KAVLI IPMU INSTITUTE FOR THE PHYSICS AND MATHEMATICS OF THE UNIVERSE

東京大学 THE UNIVERSITY OF TOKYO

Inflation and Particle Physics

LiteBIRD Kick-off Symposium @ ISAS, JAXA

Hitoshi Murayama (Berkeley, Kavli IPMU) July 1, 2019

BERKELEY CENTER FOR THEORETICAL PHYSICS

BERKELEY LAB

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Inflation for Pedestrians

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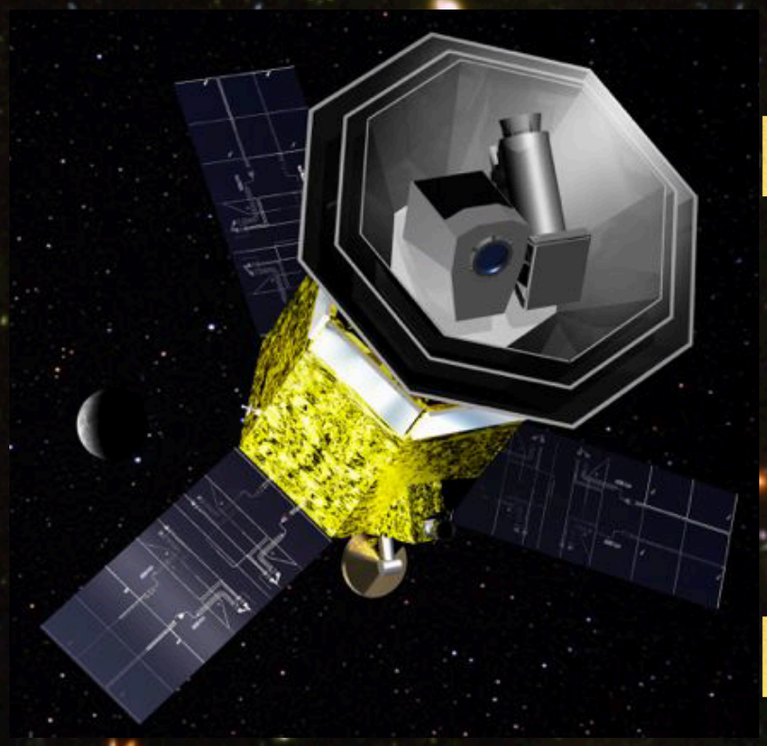
THE UNIVERSITY OF CALIFORNIA BERKELEY 1868 LET THERE BE LIGHT

BERKELEY CENTER FOR THEORETICAL PHYSICS

BERKELEY LAB



How did the Universe begin?

What is its fate?

What is it made of?

How does it work?

Where do we come from?

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DANIEL CARDLE 2003


Telescopes are
time machines

Andromeda
2.3 million light years

HSC team
Subaru
telescope

cluster of galaxies
2.1 billion light year

Abell 2218

Galaxy Cluster MACS J1149+2223

galaxy @ 13.3 billion light years

High-Redshift Galaxy MACS1149-JD

A Distant Gravitationally-Lensed Galaxy at Redshift = 9.6

Hubble Space Telescope • ACS • WFC3

NASA / ESA / STScI/ J. Hora (Harvard-Smitsonian CfA)

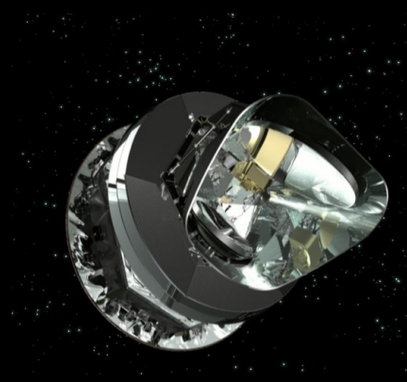
ssc2012-12a

Picture of the Big Bang

Temperature variation ~ 1/100,000

Planck Legacy Release 2018

ESA and the Planck Collaboration



History of the Universe

The Hot Big Bang

Inflation

string theory?

