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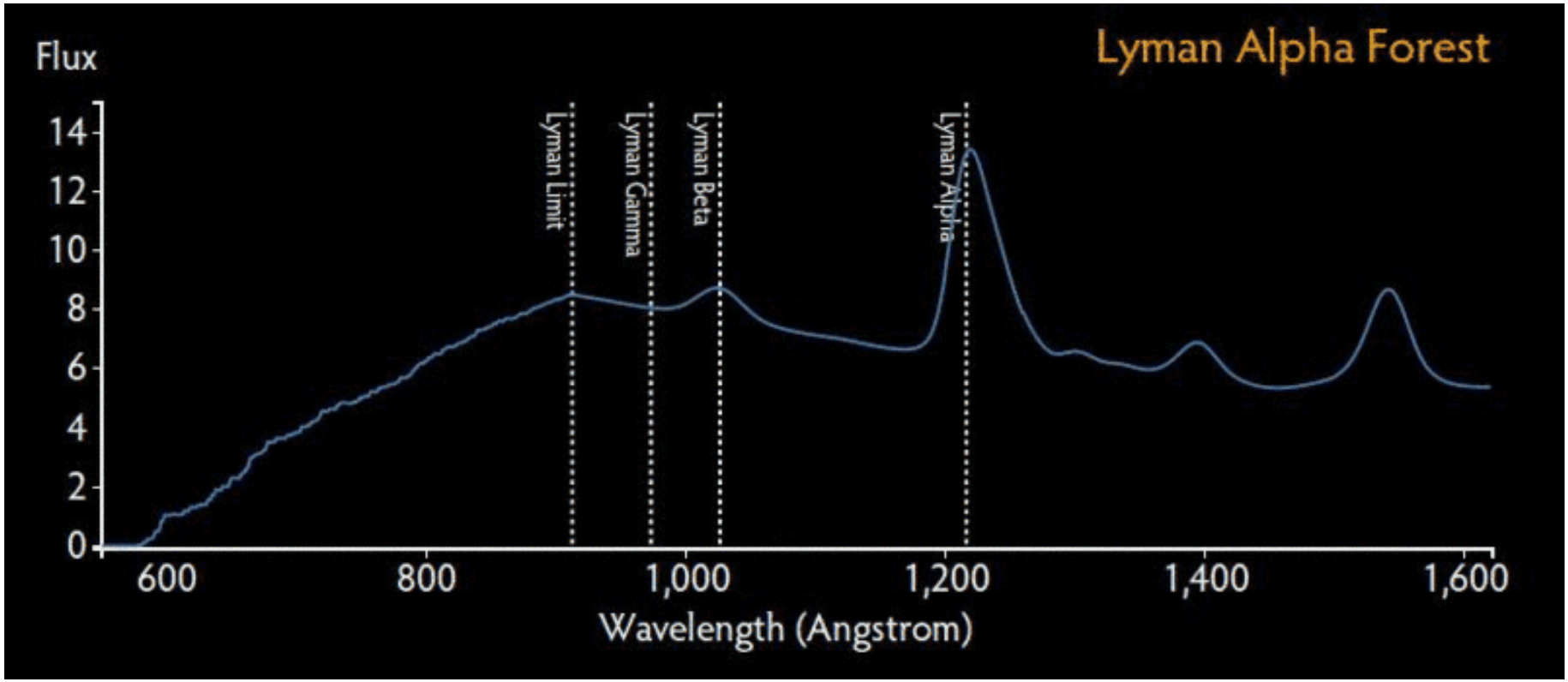
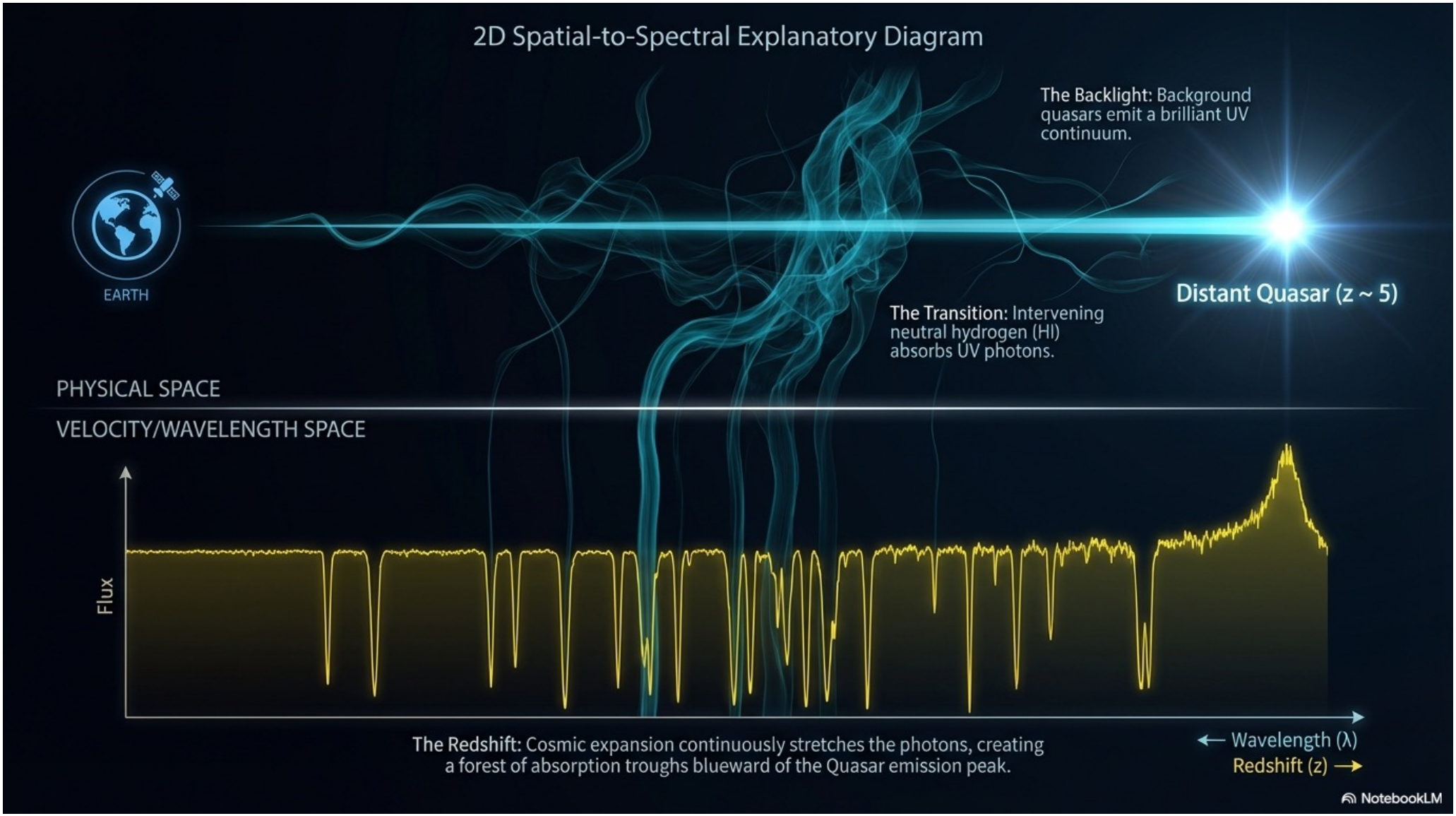
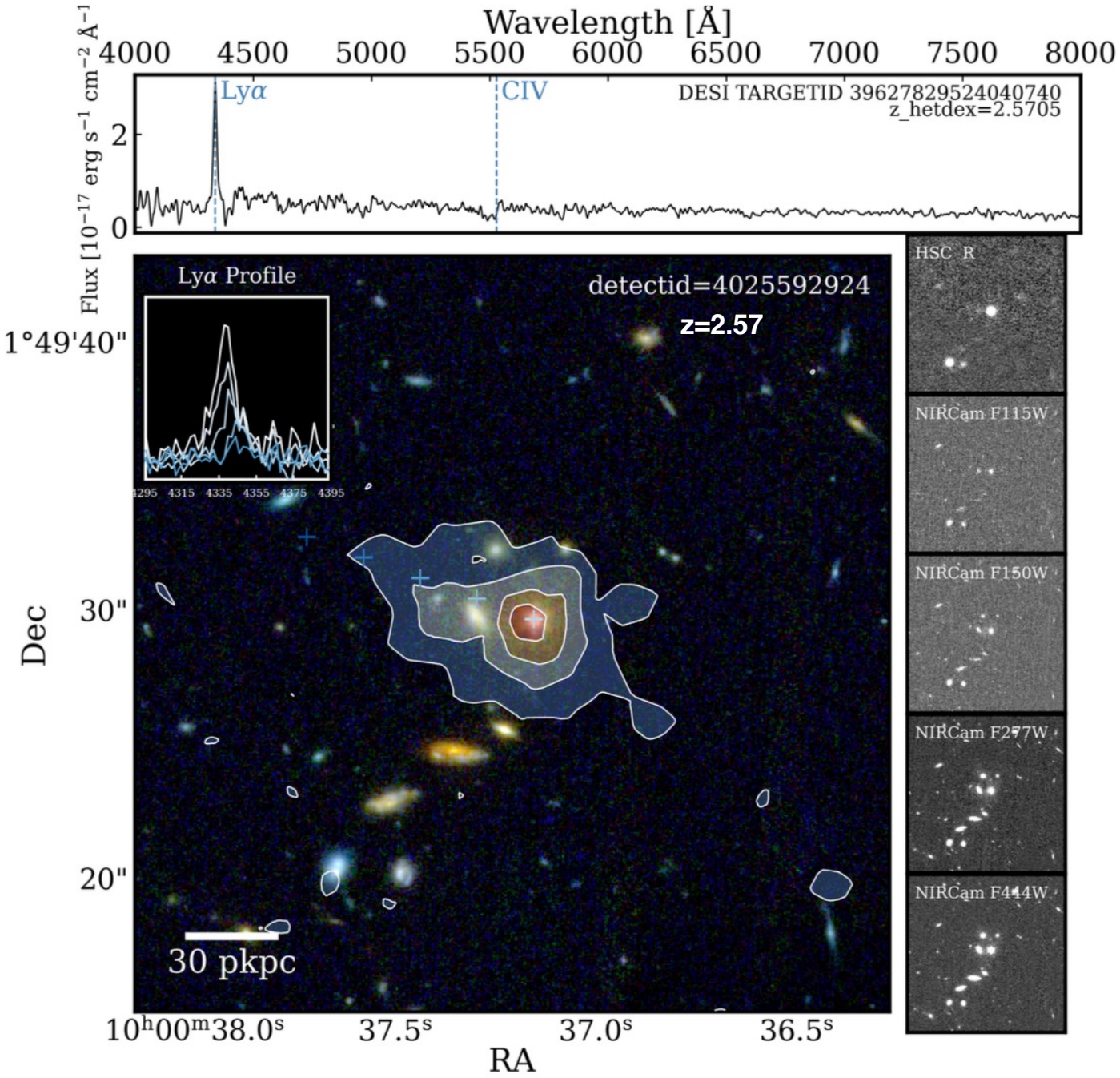
The Lyman α Forest

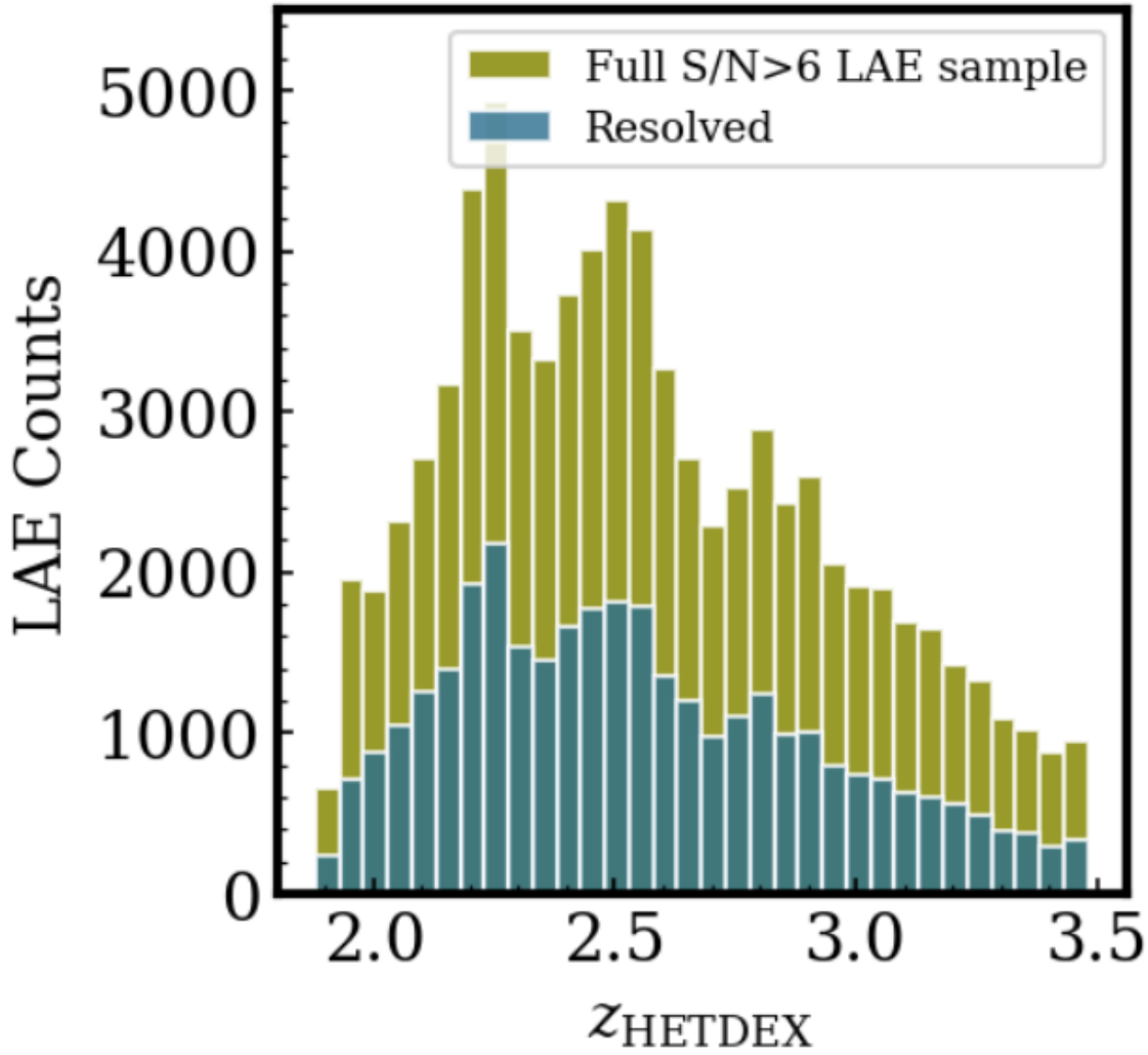
Quasars form a convenient background source for studies of intervening systems. Discovered by Roger Lynds in 1970



