Dawn of Vera Rubin Observatory LSST

Type Ia Supernova Cosmology with largest camera ever built

Bruno Sánchez
PhD in Astronomy
Postdoc at CPPM - CNRS

VERA C. RUBIN OBSERVATORY

LSST Legacy Survey of Space and Time

LSST DESC Dark Energy Science Collaboration

NSF U.S. National Science Foundation

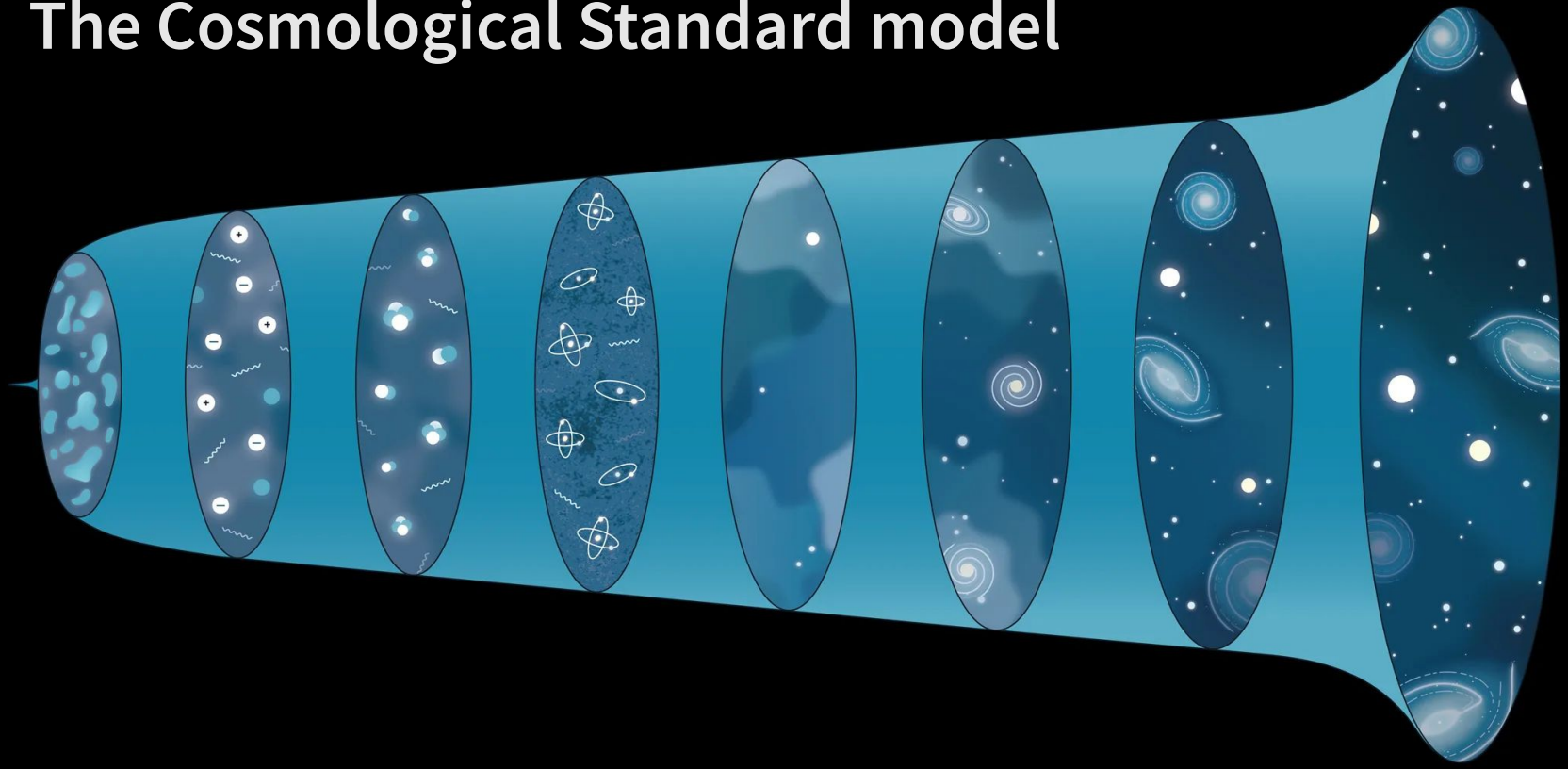
U.S. DEPARTMENT of ENERGY | Office of Science

EN 2023, LE CPPM CÉLÈBRE SES 40 ANS 40 CENTRE DE PHYSIQUE DES PARTICULES DE MARSEILLE CPPM AU CŒUR DE LA MATIÈRE ET DES LUMIÈRES

CENTRE DE PHYSIQUE DES PARTICULES DE MARSEILLE CPPM

cnrs

Motivation
The Cosmological Standard model



Credit: NASA

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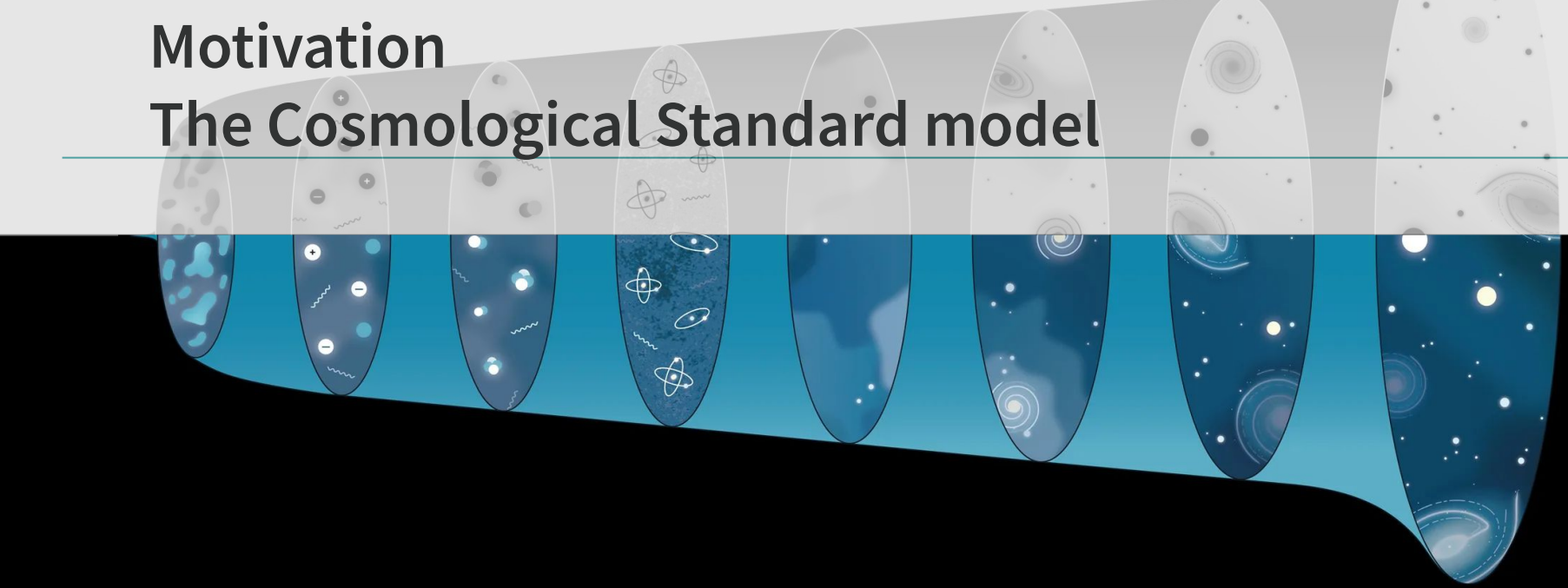
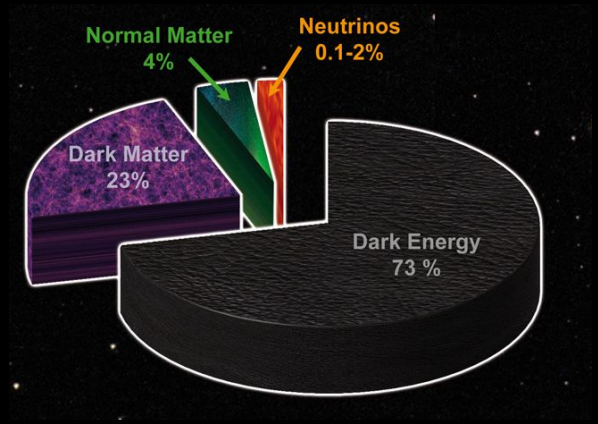
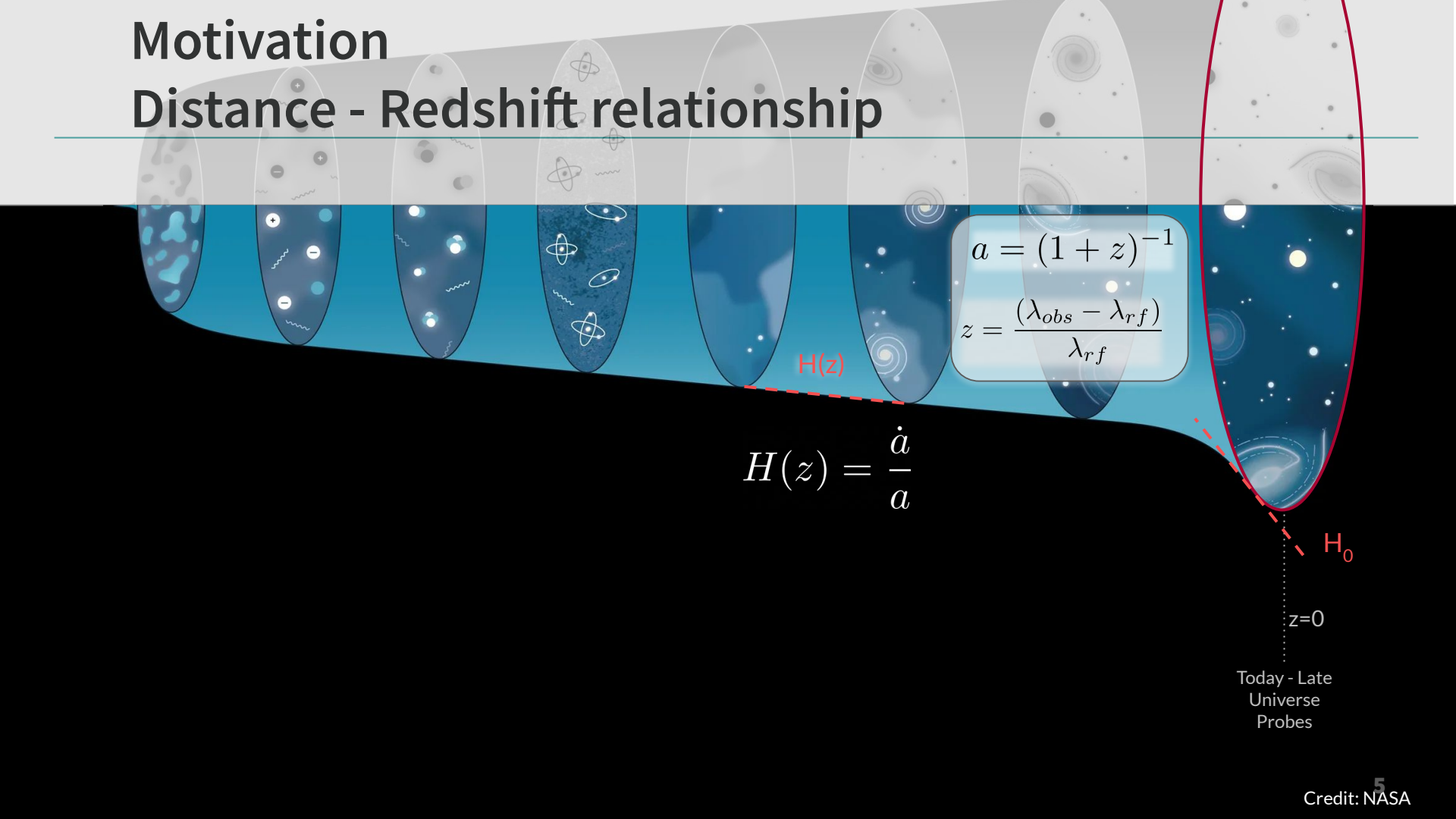


Summary & contents
The Cosmological Standard model

- Cosmological model and its parameters
- Probes of the **distance-redshift relationship:**
  - **Type Ia Supernovae**
- Current SNIa Cosmology:
  - The **DES** 2024 results & **ZTF** Survey
- Future of SNIa Cosmology:
  - The **Vera Rubin** Observatory **LSST** Survey
  - My work in the commissioning team
- Final remarks



Motivation
Distance - Redshift relationship



Credit: NASA

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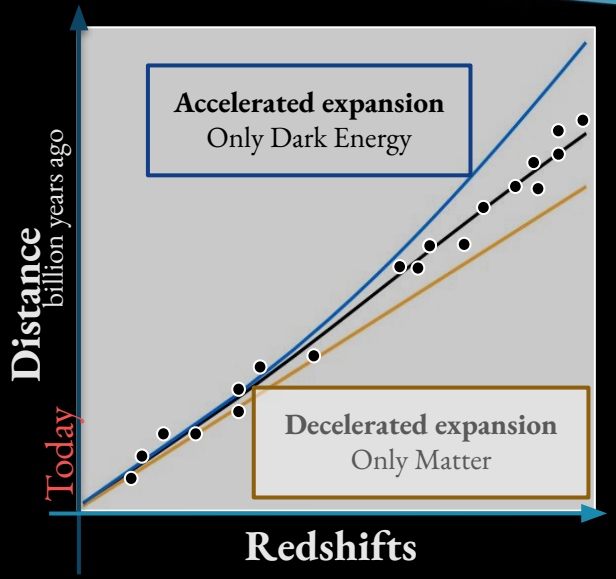


$$a = (1+z)^{-1}$$

$$z = \frac{(\lambda_{obs} - \lambda_{rf})}{\lambda_{rf}}$$

H(z)

