Title: Panel Discussion - Cosmological Puzzles (Ashtekar, Brandenberger, Geshnizjani, Sakellariadou, Yazdi)

Speakers: Abhay Ashtekar, Robert Brandenberger, Ghazal Geshnizjani, Mairi Sakellariadou, Yasaman Kouchekzadeh Yazdi

Collection: Puzzles in the Quantum Gravity Landscape: viewpoints from different approaches

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# Puzzles in Cosmology and Challenges for Quantum Gravity

Robert Brandenberger
Physics Department, McGill University

Puzzles in the Quantum Gravity Landscape Conference,
Perimeter Institute, October 23 - 27 2023

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# Dedication

Puzzles

R. Branden-berger

# Two Key Challenges

Puzzles

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- Unitarity Crisis of the current paradigm of early universe cosmology.
- Dark Energy mystery.

# Unitarity Crisis for Cosmological Inflation

J. Martin and R.B., *Phys. Rev. D63, 123501 (2002)*

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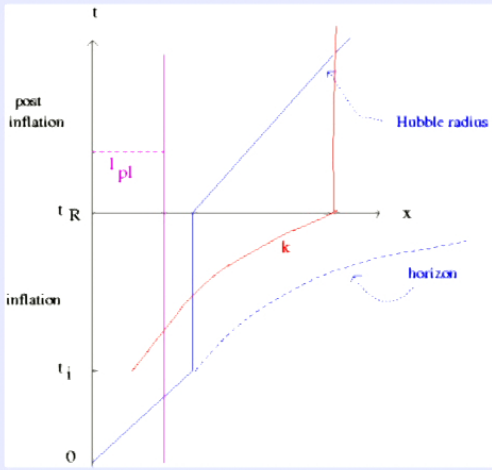


- In an effective field theory description of cosmological inflation, modes which were initially beyond the UV cutoff enter the classical regime.
- $\rightarrow$ loss of unitarity and predictability.

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# Trans-Planckian Censorship Conjecture (TCC)

A. Bedroya and C. Vafa., arXiv:1909.11063

No trans-Planckian modes exit the Hubble horizon.

$$ds^2 = dt^2 - a(t)^2 d\mathbf{x}^2$$

$$H(t) \equiv \frac{\dot{a}}{a}(t)$$

$$\boxed{\frac{a(t_R)}{a(t_i)} l_{pl} < H(t_R)^{-1}}$$

Justifications:

- Cosmological version of **Penrose's Black Hole Censorship** criterion.
- Unitarity
- Second law of thermodynamics

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# Application to EFT Descriptions of Inflation

A. Bedroya, R.B., M. Loverde and C. Vafa., arXiv:1909.11106

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TCC implies:

$$\frac{a(t_R)}{a(t_*)} l_{pl} < H(t_R)^{-1}$$

Demanding that inflation yields a causal mechanism for generating CMB anisotropies implies:

$$H_0^{-1} \frac{a(t_0)}{a(t_R)} \frac{a(t_R)}{a(t_*)} < H^{-1}(t_*)$$

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# Implications

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- **Upper bound** on the **energy scale of inflation**:

$$V^{1/4} < 3 \times 10^9 \mathrm{GeV}$$

- Standard cosmological inflation is ruled out.
- Dark Energy cannot be a bare cosmological constant.
- Quintessence models of Dark Energy are constrained (L. Heisenberg et al. arXiv:2003.13283)

# Effective Field Theory (EFT) and the CC Problem



- EFT: expand **fields** in comoving Fourier space.
- Quantize each Fourier mode like a harmonic oscillator $\rightarrow$ ground state energy.
- Add up ground state energies $\rightarrow$ CC problem.
- The usual quantum view of the CC problem is an artefact of an EFT analysis!

# Lessons and Challenges

Puzzles

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- To describe **both early and late** time cosmology we need to go beyond effective field theory.
- **Lesson from the theory of particles**: The key degrees of freedom in a quantum theory of particles are not particles but **fields**.
- $\rightarrow$ we should not expect that in a quantum theory of gravity the basic objects are the metric or matter fields.

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Puzzles

R. Brandenberger

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- $\rightarrow$ we should not expect that in a quantum theory of gravity the basic objects are the metric or matter fields.

