Observational Evidence for Dark Energy: The Future

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IPM Cosmology School & Workshop 2007 June 7

Future of Probing the Nature of Dark Energy

- SN cosmology tests
- Gravitational lensing
- Galaxy cluster abundances
- Baryon oscillations

signal!

- Particle physics experiments
- Tests of gravity on all scales

Next-Generation Facilities

Microwave background -
Better angular resolution CMB maps
Detection of clusters of galaxies vs. z

Supernovae –
Dedicated Dark Energy satellite mission
Large Synoptic Survey Telescope (LSST)

Weak Gravitational Lensing -
Both ground-based and space based

Probing the foundations of gravity -
Equivalence principle
Inverse square law

Future of Observational Dark Energy

- Type Ia Supernovae
- Baryon Acoustic Oscillation
- Weak Lensing
- Galaxy clusters

Future of Observational Dark Energy

- Luminosity distance vs. z
- Angular diameter distance vs. z + LSS
- Matter distribution + angular diameter
- LSS + substructure probe smooth cosmological constant vs. modified GR

Upcoming Experiments

- Now-2010
  - Pan-STARRS1, (ESSENCE, SNLS)
- 2010-2015
  - DES, Planck, SKA
- 2015-2020
  - LSST, JDEM

Future of SN Ia Cosmology

- Space-based Projects
  - HST
  - JDEM-like: SNAP, DESTiny, ADEPT, DUNE
- Ground-based Surveys
  - Final ESSENCE, SNLS
  - Pan-STARRS, SkyMapper
  - DES
  - LSST

Ground vs. Space for w

- dw/da != 0 means going to $z > 1$
- SNe Ia at $z > 1$ means space
- If $w(z) = w_0$ then ground is fine
- Spectroscopic confirmation bottleneck
    - Photo-typing/redshift for SNe Ia key

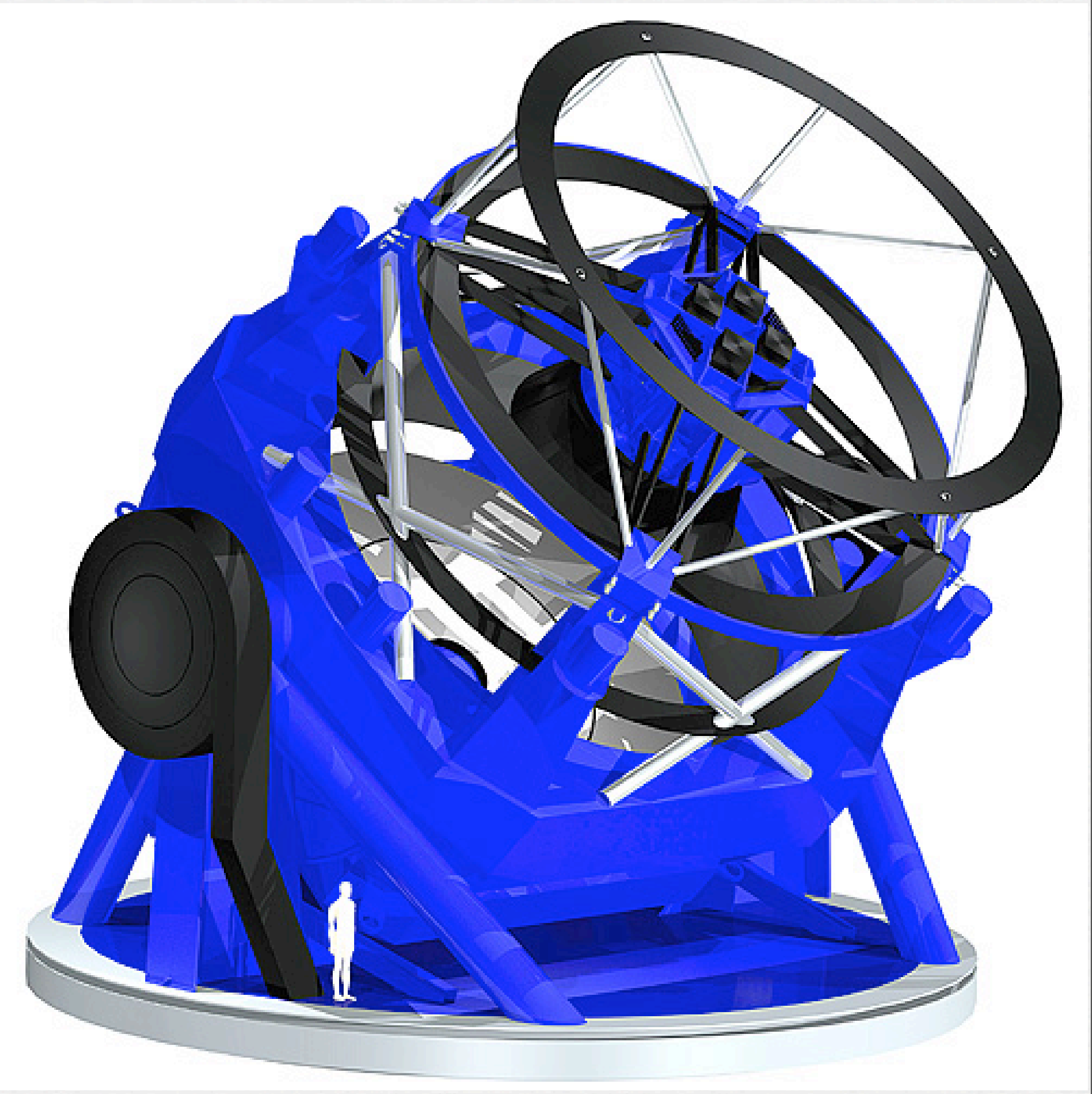
What would an optimized ground-based facility look like?

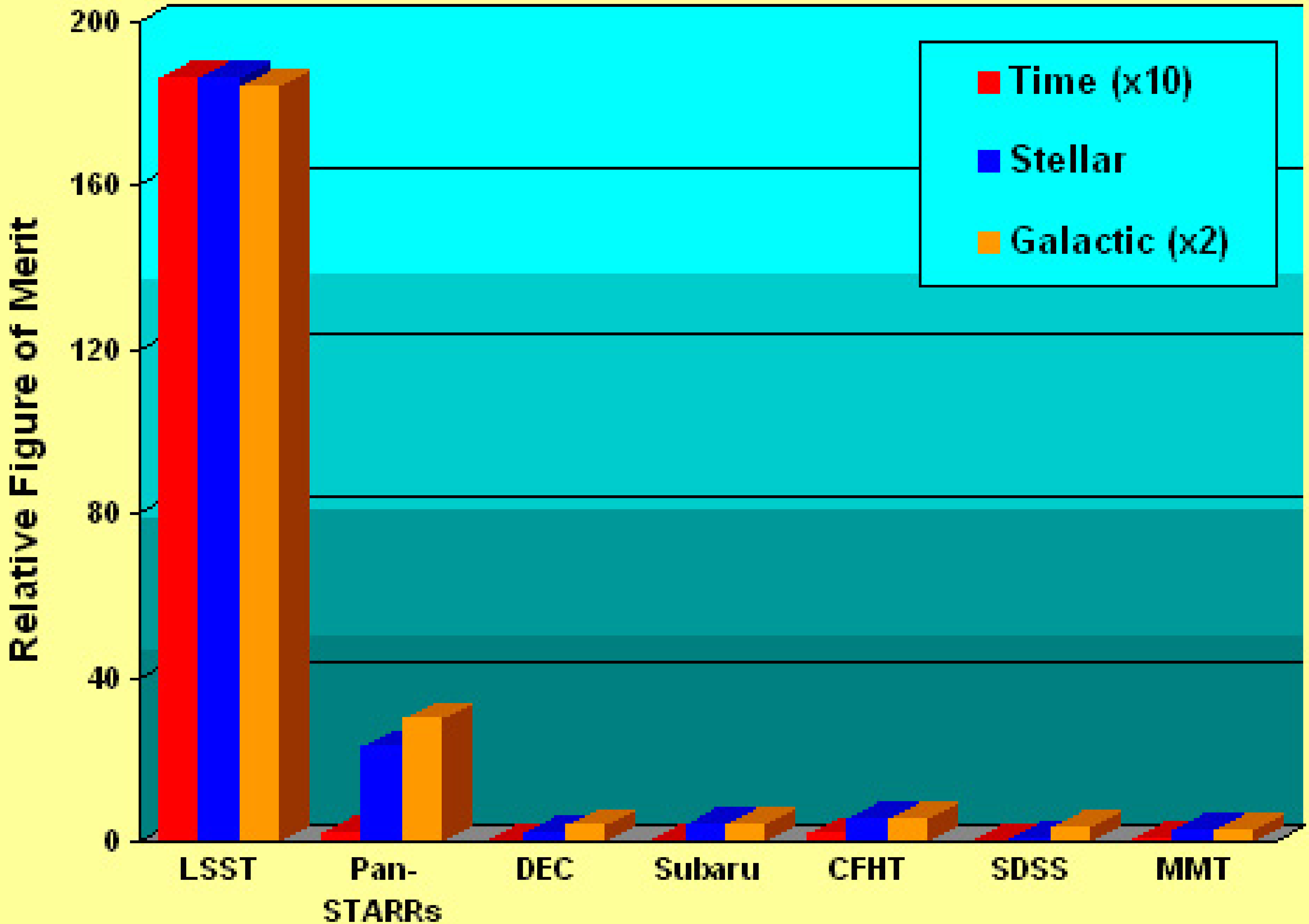
- Large collecting area
- Wide field of view
- Real-time analysis of data
- Significant leap in figure of merit
  - Collecting area x field of view

Large Synoptic Survey Telescope

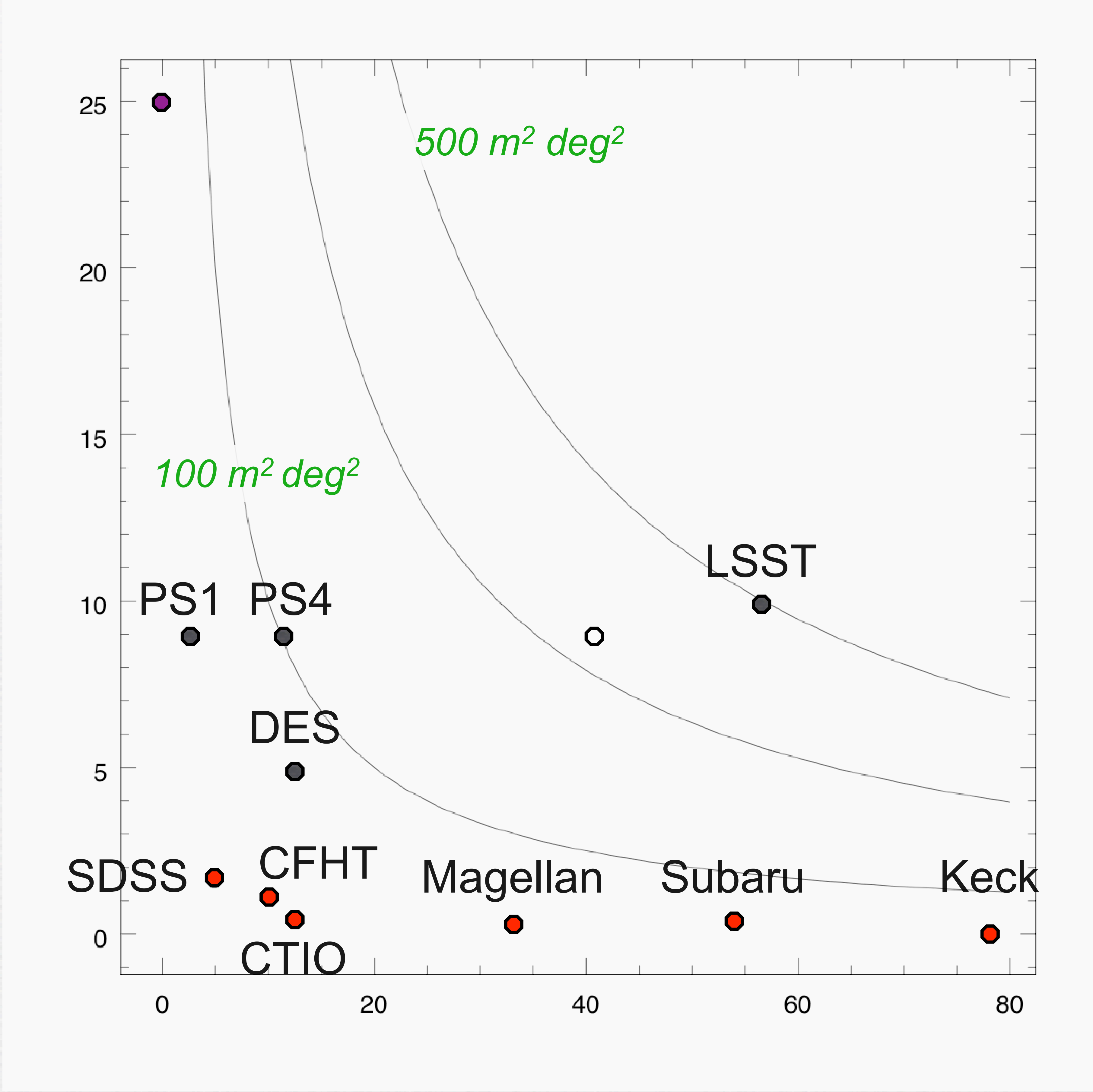
Highly ranked in Decadal Survey
Optimized for time domain
- scan mode
- deep mode

10 square degree field
6.5-m effective aperture
24th mag in 20 sec
20 Tbyte/night
Real-time analysis
Simultaneous science goals



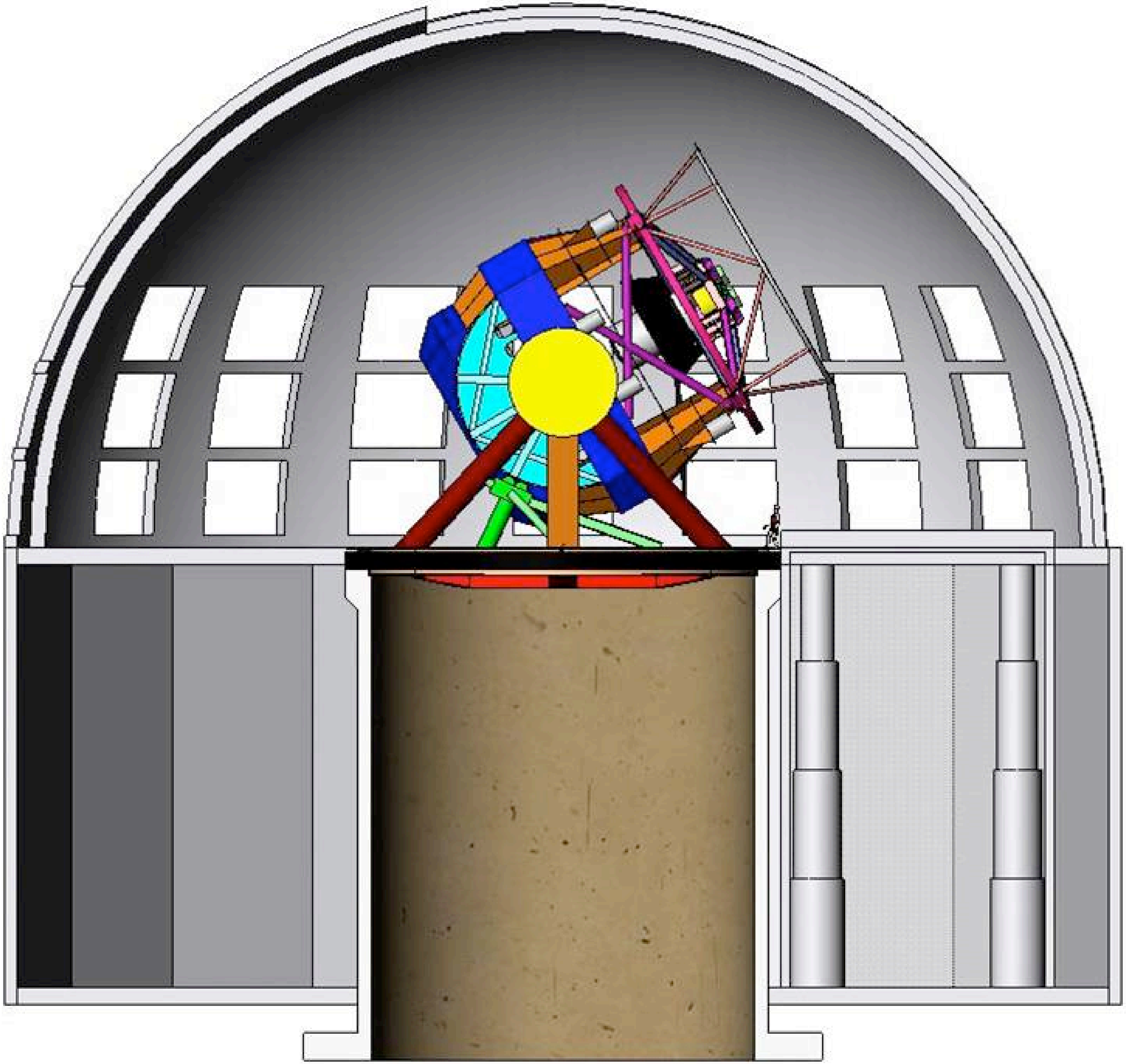


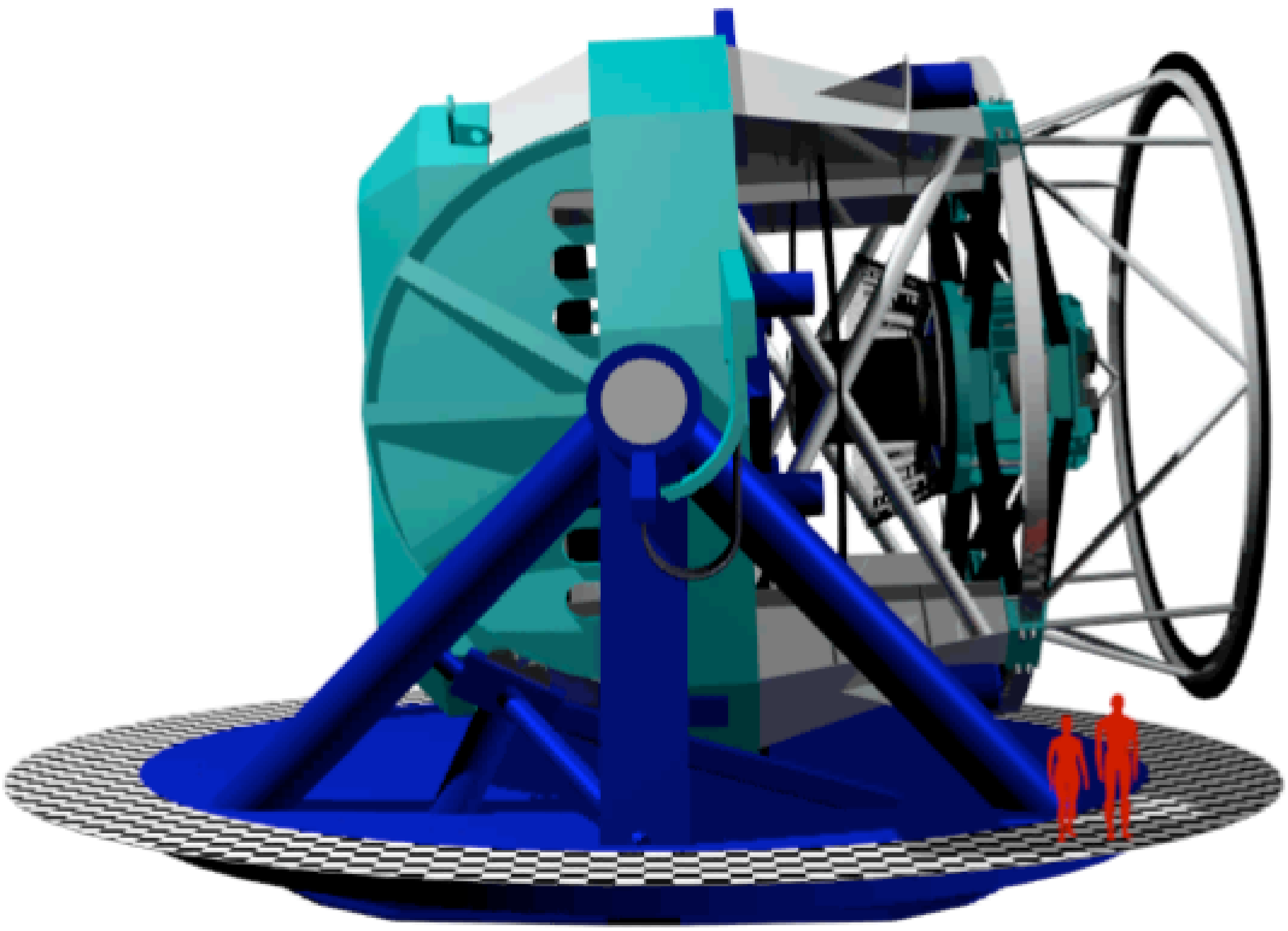
Relative Figure of Merit
200
160
120
80
40
0
Time (x10)
Stellar
Galactic (x2)
LSST
Pan-STARRs
DEC
Subaru
CFHT
SDSS
MMT