$$H(z) = \frac{\dot{a}}{a}$$

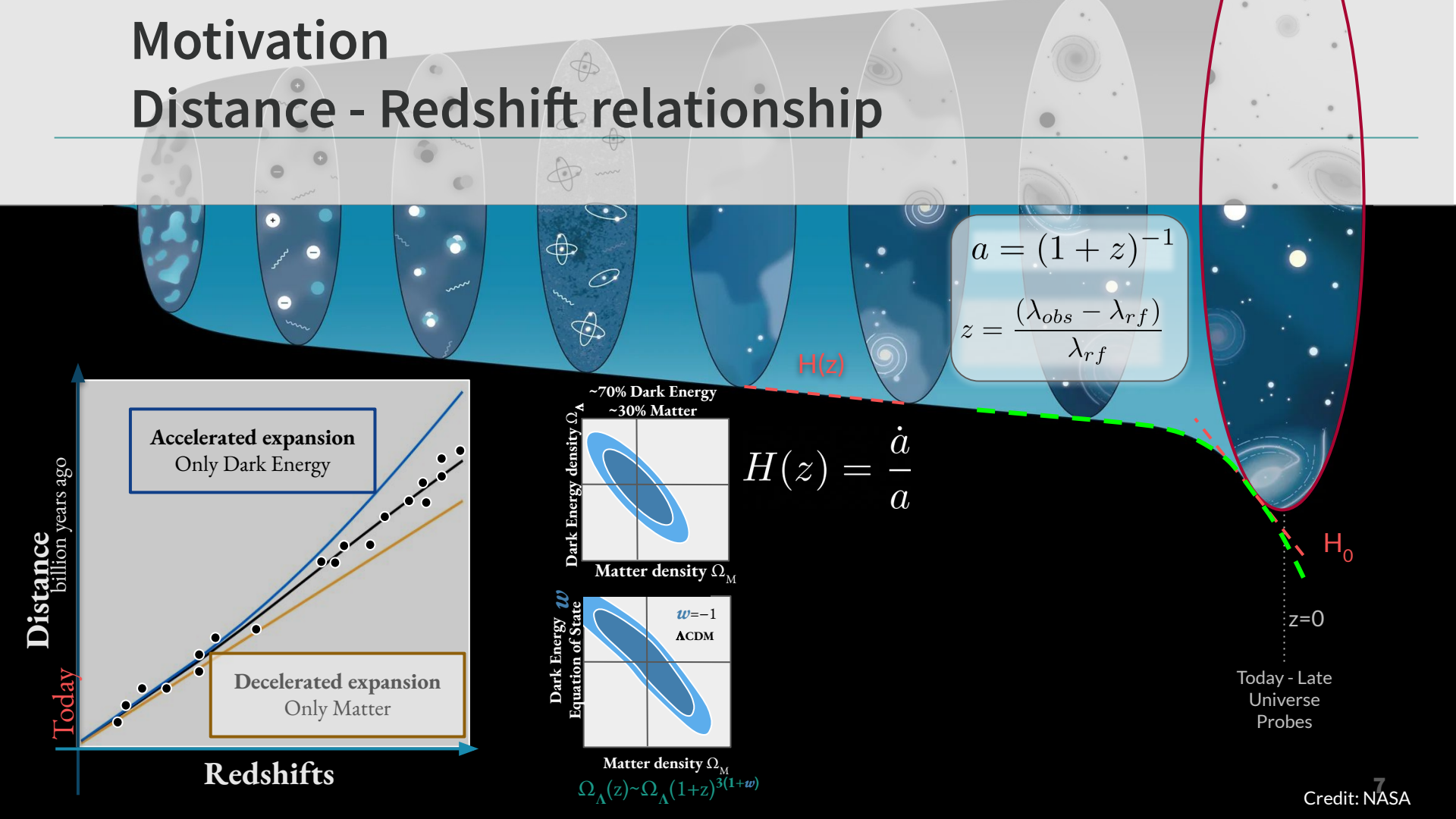
H_0

z=0

Today - Late Universe Probes

Credit: NASA

Motivation
Distance - Redshift relationship



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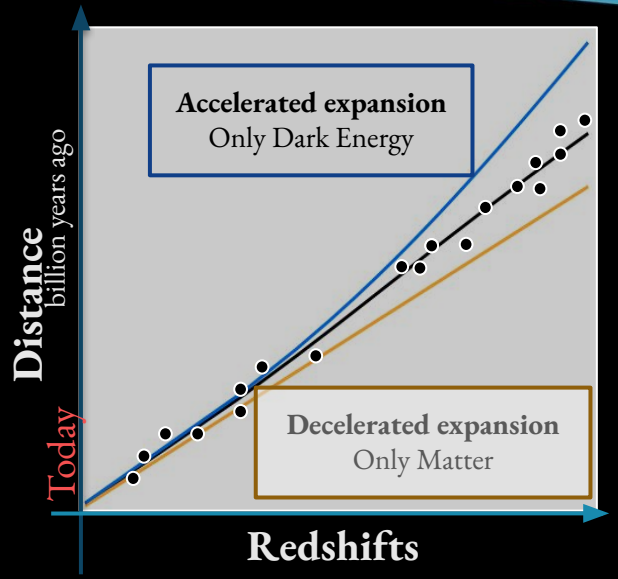


$$a = (1+z)^{-1}$$

$$z = \frac{(\lambda_{obs} - \lambda_{rf})}{\lambda_{rf}}$$

H(z)

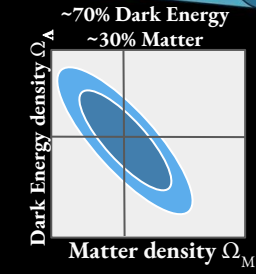
z~0.3

Dark Energy Dominates

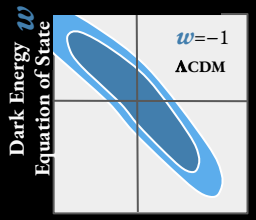
H_0

z=0

Today - Late Universe Probes



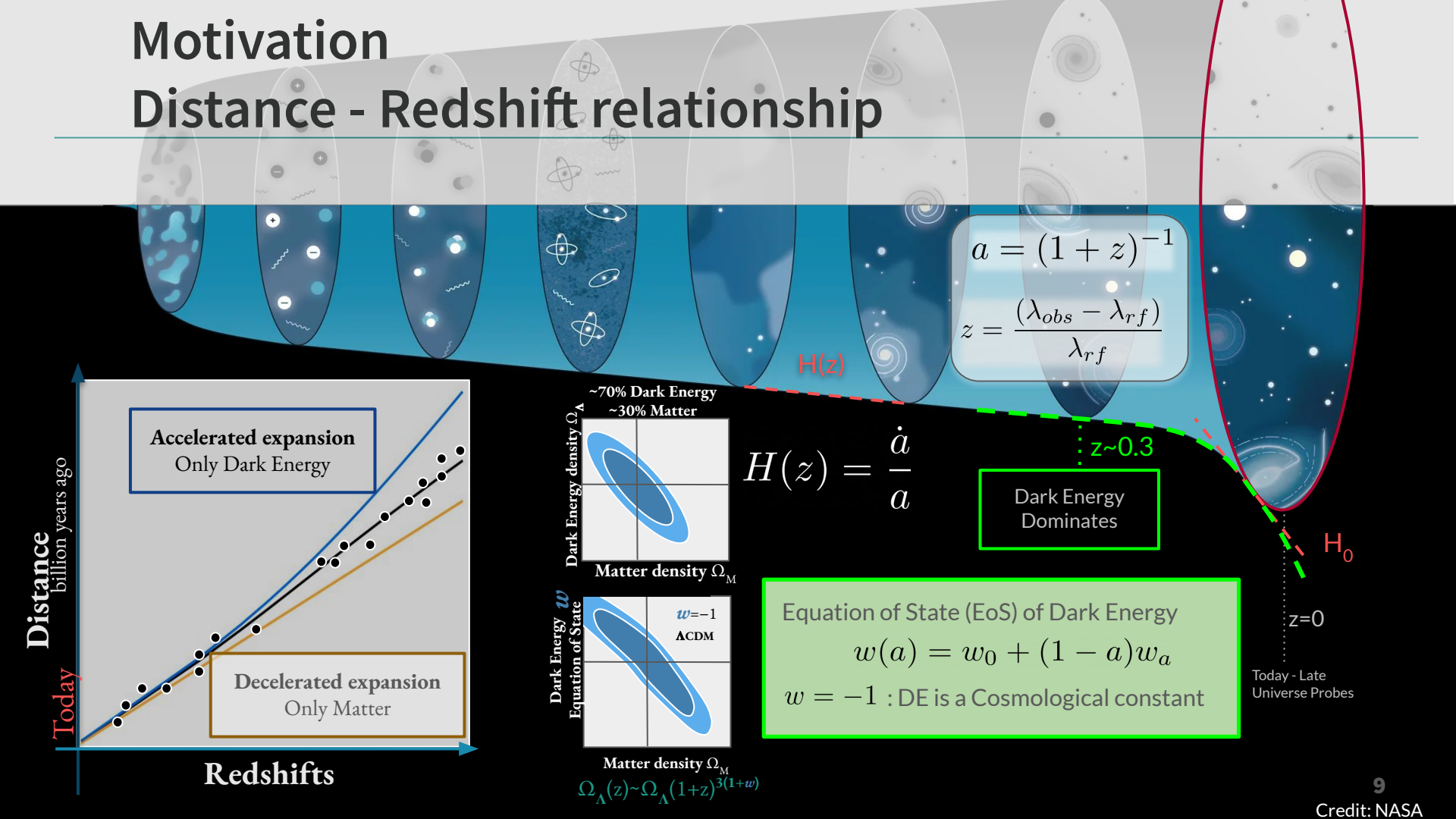
$$H(z) = \frac{\dot{a}}{a}$$



$\Omega_\Lambda(z) \sim \Omega_\Lambda(1+z)^{3(1+w)}$

Credit: NASA

Motivation
Distance - Redshift relationship



Credit: NASA

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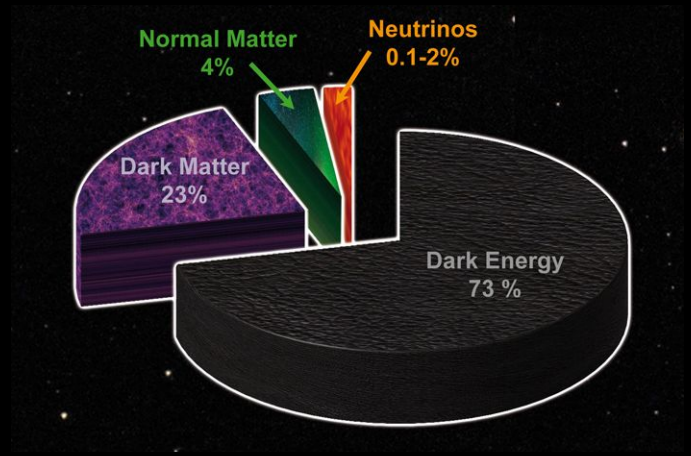
The Cosmological Standard model



$$a = (1+z)^{-1}$$

$$z = \frac{(\lambda_{obs} - \lambda_{rf})}{\lambda_{rf}}$$

H(z)

$z \sim 10^3$
CMB
Early Universe
Probes

z~1
6 billion years

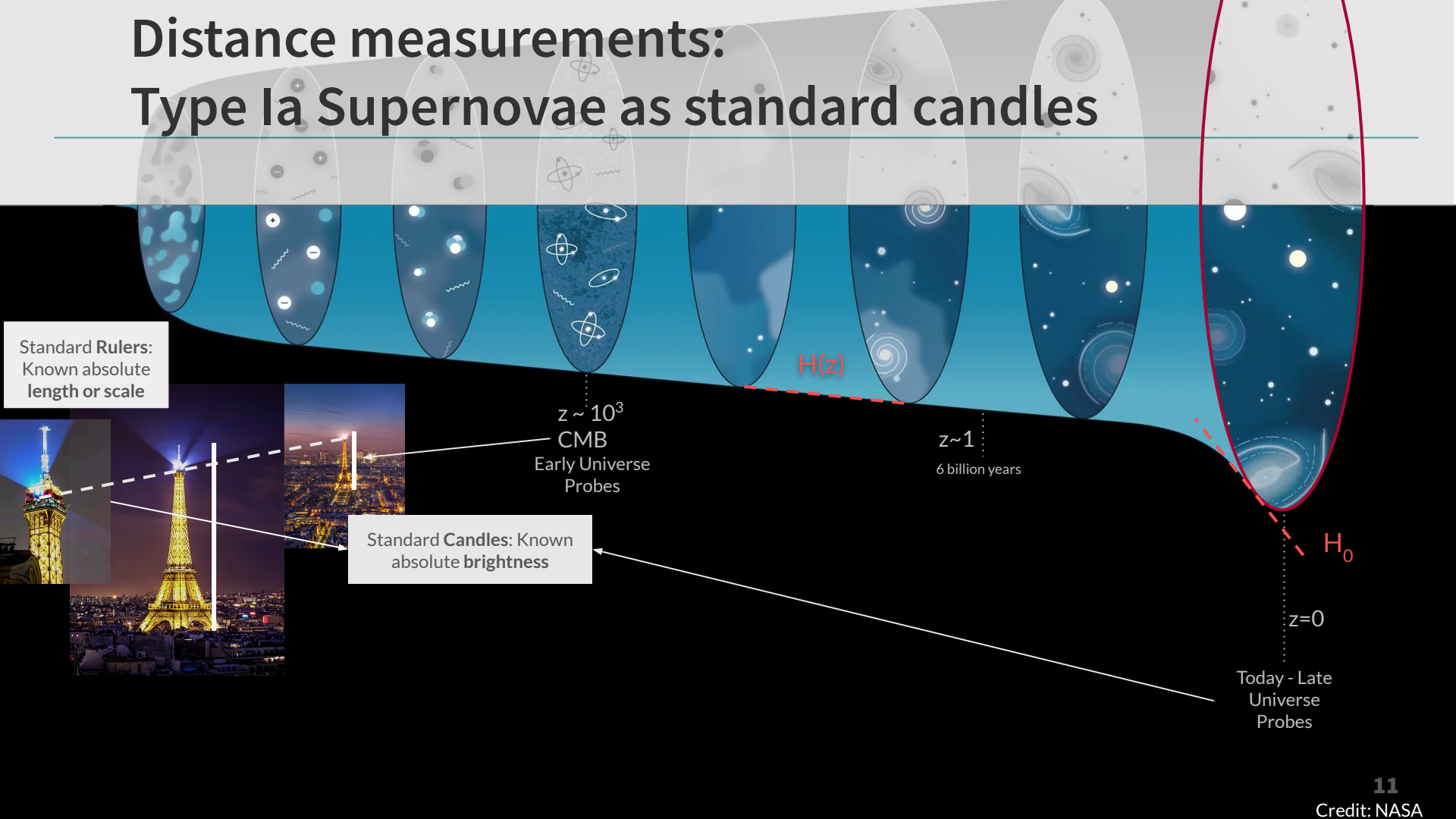
H_0

z=0
Today - Late
Universe Probes

Flat - ΛCDM	$H_0, \Omega_M, \Omega_\Lambda = (1 - \Omega_M)\}$
Flat - wCDM	$\{H_0, \Omega_M, w\}$
Flat - $w_0 w_a$CDM	$\{H_0, \Omega_M, w_0, w_a\}$

Credit: NASA

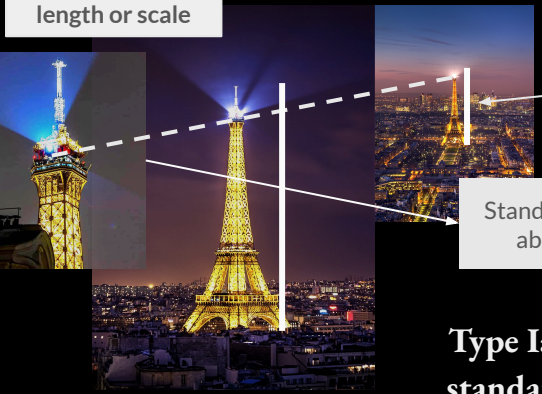
Distance measurements: Type Ia Supernovae as standard candles



Credit: NASA

Distance measurements: Type Ia Supernovae as standard candles

Standard **Rulers**: Known absolute **length or scale**



$z \sim 10^3$
CMB
Early Universe Probes

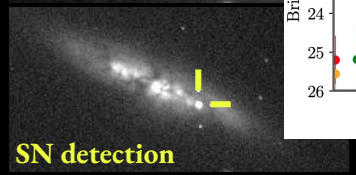
H(z)

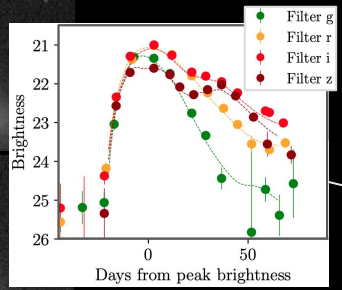
z~1
6 billion years

H_0

z=0
Today - Late Universe Probes

Standard **Candles**: Known absolute **brightness**





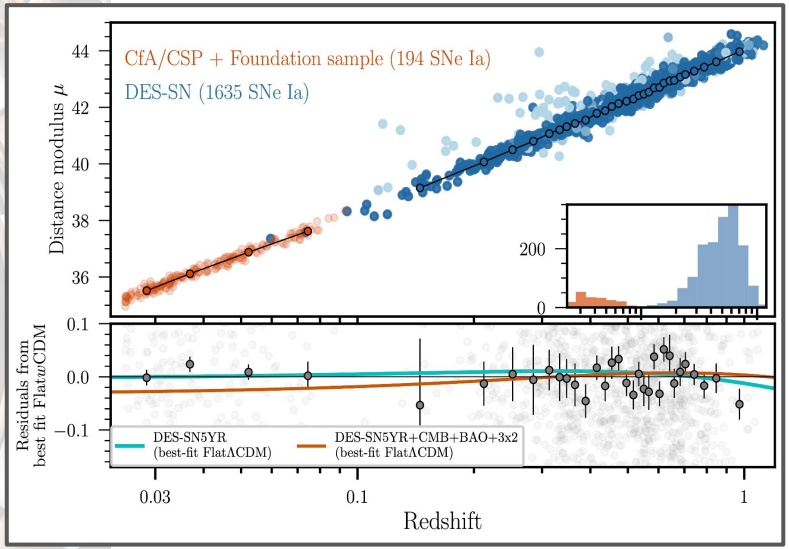
Type Ia Supernova are standardizable candles
Very homogeneous <u>intrinsic brightness at peak</u> (<10% scatter) after **several empirical** corrections.