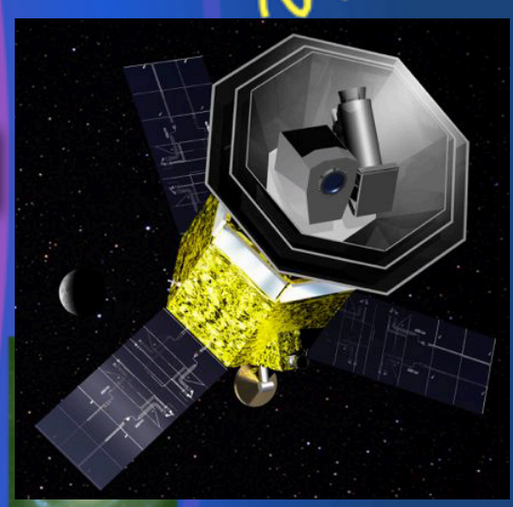
high-energy cosmic rays

Accelerators
LHC
Tevatron

Campbell's CONDENSED PARTICLE SOUP

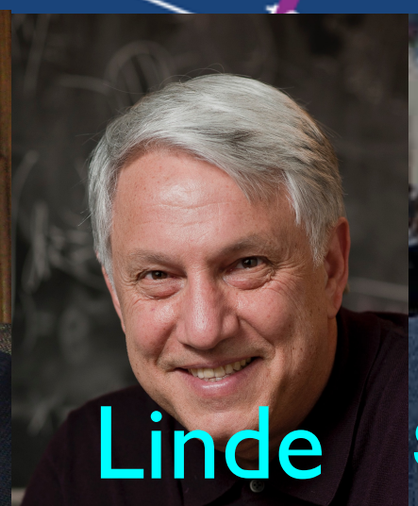
gravitational waves

telescope




Sato

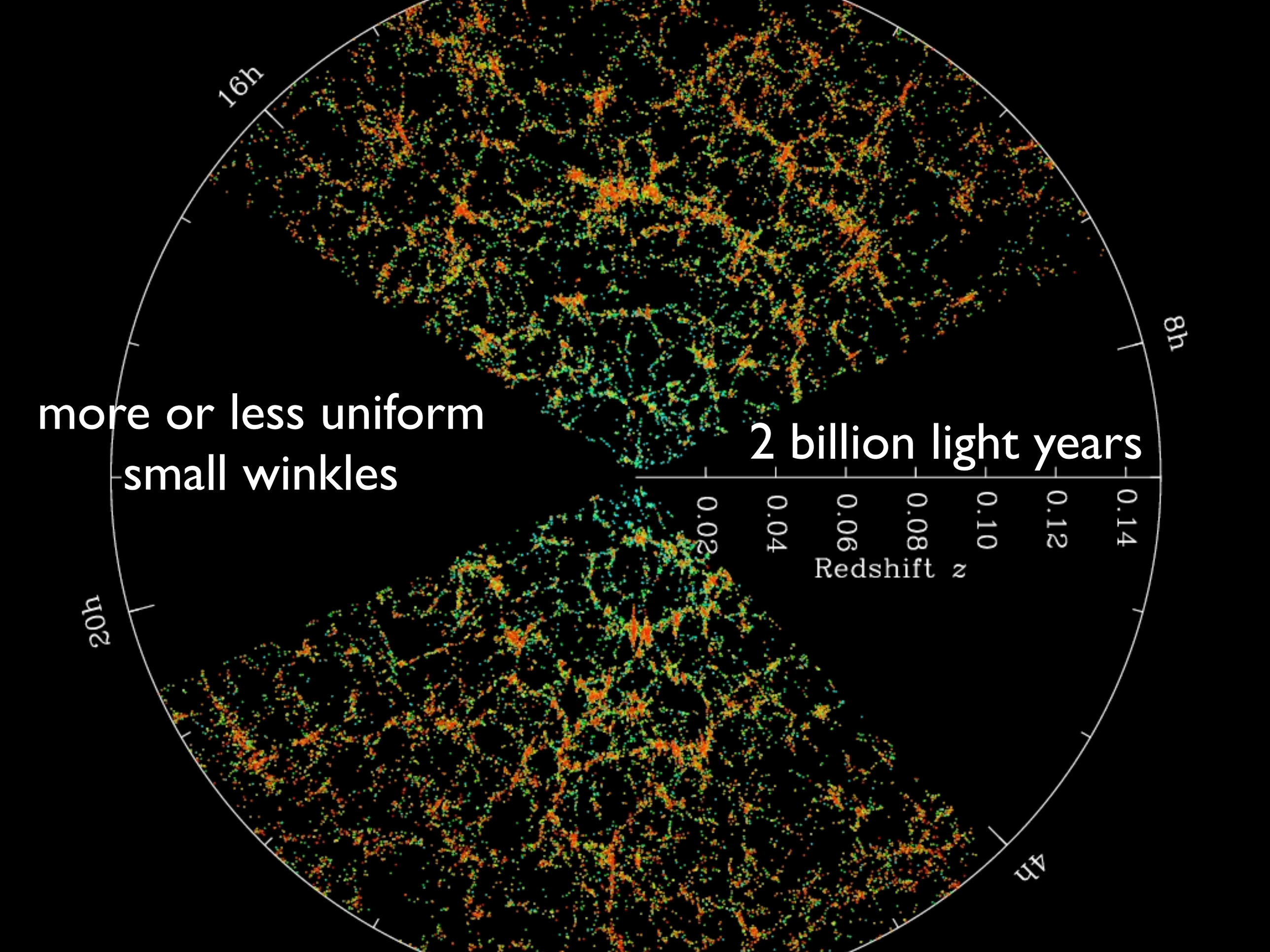

Guth


Linde


Starobinsky


Steinhardt

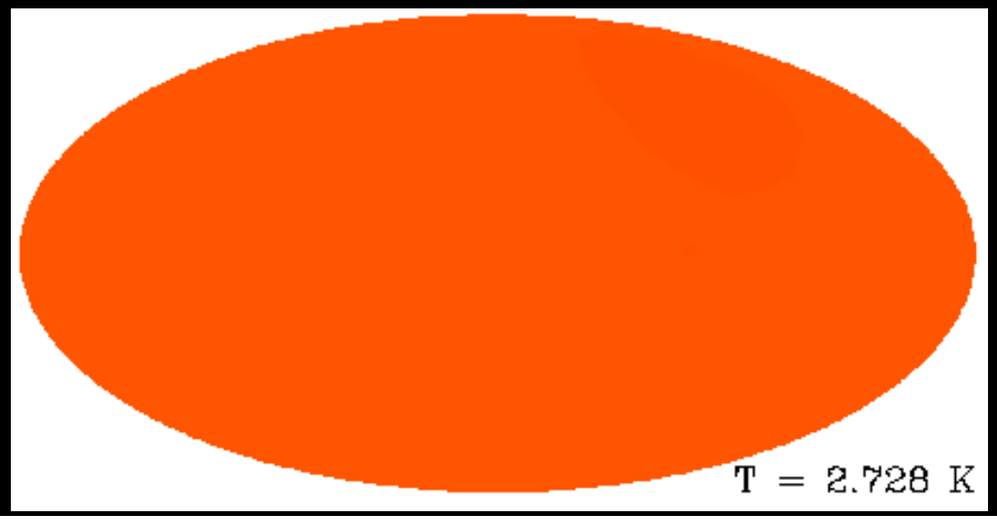

Albrecht

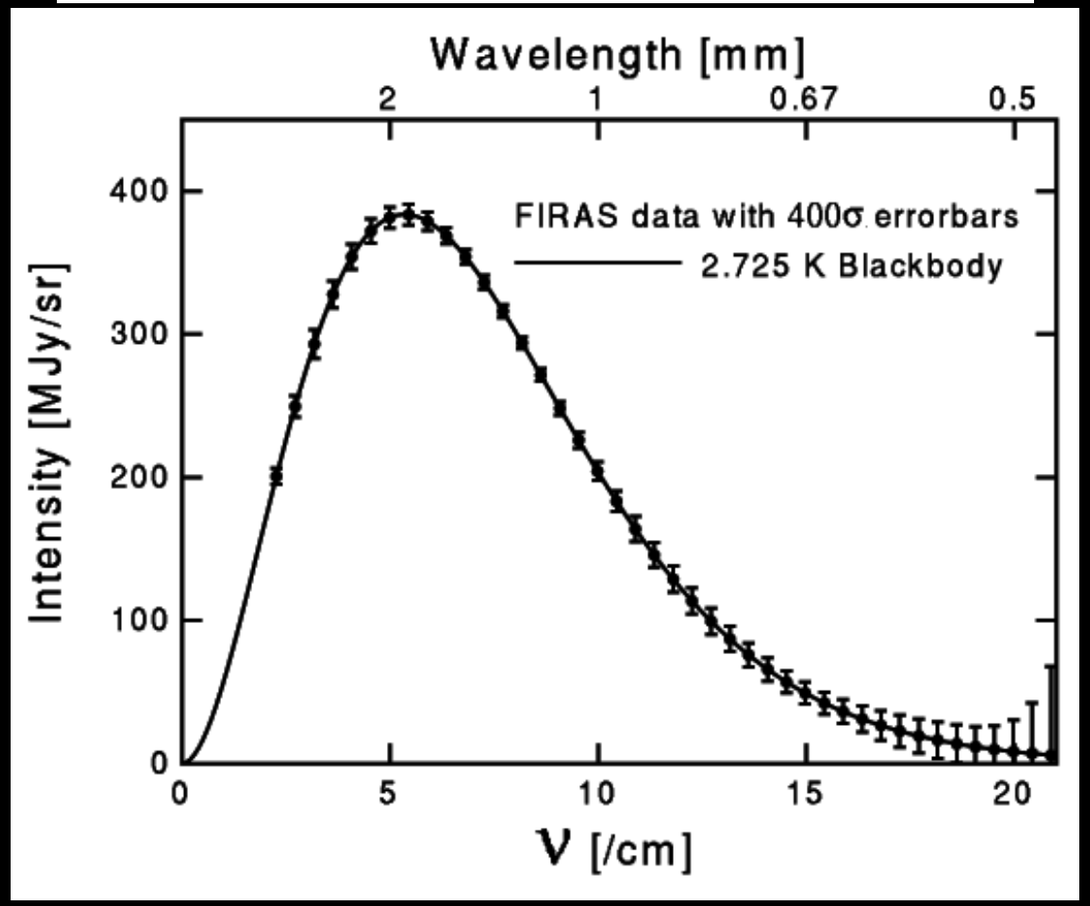


more or less uniform
small winkles

2 billion light years

How do they know each other?



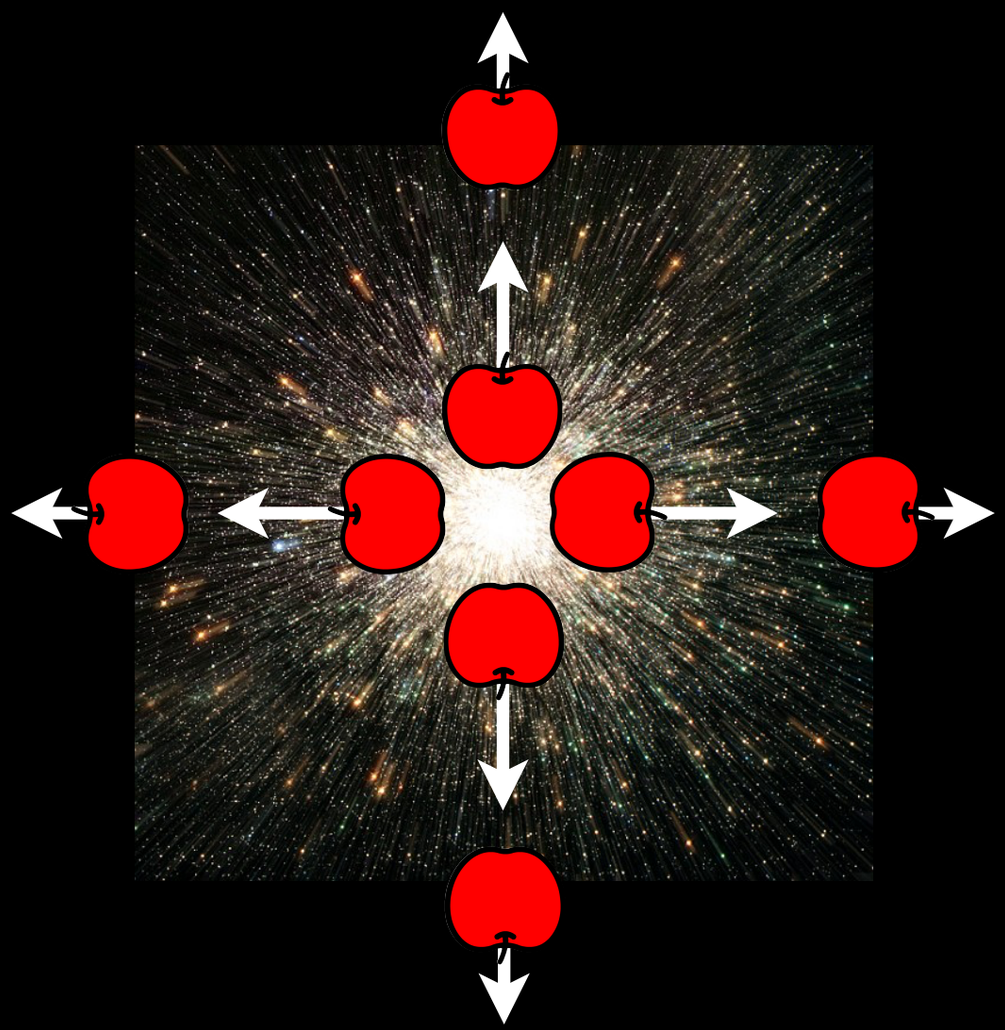


- Like having discovered two remote islands in very different parts of the world, but people speak the same language

