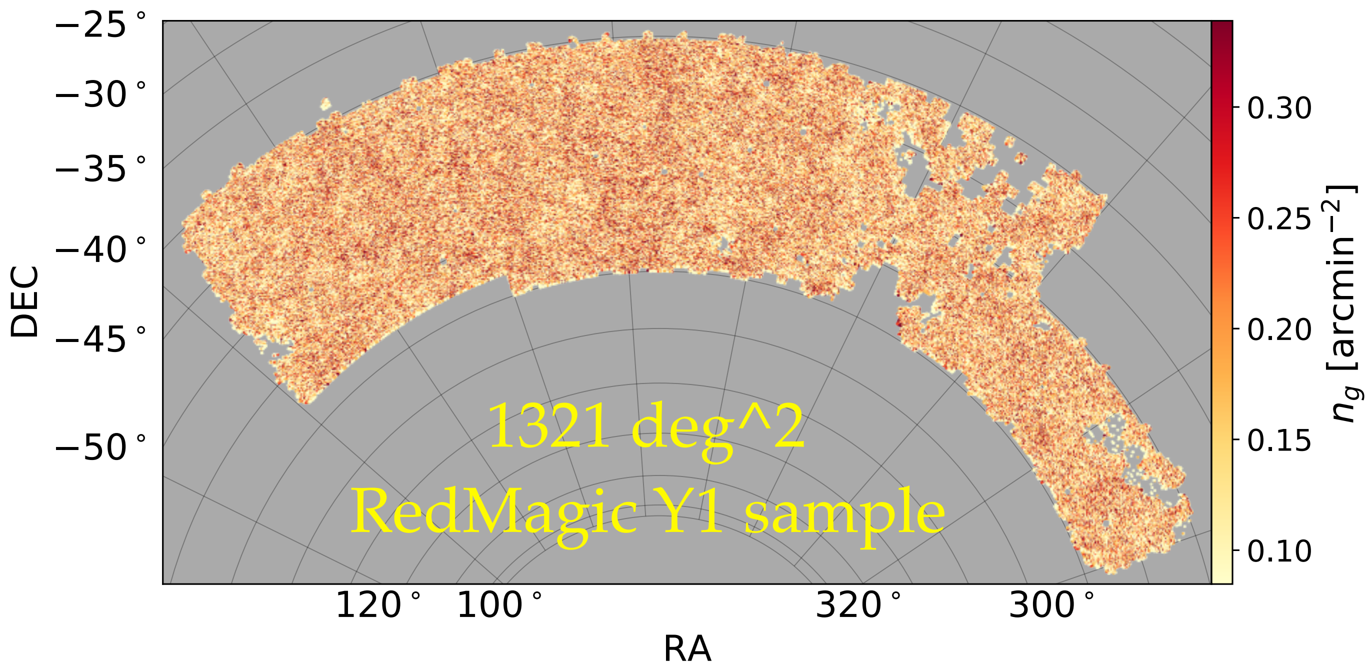
Combined

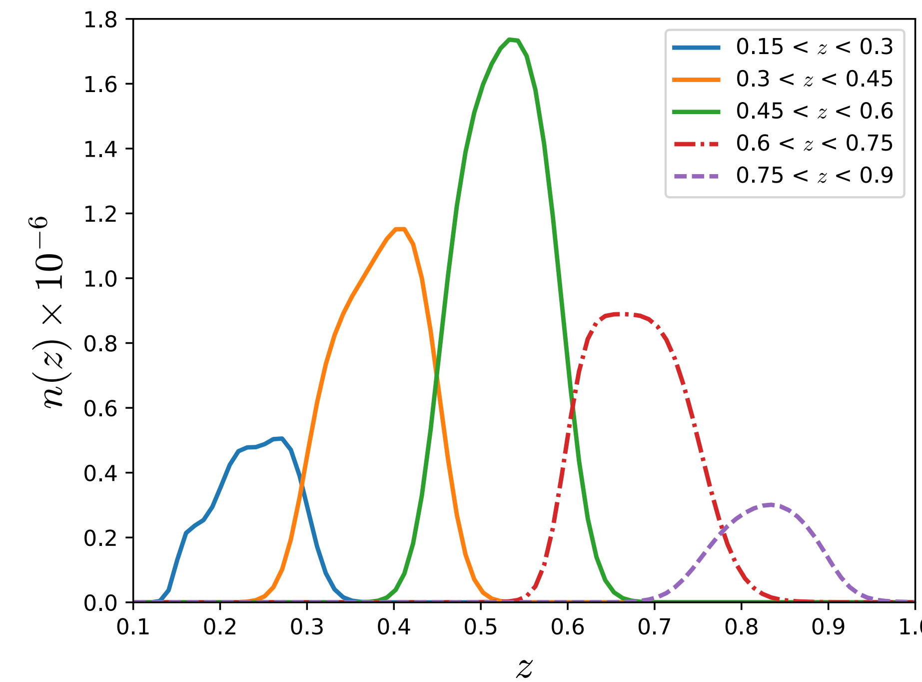
$D_V(z)/r_d = \alpha D_{V,\mathrm{fid}}(z)/r_{d,\mathrm{fid}}$.

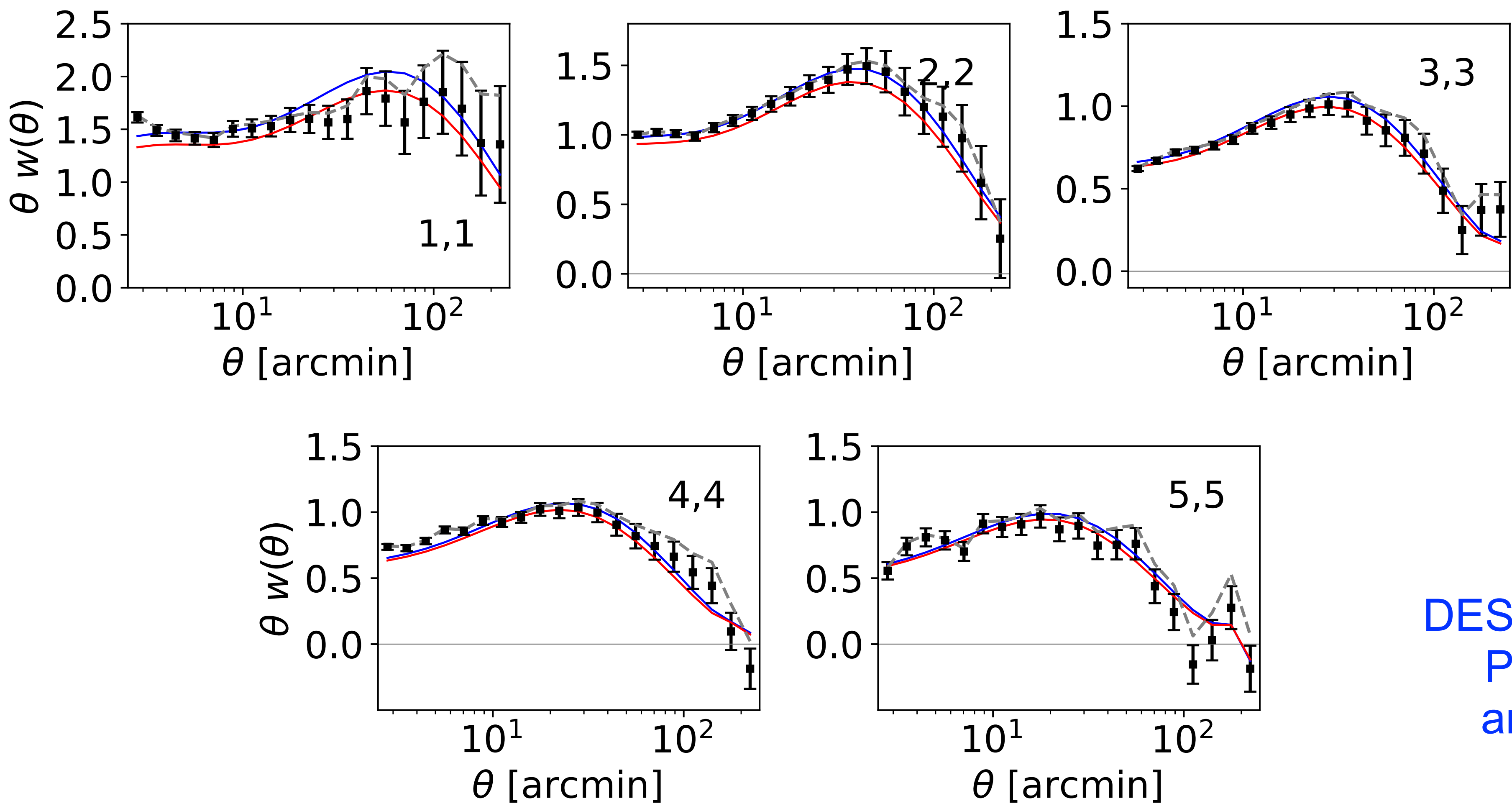
Dark Energy Survey Year 1 Results: Galaxy clustering for combined probes

J. Elvin-Poole,[1] M. Crocce,[2] A. J. Ross,[3] T. Giannantonio,[4,5,6] E. Rozo,[7] E. S. Rykoff,[8,9] S. Avila,[10,11] N. Banik,[12,13] J. Blazek,[14,3] S. L. Bridle,[1] R. Cawthon,[15] A. Drlica-Wagner,[12] O. Friedrich,[6,16] N. Kokron,[17,18] E. Krause,[9] N. MacCrann,[3,19] J. Prat,[20] C. Sánchez,[20] L. F. Secco,[21] I. Sevilla-Noarbe,[10] M. A. Troxel,[3,19]

DES - Y1 clustering results





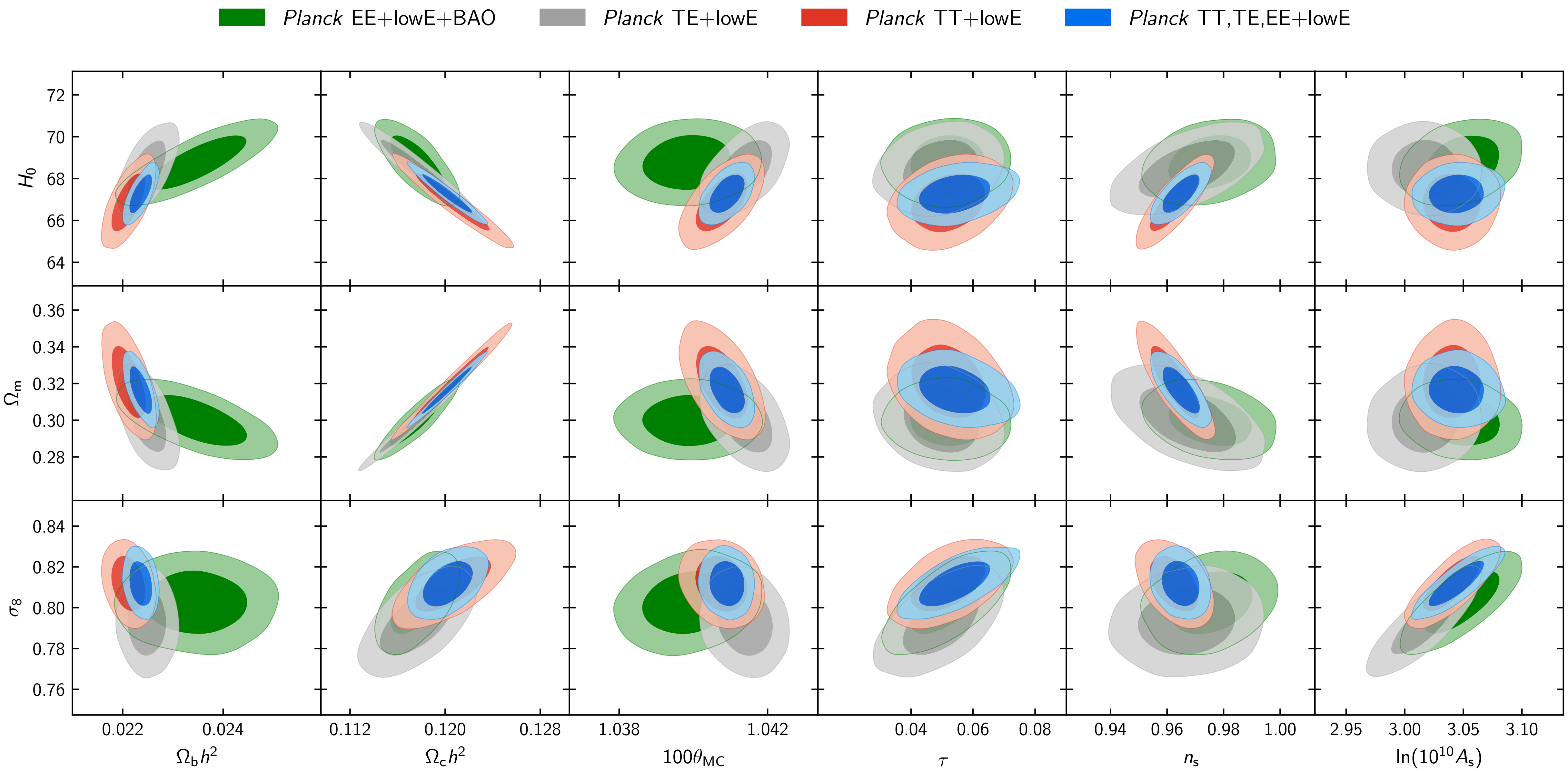


DES , Elvin-Poole et al,
Phys.Rev.D 2018,
arXiv:1708.01536

Planck 2018 results. VI. Cosmological parameters

Planck Collaboration: N. Aghanim[54], Y. Akrami[15,57,59], M. Ashdown[65,5], J. Aumont[95], C. Baccigalupi[78], M. Ballardini[21,41], A. J. Banday[95,8],

Planck-2018



$$\Omega_b h^2 = 0.02237 \pm 0.00015$$ (68 %, *Planck* TT,TE,EE +lowE+lensing).

$$\Omega_c h^2 = 0.1200 \pm 0.0012$$ (68 %, *Planck* TT,TE,EE +lowE+lensing).

$$\tau = 0.0544^{+0.0070}_{-0.0081}$$ (68 %, TT,TE,EE+lowE).

$$A_s = (2.101^{+0.031}_{-0.034}) \times 10^{-9}$$ (68 %, TT,TE,EE+lowE).

$$n_s = 0.9649 \pm 0.0042$$

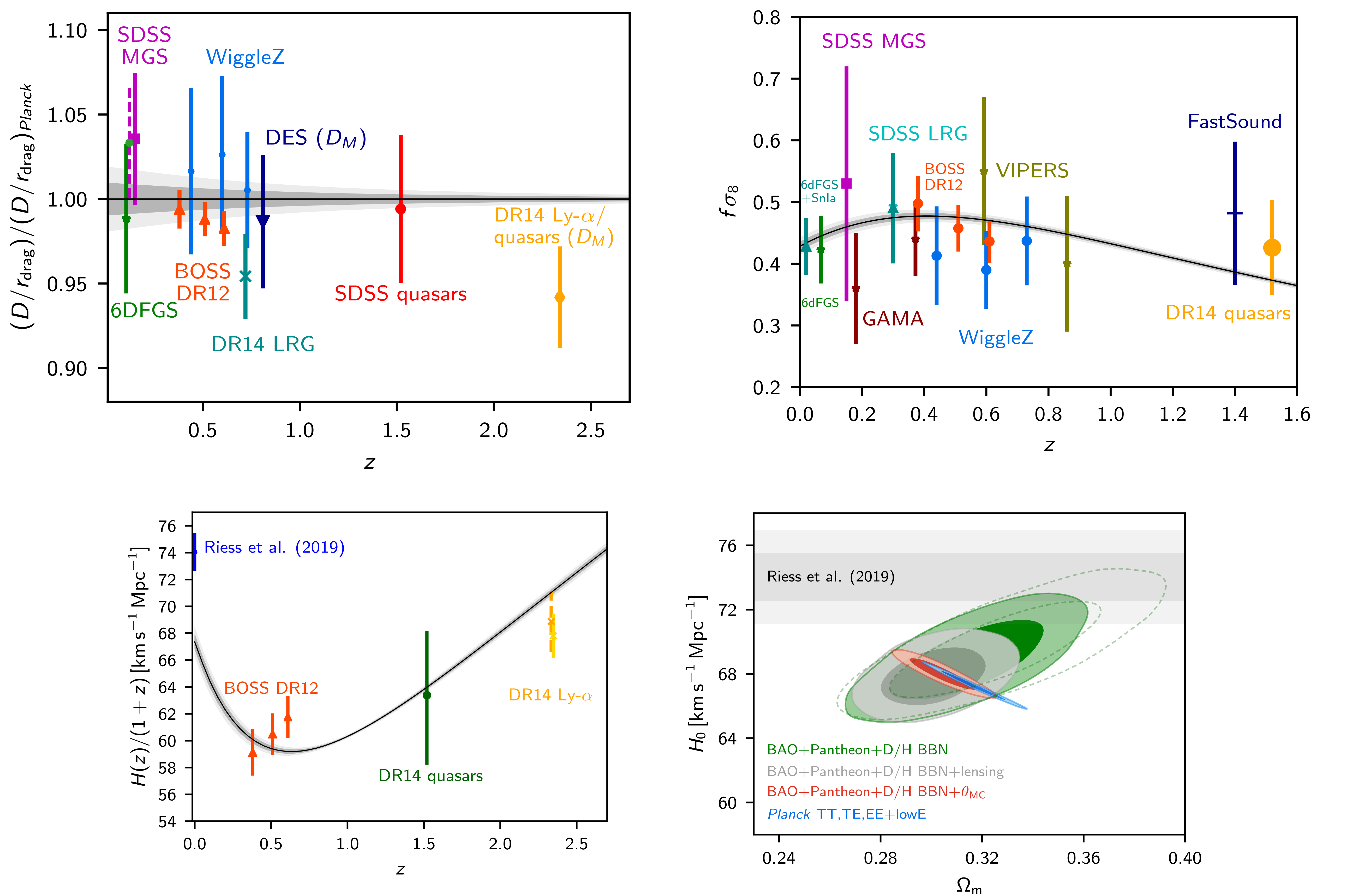
$$\Omega_\Lambda = 0.6847 \pm 0.0073$$ (68 %, TT,TE,EE+lowE+lensing).

$$\left.\begin{array}{l} H_0 = (67.27 \pm 0.60)\ \mathrm{km\ s^{-1} Mpc^{-1}}, \\ \Omega_m = 0.3166 \pm 0.0084, \end{array}\right\}$$ 68 %, TT,TE,EE +lowE.

$$\sigma_8 = 0.8111 \pm 0.0060$$ (68 %, *Planck* TT,TE,EE+lowE +lensing).

Planck Coll. A&A 2020 , arXiv:1807.06209

Planck-2018 Cosmological parameters (II)



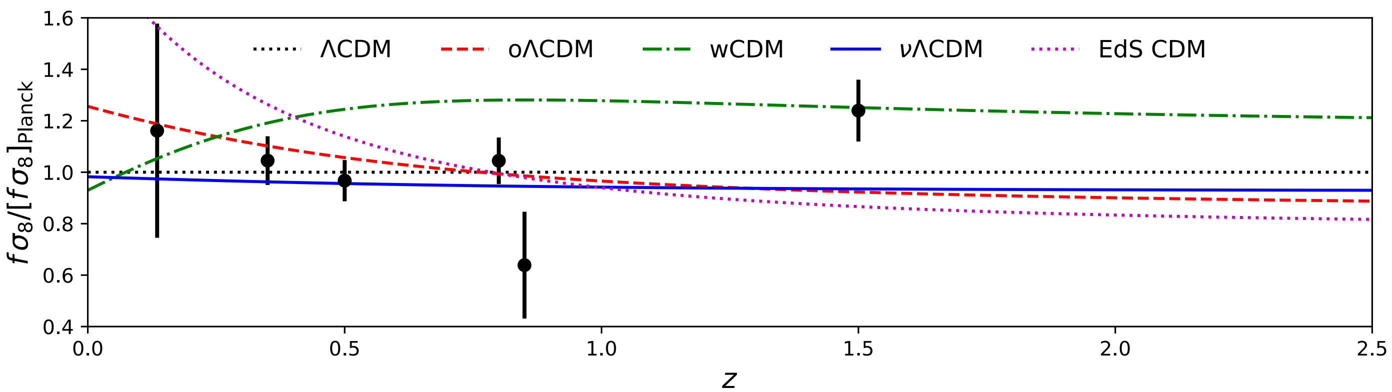
Planck Coll. A&A 2020 , arXiv:1807.06209

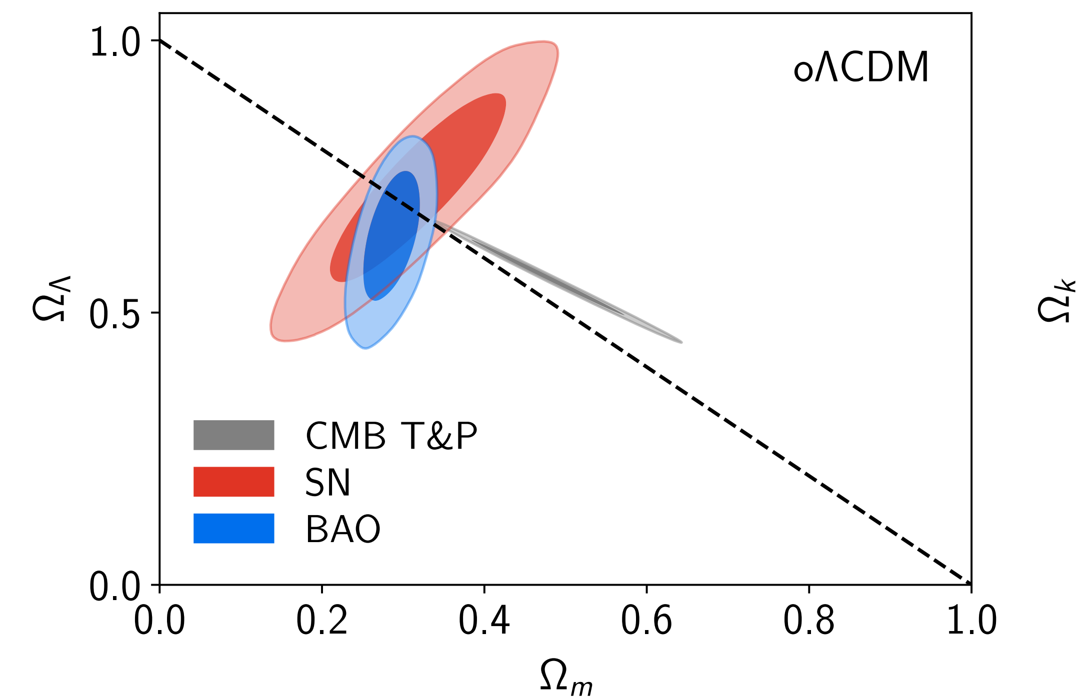
Submitted to *Physical Review D*
Preprint typeset using LaTeX style emulateapj v. 01/23/15

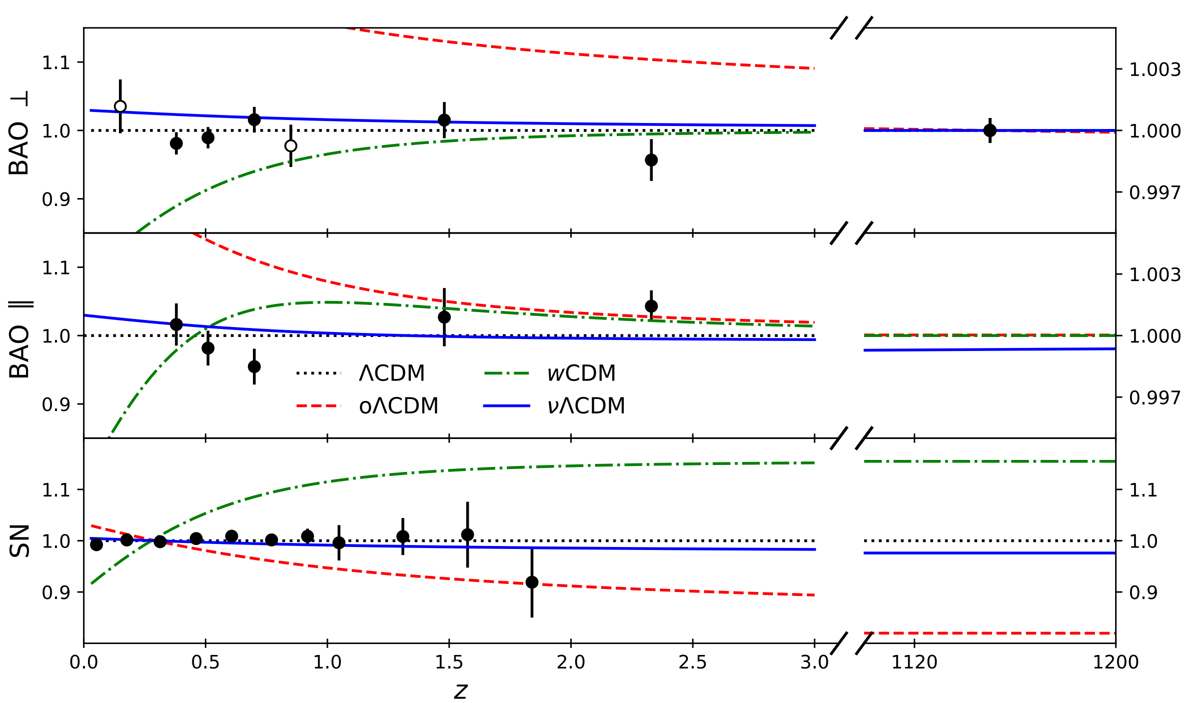
eBOSS / SDSS-IV final cosmological constraints

