Dark-energy constraints from forthcoming cluster and galaxy surveys

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PPC 2018 Workshop
Zurich 21/8/18

Overview

- A (very) brief and basic history of the concept of dark energy
- The current state of the art
- Two examples of unprecedented upcoming developments
- X-ray-detected galaxy clusters with eROSITA
- Higher-order statistics with the Euclid satellite
- Summary and conclusions

101 years ago

142 Sitzung der physikalisch-mathematischen Klasse vom 8. Februar 1917

Kosmologische Betrachtungen zur allgemeinen Relativitätstheorie.

Von A. Einstein.

Es ist wohlbekannt, daß die Poissonsche Differentialgleichung

$$\Delta\phi = 4\pi K\rho \qquad (1)$$

in Verbindung mit der Bewegungsgleichung des materiellen Punktes die Newtonsche Fernwirkungstheorie noch nicht vollständig ersetzt. Es muß noch die Bedingung hinzutreten, daß im räumlich Unendlichen das Potential ϕ einem festen Grenzwerte zustrebt. Analog verhält es sich bei der Gravitationstheorie der allgemeinen Relativität; auch hier müssen zu den Differentialgleichungen Grenzbedingungen hinzutreten für das räumlich Unendliche, falls man die Welt wirklich als räumlich unendlich ausgedehnt anzusehen hat.

Bei der Behandlung des Planetenproblems habe ich diese Grenzbedingungen in Gestalt folgender Annahme gewählt: Es ist möglich, ein Bezugssystem so zu wählen, daß sämtliche Gravitationspotentiale $g_{\mu\nu}$ im räumlich Unendlichen konstant werden. Es ist aber a priori durchaus nicht evident, daß man dieselben Grenzbedingungen ansetzen darf, wenn man größere Partien der Körperwelt ins Auge fassen will. Im folgenden sollen die Überlegungen angegeben werden, welche ich bisher über diese prinzipiell wichtige Frage angestellt habe.

§ 1. Die Newtonsche Theorie.

Es ist wohlbekannt, daß die Newtonsche Grenzbedingung des konstanten Limes für ϕ im räumlich Unendlichen zu der Auffassung hinführt, daß die Dichte der Materie im Unendlichen zu null wird. Wir denken uns nämlich, es lasse sich ein Ort im Weltraum finden, um den herum das Gravitationsfeld der Materie, im großen betrachtet, Kugelsymmetrie besitzt (Mittelpunkt). Dann folgt aus der Poissonschen Gleichung, daß die mittlere Dichte ρ rascher als $\frac{1}{r^2}$ mit wachsender Entfernung r vom Mittelpunkt zu null herabsinken muß, damit ϕ im

Einstein: Kosmologische Betrachtungen zur allgemeinen Relativitätstheorie 151

müßten wir wohl schließen, daß die Relativitätstheorie die Hypothese von einer räumlichen Geschlossenheit der Welt nicht zulasse.

Das Gleichungssystem (14) erlaubt jedoch eine naheliegende, mit dem Relativitätspostulat vereinbare Erweiterung, welche der durch Gleichung (2) gegebenen Erweiterung der Poissonschen Gleichung vollkommen analog ist. Wir können nämlich auf der linken Seite der Feldgleichung (13) den mit einer vorläufig unbekannten universellen Konstante $-\lambda$ multiplizierten Fundamentaltensor $g_{\mu\nu}$ hinzufügen, ohne daß dadurch die allgemeine Kovarianz zerstört wird; wir setzen an die Stelle der Feldgleichung (13)

$$G_{\mu\nu} - \lambda g_{\mu\nu} = -\varkappa\left(T_{\mu\nu} - \frac{1}{2} g_{\mu\nu} T\right). \qquad (13a)$$

Auch diese Feldgleichung ist bei genügend kleinem λ mit den am Sonnensystem erlangten Erfahrungstatsachen jedenfalls vereinbar. Sie befriedigt auch Erhaltungssätze des Impulses und der Energie, denn man gelangt zu (13a) an Stelle von (13), wenn man statt des Skalars des Riemannschen Tensors diesen Skalar, vermehrt um eine universelle Konstante, in das Hamiltonsche Prinzip einführt, welches Prinzip ja die Giltigkeit von Erhaltungssätzen gewährleistet. Daß die Feldgleichung (13a) mit unseren Ansätzen über Feld und Materie vereinbar ist, wird im folgenden gezeigt.

§ 5. Durchführung der Rechnung. Ergebnis.

Da alle Punkte unseres Kontinuums gleichwertig sind, genügt es, die Rechnung für einen Punkt durchzuführen, z. B. für einen der beiden Punkte mit den Koordinaten $x_1 = x_2 = x_3 = x_4 = 0$. Dann sind für die $g_{\mu\nu}$ in (13a) die Werte

$$\begin{matrix} -1 & 0 & 0 & 0 \\ 0 & -1 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & 1 \end{matrix}$$

überall da einzusetzen, wo sie nur einmal oder gar nicht differenziert erscheinen. Man erhält also zunächst

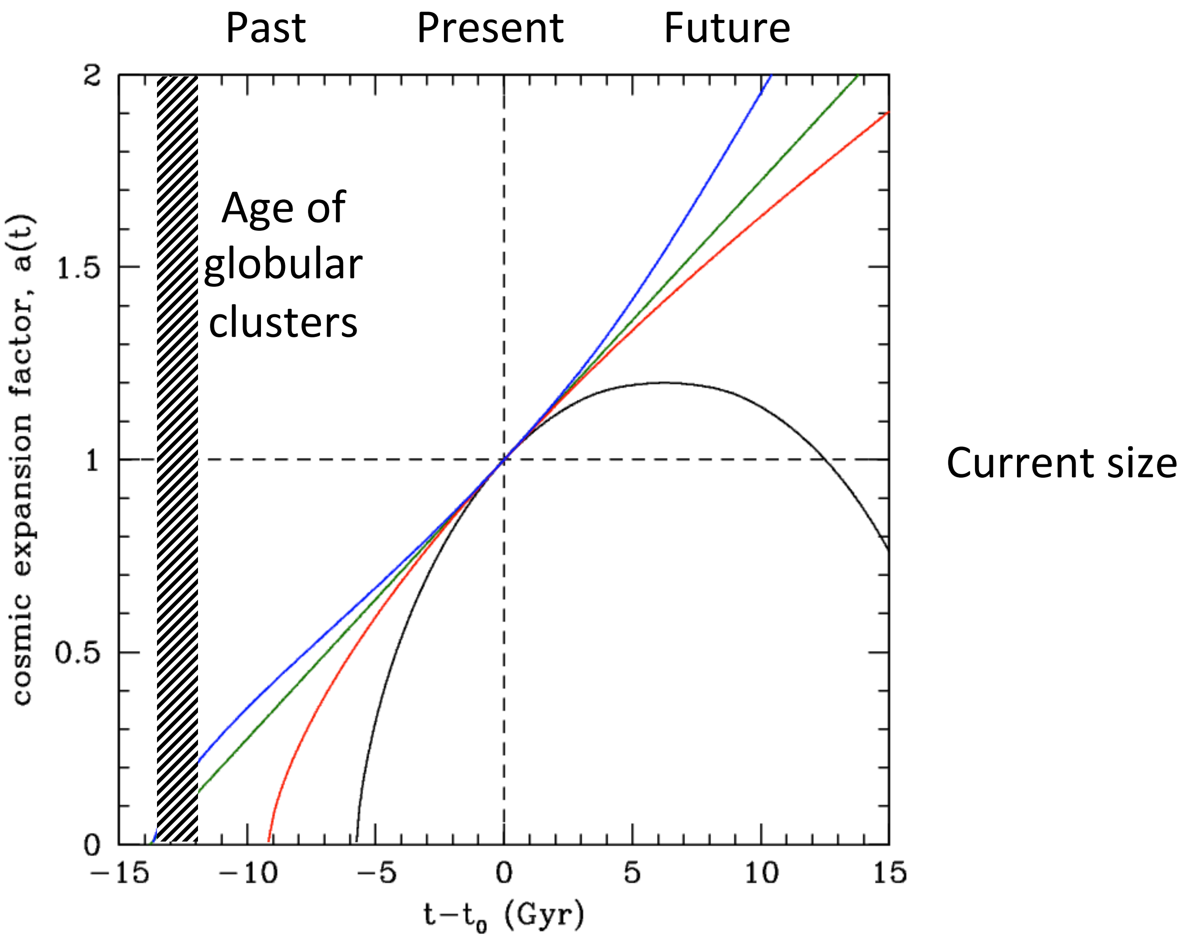
$$G_{\mu\nu} = \frac{\partial}{\partial x_1}\begin{bmatrix}\mu\nu \\ 1\end{bmatrix} + \frac{\partial}{\partial x_2}\begin{bmatrix}\mu\nu \\ 2\end{bmatrix} + \frac{\partial}{\partial x_3}\begin{bmatrix}\mu\nu \\ 3\end{bmatrix} + \frac{\partial^2 \lg\sqrt{-g}}{\partial x_\mu \partial x_\nu}.$$