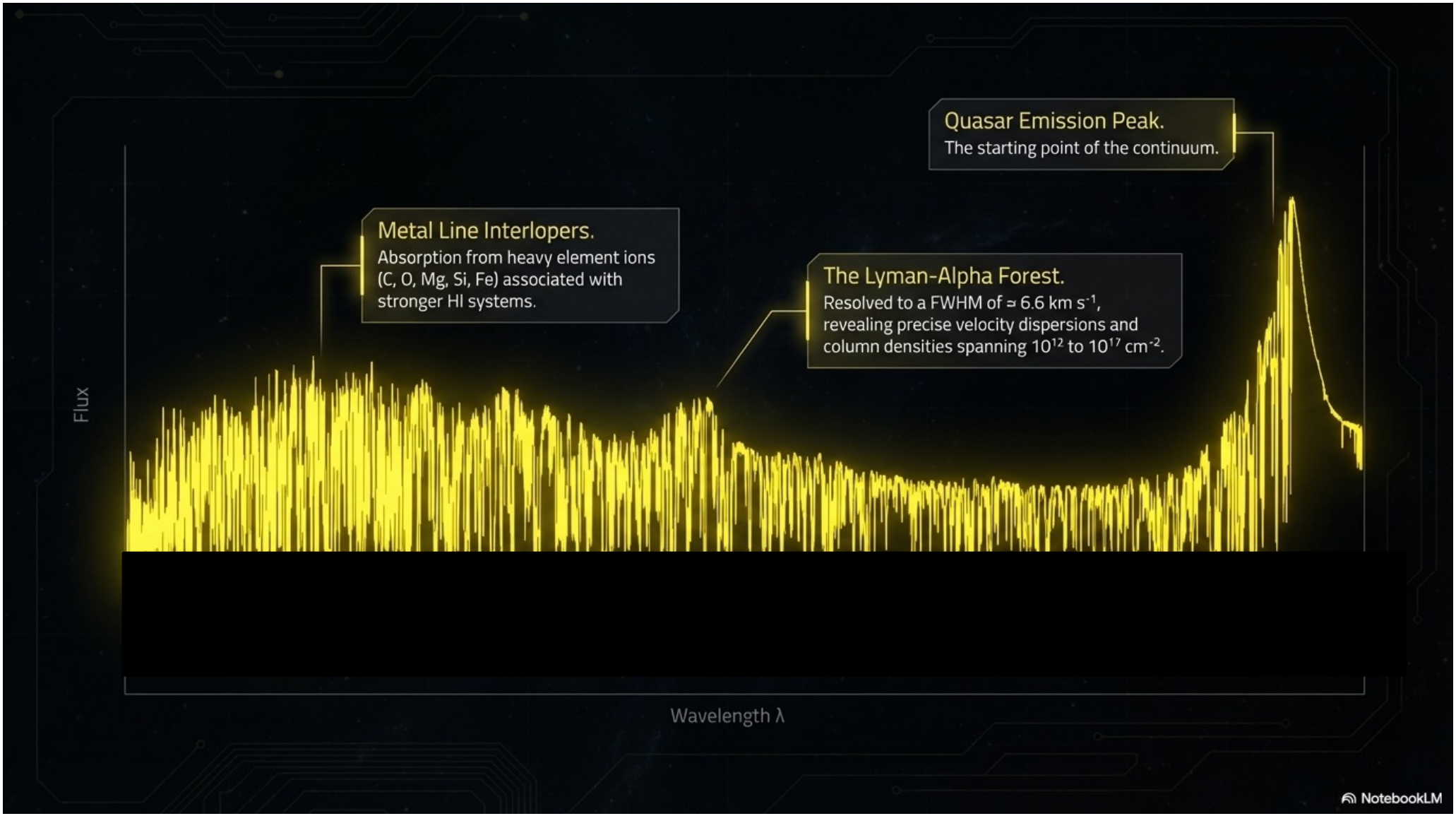

2D Spatial-to-Spectral Explanatory Diagram
The Backlight: Background quasars emit a brilliant UV continuum.
EARTH
Distant Quasar (z ~ 5)
The Transition: Intervening neutral hydrogen (HI) absorbs UV photons.
PHYSICAL SPACE
VELOCITY/WAVELENGTH SPACE
Flux
The Redshift: Cosmic expansion continuously stretches the photons, creating a forest of absorption troughs blueward of the Quasar emission peak.
← Wavelength (λ)
Redshift (z) →
NotebookLM



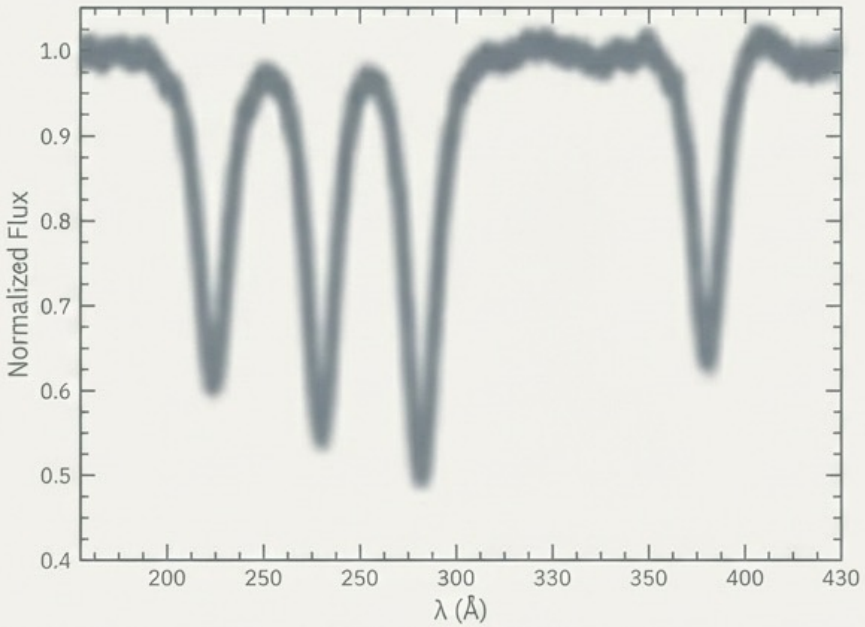
Ly α emission from the HETDEX survey Cooper et al. (2026)



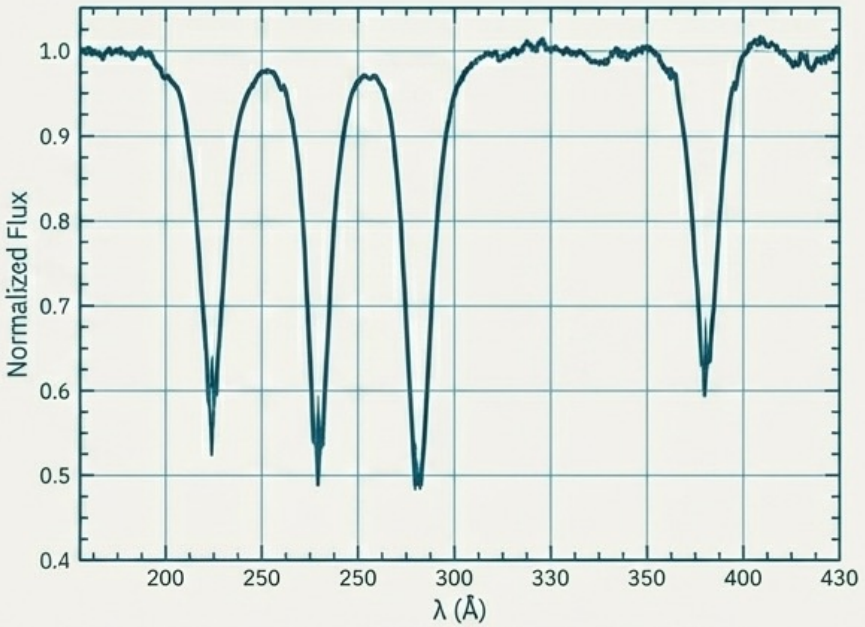
Ly α galaxies from the HETDEX survey Cooper et al. (2026)


Quasar Emission Peak.
The starting point of the continuum.
Metal Line Interlopers.
Absorption from heavy element ions (C, O, Mg, Si, Fe) associated with stronger HI systems.
The Lyman-Alpha Forest.
Resolved to a FWHM of ≃ 6.6 km s^{-1}, revealing precise velocity dispersions and column densities spanning 10^{12} to 10^{17} cm^{-2}.
Flux
Wavelength λ
NotebookLM

The Resolution Shift: Accessing Low Column Densities



Historical Constraint: Equivalent width blends lines. Limits detection to strong absorbers.

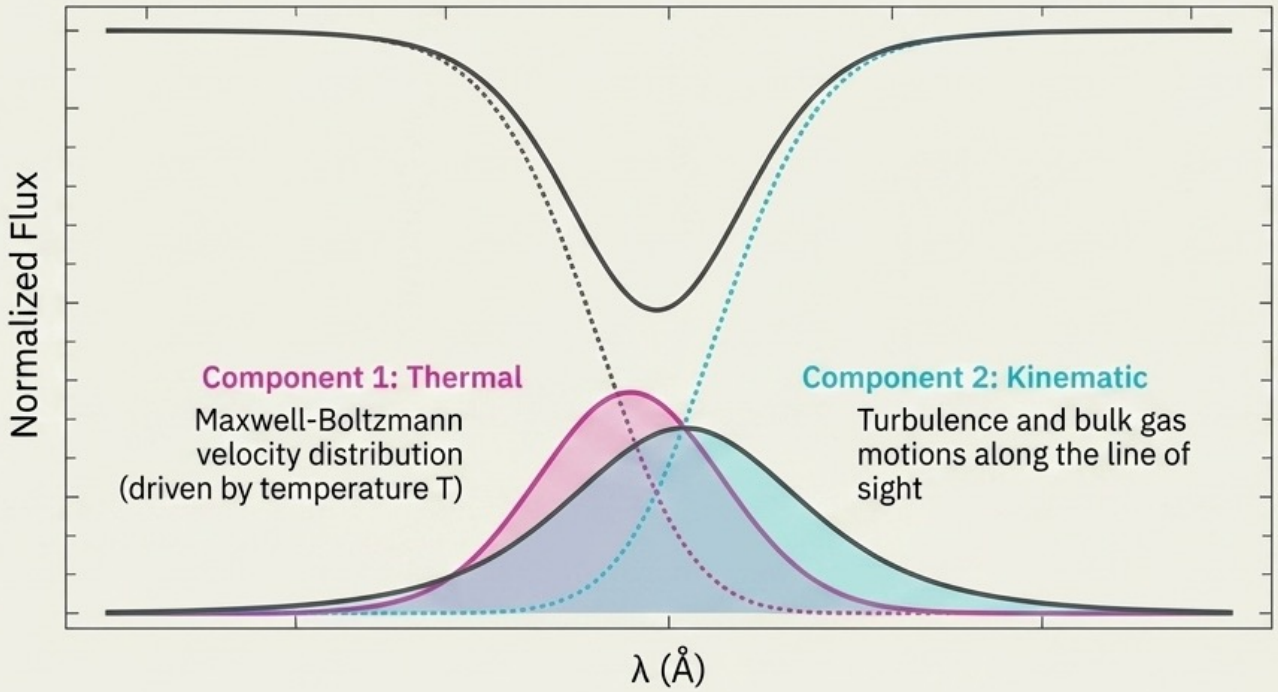


Keck I 10m HIRES allows analysis of low column density H I clouds at z > 2.

DATA CALLOUT
Reliable detection of $N_{HI} < 10^{14}$ cm^{-2} (specifically $12.8 \leq \log N_{HI} \leq 16.0$) Exposing the true structure of the forest.

Deconstructing the Forest: Voigt Profile Parameterization

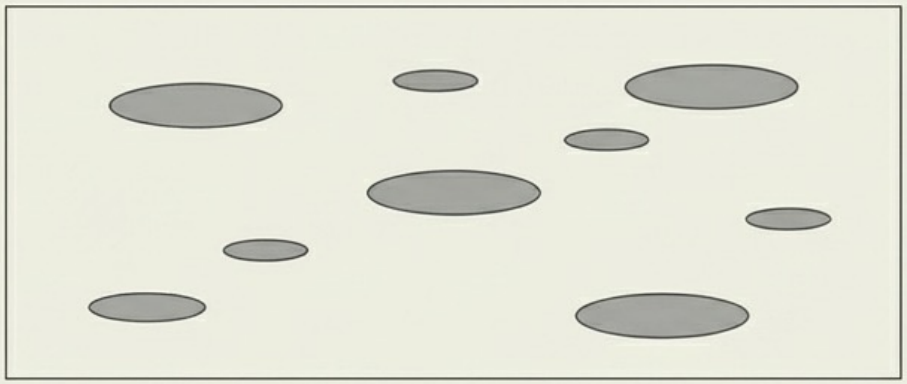
Profile fitting is not just a direct physical model, but a powerful parameterization tool to compare against simulated spectra.



