

Renovating Analysis Infrastructure for the Next Generation of Astronomical Surveys

Kaili Cao, B.A., M.S.

June 25, 2026



Blurred image: poster of the film 2001: A Space Odyssey (1968), in which a bone thrown into the air becomes a spacecraft.

© 2001: A Space Odyssey

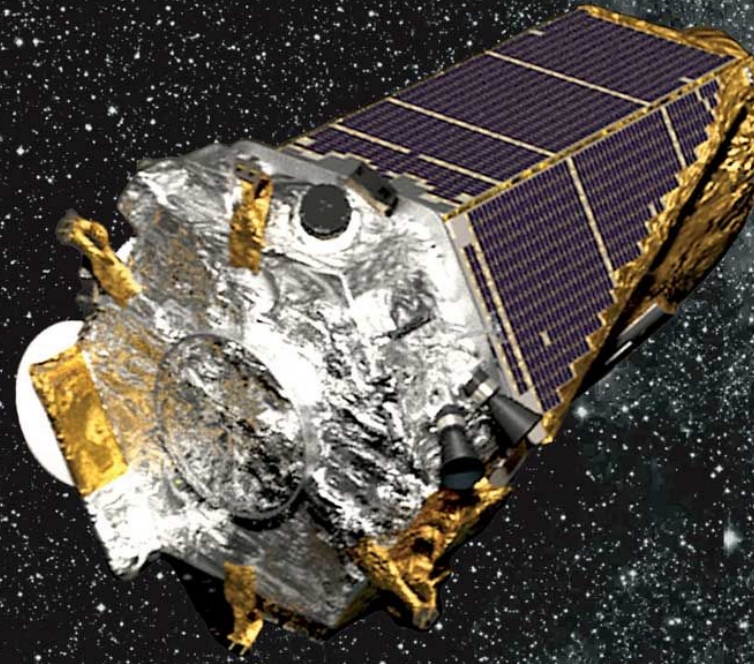
Introduction

Based on: Chapter 1



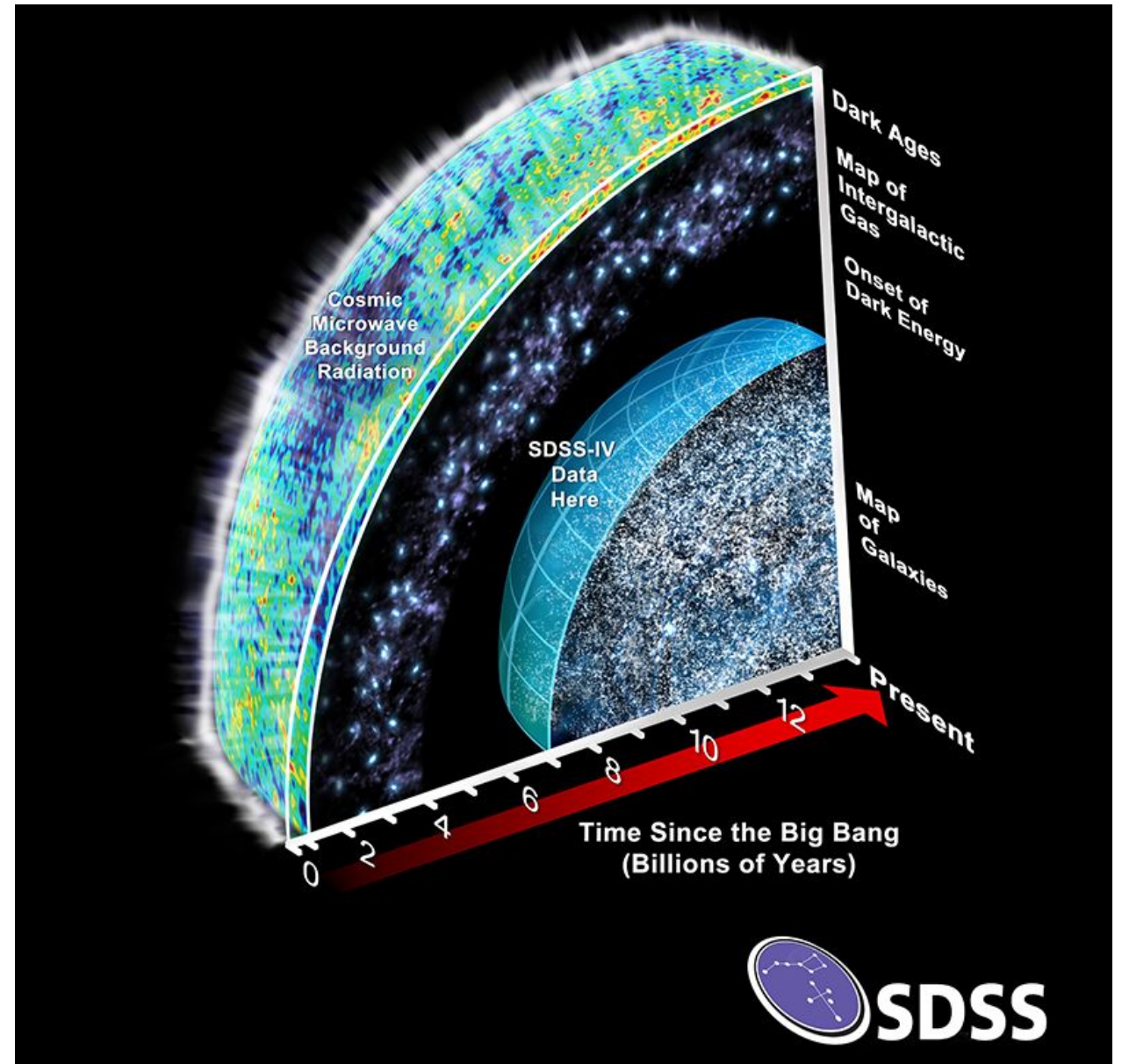
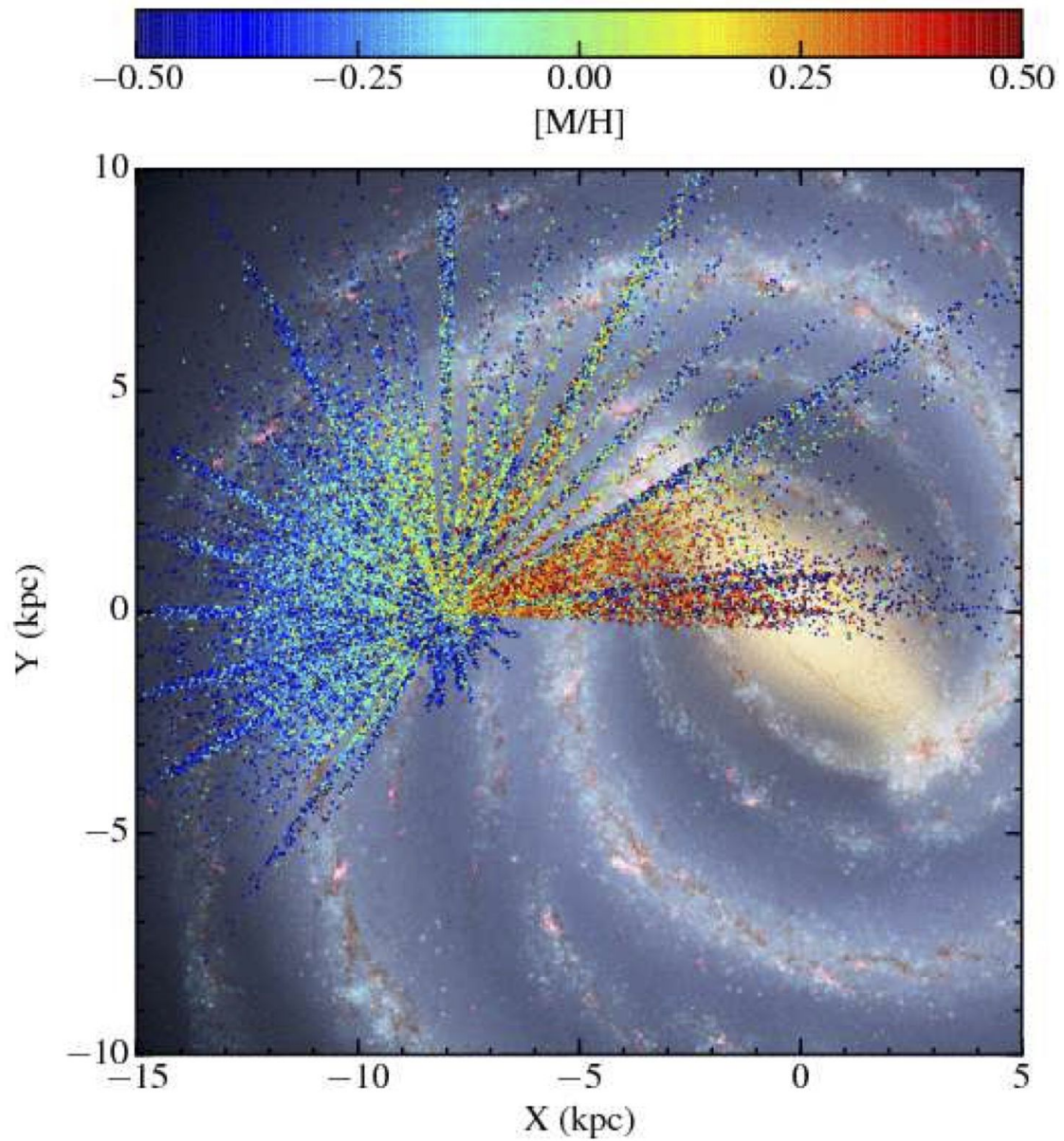


From Tycho Brahe to Johannes Kepler

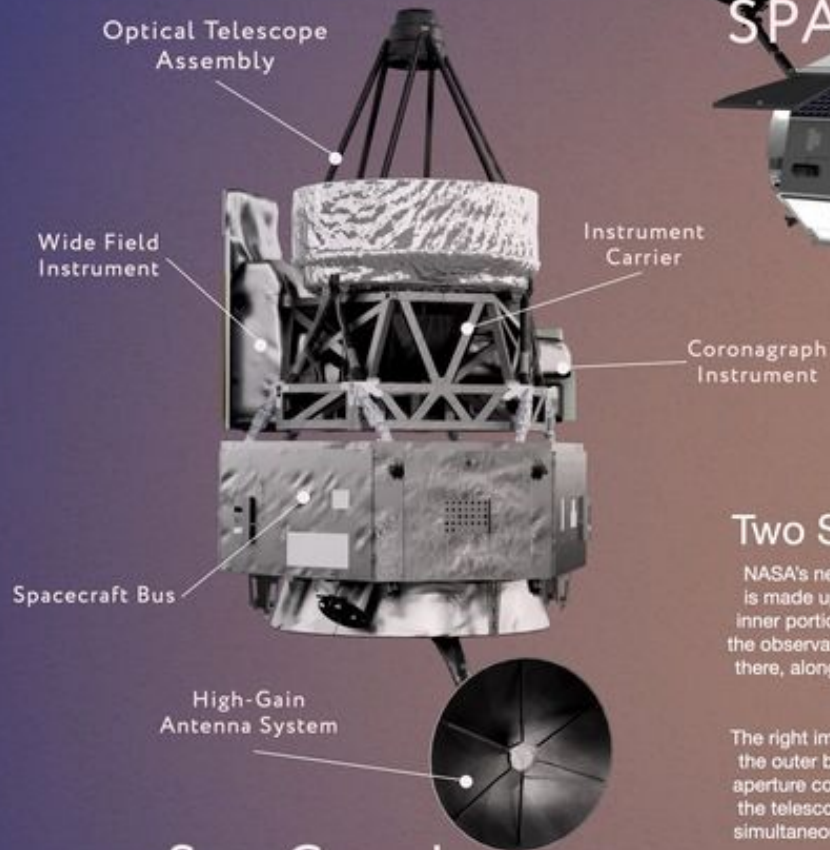


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NANCY GRACE ROMAN SPACE TELESCOPE



SPACECRAFT INTEGRATED
PAYLOAD ASSEMBLY



Solar Array Sun Shield

Deployable Aperture Cover

Outer Barrel Assembly

Two Systems, One Observatory

NASA's nearly complete Nancy Grace Roman Space Telescope is made up of two major subsystems. The left image shows the inner portion, SCIPA. It consists of the spacecraft that will deliver the observatory to its place in space and enable it to function while there, along with the integrated payload assembly (the telescope, instrument carrier, and two instruments).

