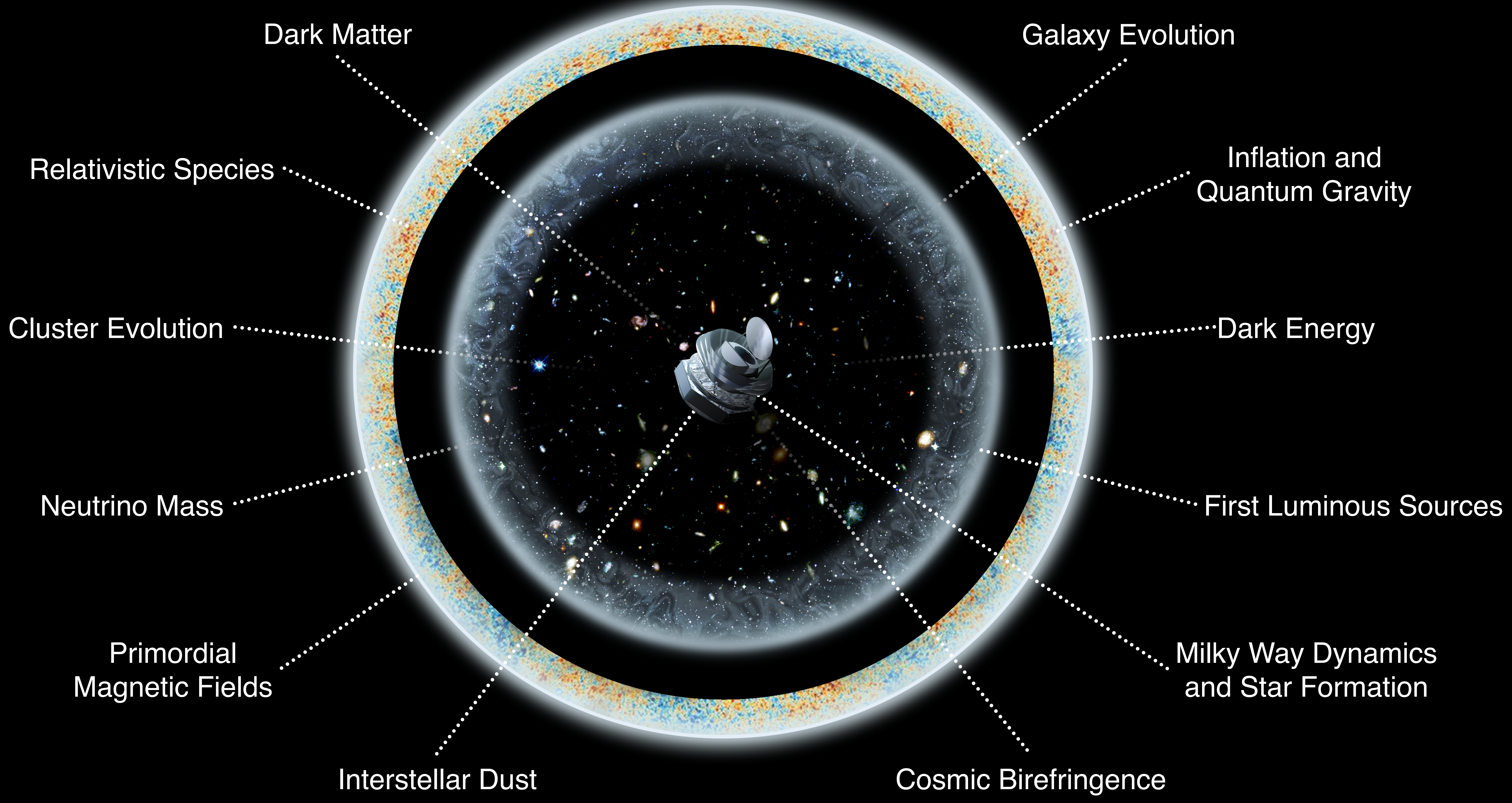
PICO

PROBE OF INFLATION
AND COSMIC ORIGINS

SHAUL HANANY
UNIVERSITY OF MINNESOTA



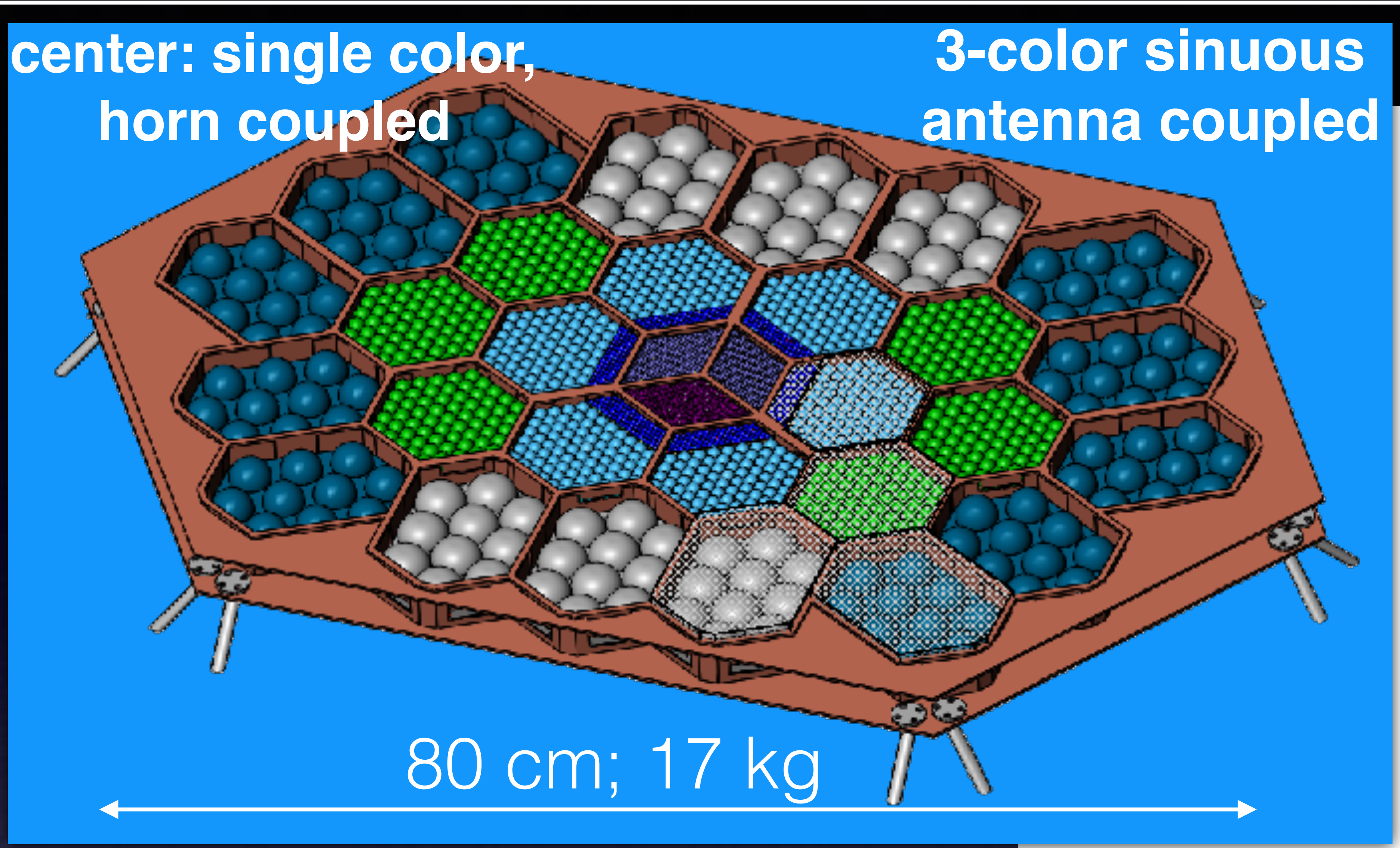
https://z.umn.edu/picomission

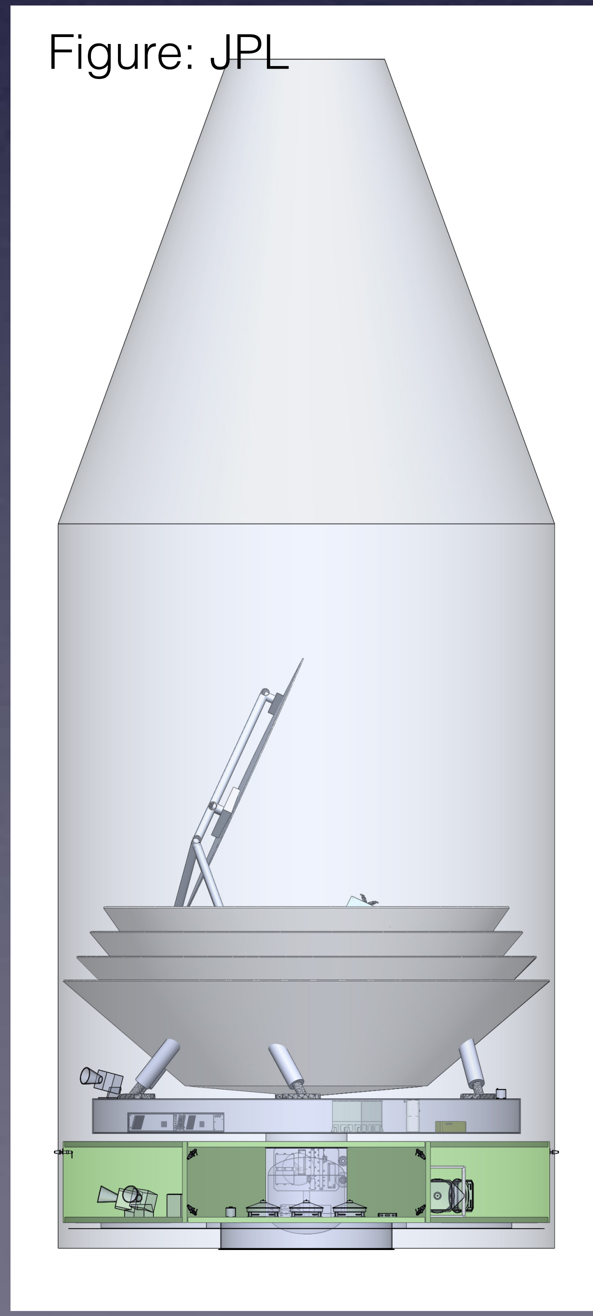
arXiv 1902.10541

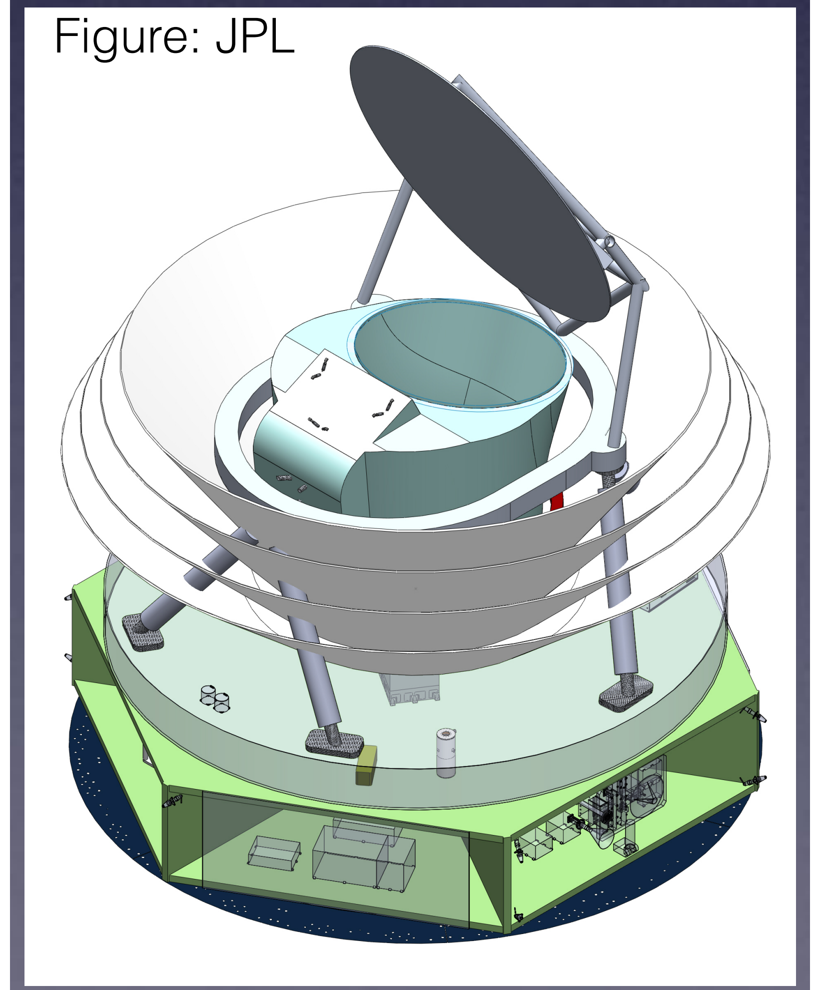
PICO: mm/submm All Sky Imaging Polarimetric Survey

