# the limits of cosmology

## observing the dark ages

22 MARCH 2017

Joseph Silk

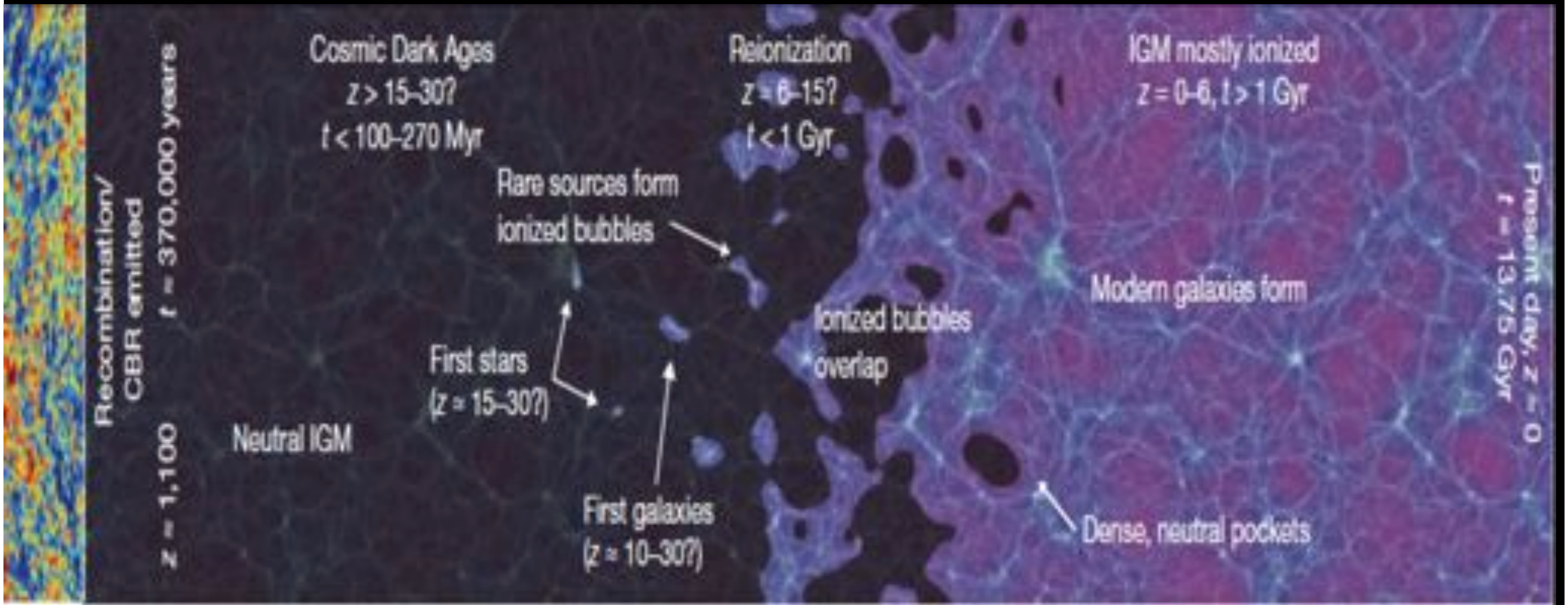
IAP/JHU

We have made remarkable progress
in cosmology in past 100 yrs.
its now a precision science
But the big questions are unanswered

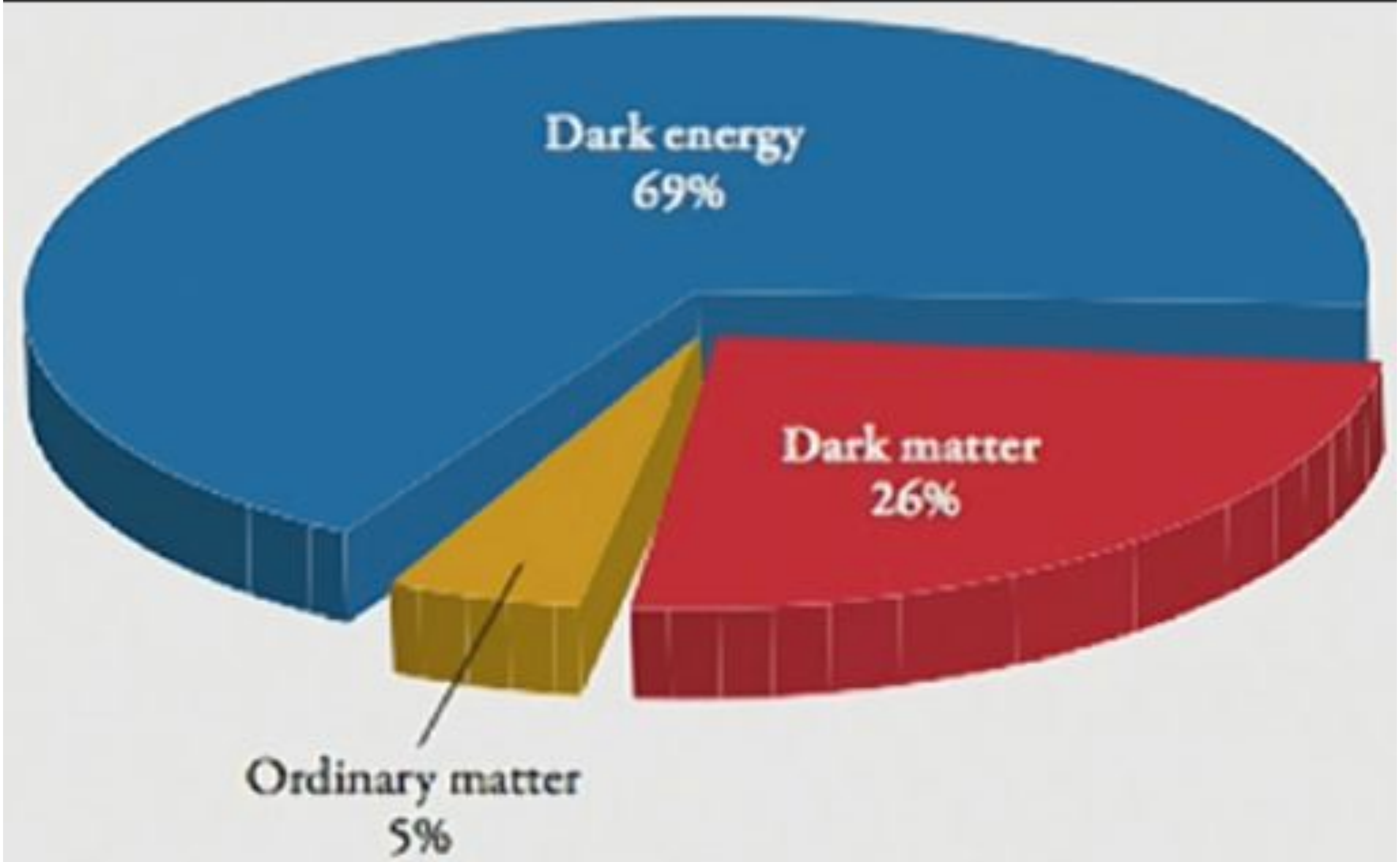
What is the matter?
Dark matter, dark energy

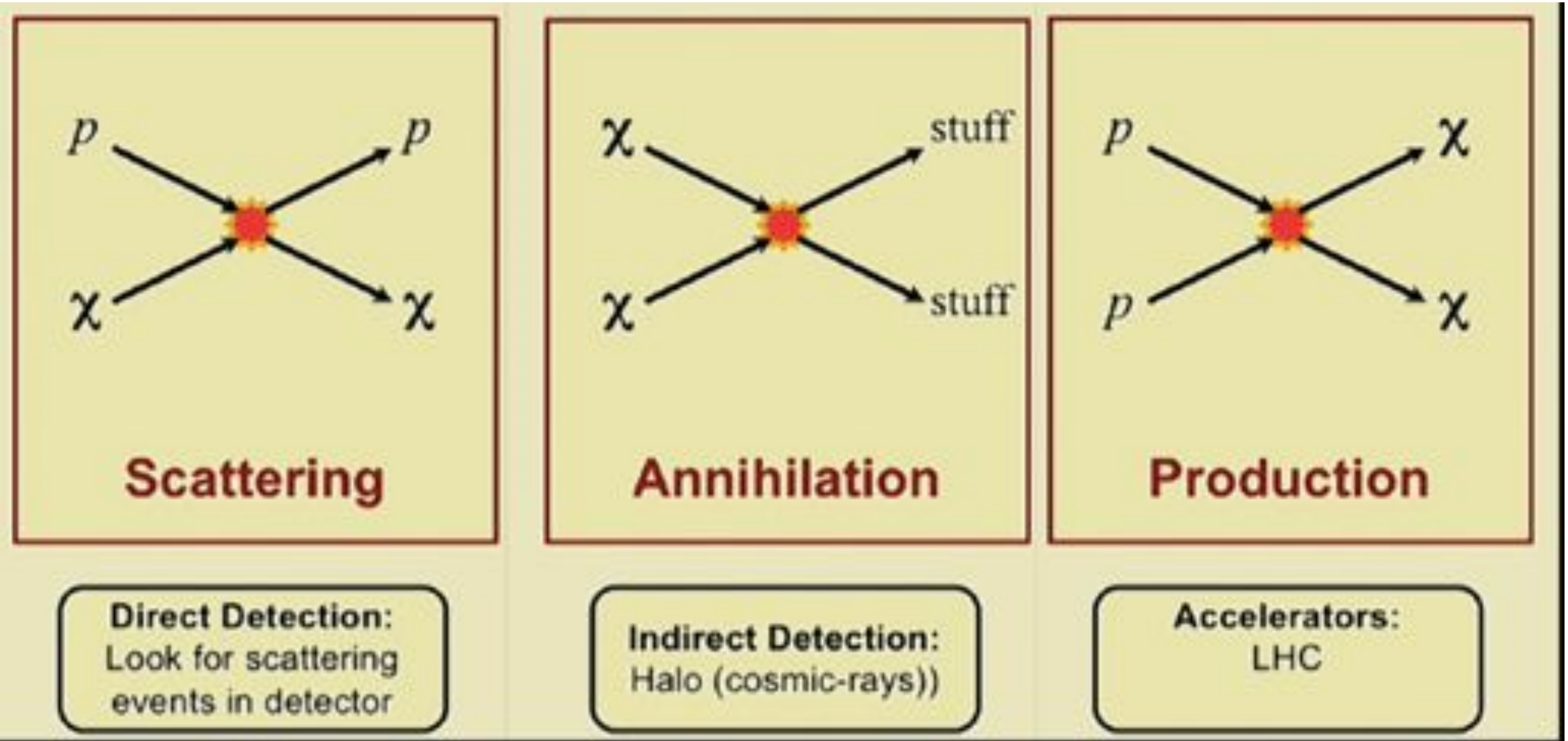
Where do we come from?
Inflation....