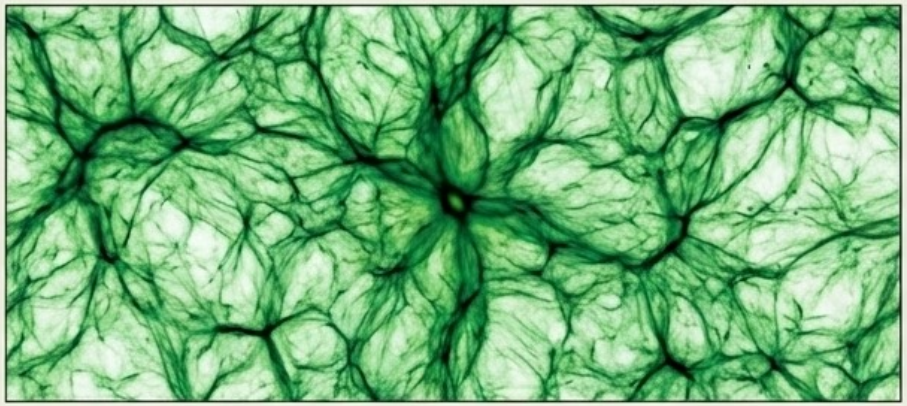
The Doppler Parameter:

$$b \equiv \sqrt{\frac{2kT}{m_p}}$$

Paradigm Shift: From Isolated Clouds to a Coherent Web



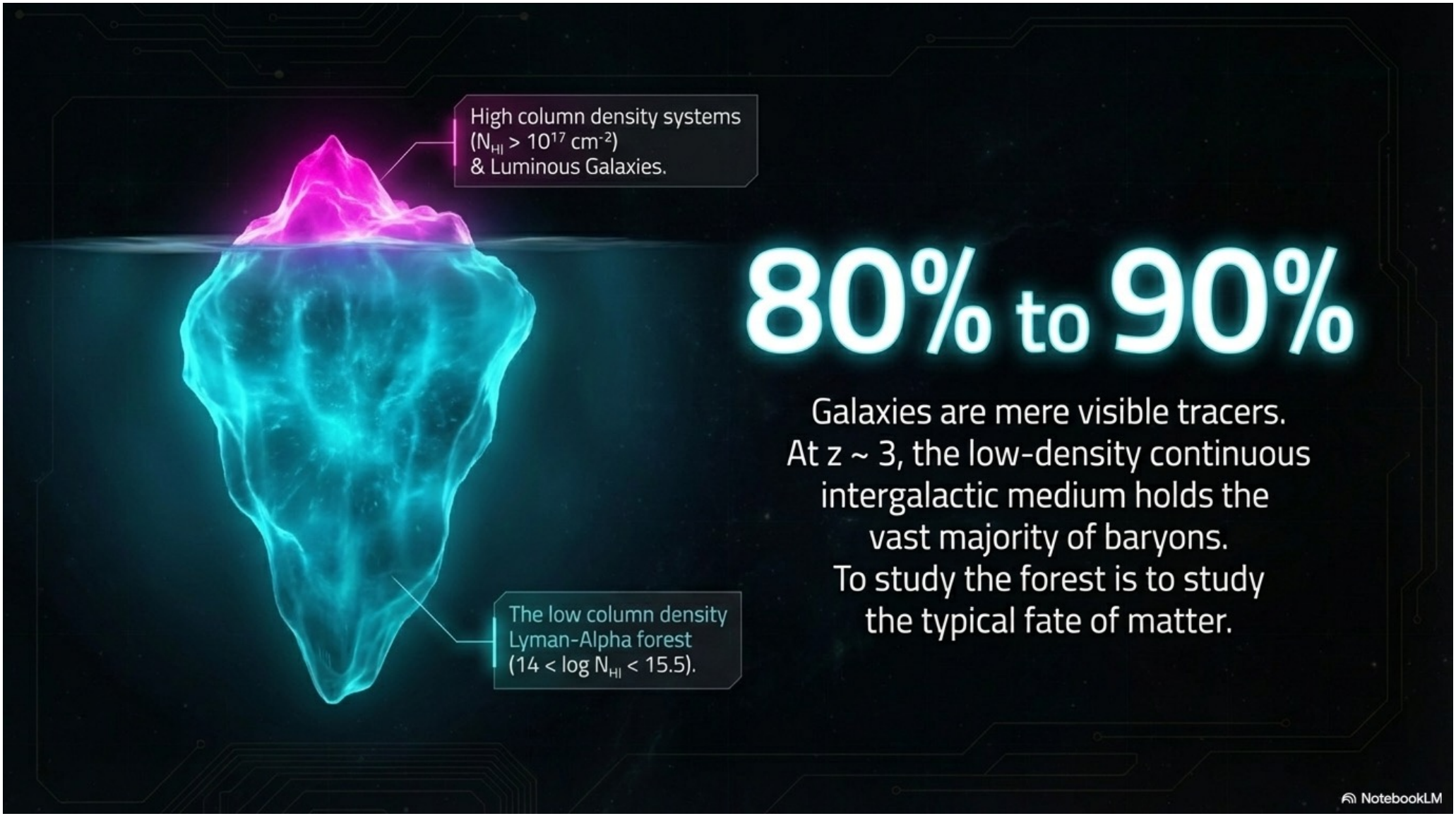
Discarded Theory: Zeldovich adiabatic pancakes / Hot Dark Matter (HDM). Gas collapsing into discrete, highly separated mega-structures. **Disproven by QSO pair transverse size studies.**



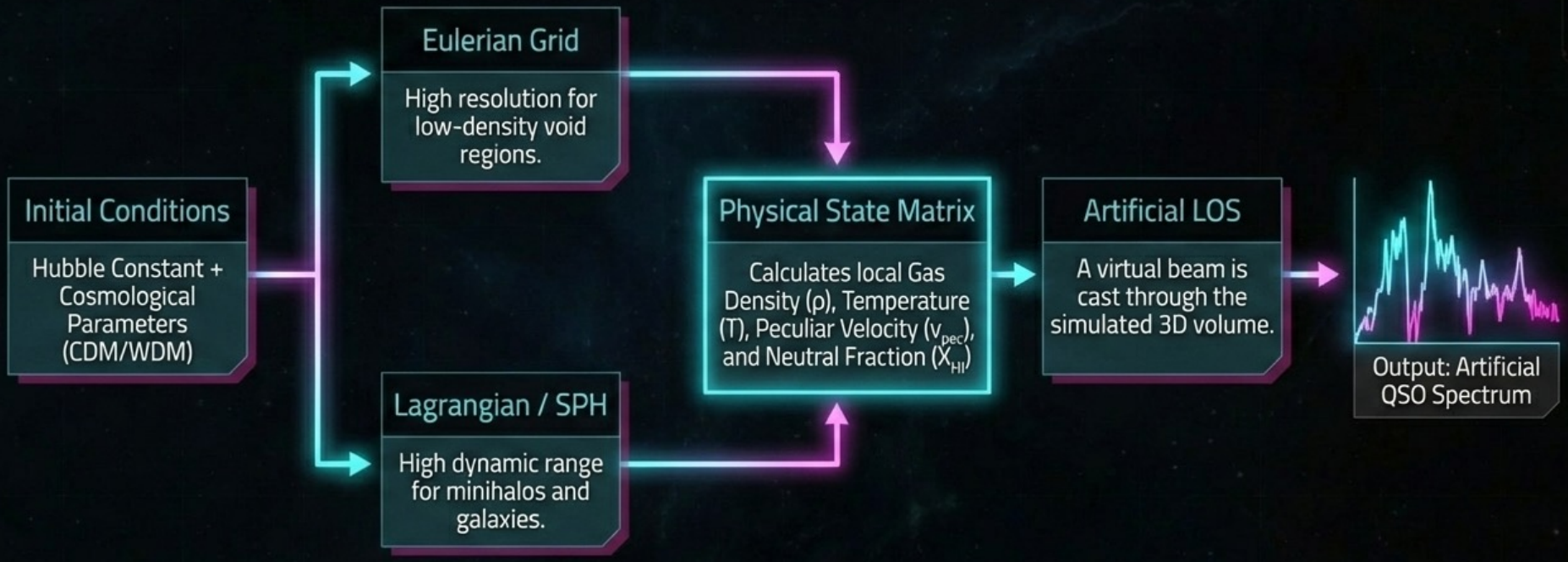
Modern Consensus: The IGM is a continuous, photoionized gaseous medium. The Ly-α forest is the observational signature of most baryons throughout cosmic history, fluctuating with the dark matter density field.

The Paradigm Shift: Re-imagining the Intergalactic Medium

	1980s Standard Model	Modern Hierarchical Model
Origin	Distinct, isolated intergalactic clouds.	Direct, continuous result of gravitational collapse.
Confinement	Pressure-confined by a hot, tenuous intercloud medium (ICM).	Gravitationally confined by the underlying dark matter distribution.
Geometry	Predominantly spherical.	A continuous web of flattened sheets, filaments, and halos.
Baryon Content	Assumed to be a negligible fraction of cosmic mass.	The main repository of all cosmic baryons at z ~ 3.


High column density systems
($N_{HI} > 10^{17}$ cm^{-2})
& Luminous Galaxies.
The low column density
Lyman-Alpha forest
($14 < \log N_{HI} < 15.5$).
80% to 90%
Galaxies are mere visible tracers.
At z ~ 3, the low-density continuous
intergalactic medium holds the
vast majority of baryons.
To study the forest is to study
the typical fate of matter.
NotebookLM

Simulating the Universe: Ab Initio Structure Formation



The Sherwood Simulation Suite

Algorithm

Parallel Tree-PM SPH code (P-GADGET-3).

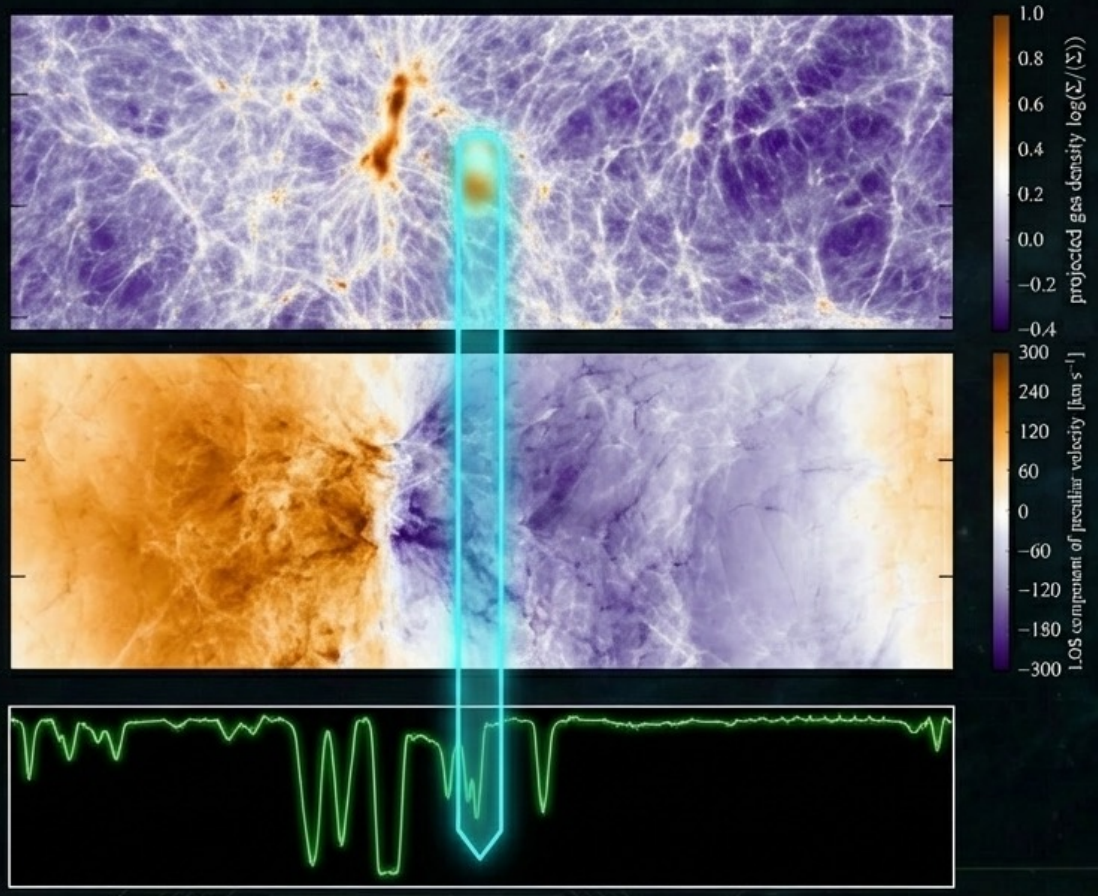
Particle Count

Up to 17.2 billion particles (spanning four orders of magnitude in mass resolution).

Computational Goal

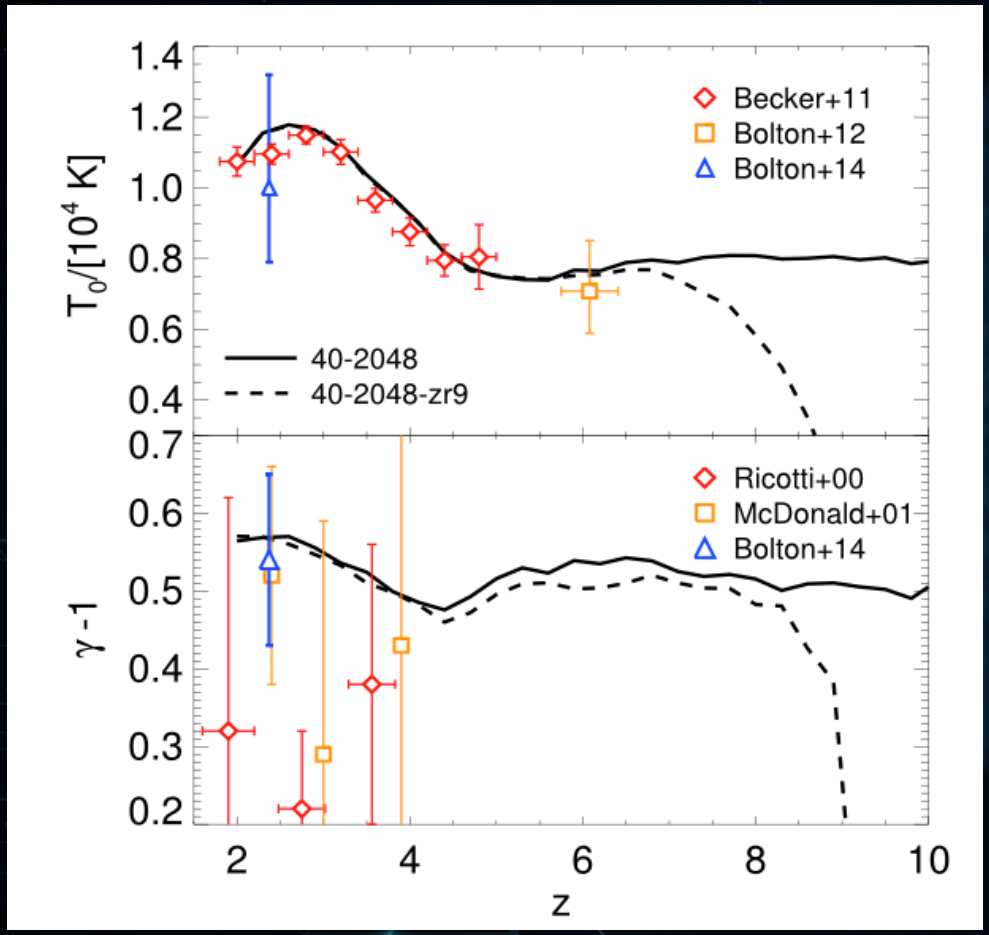
Achieve convergence at the < 10% level for the power spectrum by capturing large-scale modes without losing thermal small-scale physics.

