



Charting the Universe: the next generation of cosmological surveys

Part 1

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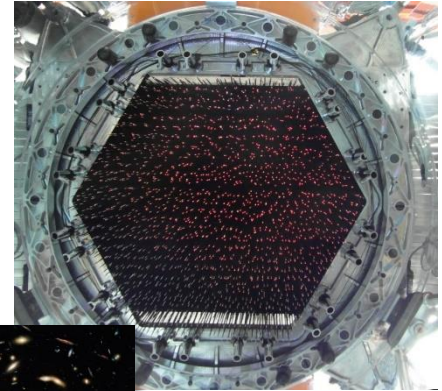


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CLUSTER OF EXCELLENCE
QUANTUM UNIVERSE

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2. Some historical notes
3. Setting the cosmological scene
4. What is there left to do (for surveys)?
5. Rubin Observatory / LSST
6. Method: SN Ia



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 \gg human timescales
 - Cannot directly observe evolution



Range

Direction

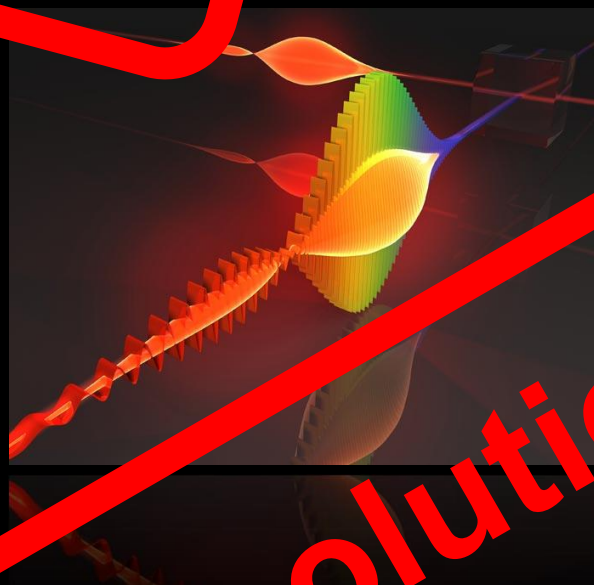
Brightness

Time of
arrival

Polarisation

Resolution

Energy



Introduction

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- ◆ The physical parameter space of these objects and processes is huge
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- ◆ Cannot experiment with any object of interest, only observe
- ◆ Many processes act on timescales \gg 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



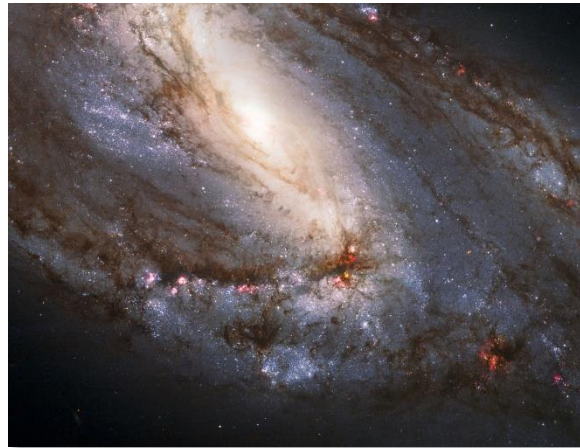
Introduction

Observations

Statistical investigations
of large samples
(surveys)

Level of detail
Statistical power, completeness

Detailed studies of
small samples



Theory

Analytical, semi-analytical, numerical

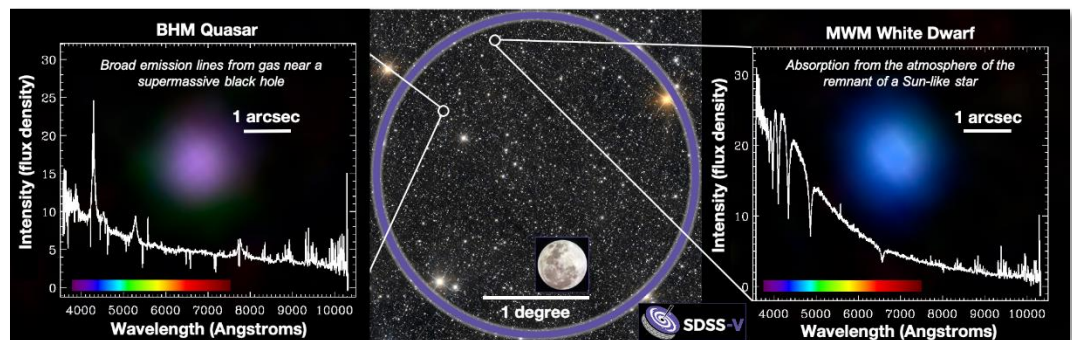
Introduction: what is a survey?

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:

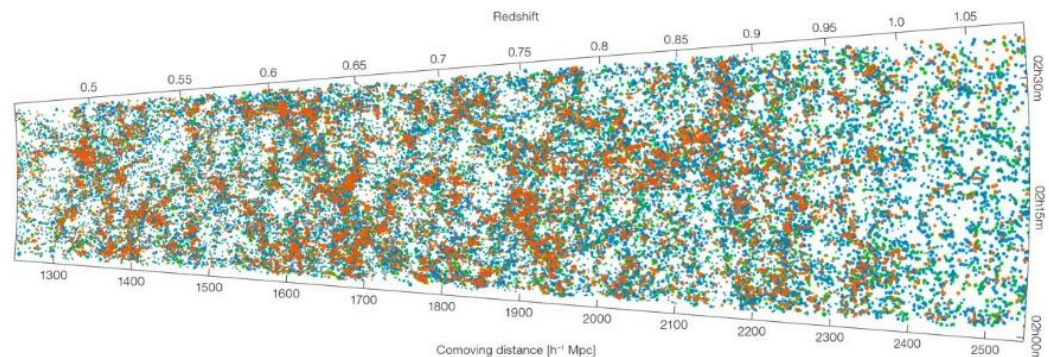
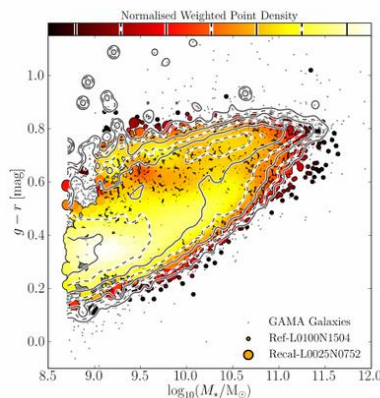
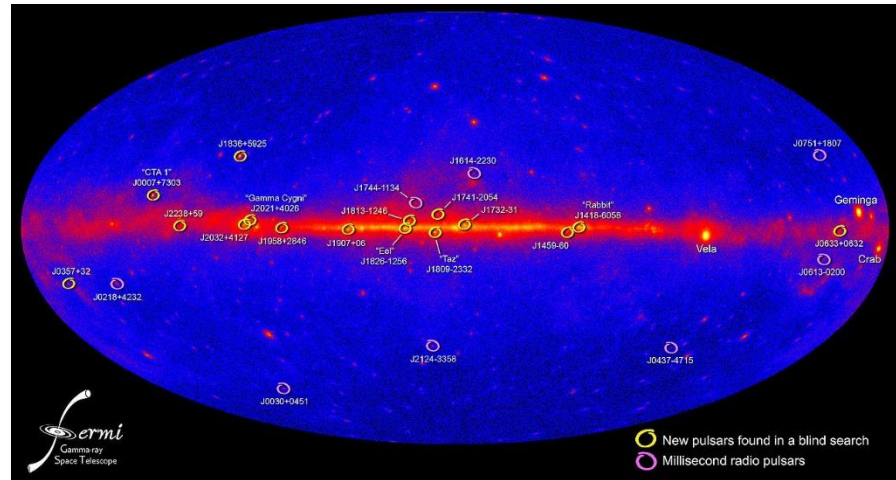
- ◆ A set of systematic, homogeneous observations with a well-defined selection function of a region of the sky or of a well-defined set of targets of relevant size.



Introduction: what is a survey?

Many different **purposes**, which have evolved over time:

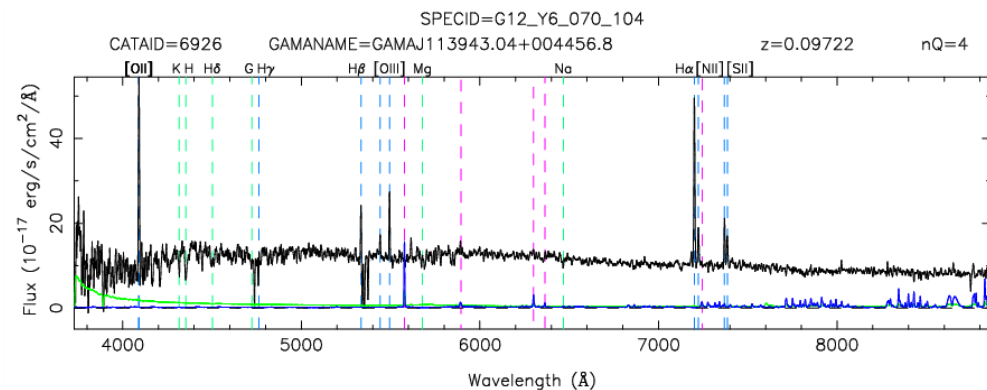
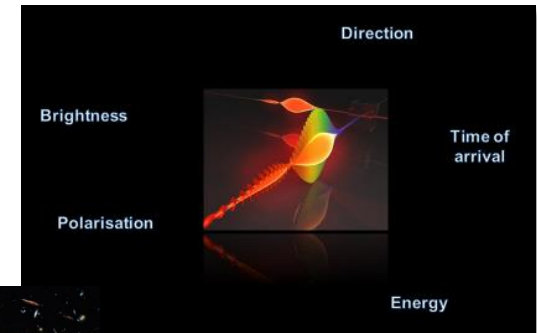
- ◆ Census
- ◆ Discovery
- ◆ Reference frame (in space and time)
- ◆ Evolution
- ◆ ...
- ◆ ...
- ◆ Statistics: (joint) distributions of properties of objects in physical parameter space



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

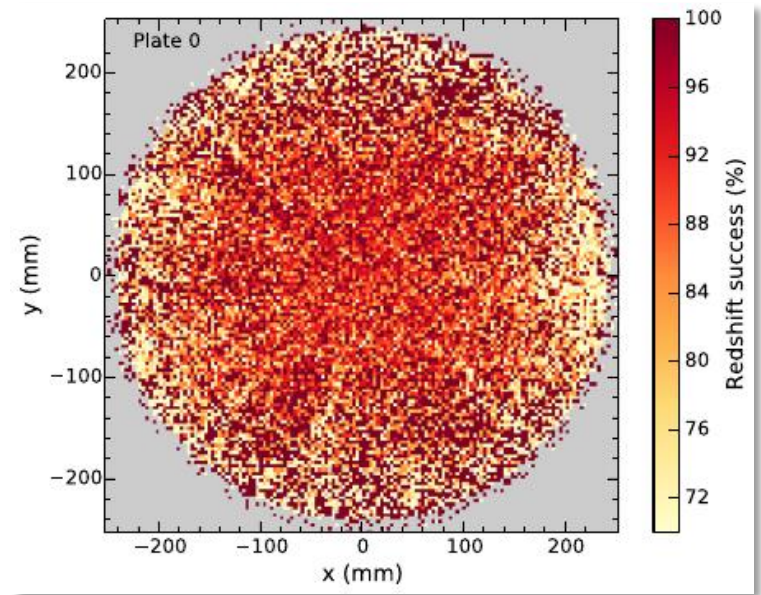
Subaru's prime focus
with the 1.5 deg FoV
Hyper Suprime-Cam



Introduction

Why are surveys hard?