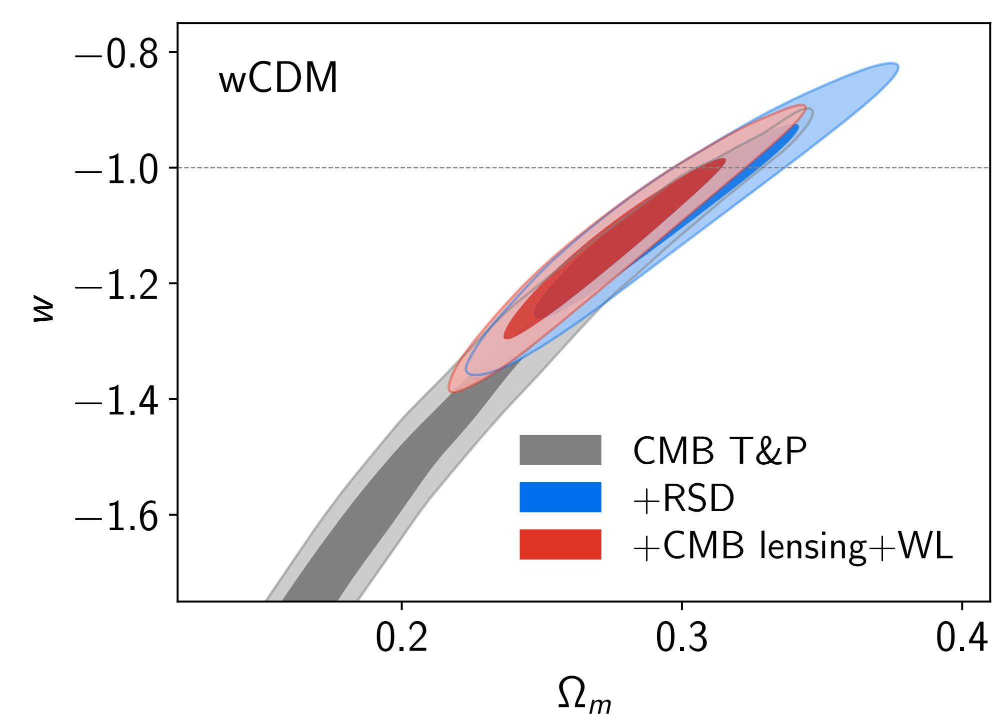
THE COMPLETED SDSS-IV EXTENDED BARYON OSCILLATION SPECTROSCOPIC SURVEY: COSMOLOGICAL IMPLICATIONS FROM TWO DECADES OF SPECTROSCOPIC SURVEYS AT THE APACHE POINT OBSERVATORY

Shadab Alam[1], Marie Aubert[2], Santiago Avila[3,4], Christophe Balland[5], Julian E. Bautista[6], Matthew A. Bershady[7,8,9], Dmitry Bizyaev[10,11], Michael R. Blanton[12], Adam S. Bolton[13,14], Jo Bovy[15,16], Jonathan Brinkmann[10], Joel R. Brownstein[14], Etienne Burtin[17], Solène Chabanier[17], Michael J. Chapman[18,19], Peter Doohyun Choi[20], Chia-Hsun Chuang[21], Johan Comparat[22], Andrei Cuceu[23], Kyle S. Dawson⋆[14], Axel de la Macorra[24], Sylvain de la Torre[25], Arnaud de Mattia[17], Victoria de Sainte Agathe[5],



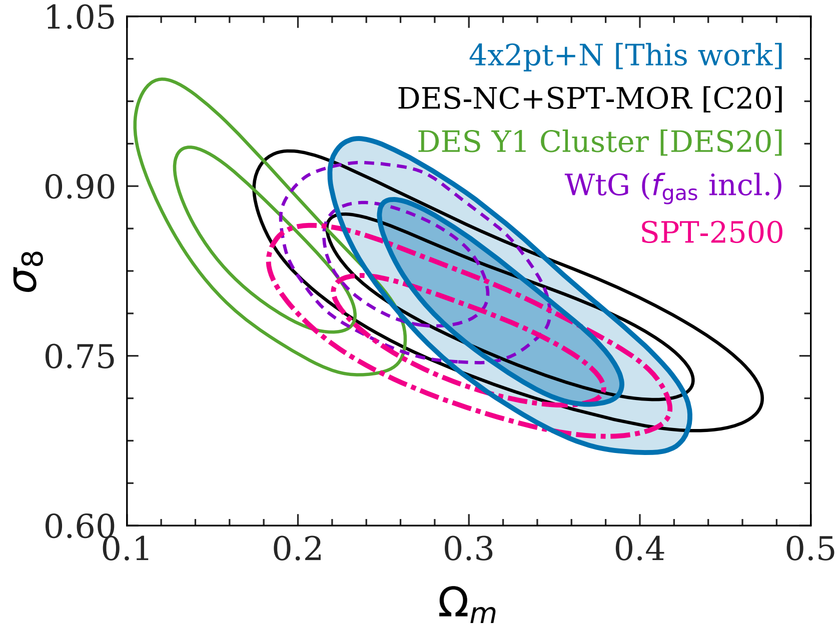


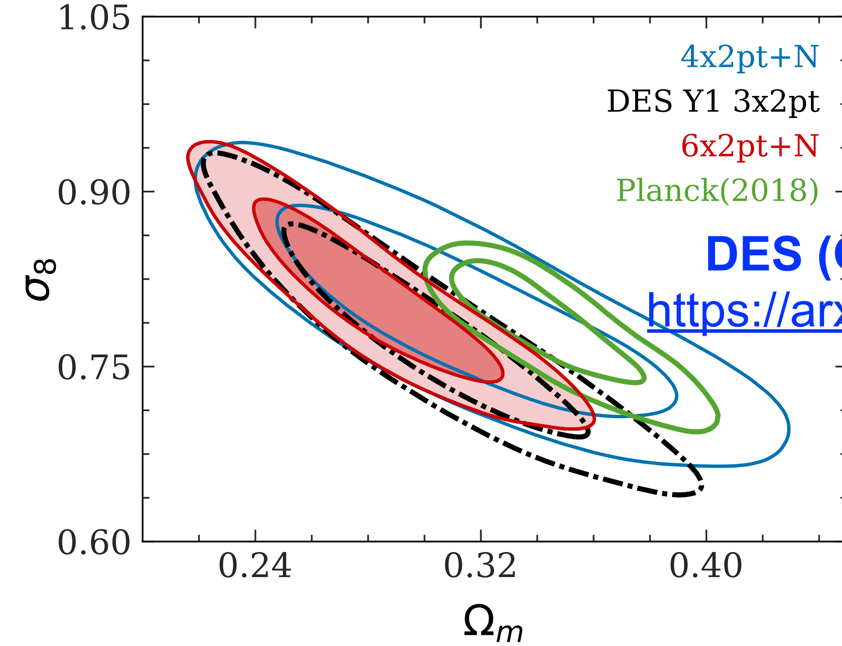




eBOSS 2020 , Alam et al, Phys.Rev.D 2020, arXiv:2007.08991

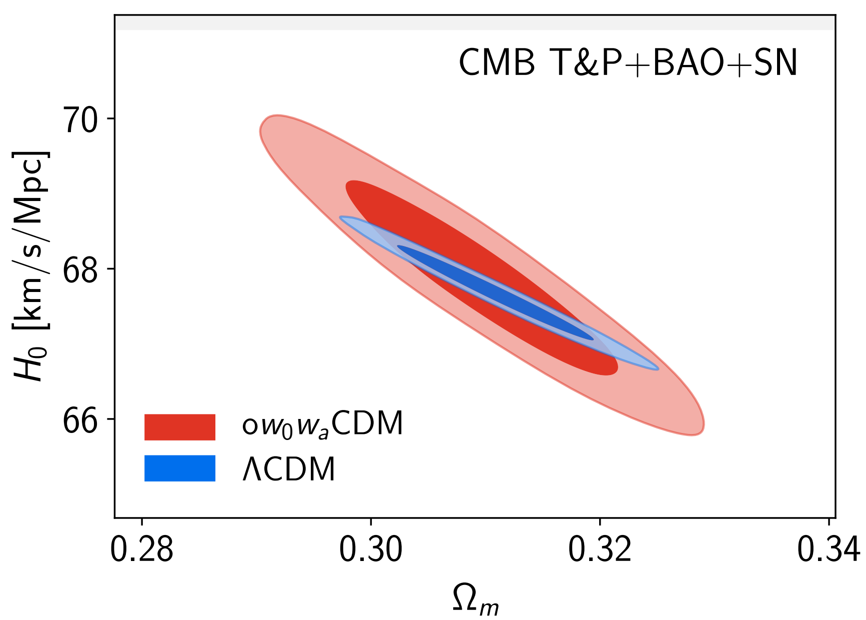
Planck, DES , eBOSS ...

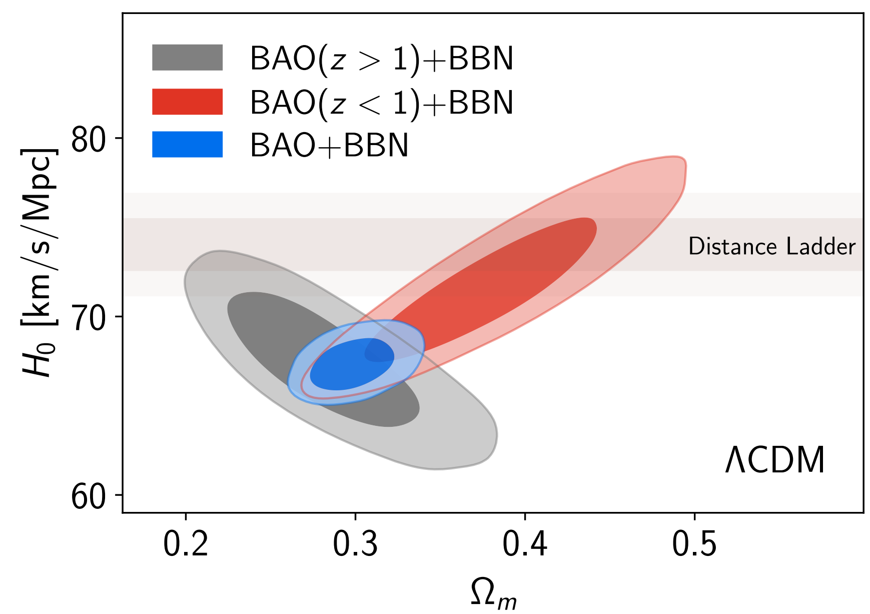




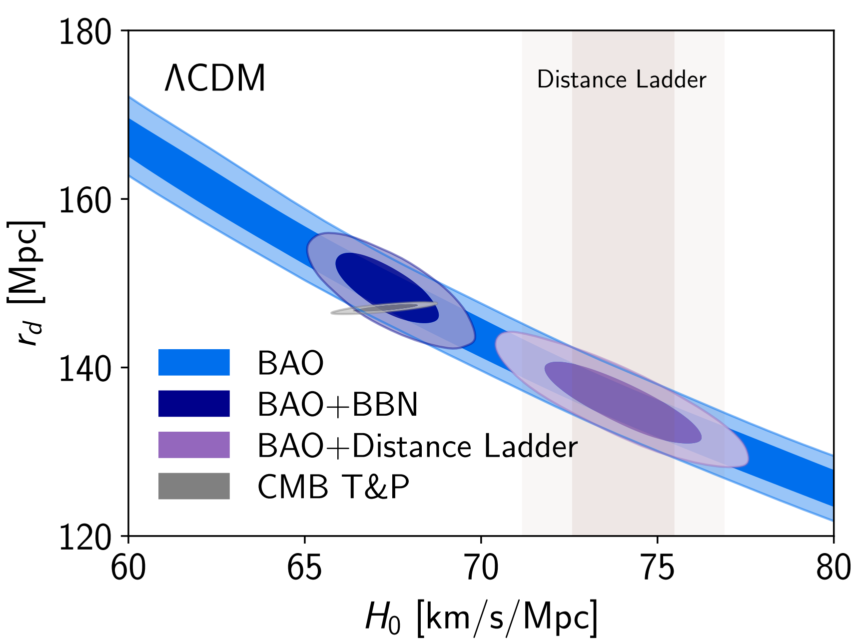
DES (Galaxy, WL, Clusters)

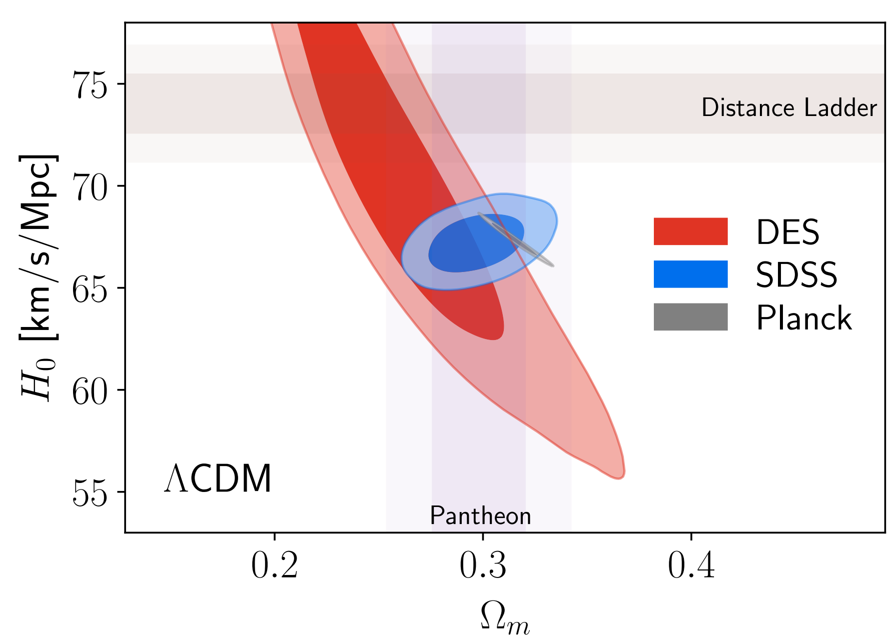
https://arxiv.org/pdf/2010.01138.pdf





Hubble parameter H_0





eBOSS 2020 , Alam et al, Phys.rev.D 2020, arXiv:2007.08991

Optical surveys
LSST

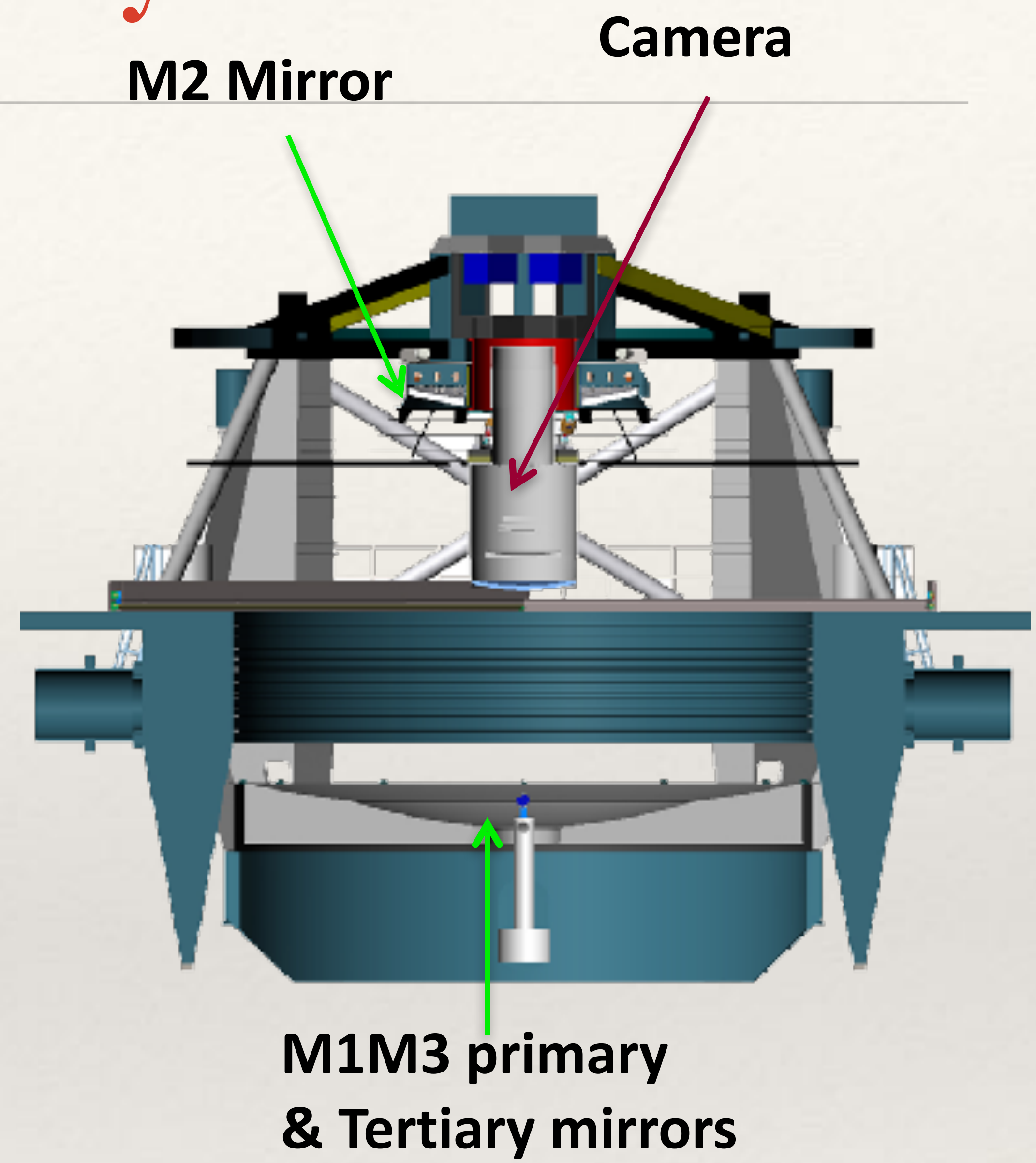
LSST Science Book - https://www.lsst.org/scientists/scibook

Ivezic et al. , ApJ 2019 , arXiv:0805.2366


Vera C Rubin Observatory
LSST (Legacy Survey of Space and Time)
Wide … Fast … Deep

Rubin Observatory / LSST

- Optical telescope **8.4 m diameter**
- Wide-field camera : **3.5°, 3.2 Gpixels**
- 6 wide-band filters **u g r i z y**
- Galaxies: r_{lim}=27.5 after 10 year coadd.
- Final catalogue: **10^{10} galaxies, 10^{10} stars**
- Final database **15 PetaBytes**
- Weak lensing up to **z ~ 3**
- 2,500,000 SNIa up to **z ~ 1**
- BAO: 3.10^9 galaxies up to **z ~ 3**
- Transients with alerts (**2.10^6/night**)
- See LSST science-book in **http://www.lsst.org**
  - Points to new positions in the sky every 39 seconds (average)
  - Tracks during exposures and slews 3.5° to adjacent fields in ~ 4 s



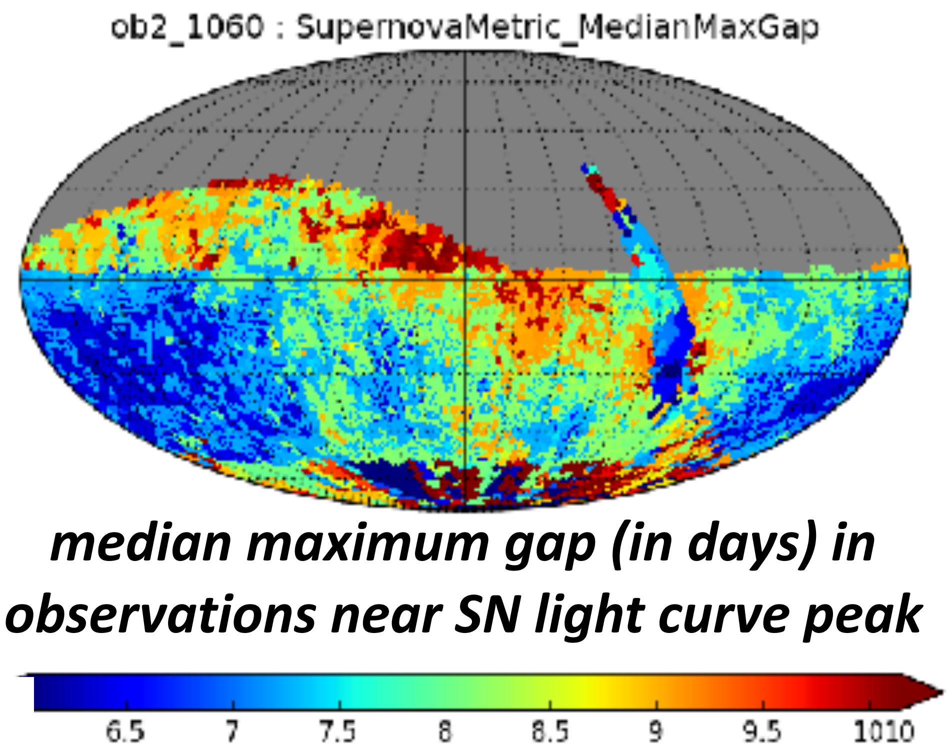
http://www.lsst.org/

VERA C. RUBIN OBSERVATORY

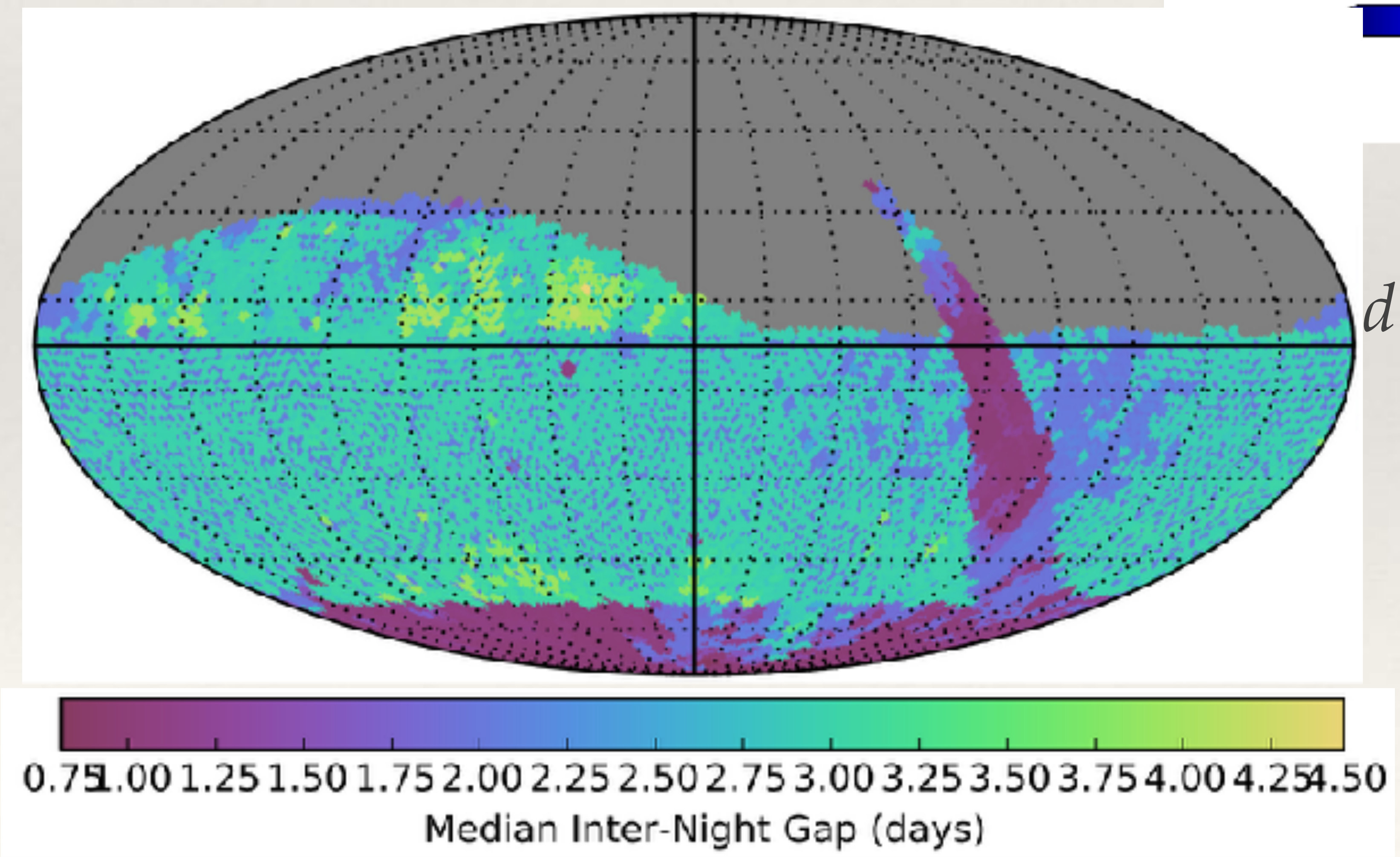
LSST "mission"

