Charting the Universe: the next generation of cosmological surveys

Part 1

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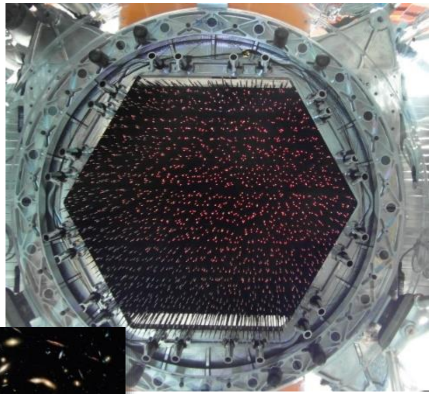
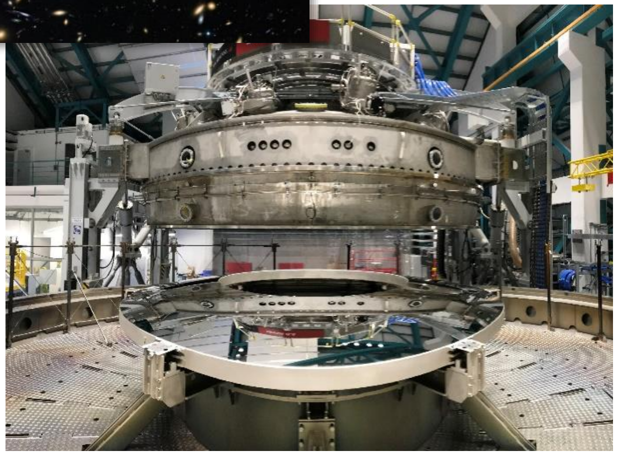
UHH Universität Hamburg
DER FORSCHUNG | DER LEHRE | DER BILDUNG

CLUSTER OF EXCELLENCE
QUANTUM UNIVERSE

Contents





Introduction

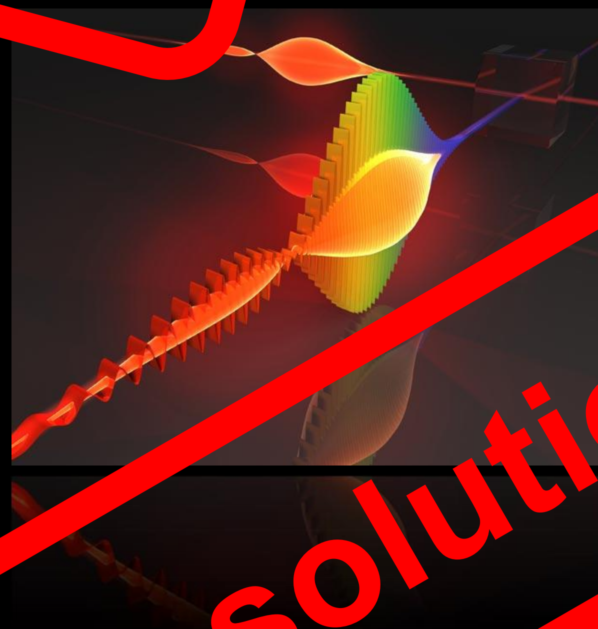
- The Universe is a big and complex place
- On every scale, it presents us with a bewildering variety of objects, phenomena and physical processes
- The physical parameter space of these objects and processes is huge
  - The corresponding observational parameter space to be explored is similarly huge and, moreover, technologically challenging

- Cannot experiment with any object of interest, only observe
- Many processes act on timescales >> human timescales
  - Cannot directly observe evolution

Range

Direction

Brightness



Time of arrival

Polarisation

Resolution

Energy

Introduction

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- Cannot experiment with any object of interest, only observe
- Many processes act on timescales >> human timescales
  - Cannot directly observe evolution

- Need lots of data to make sense of the Universe
- Requires a multi-layered approach and a multitude of methods

Introduction

Observations

Statistical investigations of large samples (surveys)

Level of detail

Statistical power, completeness

Detailed studies of small samples

Theory

Analytical, semi-analytical, numerical

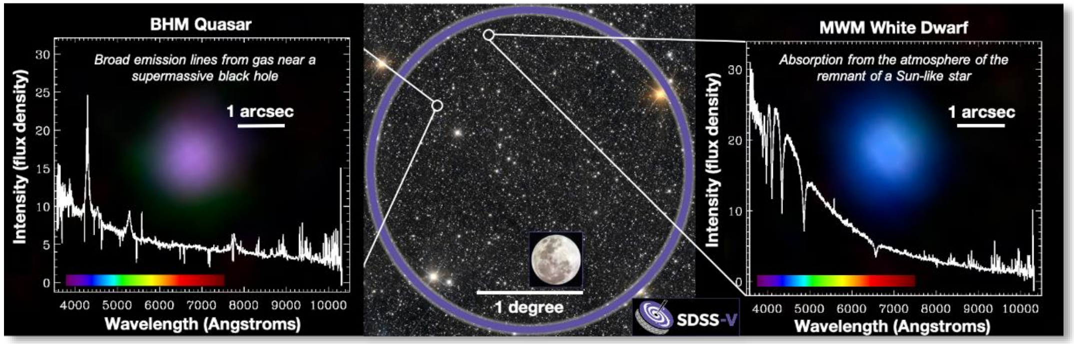
Introduction: what is a survey?

Wikipedia:

- An astronomical survey is a general map or image of a region of the sky (or of the whole sky) that lacks a specific observational target. Alternatively, an astronomical survey may comprise a set of images, spectra, or other observations of objects that share a common type or feature. […] Surveys have generally been performed as part of the production of an astronomical catalogue.

My definition:

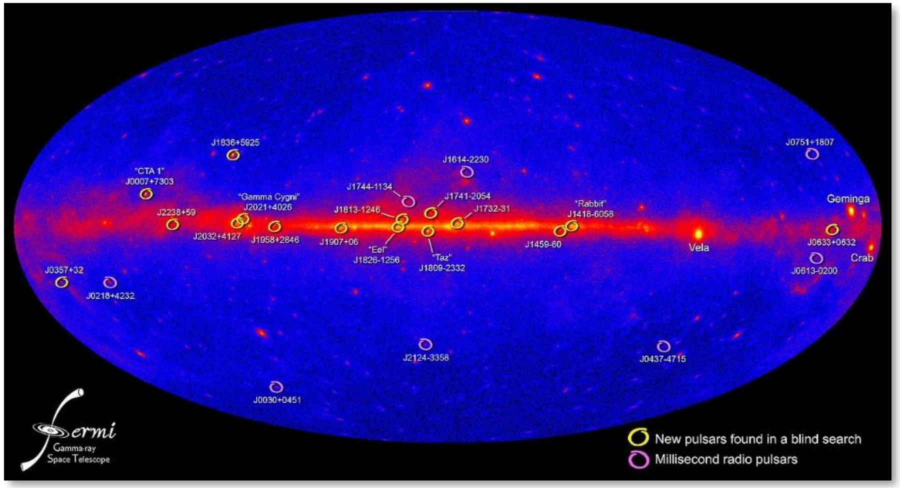
- A set of systematic, homogeneous observations with a well-defined selection function of a region of the sky or of a well-defined set of targets of relevant size.



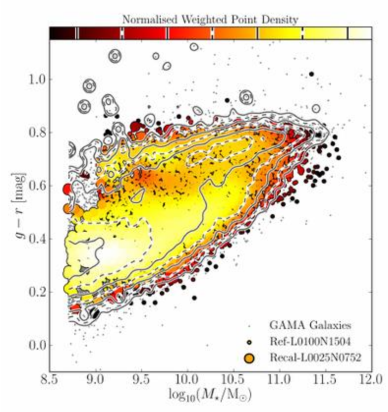
Introduction: what is a survey?

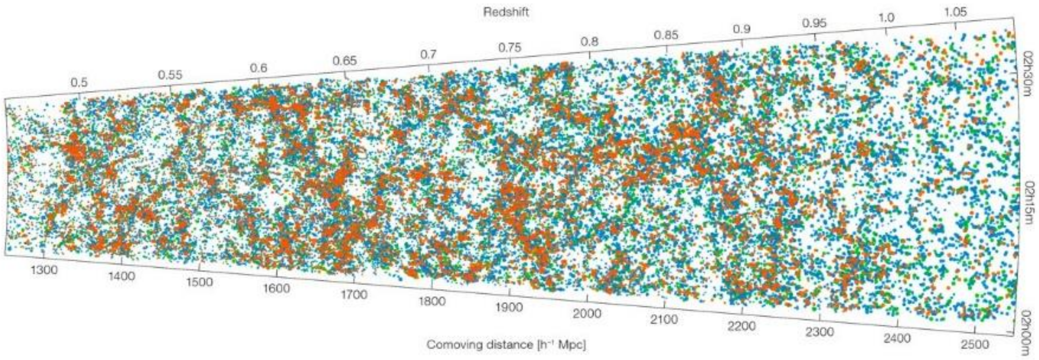
Many different purposes, which have evolved over time:

- Census
- Discovery
- Reference frame (in space and time)
- Evolution
- …
- …



- Statistics: (joint) distributions of properties of objects in physical parameter space

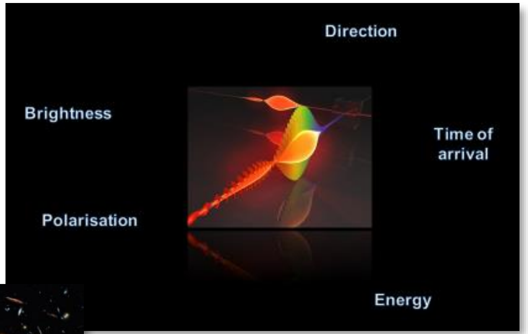


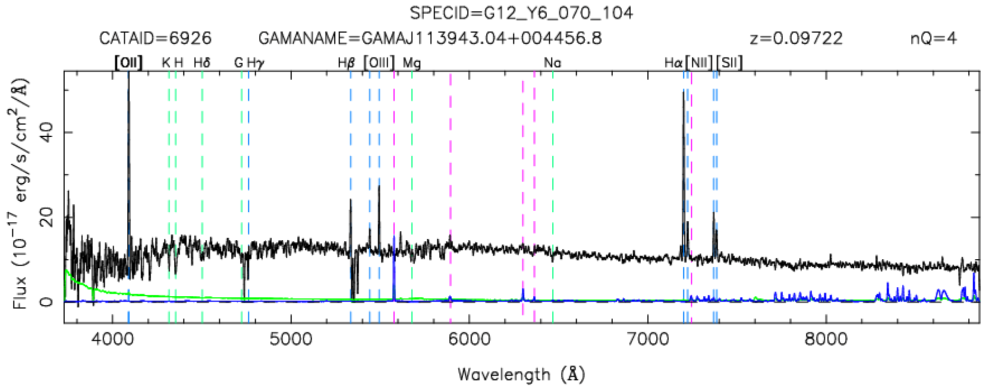


Introduction

Examples of types of surveys:

- Imaging
  - Photometric
    - Brightness
    - Structure / morphology
  - Astrometric
    - Spatial distribution
    - Distances
    - Kinematics
- Spectroscopic
  - Kinematics
    - Radial velocity / redshift
    - Rotation / velocity dispersion
    - Large-scale motions
  - Chemical composition
  - Physical properties
- Time-domain
- …
- All of the above across the entire EM spectrum





Introduction

Why are surveys hard?

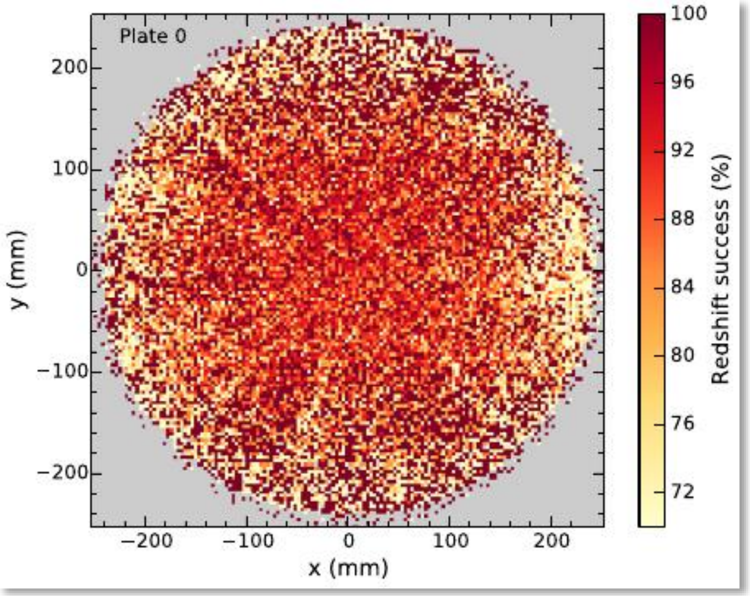
- "Of relevant size" usually implies (very) large datasets
  - Requires a sustained effort
  - Resource-intensive: hardware, telescope time, FTEs, …
  - Technologically challenging
    - Example: optical imaging: need a sensitive (i.e. large) telescope with high and uniform image quality across a large field-of-view
      → high etendue
    - Difficult due to image aberrations (coma, astigmatism)
    - Requires fast and complex optical surfaces and a high degree of telescope control
    - So far, only a single 8-m class telescope with a wide FoV: Subaru

Subaru's prime focus
with the 1.5 deg FoV
Hyper Suprime-Cam

Introduction

Why are surveys hard?