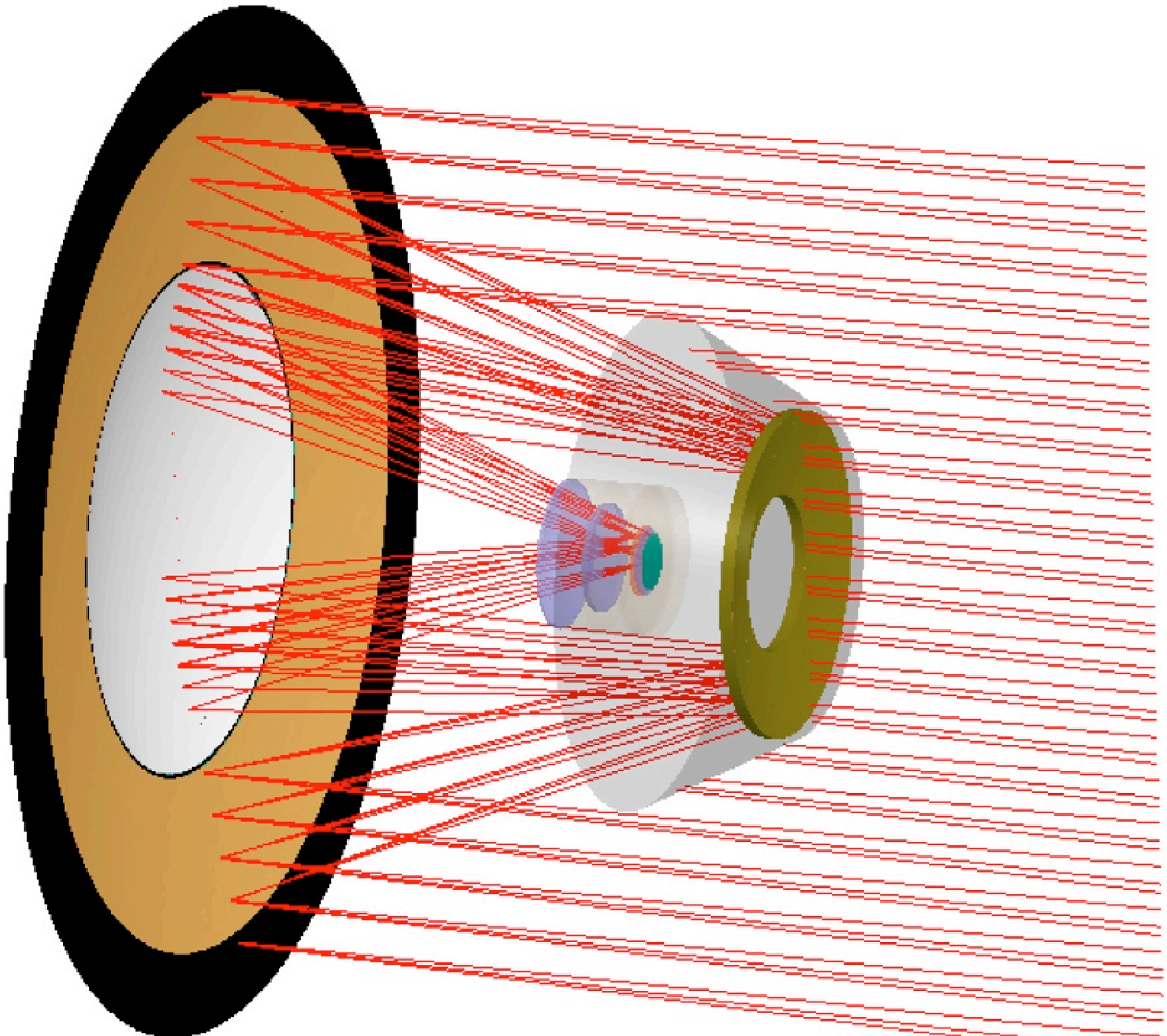


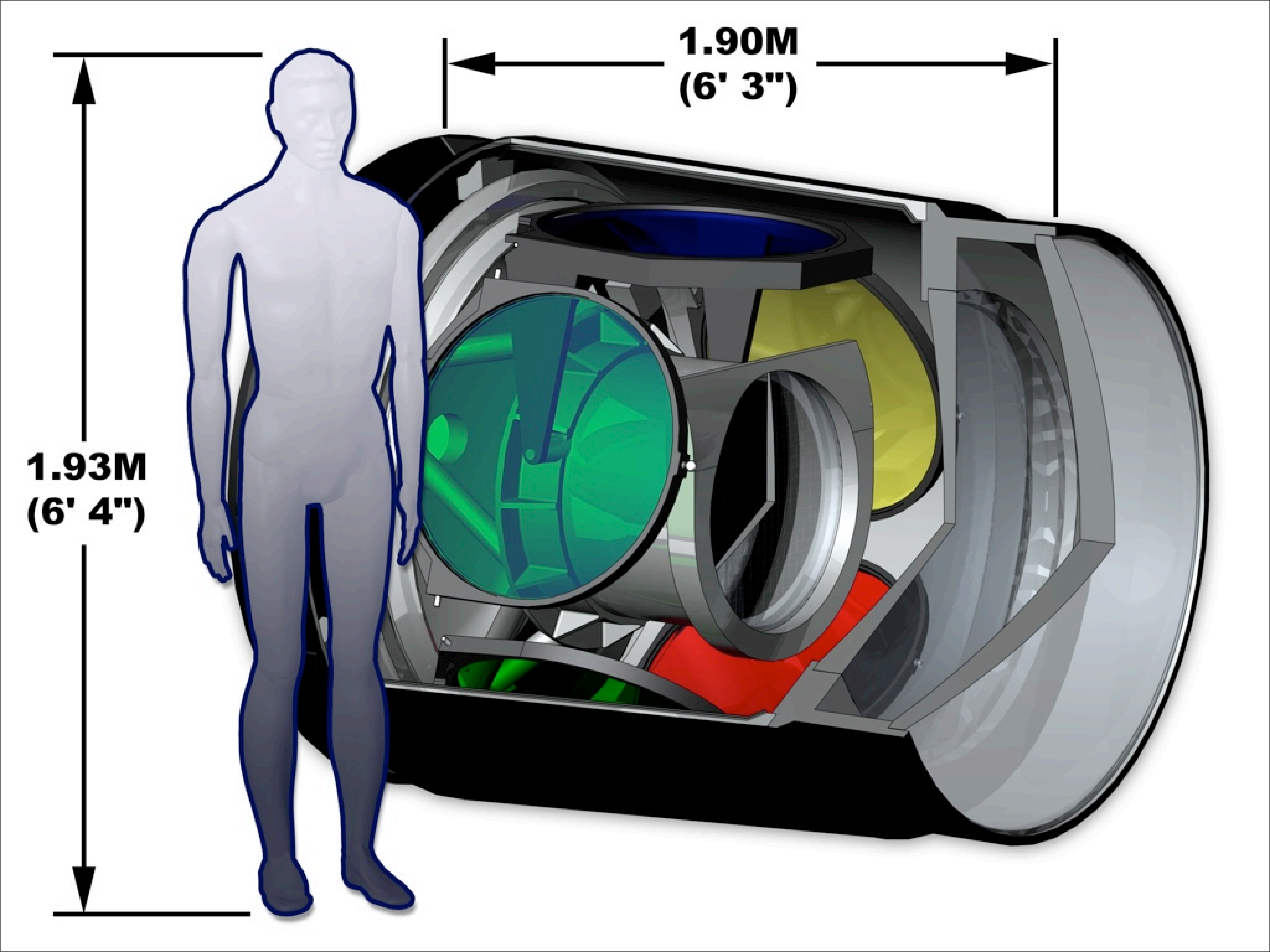
Field of View, sq degrees

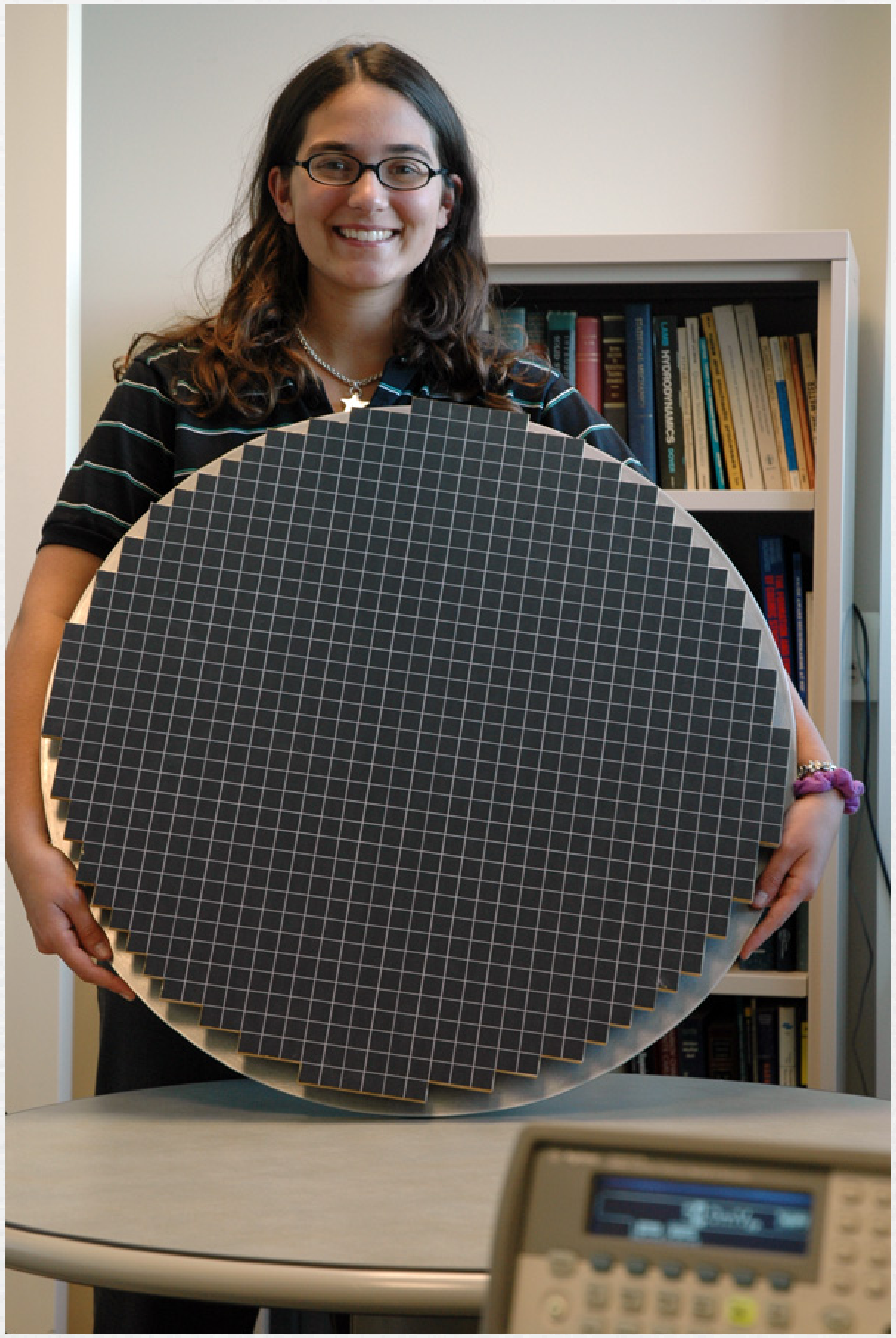
Unobscured Aperture, sq meters

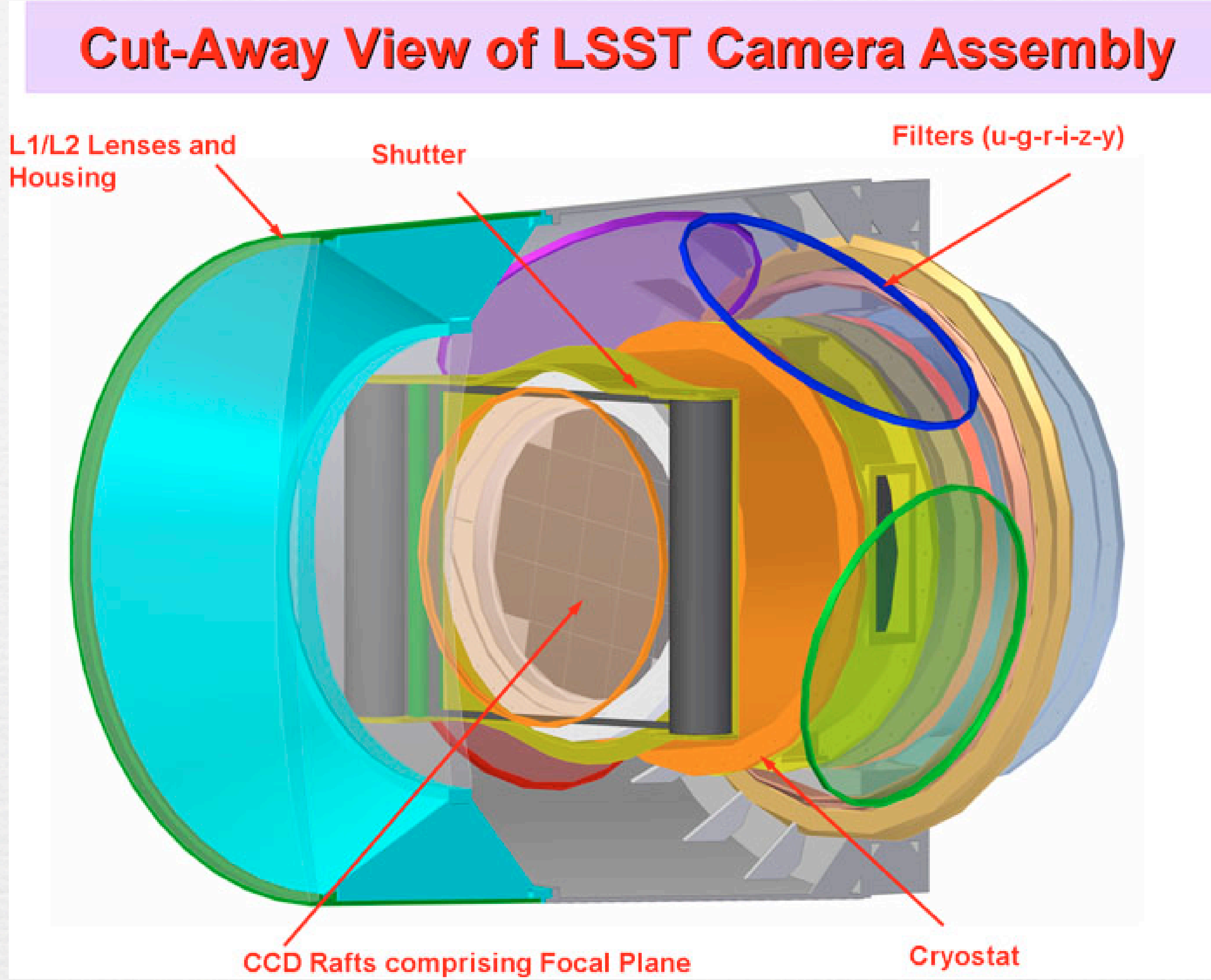







1.90M
(6' 3")
1.93M
(6' 4")

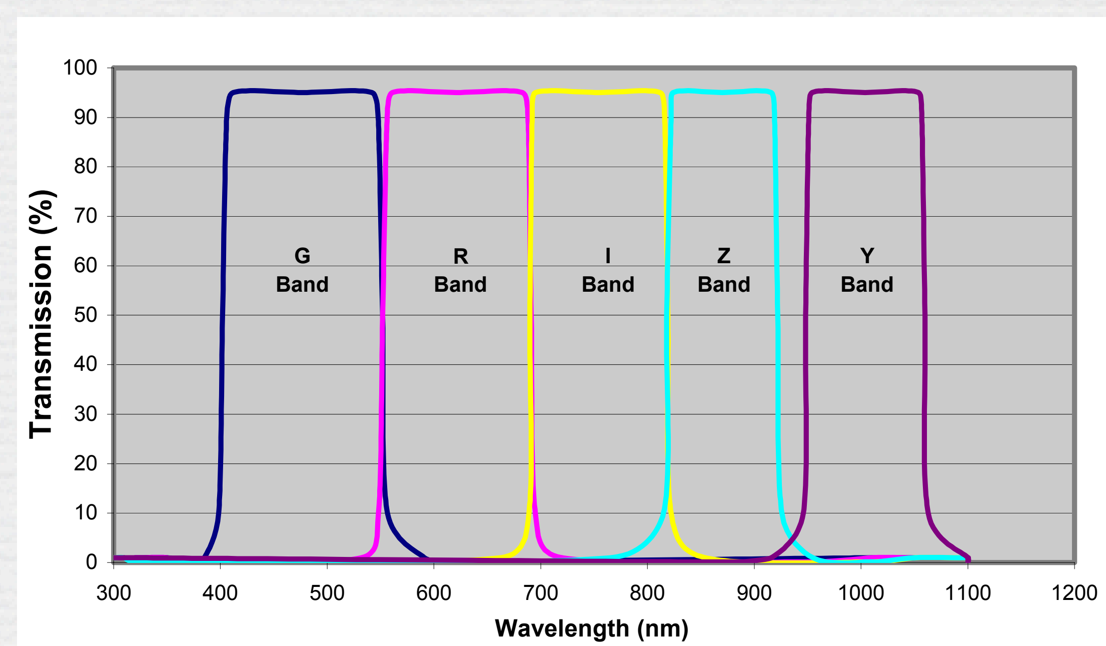




2.3 Gigapixels

20 Terabytes/night

Data of full SDSS survey/night



LSST Opens up the Skies

- Data will be immediately publicly available
- Allow small colleges and institutions to do research with big telescopes
- Will shift the nature of research

LSST Dark Energy

- Supernovae
- Weak Lensing
- Baryon Oscillations

LSST & Supernovae

LSST & Supernovae

- LSST will find huge numbers of supernovae

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- So what?

LSST & Supernovae

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- So what?
- What do you do with them?

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- What do you do with them?
- Spectra to understand physics

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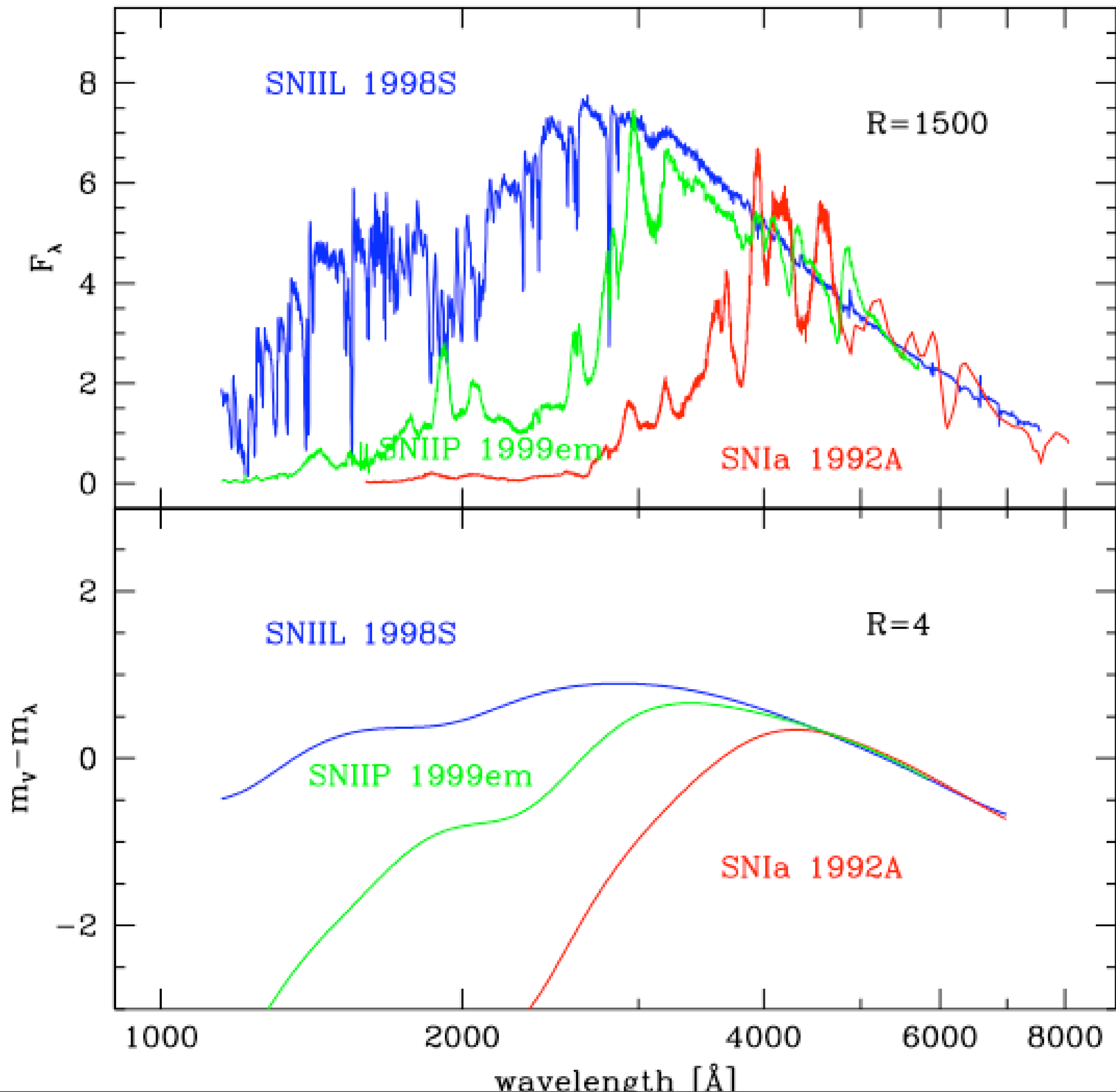
- Spectra to understand physics
    - Need additional resources