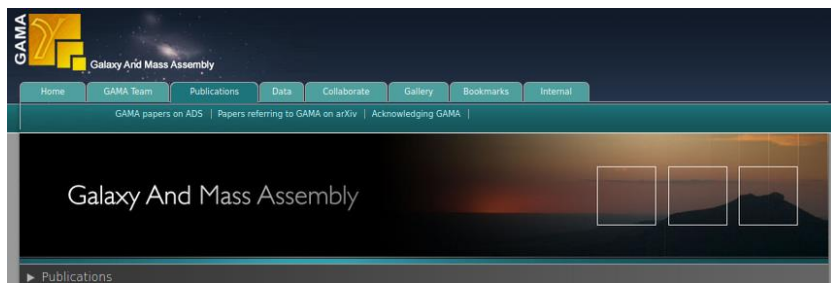
- ◆ Homogeneous, well-defined datasets
 - ◆ Whether an observation of a particular target is “successful” or not depends in a complicated way on target properties, observing system and observing conditions
 - Observing process creates a bias
 - Understanding the “selection function” is important
- ◆ 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



Refereed GAMA papers

146. *Galaxy And Mass Assembly (GAMA): Tracing galaxy environment using the marked correlation function*, U. Sureshkumar et al., 2021, A&A, 653, A35.
145. *Galaxy And Mass Assembly (GAMA): The environmental impact on SFR and metallicity in galaxy groups*, D. Sotillo-Ramos et al., 2021, MNRAS, in press.
144. *Galaxy and mass assembly (GAMA): the clustering of galaxy groups*, S.D. Riggs et al., 2021, MNRAS, 506, 21.
143. *Galaxy And Mass Assembly (GAMA) Survey: The Merging Potential of Brightest Group Galaxies*, K. Banks et al., 2021, ApJ, in press.
142. *Galaxy and mass assembly (GAMA): the inferred mass-metallicity relation from $z = 0$ to 3.5 via the $\text{H}\alpha$ emission line*, S. Bellstedt et al., 2021, MNRAS, 503, 3309.

Herschel-ATLAS - GAMA papers

25. *The causes of the red sequence, the blue cloud, the green valley, and the green mountain*, S.A. Eales et al., 2018, MNRAS, 481, 1183.
24. *The new galaxy evolution paradigm revealed by the Herschel surveys*, S. Eales et al., 2018, MNRAS, 473, 3507.
23. *H-ATLAS/GAMA: magnification bias tomography. Astrophysical constraints above $z \sim 1$* , J. Gonzalez-Nuevo et al., 2017, JCAP, 10, 024.
22. *H-ATLAS/GAMA: the nature and characteristics of optically red galaxies detected at submillimetre wavelengths*, A. Darush et al., 2016, MNRAS, 456, 2221.
21. *H-ATLAS/GAMA: quantifying the morphological evolution of the galaxy population using the $\text{H}\alpha$ emission line*, S. Eales et al., 2015, MNRAS, 452, 3489.
20. *Herschel-ATLAS: the surprising diversity of dust-selected galaxies in the local submillimetre galaxy population*, C.J.R. Clark et al., 2015, MNRAS, 452, 397.
19. *H-ATLAS/GAMA and H-ATLAS: dusty early-type galaxies in different environments*, N.K. Agius et al., 2015, MNRAS, 451, 3615.
18. *A multiwavelength exploration of the FIR/UVIR ratio in H-ATLAS/GAMA galaxies out to $z \sim 1$* , E. Ibar et al., 2015, MNRAS, 449, 2498.
17. *Herschel-ATLAS/GAMA: SDSS cross-correlation induced by weak lensing*, J. Gonzalez-Nuevo et al., 2014, MNRAS, 442, 2680.
16. *Herschel-ATLAS/GAMA: How does the far-IR luminosity function depend on galaxy group environment?*, Q. Guo et al., 2014, MNRAS, 442, 2253.
15. *Herschel-ATLAS/GAMA: the environmental density of far-infrared bright galaxies at $z \sim 0.5$* , C.S. Burton et al., 2013, MNRAS, 433, 771.
14. *Herschel-ATLAS/GAMA: What determines the far-infrared properties of radio galaxies?*, J.S. Virdee et al., 2013, MNRAS, 432, 609.

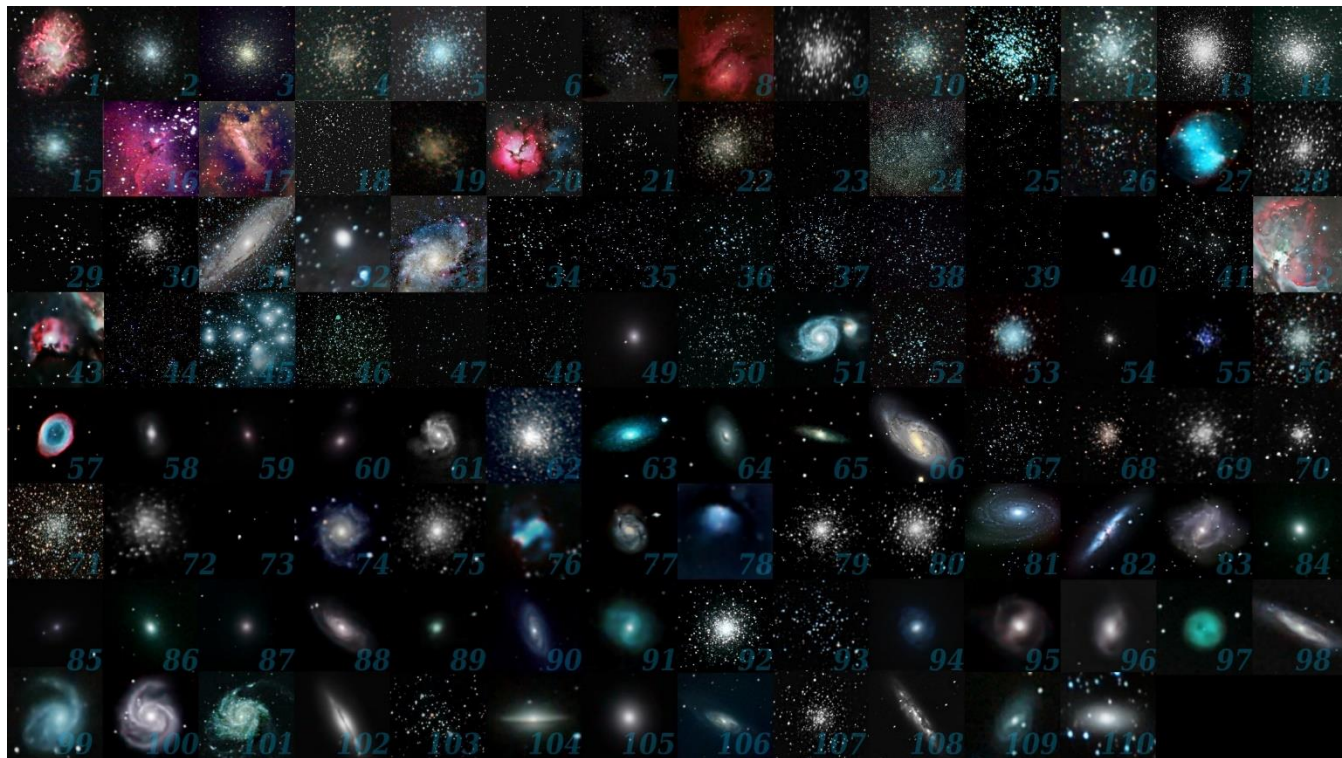
KIDS - GAMA papers

29. *Bright galaxy sample in the Kilo-Deegree Survey Data Release 4. Selection, photometric redshifts, and physical properties*, M. Bilicki et al., 2021, A&A, 653, A82.
28. *Optimised randoms: Learning and correcting for systematic galaxy clustering patterns in KIDS using self-supervised maps*, H. Johnston et al., 2021, A&A, 648, A98.
27. *Halo shapes constrained from a pure sample of central galaxies in KIDS-1000*, C. Georgiou et al., 2021, A&A, 647, A183.
26. *The halo model as a versatile tool to predict intrinsic alignments*, M.C. Fortuna et al., 2021, MNRAS, 501, 2983.
25. *Testing KIDS cross-correlation models with simulations*, J.L. van den Bosch et al., 2020, A&A, 642, A200.
24. *KIDS+GAMA: The weak lensing calibrated stellar-to-halo mass relation of central and satellite galaxies*, A. Dvornik et al., 2020, A&A, 642, A83.
23. *Clustering of red-sequence galaxies in the fourth data release of the Kilo-Deegree Survey*, M. Vakil et al., 2020, A&A, in press.
22. *KIDS+VIRGO/GAMA: Testing semi-analytic models of galaxy evolution with galaxy-galaxy-galaxy lensing*, L. Linke et al., 2020, A&A, 640, A59.
21. *GAMA+KIDS: Alignment of galaxies in galaxy groups and its dependence on galaxy scale*, C. Georgiou et al., 2019, A&A, 628, A31.
20. *Luminous red galaxies in the Kilo-Deegree Survey: selection with broad-band photometry and weak lensing measurements*, M. Vakil et al., 2019, MNRAS, 487, 3715.
19. *KIDS+GAMA: Intrinsic alignment model constraints for current and future weak lensing cosmology*, H. Johnston et al., 2019, A&A, 624, A30.
18. *The dependence of intrinsic alignment of galaxies on wavelength using KIDS and GAMA*, C. Georgiou et al., 2019, A&A, 622, A90.
17. *Testing convolutional neural networks for finding strong gravitational lenses in KIDS*, C.E. Petrillo et al., 2019, MNRAS, 482, 807.

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



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
- ◆ 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