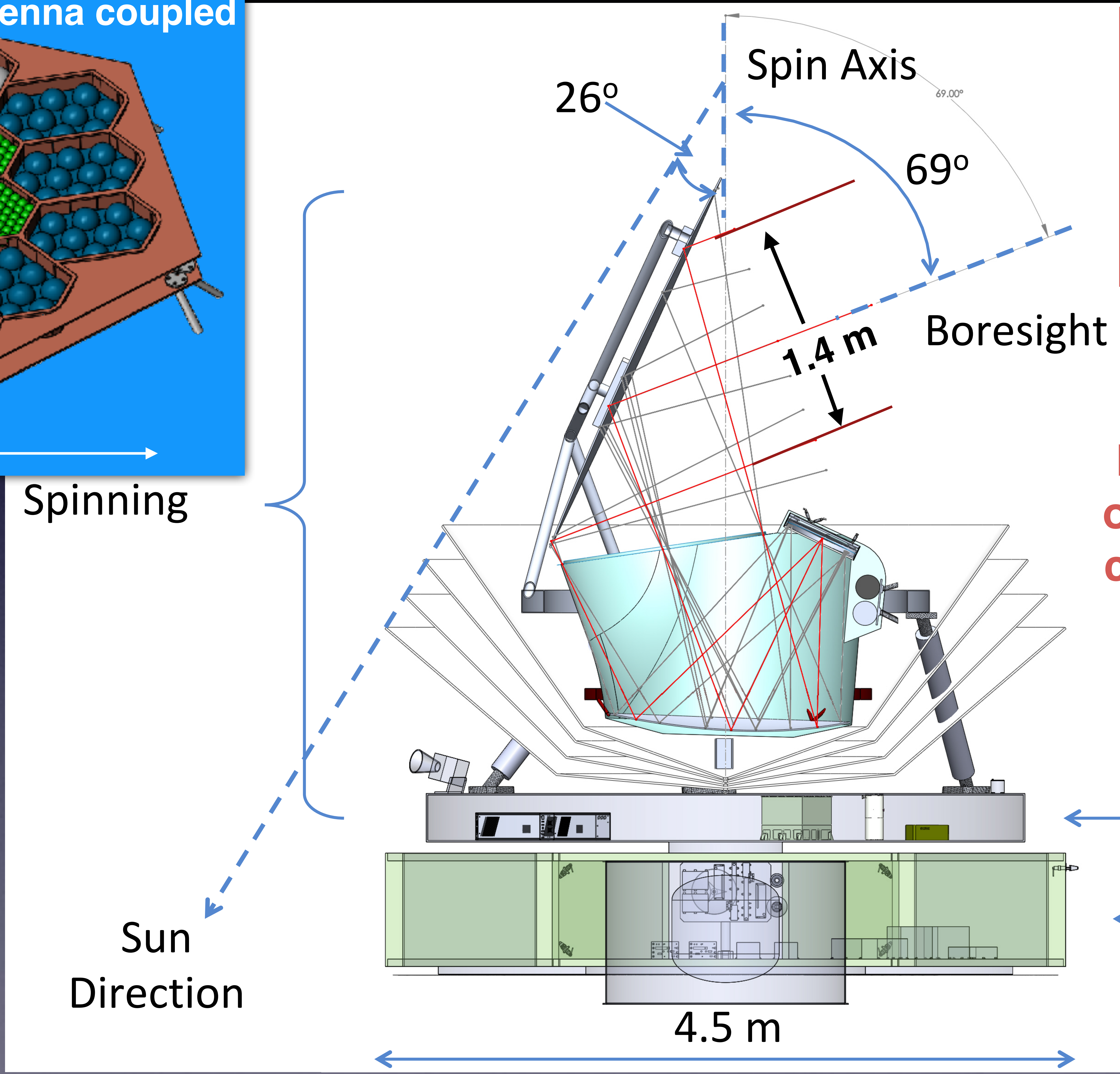
- PICO will produce the deepest maps of Stokes I, Q, U in 21 frequency bands between 20 and 800 GHz
- Maps will have resolution between 38' and 1'.
  8 maps, >200 GHz: highest resolution, full sky maps
- Ten redundant surveys: stringent control of systematic errors
- 13,000 transition edge sensor bolometers
- 5 year survey from L2
- Noise baseline: 3300 *Planck* missions (0.87 uK*arcmin)
- Noise Current estimate: 6400 *Planck* missions (0.61 uK*arcmin)

PICO Implementation: Heritage of Planck



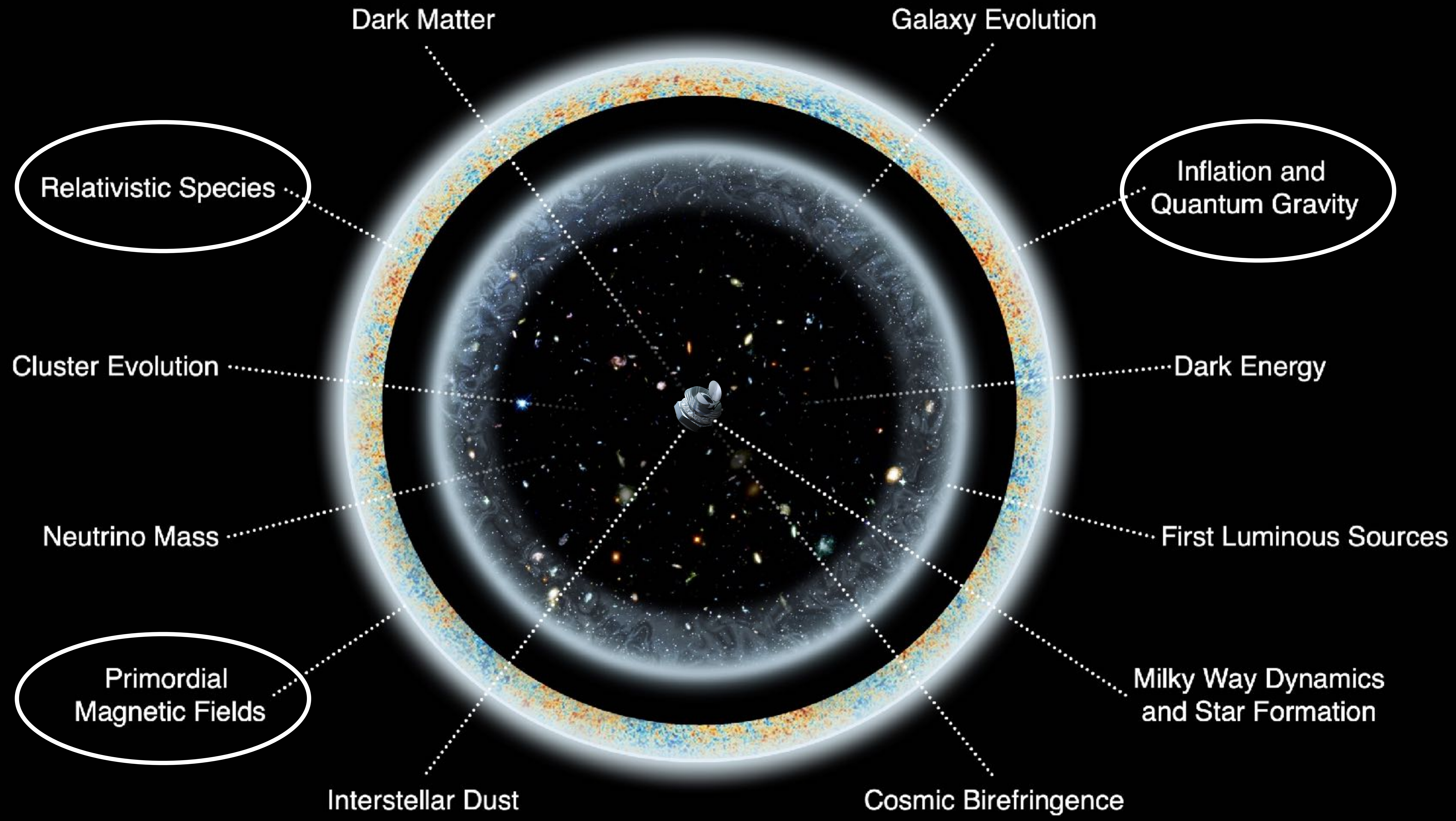






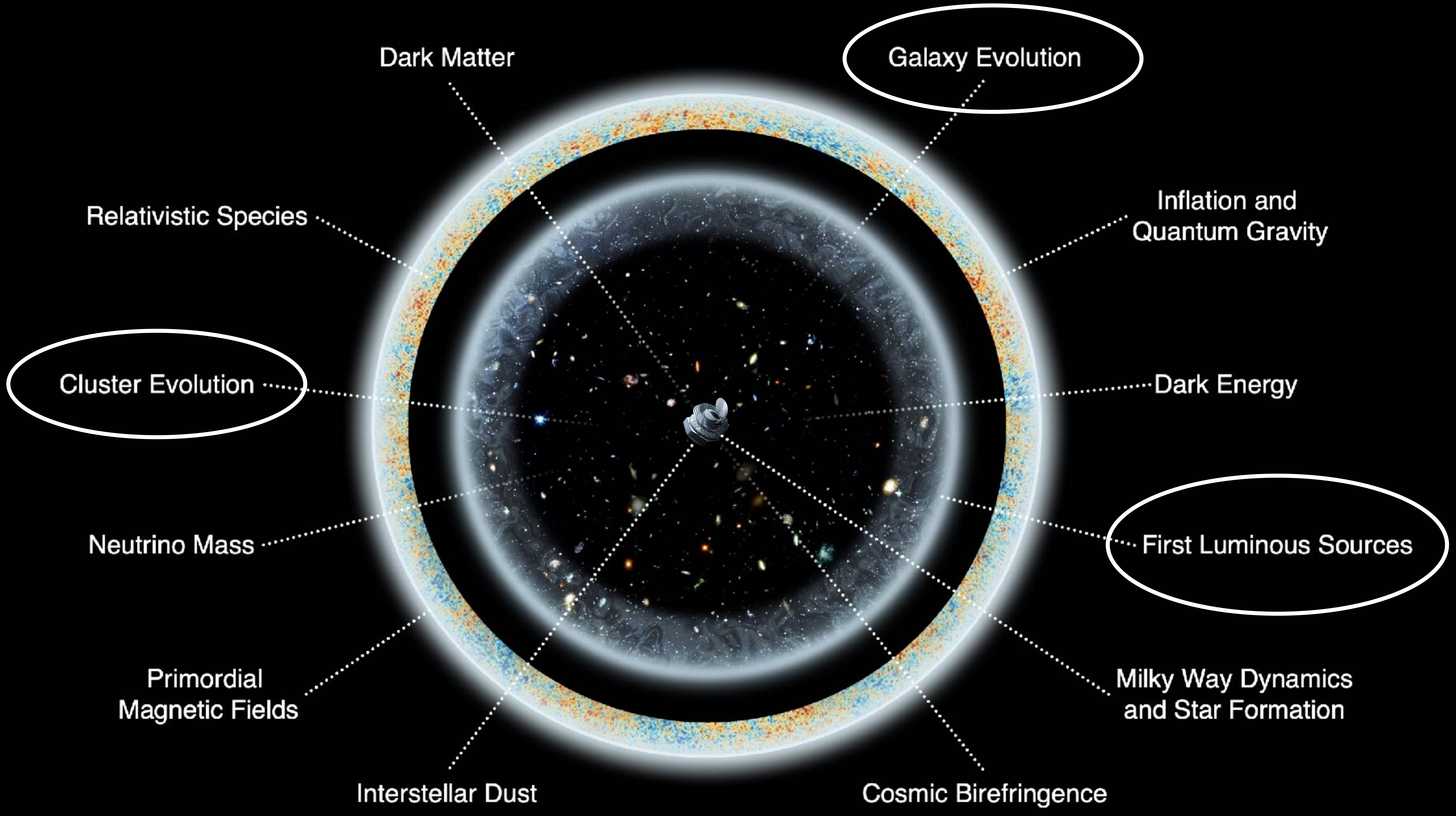
- **2-reflector "Open Dragone" Telescope**
- **Ambient temperature primary**
- **4 K aperture stop**
- **4 K secondary reflector**
- **0.1 K focal plane (cADR)**

PICO technologies are based on extensions of technologies currently used with space and sub-orbital instruments