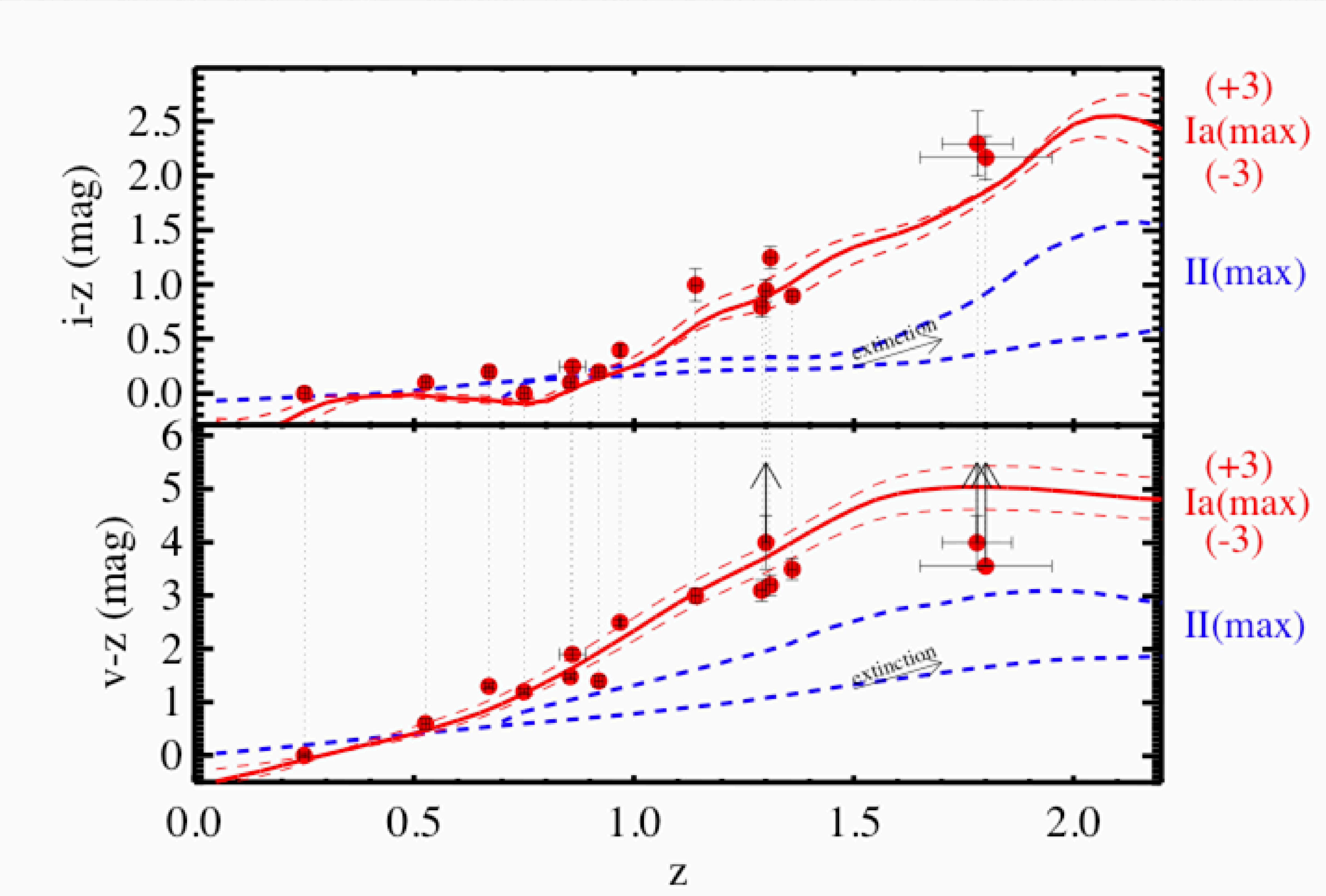
LSST & Supernovae

- LSST will find huge numbers of supernovae
- So what?
- What do you do with them?
- Spectra to understand physics
    - Need additional resources
- How to best use LSST supernovae?

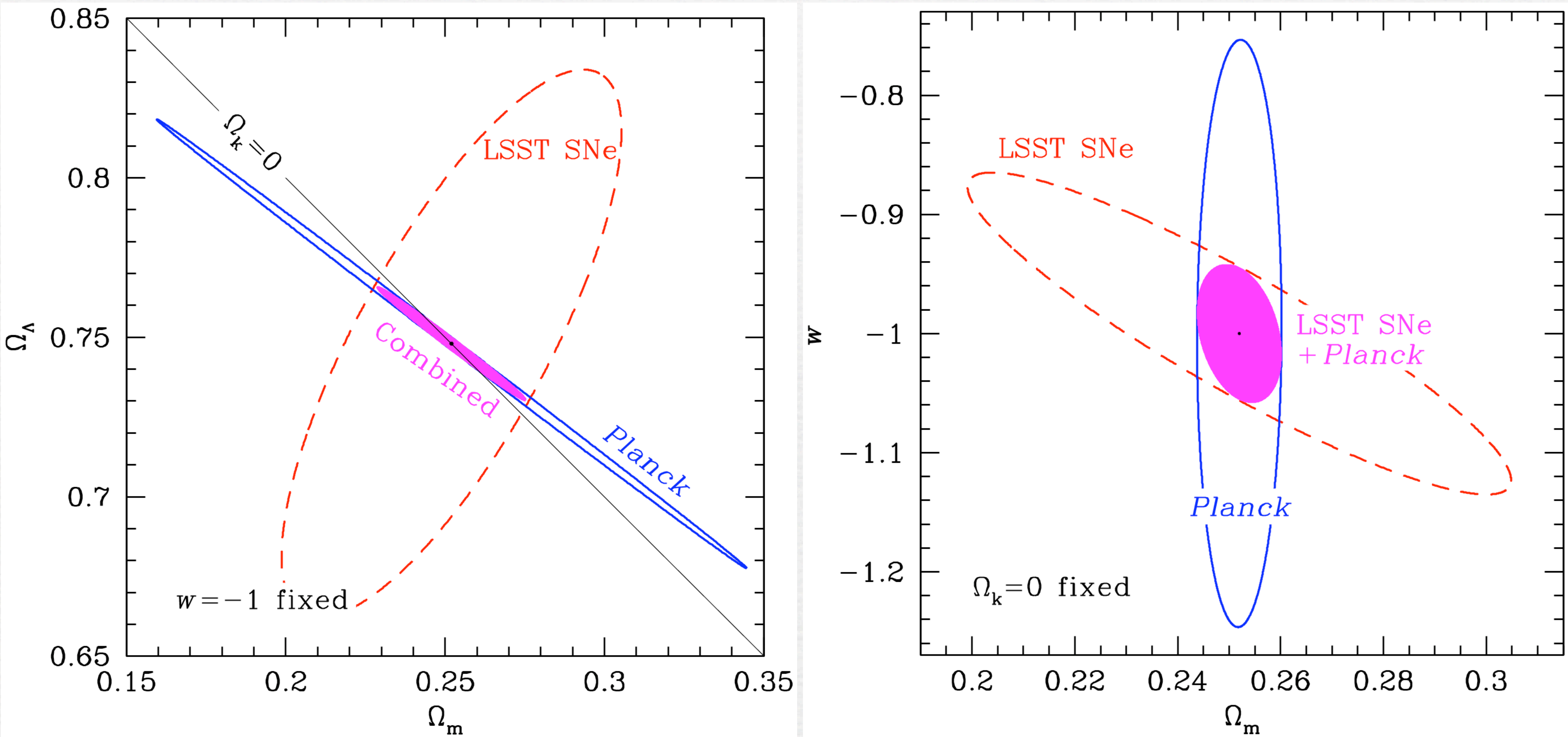
Distinguishing SN Types by Colors



Observed Colors of Higher-z Supernovae

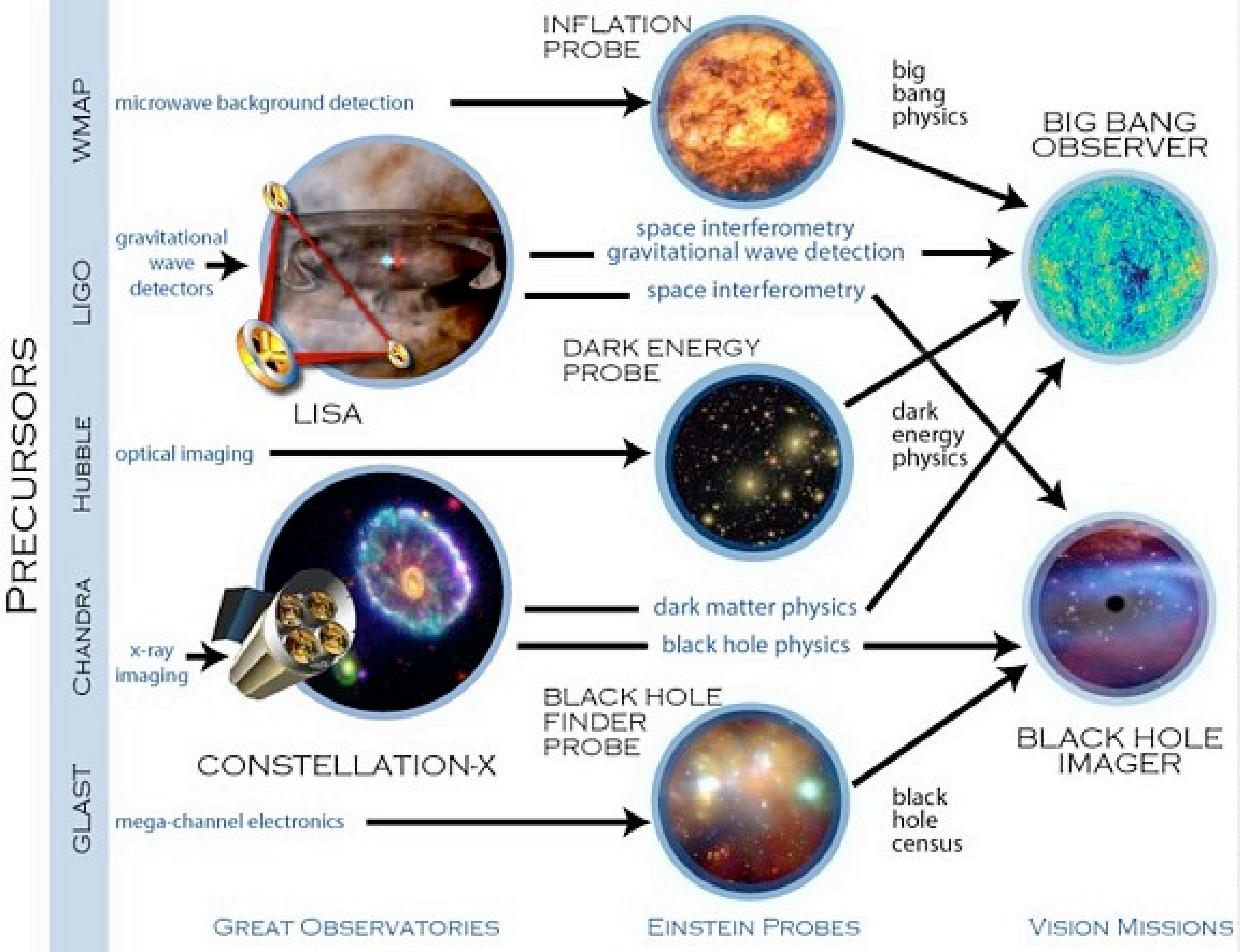


LSST SN Ia Constraints



Space-Based Missions

- Going to space is expensive
- Need ~$1 billion
- NASA funds most space astronomy in US
- So what does NASA want to do?


PRECURSORS
WMAP
LIGO
HUBBLE
CHANDRA
GLAST
microwave background detection
gravitational wave detectors
optical imaging
x-ray imaging
mega-channel electronics
LISA
CONSTELLATION-X
INFLATION PROBE
DARK ENERGY PROBE
BLACK HOLE FINDER PROBE
space interferometry gravitational wave detection
space interferometry
dark matter physics
black hole physics
big bang physics
dark energy physics
black hole census
BIG BANG OBSERVER
BLACK HOLE IMAGER
GREAT OBSERVATORIES
EINSTEIN PROBES
VISION MISSIONS

Dark Energy Probe

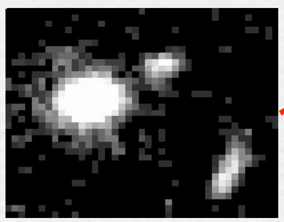
- Joint Dark Energy Mission (JDEM):
  - Competitive proposal
  - Mission to best measure dark energy
  - Complicated because no good theories to test
- Missions
  - SNAP, ADEPT, DESTiny
- NASA manned program puts JDEM in jeopardy

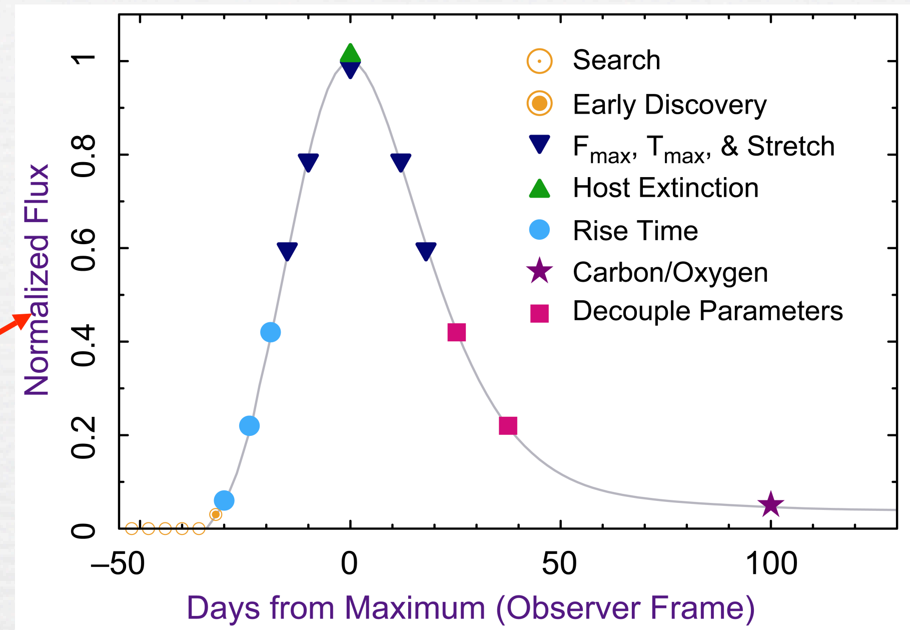
SNAP concept

Observables :

Light Curves

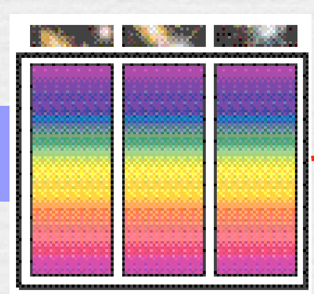
Images

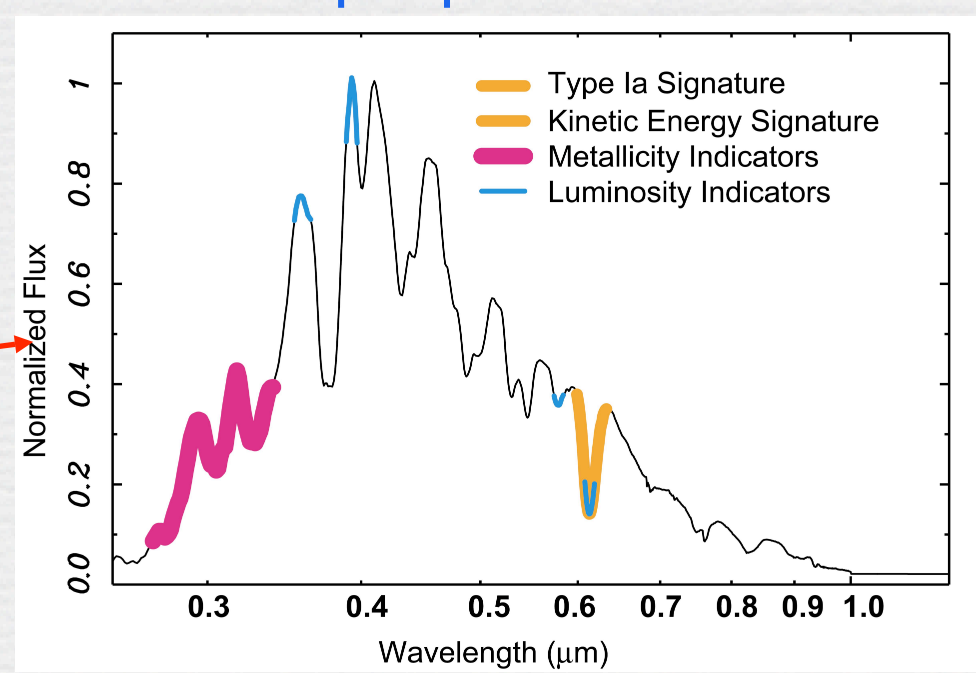




Redshift & spectral properties

Spectra

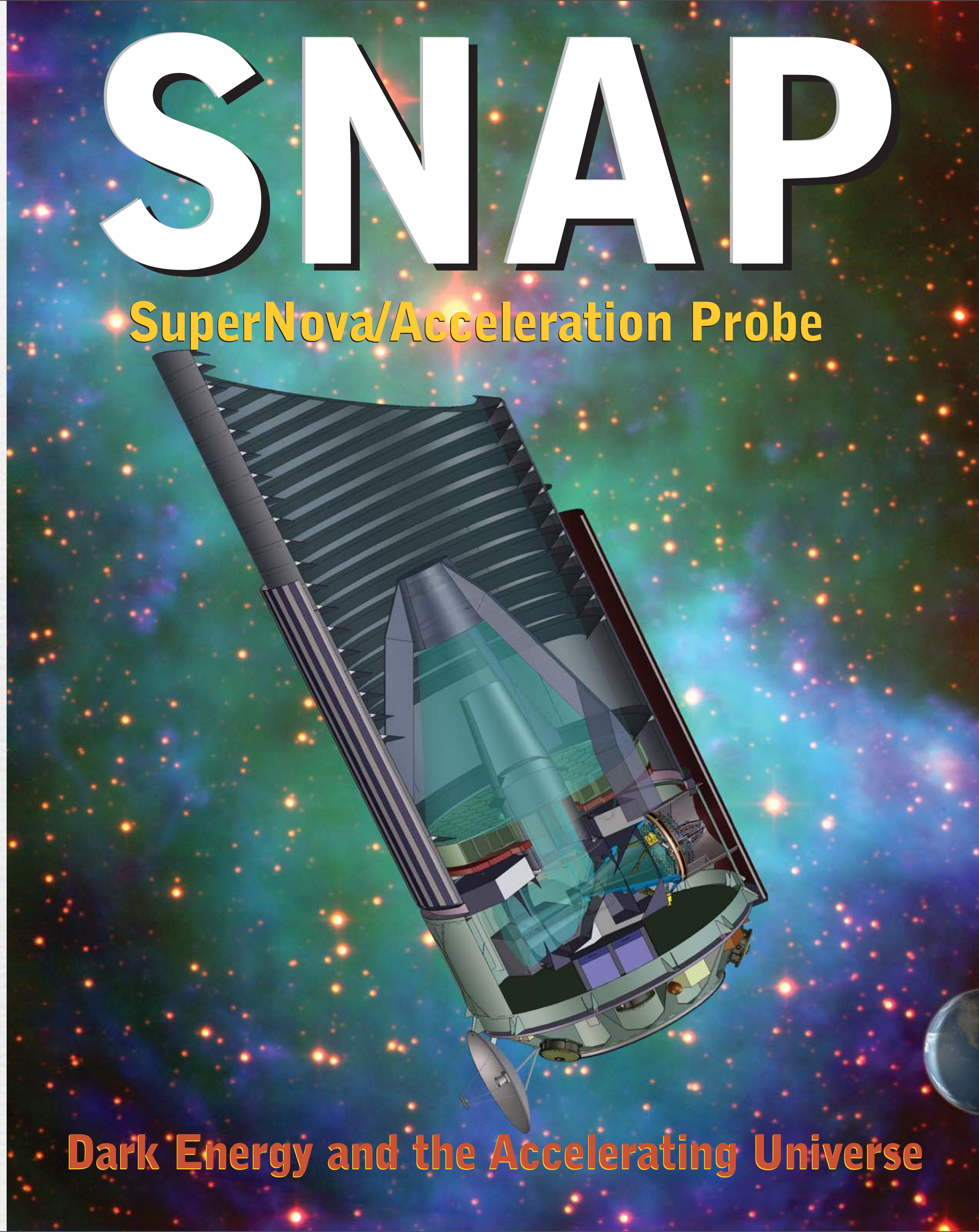




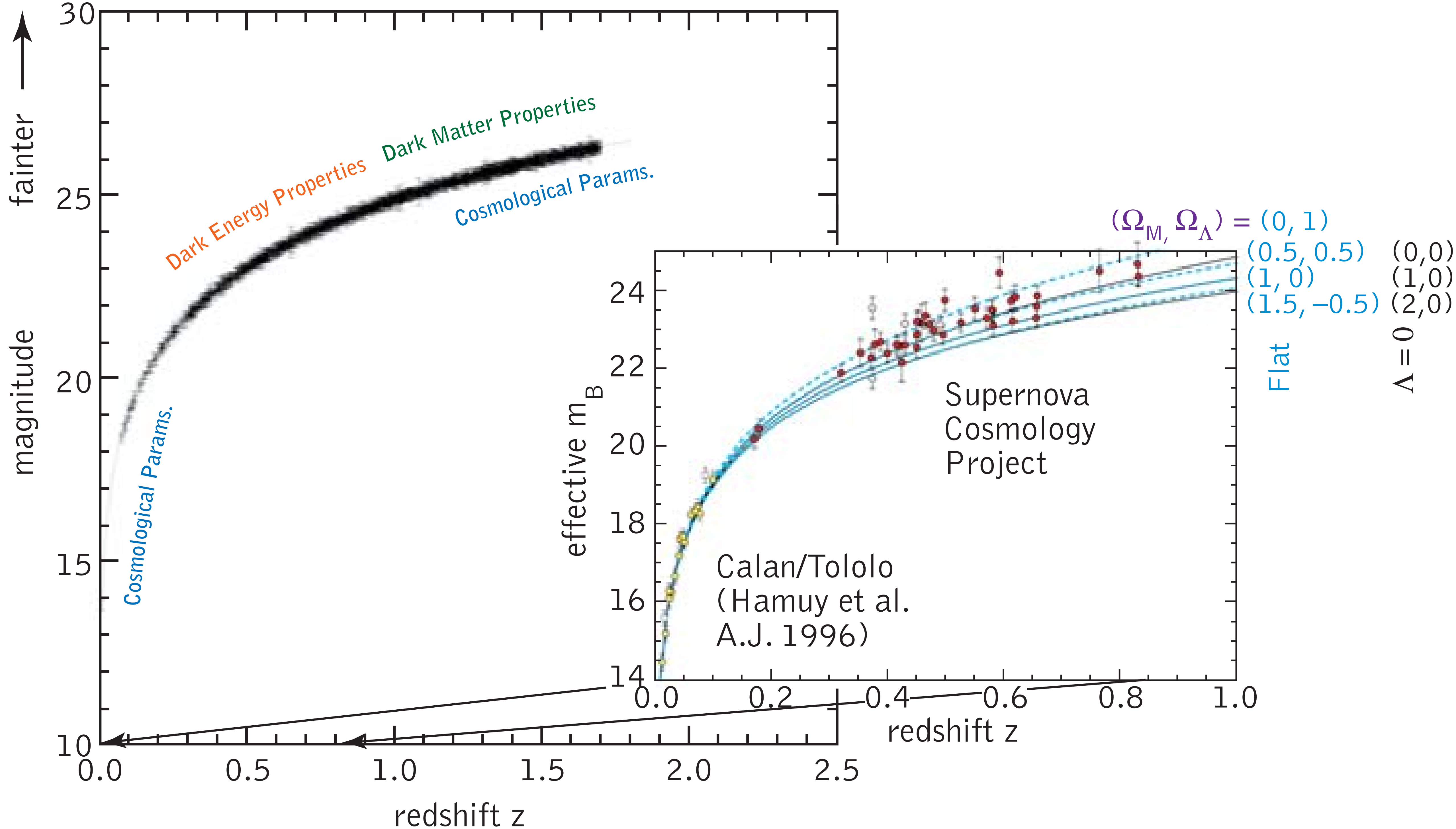
Ω_M and Ω_Λ

w and w'