« 4D » object mapping (stars, galaxies…) of 18,000 sq. deg. to an uniform depth

- (α,δ) positions on the sky
- Photometric redshifts z
- Time variations
  - -> SN, lensing, AGN…



median maximum gap (in days) in observations near SN light curve peak



d

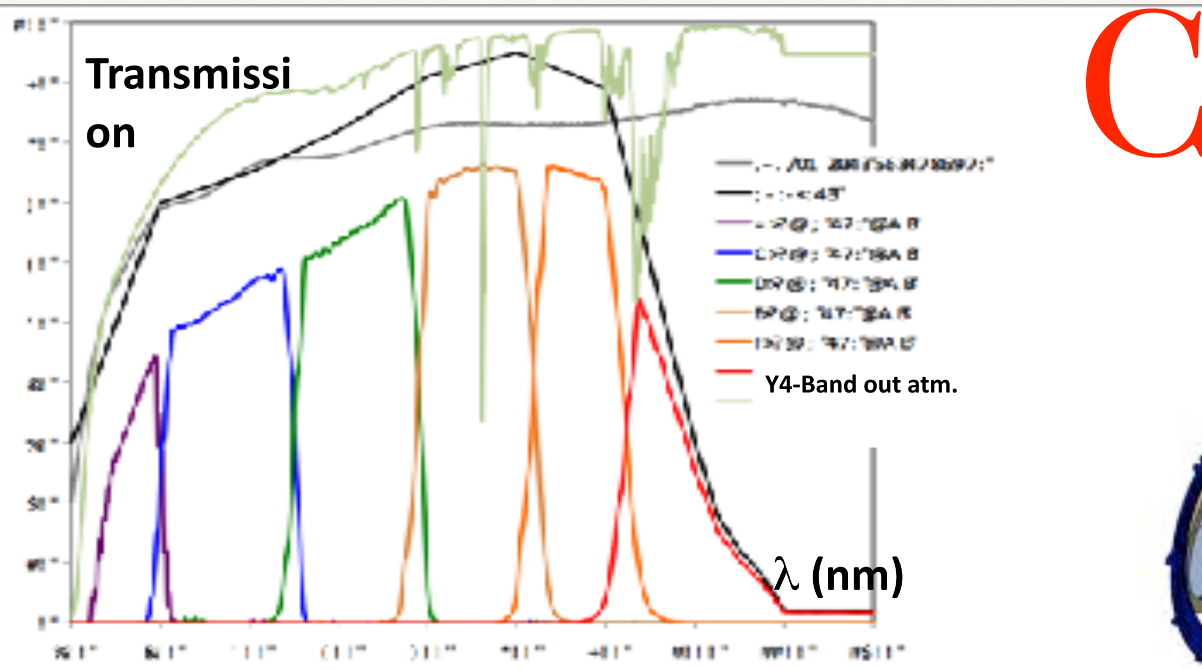
Other survey modes

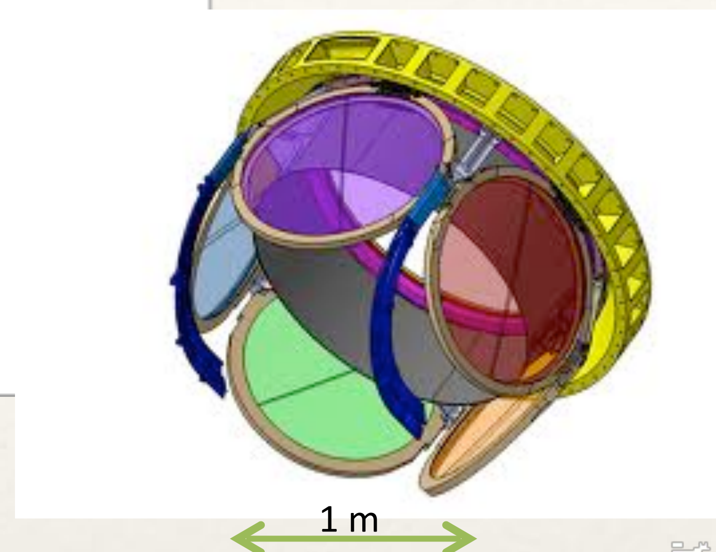
~10% of time ~1h/night

Very Deep + fast time domain + special zones

(ecliptic, galactic plane, Magellanic clouds)

Camera

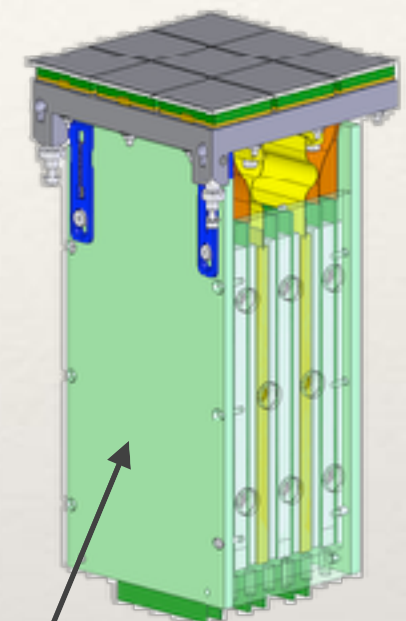


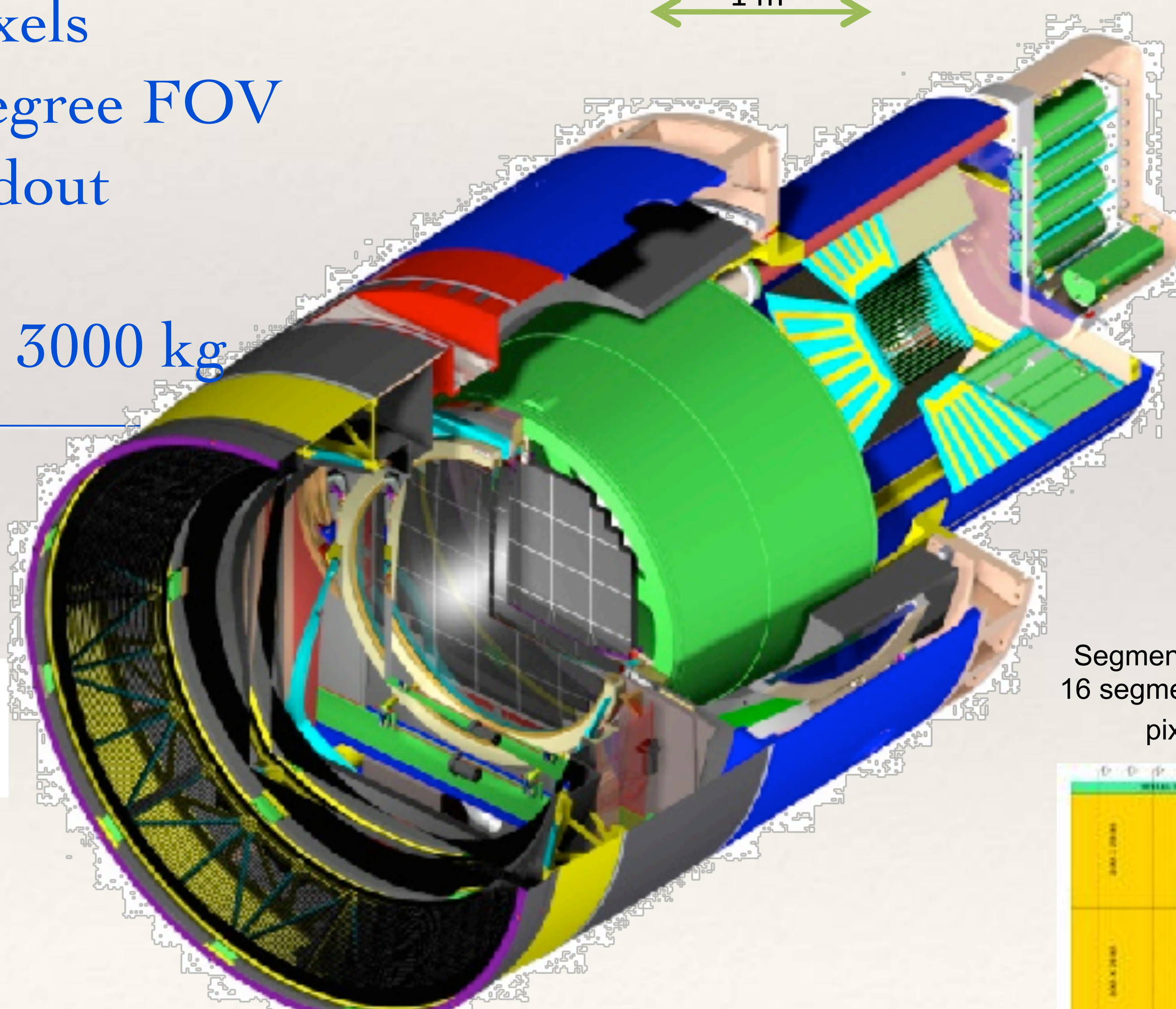


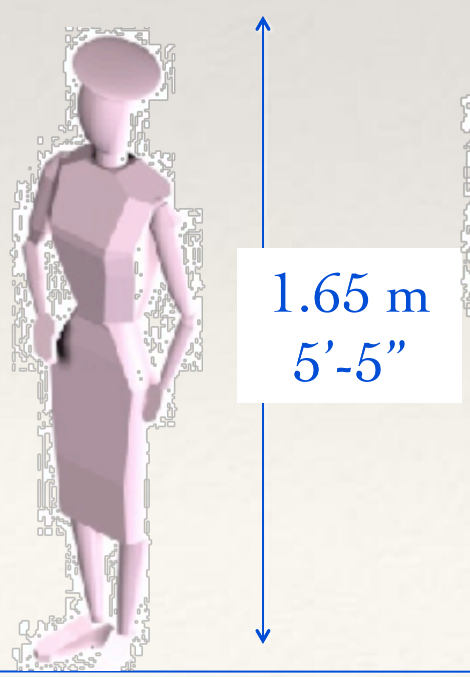
189 Science CCD
4000 X 4000 10μm pixels

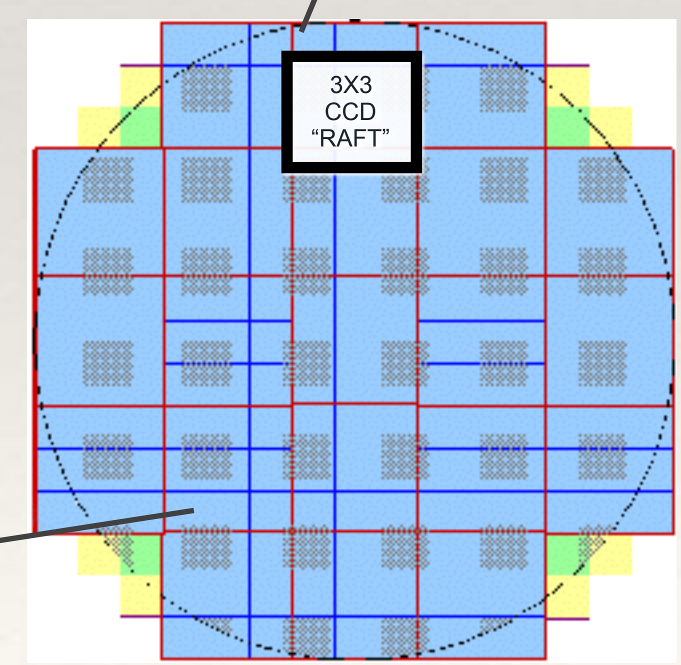
- 3.2 Gigapixels
- 0.2 arcsec pixels
- 9.6 square degree FOV
- 2 second readout
- 6 filters
- 1.65mx3.7m, 3000 kg

A raft
3x3 CCD
144 MPixels

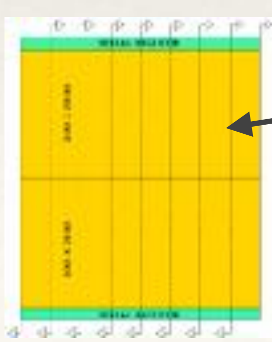






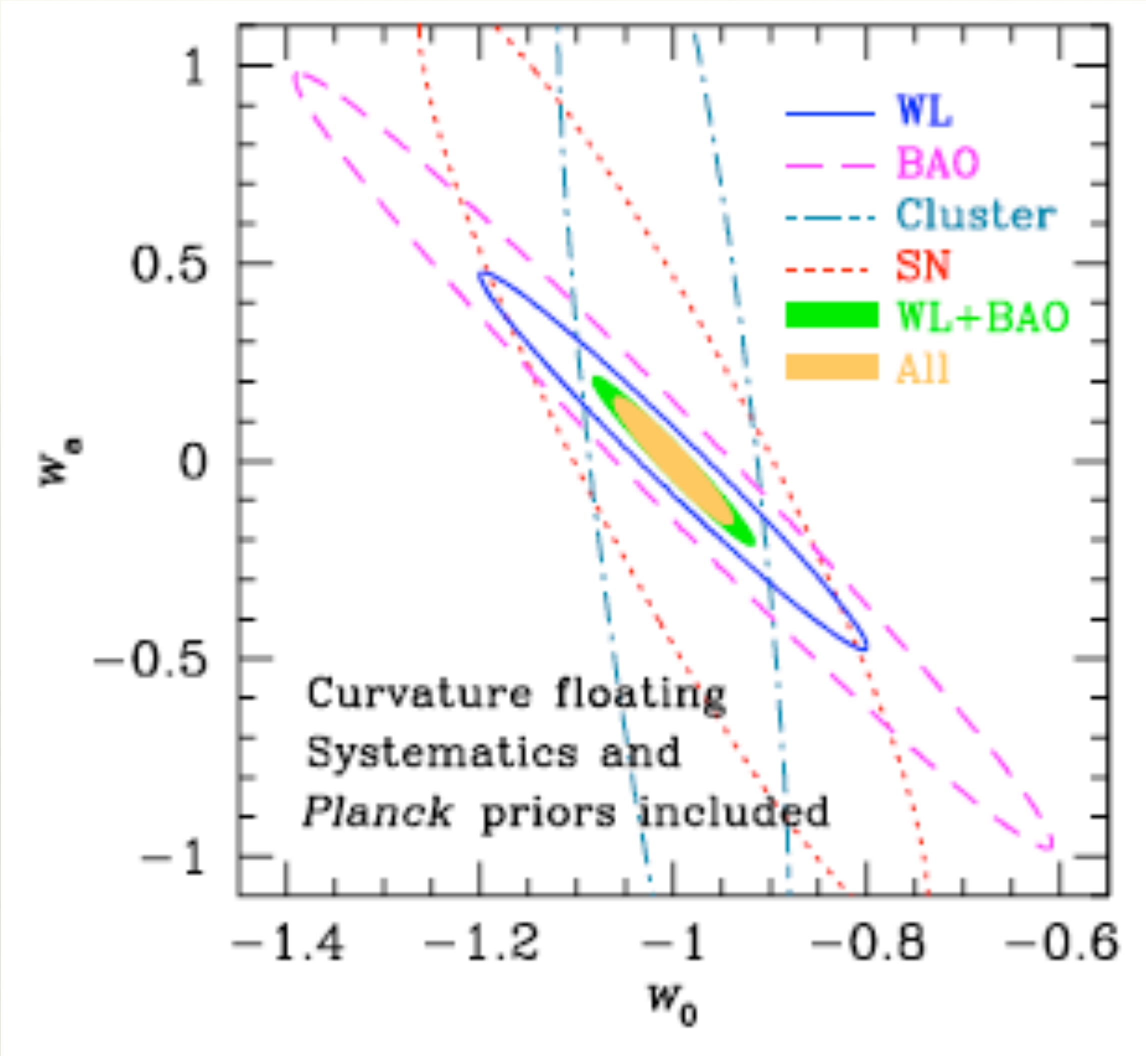


Segmented CCD
16 segments of 1M
pixels

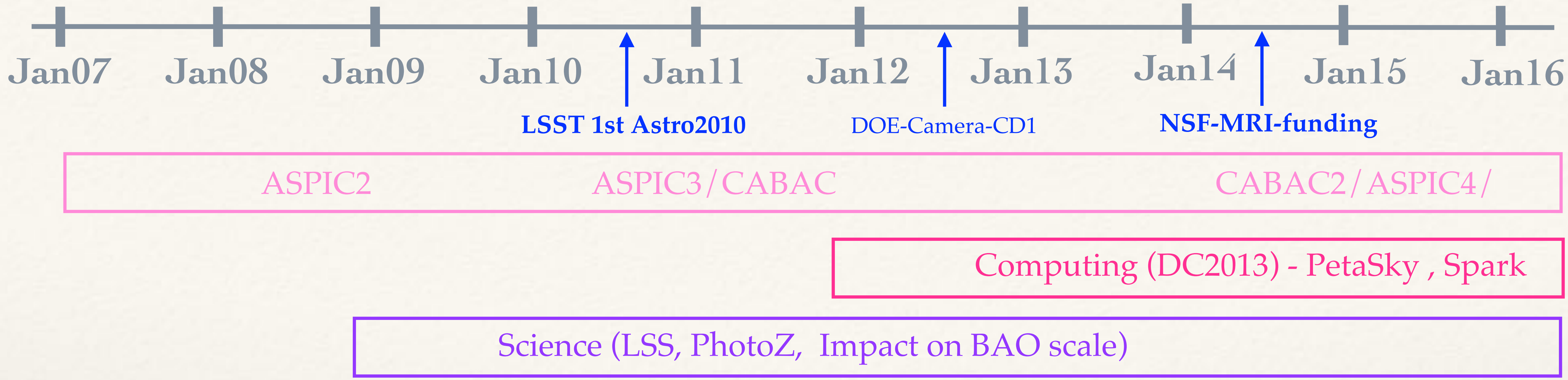


The Science Enabled by LSST

- **Time domain science**
  - Nova, supernova, GRBs
  - Source characterization
  - Gravitational microlensing
  - Interstellar scintillation
- **Finding moving sources**
  - Asteroids and comets
  - Proper motions of stars
- **Mapping the Milky Way**
  - Tidal streams
  - Galactic structure
- **Dark energy and dark matter**
  - Gravitational lensing (strong/weak)
  - LSS x WL
  - Clusters
  - SN
  - …



LSST Science Book - https://www.lsst.org/scientists/scibook



- 2007: LAL, founding member of french LSST consortium with LPNHE&APC
- 2007-2009 : R&D in electronic (ASPIC1-ASPIC2 …)
- 2009- … : Science activities , Photometric redshifts and impact on LSS & BAO
- *Aug. 2010 : LSST ranked first in the US Astro2020 decadal survey* - https://www.lsst.org/sites/default/files/docs/NAS_pr_8-10.pdf
- *Oct. 2012 : CS-IN2P3 approval on the french side*
- *April 2014 : LSST NSF-MRI funding / official construction started* - https://www.lsst.org/enews/issue/volume-7-number-3
- 2012- : LSST-computing activities , DC2013 , Sparc R&D
- 2014-2015 : CABAC2 , **ASPIC** 4
- 2016 : 1500 ASPIC-4 tested and delivered to SLAC (end of 2016-early 2017))
- 2015 : Calibration and impact of atmosphere
- 2017 : **Holospec** , holographic disperser for AuxTel, Sparc R&D
- 2019 : **Fink** broker initiative

Jan14 Jan15 Jan16 Jan17 Jan18 Jan19 Jan20 Jan25 Jan30

Construction

Camera Tests @SLAC

First light ~ 2021 ?

2023 - 2033 Survey

Covid delay

Electronic (**ASPIC**/Cabac)

Calibration/Atmosphere - **Holospec**

LSS/AngPow Microlensing CNN/ML Computing / DC

Spark R&D **Fink**

R. Ansari, G. Blanc, *T. Blaineau*, J.E. Campagne, S. Dagoret-Campagne, M.Moniez, J. Neveu, O. Perdereau, S. Plaszczynski ,
A. Abate, F. Habibi

Electronics

C. de la Taille
V. Tocut
P. Barillon
J. Jeglot
P. Vallerand
F. Wicek

Computing

C. Arnault
G. Barrand
J.N. Albert
J. Peloton

PhotoZ & BAO's (I)

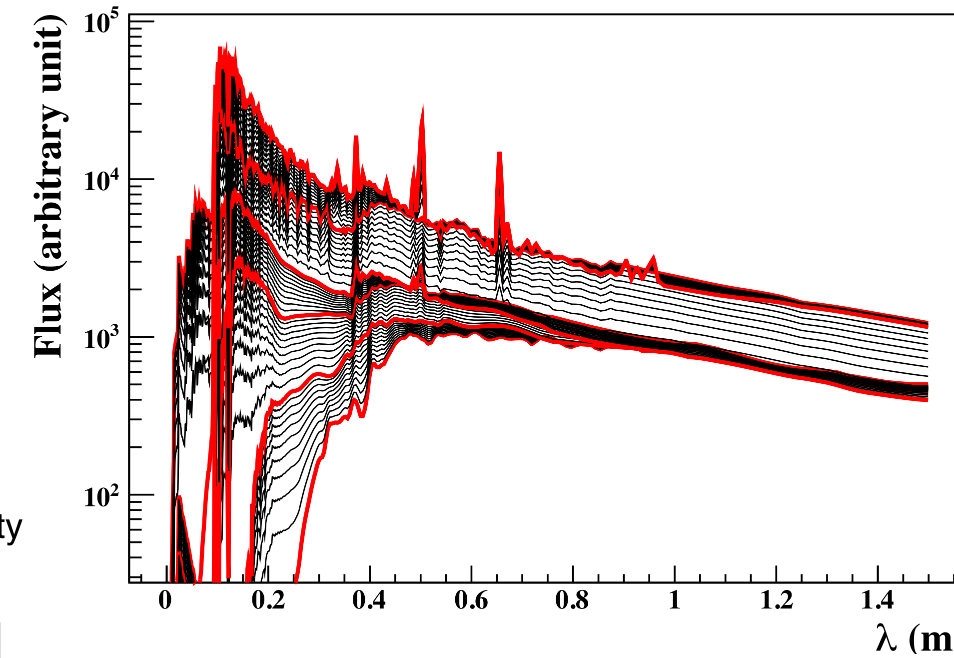
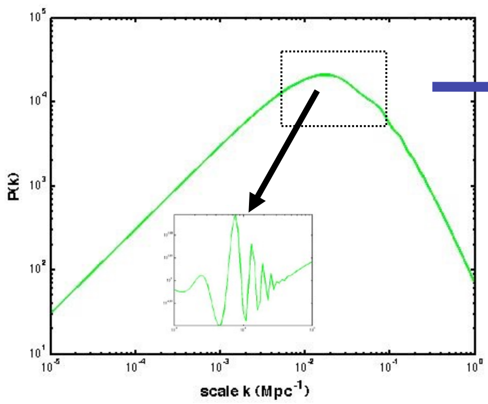


Fig. 1. SED templates are linearly interpolated from the nal six templates from Coleman et al. (1980) and Kinne (1996). The original templates are drawn in red.

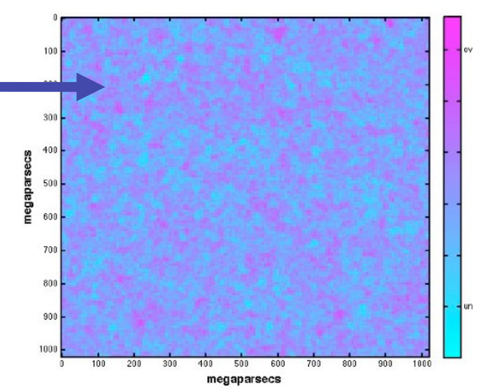
A complete galaxy photometric catalog simulation and analysis pipeline

SimLSS

Assume cosmology -> matter power spectrum

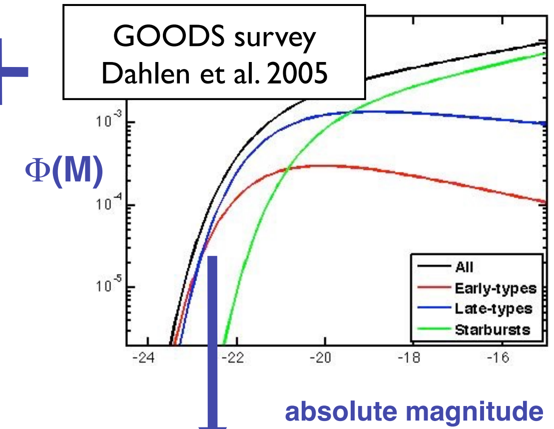


Generate 3D cuboid volume of over-densities



+

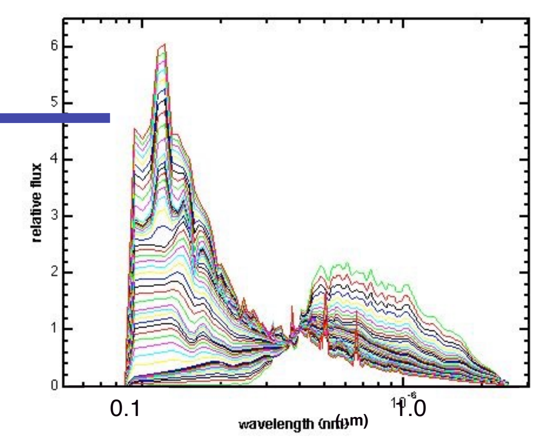
Observed galaxy luminosity functions by type



ObsSim

- Using SED+absolute magnitude compute reverse K-correction
- Calculate apparent magnitude observed through each LSST filter

Have catalogue of galaxy observations



+

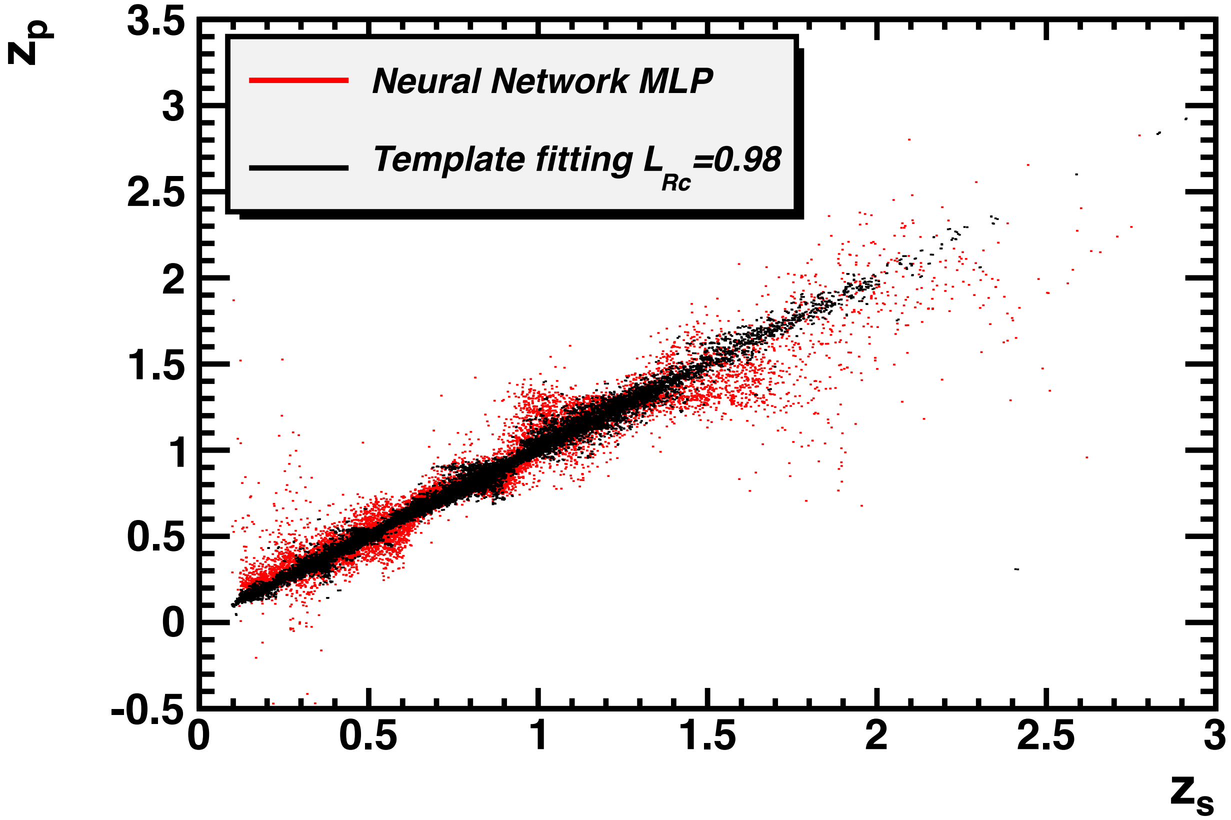
- Integrate total Φ(M): relate over-density to number density of galaxies
- Distribute absolute magnitudes according to Φ(M):
- Distribute galaxy types according to relative Φ(M)'s