Credit: NASA

Best SNIa sample today: The Dark Energy Survey

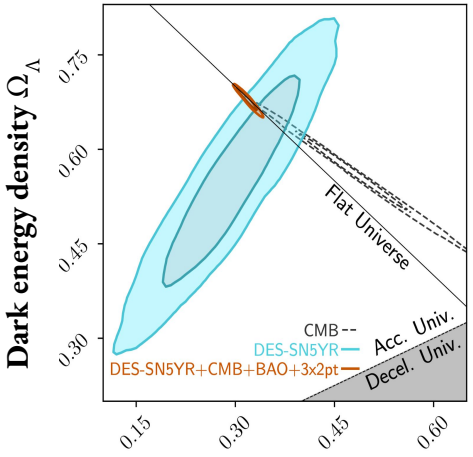
- **Blanco 4 m class telescope**
- **10** fields=~**27** sq. deg / **5yr**
- FoV. ~3.5 deg^2 - *griz* filters
- **DIA** for transient detection
- SNIa phot accuracy ~ 0.5%
- **Photometric** classification: **~1600 SNe Ia**
- Syst. errors < Stat. errors

This is the **largest** and **deepest high-z** Cosmology-SNIa sample from a **single telescope ever compiled (0.10 < z < 1.13)**



Expansion is accelerating at 99.99998% confidence

DES Collab. 2024



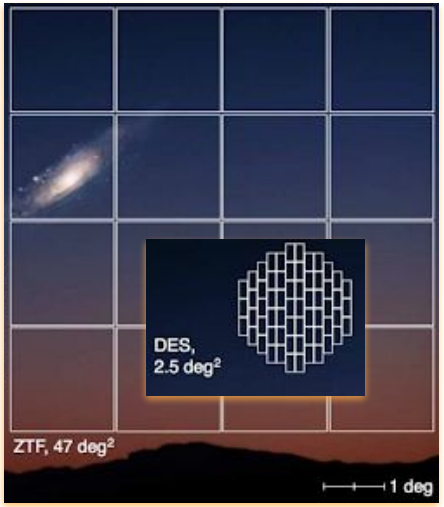
DES5YR+CMB+BAO+3x2pt

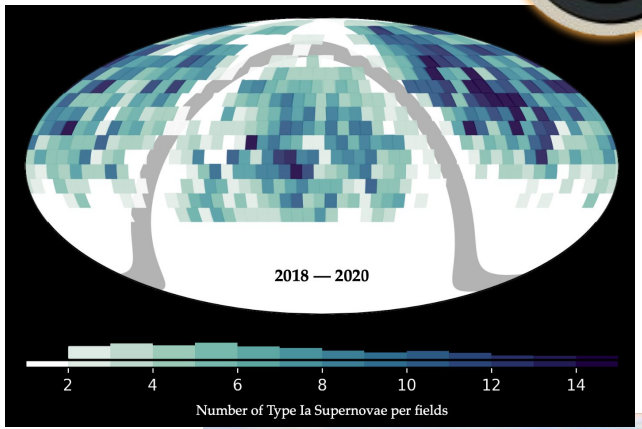
$\Omega_M = 0.318^{+0.011}_{-0.010}$

Survey run (**2014-2019**) DES SN 3YR (**2019**) Final Reusults DES SN 5YR (**2024**)

The Zwicky Transient Facility SNIa Survey

- **Full north sky** Multi instrument survey @ Palomar
- *gri* filters in the P48 Camera
- FoV. 47 deg^2
- Depth of 20.5 mag
- 1 arcsecond / pixel resolution
- Incredible cadence for SNIa and rapid transient science





2018
Survey run start

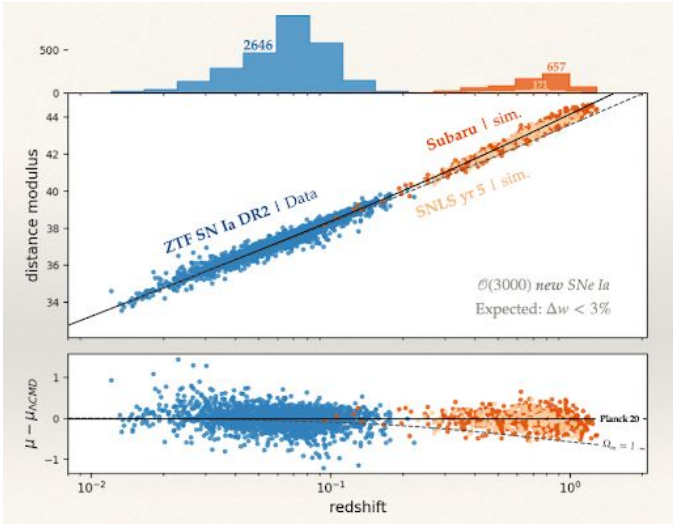
ZTF DR1
Dhawan et al. 2022

ZTF DR2 (2646 SNIa)
Rigault, Smith, et. al 2025abc

ZTF I | ZTF II | ZTF O4+III

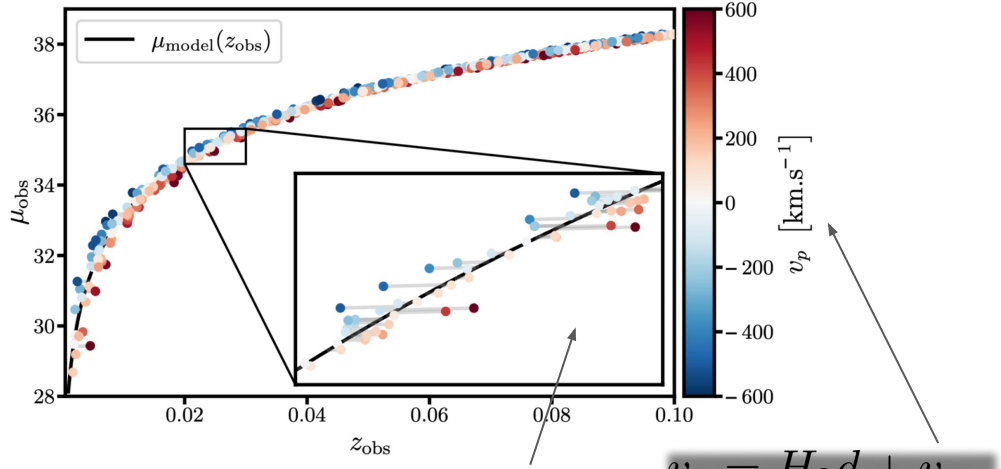
The Zwicky Transient Facility SNIa Survey

Dark Energy science



ZTF Future Hubble Diagram
(adapted from talk from **Rigault 2025**)

Peculiar velocities: growth rate of structures $f\sigma_8$

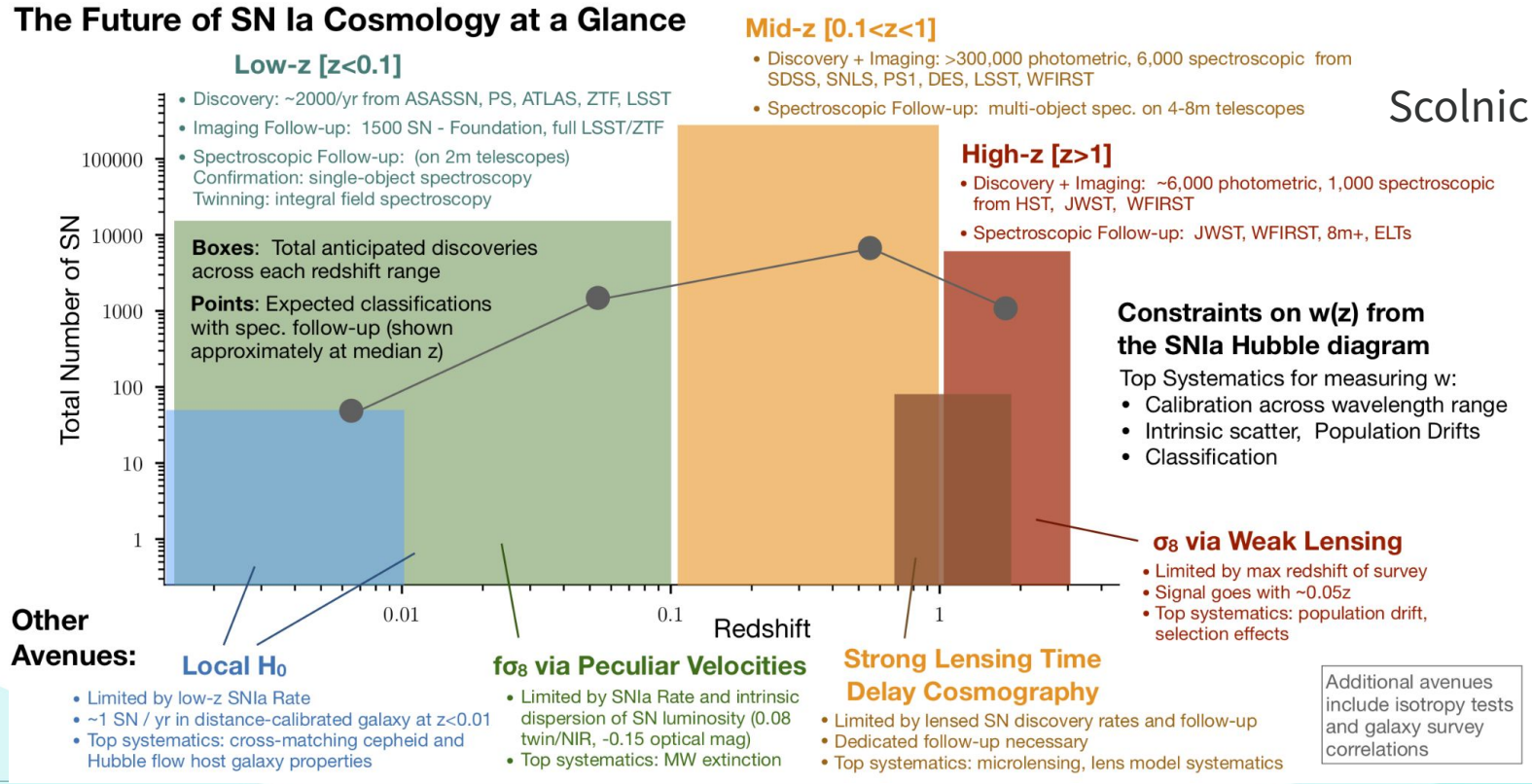


$$1 + z_{obs} = (1 + z_{cos})(1 + z_{pec})$$

$$v_r = H_0 d + v_{pec}$$

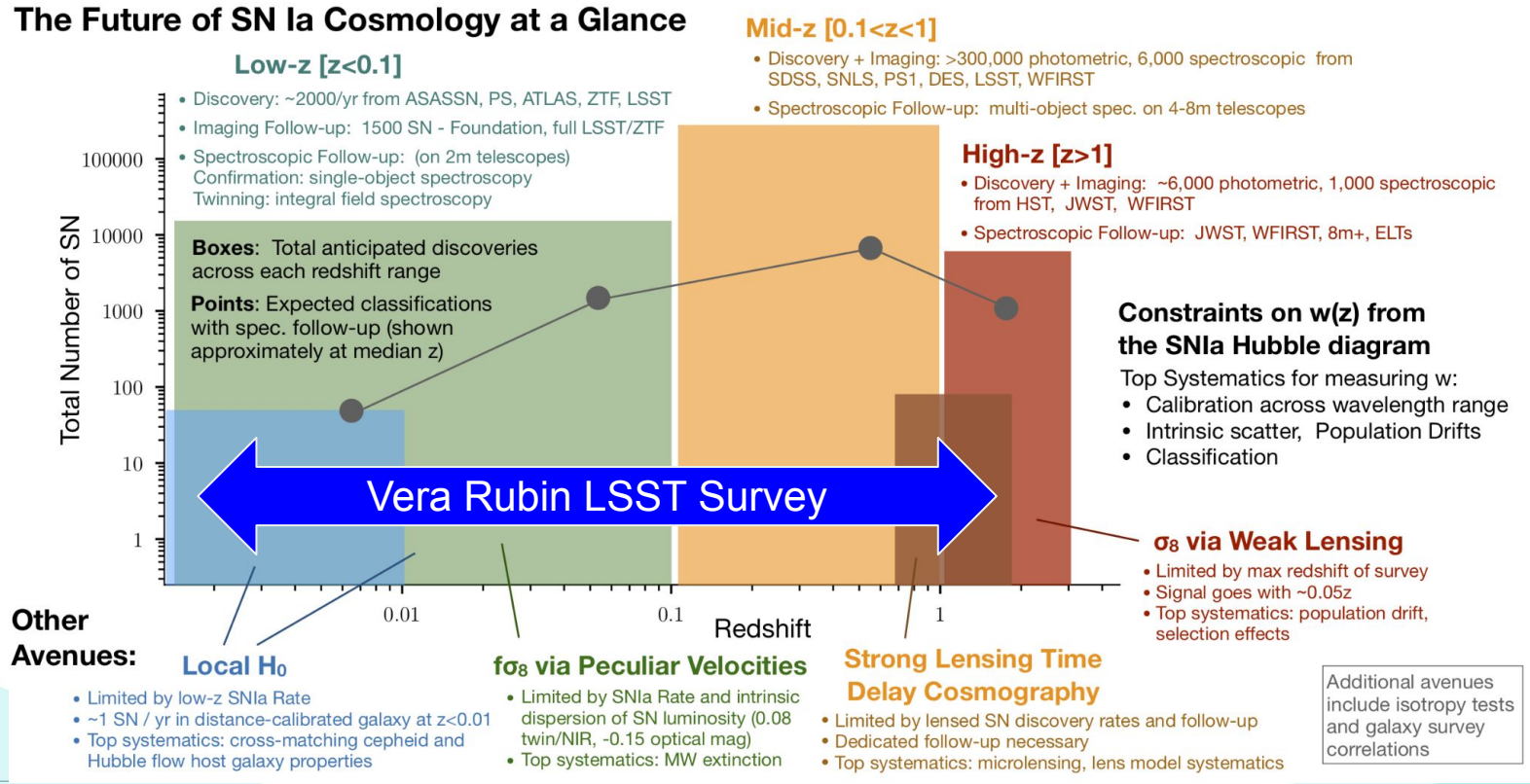
(**Carreres et al. 2023, Rosselli et. al 2025**)

Type Ia Supernova Cosmology is *booming!*

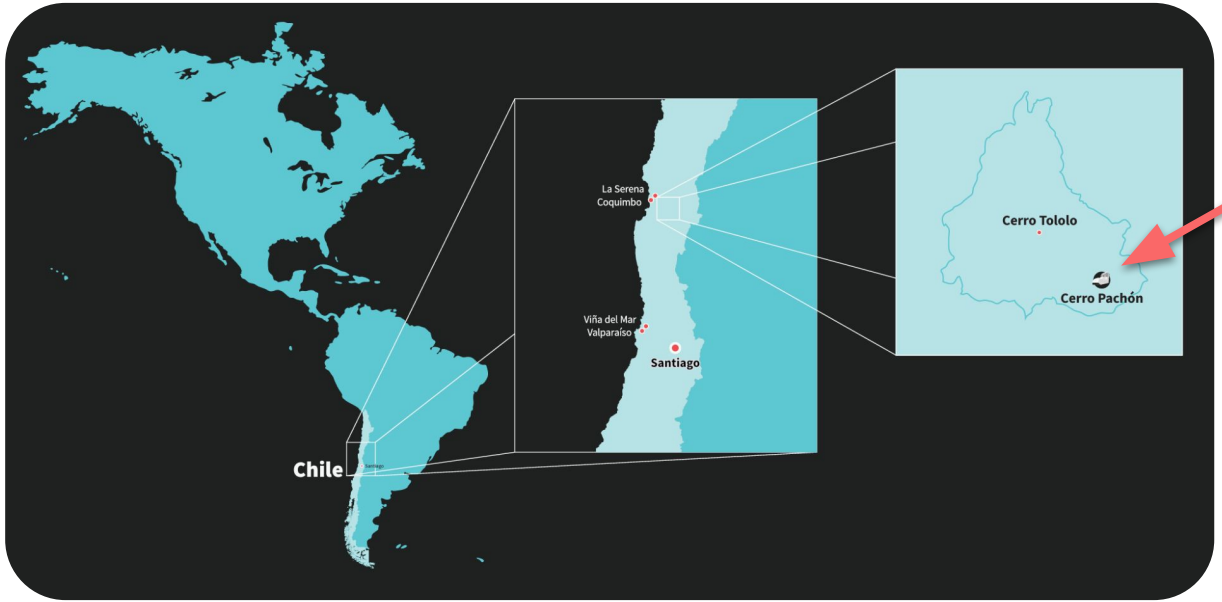


Scolnic (2019)