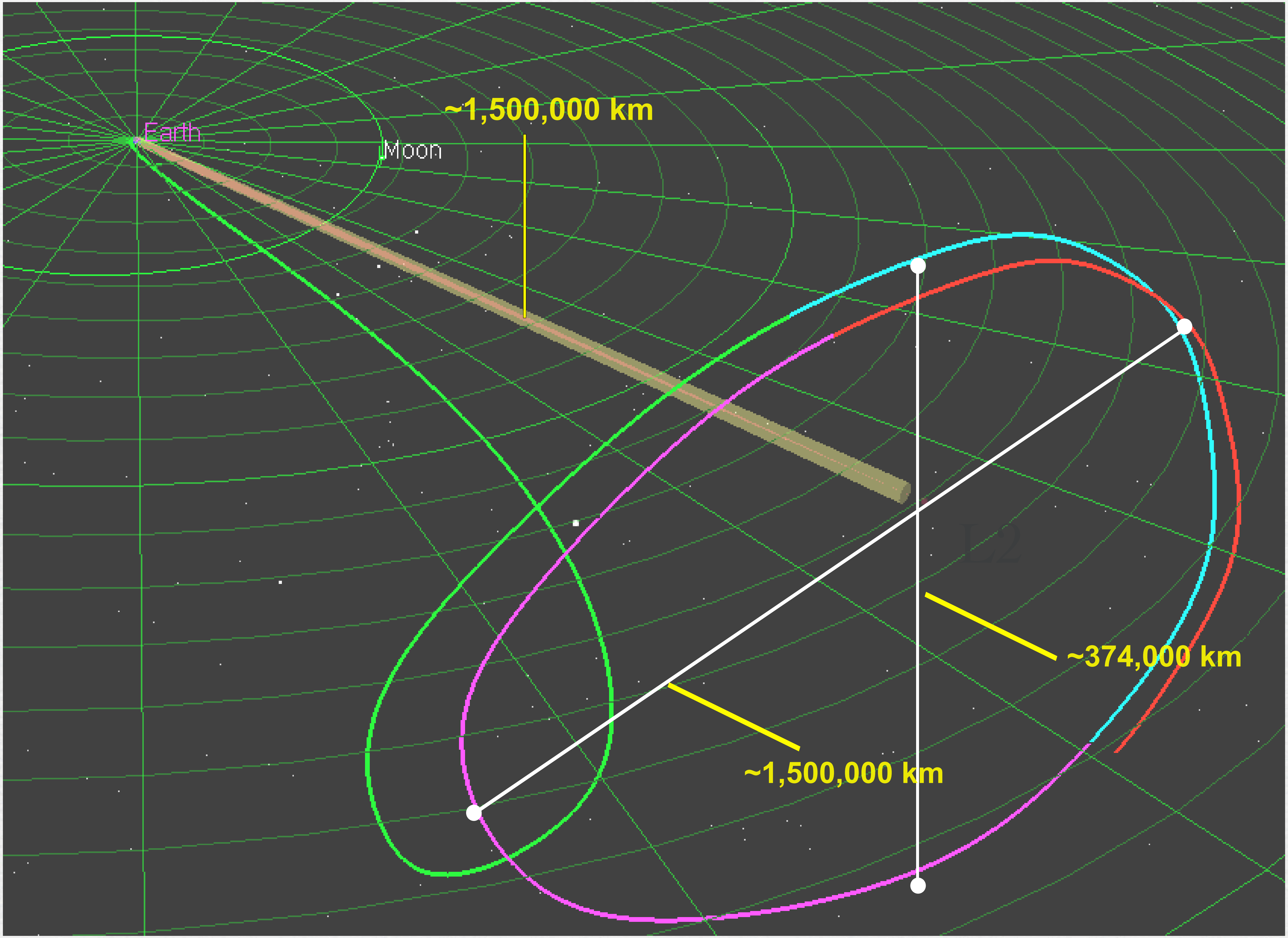
data ⟶ analysis ⟶ physics


SNAP
SuperNova/Acceleration Probe
Dark Energy and the Accelerating Universe

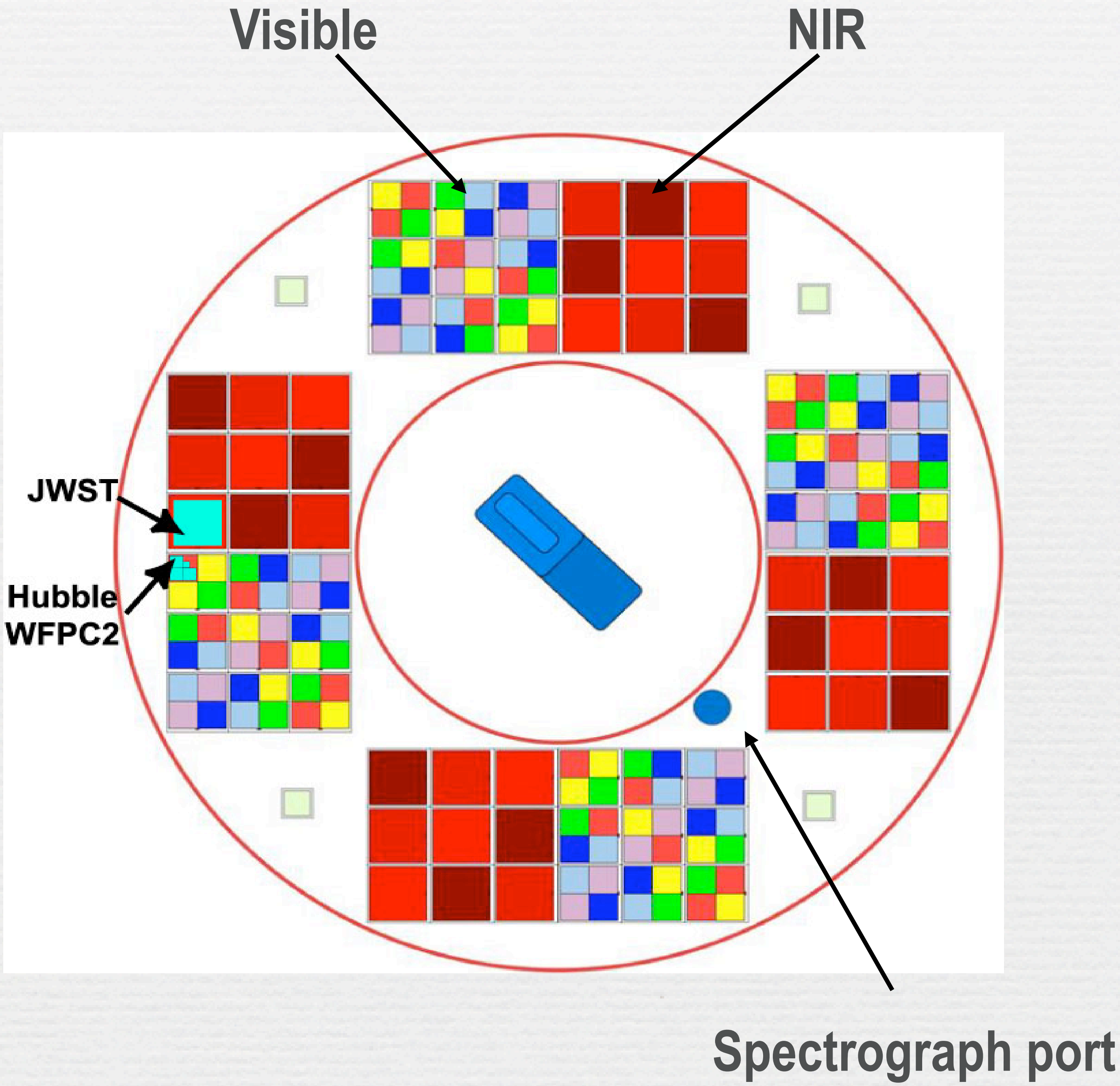
SNAP SN Ia Diagram



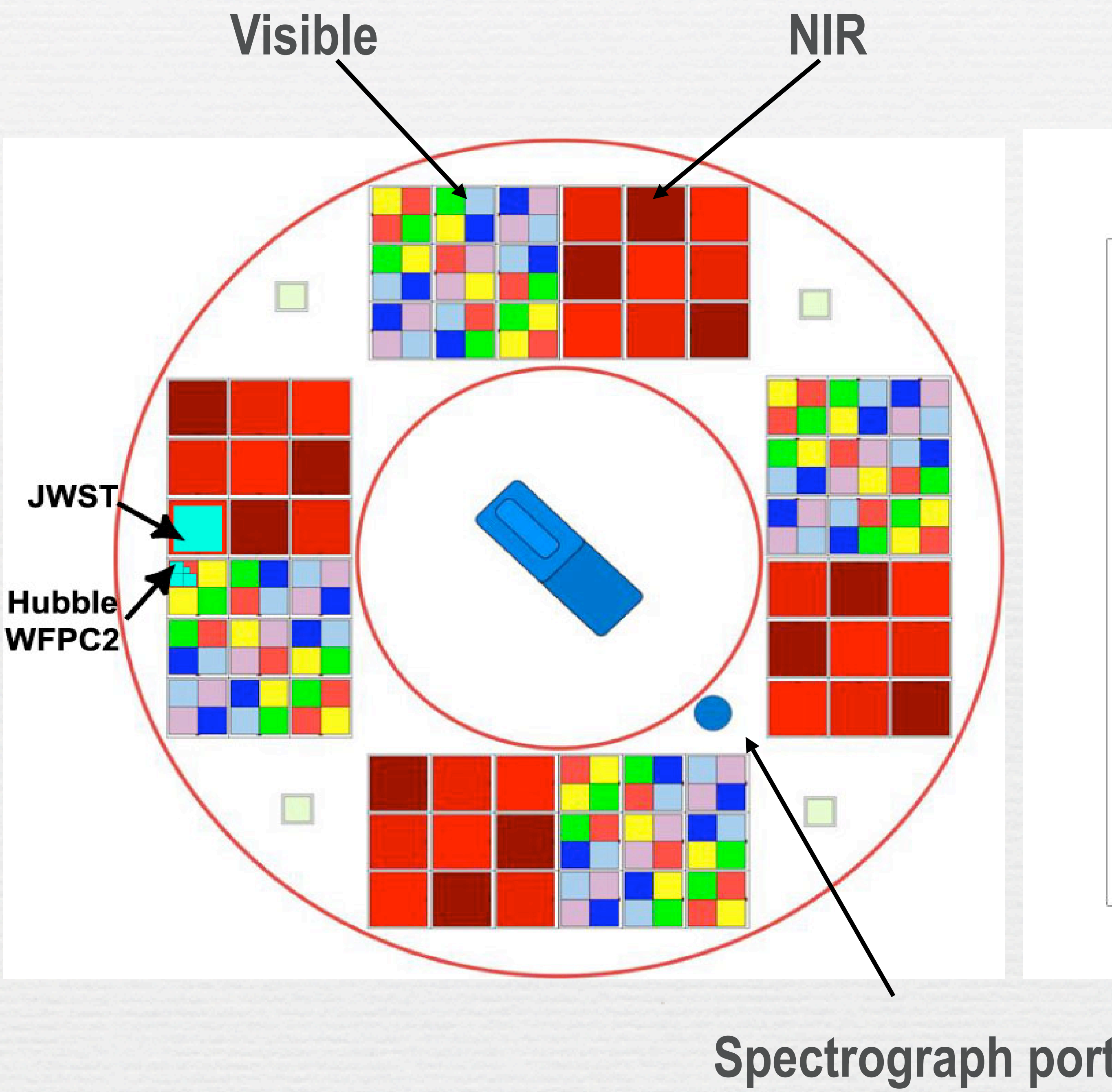
SNAP Orbit

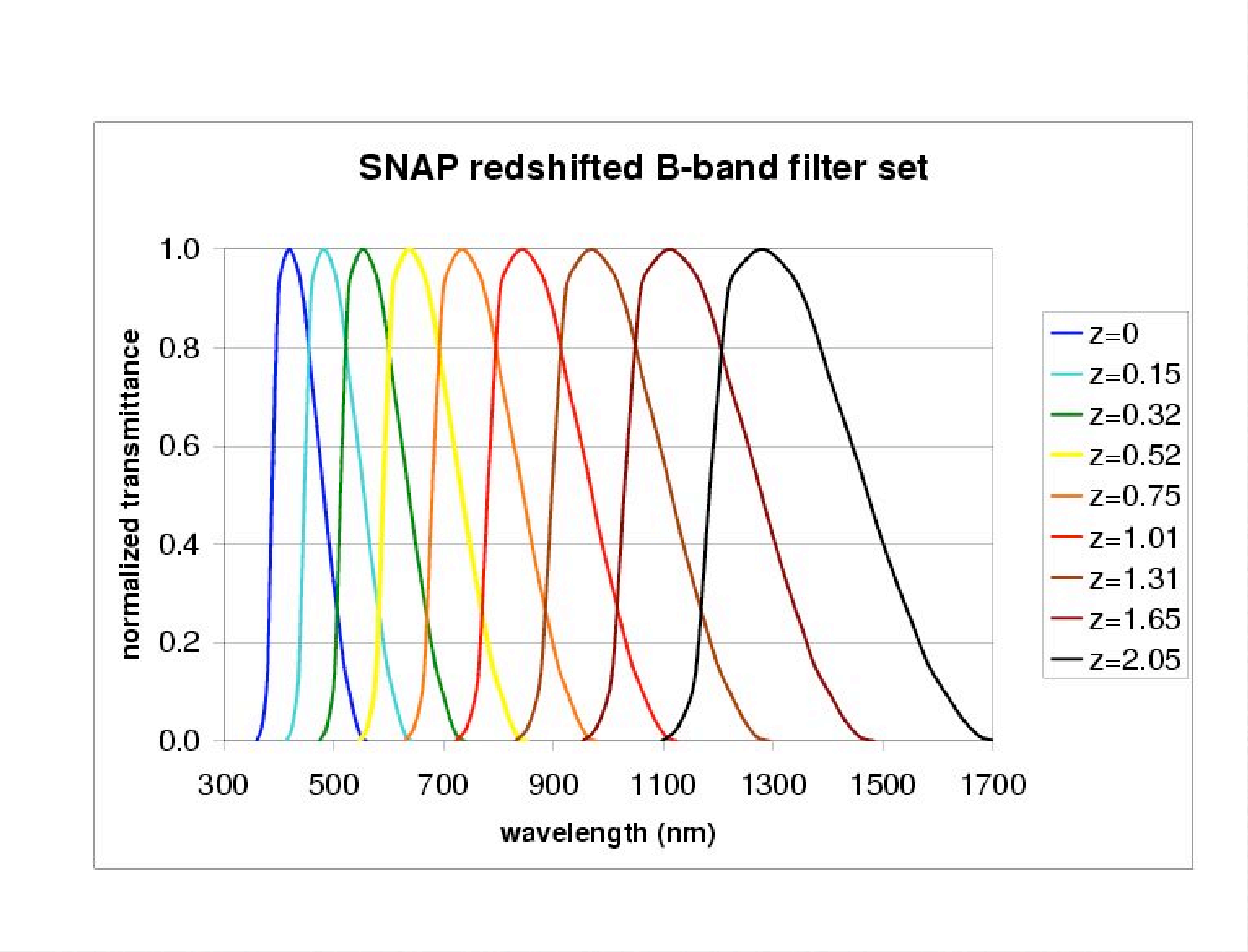


Focal plane

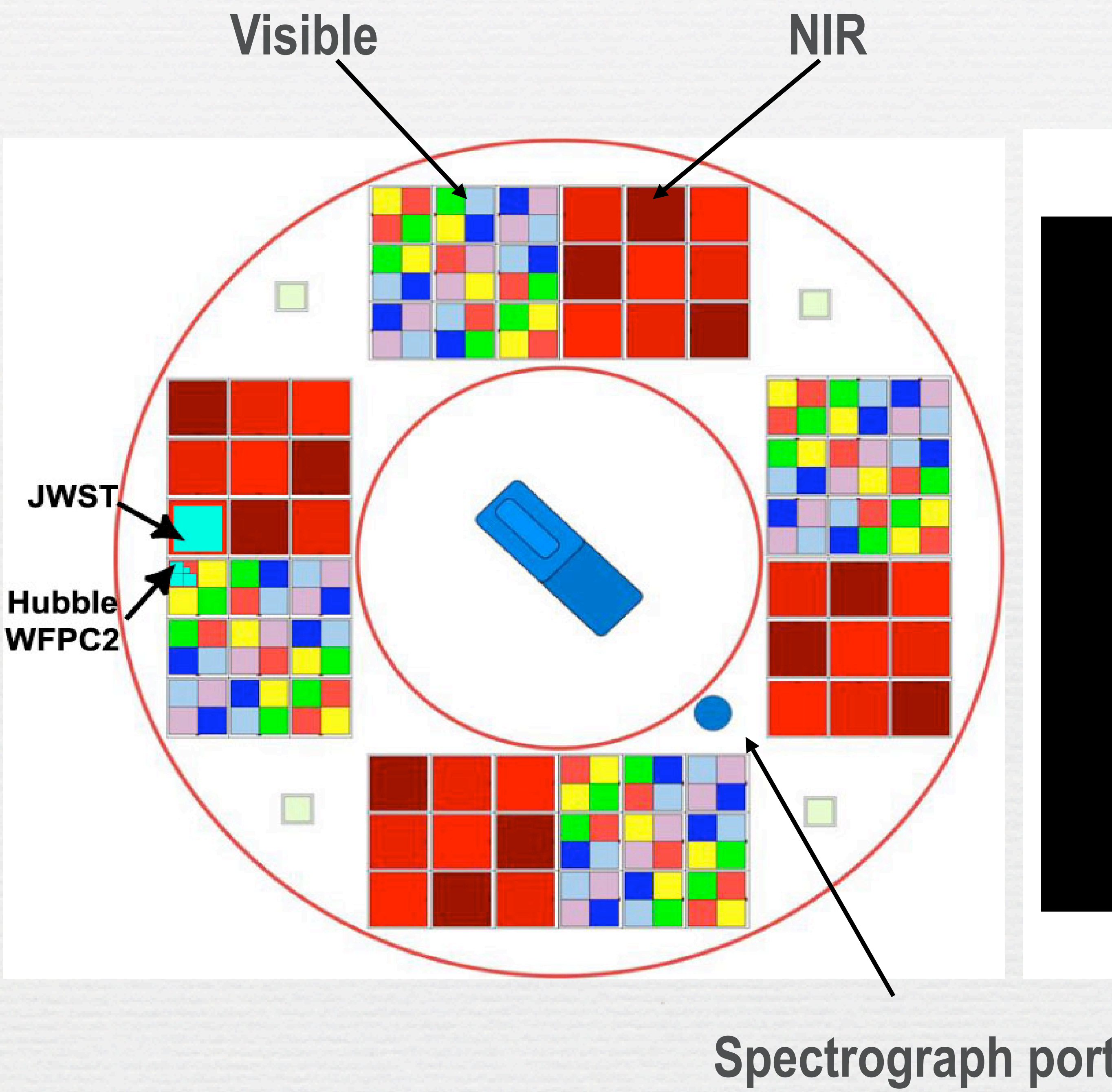


Focal plane


Visible
NIR
JWST
Hubble
WFPC2
Spectrograph port


SNAP redshifted B-band filter set
normalized transmittance
0.0
0.2
0.4
0.6
0.8
1.0
300
500
700
900
1100
1300
1500
1700
wavelength (nm)
z=0
z=0.15
z=0.32
z=0.52
z=0.75
z=1.01
z=1.31
z=1.65
z=2.05

