

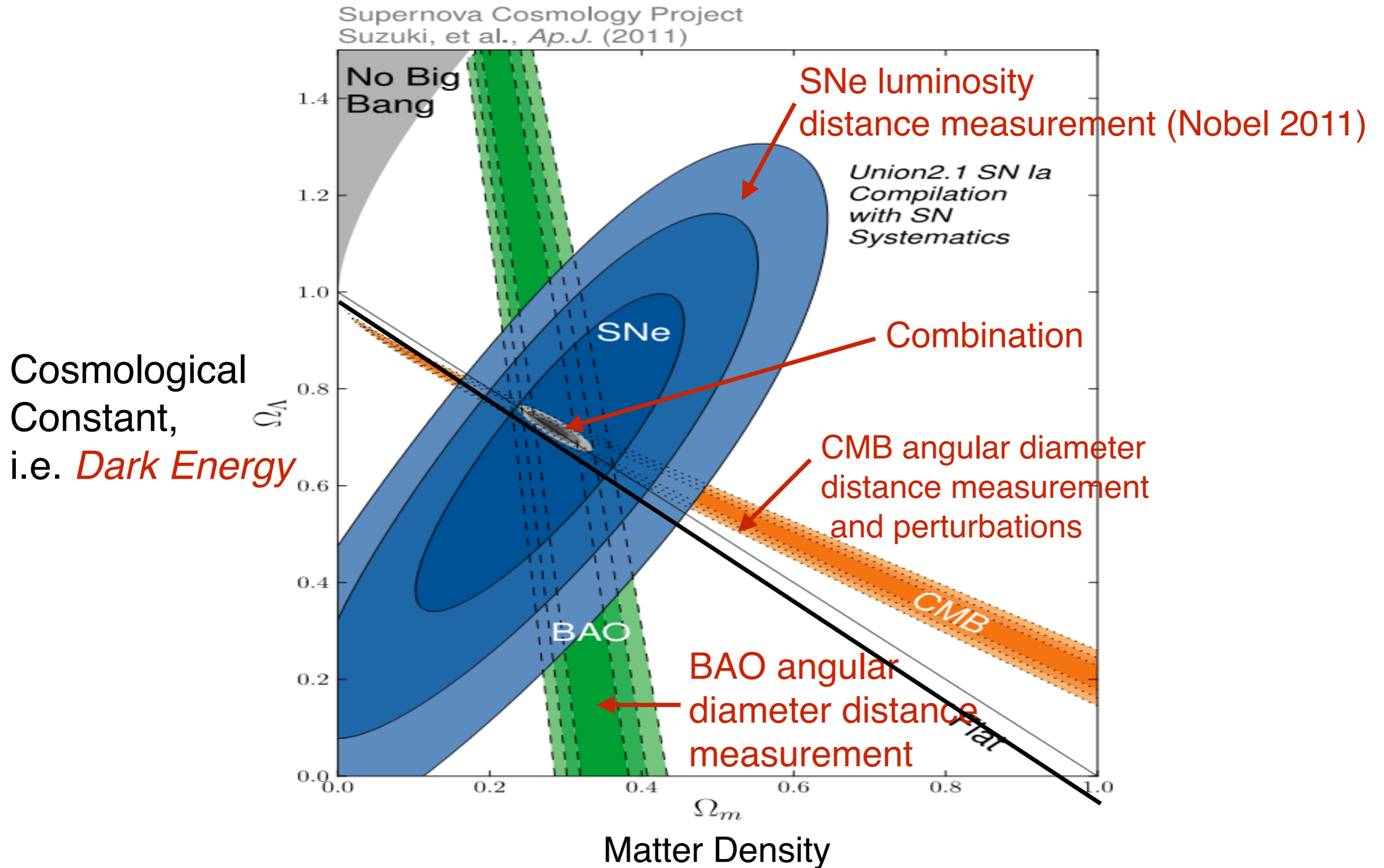
# Dark Energy Research: *A Space Odyssey*