Type Ia Supernova Cosmology is *booming!*



Meet Rubin Observatory



Located on **Cerro Pachón**, in the Coquimbo region of Chile

Jointly funded by the **U.S. National Science Foundation** and the **U.S. Department of Energy, Office of Science**

VERA C. RUBIN OBSERVATORY | U.S. National Science Foundation | U.S. DEPARTMENT of ENERGY | Office of Science

NOIRLab | AURA | SLAC NATIONAL ACCELERATOR LABORATORY

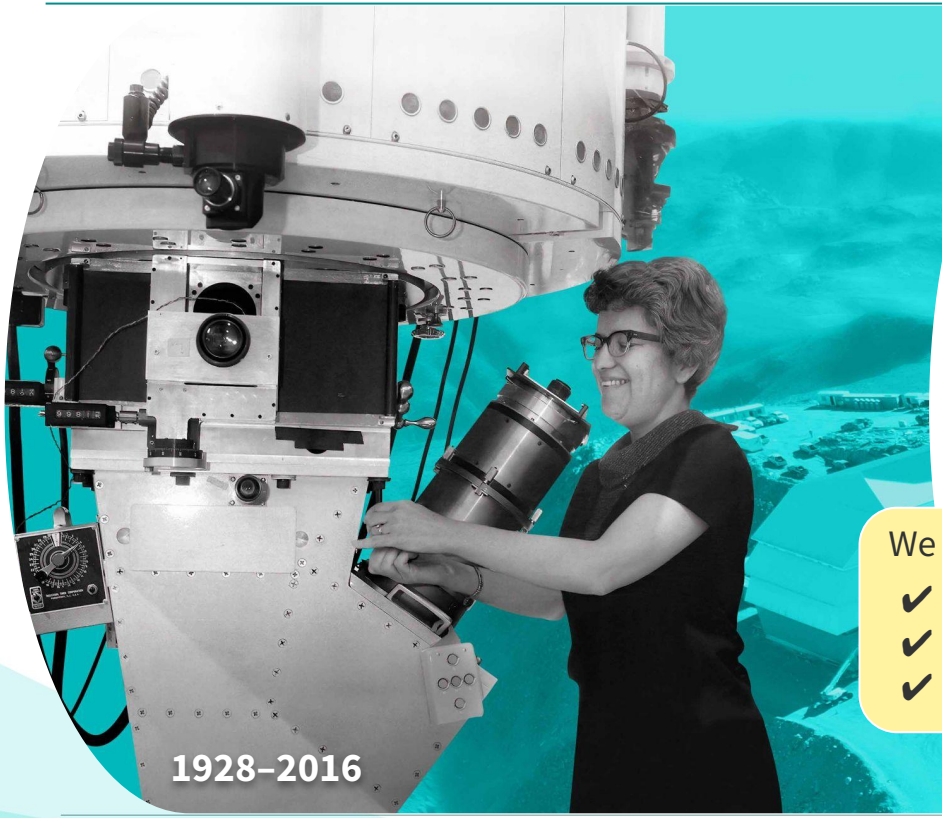
Meet Rubin Observatory & its neighbors

Southern Astrophysical Research Telescope (SOAR)

Gemini South telescope

Rubin Auxiliary Telescope

Honoring Vera C. Rubin — A Cosmic Trailblazer



Who was she?

- Provided the first convincing evidence for dark matter
- Advocated for women in astronomy

Rubin Observatory is the **first major US Observatory named for a woman**

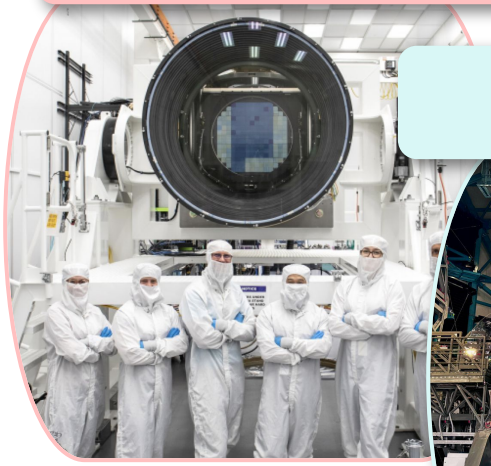
We are proud of our namesake:

✔ NSF–DOE Vera C. Rubin Observatory
✔ Vera C. Rubin Observatory
✔ Rubin Observatory

Just say no to “VRO!”

Mission: Capture the Cosmos

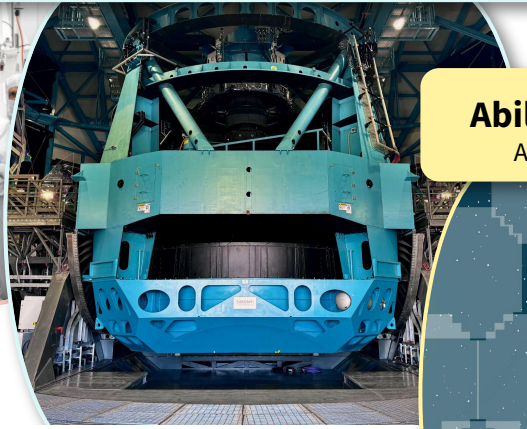
Wide Field of View
Largest digital camera ever built



J. Orrell/SLAC National Accelerator Lab

+

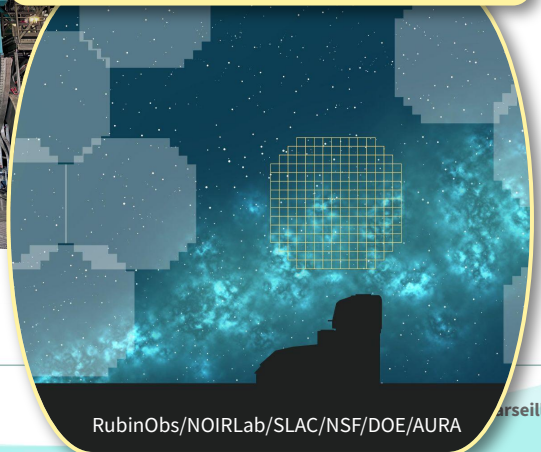
Speed
Novel three-mirror design



RubinObs/NOIRLab/SLAC/NSF/DOE/AURA

+

Ability to see faint objects
Across the entire Southern sky



RubinObs/NOIRLab/SLAC/NSF/DOE/AURA

=

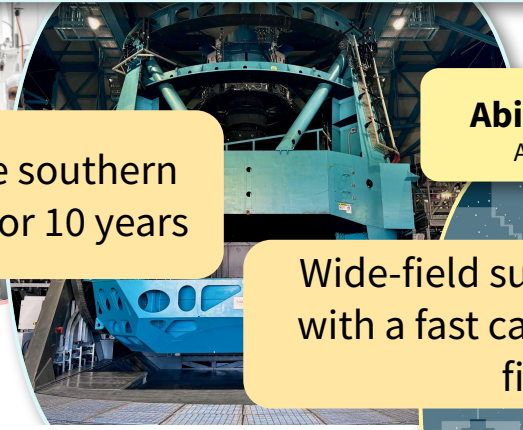
Mission: Capture the Cosmos

The greatest astronomical movie of all time

Wide Field of View
Largest digital camera ever built

J. Orrell/SLAC National Accelerator Lab

Speed
Novel three-mirror design



RubinObs/NOIRLab/SLAC/NSF/DOE/AURA

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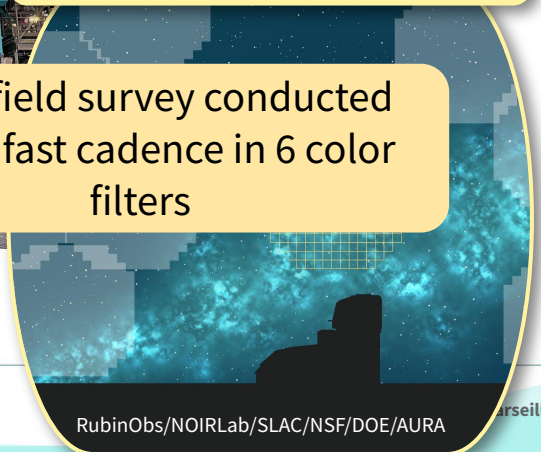


RubinObs/NOIRLab/SLAC/NSF/DOE/AURA

Repeatedly scan the southern sky every ~3 nights for 10 years

Wide-field survey conducted with a fast cadence in 6 color filters

Four Science Areas

Milky Way Structure & Formation

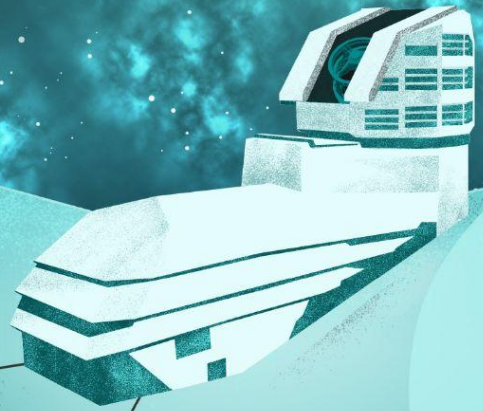
Rubin will help us make the best map of our home galaxy yet.

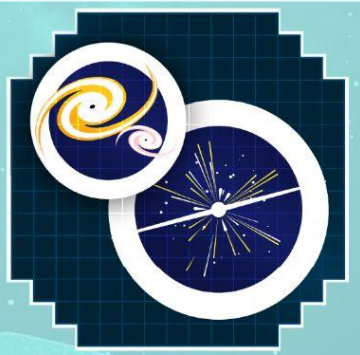
Solar System Census

Rubin will show us millions of new asteroids and comets, and so much more.

Dark Matter & Dark Energy

Rubin is a brand new tool to help us learn more about their nature & behavior.

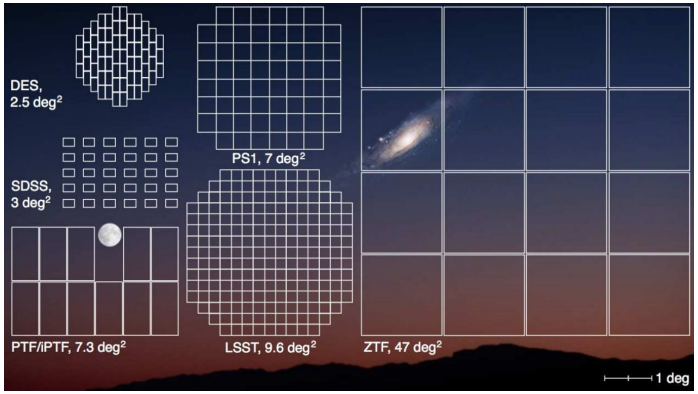


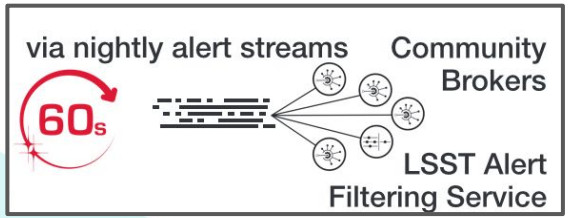


The Changing Sky

Rubin will bring the night sky to life, yielding a treasure trove of discoveries.

The future of SNIa Cosmology: Vera Rubin LSST Survey





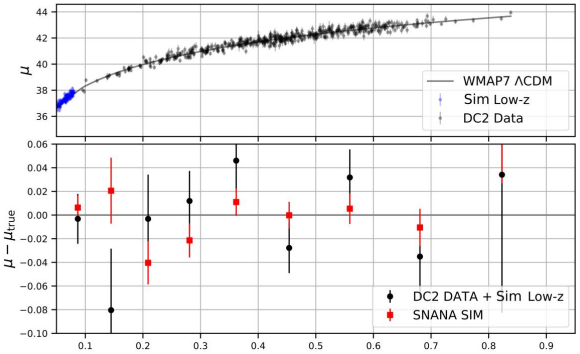
	THE DARK ENERGY SURVEY	ZTF	VERA C. RUBIN OBSERVATORY
Depth	r ~ 21.5	20.5	r ~ 23.5
Mirror Diameter	4 m	1.2 m	8 m (6.5m)
FoV	3.5 deg^2	40 deg^2	10 deg^2
Footprint	30 deg^2	18,000 deg^2	18,000 deg^2
Timing	2013 - 2019	2018 - 2027	**Starting 2025!**
Light-curve sampling	5–6 days cadence	1–3 days cadence	3–9 days cadence
Survey duration	5 years	~9 years	10 years
High-quality SN Ia light-curves	~2500	~ 40000	**~ 1 million**

LSST Dark Energy Science Collaboration SNIa probe

Big Challenges for leveraging Rubin LSST data for Cosmology probes

- SNIa sample size x100 w.r.t. precursor surveys
- Obtain x10 reduction statistical error
- We need **x10 better control of systematics**
  - Photometric biases
  - Selection biases
- Complementary probes using static and time-domain data

SNIa Cosmology inference pipeline validation with DC2 Hubble Diagram & constraints

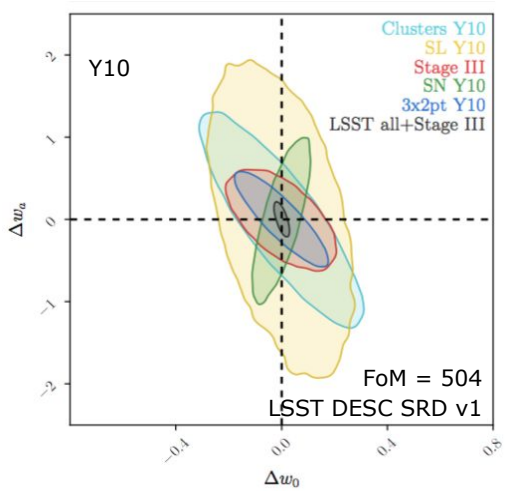


From Cosmology Fit

$\Delta w = w - w_{\rm true}$	$\Delta\Omega_M = \Omega_M - \Omega_M^{\rm true}$	χ^2/ν
-0.032 ± 0.046	-0.007 ± 0.013	11/8
-0.002 ± 0.026	0.001 ± 0.009	12/8