The right image shows the outer part, called OSD. It is made up of the outer barrel assembly, solar array sun shield, and deployable aperture cover — components that will shade, power, and protect the telescope and instruments. Technicians built the subsystems simultaneously and are running each through a suite of tests prior to joining them together.



OUTER BARREL ASSEMBLY
SOLAR ARRAY SUN SHIELD
DEPLOYABLE APERTURE COVER

Why do I want
to “renovate
analysis
infrastructure
for the next
generation of
astronomical
surveys,” and
how do I do it?

Blurred image: an AI-generated illustration of a spiral galaxy surrounded by charts and data.

© XQ, DALLE3 or Midjourney

To be
collected in
Scene 1

To be collected in Scene 2

Blurred image: the Infinity Gauntlet
holding the six Infinity Stones, from
the film Avengers: Endgame (2019).

To be
collected in
Scene 3

© Marvel, MJLogan95



Blurred image: the Avengers traveling back in time through a quantum tunnel, from the film Avengers: Endgame (2019).

Scene 1: Intersection of Kepler Seismology and APOGEE Spectroscopy (2022)

Based on: Chapters 2 and 3



The Red Giant Branch (RGB)

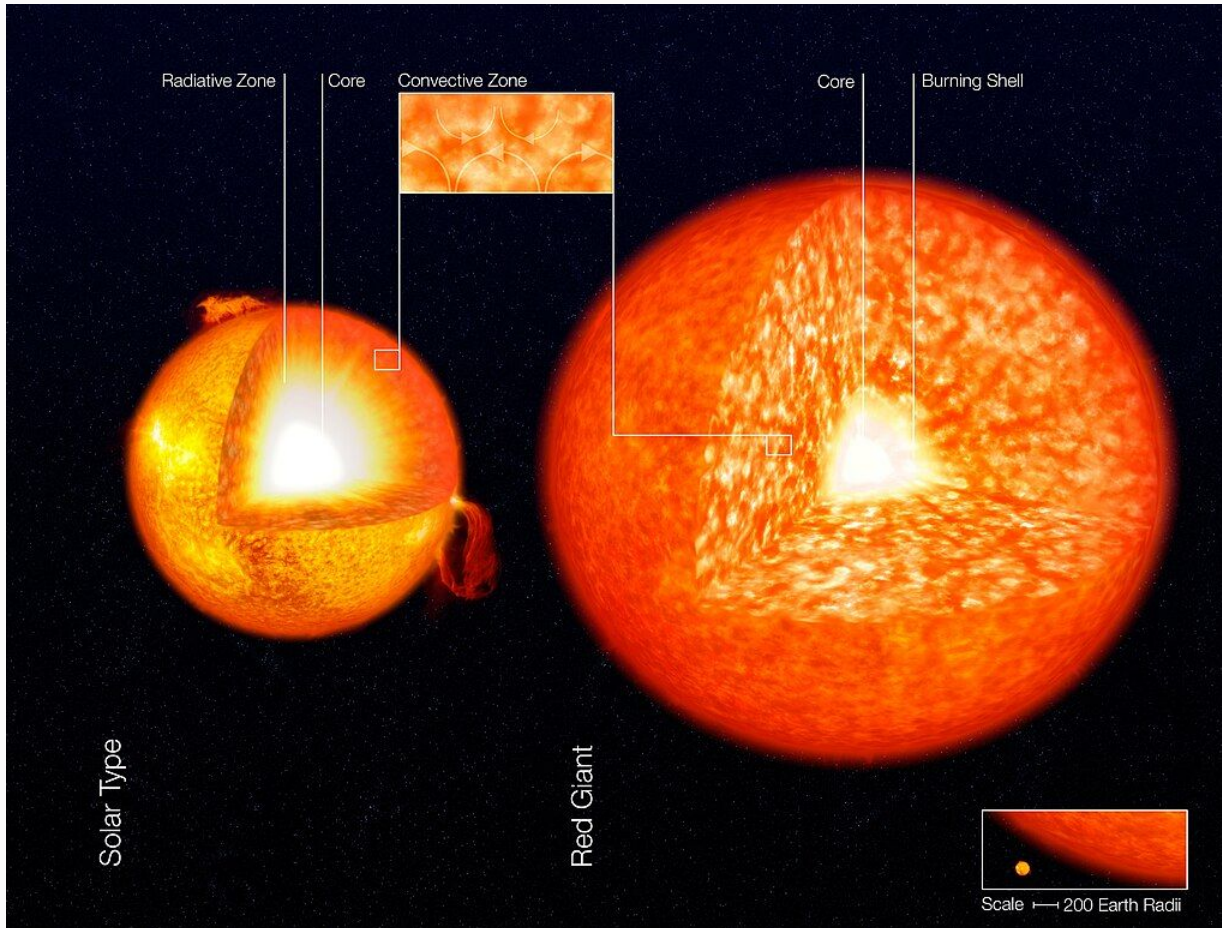
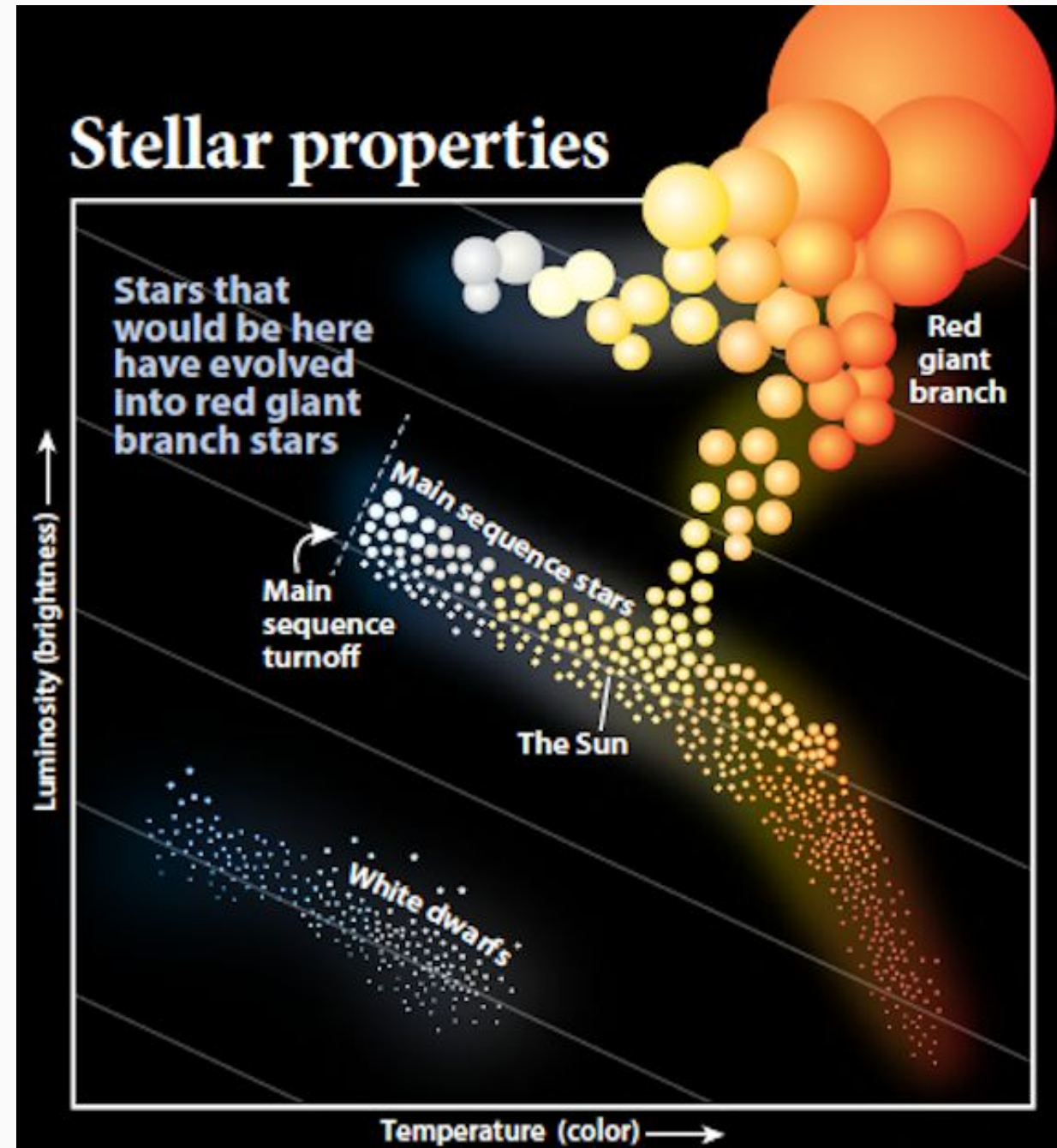


Image Credits: ESO (↗) / Roen Kelly (→)

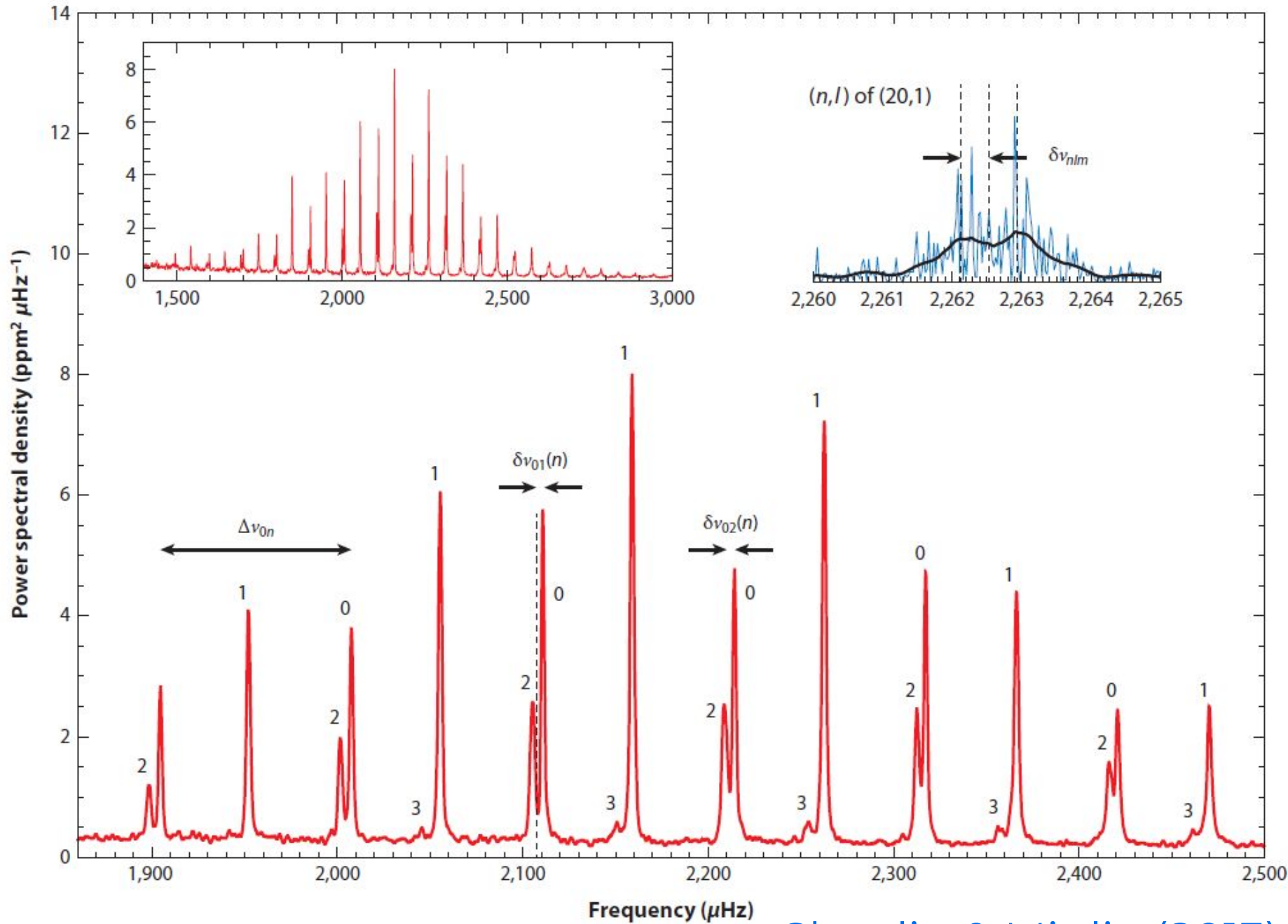


Astro- seismology

Two figures of merit:

- Frequency of the maximum power – ν_{max}
- Large-frequency spacing – $\Delta\nu$

that give us mass,
radius, (surface
gravity, mean
density,) and age!