GalSim

Gorecki A. et al, A&A 2014 , arXiv:1301.3010

Ansari R. et al, A&A 2019 , arXiv:1902.03004

PhotoZ & BAO's (II)



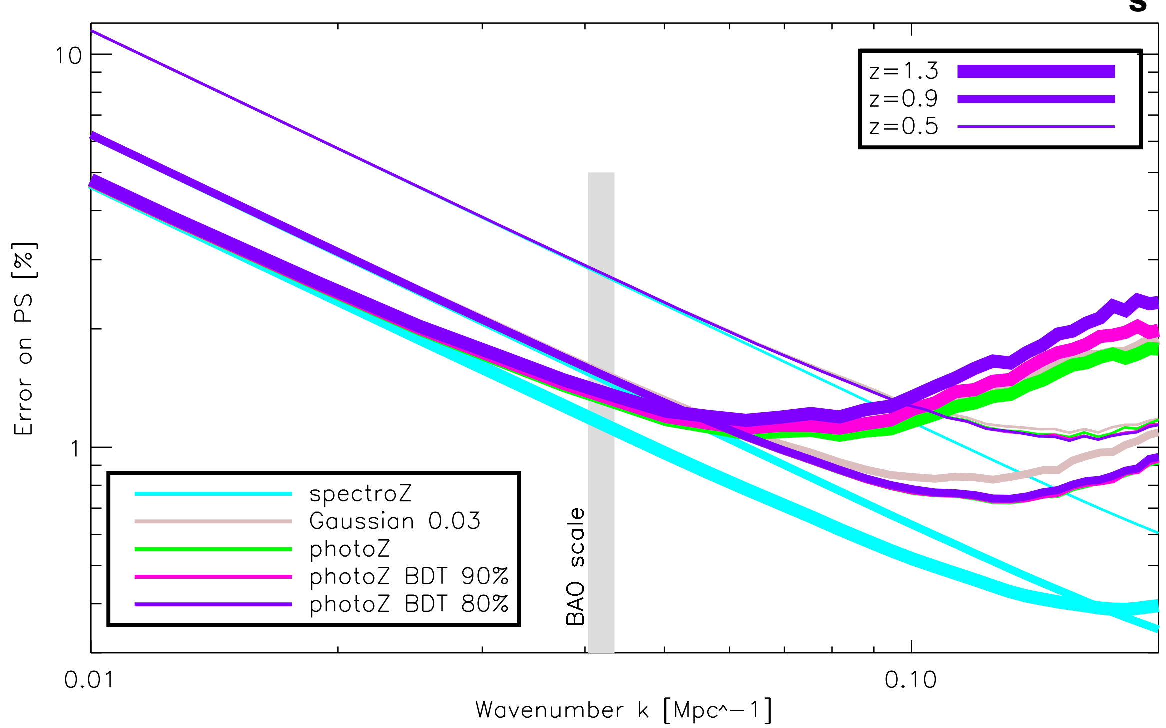
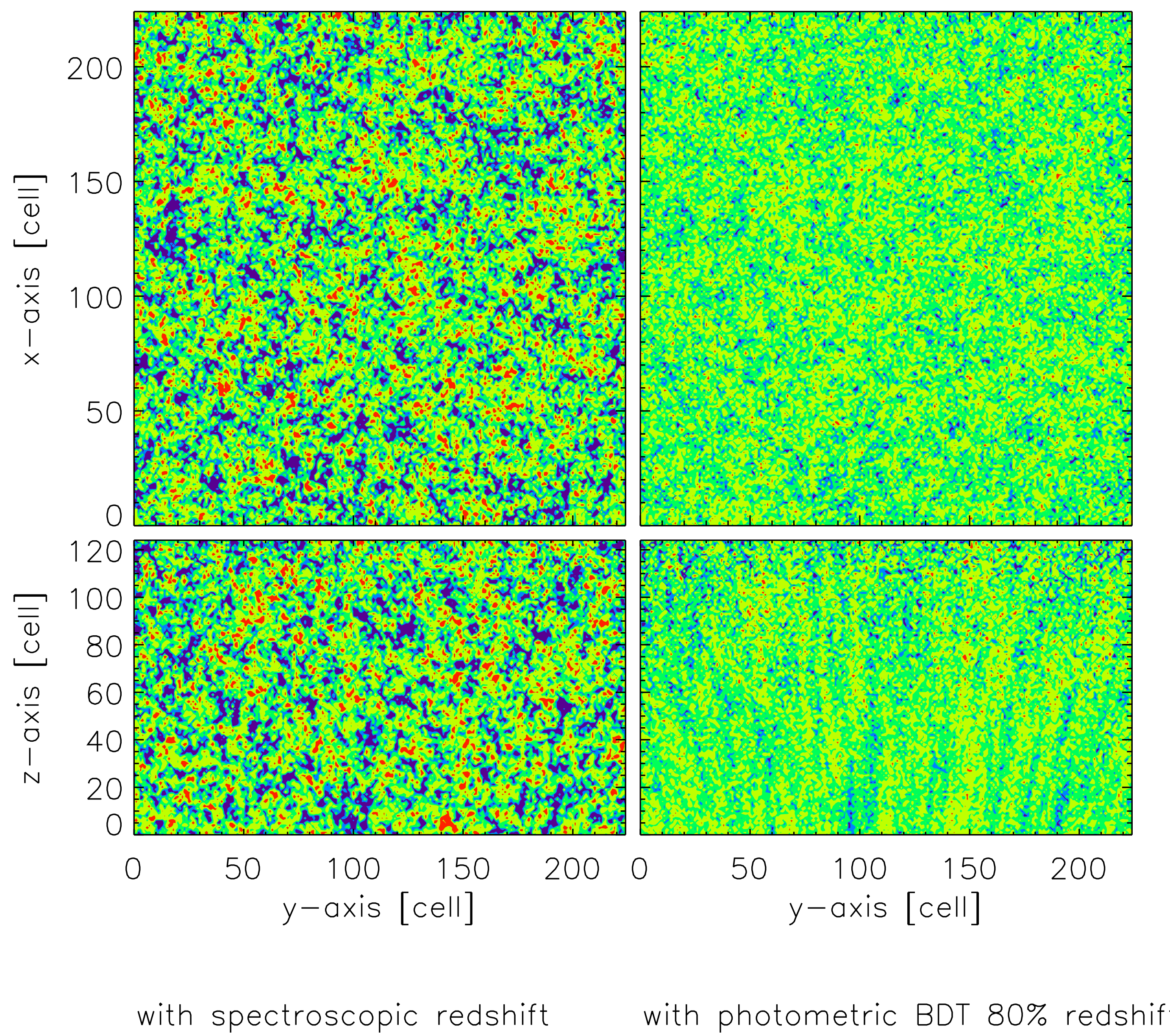


Fig. 10. Fractional statistical error $\sigma_P/P(k)$ of the recovered power spectra P_D in percent. Colors identify the different redshift error models, while the grid redshifts are distinguished by different line thicknesses. The light gray area shows the wave number corresponding to the BAO scale.



Gorecki A. et al, A&A 2014 , arXiv:1301.3010

Ansari R. et al, A&A 2019 , arXiv:1902.03004

AngPow (I)

Angular power spectrum in non-limber approx.

J.-E. Campagne, J. Neveu S. Plaszczynski, arXiv:1701.03592 A&A, 602, A72.

Selection function

$$C_\ell^{\rm thick}(z_1, z_2; \sigma_1, \sigma_2) = \frac{2}{\pi} \iint_0^\infty dz dz'\ W_1(z; z_1, \sigma_1) W_2(z'; z_2, \sigma_2) \int_0^\infty dk\ k^2\ P(k) \Delta_\ell(z,k) \Delta_\ell(z',k)$$

$$C_\ell^{\rm obs}(z_1, z_2) \approx \sum_{p=0}^{N_k-1} \sum_{i=0}^{N_{z_1}} \sum_{j=0}^{N_{z_2}} w_i w_j W(z_i, z_1) W(z_j, z_2) I_\ell(k_p, k_{p+1}; z_i, z_j).$$

$$\int_{k_p^\ell}^{k_{p+1}^\ell} dk\ f_\ell(k; z_i) f_\ell(k; z_j)$$

Calcul de I_ℓ :

« 3C-algo »

- No Limber approximation
- Clenshaw-Curtis Quadrature
- Fast Chebyshev polynomials multiplication
- Intensive use of DCT-I (FFTW)
- C++/OpenMP https://gitlab.in2p3.fr/campagne/AngPow

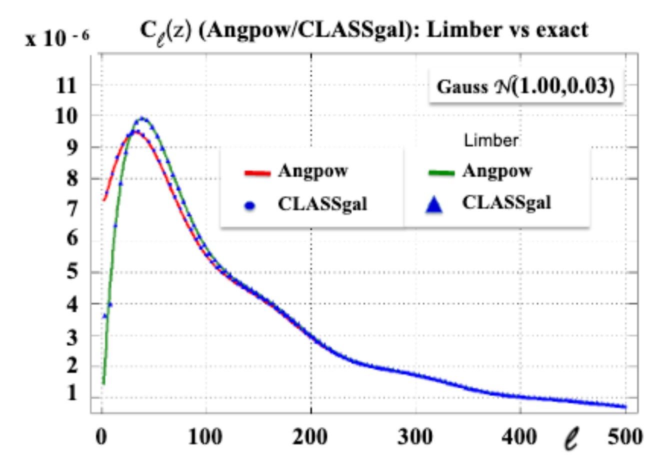


Table 1. Wall time (in seconds) measured at CCIN2P3 (on Intel Xeon CPU E5-2640 v3 processors) for the test benches described in the text, according to the number of OpenMP threads used. Results are given for the intel `icpc 15.0` and `gcc 5.2` compilers.

# Threads	1	2	4	8	16
		Linux/icpc			
Test 1	0.38	0.21	0.13	0.09	0.08
Test 2	0.76	0.41	0.23	0.15	0.11
Test 3	3.72	1.96	1.05	0.64	0.44
Test 4	9.97	5.25	2.79	1.60	1.01
		Linux/gcc			
Test 1	0.56	0.30	0.17	0.12	0.09
Test 2	1.14	0.60	0.33	0.20	0.14
Test 3	5.01	2.59	1.38	0.81	0.50
Test 4	13.80	7.07	3.71	2.12	1.27

Included in CCL v1, then it has been decoupled for new CCL evolution which has been extended keeping Limber approach. Currently, there is a « challenge approach » as a non-limber code is needed.

AngPow (II) : Angular correlation function

Closed form of the 2pts-correlation function

J.-E. Campagne, S. Plaszczynski, J. Neveu arXiv:1703.02818 ApJ, 845, 28.

$$\xi(\theta, z_1, z_2) \approx G(z_1)G(z_2)\frac{1}{2\pi^2}\int \mathrm{d}k\, k^2\, P|_{z=0}(k)$$
$$\times\left\{A(x_1,x_2,\theta) - f_a(z_2)\frac{\partial^2 A}{\partial x_2^2} - f_a(z_1)\frac{\partial^2 A}{\partial x_1^2} + f_a(z_1)f_a(z_2)\frac{\partial^4 A}{\partial x_1^2 \partial x_2^2}\right\}$$

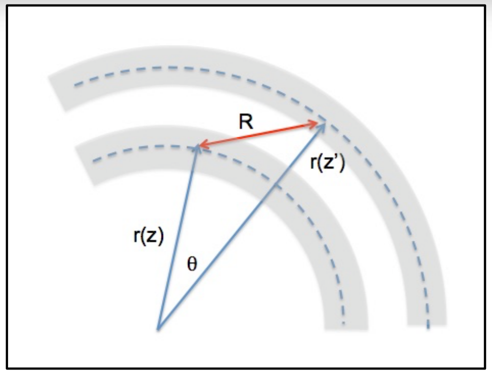
$$x_i = k\, r(z_i)$$

dens² | Dens-Kaiser | Kaiser²

$$A(x_1, x_2, \theta) = \sum_{\ell=0}^{\infty}(2\ell+1)j_\ell(x_1)j_\ell(x_2)P_\ell(\cos\theta) = \mathtt{sinc}\,[R(x_1,x_2,\theta)]$$

Addition theorem

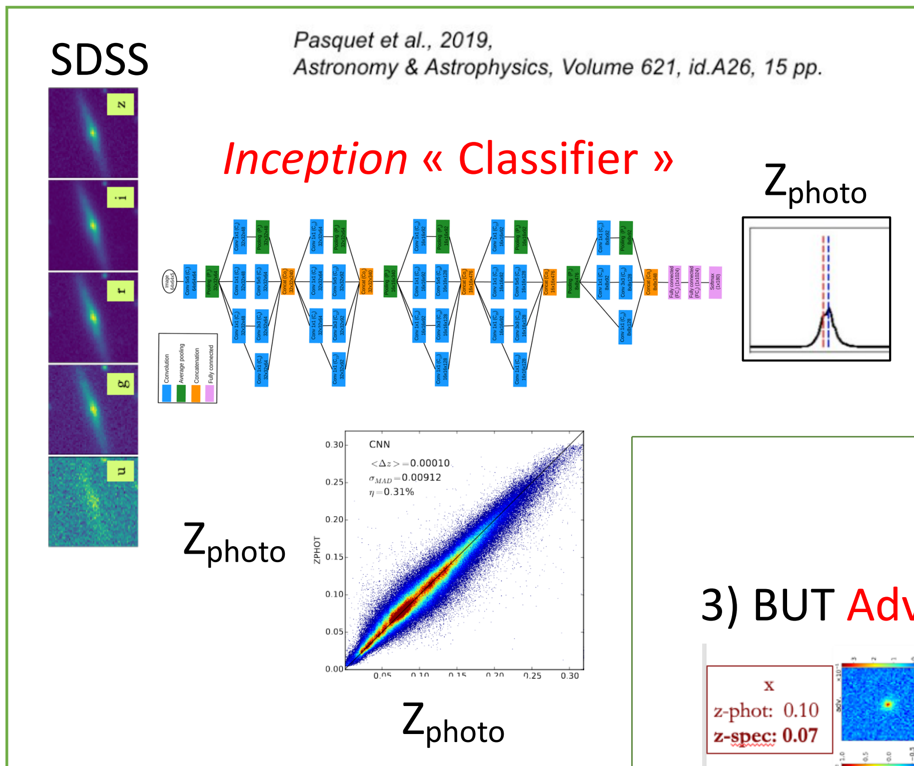
$$R^2(r_1, r_2, \theta) = r_1^2 + r_2^2 - 2r_1 r_2 \cos\theta$$
$$= (r_2 - r_1)^2 + 4 r_1 r_2 \sin^2(\theta/2)$$



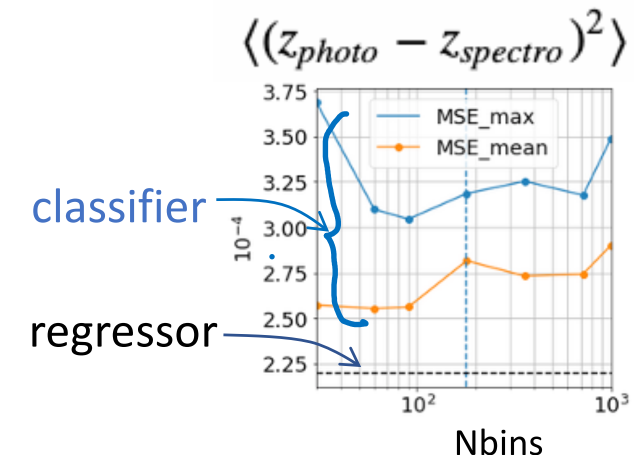
Work has been recognized and extended by C. Bonvin et al. arXiv:1708.00492 and Di Dio et al. arXiv:2004.08014

CNN & photoZ

Photometric redshift end-end ML (J.E)



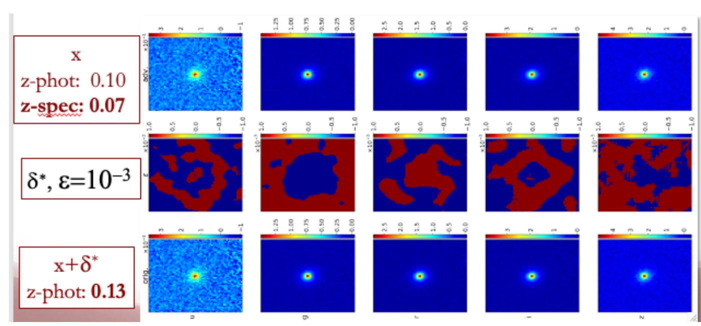
1) *Inception* Regressor: Better ☺

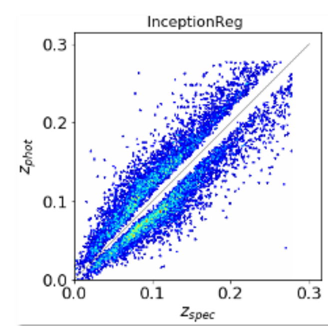


2) Other arch. : ResNet18 ok!

Arch.	B_s	MSE $\times 10^{-4}$	Bias $\times 10^{-4}$	σ_{mad} $\times 10^{-3}$	$\eta(\%)$
ResNet18	128	2.46	−5.56	10.91	0.64
	256	2.36	−13.78	10.61	0.56
	512	2.46	−5.60	10.99	0.64
	1024	3.19	−4.19	12.53	0.95
Inception (Tab. 1 [2])	128	2.20	+1.98	10.31	0.47

3) BUT Adversarial samples reflect weakness of the approach (new result in the field)





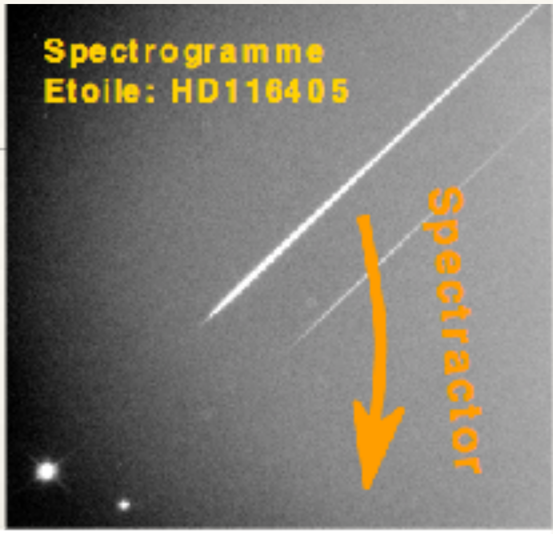
- A possible solutions is a adversarial training but performances are a bit degraded.

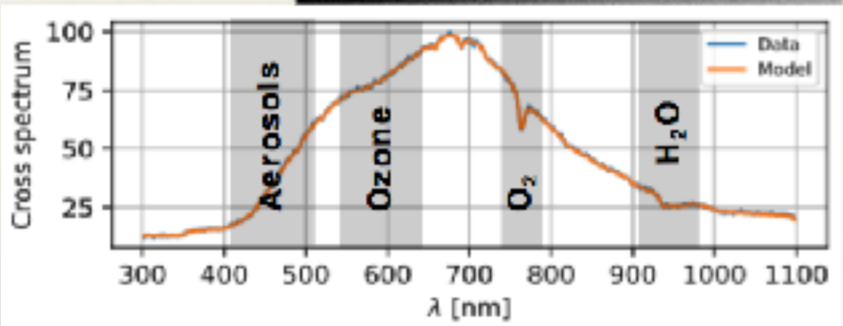
J.E. arXiv:2002.10154v1

- A completly new approach: Deep Scattering networks. JE works with S. Mallat et al. @ ENS.

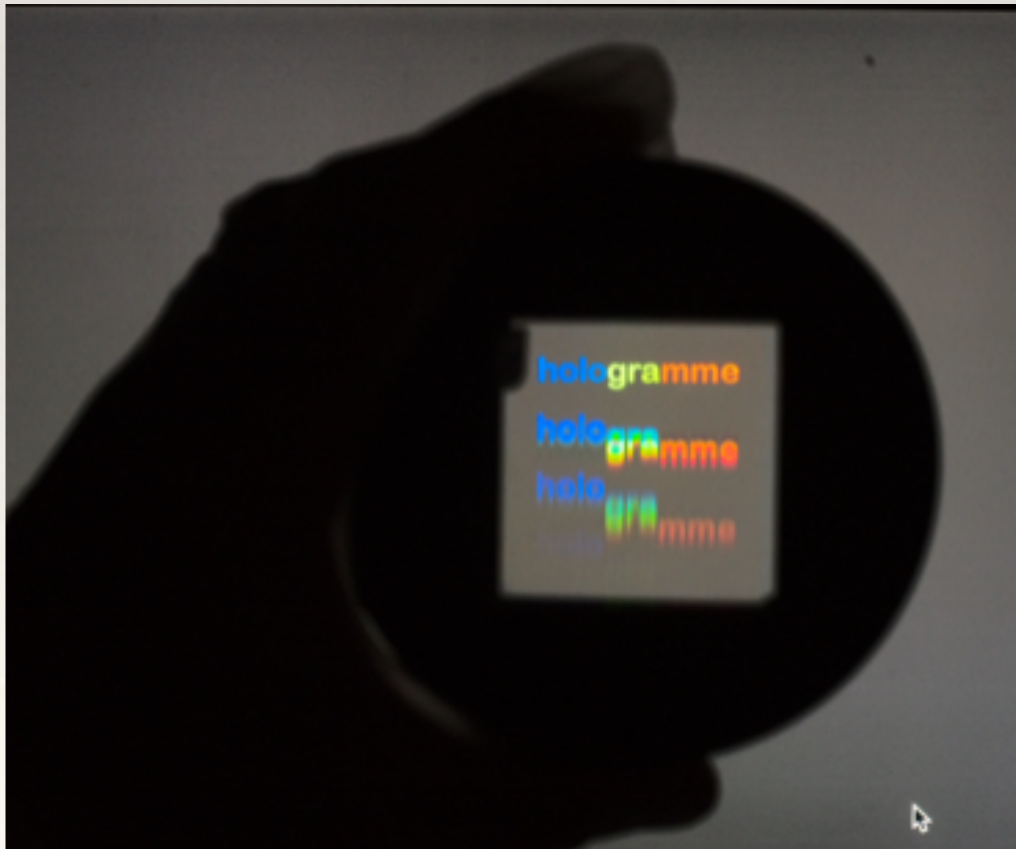
A first breakthrough result will appear in ICLR21 using a Classifier that is as best as S-of-Art for ImageNet benchmark. J.E is working with such arch. on SDSS images: results are encouraging. With such arch. we master as much as possible the operators behavior, so it make a new perspective on stability of CNN networks beyond Photo-z use-case.

Holospec/Spectractor





- AuxTel with a simple spectrograph to monitor atmospheric transmission, as component of LSST photometric calibration process
- **Spectractor** (J. Neveu) : software tool to extract spectra from AuxTel images
- **Holospec** (M. Moniez) : A hologram replacing the grating for a spectrograph in a convergent beam. To correct for distortions and defocusing of a standard grating in a non planar beam
- First prototypes tested at CTIO in June 2017 , First generation for AuxTel mid-2018, second generation (Oct.2018) tested in lab (Nov. 2018) , on sky in Pic du Midi (Feb.2019) and in Tucson
- Third generation made in July 2019, checked at LPNHE Sep. 2019. Final version in Dec. 2019 - glass coating at LMA.
- Measured and characterise at LPNHE in 2020. Send to Chili Dec 2020.



