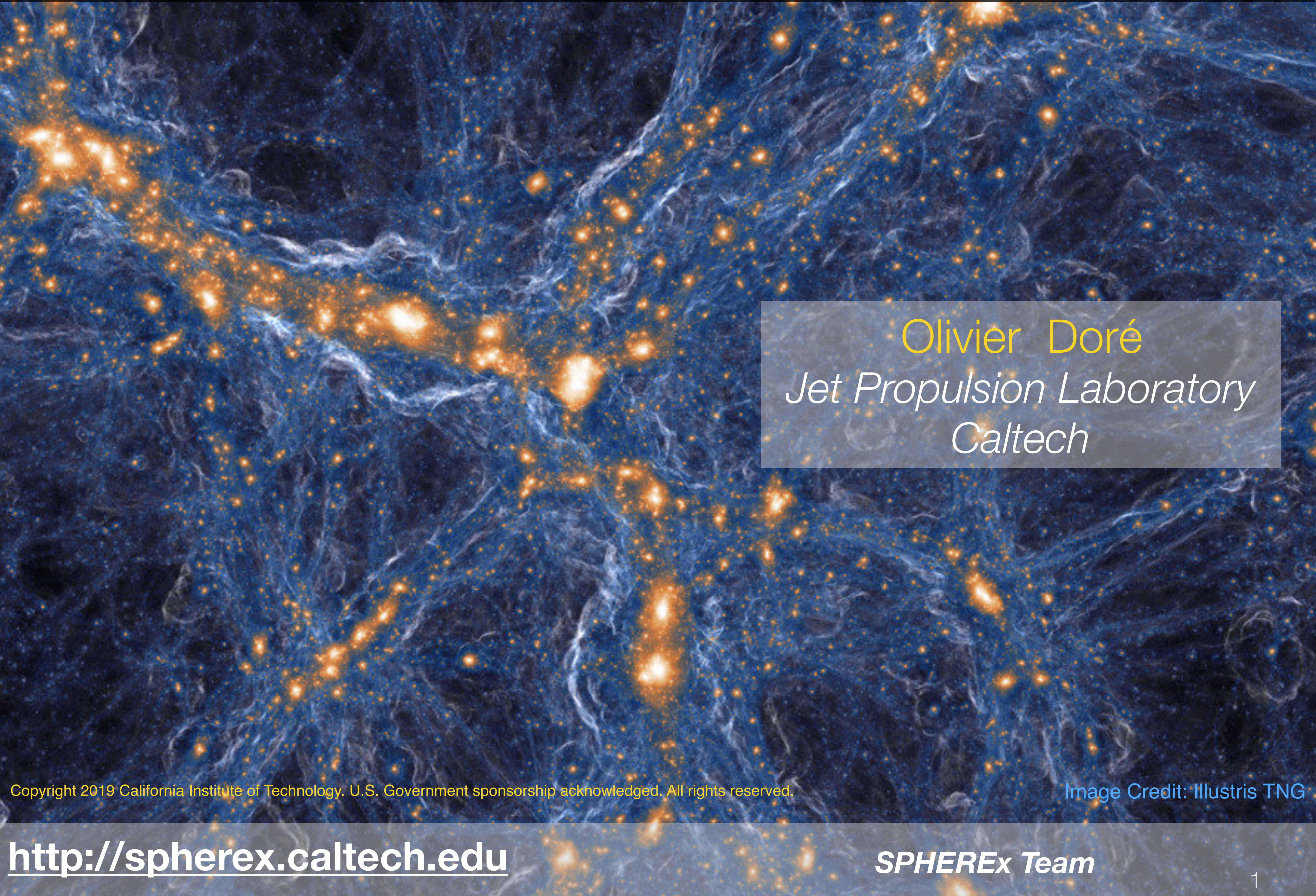
Cosmological Discoveries with SPHEREx



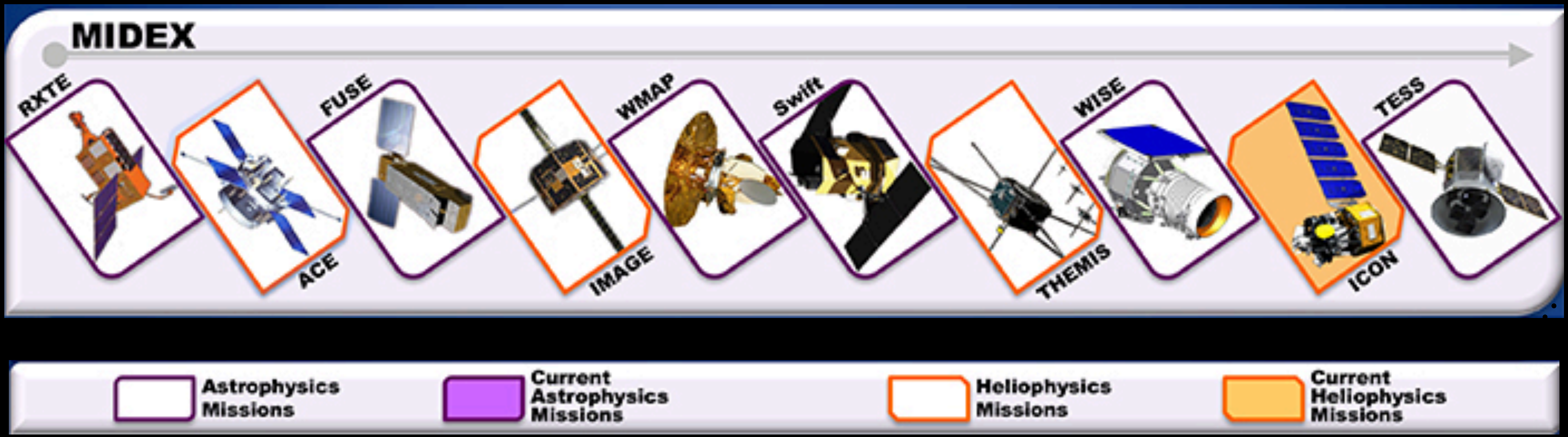
Olivier Doré
Jet Propulsion Laboratory
Caltech

Image Credit: Illustris TNG

http://spherex.caltech.edu

SPHEREx Team

ASTROPHYSICS & HELIOPHYSICS MID-EXPLORERS MISSIONS



https://explorers.gsfc.nasa.gov/

SPHEREX ADDRESSES THREE MAJOR QUESTIONS IN ASTROPHYSICS

- How did the Universe begin?
  - ➡ Probing Inflation with the 3D clustering of galaxies
    - Survey the z<1.5 Universe to fundamental limits to measure signatures of inflation (non-Gaussianity, primordial power spectrum shape) and dark energy
    - Complement Euclid & WFIRST which survey smaller area at z>1
- What are the Conditions for Life Outside the Solar System?
  - ➡ Measure broad <u>ice</u> absorption features in stellar spectra to explain how interstellar ices bring <u>water</u> and <u>organic molecules</u> into proto-planetary systems
- How did Galaxies begin?
  - ➡ Measure the extra-galactic background light (EBL) to probe the epoch of reionization (EOR)

SPHEREX: AN ALL-SKY SPECTRAL SURVEY

Spectro-Photometer for the History of the Universe, Epoch of Reionization, and Ices Explorer

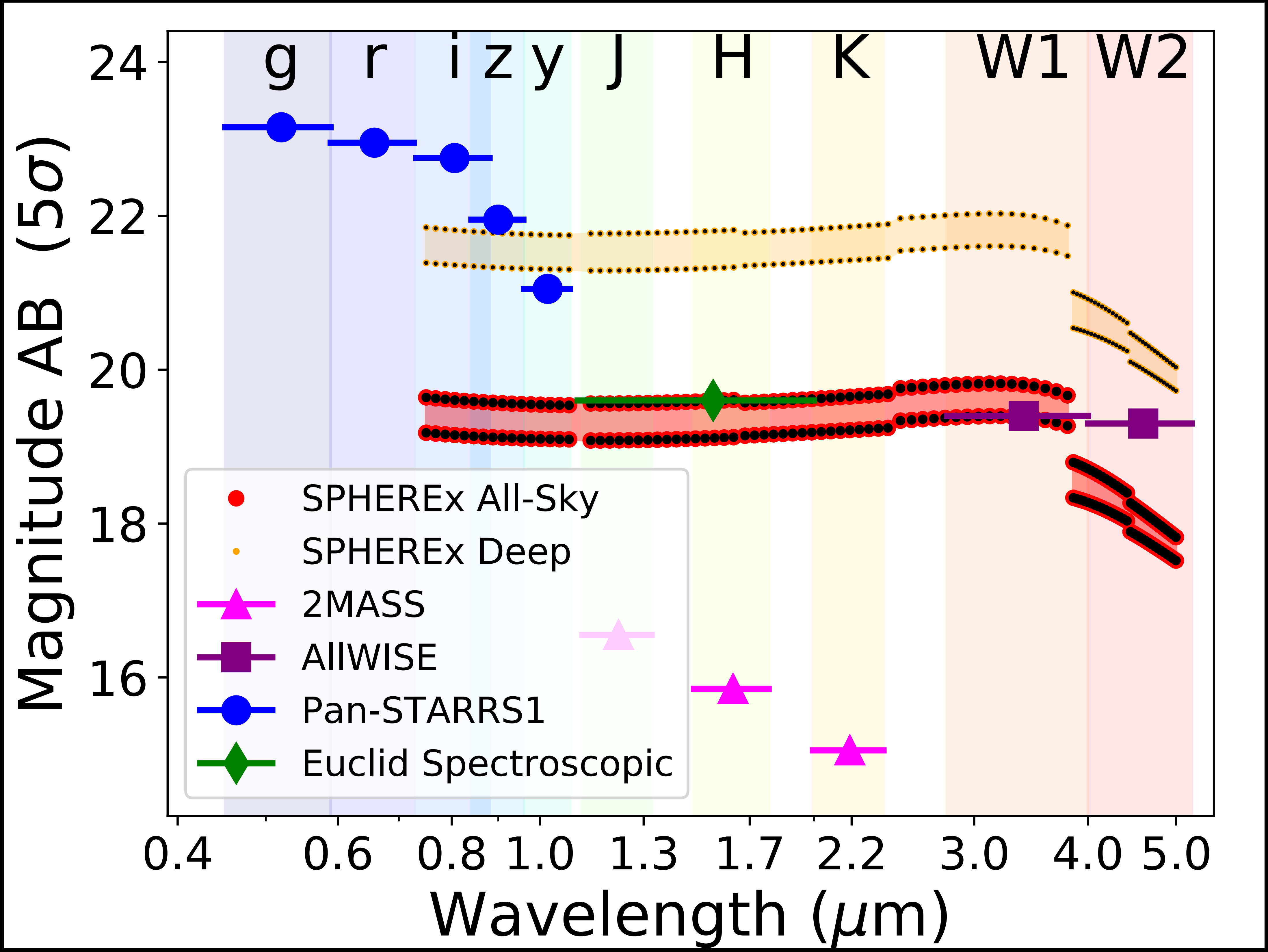
SPHEREx Dataset:

- For every 6.2” pixel over the entire sky:

  ➡ R=35-41 spectra spanning 0.75 μm < λ < 3.82 μm
  ➡ R=110-130 spectra spanning 3.82 μm < λ < 5.0 μm

- ≃ all-sky survey with 96 fine photometric bands

SPHEREX SURVEY DEPTH



Deep survey

All-sky survey

SPHEREX PROVIDES A RICH ALL-SKY SPECTRAL ARCHIVE

Galaxies

Detected
> 1 billion

Med. Accuracy z's
> 100 million

High Accuracy z's
10 million

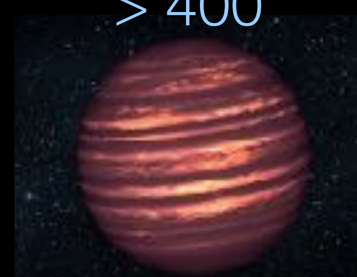
Clusters
25,000

Stars

Main Seq. Spectra
> 100 million

Dust-forming
10,000

Brown Dwarfs
> 400



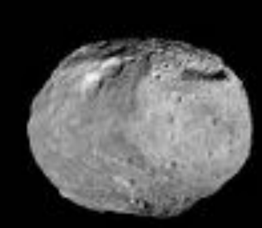
Cataclysms
> 1,000

Other

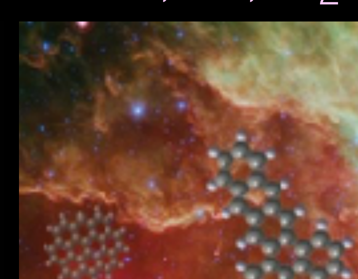
Quasars
> 1 million

Quasars z >7
3 – 300?

Asteroid Spectra
10,000



Galactic Line Maps
PAH, HI, H_2



All-Sky surveys demonstrated high scientific returns with a lasting data legacy used across astronomy

COBE
IRAS
GALEX
WMAP
Planck
WISE

OD++16,18

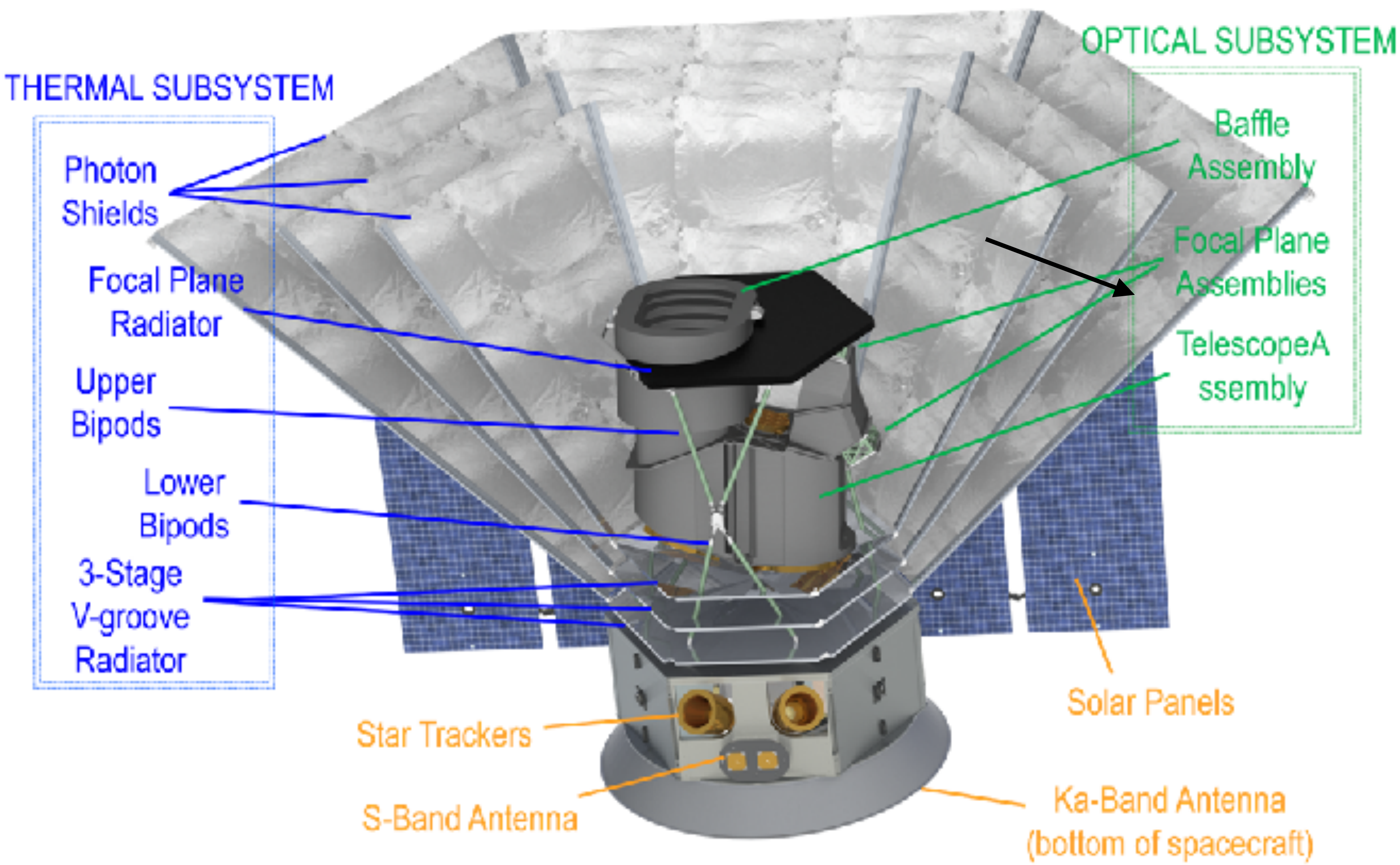
AGGRESSIVE DATA RELEASE PLAN

“CONVEYOR BELT MODEL”

- L : Launch late 2023
- L+1 : End of commissioning
- L+2n: Every ~2 months after, for 24 months:
  - ➡ Release spectral images data (L2 product)
- L+6n: Every 6 month, we complete a full sky survey.
  - ➡ Release local wavelength maps
- L+12n: Every 12 month, complete two full sky surveys
  - ➡ Release source catalogs
- L+24 : End of nominal mission.
  - ➡ Release L4 catalogs (galaxy, ices, maps, legacy catalogs)

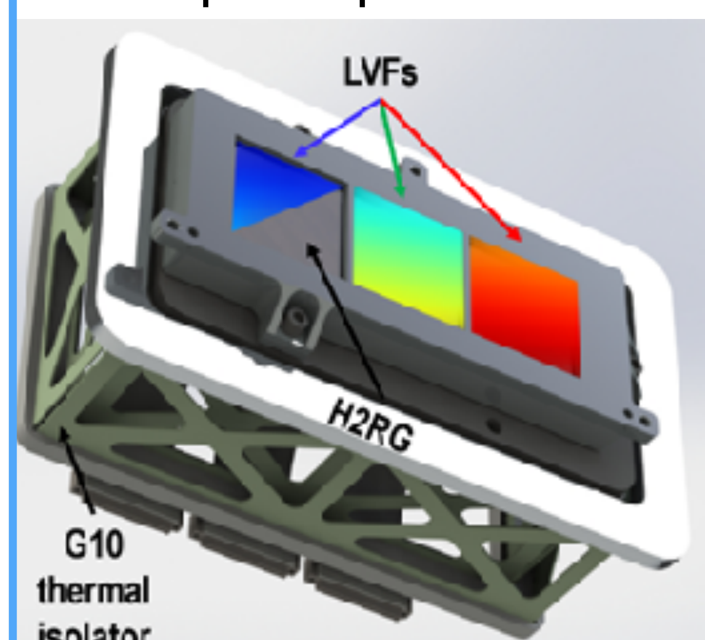
- Archive hosted by IRSA at IPAC/Caltech (irsa.ipac.caltech.edu)
  - ➡ Will also host tools to do on the fly mosaic, forced photometry on a catalog, time variable sources photometry, etc.