Chaplin & Miglio (2013)

Spectroscopy

- Effective temperature
- Surface chemical composition
- Surface gravity (less precise)
- Atmospheric microturbulence

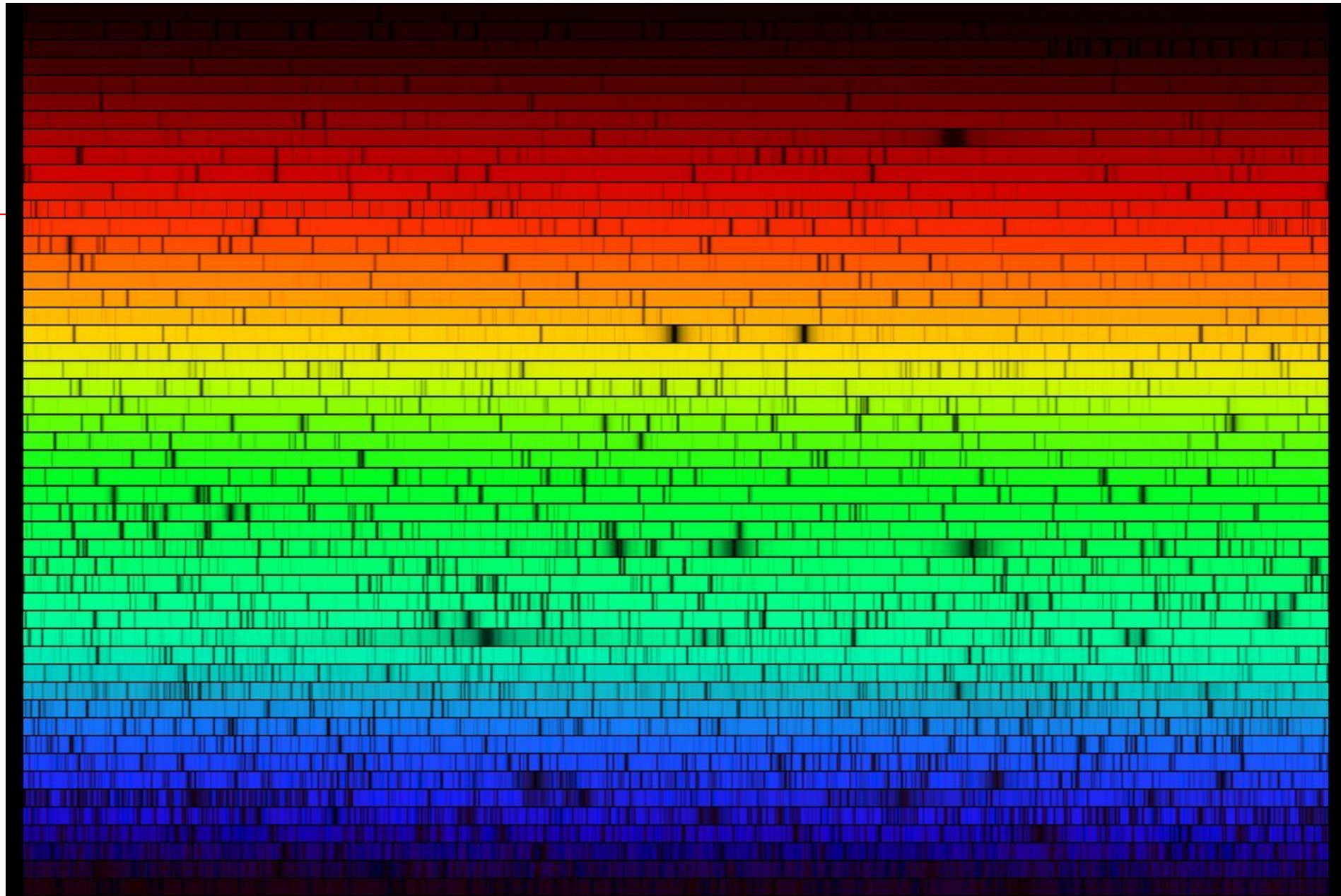
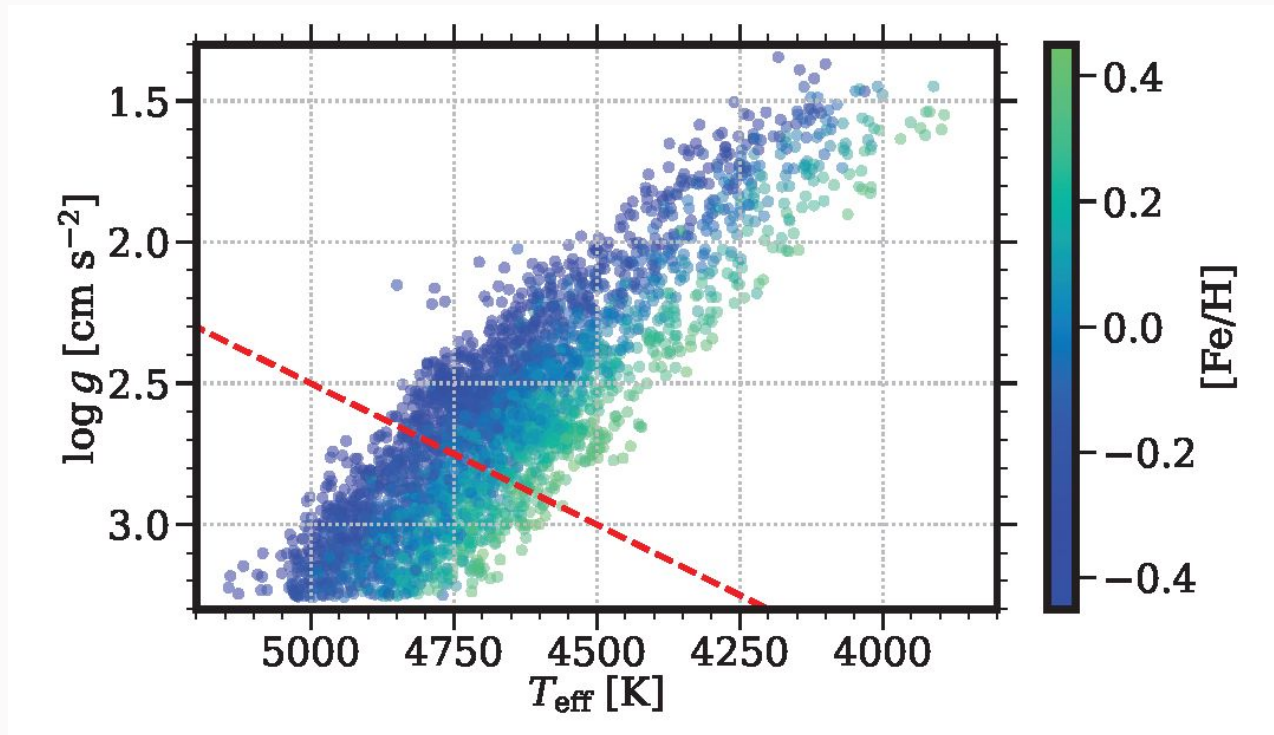


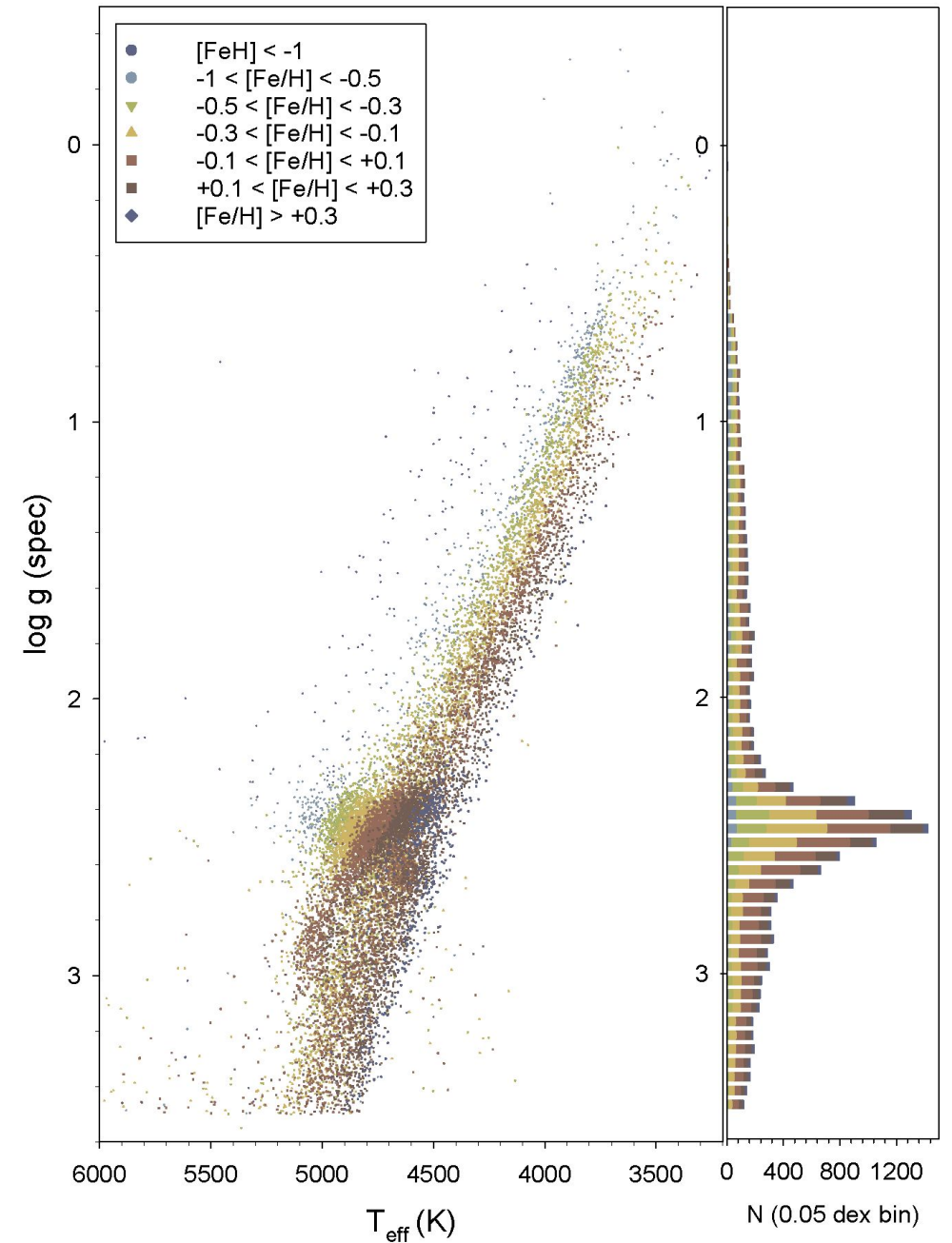
Image Credit: N.A. Sharp/KPNO/NOIRLab/NSO/NSF/AURA

The Red Giant Branch Bump (RGG)



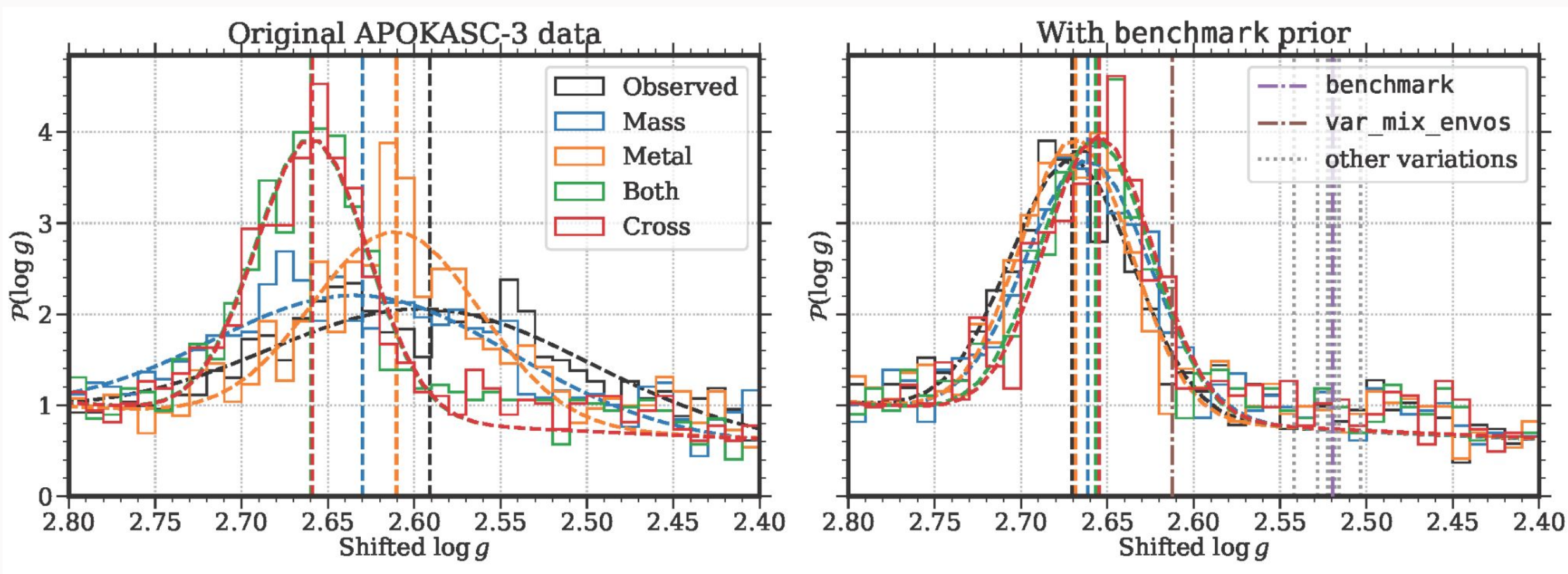
↑: [Cao & Pinsonneault \(2026\)](#)

→: [Pinsonneault et al. \(2025\)](#)



RGBB: Stacking Analysis

Left: Detrending by fitting
Right: Detrending by theory
[Cao & Pinsonneault \(2026\)](#)



Let's **throw down** the gauntlet.