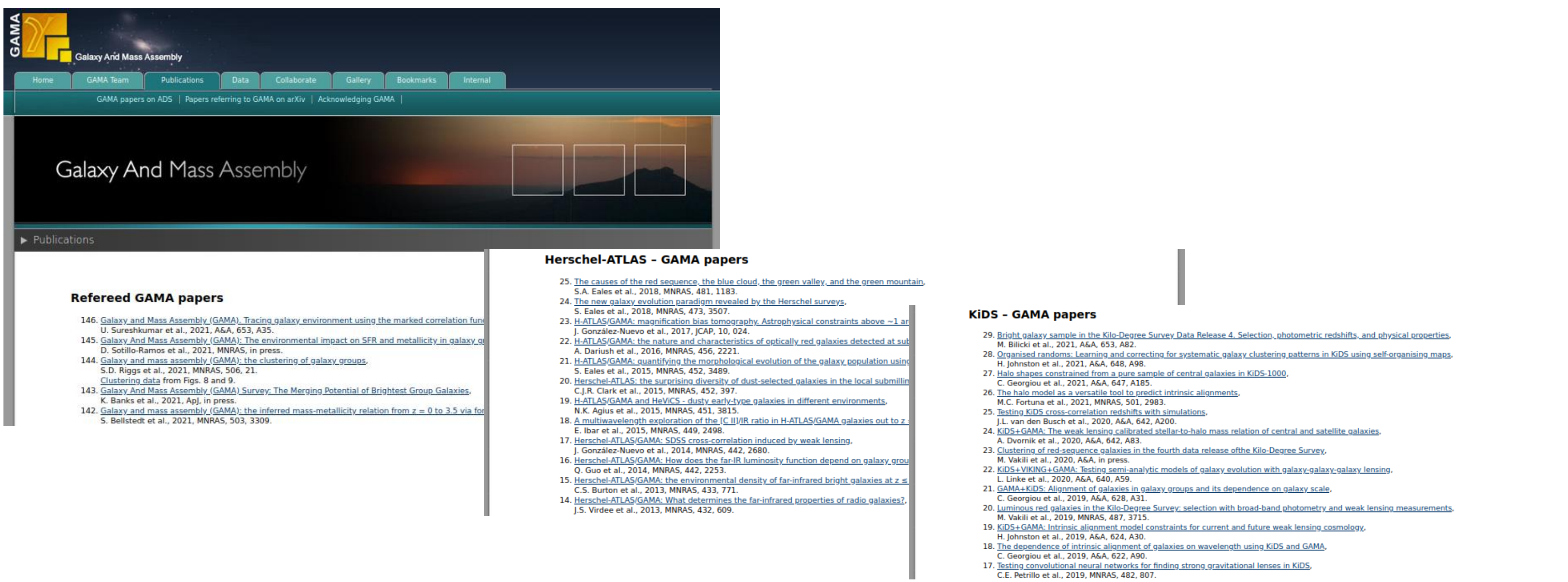
- Homogeneous, well-defined datasets
  - Whether an observation of a particular target is “successful” or not depends in a complicated way on target properties, observing system and observing conditions
  - Observing process creates a bias
  - Understanding the “selection function” is important
  - Much better control of selection function in space, but space telescopes are even harder



Introduction

Surveys are science enablers

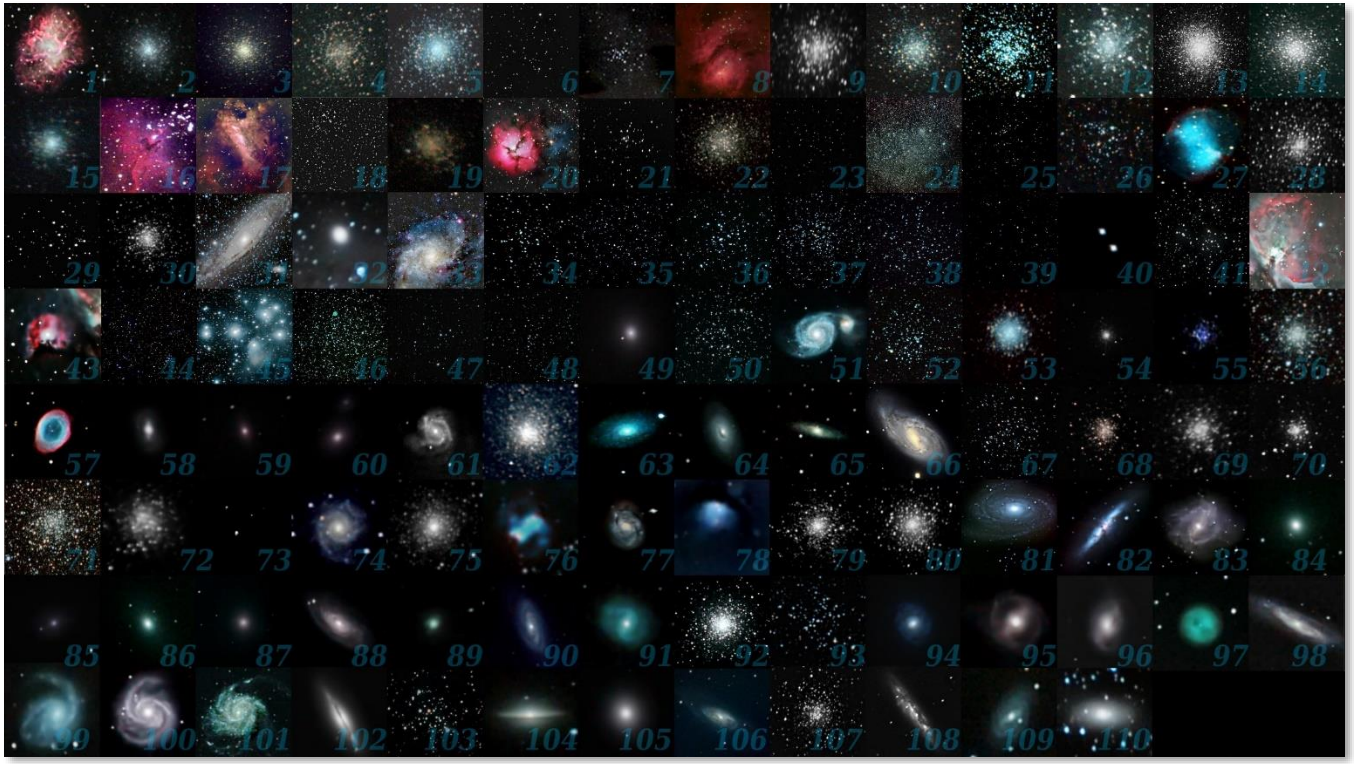
- Most surveys are extremely versatile, whether by design or not
  - The same data can be used to address many science goals
  - Favourable science return / unit telescope time
- Example: GAMA
  210 nights on a 4-m telescope → 202 papers so far and counting



Some historical notes

The 1st age of surveys: 18th – 20th century

- Based on visual and photographic “serial” observations
- Messier catalogue (1774 – 1781): haphazard collection 103 extended objects



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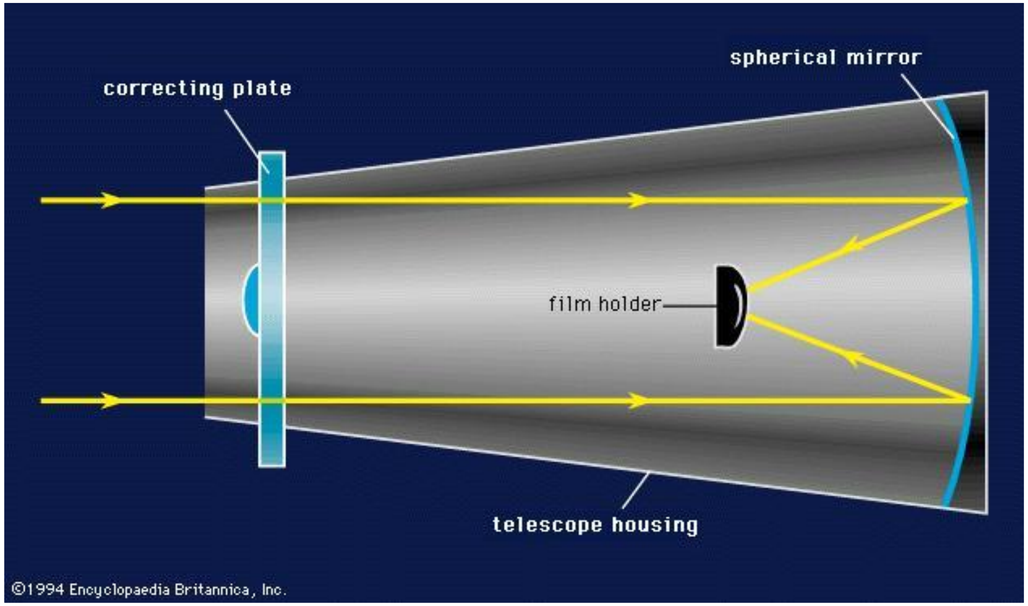
- Messier catalogue (1774 – 1781): haphazard collection 103 extended objects
- Catalogue of Nebulae and Clusters of Stars (William and Caroline Herschel, 1786 – 1802, 2500 objects) → General Catalogue of … (John Herschel, 1864, 5079 objects) → New General Catalogue (NGC, John Dreyer, 1888) + Index Catalogues (> 15,000 objects)
- Bonner Durchmusterung (1846 – 1863): all-hemispheric visual astrometric and photometric survey of all stars brighter than 9.5 mag (325,000)
- Astronomische Gesellschaft Katalog 3 (1955 – 1970): all-hemispheric photographic astrometric and proper motion of all stars brighter than 9–10 mag, coordinated effort of multiple observatories, led by Hamburg observatory
- Henry Draper Catalogue (Annie Jump Cannon and Edward Pickering, 1911 – 1924): spectroscopic classifications of 225,000 stars

Annie Jump Cannon

Some historical notes

The 2nd age of surveys: Schmidt surveys

- 1930: invention of a corrector plate by Bernhard Schmidt at Hamburg Observatory to correct for spherical aberration, coma and astigmatism



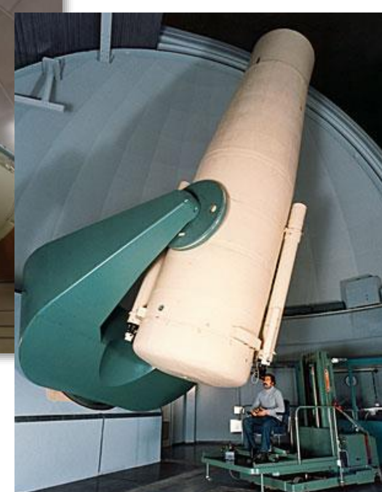
Some historical notes

The 2nd age of surveys: Schmidt surveys

- 1930: invention of a corrector plate by Bernhard Schmidt at Hamburg Observatory to correct for spherical aberration, coma and astigmatism
- ➢ Construction of large telescopes with a wide field-of-view

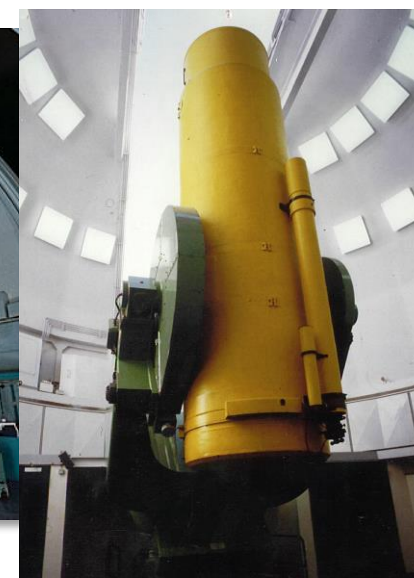
Oschin Schmidt-Telescope
(Palomar Observatory)

