COSMOLOGY & FUNDAMENTAL PHYSICS

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High-level questions

- Nature of Dark Matter ?
- Nature of Dark Energy / Gravity at the largest scales ?
- Physics of the initial conditions (inflation) ?
- How constant are fundamental constants ?

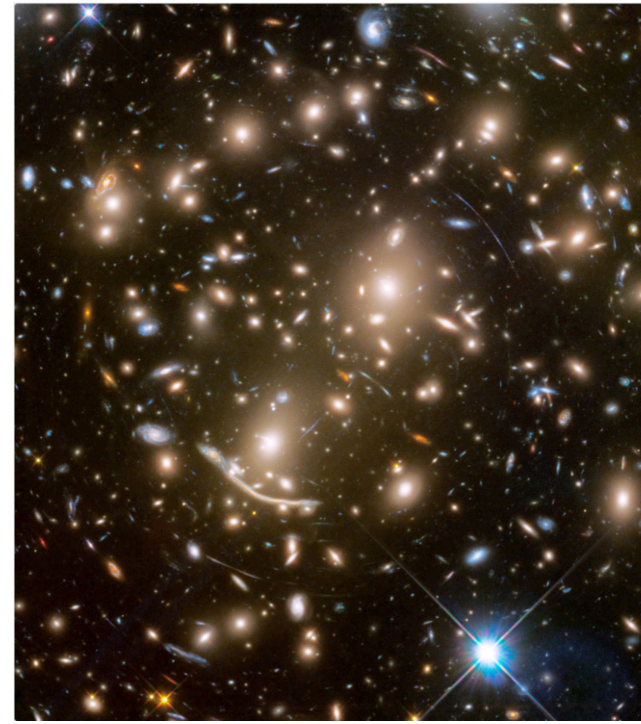
Implications for the physics beyond

➔ the Standard ΛCDM Cosmological Model

➔ the Standard Model of particle physics

Lots of astrophysics to learn in the process!!

DM nature & cosmic structure formation

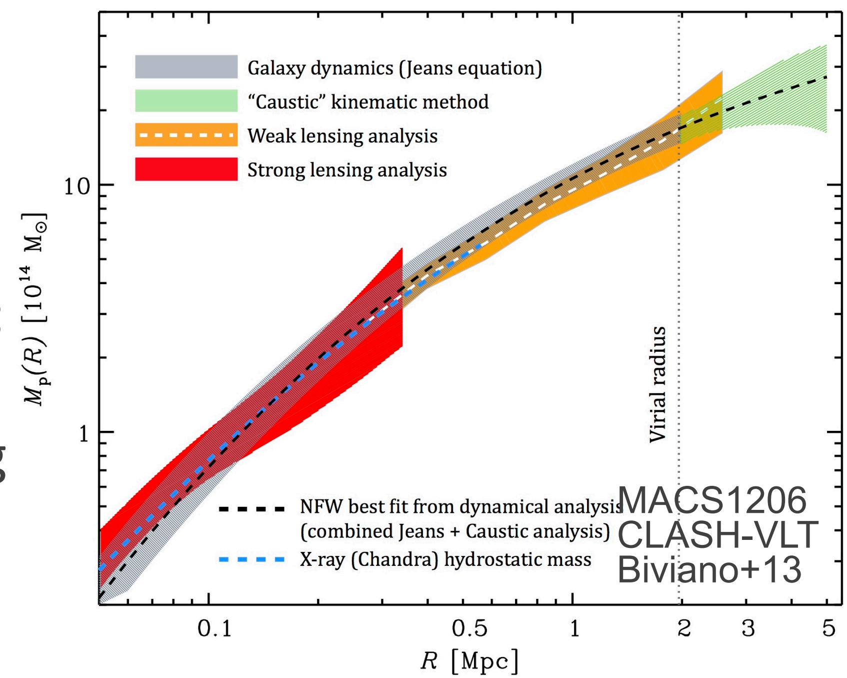


Breakthrough: unveiling DM nature (condensate? self-interacting? decaying? etc.)
➔ candidates: SUSY/WIMPS,axion-like, gravitinos, sterile neutrinos, light scalar field, PHS, etc.

Signatures:
➔ free streaming scale
➔ halo shapes and substructures
➔ effect on expansion history

How to probe DM nature?
➔ Small-scale observables:
- Dynamics of dwarf galaxies(e.g. **GAIA**) and groups/clusters (e.g. **CLASH**)
- Strong lensing in clusters and galaxies: JWST, **Euclid**, **LSST**, WFIRST

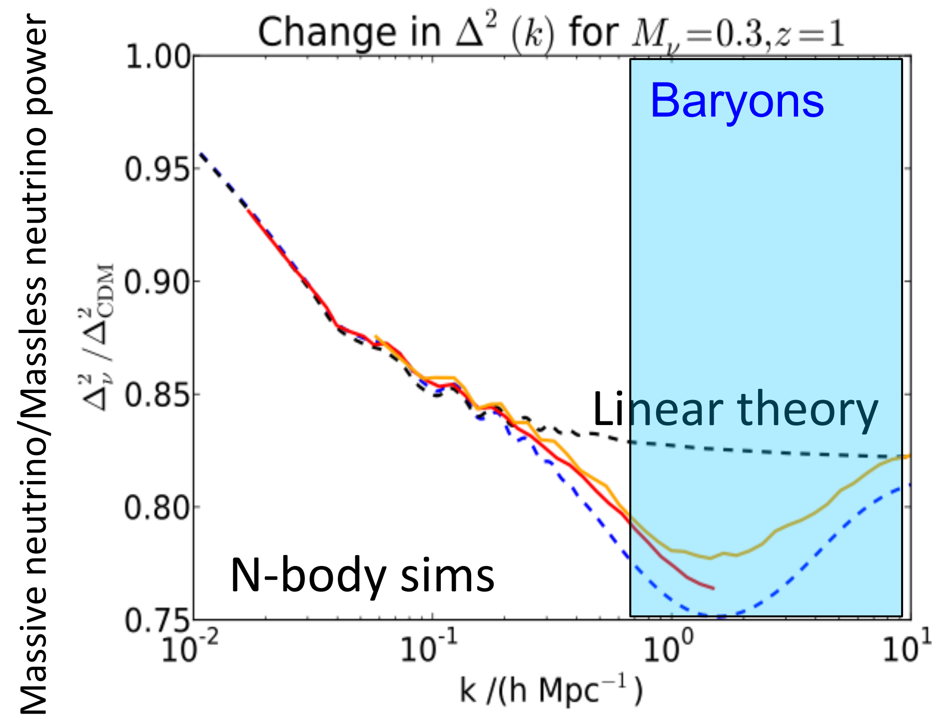
➔ Medium scales: galaxy clustering, weak lensing and IGM (DES, **Euclid**, DESI, **LSST**, **SKA,** WFIRST, **E-ELT**)



DM nature & cosmic structure formation

Neutrino masses: constrained by cosmology to a precision higher than particle physics experiments:

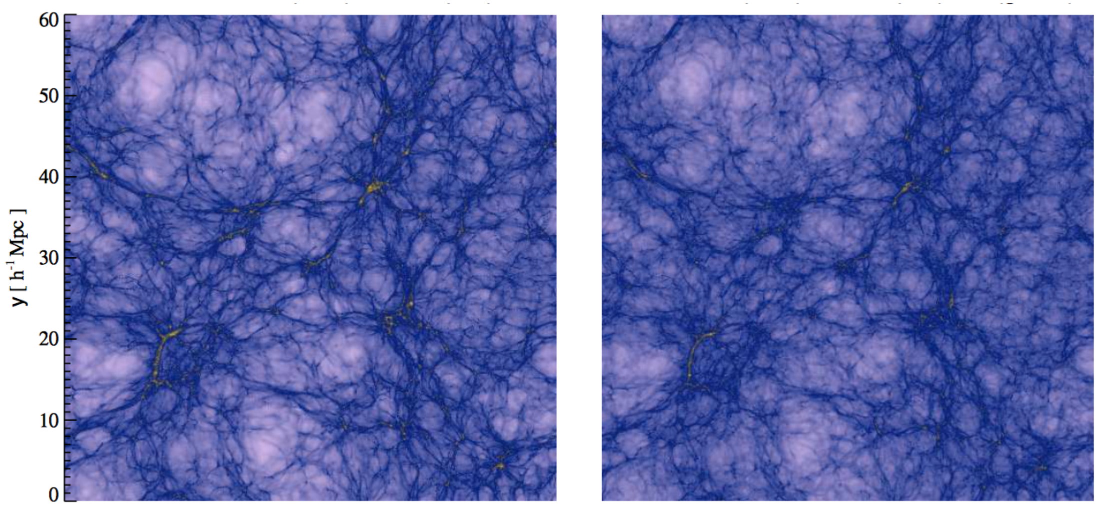
Particle physics:	0.06 eV < m_ν <6 eV
Cosmology:	m_ν<0.12 eV

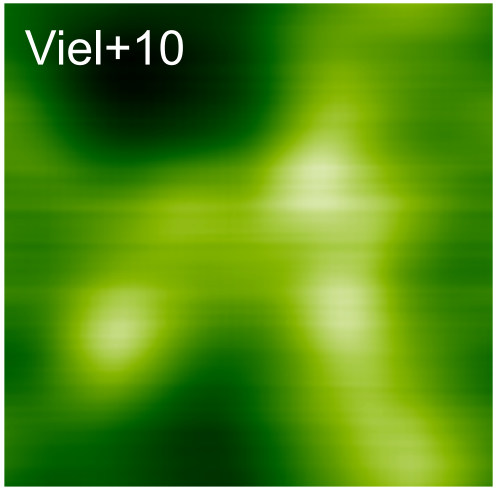


From dynamical probes (LSS/IGM) + CMB

➔ Medium-large scales: low res. investigations with lots of statistics (i.e. SDSS, **Euclid/LSST, SKA,** WFIRST)

➔ Small scales: high res. investigations (i.e. **HIRES**, strong lensing **Euclid/LSST, GAIA,** WFIRST)