Blurred image: the Infinity Gauntlet holding the six Infinity Stones, from the film Avengers: Endgame (2019).

© Marvel, MJLogan95



Lithium Depletion

Data from APO-K2

Fractions of Li detections

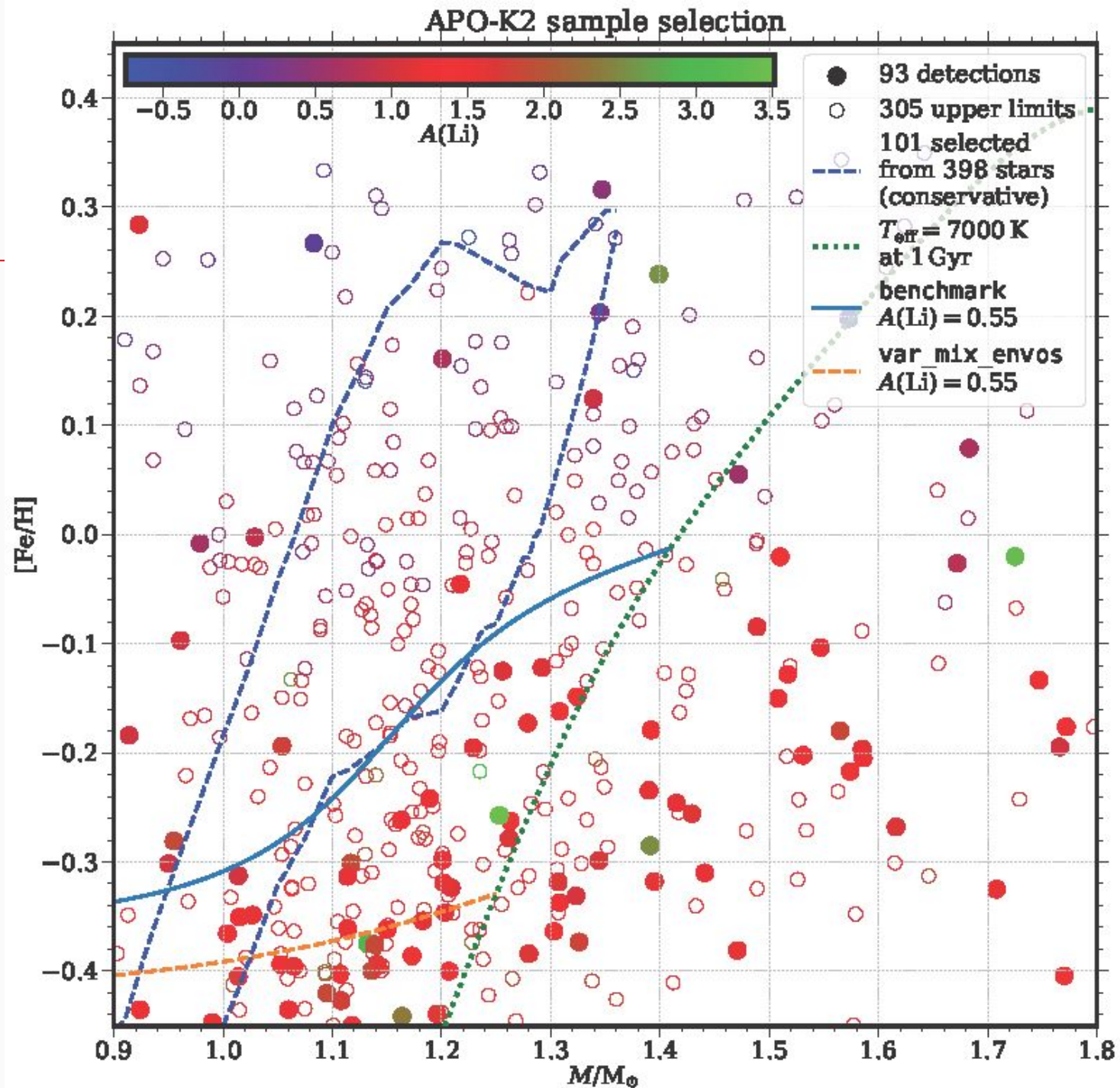
Upper left: $16/176 = 9.09\%$

Middle left: $21/87 = 24.14\%$

Lower left: $21/43 = 48.84\%$

Right: Other mechanisms?

[Cao & Pinsonneault \(2026\)](#)



Correction

Scaling Relations

$$\frac{M_{\text{seis}}}{M_{\odot}} = f_{\nu_{\text{max}}}^3 \left(\frac{\nu_{\text{max}}}{\nu_{\text{max},\odot}} \right)^3 \left(\frac{f_{\Delta\nu} \Delta\nu}{\Delta\nu_{\odot}} \right)^{-4} \left(\frac{T_{\text{eff}}}{T_{\text{eff},\odot}} \right)^{1.5}$$

$$\frac{R_{\text{seis}}}{R_{\odot}} = f_{\nu_{\text{max}}} \left(\frac{\nu_{\text{max}}}{\nu_{\text{max},\odot}} \right) \left(\frac{f_{\Delta\nu} \Delta\nu}{\Delta\nu_{\odot}} \right)^{-2} \left(\frac{T_{\text{eff}}}{T_{\text{eff},\odot}} \right)^{0.5}$$

Correction Factors

- ν_{max} comes from reference system.
- $f_{\Delta\nu}$ comes from theoretical models.

APOKASC-3

$$\left\langle f_{\nu_{\text{max}}} \left(\frac{\nu_{\text{max}}}{\nu_{\text{max},\odot}} \right) \left(\frac{f_{\Delta\nu} \Delta\nu}{\Delta\nu_{\odot}} \right)^{-2} \left(\frac{T_{\text{eff}}}{T_{\text{eff},\odot}} \right)^{0.5} \right\rangle = \frac{\langle R_{\text{Gaia}} \rangle}{R_{\odot}}$$

- Assuming theoretical $f_{\Delta\nu}$ is perfect.

This Work

$$\left\langle f_R \left(\frac{\nu_{\text{max}}}{\nu_{\text{max},\odot}} \right) \left(\frac{f_{\Delta\nu} \Delta\nu}{\Delta\nu_{\odot}} \right)^{-2} \left(\frac{T_{\text{eff}}}{T_{\text{eff},\odot}} \right)^{0.5} \right\rangle = \frac{\langle R_{\text{Gaia}} \rangle}{R_{\odot}}$$

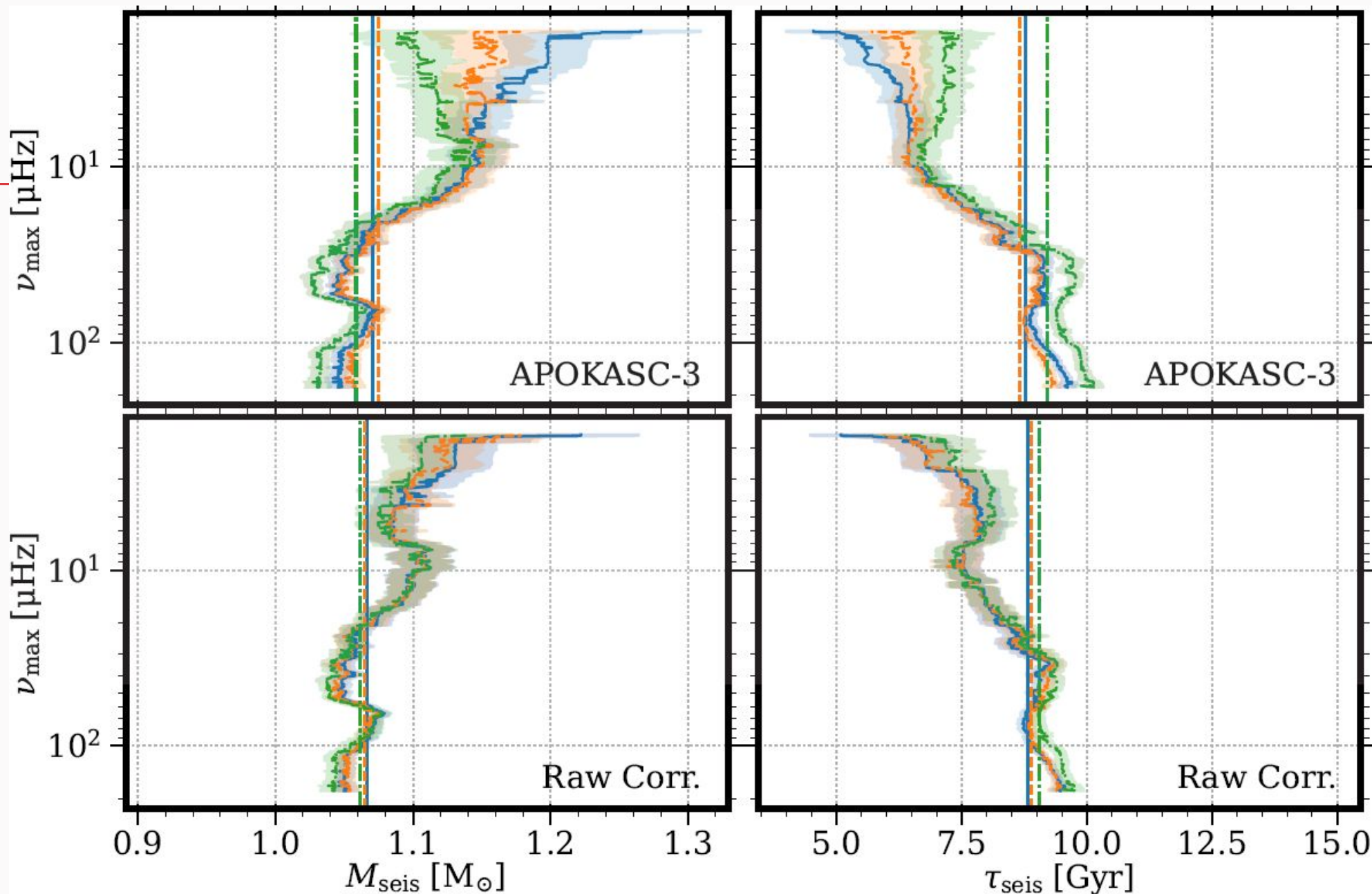
- Assuming gravity error is small.