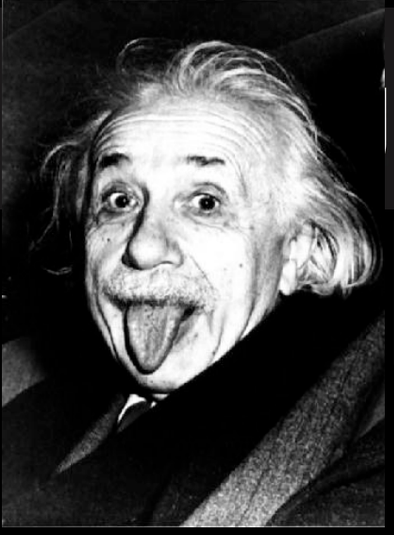
- we suspect they were together at some point

Cosmic Microwave Background (CMB)

Expansion should slow down



Gravity only pulls, never pushes



How is that possible?

Einstein's equation

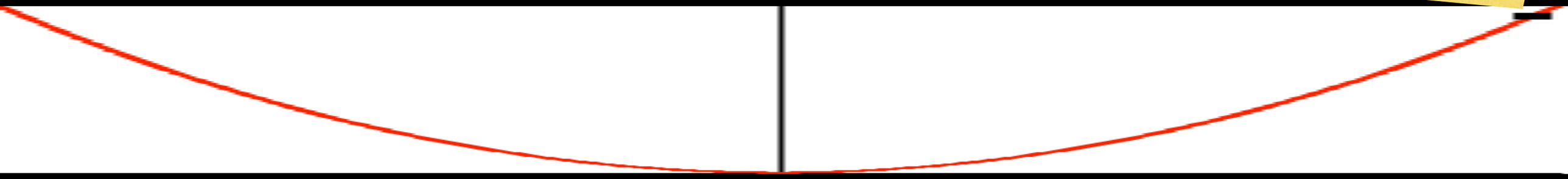
$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = 8\pi G_N T_{\mu\nu}$$

How Universe expands — what is inside

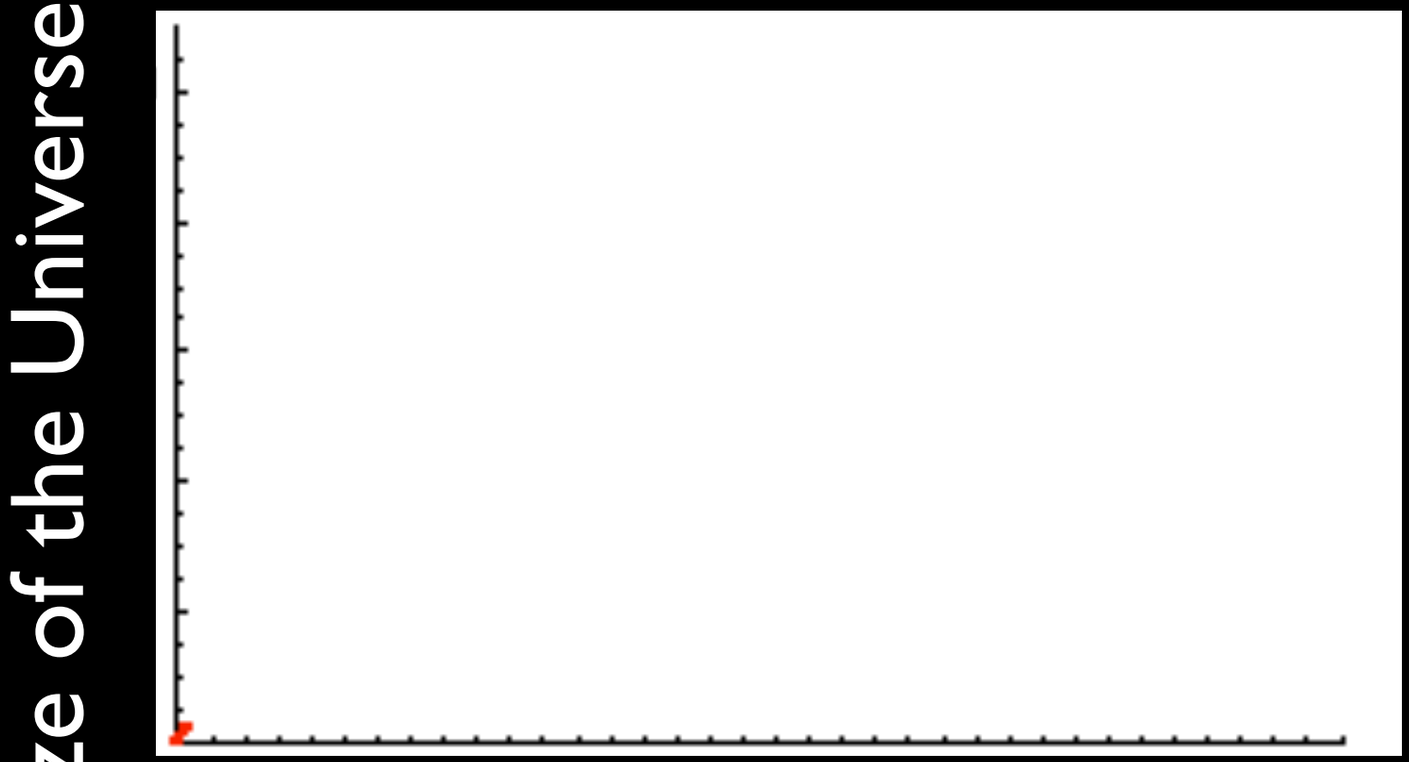
faster expansion ← more energy

Inflaton

How does it happen?



more or less constant energy in a given volume

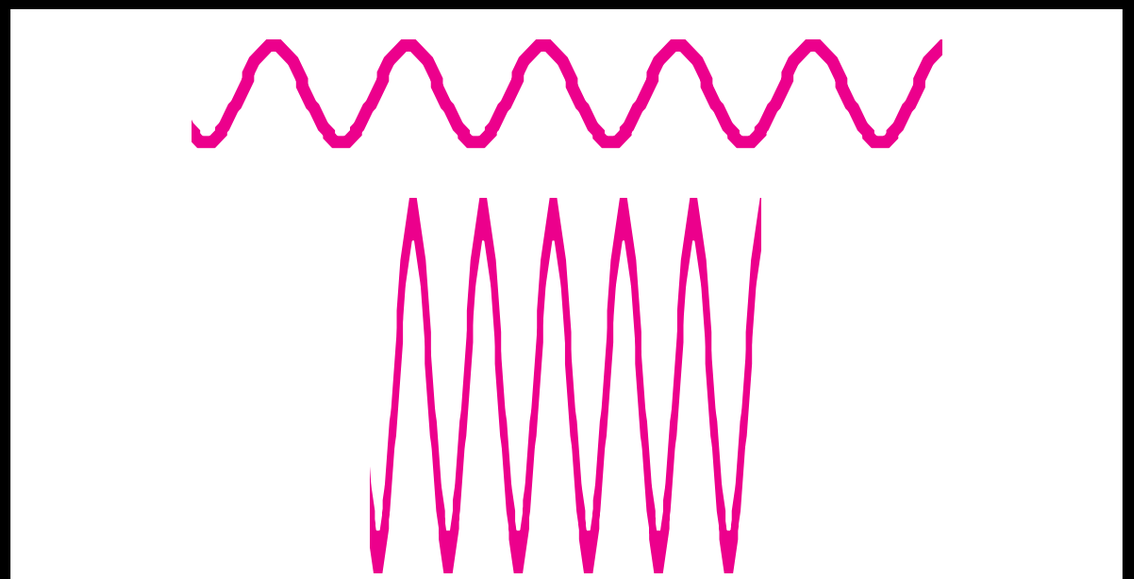


near sighted

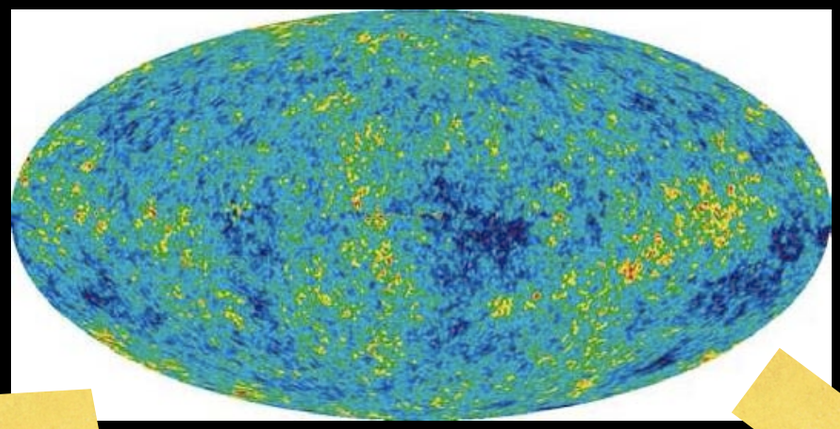
- What you are seeing one moment is *gone* by inflation the next moment
- feel very near-sighted
- "horizon"
- small space

