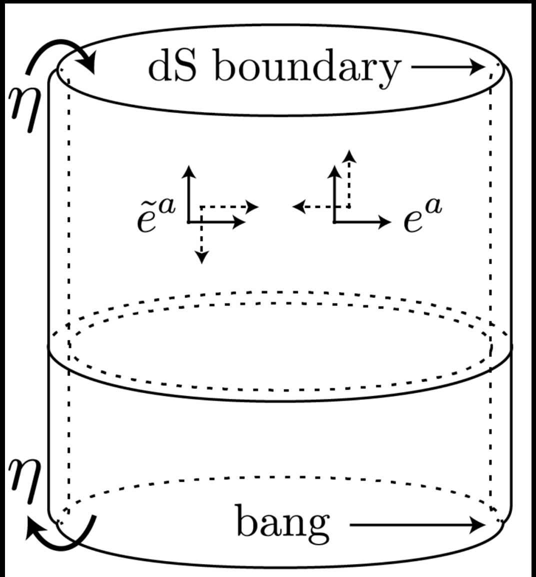
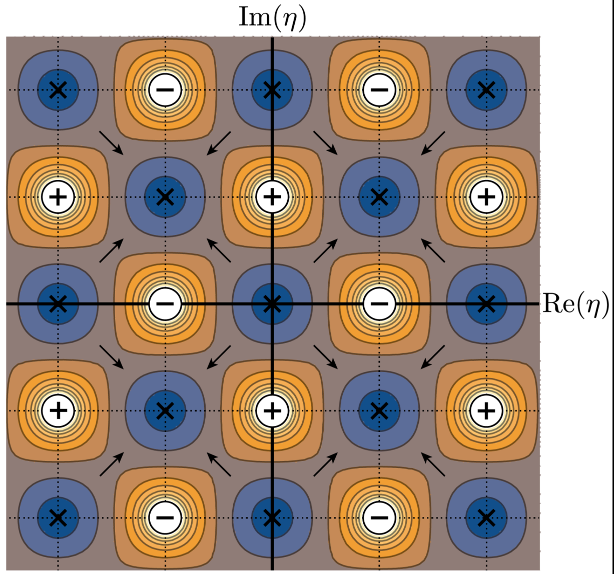
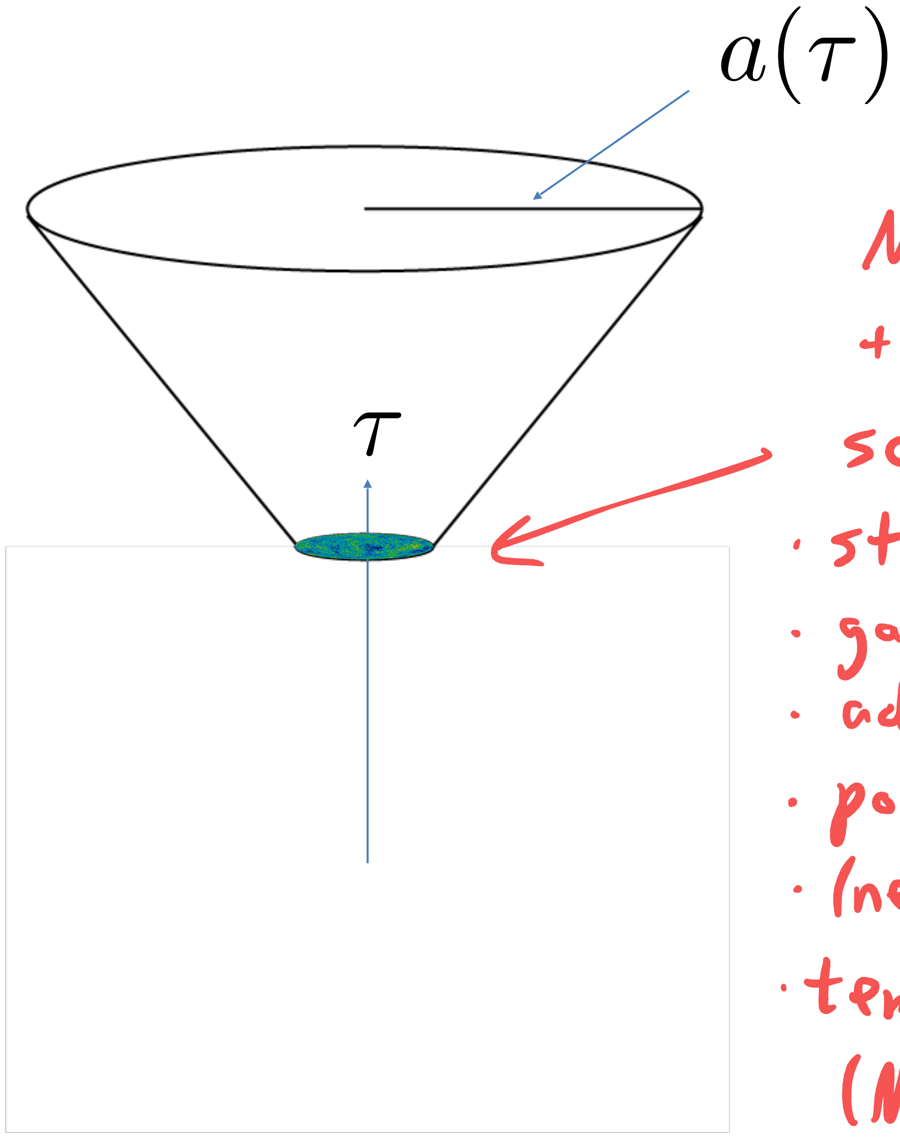
What is the simplicity of the early universe trying to tell us?