Mit Rücksicht auf (7), (8) und (13) findet man hieraus leicht, daß sämtlichen Gleichungen (13a) Genüge geleistet ist, wenn die beiden Relationen erfüllt sind

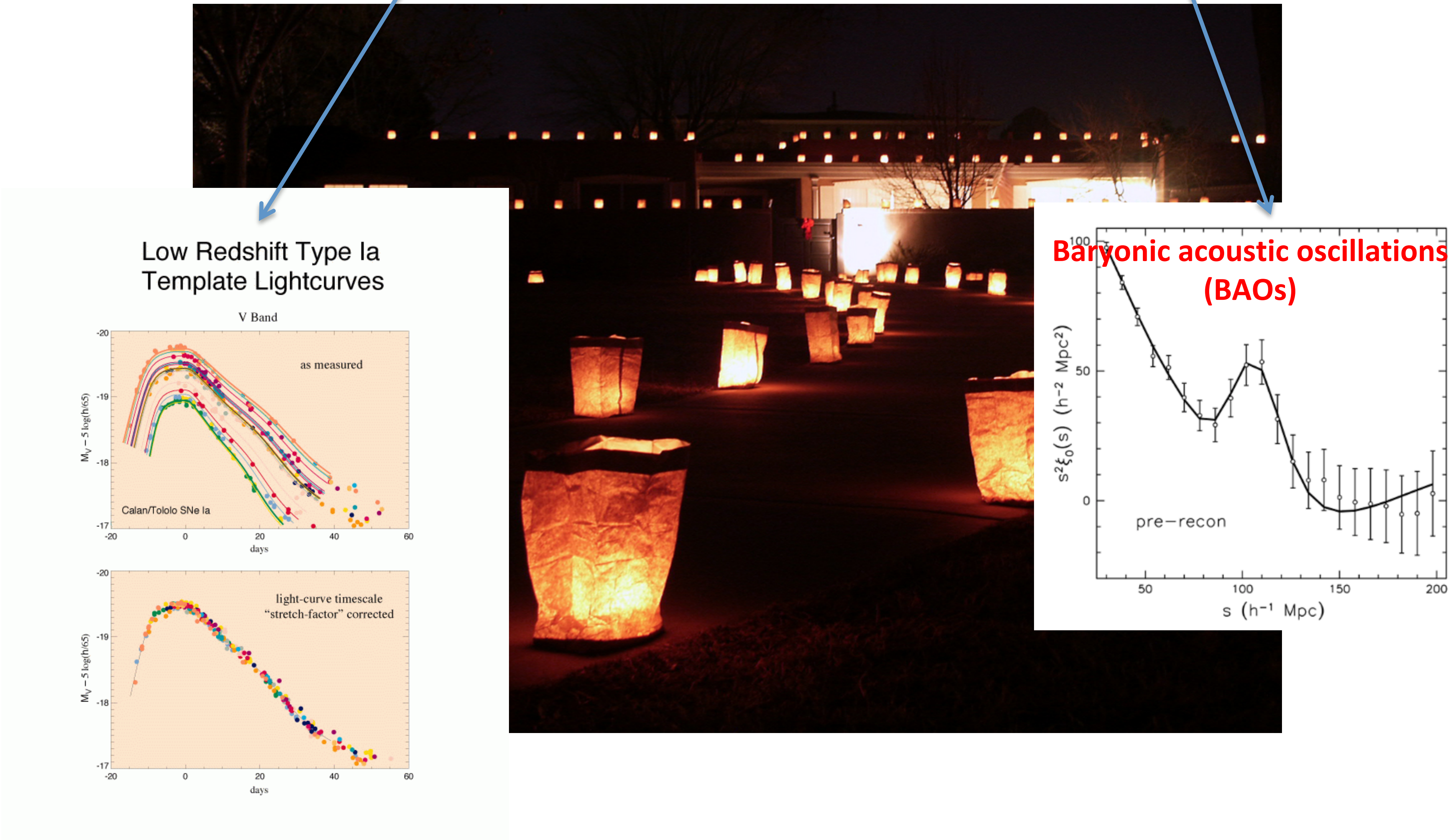
The general theory of relativity allows the addition of the term $\lambda g_{\mu\nu}$ in the field equations. One day, our actual knowledge of the composition of the fixed-star sky, the apparent motions of fixed stars, and the position of spectral lines as a function of distance, will probably have come far enough for us to be able to decide empirically the question of whether or not λ vanishes. Convinction is a good mainspring, but a bad judge!

(A. Einstein, letter to W. de Sitter, April 14 1917)