---

Olivier Doré  
*JPL/Caltech*

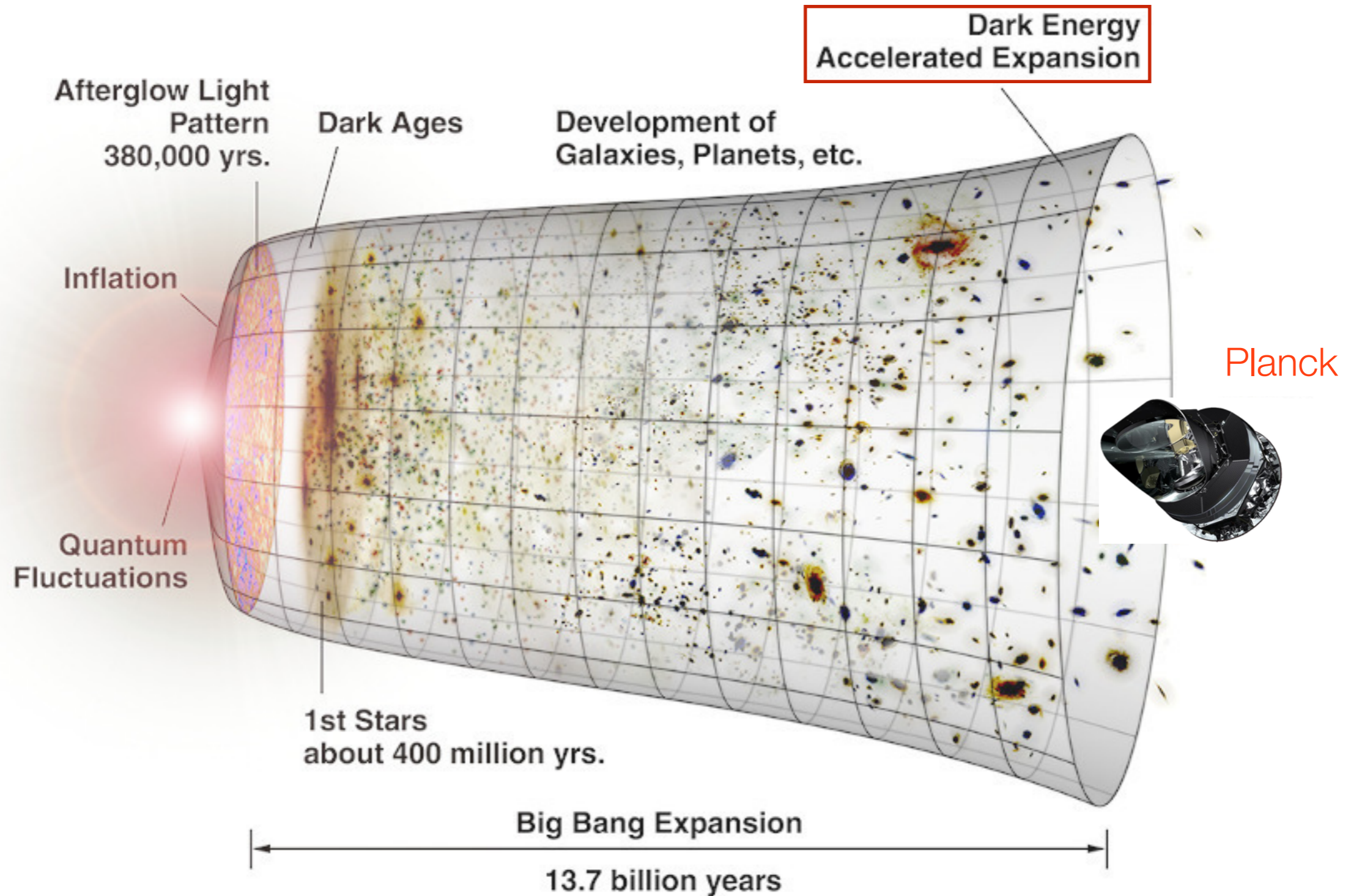
on behalf of the  
PhysPAG/Cosmic Structure SIG (CoSSIG)

# The Observational Foundations of Dark Energy



- Weak-Lensing not presented is also complementary.