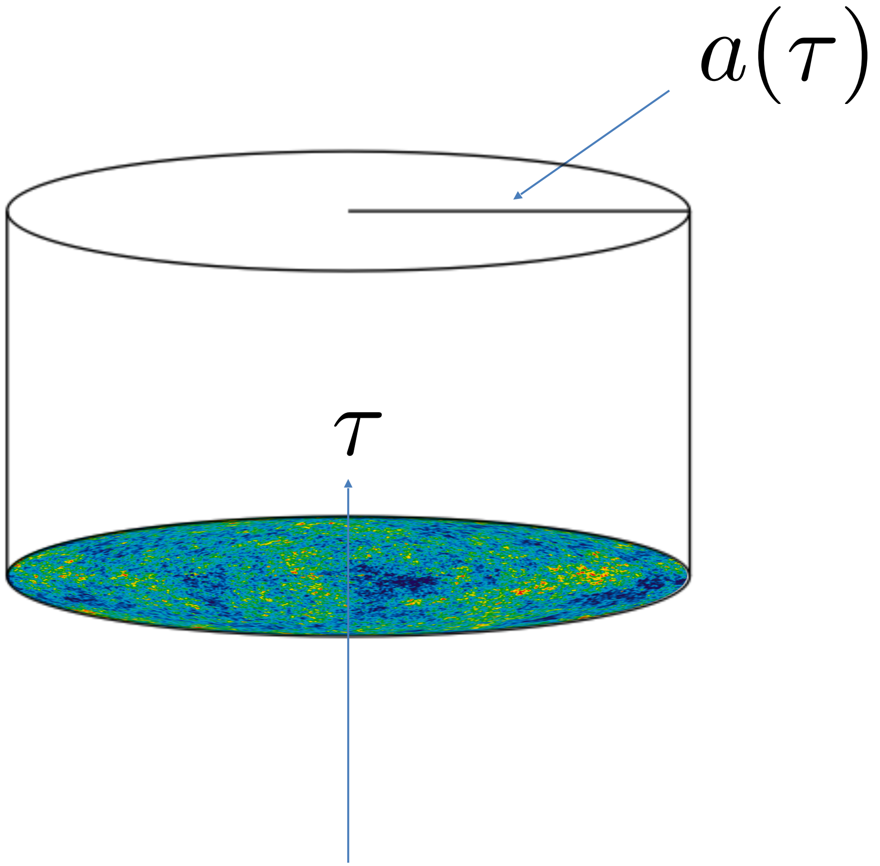
Latham Boyle
Perimeter Institute



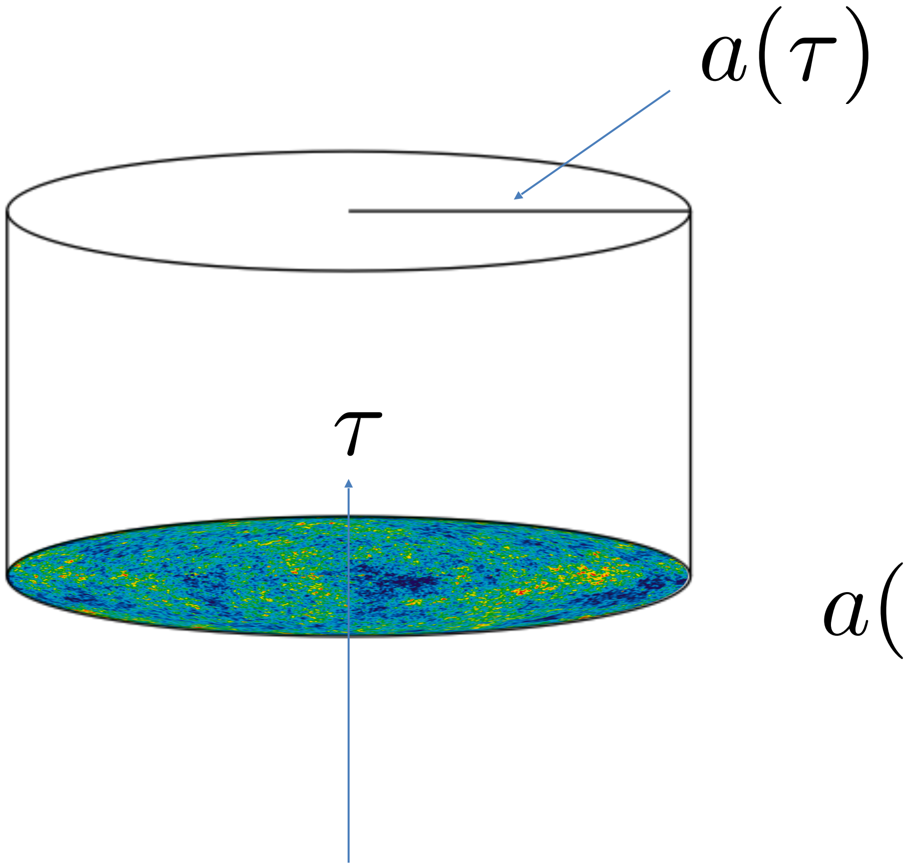
1) LB, K. Finn and N. Turok, *CPT-Symmetric Universe* arXiv:1803.08928 (Phys. Rev. Lett.)
2) LB, K. Finn and N. Turok, *The Big Bang, CPT, and neutrino dark matter* arXiv:1803.08930 (Ann. Phys.)
3) LB and N. Turok, *Two-Sheeted Universe, Analyticity & Arrow of Time*, arXiv:2109.06204
4) LB and N. Turok, *Cancelling the Vacuum Energy and Weyl Anomaly in the Standard Model with Dimension-Zero Scalar Fields*, arXiv:2110.06258
5) N. Turok and LB, *Gravitational entropy and the flatness, homogeneity and isotropy puzzles, arXiv:2201.07279*
6) LB and N. Turok, *Thermodynamic solution to the homogeneity, isotropy and flatness puzzles (and a clue to the cosmological constant)*, arXiv:2210.01142



Maximally symmetric
+ tiny (10^{-5}) random
scalar (density) perts:
· statistically symmetric,
· gaussian,
· adiabatic,
· power law,
· (nearly) scale invariant,
· temporally synchronized
(Neumann b.c.'s for ζ
at the bang)



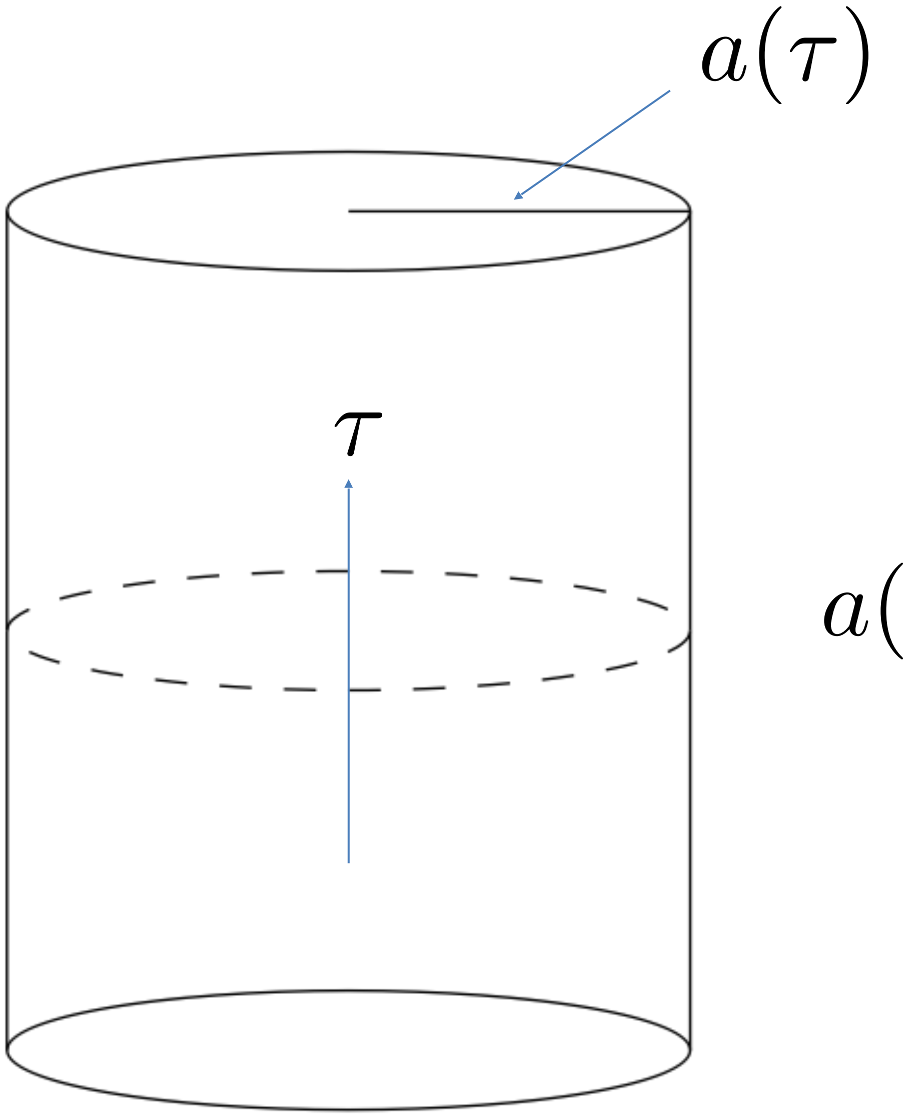
$a(\tau)$
τ



$$g_{\mu\nu} = a^2(\tau)\eta_{\mu\nu}$$

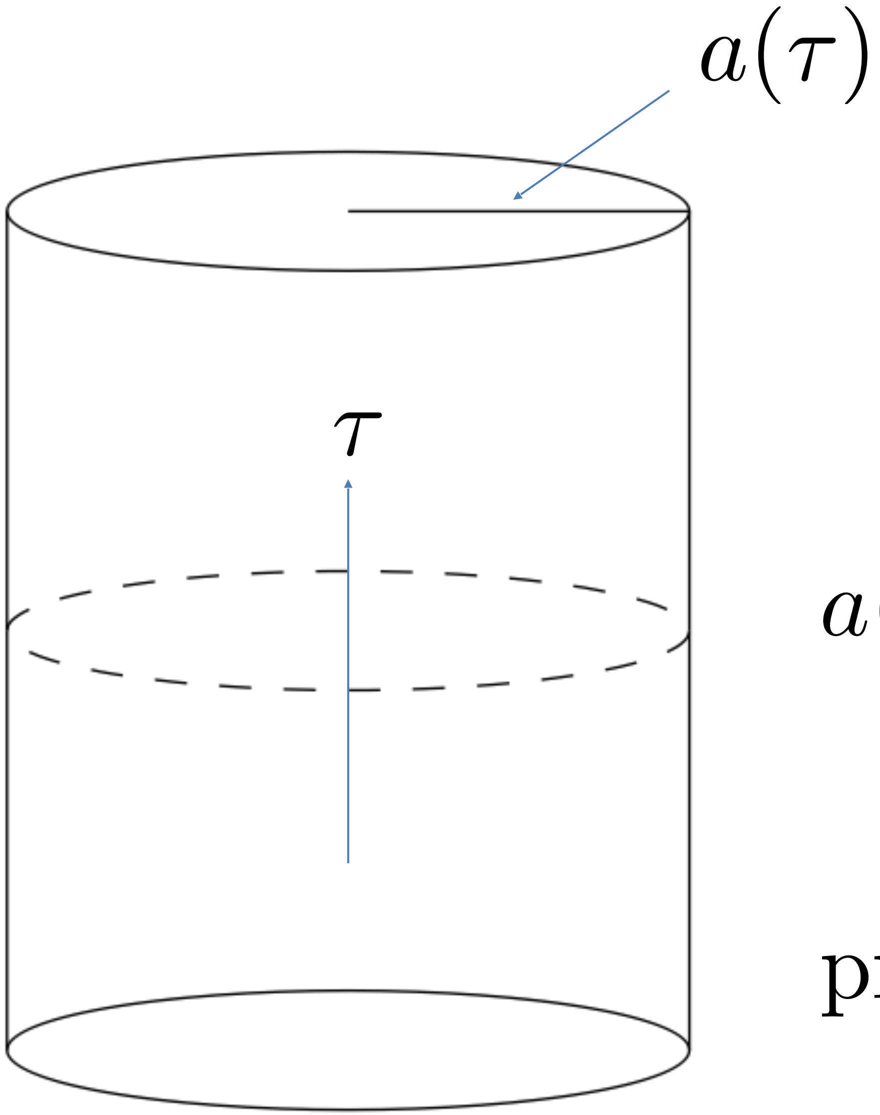
$$a(\tau) \propto \tau$$

$$g_{\mu\nu} = a^2(\tau)\eta_{\mu\nu}$$



$$a(\tau) \propto \tau$$

$$g_{\mu\nu} = a^2(\tau)\eta_{\mu\nu}$$



$$a(\tau) \propto \tau$$

new isometry:

$$\tau \to -\tau$$

preferred vacuum:

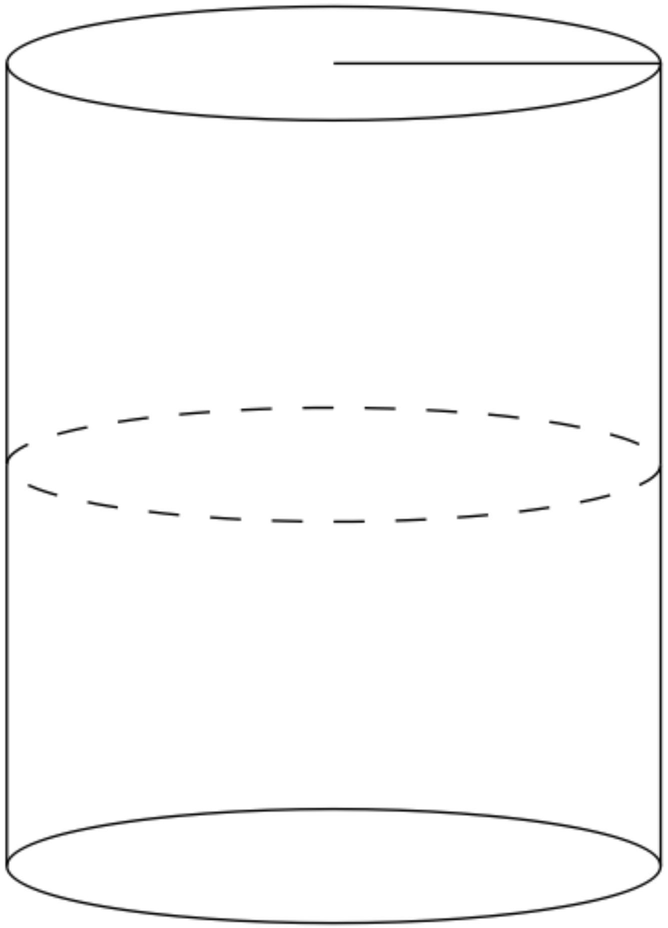
$$|0_{CPT}\rangle$$

hypothesis:

the universe does not spontaneously violate CPT

$$\psi(x) = \sum_h \int \frac{d^3\mathbf{p}}{(2\pi)^{3/2}} \left[a(\mathbf{p},h)\psi(\mathbf{p},h,x) + b^\dagger(\mathbf{p},h)\psi^c(\mathbf{p},h,x)\right]$$

$\psi_+(\mathbf{p},h,x)$ $\qquad$ $a_+, b_+ \;\Rightarrow\; |0_+\rangle$



$\psi_0(\mathbf{p},h,x)$ $\qquad$ $a_0, b_0 \;\Rightarrow\; |0_0\rangle$

$\Big(\; (\psi_0(\tau) \sim \psi_0^c(-\tau) \; \Big)$

$\psi_-(\mathbf{p},h,x)$ $\qquad$ $a_-, b_- \;\Rightarrow\; |0_-\rangle$

the standard model

$$G_\mu, W_\mu, B_\mu, h$$

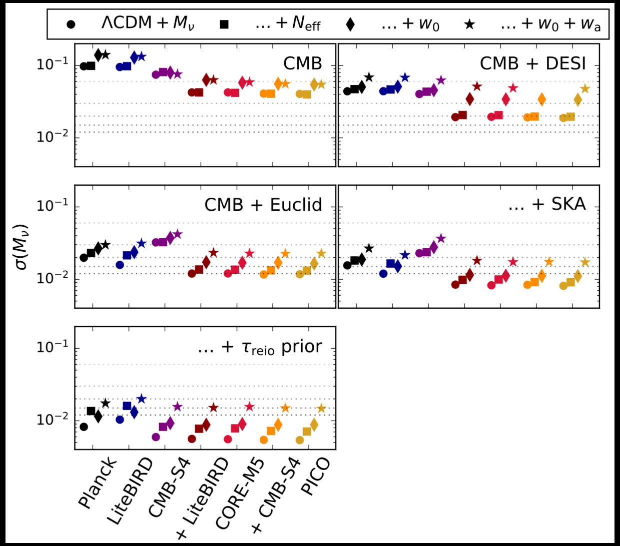
$$\left.\begin{matrix} d_L, u_L, d_R, u_R \\ d_L, u_L, d_R, u_R \\ d_L, u_L, d_R, u_R \\ e_L, \nu_L, e_R, \nu_R \end{matrix}\right\} \times 3$$

Prediction 0: dark matter neutrino is 4.8 x 10^8 GeV.

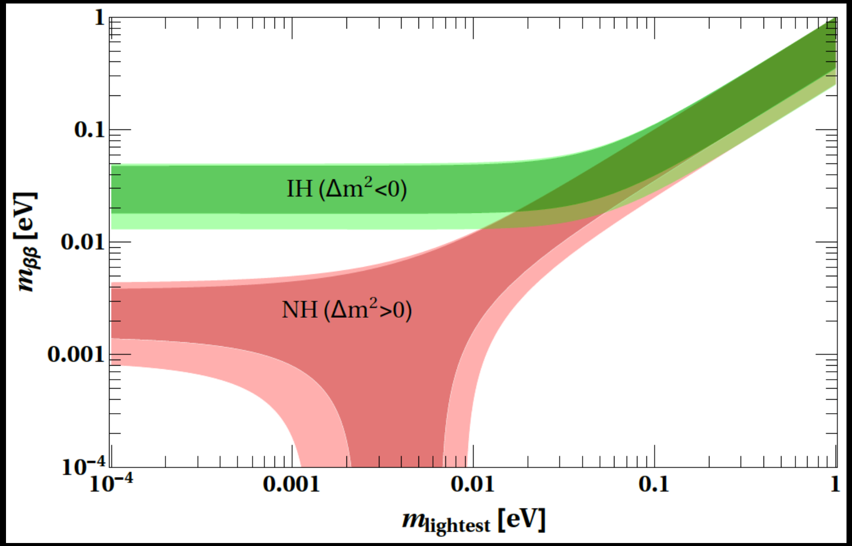
Prediction 1: one neutrino is massless

$$\sum m_\nu \approx .06 eV(NH) \text{ or } .12 eV(IH)$$

$0\nu\beta\beta$ decay:



(Brinckmann et al, arXiv:1808.05955)

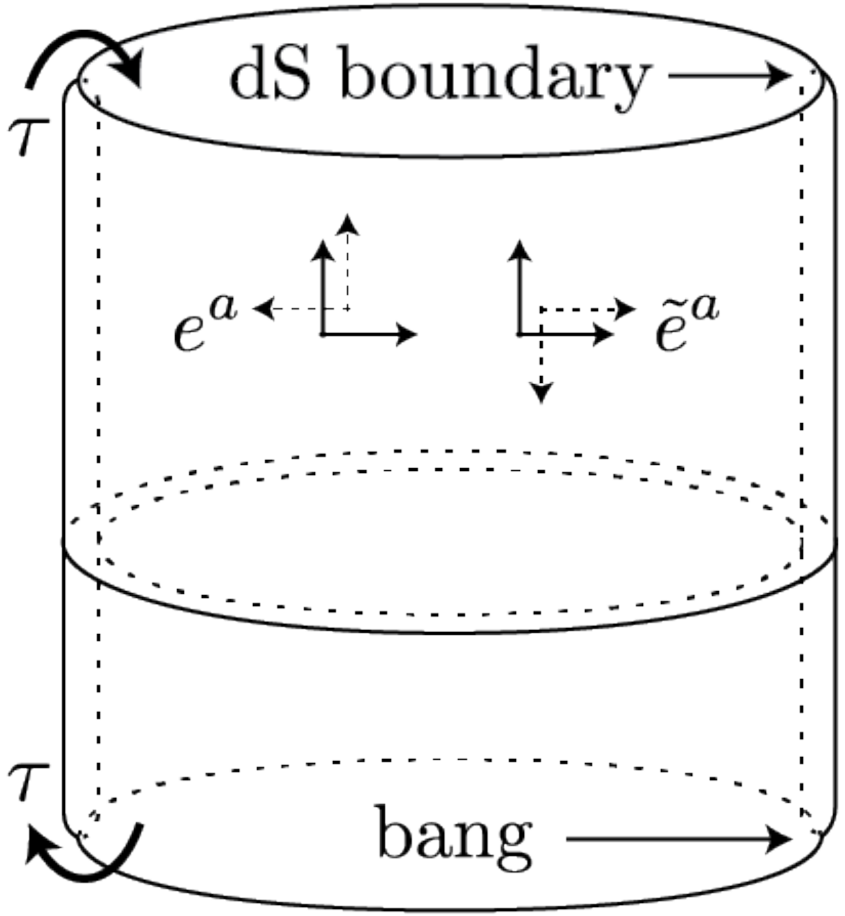


(Dell'Oro et al, arXiv:1601.07512)