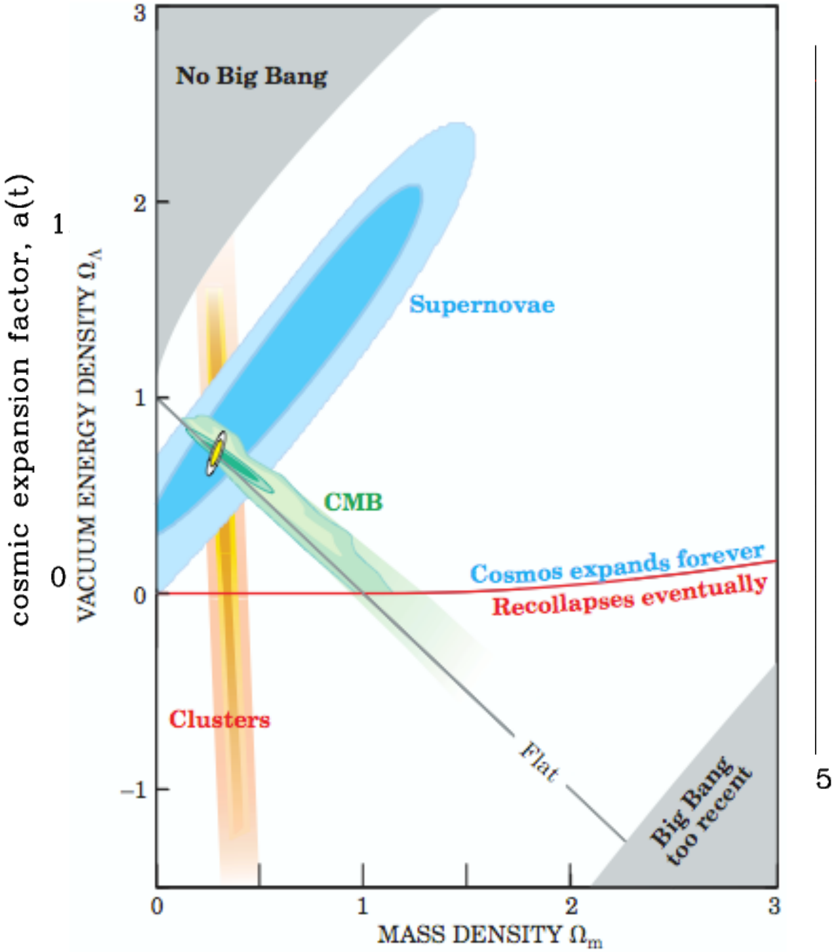
1990s: the age of the Universe

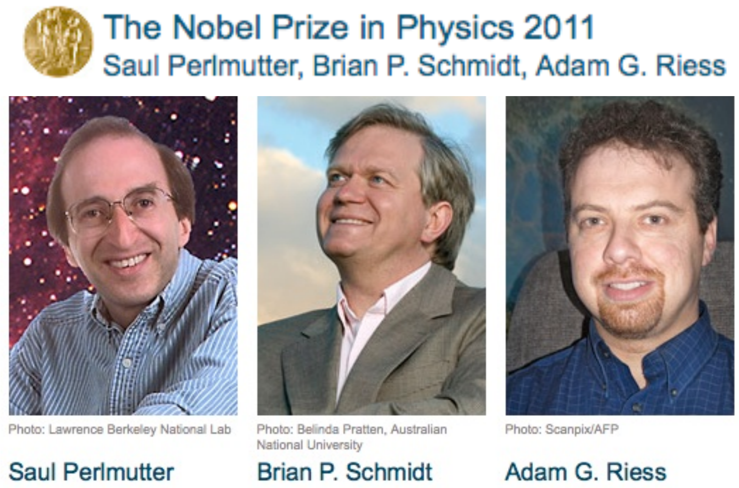


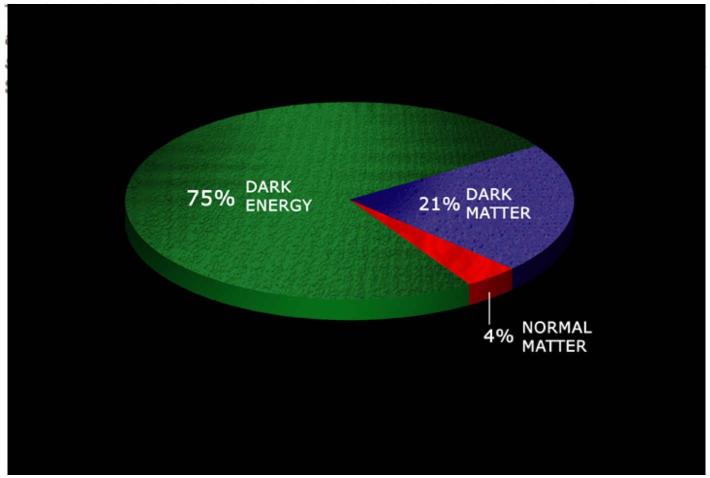
Standard candles and standard rulers



The accelerating universe

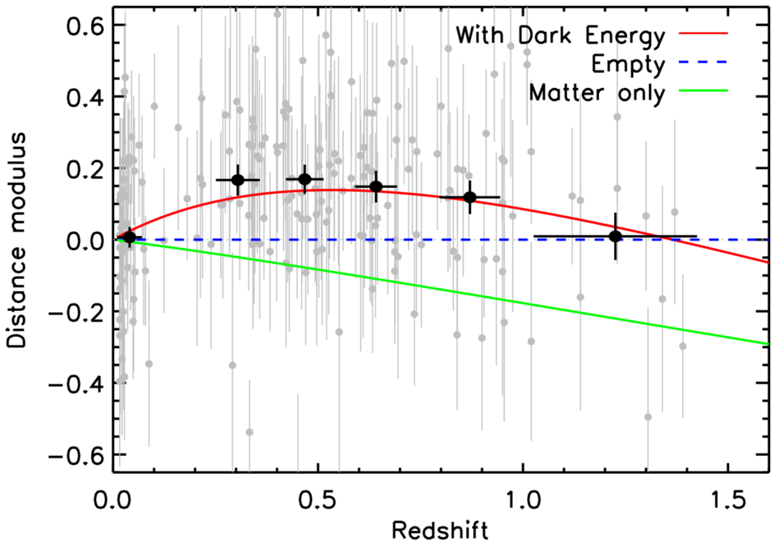




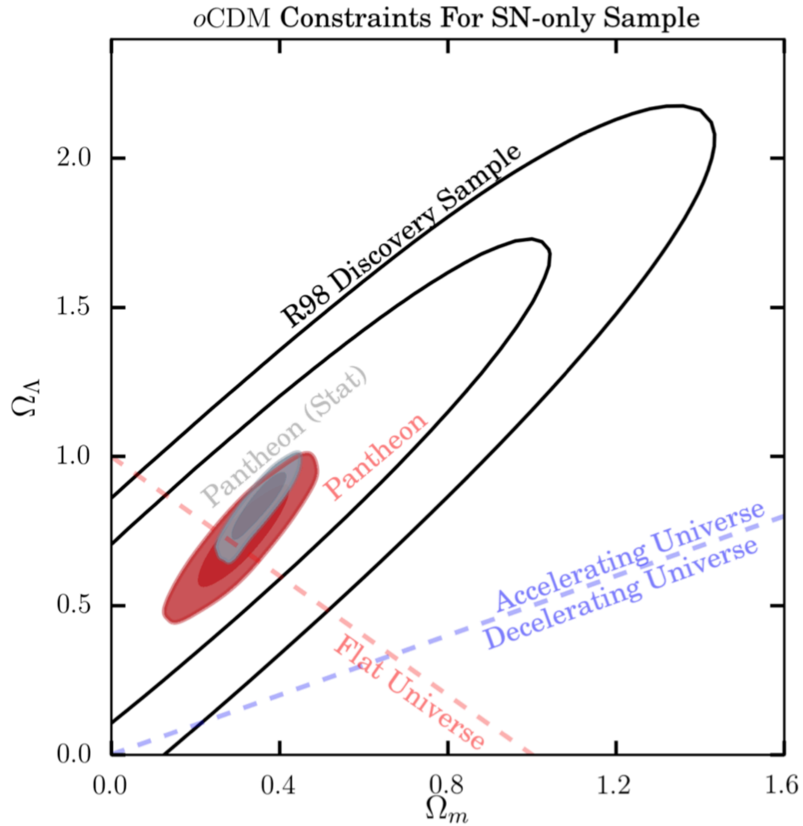


$\Omega_{tot} \approx 1$

The current state of the art

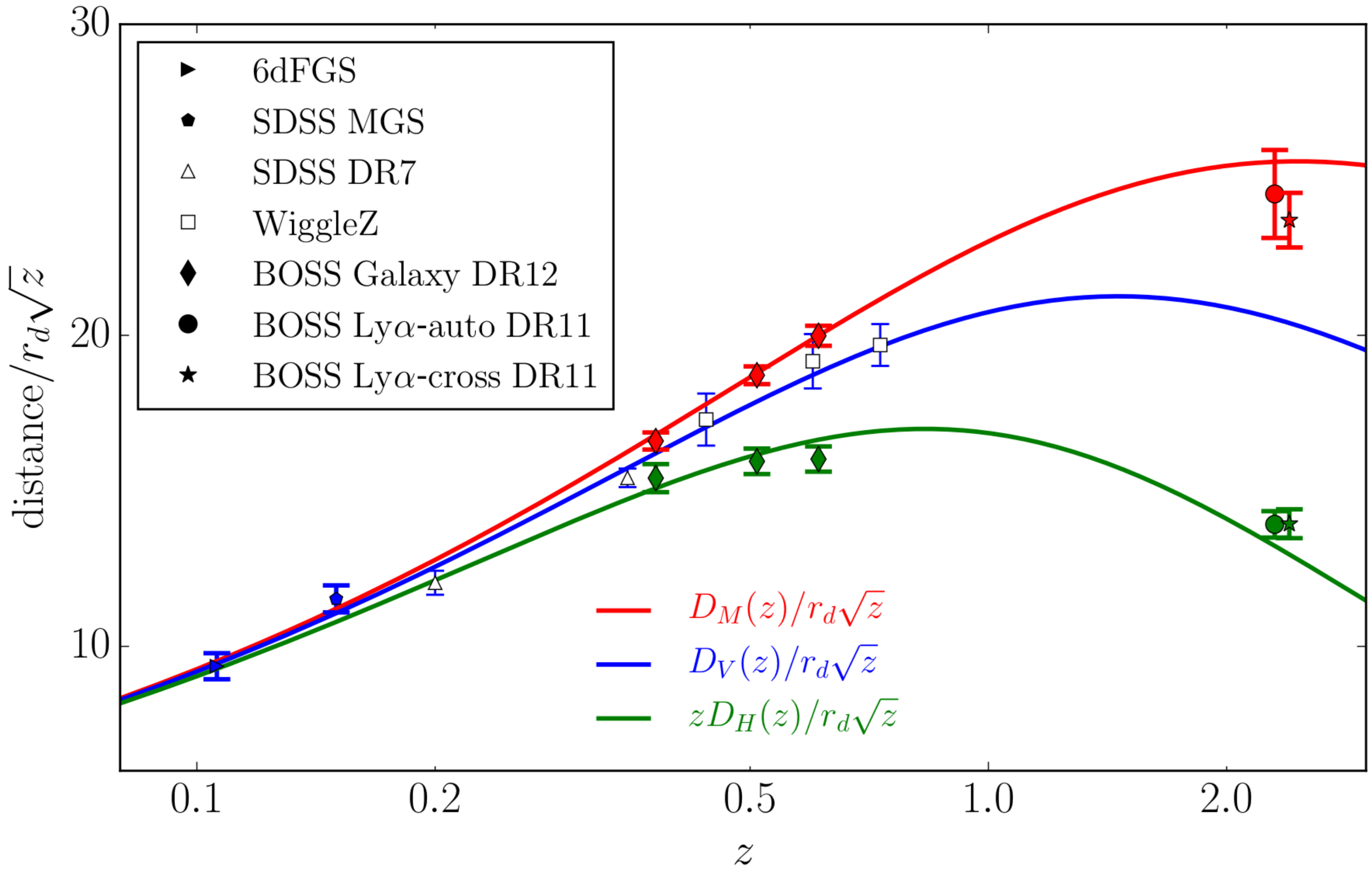


Davis (2014)



Scolnic et al. (2018)

Baryonic acoustic oscillations (BAOs)



Alam et al. (2017)