UK Schmidt-Telescope
(Siding Spring Observatory)



ESO Schmidt-Telescope
(La Silla Observatory)

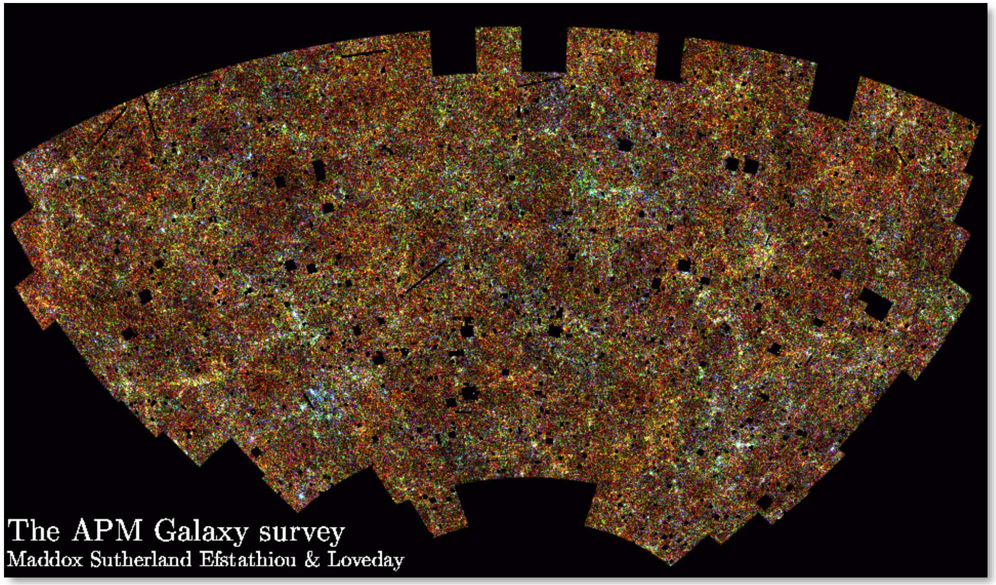
Großer Hamburger Schmidtspiegel
(Calar Alto Observatory)



Some historical notes

The 2nd age of surveys: Schmidt surveys

- 1930: invention of a corrector plate by Bernhard Schmidt at Hamburg Observatory to correct for spherical aberration, coma and astigmatism
- Construction of large telescopes with a wide field-of-view
- First all-sky photographic, three-band imaging surveys (e.g. POSS, 1950's – 80's)
- Later digitised: DSS, APM, SuperCOSMOS



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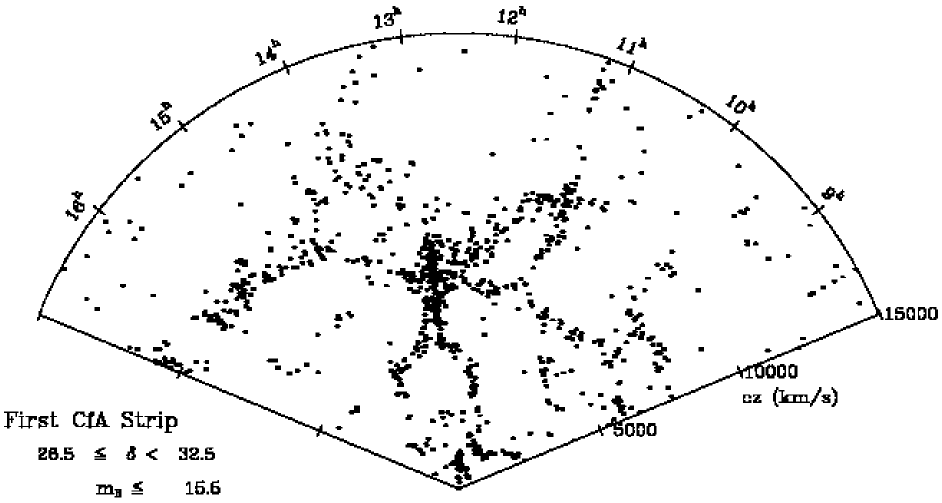
The 3rd age of surveys: going parallel

- Early redshift surveys were still “serial”: CfA (1977 – 1982, 2400 gals)
  - First exploration of large-scale structure



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- Example: 2dF: 400 fibres

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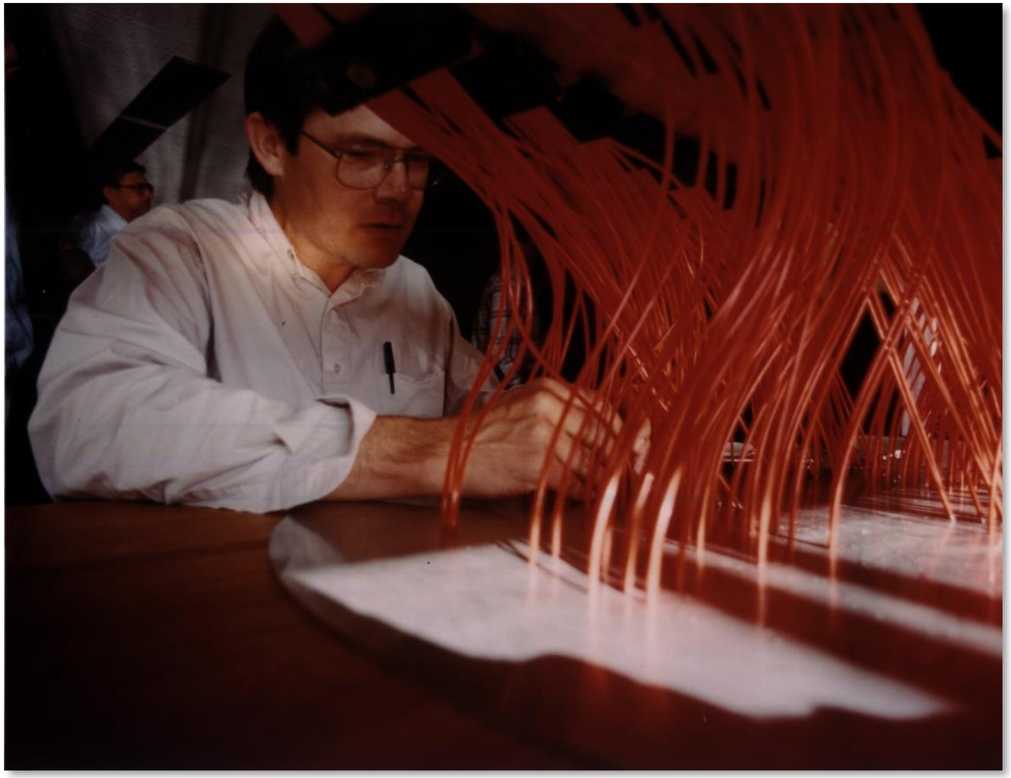

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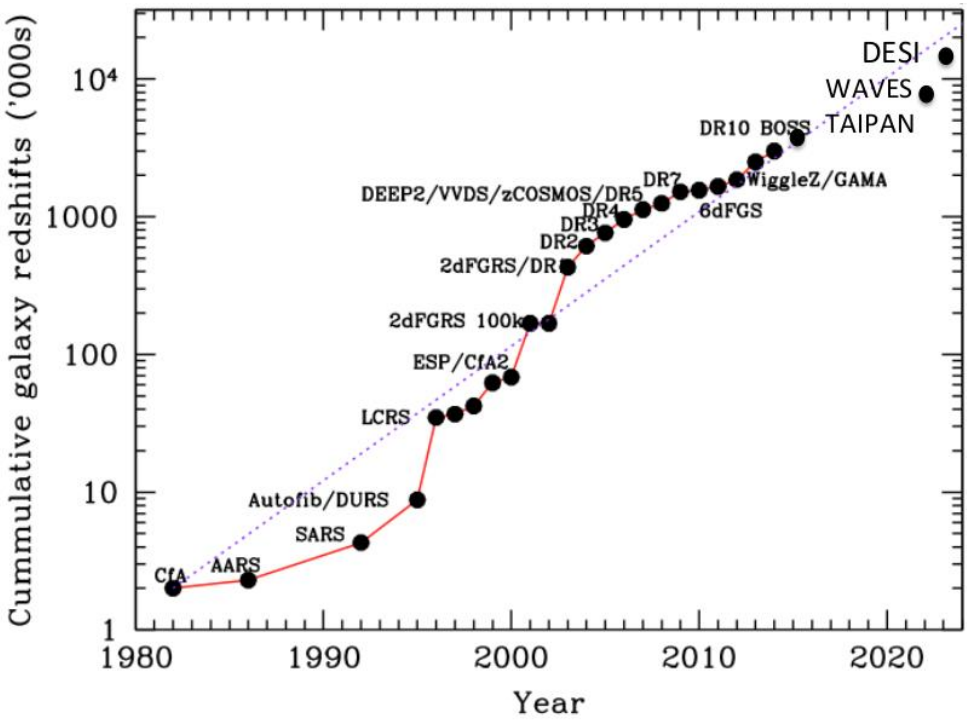

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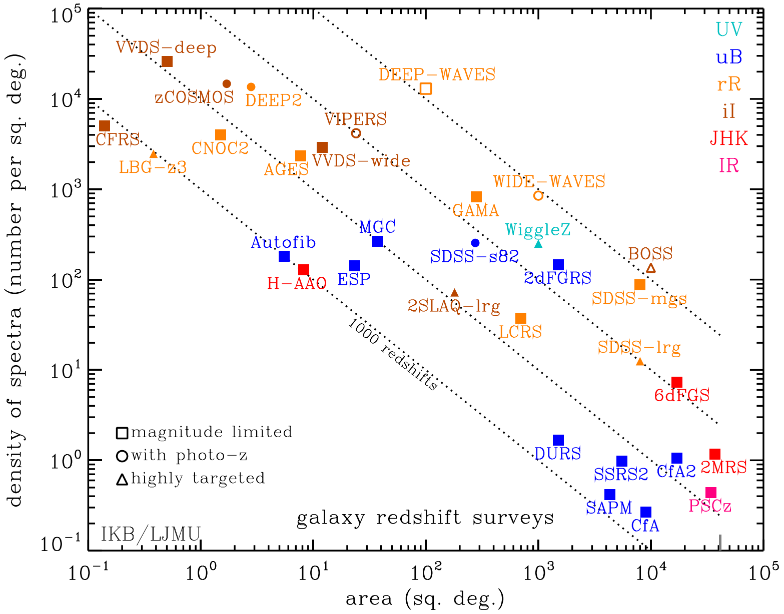

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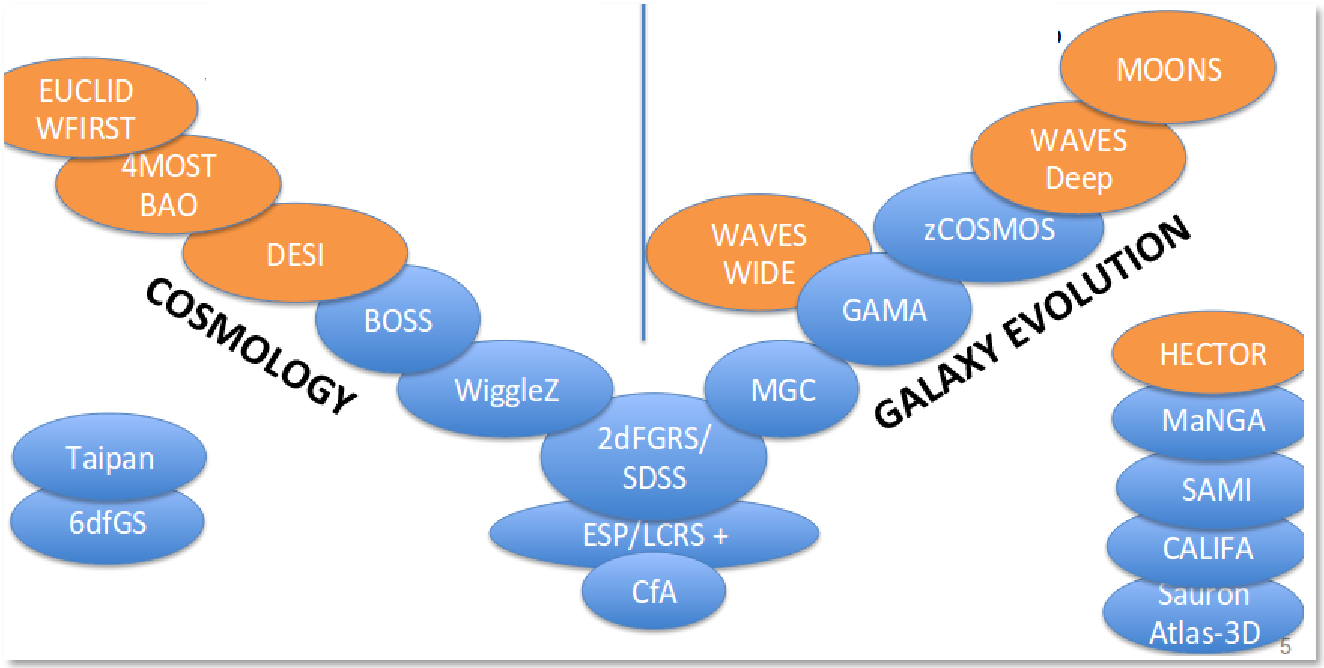