DM nature from indirect detection

<u>Indirect DM detection:</u>

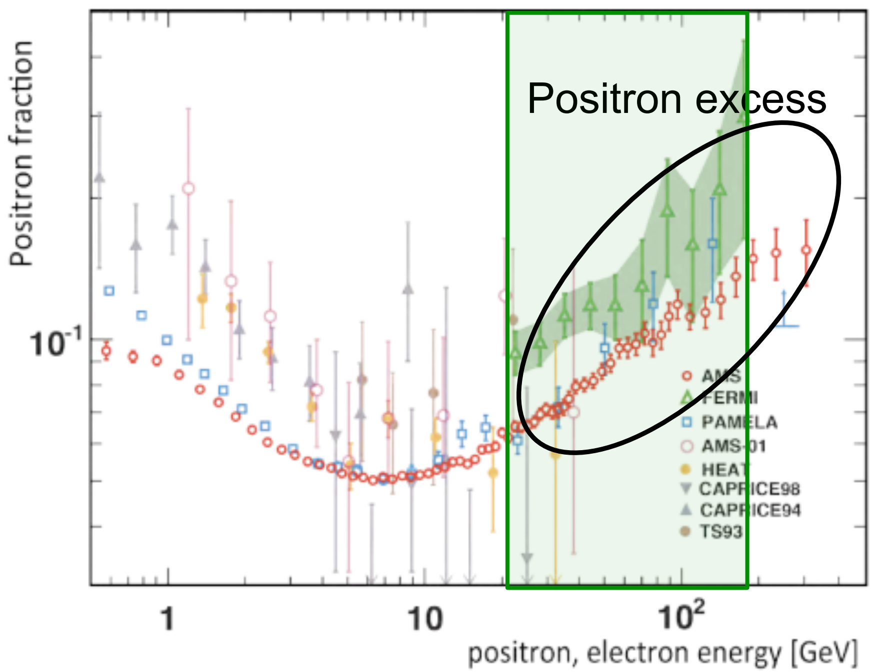
➔ID as the *best* way to detect the *cosmologically relevant* DM

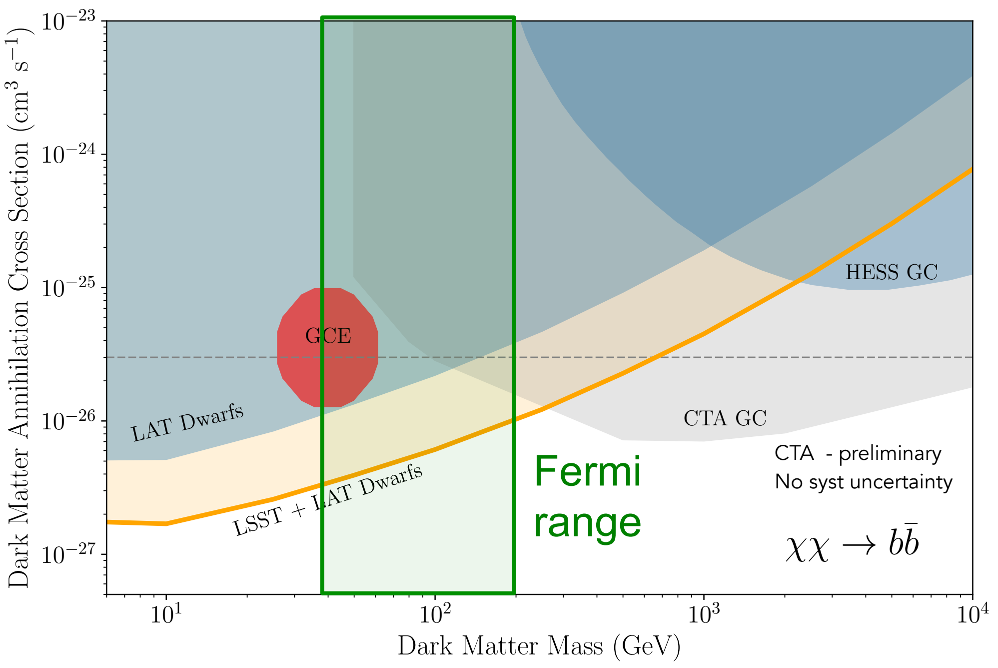
➔Complement to direct detection methods and accelerator searches.

➔Look for *unambiguous* signature of DM annihilation, decay or interactions in cosmic rays, *neutrino* and gamma-ray sky

➔ID strategy requires input from Cosmology and Particle Physics.

- DM from Cosmic Rays (Fermi, AMS, Pamela)
- CTA observations at [0.1,10] TeV to investigate the nature of the excess.





DM indirect detection in γ- and X-rays

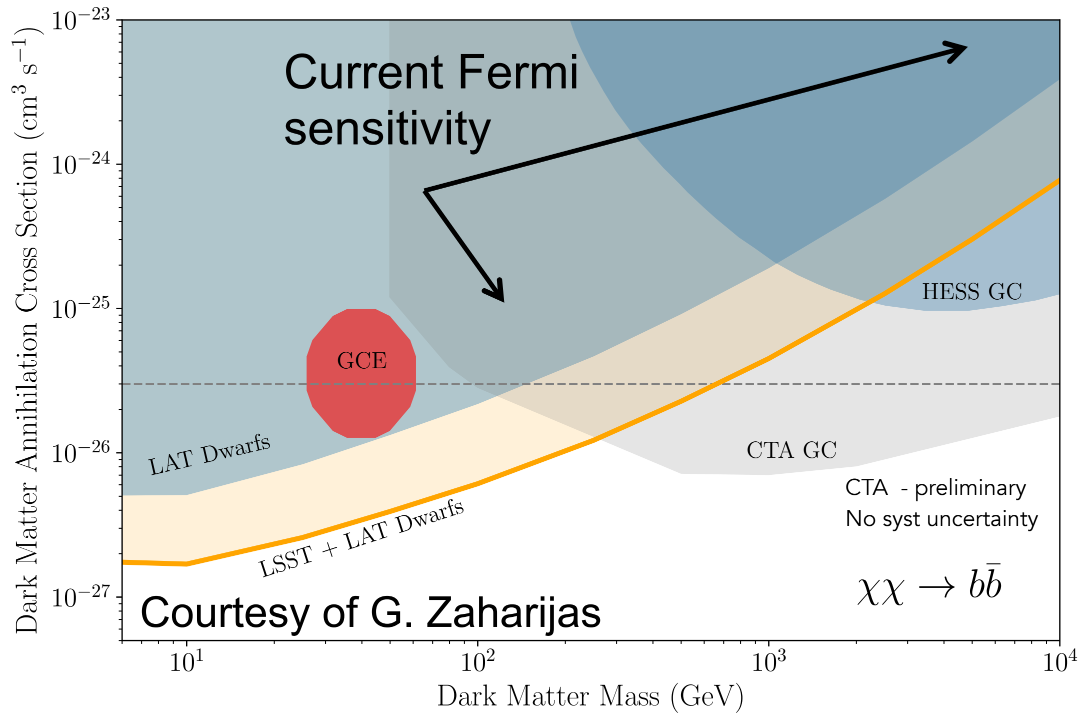
γ-ray range as the "golden channel" for ID

➔ Huge scientific success of Fermi, able to set DM strong constraints:

- **The gamma ray emission from Dwarf Spheroidals of the satellite galaxies, gamma-ray background (see plot)**
- Gamma-ray flux from diffuse gamma extragalactic background (spectrum anisotroipies).
- **"Fermi excess" from the Galactic Center (also in the plot).**

➔ These constraints are effective. (i.e below thermal x-section) for candidates lighter than ~ 1TeV.

➔ CTA to push this limit to higher masses



Soft X-rays: detection of a decaying DM particle (e.g. sterile neutrinos at ~3.5 keV) ➔ Athena to have unique sensitivity for this DM search

Hard X-rays: next generation optics for improved sensitivity and resolution up to 300 keV

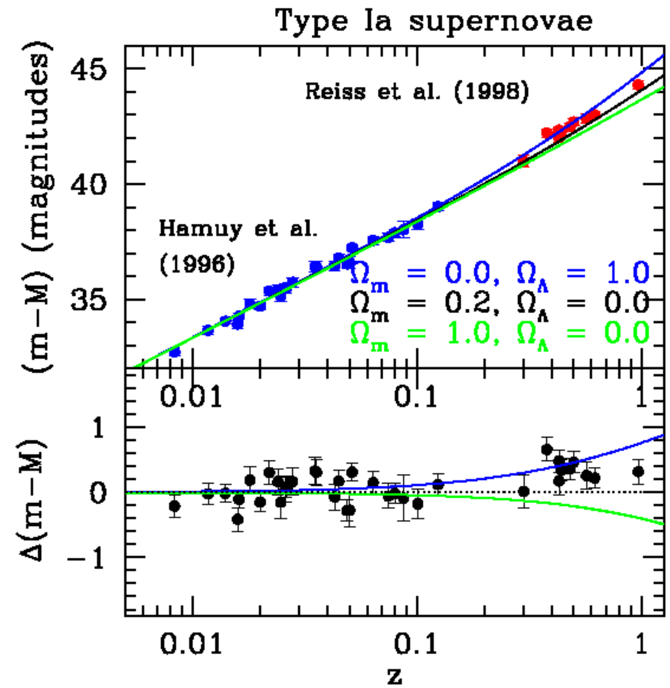
Dark Energy / Modified Gravity

Why?

To explain accelerated expansion

$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}\left(\rho + \frac{3p}{c^2}\right) \qquad p = w\rho c^2 \; ; \quad w < -1/3$$

$w = -1$: Cosmological constant
Agrees with all data



Which physics?

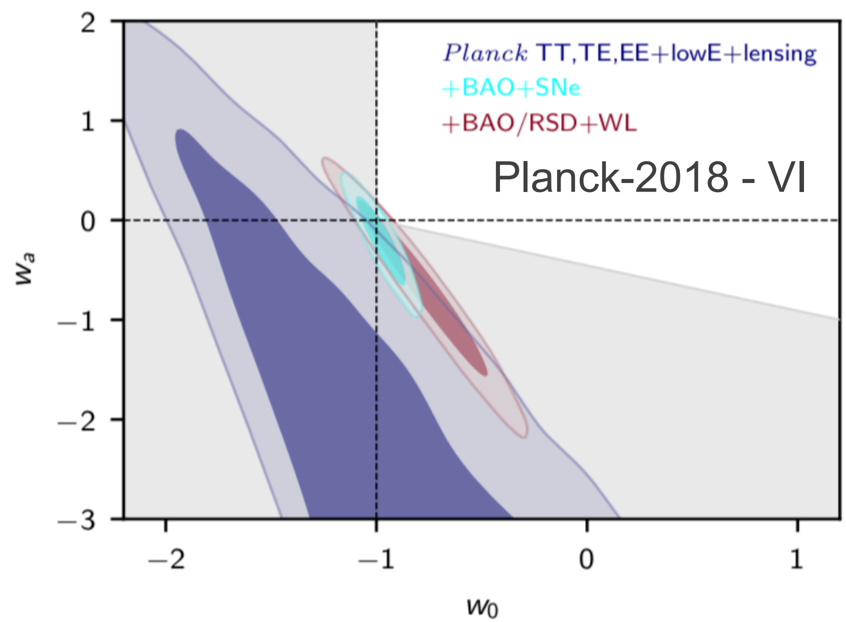
Don't know, but should explain why $\rho_\Lambda^{oss} \simeq 10^{-120}\,\rho_\Lambda^{teor}$