  ⇒big uncertainty

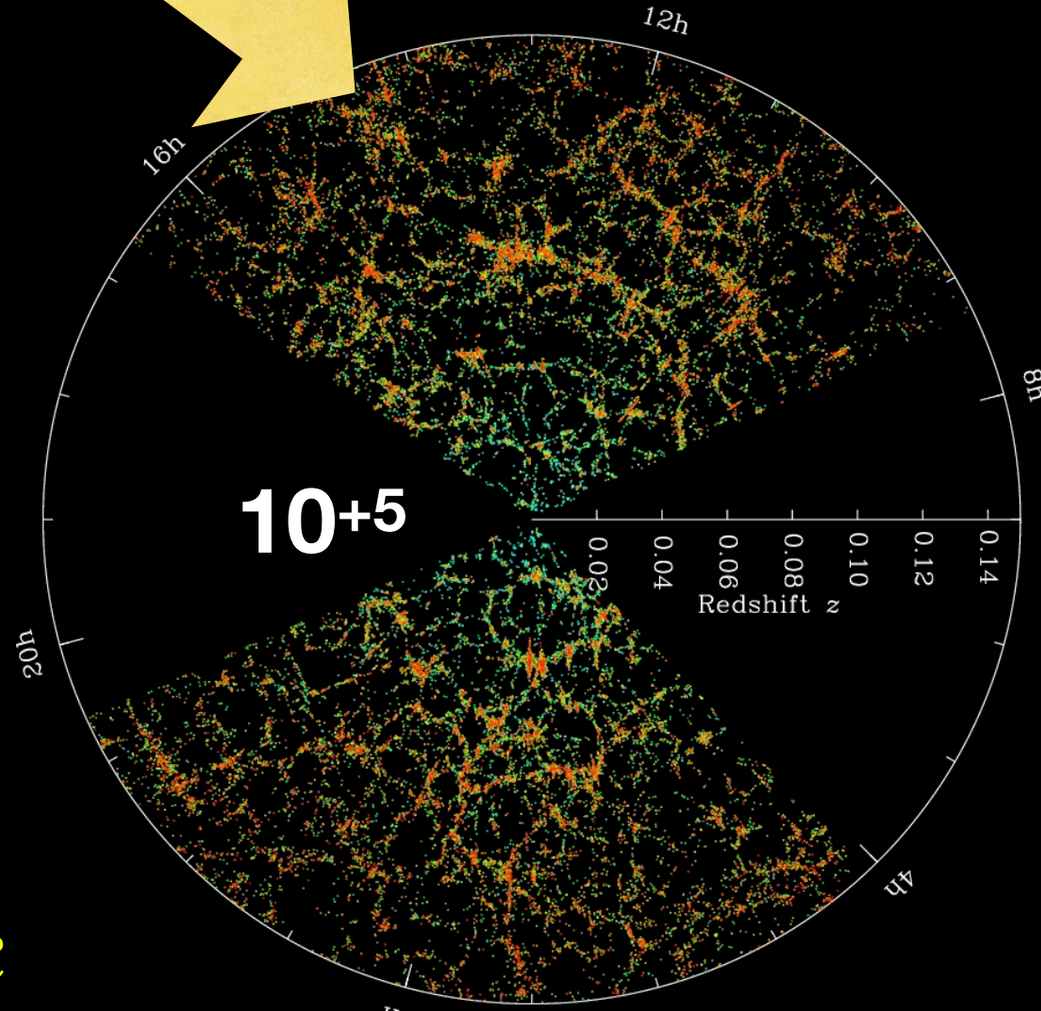
  $$\Delta E \Delta x \gtrsim \hbar c$$



Seeds for structure

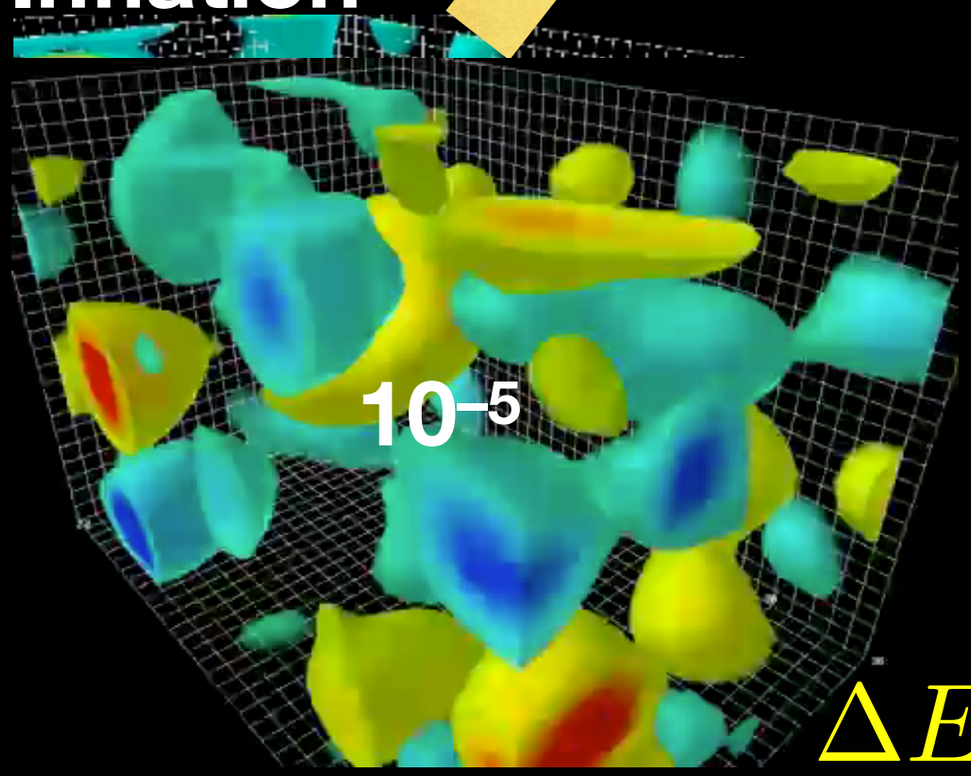


Dark Matter



10^{+5}

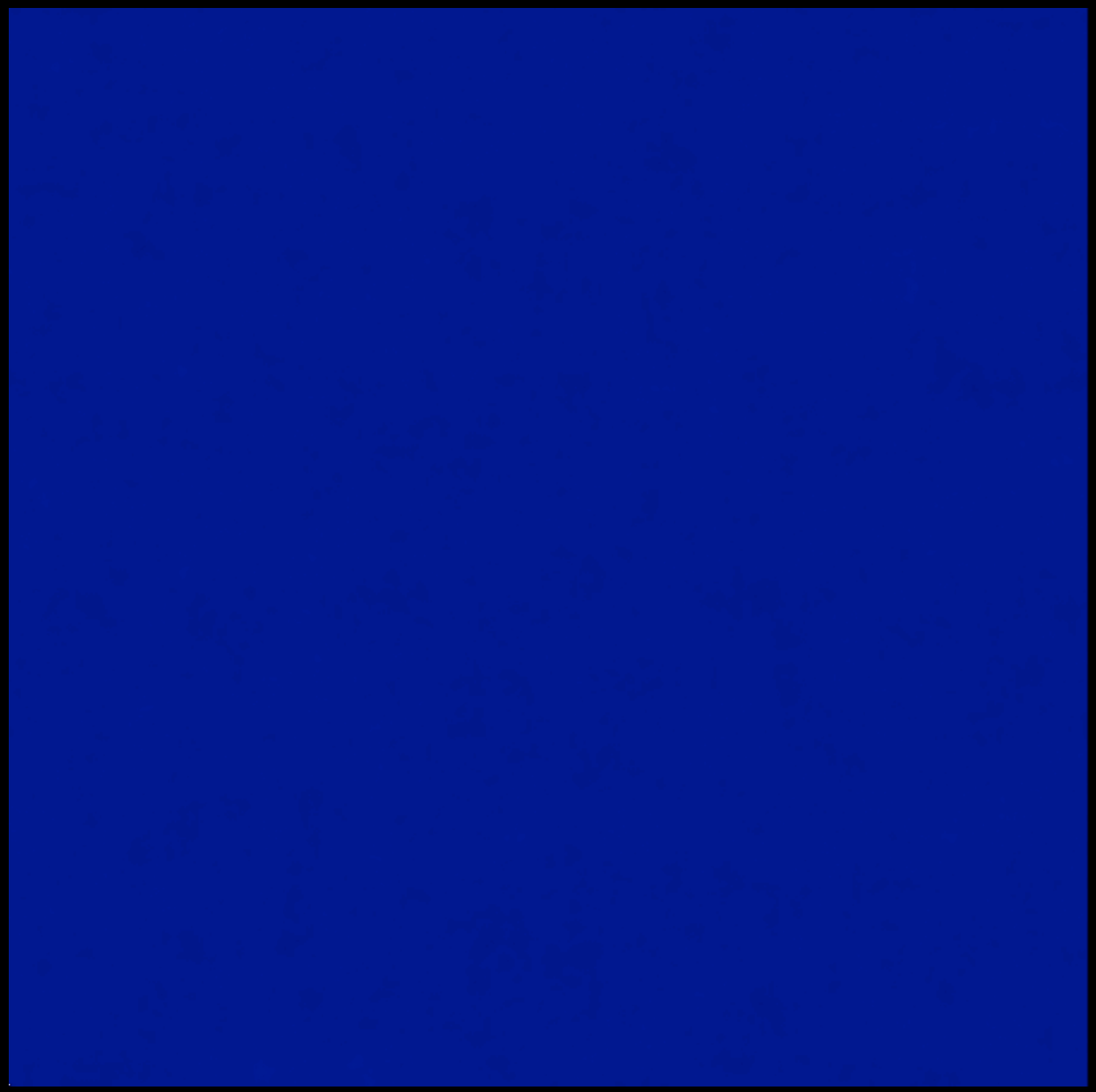
Inflation



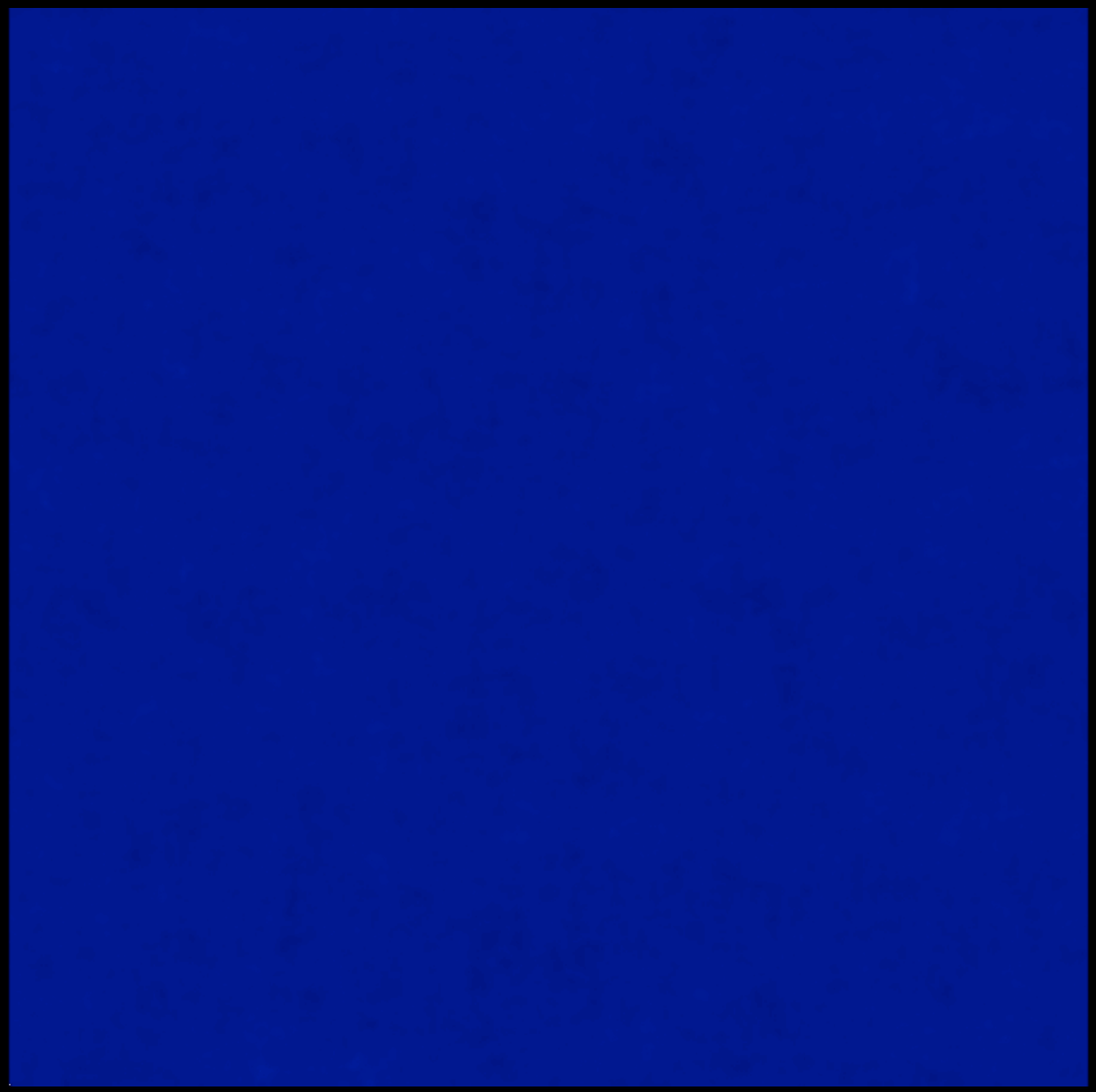
10^{-5}

$$\Delta E \Delta x \gtrsim \hbar c$$

Inflation sowed seeds
Dark Matter grew them



without dark matter

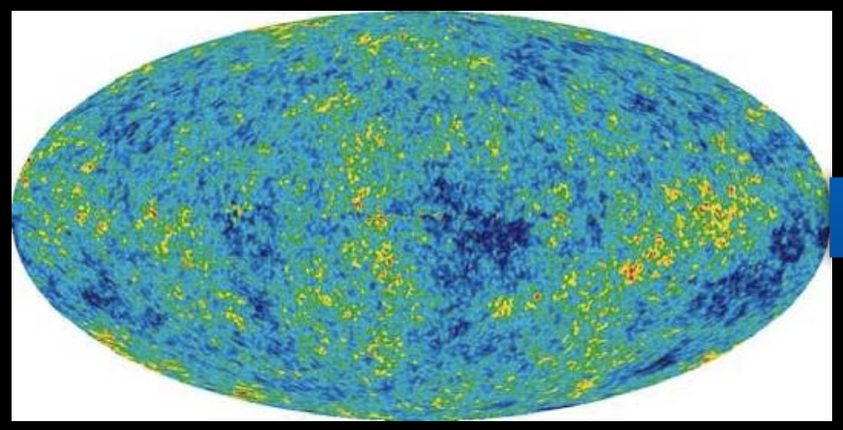


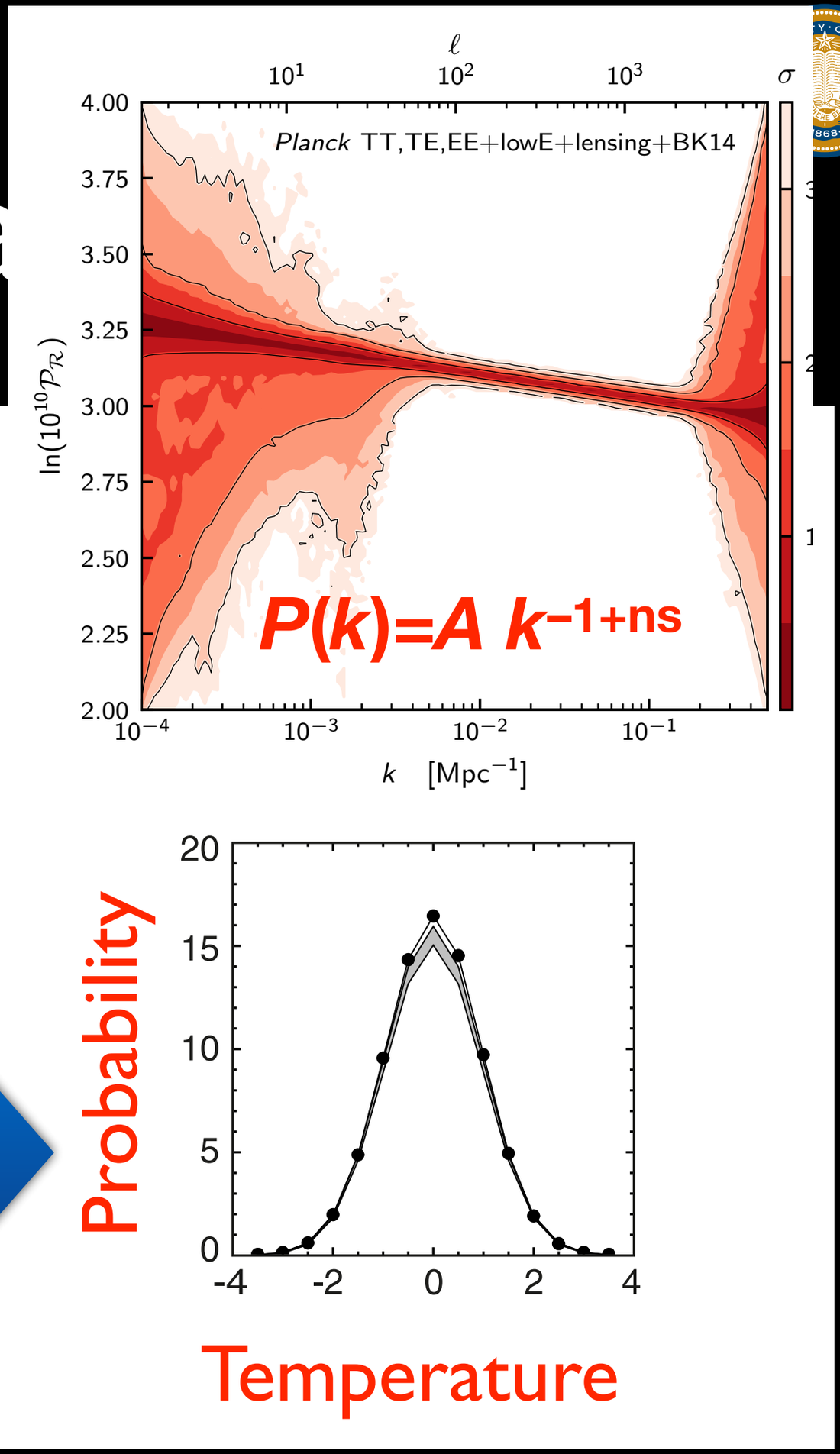
with dark matter