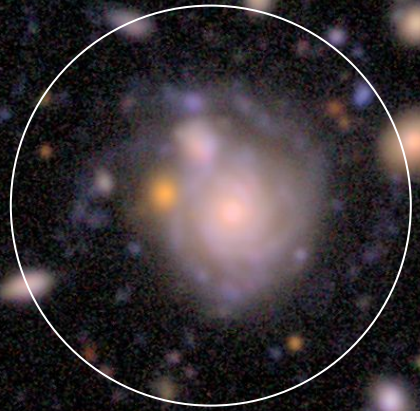
Sánchez et al. 2022

LSST DESC Dark Energy Science Collaboration — SRD Combined Probe Forecast



$$w(a) = w_0 + (1-a)w_a$$

First look images revealed last 23/06/2025



Legacy Survey of Space and Time

VERA C. RUBIN OBSERVATORY

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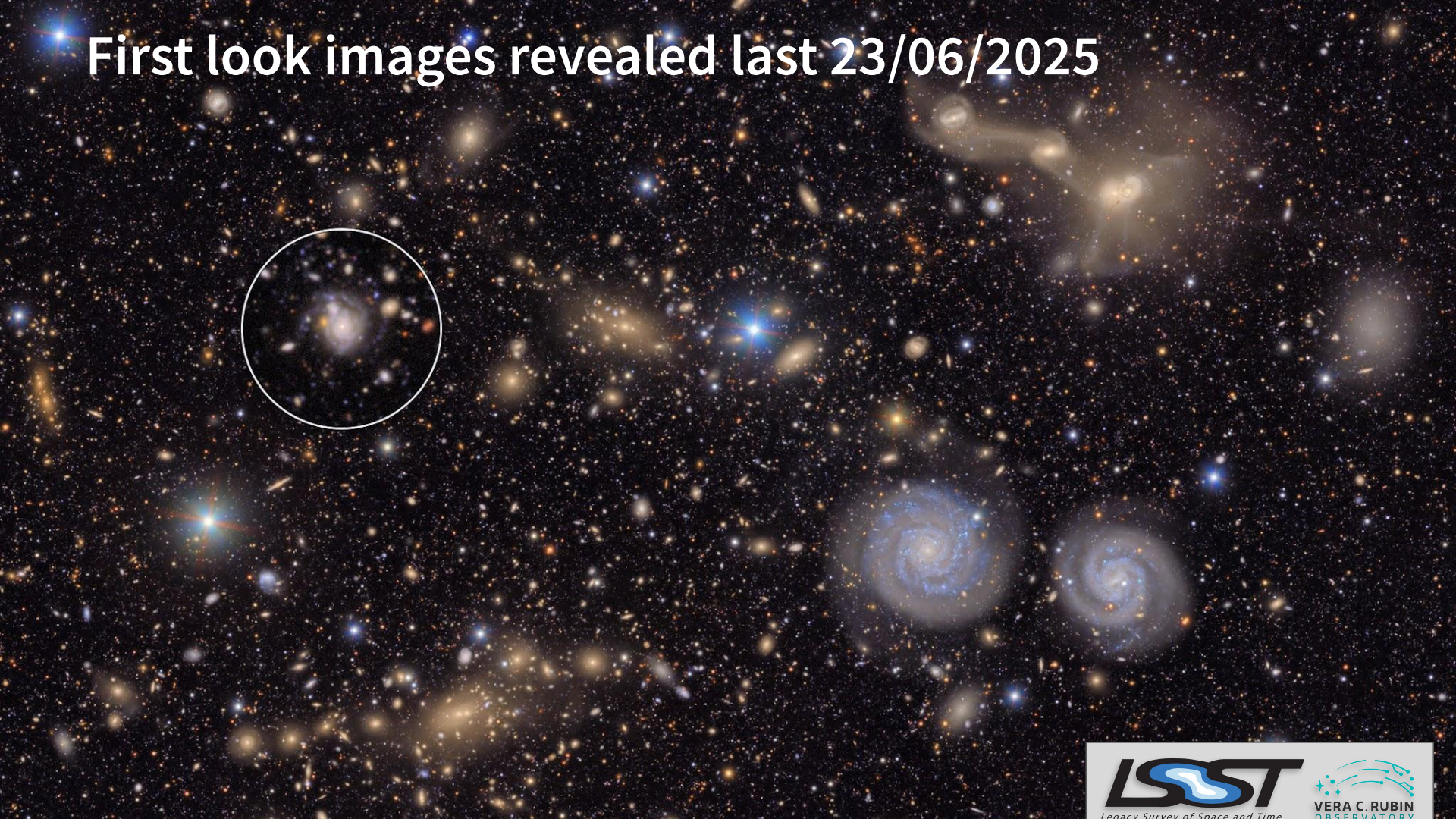
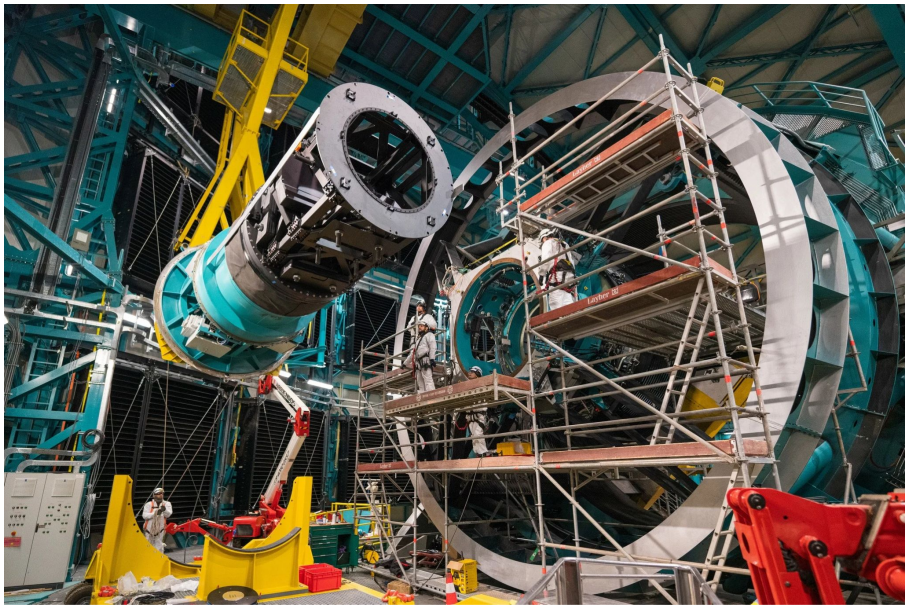


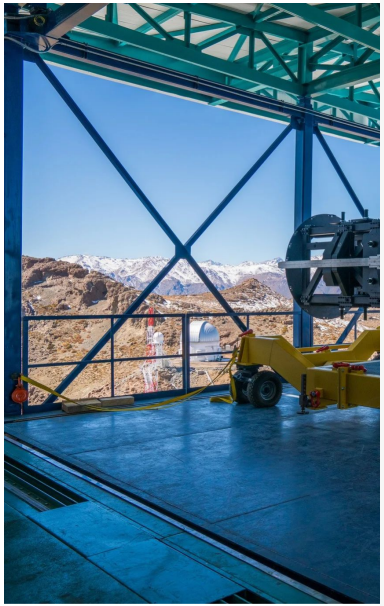
First look images revealed last 23/06/2025

LSSTComCam - DP1 Data release 30/06/2025

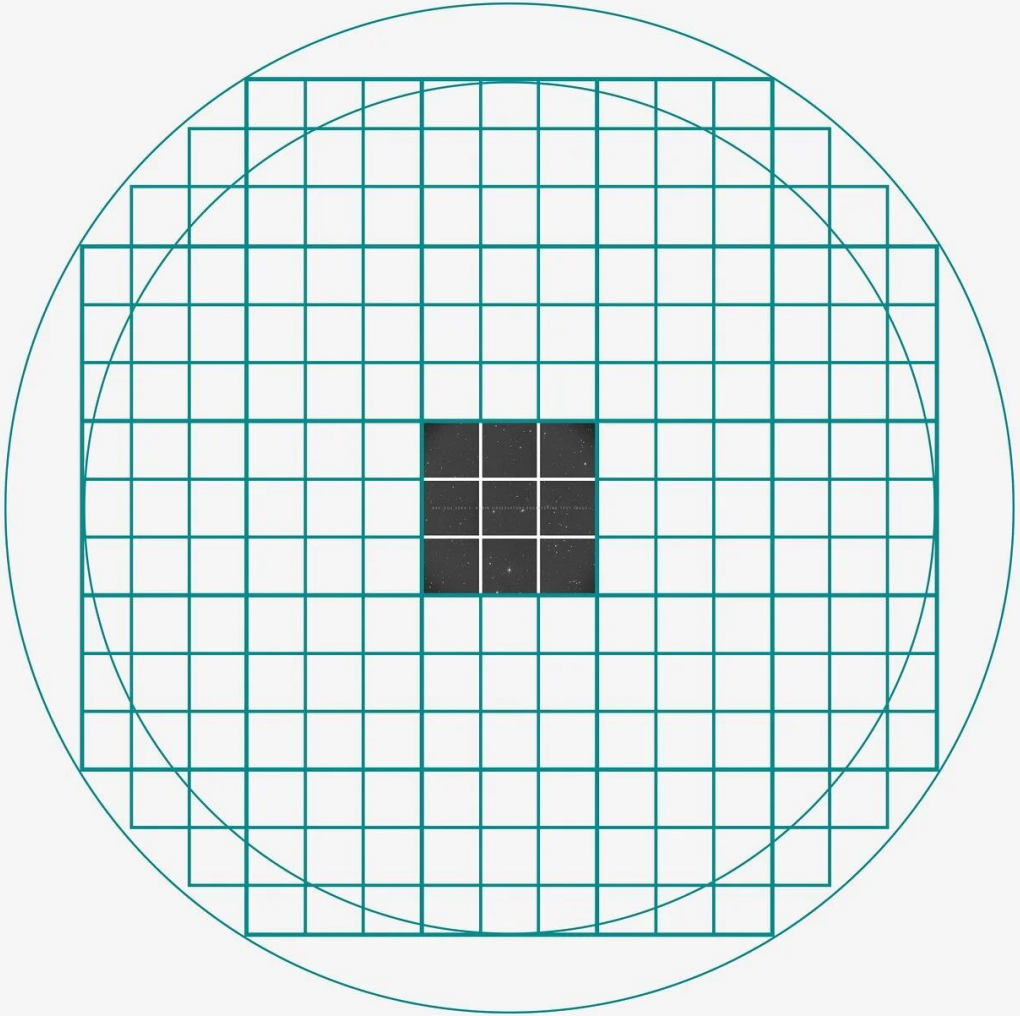


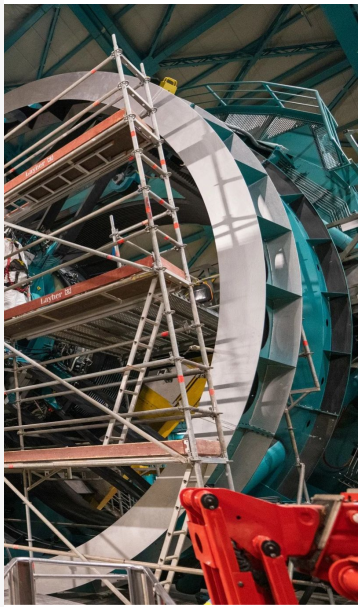
LSSTComCam being installed in the Simonyi Telescope (2024)

LSSTComC



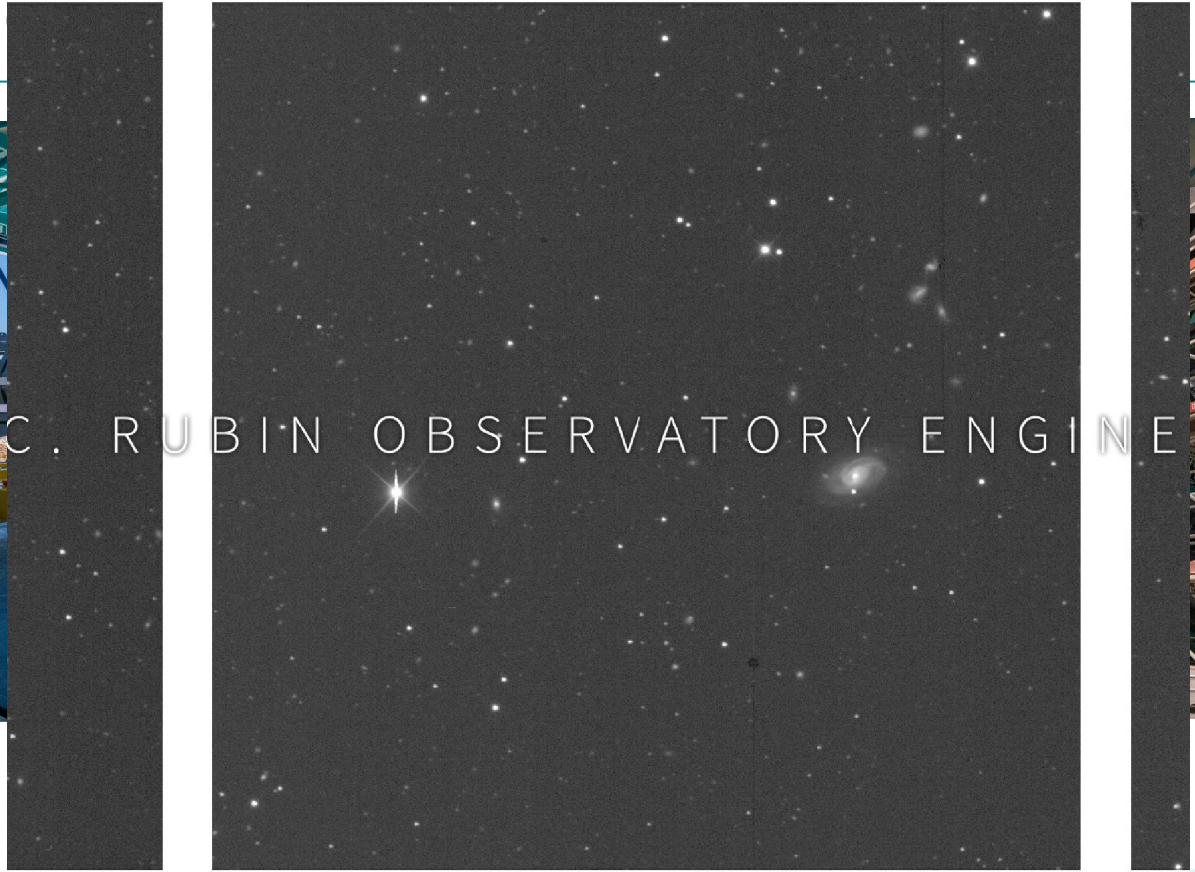
LSSTComCam be

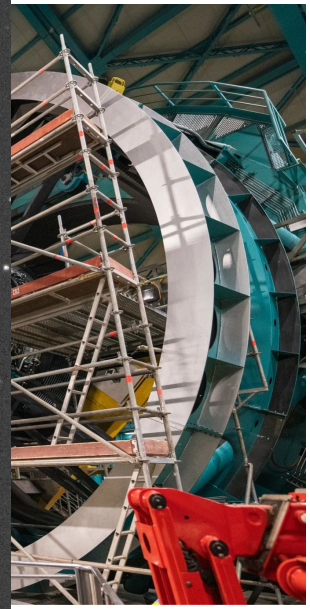




LSSTCom

LSSTComCam



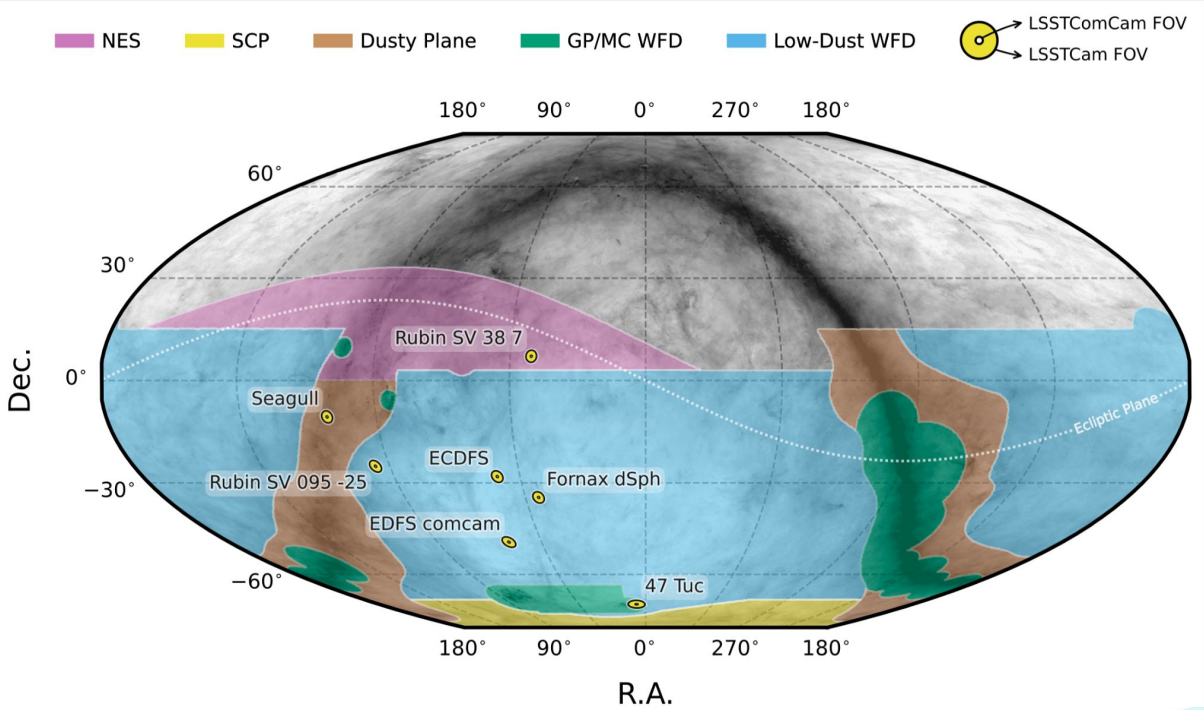


Observations with LSSTComCam released

LSSTComCam first release of metrics: [SITCOMTN-149]

Several fields with LSSTComCam observations at different epochs.