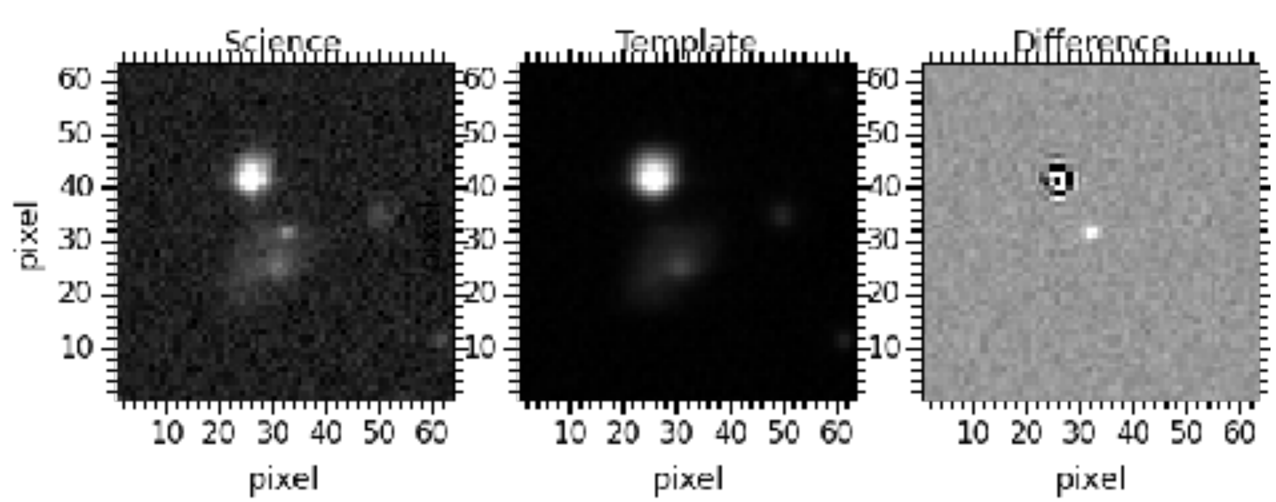
French LSST community Broker (I)

- *Les alertes et leur traitement dans LSST*
  - 1 TB alertes/nuit généré par LSST
  - Seulement O(few) brokers recevront le flux
- *Un projet pour LSST & la communauté multi-messagers française*
  - **Supernovae, microlentillage,** détection d'anomalies + astronomie multi-messagers.
  - *Piloté par LSST-France*, liens avec la *communauté multi-messagers* (10 laboratoires IN2P3, INSU, CEA, mais aussi GdR, TS2020). Partenariats en France: SVOM, XMM, GRANDMA.
  - Intégration en cours avec les outils en place (CDS, réseaux de communication, ...).
  - Avantage compétitif : les catalogues de données annuelles au CC.
- *R&D innovantes dans le big data: un atout CNRS/IN2P3*
  - Plusieurs R&D (IJCLab/IN2P3) menées depuis 3 ans autour des **technologies big data** (Apache Spark).
  - Tests et validation du cloud comme plateforme de calcul: VirtualData (UPSaclay, IN2P3, IJCLab).
    - Déploiement de Fink sous Kubernetes validé.
  - **Méthodes innovantes en Machine Learning** (Active learning, réseaux bayésiens)

Adapted from E. Gangler slides
(EAP-IN2P3-2020)

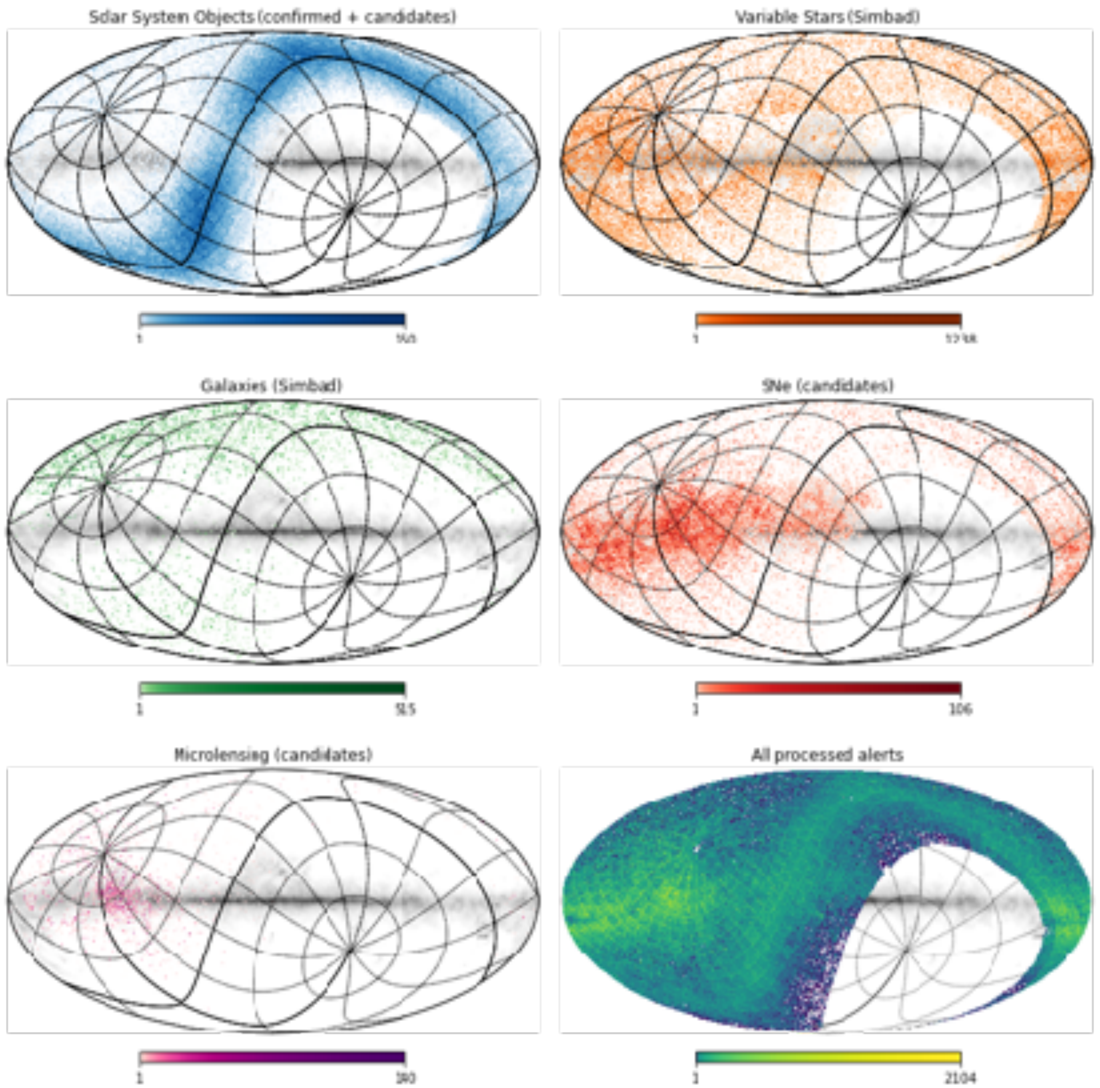
J. Peloton @IJCLab

Image d'une supernova de type Ia classifiée par Fink dans les données ZTF (Novembre 2019).



French LSST community Broker (II)

- *<u>L'initiative LSST-France en quelques dates (2020)</u>*
  - Février 2020: **MoU avec ZTF** pour l'accès aux données d'alertes en direct.
    - *60 millions d'alertes* collectées (Déc 2020)
  - Juin 2020: CODEC IJCLab (extension CDD ingénieur)
  - Septembre 2020: Soumission du *white paper* (*35 signataires*, FR/EU)
  - Octobre 2020: Organisation d'un workshop international sur les brokers, **financé par LSSTC.**
  - **Projet IN2P3** à l'intérieur du MP LSST (2021)
- *<u>Travaux en cours & prochaines étapes</u>*
  - Analyse données préliminaires LSST & ZTF-II
  - Déploiement du système et des services au CC-IN2P3.
  - Soumission de la **proposition finale à LSST DM (Q4 2020).**



Footprint of the ZTF alert stream by Fink (2019/2020)

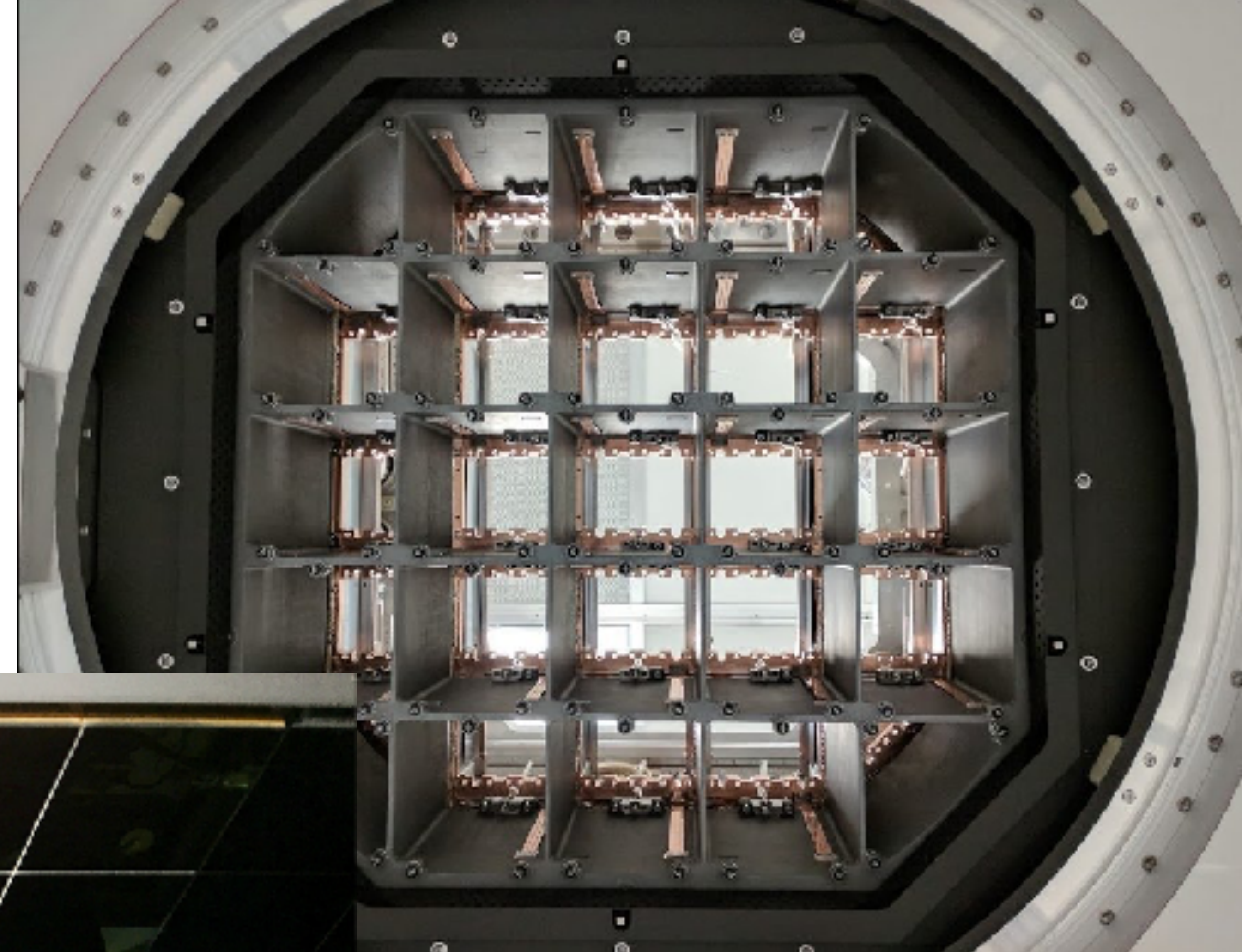
Adapted from E. Gangler slides
(EAP-IN2P3-2020)
J. Peloton @IJCLab

Rubin Observatory

Telescope and summit

August 2020

LSST camera



9th raft inserted
September 2019
SLAC

21cm Intensity Mapping
BAORadio : PAON4, Tianlai

21cm observations compared to optical

- 21 cm line is the only spectral feature in L/UHF bands (~GHz)
  ➡ Spectro-photometric observations
- Band: ~ 100 MHz … 1500 MHz - $\nu = f(z)$, z: 0 … 10

  1420 MHz @ z=0 , 946 MHz @ z=0.5 , 720 @ z=1 , 284 @ z=5, 129 @ z=10
- Radio instruments are diffraction limited:

  700 MHz: D=100 m → ~20′ , D=1km → ~2′ , D=100 km → ~1″ , 2′ → 1 Mpc @ z = 1
- Intensity measurement in radio, amplitude & phase in radio;
  ➡ Interferometry and spectroscopy in radio
- Instrumental/electronic noise (ROnoise <5 e) usually negligible in optical, dominant in radio (T_{sys}~20-100 K)
- Light pollution, atmosphere in optical / EM pollution (RFI) and ionosphere (lower frequencies) in radio

LSS/BAO/RSD @21cm : 3D $T_{21}(\alpha,\delta,z)$ maps

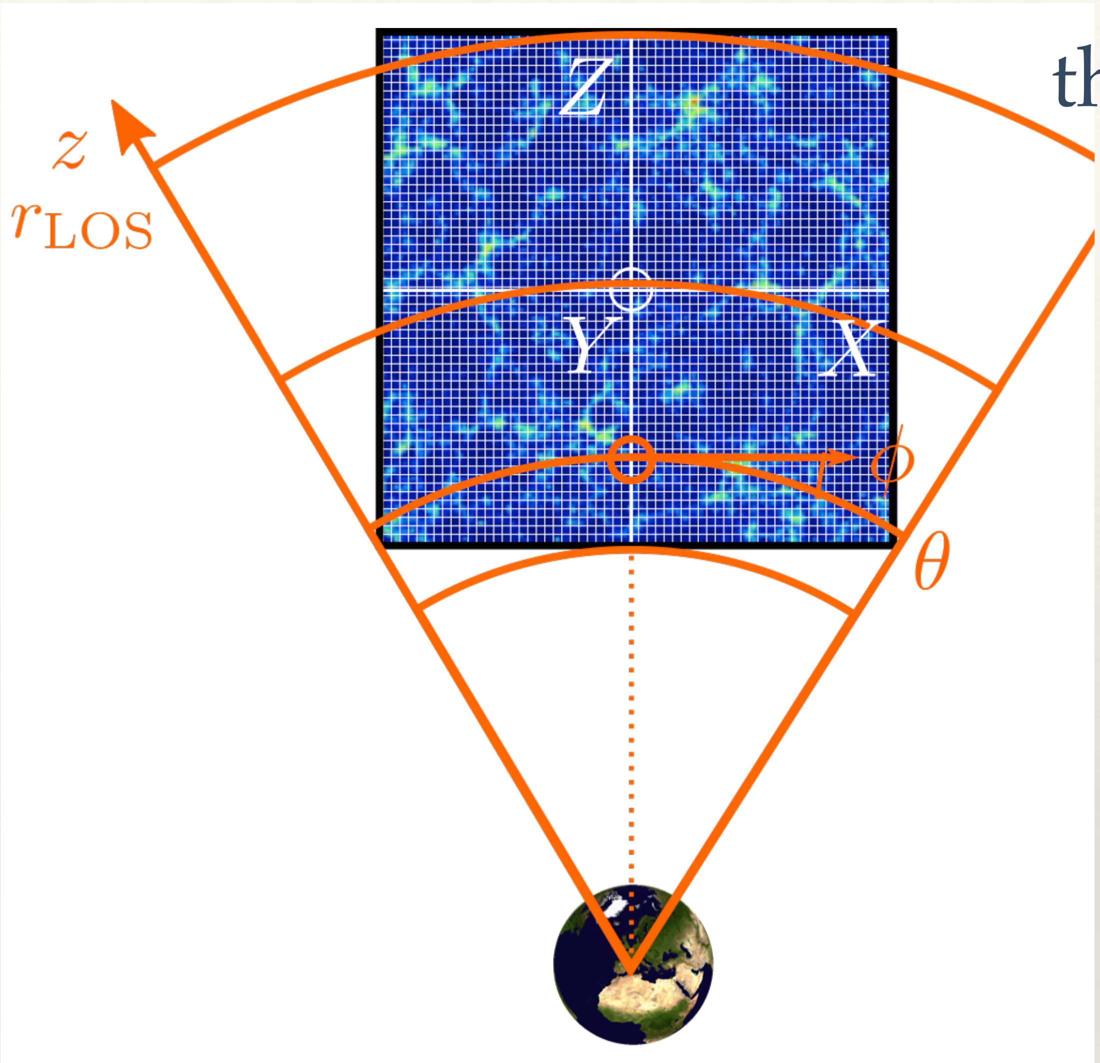
- 3D mapping of neutral hydrogen distribution through total 21 cm radio emission (no source detection)
- Needs only a modest angular resolution 10-15 arcmin
- Needs a large instantaneous field of view (FOV) and bandwidth (BW)
- Use of dense interferometric arrays (small size reflectors) to insure high sensitivity to low k and large instantaneous FOV
- Or a single dish with multi-beam focal plane receivers

- Instrument noise (Tsys)
- Foregrounds / radio sources and component separation
- Calibration, instrument stability, RFI …

- Peterson, Bandura & Pen (2006)
- Chang et al. (2008) arXiv:0709.3672
- Ansari et al (2008) arXiv:0807.3614
- Wyithe, Loeb & Geil (2008) arXiv:0709.2955
- Peterson et al (2009) arXiv:0902.3091
- Ansari et al (2012)
- Shaw et al (2014, 2015)
- de Santos et al- Bull et al (2015)
- …

21 cm 3D Intensity Mapping

- redshift ↔ Frequency
- angular direction mapping through imaging



Single Dish

- Map the sky through drift-scan or by active scanning
- Compute power spectrum P(k) or C(l, z1,z2) from sky maps
- project into appropriate basis (modes) to subtract foregrounds and extract cosmological signal

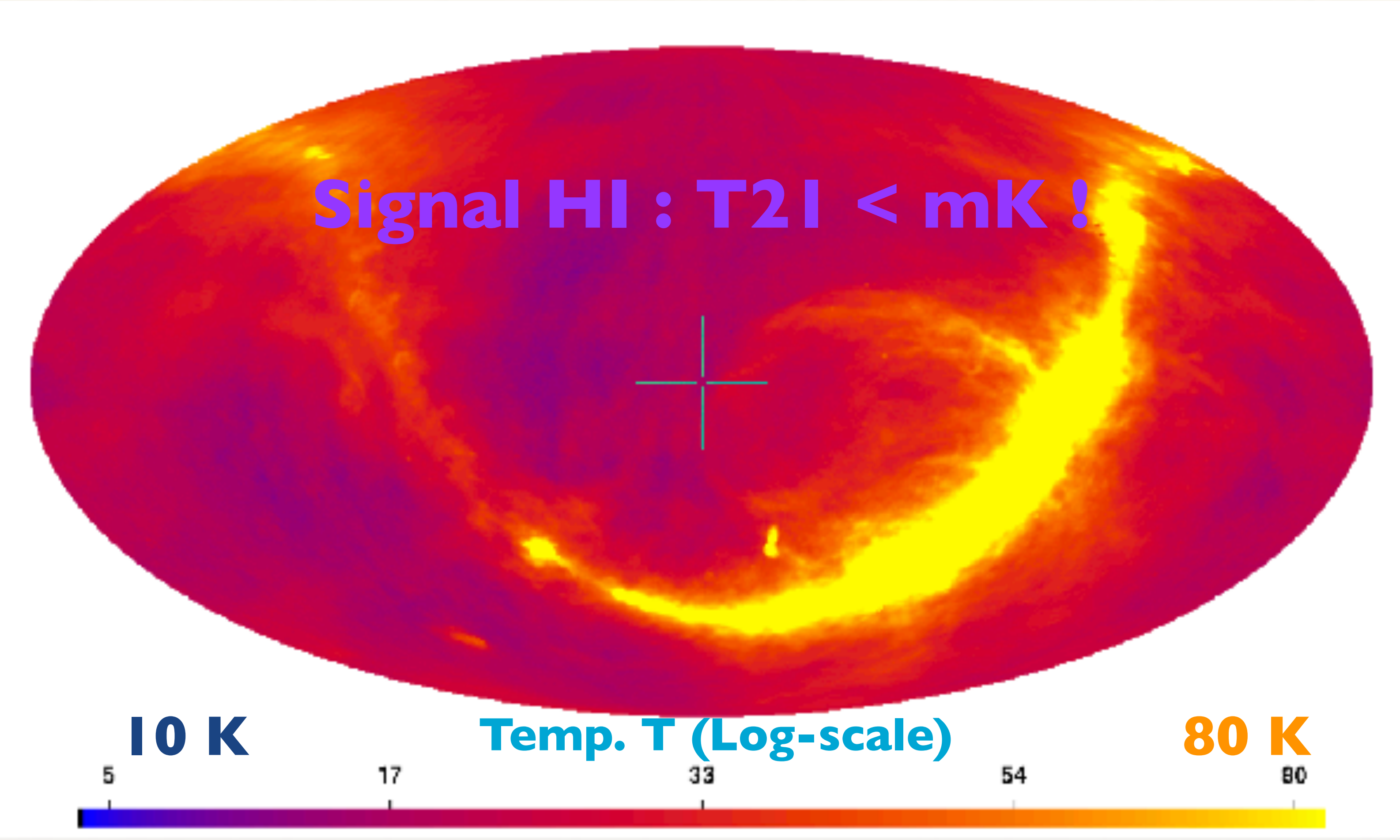
$$P_{21}(k) \sim (\bar{T}_{21})^2 \times P_{LSS}(k)$$

$$\bar{T}_{21} \simeq 4.7\,\mathrm{mK}\,\frac{\Omega_{H_I}}{10^{-3}}\,\frac{H_0(1+z)^2}{H(z)}$$

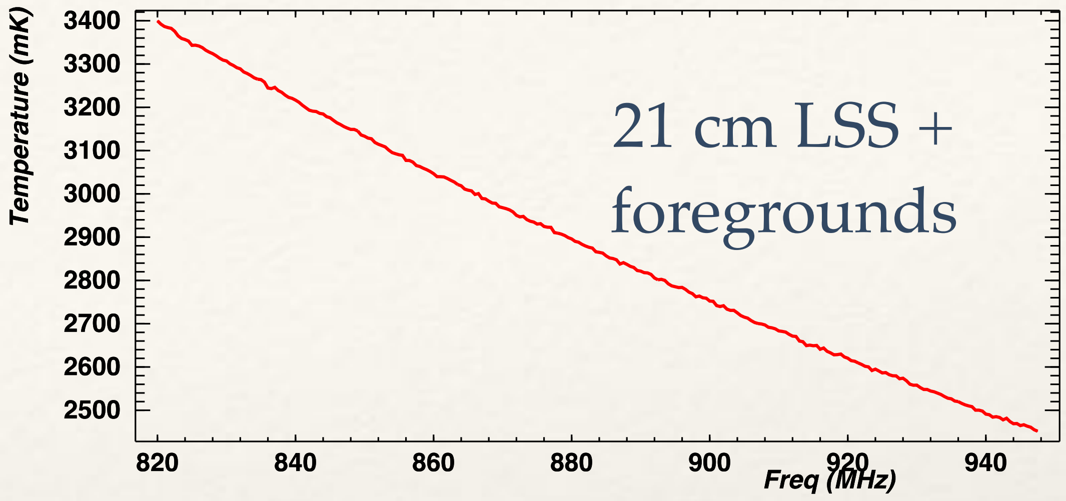
Transit Interferometers

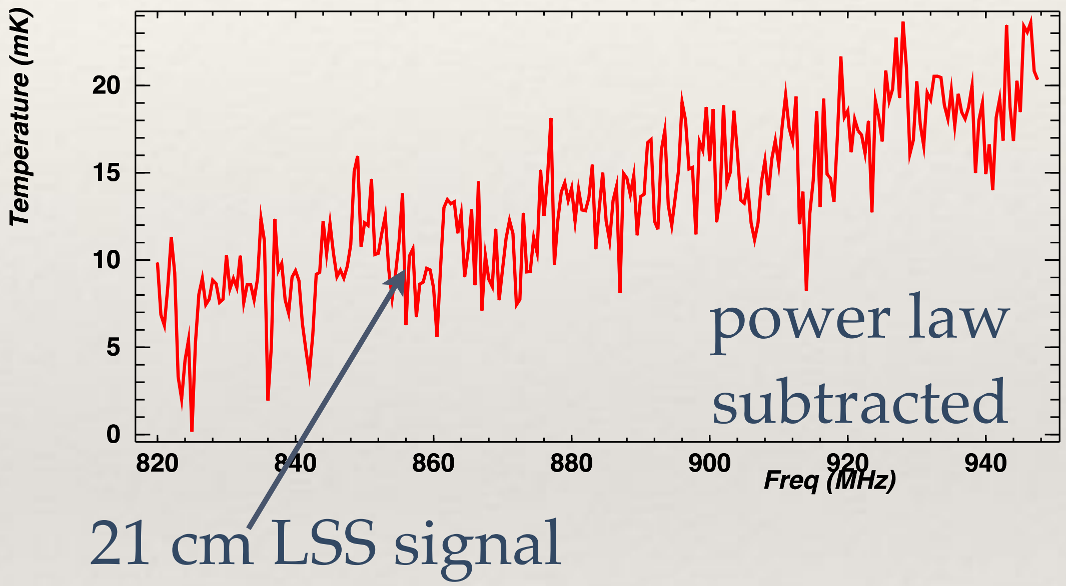
- Map the sky through drift-scan
- Reconstruct sky map from visibilities
- **m-mode decomposition in case of full EW scan**
- visibilities correspond to transverse Fourier modes k⊥

Foregrounds



http://lambda.gsfc.nasa.gov/





- Exploit foregrounds smooth frequency dependence (power law ∝ ν^β) for Galactic synchrotron and radio sources
- Instrumental effects (mode mixing), Polarisation leakage / Faraday rotation …

Wang et al. 2006 (EoR)
Ansari et al. (2012) - A&A
Shaw et al (2015) ApJ
+ many more !

IM@21cm @LAL/IJCLab (chronology)

- 2006 : Jeff Peterson (@Moriond) proposed to build large cylindrical radio-telescope to carry BAO redshift survey using the 21cm line …
- 2007 : BAORadio project in France to carry R&D on electronics (digital) for CRT and large radio arrays (**LAL-CNRS/IN2P3, Irfu-CEA, Observatoire de Paris** collaboration)
- 2007-2009 : development of some of components of the electronic system (digitisation/FFT board, clock distribution …) - Tests at Nançay on the NRT
- 2009-2010 : Tests on the **CRT** prototype at **Pittsburgh** - Site testing in Morocco (with **Fermilab**) - Ifrane meeting in July 2009 …
- 2011-2012 : FAN (Phased array prototype for the NRT), HICluster program with the NRT , contacts with **NAOC**
- 2012-2014 : **PAON** project initiated . **Tianlai** project (**NAOC**) , contributions to the instrument design
- 2015-2016 : PAON4 deployed at Nançay, development of the new NEBuLA digitiser board (White Rabbit, LAL & Obs. de Paris/Nançay) started - Developments later incorporated into the IDROGEN board, part of the DAQGEN project
- 2017-2020 : **Tianlai** (data analysis), PAON4 data analysis , **IDROGEN** board development
- 2021 : deployment of IDROGEN boards on PAON4 (slightly delayed due to Covid-19)

LAL - IN2P3/CNRS

R. Ansari
J.E. Campagne
M. Moniez
O. Perdereau
J. Zhang
A.S. Torrento
Q. Huang

D. Breton
C. Beigbeder
T. Cacaceres
D. Charlet
B. Mansoux
C. Pailler
M. Taurigna

IRFU - CEA

C. Magneville
C. Yèche
J. Rich
J.M. Legoff

P. Abbon
E. Delagnes
H. Deschamps
C. Flouzat
P. Kestener

Observatoire de Paris

P. Colom
J.M. Martin
J. Borsenberger
J. Pezzani
F. Rigaud
S. Torchinsky
C. Viou

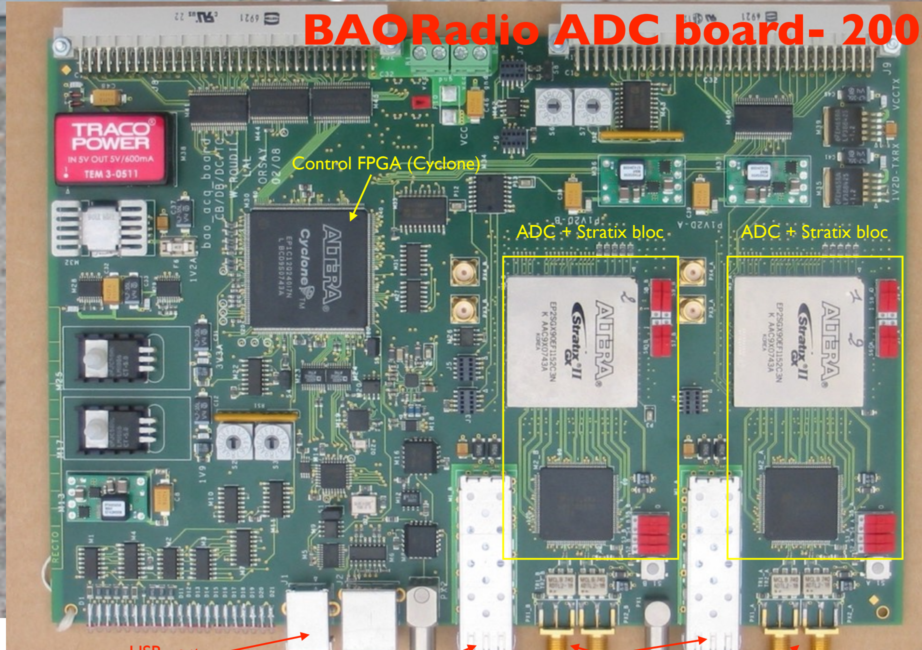
Nançay 2009, NRT

D. Charlet, C. Pailler, C. Yèche, C. Magneville

CRT (CMU, Pittsburgh)

J. Peterson, K. Bandura …

BAORadio @ CRT-Pittsburgh - Nov 2009



Au pays de l'énergie noire

Par Christophe Magneville et Christophe Yèche

Le contenu énergétique de l'Univers est dominé par une composante qui n'est ni de la matière ni du rayonnement : l'énergie noire. Cette composante mystérieuse, détectée pour la première fois en 1998, a révolutionné notre vision de l'évolution de l'Univers et constitue une des découvertes majeures de la fin du XXᵉ siècle. Le projet CRT de radiotélescope au Maroc permettra une meilleure compréhension de l'origine et des propriétés de cette énergie noire.