An Innovative Architecture Based on Mature Technologies



Wide field telescope

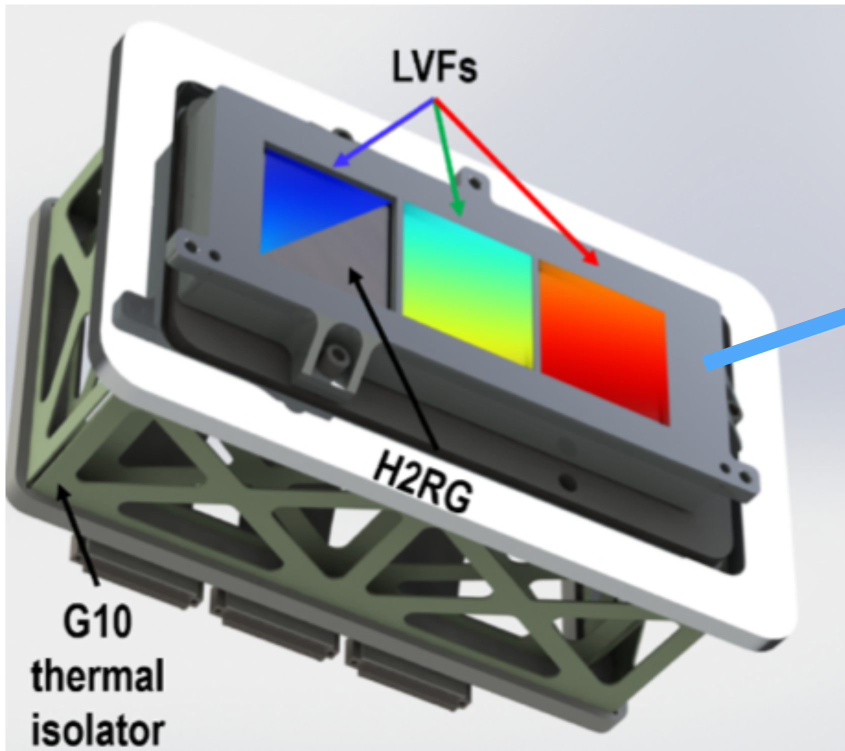
Compact spectrometer

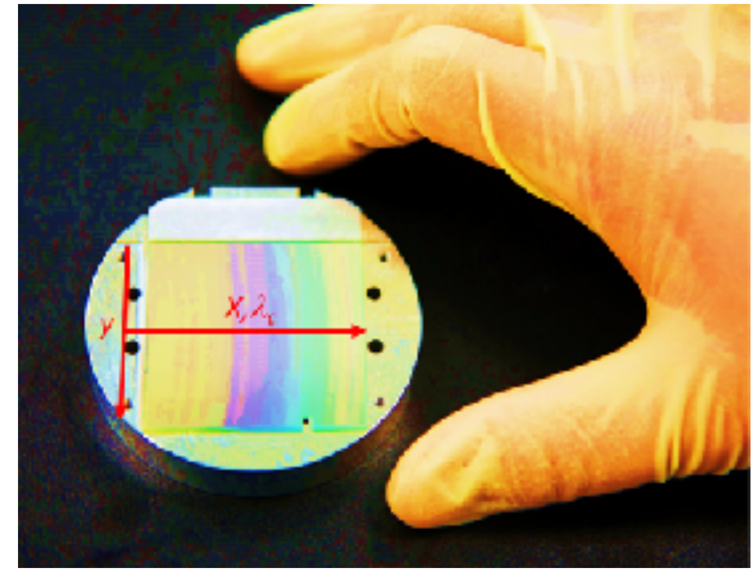


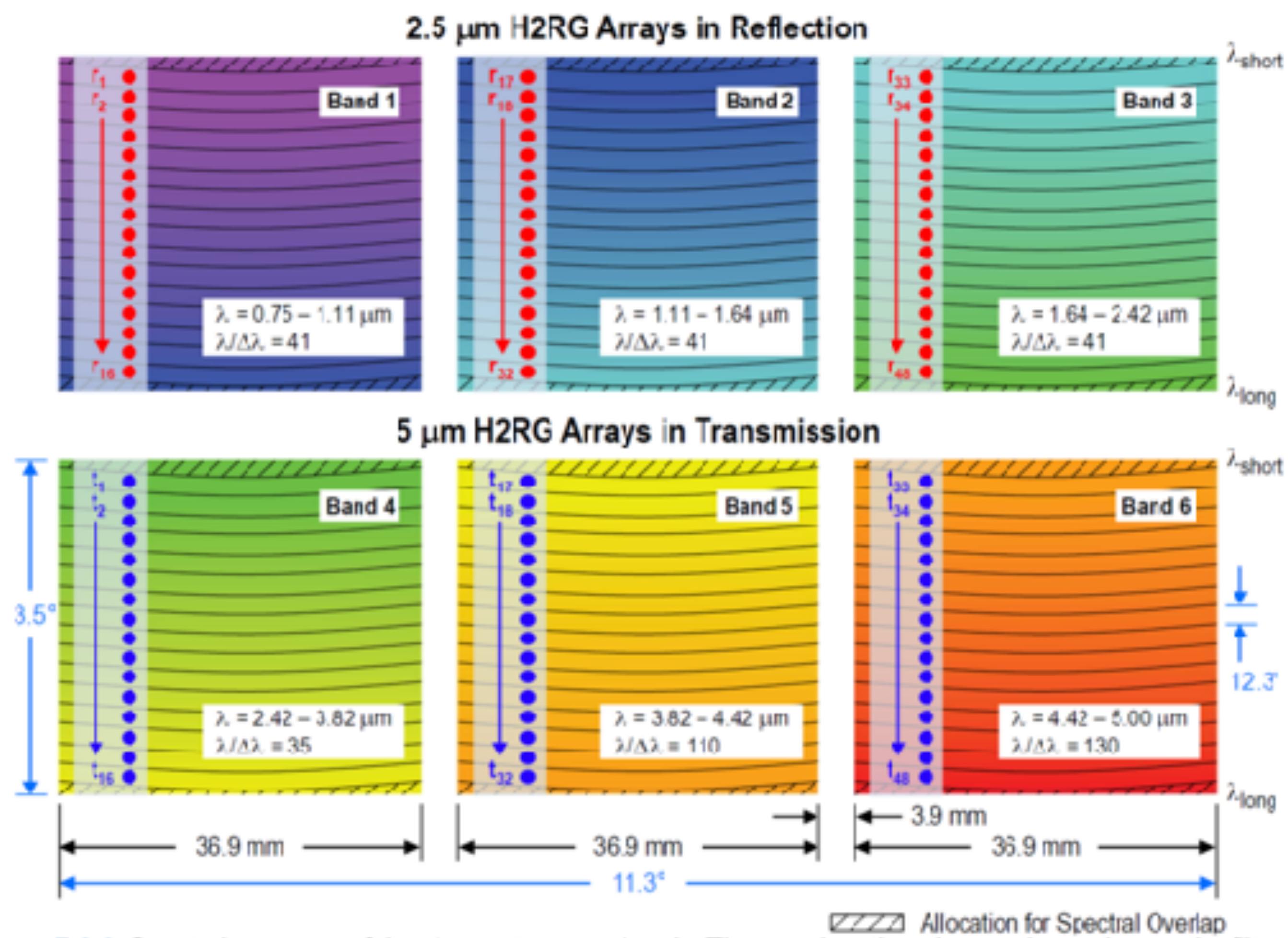
Parameter	Value
Telescope eff. diameter	20 cm
Field of view	3.5 x 11 deg.^{2}
Pixel size	6.2 arcsec
Wavelength range	0.75 – 5 μm
Resolving power $\lambda/\Delta\lambda$	35-130

Pre-Decisional Information
For Planning and Discussion Purposes Only

High-Throughput LVF Spectrometer

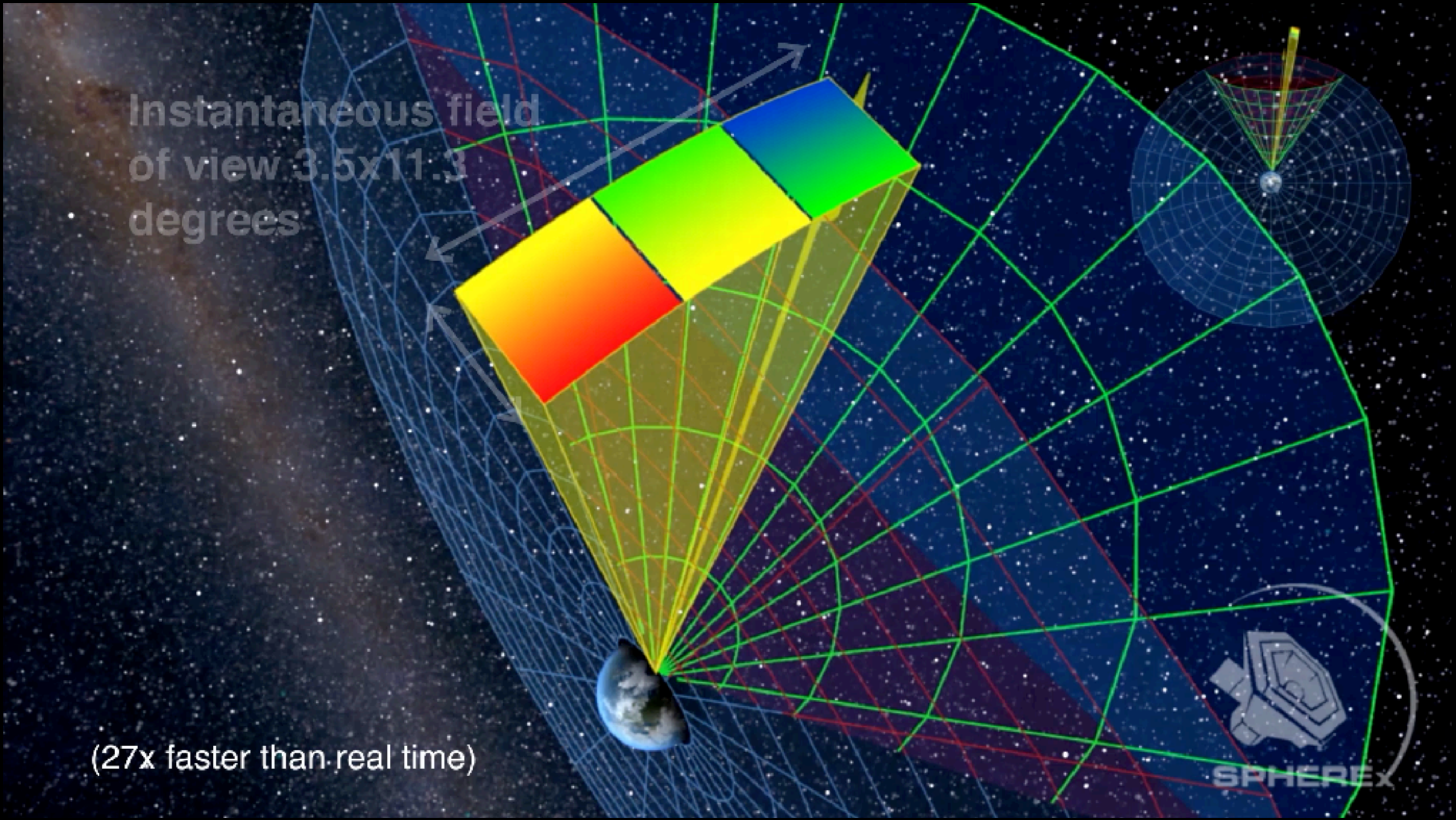






Spectra obtained by stepping source over the FOV in multiple images: no moving parts

PRE-PROGRAMED SCANNING STRATEGY



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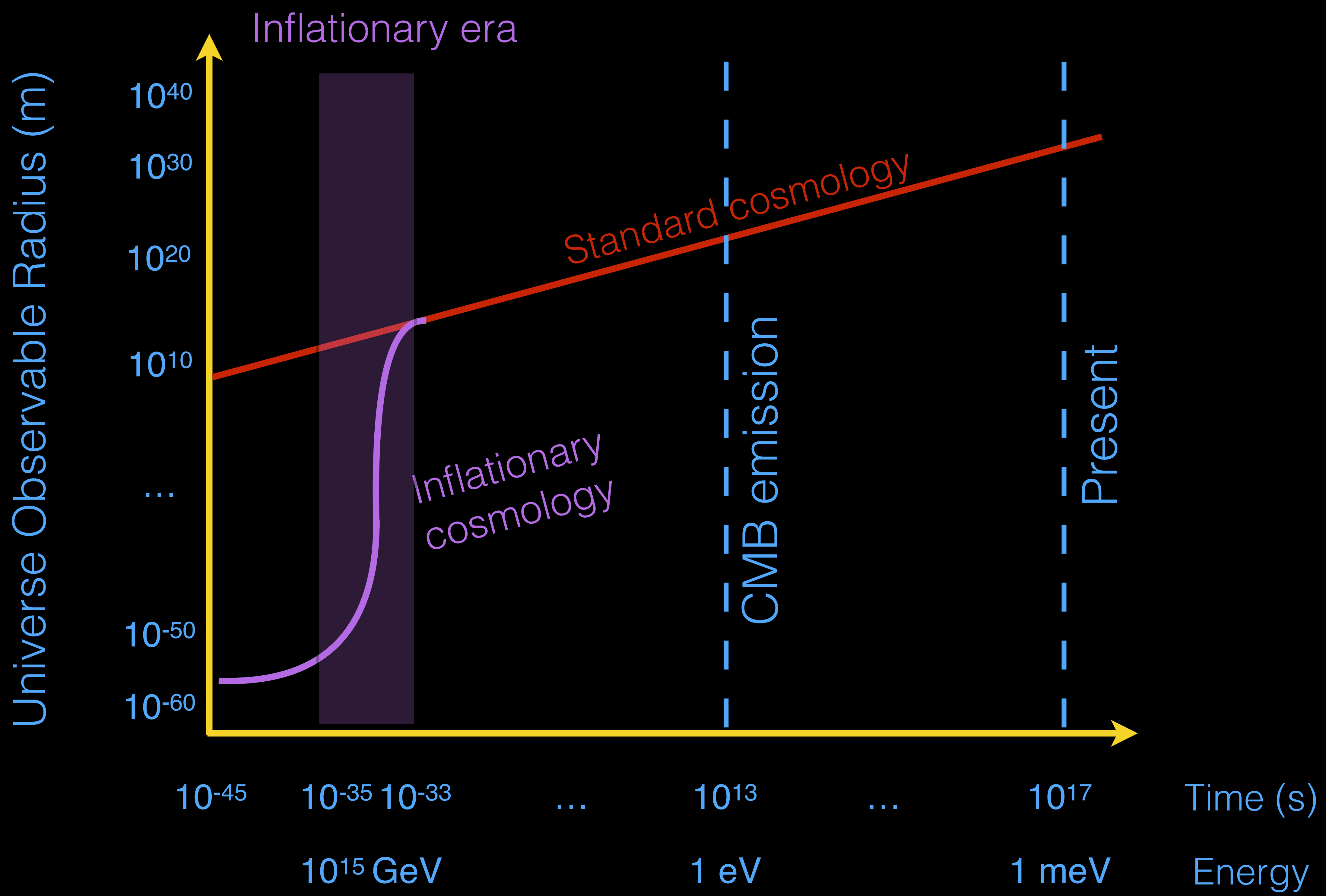
Michael Zemcov	RIT