Extra scalar degree of freedom in field equations

Signatures:

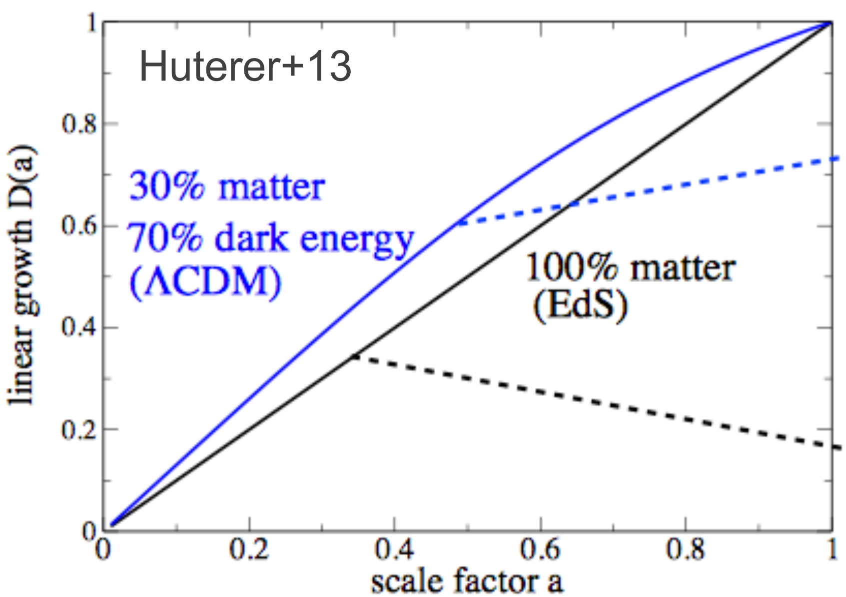
- expansion rate: SN-Ia, BAO, CMB
- growth of structures: RSD, cosmic shear, galaxy clusters, ISW, ...

<u>Key science driver</u> of all ongoing and future surveys: DES, eROSITA, DESI, **LSST**, **Euclid**, **SKA**, WFIRST

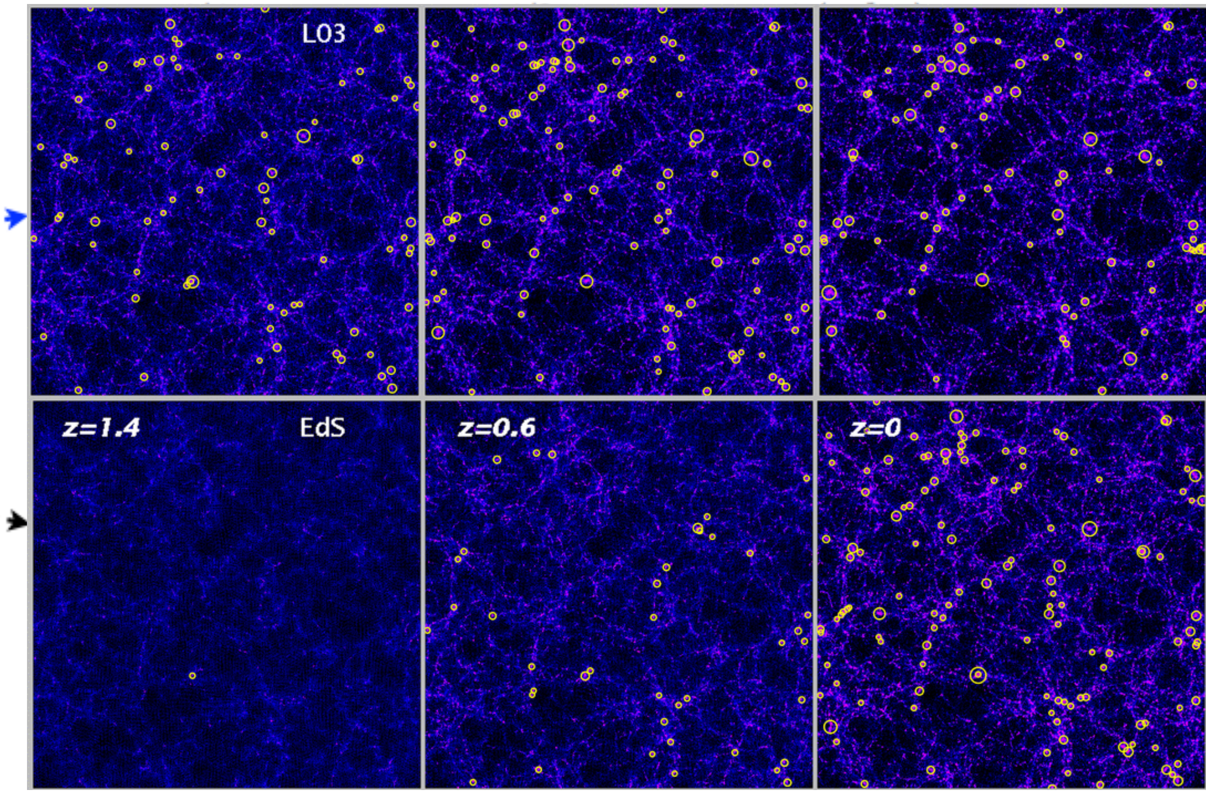


Expansion and Growth

➔ One-to-one relationship between expansion and growth



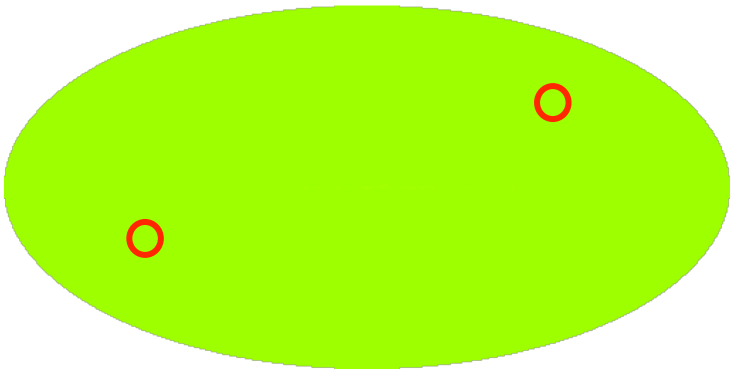
SB & Guzzo 01



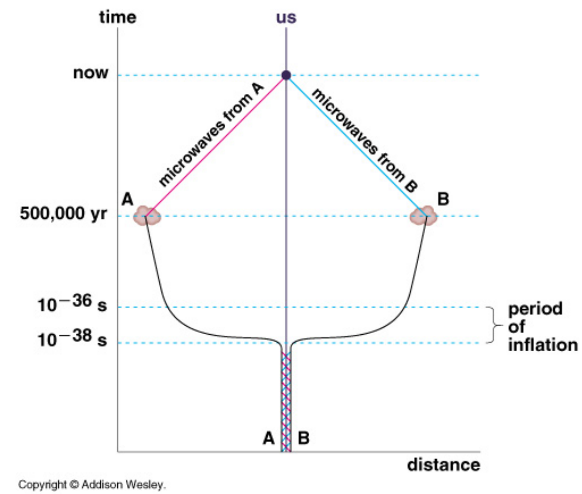
Inconsistencies between expansion and growth
➔ Signature for new physics

Initial conditions: inflation

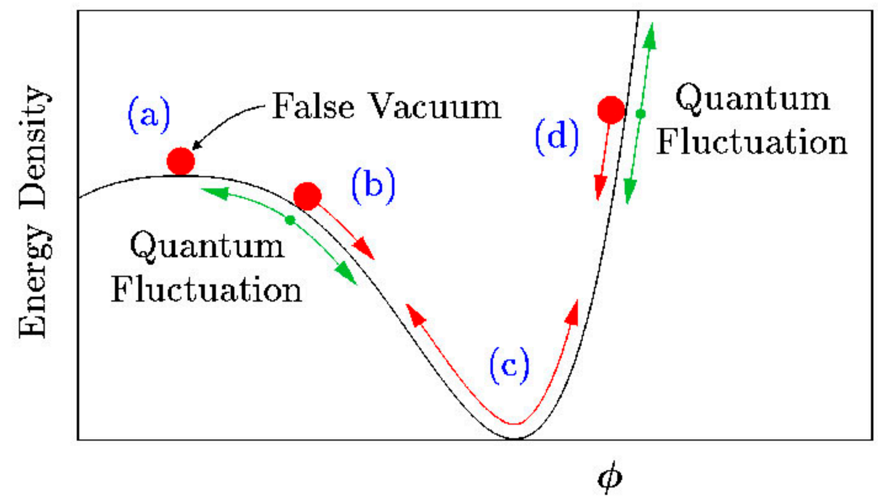
Why? To solve the “horizon problem”



How? Phase of accelerated expansion



Which physics? Expansion dominated by “false vacuum” energy in the potential of a scalar field, slowly rolling to the “true vacuum”



Features and predictions:

- No topological defects within the horizon
- ~ flatness Ω_k~0
- ~ Gaussian density perturbations f_{NL}<<1
- Spectrum of density perturbations:
  $P(k) \sim k^n$; n~1, dn_s/dk~0
- Spectrum of tensor perturbations (GW): B-modes in the CMB polarization

- Agreement with all CMB and LSS data
- Precise measurement as a probe of physics of inflation

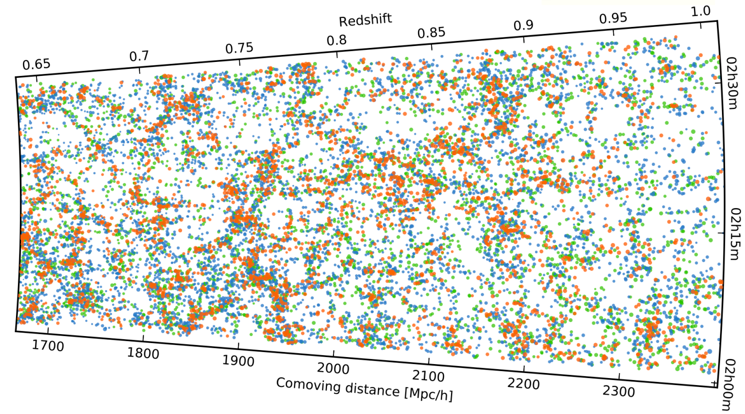
LSS: Combining imaging & spectroscopy

$$ds^2 = a^2(\tau)\left[-\left(1+\frac{2\Phi}{c^2}\right)c^2 d\tau^2 + \left(1-\frac{2\Psi}{c^2}\right)dl^2\right]$$