# A New Approach: BFSS Matrix Theory Cosmology

S. Brahma, RB and S. Laliberte., arXiv:2107.11512, arXiv:2206.12468

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- Starting point: BFSS matrix quantum mechanics: a quantum mechanical model of 10 $N \times N$ Hermitean matrices. No space!
- In this limit $N \to \infty$ this yields a non-perturbative definition of superstring theory.
- Consider this model in a **high temperature state**.
- Matsubara zero modes of the matrices yield an emergent space-time which is **continuous** in the $N \to \infty$ limit.
- Only three dimensions of space become classical - these are infinite in the $N \to \infty$ limit.
- Emergent cosmological metric which is spatially flat.
- The nonzero Matsubara modes yield thermal fluctuations with scale-invariant scalar and tensor spectra.
- No cosmological constant

# Emergent Early Universe Cosmology

A. Nayeri, R.B. and C. Vafa, *Phys. Rev. Lett. 97:021302 (2006)*

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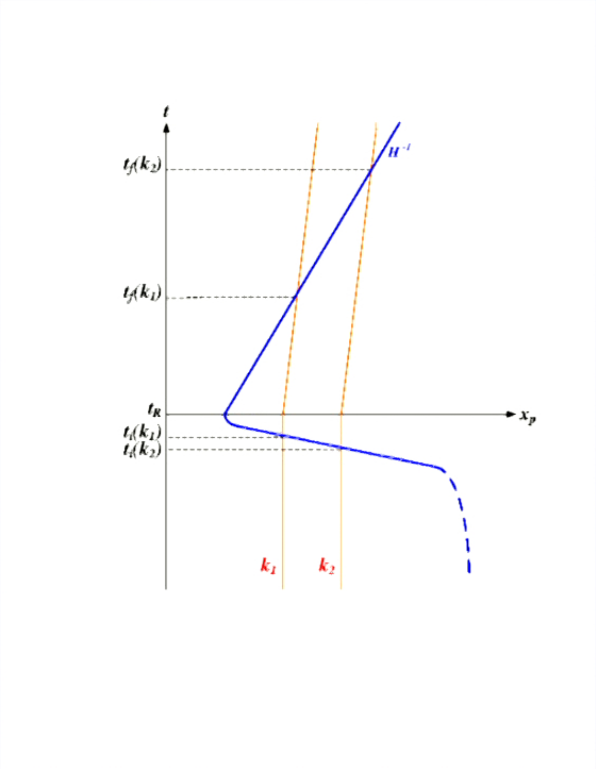


N.B. Perturbations originate as thermal fluctuations.

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# Puzzles in quantum cosmology?