Focal plane



Visible
NIR
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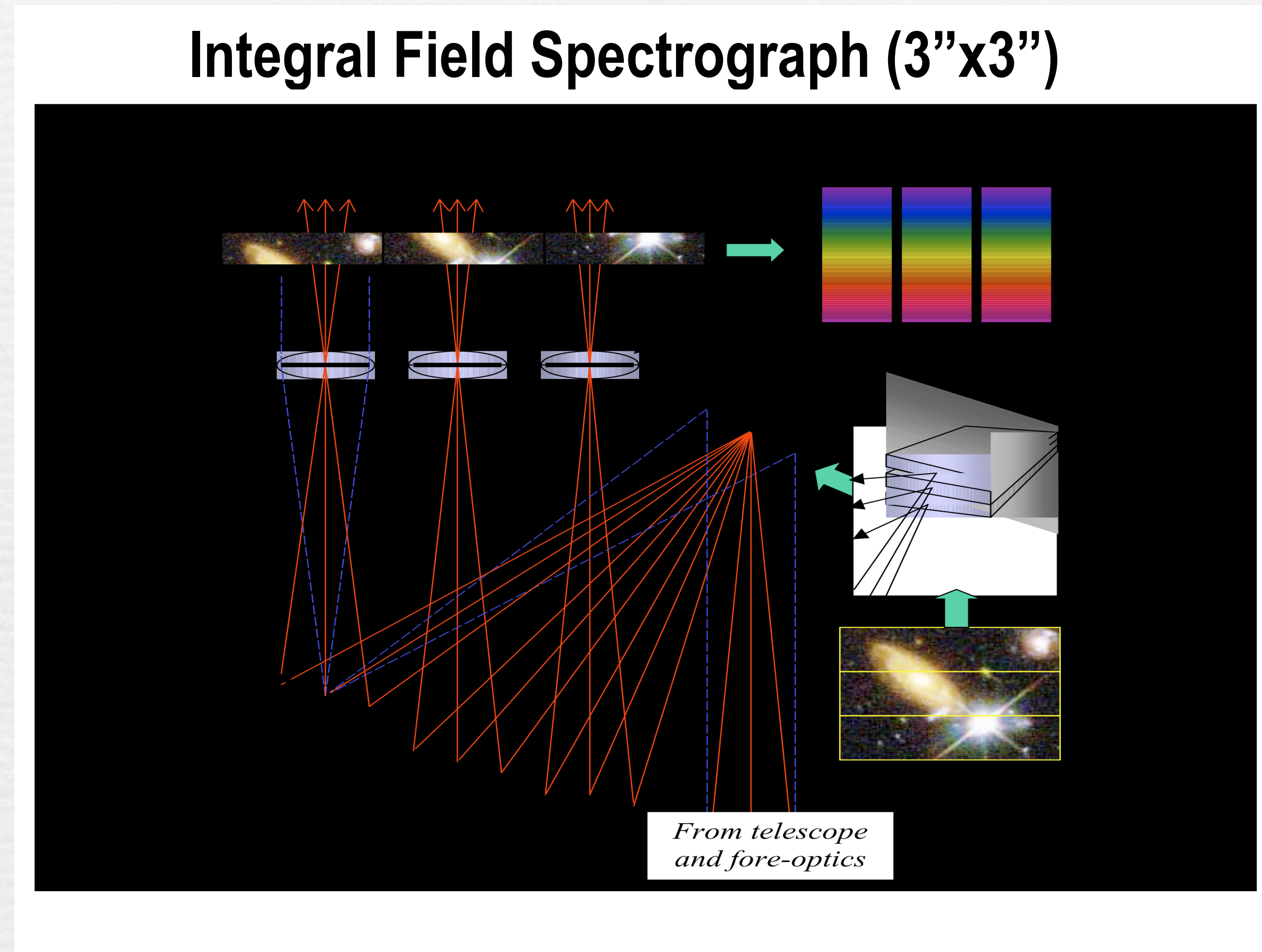


Integral Field Spectrograph (3”x3”)
From telescope
and fore-optics

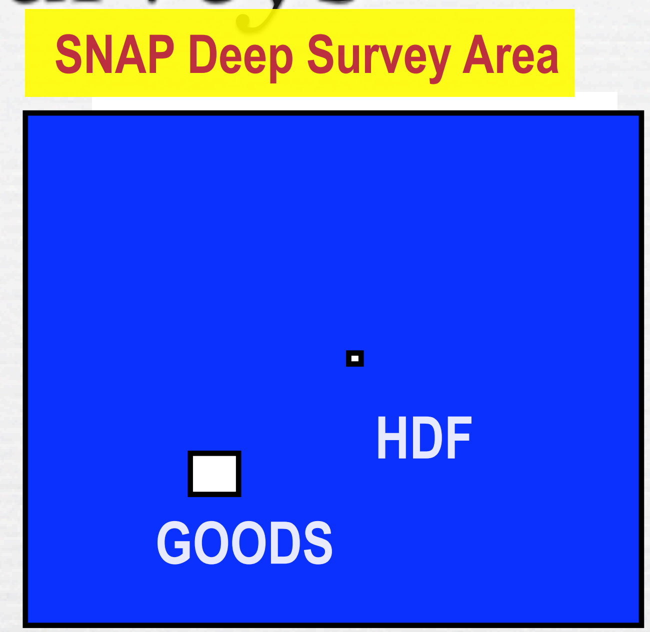
Physics with SNAP: Deep & Large Space Surveys

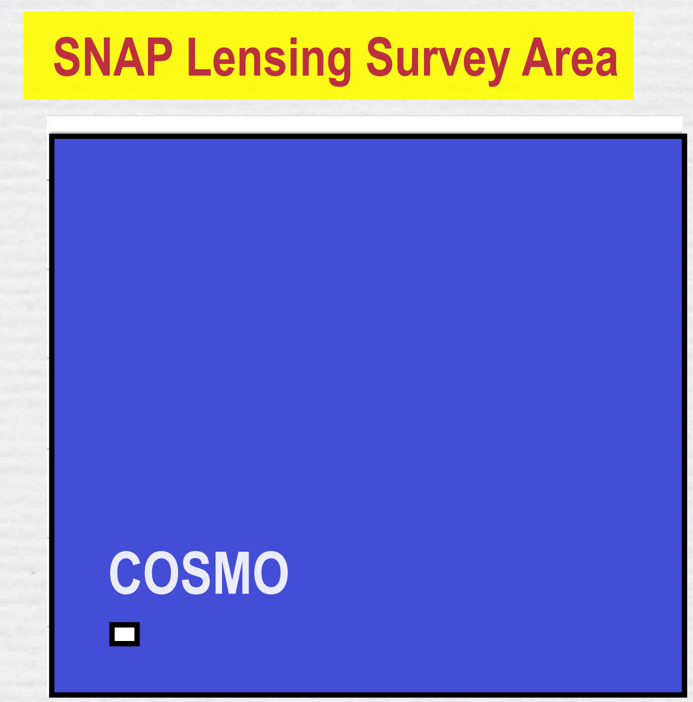
- The SNAP surveys will have an unprecedented combination of depth, solid-angle, angular resolution, temporal sampling, and wavelength coverage

- Hubble Deep Fields illustrate the impact of a deep space survey.

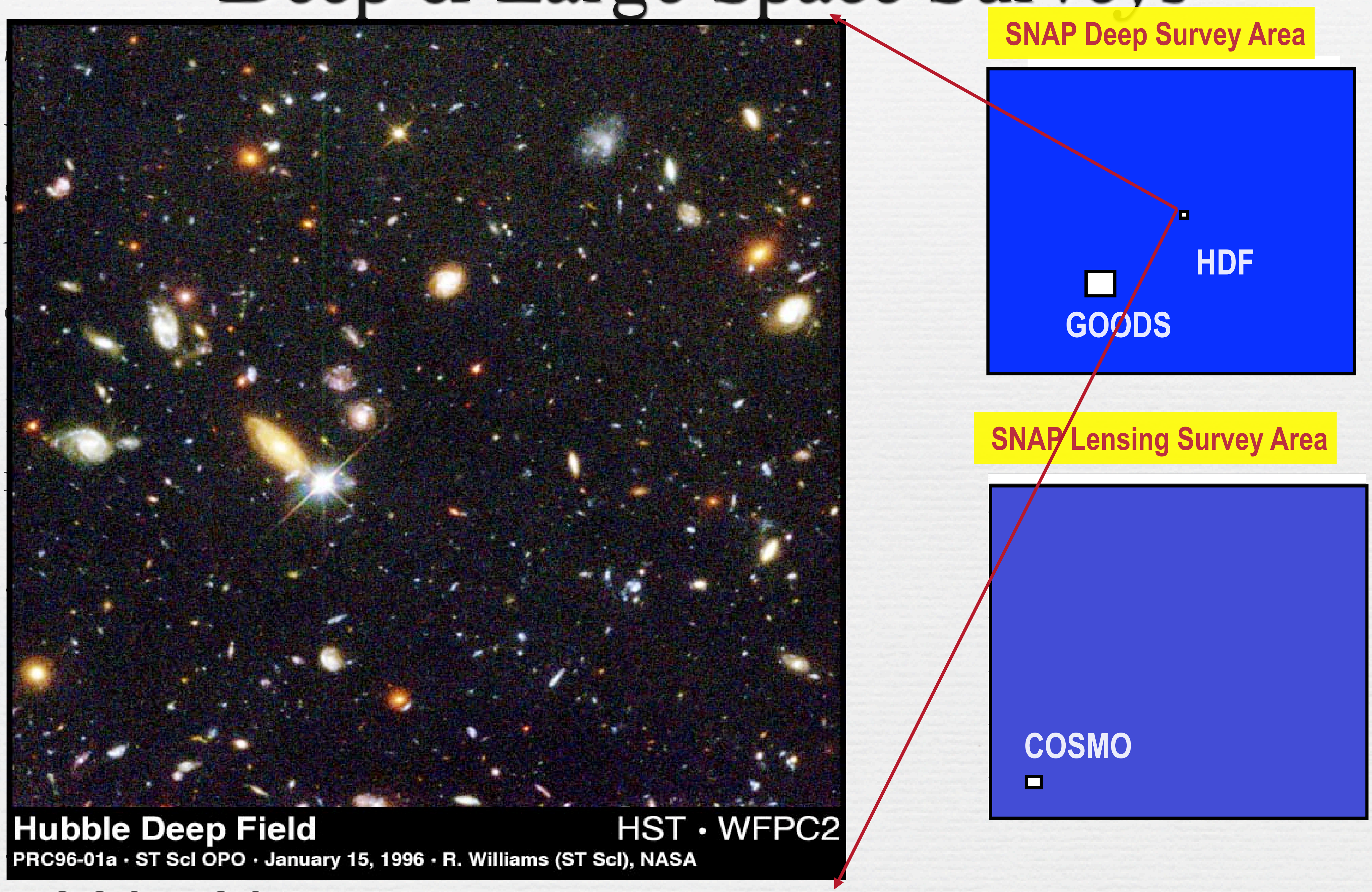
- SNAP SN survey 5,000 x HDF.
  - SNAP m_{AB} = 27.7 per filter (30.4 co-added) every 4 days

- SNAP lensing survey ~10^6 x HDF, 500 x COSMOS!





Physics with SNAP: Deep & Large Space Surveys



x COSMOS!

Physics with SNAP: Deep & Large Space Surveys

- The SNAP surveys will have an unprecedented combination of depth, solid-angle, angular resolution, temporal sampling, and wavelength coverage

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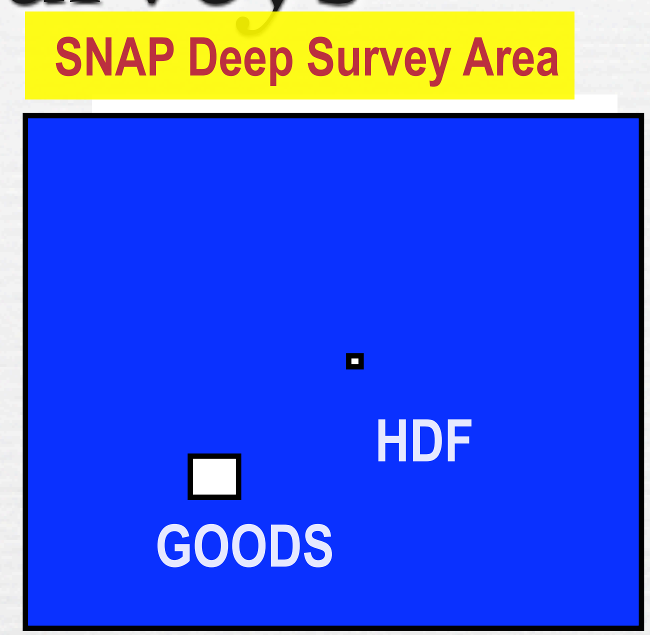
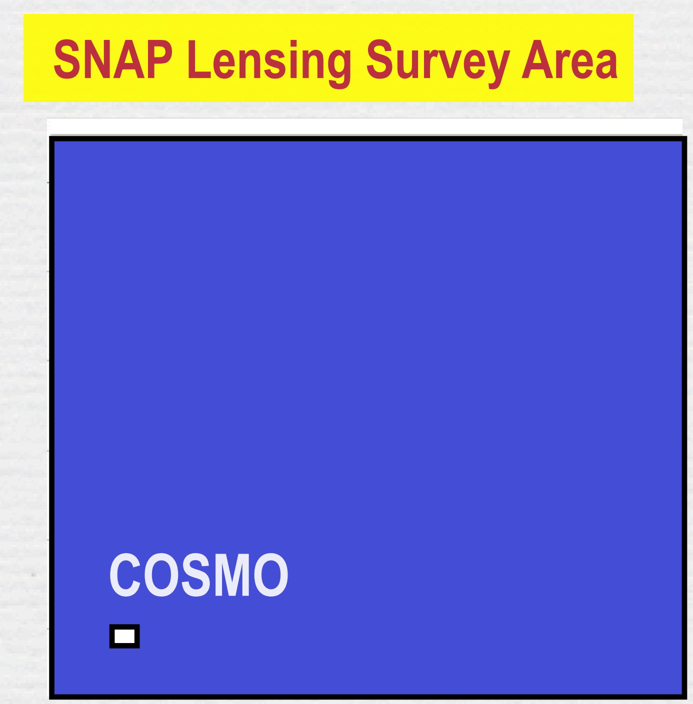
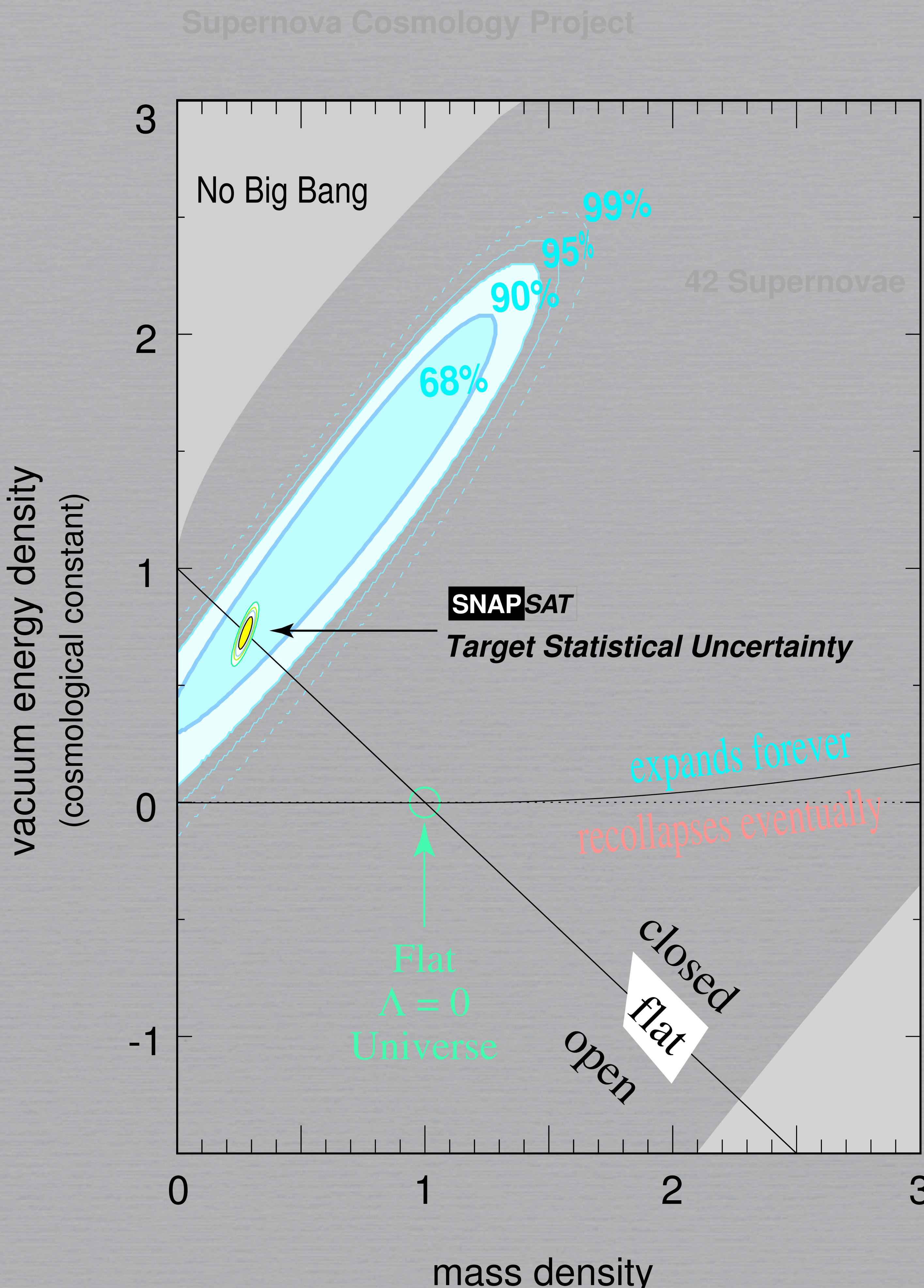
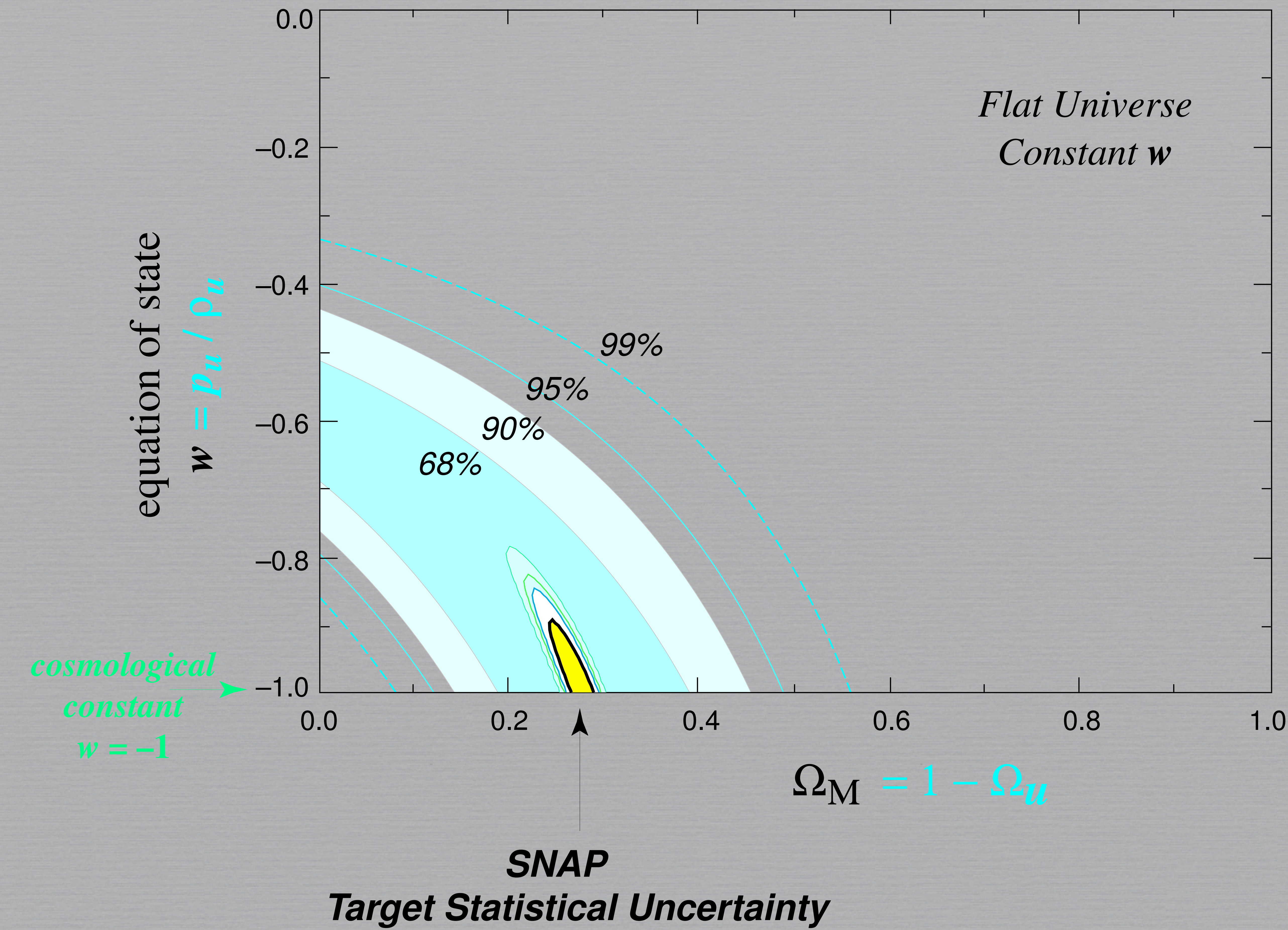