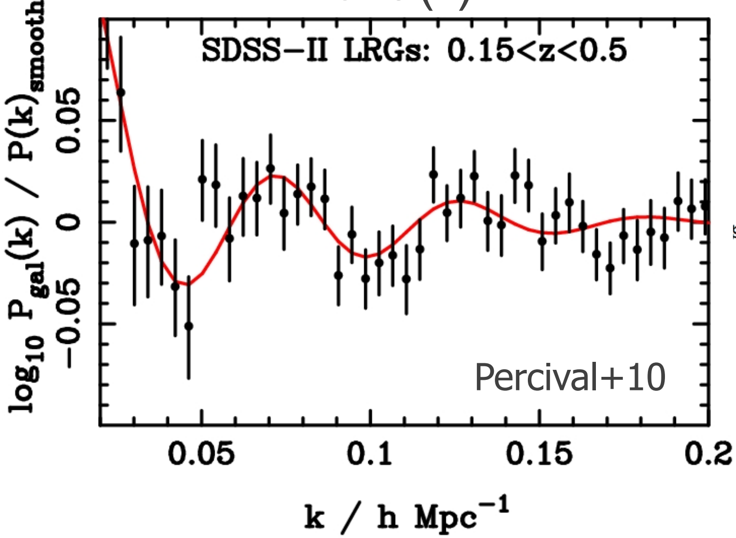
Φ : governs motion of matter

$\Phi + \Psi$: governs motion of light

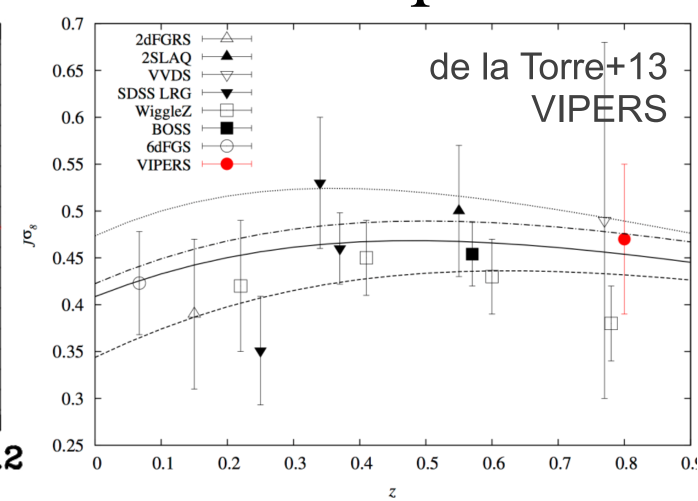
$\boxed{\Phi = \Psi \text{ for GR}}$



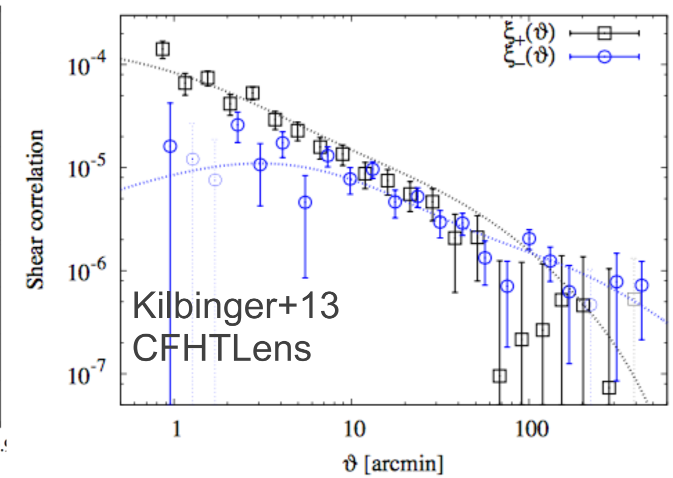
BAO: a(τ)



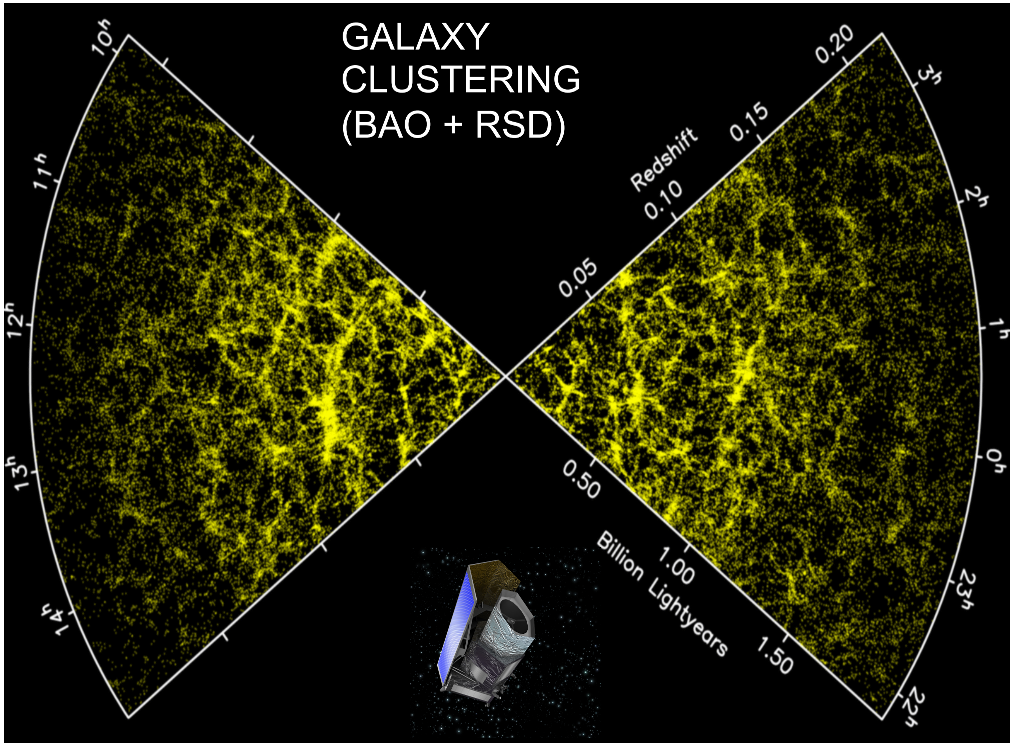
RSD: Φ



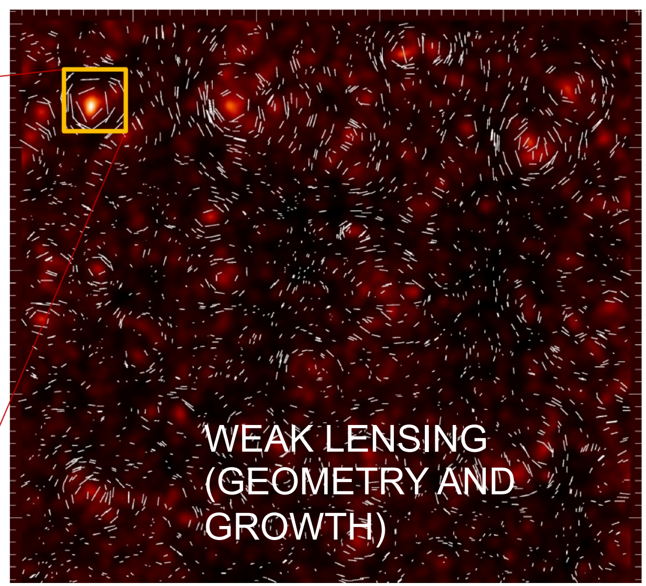
Cosmic shear: $\Phi + \Psi$



Euclid(/LSST) – THE cosmology experiment



GALAXY CLUSTERS (GEOMETRY AND GROWTH)



- Visible imaging (1 band)
- Infrared imaging (Y,J,H)
- Infrared slitless spectroscopy
- Launch 2021

- 15,000 deg^2 survey
- Images for 2x10^9 galaxies
- Spectra for ~4-5 x 10^7 galaxies (0.9<z<1.8)

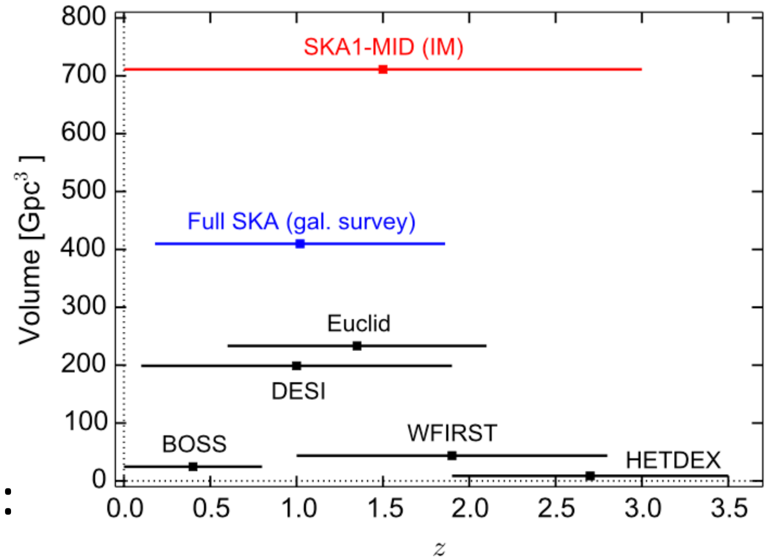
Objectives:

- Build a map of dark and luminous matter over 1/3 of the sky and to z~2
- Unveil the nature of dark matter
- Trace the origin of cosmic acceleration
- Use multiple probes → max control over systematic errors

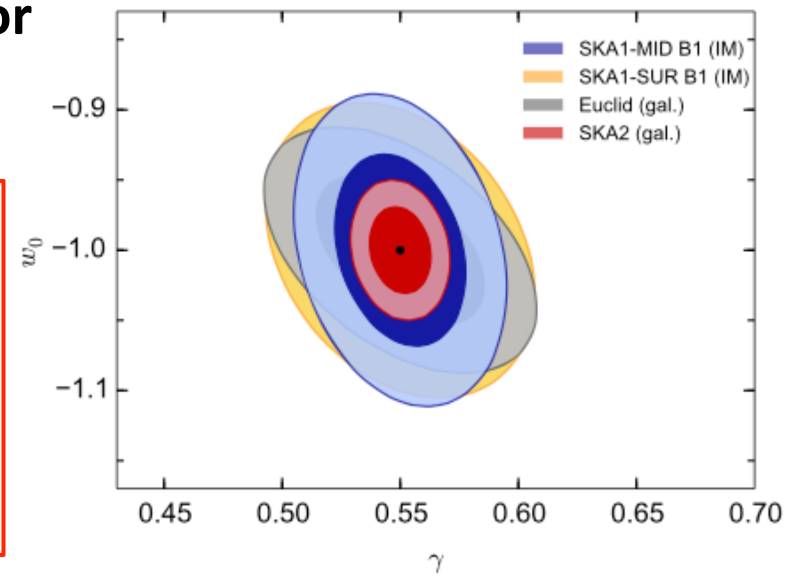
SKA – Surveys for Cosmology

1. **HI Intensity Mapping** [BAO, super-horizon, etc.]
   All-sky (3π sr); low-res. >30'; 0<z<3

2. **HI Threshold:** galaxy redshift survey [BAO, RSD]
   SKA1: 5 10^6 gals @ z<0.5
   SKA2: ~10^9 gals @ z<2



3. **Continuum** [weak lensing, angular clustering, ISW]:
   → All-Sky Survey (~ 1-2" res.)
   → Weak Lensing Survey (0.5" res.):
   NB: Commensality with HI/Continuum surveys for galaxy evolution



Euclid + SKA: huge synergies
→ Scientific: beat systematics, complementary constraints, multi-tracers, etc.
→ Programmatics: e.g. simulations, likelihood definitions and coding, etc.