**Ghazal Geshnizjani**

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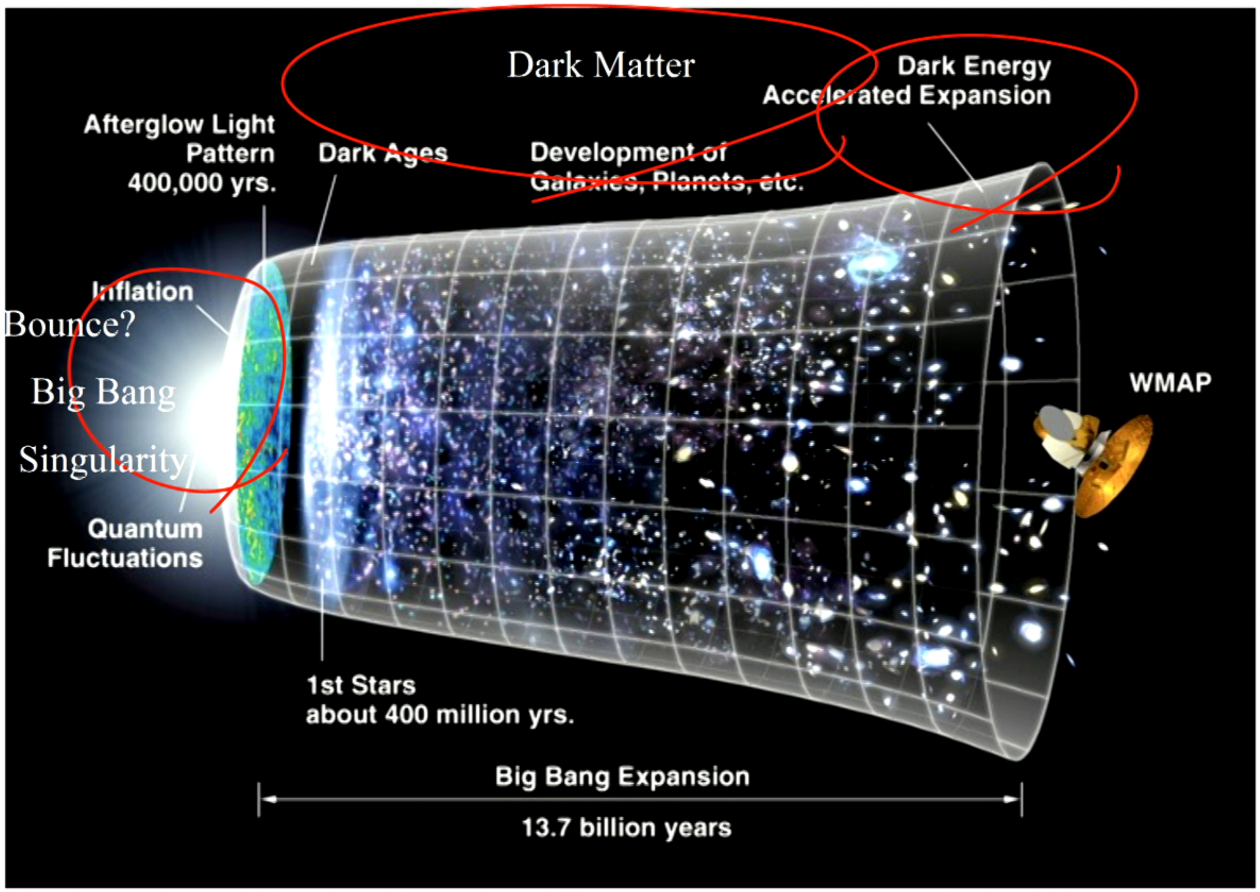
# The Jigsaw Puzzle



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## Early Time/Initial Conditions:

- Inflation, Bounce or another phase?
- Big Bang Singularity?
- QFT in Curved space time:
  - Vacuum Quantum fluctuations ——> seeds of Large scale structure
- Observational tools: CMB and Matter Power Spectrum, Non-Gaussianity, Gravitational waves? Neutrinos?

## Late Time:

- OLD Cosmological constant problem
- NEW twist: Lambda/Dark Energy/Modified Gravity
  - Could it even be a constant? (Yasaman)
- Observation: CMB, Supernovae, Gravitational waves

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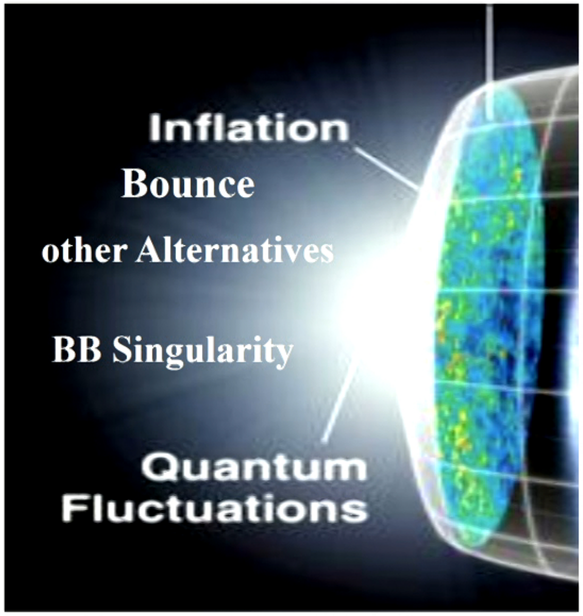
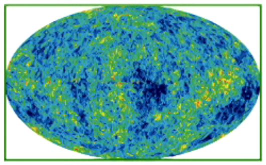
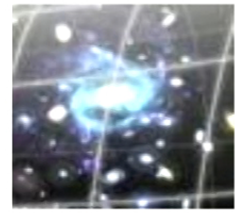
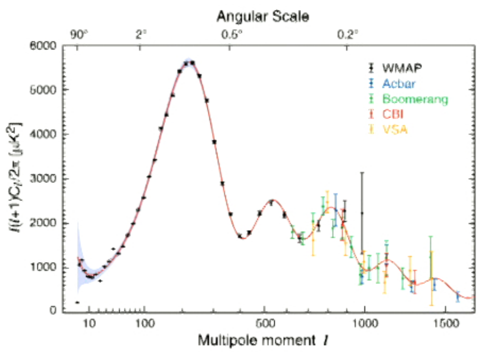
# Quantum cosmology era?