Figure 2 (Part 1.5)

Dual reduction
in systematics:

Consistency
between
methods

Agreement
with vertical
lines (medians)



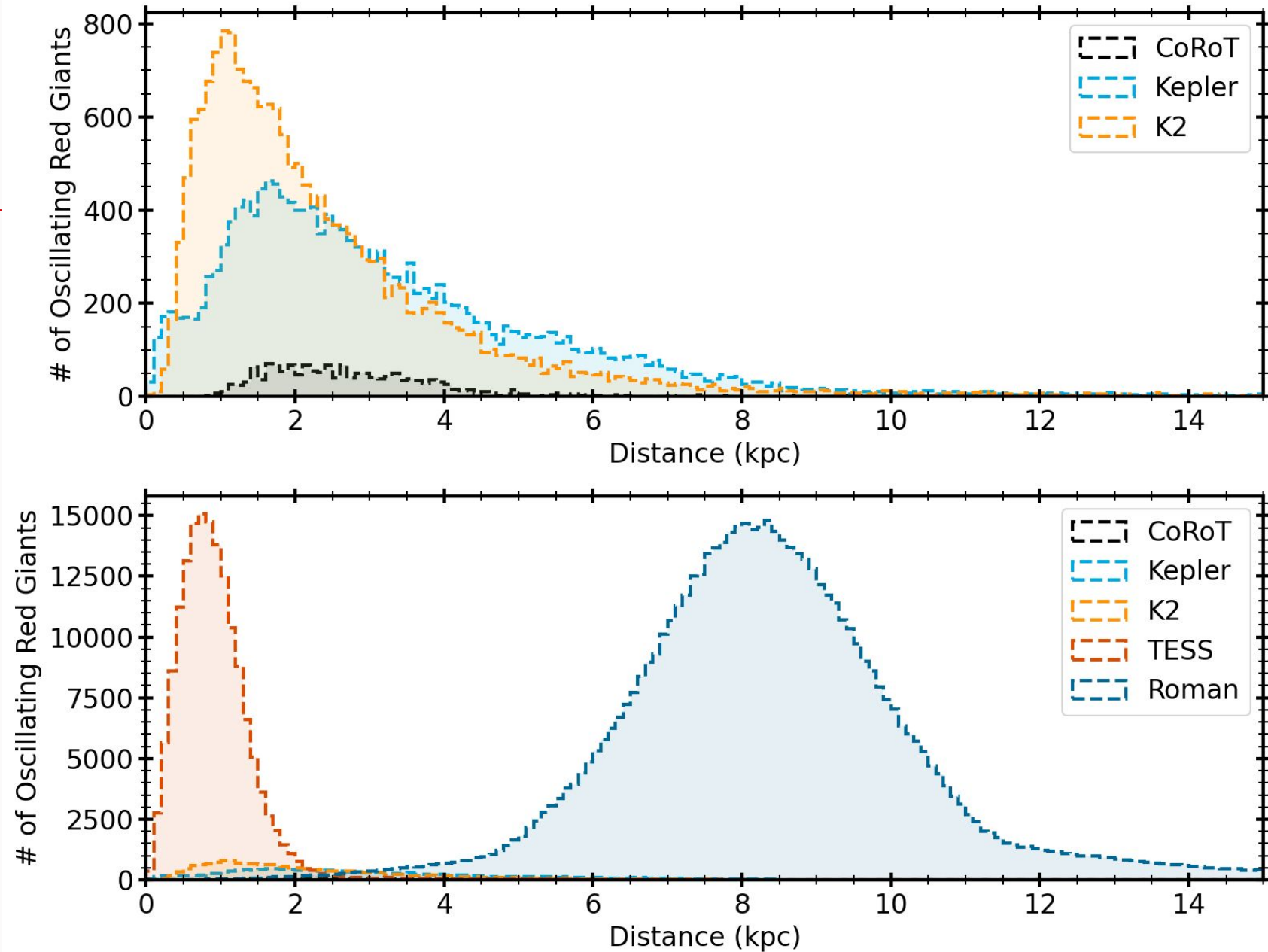
Roman Astero-seismology

Larger number of
oscillating red giants

In the Galactic Bulge
and Galactic Center
fields

[Huber et al. \(2023\)](#)

[Weiss et al. \(2025\)](#)



To be collected in Scene 2

Asteroseismology
– DynFlux

Stellar Modeling
– ContStar

Blurred image: the Infinity Gauntlet holding the six Infinity Stones, from the film Avengers: Endgame (2019).

To be collected in Scene 3

© Marvel, MJLogan95



Blurred image: the Avengers traveling back in time through a quantum tunnel, from the film Avengers: Endgame (2019).

Scene 2: Interface between Undersampled and Oversampled Images (2023)

Based on: Chapters 4 to 6

HIGH-LATITUDE WIDE-AREA SURVEY



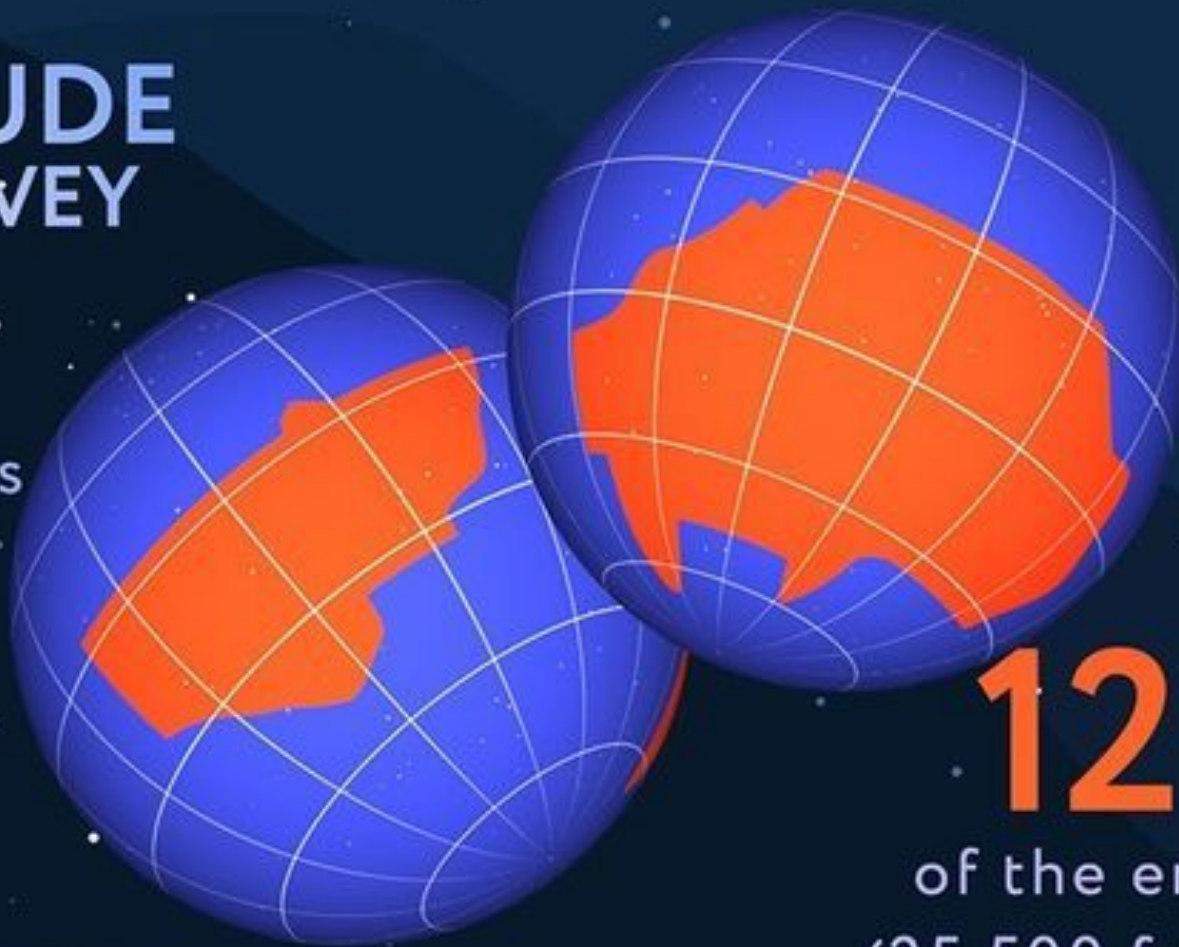
520 days over five years



Exposure times from
11 to 150 minutes



5,100 square degrees



12%

of the entire sky
(25,500 full moons)