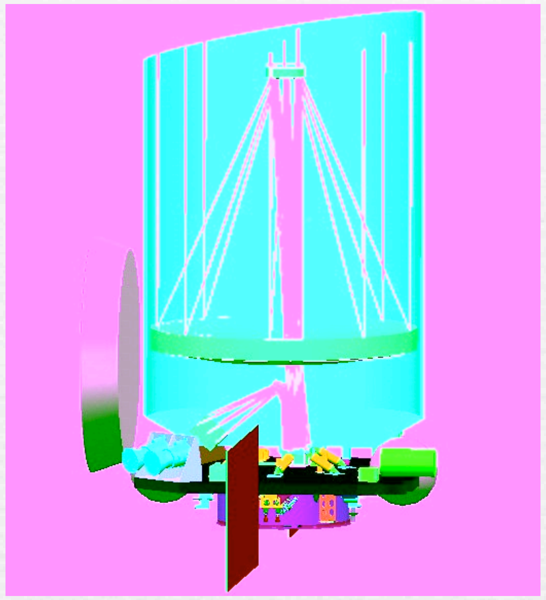


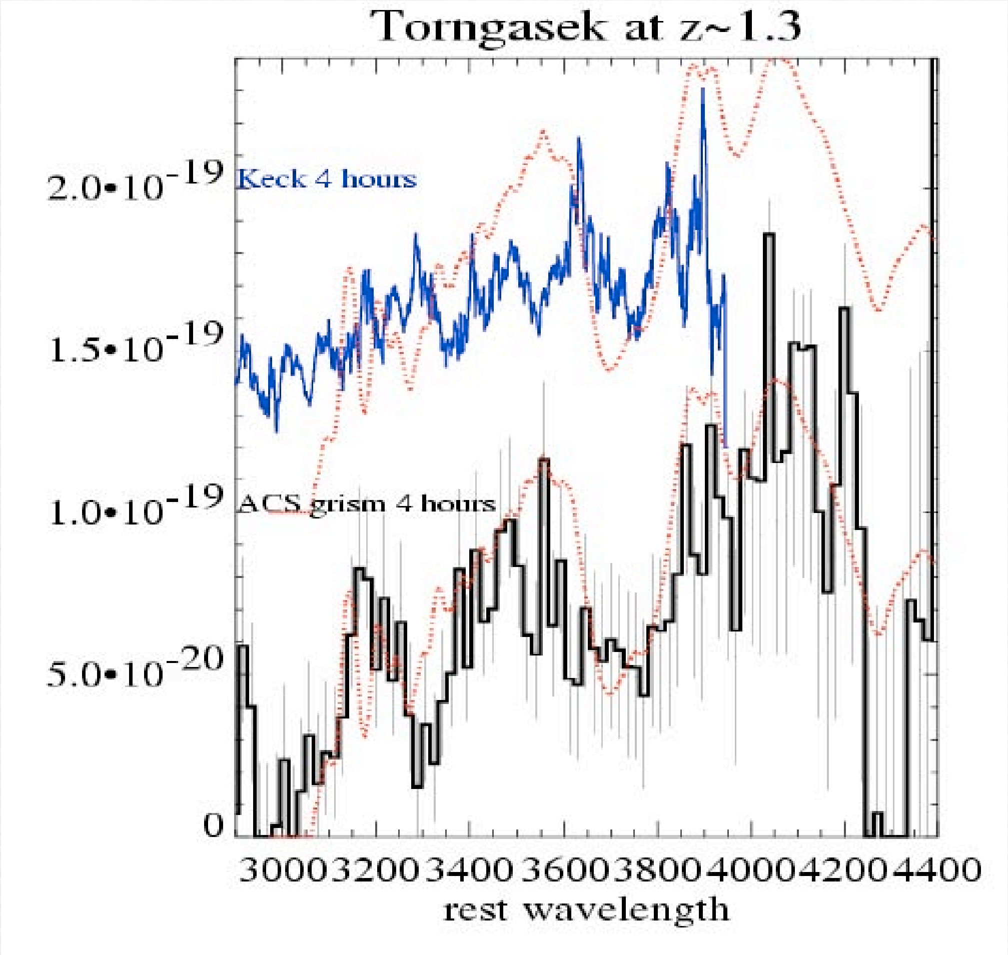
Supernova Cosmology Project
No Big Bang
99%
95%
90%
68%
42 Supernovae
SNAPSAT
Target Statistical Uncertainty
expands forever
recollapses eventually
Flat
Λ = 0
Universe
closed
flat
open
vacuum energy density
(cosmological constant)
mass density
3
2
1
0
-1
0
1
2
3



Flat Universe
Constant w
equation of state
w = p_u / ρ_u
99%
95%
90%
68%
0.0
−0.2
−0.4
−0.6
−0.8
−1.0
0.0
0.2
0.4
0.6
0.8
1.0
cosmological
constant
w = −1
Ω_M = 1 − Ω_u
SNAP
Target Statistical Uncertainty

JDEM/DESTINY





Thinking the Unthinkable for JDEM: DESTINY

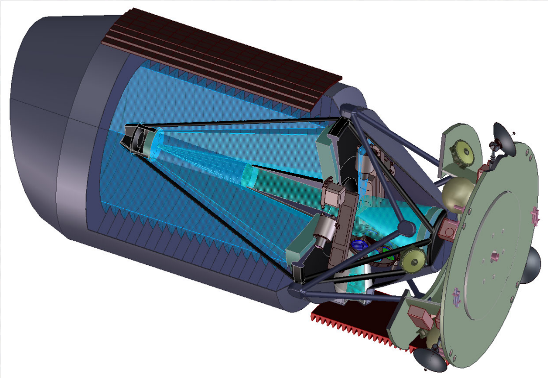
- Use IR detectors only $0.85\mu - 1.7\mu$
- Use a grism for much simpler spectrograph
- Divide labor with ground-based systems at z~0.5 (going lower drives field-of-view and pixel size)
- Focus simpler mission on SN and the Dark Energy

Dark Universe Explorer (DUNE)

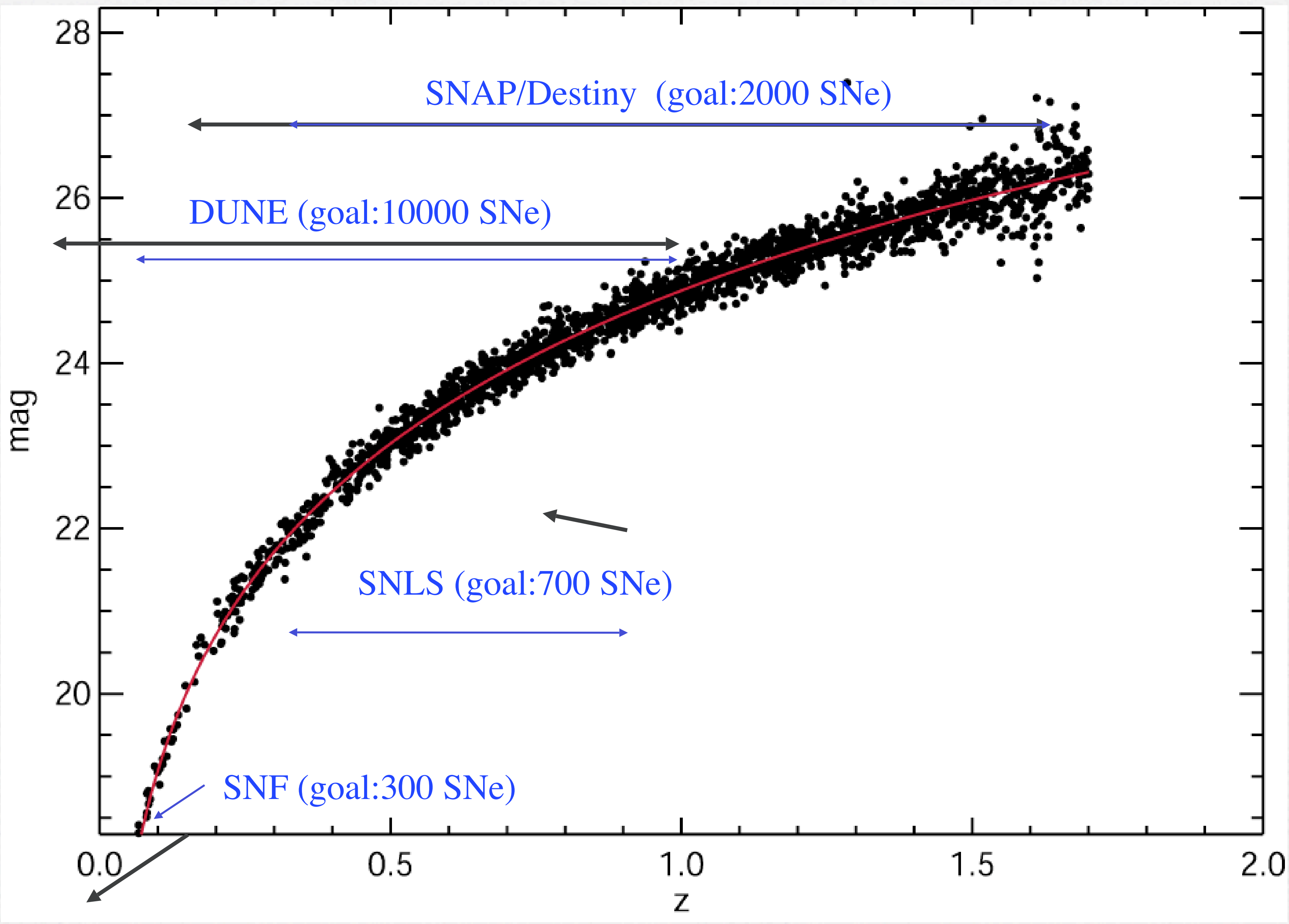
Proposed (2004) as weak lensing probe
- 1.2 m telescope
- 0.5 sq. deg. Imager
- visible only - 1 filter

Currently in phase O study at French Space Agency
If approved .. launch by 2011-12 ?

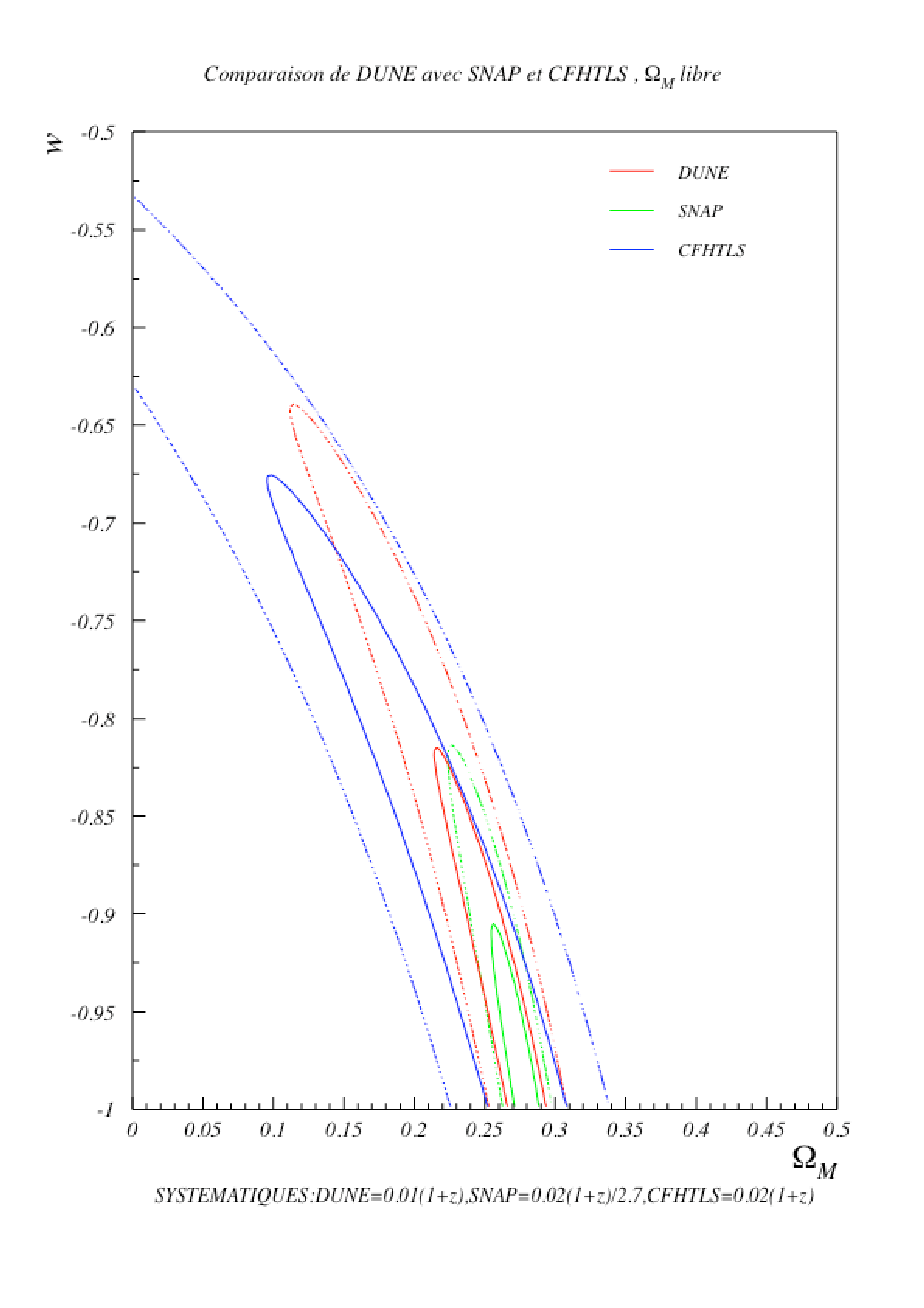
A SN program for DUNE
- 2x60 sq deg. (UBVRIZ, I=26) - cadence: 4days
- Photométric id of SNe (UBV restframe)
- Ground based spectroscopy (host galaxies)
- => 10000 SNe $0.1<z<1$ in ~18 months
  - statistical uncertainties on w, w’ (80%xSNAP)
  - calibration/systematic uncertainties ?

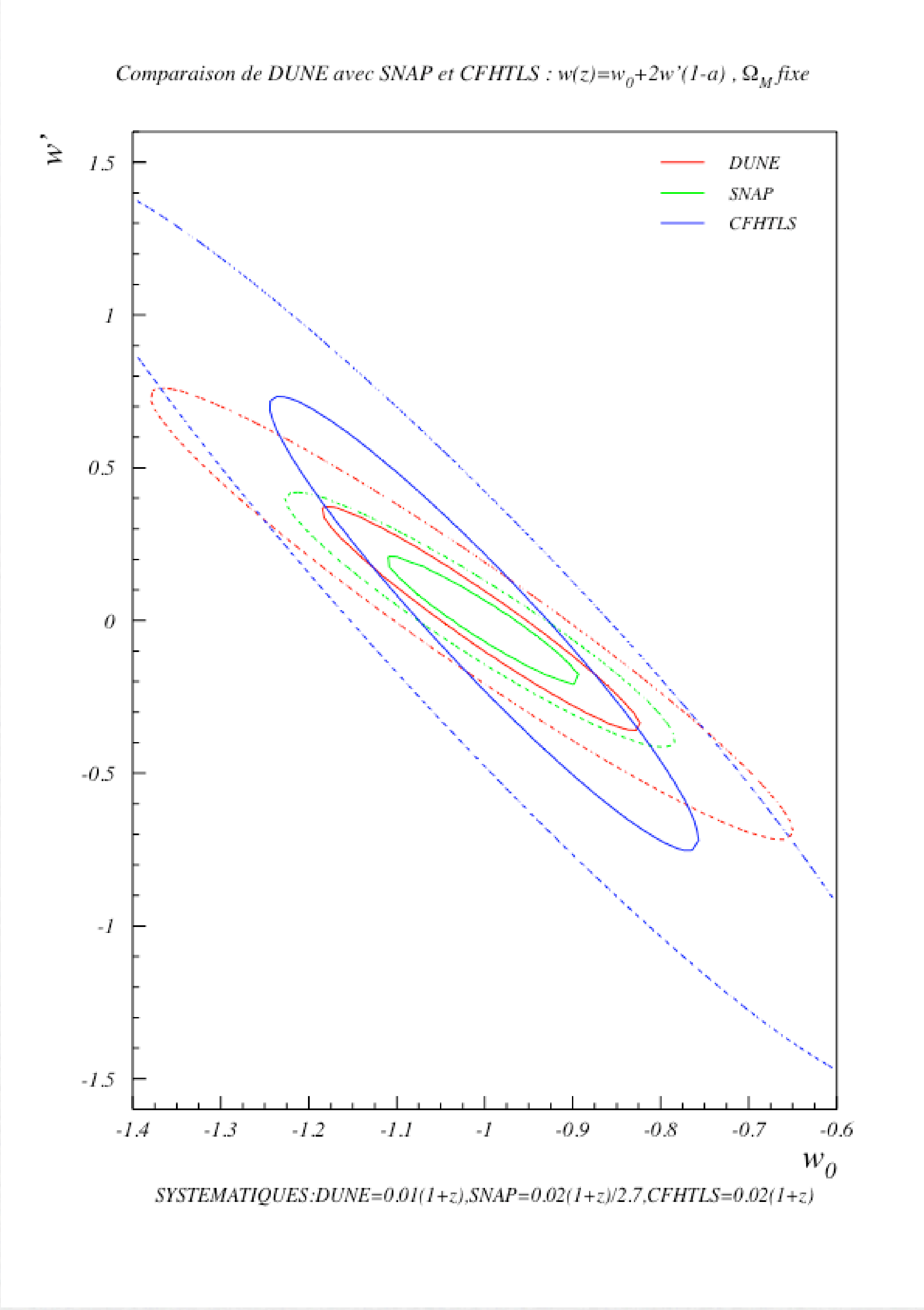


SNLS vs DUNE vs SNAP (simulation)