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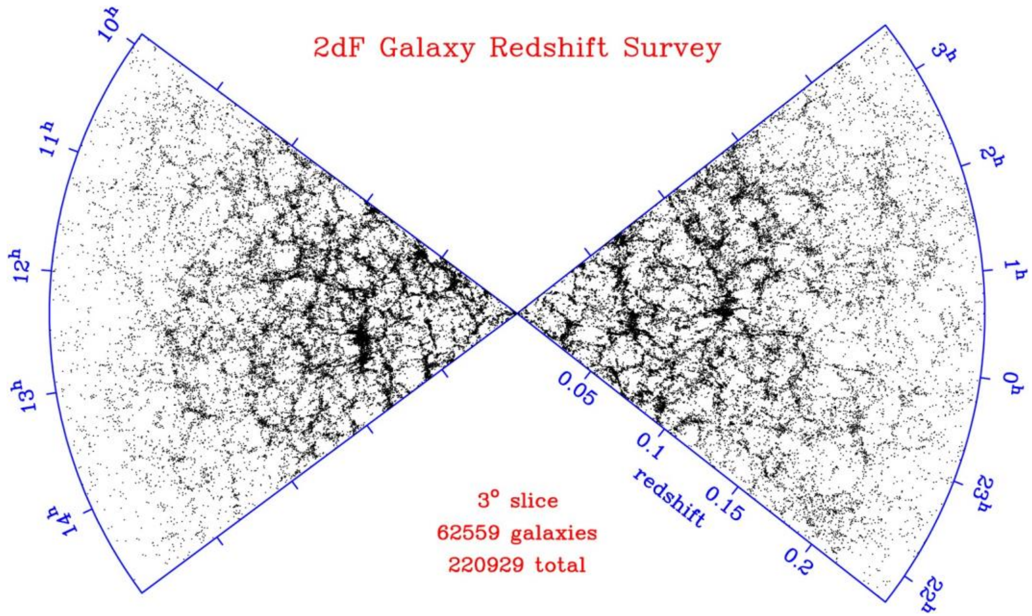
- 2dF Galaxy Redshift Survey (1997 – 2002, 220,000 gals)
  - Discovery of Baryonic Acoustic Oscillations



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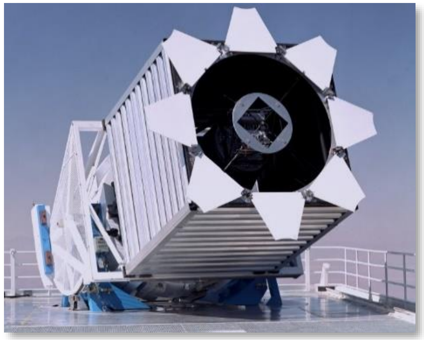
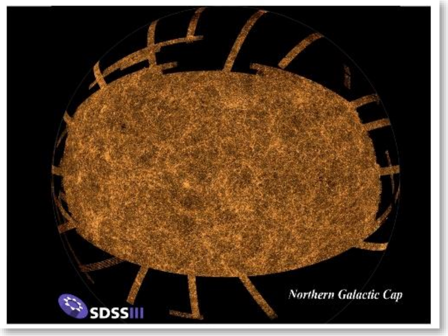
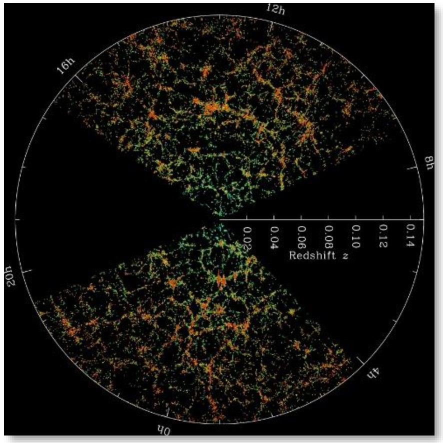
- Huge number of both wide and deep surveys
- 2dF Galaxy Redshift Survey (1997 – 2002, 220,000 gals)
- From 2000: Sloan Digital Sky Survey: all-hemispheric, multi-band, deep imaging + spectroscopy of 10^6 galaxies to $r < 17.8$ mag
  - Transformational



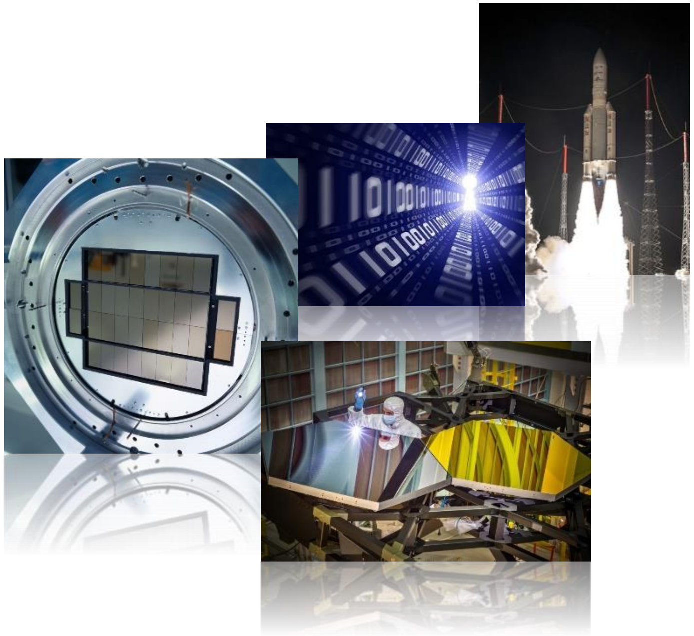




Some historical notes

The 4th age of surveys: the era of industrialisation

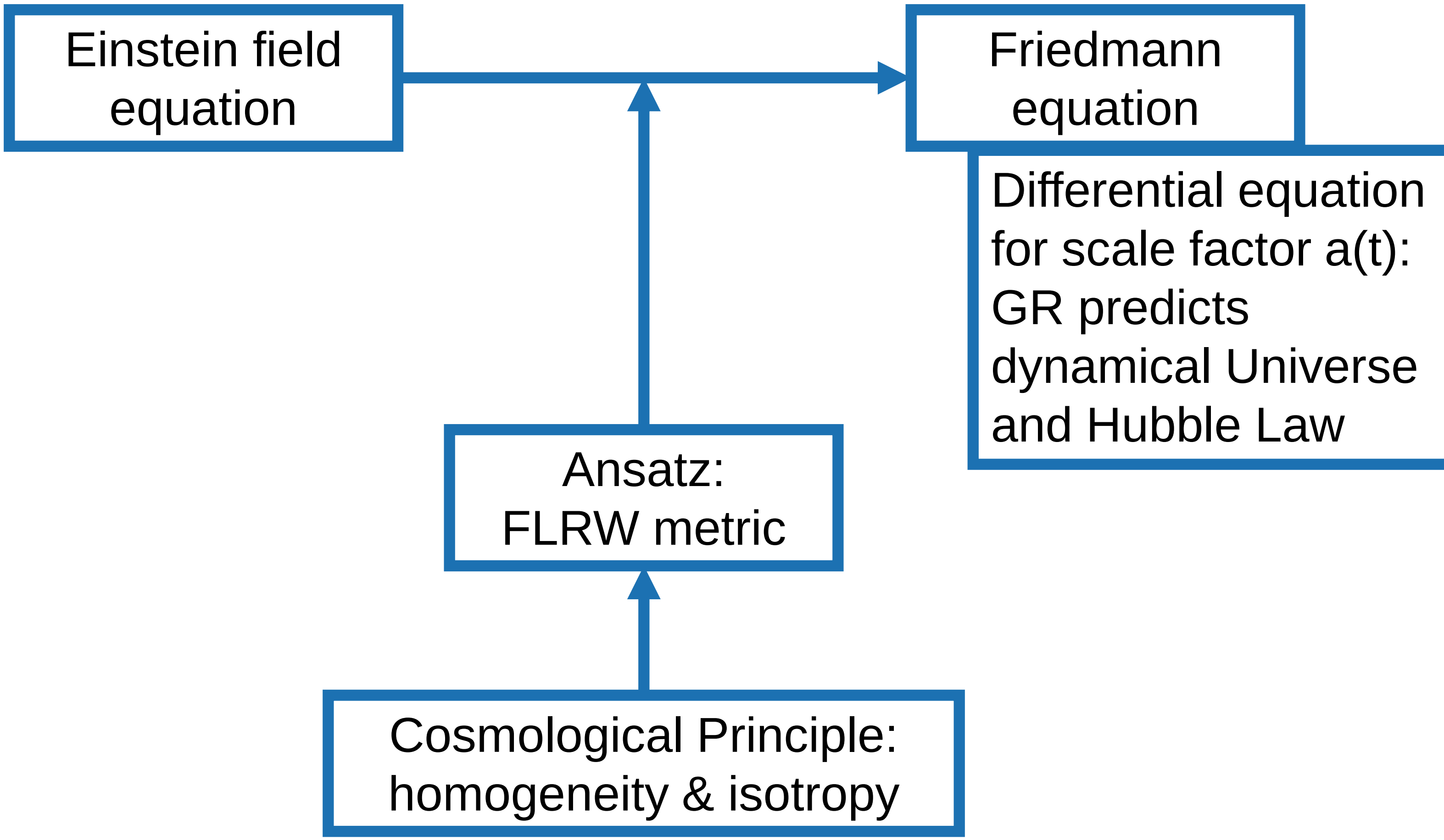
- Began with SDSS
- New set of ground-based and space-borne imaging and spectroscopic facilities that exploit technological advances:
  - Larger telescopes
  - More complex instrumentation
  - Detectors
  - Materials
  - System control
  - Computing
  - Space faring technology



- ➢ Complete exploration of a large fraction of the observable Universe
- ➢ Particle-physics-like scale of operations

Questions?