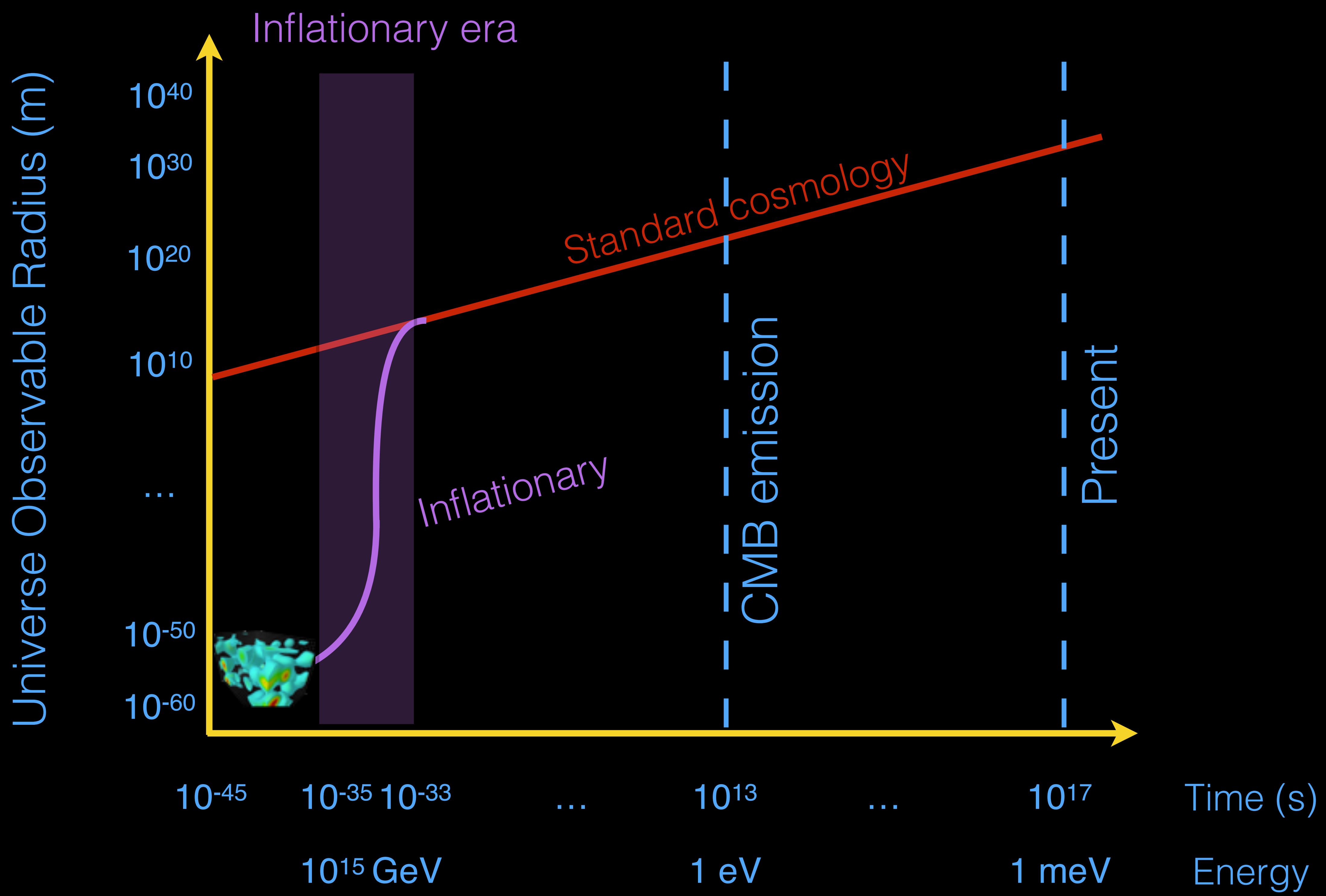
Image Credit: Illustris TNG

INFLATION INVESTIGATION

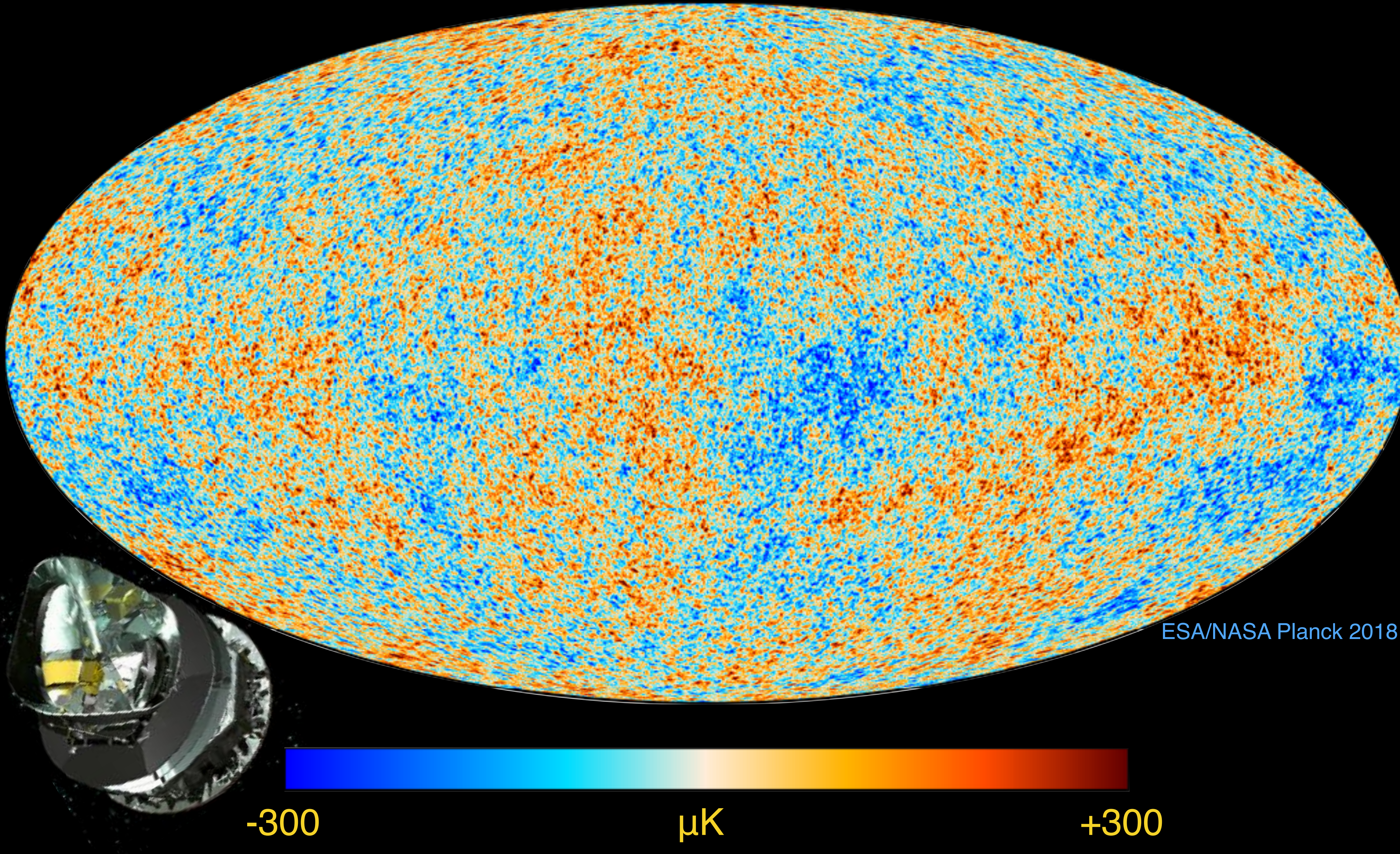
THE EARLY UNIVERSE EXPANDED EXPONENTIALLY



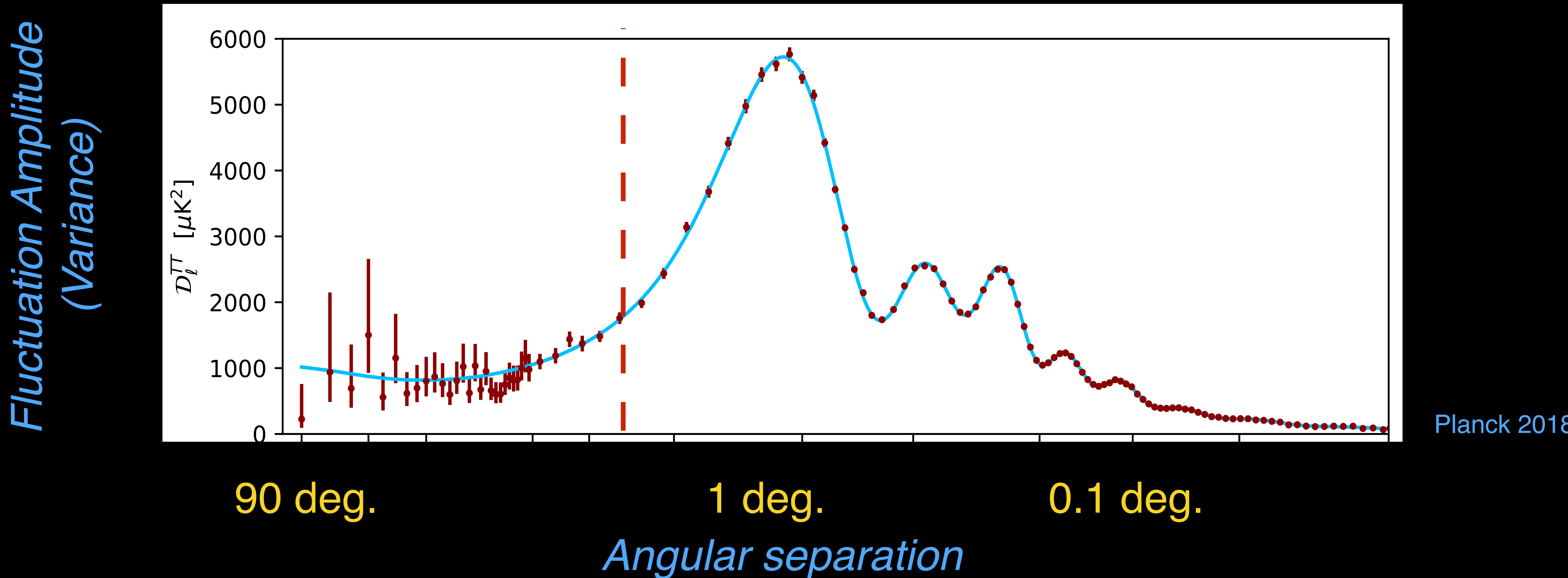
INFLATION STRETCHES OUT QUANTUM FLUCTUATIONS



PLANCK MAP OF THE YOUNG UNIVERSE



PREDICTIONS VERIFIED:
PRECISION THEORY MEETS PRECISION MEASUREMENTS



- Inflation <u>predictions</u> (1980s)
  - ➡ The universe is nearly flat: $\Omega_K = 0$
  - ➡ Nearly scale-invariant pert.: $0.92 < n_s < 0.98$
  - ➡ All constituents have same perturbations
  - ➡ Background of gravitational wave pert.
  - ➡ Mostly Gaussian fluctuations
- <u>Measurements</u> (Planck 2018)
  - ➡ $\Omega_K = -0.011 \pm 0.013$ (95% CL)
  - ➡ $n_s = 0.9626 \pm 0.0057$ (68% CL)
  - ➡ More than 98.3% true (95% CL) in variance
  - ➡ On-going search r<0.064 (95% CL, w/ BICEP)
  - ➡ True to 1 part in 100,000

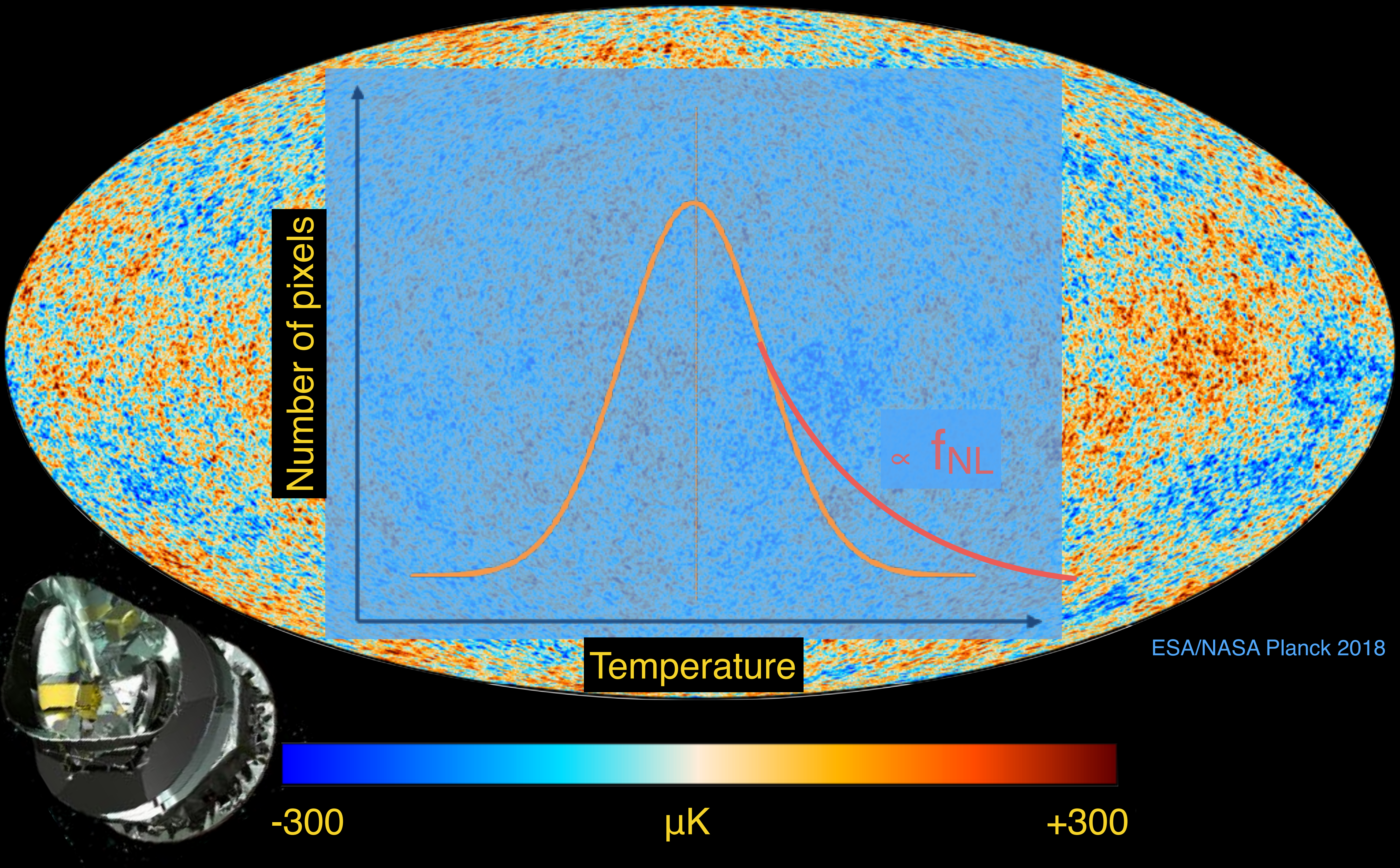
Guth, Starobinsky, Linde, Steinhardt, Albrecht, Mukhanov, Chibisov, Hawking, Bardeen, Turner, Pi … ~80

INFLATION PASSES OBSERVATIONAL TESTS:

HOW DOES INFLATION WORK?!