Validations of all system components and pipelines
In particular **Difference Image Analysis**



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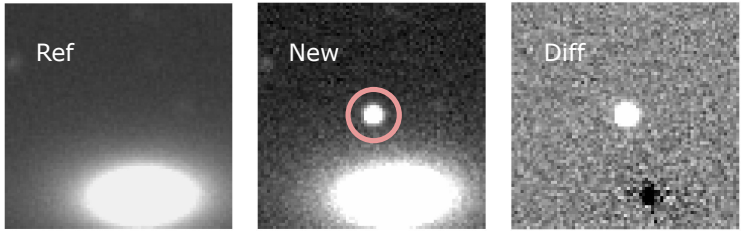
Field Name	RA	DEC	Band					
	deg	deg	u	g	r	i	z	y
47 Tucanae Globular Cluster	6.128	-72.090	6	10	32	19	0	5
Extended Chandra Deep Field South	53.160	-28.100	43	230	237	162	153	30
Rubin SV Euclid Deep Field South	59.150	-48.730	20	61	87	42	42	20
Fornax Dwarf Spheroidal Galaxy	40.080	-34.450	0	5	25	12	0	0
Rubin SV Low Galactic Latitude Field	95.040	-25.000	33	82	84	23	60	10
Rubin SV Low Ecliptic Latitude Field	37.980	7.015	0	44	40	55	20	0
Seagull Nebula	106.300	-10.510	10	37	43	0	10	0

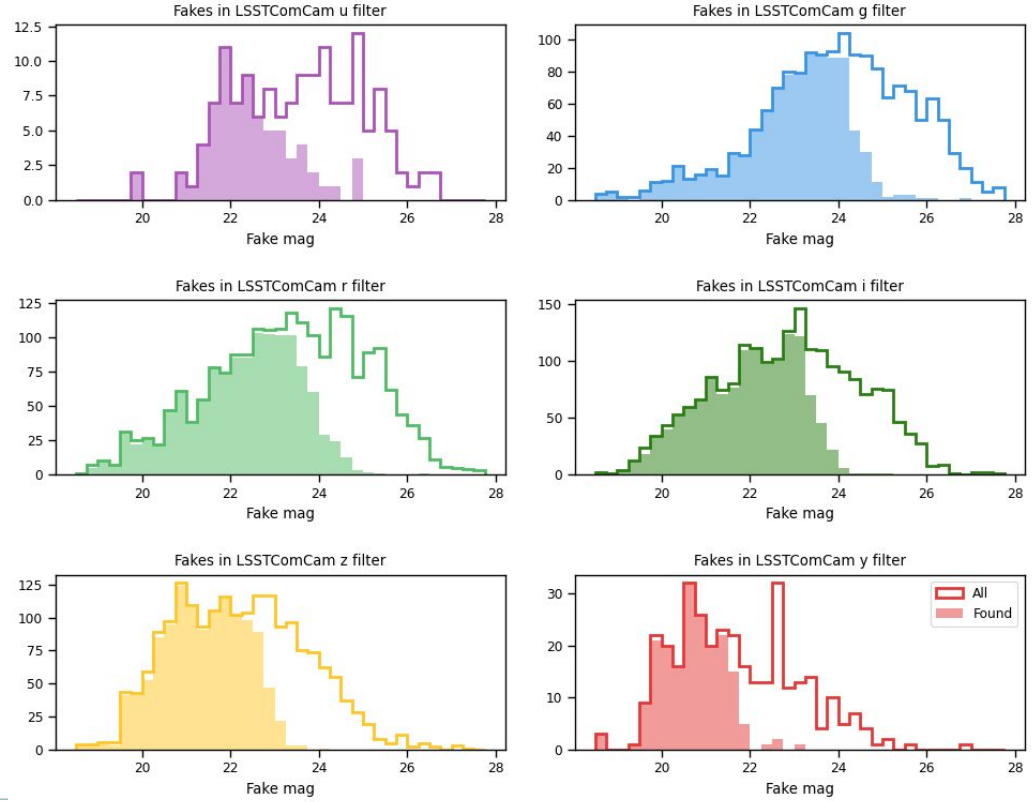
Synthetic sources in LSSTComCam images

Large campaign of ~1.5 x 10^6 sources
- Injection of **point sources**
- Training set building for Real/Bogus
- Preliminary DP1 preview report

Difference Image Analysis (DIA)



The first metric to check is the fraction of detections.



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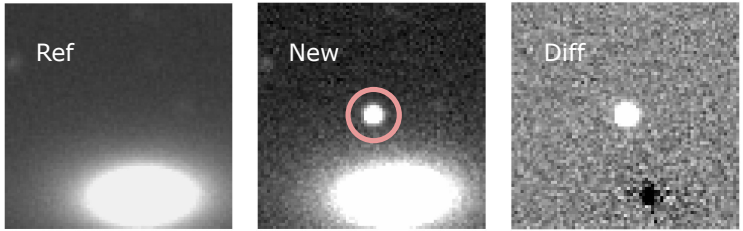

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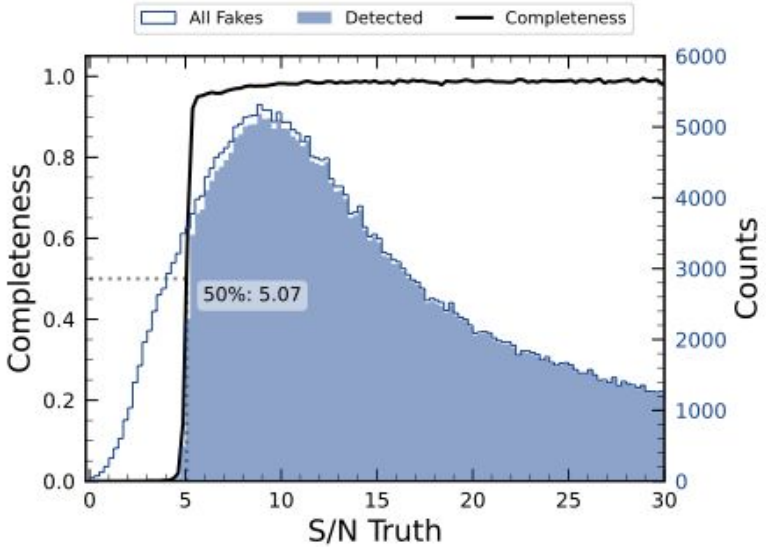
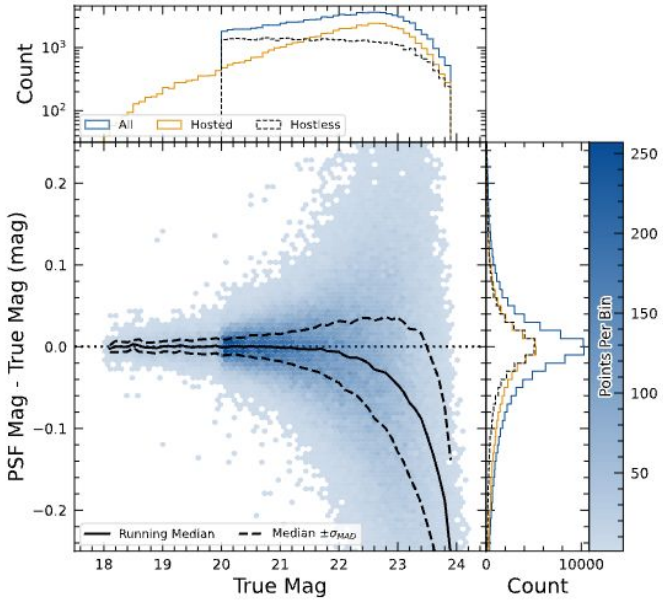
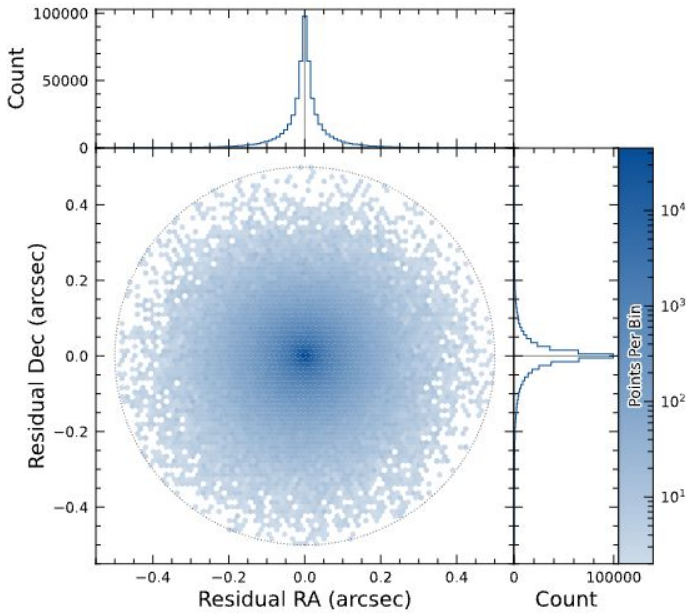


We define the value of
$S/N_{1/2}$:= SNR at which
Recall = 50%.
(Lower $SNR_{1/2}$ is more sensitive)

Synthetic sources in LSSTComCam images



PSF photometry vs fake true magnitudes



Astrometric measurement of our Fakes position

Conclusions

- The DES-5Yr paved the way for high-z Photometric Classified SNIa samples
- Soon the present of SNIa Cosmology will be ZTF
  - Exquisite quality and large amount of low-z data for anchor and astrophysical systematics understanding
- The future SNIa Cosmological probe is the Vera Rubin LSST Survey
  - Starts the survey in a few months
  - Will yield 2 orders of magnitude increase in statistical sample
- Combinations with low-z samples like ZTF could unlock mystery of Dark energy evolution
- LSST Survey is finishing commissioning:
  - Rigourous testing of pipelines using advanced simulations on-data techniques

Thanks for listening!

> Don’t shoot for the stars, we already know what’s there. Shoot for the space in between because that’s where the real mystery lies.
>
> —*Vera C. Rubin*

FL Images @ rubinobservatory.org

VERA C. RUBIN OBSERVATORY

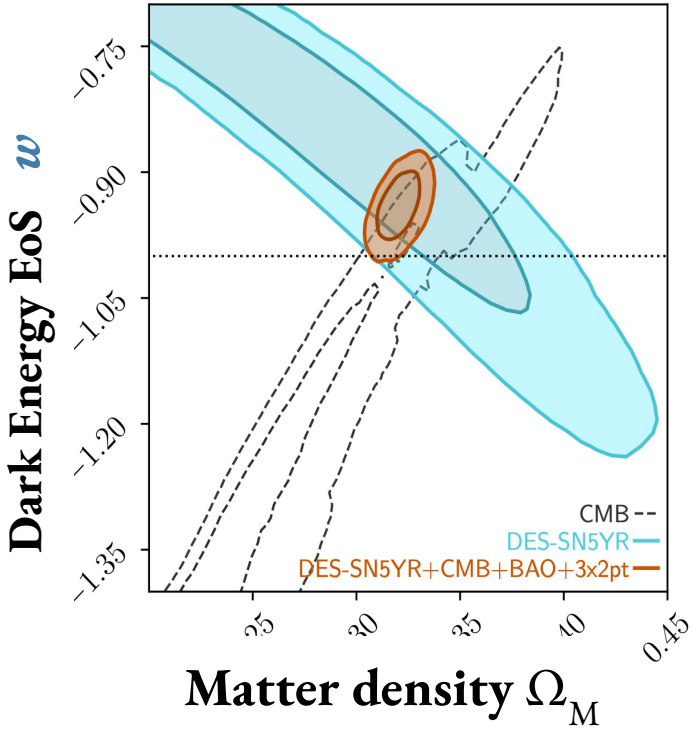
U.S. National Science Foundation

U.S. DEPARTMENT of ENERGY | Office of Science

Backup Slides

Cosmological Constraints from DES-SN5Y

Constraints Flat wCDM | Ω_M Matter Density & w Dark Energy Equation of State



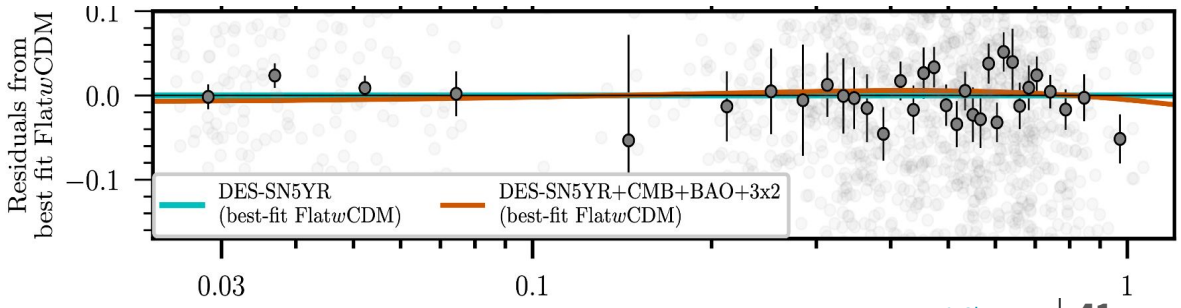
The DES Collaboration, 2024

Dark Energy Equation of State (EoS):
$w = -1 \rightarrow$ cosmological constant

DES-SN alone $w = -0.80^{+0.14}_{-0.16}$ (~1.25σ to -1)

DES5YR + CMB + BAO + 3x2pt

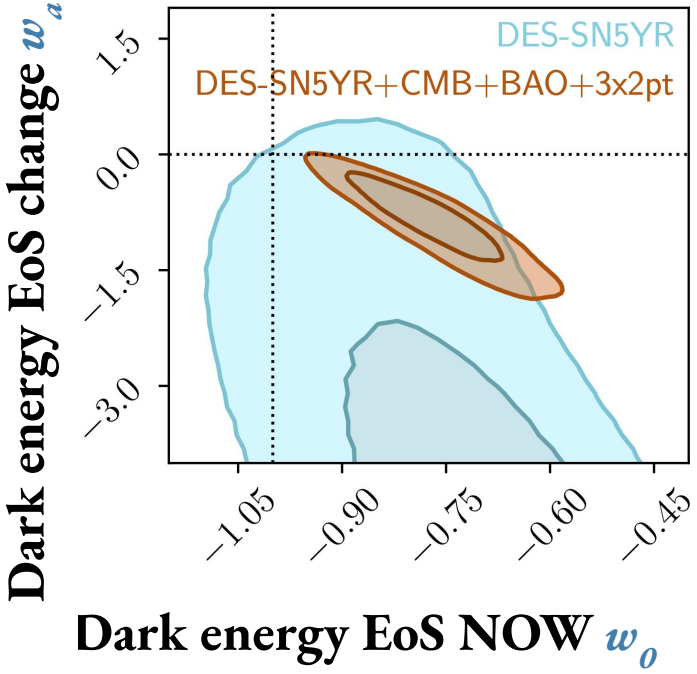
$w = -0.941 \pm 0.026$ (~2.25σ to -1)