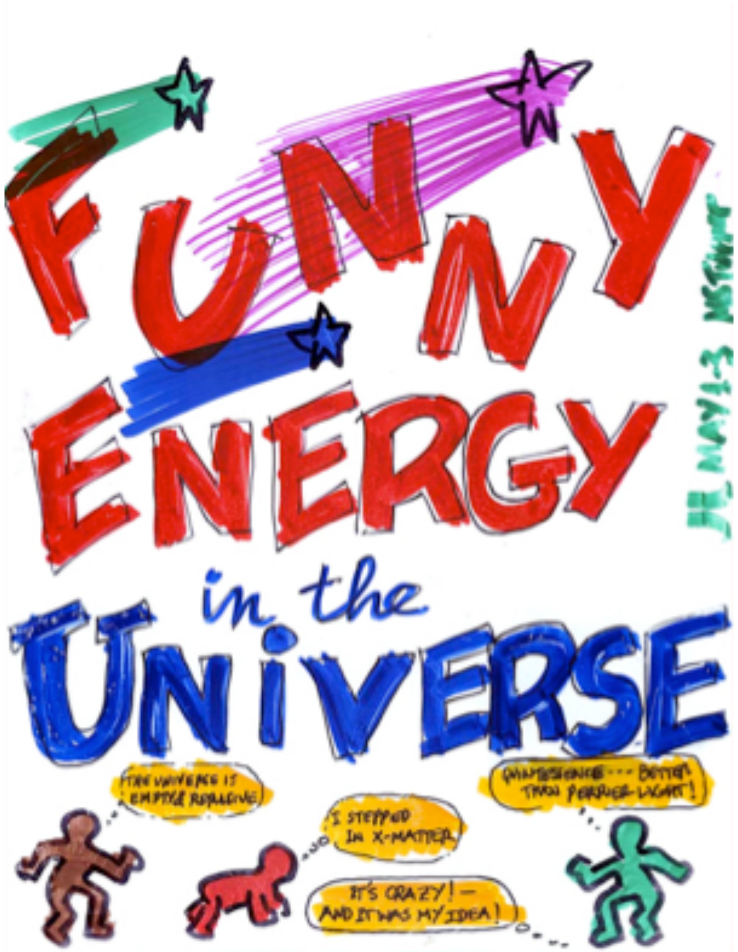
Dark energy, a primer

- Let's assume a smooth component dominates the universe. The observed acceleration and the Friedmann equation

$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}\left(\rho + \frac{3p}{c^2}\right)$$

then imply $p < -\rho / 3$

- We dub this hypothetical component `dark energy'



Michael Turner 1998

What could it be?

- The cosmological constant, Λ (Einstein 1917)

$$R_{\mu\nu} - \frac{1}{2}R\, g_{\mu\nu} + \Lambda\, g_{\mu\nu} = \frac{8\pi G}{c^4}T_{\mu\nu} \qquad \frac{\ddot{a}}{a} = -\frac{4\pi G}{3}\left(\rho + \frac{3p}{c^2}\right) + \frac{\Lambda c^2}{3}$$

- Quantum-vacuum energy (Zel'dovich 1968)

$$T_{ab}^{(\mathrm{vac})} = \frac{\Lambda}{8\pi}g_{ab} \qquad \rho_{\mathrm{vac}} = \frac{\Lambda}{8\pi} \qquad w = \frac{p}{\rho} = -1$$

- Quintessence - An unknown scalar field, ϕ

$$w = \frac{\frac{1}{2}\dot{\phi}^2 - V(\phi)}{\frac{1}{2}\dot{\phi}^2 + V(\phi)},$$

- A sign that Einstein's gravity needs modifications on large scales (see Heisenberg's talk)

- Misinterpretation of the observations (backreaction, inhomogeneous models, etc.)

Dark-energy parameterization

- The dark energy component can be characterized by its equation of state parameter $w=p/\rho$
- The simplest possibility is to assume w = constant in time (wCDM), although it is physically motivated only for Λ
- The next level of complexity is a two-parameter model. The most widely used is the Chevallier-Polarski-Linder parameterization, $w=w_0+(1-a)w_a$
- This, however, maps only onto subspaces of physical dark-energy models (e.g. Scherrer 2015)

Figure of merit

- It is customary to compare dark-energy probes in terms of a conveniently defined figure of merit
- A popular choice is inversely proportional to the area of their 68.3 per cent (marginalized) joint credible regions

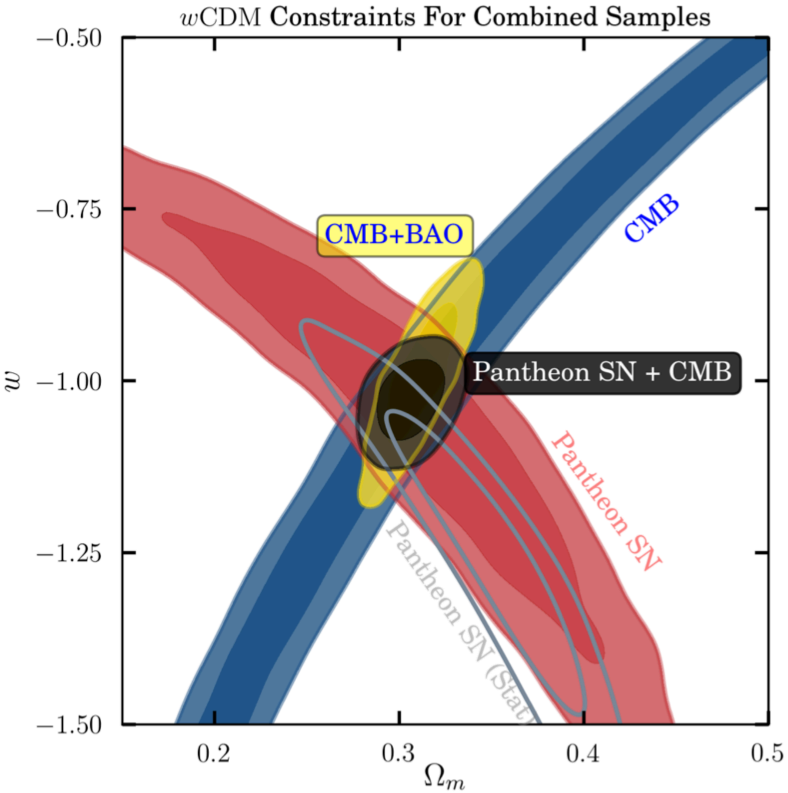
$$\mathrm{FoM} = \frac{1}{\sqrt{\det \mathrm{Cov}(w_0, w_a)}}$$

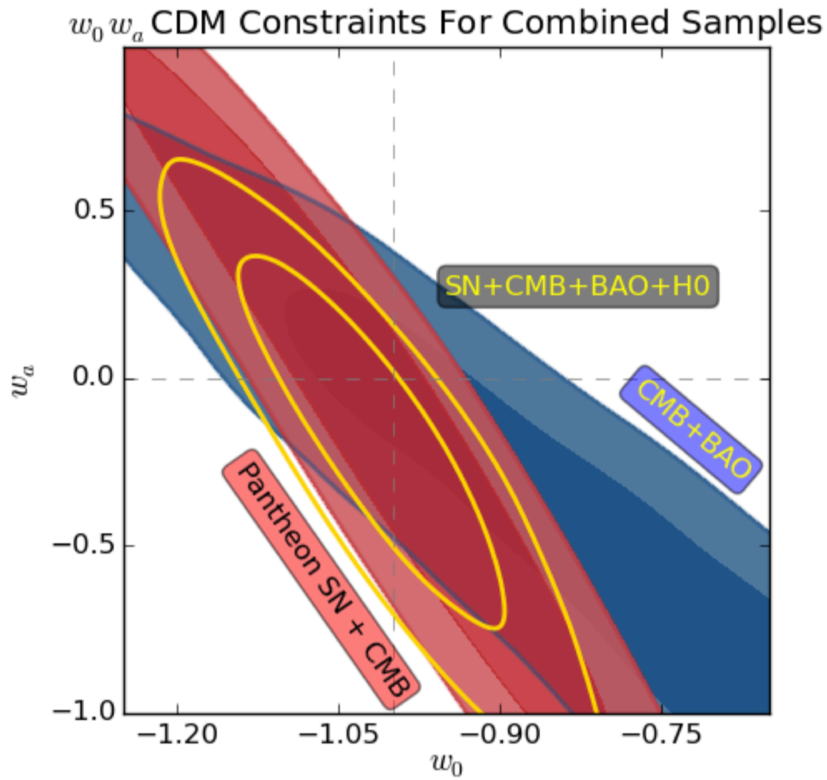
- The higher the FoM, the more suitable an experiment is to constrain the dark-energy parameter set
- Warning: it depends on the adopted parameterization

Albrecht et al. (2006), Wang (2008), Mortonson et al. (2010)

Combining probes

Scolnic et al. (2018)





SN+CMB+BAO+H_0

w= -1.047 ± 0.038

w_0 = -1.007 ± 0.089

w_a = -0.222 ± 0.407

FoM = 63.2

A glimpse into the future

- Together with the neutrino masses and the statistical nature of primordial perturbations, dark-energy is the main science driver of the next generation of surveys
- Wide-angle spectroscopic surveys: DESI, Euclid, HETDEX, SKA, SPHEREx, SuMiRe, WFIRST(?)
- Wide-angle photometric surveys: J-PAS, LSST
- X-ray-cluster surveys: eROSITA
- Main goal now is to look for deviations from w = -1 by increasing the FoM

Dark-energy probes

$$D_+'' + \left(\frac{3}{a} + \frac{\mathrm{d}\ln H}{\mathrm{d}\,a}\right) D_+' - \frac{3\Omega_\mathrm{m}}{2a^5\,(H^2/H_0^2)} D_+ = 0$$

Sensitive to the growth of structure?