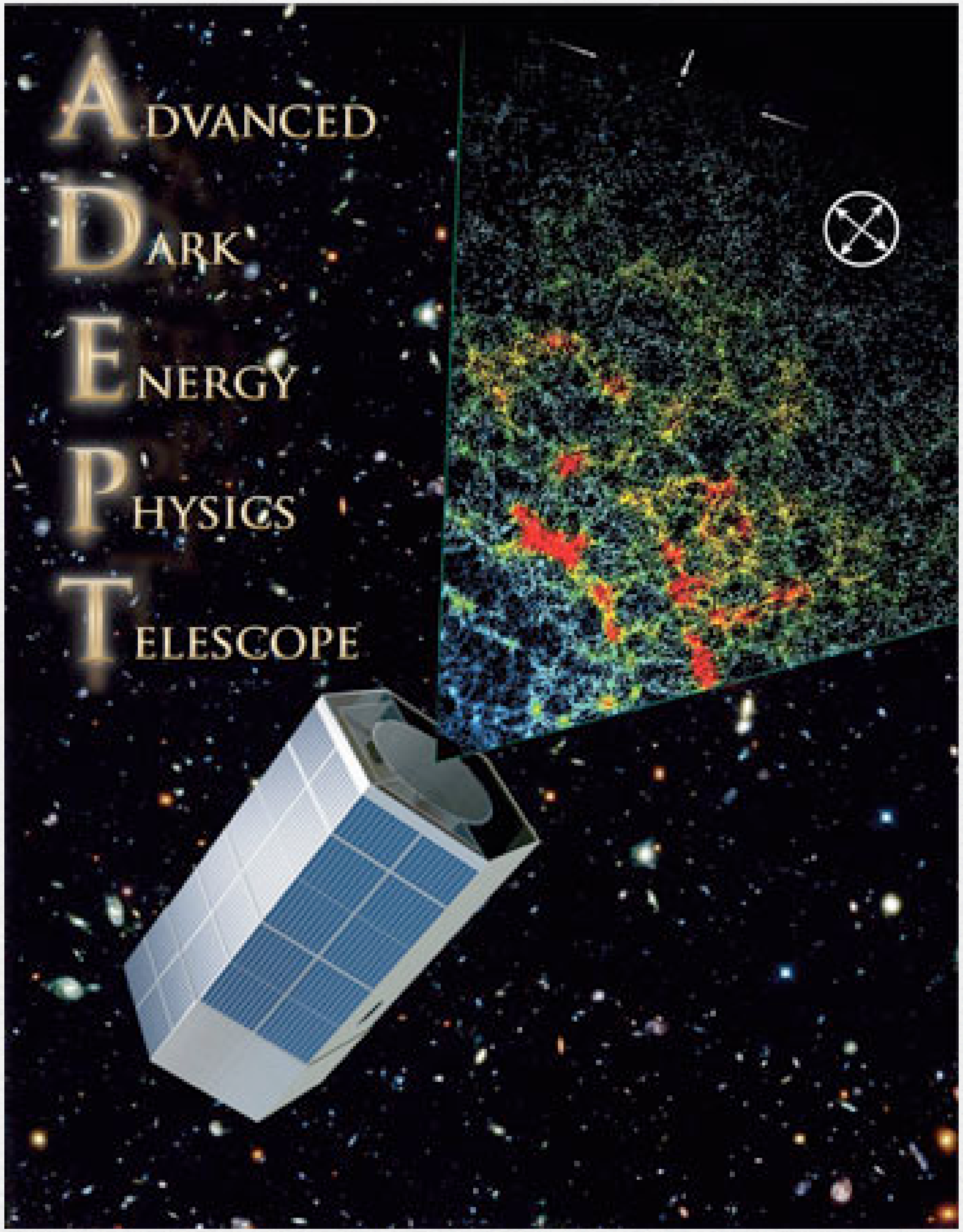
SNLS vs DUNE vs SNAP





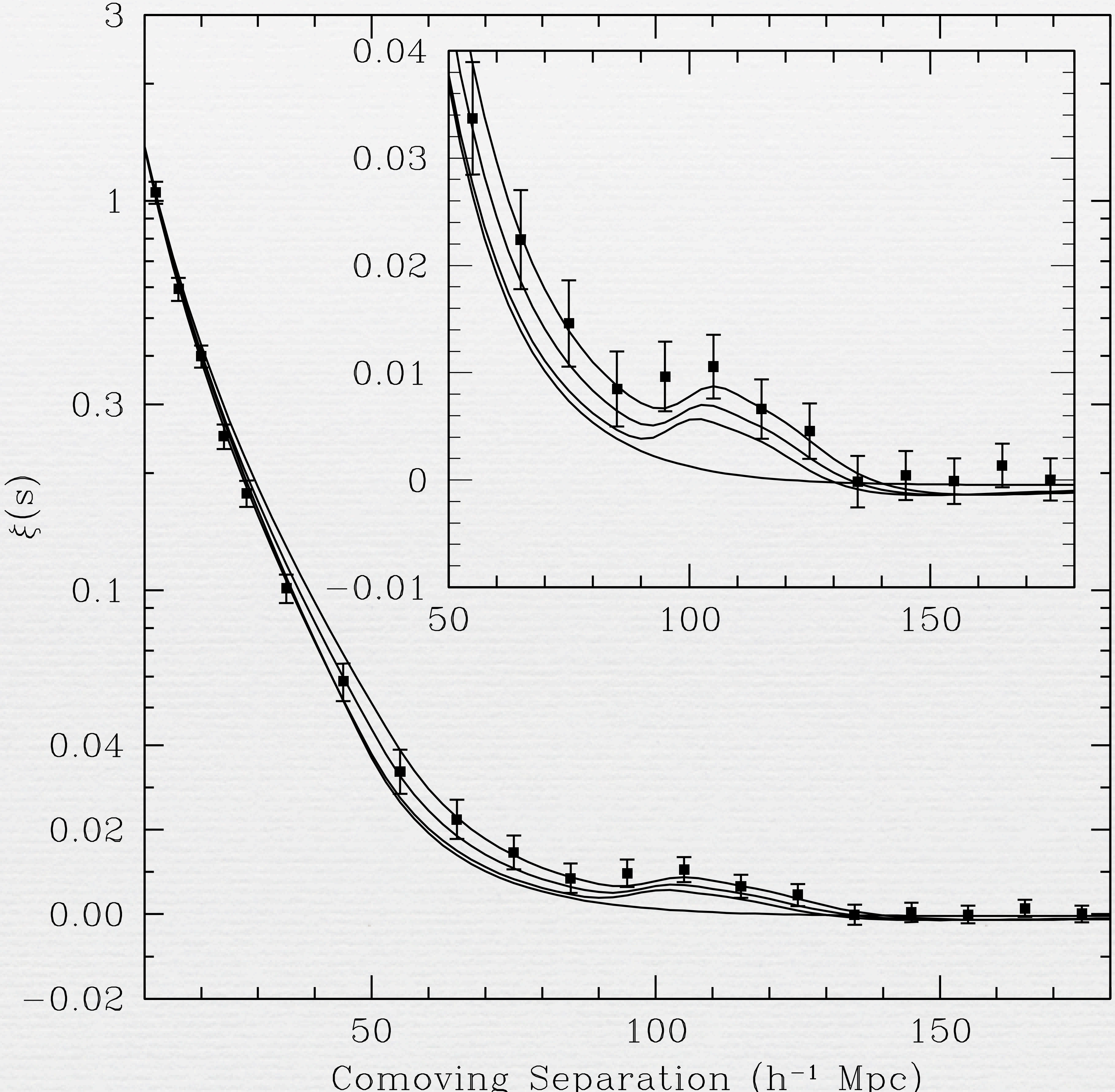
JDEM Finalist: ADEPT

BAO+SNe+lensing*



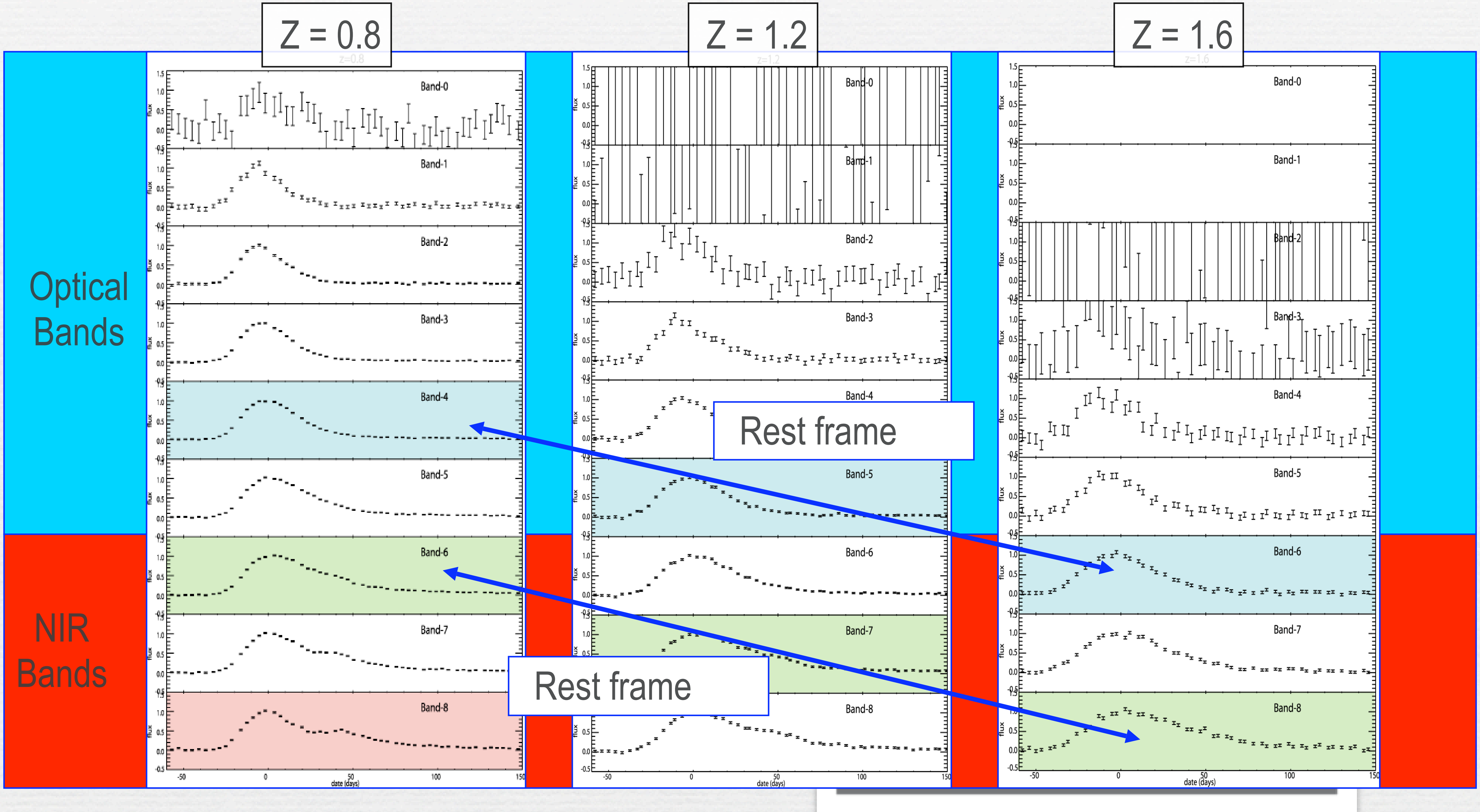
P.I.: C. Bennett (JHU)

*Provides 10^8 spectroscopic redshifts for LSST and Pan-starrs



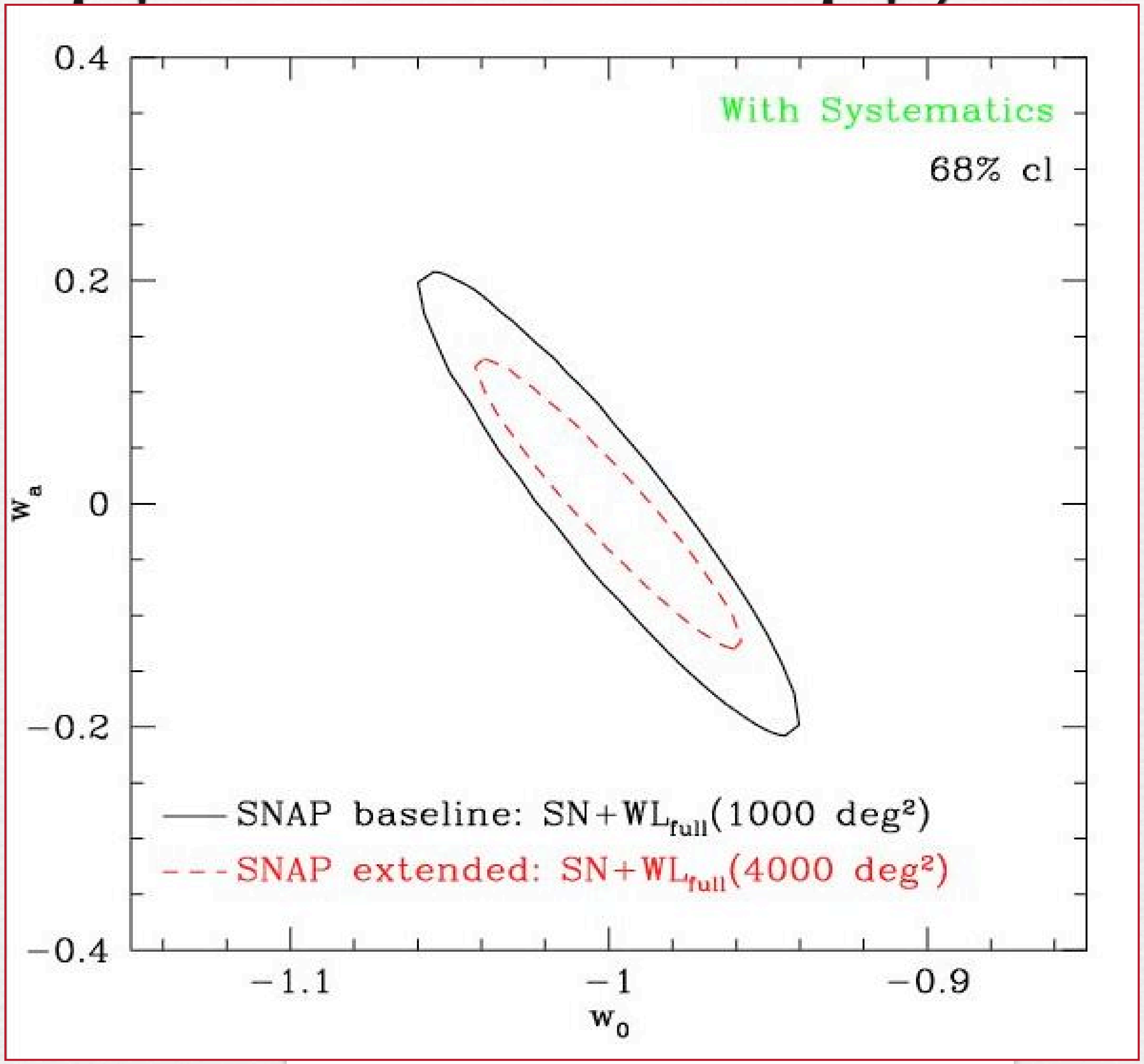
(Eisenstein 2005)

Lightcurve Redshift Series



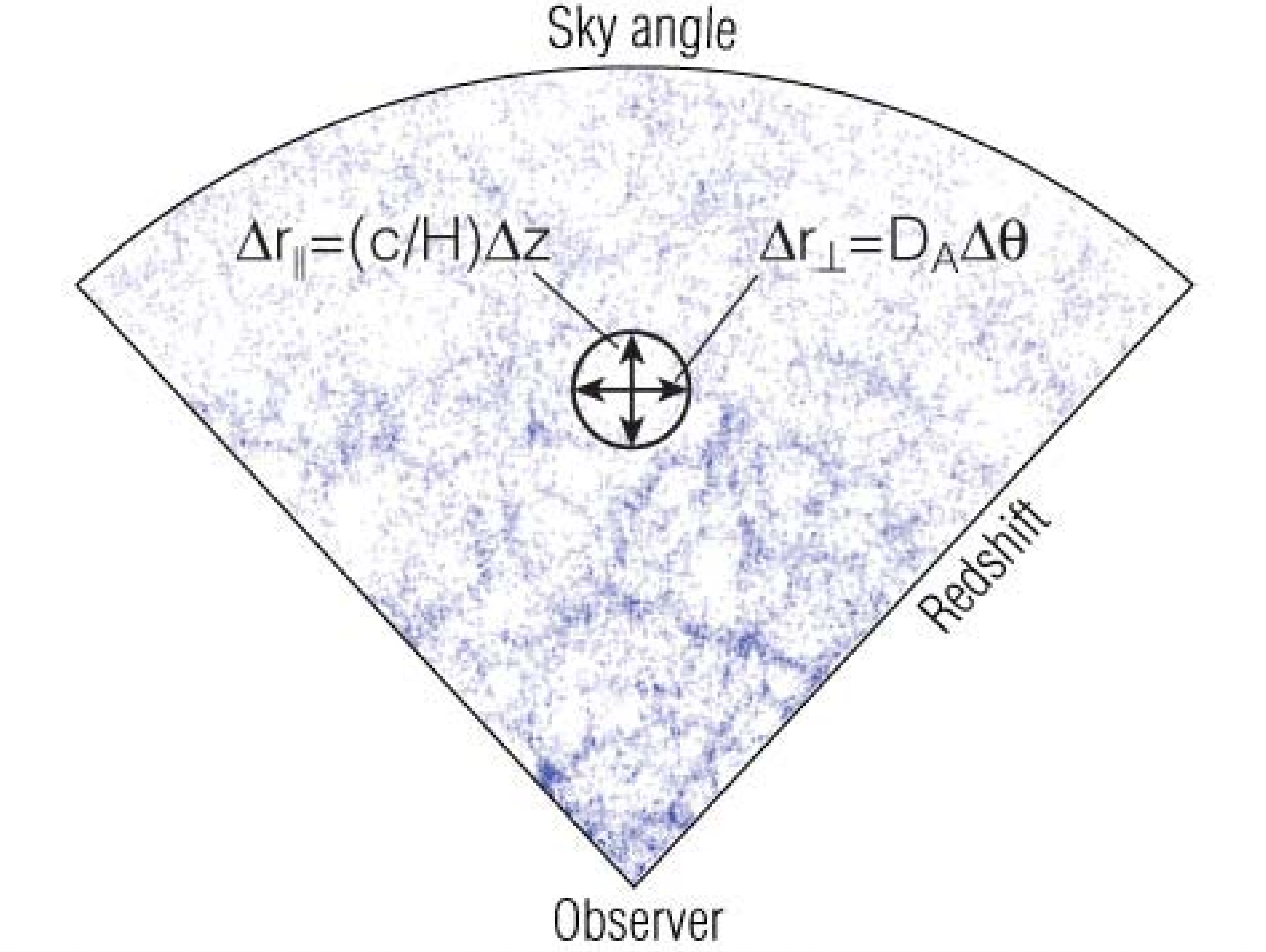
Extracting Cosmology

- The final step of the simulation is extracting the cosmological parameters
- The plot is an example of the cosmology to be obtained from SNAP results only (no CMB priors)



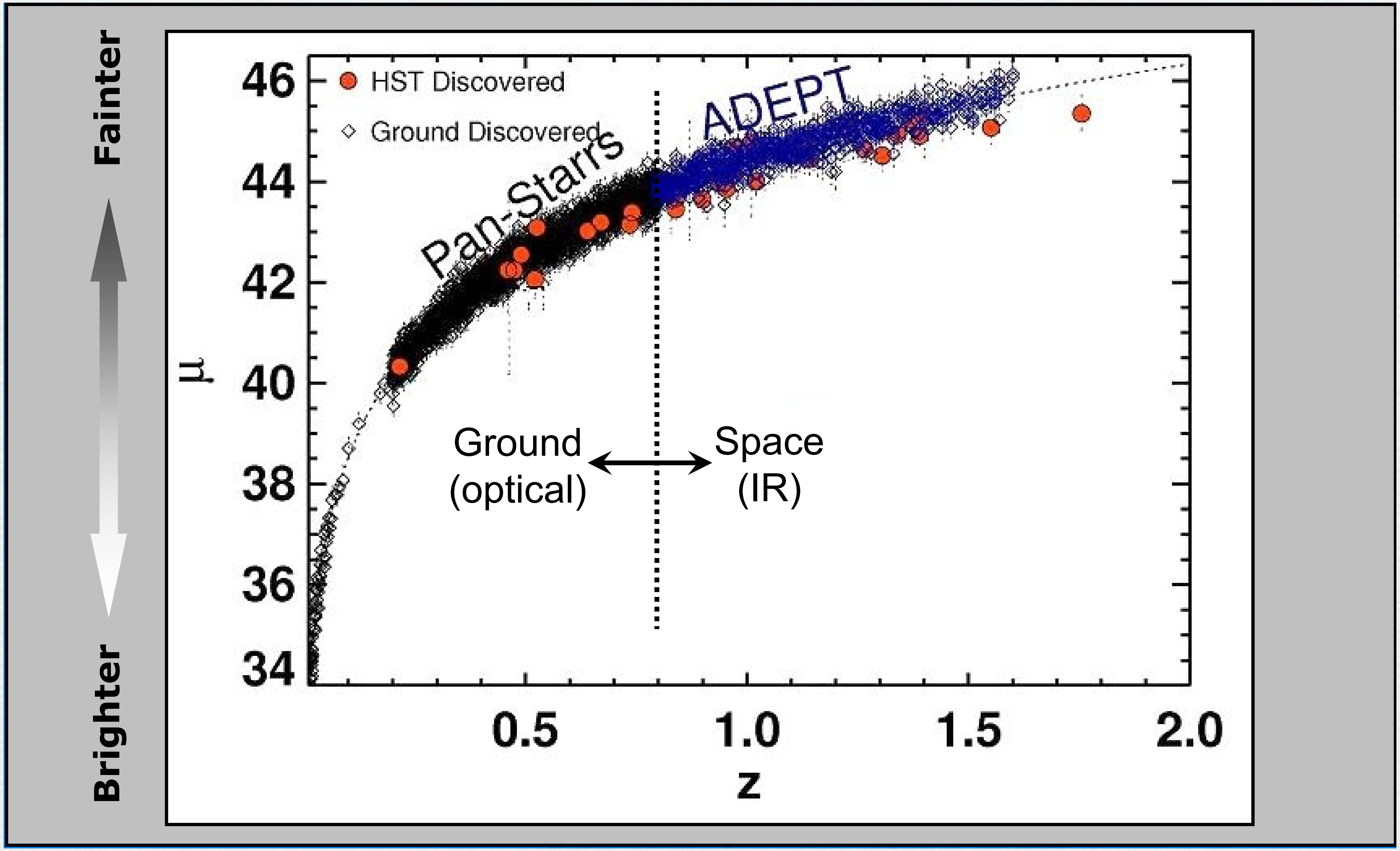
courtesy Eric Linder

BAO



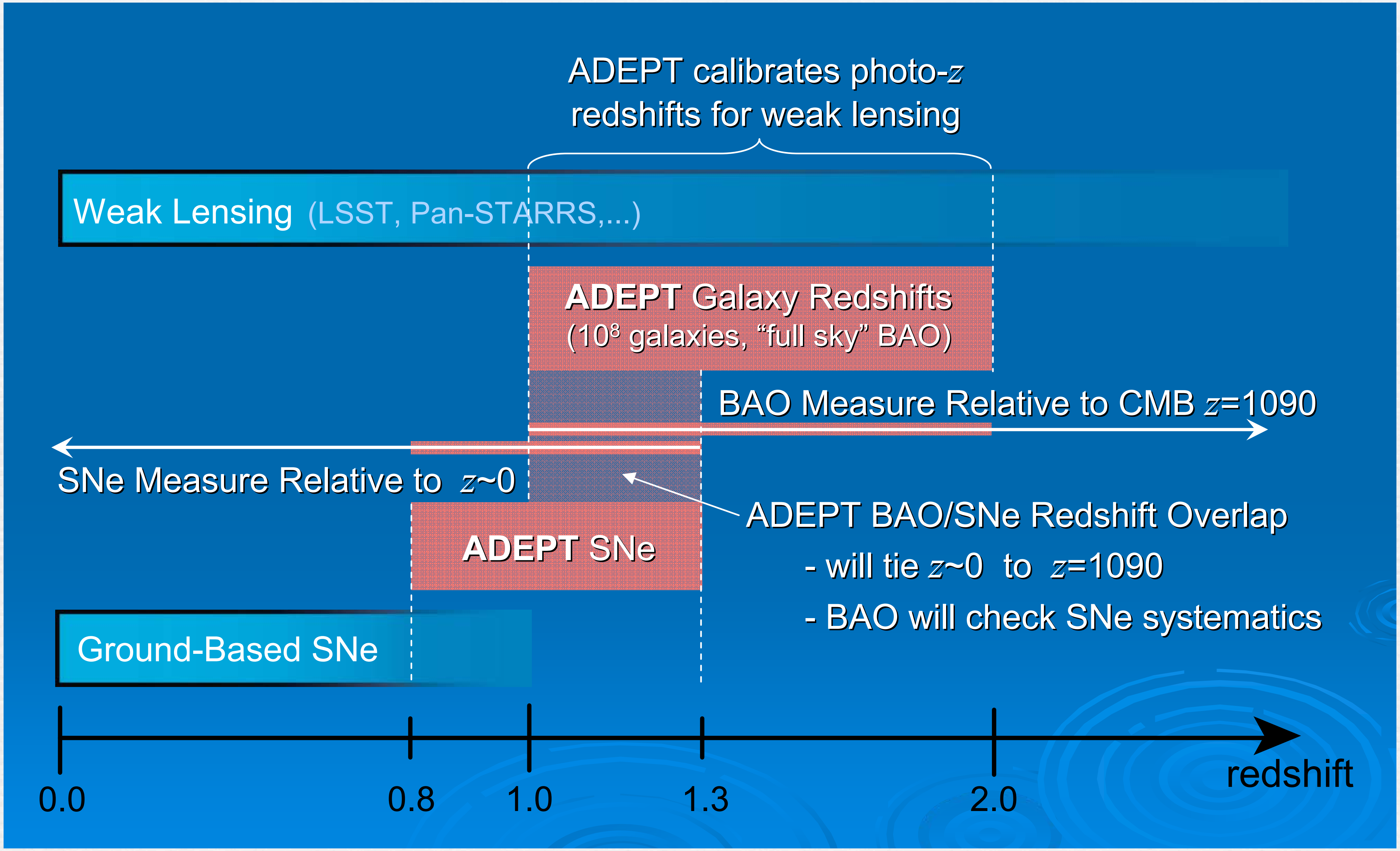
Sky angle
$\Delta r_{\parallel} = (c/H)\Delta z$
$\Delta r_{\perp} = D_A \Delta\theta$
Redshift
Observer