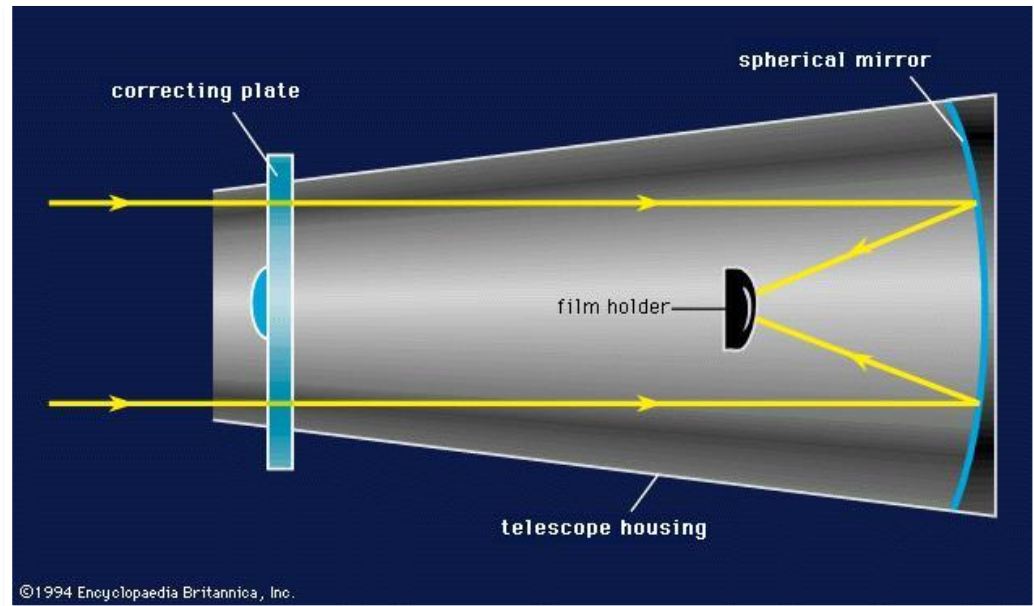


Annie Jump Cannon

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

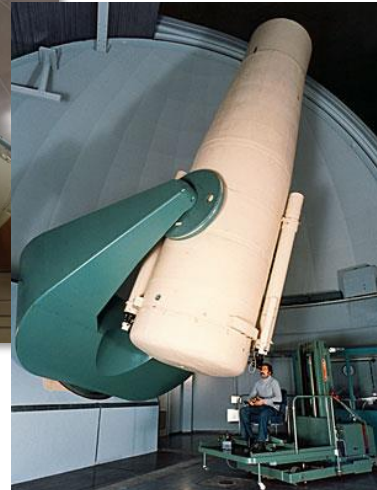
The 2nd age of surveys: Schmidt surveys

- ◆ 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



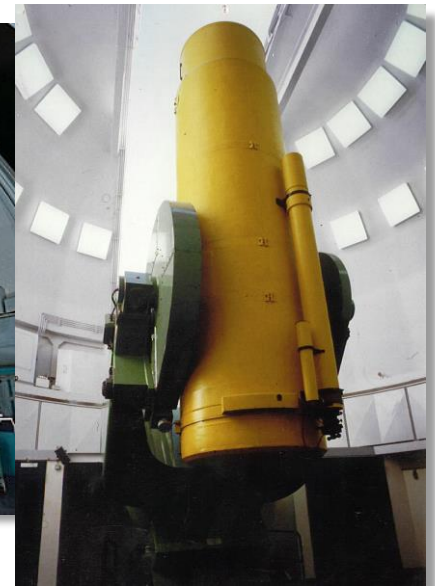
UK Schmidt-Telescope
(Siding Spring Observatory)

Oschin Schmidt-Telescope
(Palomar Observatory)



ESO Schmidt-Telescope
(La Silla Observatory)

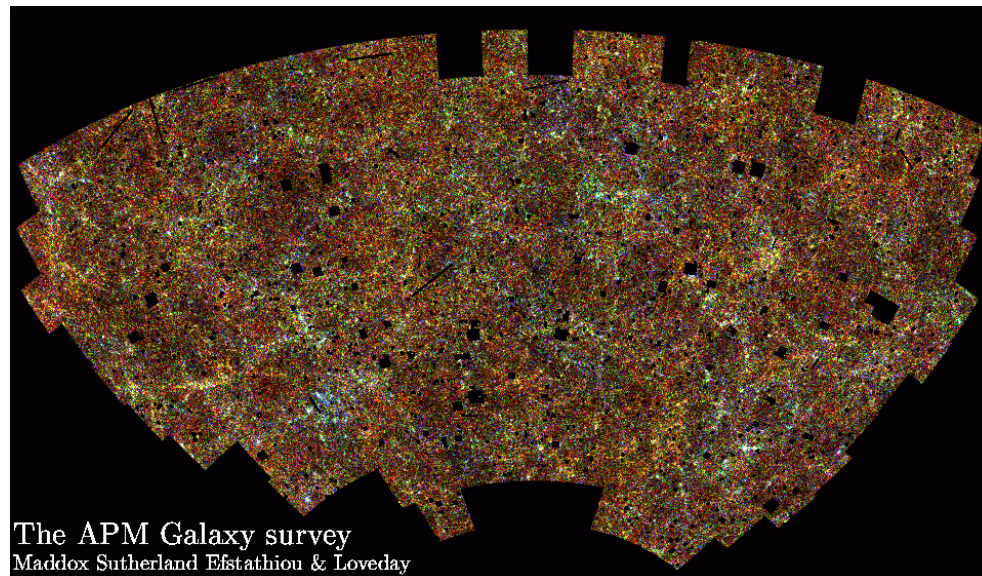
Großer Hamburger Schmidtspiegel
(Calar Alto Observatory)



Some historical notes

The 2nd age of surveys: Schmidt surveys

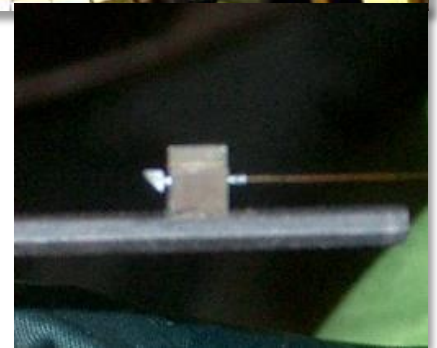
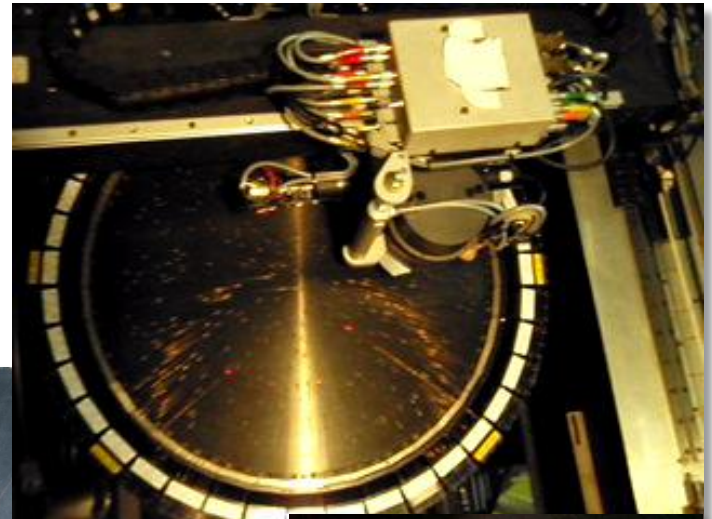
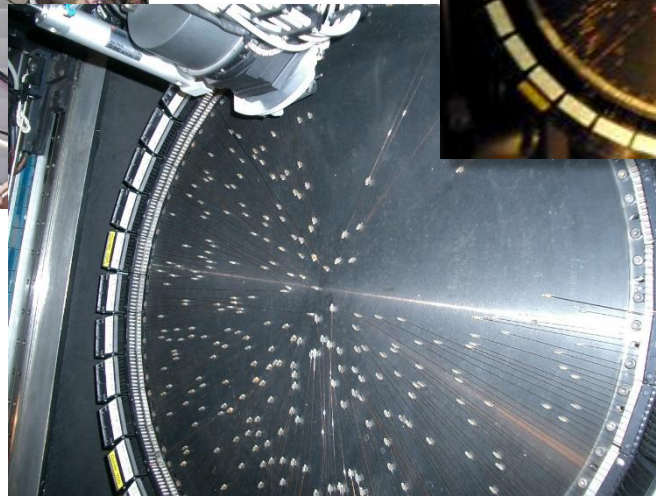
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- Construction of large telescopes with a wide field-of-view
- First all-sky photographic, three-band imaging surveys (e.g. POSS, 1950's – 80's)
- ◆ Later digitised: DSS, APM, SuperCOSMOS



Some historical notes

The 3rd age of surveys: going parallel

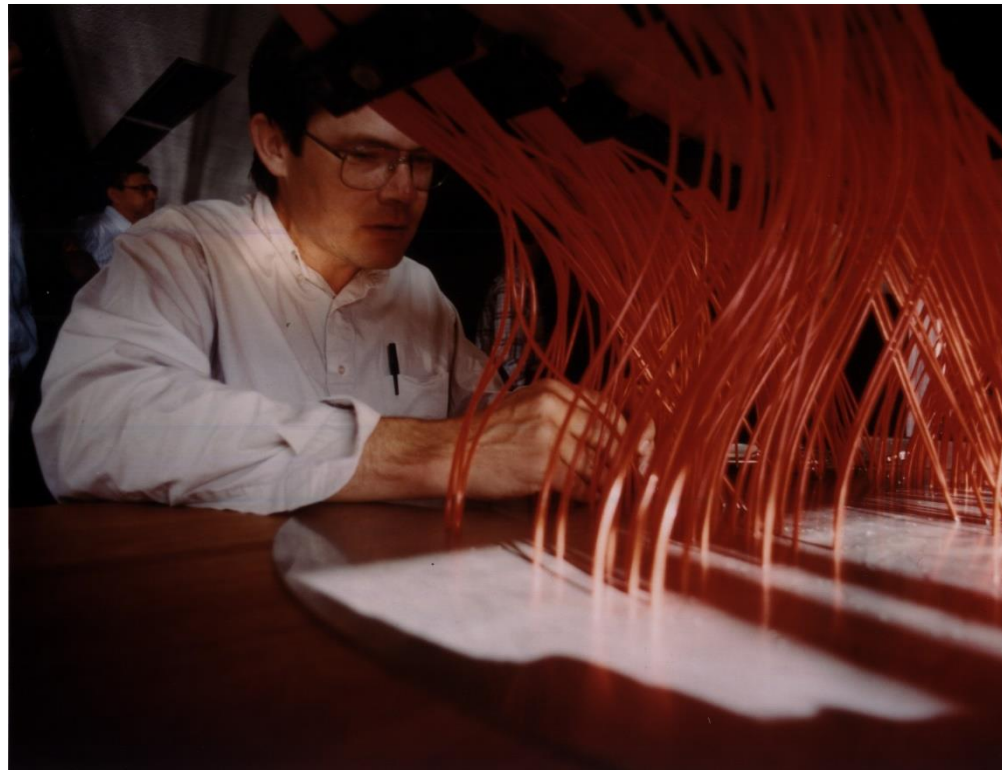
- ◆ Early redshift surveys were still “serial”: CfA (1977 – 1982, 2400 gals)
- First exploration of large-scale structure
- ◆ 1990's: development of multi-object spectrographs
- ◆ Example: 2dF: 400 fibres



Some historical notes

The 3rd age of surveys: going parallel

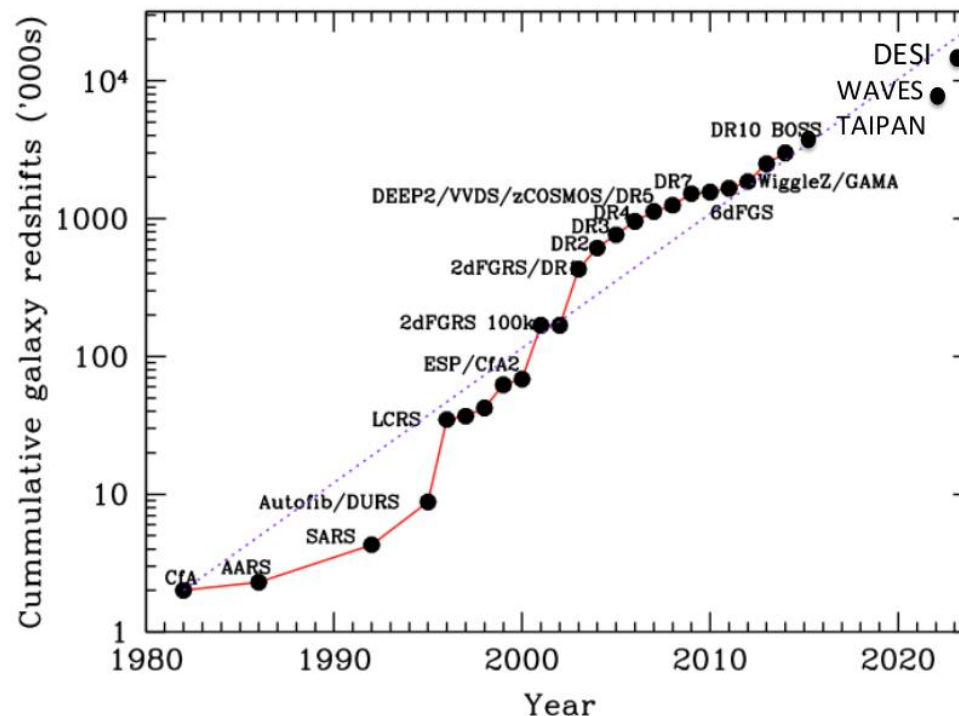
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- ◆ Example: SDSS