From Real Space to Redshift Space



Absorption features are frequently offset from the physical location of the gas. Peculiar velocity gradients (gravitational infall around high-density regions) actively shift the Lyman-Alpha lines in velocity space.

The Thermal History of the IGM



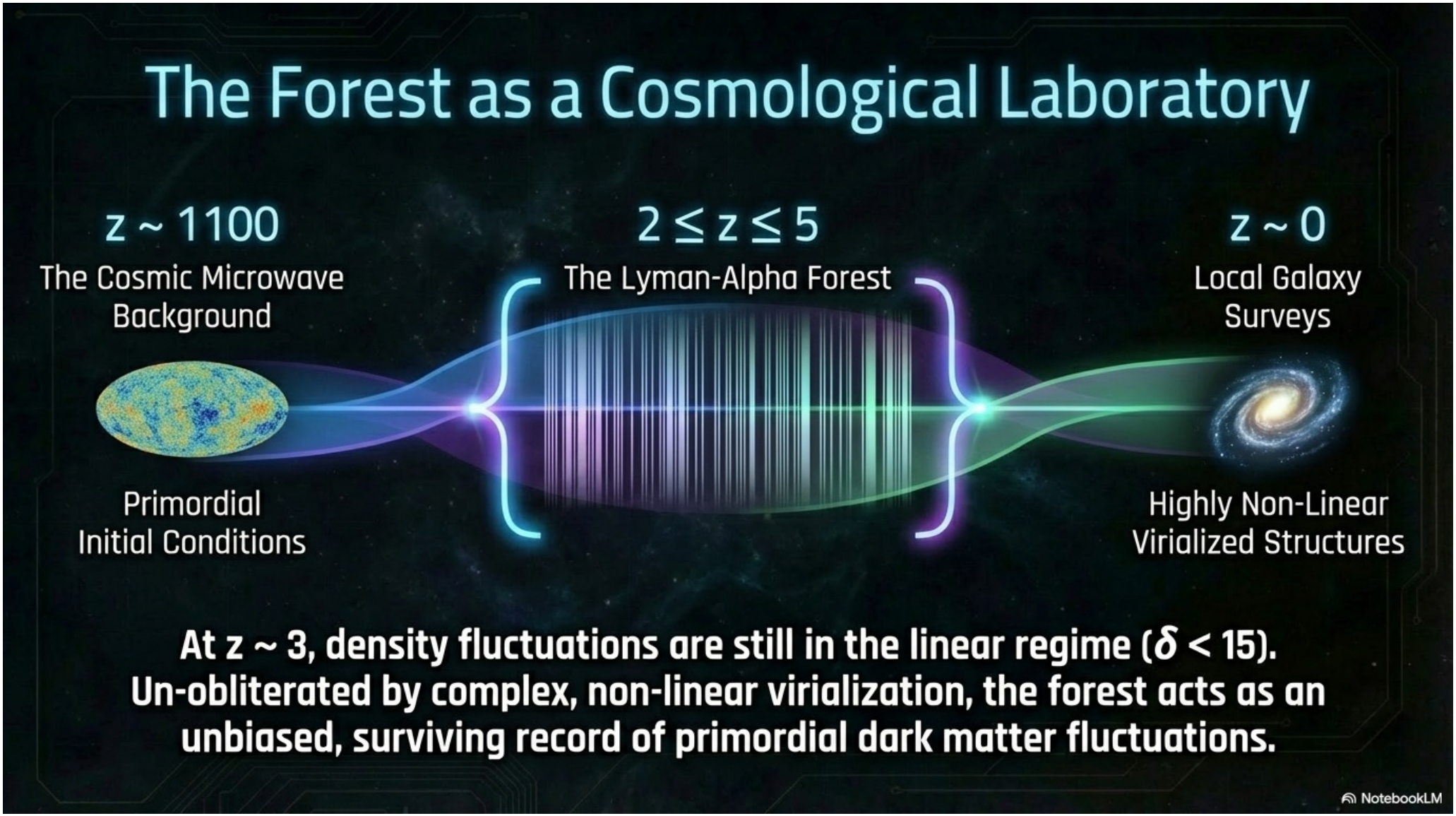
$$T = T_0 \Delta^{\gamma-1}$$

Gas is partly confined by gravity and ram pressure, settling into cooling layers.

The exponent γ accounts for denser regions being warmer (photoionization heating) balanced by adiabatic expansion.

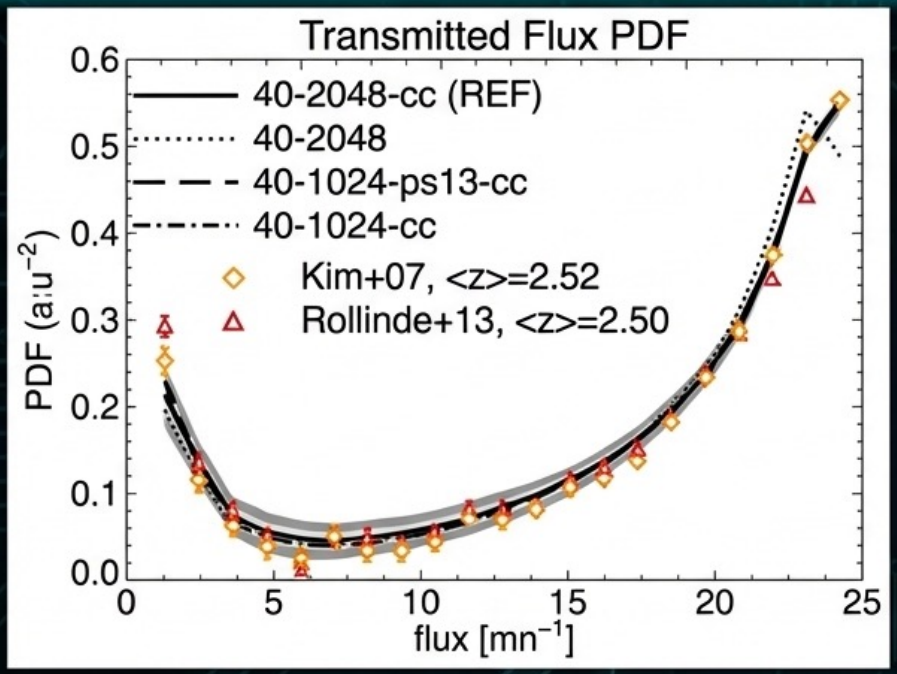
Simulations are finely tuned to match this observationally derived Equation of State.

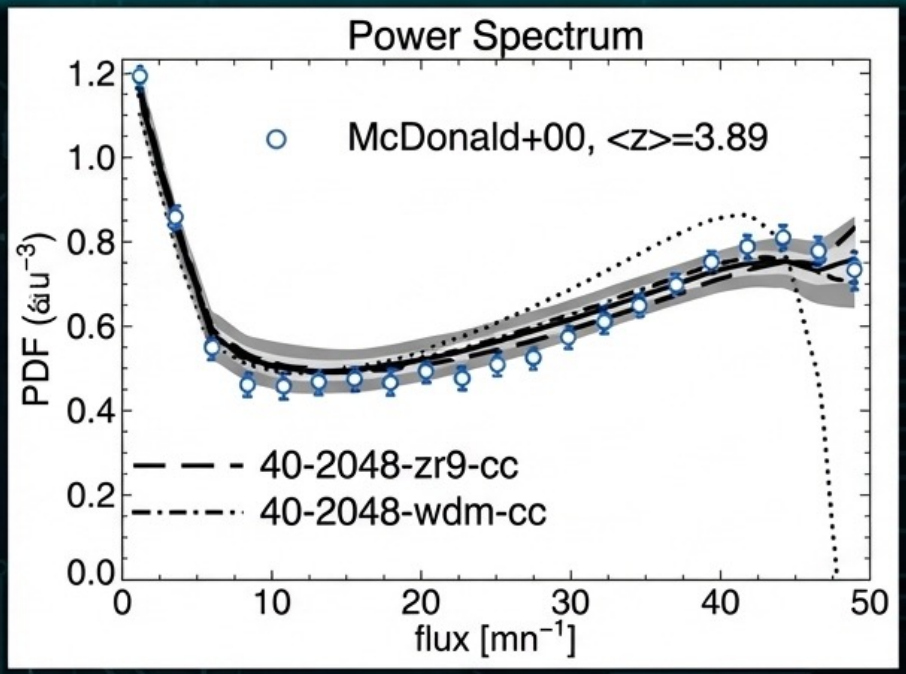
The Forest as a Cosmological Laboratory



At z ~ 3, density fluctuations are still in the linear regime ($\delta < 15$). Un-obliterated by complex, non-linear virialization, the forest acts as an unbiased, surviving record of primordial dark matter fluctuations.

Validating the Power Spectrum

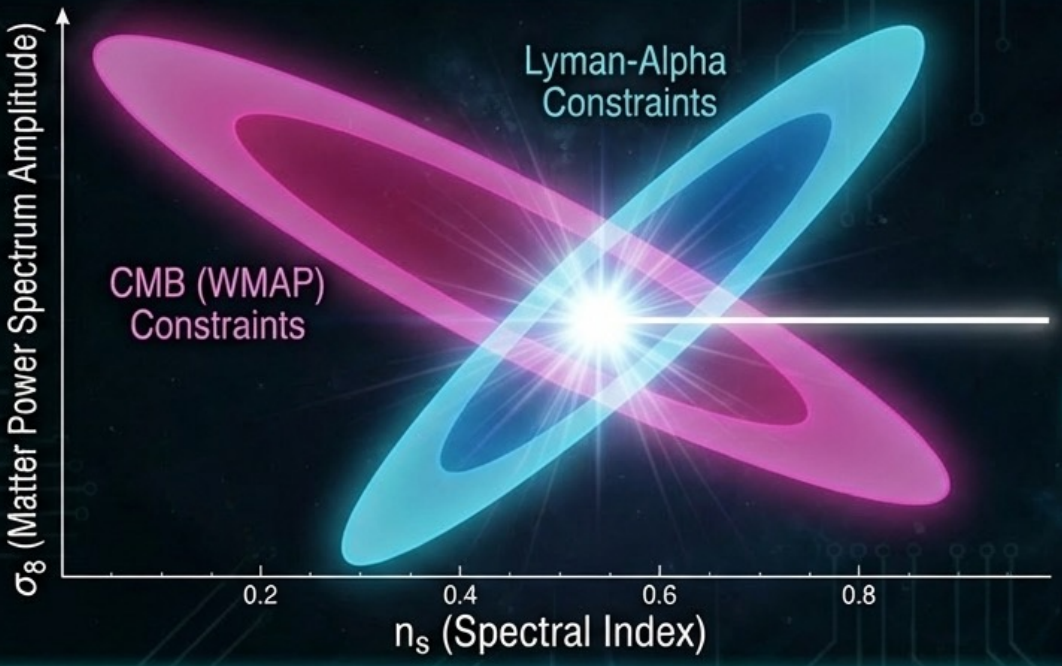




Exceptional Agreement

By comparing the statistical distribution of pixel fluxes and the power spectrum of the transmitted flux, the simulations demonstrate extreme fidelity to high-resolution observations at z=2 to z=5.

Precision Cosmology: The WMAP Intersection



$\sigma_8 = 0.78 \pm 0.03$

$n_s = 0.96 \pm 0.01$

The long lever arm of the forest extends measurements to highly complementary small scales. Combined with the CMB, it breaks degeneracies and significantly tightens constraints on primordial density fluctuations.