Inflation is Dad
Dark Matter is Mom

Looks pla

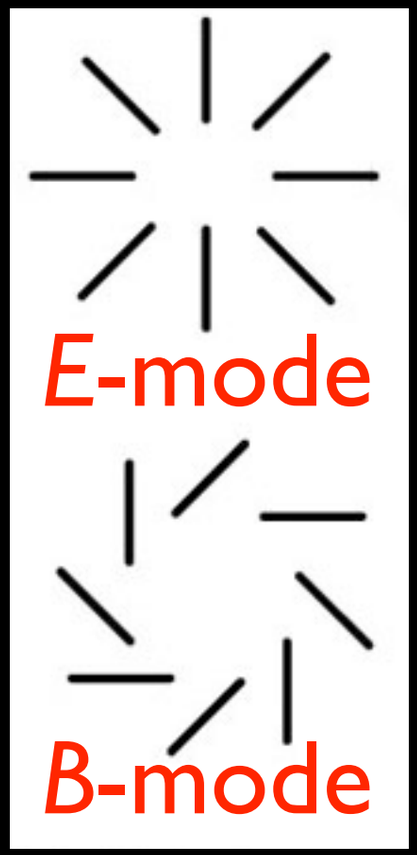
- Uncertainty principle leads to Gaussian distribution for the simplest cases
- Indeed!
- Matches simplest models of inflation





Still many mysteries

- What caused inflation?
- Which moment?
- How much?
- Definitive proof?



polarization

History of the Universe

380kyr

13.8Byr

Accelerators
LHC
Tevatron
RHIC

high-energy cosmic rays

Inflation

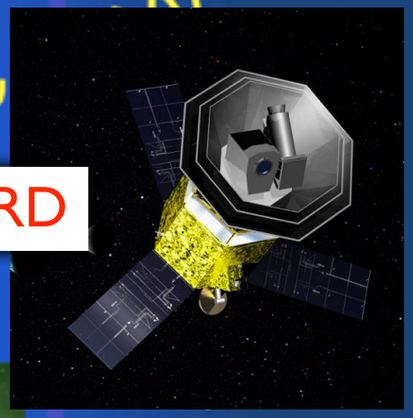
Big Bang

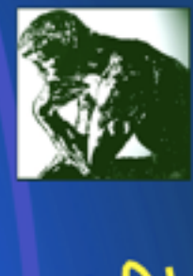