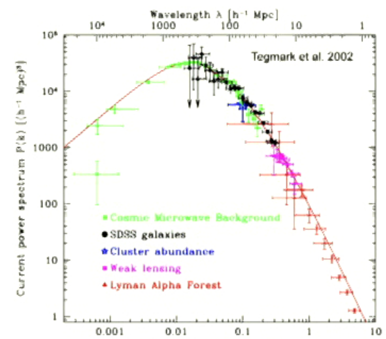


# Anisotropies of order $10^{-5}$!
# Scale Invariant Power Spectrum







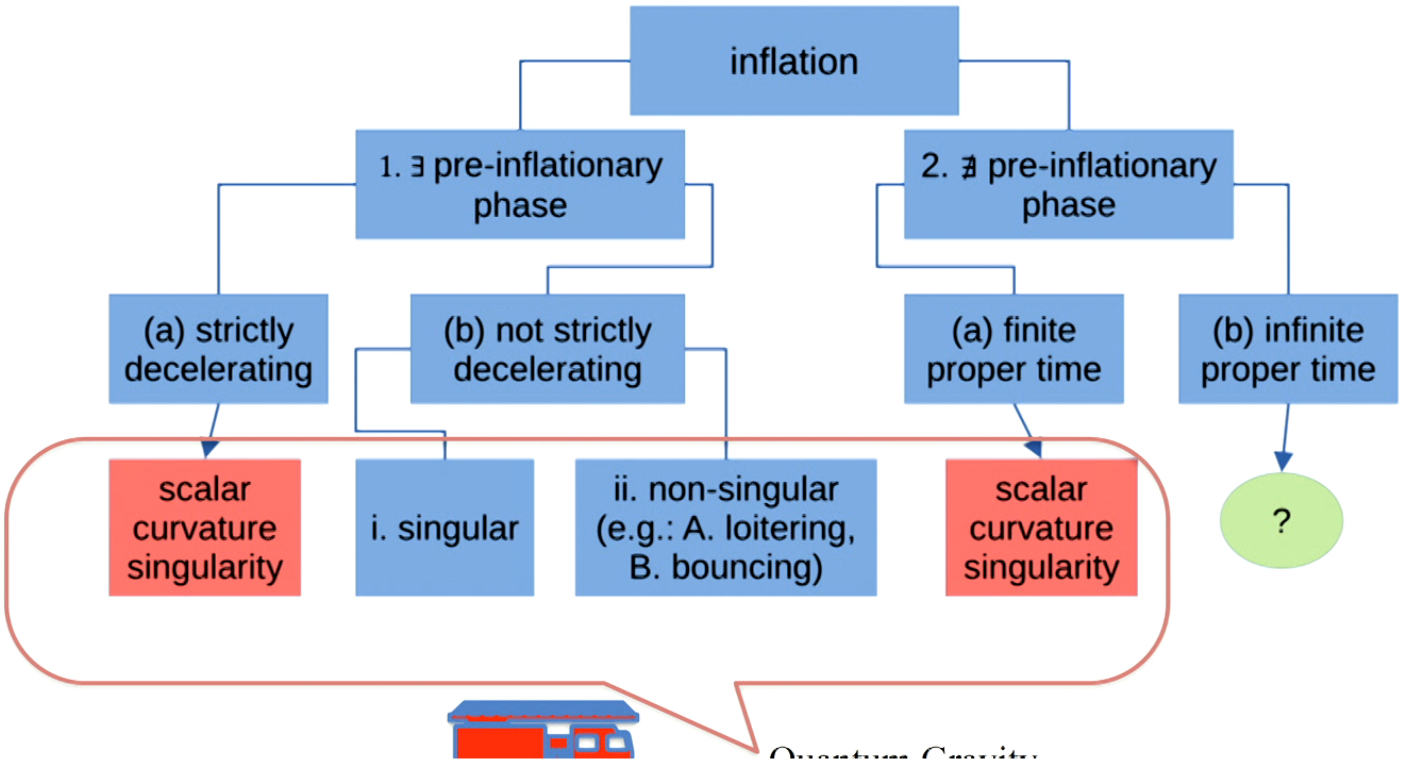




$$< \zeta(\mathbf{x})\zeta(\mathbf{x}+\mathbf{r}) > \quad \longleftrightarrow \quad \mathcal{P}_k^{\zeta} \equiv |\,\zeta_k\,|^2\, k^3 \quad \longleftrightarrow \quad k^{-1}|\delta\rho_k^2|$$