Cosmological Constraints from DES-SN5Y

Constraints Flat $w_0 w_a$CDM | w Dark Energy Equation of State Now and Evolution

$$w(a) = w_0 + (1 - a)w_a$$



DES-SN alone

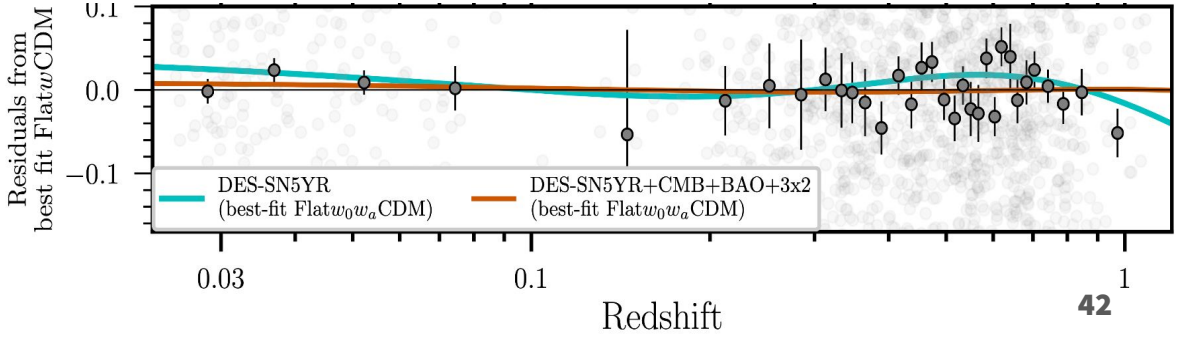
$w_0 = -0.36^{+0.36}_{-0.30}$

$w_a = -8.8^{+3.7}_{-4.5}$

DES5YR + CMB + BAO + 3x2pt

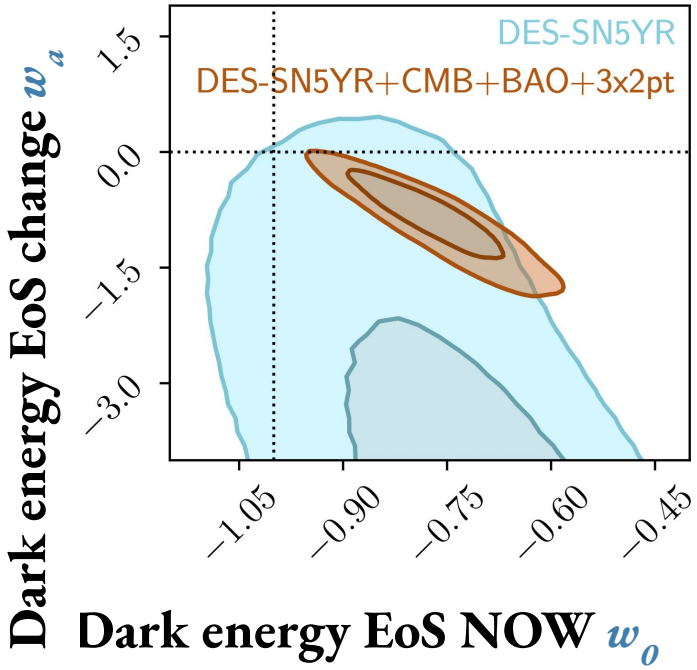
$w_0 = -0.773^{+0.075}_{-0.067}$

$w_a = -0.83^{+0.33}_{-0.42}$



ES Collaboration, 2024

DES-5YR Summary Conclusions and findings

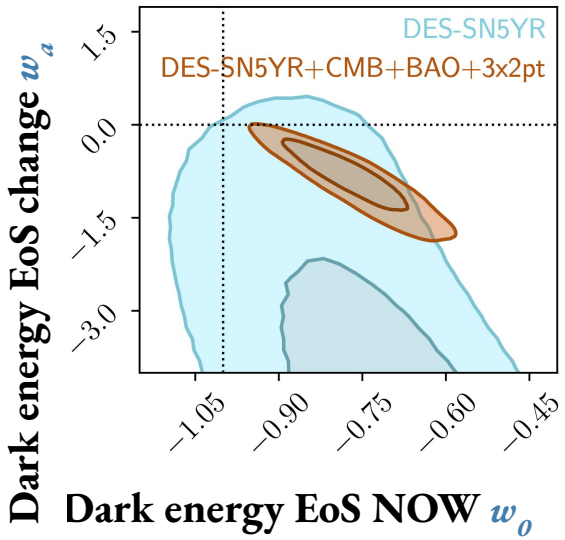


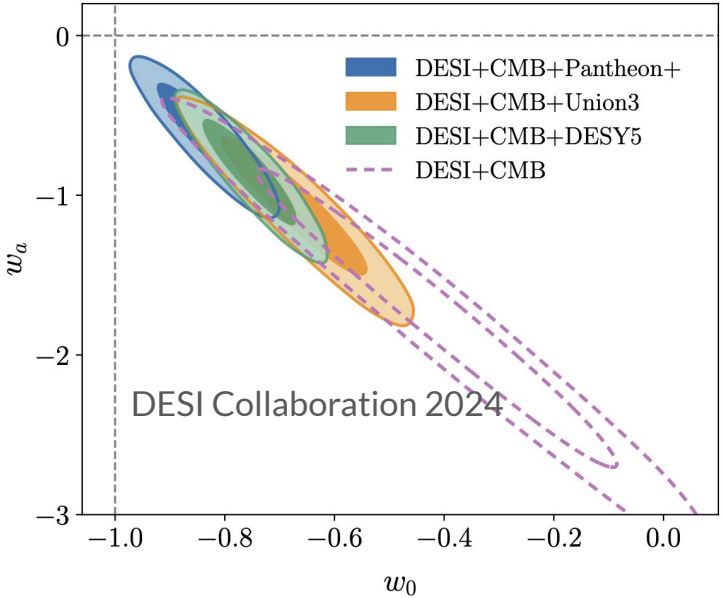
- Universe expansion is indeed **accelerating**
- The best fit: standard Flat-ΛCDM
- Deviations from $w = -1$ are at most ~1.25σ and ~2.25σ
- Varying w is **weakly** preferred when allowing for it
- We can safely say that the data favours in any case $w \geq -1$ ruling out models with lower EoS.

DES-5YR Summary Conclusions and findings

DESI BAO measurements and Lyman Alpha forest cosmology probe rejects Flat-ΛCDM with ~3.1σ using CMB probes

In combination with DES-5Yr this increases to ~4.2σ in favor of a possible evolving Dark Energy EoS

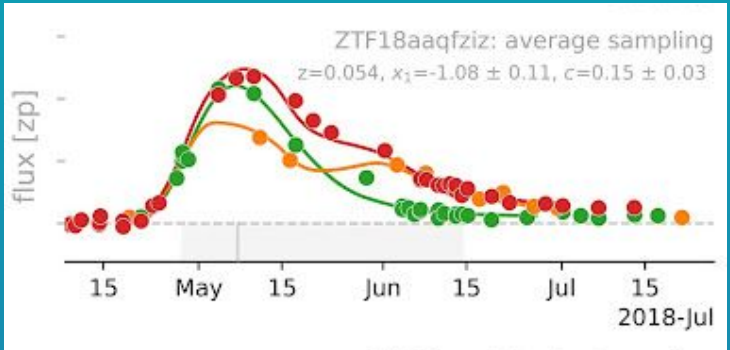


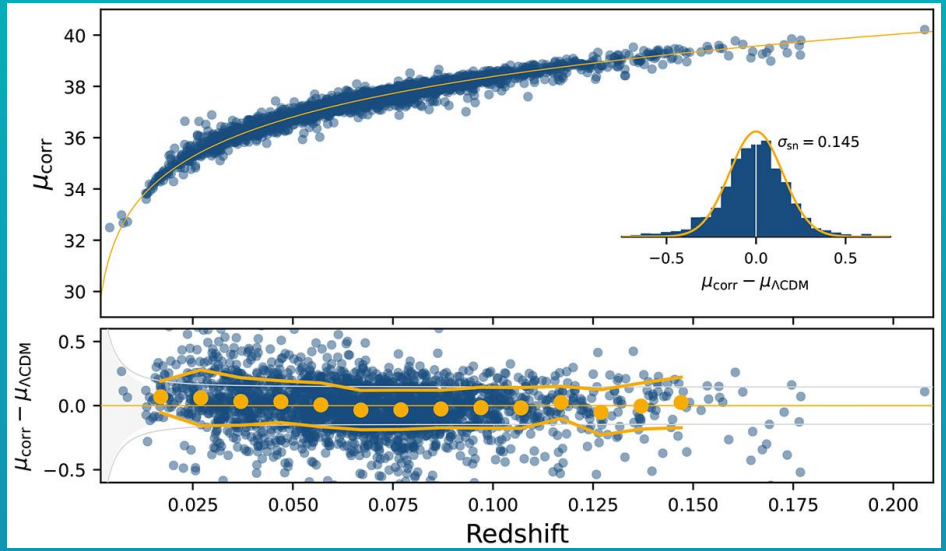


The Zwicky Transient Facility SNIa Survey

- **Complete sample** for z~0.06
- A fully spectroscopically classified sample of ~3k. events
- High cadence and light-curve coverage
- Many more *photometrically* classified SNIa

Certainly the best low-z SNIa anchor sample for the future in cosmology





ZTF Hubble Diagram with 2646 spectroscopically confirmed SNIa (arbitrary zeropoint).
Rigault et al. 2025

Cutting Edge Technology for a New Era

Olivier Bonin/SLAC National Accelerator Laboratory

LSST Camera

Largest digital camera ever (3200 Mpx)
6 filters, near-ultraviolet to near-infrared

Simonyi Survey Telescope

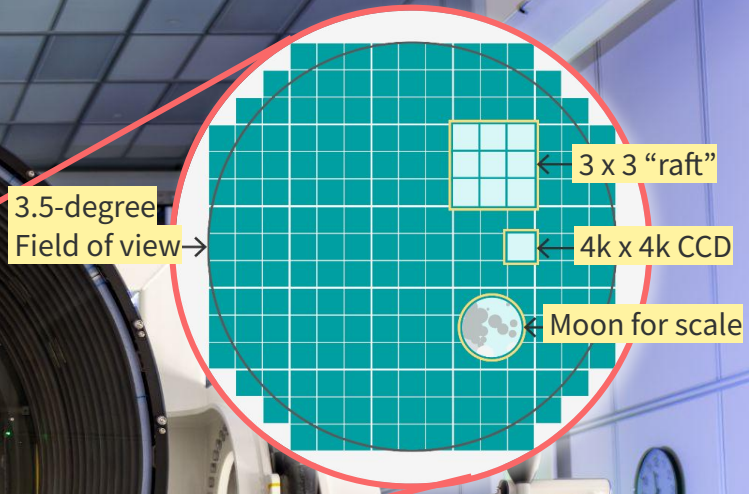
Novel three-mirror design = fast
Full-sky scan every 3-4 nights

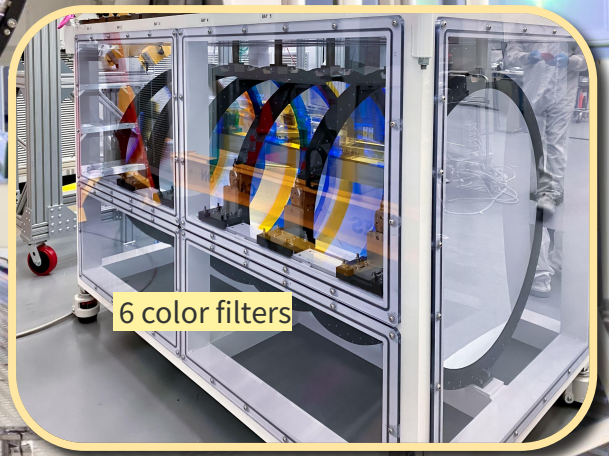
Global Data Management System

20 TB/night transferred to US, France, UK
~10 million changes identified each night

LSST Camera

- **Largest camera in the world**
  ★ 3200 megapixels ★
- 400 Ultra HD TV screens needed to display a single image
- Field of view = ~45 times the area of the full moon
- 6 color filters spanning UV to near-infrared





J. Orrell/SLAC National Accelerator Laboratory

Simonyi Survey Telescope

- 2-in-1 primary/tertiary mirror — first of its kind
- Compact telescope quickly moves 300 tons of steel + optical equipment
- Automated (with oversight)
- Large aperture & high reflectivity to detect faint objects

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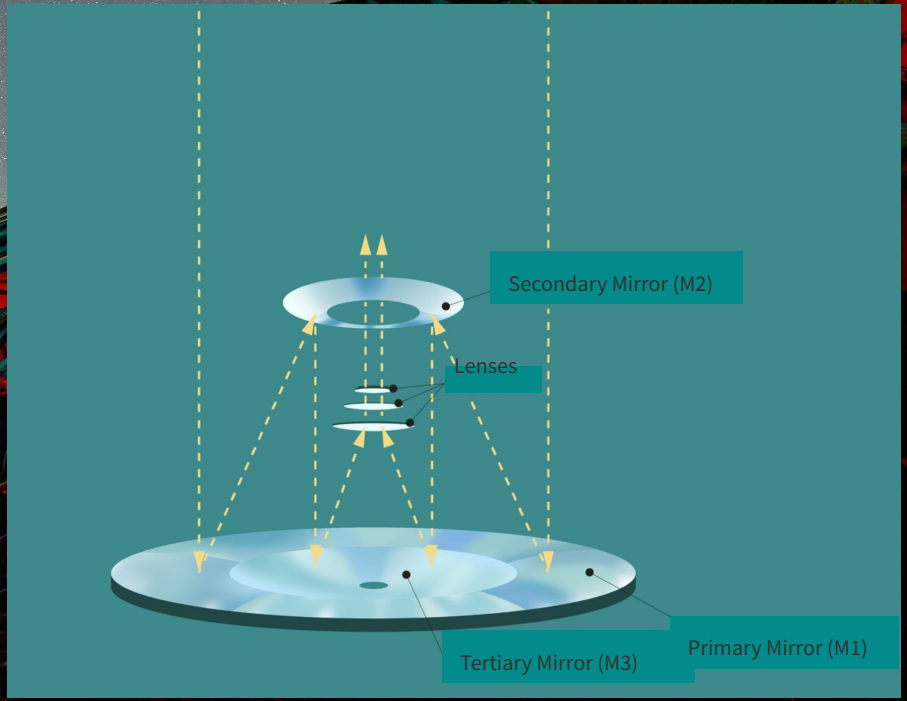
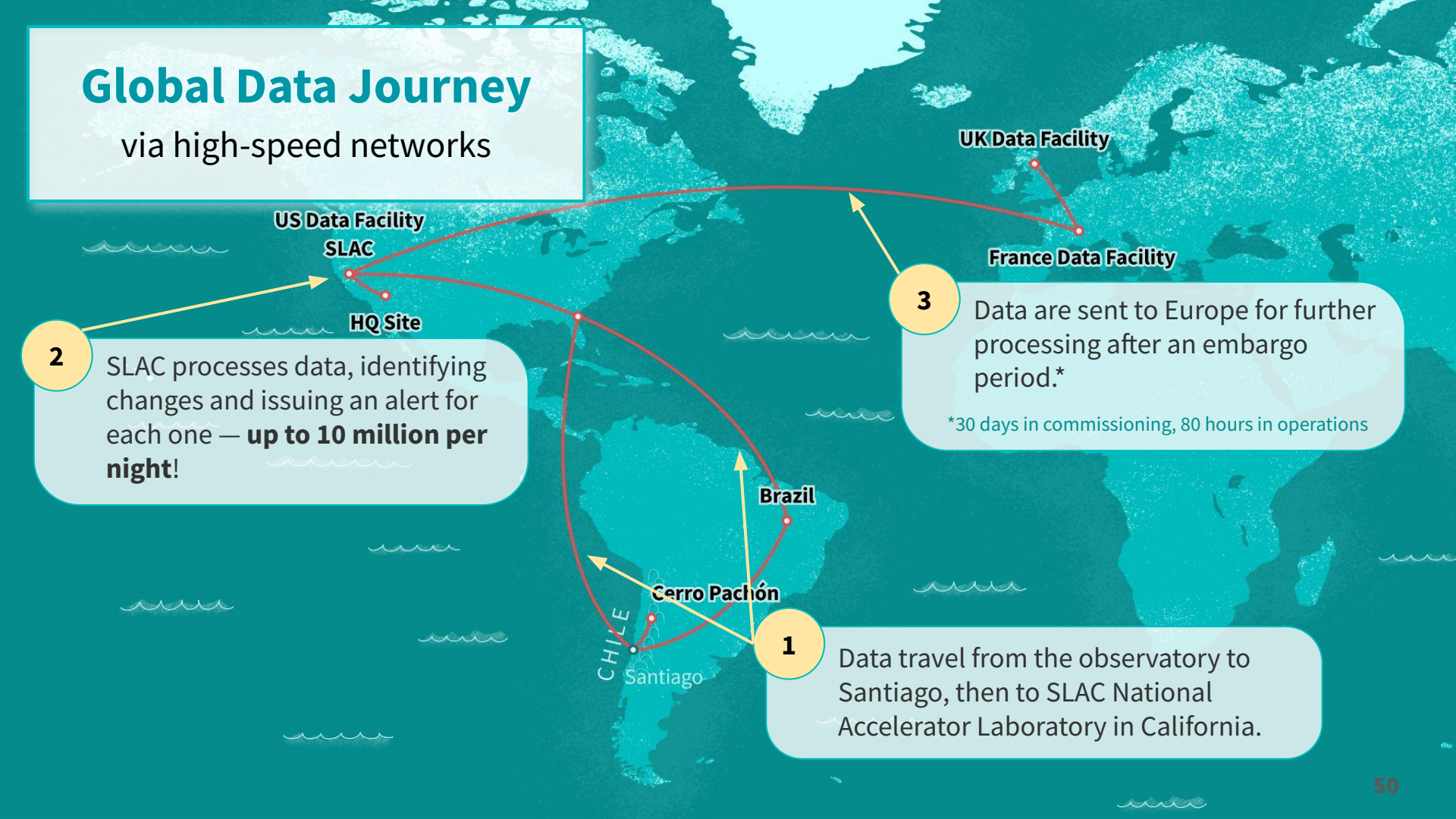