Distance indicators and expansion tests

Cosmology with SNe

DES will increase statistics by 10 (FoM~100)

Main limitation is spectroscopic follow-up

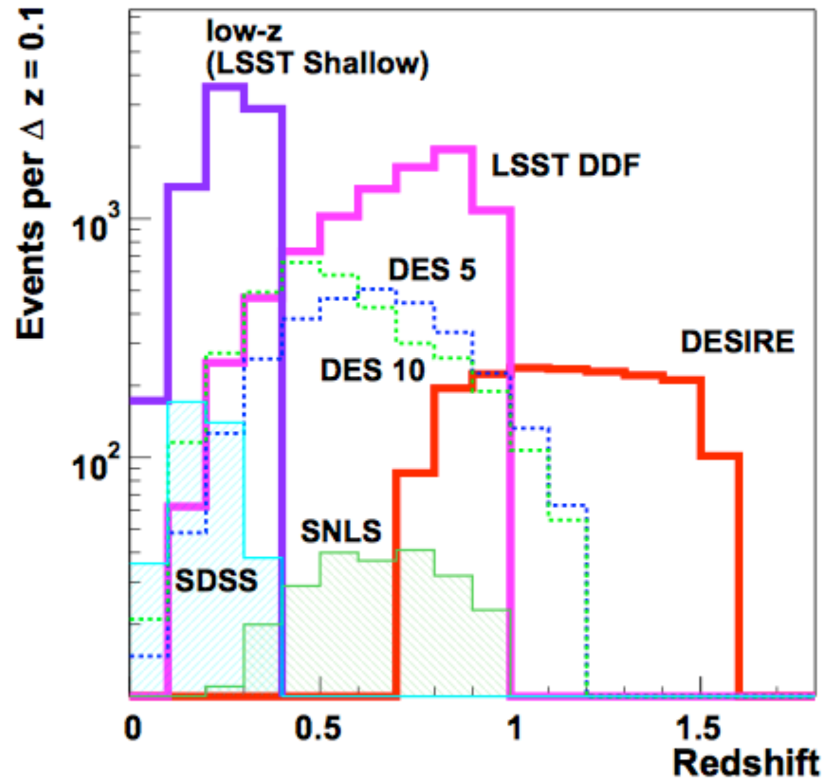
LSST will increase statistic by 100
100.000 SNIa in the range 0<z<1 (FoM ~150)

Spectroscopic follow-up is the bottle-neck

High-redshift SNIa, z>1 need near-IR from space

DESIRE: a proposal for a high-z **Euclid** SN search (Astier et al 2014) (FoM ~200)

Not a top priority for the mission



WFIRST : High-z SN search is a major component (180d of observing time)
The 2.4m mirror will assure not only light curves, but most important, live spectra

To date marginal European involvement

➔ Follow-up of a nearby sample is still very much needed for:
- anchoring the Hubble diagram, standardization of SNIa luminosity
- requires accurate (within few %) spectrophotometric calibration

SOXS proposal or the NTT

The lesson of the CMB (see talk by M. Bersanelli)

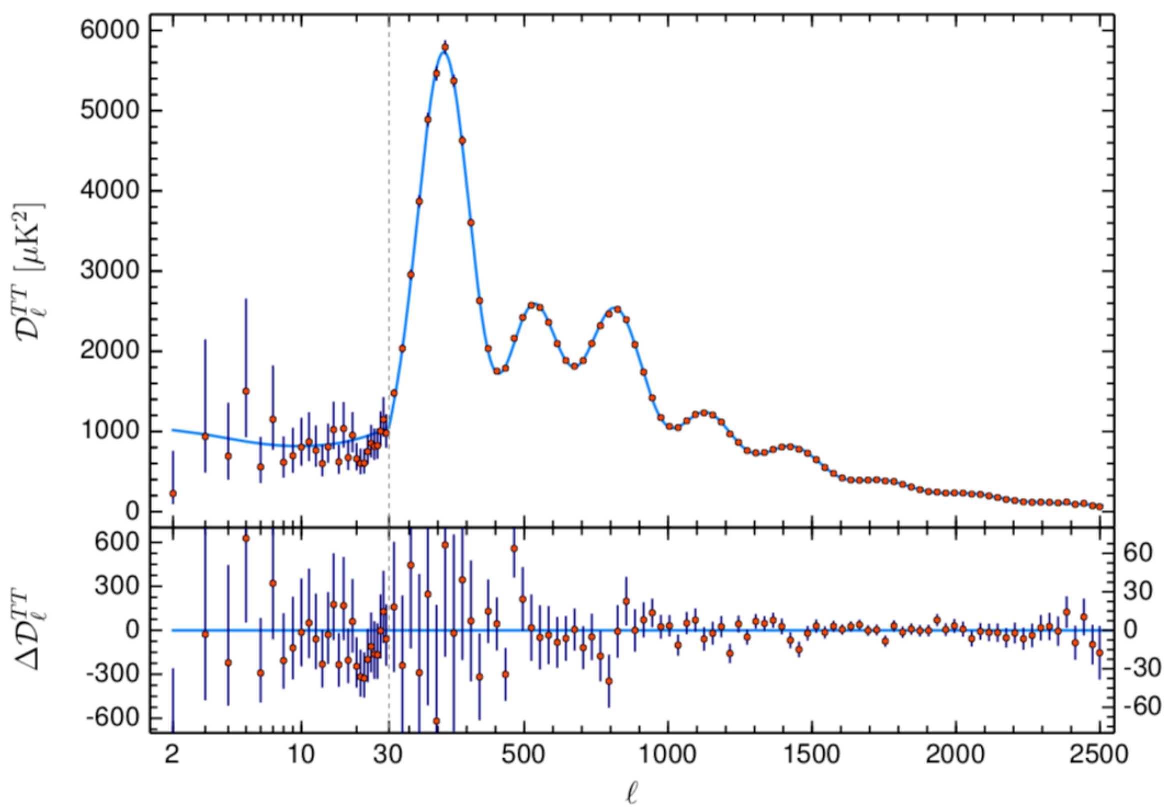
Difficult measurement, BUT: ➔ Everything is linear: $\Delta T/T \sim 10^{-5}$

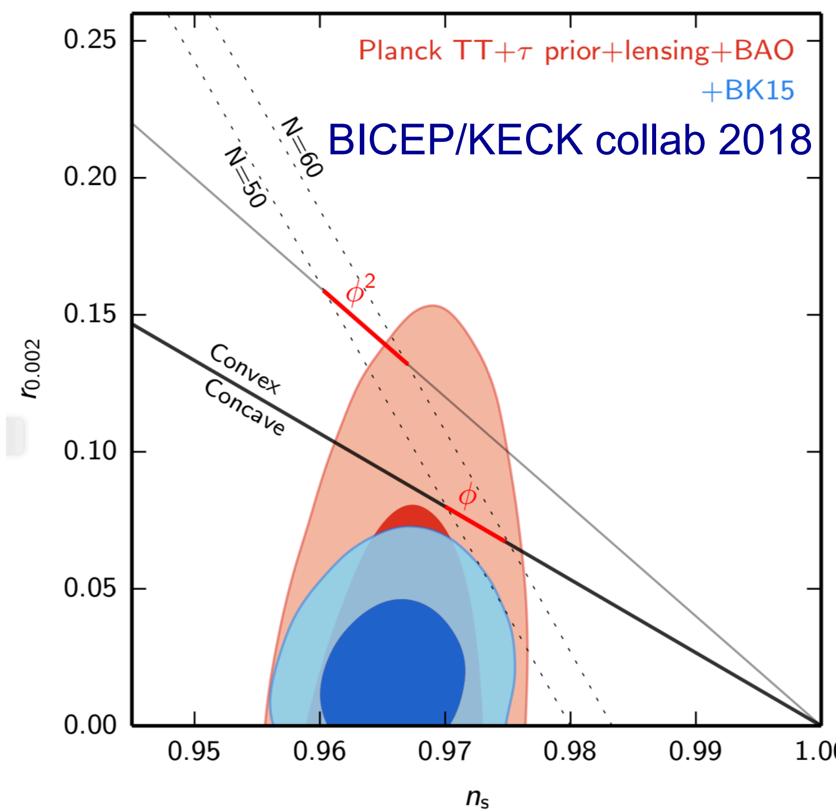
➔ Physics is well understood

➔ Undergoing transition from precise T measurements to precise **polarization** and **spectral distortion measurements**

Planck 2018 - VI: TT spectrum compared to base ΛCDM

BICEP2/Keck + WMAP + Planck joint analysis of B-mode polarization





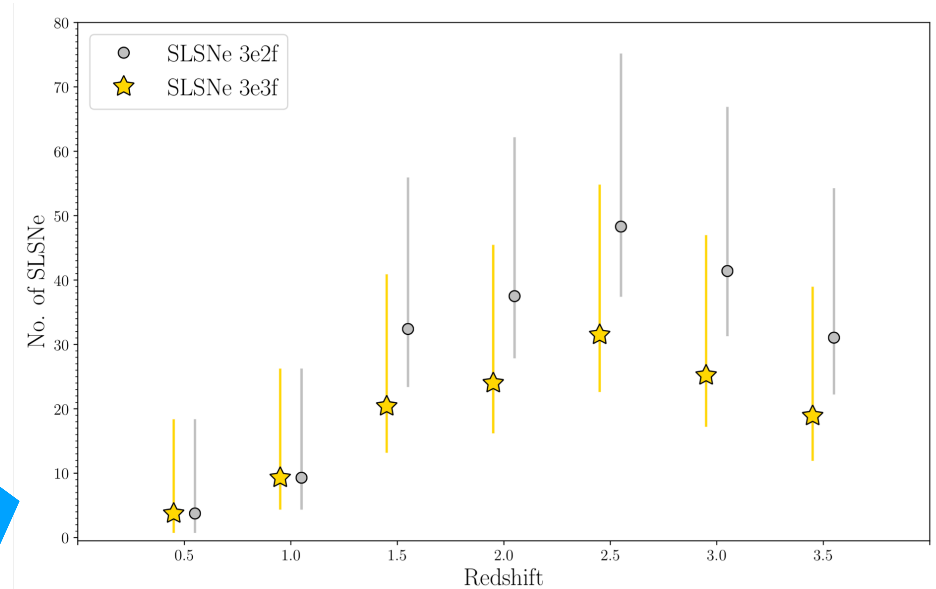
Distance indicators and expansion tests

Dark Energy with SNe

DES is increasing the statistics by 10 (DE FoM~100)