- Two observational paths are been actively pursued:
  - ➡ To measure the Energy Scale of Inflation through the signature, in *the polarization of the CMB*, of the gravitational wave background it created (BICEP, KECK, Planck…)
  - ➡ To measure "primordial non-Gaussianity" to understand the complexity of the physical process driving Inflation

PLANCK MAP IS GAUSSIAN



CMB CONSTRAINTS ON PRIMORDIAL NON-GAUSSIANITY

$$\Phi = \Phi_G + f_{NL}^{loc}\ \Phi_G^2$$

- Measuring f_{NL} is a unique probe of inflation:
  - ➡ Probes interactions in the primordial Lagrangian
  - ➡ Distinguish between single field and multi-field inflation

- Current limit using Planck (T+P) bispectrum:
  - ➡ $f_{NL} = 0.8 \pm 5$ (68%)

- Future limits with a perfect CMB experiment (T+P, l<3000):
  - ➡ $f_{NL} \lesssim 2$ (68%)

Planck 2015. XVII

PRIMORDIAL NON-GAUSSIANITY INTRODUCES MODE COUPLING

- Peak-background split insights:

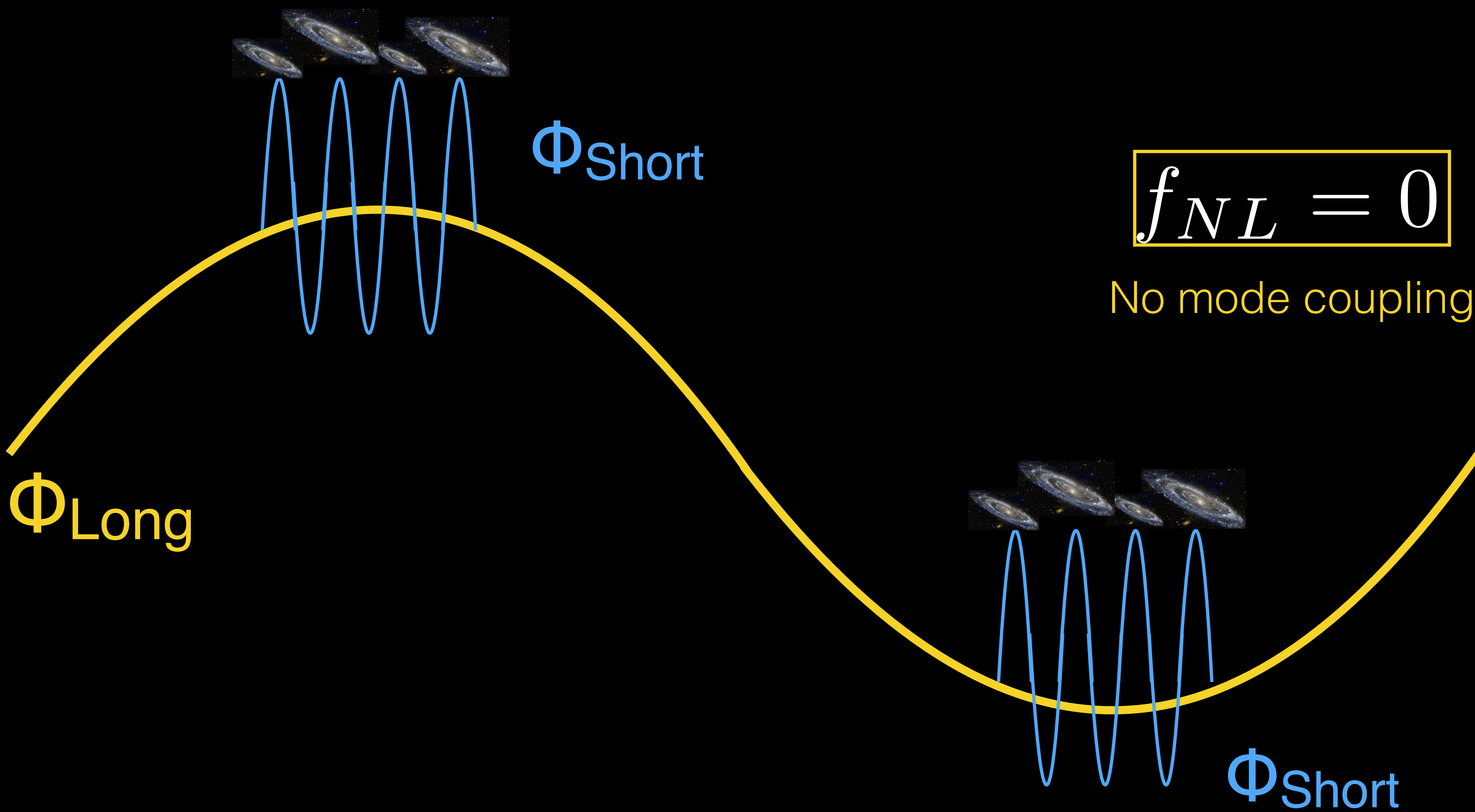
$$\Phi = \Phi_G + f_{NL}^{loc}\ \Phi_G^2$$

$$\Phi = \Phi_{Long} + \Phi_{Short}$$

$$\Phi = \Phi_{Long} + \boxed{f_{NL}^{loc}\ \Phi_{Long}\Phi_{Short}} + f_{NL}^{loc}\ \Phi_{Short}^2 + \ldots$$

Slosar++07, Desjacques++16

PRIMORDIAL NON-GAUSSIANITY AND GALAXY BIASING



$$f_{NL} = 0$$

No mode coupling

$$\delta_{galaxy} = b\ \delta_{matter}$$

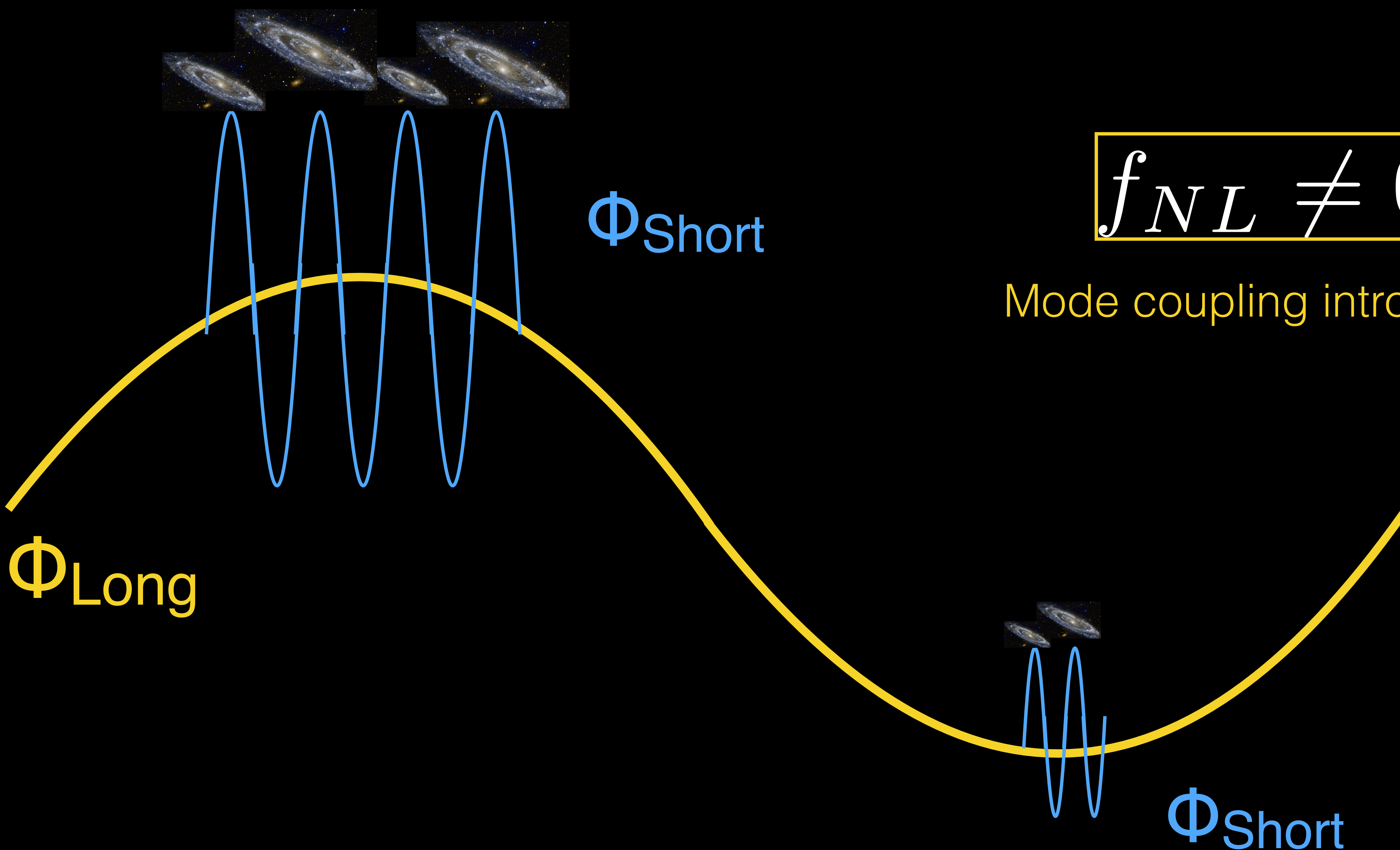
Galaxy bias (linear)

Slosar et al. 07

PRIMORDIAL NON-GAUSSIANITY AND GALAXY BIASING

$$f_{NL} \neq 0$$

Mode coupling introduced



$$\delta_{galaxy} = b\delta_{matter} + cf_{NL}\Phi_{Long} = (b + \Delta(b))\ \delta_{matter}$$

$$\Delta(b) \propto\ (b-1)\frac{f_{NL}}{k^2}$$

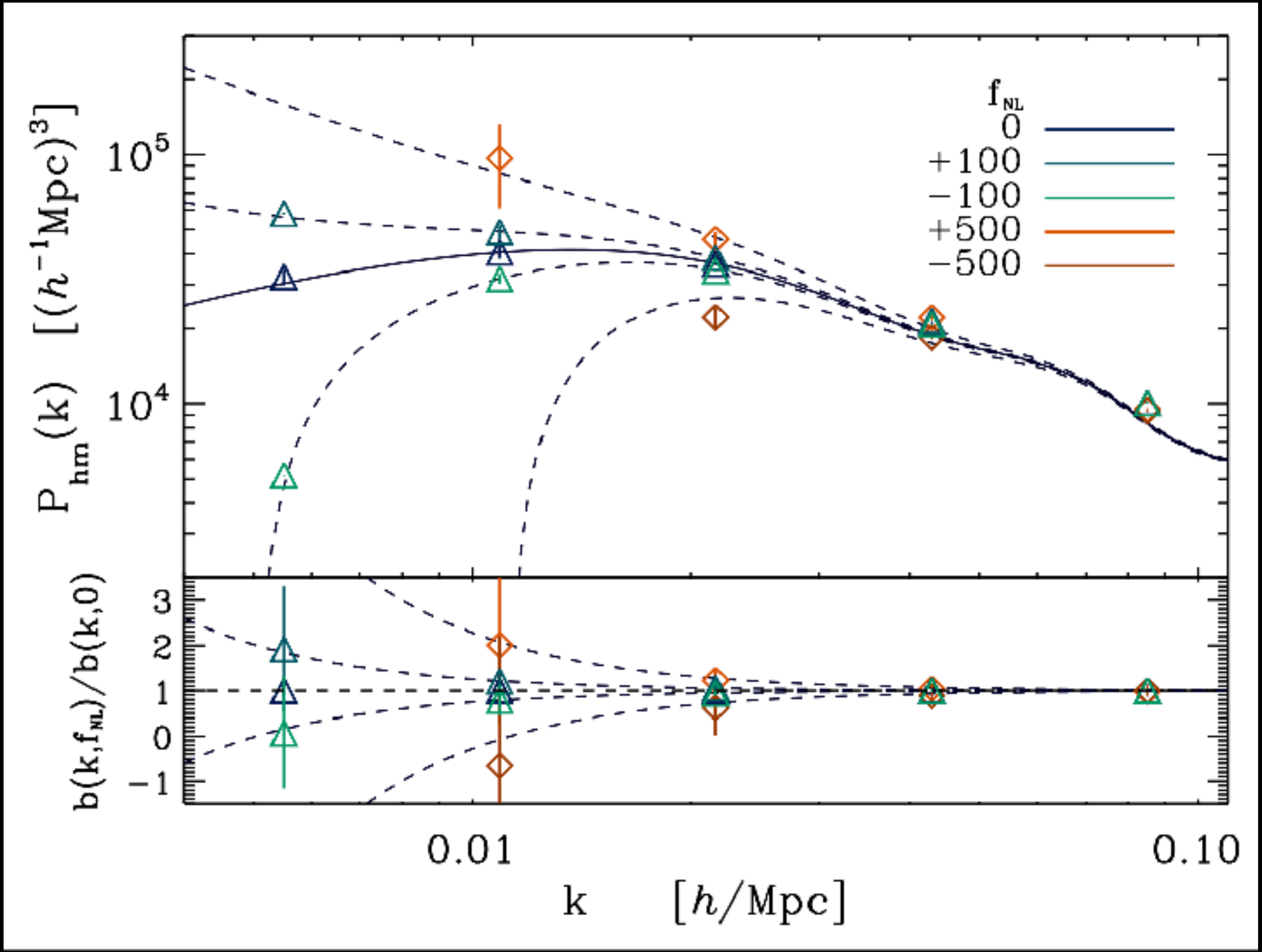
← Scale dependent galaxy bias

PRIMORDIAL NON-GAUSSIANITY AND BIASING

$$b_{NG}^{loc}(q) \propto f_{NL}^{loc} \frac{1}{T(q)q^2}$$

bias(k) $P_{mm}(k)$

bias(k)



Dalal, OD, Huterer, Shirokov 07

SINGLE FIELD INFLATION PREDICTION

- No mode coupling
- Single field consistency relation

$$f_{NL}^{loc} = -\frac{5}{4}(n_s - 1) \simeq 0$$

Maldacena 2003,
Creminelli & Zaldarriaga 2004
de Putter, Green, OD 16

SINGLE FIELD INFLATION
MULTI-FIELD INFLATION

- To study what a f_{NL} measurement can teach us, we focus on a subset of two-field models:
  - ➡ Φ, an "inflaton" field, dominates background and curvature perturbations at Horizon exit.
  - ➡ X, a "spectator" field, subdominant at Horizon exit but contributes to final curvature perturbation production later.
  - ➡ Natural extension of single field inflation.