# THE DARK AGES OF THE UNIVERSE

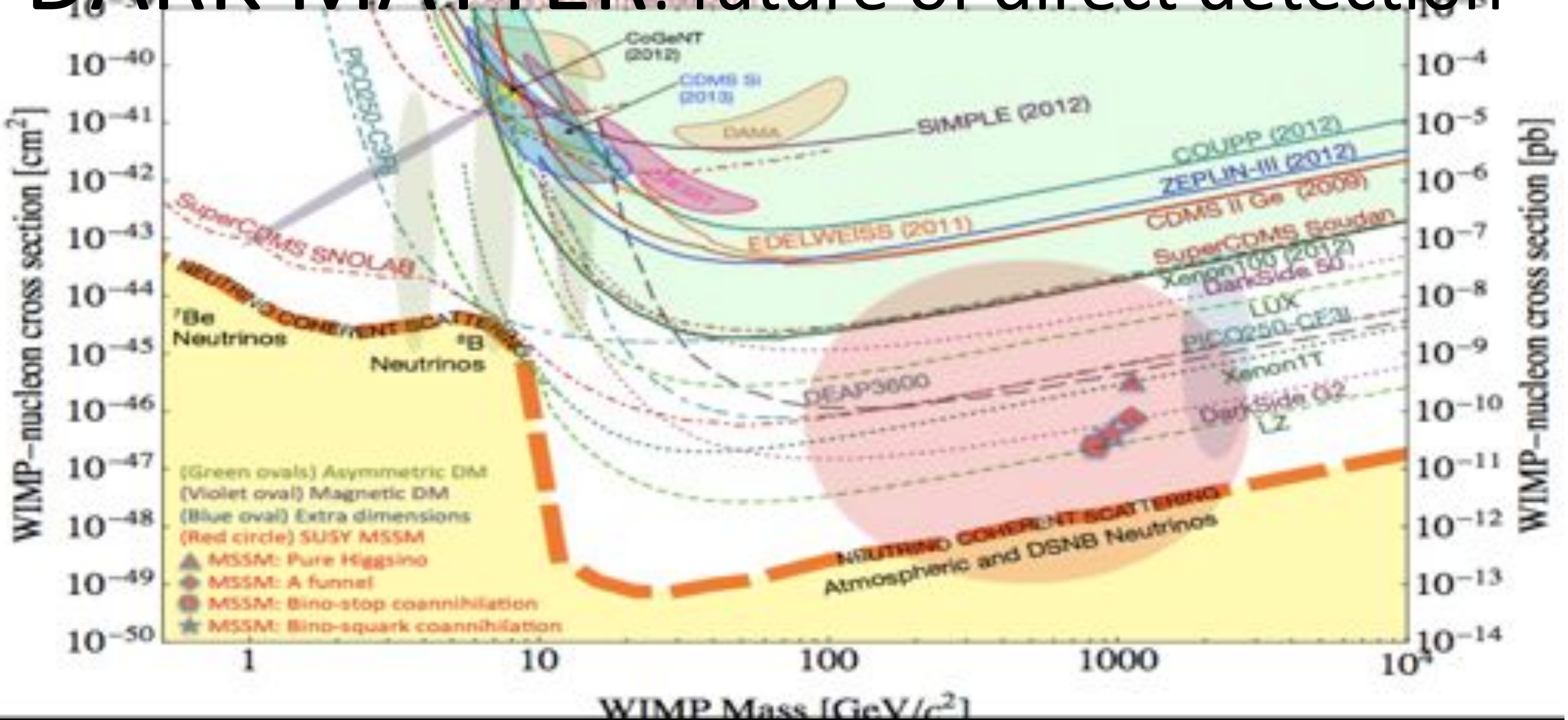


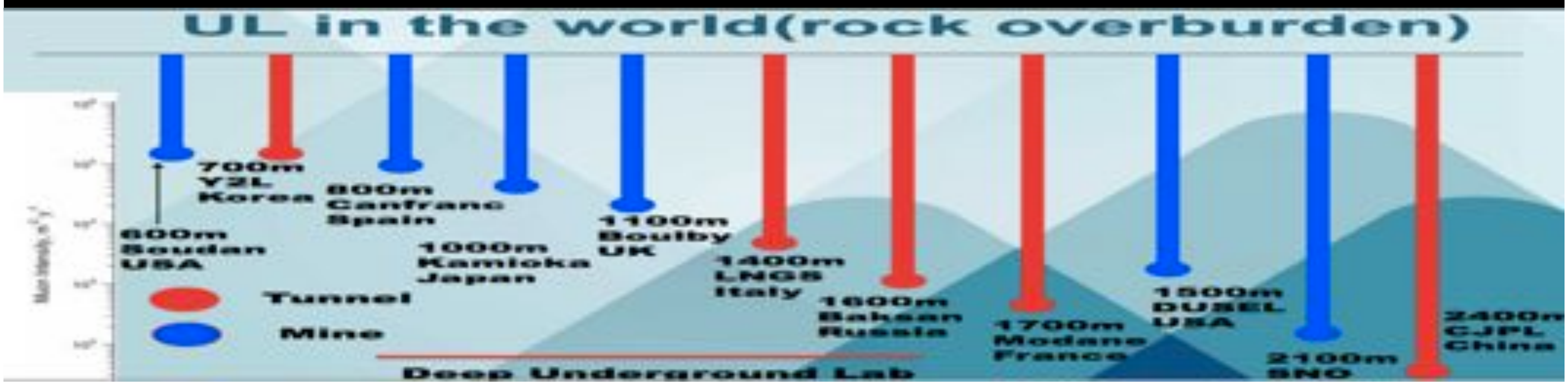
# Modern observations of the expanding universe require dark matter and dark energy




p
p
χ
χ
Scattering
χ
stuff
χ
stuff
Annihilation
p
χ
p
χ
Production
Direct Detection:
Look for scattering events in detector
Indirect Detection:
Halo (cosmic-rays))
Accelerators:
LHC