Dark Energy



Dark Matter



Galaxies



Solar System

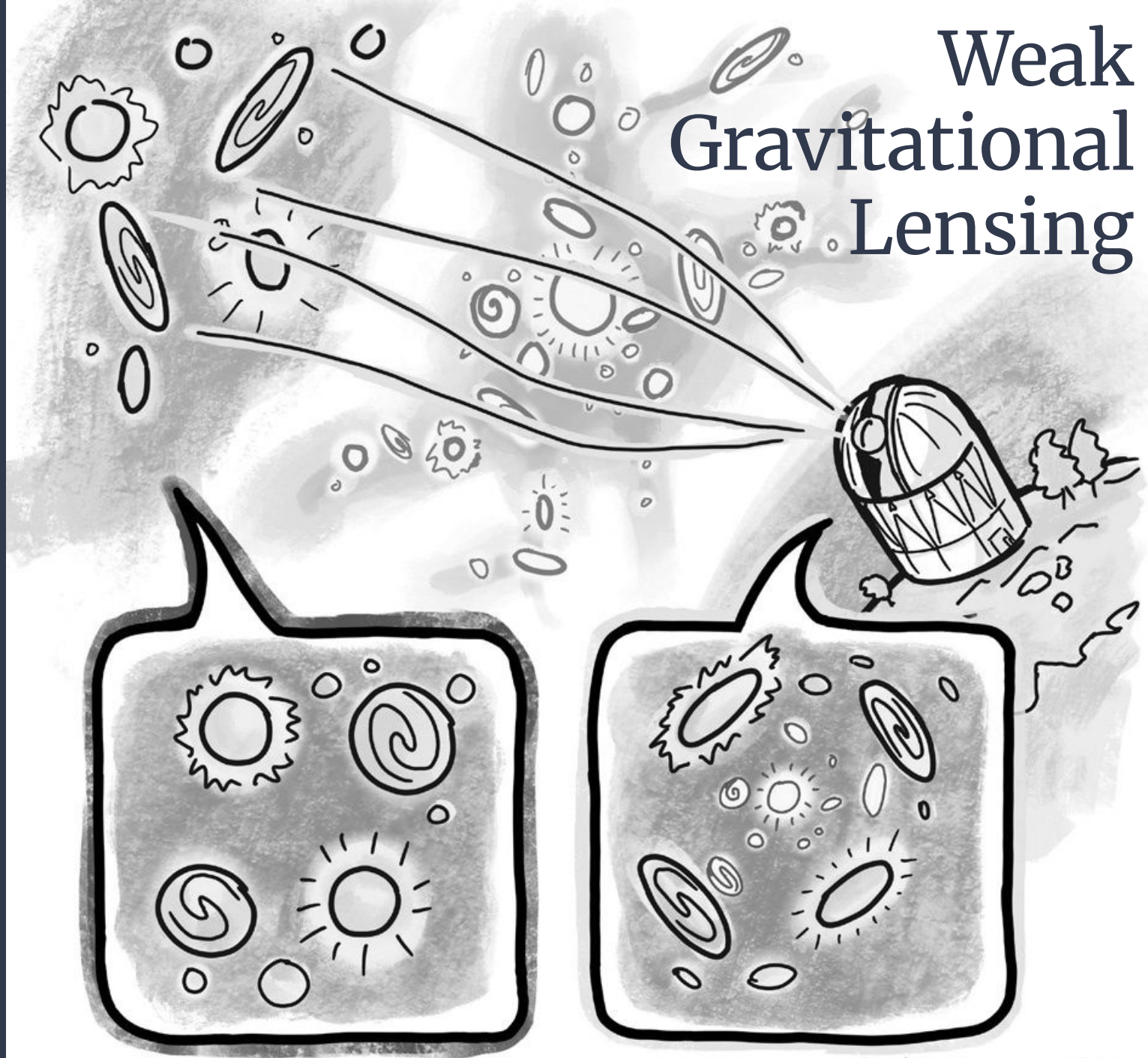


Milky Way

*Credit: NASA's
Goddard Space
Flight Center*

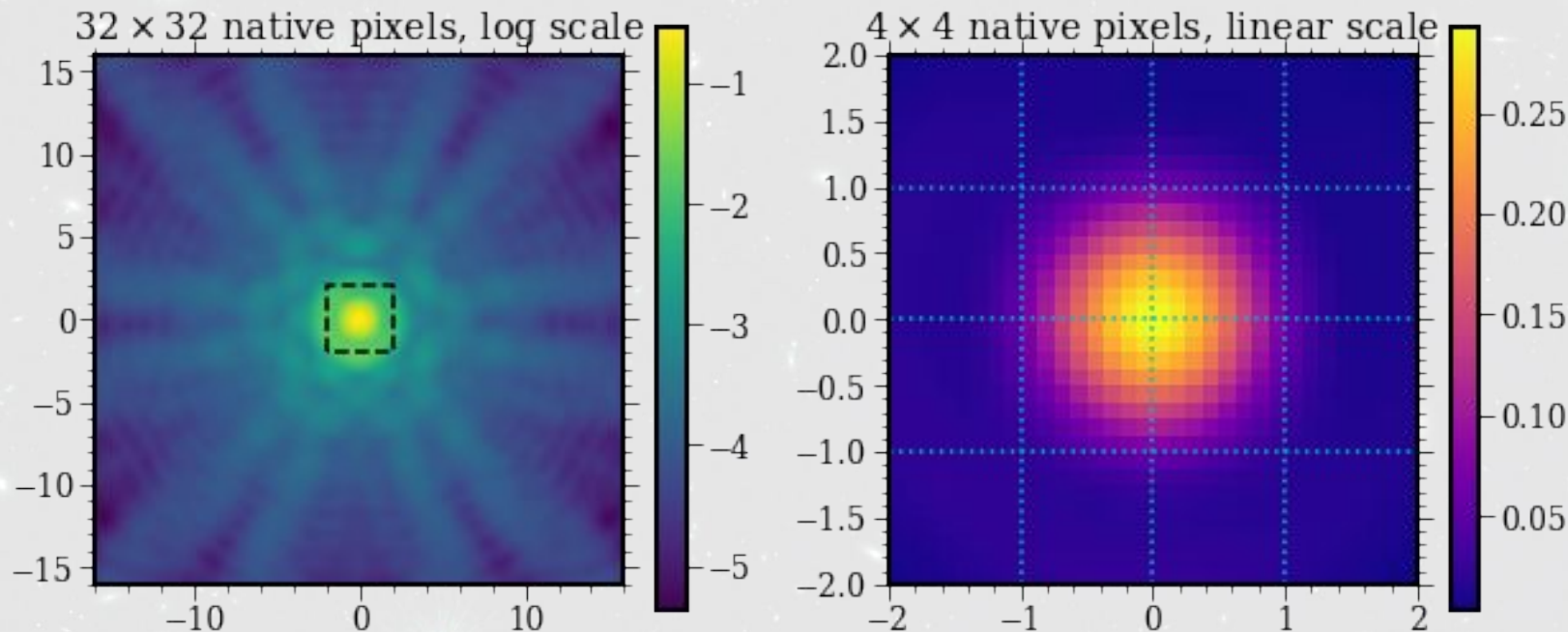
Our Project
Infrastructure
Team:
Maximizing
Cosmological
Science with the
Roman High
Latitude Imaging
Survey

Weak
Gravitational
Lensing



Why do we coadd images? – “Oversample, we must!”

- Roman point spread functions (PSFs)
 - = Airy disk ($\sim \lambda/D$) + linear obscuration + diffraction spikes + detector effects
 - An example in **Y106** band shown below



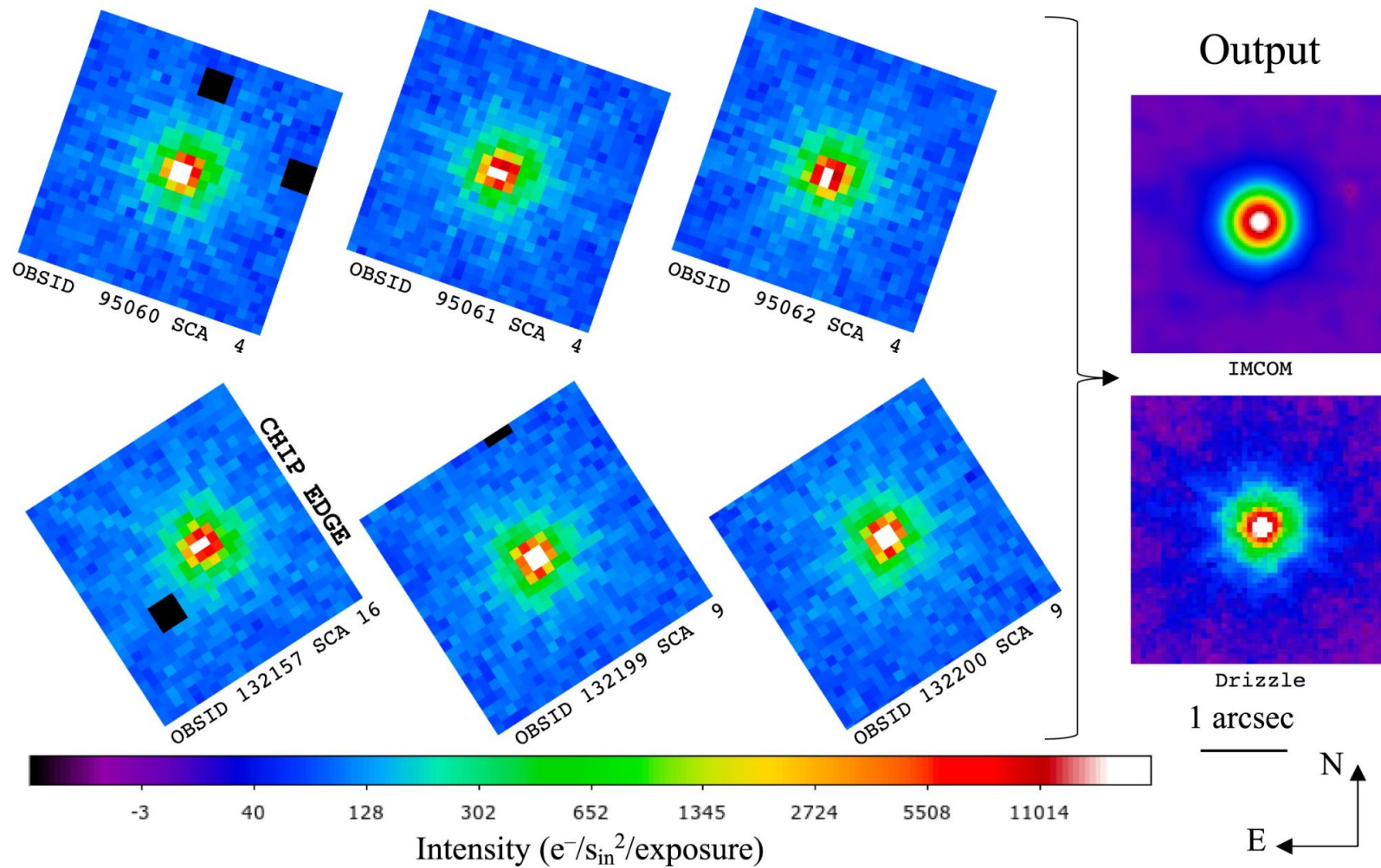
Blurred image: Master Yoda from Star Wars, holding a green lightsaber.

Image credits: Lucasfilm Ltd., Janson_G

How do we coadd images? – Through linear combinations.

- Linear combination of input **signals**:
$$H_{\alpha} = \sum_{i=0}^{n-1} T_{\alpha i} I_i$$
 - H : output signal, α : output pixel index, $\mathbf{R}_{\alpha}$: output pixel position
 - I : input signal, i : input pixel index, $\mathbf{r}_i$: input pixel position
 - T : coaddition weight, n : number of (selected) input pixels
- Linear combination of input **PSFs**:
$$\text{PSF}_{\alpha, \text{out}}(\mathbf{R}_{\alpha} - \mathbf{s}) = \sum_{i=0}^{n-1} T_{\alpha i} G_i(\mathbf{r}_i - \mathbf{s})$$
 - PSF_{out} : reconstructed output PSF, Γ : target output PSF
 - IMCOM minimizes discrepancy between PSF_{out} and Γ (“leakage”).

IMCOM (B. Rowe et al. 2011): Image Coaddition with Control over Output Point Spread Function



←: 3 dithers × 2 passes
(typical for Medium and
Wide Tiers of HLWAS)

↗: IMCOM (IMage
COMbination) – **optimal**
image coaddition

↘: Drizzle – **efficient**
image coaddition

*Credit: Figure 9 from
C. Hirata et al. 2024*

One day

Time to reconstruct a Roman WFI image $[(7.5 \text{ arcmin})^2]$
with a single CPU core using IMCOM.

One day →
Half an hour

Time to reconstruct a Roman WFI image $[(7.5 \text{ arcmin})^2]$
with a single CPU core using IMCOM → Effortless.

Collected in
Scene 1

Image Analysis
– Fetterless

Image Reconstruction
– Effortless

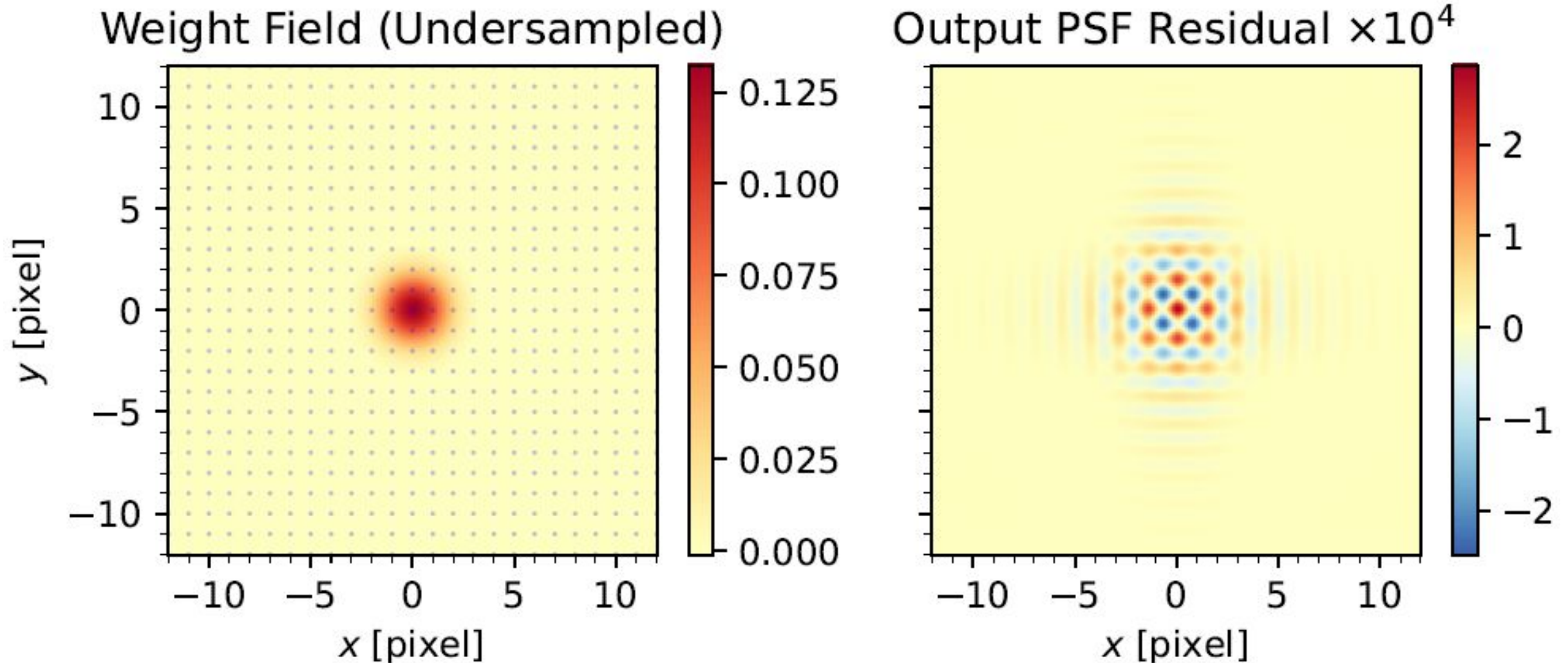
Blurred image: the Infinity Gauntlet
holding the six Infinity Stones, from
the film Avengers: Endgame (2019).