- Fraction of the primordial curvature perturbation contributed by X is quantified by R
  - ➡ R~0: Inflaton dominated regime
  - ➡ R~1: Spectator dominated regime

$$R \equiv \frac{\mathcal{P}_{\xi|\chi}}{\mathcal{P}_{\xi}} = \frac{N_{\chi\star}^2}{N_{\phi\star}^2 + N_{\chi\star}^2}$$

de Putter, Gleyzes, OD 16

SINGLE FIELD INFLATION MULTI-FIELD INFLATION

$$W(\Phi, \chi) = U(\Phi) + V(\chi)$$

- U potential is not critical to f_{NL}:

$$U(\phi) = \frac{1}{2} m_\phi^2 \phi^2$$

- We consider three cases for V:
  - ➡ (Quadratic-) Axion in the Horizon crossing approximation

$$V(\chi) = \frac{1}{2} V_0 \left[1 + \cos\left(\frac{2\pi\chi}{f}\right)\right]$$

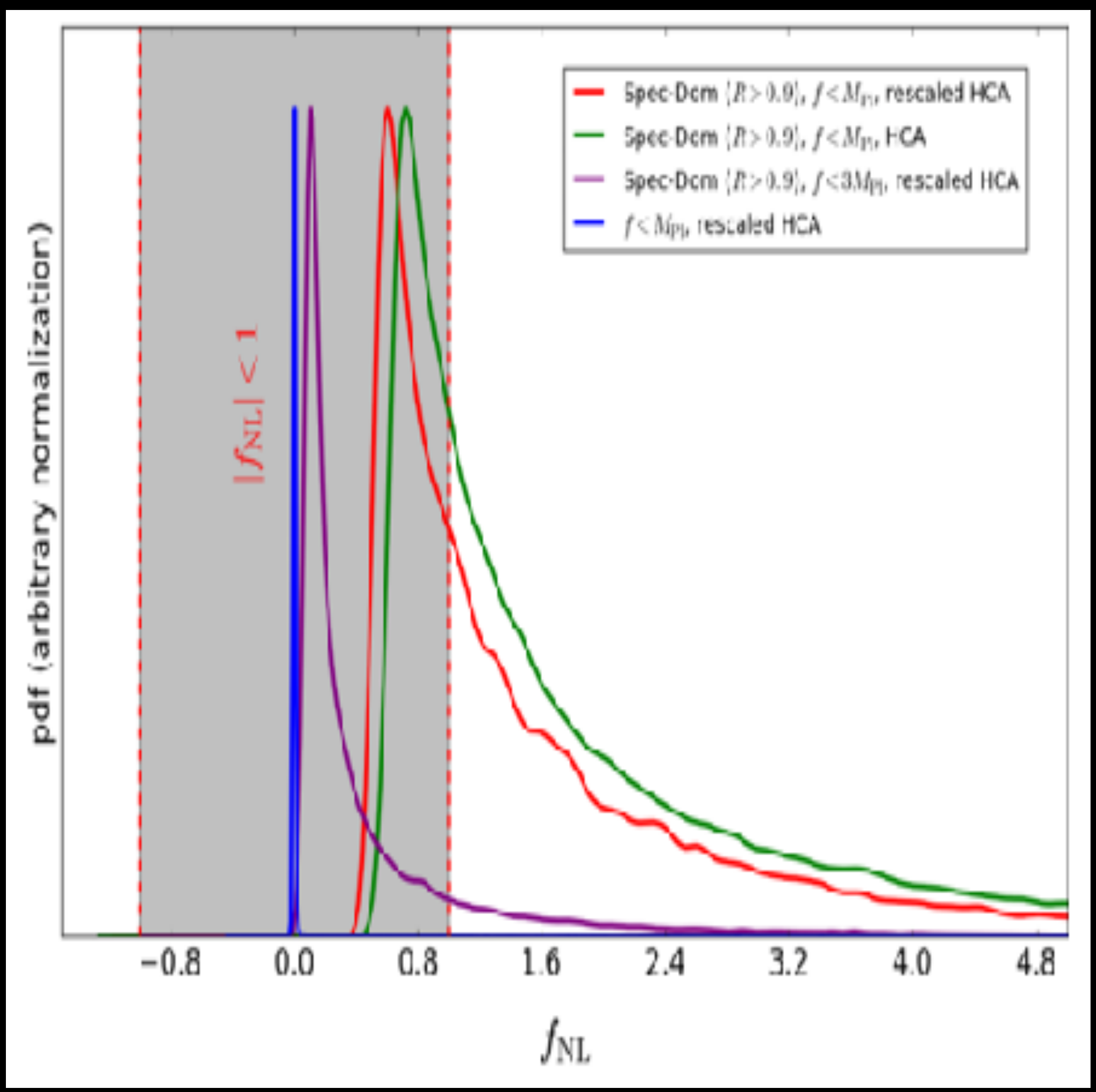
  - ➡ Modulated reheating
  - ➡ …

$$V(\chi) = \frac{1}{2} m_\chi^2 \chi^2$$

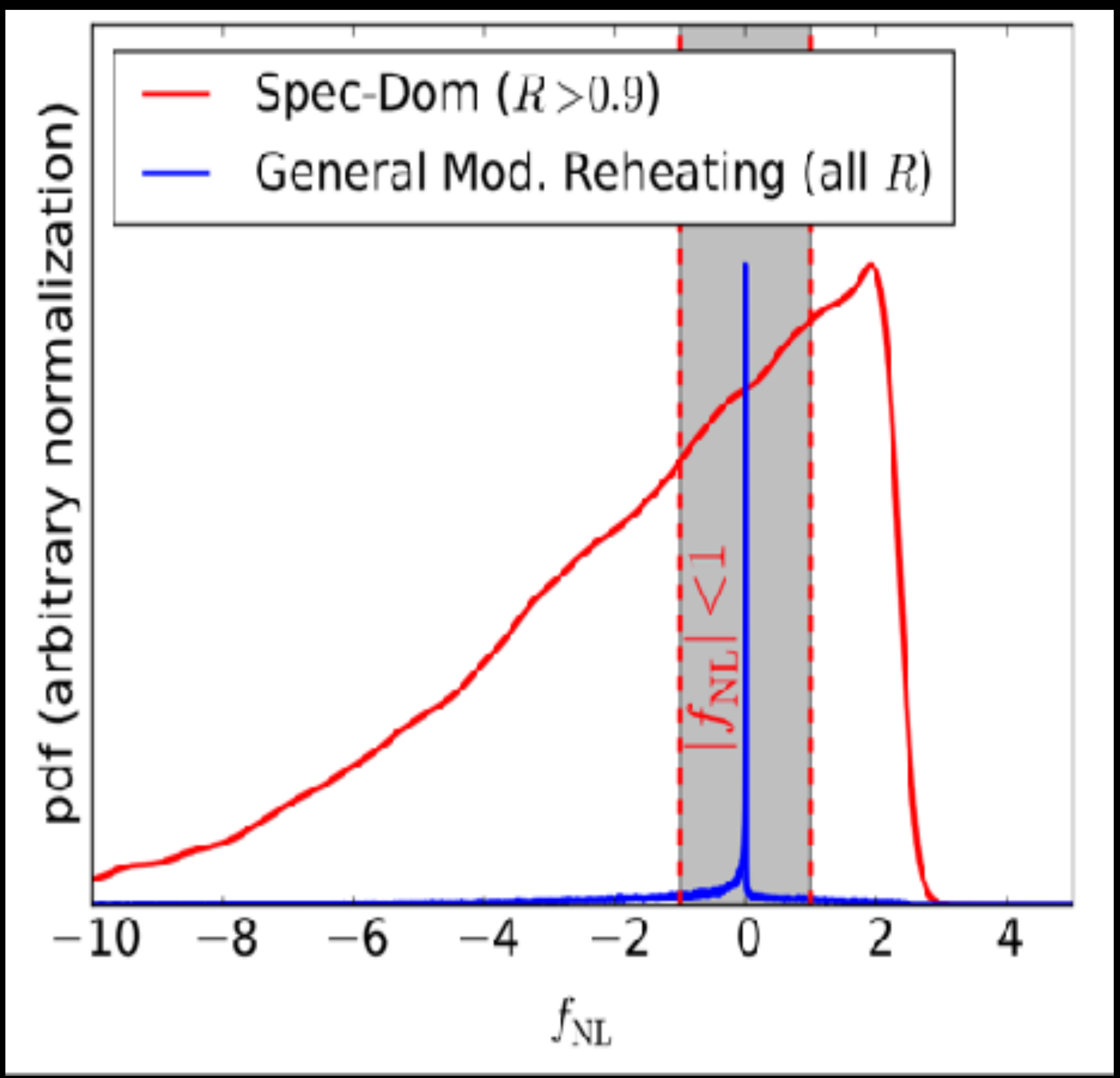
de Putter, Gleyzes, OD 16

POSTERIOR DISTRIBUTION OF FNL GIVEN PLANCK

Quadratic-Axion Potential



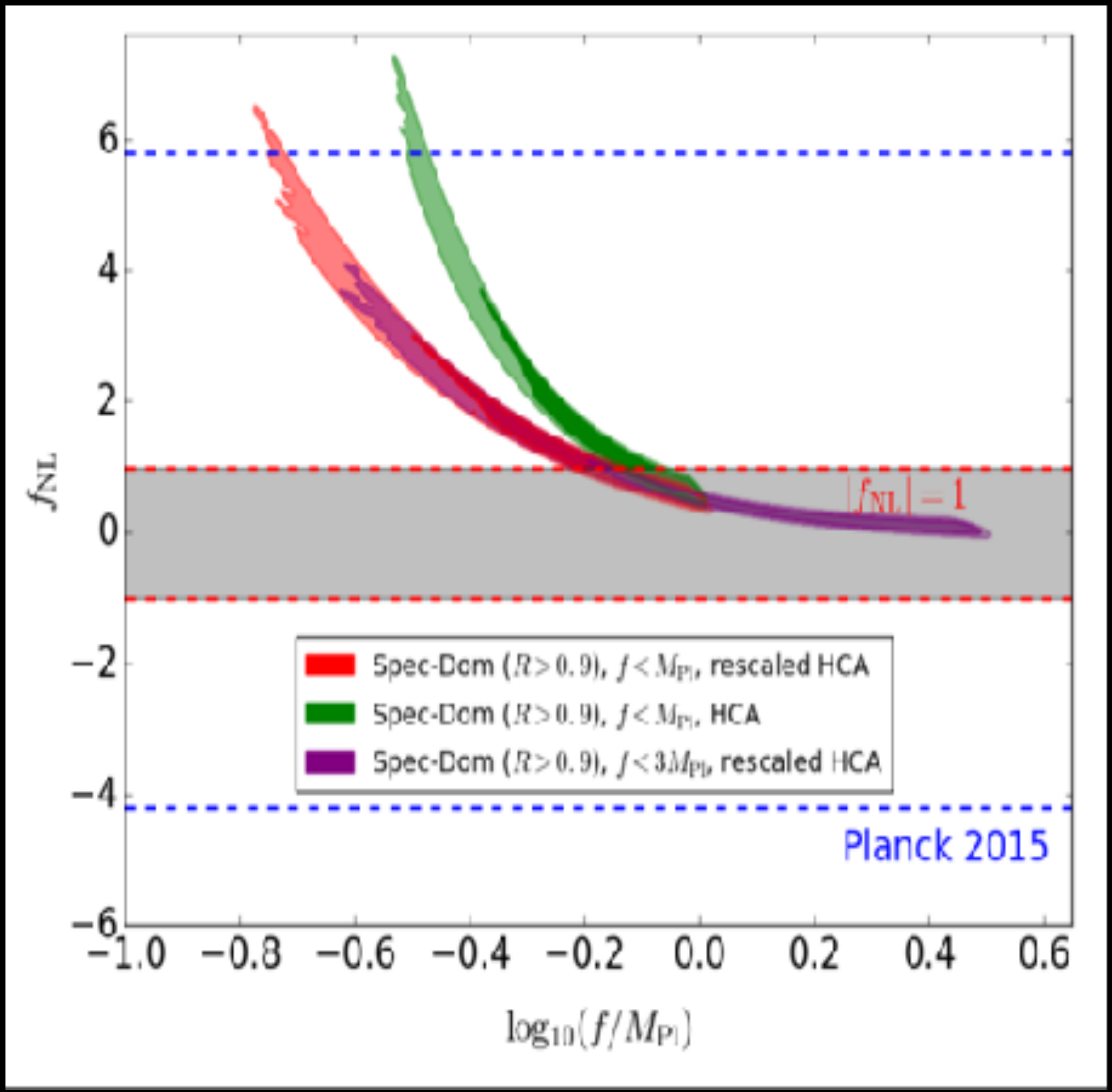
Modulated Reheating



de Putter, Gleyzes, OD 16

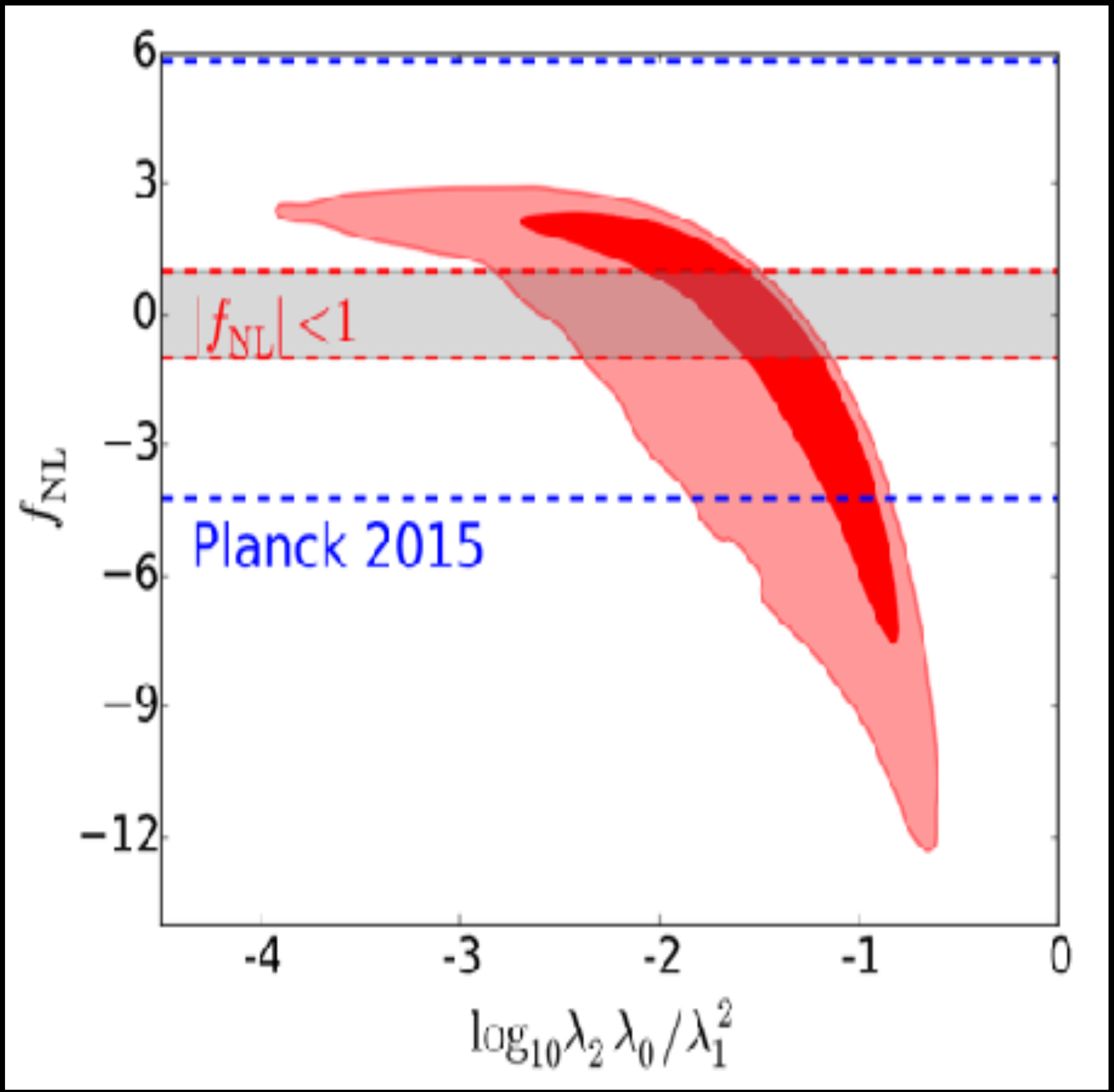
INSIGHTS TO BE GAINED FROM FNL MEASUREMENTS