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Journal Class

- **The search for Population III: Confirmation of a HeII emitter with no metal lines at z=10.6**
- Maiolino, R. et al. 2026

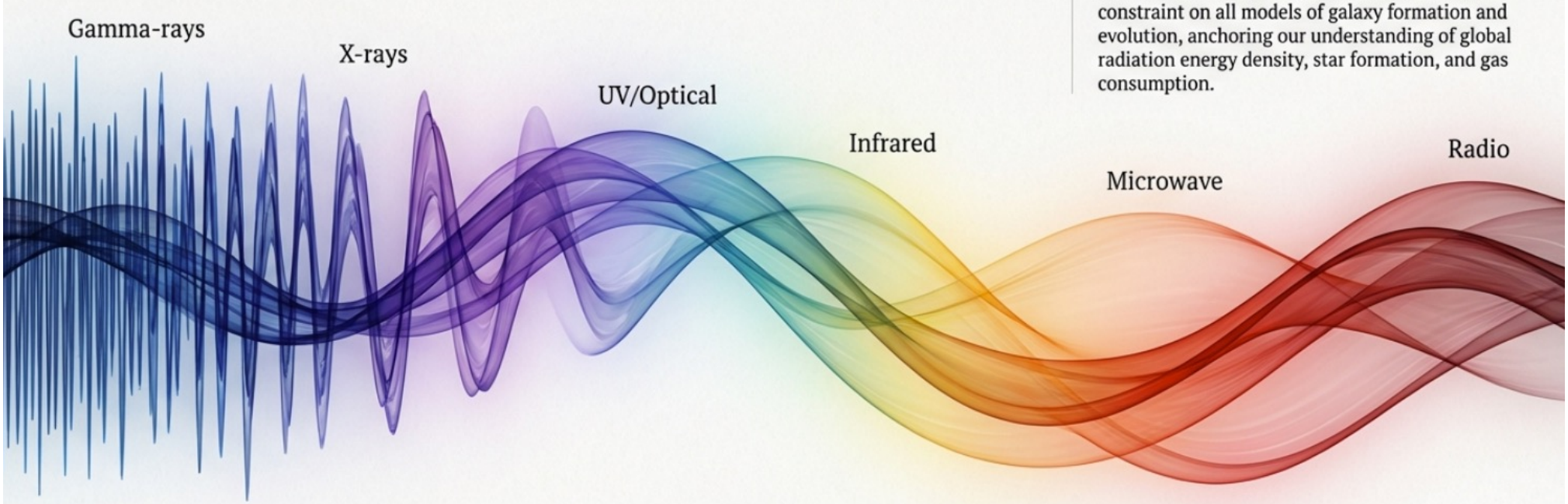
Discussion leader: **Sara Stamer**

Note: To encourage discussion everybody must pose at least one question during the group discussion

The Fossil Light of the Cosmos

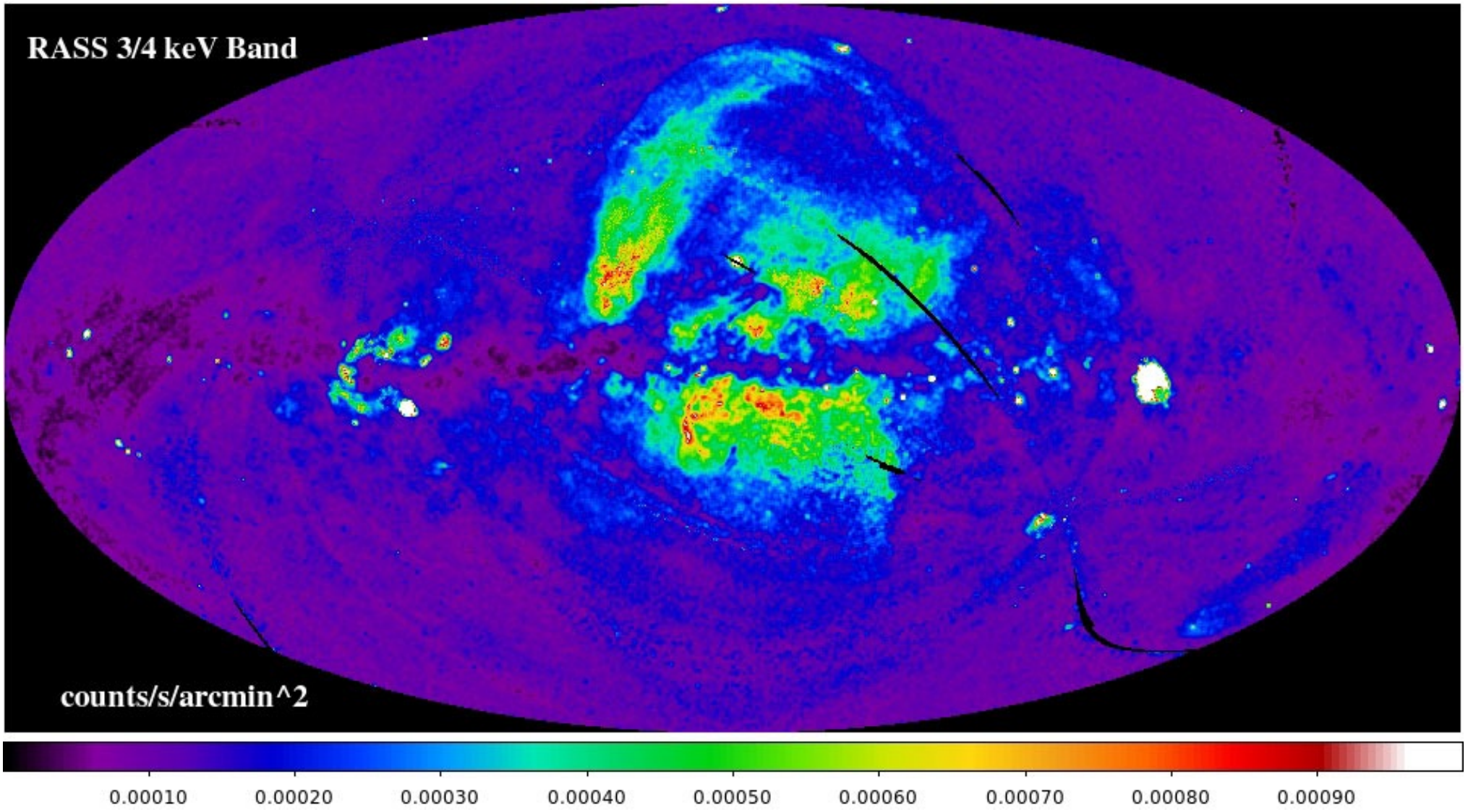
Decoding the Extragalactic Background Light (EBL) from Gamma-rays to Radio.

The Extragalactic Background Light (EBL) is the integrated intensity of all electromagnetic radiation emitted throughout the history of the universe. It captures the redshifted energy from all stars, galaxies, Active Galactic Nuclei (AGN), and primordial phenomena since the Big Bang. It serves as a critical constraint on all models of galaxy formation and evolution, anchoring our understanding of global radiation energy density, star formation, and gas consumption.



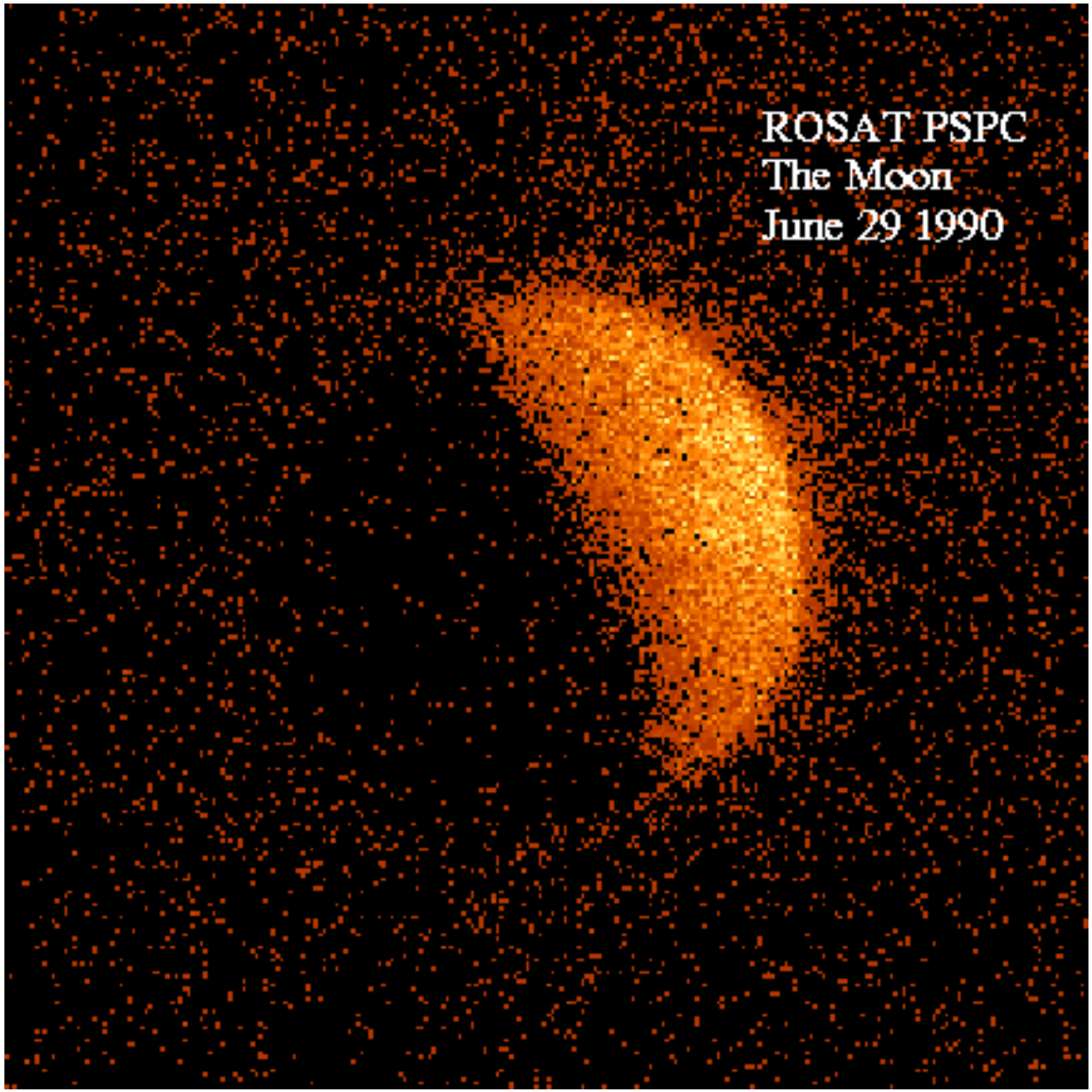
Slides from Google Notbook LLM based on papers by Cooray et al. 2015, Dowell & Taylor 2018, and Singal et al. 2018

ROSAT

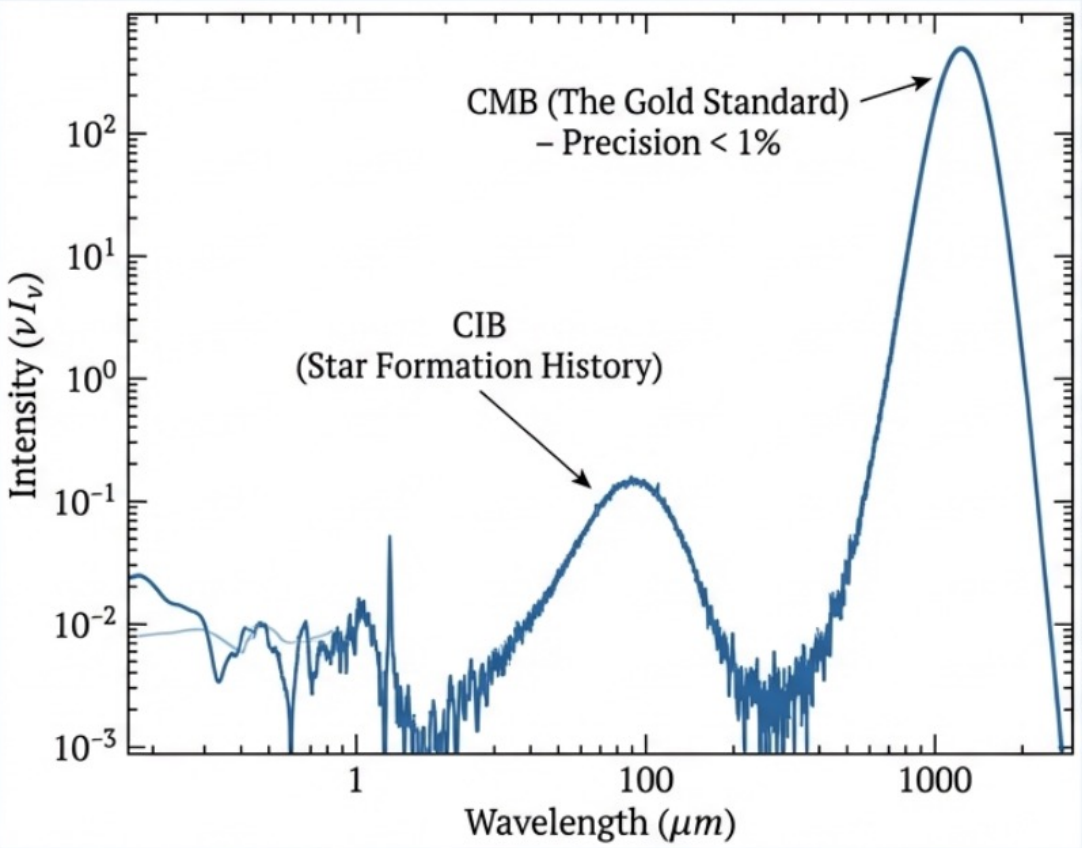


Snowden et al. 1995

ROSAT



The Cosmic Ledger: What We Know



The Gold Standard (CMB)
The Cosmic Microwave Background is the dominant energy component (960 nW m^{-2} sr^{-1}). Measured by COBE/FIRAS, its spectrum is a perfect blackbody ($T = 2.7260 \pm 0.0013$ K) with precision better than 1%.