Are we really testing predictions of quantum field theory in expanding back ground?
Hawking Radiation? Unruh effect? (Robert)

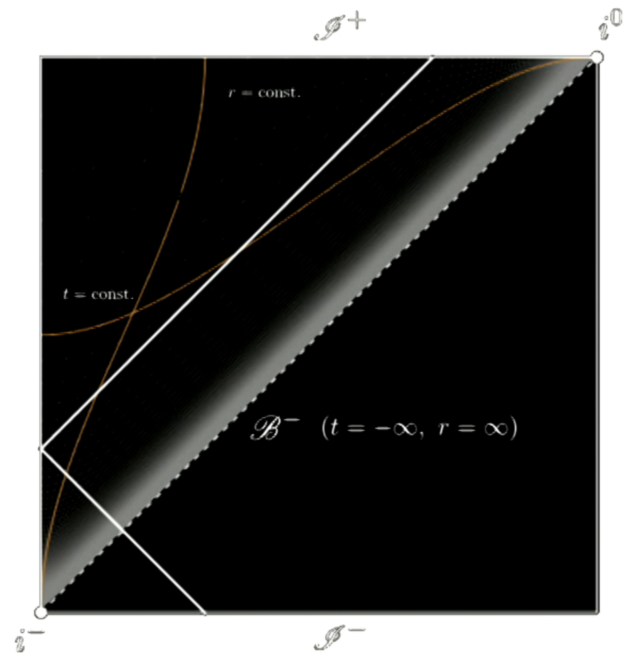
# Does inflation address Big Bang Singularity?

GG, E. Ling, J. Quintin 2023



Derived asymptotic conditions on the extendibility of Inflationary backgrounds in the past.
Used geometrical method to prove that spacetime close enough to dS in the asymptotic past are continuously extendible.

However …




**Proposition (G.G., E. Ling, J. Quintin '23)**

*Under appropriate assumptions of the scale factor, a $k = 0$ FLRW spacetime is past-asymptotically de Sitter if and only if*

$$\rho(-\infty) = -p(-\infty).$$

$\Lambda$ appears as an initial condition 😰

# Puzzles in Quantum Gravity Landscape

## Panel: Beyond QFT approaches to Quantum Gravity

*Mairi Sakellariadou*

KING'S College LONDON

# Strong affinities between

# Cosmology

# and

# Quantum Gravity

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## Fundamental questions in cosmology:

- Origin of an early-time exponential expansion (*scalar field inflation vs alternatives*)
- Origin of late-time accelerated expansion (*dark energy*)
- Origin of cosmological perturbations (*inflaton field / bounce models / quantum fluctuations of geometry*)
- Origin of dark matter
- Emergence of space and time (*standard cosmology: Universe emerged from a singularity*)
- Explanation of spacetime dimensionality

Two types of approaches:

- **Bottom-up** (driven by data) models of gravity **not** embedded in a fundamental theory

  e.g., f(R)

- **Top-down** (fundamental) models

  e.g., - flux-compactification models of inflation in string cosmology
  - bouncing cosmological scenario of LQC
  - early-time exponential expansion of GFC

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**Cosmology:** test of **Quantum theory of Gravity** (*quantum theory of ST geometry*)

Tool: **GWs**

**GW generation** (via a waveform analysis), **propagation** (via a modified dispersion relation, birefringence, amplitude damping), **polarisation,** and **remnant properties**

e.g., - Dvali-Gabadadze-Porrati models of DE with small transition steepness ruled out from GW170817

- GFT, SF, LQC could generate a signal detectable with standard sirens

- QG theories where spectral dim of ST changes with probed scale, brane-world models, Horndeski theories and their extensions (DHOST) lead to f-dependent speed of graviton : LISA