Some historical notes

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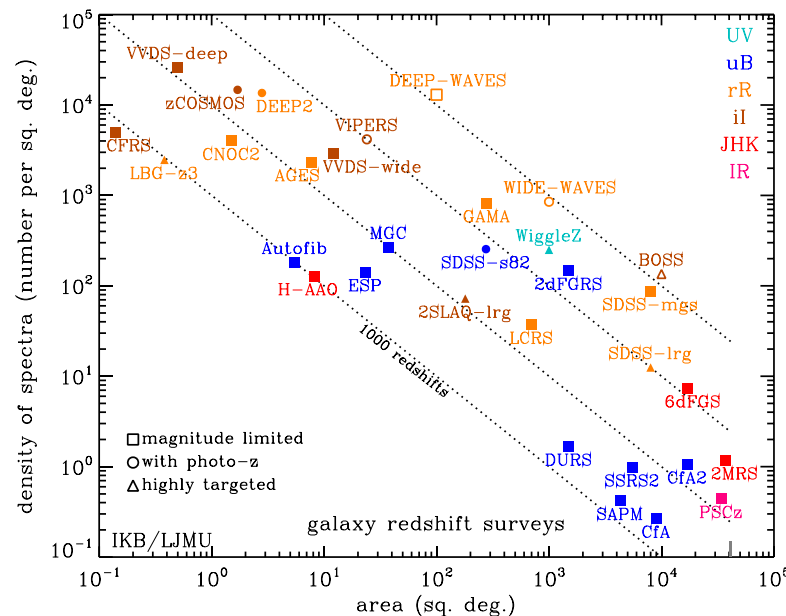
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Some historical notes

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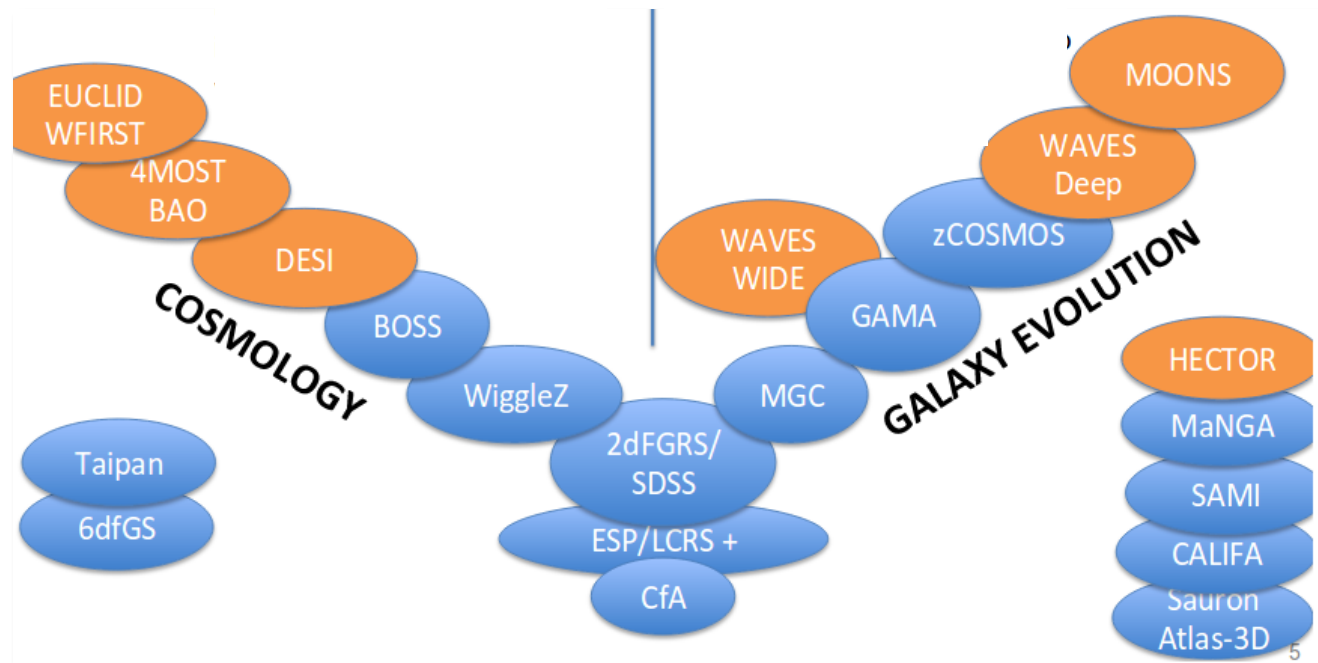
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- ◆ Huge number of both wide and deep surveys



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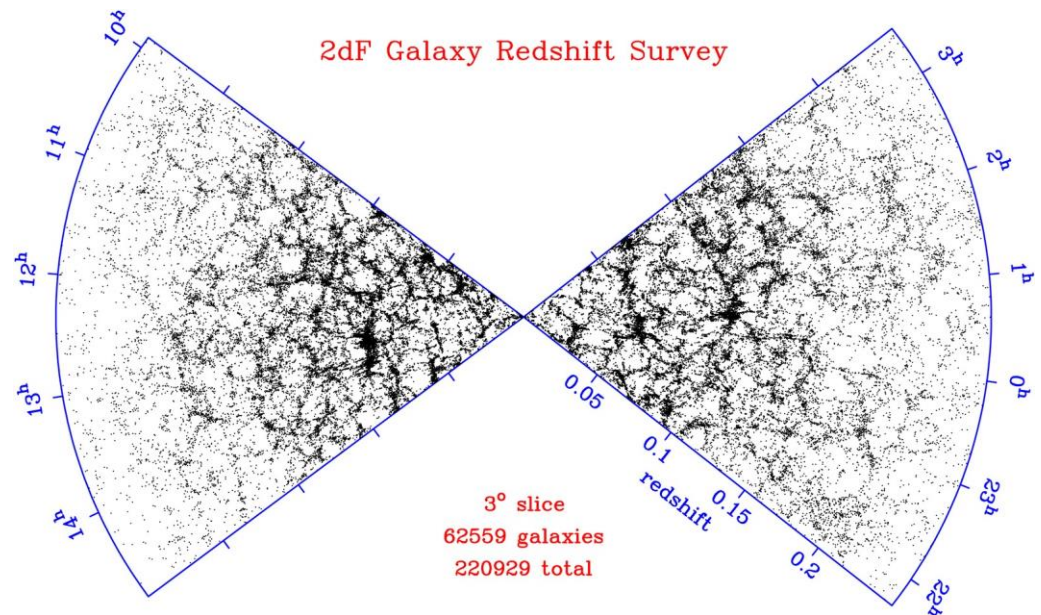
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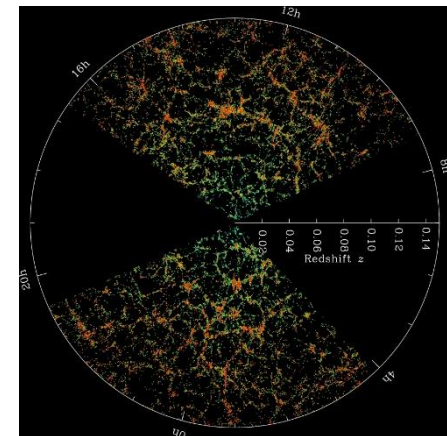
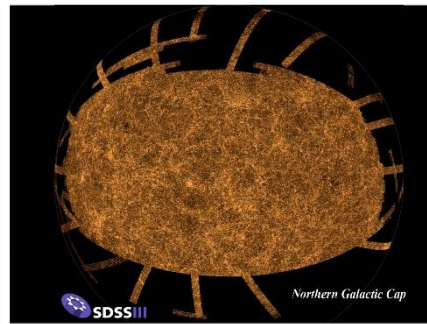
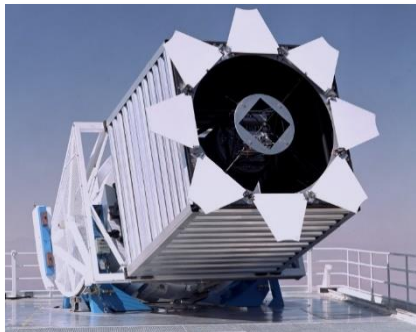
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 - The rise of large-scale extragalactic spectroscopic surveys
- ◆ Huge number of both wide and deep surveys
- ◆ 2dF Galaxy Redshift Survey (1997 – 2002, 220,000 gals)
 - Discovery of Baryonic Acoustic Oscillations



Some historical notes

The 3rd age of surveys: going parallel

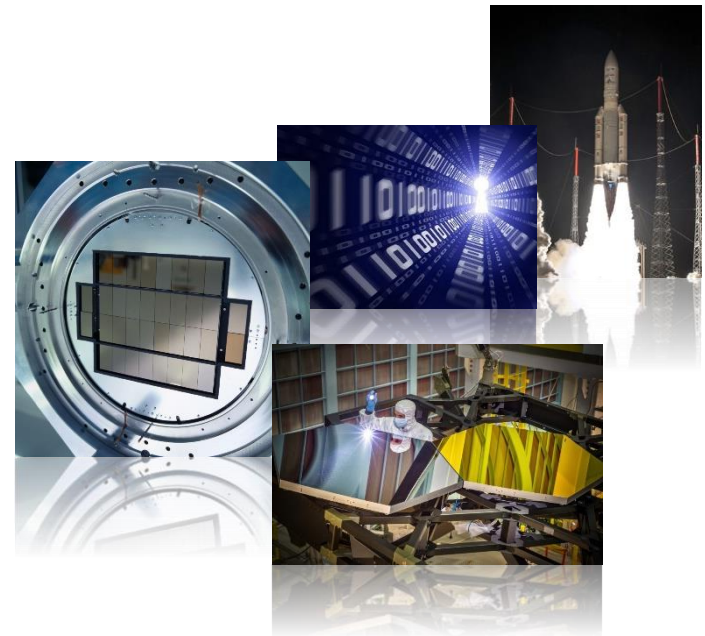
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- ◆ Huge number of both wide and deep surveys
- ◆ 2dF Galaxy Redshift Survey (1997 – 2002, 220,000 gals)
- ◆ From 2000: Sloan Digital Sky Survey: all-hemispheric, multi-band, deep imaging + spectroscopy of 10^6 galaxies to $r < 17.8$ mag
 - Transformational