To be
collected in
Scene 3

© Marvel, MJLogan95



Foreseeable Future: Efficient Optimal Image Reconstruction with **Effortless** (Cao 2026*)

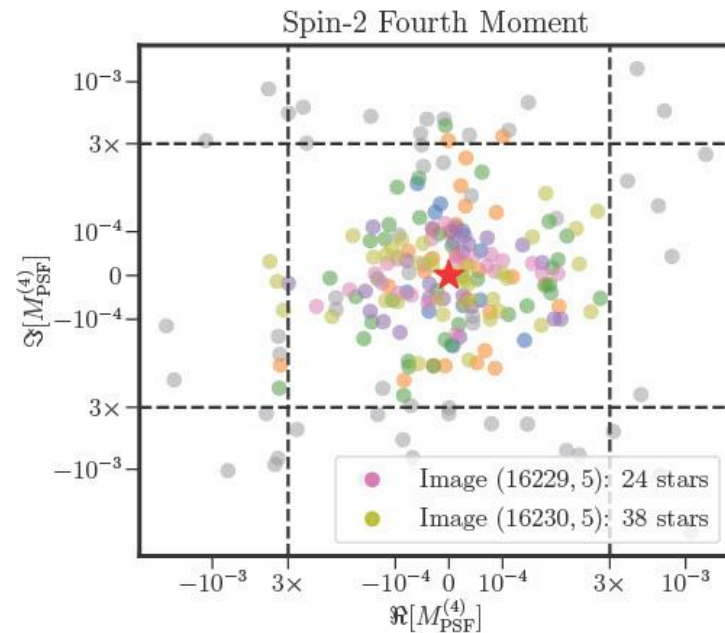
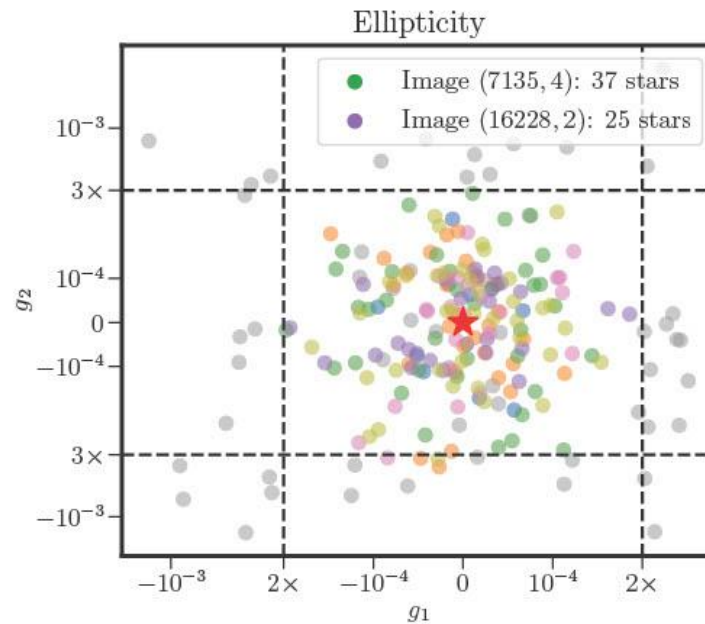
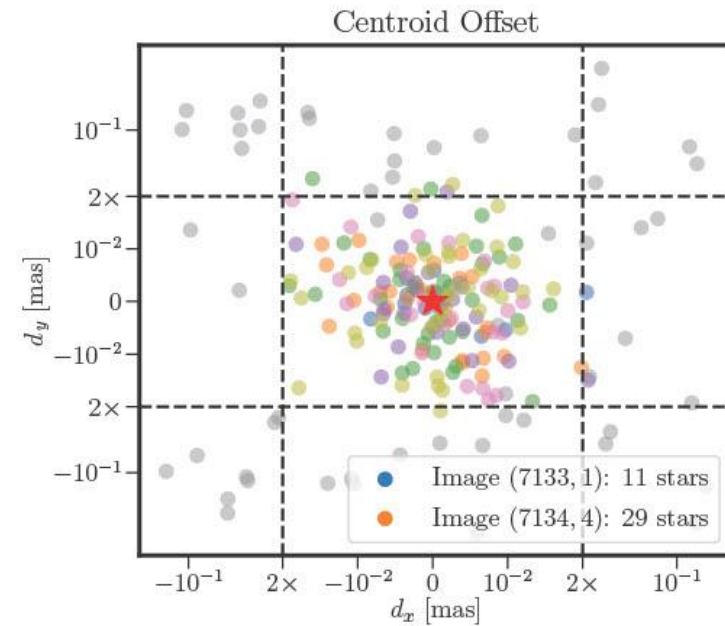
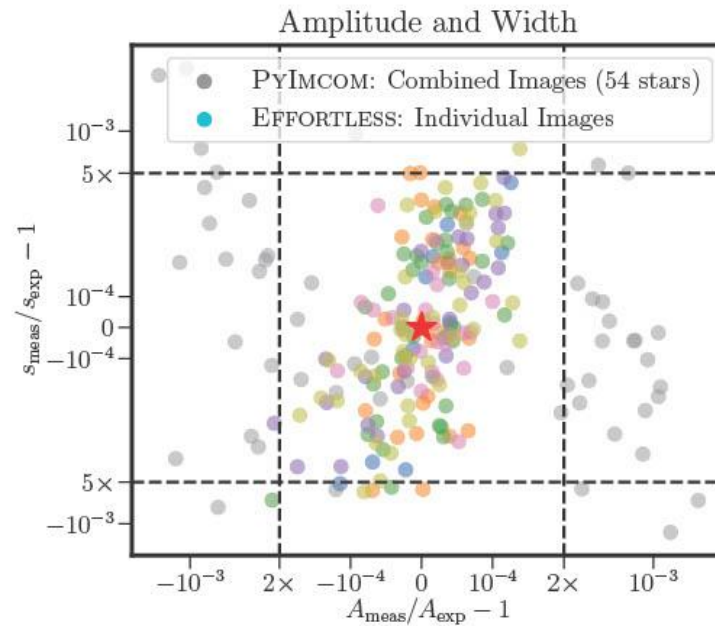


Foreseeable Future: Efficient Optimal Image Reconstruction with **Effortless** (Cao 2026*)



Effortless (Cao 2026*) features:

- $\sim 50\times$ faster
- Comparable or better results (for noiseless point sources) using individual images
- Better design
- White box





ASTROPHYSICS FLEET

New “eyes,”
new “visual cortex.”

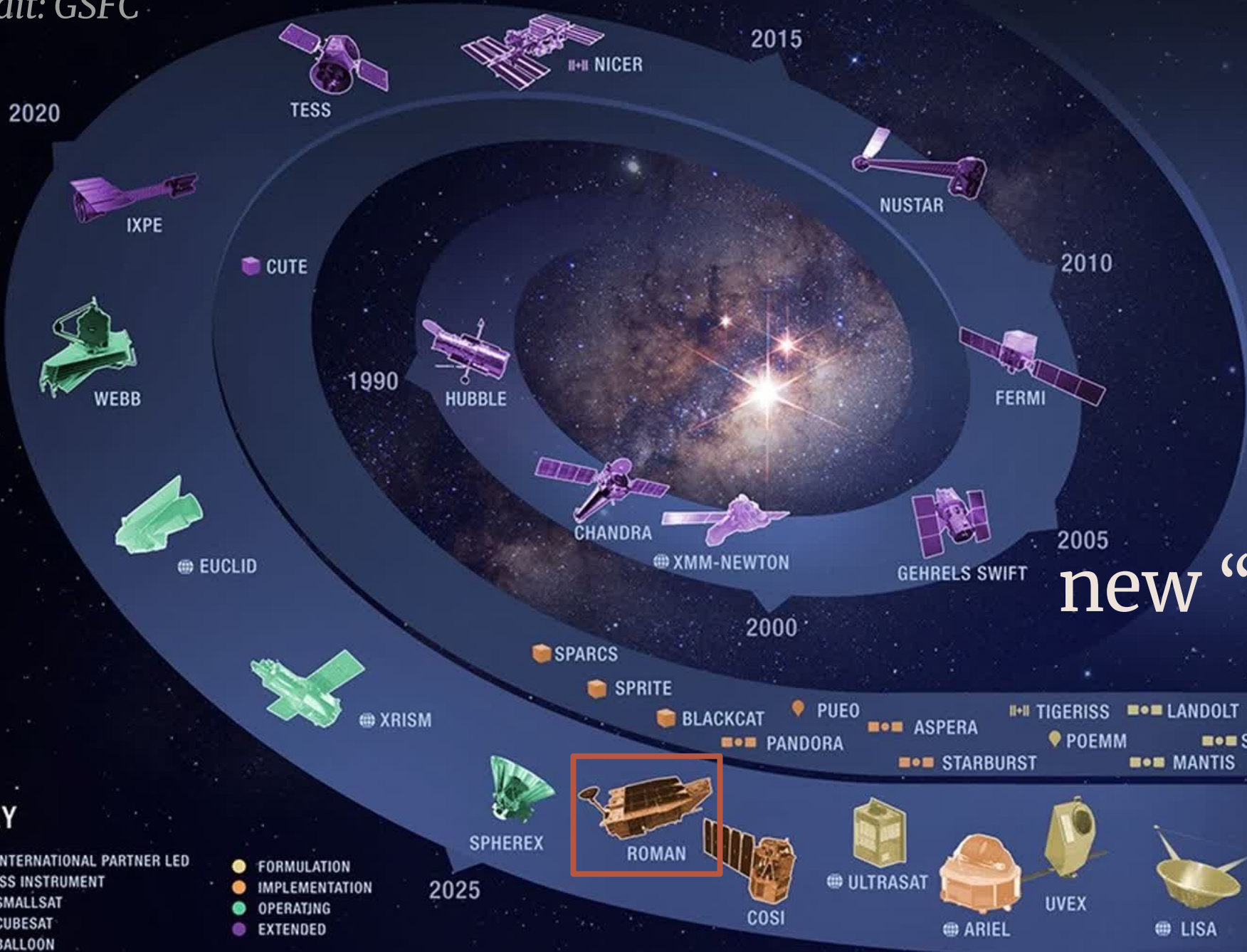
KEY

- INTERNATIONAL PARTNER LED
- ISS INSTRUMENT
- SMALLSAT
- CUBESAT
- BALLOON

- FORMULATION
- IMPLEMENTATION
- OPERATING
- EXTENDED

PIONEERS & CUBESATS

TRADITIONAL MISSIONS



Blurred image: the Avengers traveling back in time through a quantum tunnel, from the film Avengers: Endgame (2019).

Scene 3: Confluence of Observed and Imagined Universes (2025)

Based on: Chapter 7

What if the *Maker of the Universe* came to tell us the correct cosmological model and parameters?

We would say:

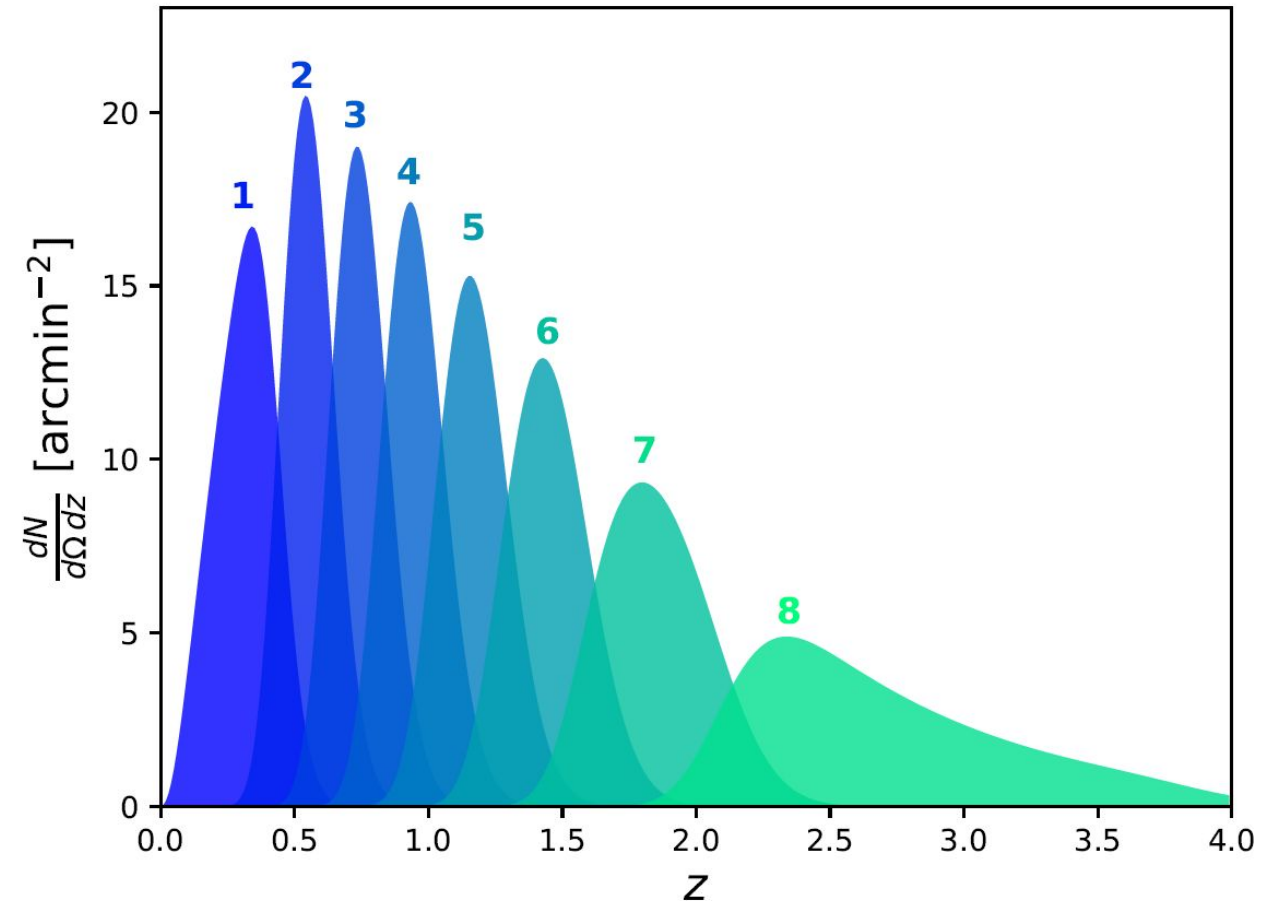
- a) We already know, but thanks!
- b) Thank you for taking our jobs...
- c) That does not sound very likely.
- d) You answer here: ____