# DARK MATTER: future of direct detection

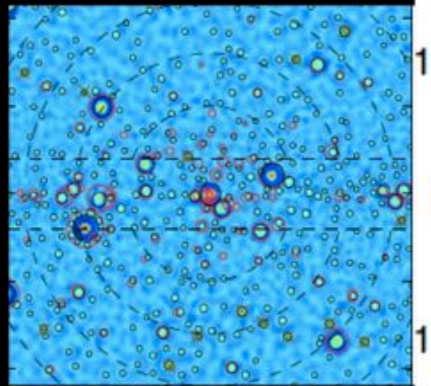


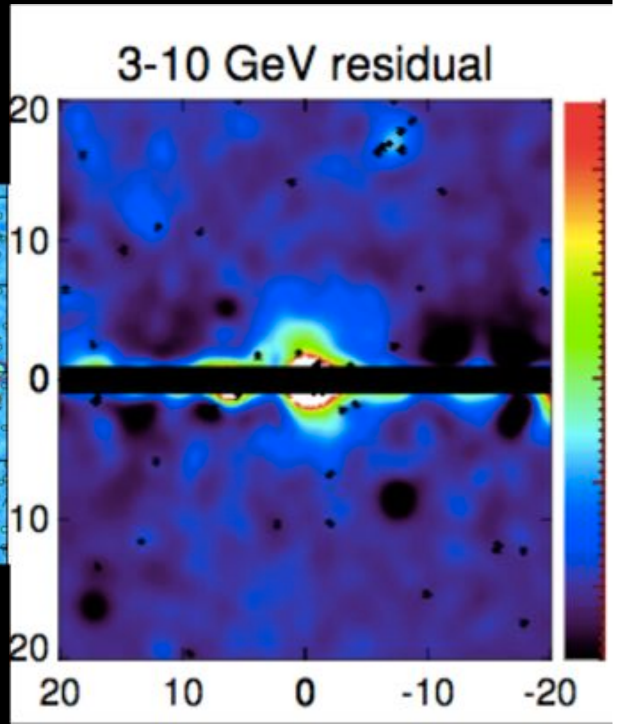



# DARK MATTER: status of indirect detection

Annihilations of majorana WIMPS produce high energy $\gamma$, $\nu$, $e^+$…

thermal freeze-out
In early universe
$\sigma_{ann} \sim 10^{-36}$ cm$^2$



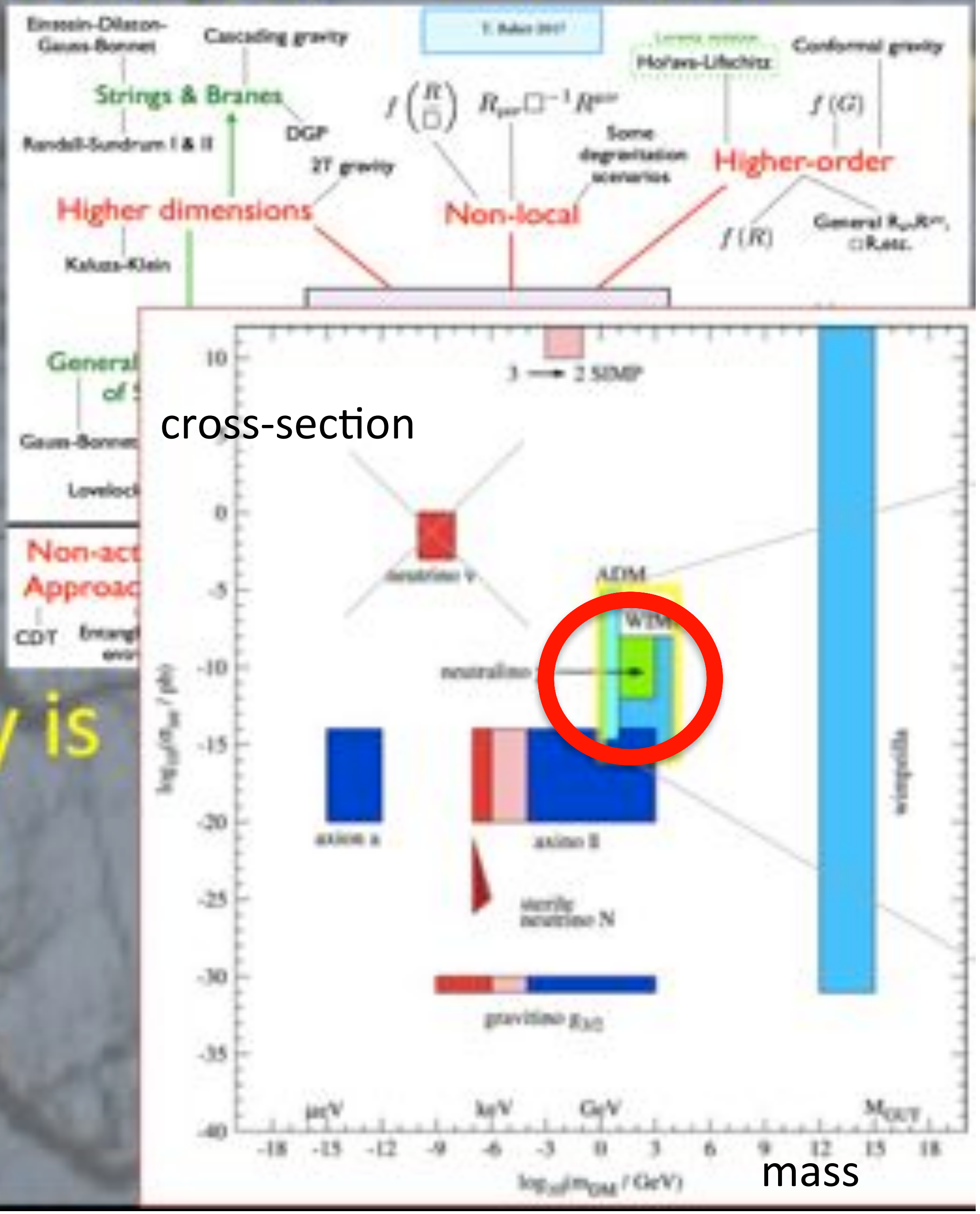



# DARK MATTER

What if we don't find dark matter
in the next decade(s)?

So far, modifying gravity is ugly and doesn't work!

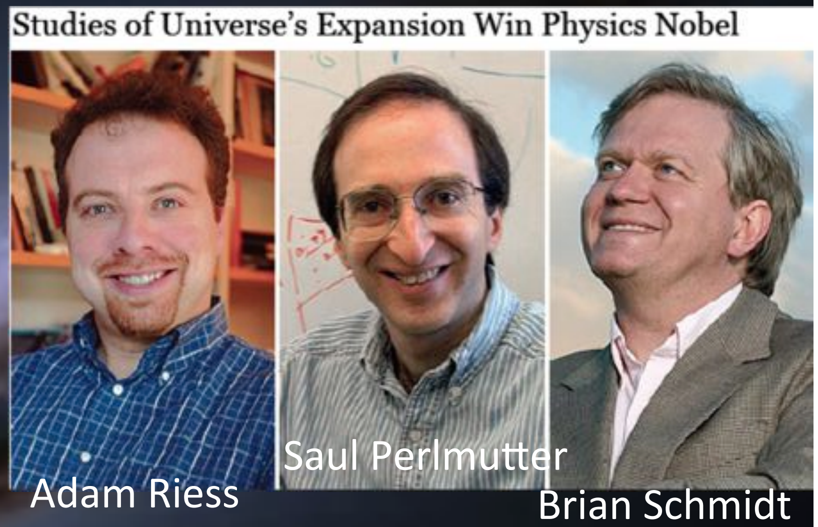
Look elsewhere

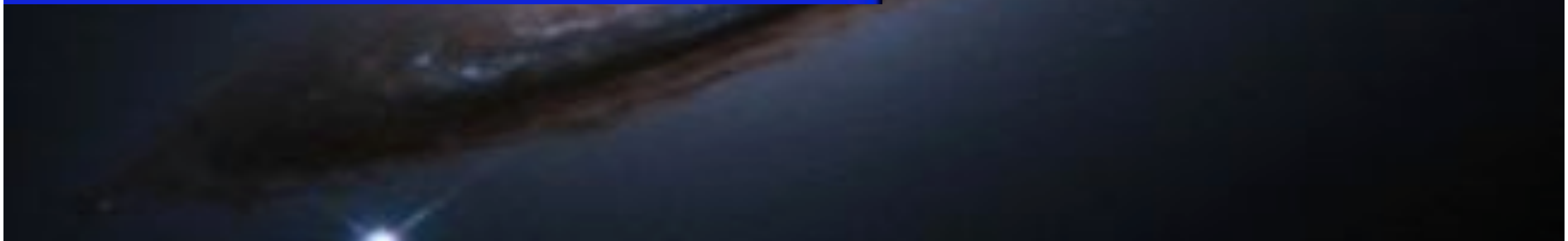


# DARK ENERGY accelerates

**we measure dark matter minus dark energy**

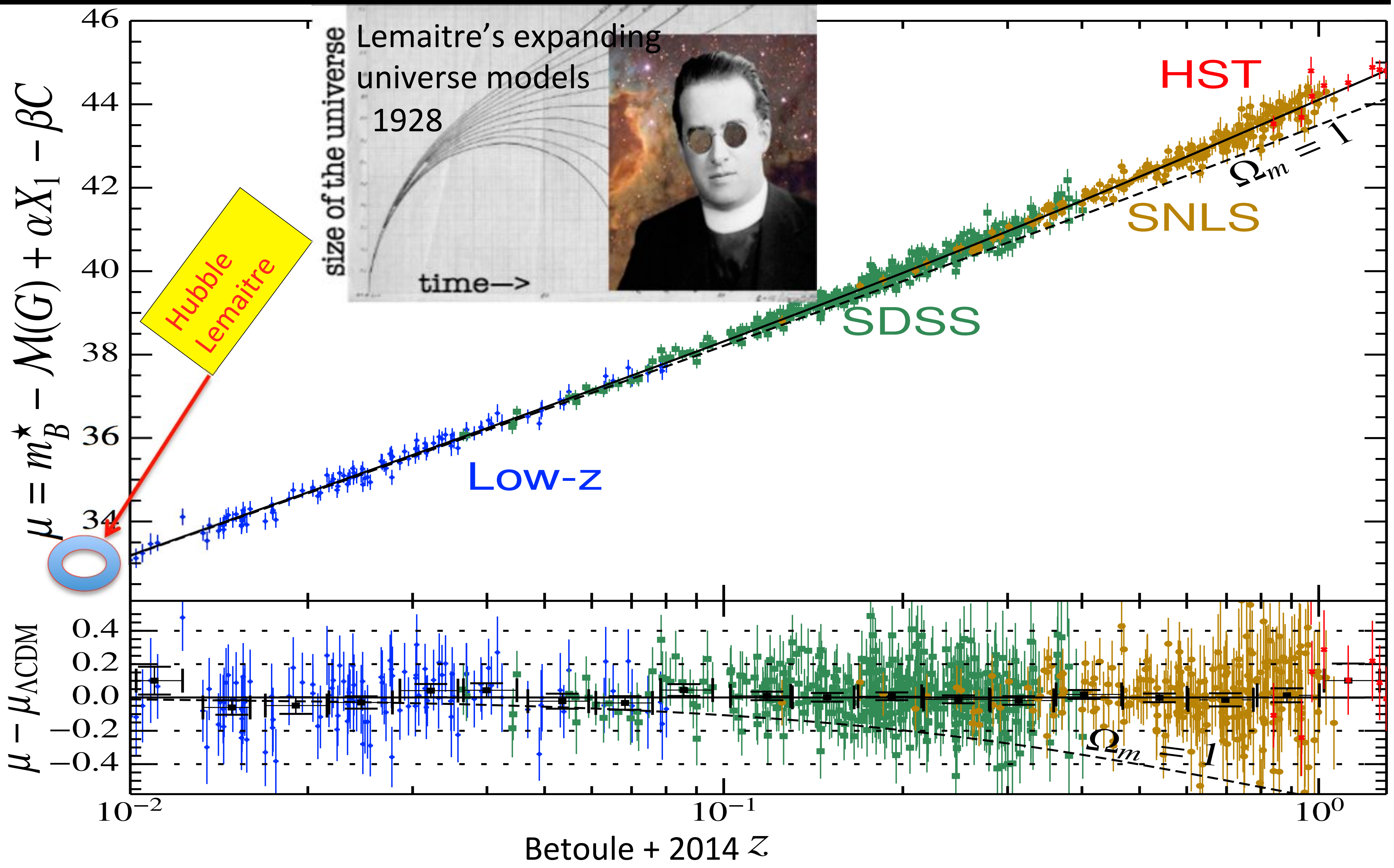
| CURVATURE | = | ENERGY-MOMENTUM |
|---|---|---|
| $G_{\mu\nu}$ | = | $8\pi T_{\mu\nu}$ |
| $G_{\mu\nu} - \Lambda g_{\mu\nu}$ | = | $8\pi T_{\mu\nu}$ |
| $G_{\mu\nu}$ | = | $8\pi T_{\mu\nu} + \Lambda g_{\mu\nu}$ |