Ch. Yèche, E. Delagnes, P. Abbon, Ch. Magneville (Irfu) et R. Ansari (LAL)

électronique dans la gamme des fréquences autour du GHz, utilisés par la téléphonie mobile, rendent ce projet technologiquement réalisable.

Le CRT va explorer la nature de l'énergie noire avec une sensibilité dix fois supérieure aux instruments actuels. Il pourrait être construit sur un site au Maroc, grâce à un partenariat entre l'université d'Al Akhawayn à Ifrane (Maroc), l'université Carnegie-Mellon et Fermilab (Etats-Unis), l'Irfu et le LAL (France). Le Maroc constitue un excellent pays d'accueil pour ce projet car il allie un bon niveau de développement technologique et universitaire avec la possibilité de disposer de régions peu affectées par les bruits des ra-

Site testing in Morocco - Jan 2009
(Dave Mc. Ginnis, FNAL - blue jacket)

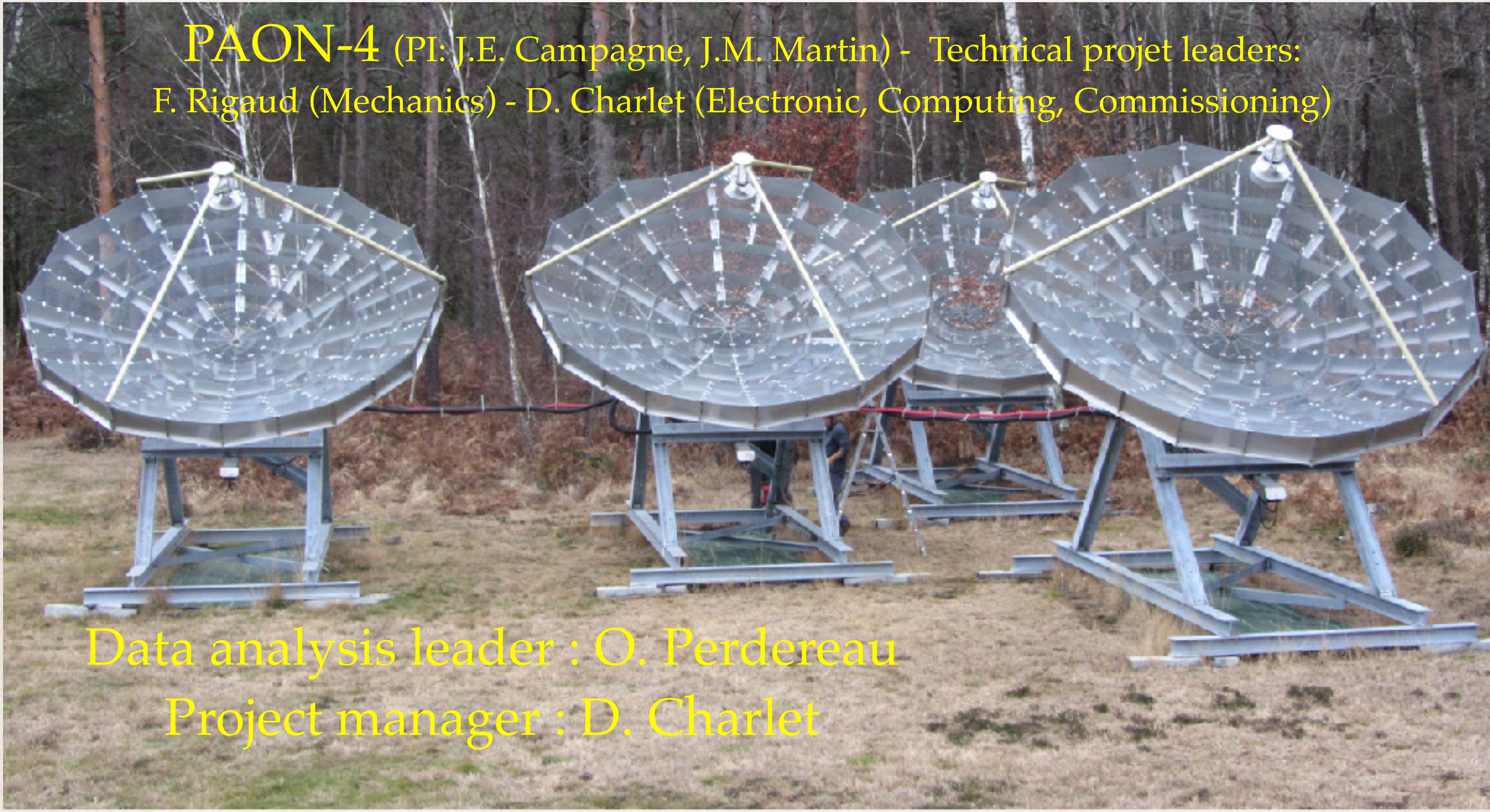
Site testing in Morocco - Jan 2009
C. Magneville, C. Yèche, P. Abbon (Irfu-CEA)

CRT meeting at Ifrance, Morocco, June 2009
Jim Rich, Jeff. Peterson

PAON-4 (2014-…)/ NEBuLA-IDROGEN (2016-…)

- PAON : PAraboles à l'Observatoire de Nançay (paon → peacock)
- PAON-4 : 4 × D=5m reflectors, dense array configuration, transit observation mode
- Total surface ~ 75 m^2, 8 = 4 x 2 (pol) récepteurs , 36 visibilities ~ 2 GBytes/s maximum data flow
- 38 S < Elevation < 15 N → 10 < δ < 60 at Nançay
- 250 MHz band , 1250-1450 MHz
- Reconstructed map resolution ~ 1 deg @ 1400 MHz
- Aims: RFI cleaning , Tsys and antennae correlation, test of calibration and 3D transit mode map making
- Sensitivity level ~50 mK (/ 1deg^2 x 1 MHz pixels) over ~ 5000 deg^2
- NEBuLA/IDROGEN : Numériseur à Bande Large pour l'Astronomie - New generation digitiser board that could be deployed close to the antennae, over ~ km sized area …

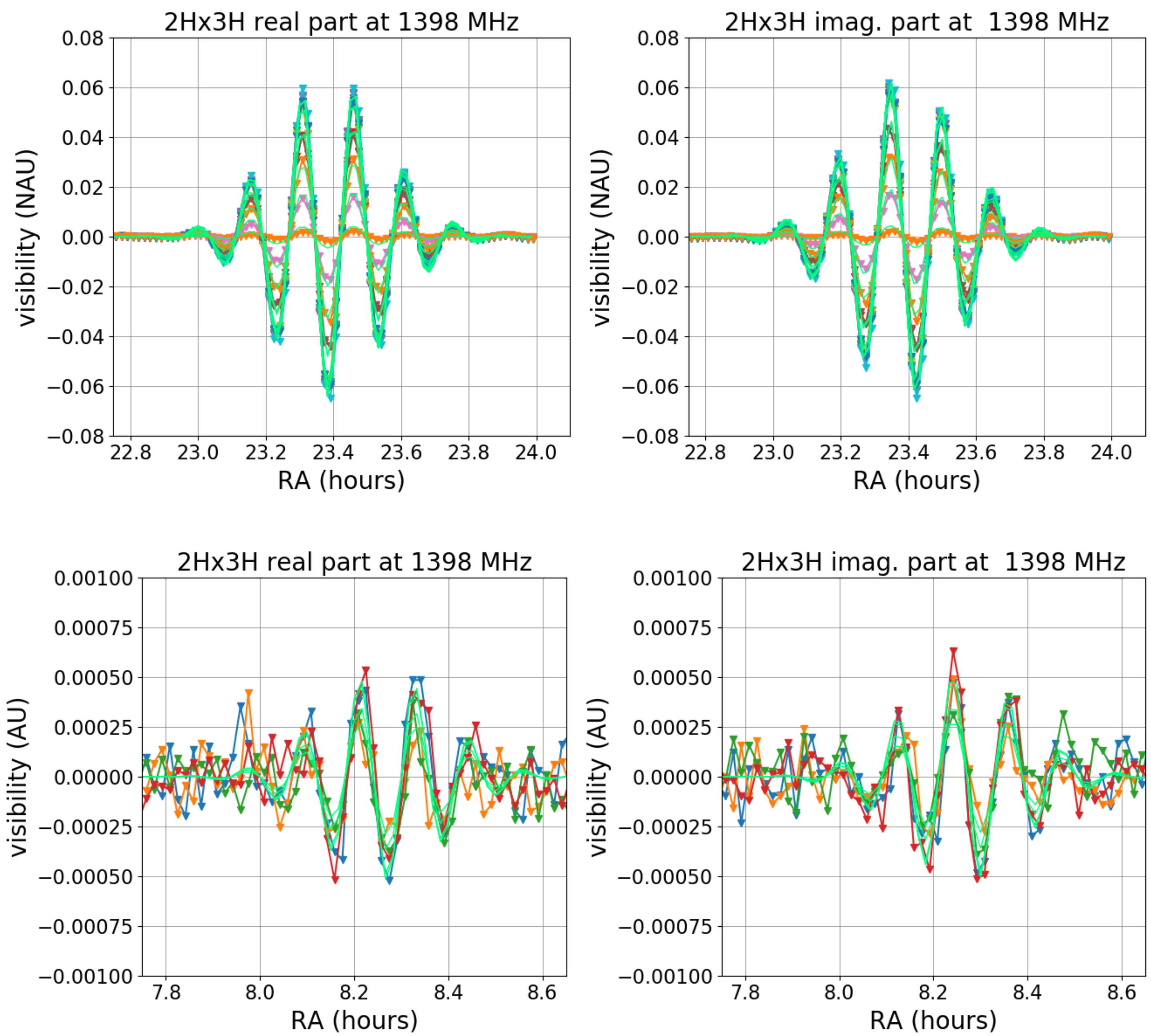
PAON4



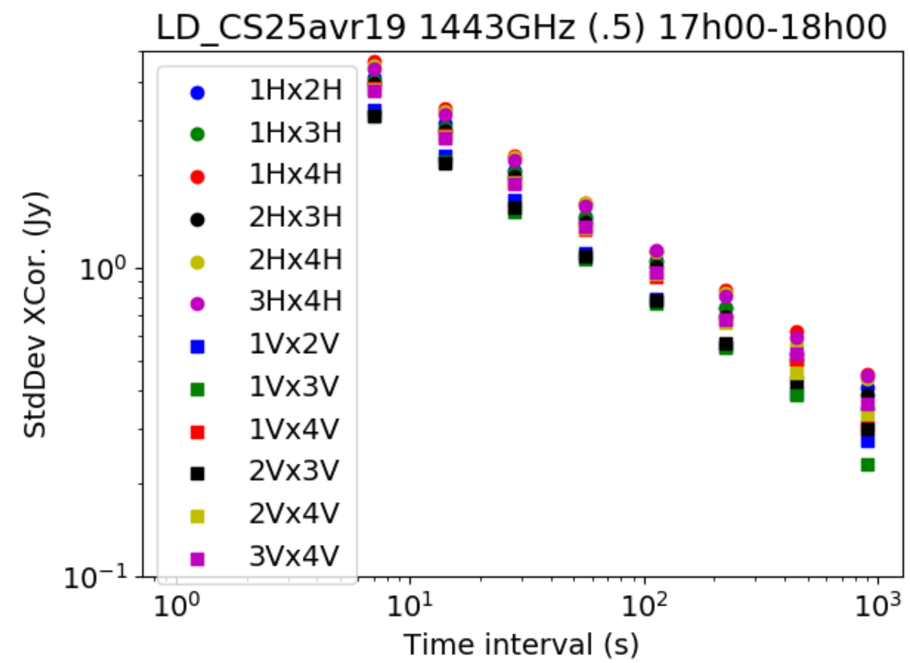
4 x 5m dishes, in compact transit interferometer configuration
L-band (~ 1250-1500 MHz → 1275 - 1475 MHz)

Inauguration PAON-4 à Nançay - 2 Avril 2015
en présence des directeurs de laboratoires (LAL,USN-Nançay) et du président de l'Observatoire

PAON4 : some results from 2018-2019 observations/analysis



CasA transits (top) , 3C196 (bottom) - PAON4 observations (different declinations) - compared with expected signals



Noise level evolution with integration time (cross-correlations)

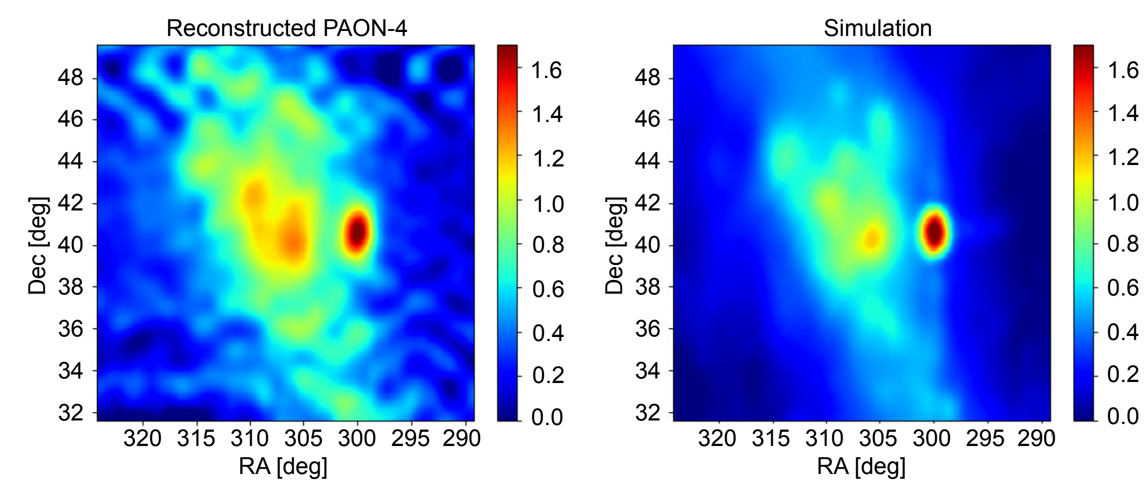


Figure 16. Example of a reconstructed map in a $\sim 35° \times 18°$ region around Cyg A, covering the area $(32° < \delta < 50°)$ in declination and $(290° < \alpha < 325°)$ in right ascension, from November 2016 data (left). Right panel shows the simulated map.(Huang 2019)

Reconstructed and simulated PAON4 maps

R. Ansari et al, MNRAS 2020 , arXiv:1910.07956

天籁 TIANLAI

TIANLAI

NAOC 中国科学院国家天文台

NATIONAL ASTRONOMICAL OBSERVATORIES ,CHINESE ACADEMY OF SCIENCE

CETC 中国电子科技集团公司第五十四研究所

CASIA Institute of Automation Chinese Academy of Sciences

cnrs IN2P3 Les deux infinis

CITA ICAT

Carnegie Mellon University

l'Observatoire de Paris

cea IRF

WISCONSIN UNIVERSITY OF WISCONSIN–MADISON

Fermilab

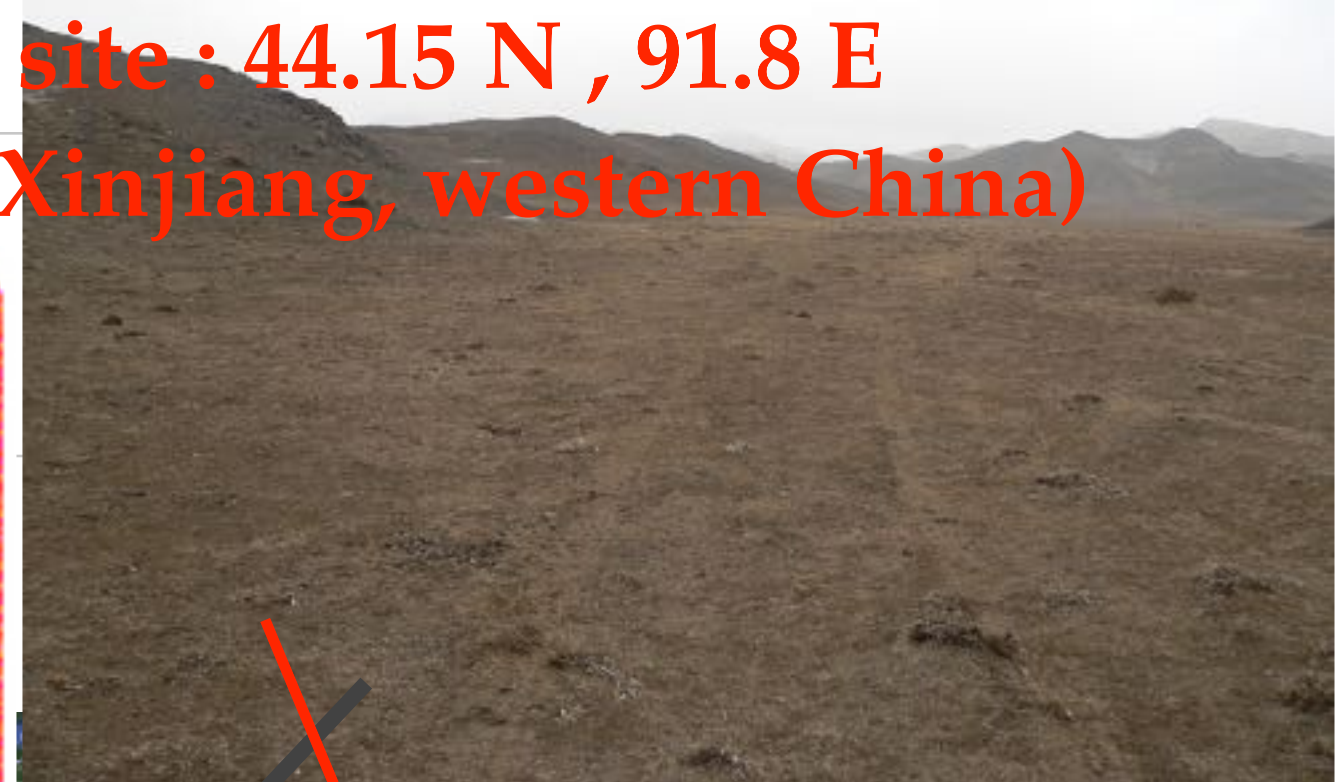
Tianlai

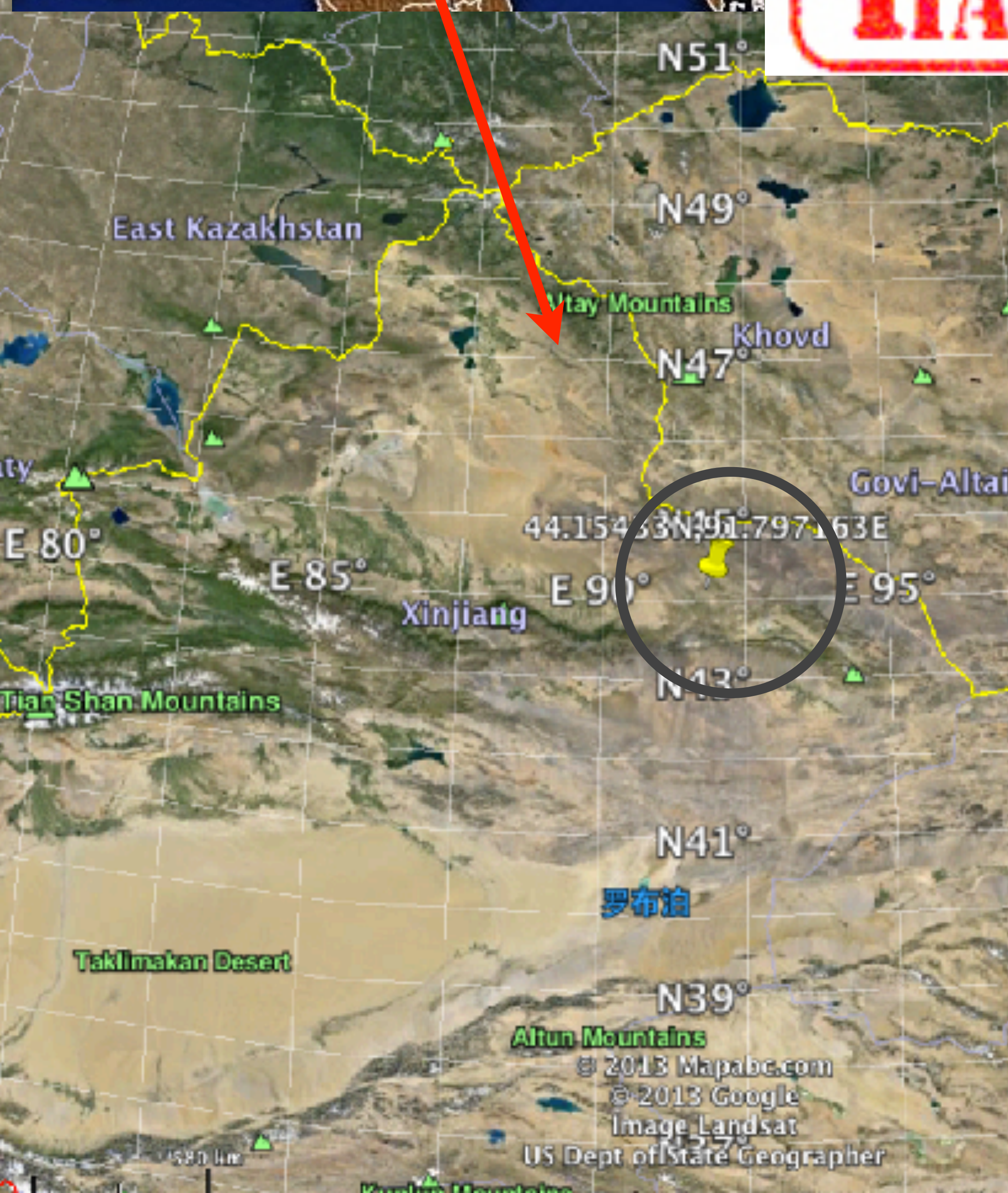
- Projet mené par le NAOC (PI: X. Chen) en partenariat avec Canada, États-Unis, Corée du Sud, France
- Collaboration constituée en 2011-2012 - Financement obtenu en 2012 (?) pour une première phase
- En chine: participation de l'*Institute of Automation* (électronique numérique) et *Institute 54* (Antennes, électronique Analogique) + …
- Recherche de sites à travers le territoire chinois - Choix du site en 2013
- Début d'aménagement du site à l'été 2014: construction d'une route (piste) et ligne électrique 10 kV, fibres optiques (7 km) depuis le village le plus proche - Construction du lieu de vie et salles électronique/informatique
- Réseau de 3 cylindres (15mx40) et un réseau de 16 réflecteurs (D=6 m) déployé à l'été 2015
- Phase Tianlai pathfnder: 96 (dual-pol) récepteurs sur les 3 cylindres - Corrélateur 192 voies (FPGA+DSP) en cours d'installation + corrélateur 32 voies pour le réseau des 16 antennes

Tianlai site : 44.15 N , 91.8 E

Hongliuxia Xinjiang, western China)