possible dark matter relicts

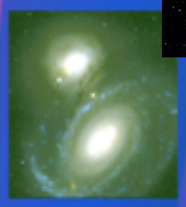
dark matter

cosmic microwave background visible

LiteBIRD







t 10-44 10-37 s
T 10 32 10 28
E 10 19 10 15

10 -10 s
10 15
10 2

10 -5 s
10 12
10 -1

10 2 s
10 9
10 -4

3x10 5 y
3000
3x10 -10

10 9 y
15

12x10 9 y
2.7
2.3x10 -13

(sec,yrs)
(Kelvin)
(GeV)

Today

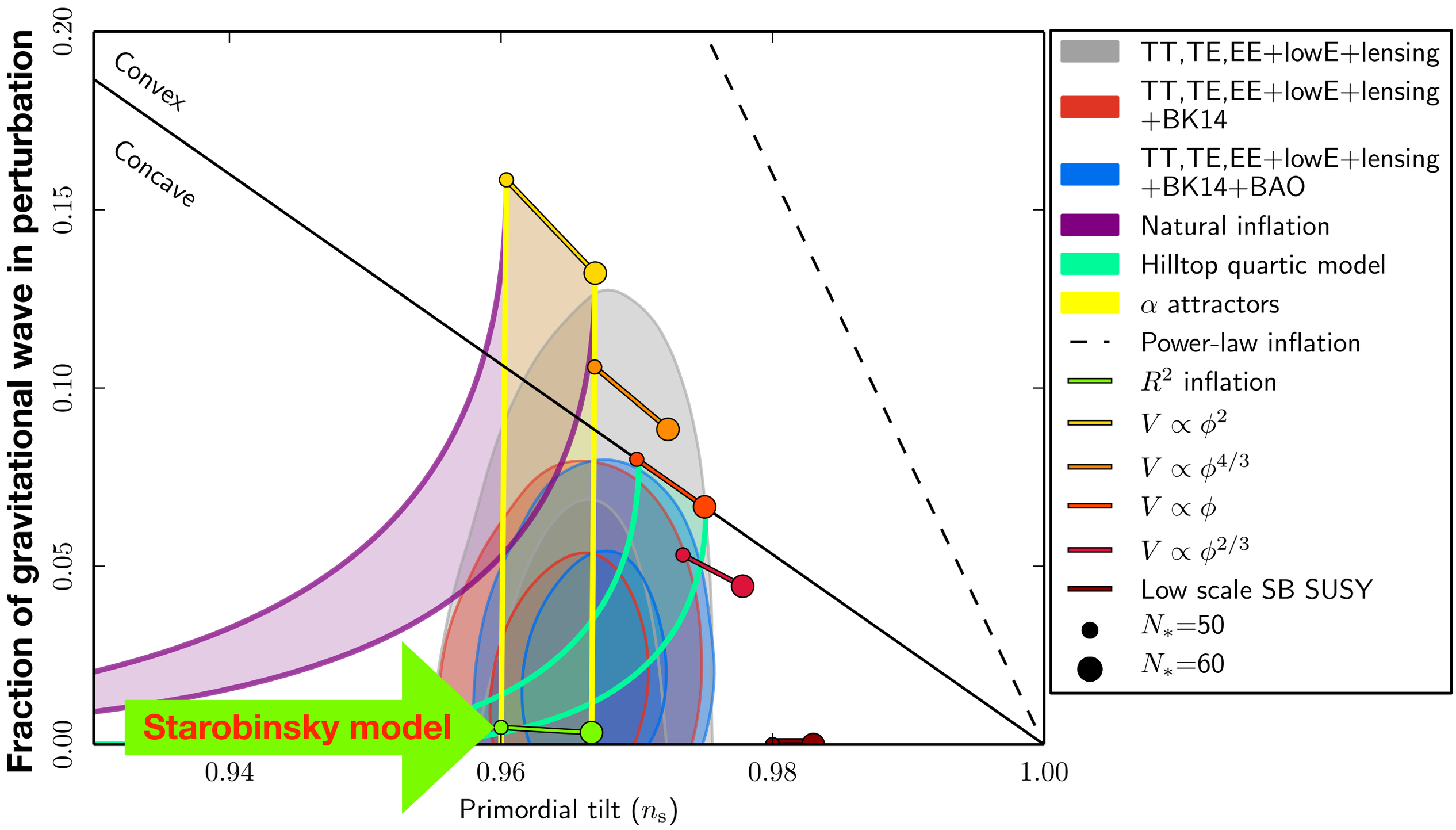
Key:
q quark
g gluon
e electron
μ muon τ tau
ν neutrino
W, Z bosons
qq̄ meson
qqq bar
ion
atom
photon
galaxy
black hole