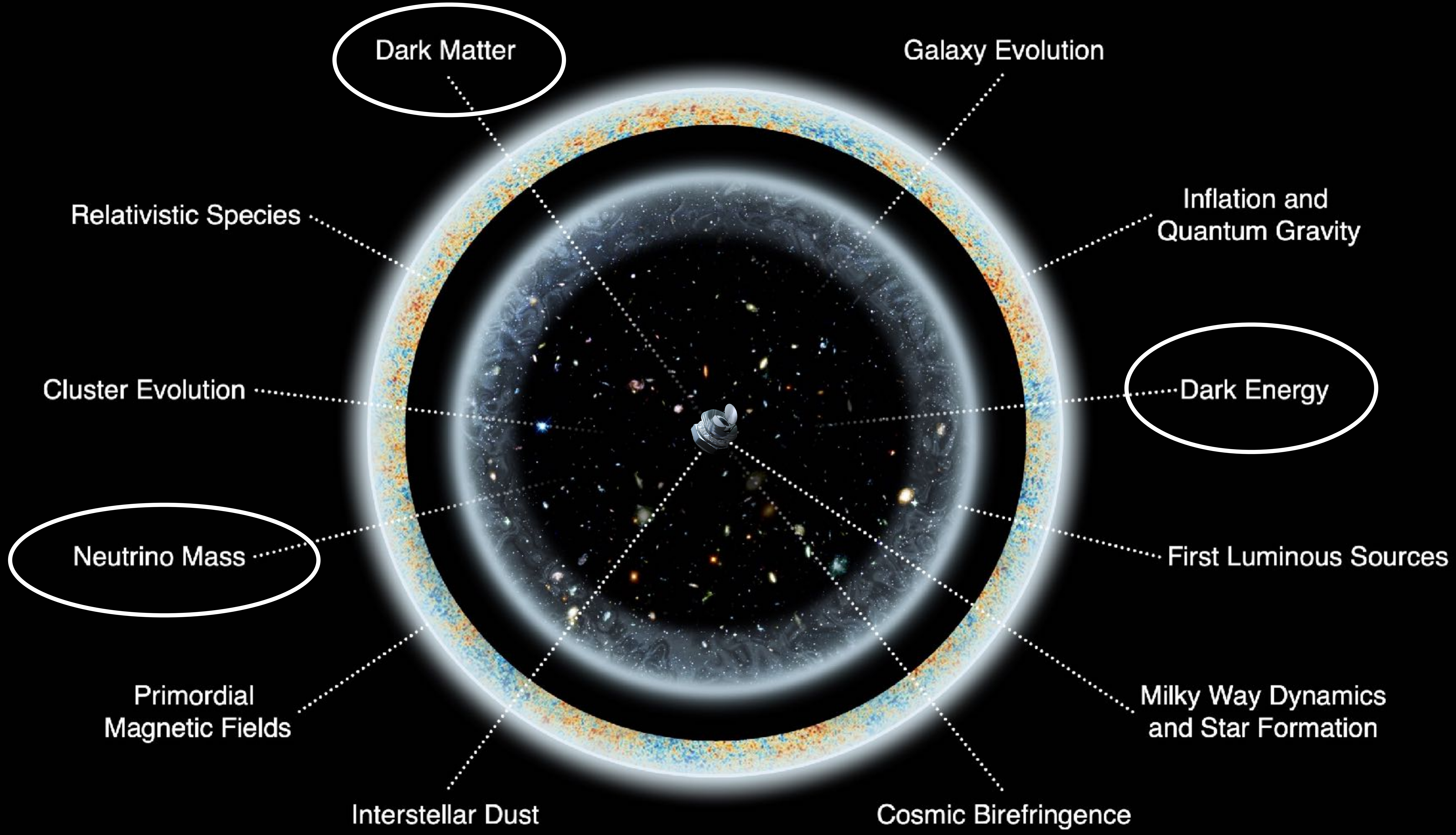
https://z.umn.edu/picomission

arXiv 1902.10541



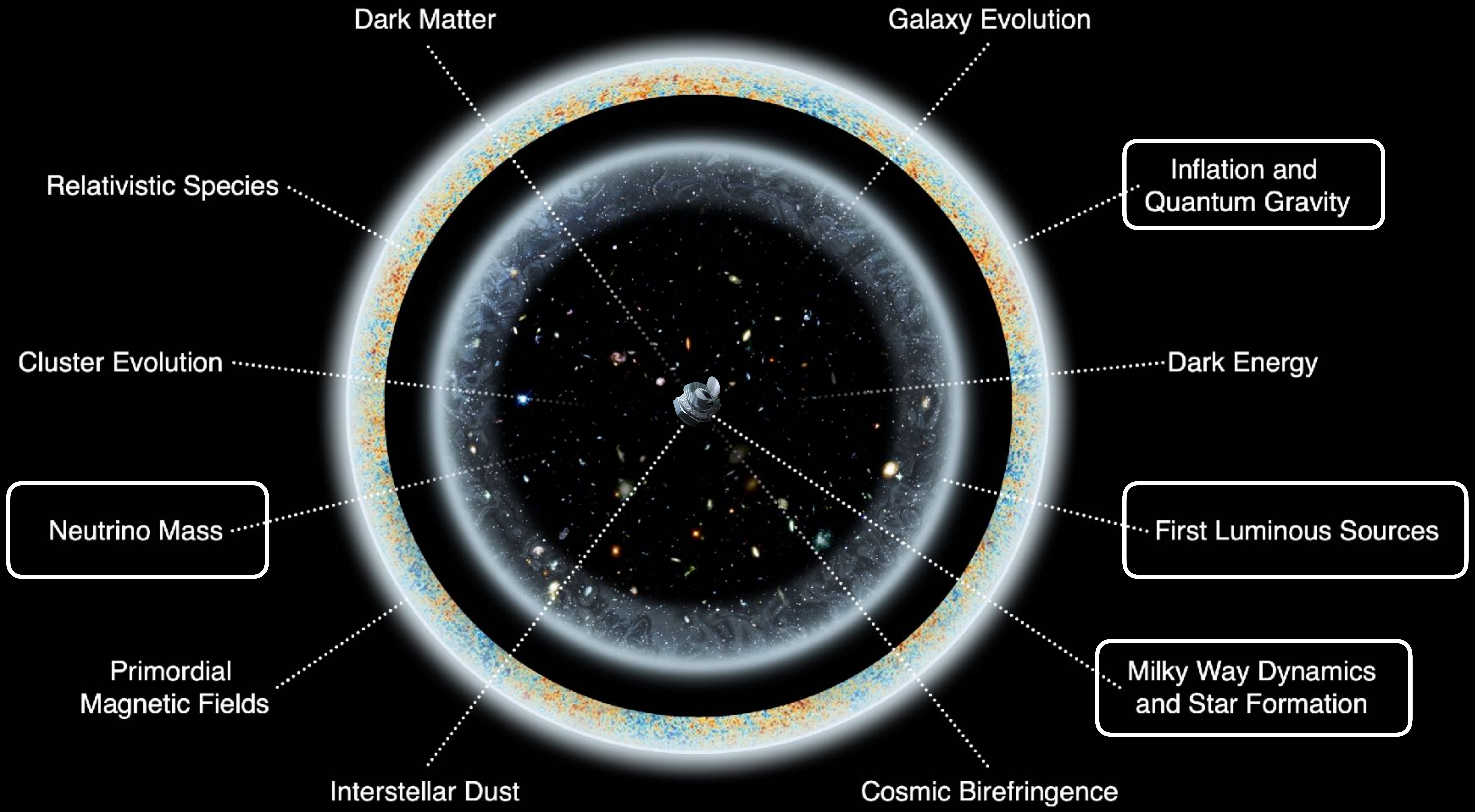
https://z.umn.edu/picomission

arXiv 1902.10541



https://z.umn.edu/picomission

arXiv 1902.10541



https://z.umn.edu/picomission

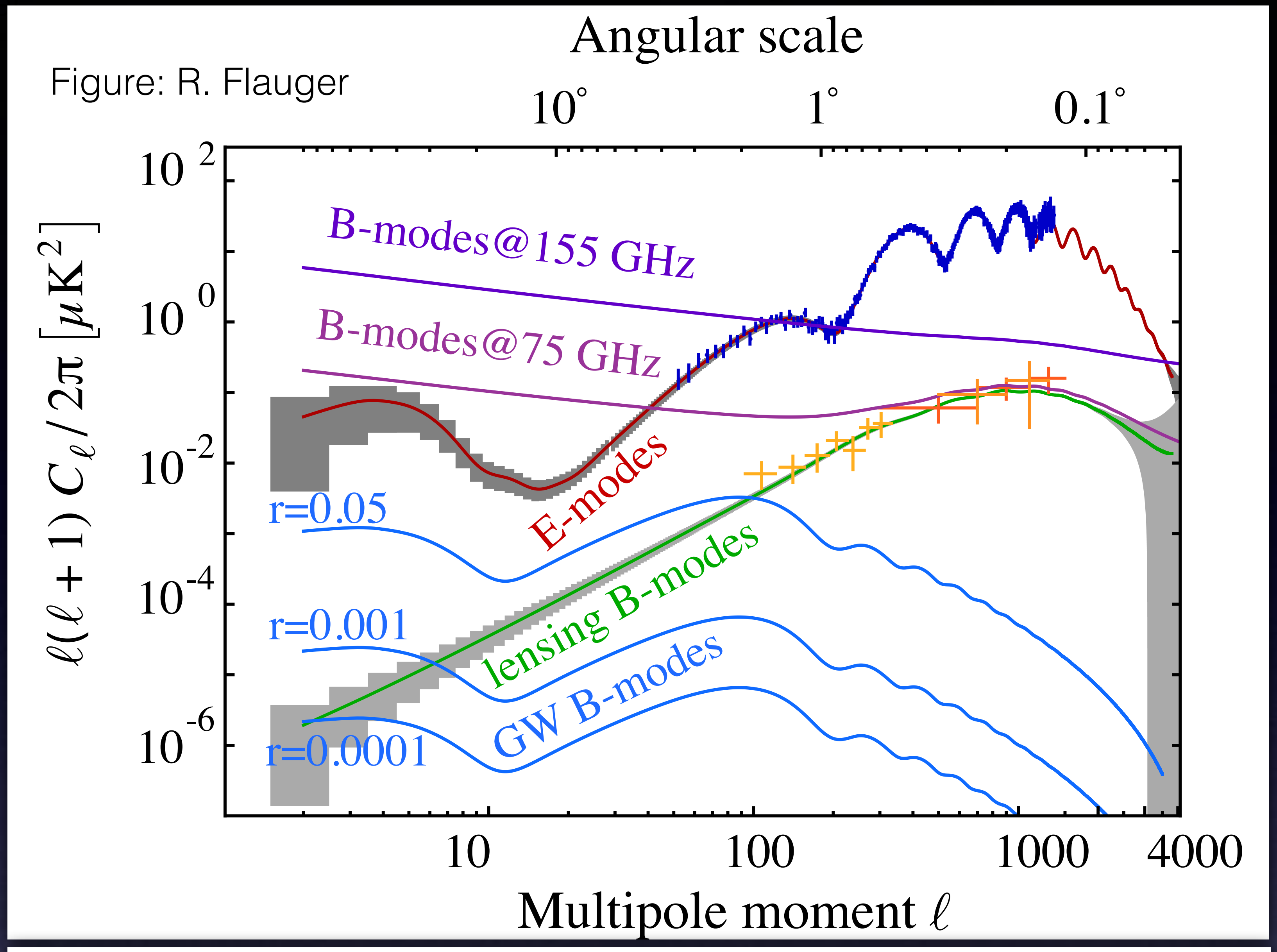
arXiv 1902.10541

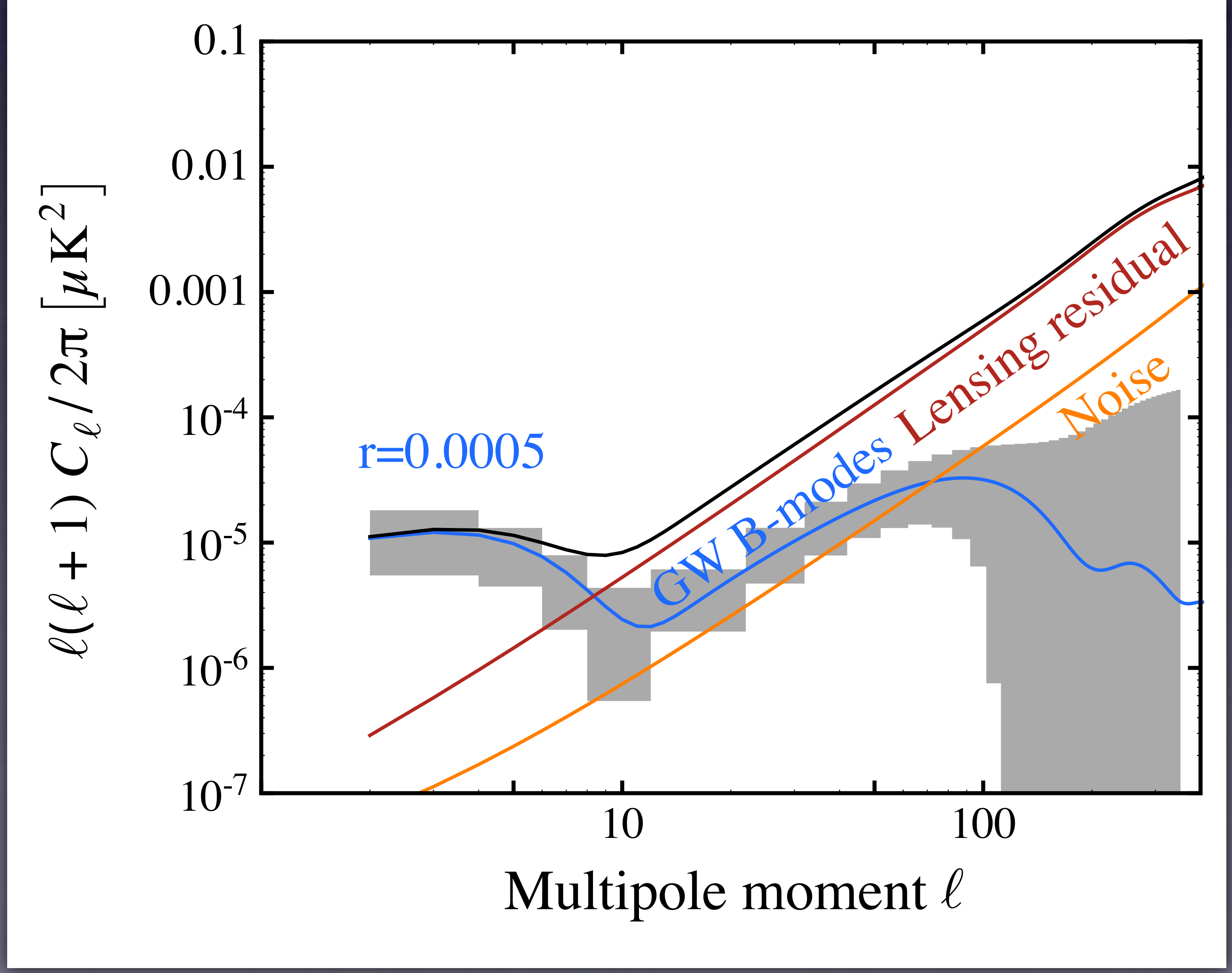
Explore How the Universe Began: Inflation

- What is the energy scale of Inflation? What is the physics driving Inflation? Can we directly observe the epoch of quantum gravity?
- $E_{\text{inf}} = 3.7 \cdot 10^{16} r^{1/4}\ \text{GeV}$
- $B_{80} = 0.08 r\ \mu\text{K}^2$
- Currently $r < 0.06\ (95\%)$ (BKA+Planck)
- Signal is substantially weaker than Galactic foregrounds and mostly below Lensing foregrounds
- PICO requirement

$$r < 2 \cdot 10^{-4}\ (95\%);\ \ r = 5 \cdot 10^{-4}\ (5\sigma)$$

- 300 times lower than current constraint

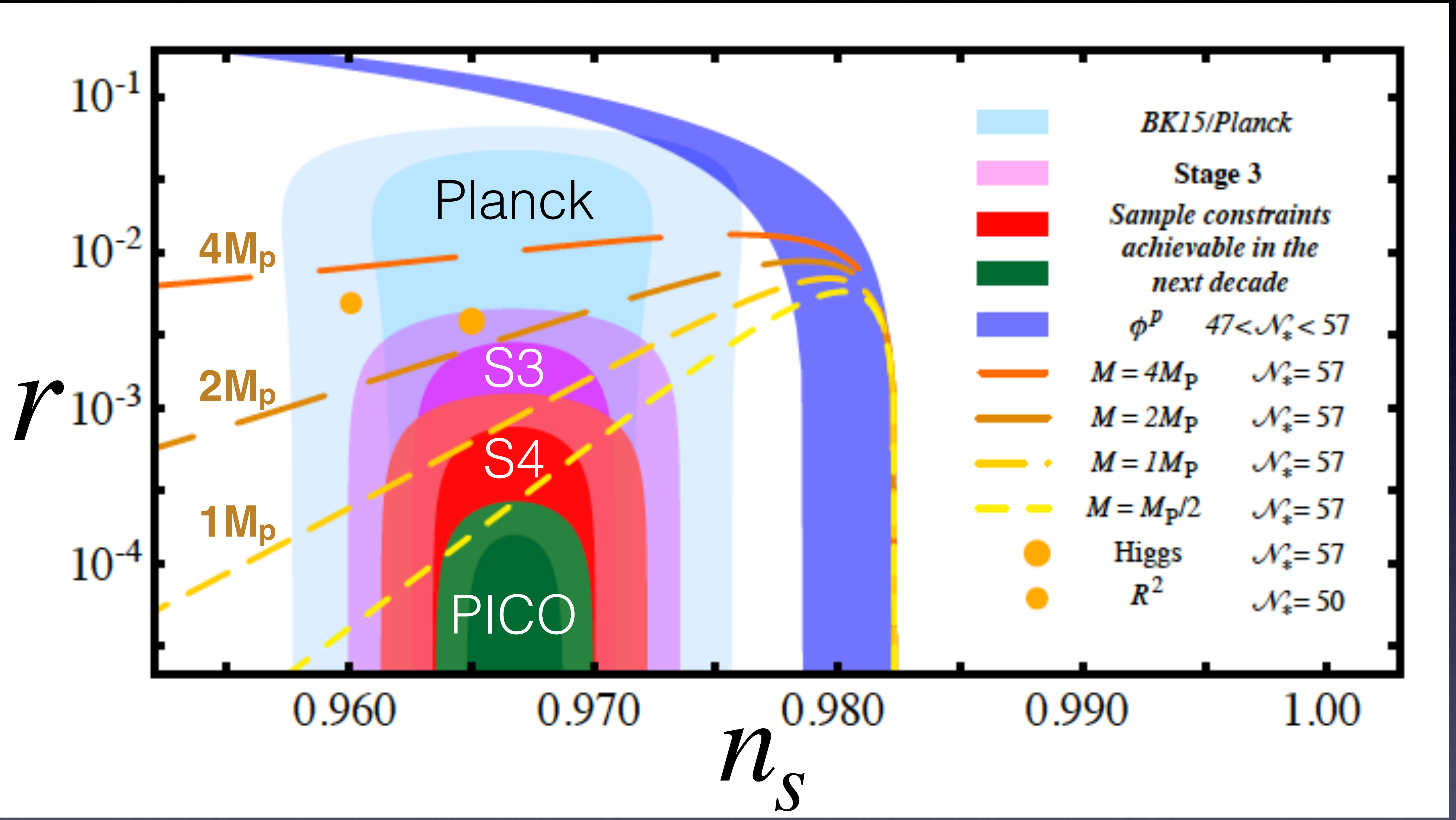




Detect Inflation or Rule Out Key Textbook Models

Textbook Inflation models that naturally explain the spectral index and have superPlanckian mass scale

Only the PICO exclusion will reject all models with superPlanckian scale in the potential with high confidence



"If this threshold is passed without detection, most textbook models of inflation will be ruled out, and the data would force a significant change in our understanding of the primordial Universe"

(Shandera et al. 2019, Community endorsed decadal white paper)

Can the foregrounds be handled ?