Global Data Journey

via high-speed networks



1 Data travel from the observatory to Santiago, then to SLAC National Accelerator Laboratory in California.

2 SLAC processes data, identifying changes and issuing an alert for each one — **up to 10 million per night**!

3 Data are sent to Europe for further processing after an embargo period.*

*30 days in commissioning, 80 hours in operations

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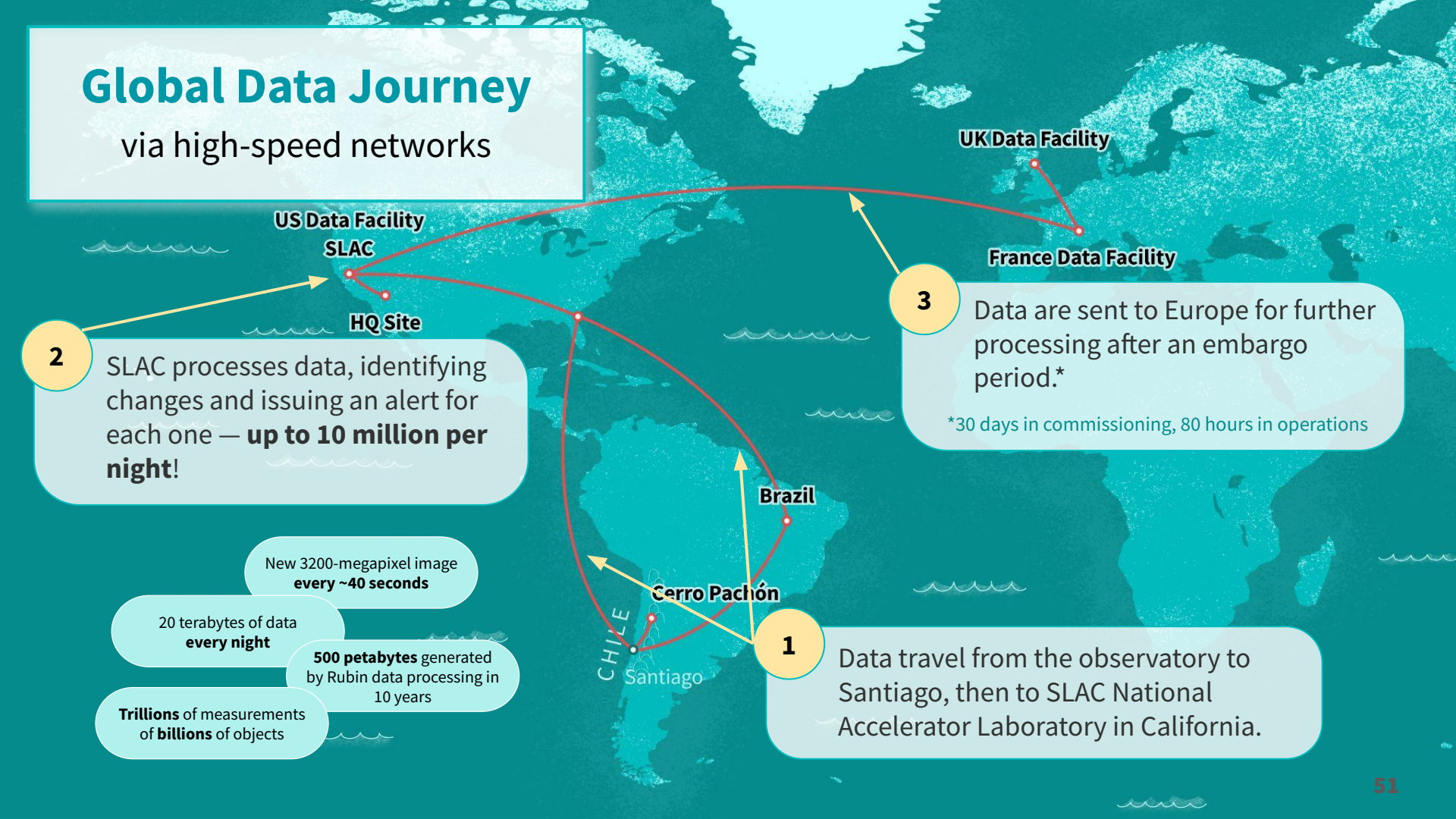

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*30 days in commissioning, 80 hours in operations

New 3200-megapixel image **every ~40 seconds**

20 terabytes of data **every night**

500 petabytes generated by Rubin data processing in 10 years

Trillions of measurements of **billions** of objects

Fast Data for a Dynamic Universe

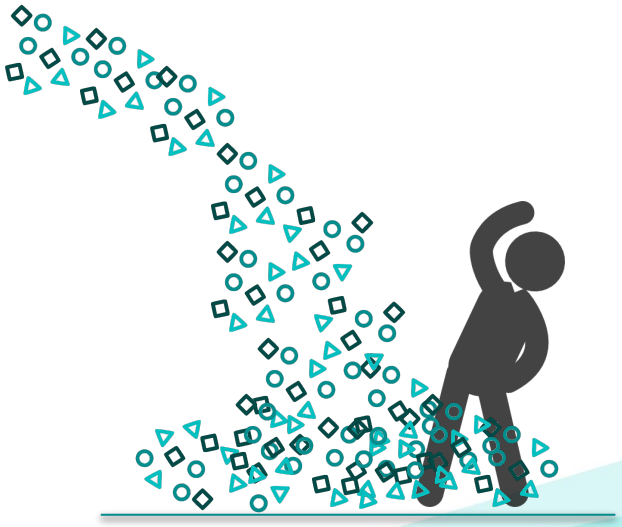
Produced by Rubin

Prompt Products

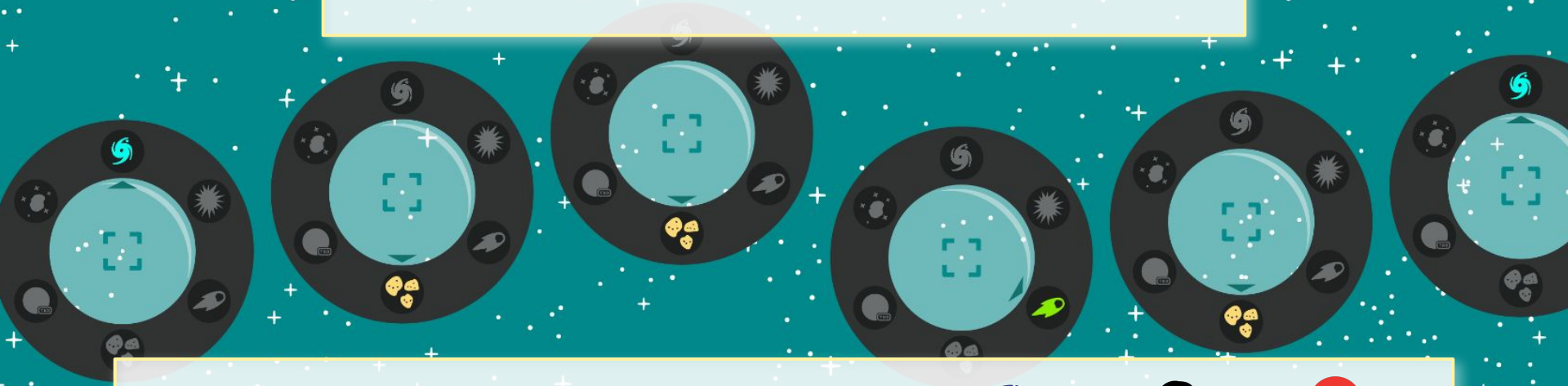
Near-real-time processed data released within minutes to days

- **Alerts (within minutes):** Notify scientists of detected sky changes
- **Catalogs (~24 hours):** Databases of information about detected objects
- **Raw & Processed Images (~80 hours):** Available to data-rights holders

Up to 10 million alerts per night
Alert stream or alert tsunami?



Navigating the Alert Stream



- To manage, Rubin uses **community brokers** — software systems that process & serve alerts to scientists
- Scientists access alerts via broker websites & can filter on their research area
- Alerts are **world public**

Alerce

Antares

AMPEL

Fink

Lasair

Babamul

Pitt-Google Broker

Vast Data for a Deep Universe

Produced by Rubin

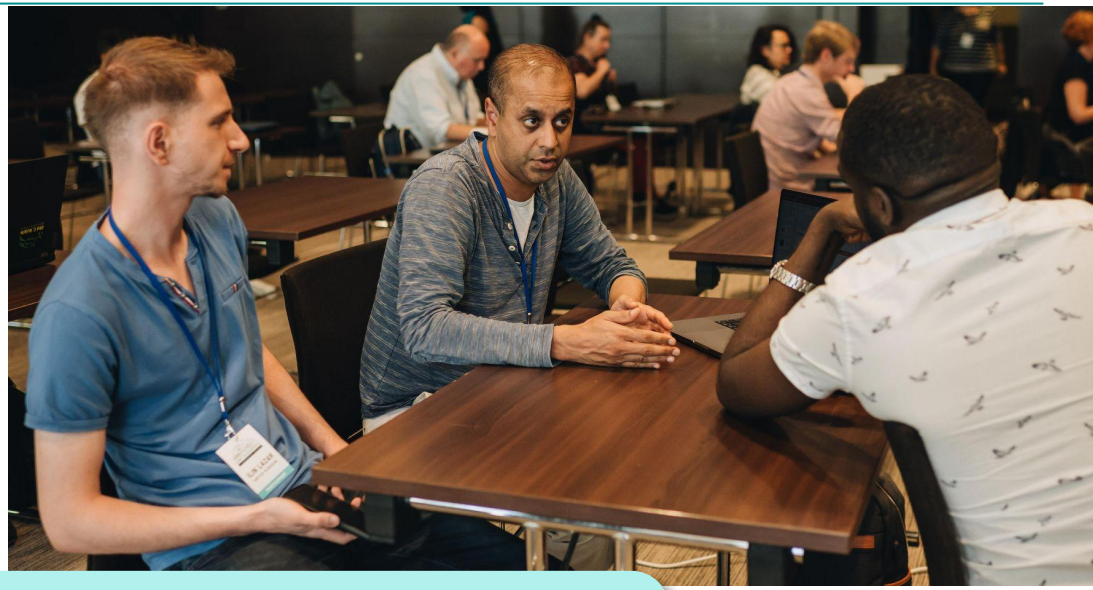
Annual Data Releases

Calibrated images and catalogs of billions of objects, including positions, shapes, and brightness

1. Take all data collected to date
2. Combine to emulate longer exposures…
3. …to reveal fainter objects and extract most info possible

Data for Everyone, Everywhere

- Making data **accessible to everyone**
- Enabling scientists from **all over the world and all backgrounds** to participate
- Volunteers **around the world** will contribute via Zooniverse **citizen science**



Scientists at LSST@Europe5 in 2023
Credit: LSST-DA/T. Licul

This is the first time this much astronomical data will be available to so many people

Rubin Education and Public Outreach (EPO)

Rubin data isn't just for scientists…it's for everyone!

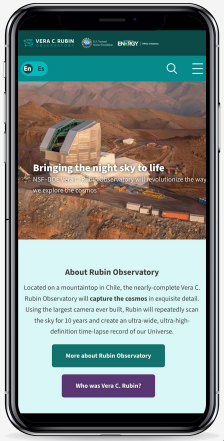
Rubin's EPO program provides online opportunities for engagement:

Formal education

Free, online, classroom-ready materials for students

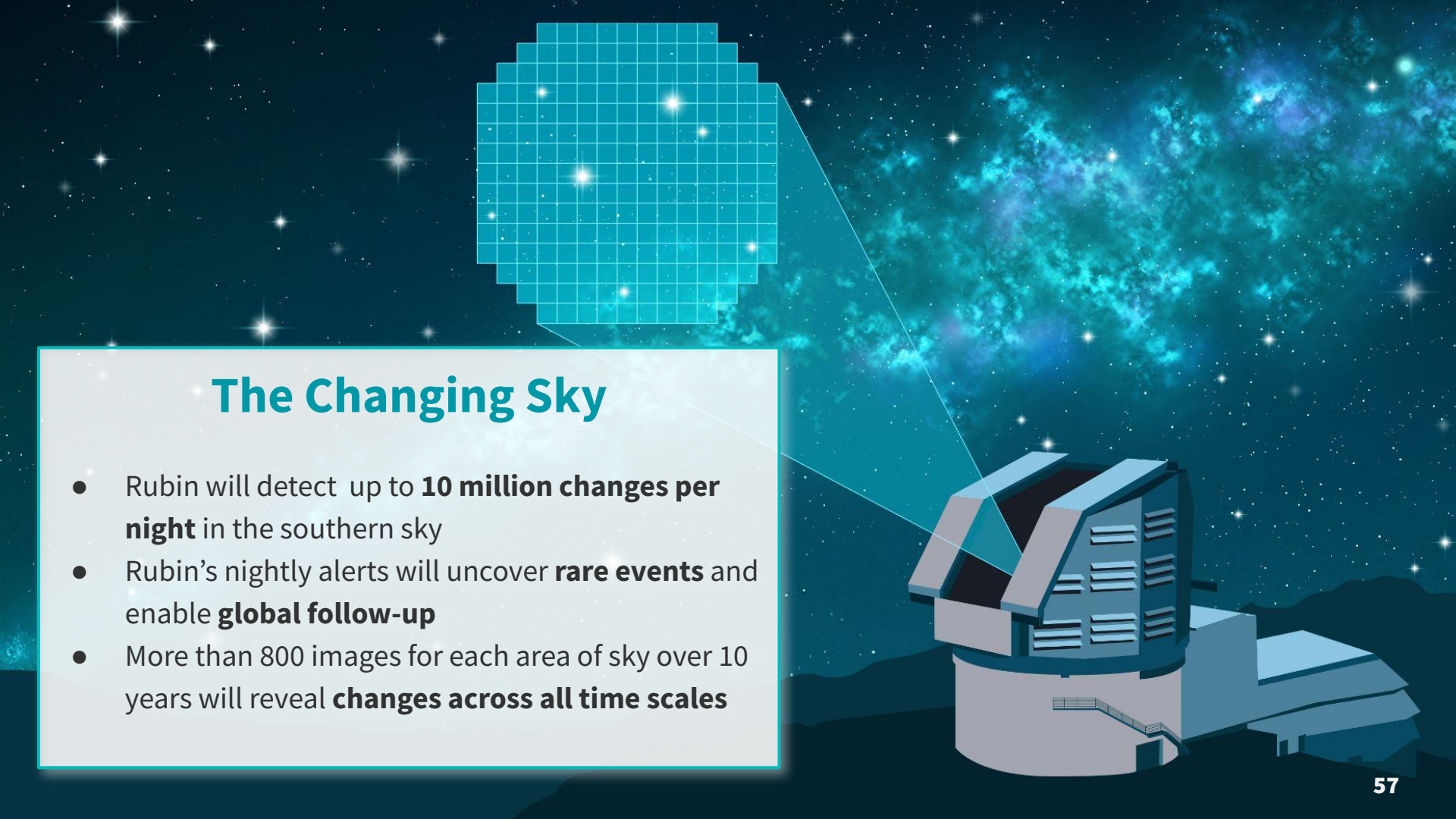
Public Outreach

Mobile-friendly website, visuals, videos, interactives, and more



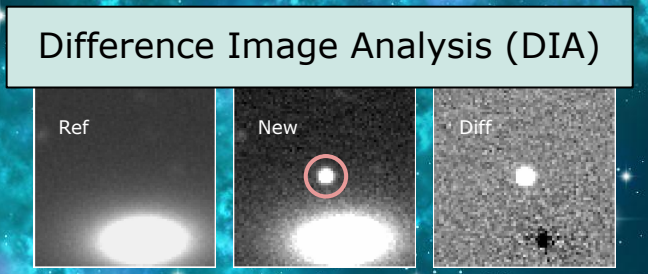
Citizen Science

Opportunities to contribute to Rubin research on Zooniverse



The Changing Sky

- Rubin will detect up to **10 million changes per night** in the southern sky
- Rubin's nightly alerts will uncover **rare events** and enable **global follow-up**
- More than 800 images for each area of sky over 10 years will reveal **changes across all time scales**



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