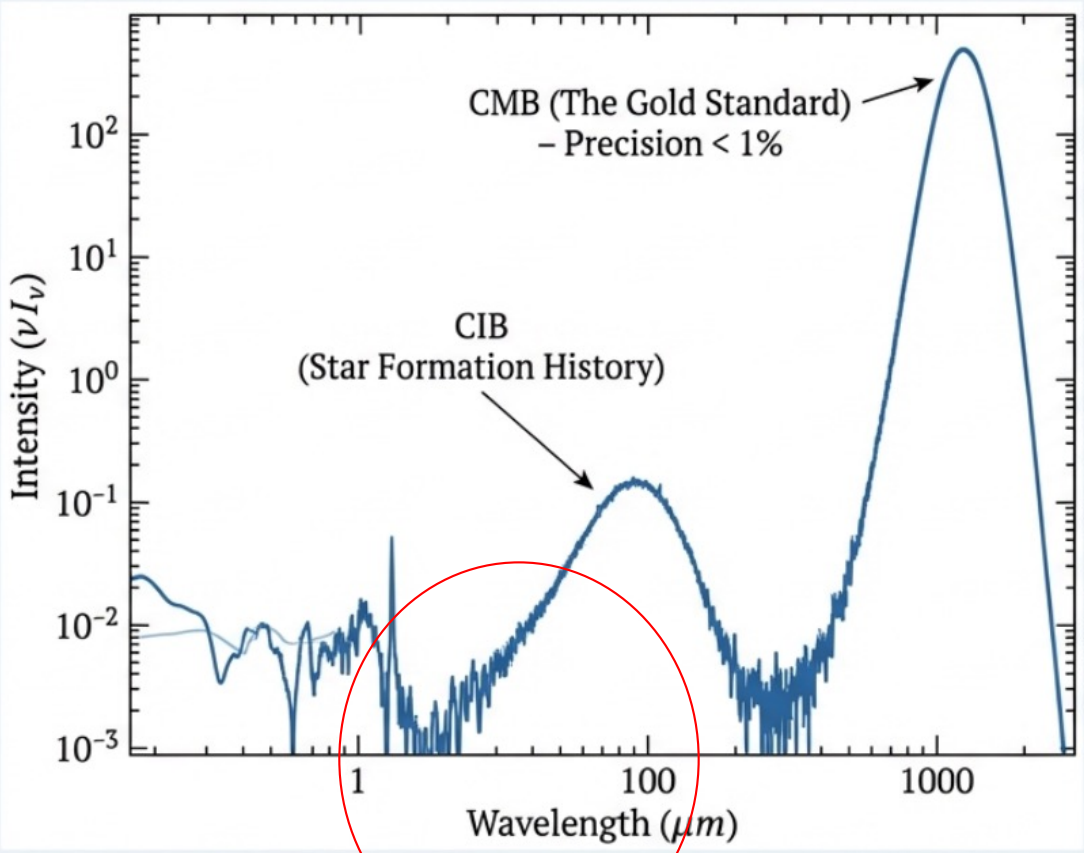
The Cosmic Infrared Background (CIB)
Peaking at 100 μm, this background is energetically comparable to the optical background (~30 nW m^{-2} sr^{-1}).

Resolved Sources
We have successfully resolved the CIB into discrete sources—primarily dusty, star-forming galaxies at high redshifts ($z > 1$)—using instruments like Herschel/SPIRE.

Takeaway: From microwaves to infrared, the "energy budget" of the universe largely balance

1 micron = 1000 nm = 10,000 Angstroms

The Cosmic Ledger: What We Know



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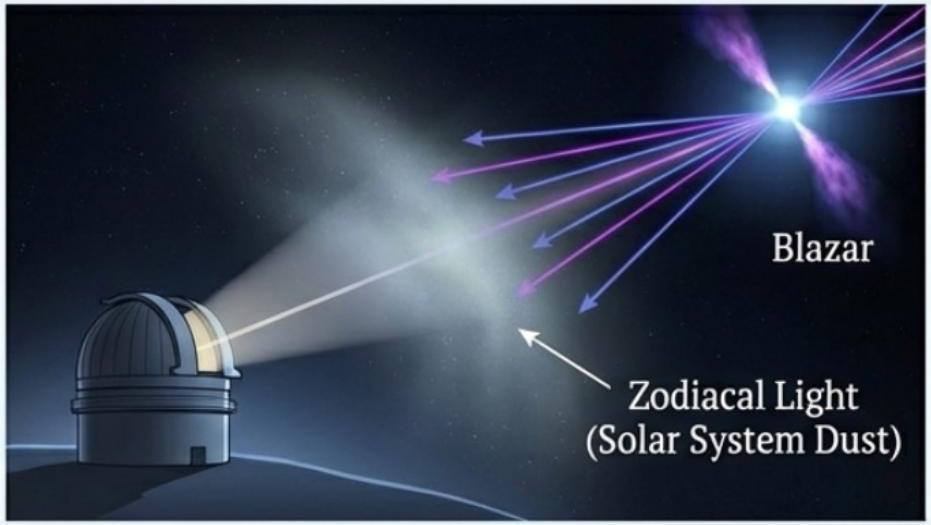
The High-Energy and Optical Windows

Gamma-rays (CGB) & X-rays (CXB)

Measured by Fermi-LAT, Chandra, and XMM-Newton.

80–90% of the X-ray background is resolved into discrete AGNs and galaxy clusters. We know the sources.

Optical/Near-IR (COB)



The Challenge: Direct measurement blocked by interplanetary dust.

The Solution: Indirect measurement via Gamma-ray absorption from distant Blazars.

Even with local interference, the models are consistent.

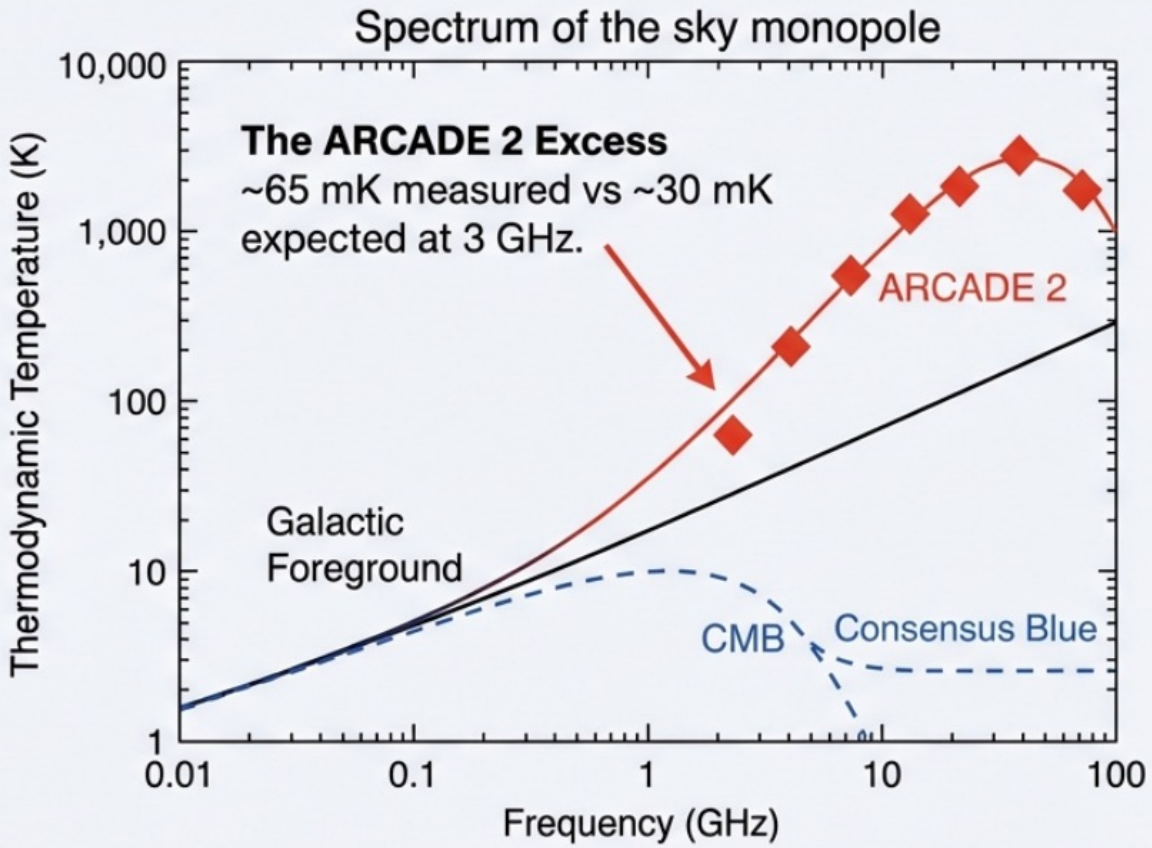
The Anomaly: A Radio Excess

Key Insight: In the radio window, the sky is significantly brighter than it should be.

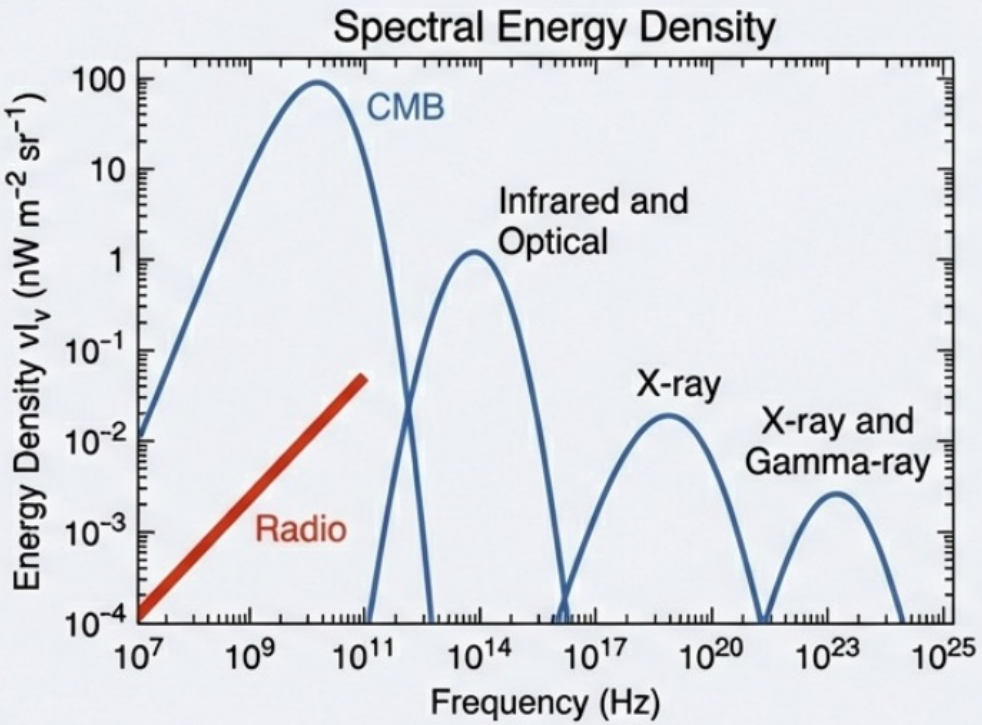
The Data:

The ARCADE 2 balloon experiment (3–90 GHz) reported a background temperature several times higher than the integrated sum of all known radio sources.

This excess follows a power law at low frequencies, rising above the Cosmic Microwave Background.



The Least Well Understood Background



Analysis

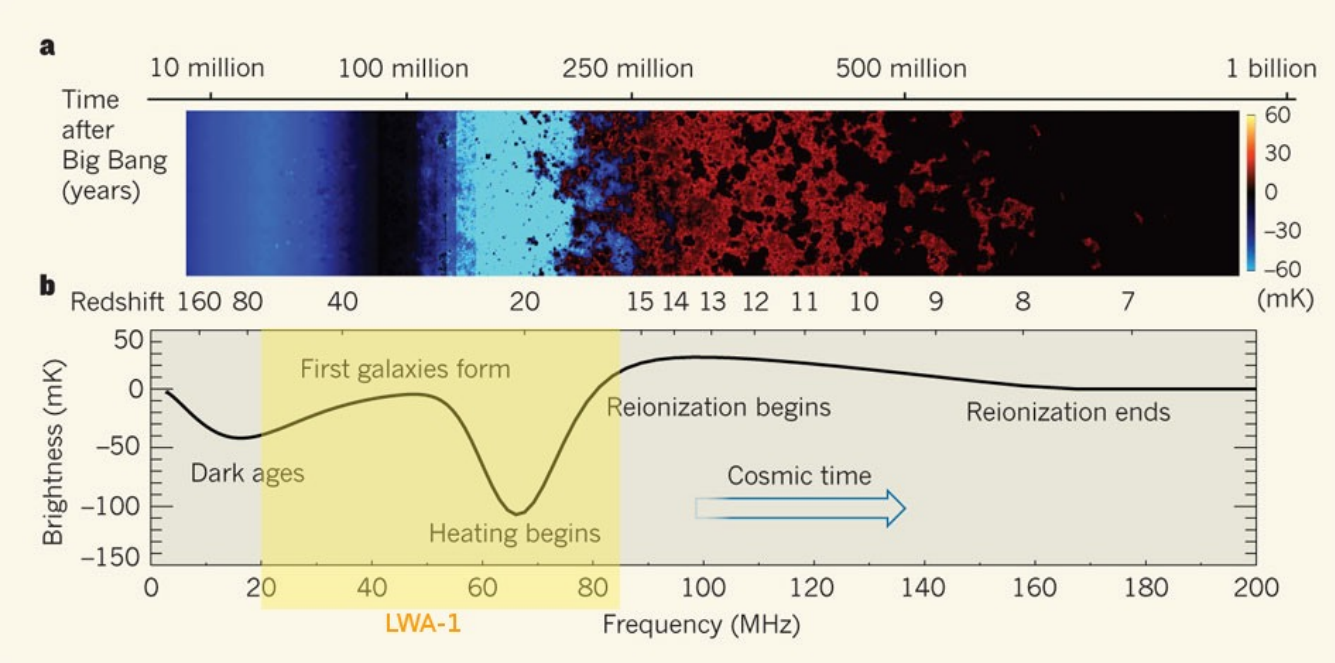
While the CIB and CXB are largely resolved into point sources, the Radio Synchrotron Background (RSB) remains diffuse and unaccounted for.

Process of Elimination

1. It is not instrumental error (confirmed by multiple surveys).
2. It is not the CMB (distinct spectral index).
3. It is not a simple sum of known galaxies (would require 5x the known population).

"The radio monopole level is... several times higher than can be straightforwardly explained by known Galactic and extragalactic sources." — Singal et al. (2018)

Cosmic Dawn



The predicted brightness temperature of the 21cm line from the HI gas is displayed as a function of time, redshift & frequency.

Figure 1 from Pritchard & Loeb, 2010 Nature 469 772

$$\delta T_b \approx 27 x_{HI} \sqrt{\frac{1+z}{10}} \left(\frac{T_s - T_r}{T_s} \right) \text{ mK}$$

The Dark Ages through Cosmic Dawn encompasses the formation of the 1st galaxies & black holes. The LWA offers a unique window into this era.