- Right: one sky model; 21 bands; PICO noise; nside=512; analyzed with GNILC; 50% of sky; 85% delensing
- Left: several sky models
- residual foregrounds are x5-10 below r for \ell=5; x3-4 below r for \ell=100

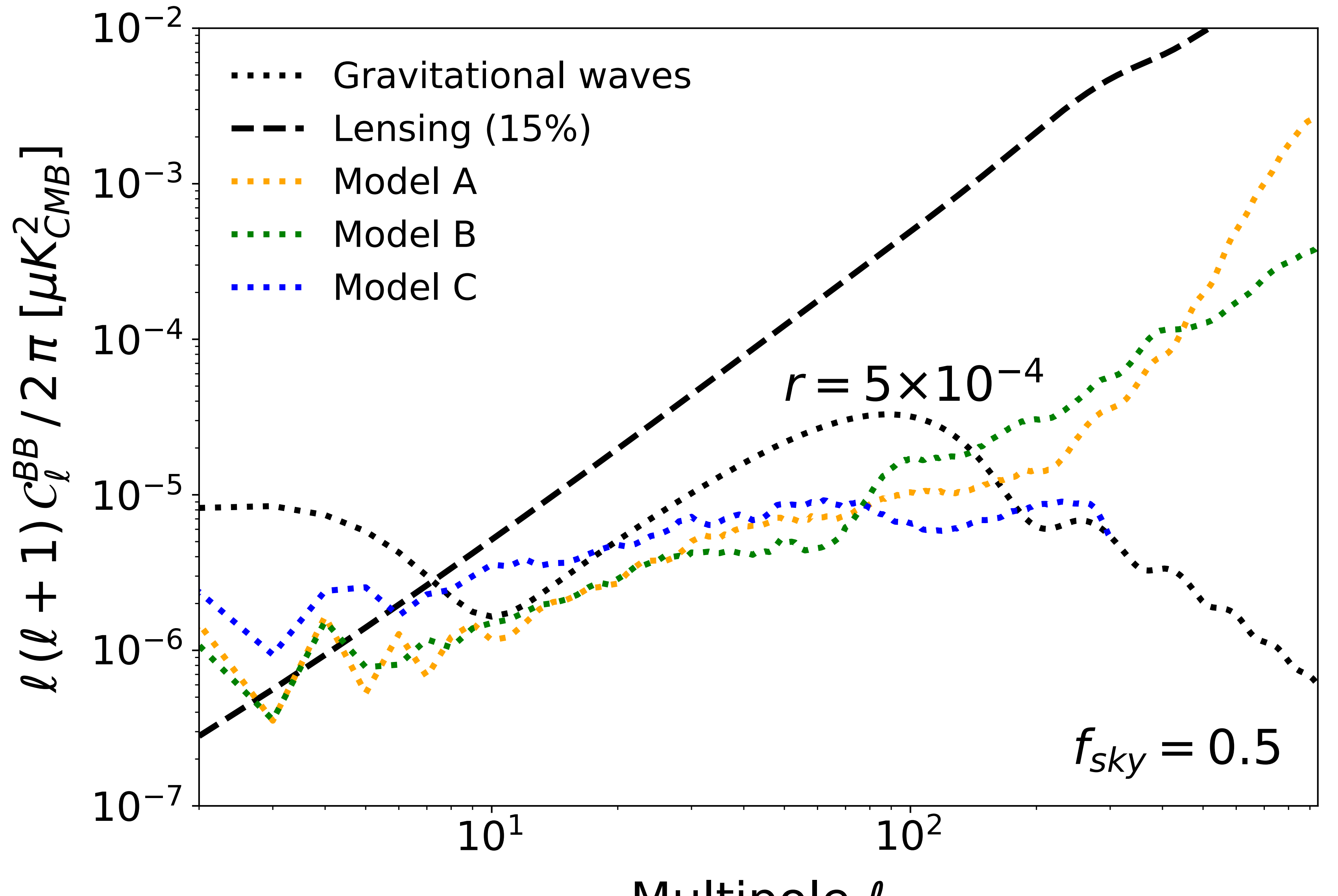


Figure: Remazeilles

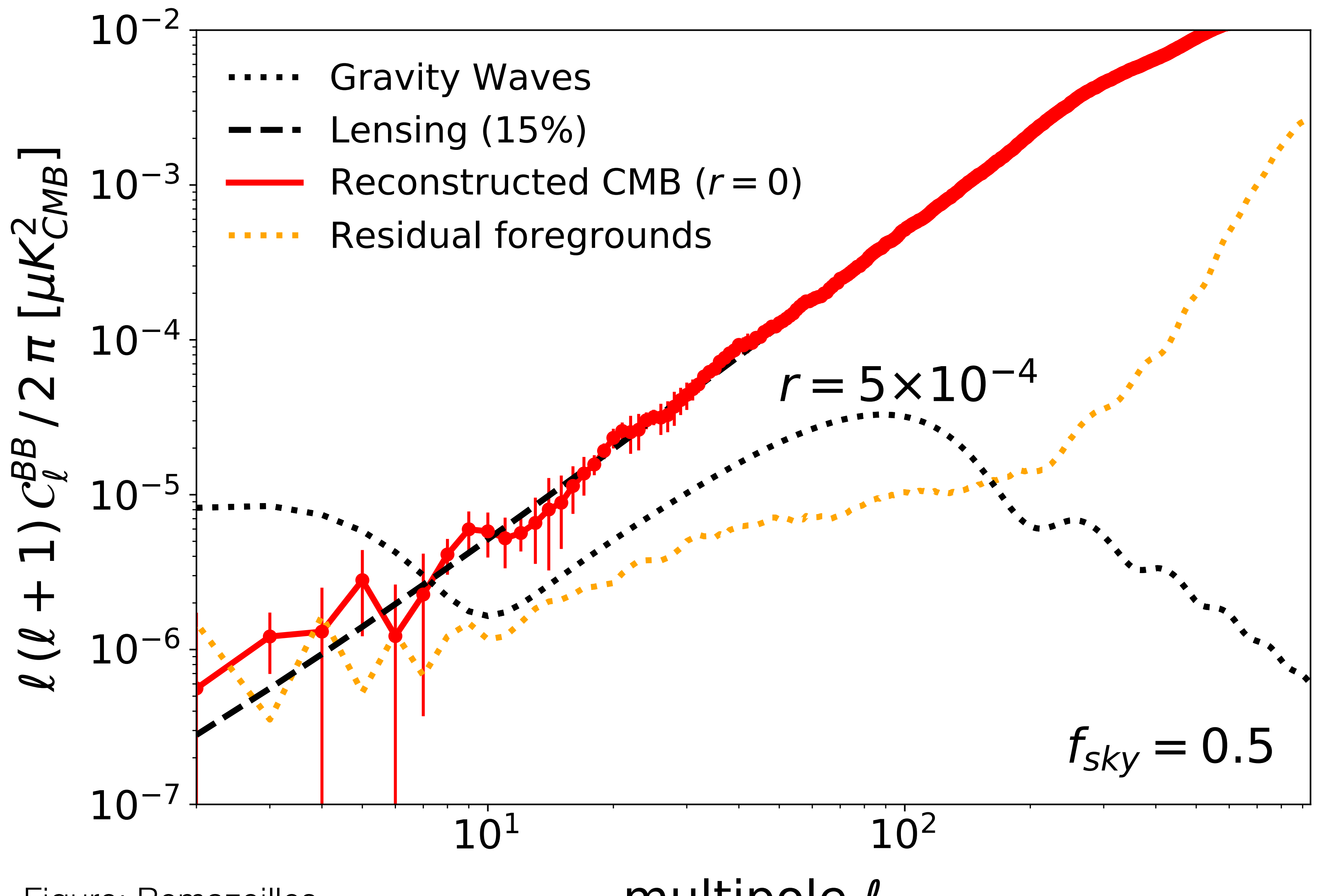


Figure: Remazeilles

- Bottom left: reconstructing CMB and foregrounds with 21 bands has no r bias (r=0.001)
- Bottom right: removing low/high frequencies introduces bias