"See" the inflation directly

Gravitational Wave exists!

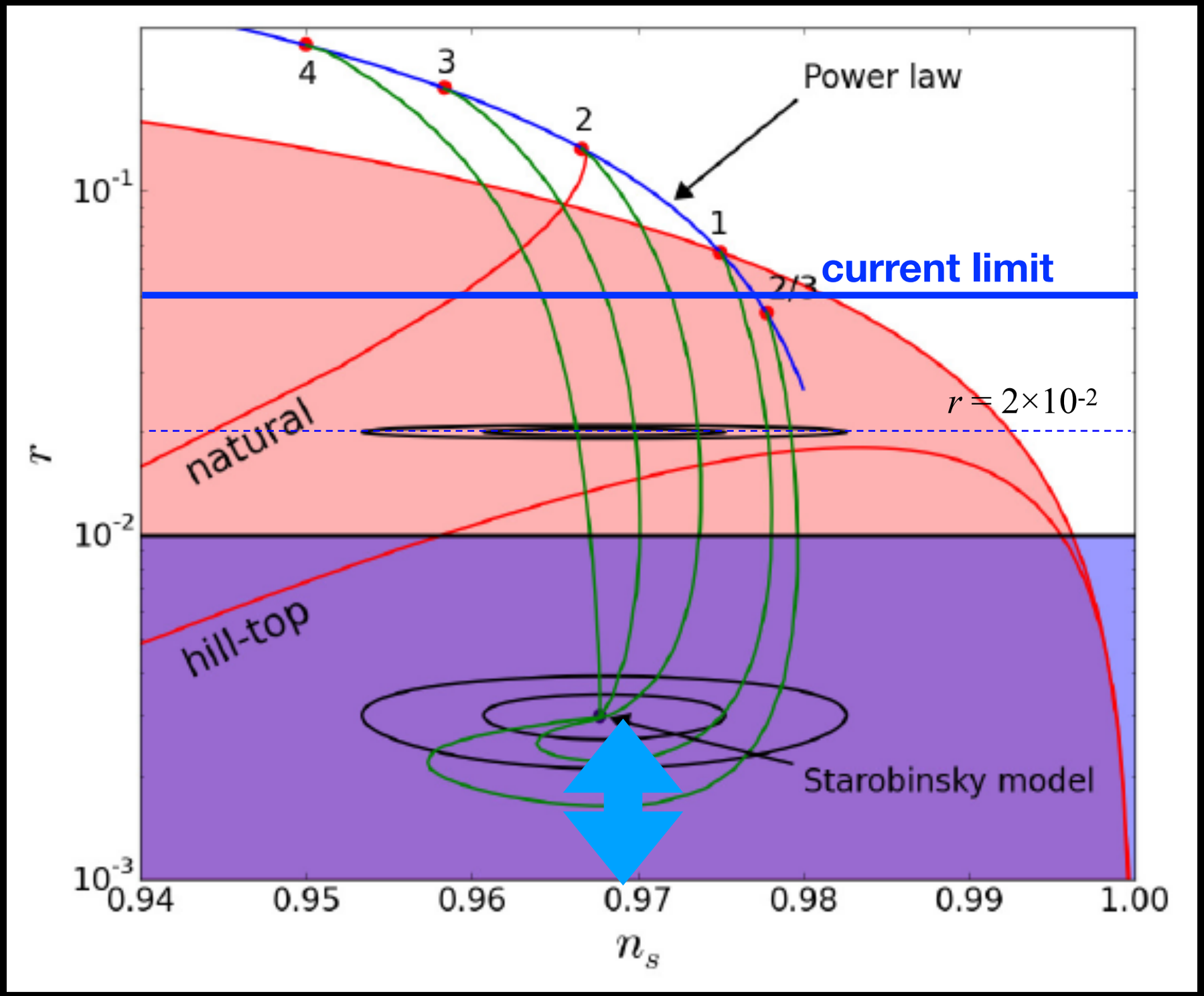
Scale of Effect Vastly Exaggerated

The whole Earth stretches only by 10^{-14}cm


Fraction of gravitational wave in perturbation
0.20
0.15
0.10
0.05
0.00
Convex
Concave
Starobinsky model
0.94
0.96
0.98
1.00
Primordial tilt (n_s)
TT,TE,EE+lowE+lensing
TT,TE,EE+lowE+lensing +BK14
TT,TE,EE+lowE+lensing +BK14+BAO
Natural inflation
Hilltop quartic model
α attractors
Power-law inflation
R^2 inflation
$V \propto \phi^2$
$V \propto \phi^{4/3}$
$V \propto \phi$
$V \propto \phi^{2/3}$
Low scale SB SUSY
N_*=50
N_*=60

$$P(k)=A\,k^{-1+ns}$$

What we expect with LiteBIRD



We absolutely need δr=10^{-3}

String Theory

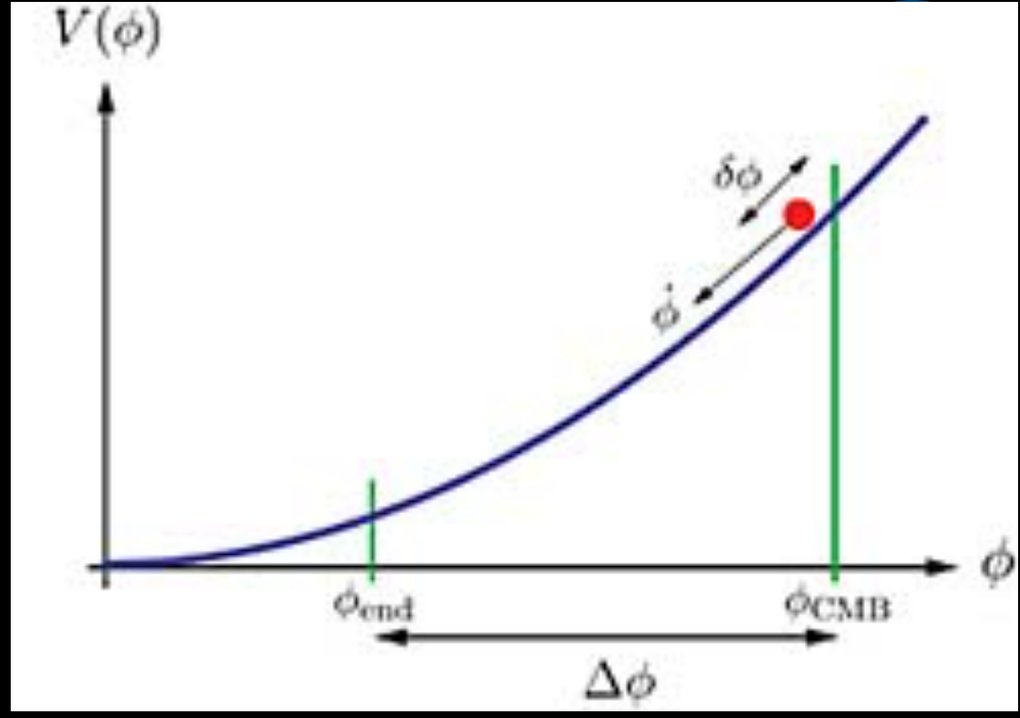
- Inflaton field cannot go over a large distance $\Delta\phi \lesssim M_{\rm Planck}$