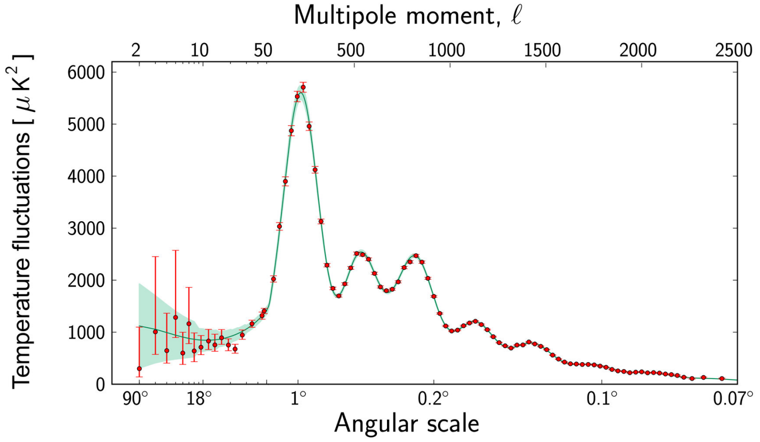
Prediction 2: dark matter is cold

Prediction 3: no primordial gravitational waves

Consider fields on this 2-sheeted spacetime



- solns respecting background symmetry
- analytic at the bang $\Rightarrow$ reflecting b.c.
- $\Rightarrow$ no primordial vector perturbations
- $\Rightarrow$ Neumann b.c.'s for scalar perturbation ζ
- essential singularity at dS boundary $\Rightarrow$ no b.c.
- $\Rightarrow$ thermodynamic arrow of time



The gravitational entropy of the universe: LB and N. Turok, arXiv:2210.01142

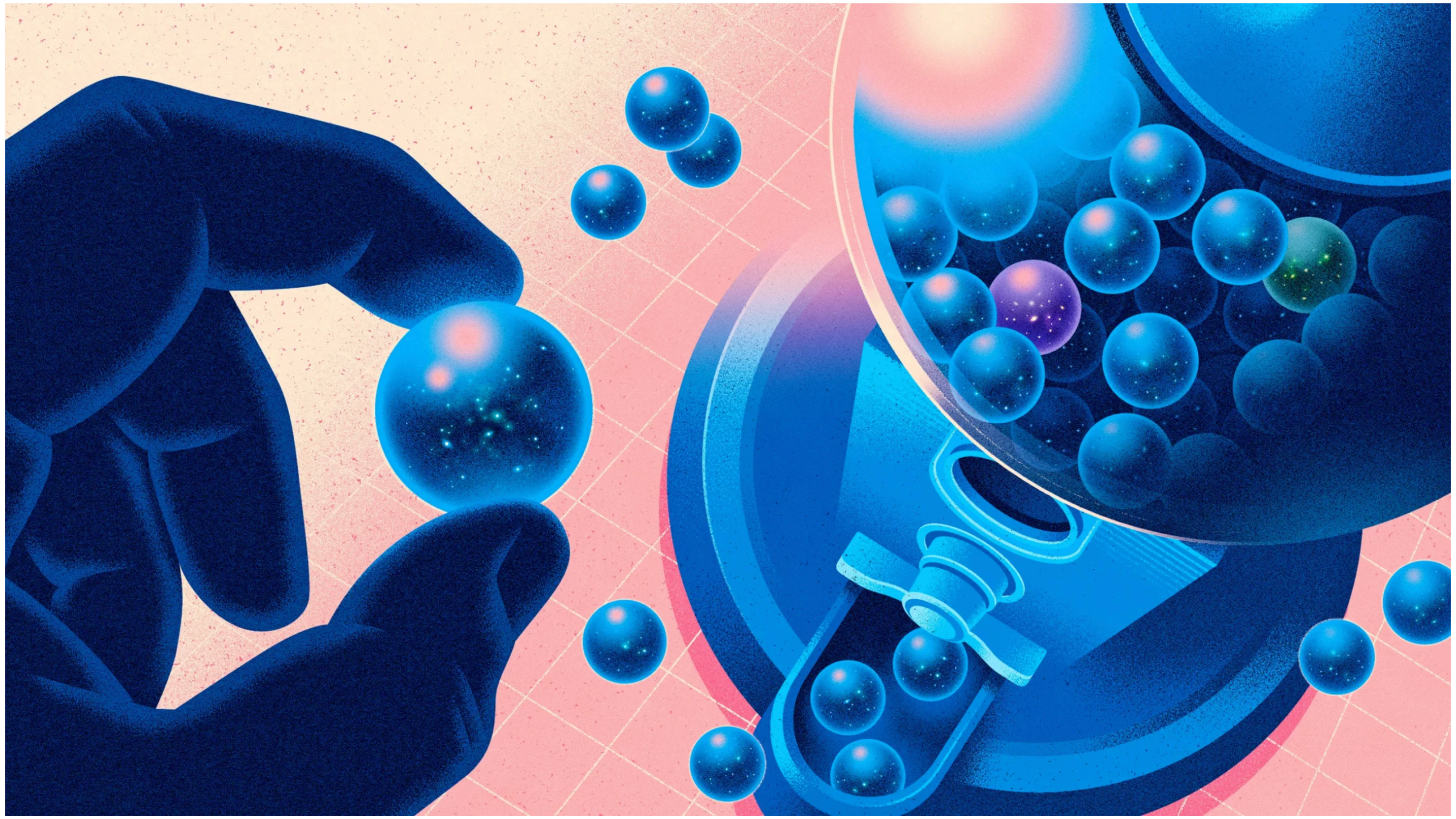
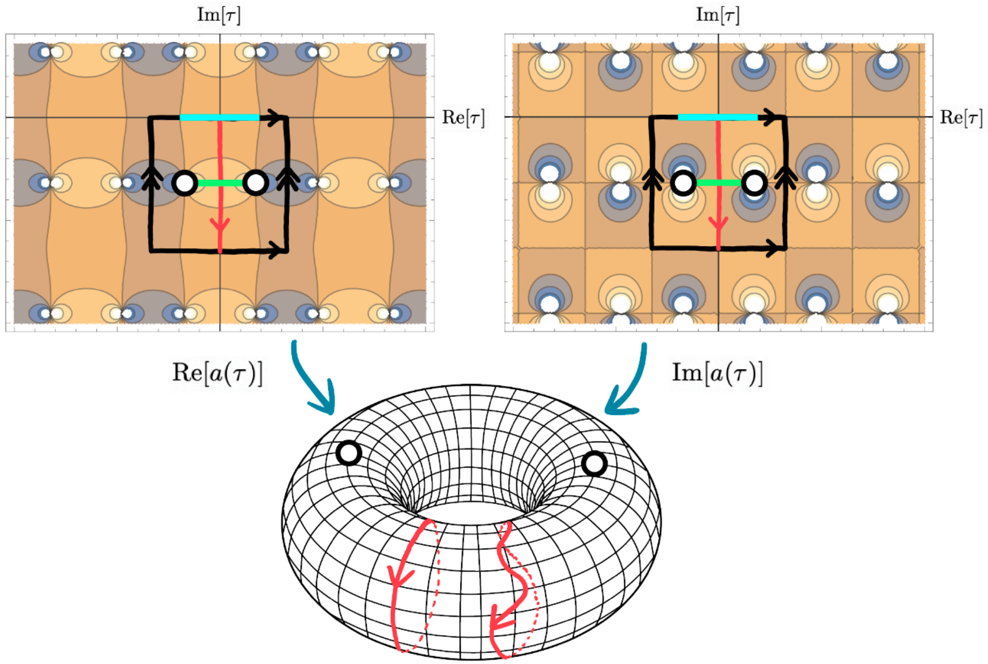


Image Credit: Quanta Magazine

Step 1. Obtain general solution for the cosmic scale factor:

$$H^2 = \frac{8\pi G}{3}\left(\frac{r}{a^4} + \frac{\mu}{a^3} + \lambda\right) - \frac{\kappa}{a^2}$$



Step 2. Obtain general formula for the *gravitational* entropy of an FRW universe:

Flat universes and tiny positive Lambda are favoured!