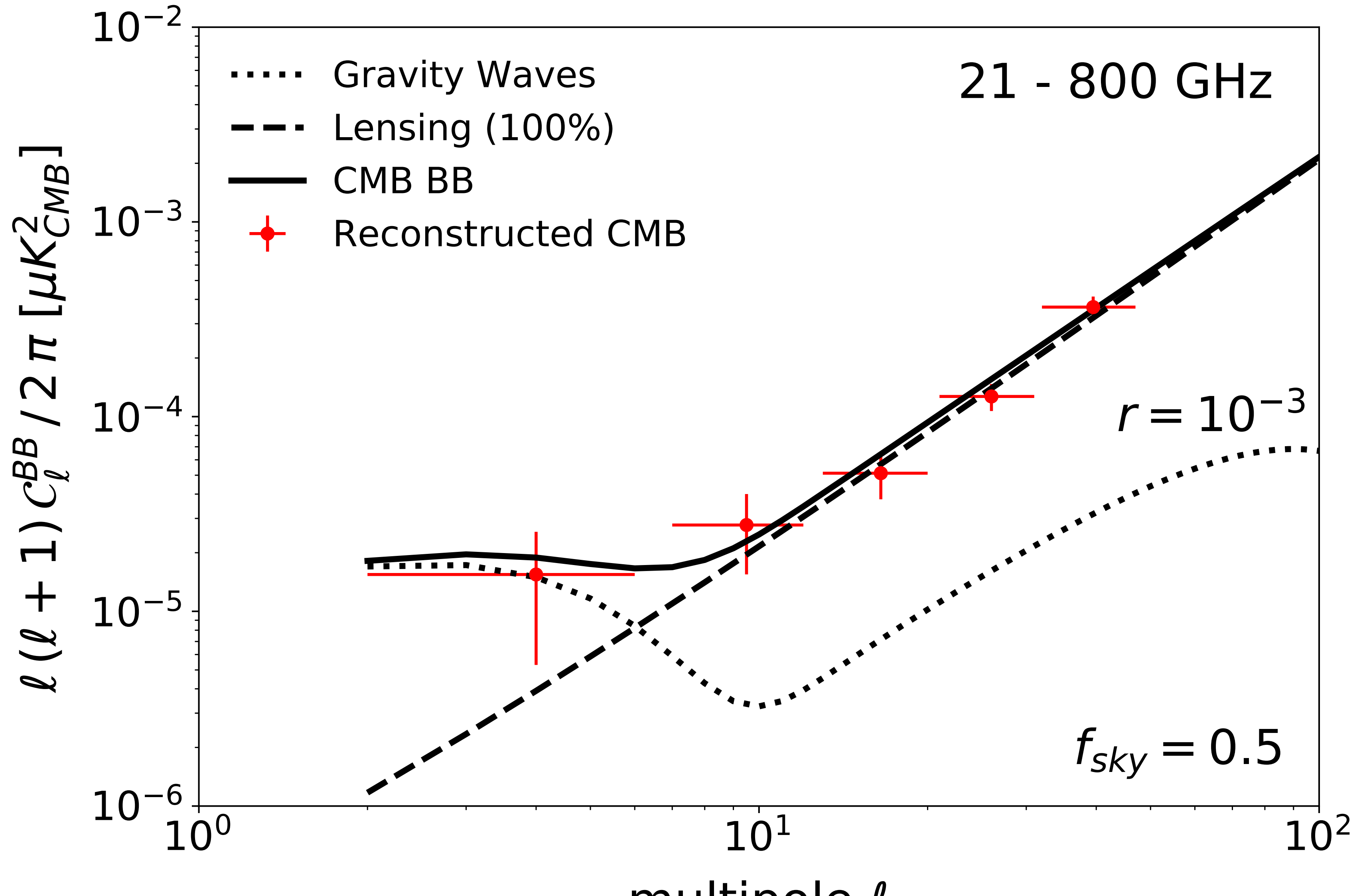


Figure: Remazeilles

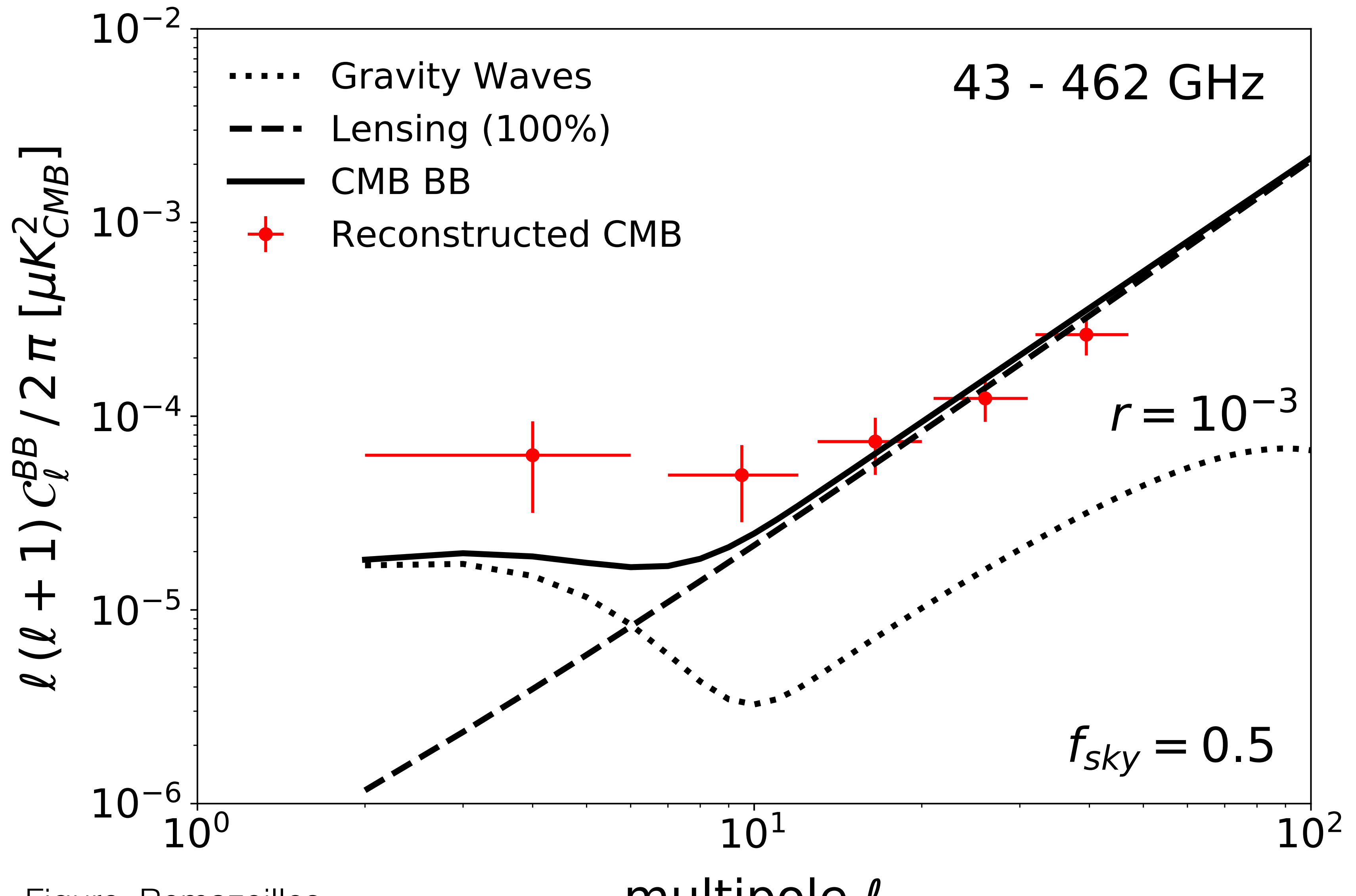


Figure: Remazeilles

Explore How Universe Evolves: First Luminous Sources

- What lights up the Universe? Are the first luminous sources star forming galaxies, super-massive black holes, or dark matter annihilation? How long does this period last?

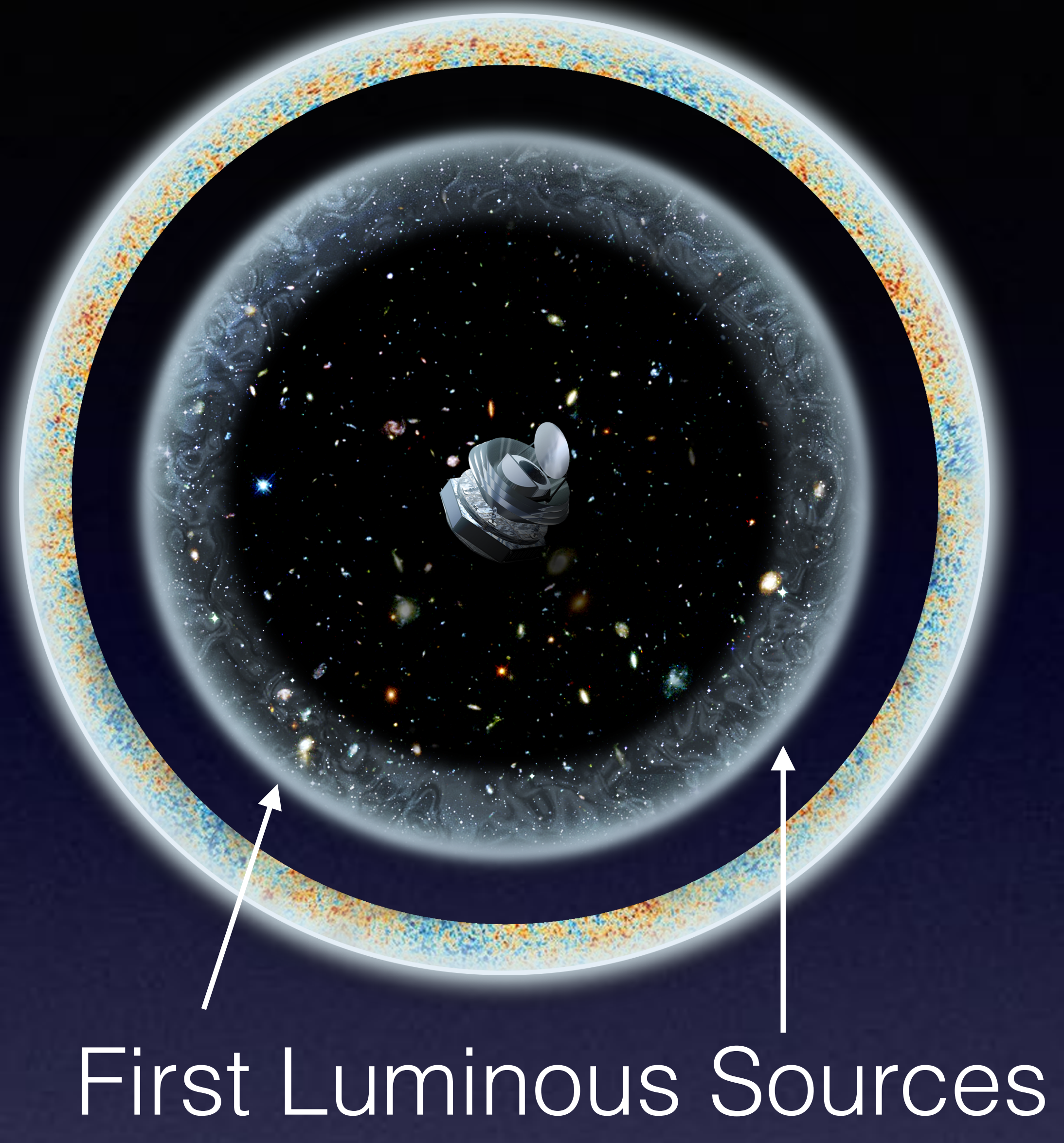


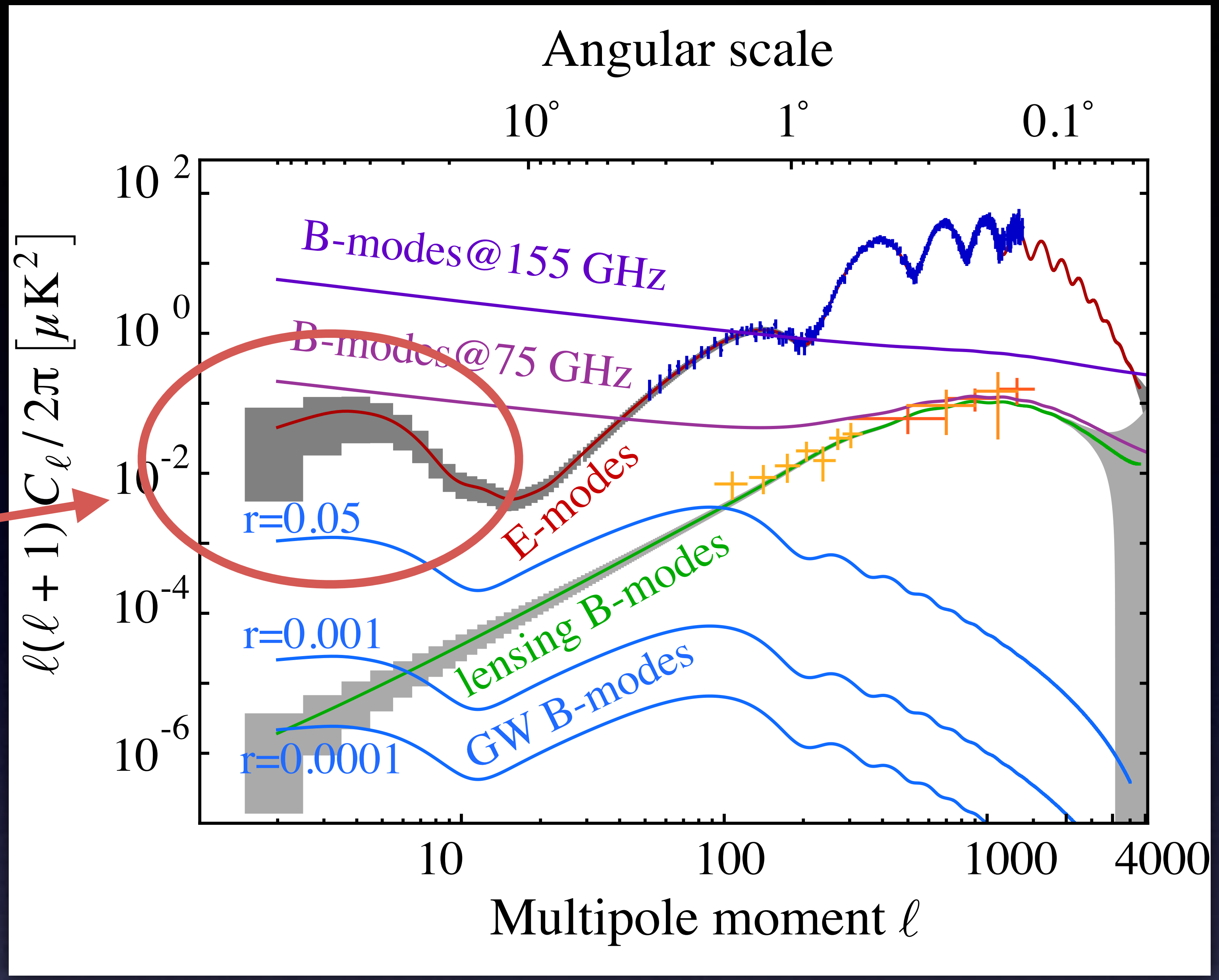
Figure: Flauger

Determine the Nature of the First Luminous Objects

- What lights up the Universe? Are the first luminous sources star forming galaxies, super-massive black holes, or dark matter annihilation? How long does this period last?

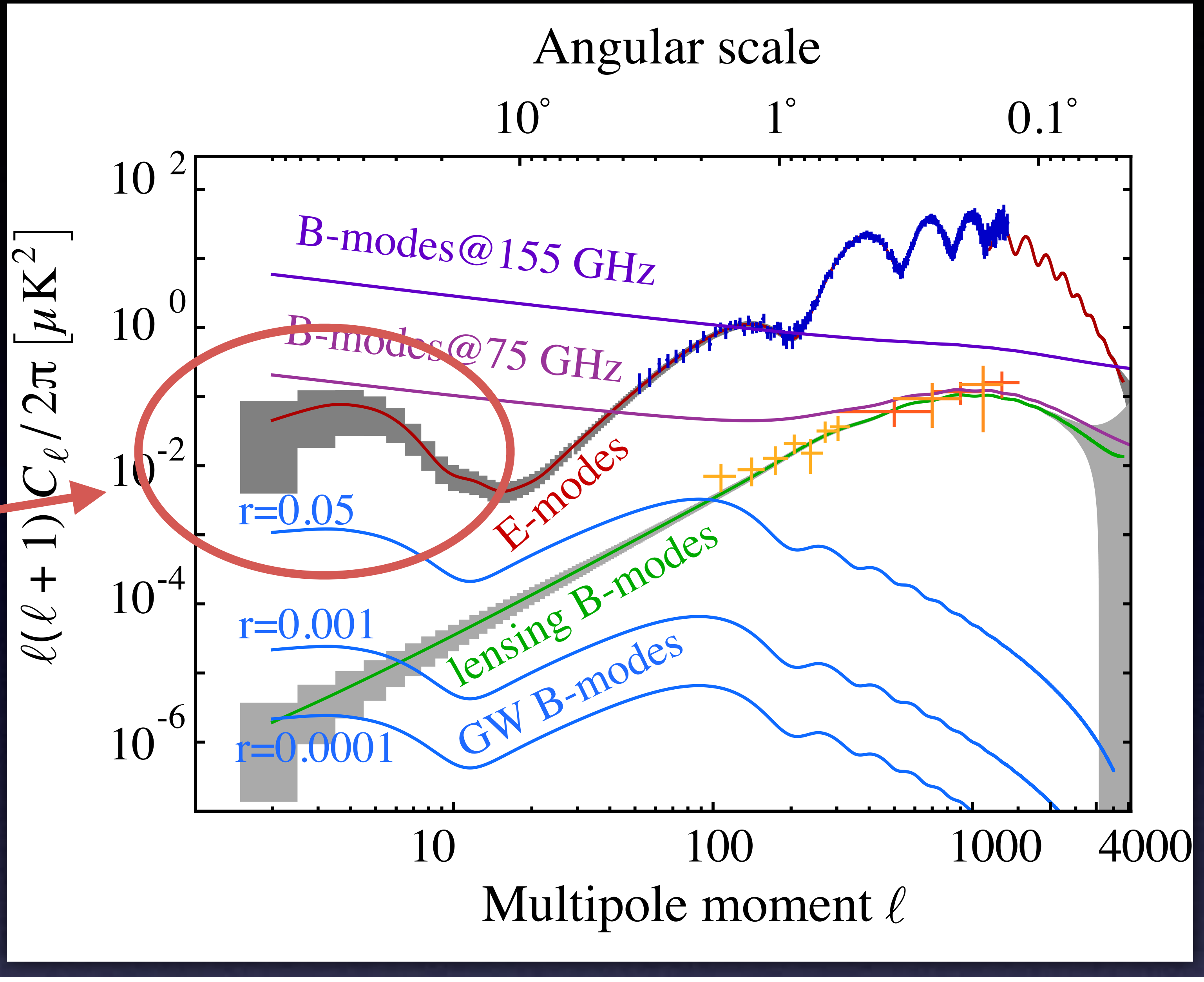
- Low ℓ EE -> probe of τ, the optical depth to reionization