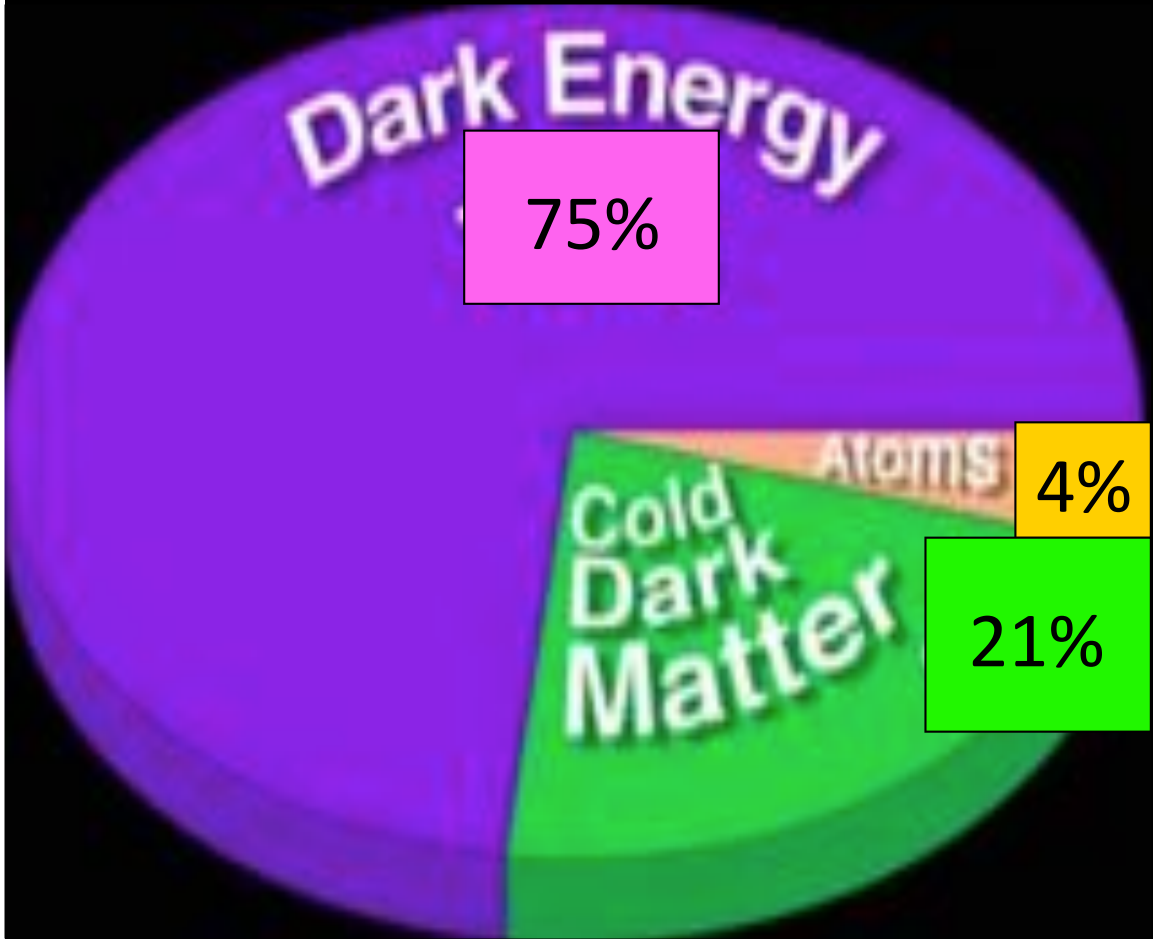


Distant type Ia supernovae are too faint!

# ACCELERATION






observe

$$\rho_{\text{vac}} \approx 10^{-10}\,\text{eV}^4$$

predict

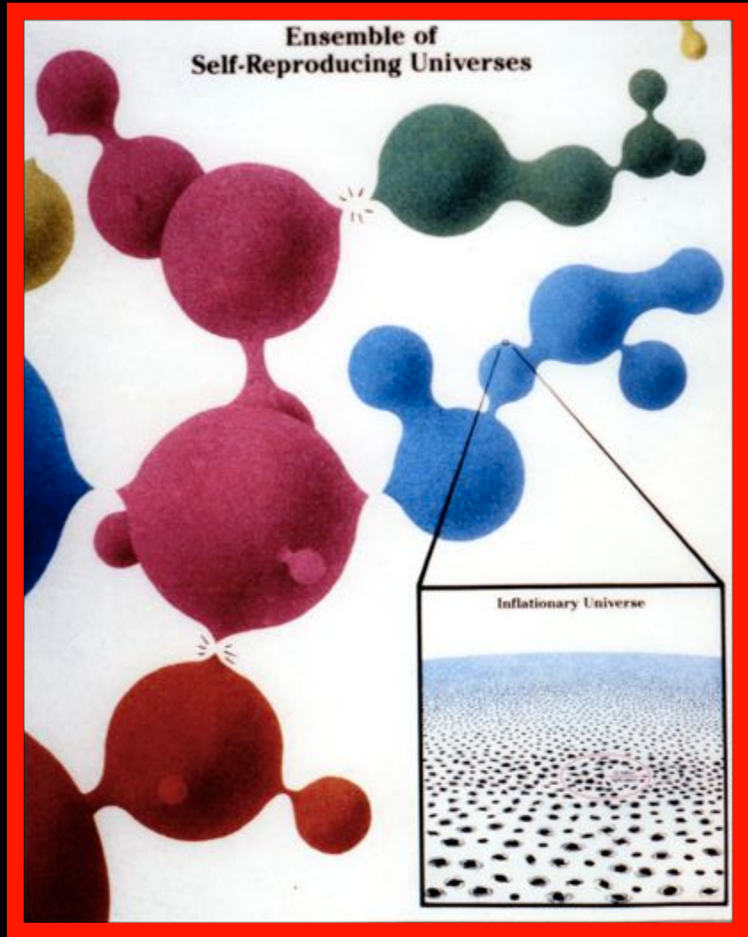
$$M \sim M_{Planck} = G^{-1/2} = 10^{28}\ \text{eV} \;\Rightarrow\; \rho_{vac} \sim 10^{112}\,\text{eV}^4$$

The worst prediction in physics!

# MULTIVERSE

**We live in one tiny pocket where the value of the cosmological constant is consistent with our kind of life** — **Leonard Susskind**