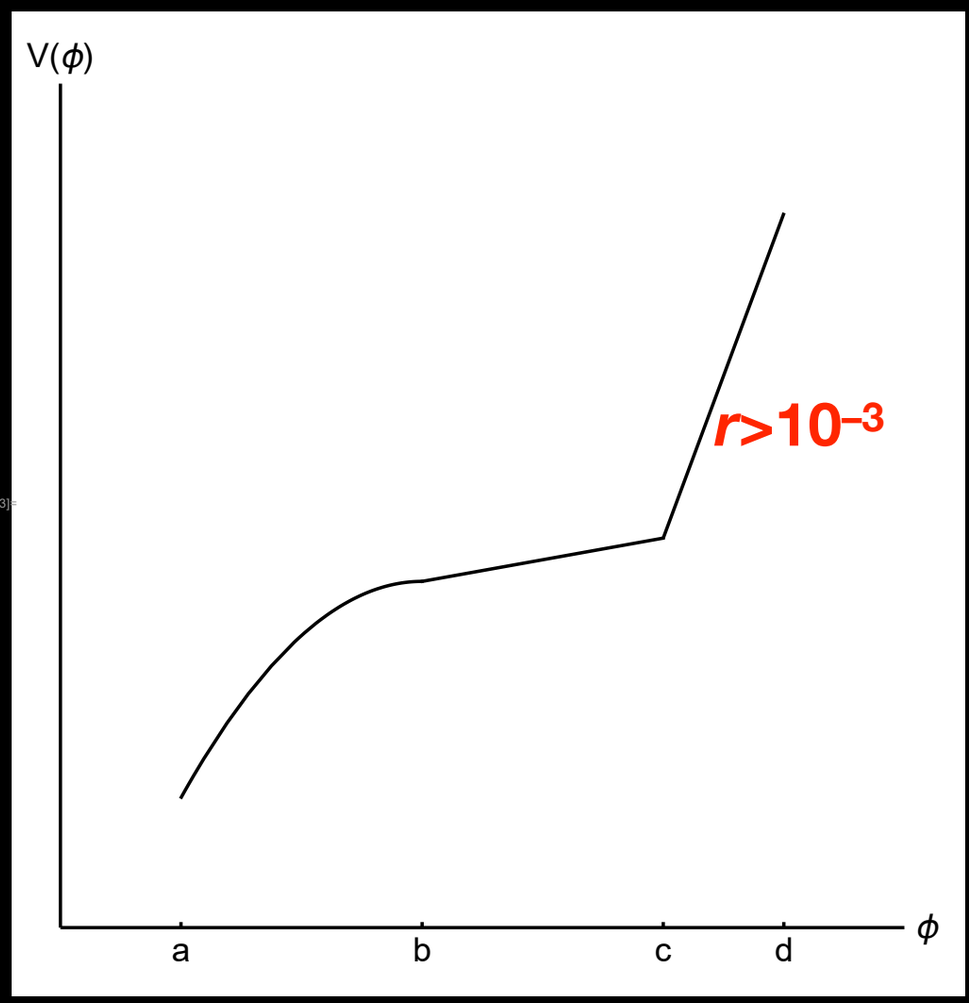
  H. Ooguri and C. Vafa, hep-th/0605264

  - can't expect large tensor component

$$r \approx 8\left(\frac{d\phi}{dN}\right)^2 \lesssim 10^{-3}$$

- bad news for CMB S4, LiteBIRD?
- Inflation may move substantially only for several initial *e*-folds
- Can expect much larger *r*!
- Still observation will put string theory on the edge





HM, Masahito Yamazaki and Tsutomu T. Yanagida, arXiv:1809.00478

Chien-I Chiang, Jacob Leedom, HM, arXiv:1811.01987

DASI
CBI
MAXIPOL
BOOMERanG
CAPMAP
WMAP-9yr
QUaD
QUIET-Q
QUIET-W
BICEP1-3yr
ACTPol
BKP
SPTpol
POLARBEAR

Lensing B-mode

Primordial B-mode
(r=0.01)

$l(l+1)C_l^{BB}/(2\pi)$ (μK^2)

Multipole Moment, ell

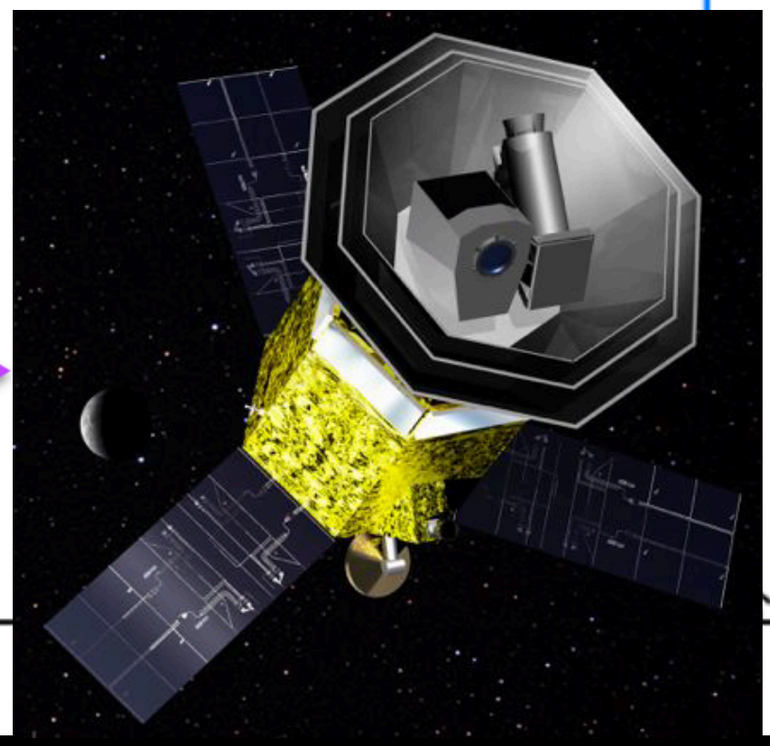
Figure courtesy of Dr. Chinone

DASI
CBI
MAXIPOL
BOOMERanG
CAPMAP
WMAP-9yr
QUaD
QUIET-Q
QUIET-W
BICEP1-3yr
ACTPol
BK14
SPTpol
POLARBEAR
Simons Array
LiteBIRD

$l(l+1)C_l^{BB}/(2\pi)$ (μK^2)

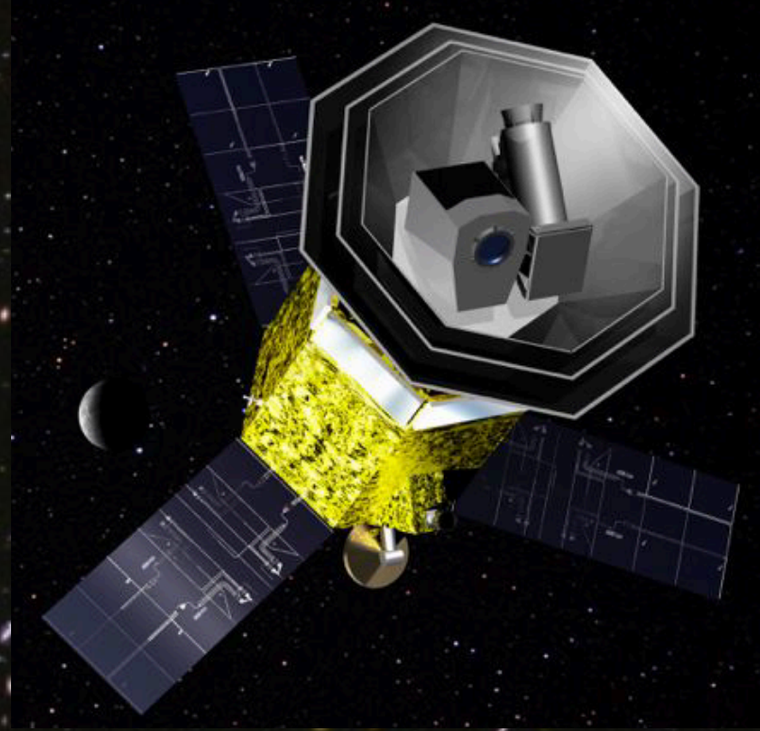
r=0.01

LiteBIRD



now downselect by JAXA 2019, expected launch 2027

LiteBIRD



- CMB B-mode polarization is unique Universe *before* the Big Bang
- We can prove inflation (and meet our Dad!)
- specify “who” was our Dad
- probe theories that unify gravity and quantum physics

Dad
Inflation

us