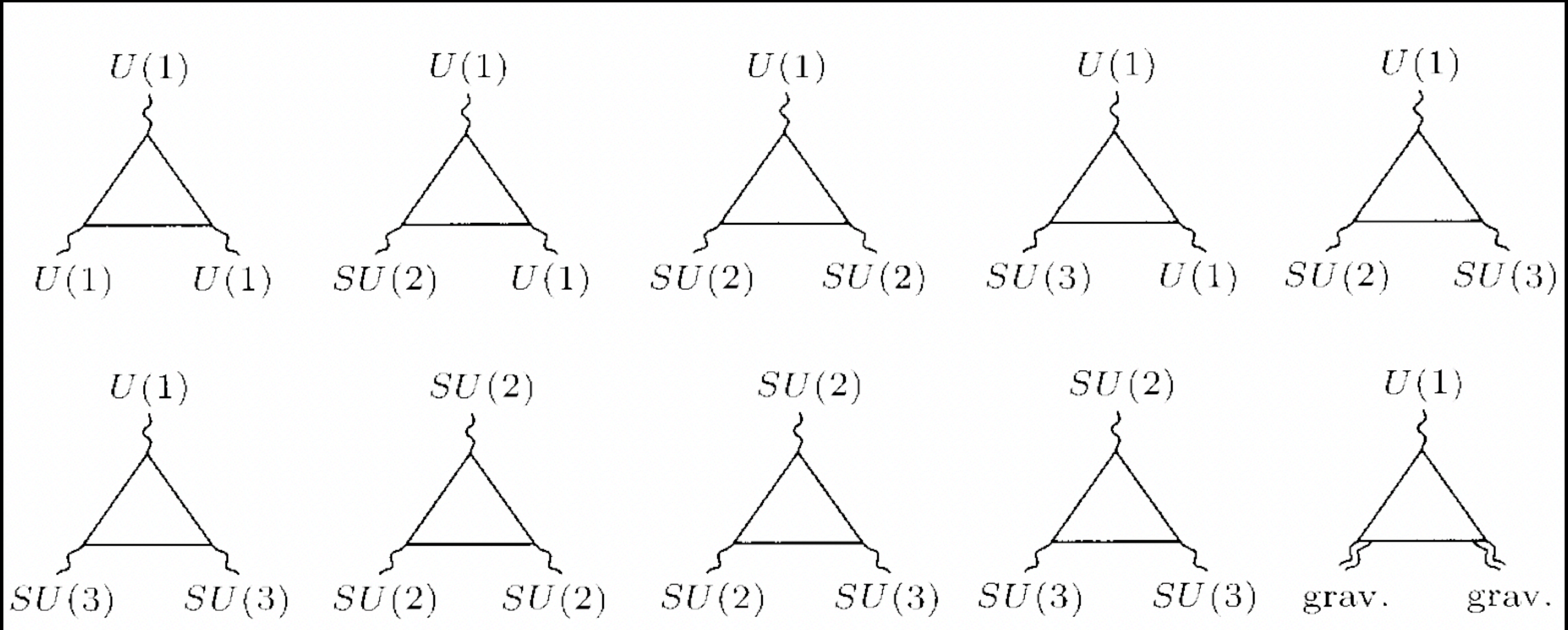
Step 3. Add cosmological perturbations (small inhomogeneities and isotropies):

If the Big Bang is a mirror, these *cost* entropy!

Grav. entropy is largest for universes like ours: homogeneous, isotropic and flat (with tiny positive Lambda)!

A measure on the space of universes.

In Standard Model, gauge and gravitational anomalies must cancel:



What about local scale ("Weyl") invariance?

- Emphasized by Weyl, Dirac, Dicke,…, 't Hooft:
  - Natural generalization of diff invariance (gen. covariance)
- Ignoring Higgs, Standard Model is *classically* Weyl invariant.
- But Weyl symmetry is anomalous:

$$\langle T^\mu_\mu \rangle = c\, C^2 - a\, E$$

Cancelling Weyl anomalies and Vacuum Energy?

$$a = \frac{1}{360(4\pi)^2}\left[\, n_0 + \frac{11}{2} n_{1/2} + 62 n_1 \qquad\qquad \right]$$

$$c = \frac{1}{120(4\pi)^2}\left[\, n_0 + 3\, n_{1/2} + 12 n_1 \qquad\qquad \right]$$

$$E_{\mathbf{k}} = \frac{\hbar\omega}{2}\left[\, n_0 - 2n_{1/2} + 2n_1 \qquad\qquad \right]$$

Cancelling Weyl anomalies and Vacuum Energy?

$$a = \frac{1}{360(4\pi)^2}\left[\, n_0 + \frac{11}{2} n_{1/2} + 62 n_1 - 28 n_0' \,\right]$$
$$c = \frac{1}{120(4\pi)^2}\left[\, n_0 + 3\, n_{1/2} + 12 n_1 - \, 8\, n_0' \,\right]$$

$$E_{\mathbf{k}} = \frac{\hbar\omega}{2}\left[\, n_0 - 2n_{1/2} + 2n_1 + 2n_0' \,\right]$$

$$S_4[\varphi] = \frac{1}{2}\int d^4x \sqrt{g}\, \varphi\, \Delta_4\, \varphi$$

$$\Delta_4 = \Box^2 + 2R^{\mu\nu}\nabla_\mu \nabla_\nu - \frac{2}{3} R\,\Box + \frac{1}{3}(\nabla^\mu R)\nabla_\mu$$

See Fradkin and Tseytlin, Nucl. Phys. B203 (1982), 157.

Cancelling Weyl anomalies and Vacuum Energy?

$$
\begin{aligned}
a &= \frac{1}{360(4\pi)^2}\left[\, n_0 + \frac{11}{2} n_{1/2} + 62 n_1 - 28 n_0' \,\right] \\
c &= \frac{1}{120(4\pi)^2}\left[\, n_0 + 3\, n_{1/2} + 12 n_1 - \ 8\, n_0' \,\right]
\end{aligned}
$$

$$E_{\mathbf{k}} = \frac{\hbar\omega}{2}\left[\, n_0 - 2n_{1/2} + 2n_1 + 2n_0' \,\right]$$

$$n_{1/2} = 4n_1, \quad n_0' = 3n_1, \quad n_0 = 0.$$

Matches standard model!

$$n_1 = 8 + 3 + 1 = 12$$

$$n_{1/2} = 3 \times 16 = 48$$

Dimension-zero scalars: notable features

$$\langle\varphi(t,\mathbf{x})\varphi(t,\mathbf{x}')\rangle = \int \frac{d^3k}{(2\pi)^3} \mathrm{e}^{i\mathbf{k}\cdot(\mathbf{x}-\mathbf{x}')} \frac{1}{4k^3}$$

Scale invariant!

No new local degrees of freedom.

See Bogoliubov, Logunov, Oksak & Todorov (1990) and V.O. Rivelles (2003).

Summary

Analytic extension of the cosmological solution of the Einstein equations leads to:

1) Big Bang as a mirror
2) formula for gravitational entropy

These ideas yield new explanations/predictions for various observed features of our universe, including:

1) dark matter
2) thermodynamic arrow of time
3) absence of tensor perts (gravitational wave)
4) absence of vector perts (vorticity)
5) Neumann initial conditions for scalar (density) perts
6) The homogeneity, isotropy and flatness (and smallness of Lambda)

Finally, we saw how (without introducing new d.o.f.) 36 dimension-zero scalars can:

1) cancel both Weyl anomalies and the vacuum energy
2) explain 3 generations
3) yield a scale invariant power spectrum (without inflation)

Much still to be understood!

References

CPT-Symmetric Universe and Dark Matter:

- LB, K. Finn, N. Turok, *CPT-Symmetric Universe* arXiv:1803.08928 (Phys. Rev. Lett.)
- LB, K. Finn, N. Turok, *The Big Bang, CPT, and neutrino dark matter* arXiv:1803.08930 (Ann. Phys.)

Big Bang as Mirror and the Arrow of Time:

- LB, N. Turok, *Two-Sheeted Universe, Analyticity & Arrow of Time,* arXiv:2109.06204

Gravitational Entropy:

- N. Turok, LB, *Gravitational entropy and the flatness, homogeneity and isotropy puzzles, arXiv:2201.07279*
- LB, N. Turok, *Thermodynamic solution to the homogeneity, isotropy and flatness puzzles (and a clue to the cosmological constant),* arXiv:2210.01142

Dimension-Zero Scalars:

- LB, N. Turok, *Cancelling the Vacuum Energy and Weyl Anomaly in the Standard Model with Dimension-Zero Scalar Fields*, arXiv:2110.06258

Penrose Tilings, Self-Similar Quasicrystals:

- LB, P. J. Steinhardt, *Self-Similar One-Dimensional Quasilattices* (Phys. Rev. B 2022)
- LB, P. J. Steinhardt, *Coxeter Pairs, Ammann Patterns and Penrose-like Tilings* (Phys. Rev. B 2022)
- LB, M. Dickens, F. Flicker, *Conformal Quasicrystals and Holography* (Phys. Rev. X 2020)
- LB, J. Kulp, *Holographic Foliations: Self-Similar Quasicrystals from Regular Hyperbolic Tessellations (in prep, 2022)*
- LB and Zhi Li, *Self-Similar Quasicrystals as Quantum Error Correcting Codes* (in prep, 2022)