Weak Lensing Observables: 3×2 pt (Three Two-Point Correlation Functions)

Cosmic shear: autocorrelation of galaxy **shapes**

Galaxy-galaxy lensing (GGL): cross-correlation of galaxy **shapes** and galaxy **positions**

Galaxy clustering: autocorrelation of galaxy **positions**



Credit: Haley Bowden

Cosmological Parameter Inference Pipeline (CPIP)

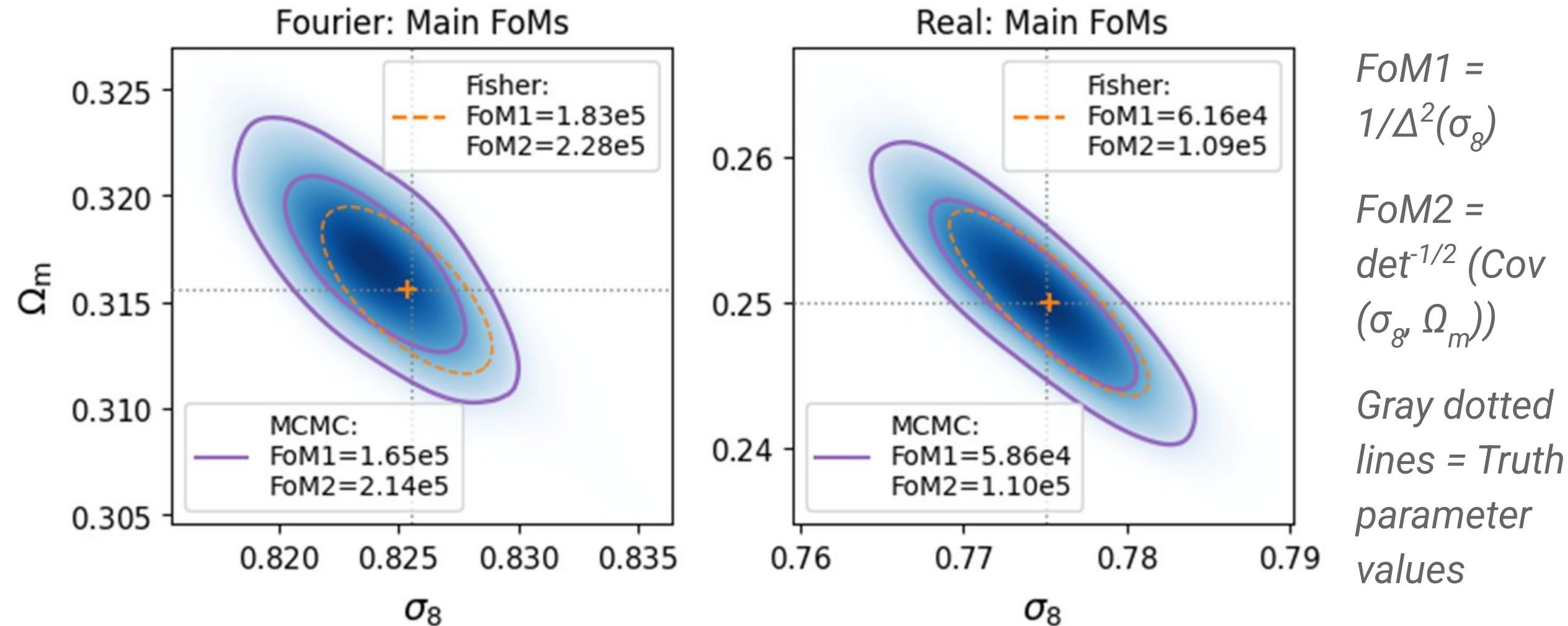


COCOA

COBAYA-COSMOLIKE JOINT ARCHITECTURE

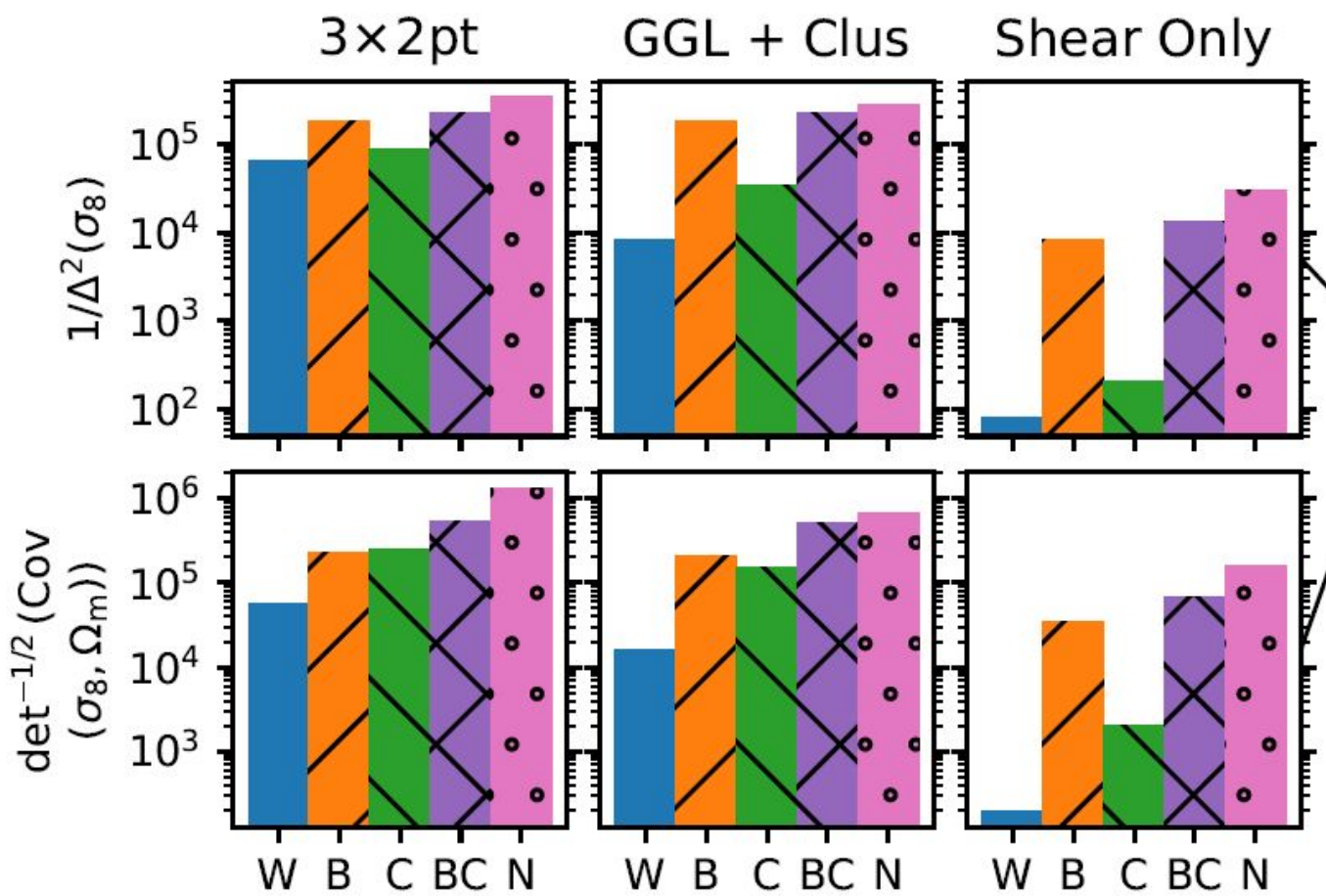
Fisher Forecasts for Constraining Power

(Below: Figure 6 in K. Cao et al. 2026, submitted)



Constraining Power from Different Probes

(Part of Figure 7 in K. Cao et al. 2026, submitted)



W: infinitely wide priors on all (i.e., both cosmological and “nuisance”) parameters

B: benchmark priors on photo-z bias (Δz ; 0.002) and shear bias (m ; 0.005)

C: infinitely narrow priors on other studied cosmological parameters (n_s , Ω_b , and h_0)

BC: benchmark priors on Δz and m (B) + infinitely narrow priors on n_s , Ω_b , and h_0 (C)

N: infinitely narrow priors on all parameters other than σ_8 , Ω_m , and galaxy bias (b)

Collected in
Scene 1

Collected in Scene 2

Cosmological
Simulations
– ContCosmos

Cosmological
Inference
– Depth Padding

Blurred image: the Infinity Gauntlet
holding the six Infinity Stones, from
the film Avengers: Endgame (2019).

© Marvel, MJLogan95



Blurred image: an AI-generated picture of a human hand and a robotic hand reaching toward each other against a starry sky.

© Google Gemini

Conclusion

Based on: Chapter 8 and Acknowledgements

Why do I want
to “renovate
analysis
infrastructure
for the next
generation of
astronomical
surveys,” and
how do I do it?

	Stellar Astrophysics	Cosmology
Theoretical Modeling	Chapter 2 Modeling Red Giants	Chapter 7 Fisher Forecasts
Data Analysis	Chapter 3 Astero seismic Scaling Relations	Chapters 4 to 6 Image Reconstruction
Blurred image: an AI-generated illustration of a spiral galaxy surrounded by charts and data.		
© XQ, DALLE3 or Midjourney		

Asteroseismology
– DynFlux

Stellar Modeling
– ContStar

Image Analysis
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Image Reconstruction
– Effortless

Cosmological
Simulations
– ContCosmos

Cosmological
Inference
– Depth Padding

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Thanks to:

- My advisors
- Other or former members of my advising committee
- Other faculty members, postdoctoral researchers, and fellow students at The Ohio State University
- Ohio Supercomputer Center



© NASA, ESA, and The Hubble Heritage Team (STScI/AURA)



Thanks to my collaborators, especially:

- “Maximizing Cosmological Science with the Roman High Latitude Imaging Survey” Roman Project Infrastructure Team
- “Astero-seismology Using The Galactic Bulge Time Domain Survey” Wide-Field Science Team
- Stellar modeling community developing and utilizing the Modules for Experiments in Stellar Astrophysics and the Yale Rotating Evolutionary Code
- Nancy Grace Roman Space Telescope community
- Institutions and individuals who have considered my application for their postdoctoral positions



Blurred image: the seal of The Ohio State University on the Oval walkway in autumn.

Thanks to Ohio State offices, especially:

- Administrative offices of the Center for Cosmology and AstroParticle Physics (CCAPP), the Department of Astronomy, and the Department of Physics

Blurred image: the cover of How to Read a Book by Mortimer J. Adler and Charles Van Doren.

Thanks to:

- Authors of the textbooks, non-fictions, fictions, newsletters, and articles that I have read
- Contributors to the online courses, documentaries, informational videos, movies, and TV series that I have watched
- Creators of the music I have listened and video games I have played
- My family and friends
- ... and you



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