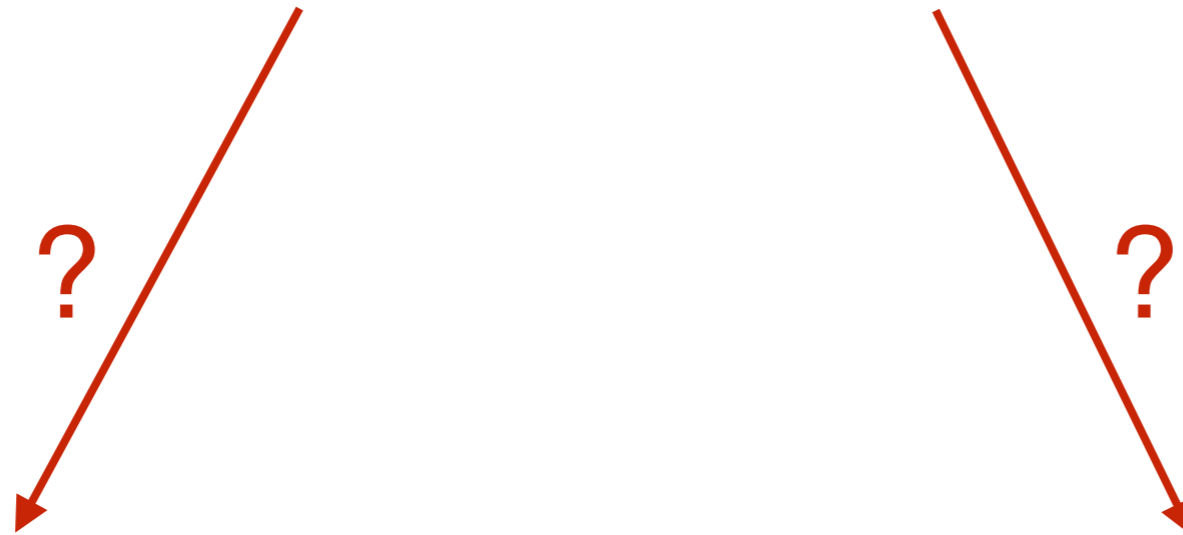
# Dark Energy is a “Recent” Phenomena



# Dark Energy Requires a Modification to Einstein's Equation

---

$$G_{\mu\nu} = 8\pi T_{\mu\nu}$$



- A cosmological constant  $\Lambda$ ?
- Deviation from general relativity on cosmological scales?

- New matter interaction?
- New matter component?
- Inhomogeneous Universe?

- Each of these modifications will lead to different observational signatures either in the expansion history of the Universe or in the growth of large scale structures:
  - ➔ To observationally and unambiguously solve this puzzle will require multiple probes (also critical for cross-checks)