## Strong affinities between Cosmology and Quantum Gravity

***But one should keep in mind that a "correct" theory of QG must not only be a consistent theory, but it must also explain the Universe in which we live, i.e. the theory must have some predictability and in agreement with***

- **ST metric is Lorentzian and not Euclidean**
- **ST is not AdS** ($\Lambda$ must be non-negative)
- **ST dimensionality is 4**

DIAS

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# Cosmological Puzzles

## Puzzles in the Quantum Gravity Landscape

### Perimeter Institute

Science Foundation Ireland sfi For what's next

YASAMAN K. YAZDI

OCTOBER 25, 2023

IRISH RESEARCH COUNCIL
An Chomhairle um Thaighde in Éirinn

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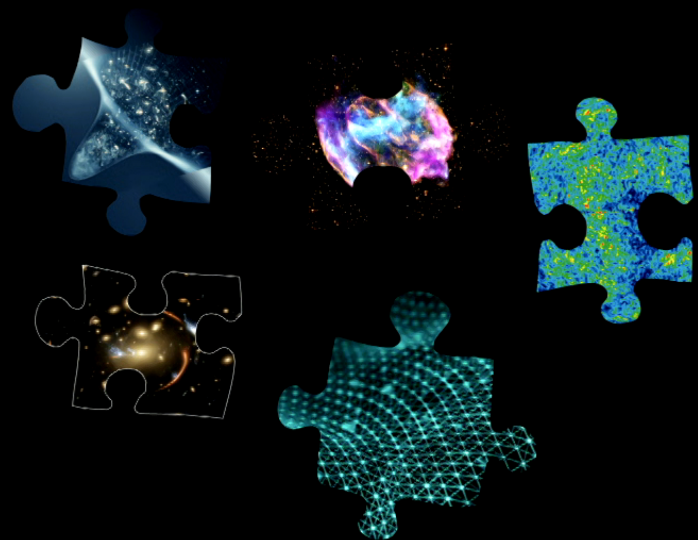
## Where do you see progress as most likely and/or imminent in understanding the quantum aspects of cosmology? Why?

- A model that fits all current high precision cosmological data. Resolution of tensions.
- New signatures/predictions that we can look for in current or future experiments/observations.
- A narrative for what we see in the universe that is well motivated and plausible.

# Progress: a narrative for what we see in the universe that is well motivated and plausible.



- Focus on cosmological questions in approaches to quantum gravity.
- Focus less on the number of parameters and quantitative aspects (to a degree) of new models. Focus more on the motivations behind an idea

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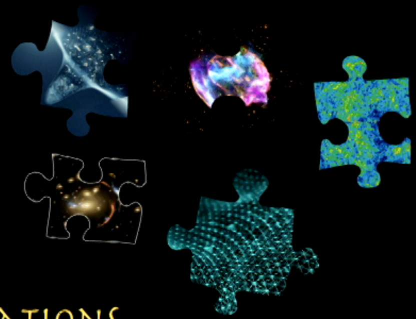
## How should we focus our intellectual and/or experimental/observational resources to address our puzzles in quantum cosmology?



- ALTERNATE/INTERPLAY BETWEEN THEORY AND OBSERVATIONS.
- THEORISTS AND OBSERVATIONAL COSMOLOGISTS SHOULD TALK TO EACH OTHER MORE.