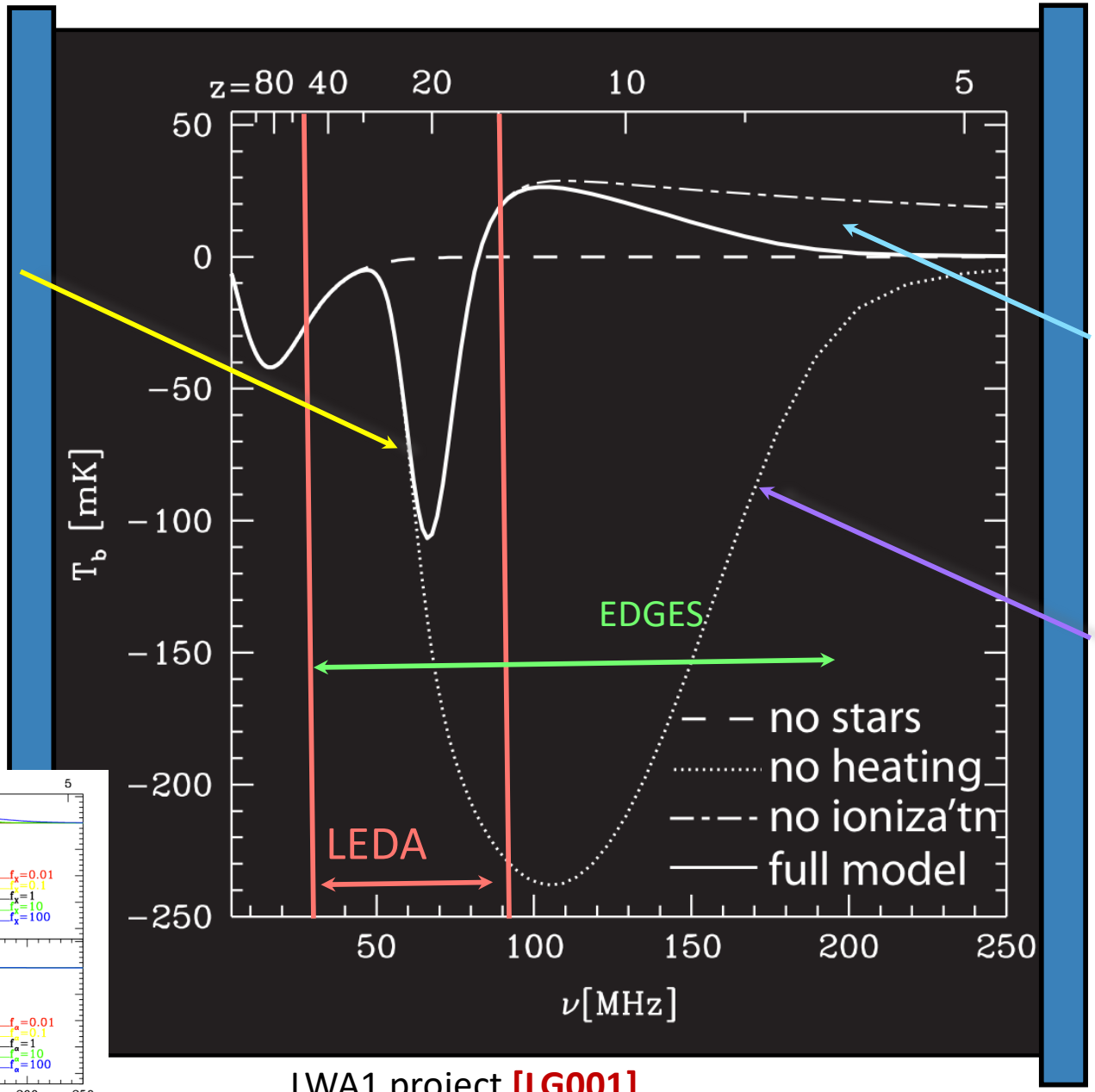
$$T_s^{-1} = \frac{T_\gamma^{-1} + x_\alpha T_\alpha^{-1} + x_c T_K^{-1}}{1 + x_\alpha + x_c}$$

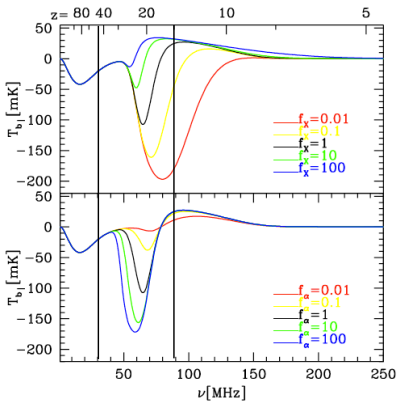
CMB Photons Lyman-α Photons Collisions

LWA Long Wavelength Array

Cosmic Dawn

Lyman-α photon production (likely from stars) determines magnitude of decoupling from the dashed curve





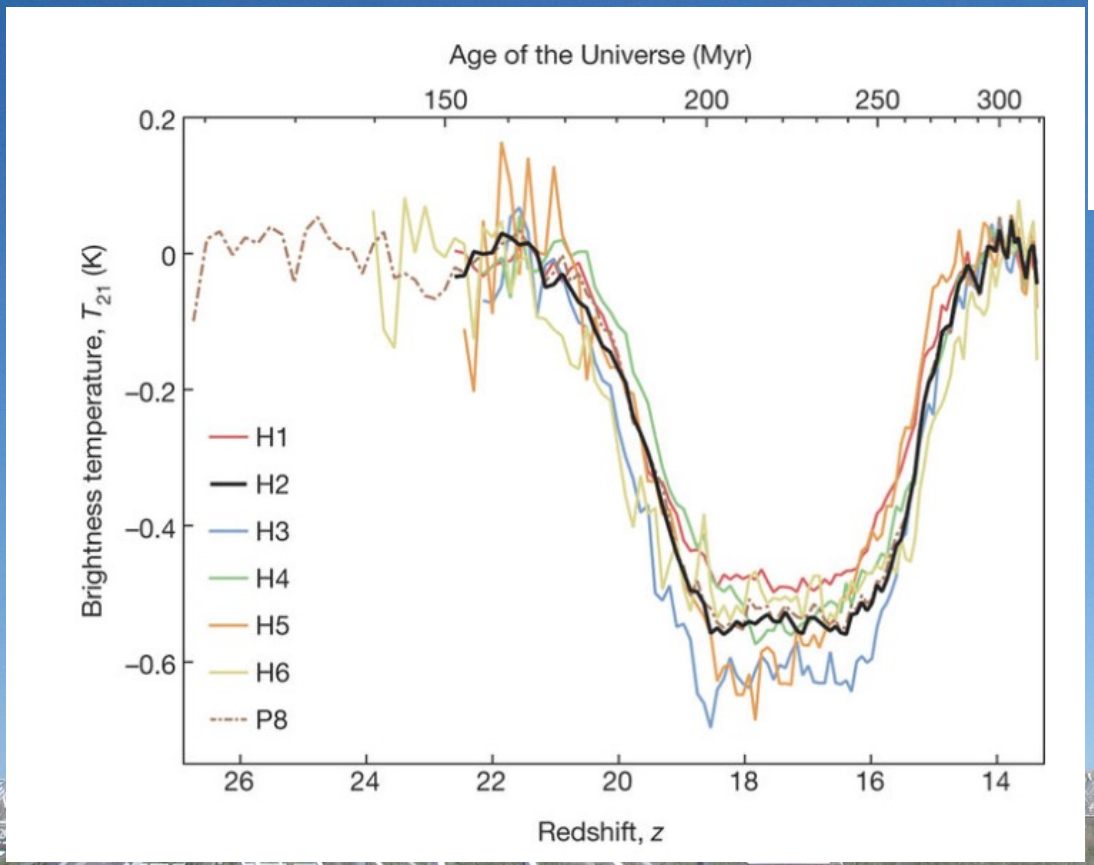
LWA1 project **[LG001]**

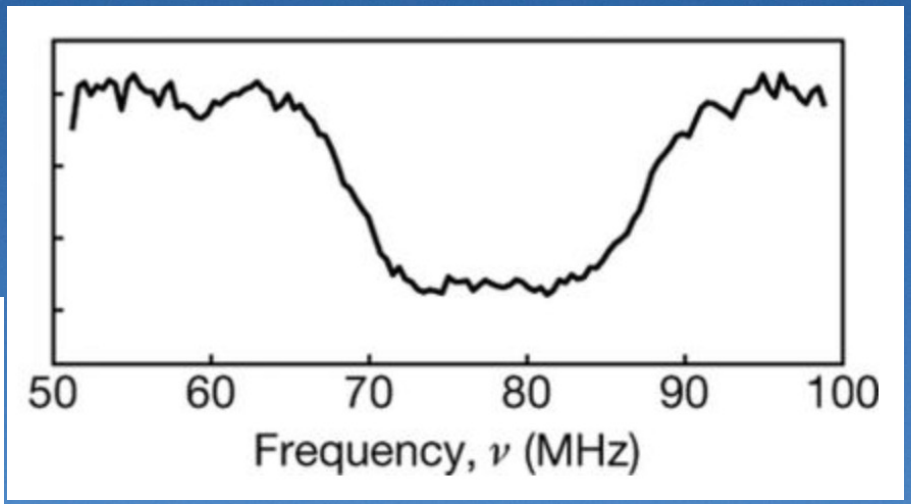
Production of ionizing photons determines the difference between dash-dot and solid curves

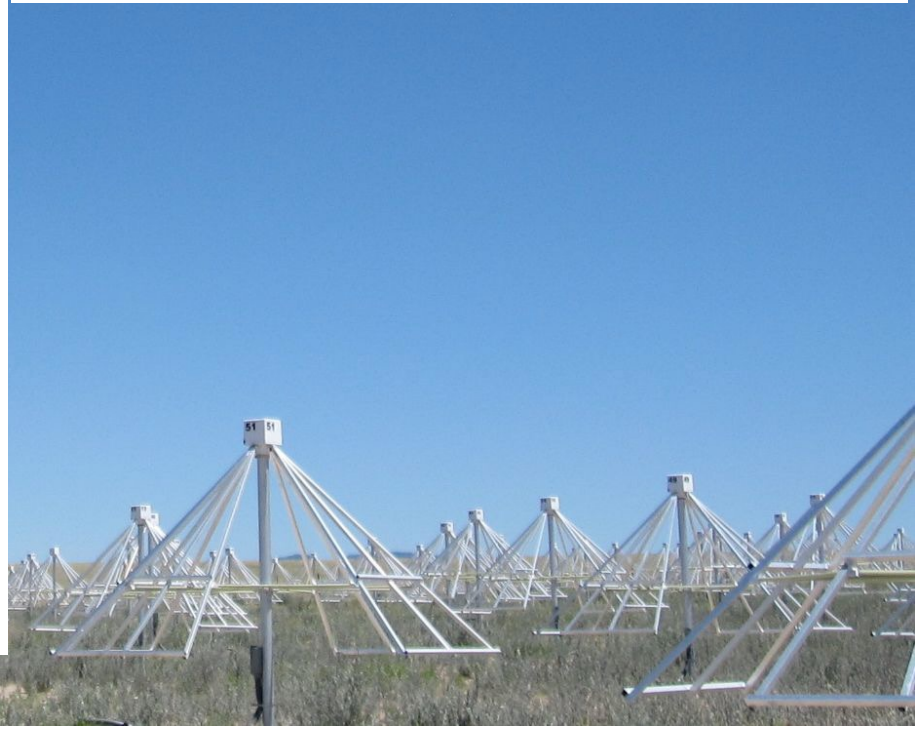
Case where IGM not reheated prior to reionization. It takes just 10^{-3} eV per baryon to significantly change this curve.

EDGES Detection of HI at z=17

Bowman et al. 2018

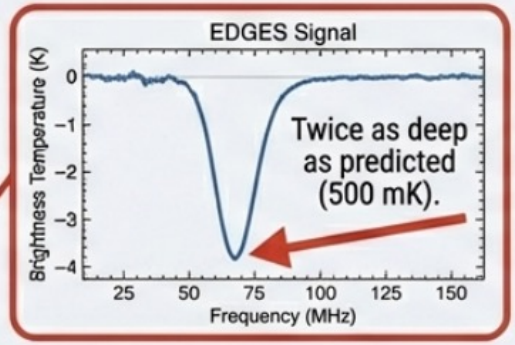






The “Cosmic Dawn” Connection

How the Radio Background alters our view of the early Universe.



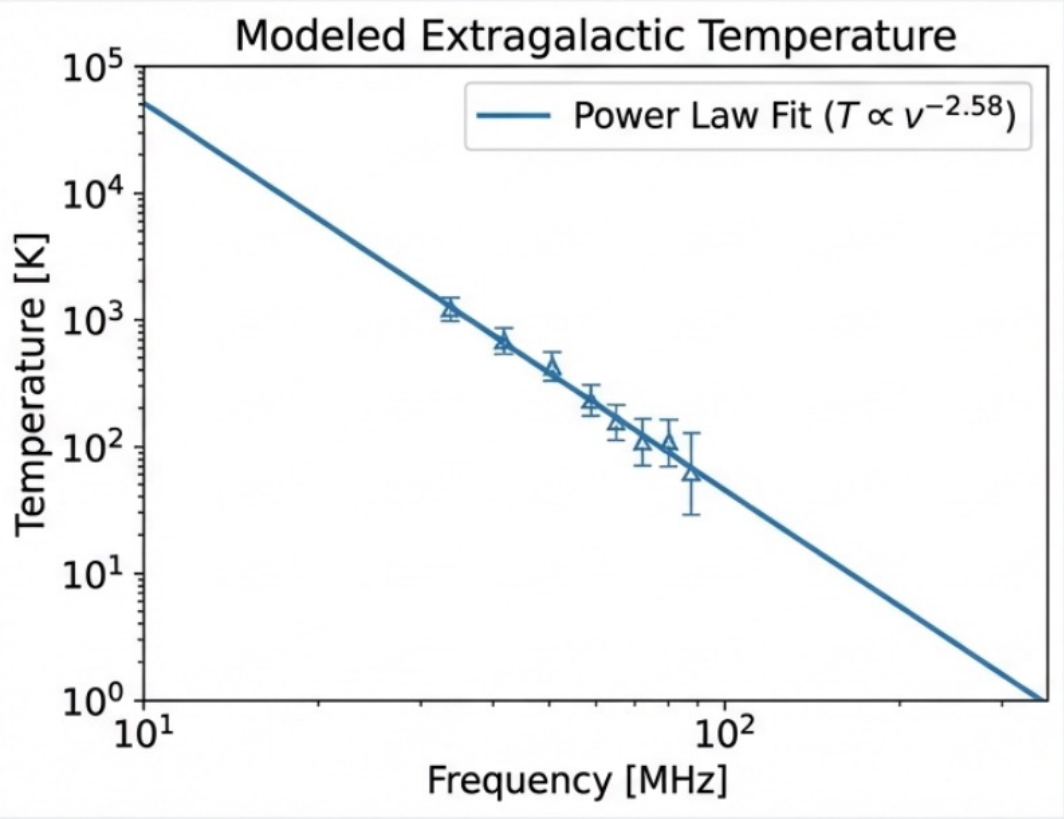
78 MHz Absorption Trough.