	N	**Y**
Y	**Redshift-space distortions (velocity field)**	**Cosmic shear** **Galaxy clusters**
N		BAOs CMB Supernovae Ia

Sensitive to the expansion history?

Disagreement between the different classes would falsify the smooth dark-energy scenario and provide evidence for modifications of Einstein gravity on cosmological scales

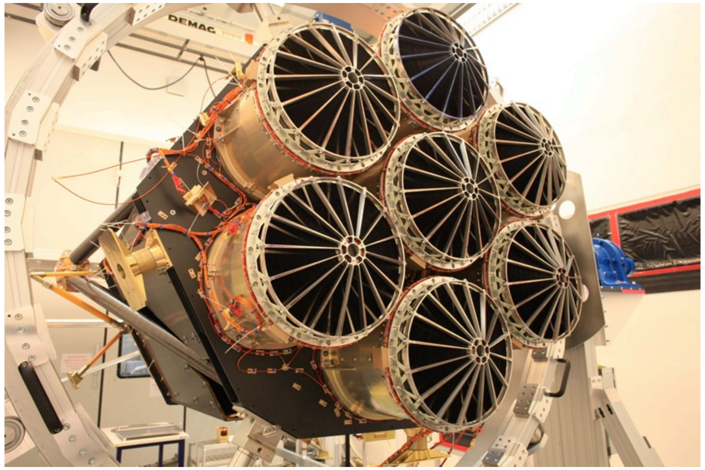
$$\frac{H^2}{H_0^2} = \left(\frac{\Omega_\mathrm{m}}{a^3} + (1-\Omega_\mathrm{m})\exp\left\{-3\int_1^a [1+w(x)]\,\mathrm{d}\ln x\right\}\right)$$

eROSITA

- Short for Extended ROentgen Survey with an Imaging Telescope Array

- X-ray telescope with unprecedented characteristics assembled and tested by a consortium of German institutions led by MPE

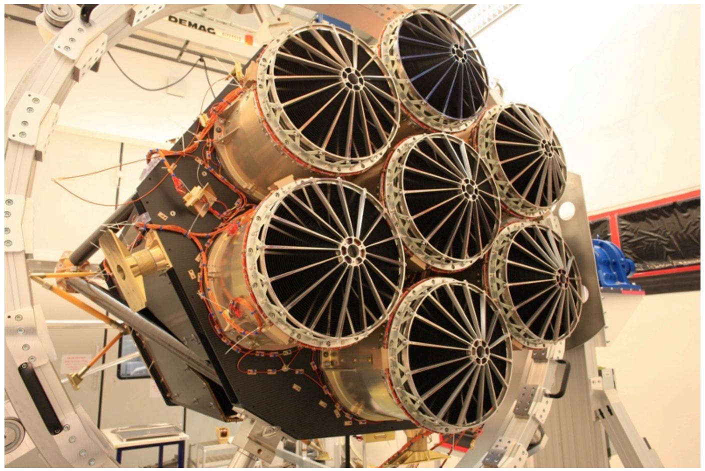
- Will be shipped to an L2 orbit on-board the Russian Spectrum-Roentgen-Gamma (SRG) satellite



At the end of its first year of operations, eROSITA will have detected as many new sources as have been catalogued in 50 years of X-ray astronomy (~10^6)

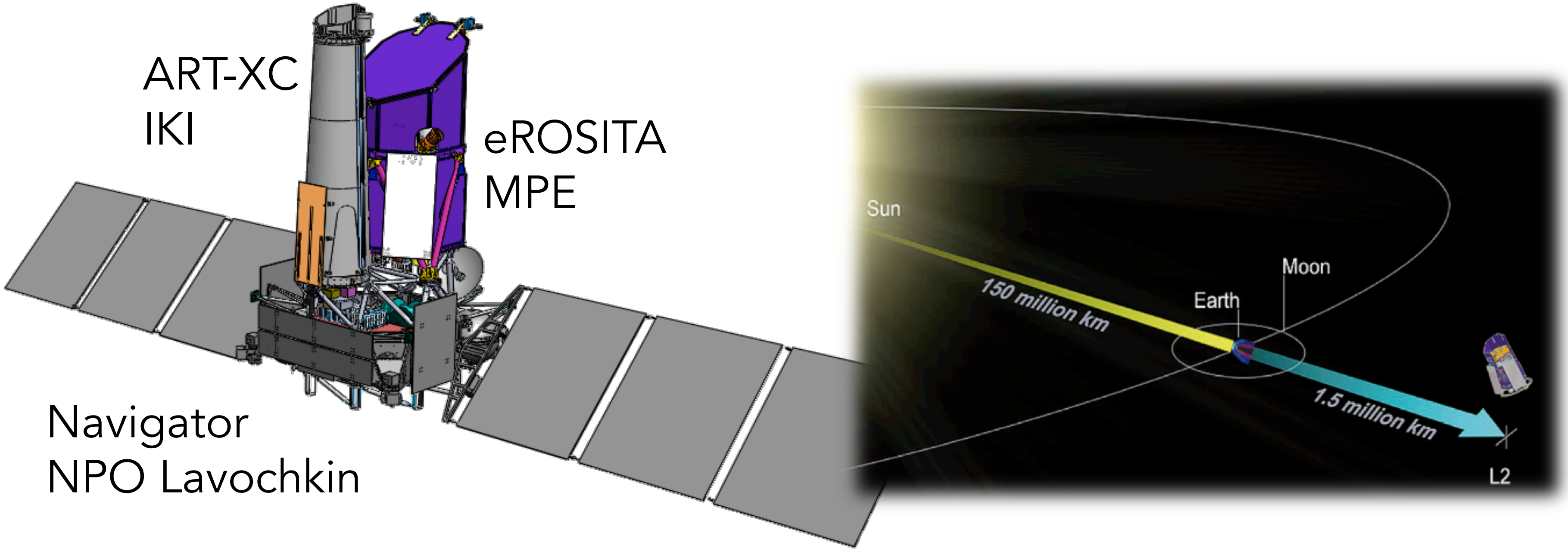
Summary

- **eROSITA: Next Generation all-sky X-ray survey**
  - 0.5-2 keV: 30× deeper than ROSAT
  - 2-10 keV: 100× deeper than HEAO-1; 10× XMM Slew
- Image quality comparable to XMM-Newton, better spectral resolution
- **Driving science**: detect 100,000 clusters (LSS, cosmology)
  - 3Million AGN, including obscured objects
- Built by consortium led by MPE; **eROSITA is ready**
- All SRG flight H/W ready, too. Final tests underway


Courtesy by A. Merloni (MPE)