Setting the cosmological scene



Setting the cosmological scene

- FLRW metric: $$ds^2 = -c^2\,dt^2 + a^2(t)[d\chi^2 + \Sigma^2(\chi)(d\theta^2 + \sin^2\theta\, d\phi^2)]$$

$$\Sigma(\chi) = \begin{cases} \sin\chi & k = +1 \\ \chi & k = 0 \\ \sinh\chi & k = -1 \end{cases}$$

- Hubble parameter: $$H = \frac{\dot{a}}{a}$$
- Redshift: $$1 + z = \frac{a_0}{a}$$
- Friedmann equation: $$H(z) = H_0 \left[\sum_i \Omega_i (1+z)^{3(1+w_i)} + \Omega_k (1+z)^2\right]^{\frac{1}{2}}$$

Density parameter = ρ_i / ρ_c

- Equation of state: $$p_i = w_i c^2 \rho_i$$

Equation of state parameter

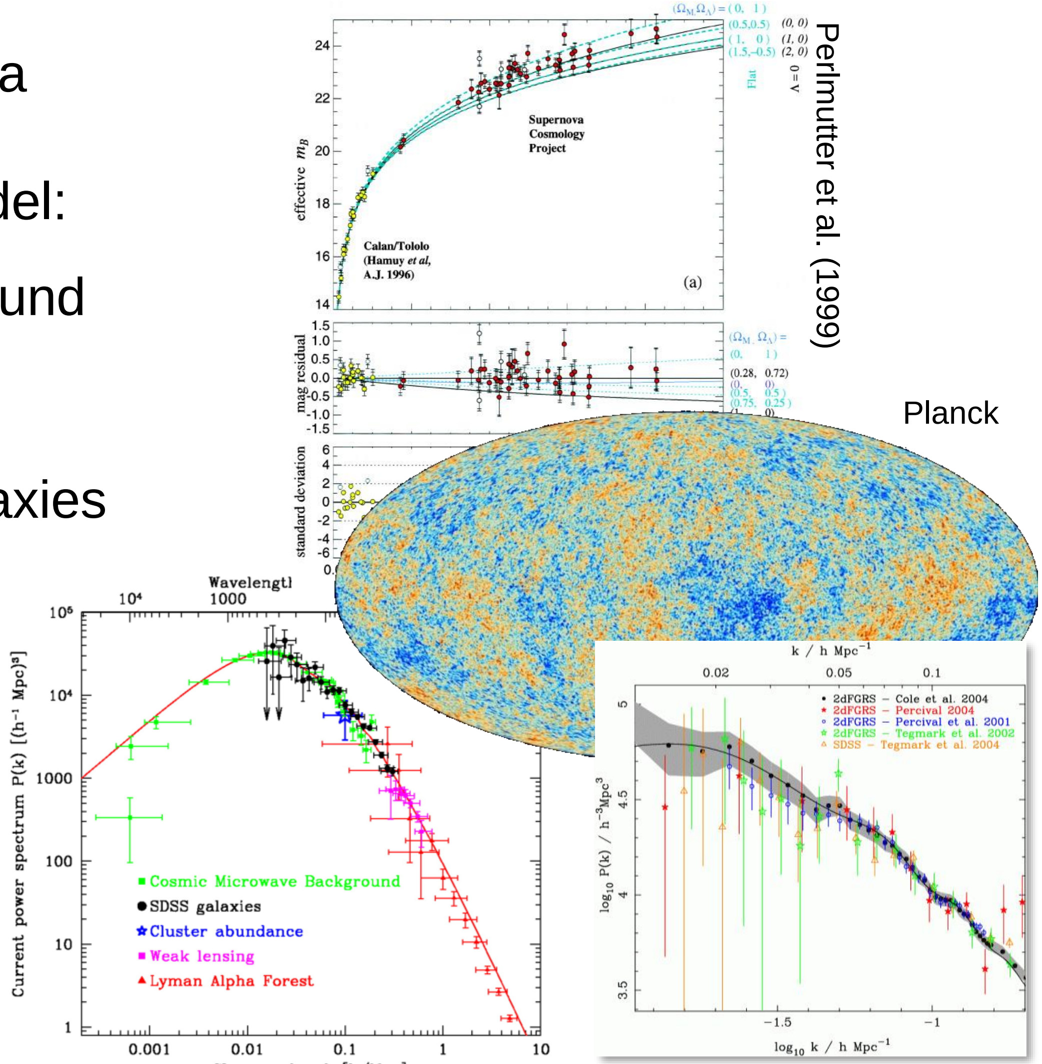
Setting the cosmological scene

- Which of the possible solutions to the Friedmann equation corresponds to reality? In other words, what is the stress-energy tensor of the Universe?
- For each mass-energy component i, what is its density and equation of state parameter [ρ_i, w_i] (and what is H_0)?
- What can we measure?
  - Ω_{tot} by summing up all known forms of matter and energy
  - Expansion history
  - Spatial curvature
  - Clustering, evolution and dynamics of density perturbations
  - Combination of any of the above
- ➢ Development of many “cosmological tests” over the decades

Setting the cosmological scene

Past decades: development of a wide array of observations to constrain the cosmological model:

- Cosmic Microwave Background
- Type Ia Supernovae
- Large scale structure of galaxies and intergalactic medium
- Galaxy cluster abundance
- Weak lensing
- …



Perlmutter et al. (1999)

Planck

Tegmark et al. (2004)

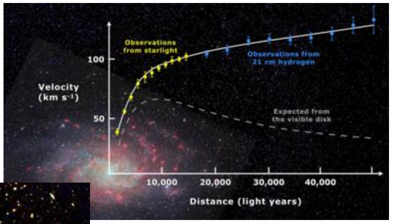
Cole et al. (2005)

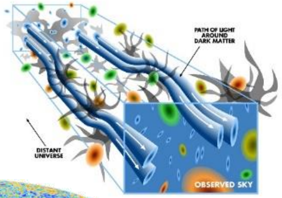
Setting the cosmological scene

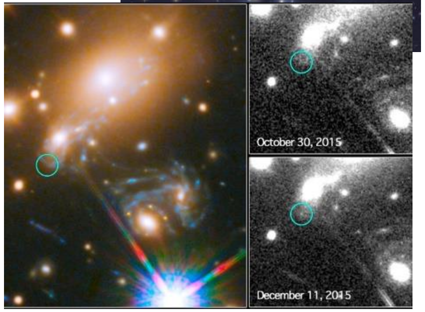
Weirdness 1: the Universe is full of Dark Matter

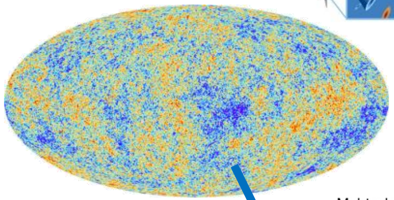
Evidence:

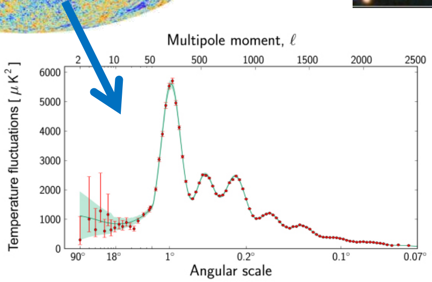
- Dynamical
  - Flat rotation curves of spiral galaxies
  - Velocity dispersion of stars in giant elliptical and dwarf spheroidal galaxies
  - Velocity dispersion of galaxies in clusters
- Lensing
  - Weak lensing by large-scale structure and cluster mergers
  - Strong lensing by individual galaxies and clusters
- Structure formation
  - Abundance of clusters
  - Large-scale distribution of galaxies
  - Power spectrum of CMB anisotropies

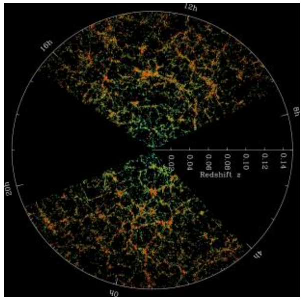






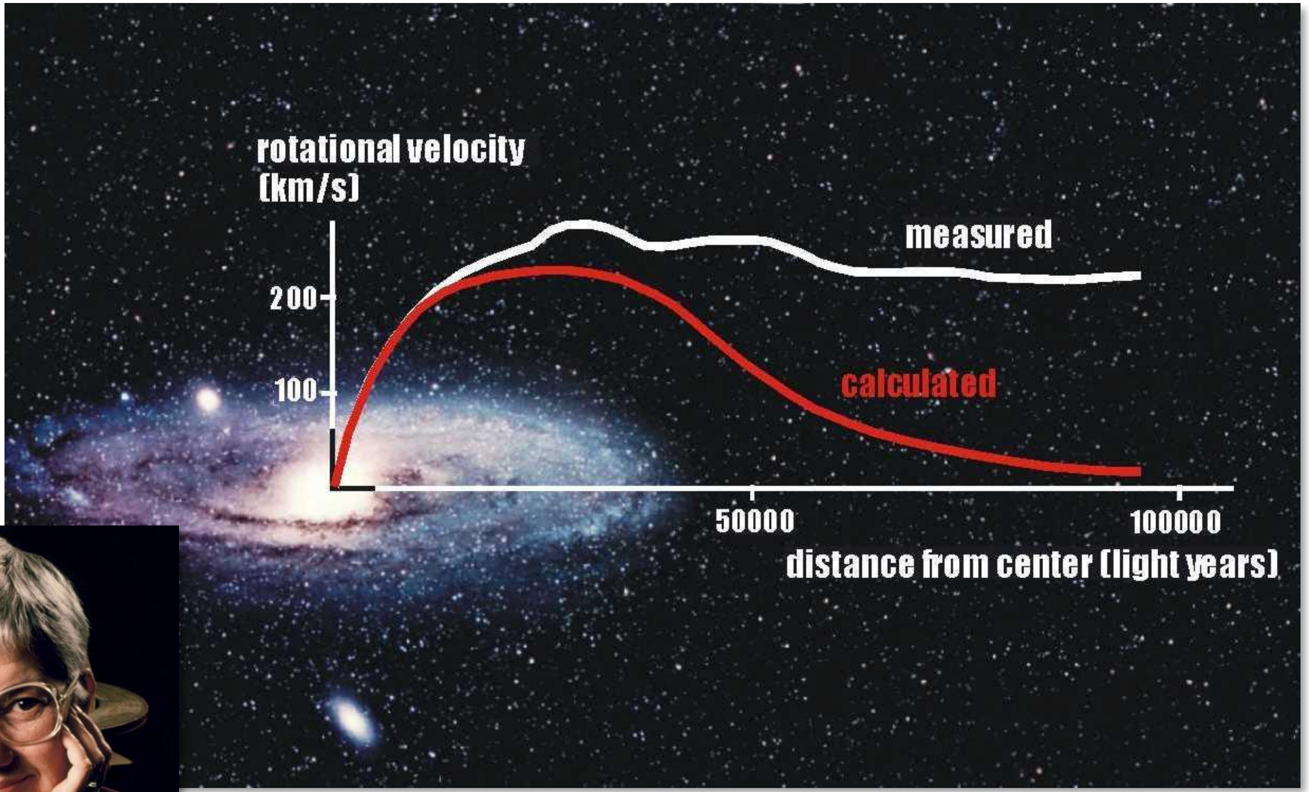






Digression

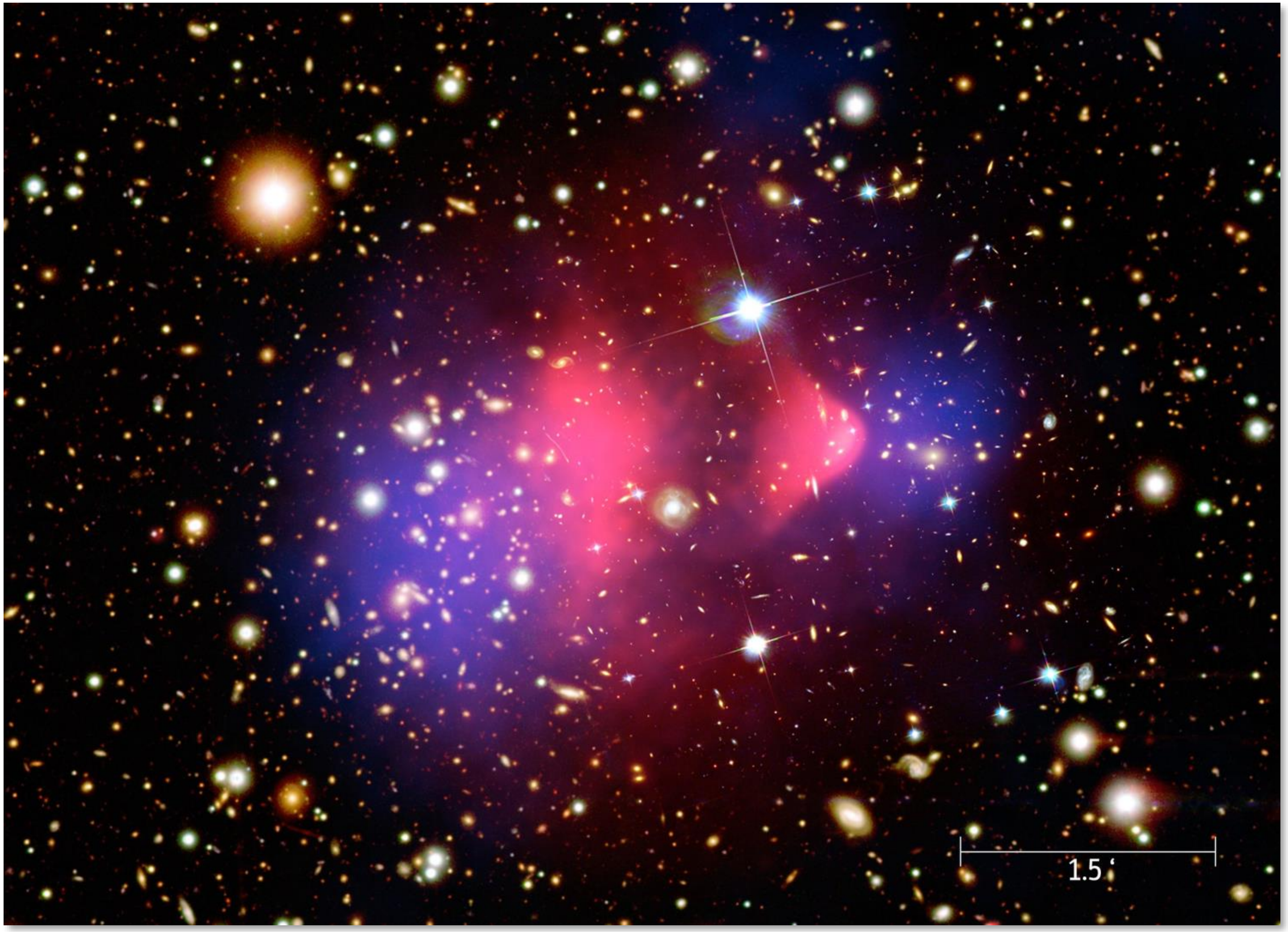
- This is NOT our only or even our best evidence of Dark Matter:



Vera Rubin

Digression

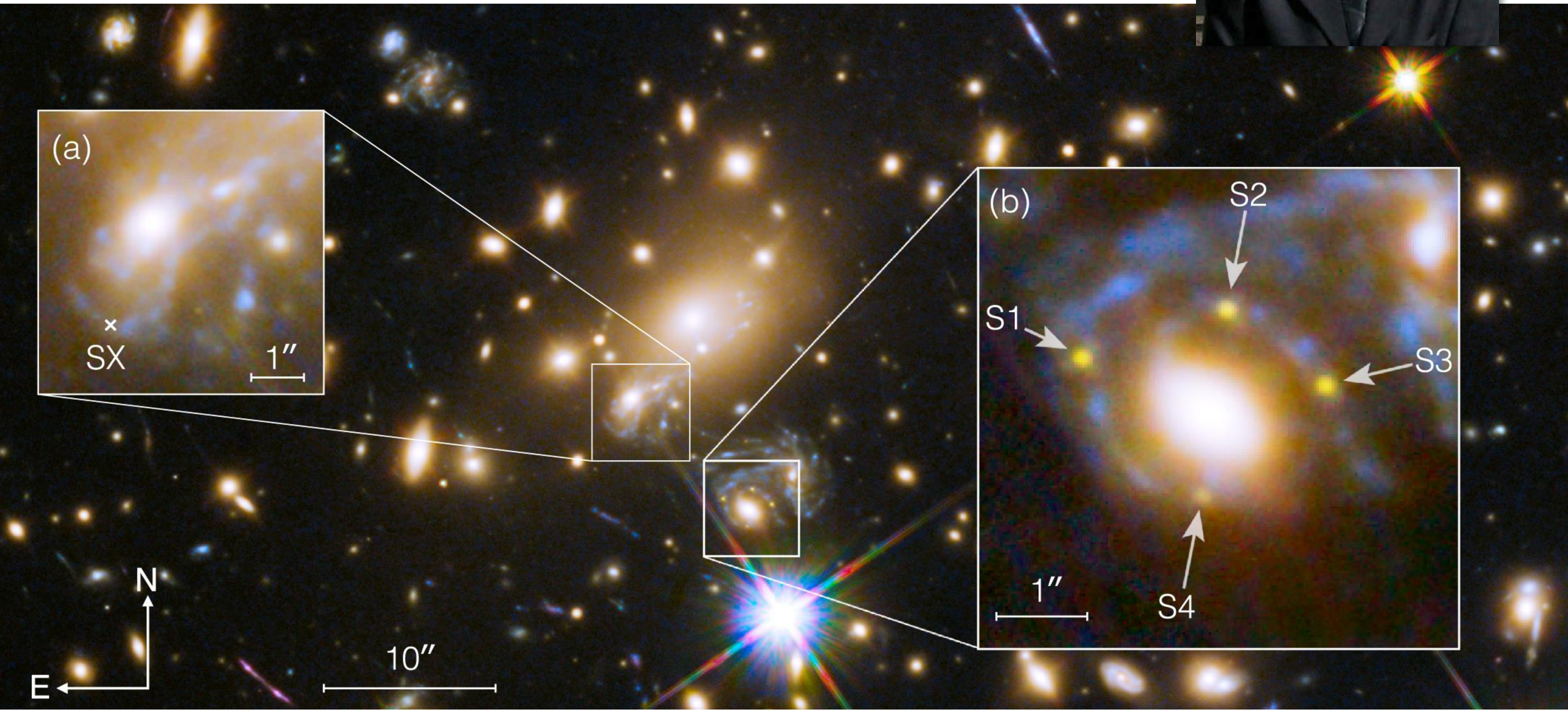
- Bullet cluster:



Digression

- SN Refsdal:

Sjur Refsdal



Grillo et al. (2018)

Digression

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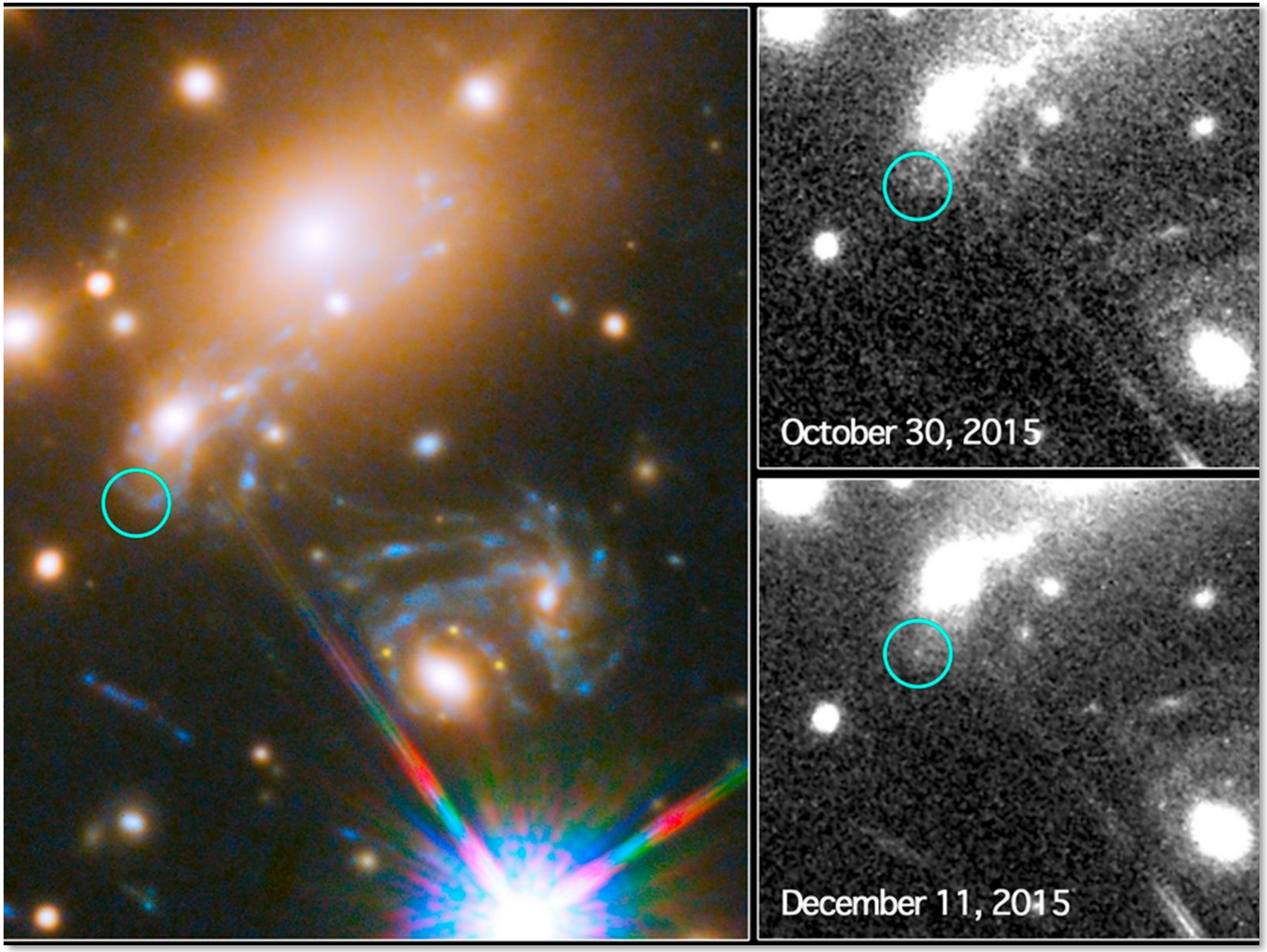
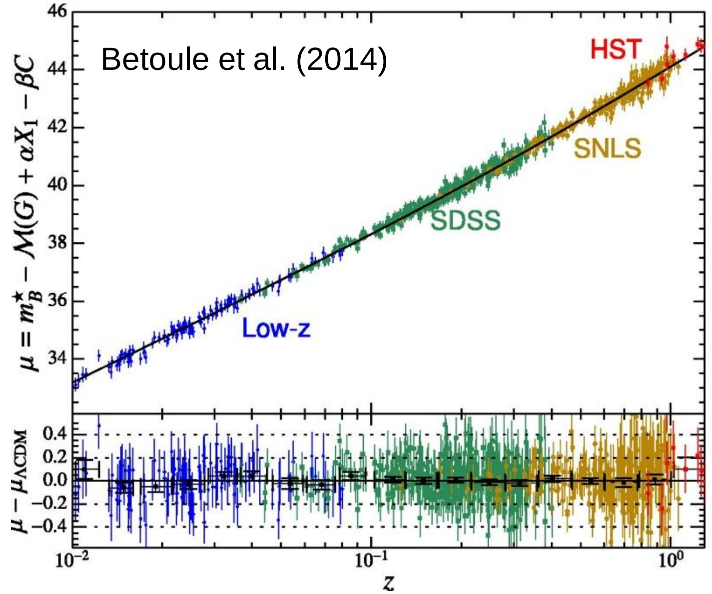
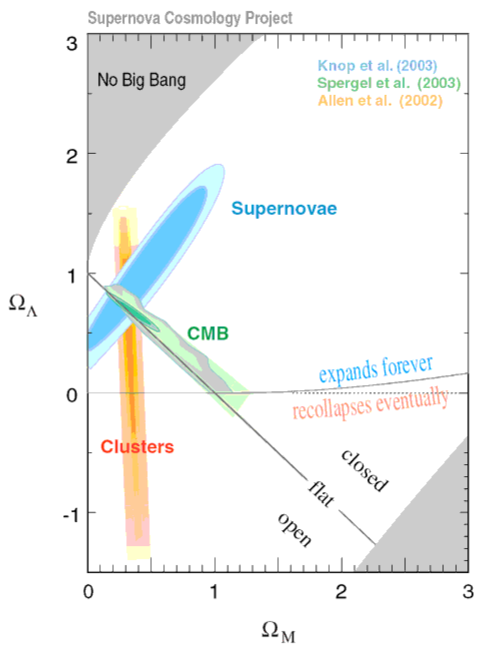


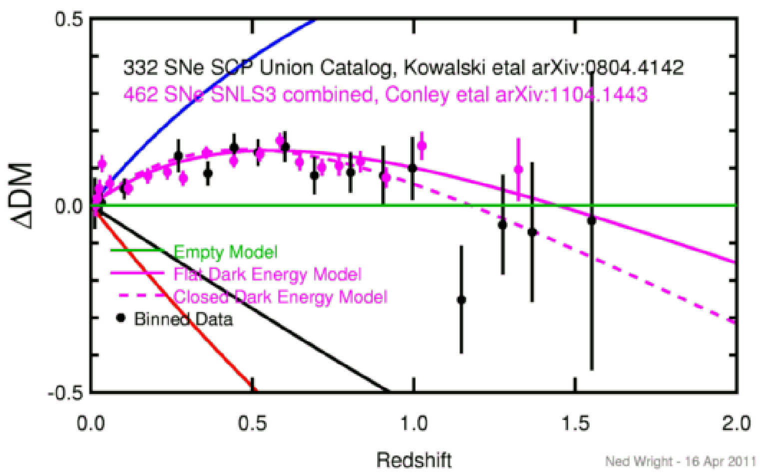
Setting the cosmological scene

Weirdness 2: the expansion of the Universe has "recently" begun to accelerate

- Evidence:
  - SNIa
  - Combination of CMB (Universe is flat) and cluster abundance ($\Omega_M < 1$)