Quadratic-Axion Potential



f~ axion decay constant

Modulated Reheating

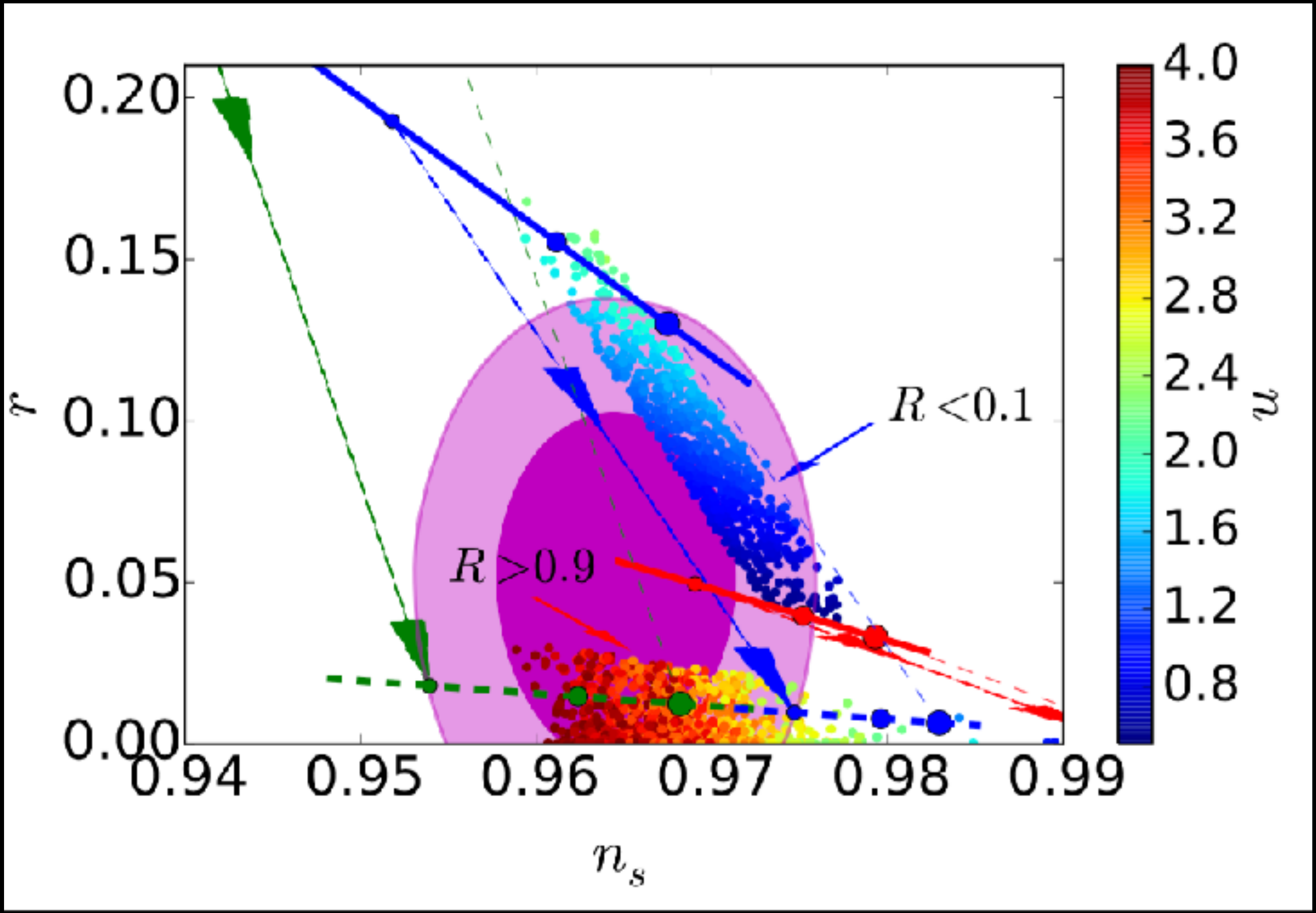


Inflation decay rate and its dependence on X

de Putter, Gleyzes, OD 16

OBSERVATIONAL PROSPECTS

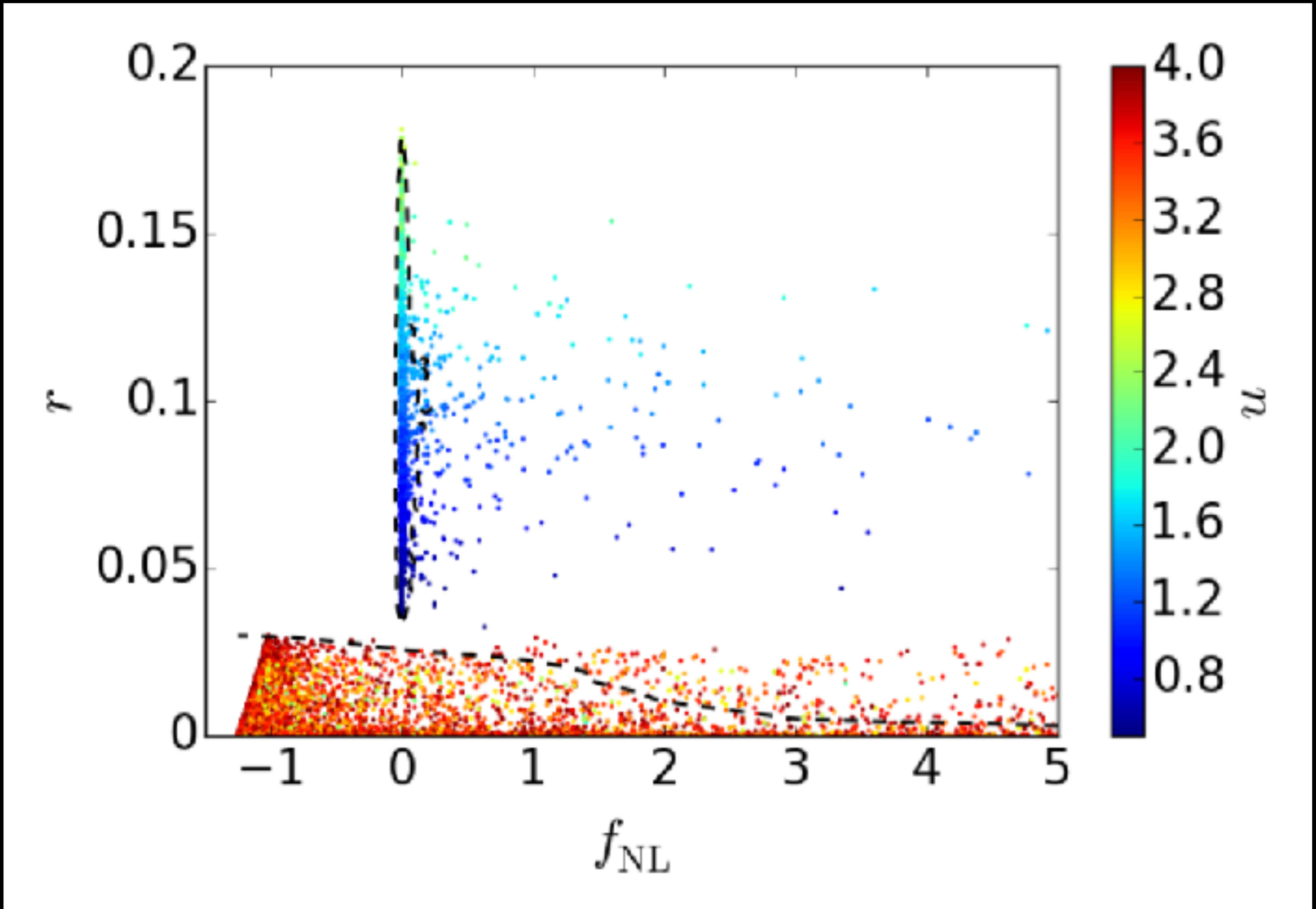
Modulated Reheating



de Putter, Gleyzes, OD 16

COMPLEMENTARITY BETWEEN THE PNG PROGRAM AND THE B-MODE PROGRAM

Curvaton Model



de Putter, Gleyzes, OD 16

QUANTIFYING PRIMORDIAL NON-GAUSSIANITY DISCOVERY POTENTIAL

- Assuming spectator field dominance (R>0.9)

- Quadratic-Axion:

  ➡ With Planck f_{NL}: P($|f_{NL}|$ > 1) = 58%

  ← Strong discovery potential

  ➡ Without Planck f_{NL}: P ($|f_{NL}|$ > 1 (10)) = 63 (6)%

- Modulated reheating

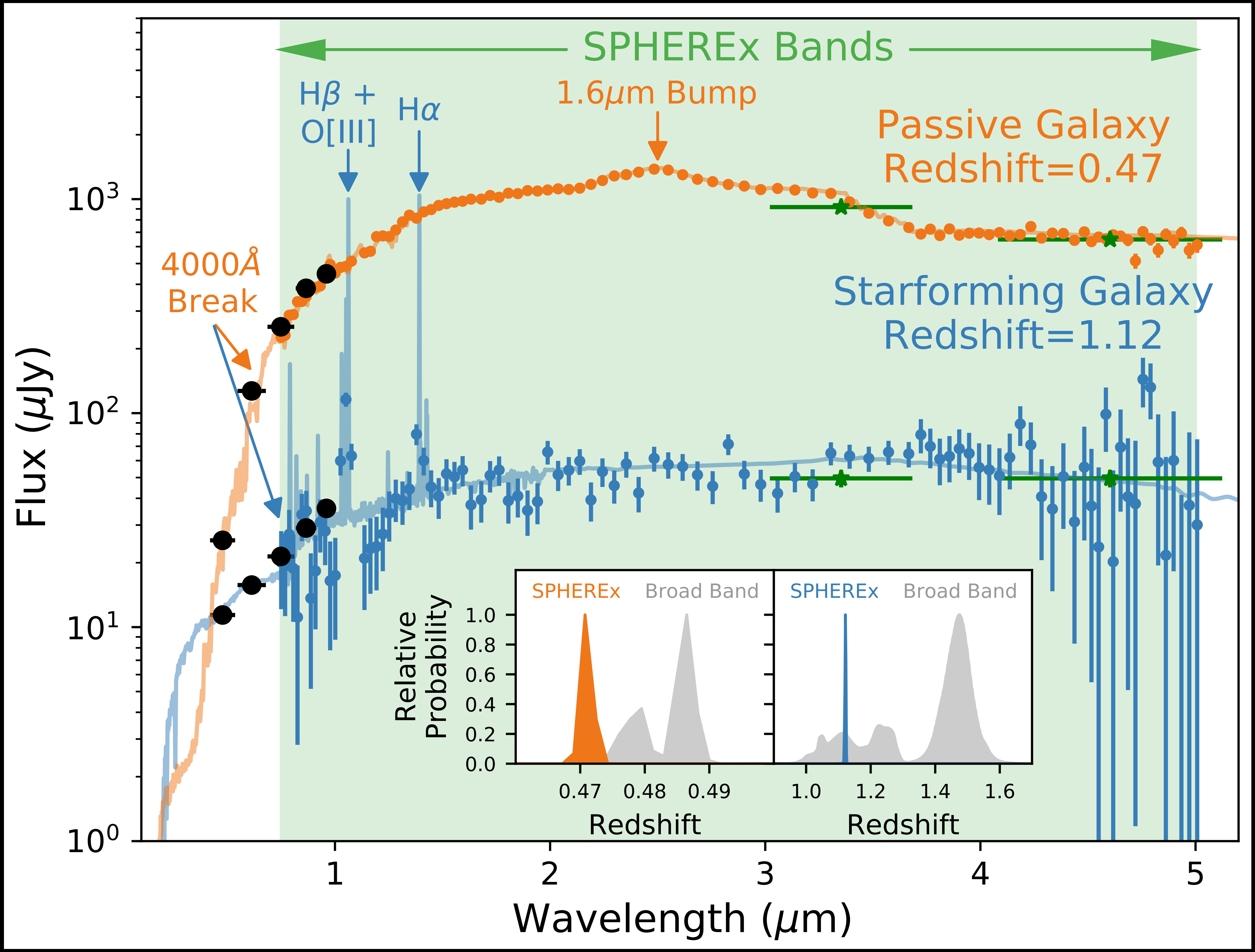
  ➡ With Planck f_{NL}: P($|f_{NL}|$ > 1) = 72%

  ← Planck already reduced the parameter space but more to cover

  ➡ Without Planck f_{NL}: P ($|f_{NL}|$ > 1 (10)) = 92 (60)%

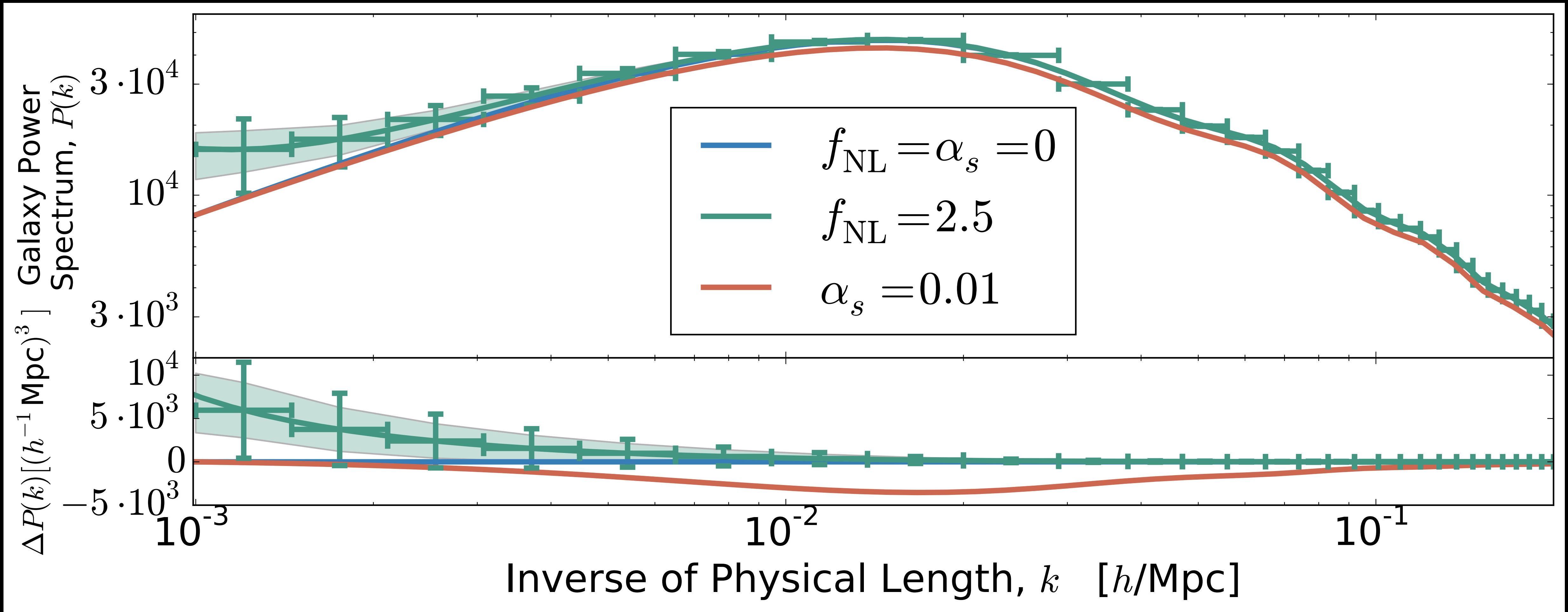
de Putter, Gleyzes, OD 16

BUILDING A 3-D GALAXY CATALOG WITH SPHEREX

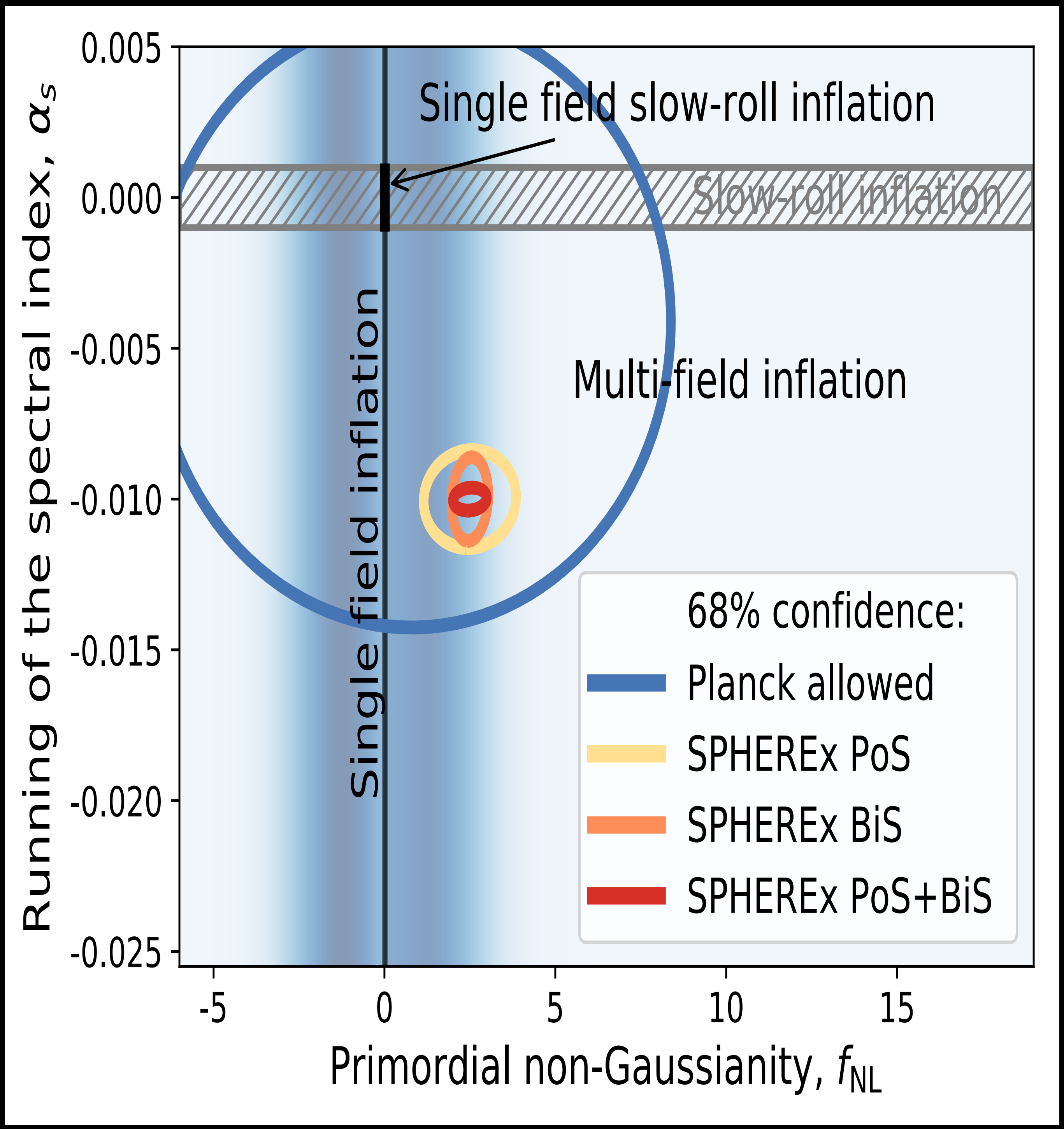


Stickley++16

POWER SPECTRUM MEASUREMENT



SPHEREX AND INFLATION



- SPHEREx produces a unique 3-D galaxy survey
  - ➡ Optimized for large scales to study inflation
  - ➡ Two independent tests of non-Gaussianity
- SPHEREx improves non-Gaussianity accuracy by a factor of ~10
  - ➡ Improves Δf_{NL} ~ 5 accuracy today to $\Delta f_{NL} < 0.5$
- Discriminates between models
  - ➡ Single-field inflation $f_{NL} << 1$
  - ➡ Multi-field inflation $f_{NL} \gtrsim 1$