SRG: Mission Profile

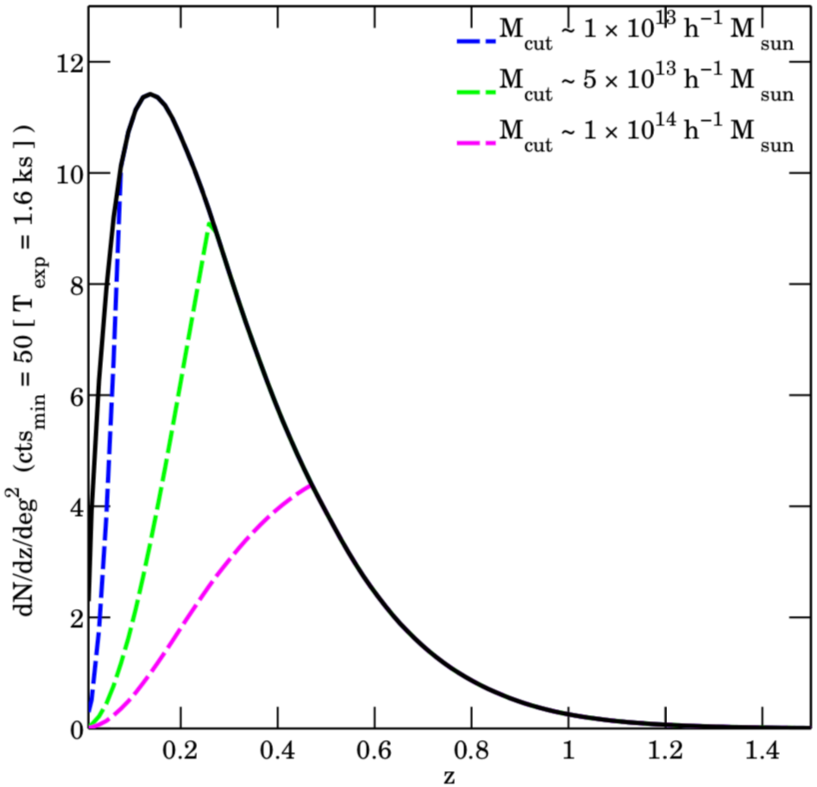


- **Final Tests and Integration:** till November/December 2018
- **Launch**: March/April 2019 from Baykonour, Proton–Block-DM
- **3/4 Months**: flight to L2, PV and calibration phase
- **4 years**: 8 all sky surveys (**eRASS:1-8**; scanning: 6 rotations/day)
- **2.5 years**: pointed observations, including ~20% GTO (TBC). 1 AO per year

Courtesy by A. Merloni (MPE)

eROSITA's all sky survey (eRASS)

Pillepich et al. (2012, 2018)



- Energy band: 0.5-2.0 keV
- Sky coverage: 65.8%
- Integration time: 8 × 200 s
- Cluster detection threshold: 50 photons
- Expected number of clusters: $\approx 10^5$ with $M_{500} > 5 \times 10^{13}\ h^{-1}\ M_\odot$
- Optical and NIR campaigns to provide spectroscopic redshifts at least for z<0.7

DE with eROSITA clusters goals, method, and systematics

- Goal: Use the redshift evolution of the cluster number density (and 2-point clustering) as a cosmological probe

- Method I: Expected number density of clusters as a function of mass and redshift from numerical simulations

- Method II: X-ray luminosity and mass linked by an empirical scaling relation with scatter

- Problem I: matched filters for detection assume a density profile

- Problem II: Corrections due to baryonic physics are poorly known and difficult to model. Need concerted effort from the community.

- Problem III: Redshift dependence and validity of scaling relations at the low-mass end are crudely known

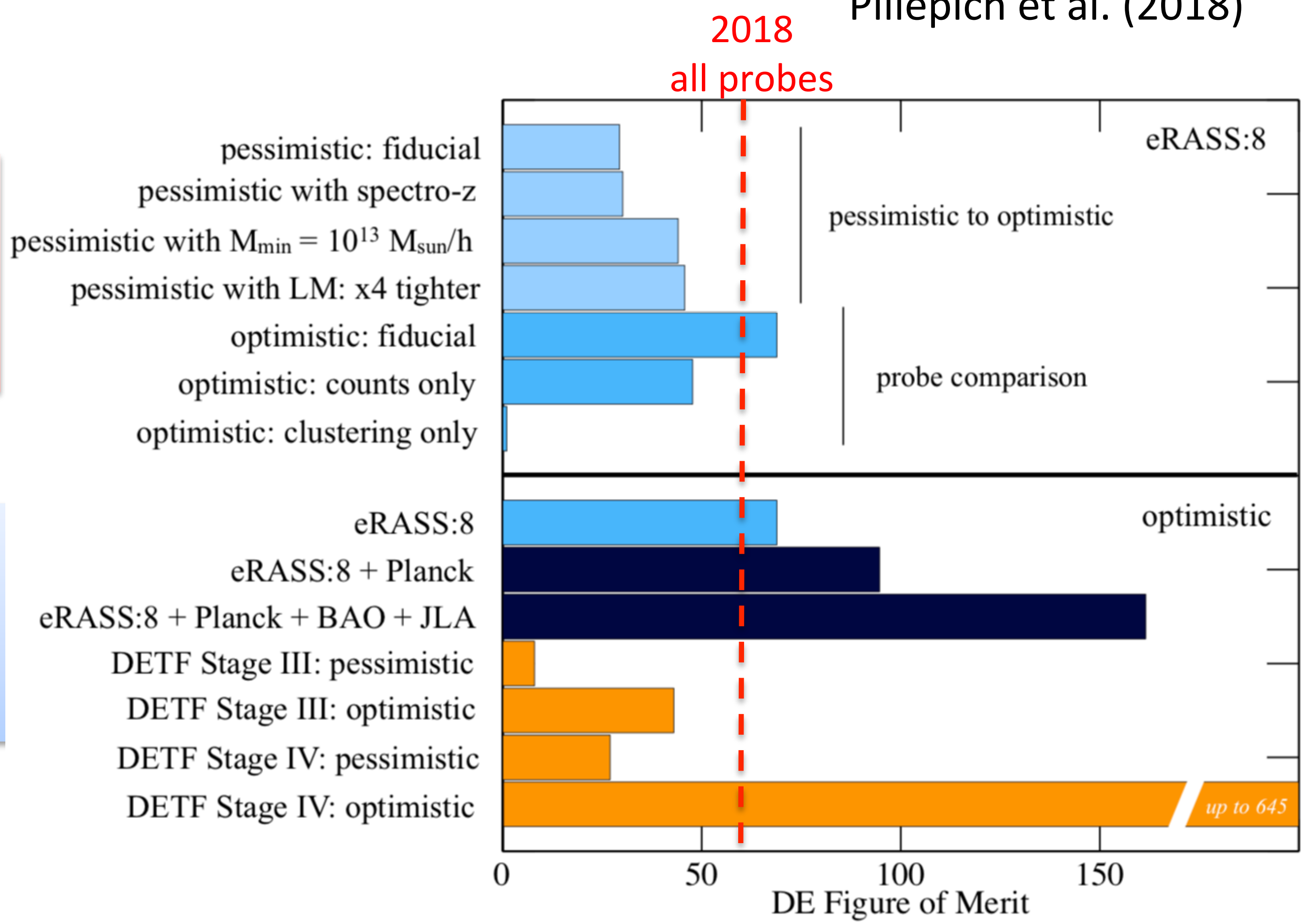
Self calibration: the scaling relation is simultaneously fit with the cosmology assuming a functional form and using priors on its parameters

Dark-energy forecast

Pillepich et al. (2018)

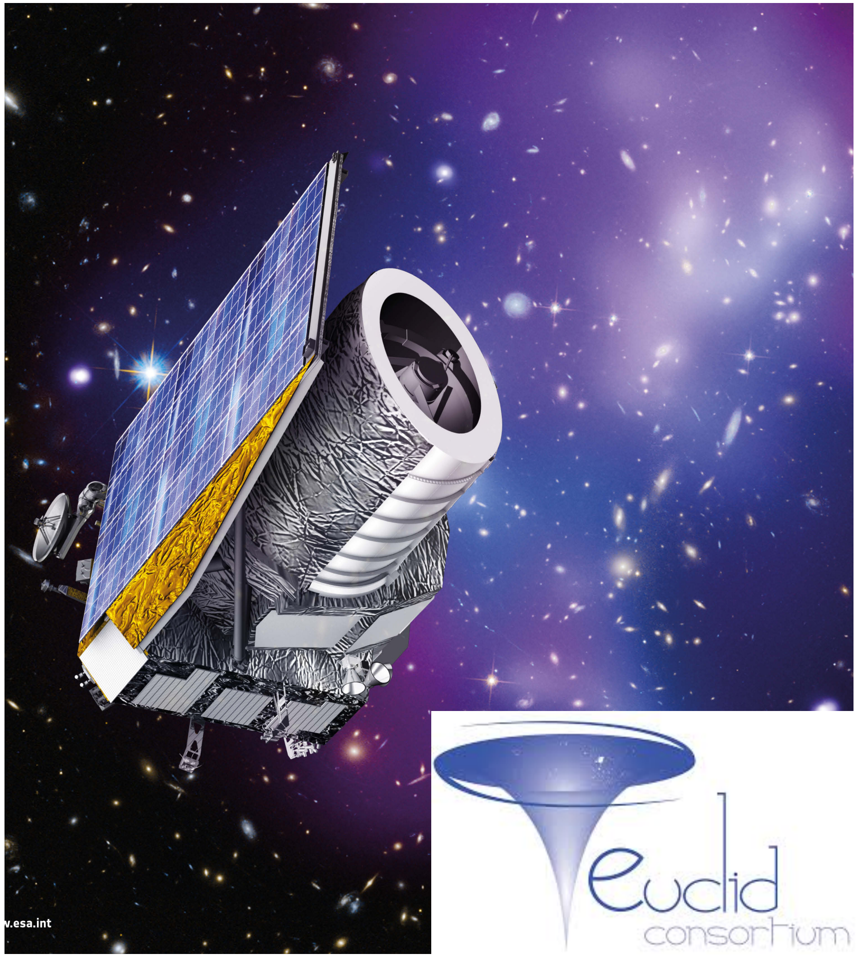
PESSIMISTIC SCENARIO
photometric redshifts only;
current priors on LM relation;
minimum mass: $5 \times 10^{13}\ h^{-1}\ M_\odot$

OPTIMISTIC SCENARIO
spectroscopic redshifts;
$4 \times$ tighter priors on LM relation;
minimum mass: $1 \times 10^{13}\ h^{-1}\ M_\odot$



eROSITA will be the first `STAGE IV' dark-energy experiment to come on line!