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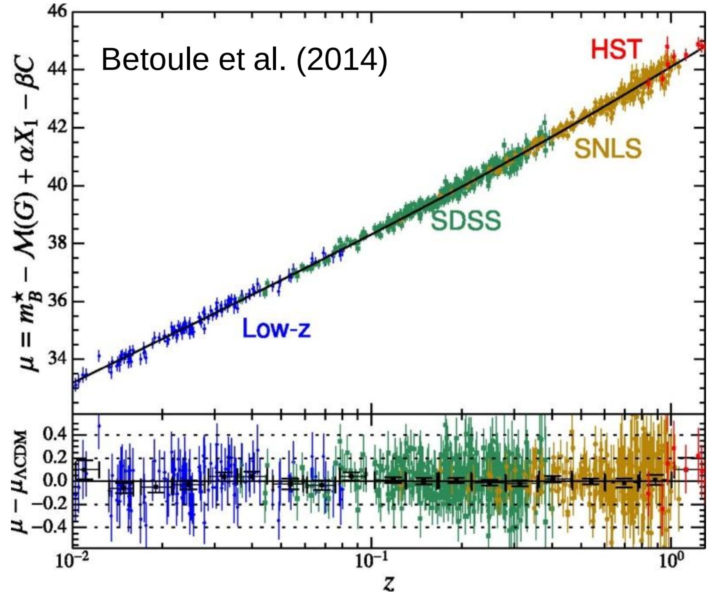
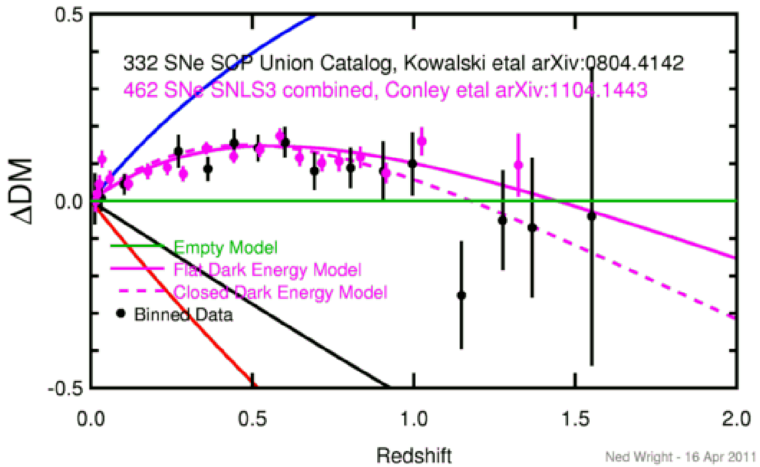


- ➢ The universe is full of Dark Energy
- So far, all data are consistent with DE being in its simplest possible form: a cosmological constant (w = −1)



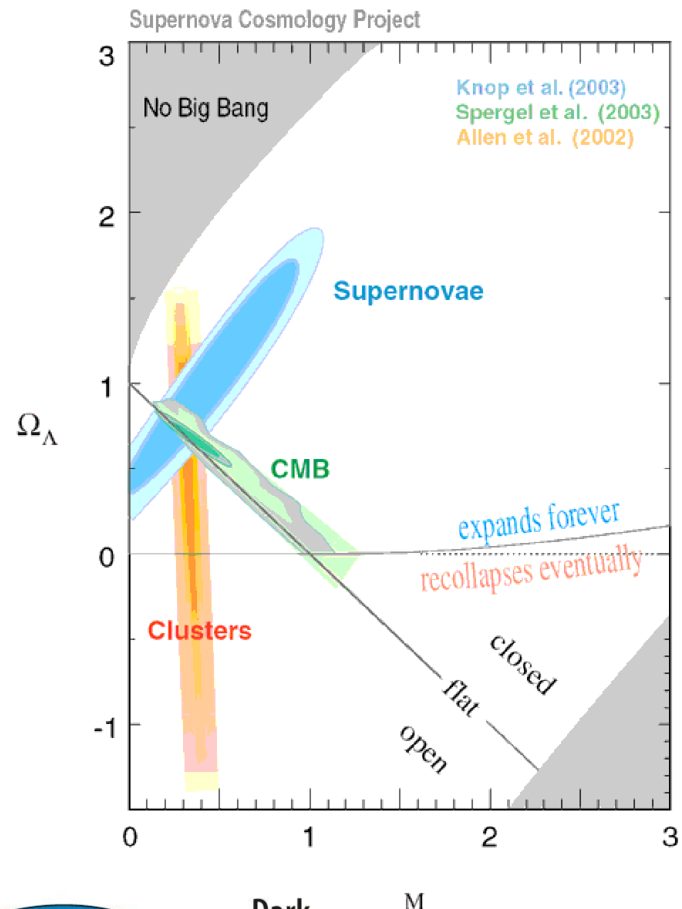
The ΛCDM standard model of cosmology

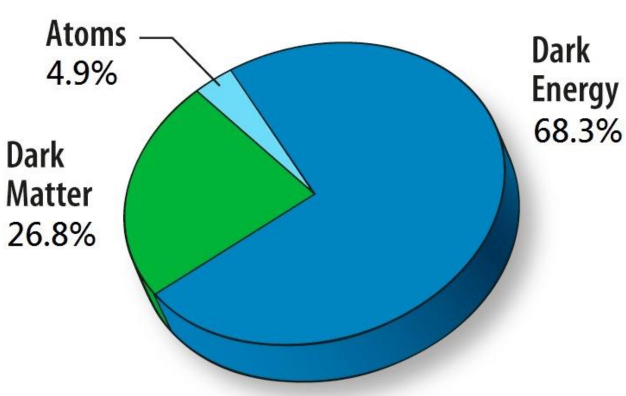
Parameter	TT+lowE 68% limits	TE+lowE 68% limits	EE+lowE 68% limits	TT,TE,EE+lowE 68% limits	TT,TE,EE+lowE+lensing 68% limits	TT,TE,EE+lowE+lensing+BAO 68% limits
$\Omega_b h^2$	0.02212 ± 0.00022	0.02249 ± 0.00025	0.0240 ± 0.0012	0.02236 ± 0.00015	0.02237 ± 0.00015	0.02242 ± 0.00014
$\Omega_c h^2$	0.1206 ± 0.0021	0.1177 ± 0.0020	0.1158 ± 0.0046	0.1202 ± 0.0014	0.1200 ± 0.0012	0.11933 ± 0.00091
$100\theta_{MC}$	1.04077 ± 0.00047	1.04139 ± 0.00049	1.03999 ± 0.00089	1.04090 ± 0.00031	1.04092 ± 0.00031	1.04101 ± 0.00029
τ	0.0522 ± 0.0080	0.0496 ± 0.0085	0.0527 ± 0.0090	$0.0544^{+0.0070}_{-0.0081}$	0.0544 ± 0.0073	0.0561 ± 0.0071
$\ln(10^{10} A_s)$	3.040 ± 0.016	$3.018^{+0.020}_{-0.018}$	3.052 ± 0.022	3.045 ± 0.016	3.044 ± 0.014	3.047 ± 0.014
n_s	0.9626 ± 0.0057	0.967 ± 0.011	0.980 ± 0.015	0.9649 ± 0.0044	0.9649 ± 0.0042	0.9665 ± 0.0038
H_0 [$\mathrm{km\,s^{-1}\,Mpc^{-1}}$] . .	66.88 ± 0.92	68.44 ± 0.91	69.9 ± 2.7	67.27 ± 0.60	67.36 ± 0.54	67.66 ± 0.42
Ω_Λ	0.679 ± 0.013	0.699 ± 0.012	$0.711^{+0.033}_{-0.026}$	0.6834 ± 0.0084	0.6847 ± 0.0073	0.6889 ± 0.0056
Ω_m	0.321 ± 0.013	0.301 ± 0.012	$0.289^{+0.026}_{-0.033}$	0.3166 ± 0.0084	0.3153 ± 0.0073	0.3111 ± 0.0056
$\Omega_m h^2$	0.1434 ± 0.0020	0.1408 ± 0.0019	$0.1404^{+0.0034}_{-0.0039}$	0.1432 ± 0.0013	0.1430 ± 0.0011	0.14240 ± 0.00087
$\Omega_m h^3$	0.09589 ± 0.00046	0.09635 ± 0.00051	$0.0981^{+0.0016}_{-0.0018}$	0.09633 ± 0.00029	0.09633 ± 0.00030	0.09635 ± 0.00030
σ_8	0.8118 ± 0.0089	0.793 ± 0.011	0.796 ± 0.018	0.8120 ± 0.0073	0.8111 ± 0.0060	0.8102 ± 0.0060
$S_8 \equiv \sigma_8(\Omega_m/0.3)^{0.5}$.	0.840 ± 0.024	0.794 ± 0.024	$0.781^{+0.052}_{-0.060}$	0.834 ± 0.016	0.832 ± 0.013	0.825 ± 0.011
$\sigma_8 \Omega_m^{0.25}$	0.611 ± 0.012	0.587 ± 0.012	0.583 ± 0.027	0.6090 ± 0.0081	0.6078 ± 0.0064	0.6051 ± 0.0058
z_{re}	7.50 ± 0.82	$7.11^{+0.91}_{-0.75}$	$7.10^{+0.87}_{-0.73}$	7.68 ± 0.79	7.67 ± 0.73	7.82 ± 0.71
$10^9 A_s$	2.092 ± 0.034	2.045 ± 0.041	2.116 ± 0.047	$2.101^{+0.031}_{-0.034}$	2.100 ± 0.030	2.105 ± 0.030
$10^9 A_s e^{-2\tau}$	1.884 ± 0.014	1.851 ± 0.018	1.904 ± 0.024	1.884 ± 0.012	1.883 ± 0.011	1.881 ± 0.010
Age [Gyr]	13.830 ± 0.037	13.761 ± 0.038	$13.64^{+0.16}_{-0.14}$	13.800 ± 0.024	13.797 ± 0.023	13.787 ± 0.020
z_*	1090.30 ± 0.41	1089.57 ± 0.42	$1087.8^{+1.6}_{-1.7}$	1089.95 ± 0.27	1089.92 ± 0.25	1089.80 ± 0.21
r_* [Mpc]	144.46 ± 0.48	144.95 ± 0.48	144.29 ± 0.64	144.39 ± 0.30	144.43 ± 0.26	144.57 ± 0.22
$100\theta_*$	1.04097 ± 0.00046	1.04156 ± 0.00049	1.04001 ± 0.00086	1.04109 ± 0.00030	1.04110 ± 0.00031	1.04119 ± 0.00029
z_{drag}	1059.39 ± 0.46	1060.03 ± 0.54	1063.2 ± 2.4	1059.93 ± 0.30	1059.94 ± 0.30	1060.01 ± 0.29
r_{drag} [Mpc]	147.21 ± 0.48	147.59 ± 0.49	146.46 ± 0.70	147.05 ± 0.30	147.09 ± 0.26	147.21 ± 0.23
k_D [$\mathrm{Mpc^{-1}}$]	0.14054 ± 0.00052	0.14043 ± 0.00057	0.1426 ± 0.0012	0.14090 ± 0.00032	0.14087 ± 0.00030	0.14078 ± 0.00028
z_{eq}	3411 ± 48	3349 ± 46	3340^{+81}_{-92}	3407 ± 31	3402 ± 26	3387 ± 21
k_{eq} [$\mathrm{Mpc^{-1}}$]	0.01041 ± 0.00014	0.01022 ± 0.00014	$0.01019^{+0.00025}_{-0.00028}$	0.010398 ± 0.000094	0.010384 ± 0.000081	0.010339 ± 0.000063
$100\theta_{s,eq}$	0.4483 ± 0.0046	0.4547 ± 0.0045	0.4562 ± 0.0092	0.4490 ± 0.0030	0.4494 ± 0.0026	0.4509 ± 0.0020

Planck collaboration (2021)

Our Universe

- Best measurements:
  $\Omega_\Lambda \approx 0.68$
  $\Omega_M \approx 0.32$ ($\Omega_b \approx 0.05$)
  $\Omega_{rad} \approx 10^{-5}$
  $H_0 \approx 70$ km/s/Mpc
- The Universe
  - is flat
  - is infinite
  - accelerates!
  - expands for ever
  - is 13.8×10^9 yr old
  - consists of unknown mass/energy components at the 95% level!