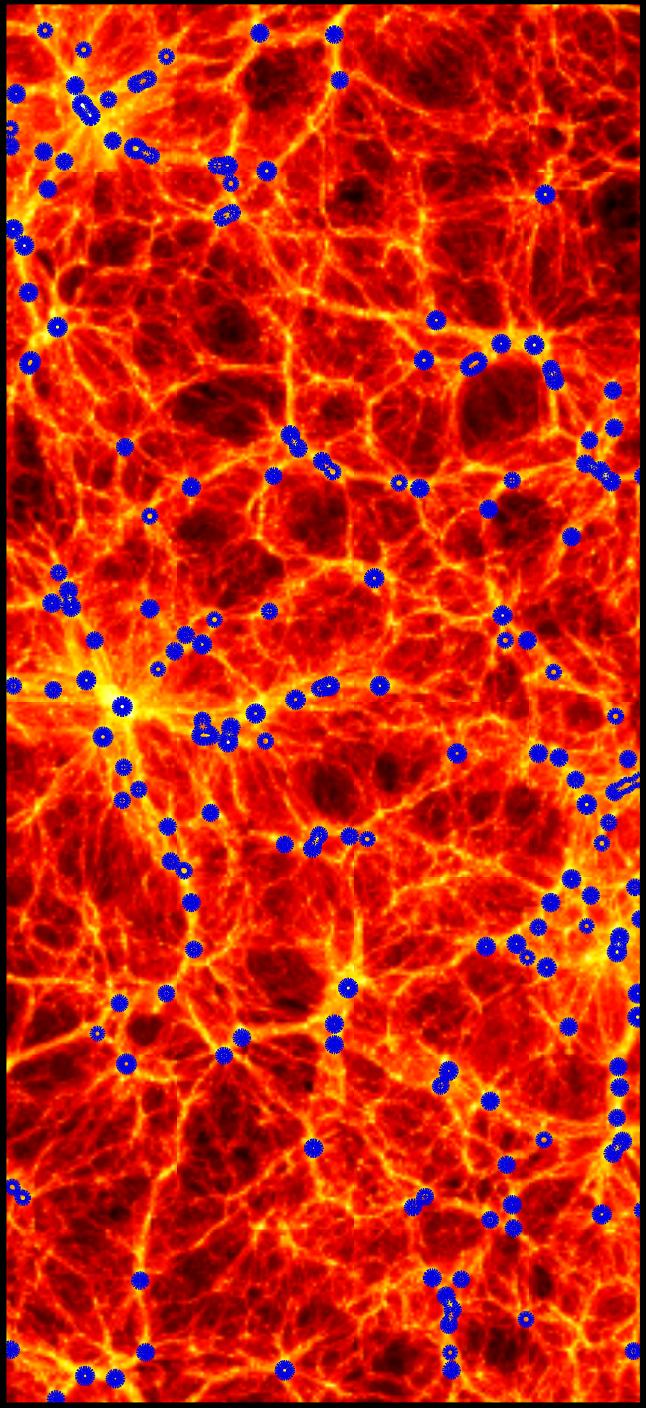
MAIN SYSTEMATICS EFFECTS

- Allocated systematic budget level set at the $\delta n/n = 0.2\%$ rms/dex
  - ➡ ~mmag controls of all effects over ~30 deg. scales

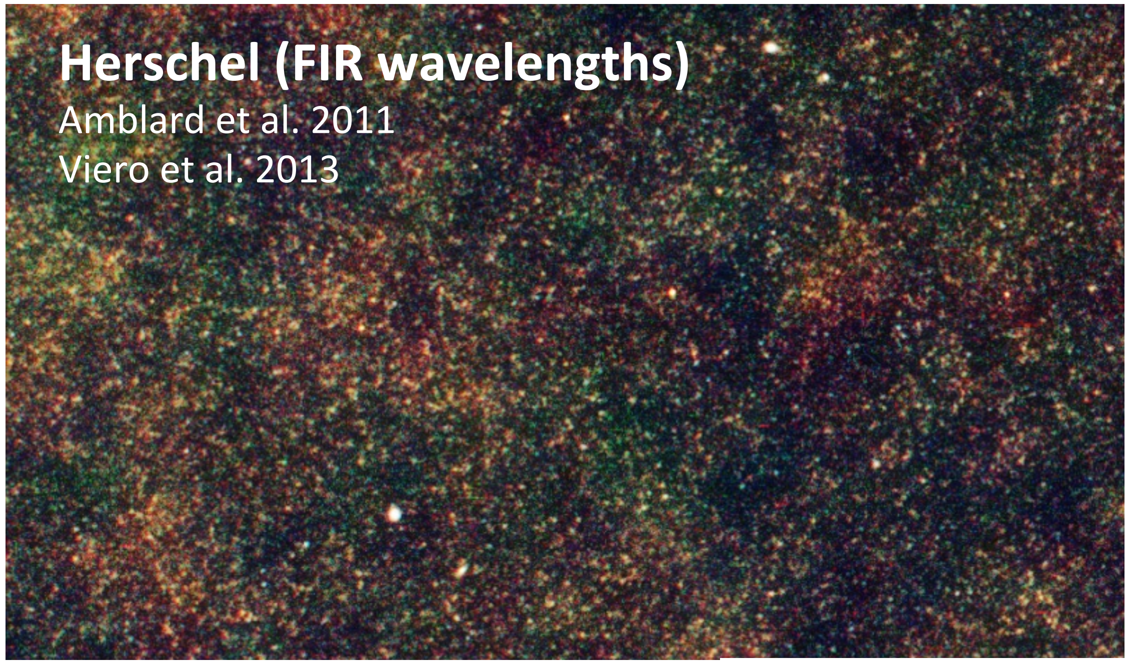
- Dominant expected systematic effects (for cosmology):
  - ➡ Galactic extinction: 3 mmag rms before mitigation and $\delta n/n = 0.06\%$ rms/dex after mitigation
  - ➡ Selection non-uniformity: 0.2 mag rms before mitigation and $\delta n/n = 0.06\%$ rms/dex after mitigation
  - ➡ Redshift errors due to non-uniform noise: 0.2 mag rms before mitigation and $\delta n/n = 0.017\%$ rms/dex after mitigation
  - ➡ Calibration stability: <1% drift over 4 surveys and $\delta n/n = 0.05\%$ rms/dex after mitigation
  - ➡ Non-uniformity in external catalogs: 0.1% rms/dex after mitigation

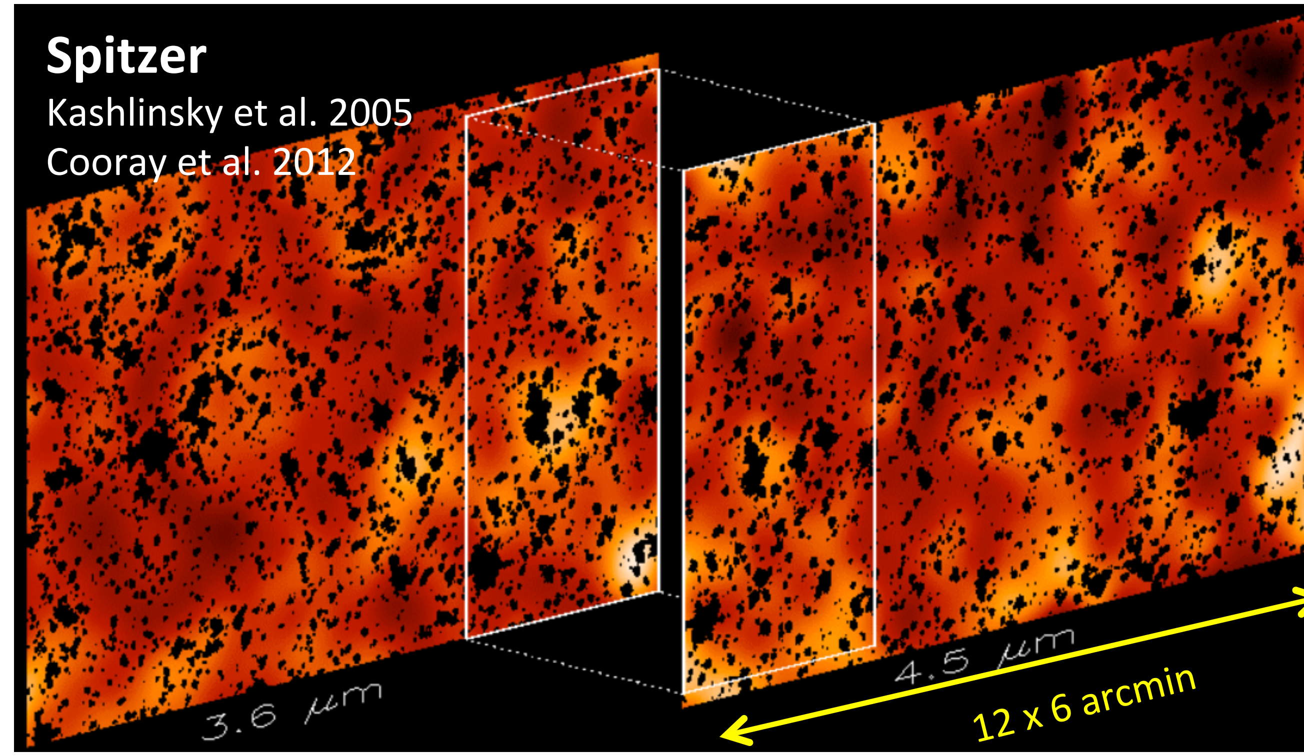
EXTRA-GALACTIC BACKGROUND LIGHT INVESTIGATION

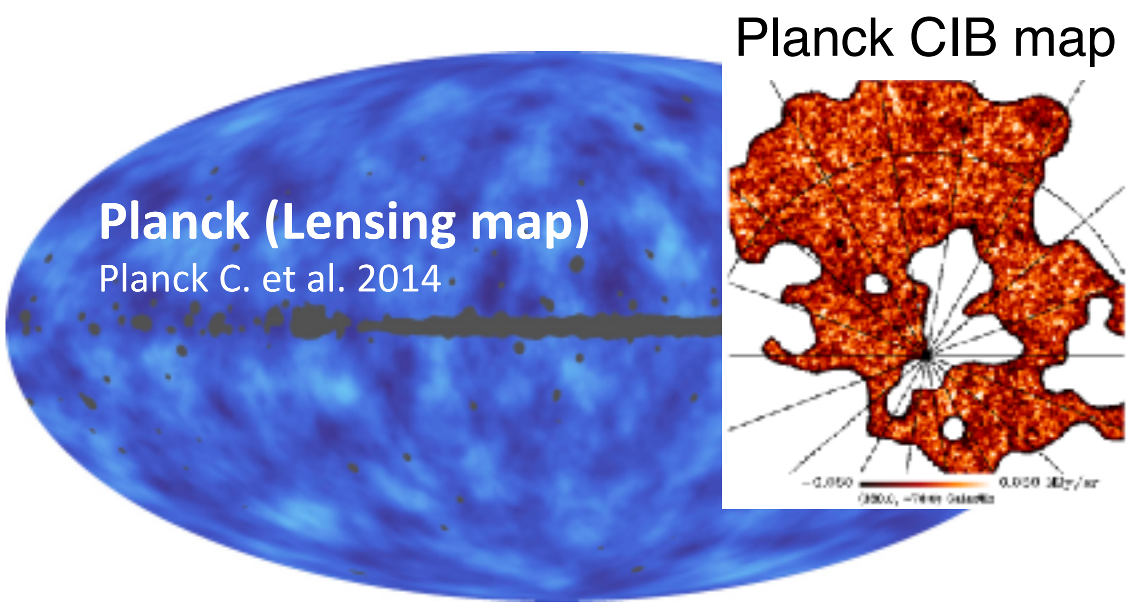
ASTRONOMY IN THE INTENSITY MAPPING REGIME