- PICO: $\sigma(\tau) = 0.002$ (cosmic variance limited)



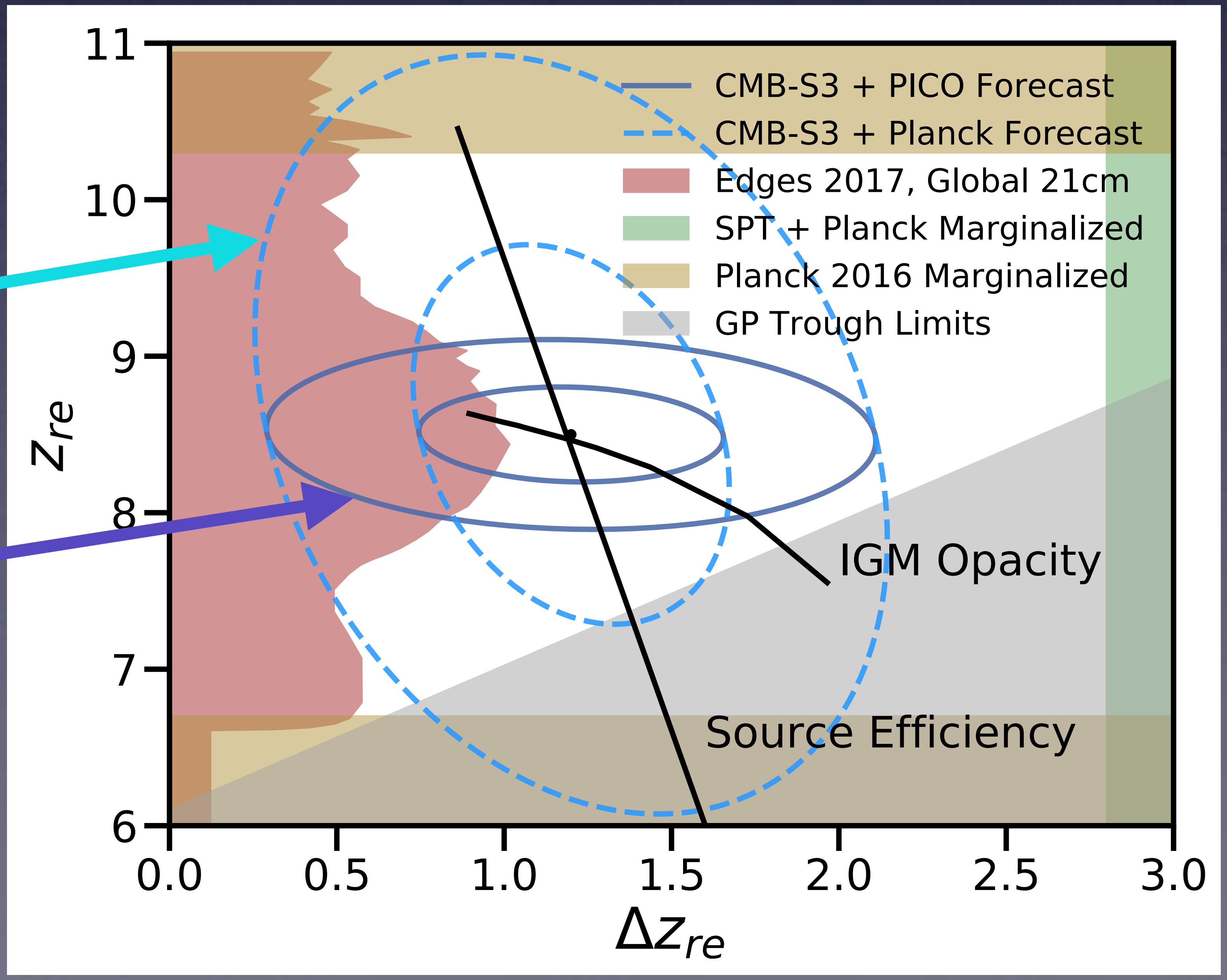
Determine the Nature of the First Luminous Objects

- What lights up the Universe? Are the first luminous sources star forming galaxies, super-massive black holes, or dark matter annihilation? How long does this period last?
- Low ℓ EE -> probe of τ, the optical depth to reionization
- PICO: $\sigma(\tau) = 0.002$ (cosmic variance limited)
- PICO will determine z_{re}
  With kSZ (Δz_{re}) constrain physical models of reionization



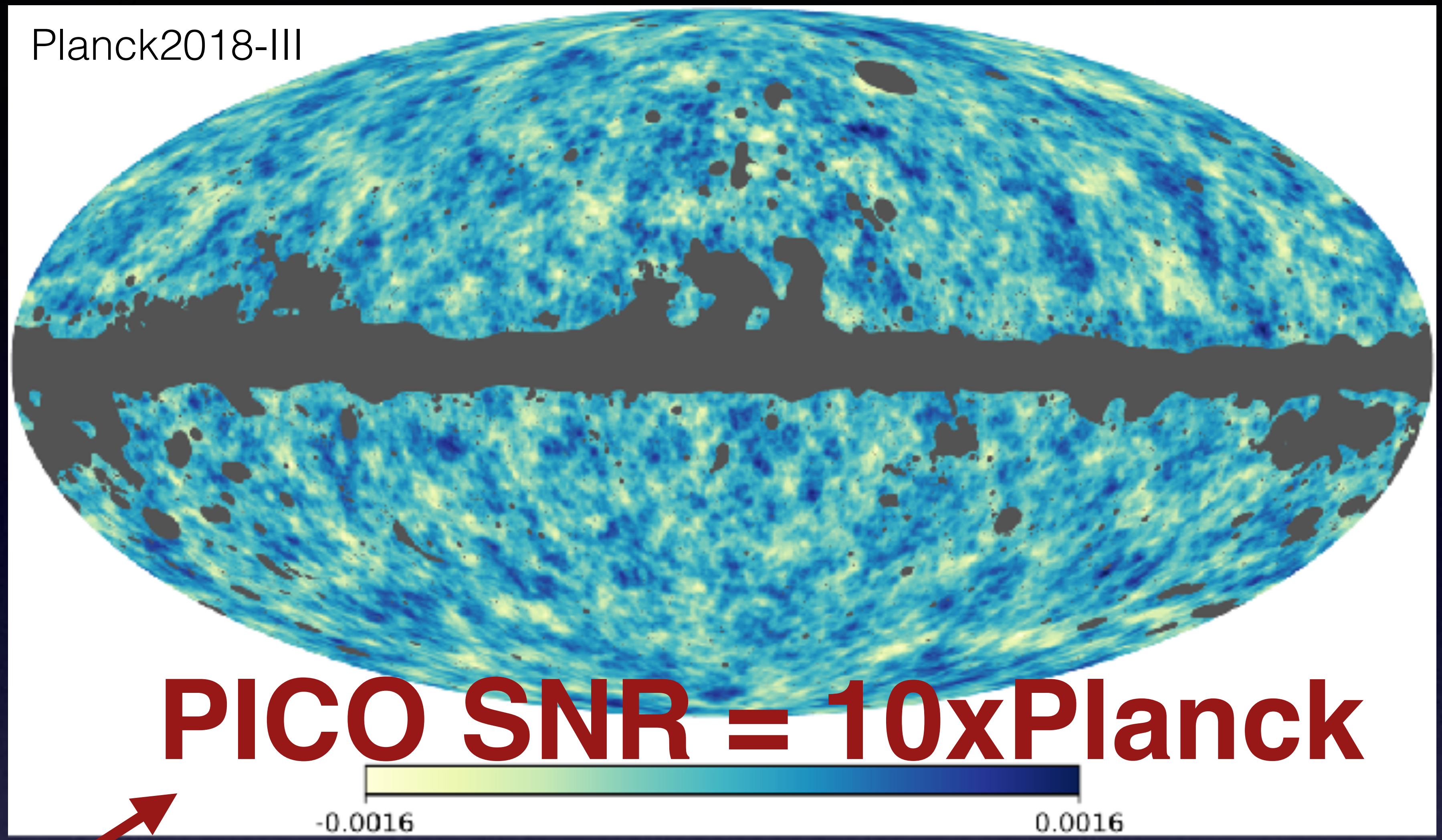
Planck + Stage3

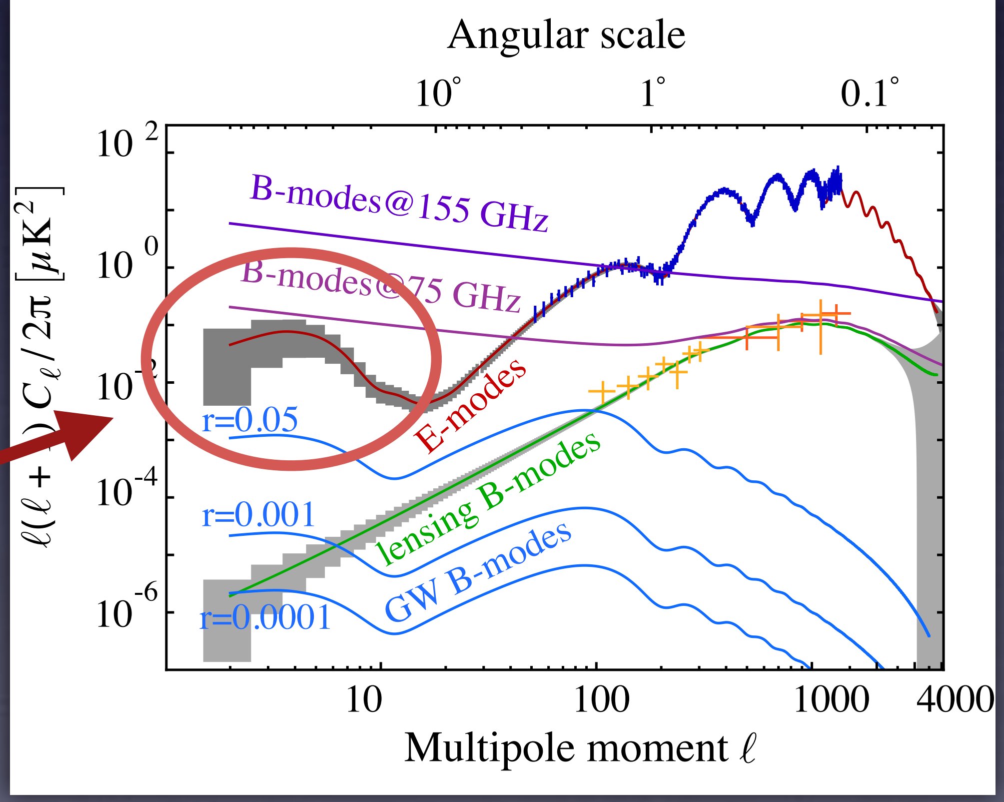
PICO + Stage3



How Does the Universe Evolve: Neutrino Mass

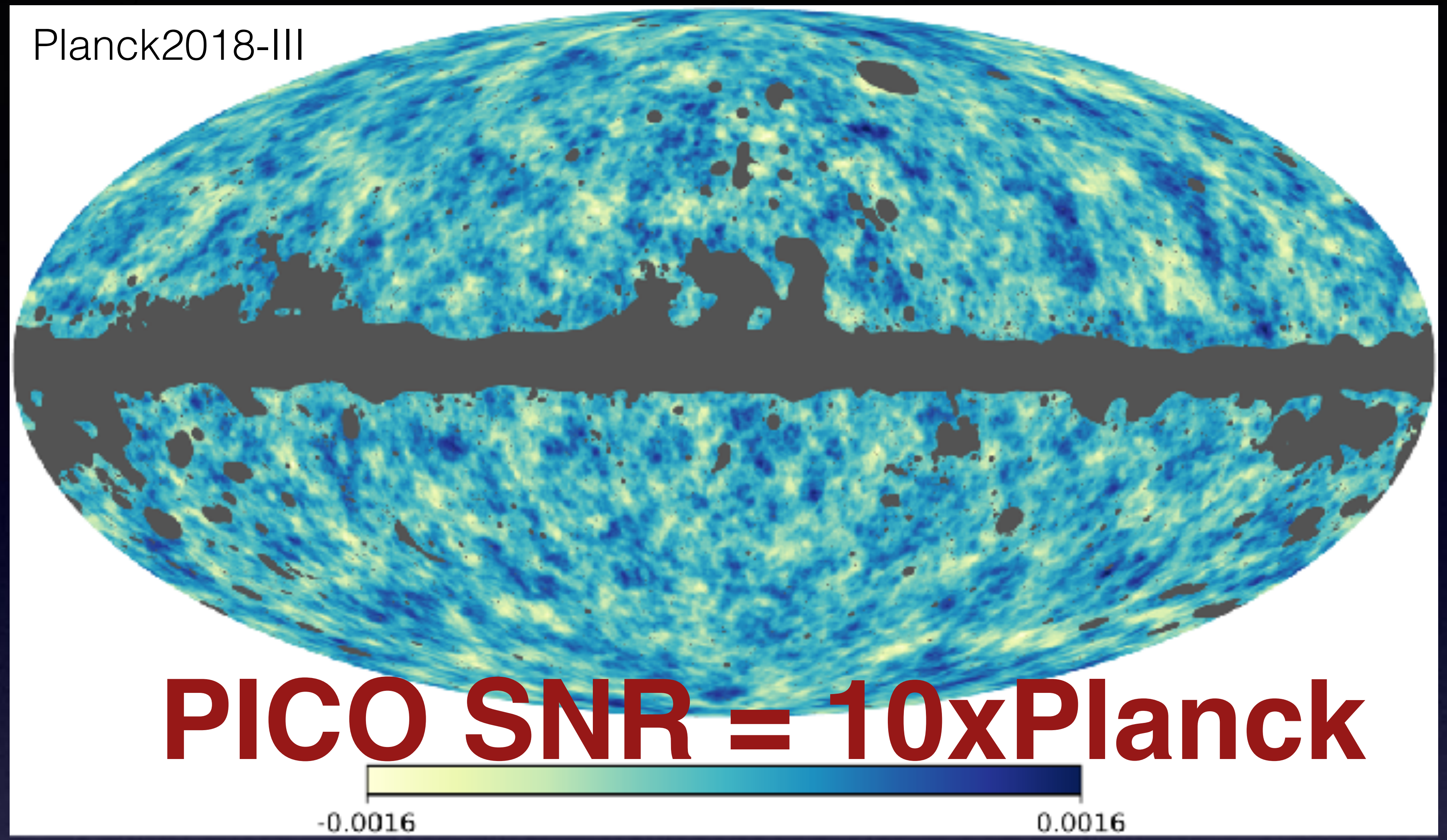
- Only cosmology can determine the absolute mass scale if it is near the minimum allowed $\Sigma m_\nu = 58\ \mathrm{meV}$
- Growth of structures is affected by sum of neutrino mass
- Sum of neutrino mass requires
    - Matter density (Baryon acoustic oscillations: DESI/Euclid)
    - Growth of structure (PICO)
    - Optical depth to reionization τ (PICO)
- Only PICO can provide both data inputs with a consistent, self-calibrated dataset
-