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

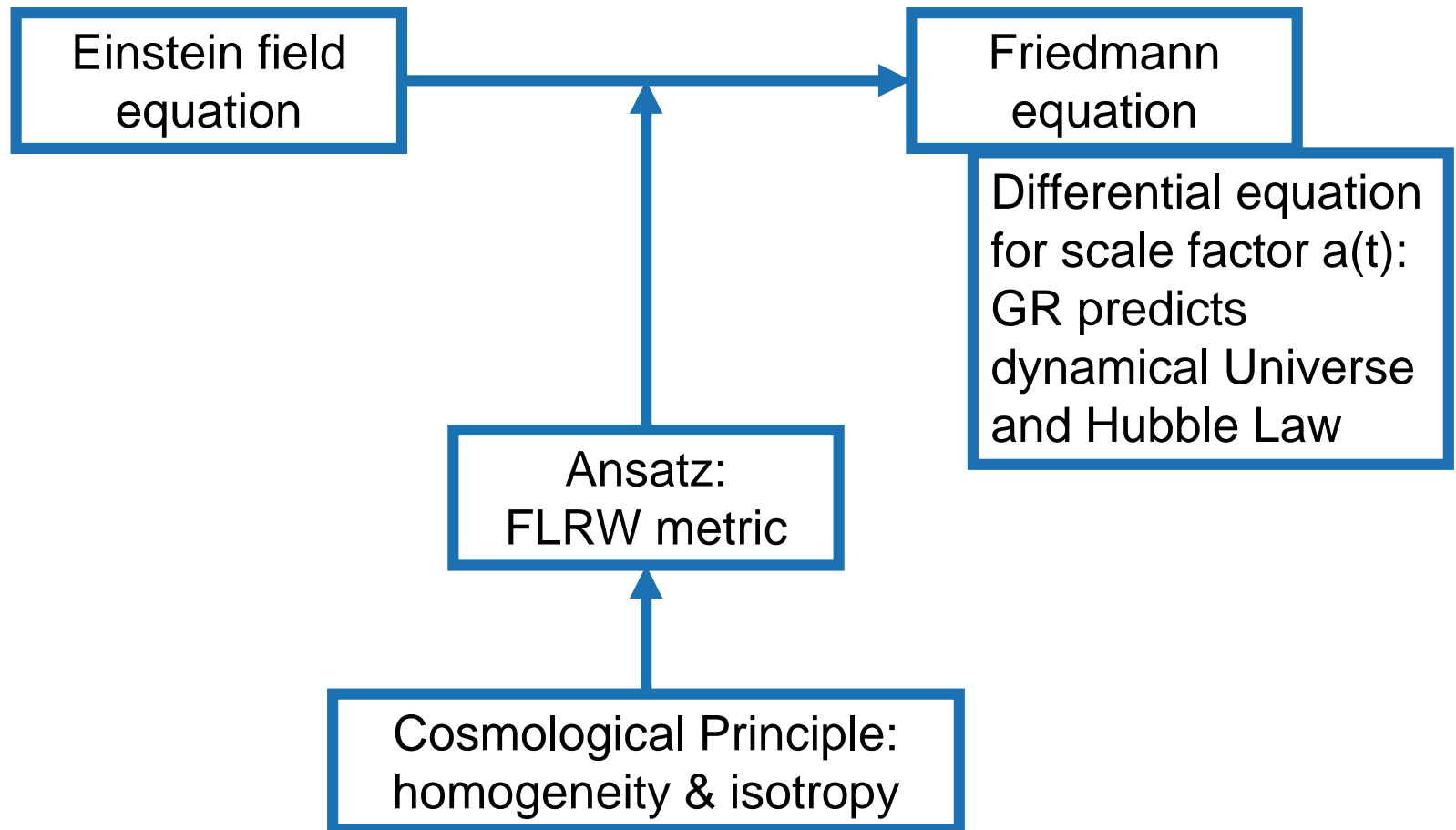


- Complete exploration of a large fraction of the observable Universe
- Particle-physics-like scale of operations

Questions?




Setting the cosmological scene




Setting the cosmological scene

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

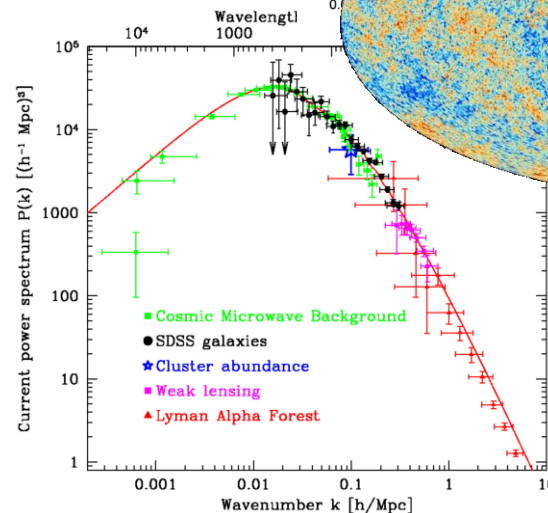
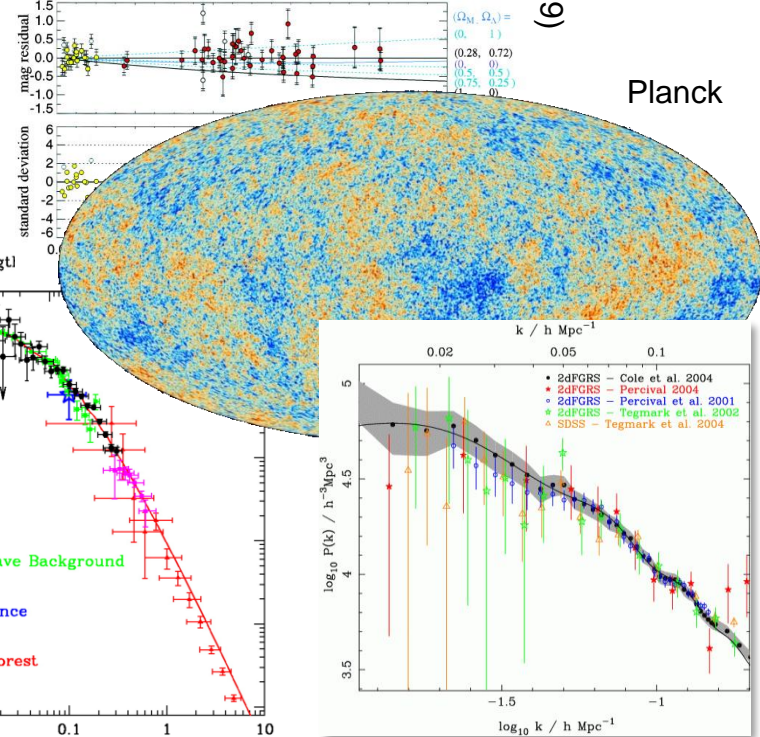
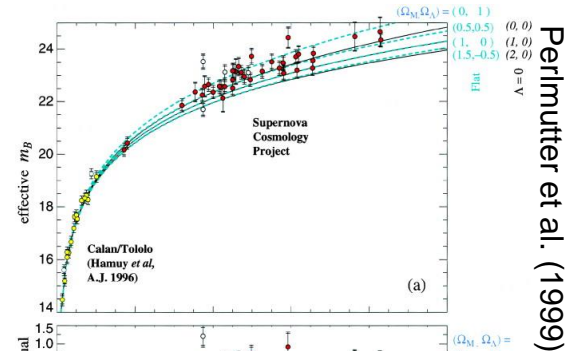
Setting the cosmological scene

- ◆ 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 $[\rho_i, w_i]$ (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
- ◆ ...



Tegmark et al. (2004)

Cole et al. (2005)

Setting the cosmological scene

Weirdness 1: the Universe is full of Dark Matter

Evidence:

◆ Dynamical

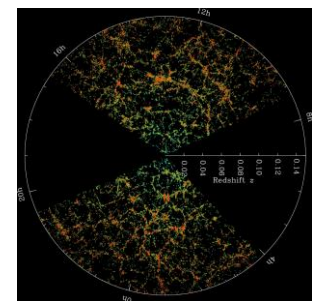
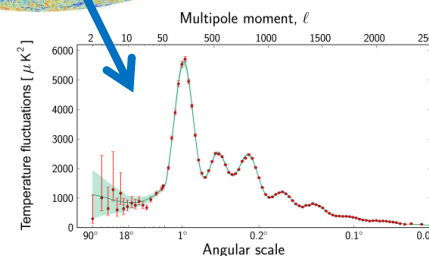
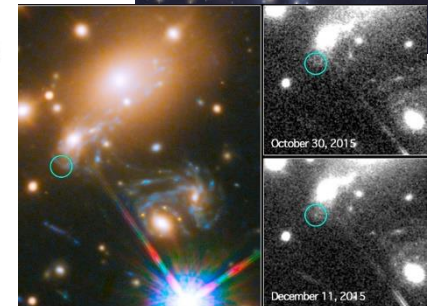
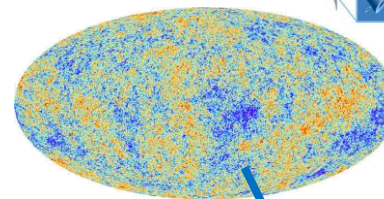
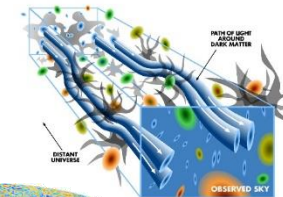
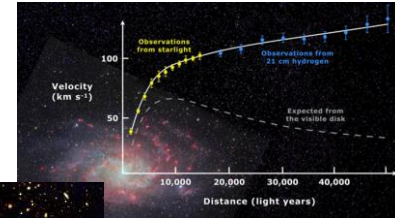
- ◆ Flat rotation curves of spiral galaxies
- ◆ Velocity dispersion of stars in giant elliptical and dwarf spheroidal galaxies
- ◆ Velocity dispersion of galaxies in clusters

◆ Lensing

- ◆ Weak lensing by large-scale structure and cluster mergers
- ◆ Strong lensing by individual galaxies and clusters

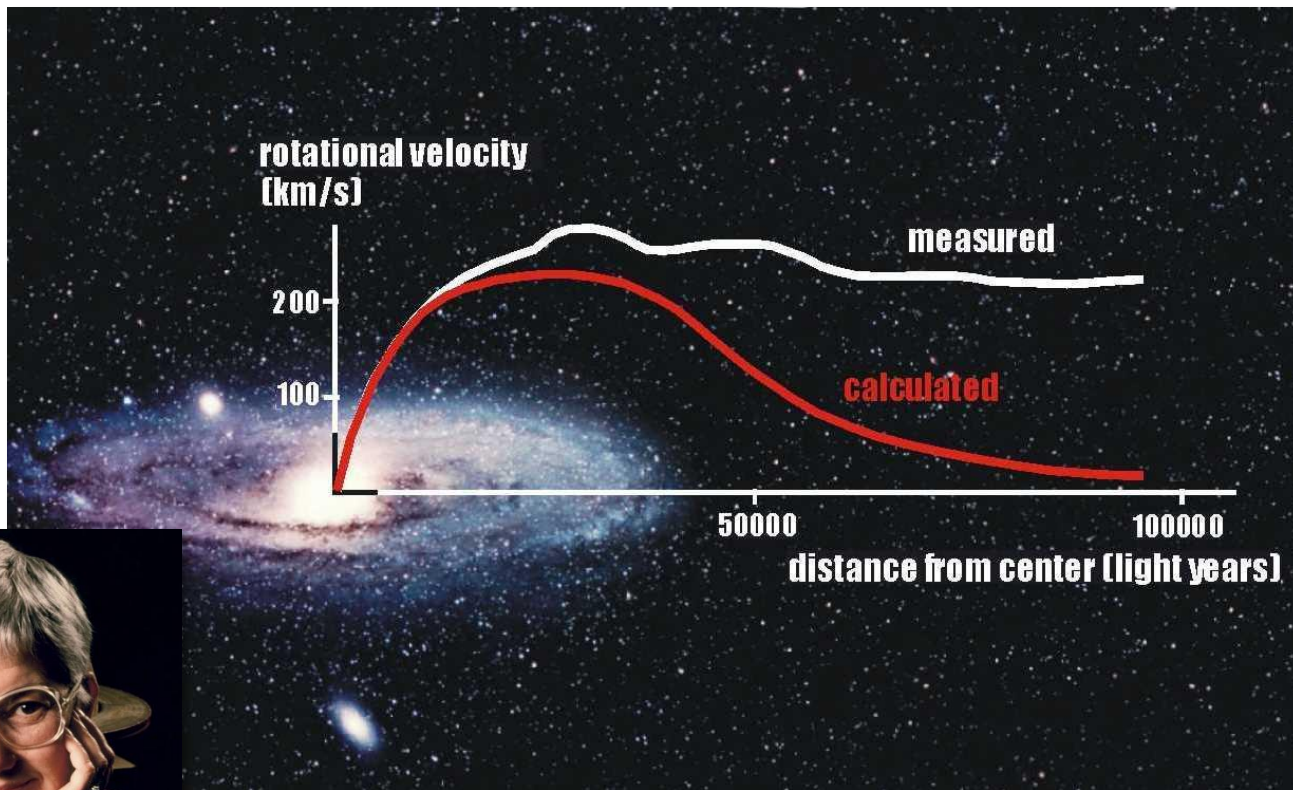
◆ Structure formation

- ◆ Abundance of clusters
- ◆ Large-scale distribution of galaxies
- ◆ Power spectrum of CMB anisotropies