**Progress: a narrative for what we see in the universe that is well motivated and plausible.**

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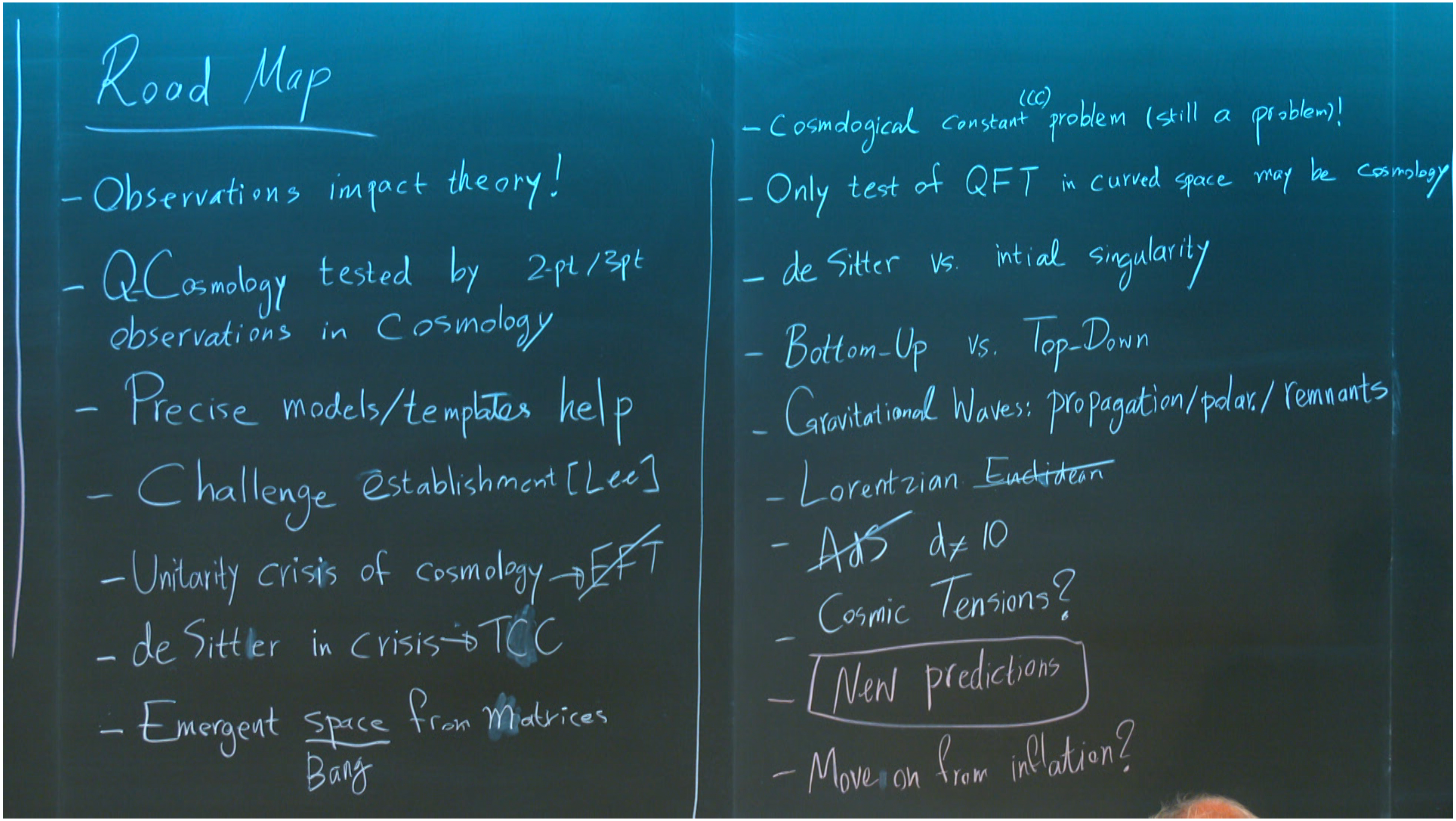
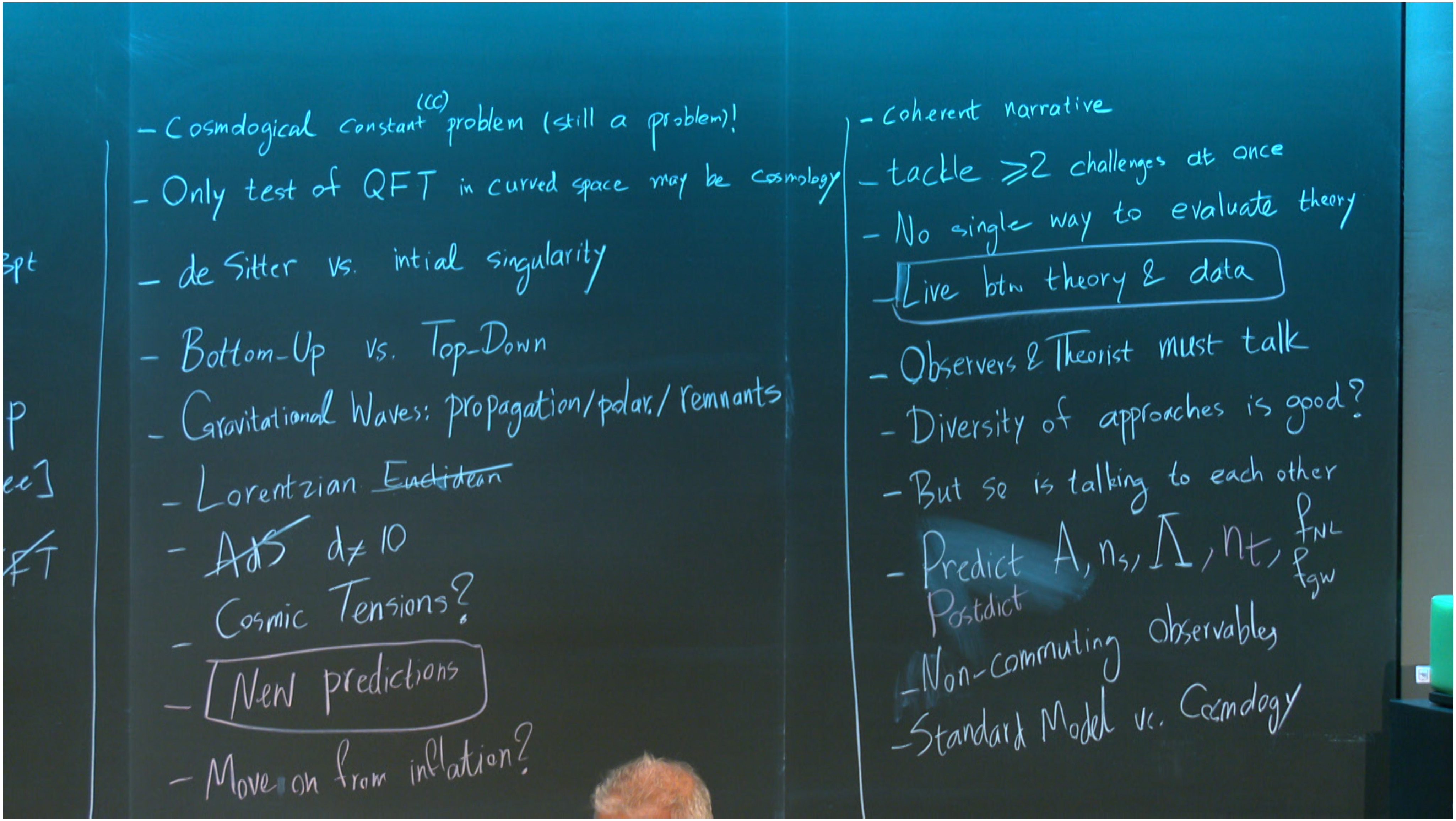
## Where do you see as promising areas of collaboration or synergy amongst different approaches?