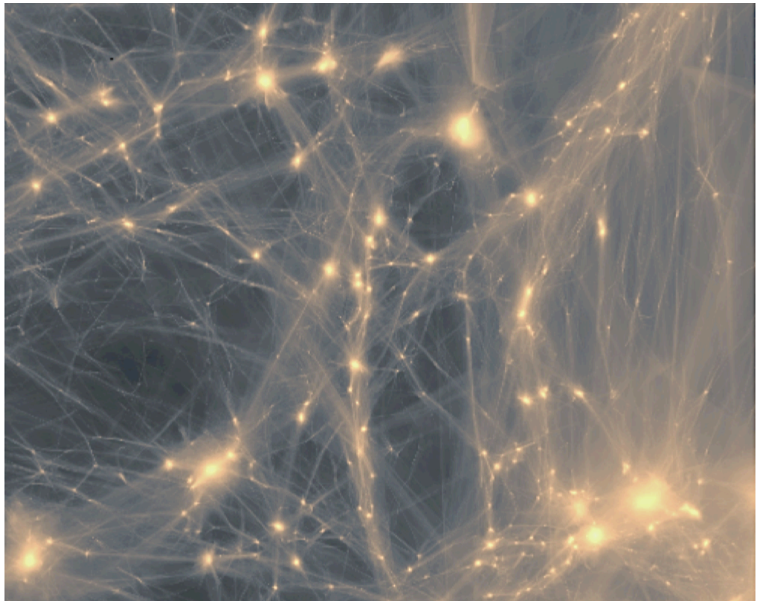
The Euclid mission



- ESA M-class mission selected within the Cosmic Vision 2015-2025 program as a dark-energy probe
- Launch date: 2021
- Duration: 6.25 yr
- Instruments: visible imager +
  NIR spectrometer and photometer
- Wide survey: 15,000 sq deg
  (excluding galactic and ecliptic planes)
- Probes: cosmic shear (1.5 billion galaxy shapes at $z<2$ with photo-z's) + galaxy clustering (35 million galaxies at $0.7<z<2.0$ with spec-z's)
- FoM > 350 Euclid main probes alone
  FoM > 3500 with Planck (Laureijs et al. 2011, Giannantonio et al. 2012, Amendola et al. 2018)

Higher-order statistics

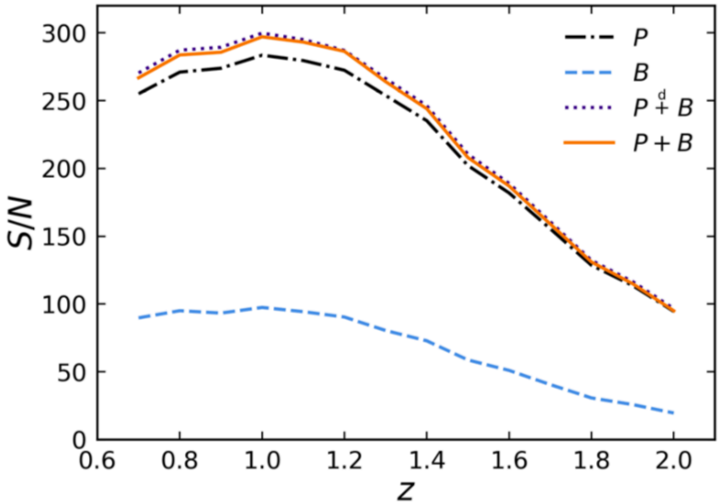
Kaehler et al. (2012)



- It is customary to extract information from galaxy catalogs using 2-point statistics

- Since the galaxy distribution is highly non-Gaussian, higher-order statistics should contain additional information

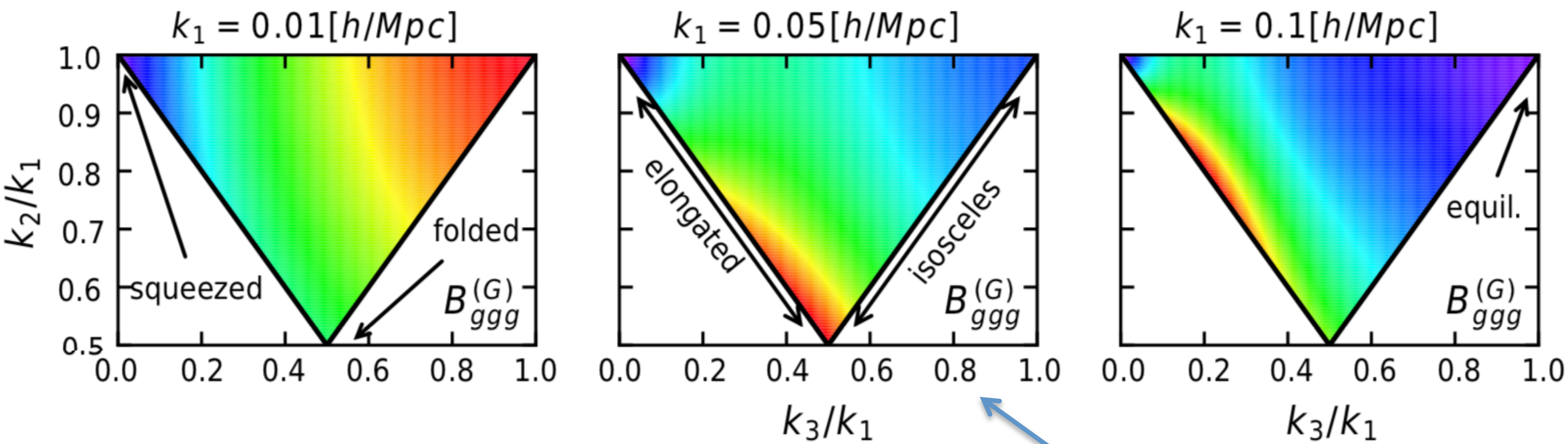
Yankelevich & CP (2018)



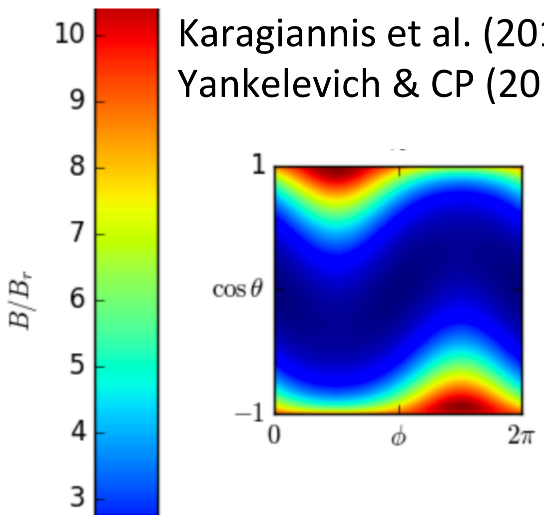
- Surveys of the next generation will measure 3-point statistics robustly and accurately

Galaxy bispectrum in redshift space

$$\left\langle \delta_g(\vec{k}_1)\delta_g(\vec{k}_2)\delta_g(\vec{k}_3)\right\rangle = B(k_1,k_2,k_3,\vartheta,\varphi)\ \delta_D^{(3)}(\vec{k}_1+\vec{k}_2+\vec{k}_3)$$



Karagiannis et al. (2018)
Yankelevich & CP (2018)



Complex dependence on the shape and spatial orientation of closed triangles of wavevectors

Challenges

- The galaxy bispectrum is fully generated by non-linear effects (dynamics, bias, redshift-space distortions) and more difficult to model than the power spectrum
- Although many recent theoretical improvements (EFT for bias, new flavors of perturbation theories, numerical emulators), the range of validity of the models limits the scales that can be analyzed
- The huge number of possible configurations makes it difficult to evaluate robust covariance matrices for the estimator
- The likelihood function of the estimator is Gaussian only on the largest scales