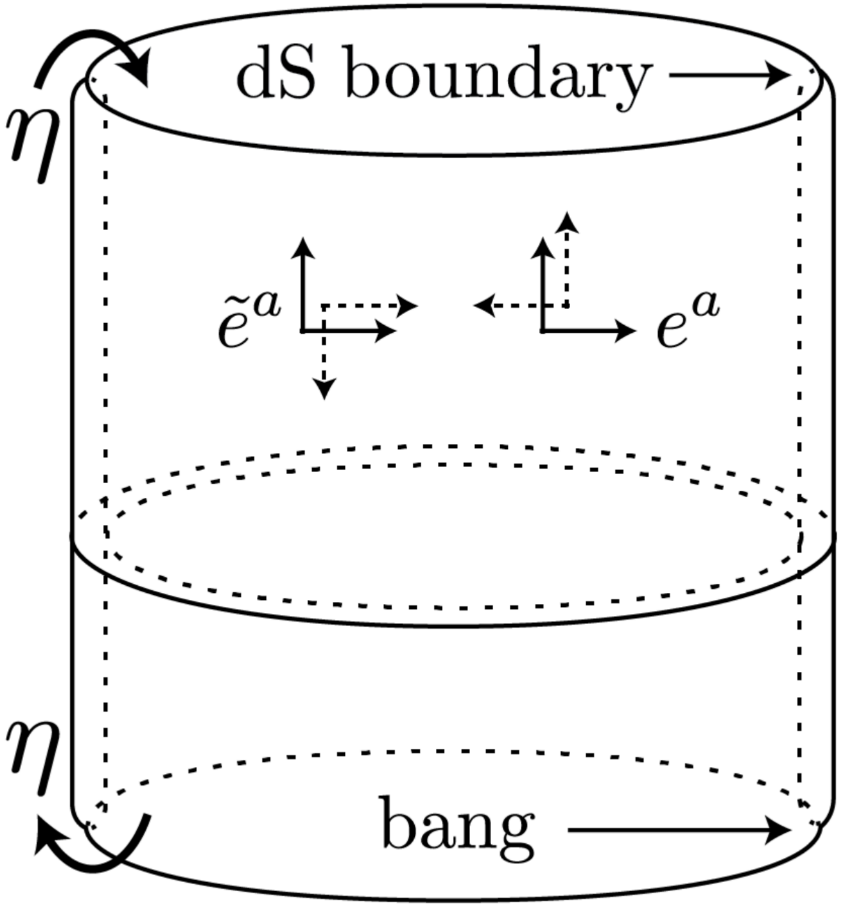
Thank you for listening!

$$\psi_0(\mathbf{p},h,x) = \alpha(\mathbf{p})\psi_+(\mathbf{p},h,x) + \beta(\mathbf{p})\psi_+^c(-\mathbf{p},h,x)$$

$$\langle 0_0 | a_+^\dagger(\mathbf{p},h) a_+(\mathbf{p},h) | 0_0 \rangle = |\beta(\mathbf{p})|^2 = e^{-\pi p^2 \frac{M_{\mathrm{pl}}}{m_{\mathrm{dm}}} \sqrt{\frac{3}{\rho_{\mathrm{rad}}}}}$$

Like Hawking Radiation

Reflecting b.c.'s at the Big Bang:



- Dirichlet (Neumann) b.c.'s for scalar field in static (expanding) frame. $\varphi(x)$
- Neumann (Dirichlet) b.c.'s for tetrad field in static (expanding) frame. $e^a_\mu(x)$
- Implications:
  - No primordial vector perturbations (vorticity)
  - No decaying-mode scalar perturbations (density perts)
  - No decaying-mode tensor perturbations (grav waves)

dark matter

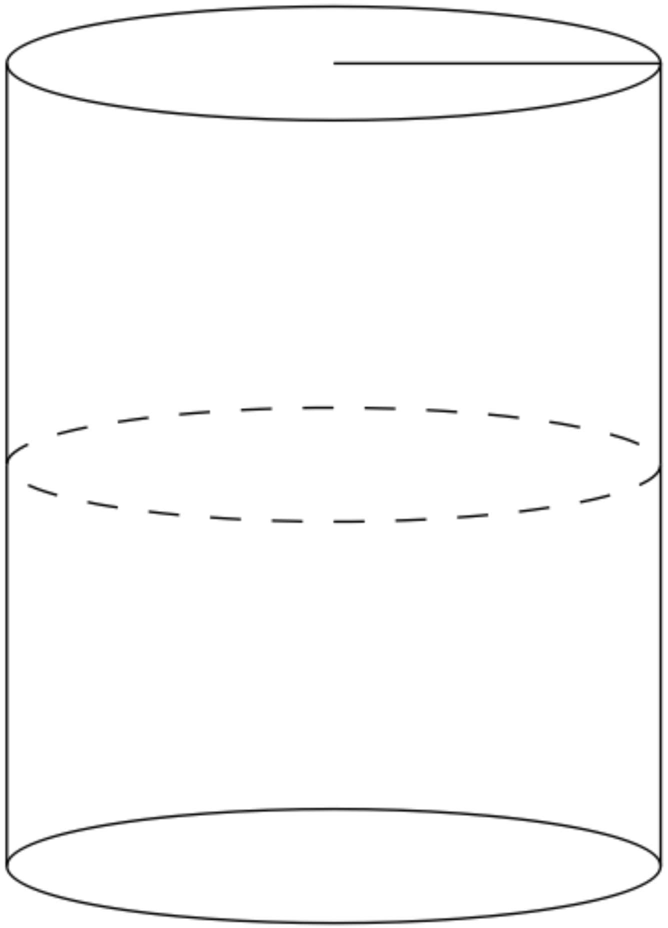
One stable neutrino: $\nu_R^{(1)}$ $\quad$ ($\mathbb{Z}_2$ symmetry: $\nu_R^{(1)} \to -\nu_R^{(1)}$)

$$\frac{n_{\rm dm}}{s_{\rm rad}} = C\left(\frac{m_{dm}}{M_{pl}}\right)^{3/2} \qquad (C = 0.003476...)$$

$$m_{dm} = 4.8 \times 10^8 \mathrm{GeV}$$

$$\psi(x) = \sum_h \int \frac{d^3\mathbf{p}}{(2\pi)^{3/2}} [a(\mathbf{p},h)\psi(\mathbf{p},h,x) + b^\dagger(\mathbf{p},h)\psi^c(\mathbf{p},h,x)]$$

$\psi_+(\mathbf{p},h,x)$ $\qquad$ $a_+, b_+ \;\Rightarrow\; |0_+\rangle$



$\psi_0(\mathbf{p},h,x)$ $\qquad$ $a_0, b_0 \;\Rightarrow\; |0_0\rangle$

$\Big(\; (\psi_0(\tau) \sim \psi_0^c(-\tau) \; \Big)$

$\psi_-(\mathbf{p},h,x)$ $\qquad$ $a_-, b_- \;\Rightarrow\; |0_-\rangle$

AdS Boundary Conditions (as rephrased by Hawking '83)

boundary conditions have been discussed by Breitenlohner and Freedman [6]. They formulated two sets of reflective boundary conditions which can be expressed as

$$2^s t^{AA'} t^{BB'} \dots t^{LL'} \varphi_{AB\dots L} = \pm \bar{\varphi}^{A'B'\dots L'} . \qquad (8)$$

In the case of spin zero, the boundary conditions were

$$\varphi = \pm\bar{\varphi} , \qquad t^{AA'} \nabla_{AA'} \varphi = \mp t^{BB'} \nabla_{BB'} \bar{\varphi} . \qquad (9)$$

When applied to the Bang, correspond to our CPT condition!

A $U/\bar{U}$ pair?