- DIFFERENT APPROACHES TO QUANTUM GRAVITY START FROM DIFFERENT PRINCIPLES.
- WE DON'T NECESSARILY NEED TO COLLABORATE OR COMBINE TECHNIQUES FROM DIFFERENT APPROACHES.
- BUT WE DO NEED TO TALK TO EACH OTHER MORE. BE CRITICAL BUT ALSO TAKE INITIATIVE TO GIVE POSITIVE AND CONSTRUCTIVE FEEDBACK TO OTHER APPROACHES.

**Progress: a narrative for what we see in the universe that is well motivated and plausible.**


Road Map
- Observations impact theory!
- QCosmology tested by 2-pt/3pt observations in Cosmology
- Precise models/templates help
- Challenge establishment [Lee]
- Unitarity crisis of cosmology → EFT
- de Sitter in crisis → TCC
- Emergent Space from Matrices
Bang
- Cosmological constant (CC) problem (still a problem)!
- Only test of QFT in curved space may be cosmology
- de Sitter vs. intial singularity
- Bottom-Up vs. Top-Down
- Gravitational Waves: propagation/polar./remnants
- Lorentzian Euclidean
- AdS d≠10
- Cosmic Tensions?
- New predictions
- Move on from inflation?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- Cosmic Tensions?
- New predictions
- Move on from inflation?
- coherent narrative
- tackle ≳2 challenges at once
- No single way to evaluate theory
- Live btw theory & data
- Observers & Theorist must talk
- Diversity of approaches is good?
- But so is talking to each other
- Predict A, n_s, Λ, n_t, f_NL, f_gw
Postdict
- Non-commuting observables
- Standard Model vs. Cosmology