# NASA Is Developing A Robust DE/LSS Portfolio

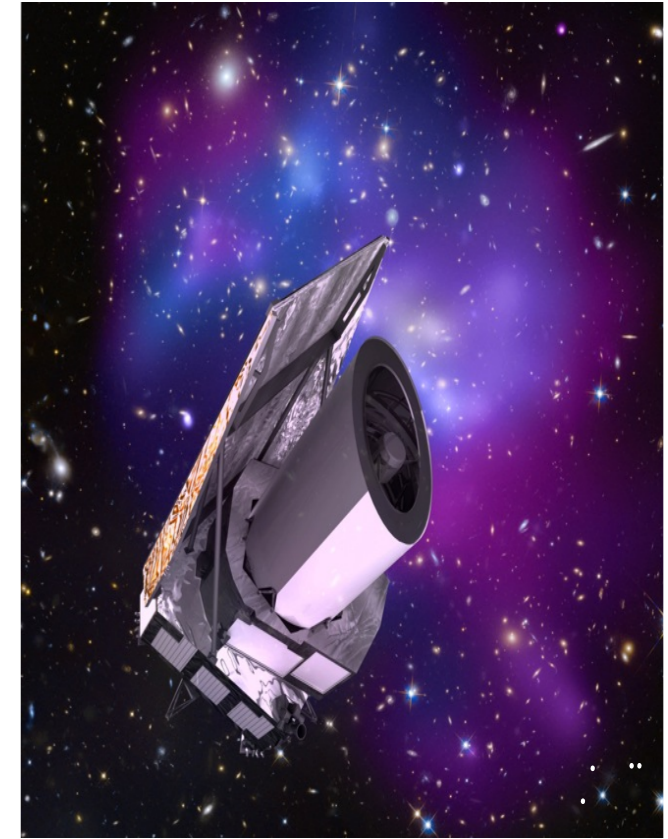
---

- NASA committed to play a key role in the ESA led mission Euclid.
- NASA is actively studying the WFIRST-AFTA concept.
- Together, they cover the full range of cosmological probes required to distinguish dark energy and modified gravity models, while mitigating systematics:
  - ➔ **Supernovae Type IA:**
    - ▶ Act as standard candles to measure the expansion history (⇒WFIRST-AFTA)
  - ➔ **Weak gravitational lensing:**
    - ▶ The apparent distortion of galaxy shapes by foreground dark matter measures the growth of structure (⇒Euclid, WFIRST-AFTA)
  - ➔ **Galaxy clustering:**
    - ▶ Baryon acoustic oscillations (BAO) act as a standard ruler to measure the expansion history (⇒Euclid, WFIRST-AFTA)
    - ▶ Redshift space distortions (RSD) measure the growth of structure (⇒Euclid, WFIRST-AFTA)
- Dark energy/cosmological studies are done statistically, and require great precision and attention to systematics:
  - ➔ **Wide field space missions like Euclid or WFIRST-AFTA allow for large statistics and control of systematics.**
  - ➔ **WFIRST and Euclid are distinct and highly complementary.**
- These data-sets will also enable ground breaking cosmological measurements others than DE, i.e., the sum of the neutrino mass, the neutrino mass hierarchy, the shape of the primordial power spectrum to constrain inflation theories, etc.

# Euclid Project, Timeline and US Effort

---

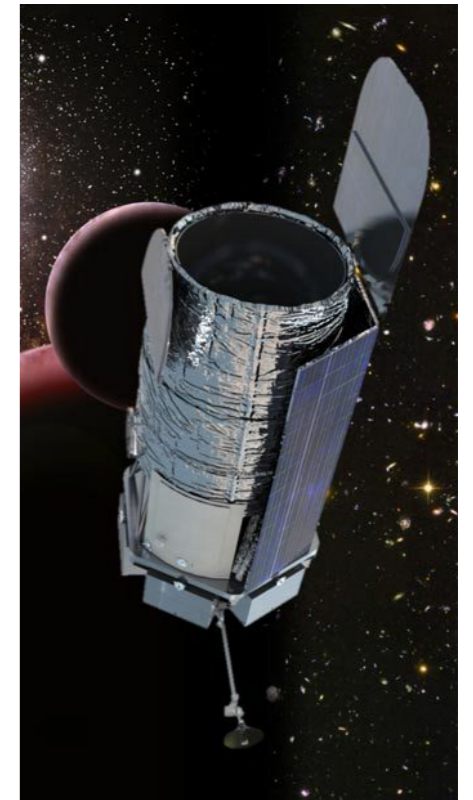
- 2004: Dark Universe Mission proposed as a Theme to ESA's Cosmic Vision program
- Oct 2007: DUNE and SPACE jointly selected for an ESA Assessment Phase
- April 2010: Formation of single Euclid Consortium
- July 2011: Final Euclid Proposal-Red Book
- Oct 2011: Cosmic Vision Approval of Euclid
  
- Fall 2012: NASA Joins, nominates 40 US scientists for membership in Euclid Consortium
- 2014: NASA established the Euclid NASA Science Center at IPAC (ENSCI) to support US-based investigations using Euclid data (<http://euclid.caltech.edu>)
  
- 2015-...: US team is fully integrated with the consortium and many US team members co-lead important WGs or WPs, e.g., Yun Wang (IPAC) co-leads the galaxy clustering group.
  
- 2021: Expected launch
- 2021-2028: Science operations



# Wide Field Infrared Survey Telescope

---

- WFIRST was the top ranked large-scale space-based mission in the Astro2010 Decadal Survey (and its coronagraph satisfies the #1 medium-scale priority, i.e., to prepare for 2020s planet imaging mission ).
- WFIRST is now referred to as the WFIRST-AFTA in places:
  - ➔ AFTA is the version of WFIRST that uses a 2.4 m telescope
  - ➔ This asset comes from the National Reconnaissance Office (NRO)
- Offers a fundamentally new regime of DE (and other) research:
  - ➔ A wide field HST
- Funding and status:
  - ➔ The WFIRST SDT published its final report
  - ➔ FY14 and FY15 appropriation for a total of \$106.5M supports technology development for detectors and coronagraph, and Agency/ Administration decision for formulation to begin FY 2017, should funding be available.
  - ➔ Funds will also support assessment of the 2.4m telescopes, mission design trades, payload accommodation studies, and observatory performance simulations.
- NASA decision is not expected on new start before early 2016.