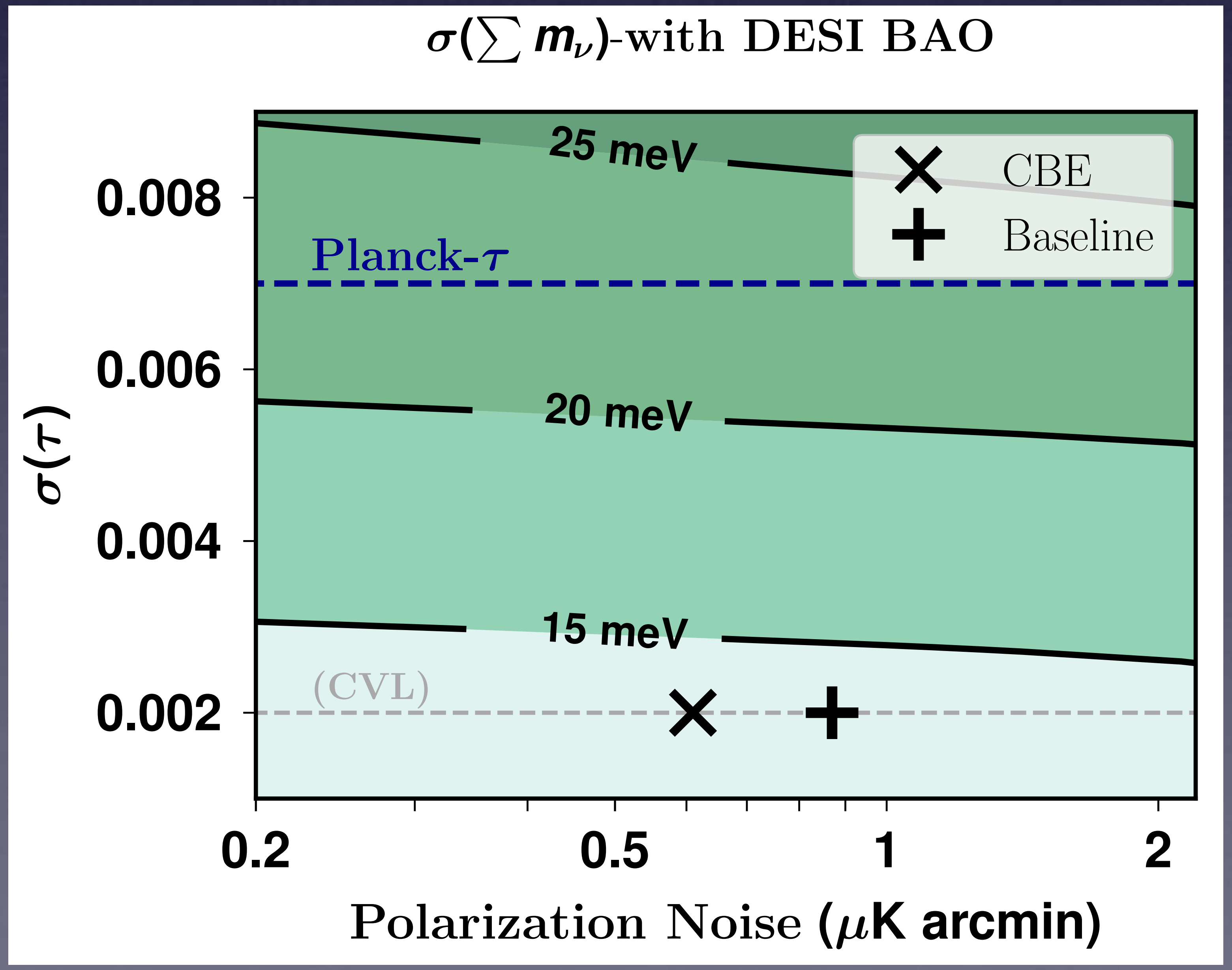




At Least 4σ Determination of Neutrino Mass

- Only cosmology can determine the absolute mass scale if it is near the minimum allowed $\Sigma m_\nu = 58 \text{ meV}$
- Growth of structures is affected by sum of neutrino mass
- Sum of neutrino mass requires
  - Matter density (Baryon acoustic oscillations: DESI/Euclid)
  - Growth of structure (PICO)
  - Optical depth to reionization τ (PICO)
- Only PICO can provide both data inputs with a consistent, self-calibrated dataset
- $\sigma\left(\Sigma m_\nu\right) = 14 \text{ meV}$, 4σ, one of three independent constraints





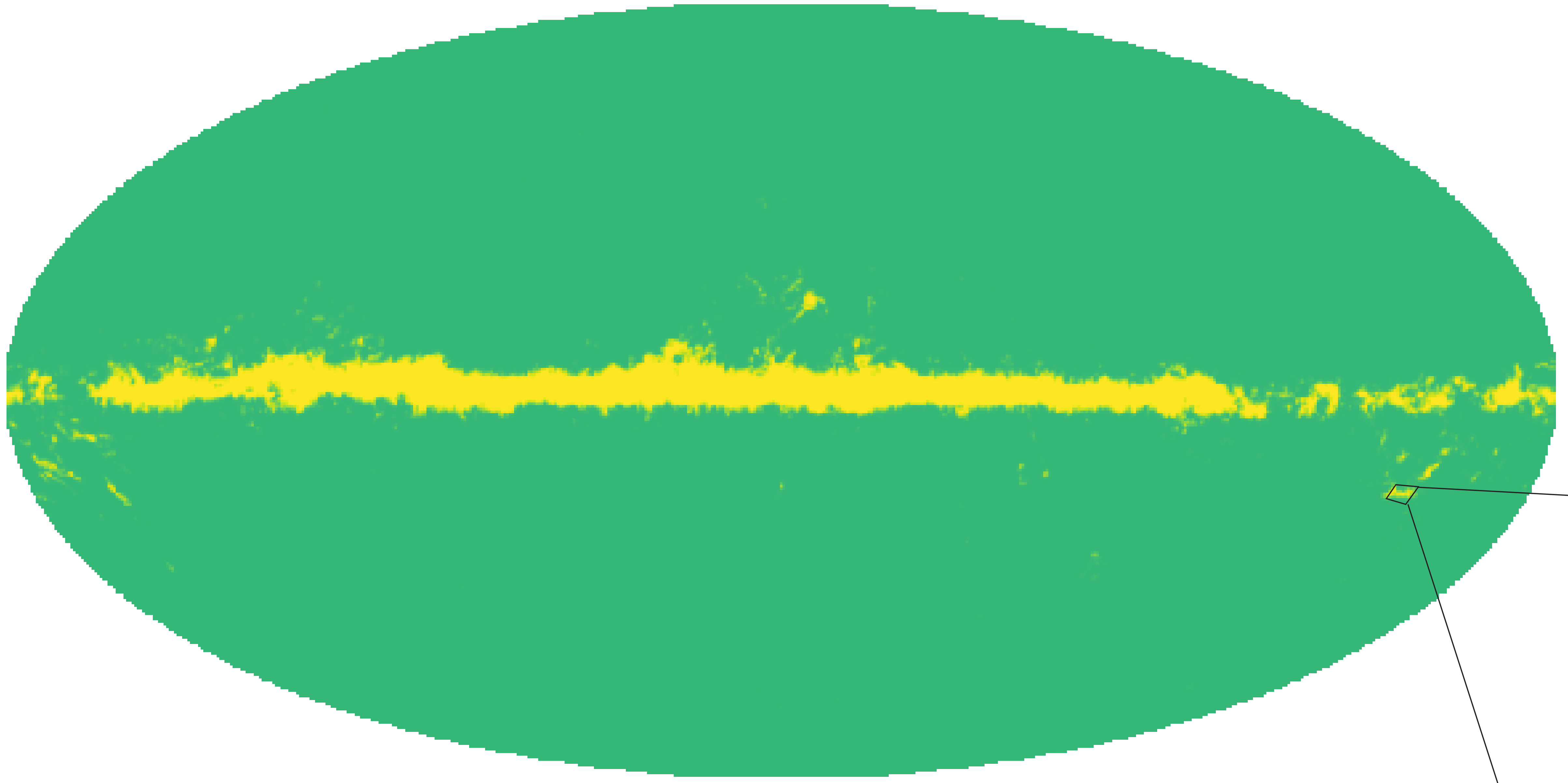
Solve Puzzle of Low Star Formation Efficiency

Figure: R. Flauger

- Milky Way stars form at much lower rate than would be expected from gravitational collapse
- Gas turbulence and magnetic fields slow collapse from the diffuse ISM to molecular clouds to star forming regions
- What is the ratio of energy stored in the magnetic field to that stored in turbulent motion? How does this ratio vary over spatial scales from the diffuse ISM to dense cores, which host star formation?
- Need measurements of magnetic fields over scales of galaxy down to dense cores
- Millimeter-wave polarimetry gives magnetic field parameters

Solve Puzzle of Low Star Formation Efficiency

86,000,000 independent B field measurements; x1000 more than Planck



Planck 353 GHz polarization 5′ resolution, $\sigma_p < 0.67\%$

PICO 799 GHz polarization 1′ resolution, $\sigma_p < 0.67\%$

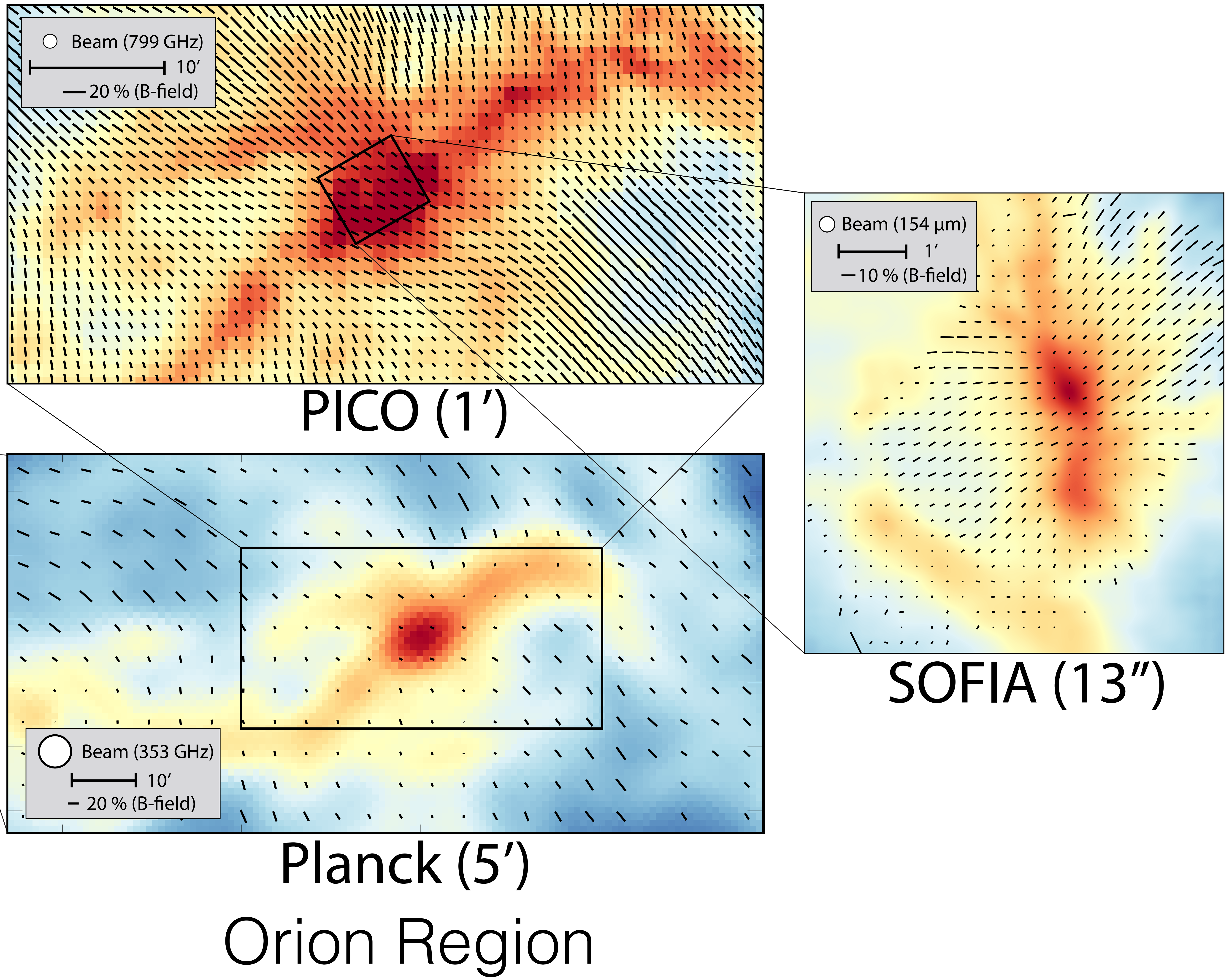


Figure: Chuss + Fissel

Legacy Surveys Available only with PICO Data

Science

- Early galaxy formation and dark matter substructure
- Early cluster formation
- Correlation of dust with galaxy properties
- Physics of jets in radio sources
- Ordering of magnetic fields in external galaxies