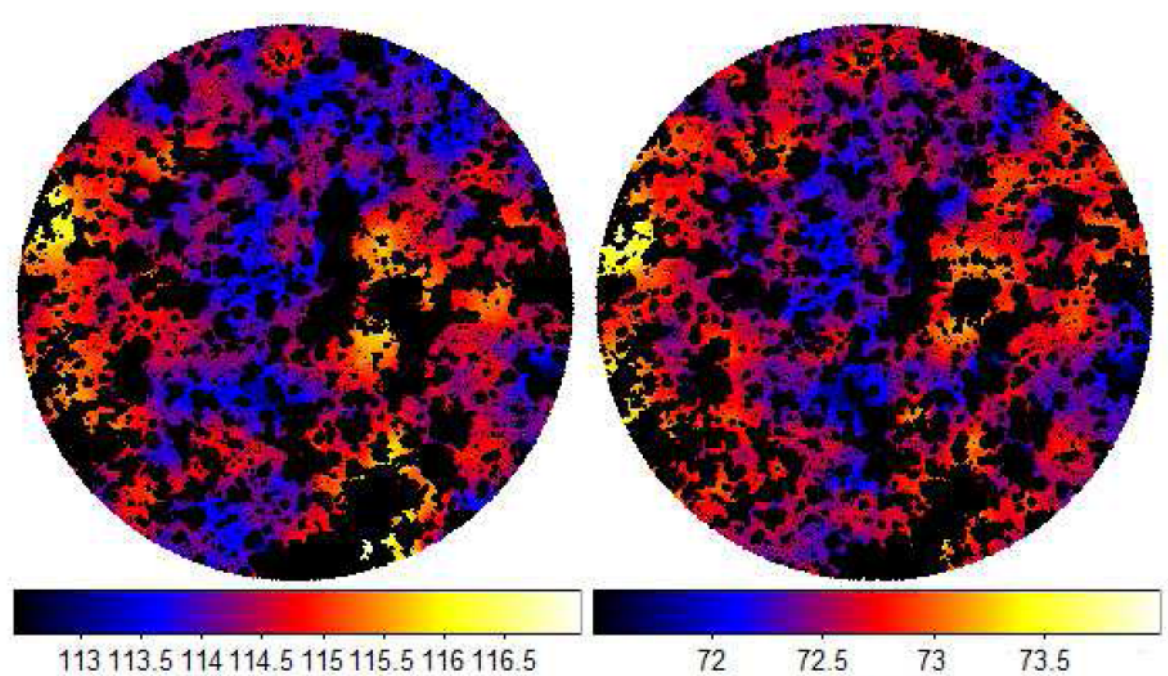


PROBING THE EBL WITH SPATIAL FLUCTUATIONS IN NIR OR MM









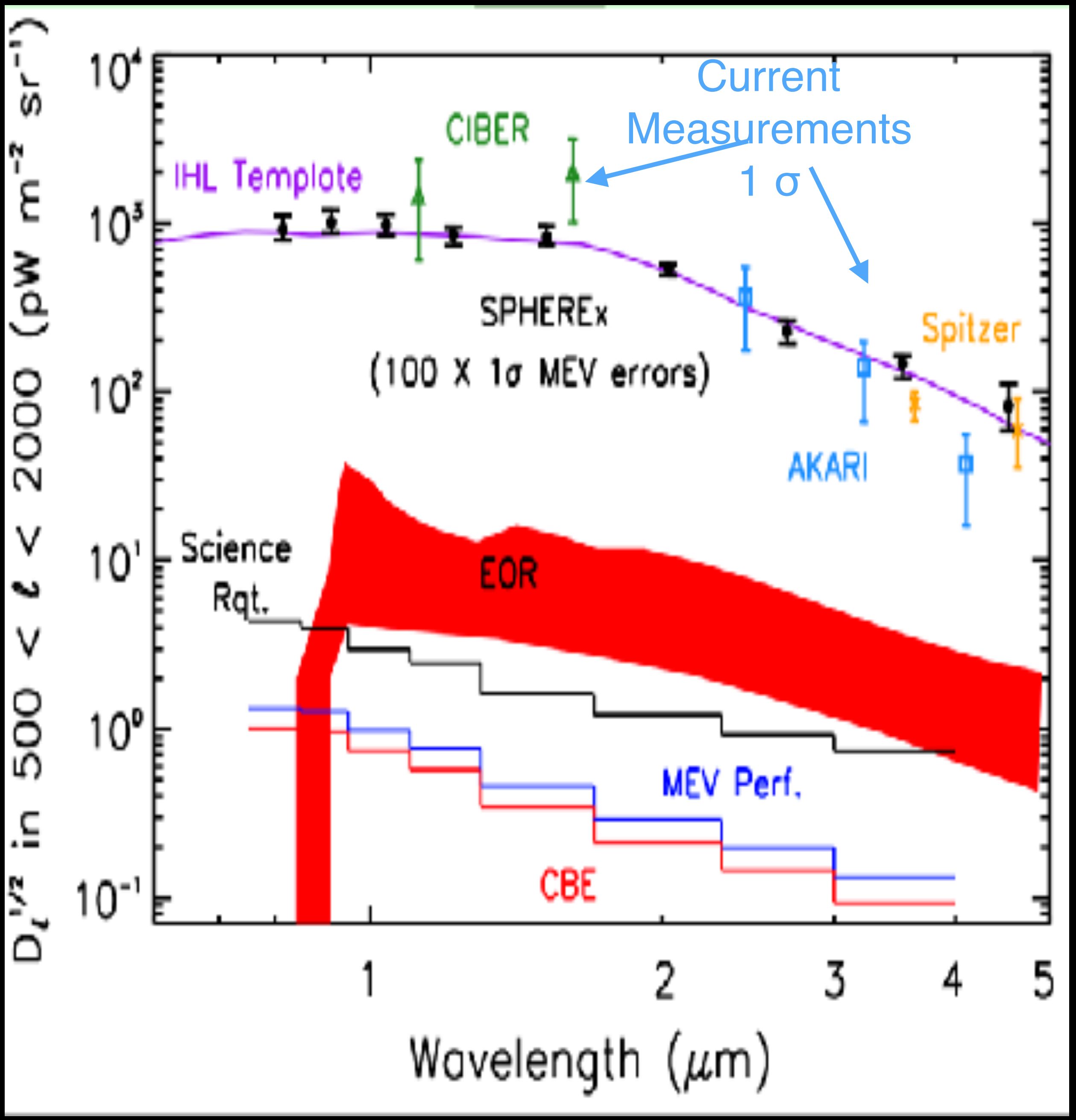
Successful Applications at Longer Wavelengths

- Herschel EBL: Viero et al. 2013
- Planck EBL: Planck C. et al. 2013 XXX
- Planck EBL x CMB Lensing: Planck C. et al. 2014 XVIII
- Herschel EBL x CMB Lensing: Many

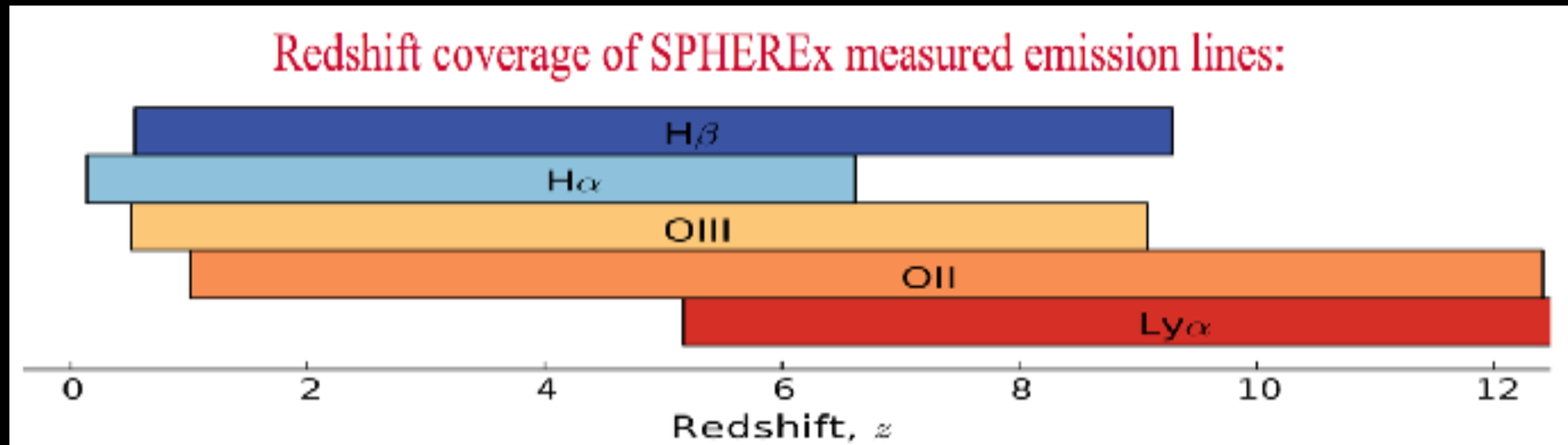
PROBING THE EPOCH OF REIONIZATION

- SPHEREx orbits enable deep/frequent observations of about 200 sq. deg near the ecliptic poles (great for systematics!)
- SPHEREx wavelength coverage and resolution will enable large-scale measurement of spatial fluctuations in the Extragalactic Background Light (EBL)
- In particular, SPHEREx will monitor/explain the Intra-Halo Light and its evolution (CIBER, Zemcov++14)
- SPHEREx has the raw sensitivity to probe the expected EOR signal (but separation with low z signal will be challenging)
- The sensitivity in this region will enable deep intensity mapping regimes using multiple lines at all redshift, and maybe Lyα at high redshift (see Croft++15, 18)

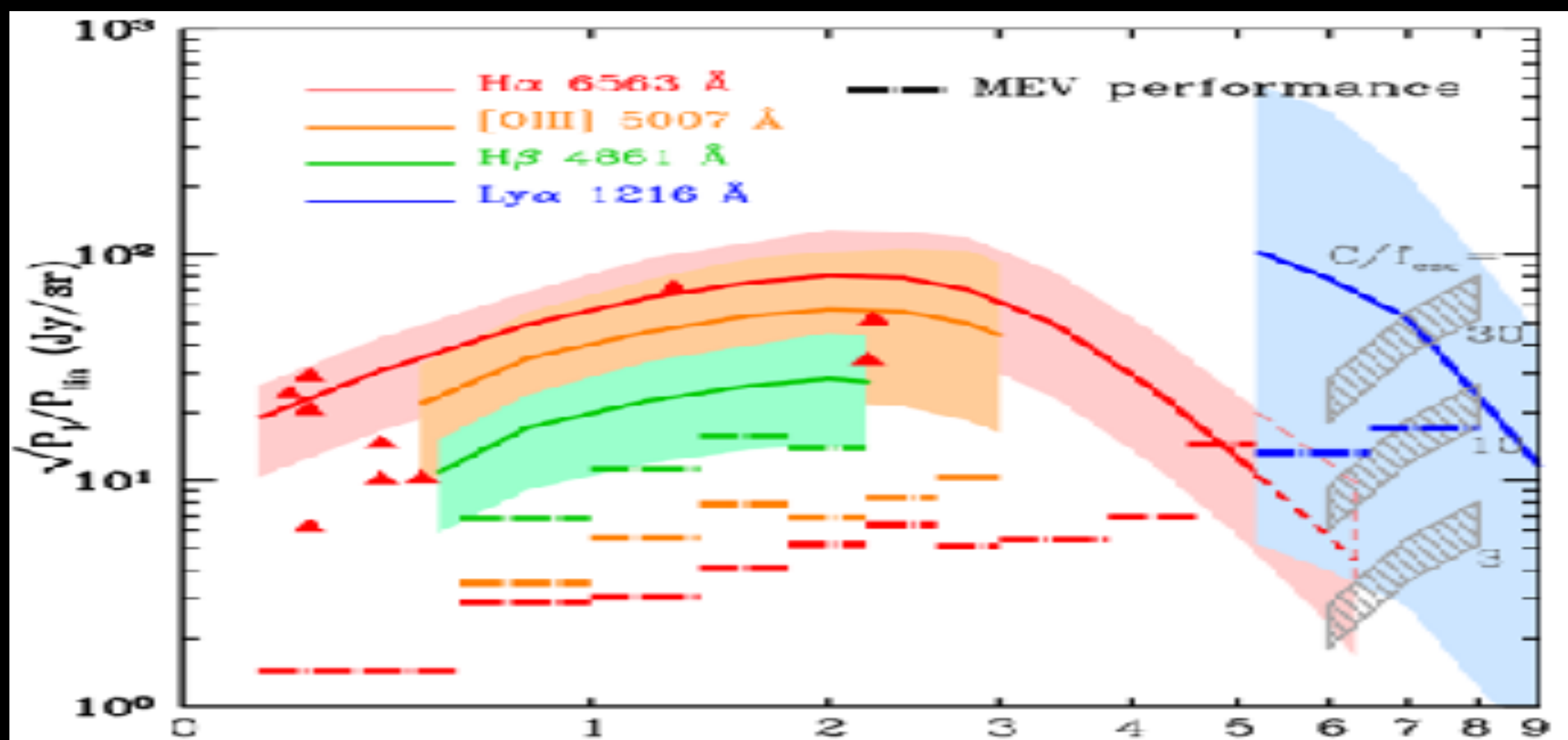
Fluctuations in Continuum Bands



LINE INTENSITY MAPPING WITH SPHEREX



Clustering amplitude (bias)



Redshift, *z*

- SPHEREx measures with high SNR the line L weighted bias at multiple z with multiple lines.
- Enough sensitivity for BAO measurements till z~6 but some contaminants to deal with.

ICE INVESTIGATION

What Are the Conditions for Life Outside the Solar System?

Sourced by biogenic molecules: H_2O, CO, CO_2, CH_3OH…

Current debate:

Did earth’s water come from the Oort cloud, Kuiper belt or closer?

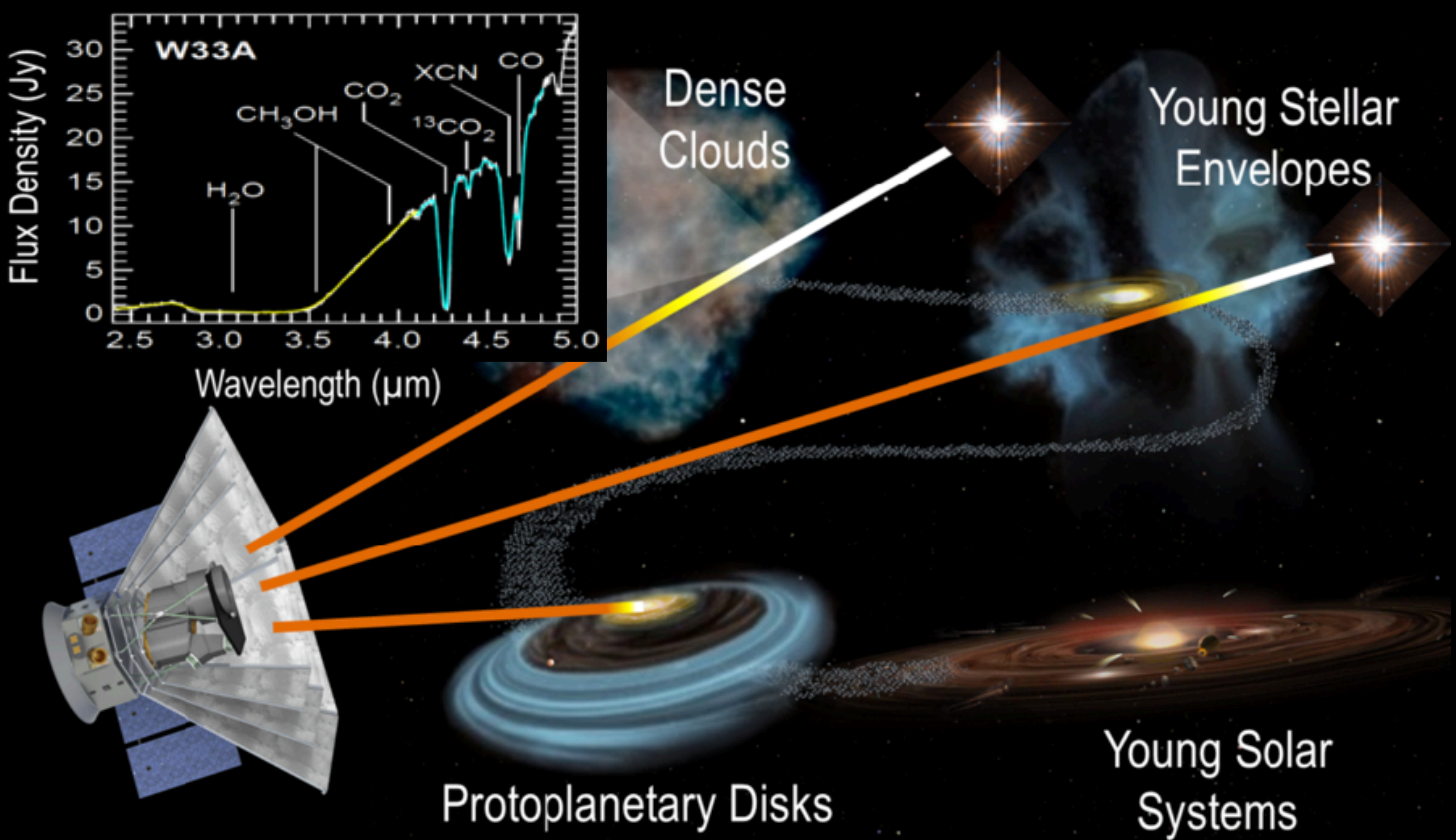
Did water arrive from the late bombardment (~500 MY) or before?

More than 99 % interstellar water is locked in ice

‘Follow the Water’ means ‘Follow the Ice’

SPHEREx will measure the H_2O, CO, CO_2, CH_3OH ice content in clouds and disks, determining how ices are inherited from parent clouds vs. processed in disks

SPHEREX SURVEYS ICES IN ALL PHASES OF STAR FORMATION



SPHEREx will measure ice abundance towards >> 20,000 sources and determine how water and biogenic ices evolve from molecular clouds to young stars to proto-planetary disks

SUMMARY

- SPHEREx selected as the next MIDEX. Launch planned late 2023.
- SPHEREx will create the first all sky near-infrared spectroscopic survey:
  - ➡ A public dataset of lasting legacy.
- SPHEREx offers a simple and very robust design and modus operandi:
  - ➡ Naturally enables a high control of systematics thanks to multiple built-in redundancy.
- SPHEREx will enable multiple and powerful studies:
  - ➡ Primordial non-Gaussianity to learn about Inflation.
  - ➡ Extra-galactic background light from z=0 till the reionization era.
  - ➡ Origin of water and biogenic ices in young stellar objects and proto-planetary systems.
  - ➡ …
- SPHEREx has strong synergies with current and future observatories
  - ➡LSST, DESI, JWST, WFIRST, TESS, e-ROSITA, SO, CMB-S4…
  - ➡Exciting decade

http://spherex.caltech.edu

FIN