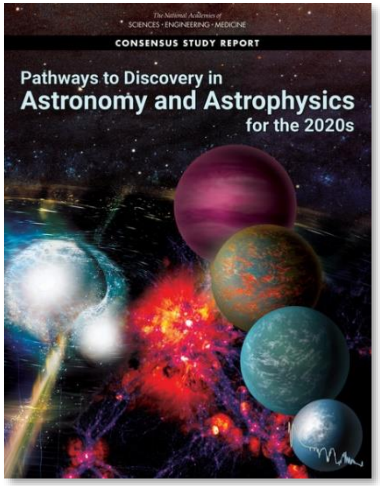


So what is there left to do (for surveys)?

Two elephants in the room:

COSMOLOGY IN THE 2020S AND BEYOND

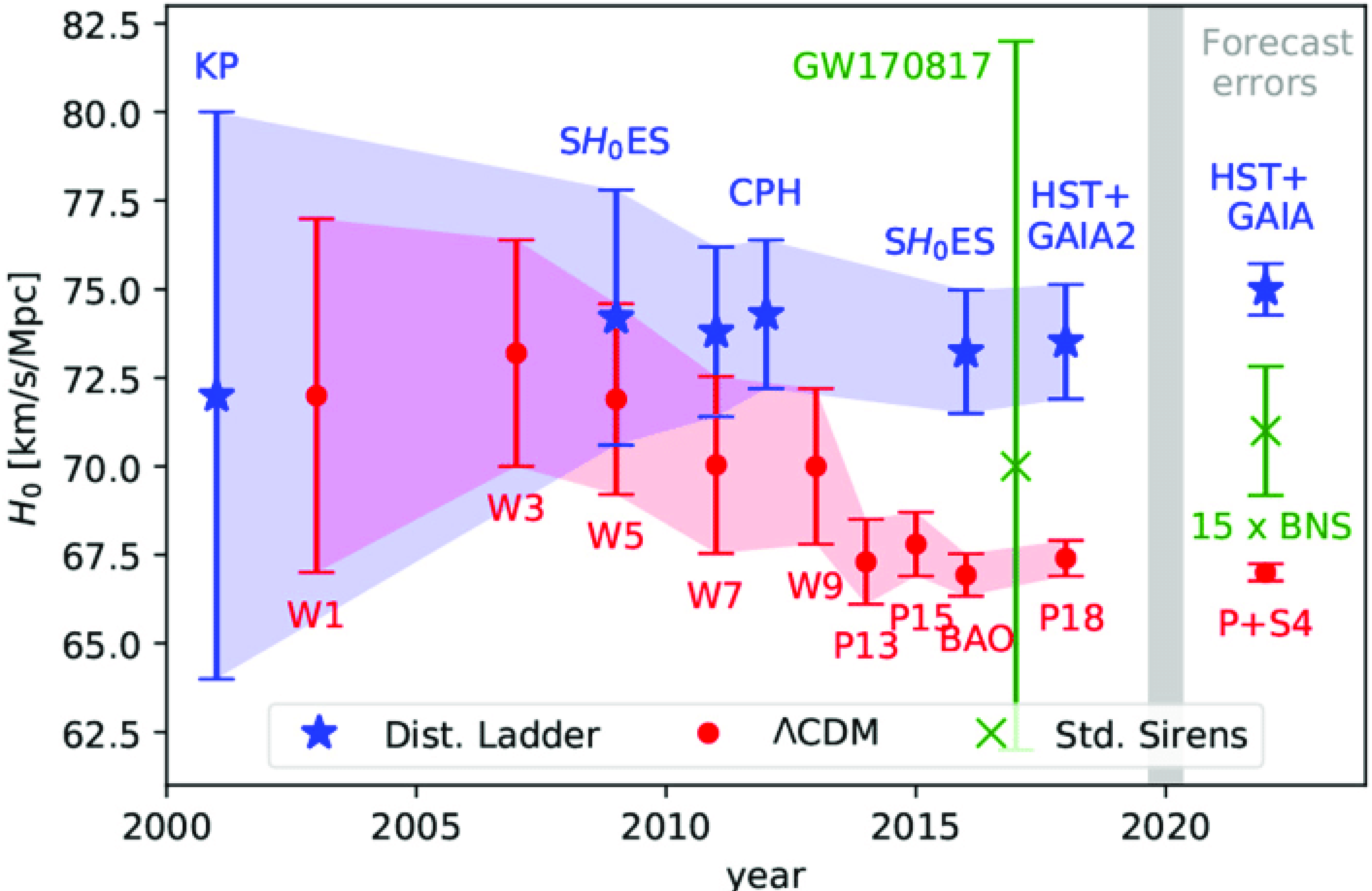
With both compelling mysteries and extensive observational means by which to explore them, this will be an amazing decade for cosmology. In this report, the panel identifies four major science questions for the upcoming decade: (1) What set the Hot Big Bang in motion? (2) What are the properties of dark matter and the dark sector? (3) What physics drives the cosmic expansion and large-scale evolution of the universe? (4) How will measurements of gravitational waves reshape our cosmological view? The panel also identified a discovery area: The Dark Ages as a cosmological probe.



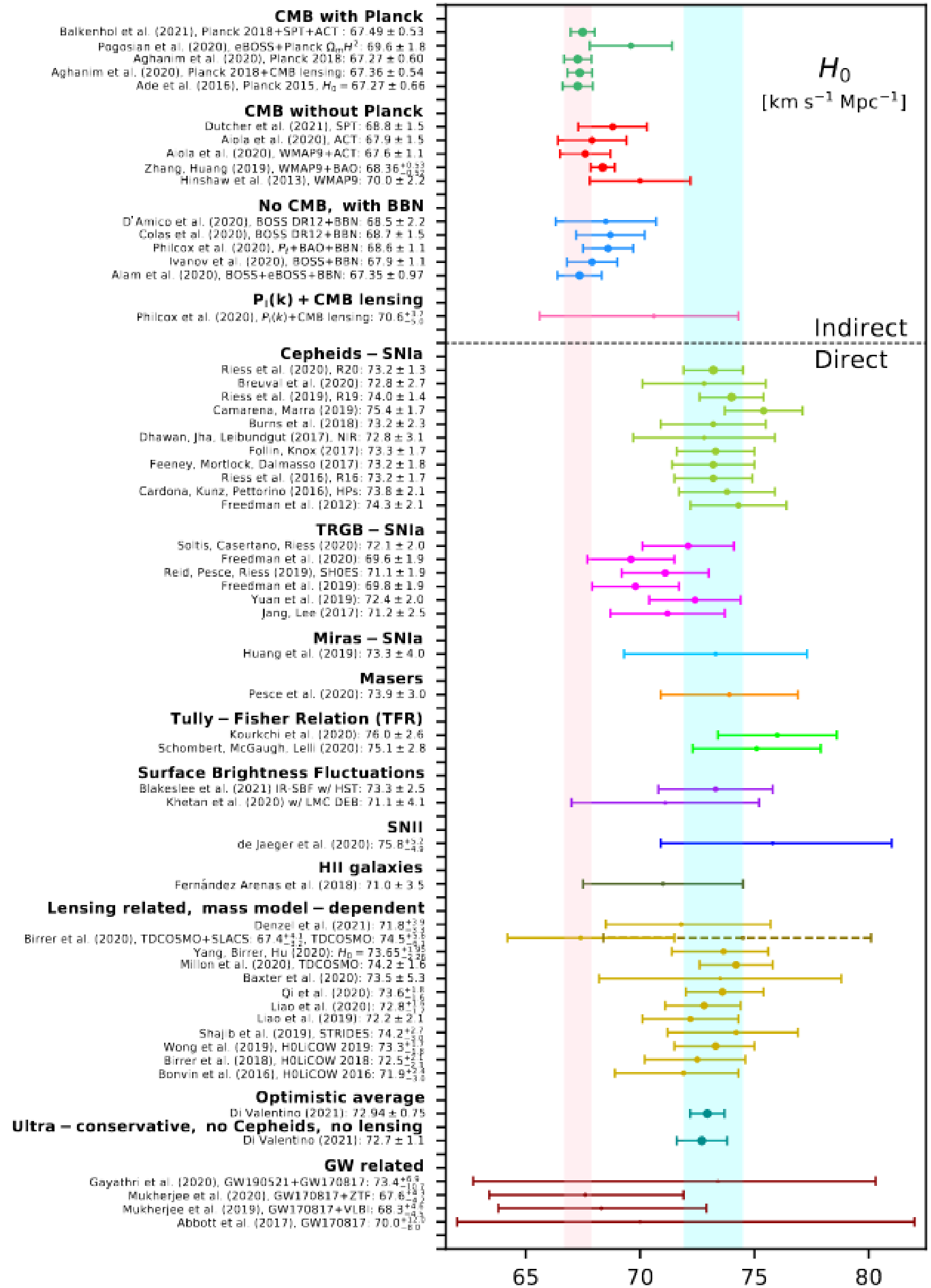
So what is there left to do (for surveys)?

Is the model beginning to crack?

- Hubble tension



Ezquiaga et al. (2018)



Di Valentino et al. (2021)

So what is there left to do (for surveys)?

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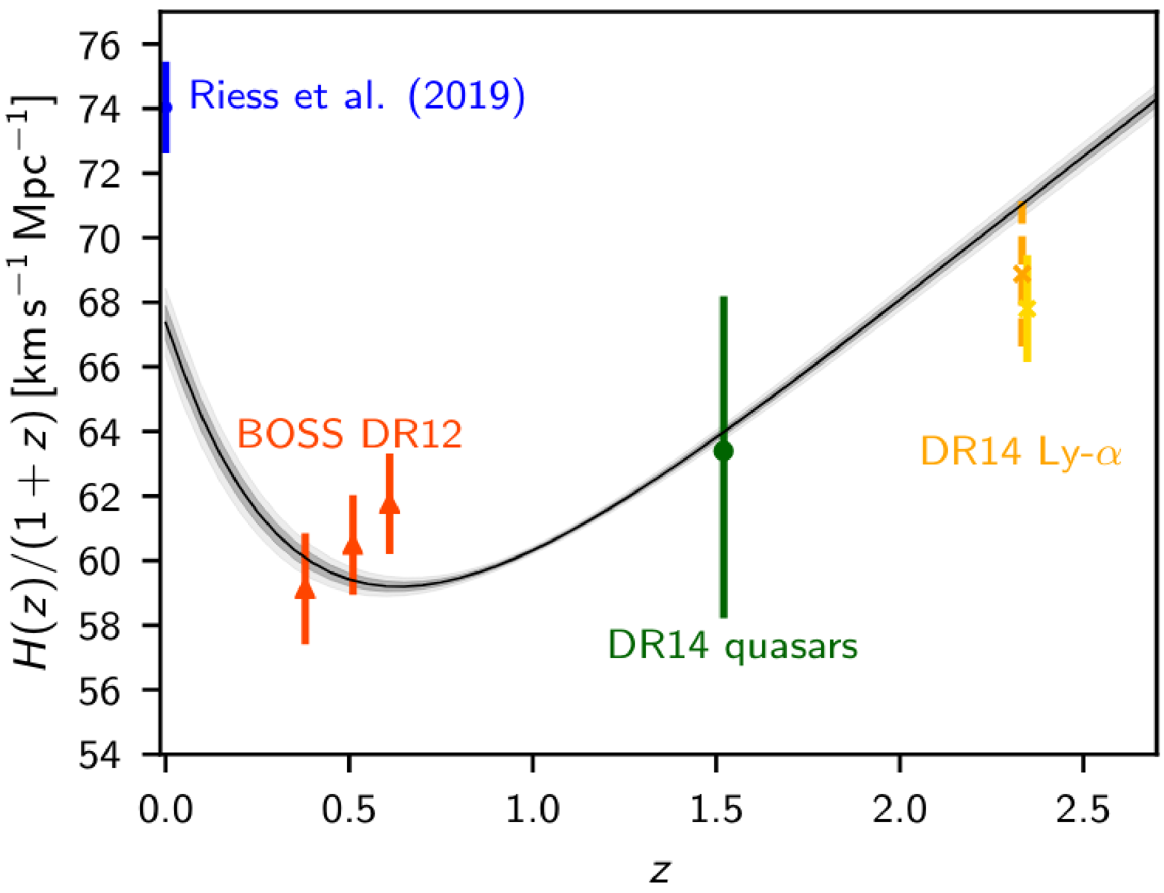

Planck Collaboration (2021)

Questions?