Eternal inflation produces a nearly infinite number of inaccessible universes

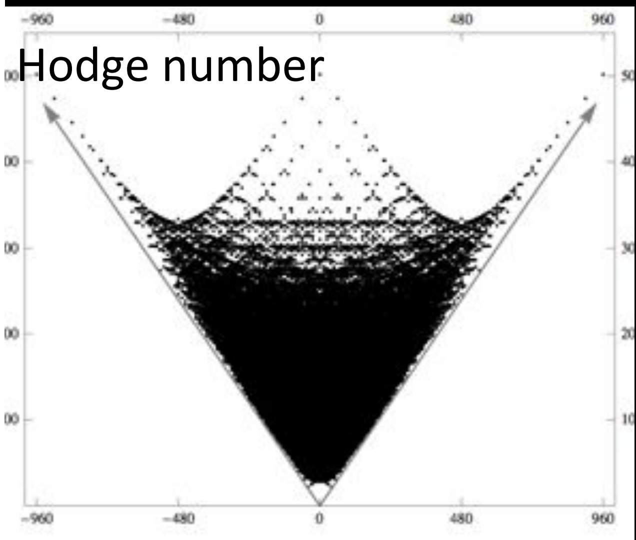



**The multiverse theory can't make any predictions … it can explain anything…** — **George Ellis**

# Multiverse: an astrophysical explanation?

e.g. a very big void

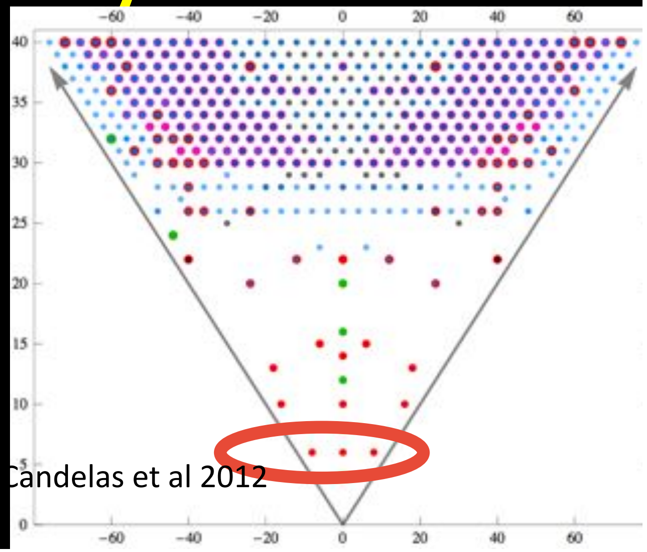

# or a fundamental physics theory?

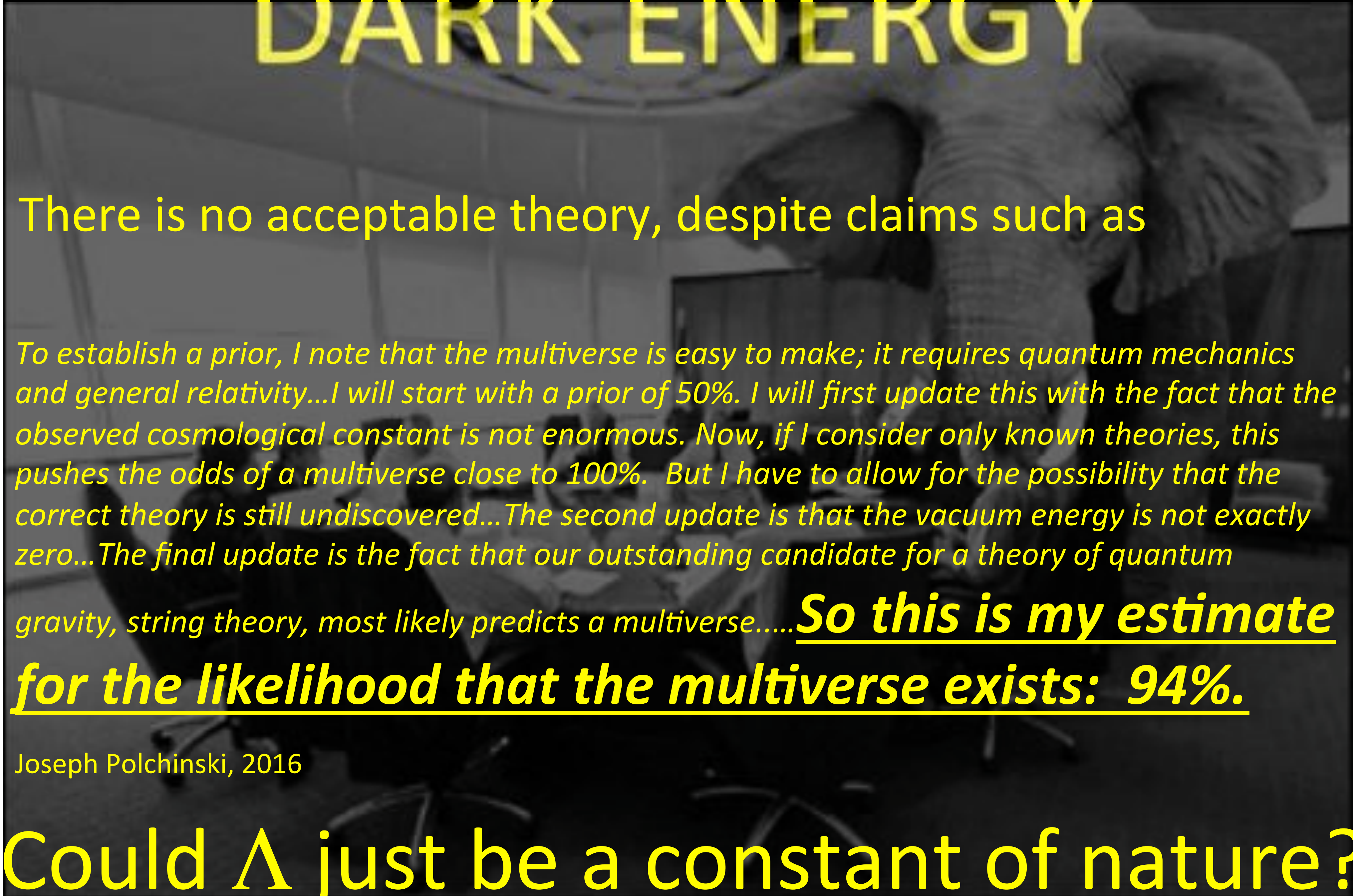



$10^{500}$ Calabi-Yau manifolds to 3

But now its $10^{172000}$ !

Taylor & Wang 2016





# DARK ENERGY

There is no acceptable theory, despite claims such as

*To establish a prior, I note that the multiverse is easy to make; it requires quantum mechanics and general relativity…I will start with a prior of 50%. I will first update this with the fact that the observed cosmological constant is not enormous. Now, if I consider only known theories, this pushes the odds of a multiverse close to 100%. But I have to allow for the possibility that the correct theory is still undiscovered…The second update is that the vacuum energy is not exactly zero…The final update is the fact that our outstanding candidate for a theory of quantum gravity, string theory, most likely predicts a multiverse.….* ***So this is my estimate for the likelihood that the multiverse exists: 94%.***

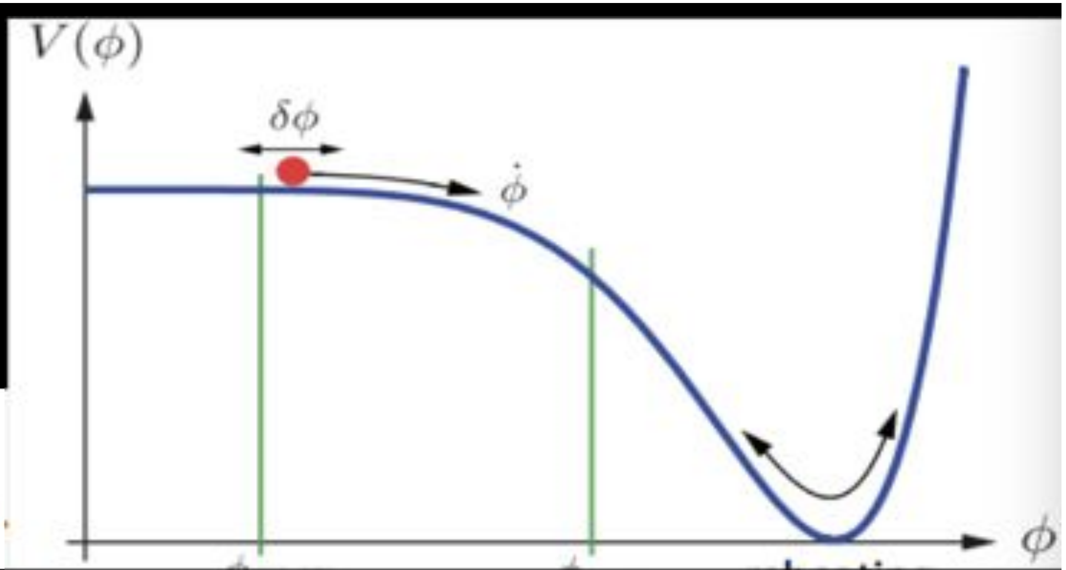
Joseph Polchinski, 2016

Could $\Lambda$ just be a constant of nature?