TIANLAI





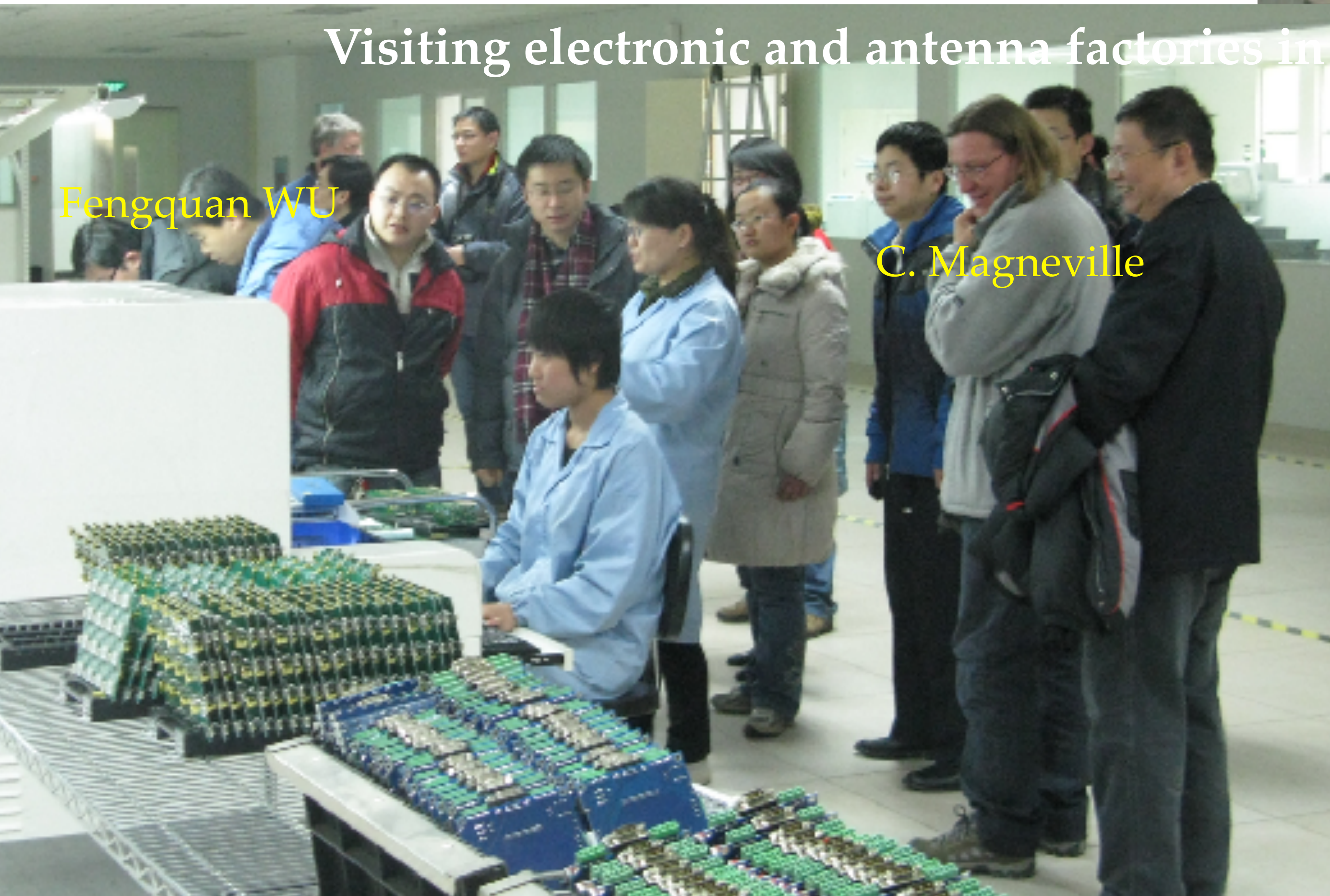
Sep. 2015

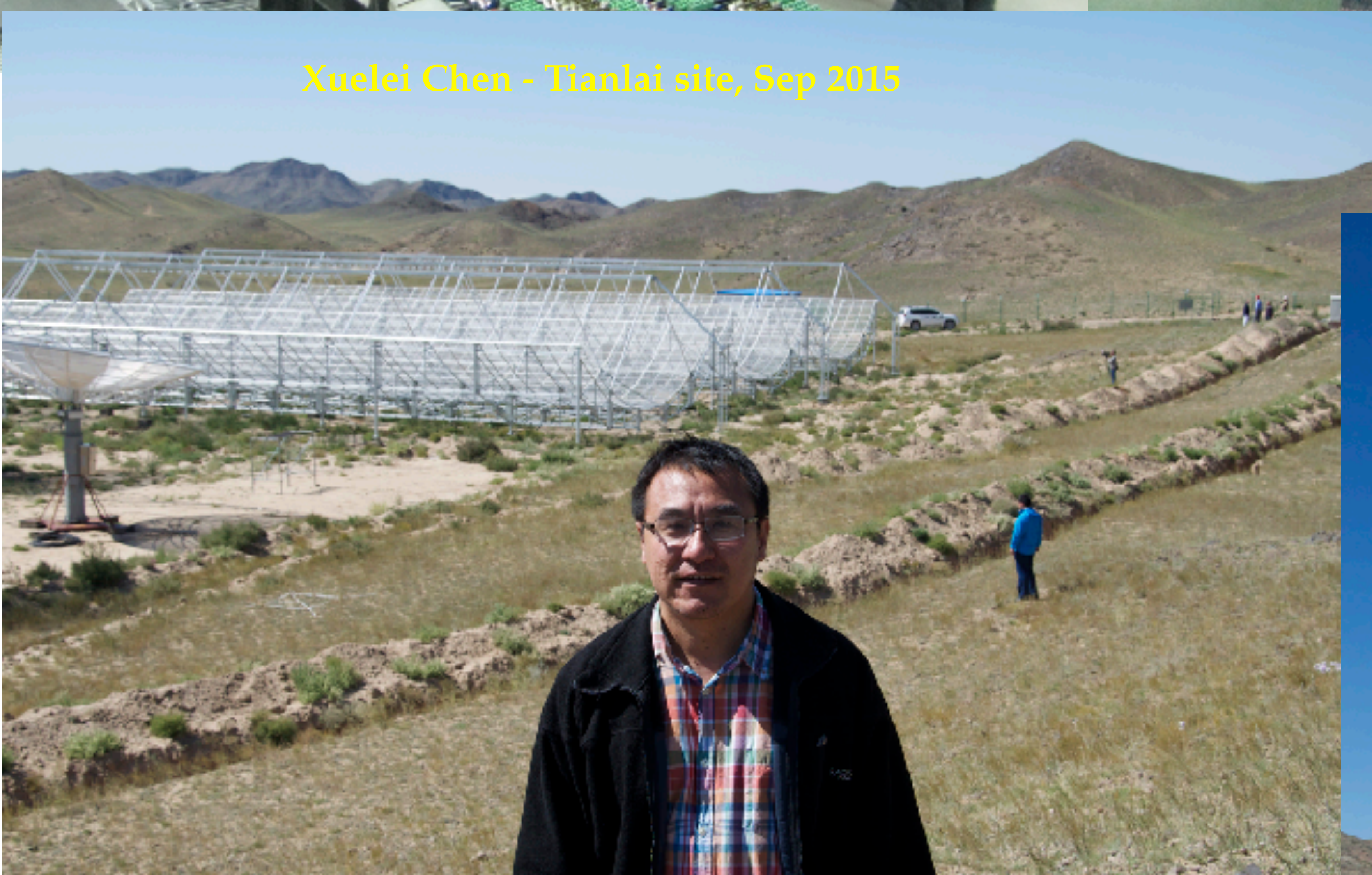
Tianlai Pathfinder

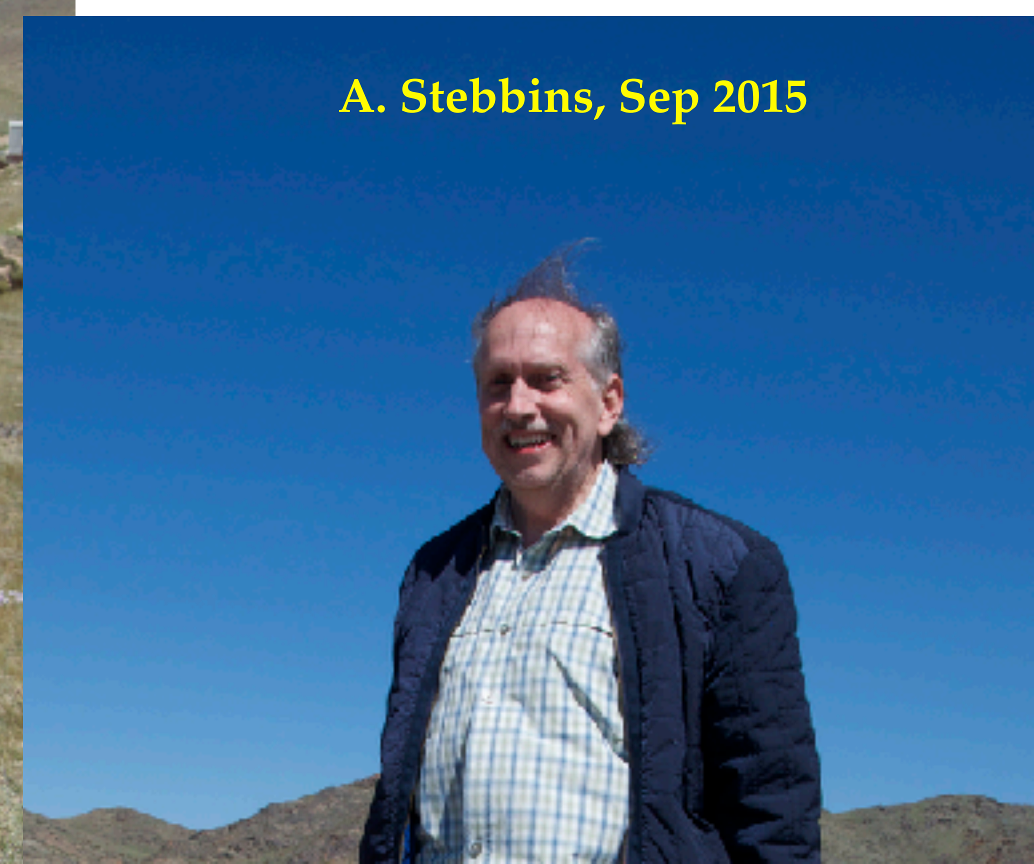
- Cost: Instruments: $1.5M from MOST + $0.6M from CAS
  Site construction : ~ $0.5M from NAOC
- Cylinder array:
  3x15mx40m cylinders, 96 dual polarization receiver units
- Dish array: 16 x 6m dishes, 16 dual pol. receivers,
- Frequency : 400-1400MHz (Redshift z=0-2.5)
- Current frequency coverage: 700-800 MHz
- If successful: possible the array up to 110mx110m, 1000~3000 receivers, with full wavelength range

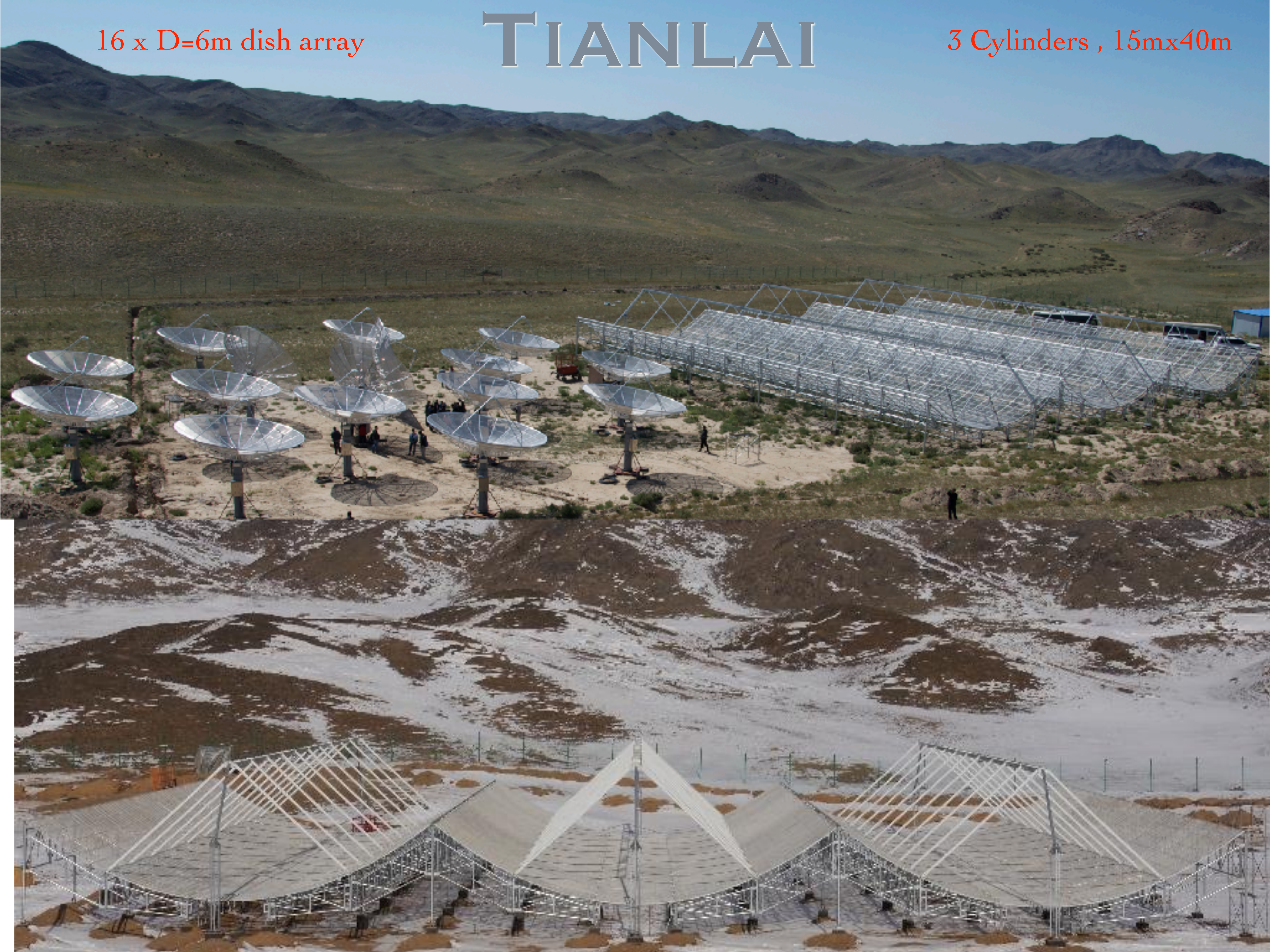
Information provided by
Fengquang Wu (NAOC)

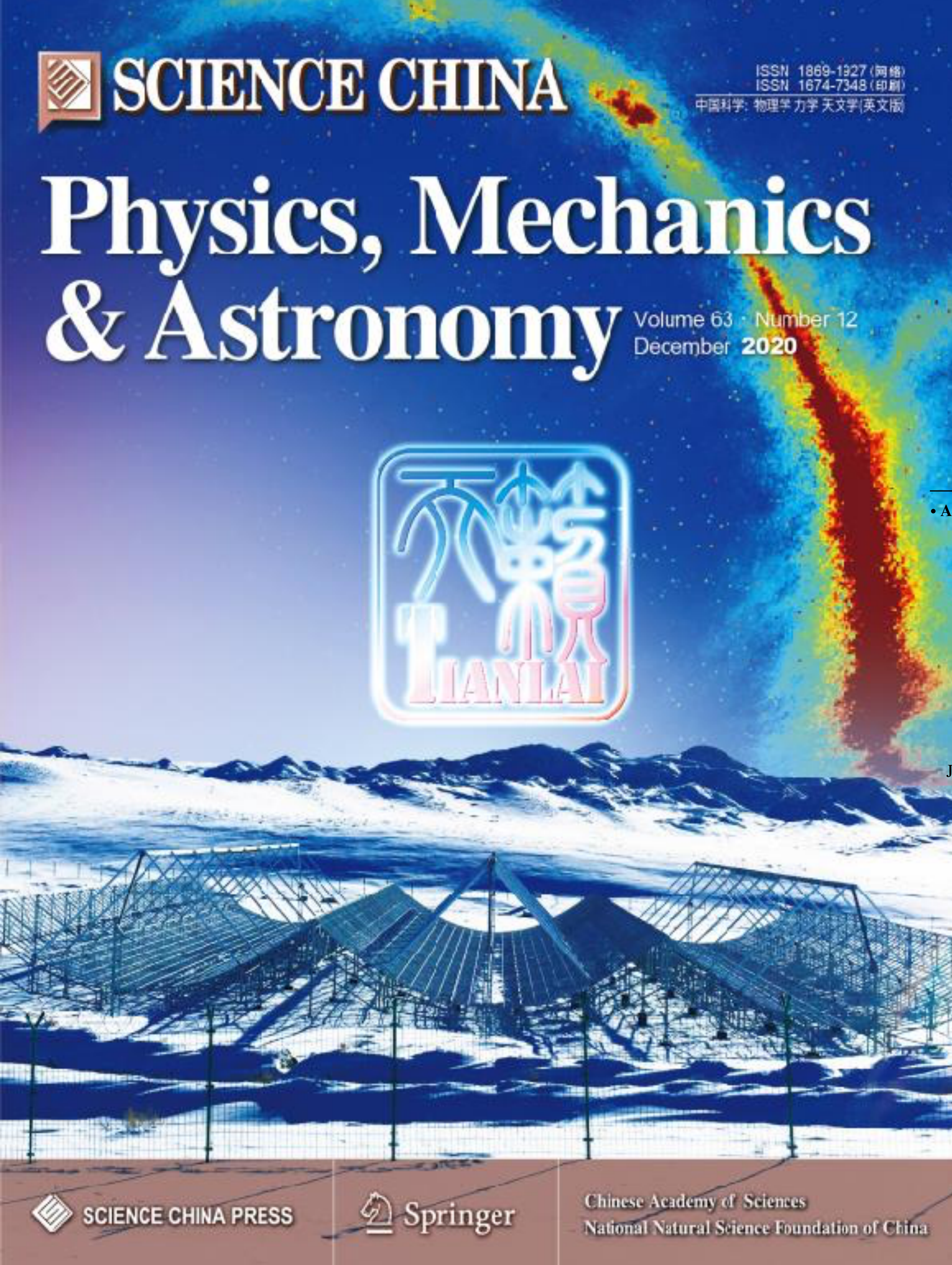
Visiting electronic and antenna factories in China, Tianlai project meeting, Feb. 2012








TIANLAI
16 x D=6m dish array
3 Cylinders , 15mx40m



Tianlai Cylinder (1st publication) 2020

SCIENCE CHINA
Physics, Mechanics & Astronomy
CrossMark

• Article •

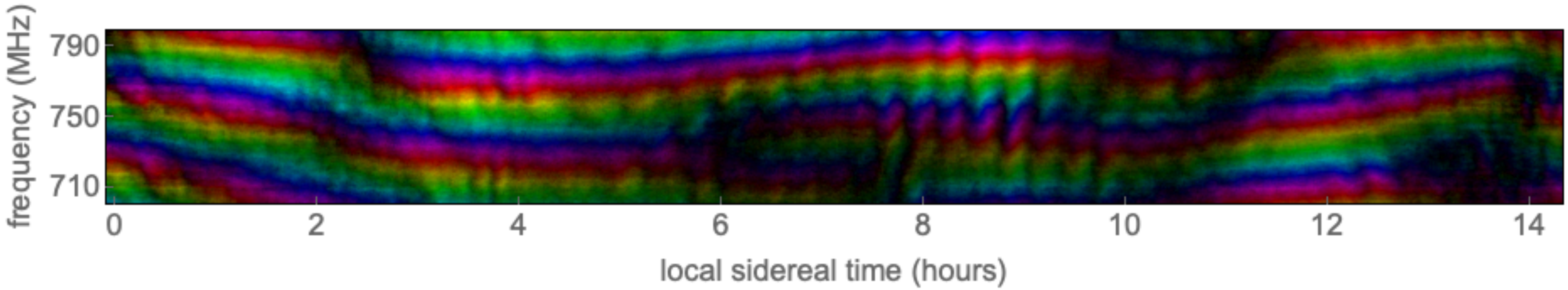
2020 Vol. No.: 000000
https://doi.org

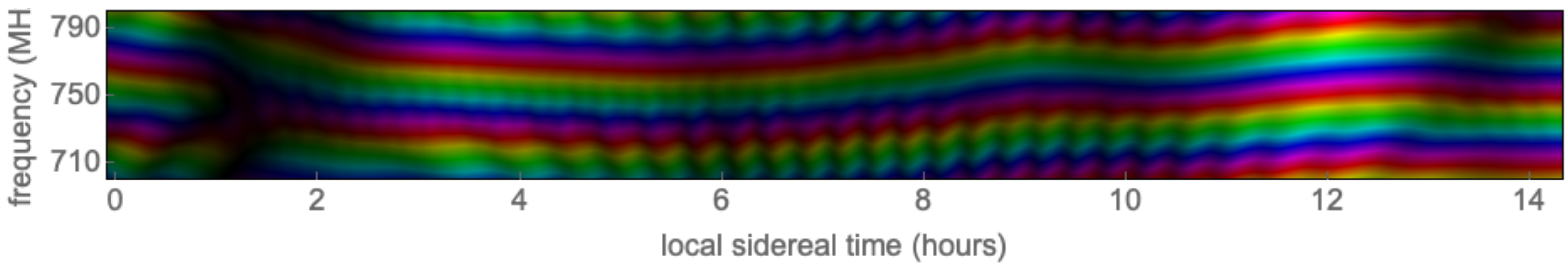
The Tianlai Cylinder Pathfinder Array: System Functions and Basic Performance Analysis

Jixia LI[1,2], Shifan ZUO[3,1], Fengquan WU[1], Yougang WANG[1], Juyong ZHANG[4], Shijie SUN[1,2], Yidong XU[1], Zijie YU[1,2], Reza ANSARI[5], Yichao LI[6], Albert STEBBINS[7], Peter TIMBIE[8], Yanping CONG[1,2], Jingchao GENG[9], Jie HAO[10], Qizhi HUANG[1], Jianbin LI[1], Rui LI[11], Donghao LIU[1], Yingfeng LIU[1,2], Tao LIU[4], John P. MARRINER[7], Chenhui NIU[1], Ue-Li PEN[12], Jeffery B. PETERSON[13], Huli SHI[1], Lin SHU[10], Yafang SONG[10], Haijun TIAN[14], Guisong WANG[9], Qunxiong WANG[14], Rongli WANG[4], Weixia WANG[11], Xin WANG[15], Kaifeng YU[1,2], Jiao ZHANG[16], Boqin Zhu[1], Jialu ZHU[4], and Xuelei CHEN *[1,2,17]

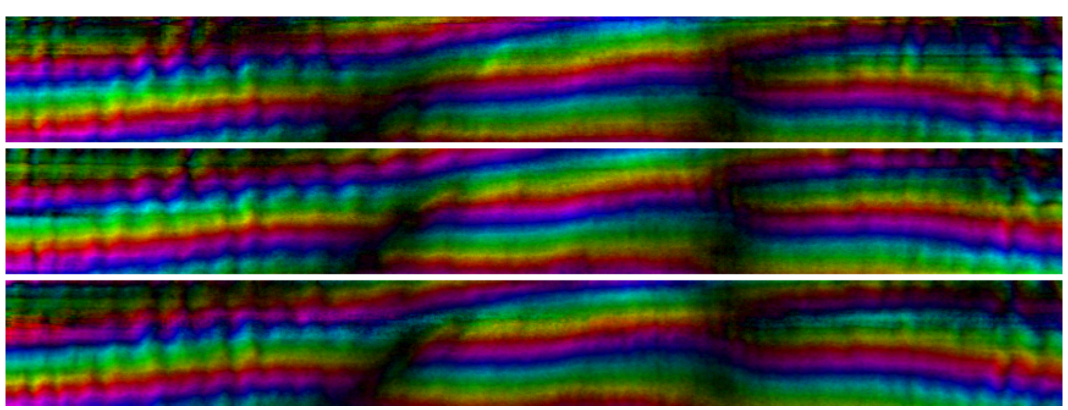
Jixia Li et al, 2020 , arXiv:2006.05605

Tianlai Dish Array (1st publication)2020

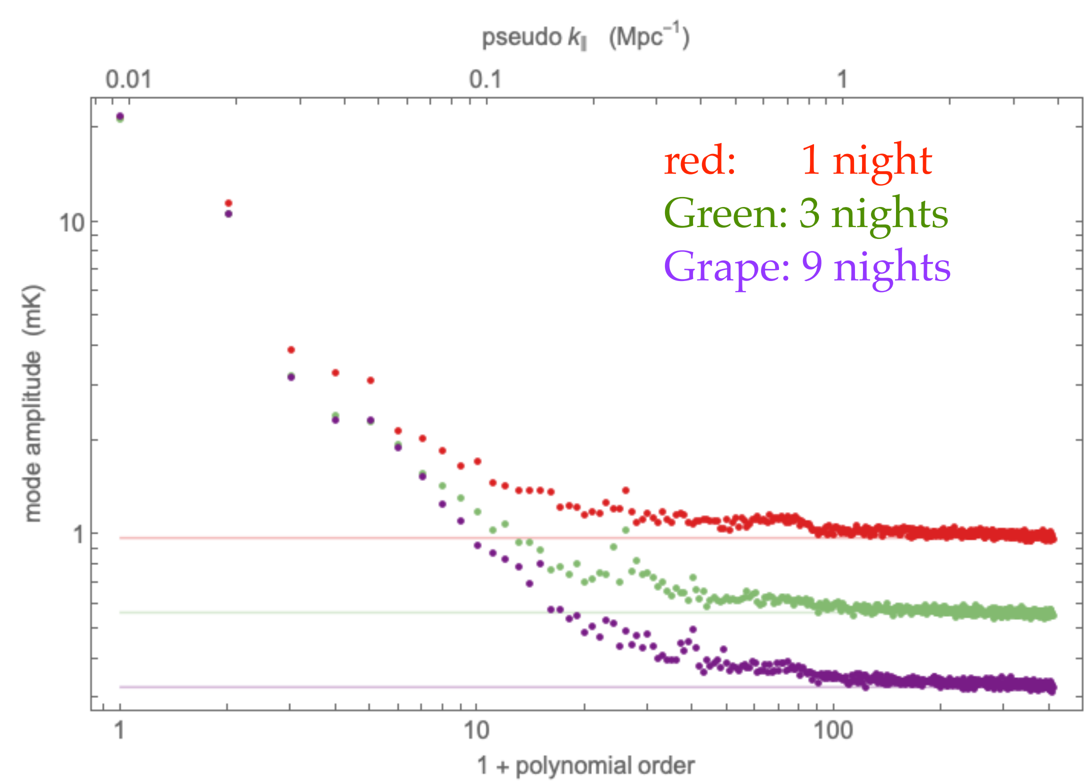




NCP observations - 10 nights averaging , top: data, bottom: simulations , < 1 mK sensitivity for single baseline (2V-10V)