SNe Ia



(Bennett, Riess)

ADEPT DE Probes



(Bennett, Riess)

Baryon Acoustic Oscillation Surveys: All-sky, Space-based wins (Gen IV)

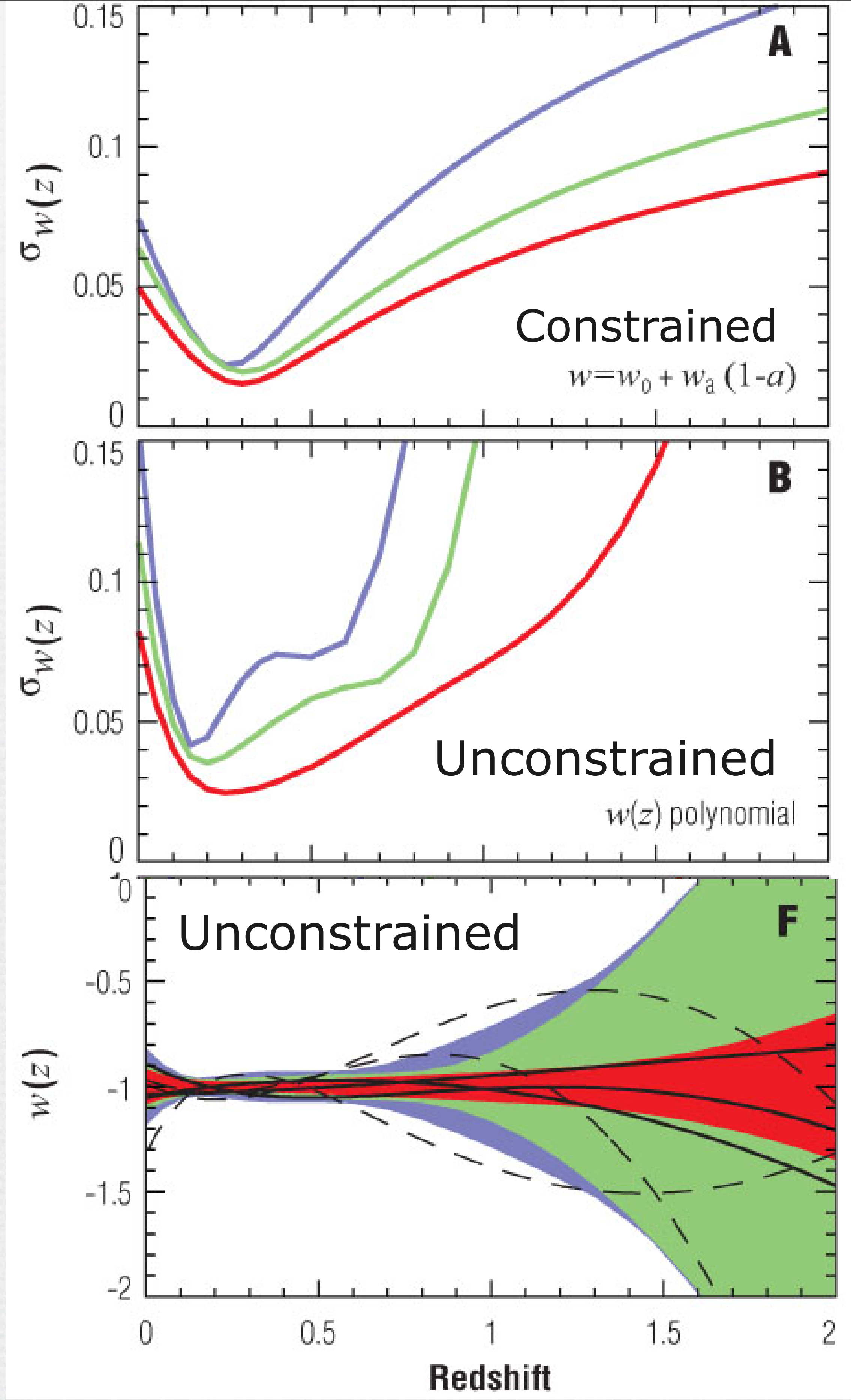
Survey[a]	Redshift range	Sky area (deg^2)	Millions of Galaxies	Volume (h^{-3} Gpc^3)	Volume (Gpc^3)[c]	Effective Volume[b] (h^{-3}Gpc^3)	Effective Volume[b] (Gpc^3)[c]
ADEPT	**$1<z<2$**	**28,600**	**~100**	**100**	**390**	**60**	**180**
SDSS DR4 Main+ 2dF	$z<0.3$	7,000	0.7	0.4	1.2	0.17	0.50
SDSS LRG	$0.16<z<0.47$	3,800	0.047	0.75	2.2	0.18	0.52
SDSS-II 8-yr LRG	$0.16<z<0.47$	7,600	0.094	1.5	4.4	0.36	1.0
FMOS/Subaru (200 nights)	$1.4<z<1.7$	300	0.6	0.3	1.0	0.24	0.7
AAOmega/AAT (500 nights)	$0.5<z<0.8$	4,500	0.45	2.3	6.7	1.1	3.2
WFMOS/Subaru (150 nights)	$0.5<z<1.3$	2,000	2.	4.	12	1.3	3.8
WFMOS/Subaru (150 nights)	$2.3<z<3.3$	300	0.6	1.2	3.5	0.4	1.2
HETDEX	$1.8<z<3.8$	200	1.	1.6	4.7	0.4	1.2

a. The SDSS surveys in the 2nd and 3rd rows are the only ones completed; the rest are planned or proposed. They are all spectral line surveys. LSST plans a large (~10,000 deg^2) photometric redshift survey, perhaps observing $>10^8$ galaxies at $0.5 < z < 3.5$. The photometric redshift errors would degrade the equivalent effective volume of the LSST survey to $<5h^{-3}$ Gpc^3.

b. Effective volume accounts for the limited sampling of the survey volume due to the discrete number of galaxies as a function of redshift. It is evaluated at the scale of the BAO, $k = 0.15h$ Mpc^{-1}.

c. Assumes $h = 0.7$.

- **Future ground**: Gen III
- Future ground + Space SNe $z \leq 1.7$:
- ADEPT: Future ground + ADEPT

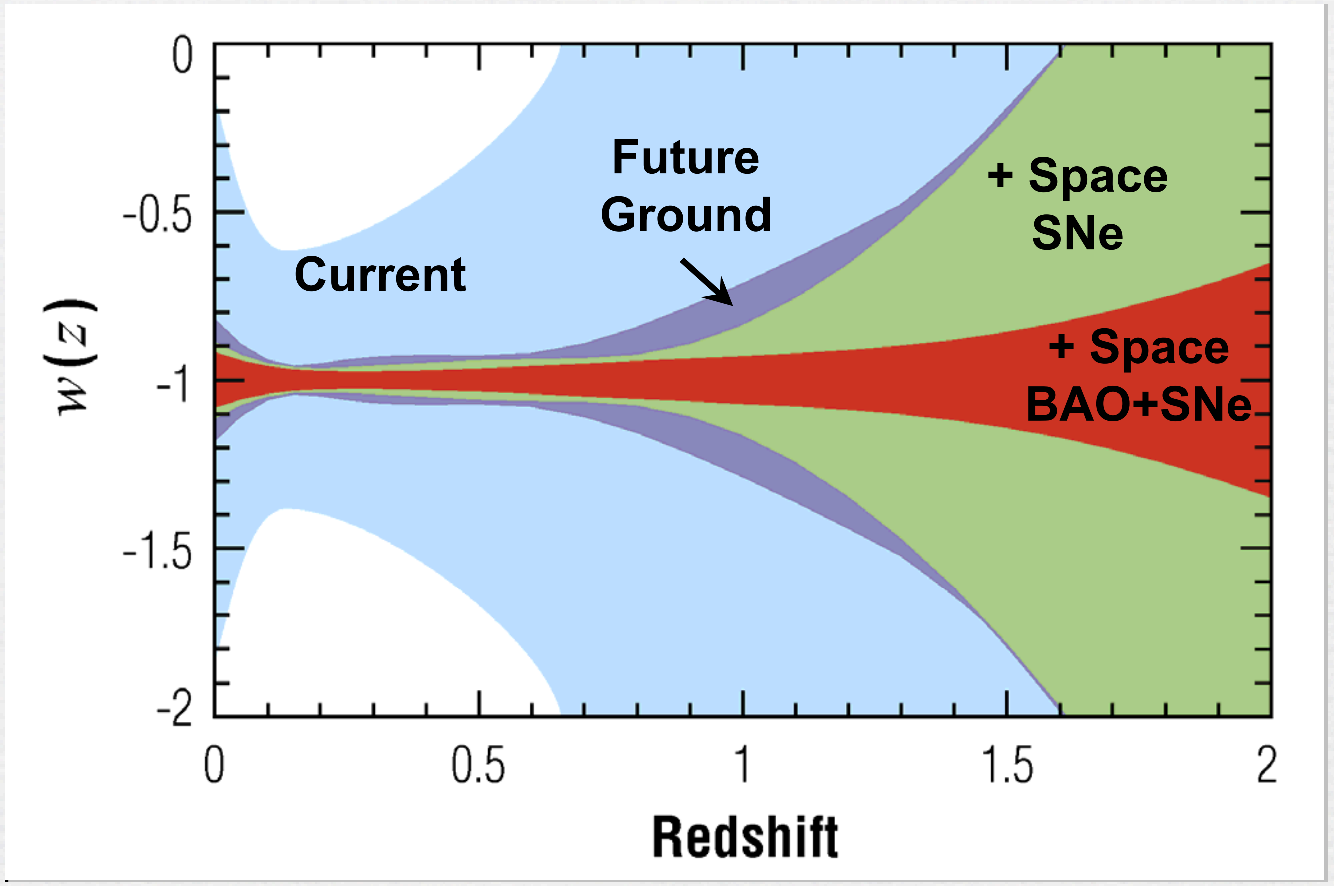


From D. Eisenstein et al

- Markov chains are run with w(z) represented in a 5 parameter quartic polynomial in ln (1 + z).
- Ω_m, h, Ω k, and w(z)free to vary, with priors set on $\Omega_m h^2$ (1% precision) and the CMB angular size of the acoustic scale at z = 1100.
- We assume 0.5% SNe distance calibration per Δ z = 0.1 redshift bin.

The w(z) constraint regions from the Markov chains as shaded areas. The solid black lines are sample Markov chain models that represent 3 possible w(z) models that would be unresolved by ADEPT ($\Delta\chi^2 = 4$); the dashed black lines are models resolved by ADEPT, but unresolved by future ground data.

BAO+SNeIa w(z)

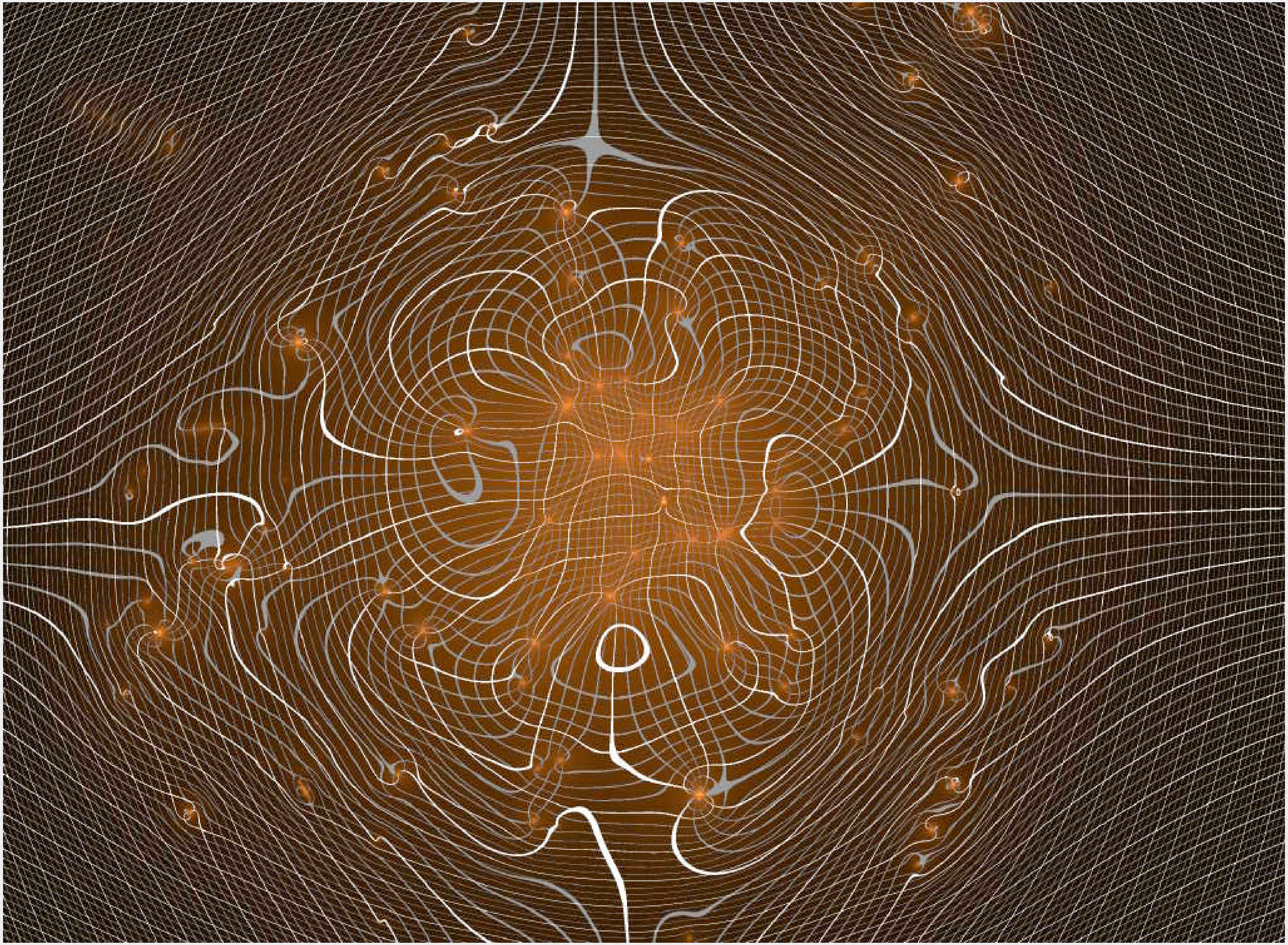


(Bennett)

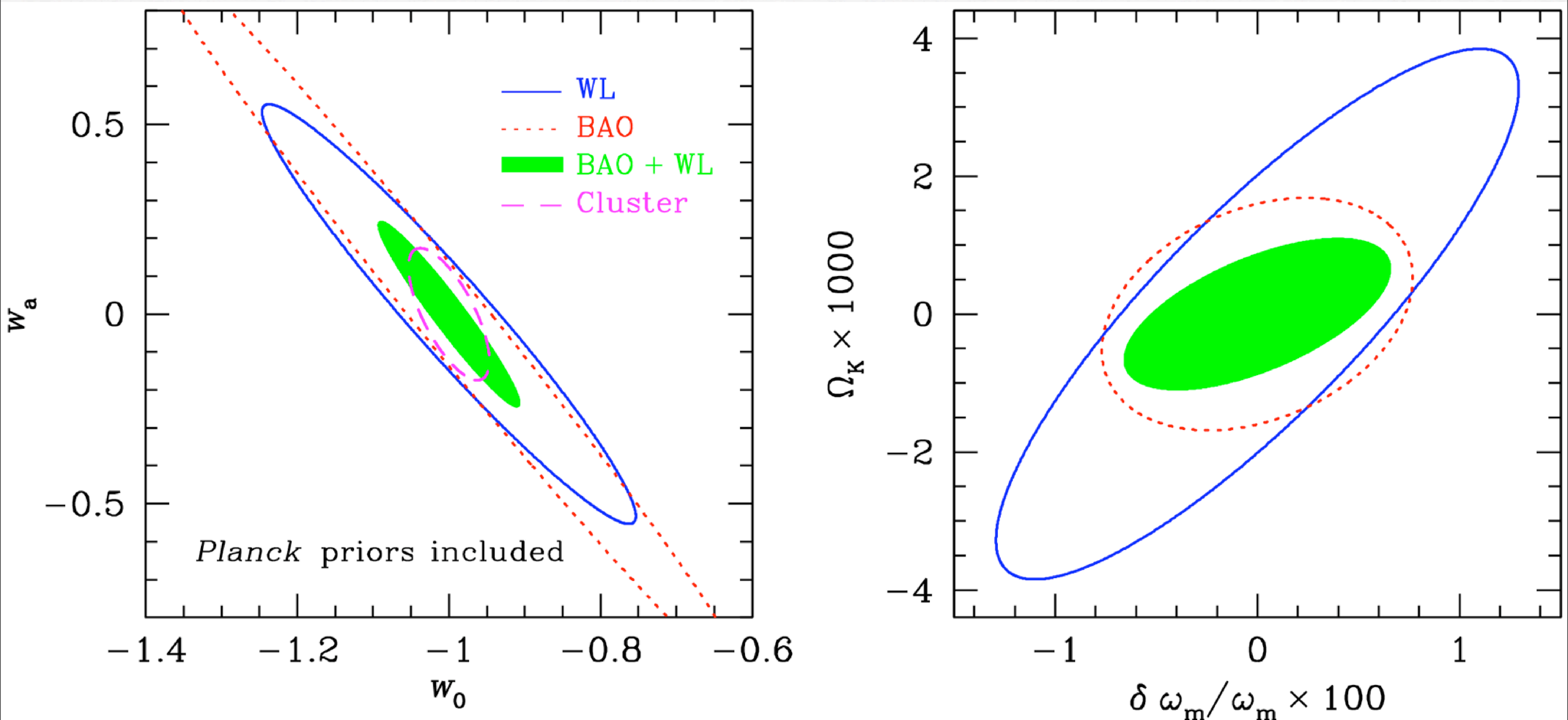
Future of Cosmology

- Luminosity Distance
  - SNeIa: SNAP; PanSTARRS, LSST
  - GRBs?
- Angular Diameter Distance
- Large Scale Structure
  - Baryon Acoustic Oscillations
  - Lensing/Shear
- Cosmic Microwave Background
  - Planck
- Gravity
  - LIGO, LISA

Weak Lensing



LSST BAO+WL



http://www.lsst.org/Science/images/cwbe.gif

Beyond O/IR

- Radio (lambda > 1 millimeter)
  - SPT, ACT
  - SKA

Future Dark Energy Survey *(an incomplete list)*

- Essence (2002-2007): 200 SNe Ia, $0.2 < z < 0.7$, 3 bands, $\Delta t \sim 2d$
- Supernova Legacy Survey (2003-2008): 2000 SNe Ia to $z=1$
- ESO VISTA (2005?-?): few hundred SNe, $z < 0.5$
- CFHT Legacy (2003-2008): 2000 SNe Ia, 100's high z SNe, 3 bands, $\Delta t \sim$ 15d
- Pan-STARRS (2006-?): all sky WL, 100's SNe y^{-1}, $z < 0.3$, 6 bands, $\Delta t = 10d$
- HETDEX (?): 200 sq deg BAO, $1.8 < z < 3$.
- WFMOS on Subaru (?): 2000 sq deg BAO, $0.5<z<1.3$ and $2.5<z<3.5$
- ALPACA (?): 50,000 SNe Ia per yr to $z=0.8$, $\Delta t = 1d$, 800 sq deg WL & BAO with photo-z's
- Dark Energy Survey (?): cluster at $0.1<z<1.3$, 5000 sq deg WL, 2000 SNe at $0.3<z<0.8$
- LSST (2013-): 10^6 SNe Ia y^{-1}, $z < 0.8$, 6 bands, $\Delta t = 4d$; 20,000 sq deg WL & BAO with photo-z's.

How many methods should we use to probe DE?

- The challenge to solving the DE mystery will not be the statistics of the data obtained, but the tight control of systematic effects inherent in the data.
- A combination of the three most promising methods (each optimized by having its systematics minimized by design) provides the tightest control of systematics.

How To Organize Theory?

- More money?
- Selective culling?
- Make part of experiments?
- Performance enhancing drugs?

Theory Workshops on The Moon!