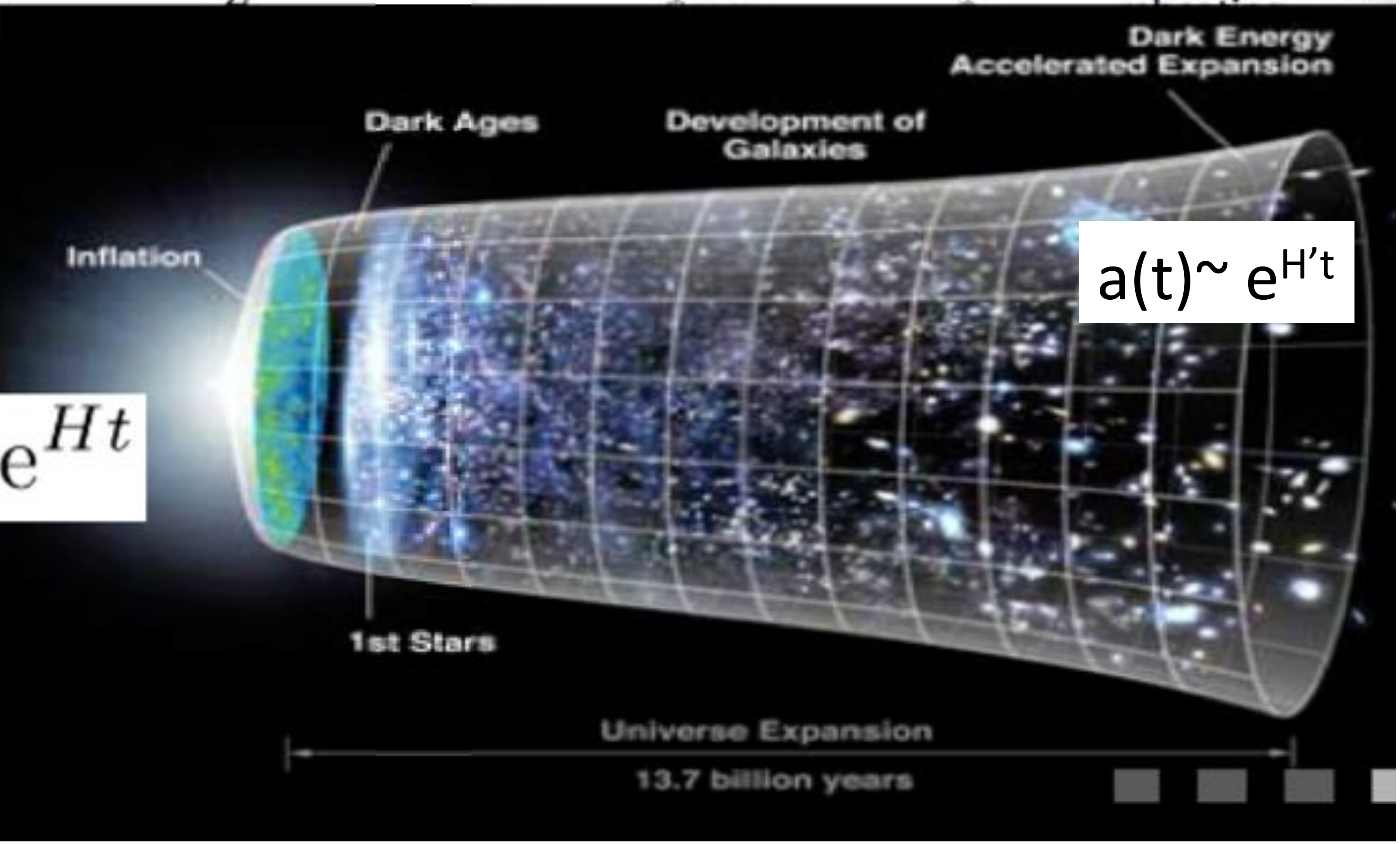
# Inflation via slow roll

$$\frac{\ddot{a}}{a} = -\frac{1}{6M_{\rm Pl}^2}\sum_i(\rho_i + 3p_i)$$

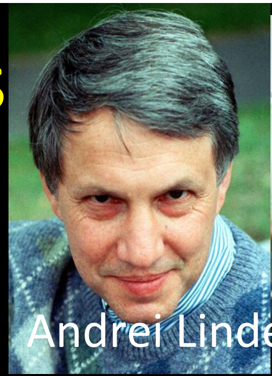
$$\rho = \frac{\dot{\phi}^2}{2} + V(\phi), \quad p = \frac{\dot{\phi}^2}{2} - V(\phi)$$




$$a(t) \sim \mathrm{e}^{Ht}$$



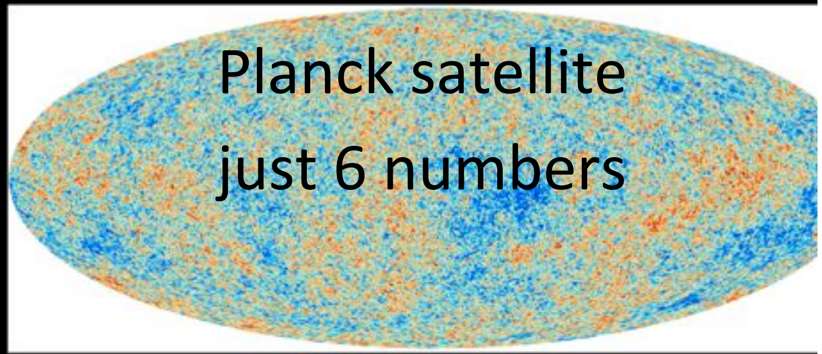
# 1980s inflation made 3 predictions





1. flatness of space
2. size of the universe
3. primordial density fluctuations

## 2017: most trust inflation



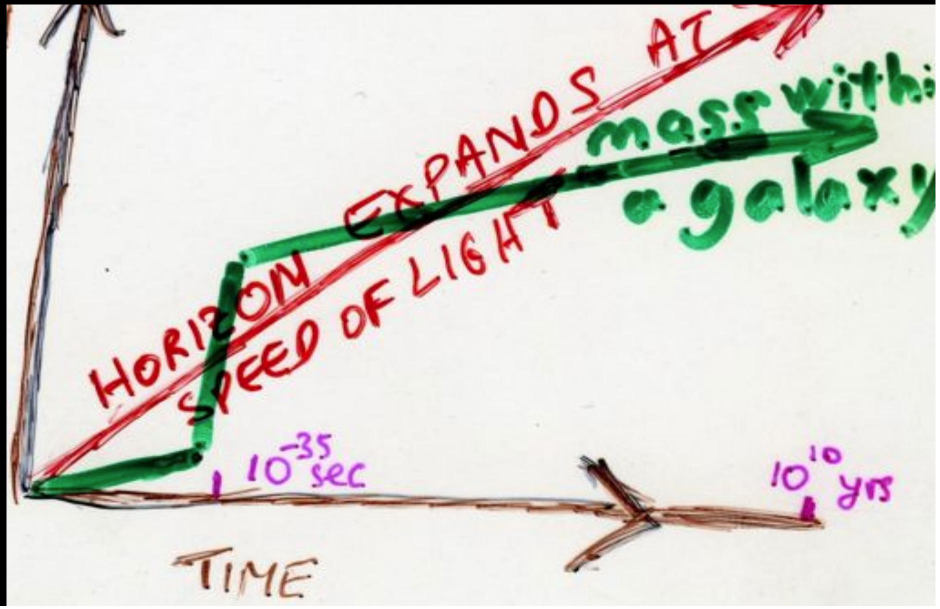

# PREDICTIONS

**Gaussianity of fluctuations**

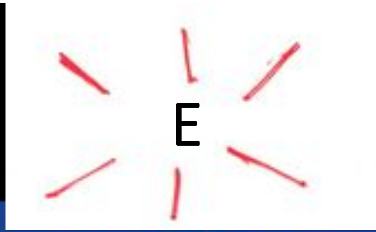
$f_{NL}$ $\delta T/T < 0.01\%$

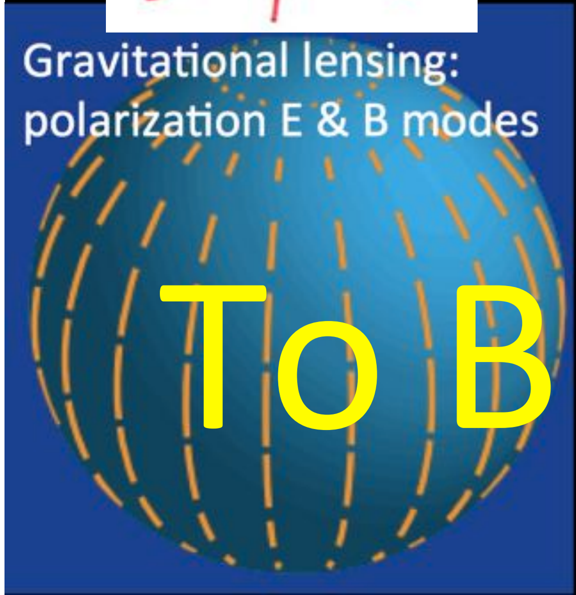
**Gravity wave background**

T/S < 0.08   B mode

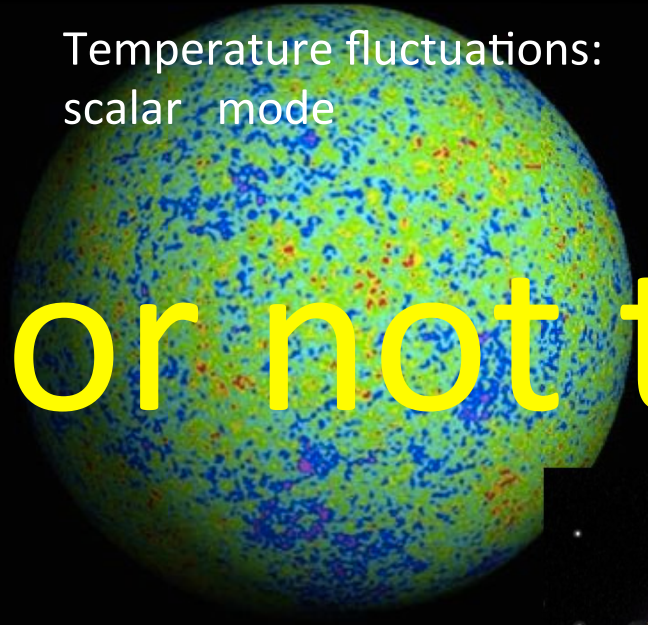


# To B or not to B?

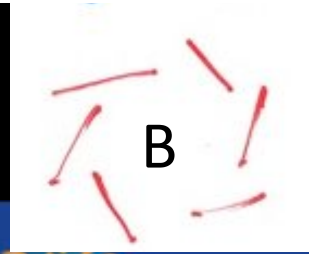


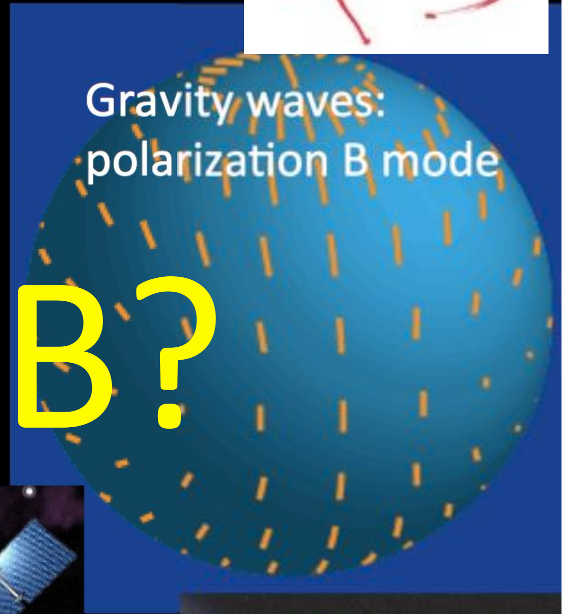



Gravitational lensing: polarization E & B modes

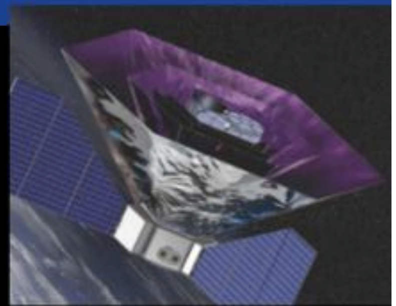


Temperature fluctuations: scalar mode



Gravity waves: polarization B mode



Satellites: LiteBIRD (JAXA launch in 2022?)