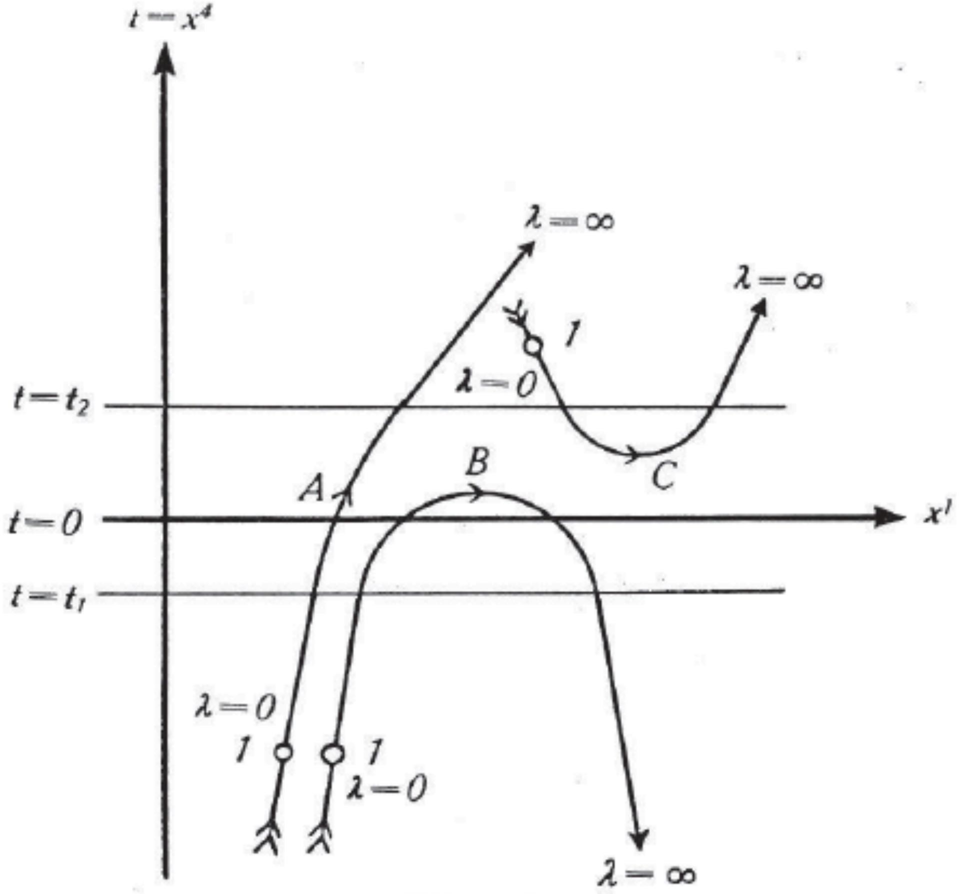
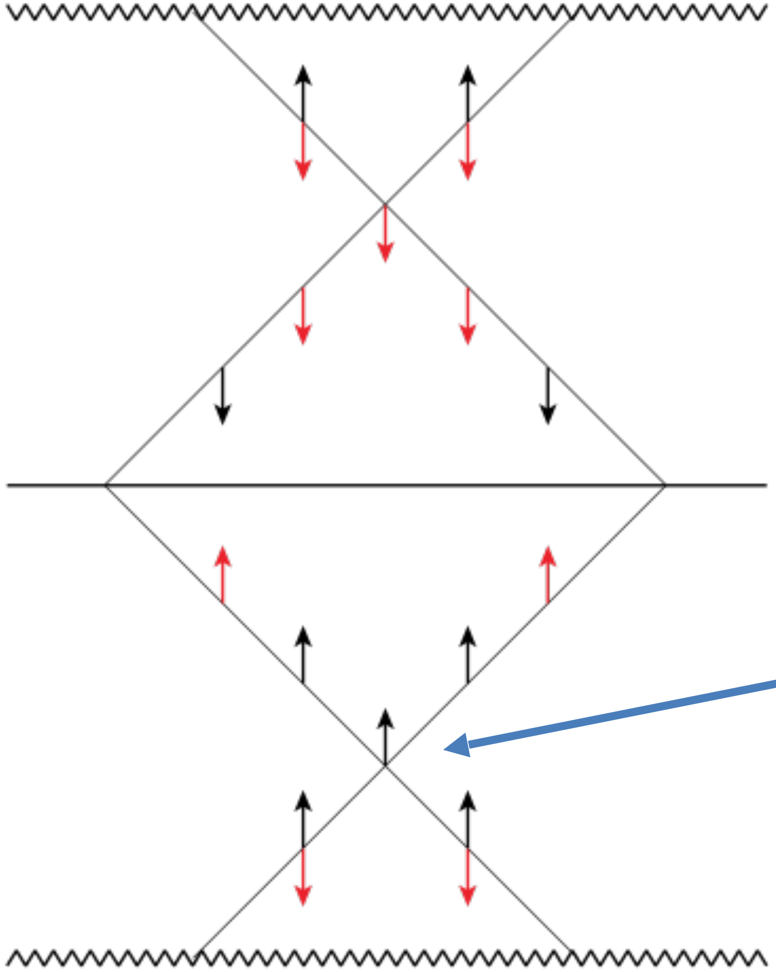


Fig. 1.

(Stueckelberg, 1941)

Electrodynamic Arrow of Time



Tetrode-Fokker-Wheeler-Feynman

$$S = -\sum_a m_a \int da + \sum_{a<b} e_a e_b \int\int da_\mu db^\mu \delta(ab_\nu ab^\nu)$$

F = (R + A)/2

+ (R – A)/2

Experimental confirmation?

L. Anchordoqui et al.
1803.11554

Upgoing ANITA events as evidence of the CPT symmetric universe

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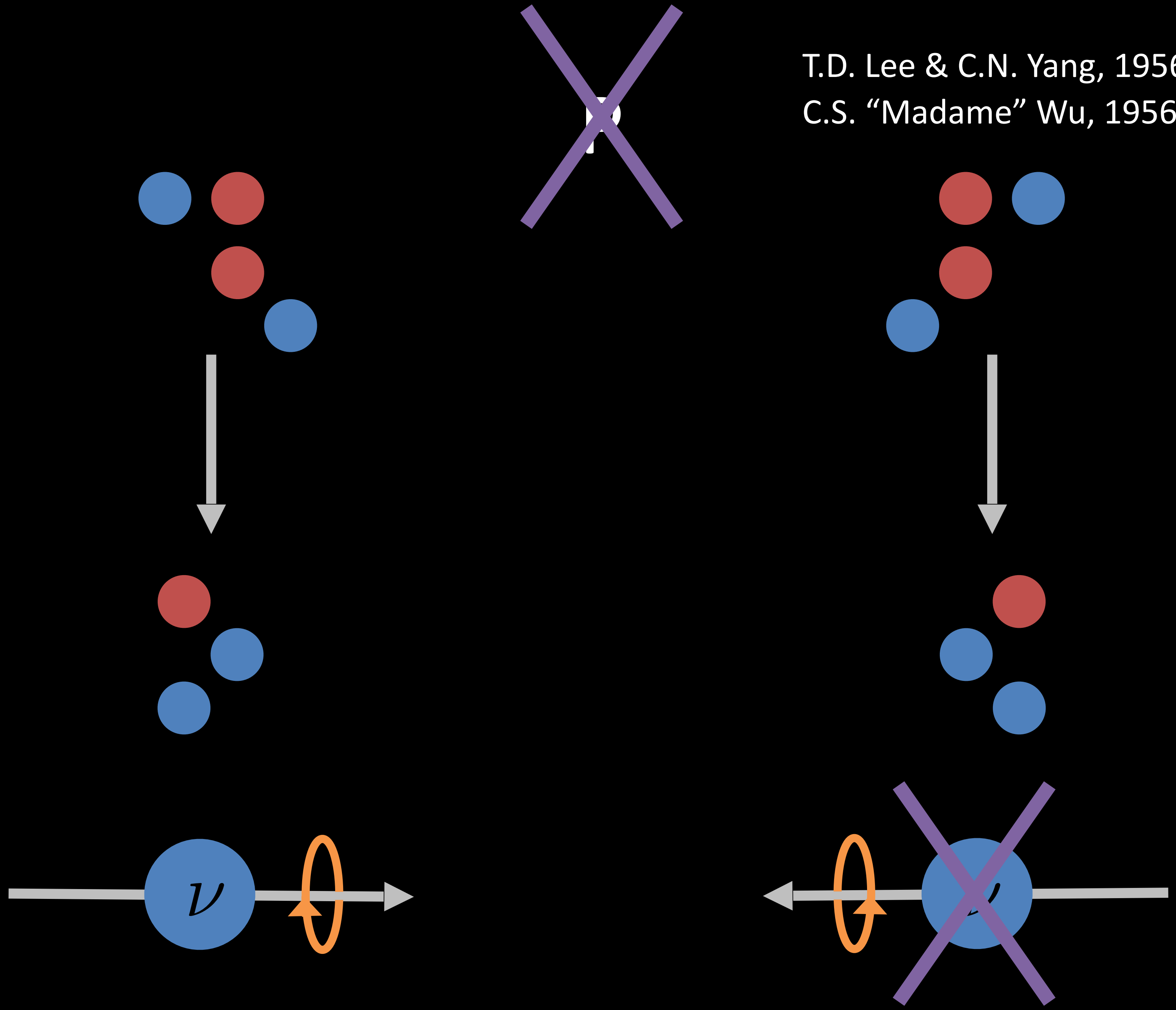
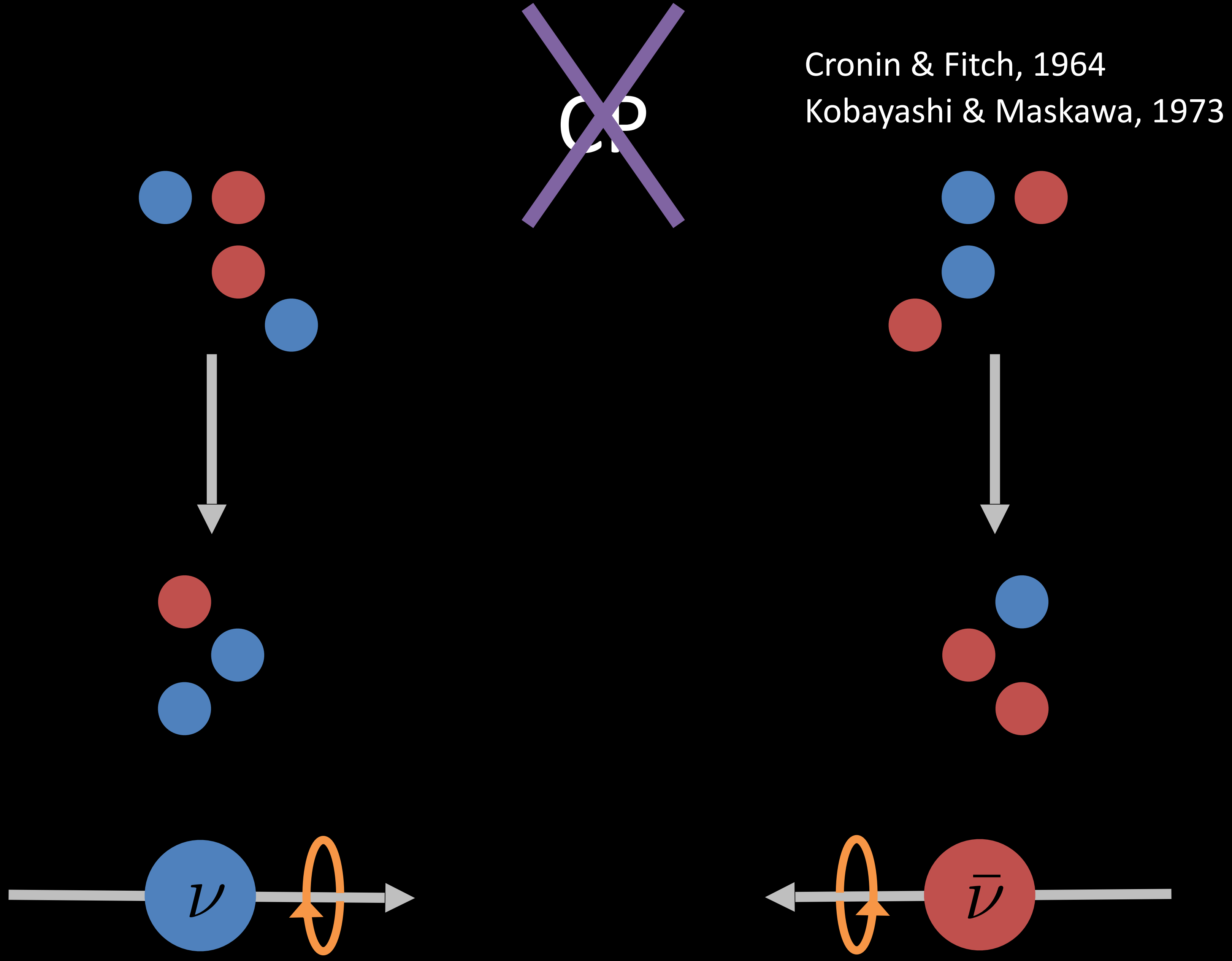
[2] *Department of Physics, Graduate Center, City University of New York, NY 10016, USA*
[3] *Department of Astrophysics, American Museum of Natural History, NY 10024, USA*
[4] *Department of Physics, University of Wisconsin, Madison, WI 53706, USA*
[5] *Department of Physics & Astronomy, University of Hawaii at Manoa, Honolulu, HI 96822, USA*
[6] *Department of Physics & Astronomy, Vanderbilt University, Nashville TN 37235, USA*