<http://wfirst.gsfc.nasa.gov/>

# WFIRST-AFTA Dark Energy/Cosmology Roadmap

## Supernova Survey

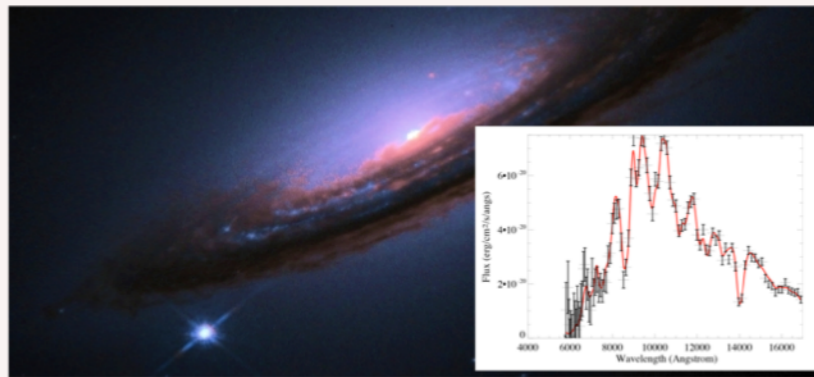
wide, medium, & deep imaging  
+  
IFU spectroscopy

---

2700 type Ia supernovae  
 $z = 0.1-1.7$



**standard candle distances**  
 $z < 1$  to 0.20% and  $z > 1$  to 0.34%



## High Latitude Survey

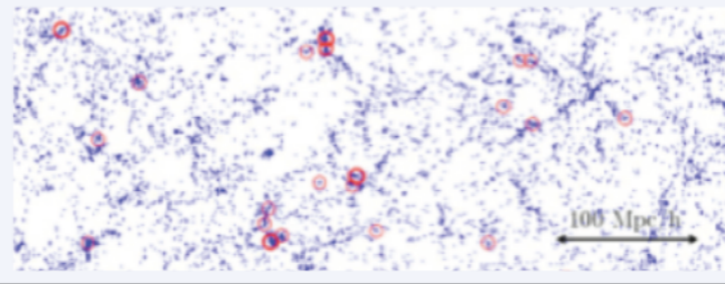
spectroscopic: galaxy redshifts  
16 million H $\alpha$  galaxies,  $z = 1-2$   
1.4 million [OIII] galaxies,  $z = 2-3$

imaging: weak lensing shapes  
380 million lensed galaxies  
40,000 massive clusters



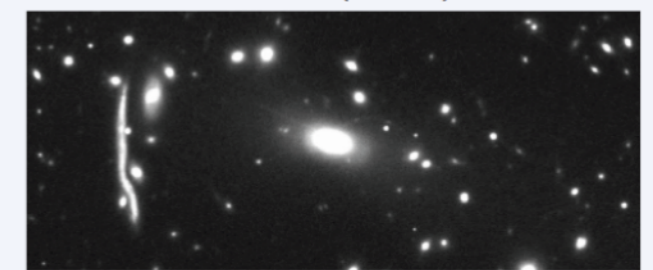
### standard ruler

<b>distances</b>	<b>expansion rate</b>
$z = 1-2$ to 0.5%	$z = 1-2$ to 0.9%
$z = 2-3$ to 1.3%	$z = 2-3$ to 2.1%



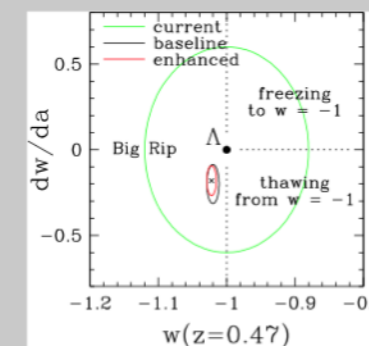
### dark matter clustering

$z < 1$  to 0.21% (WL); 0.24% (CL)  
 $z > 1$  to 0.78% (WL); 0.88% (CL)  
1.1% (RSD)