PIXIE (NASA launch in 2022?)

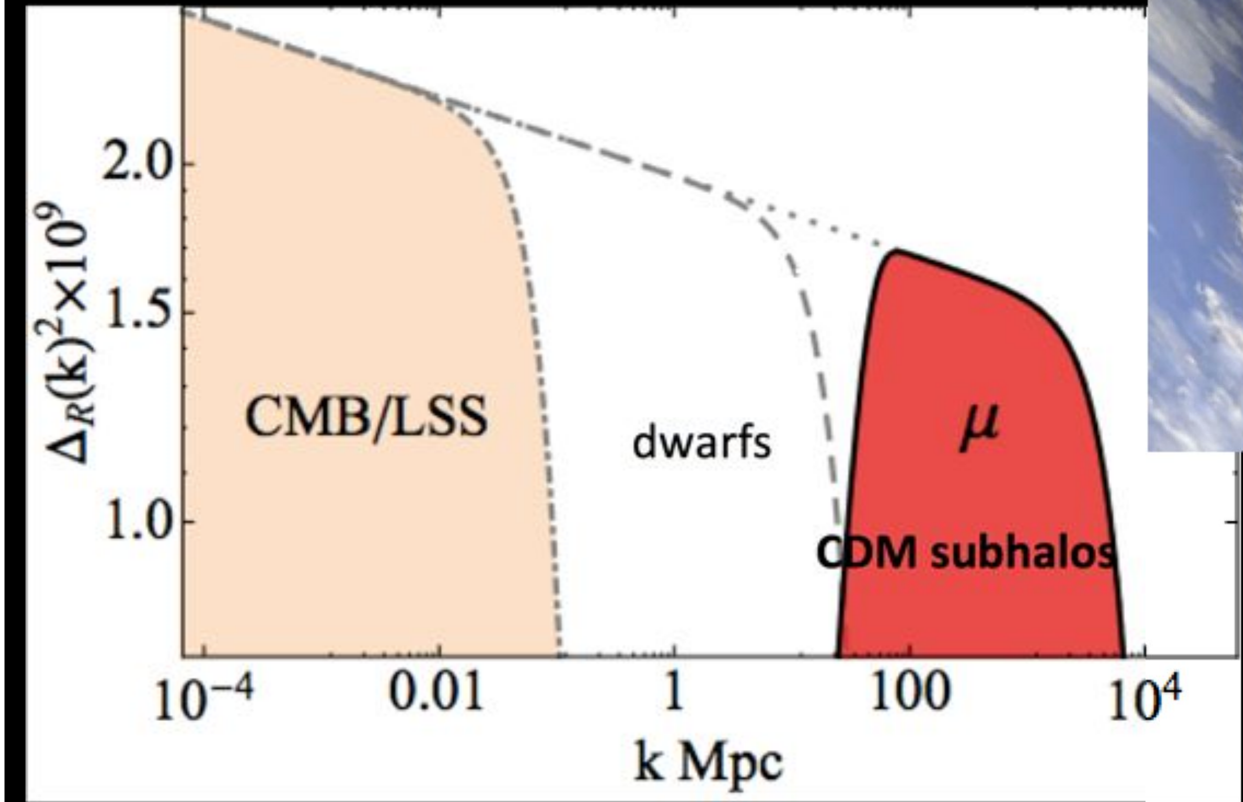
ground/balloon: CMB-S4, c. 2020



But there is no guarantee of a signal!

# A search for spectral distortions

## Guaranteed signal

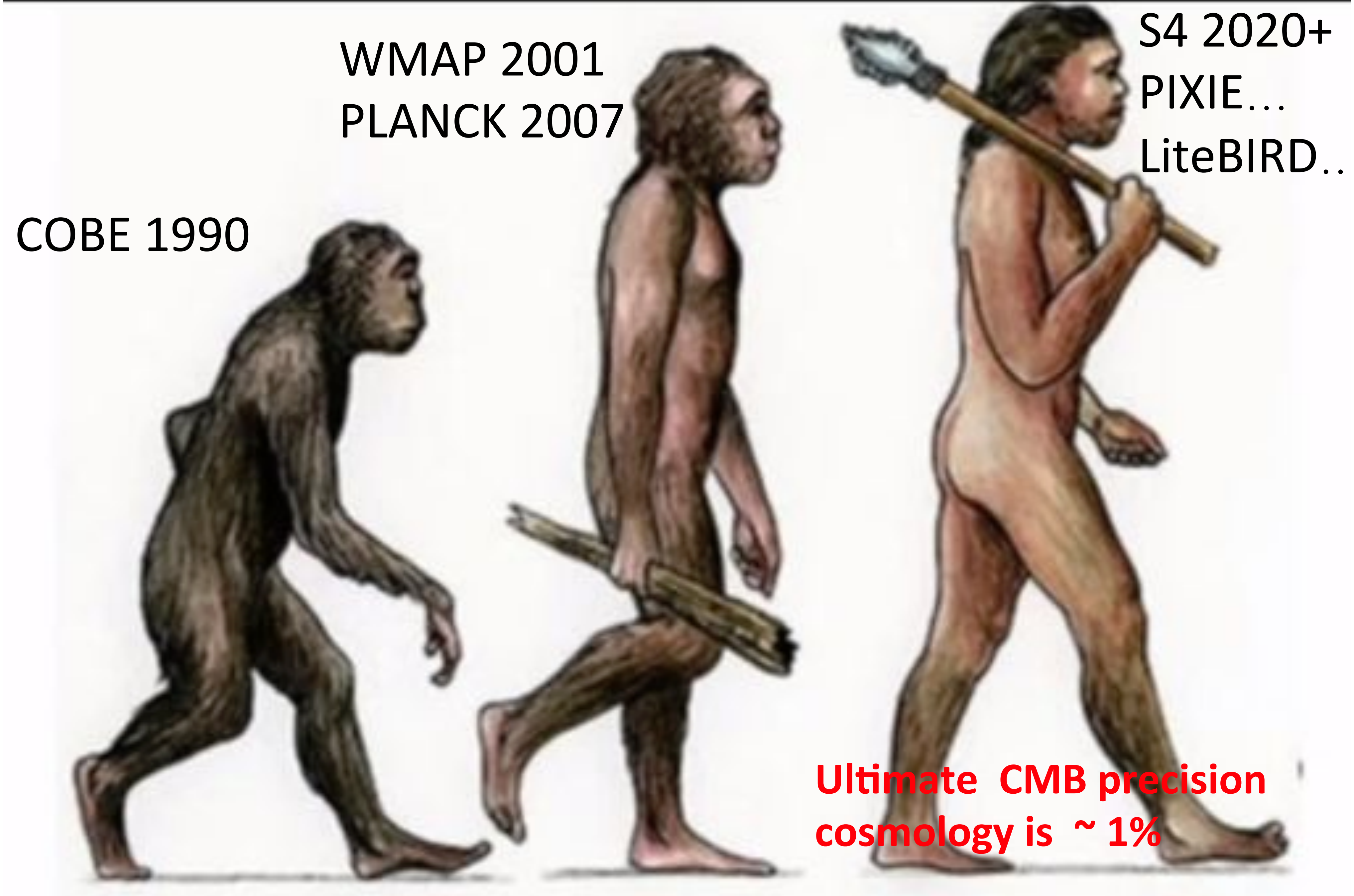



But PIXIE won't be sensitive enough

Pajer & Zaldarriaga 2013

Can we do more?

[redacted]


COBE 1990
WMAP 2001
PLANCK 2007
S4 2020+
PIXIE…
LiteBIRD..
Ultimate CMB precision
cosmology is ~ 1%

# A different direction

SEEK NON-RANDOM PATTERNS ON THE SKY TO PROBE INFLATION
we call this non-gaussianity and its guaranteed!

The Planck satellite already rules out the simplest inflation theories

Inflation most likely is complex,
predicts possibly very low gravity waves
but generically predicts nongaussianity

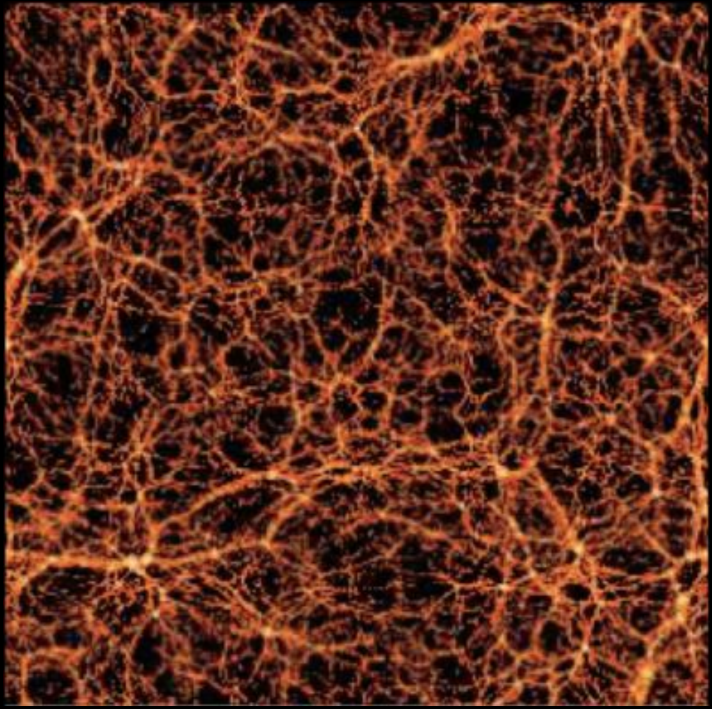
Even in simplest inflation models, there is some non-gaussianity, since corrections involve square of a gaussian , which is non-gaussian.