We explain the two upgoing ultra-high energy shower events observed by ANITA as arising from the decay in the Earth's interior of the quasi-stable dark matter candidate in the CPT symmetric universe. The dark matter particle is a 480 PeV right-handed neutrino that decays into a Higgs boson and a light Majorana neutrino. The latter interacts in the Earth's crust to produce a τ lepton that in turn initiates an atmospheric upgoing shower. The fact that both events emerge at the same angle from the Antarctic ice-cap suggests an atypical dark matter density distribution in the Earth.

T.D. Lee & C.N. Yang, 1956

C.S. “Madame” Wu, 1956

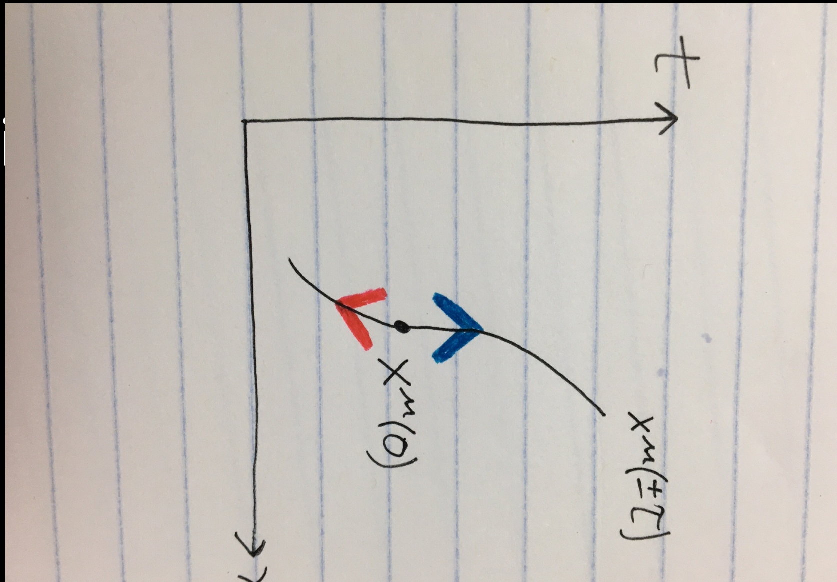



CP
Cronin & Fitch, 1964
Kobayashi & Maskawa, 1973
ν
ν̄

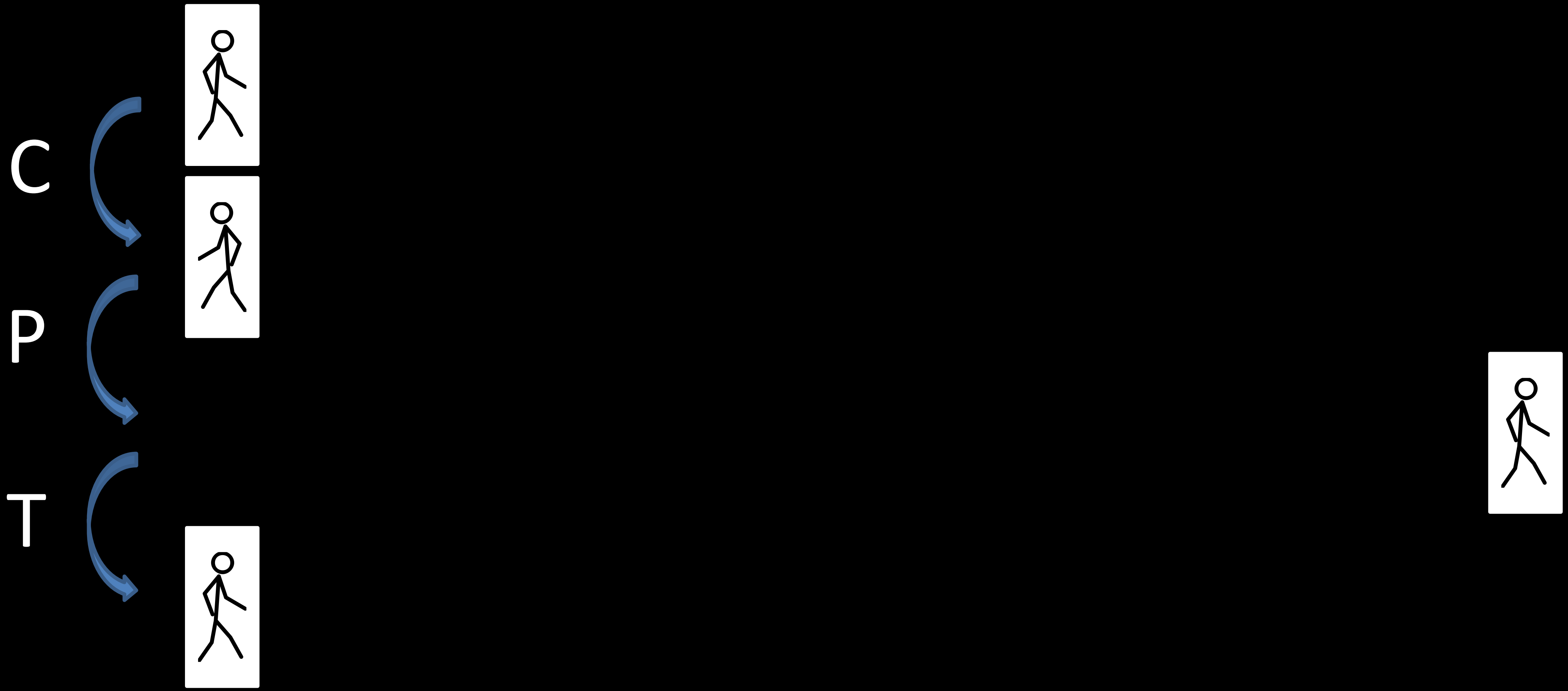
What is an anti-particle?

- Schrodinger:
  - relativistic wave equation → negative frequency solutions
- Dirac:
  - negative frequency solutions → antiparticles!
- Stueckelberg:
  - anti-particle → particle moving backward in ti

$$d\tau^2 = g_{\mu\nu} dx^\mu dx^\nu$$



CPT Thrm: Coleman’s “Proof By Locomotion”



CPT Thrm: another perspective

- P and T are not in SO(3,1):

$$P = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & -1 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & -1 \end{pmatrix} \qquad T = \begin{pmatrix} -1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

- But PT *is* in SO(3,1):

$$PT = \begin{pmatrix} -1 & 0 & 0 & 0 \\ 0 & -1 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & -1 \end{pmatrix} = \begin{pmatrix} \cosh i\pi & 0 & 0 & \sinh i\pi \\ 0 & \cos\pi & -\sin\pi & 0 \\ 0 & \sin\pi & \cos\pi & 0 \\ \sinh i\pi & 0 & 0 & \cosh i\pi \end{pmatrix}$$