Digression

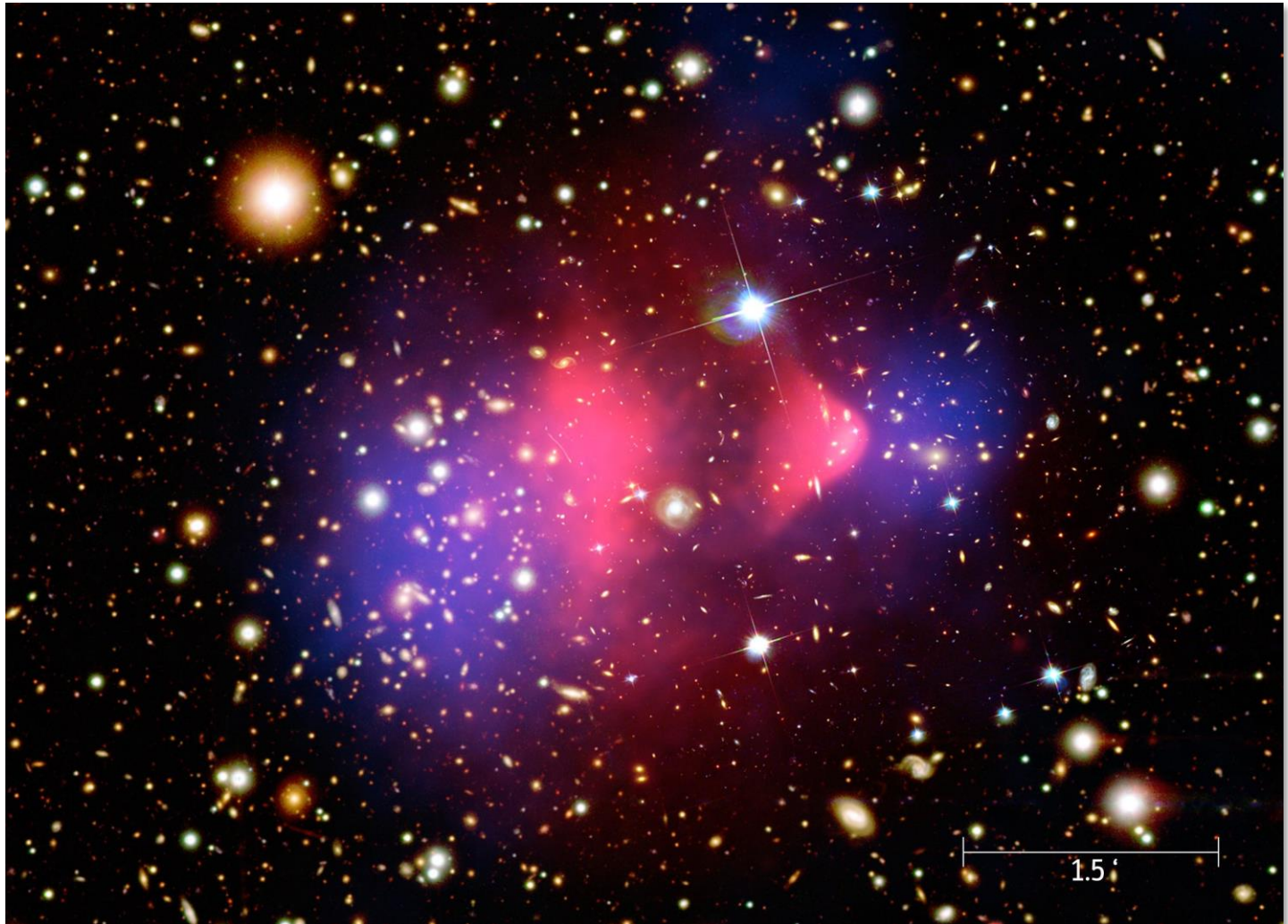
- ◆ This is NOT our only or even our best evidence of Dark Matter:



Vera Rubin

Digression

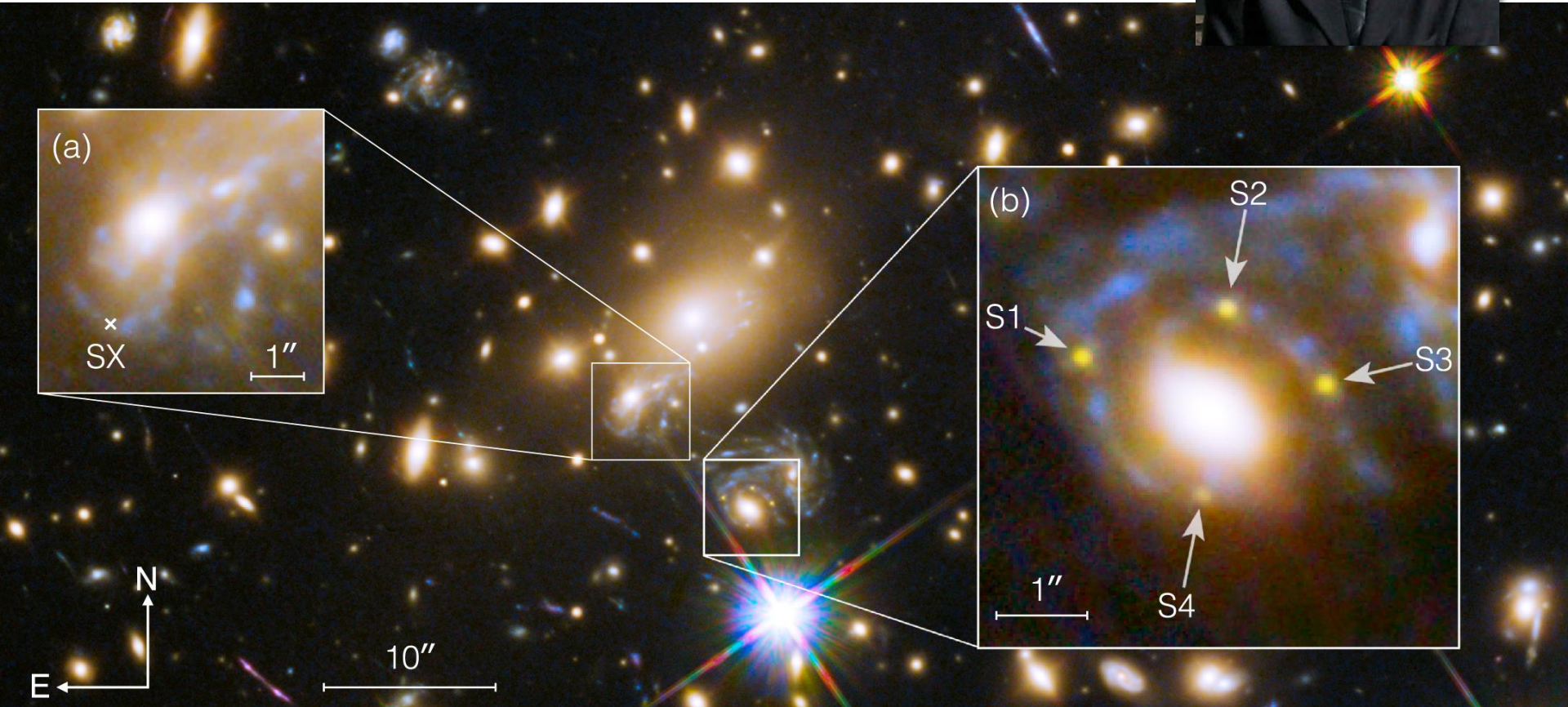
- ◆ Bullet cluster:



Digression

- ◆ SN Refsdal:

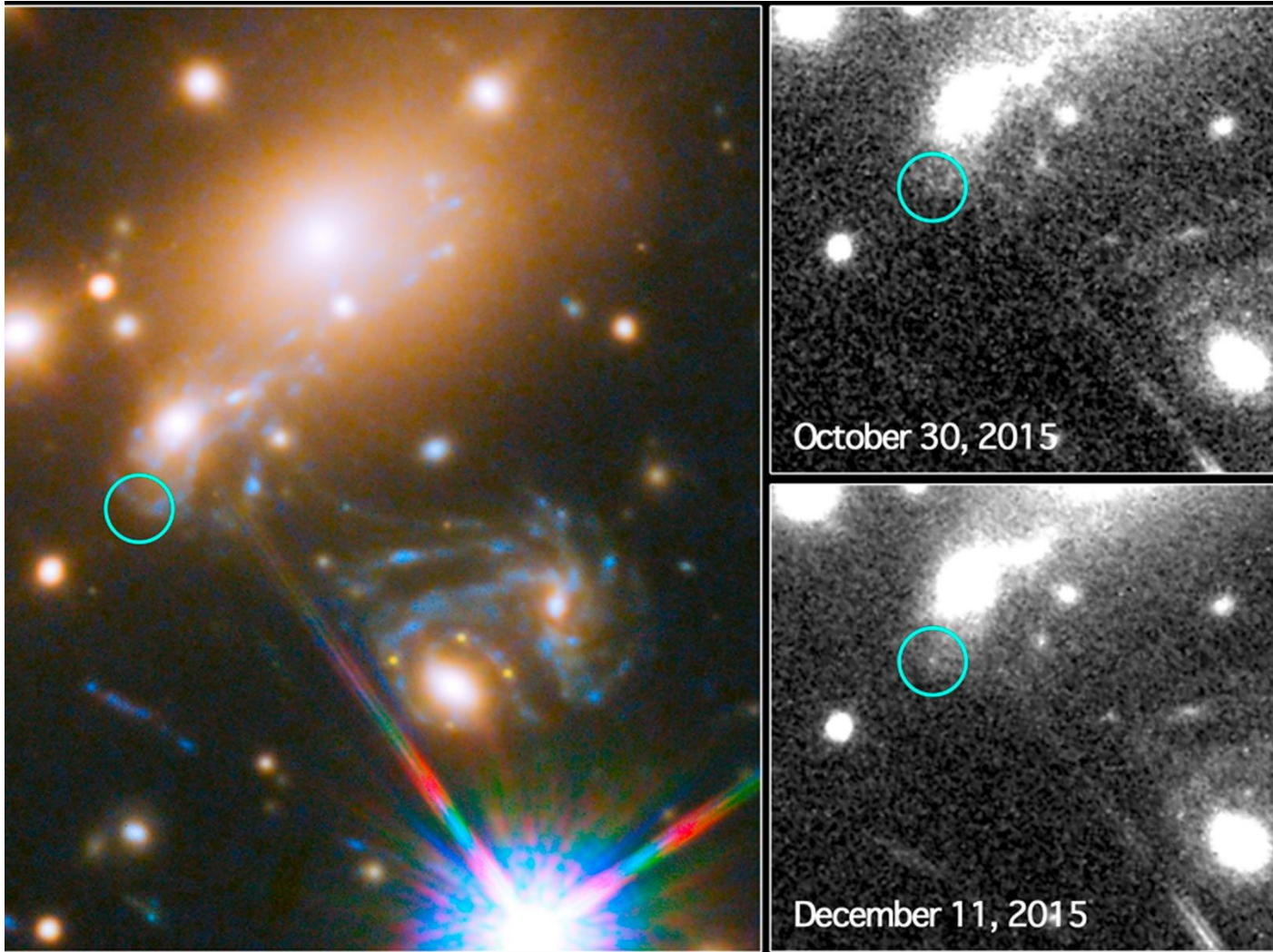
Sjur Refsdal



Grillo et al. (2018)