Big Bang — Dark Ages — Cosmic Dawn (First Stars) — Modern Universe

The Conflict: To explain this deep trough, one of two things must be true:
Option A: Colder Gas The primordial gas was cooled by interactions with Dark Matter.
Option B: Hotter Background The background radiation field was much stronger than the CMB alone—specifically, it included the **Radio Synchrotron Background**.

If the RSB is real and primiordial, it fundamentally changes the physics of the Epoch of Reionization.

Corroborating the Excess: New Evidence

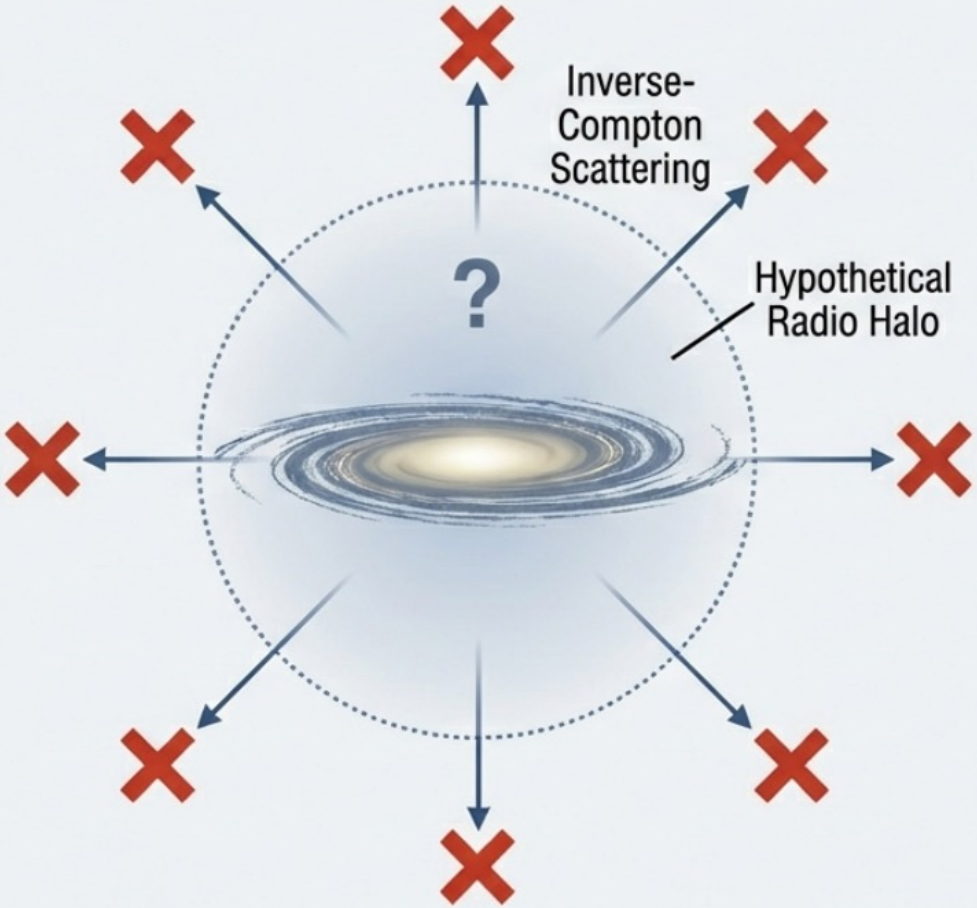


The Study: Dowell & Taylor (2018) using the Long Wavelength Array (LWA1).

The Finding: The background is real and fits a smooth power law ($T \propto \nu^{-2.58}$) with no breaks.

The Link: At the 21-cm rest frame, this adds **~603 mK** of temperature, supporting the 'Hotter Background' hypothesis for Cosmic Dawn.

Suspect 1: A Massive Galactic Halo?

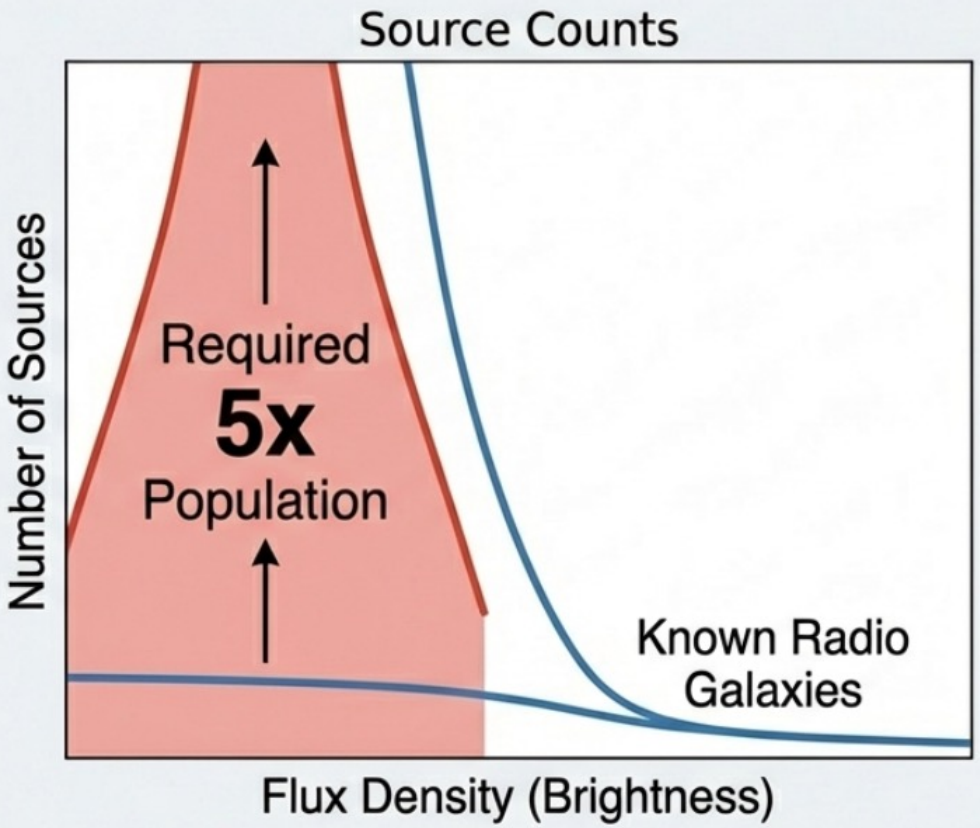


The Theory: Could the excess signal originate from a large, spherical halo of synchrotron-emitting electrons surrounding the Milky Way?

The Rebuttal:
1. X-Ray Constraints: The same electrons required to produce the radio background would interact with photons to produce a diffuse X-ray background via Inverse-Compton scattering. We do not observe this X-ray flux.
2. The Anomaly Argument: A halo of this magnitude would make the Milky Way anomalous compared to other spiral galaxies.

Verdict: Unlikely.

Suspect 2: Unresolved Point Sources?



The Theory: Is the background just the sum of billions of faint, ordinary radio galaxies we can't see yet?

The Rebuttal:

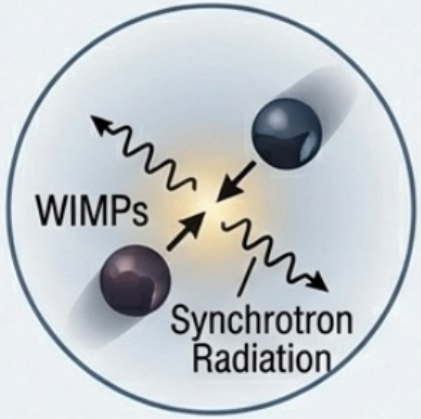
- **Deep Counts:** Interferometric surveys show source counts converging. We have likely seen the bulk of the population.
- **The Number Problem:** To explain the excess, we would need a completely new population of sources at the nano-Jansky level, outnumbering known galaxies by a vast margin.

Verdict: No evidence for such a vast population.

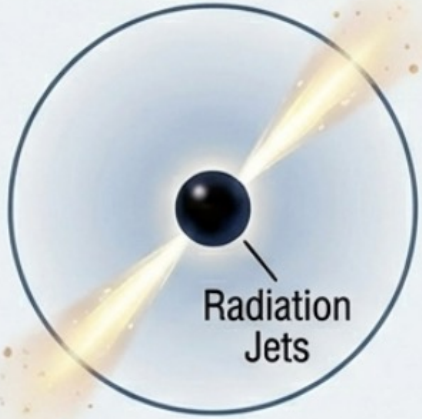
Look at number counts for radio sources

Suspect 3: Exotic Physics & Dark Matter

Dark Matter Annihilation



Primordial Black Holes



Cluster Mergers

When standard astrophysics fails, we look to the exotic.

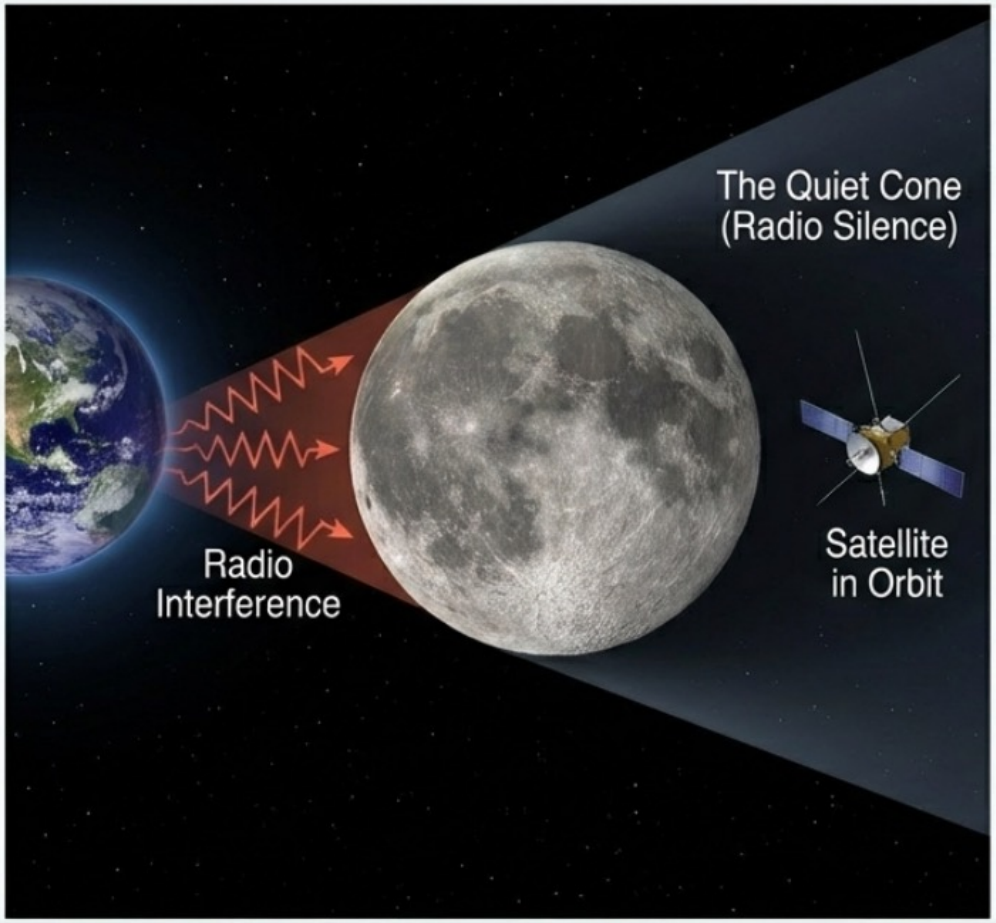
Current Hypotheses:

- **Dark Matter:** Decaying WIMPs in halos or filaments producing synchrotron radiation.
- **Primordial Black Holes:** Radiation from the early universe.
- **Quark Nuggets:** Theoretical dense matter interactions.

Status: These theories provide potential mechanisms but require 'fine-tuning' to match the observed smooth power law.

Problem – If you want to influence Cosmic Dawn signal at $z \sim 20$, then the RSB has to be produced at very early times – not easy!

The Path Forward: Future Missions



The Challenge: Measurement is hindered by Galactic foregrounds and terrestrial Radio Frequency Interference (RFI).

Required Tools:

- **Absolute Calibration:** Surveys must prioritize zero-level temperature calibration, not just relative changes.
- **New Frequencies:** Mapping at **120 MHz and 300 MHz** to bridge the gap between LWA1 and ARCADE 2.
- **Location:** The Dark Side of the Moon (e.g., DARE mission) to escape Earth's electronic noise and ionosphere.

Summary: The Unsolved Mystery

- ✅ **Gamma-Rays:** Resolved (Blazars).
- ✅ **X-Rays:** Resolved (AGNs).
- ✅ **Optical:** Resolved (Stars/Galaxies).
- ✅ **Microwave:** Resolved (CMB).
- ❌ **Radio: UNSOLVED** (Excess of ~500 mK).

1. The Ledger We have precisely mapped the Universe's energy history across almost the entire spectrum.

2. The Anomaly The Radio window contains a bright, unexplained background that exceeds known source counts by a factor of ~5.

3. The Stakes This excess is this excess is potentially linked to the 'Cosmic Dawn.' It suggests either a hidden population of sources or fundamental changes to our understanding of physics.

The radio sky is not quiet. It is humming with a signal we have yet to decode.