LSST will increase statistics by 100
100.000 SNIa in the range 0<z<1 (FoM ~150)

Euclid currently, not expected to give a significant contribution for SNIa (despite a dedicated survey could give FoM~200, Astier et al. 2014).
But … Super-Luminous SNe (SLSN) can be used to extend the Hubble diagram to z~3.5

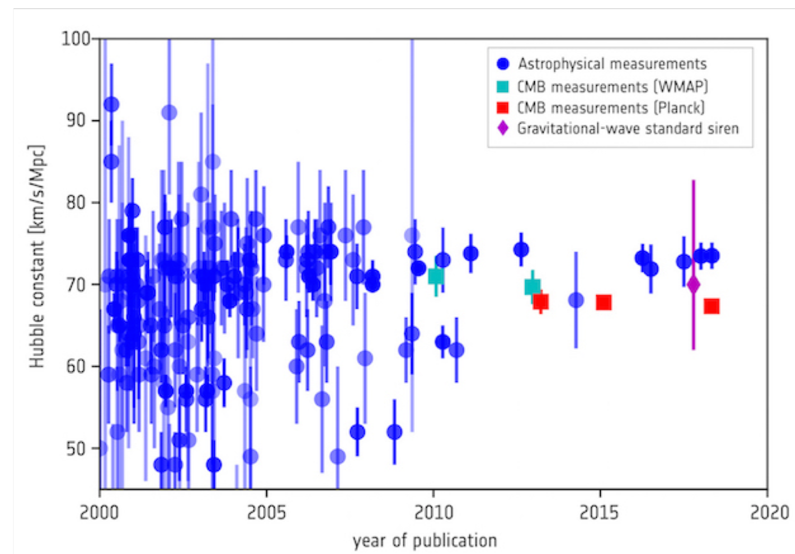


Inserra et al. 2019 A&A 609, A83

WFIRST : High-z SN search is a major component (180d of observing time)
Not only light curves, but most important, live spectra. *if/when ??*

H_0 tension

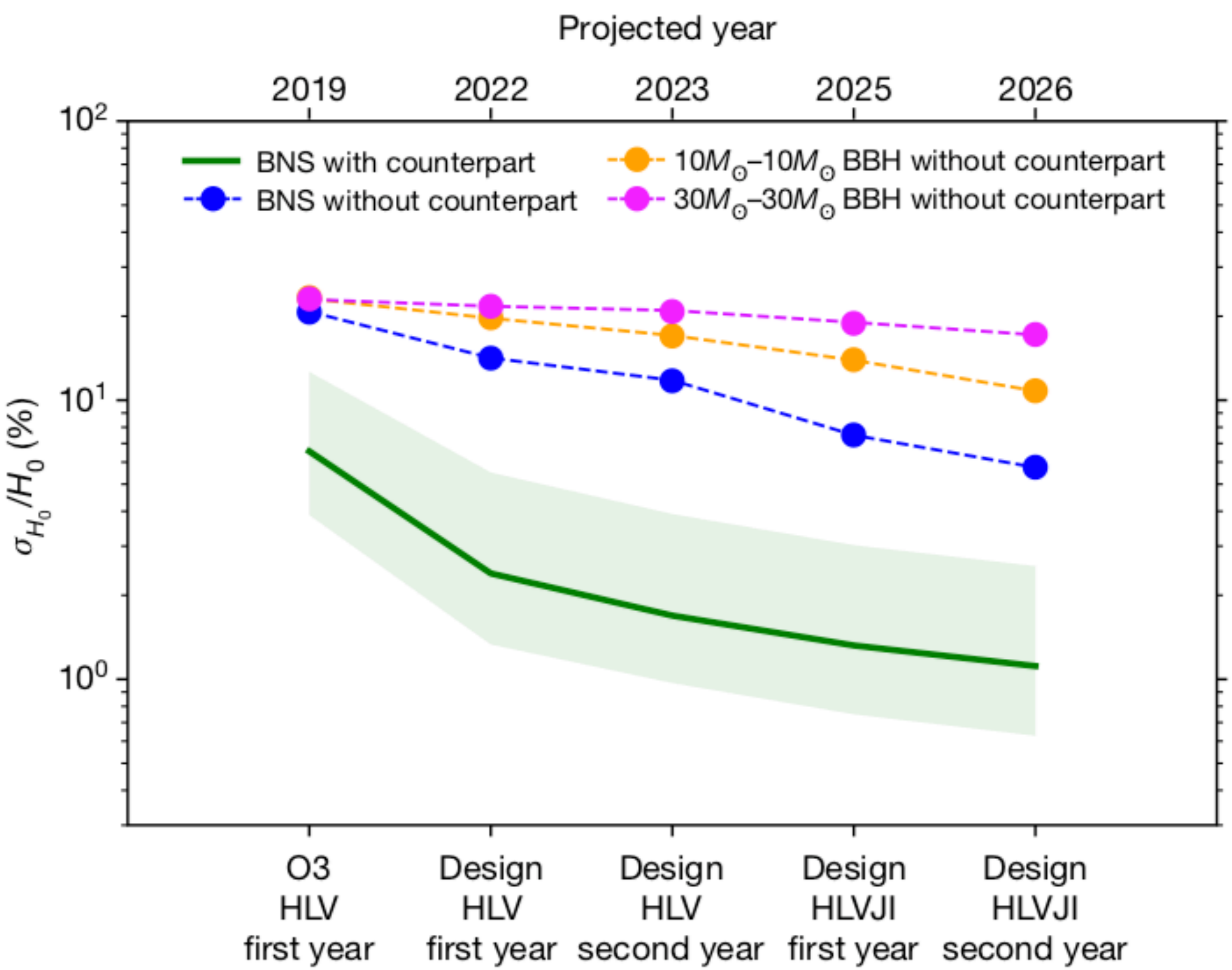
Follow-up of nearby SNe is needed for:
- understand systematics (evolution/diversity, reddening)
- standardization of SNIa in near infrared, SLSN calibration
- comparison with different luminosity distance calibrators (eg. SBF)



Spectroscopy is the bottle-neck → *SOXS at the NTT*

A new spectroscopic facility dedicated to transients

H_0 from standard sirens (GW)



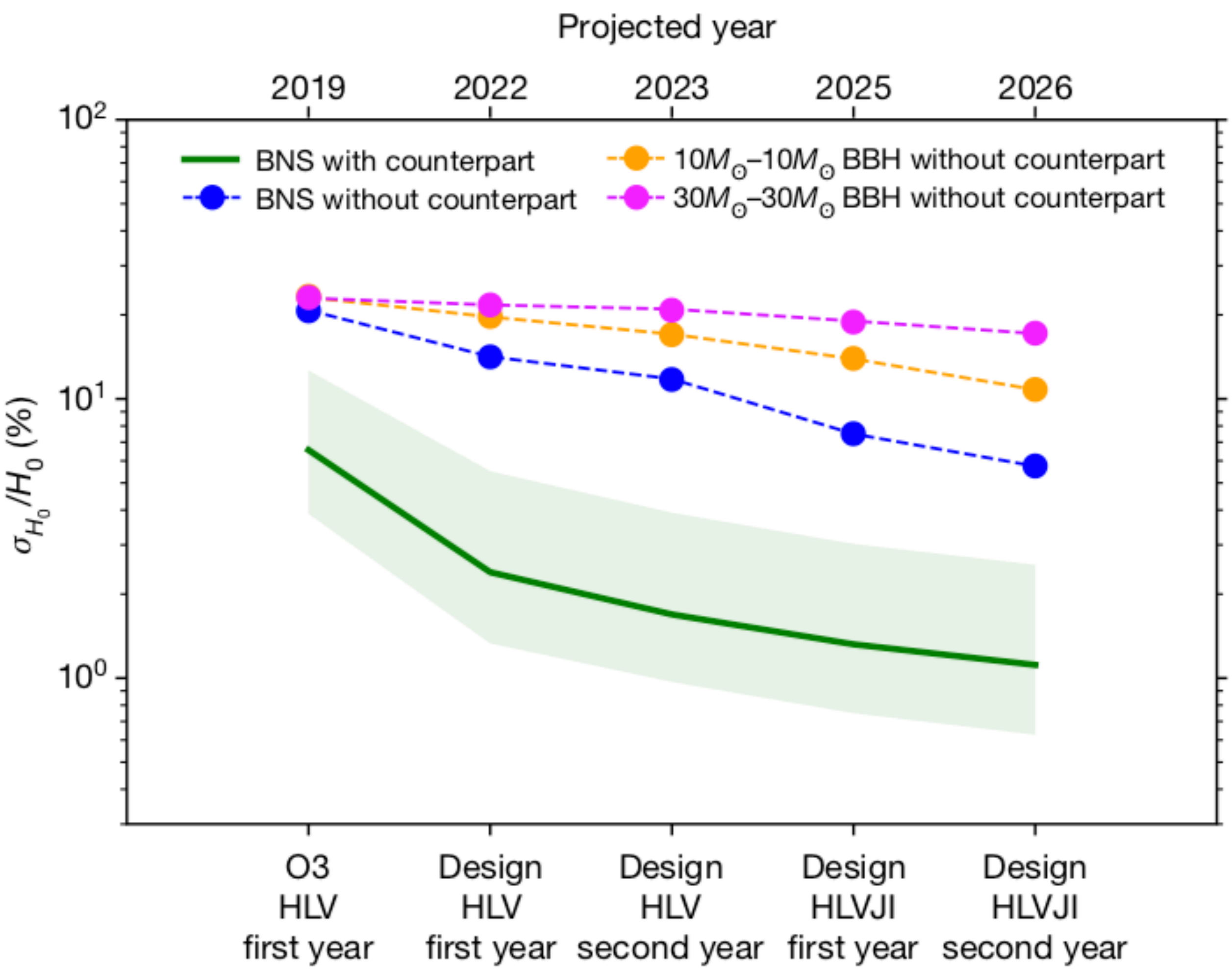
Abbott+2018:

➔Measurement of H_0 from GW170817, combining distance from GW signal with redshift of the EM counterpart

Chen+2018:

➔2% precision in H_0 measurement with Ligo+Virgo+KAGRA in 5 years

H_0 from standard sirens (GW)



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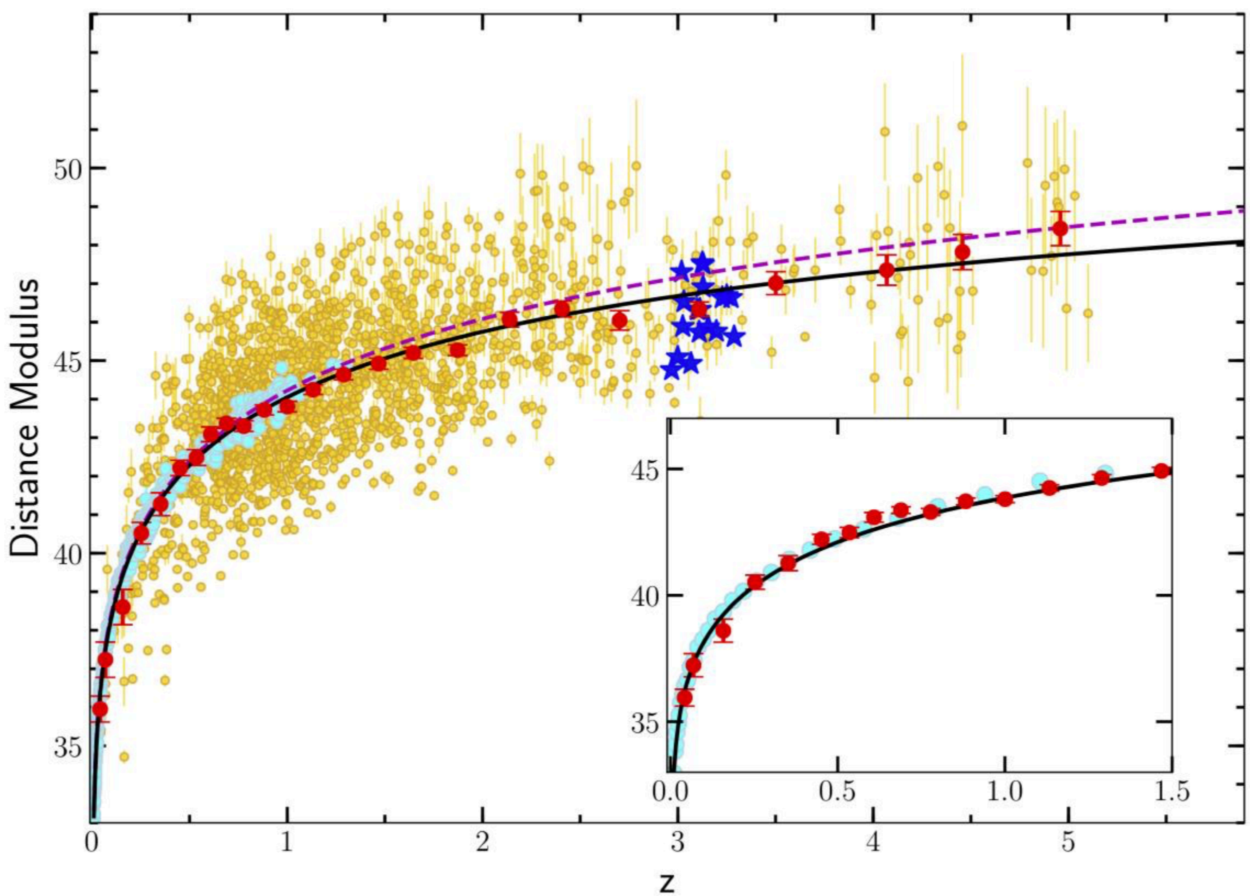
Quasars as distance indicators



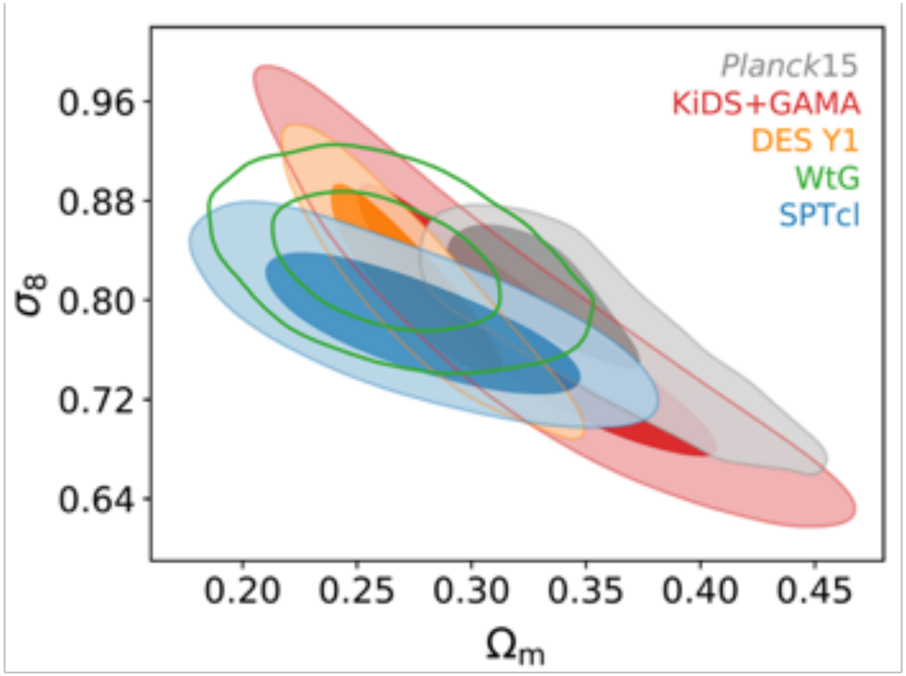
➔Breaking the z~2 limit of SN-Ia

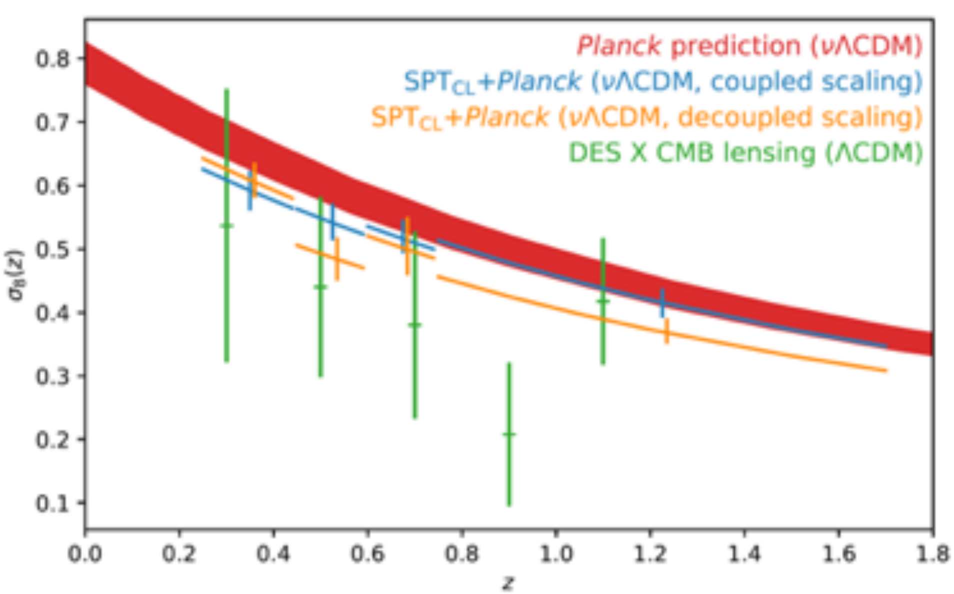
Risaliti & Lusso 2019:
➔Based on non-linear correlation between UV and X-ray quasar luminosities

➔Also GRB as distance indicators at z>2
Role of the THESEUS mission (Amati+2017)

Is there a σ_8 tension?

Bocquet+2018





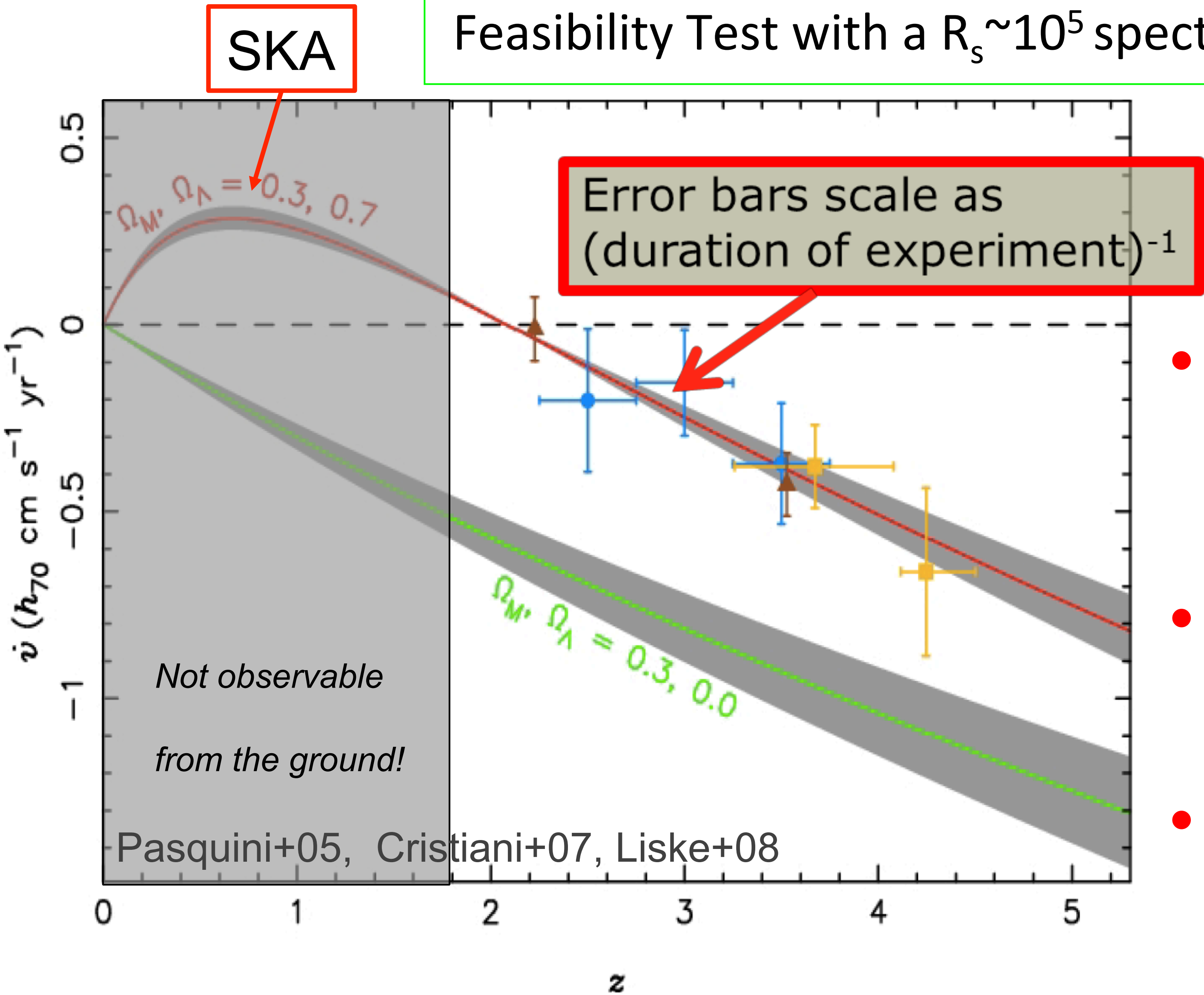
Independent low-significance indications for a tension between the amplitude of perturbations (σ_8)