Digression

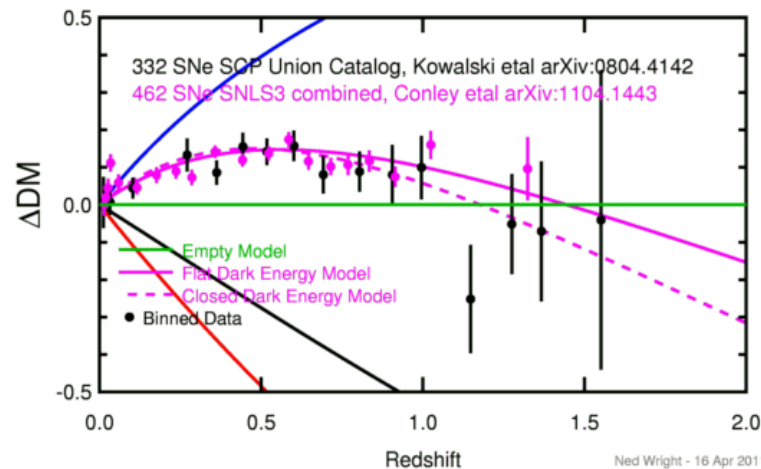
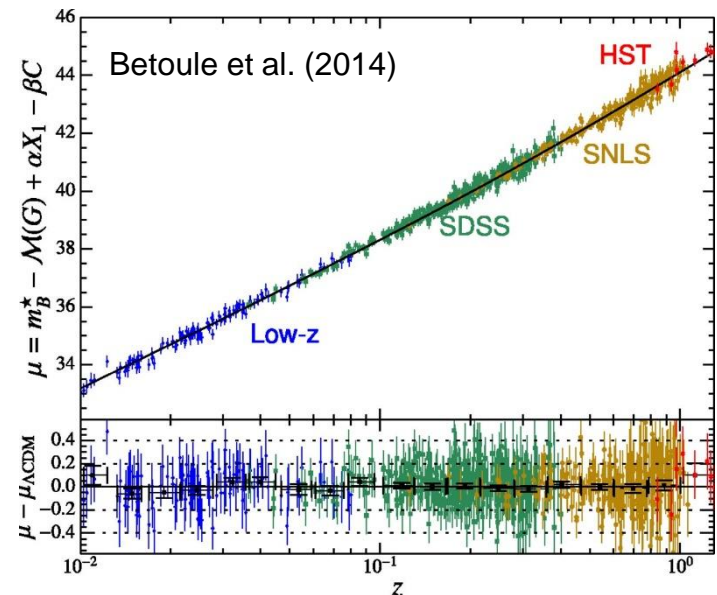
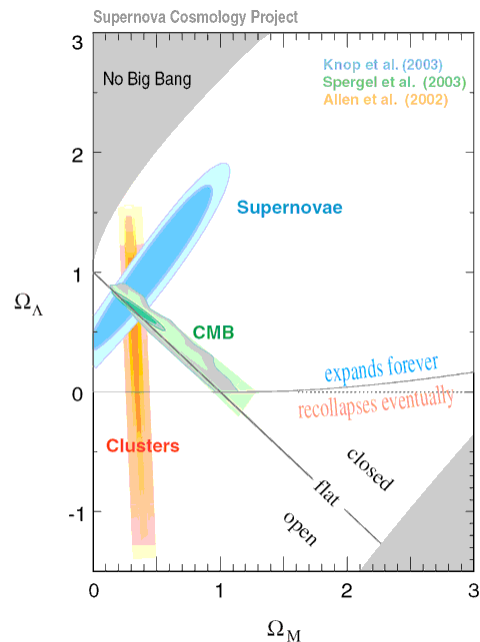
- ◆ SN Refsdal:



Setting the cosmological scene

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

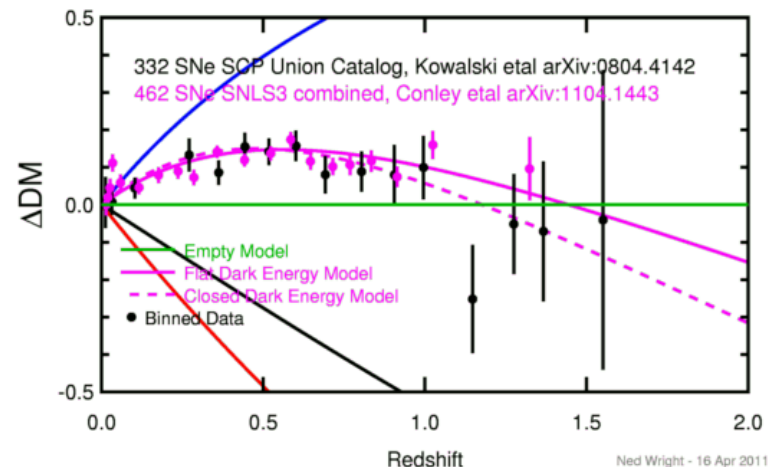
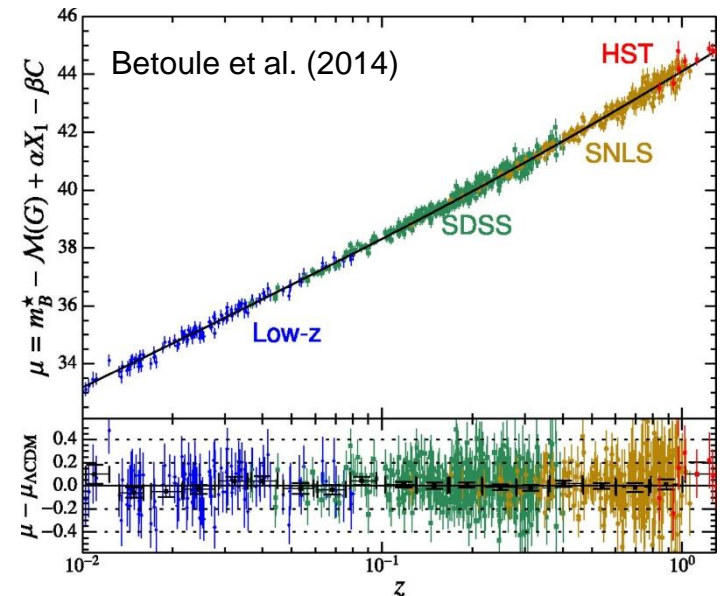
- ◆ Evidence:
 - ◆ SNIa
 - ◆ Combination of CMB (Universe is flat) and cluster abundance ($\Omega_M < 1$)



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 ($\Omega_M < 1$)
- 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 Λ CDM 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 [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_s [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 [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} [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

Our Universe

- ◆ Best measurements:

$$\Omega_{\Lambda} \approx 0.68$$

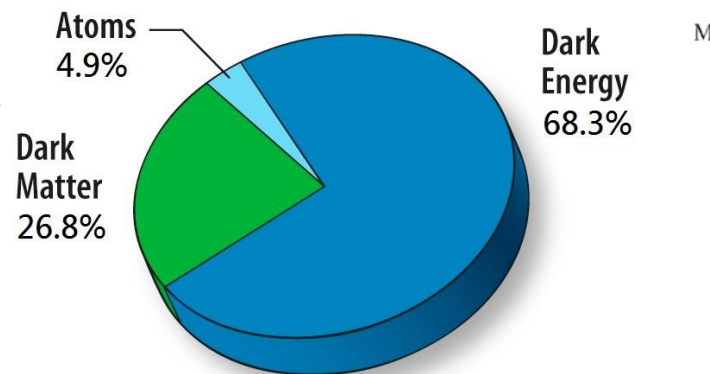
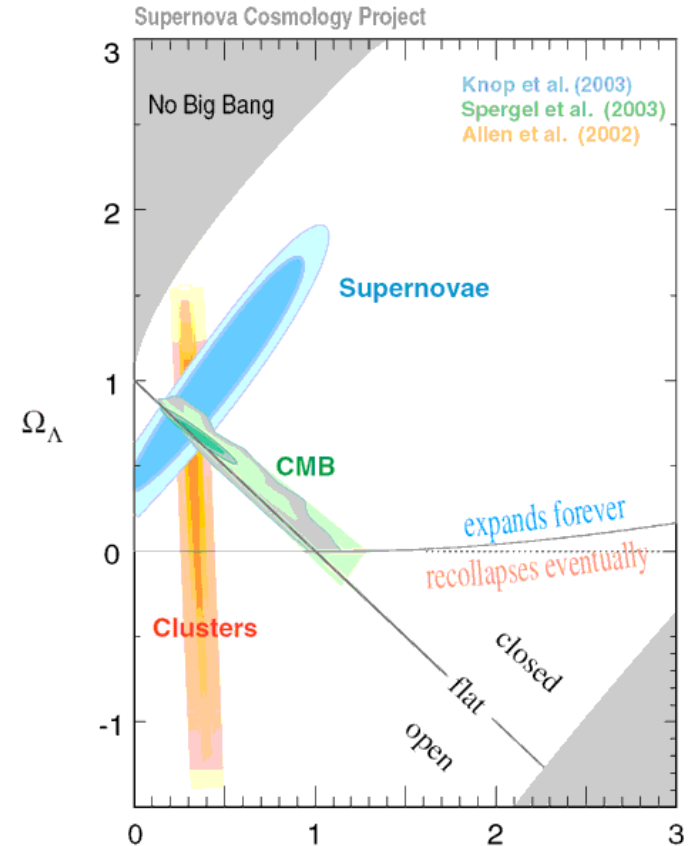
$$\Omega_{\text{M}} \approx 0.32 \ (\Omega_{\text{b}} \approx 0.05)$$

$$\Omega_{\text{rad}} \approx 10^{-5}$$

$$H_0 \approx 70 \text{ km/s/Mpc}$$

- 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!



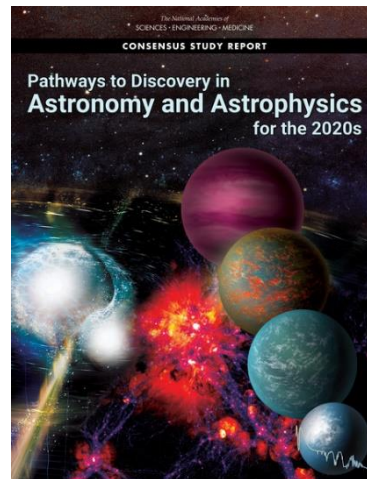
So what is there left to do (for surveys)?