A possible solution could be to look at compressed datasets (e.g. bispectrum multipoles) trying to minimize the information loss (Gagrani & Samushia 2017, Byun et al. 2017, Gualdi et al. 2018, Yankelevich & CP 2018)

Dark-energy forecast

FoM for $k<k_{max}= 0.15\ h\ Mpc^{-1}$ (conservative)

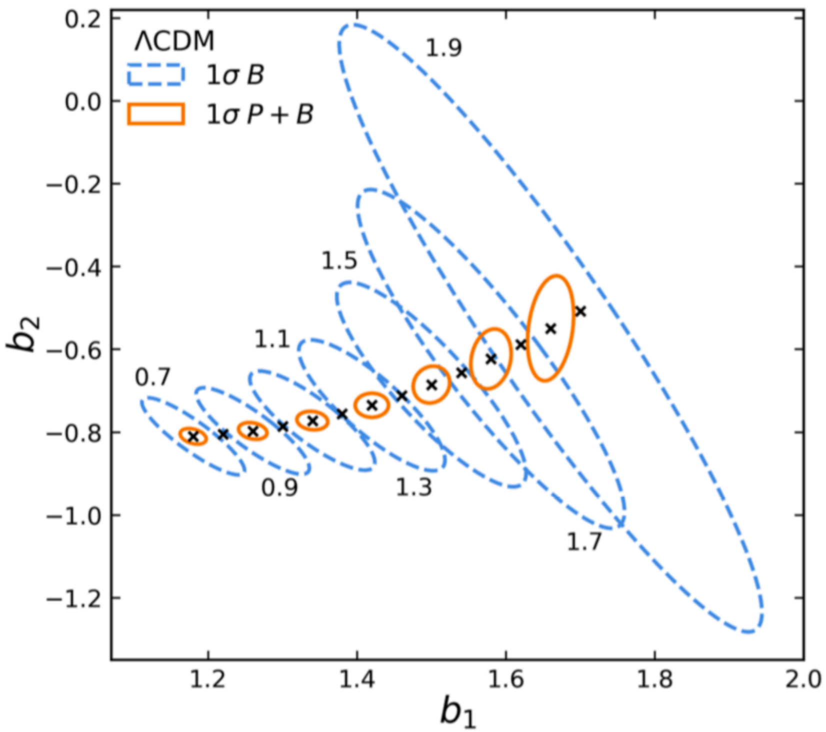
	P	B	P+B
Euclid (g-clustering)	6.7	3.1	17.5
Euclid + Planck	147.3	94.6	163.0

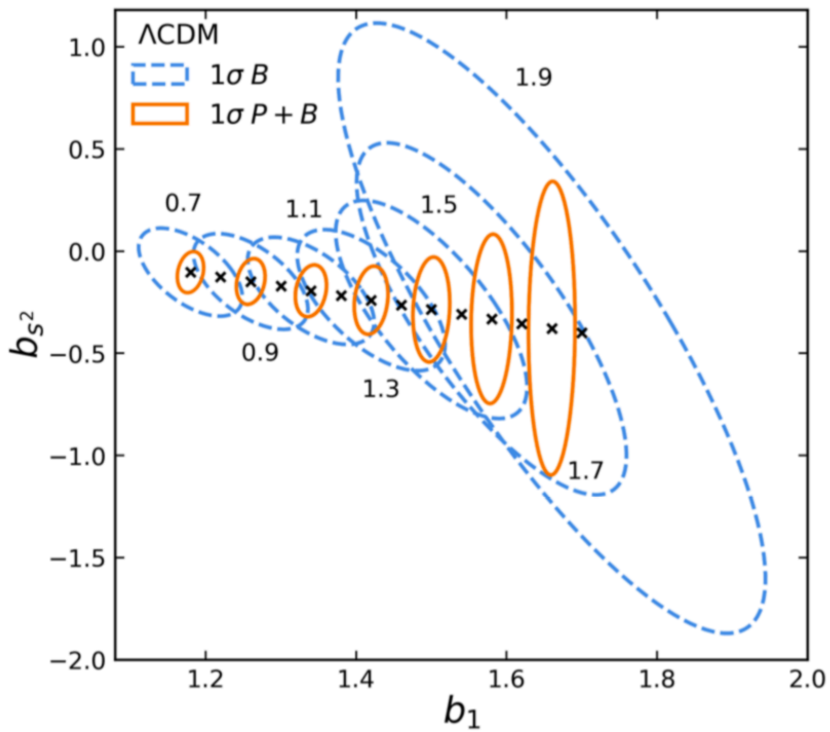
Yankelevich & CP (2018)

The relative constraining power of the bispectrum rapidly grows with k_{max}. For $k_{max} \approx 0.4\ h\ Mpc^{-1}$, B is more constraining than P.

Galaxy biasing

Constraints on renormalized bias parameters





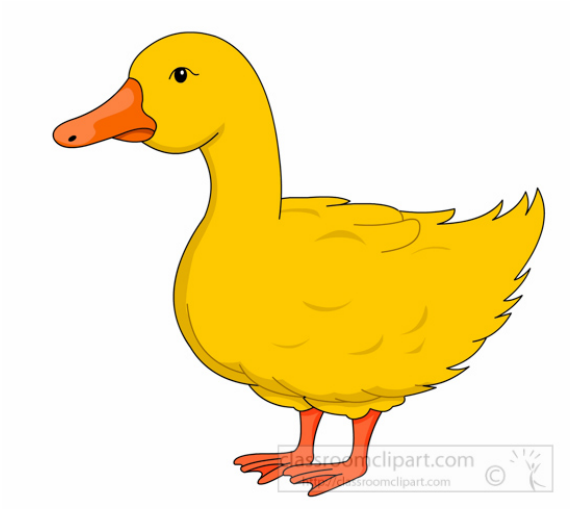
Yankelevich & CP (2018)

Conclusions

- There is solid evidence from independent probes that the Universe is undergoing accelerated expansion at late times
- No significant deviations from the predictions of general relativity with a cosmological constant have been recorded
- Future surveys will test the standard model in a more stringent way
- Single experiments like eROSITA and Euclid will provide better constraints on the dark-energy equation of state than the current ones from all existing probes combined
- This improvements call for another level of control on observational and theoretical systematics
- If no deviations from $w = -1$ will be seen in 10 years, should we then accept that vacuum energy gravitates and has a surprisingly low value?

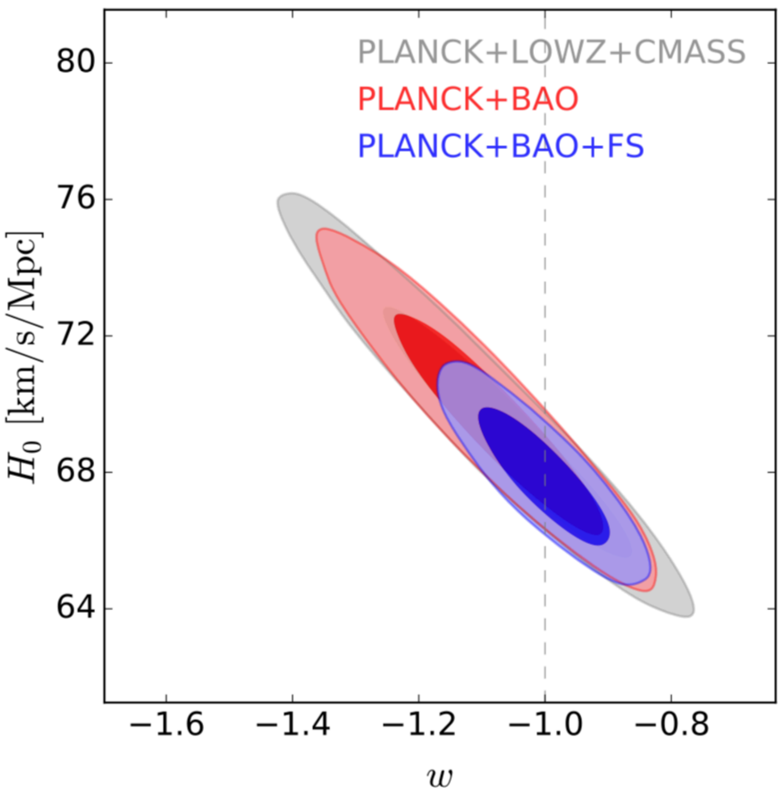
Borrowing George Efstathiou's words:

- ❑ when do we stop?



If it walks like a duck, and talks like a duck, it's probably a duck.

dark energy may just be Λ


PLANCK+LOWZ+CMASS
PLANCK+BAO
PLANCK+BAO+FS
H_0 [km/s/Mpc]
80
76
72
68
64
−1.6
−1.4
−1.2
−1.0
−0.8
w