➔ΛCDM-extrapolated from Planck measurements, and

➔ measured from low-z probes of cosmic growth (e.g. galaxy clusters, cosmic shear)

Sandage Test of Cosmic Expansion

Feasibility Test with a R_s~10^5 spectrograph at the E-ELT



- Different coloured points reflect different targeting strategies
- 4000 hrs on 39-m E-ELT over 21.5 years, *or*
- 1200 hrs on 39-m E-ELT over 40 years

How constant are fundamental constants?

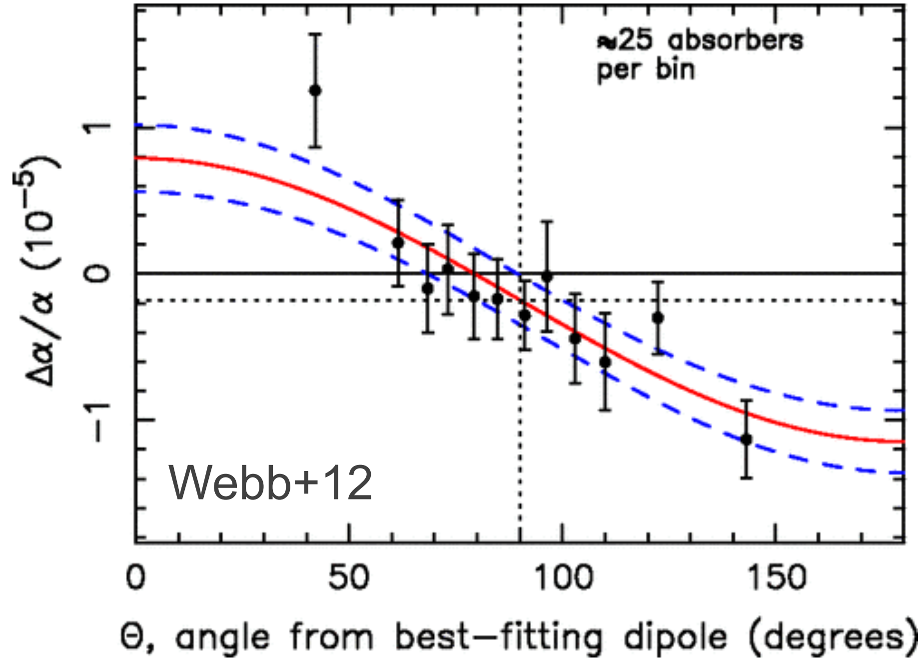
High-risk/high gain:
worth a bet!

- How to probe?
  - Alkaline-doublets: changes in frequency of atomic and molecular transitions
  - QSO-absorption systems of atomic or molecular gas
- Status
  - no variation of α with time ~ 5 ppm
  - consistent with spatial variation (at 4.1 σ)
  - but systematics…

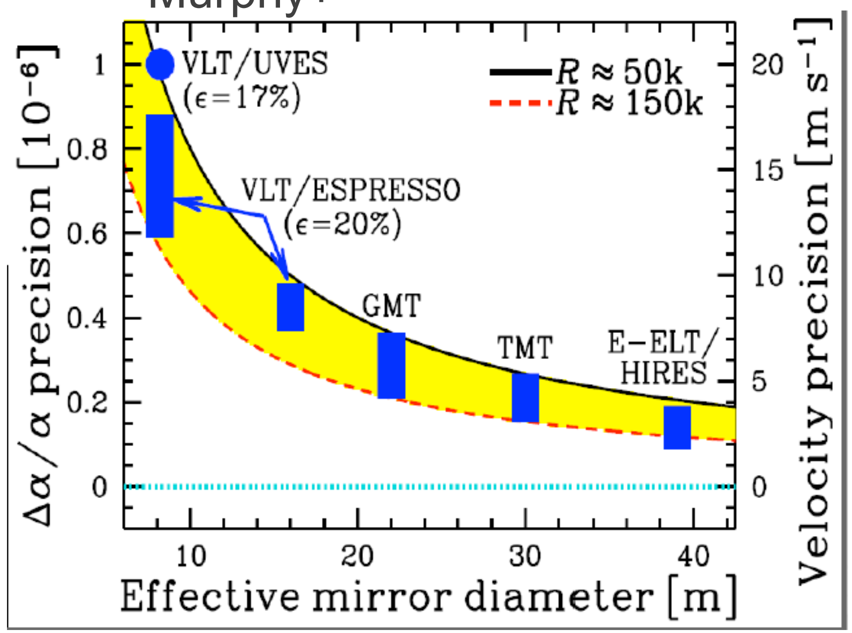
- Precision achievable with future facilities:
  - ESPRESSO@VLT first HR spectrograph designed for this science

- Should we push in some direction? E.g. HIRES
  - HIRES ~ one order of mag gain in sensitivity

- Role of Italian community?
  - Thanks to ESPRESSO could play a leading role in the next years



Murphy+



Programmatics (highly personal)

1. A unique strategy for cosmological surveys:
   - Euclid/LSST
   - SKA
   - Follow-up observations (4MOST, MOONS, MSE,...)
2. Which involvement in next-generation CMB experiments?
   - LSPE/STRIP
   - LiteBIRD (if selected)
   - ....
3. HPC: what next after CHIPP?
4. Coordination with ASI & INFN necessary
   Meeting "Euclid and Beyond" held in Rome (Feb 11-14)

➔ Cosmology as an intrinsically multi-disciplinary and multi-wavelength research field

➔ How to reflect this in the current INAF organization in "Raggruppamenti Scientifici Nazionali"?

A schematic summary

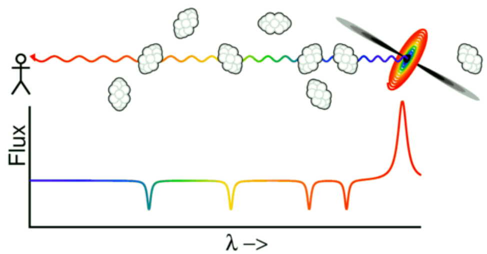
	Euclid (LSST)	SKA	E-ELT	CTA	Athena	CMB Stage-IV	HPC infrastructures
Nature of Dark Matter							
Nature of Dark Energy							
Gravity on large scales							
Physics of initial conditions							
Fundam. constants							

Highly relevant

Possibly interesting

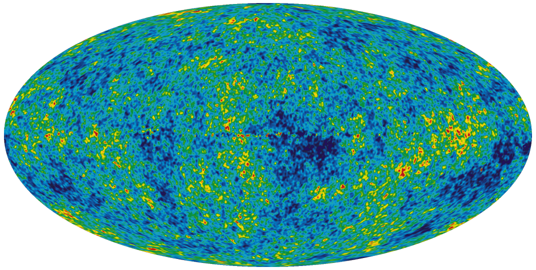
Not much relevant

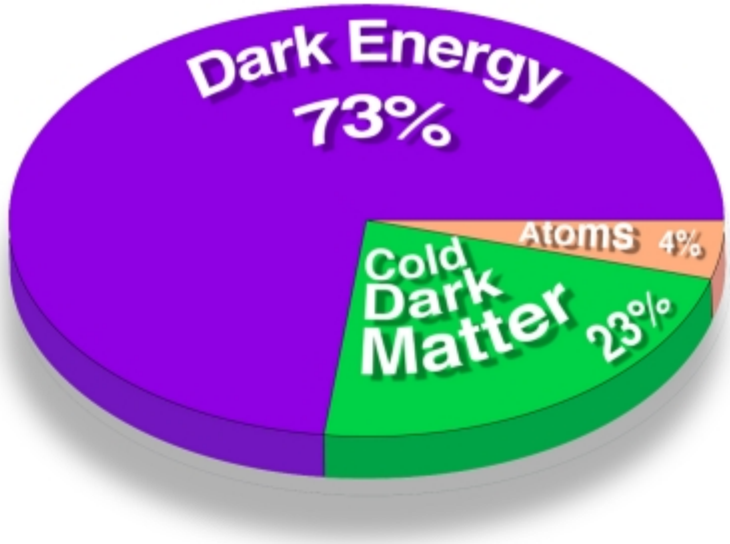
The “concordance” model



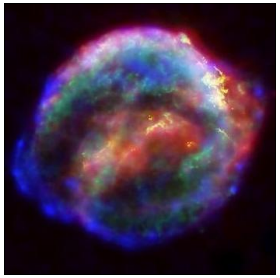
Ly-alpha forest

CMB



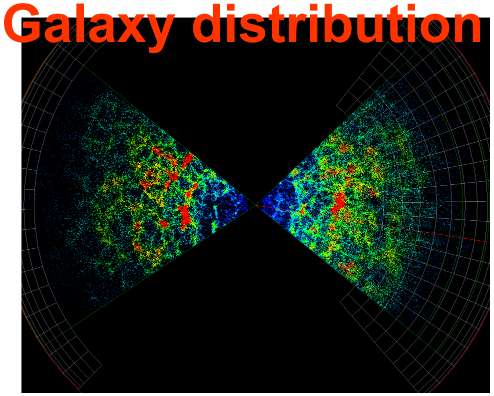


Sn-Ia



Gravitational lensing

Galaxy distribution



Galaxy clusters