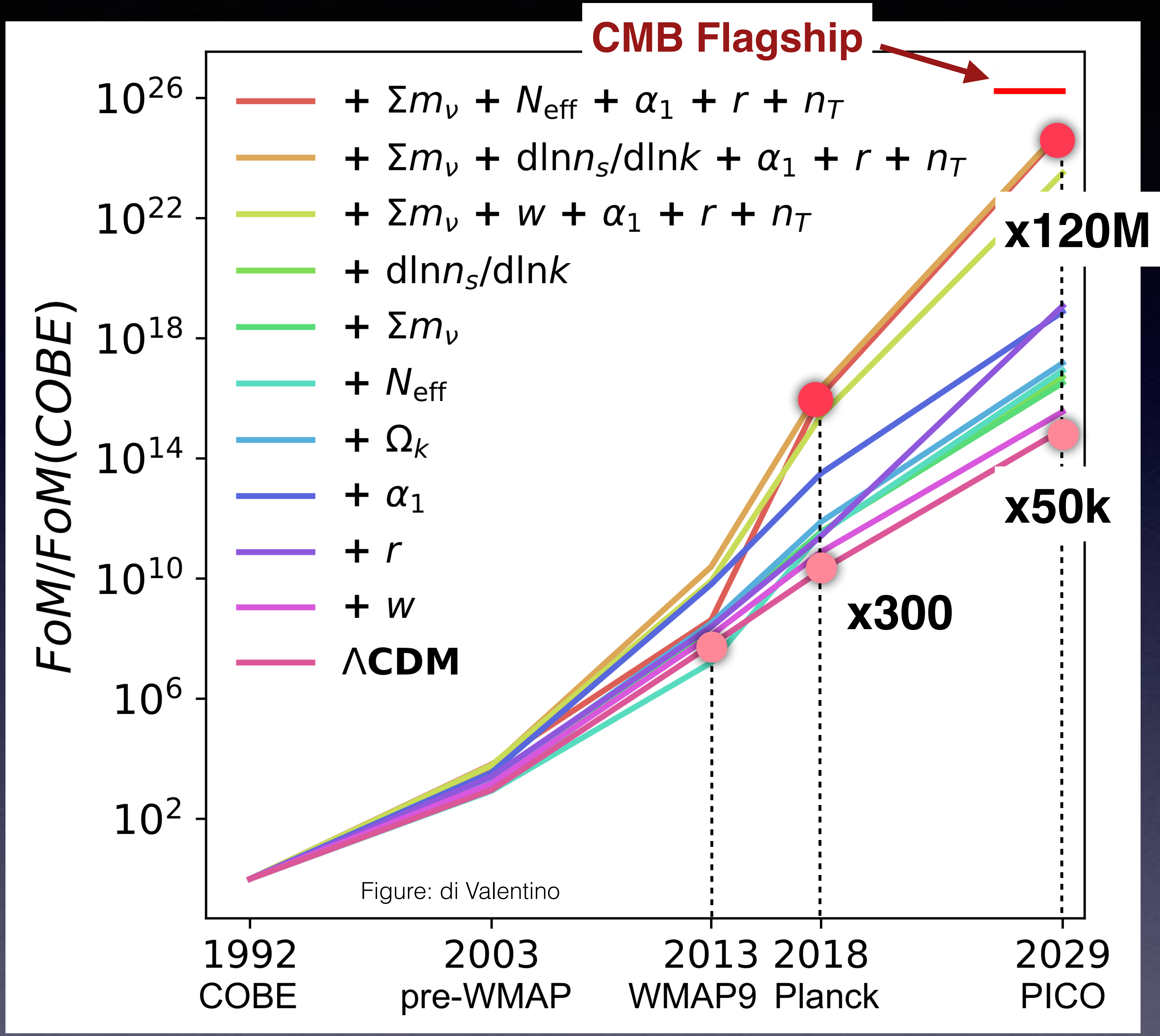
Catalog

- 4500 strongly lensed galaxies, $z\sim5$; (x400)
- 50,000 proto-clusters, $z\sim4.5$; (x1000)
- 30,000 galactic dust SEDs, $z<0.1$;(x10)
- 2000 polarized radio sources; (x10)
- Polarization of few thousand dusty galaxies (x1000);

Data will be mined for years by astrophysicists in many sub-disciplines

Set Cosmological Paradigm for the 2030s

- 6-parameter ΛCDM describes the Universe well
- But tensions exist
  - 3.4σ between supernovae and CMB measurements of Ho
  - 2σ in measurements of σ8 (amplitude of fluctuations)
  - What is most of the Universe made of?
- Constraint on 6-parameter ΛCDM:
  - PICO/Planck = 50,000 (Planck/WMAP9 = 300)
- Constraint on 11-parameter ΛCDM+:
  - PICO/Planck = 1.2×10^8



ΛCDM will either survive this stringent scrutiny, or a new cosmological paradigm will emerge

Why PICO, Why Now

- Transformative science; Much of the science can only be done from space

Figure: R. Flauger

- Further progress with CMB requires a leap in sensitivity, foreground characterization, and systematic control. Space is the most cost-effective approach.

Figure: R. Flauger

- PICO is the only instrument with the combination of sky coverage, resolution, frequency bands, and sensitivity to achieve all of the science with one platform.

- A space mission is best suited to provide the level of control of systematic uncertainties necessary

- PICO relies on current technologies or straightforward extensions

PICO has strong community support

213 Authors and Endorsers

Authors

Marcelo Alvarez [9,16]
Emmanuel Artis [12]
Peter Ashton [24,16,9]
Jonathan Aumont [25]
Ragnhild Aurlien [26]
Ranajoy Banerji [26]
R. Belen Barreiro [27]
James G. Bartlett [5,6]
Soumen Basak [28]
Nick Battaglia [7]
Jamie Bock [8,6]
Kimberly K. Boddy [2]
Matteo Bonato [29]
Julian Borrill [9,10]
François Bouchet [30]
François Boulanger [31]
Blakesley Burkhart [32]
Jens Chluba [33]
David Chuss [11]
Susan E. Clark [18,34]
Joelle Cooperrider [6]
Brendan P. Crill [6]
Gianfranco De Zotti [35]
Jacques Delabrouille [5,12]
Eleonora Di Valentino [36]
Joy Didier [37]
Olivier Doré [6,8]
Hans K. Eriksen [26]
Josquin Errard [5]
Tom Essinger-Hileman [21]
Stephen Feeney [17]
Jeffrey Filippini [38]
Laura Fissel [14]
Raphael Flauger [15]
Unni Fuskeland [26]
Vera Gluscevic [39]
Krzysztof M. Gorski [6]
Dan Green [16]
Shaul Hanany [1]
Brandon Hensley [4]
Diego Herranz [27]
J. Colin Hill [17,18]
Eric Hivon [30]
Renée Hložek [40]
Johannes Hubmayr [19]
Bradley R. Johnson [41]
William Jones [4]
Terry Jones [1]
Lloyd Knox [20]
Al Kogut [21]
Marcos López-Caniego [42]
Charles Lawrence [6]
Alex Lazarian [43]
Zack Li [4]
Mathew Madhavacheril [4]
Jean-Baptiste Melin [12]
Joel Meyers [44]
Calum Murray [5]
Mattia Negrello [45]
Giles Novak [46]
Roger O'Brient [6,8]
Christopher Paine [6]
Tim Pearson [8]
Levon Pogosian [47]
Clem Pryke [1]
Giuseppe Puglisi [48,49]
Mathieu Remazeilles [33]
Graca Rocha [6,8]
Marcel Schmittfull [18]
Douglas Scott [50]
Peter Shirron [21]
Ian Stephens [51]
Brian Sutin [6]
Maurizio Tomasi [52]
Amy Trangsrud [6]
Alexander van Engelen [23]
Flavien Vansyngel [53]
Ingunn K. Wehus [26]
Qi Wen [1]
Siyao Xu [43]
Karl Young [1]
Andrea Zonca [54]

Endorsers

Maximilian Abitbol
Zeeshan Ahmed
David Alonso
Mustafa A. Amin
Adam Anderson
James Annis
Jason Austermann
Carlo Baccigalupi
Darcy Barron
Ritoban Basu Thakur
Elia Battistelli
Daniel Baumann
Karim Benabed
Bradford Benson
Paolo de Bernardis
Marco Bersanelli
Federico Bianchini
Daniel Bilbao-Ahedo
Colin Bischoff
Sebastian Bocquet
J. Richard Bond
Jeff Booth
Sean Bryan
Carlo Burigana
Giovanni Cabass
Robert Caldwell
John Carlstrom
Xingang Chen
Francis-Yan Cyr-Racine
Paolo de Bernardis
Tijmen de Haan
C. Darren Dowell
Cora Dvorkin
Chang Feng
Ivan Soares Ferreira
Aurelien Fraisse
Andrei V. Frolov
Nicholas Galitzki
Silvia Galli
Ken Ganga
Tuhin Ghosh
Sunil Golwala
Riccardo Gualtieri
Jon E. Gudmundsson
Nikhel Gupta
Nils Halverson
Kyle Helson
Sophie Henrot-Versillé
Thiem Hoang
Kevin M. Huffenberger
Kent Irwin
Marc Kamionkowski
Reijo Keskitalo
Rishi Khatri
Chang-Goo Kim
Theodore Kisner
Arthur Kosowsky
Ely Kovetz
Kerstin Kunze
Guilaine Lagache
Daniel Lenz
François Levrier
Marilena Loverde
Philip Lubin
Juan Macias-Perez
Nazzareno Mandolesi
Enrique Martínez-González
Carlos Martins
Silvia Masi
Tomotake Matsumura
Darragh McCarthy
P. Daniel Meerburg
Alessandro Melchiorri
Marius Millea
Amber Miller
Joseph Mohr
Lorenzo Moncelsi
Pavel Motloch
Tony Mroczkowski
Suvodip Mukherjee
Johanna Nagy
Pavel Naselsky
Federico Nati
Paolo Natoli
Michael Niemack
Elena Orlando
Bruce Partridge
Marco Peloso
Francesco Piacentini
Michel Piat
Giampaolo Pisano
Nicolas Ponthieu
Giuseppe Puglisi
Benjamin Racine
Christian Reichardt
Christophe Ringeval
Karwan Rostem
Anirban Roy
Jose-Alberto Rubino-Martin
Matarrese Sabino
Maria Salatino
Benjamin Saliwanchik
Neelima Sehgal
Sarah Shandera
Erik Shirokoff
Anže Slosar
Tarun Souradeep
Suzanne Staggs
George Stein
Radek Stompor
Rashid Sunyaev
Aritoki Suzuki
Eric Switzer
Andrea Tartari
Grant Teply
Peter Timbie
Matthieu Tristram
Caterina Umiltà
Rien van de Weygaert
Vincent Vennin
Licia Verde
Patricio Vielva
Abigail Vieregg
Jan Vrtilek
Benjamin Wallisch
Benjamin Wandelt
Gensheng Wang
Scott Watson
Edward J. Wollack
Zhilei Xu
Siavash Yasini

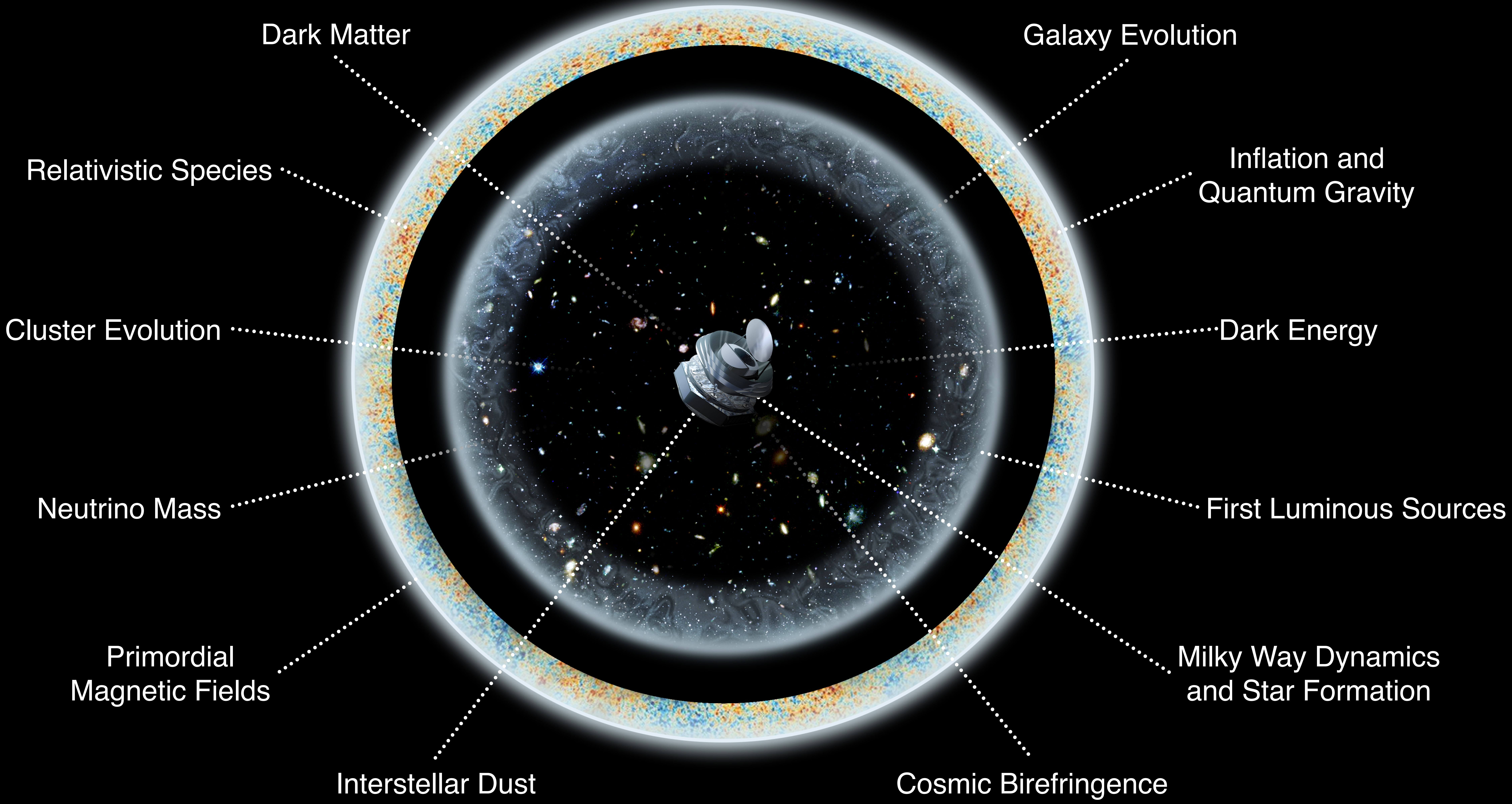
https://z.umn.edu/picomission

arXiv 1902.10541

PICO

PROBE OF INFLATION
AND COSMIC ORIGINS

SHAUL HANANY
UNIVERSITY OF MINNESOTA



https://z.umn.edu/picomission

arXiv 1902.10541