history of dark energy  
+  
deviations from GR

$w(z)$ ,  $\Delta G(z)$ ,  $\Phi_{REL}/\Phi_{NREL}$



From WFIRST-AFTA SDT Final Report

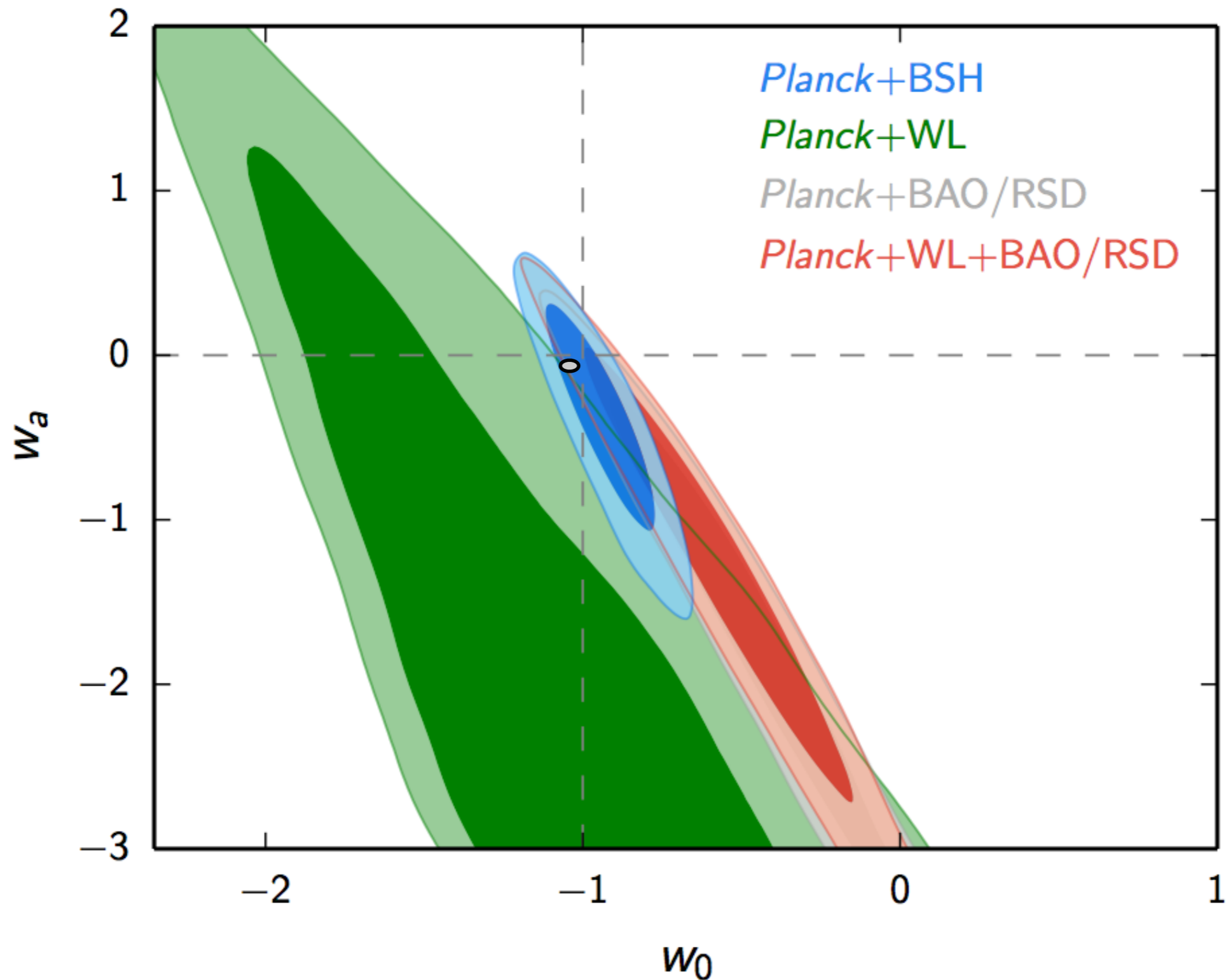


# Cosmic Structures Science Interest Group

---

- *CoSSIG* was created mid-March and is co-led by Rachel Bean (Cornell) & Olivier Doré (JPL/Caltech).
- The goal is to formulate a coherent US LSS based cosmology community response to recent calls by NASA HQ. The CMB based science is covered by the IPSIG.
- The science covers all the cosmology enabled by LSS, e.g., dark energy but also the numerous probes of inflation, neutrino masses, ...
- This science relies on multiple wavelengths and is cutting across PAGs and SIGs. We will make sure there is cross-talk and coordination.
- Inputs from all members of the community are welcomed.
- We had the first community discussion in a conference in Aspen in March 15.
- We are now setting up a website and an email list.
- Expect to hear from us very soon or email us!

# Dark Energy Equation of State Status and Prospects



Planck 2015 XIV

# Summary

---

- The existence of Dark Energy is a robust and will require new fundamental physics.
- The answer to this puzzle will come from multiple observational signatures/probes and most likely multiple missions.
- A strong portfolio of space experiments is being developed and studied:
  - ➔ **Euclid**
  - ➔ **WFIRST-AFTA**
- These missions are strongly complementary to each-other but also strongly benefit from the vigorous on-going ground based effort (e.g., **DES, HSC, DESI, PFS, LSST**)