Two elephants in the room:



COSMOLOGY IN THE 2020S AND BEYOND

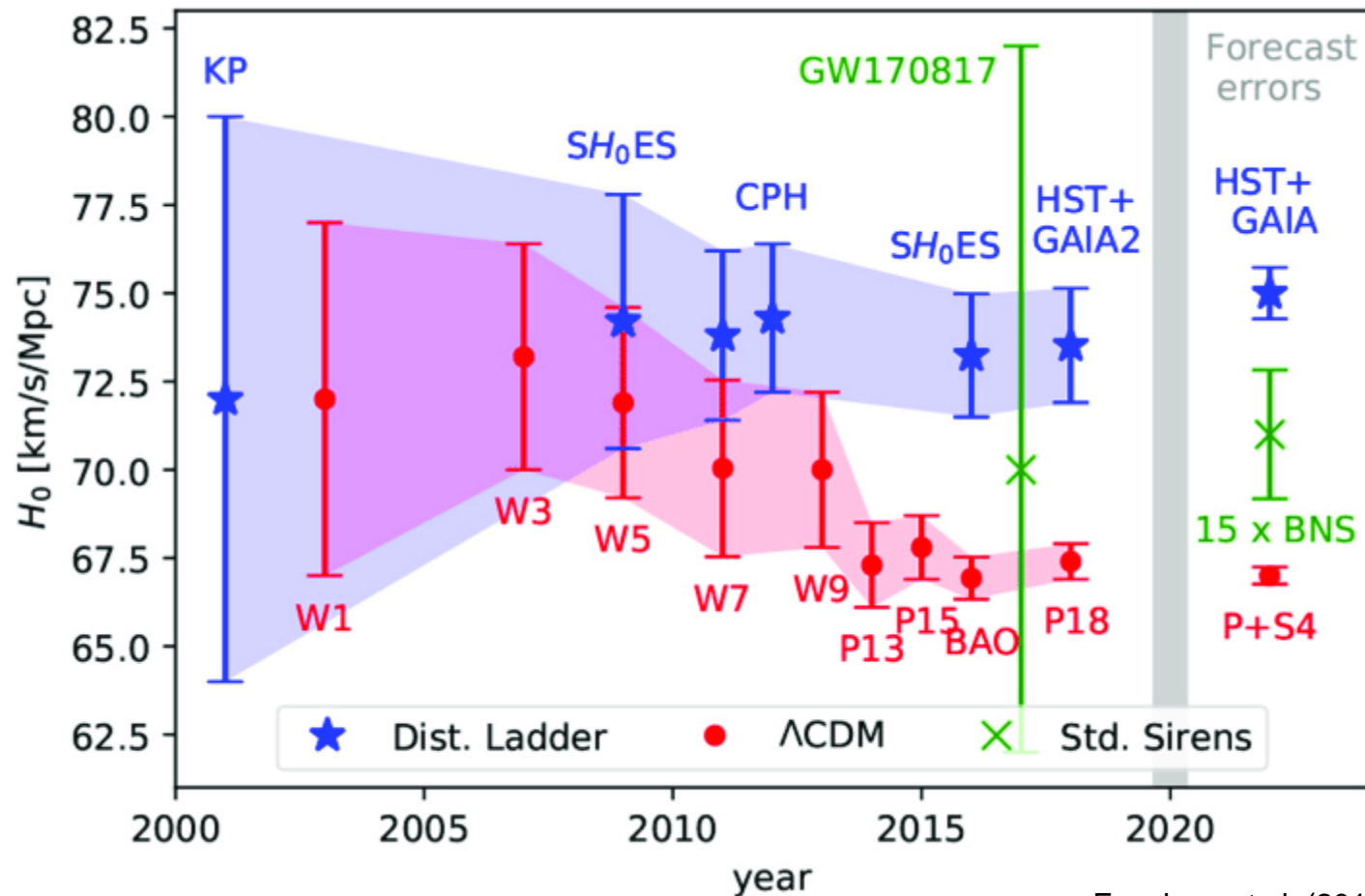
With both compelling mysteries and extensive observational means by which to explore them, this will be an amazing decade for cosmology. In this report, the panel identifies four major science questions for the upcoming decade: (1) What set the Hot Big Bang in motion? (2) What are the properties of dark 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.



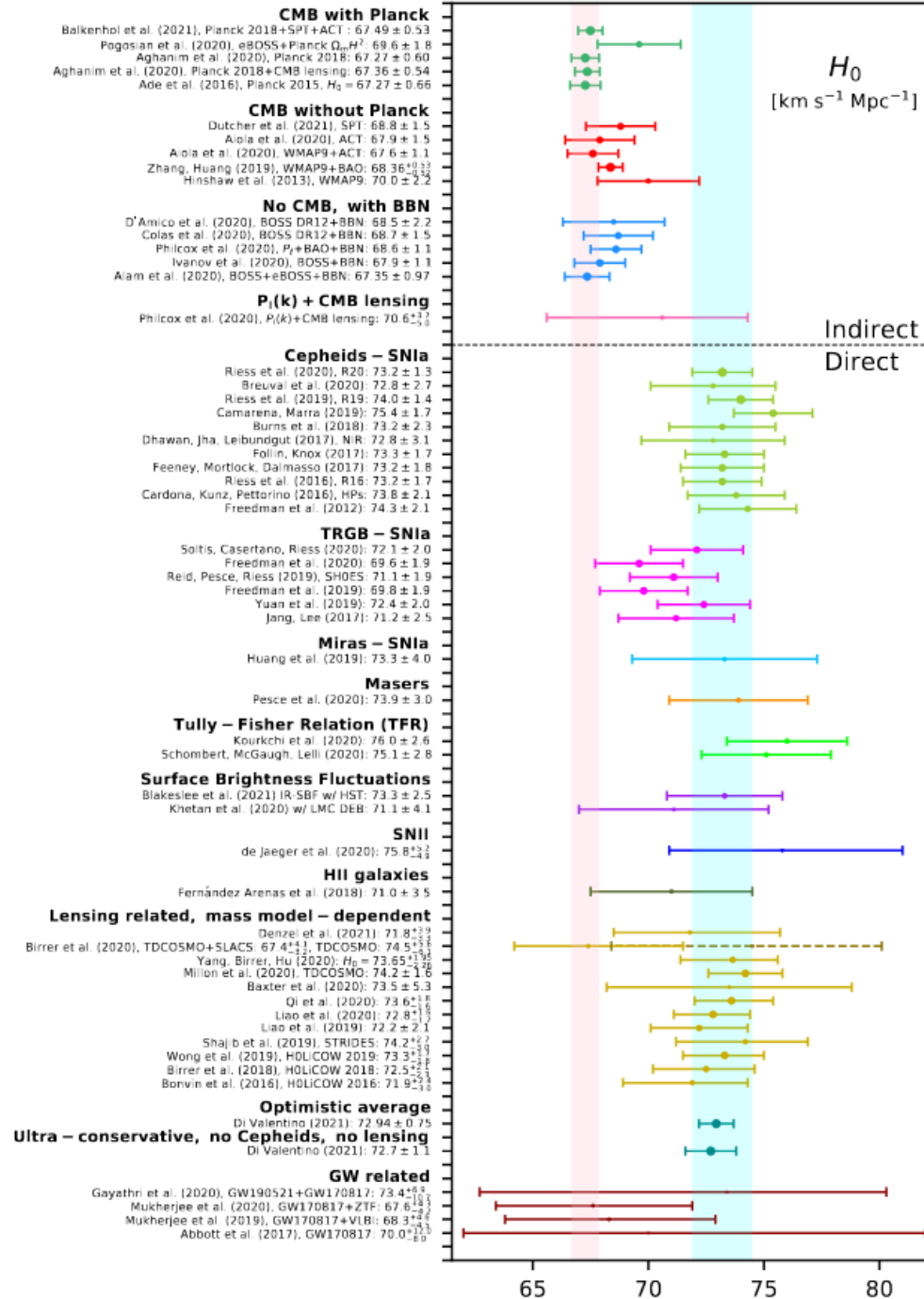
So what is there left to do (for surveys)?

Is the model beginning to crack?

- ◆ Hubble tension



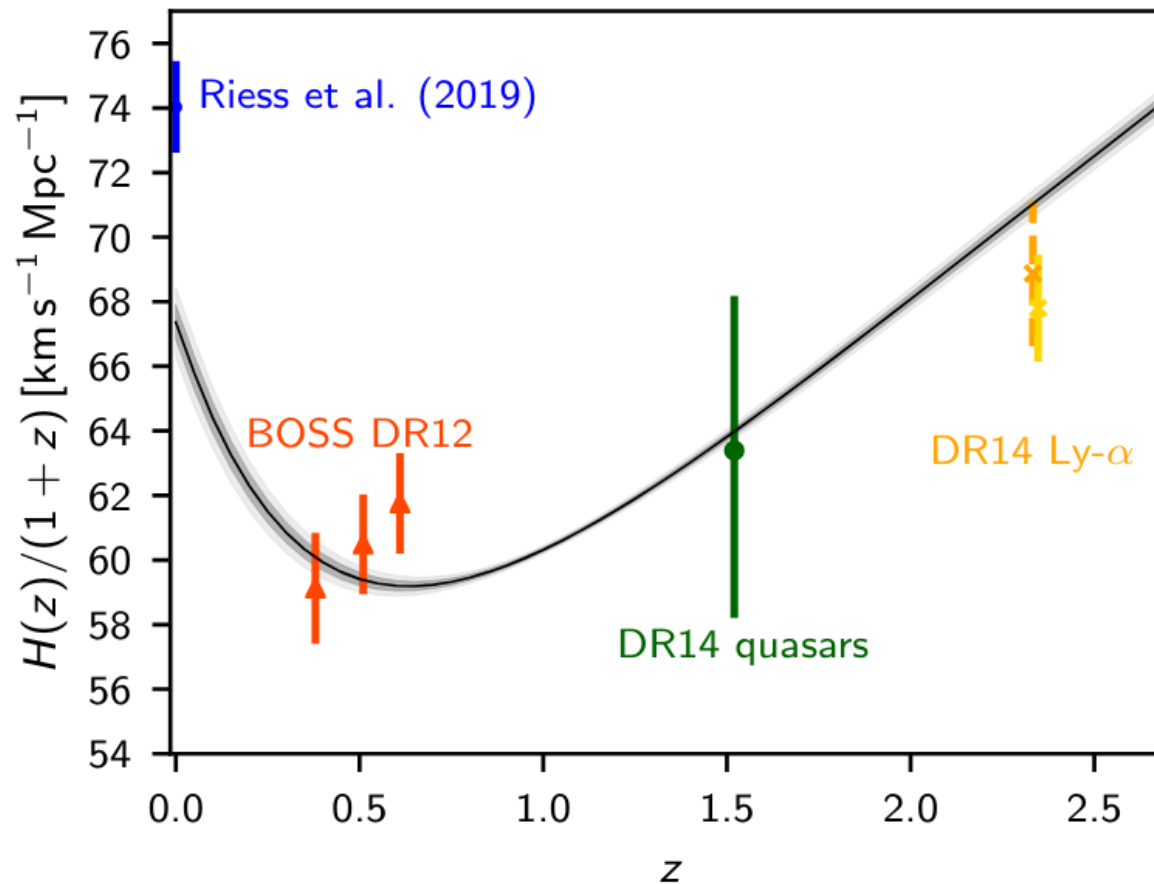
Ezquiaga et al. (2018)



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

Is the model beginning to crack?

- ◆ Hubble tension



Planck Collaboration (2021)

Questions?