3 nearly redundant baselines



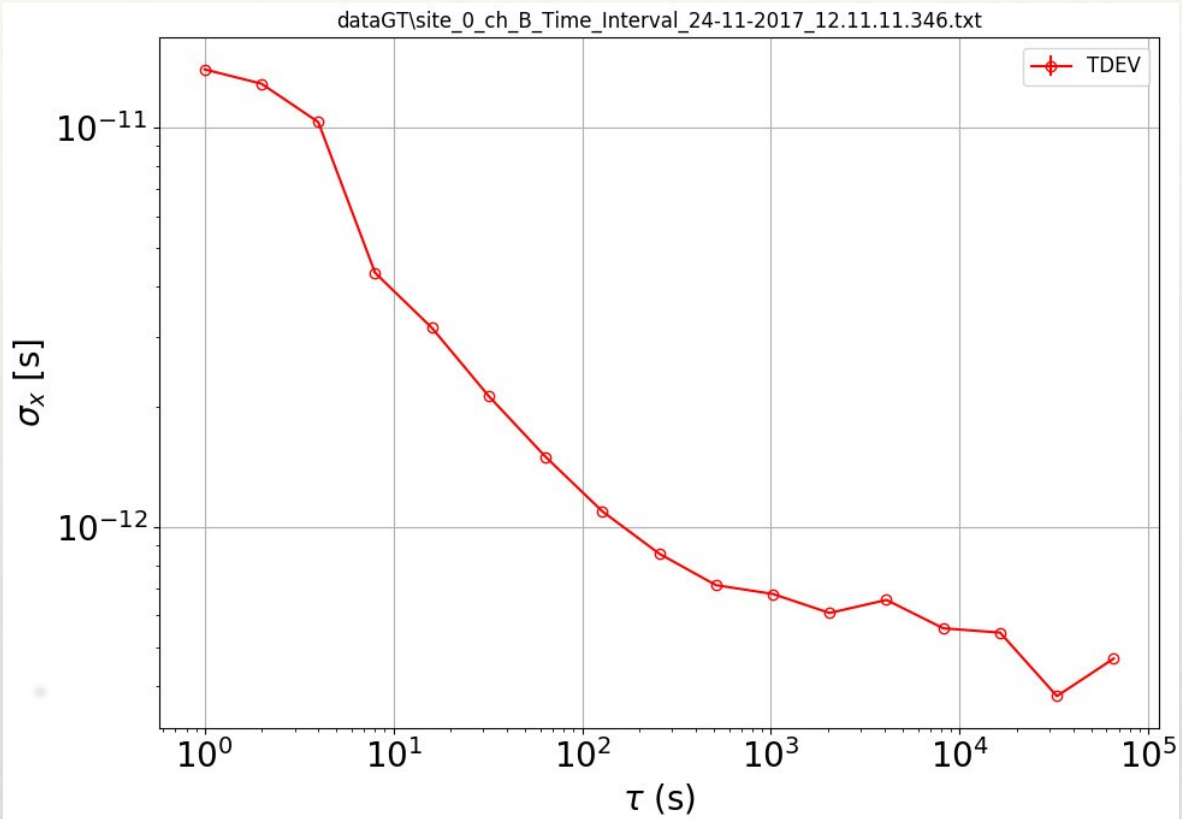
NCP k‖ Legendre mode decomposition

JF. Wu et al, 2020 , arXiv:2011.05946

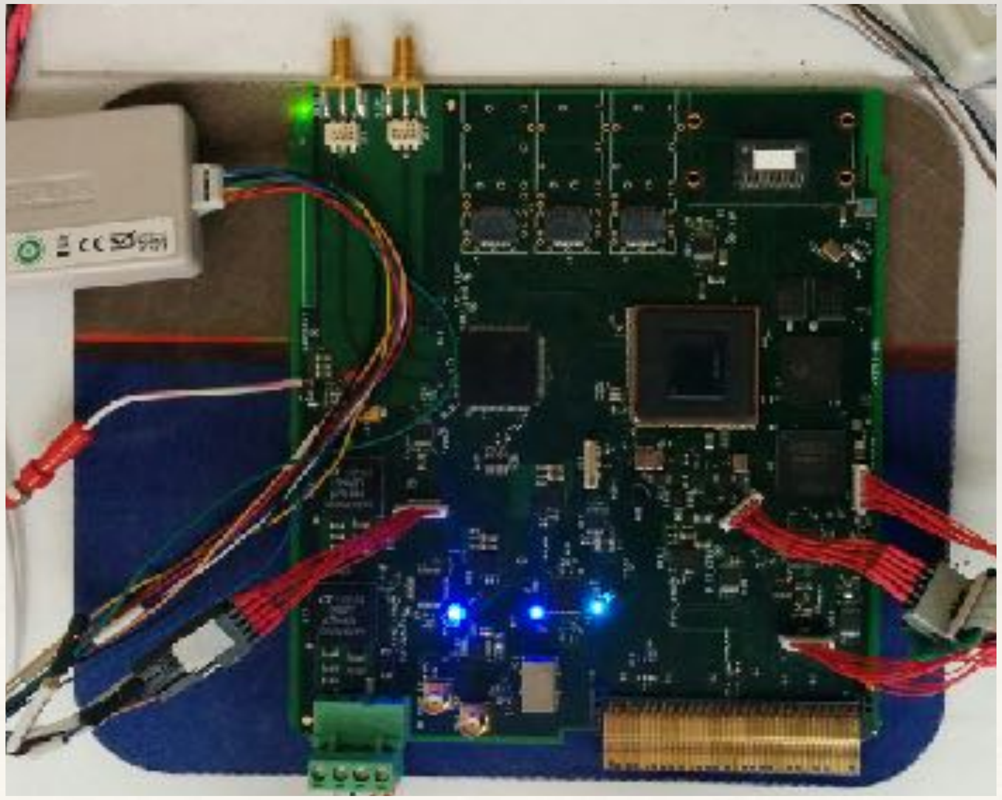
From NEBuLA to DAQGEN/IDROGEN

D. Charlet (LAL) , C. Viou (Nançay)

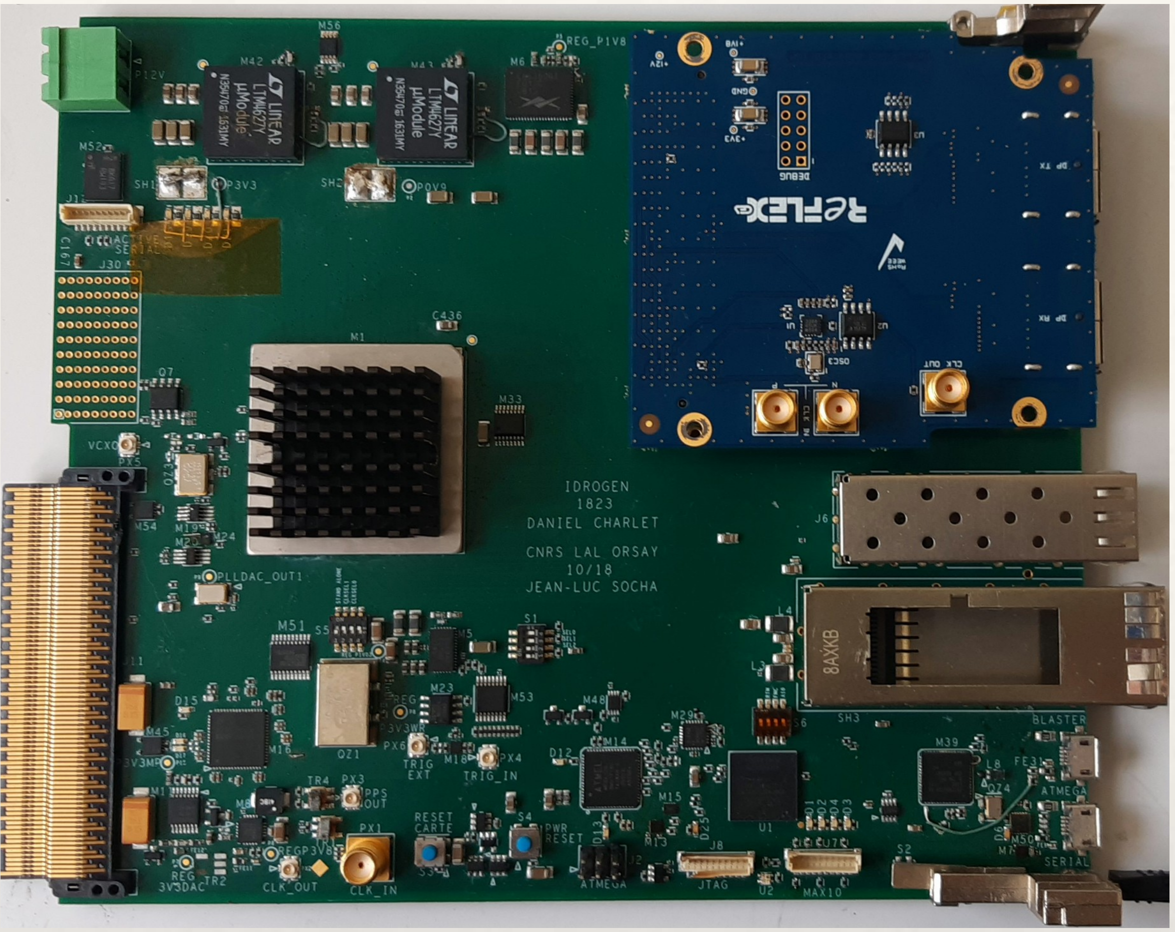
- Direct sampling after the LNA + filters (no mixer)
- Up to 500 MHz bandwidth
- designed to be put near the antennae
- optical data output & control / synchronisation
- White Rabbit technology for clock synchronisation through (optical) ethernet
- board configuration through the optical ethernet link
- data (waveform or frequency components) transferred through optical links (10G ethernet), possibly higher rates in the future



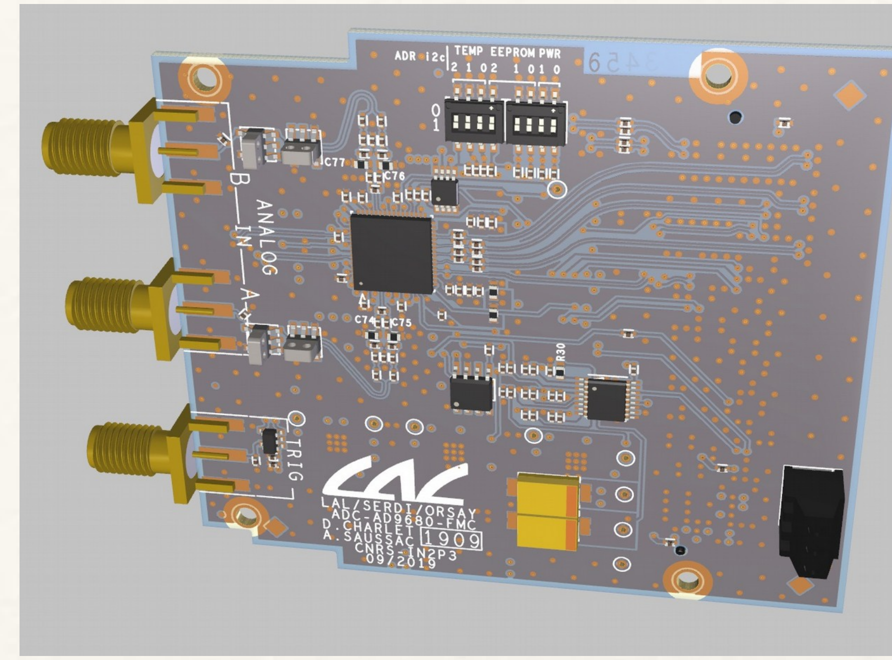
- In collaboration with SYRTE
  - Observatoire de Paris
  - Time-Frequency laboratory
- 400 fs after 1000 s and 1 km fibre



IDROGEN status (Fall. 2020)



IDROGEN board (v2) with commercial ADC (mezzanine) board -2019



Mezzanine ADC board designed and fabricated (2020), will be tested in fal

RF tight boxes/housing made for PAON4

- IDROGEN board v3 (v2.b) being produced for PAON4 and other users (IN2P3 labs)
- Firmware development continues
- IDROGEN softwares : acquisition and slow control (M. Taurigna, C. Cheikali)
- Expect deployment on PAON4 at the end of 2020
- A new version of the board, smaller size could be designed and produced by removing xTCA interface

For technical details, see D. Charlet & C. Viou presentation at the 2019 Orsay workshop

Future

AuxTel commissioning

LSST ComCam (2021?)

Rubin observatory Telescope and camera commissioning 2022 ?

DESI : operations start 2021 ?

Euclid launch : end of 2022

IDROGEN@PAON4 in 2021

Observations with PAON4 … 2023

Tianlai analysis … 2024

Future … fiction

21cm x optical surveys cross correlations (HIRAX × LSST)

WL with SKA

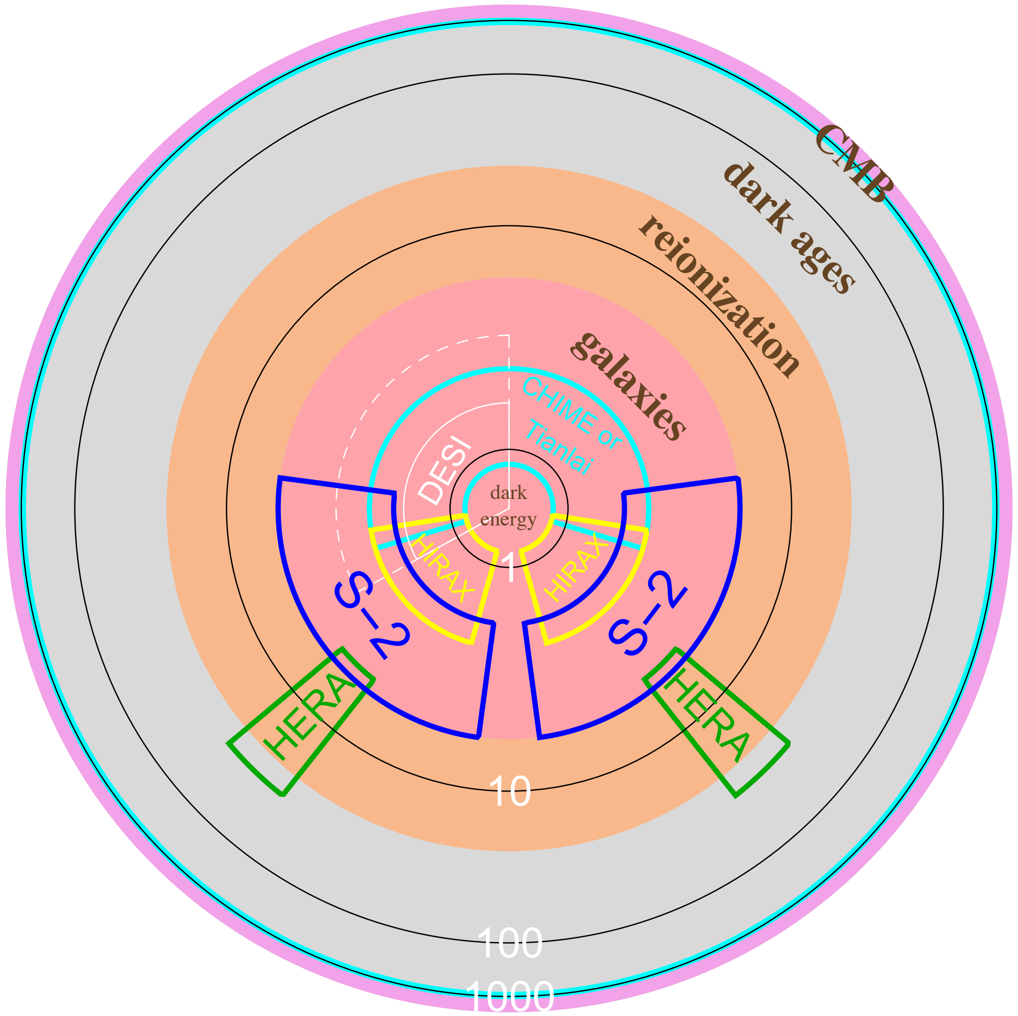
Map LSS with a single tracer and spectroscopic redshift resolution over a wide range of redshifts

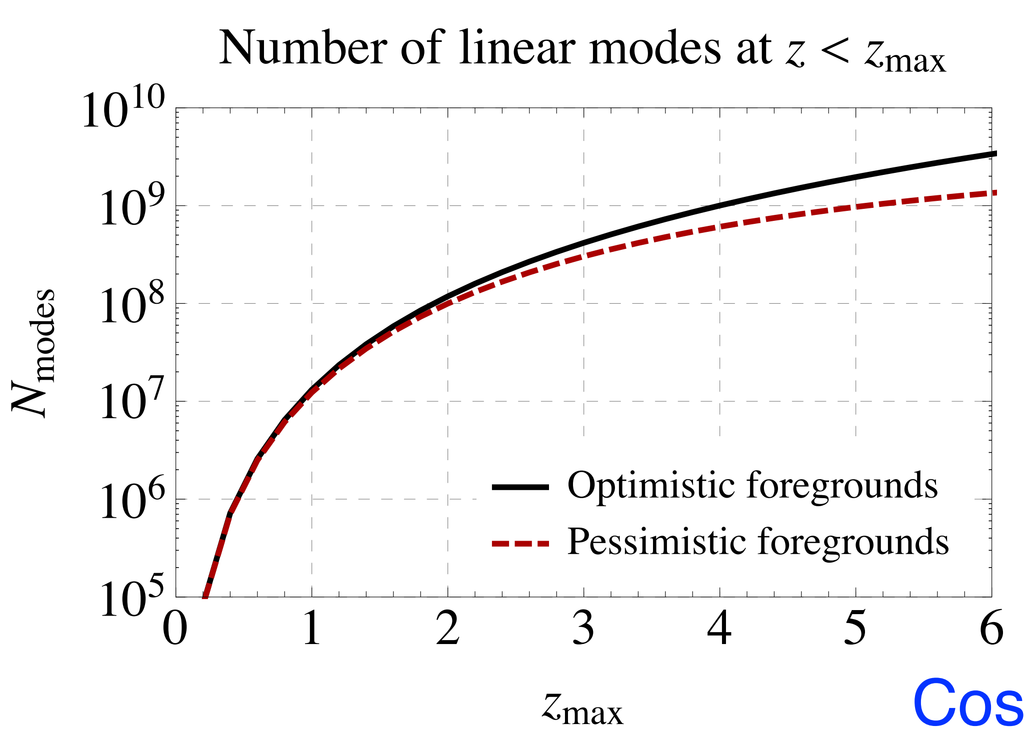
→ Intensity Mapping and H_I as the tracer → PUMA

Primordial Non Gaussianities from LSS / 21cm IM

…

Hydrogen Intensity Mapping Experiment



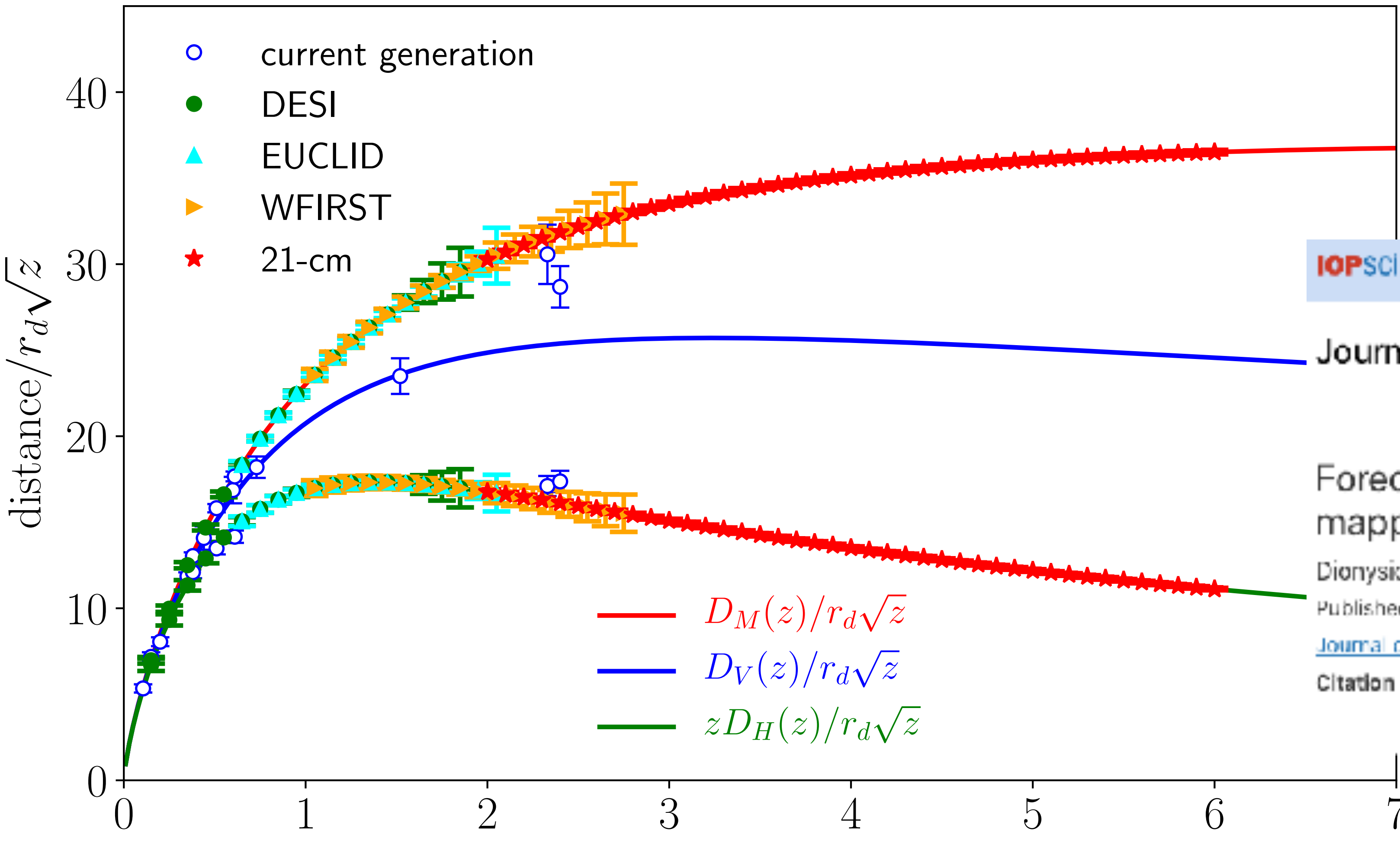


HIME potential for DE & BAO

Huge volume, redshift range

https://www.puma.bnl.gov

Cosmic Visions HIME , A. Slosar et al, arXiv:1810.0957

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Journal of Cosmology and Astroparticle Physics

Forecasts on primordial non-Gaussianity from 21 cm intensity mapping experiments

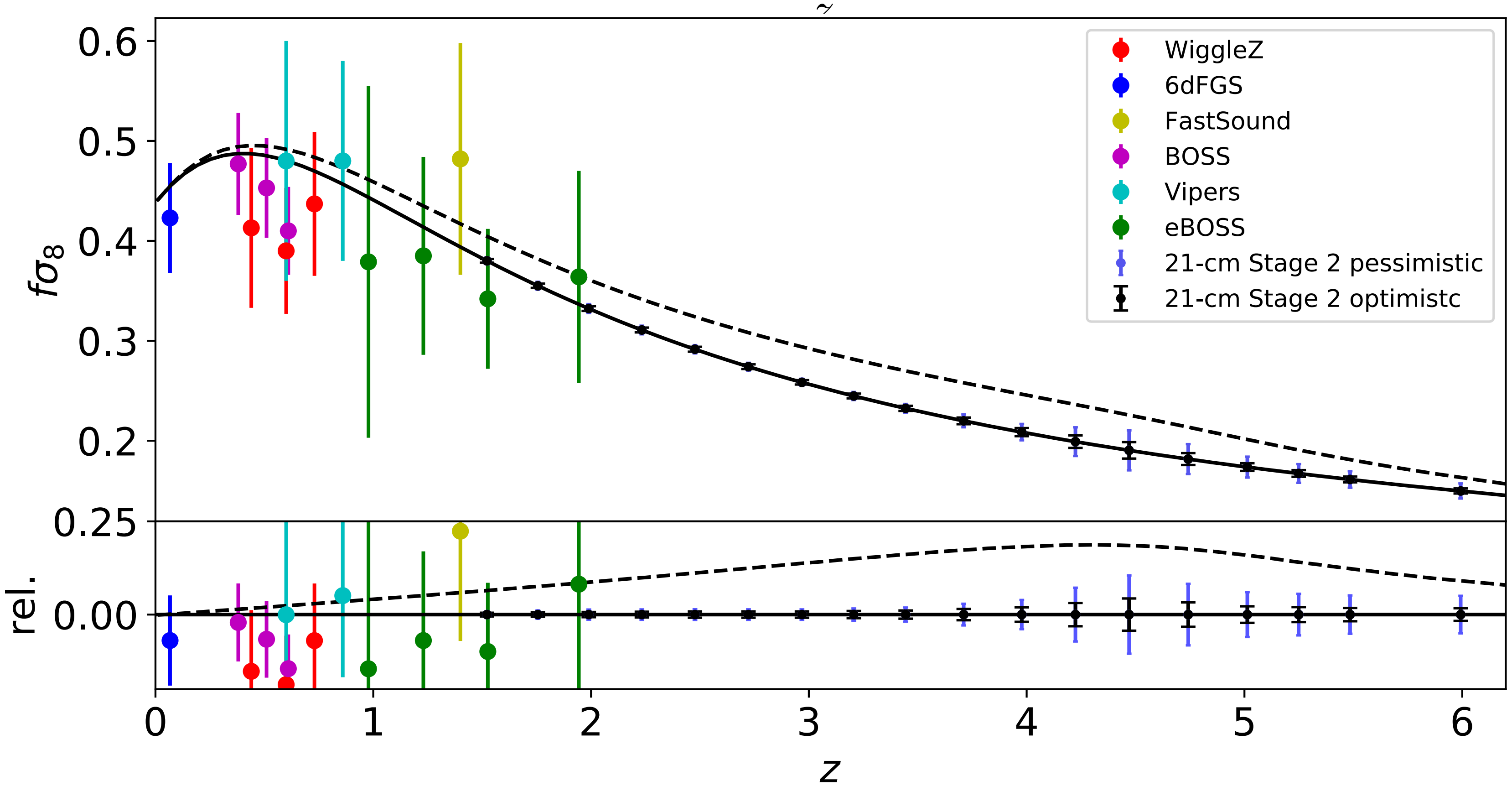
Dionysios Karagiannis[a,c], Anže Slosar[b] and Michele Liguori[a,c]

Published 25 November 2020 • © 2020 IOP Publishing Ltd and Sissa Medialab

Journal of Cosmology and Astroparticle Physics, Volume 2020, November 2020

Citation Dionysios Karagiannis et al JCAP11(2020)052

Primodial NG from 21cm LSS ,
Karagiannis et al,
arXiv:1911.03964



Cosmic Visions HIME , A. Slosar et al, arXiv:1810.0957

END