Non-gaussianity is larger in complex inflation models. But its still very small!

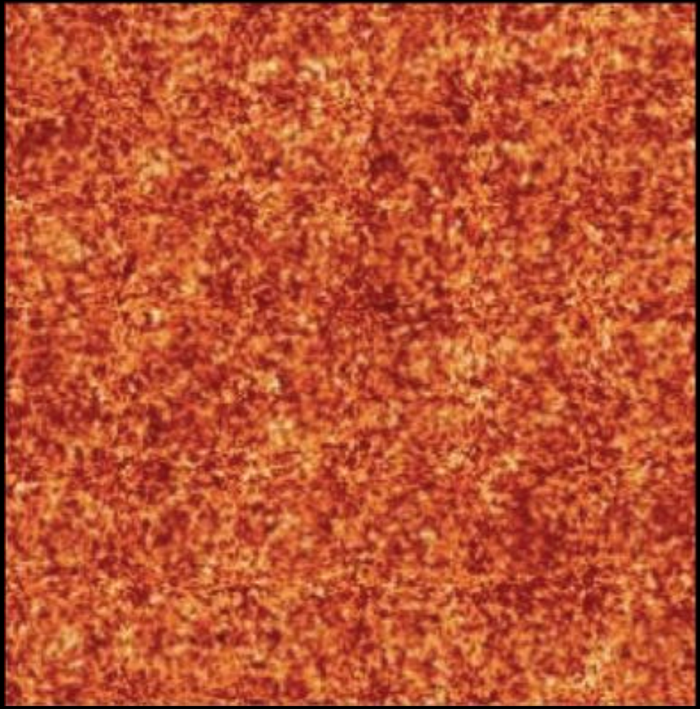
# NON-GAUSSIANITY

## is an essential part of the observed universe

This is our universe



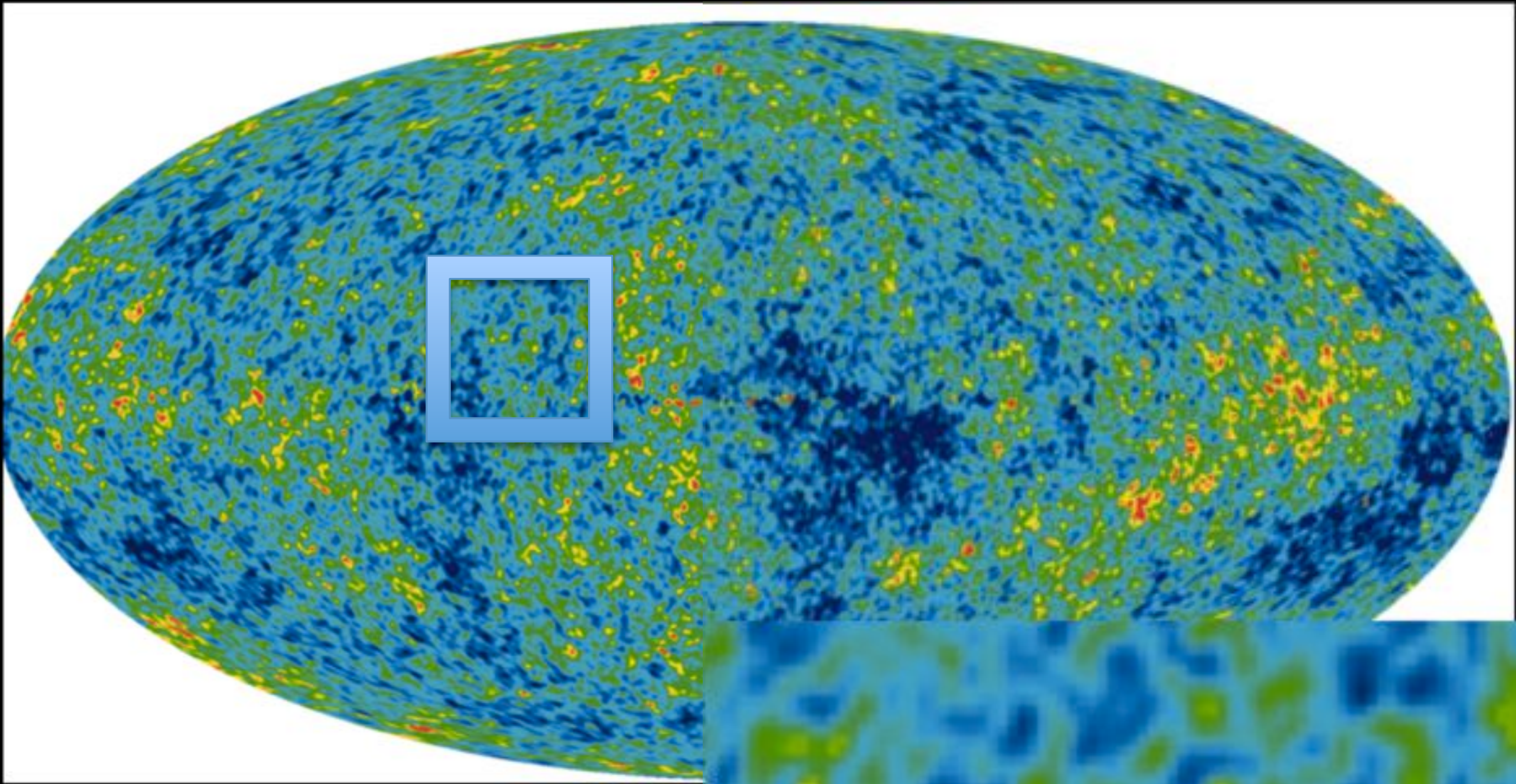
This is not

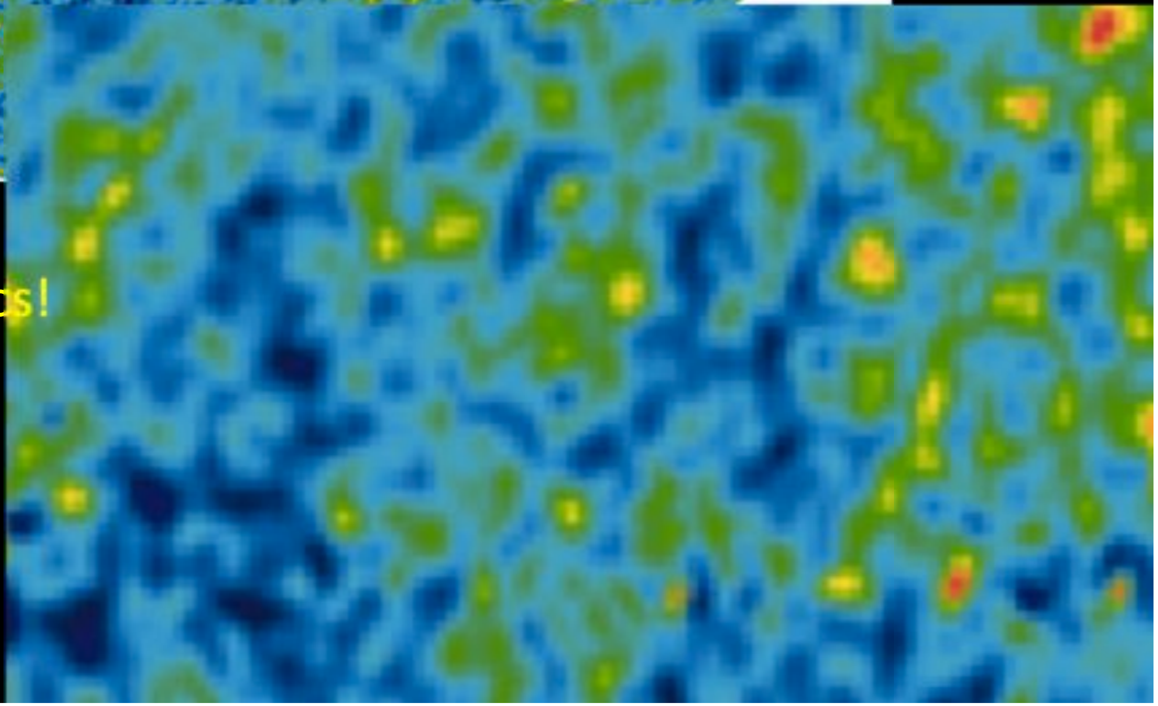


These simulations of galaxy clustering have exactly the same power

## A nuisance for the primordial universe

# An example of nongaussian foregrounds





Seek primordial nongaussianity
But be very careful with your statistics!

# ULTIMATE PROBE OF INFLATION

Only robust prediction of inflation is **non-gaussianity**

The signal is a small fraction $f_{nl}\,\delta T/T$ of temperature fluctuations $\delta T/T$

$f_{nl} < 10$ (current limit) vs ~1 (multifield prediction)

we'd like to get to ~0.01 (vanilla inflation, guaranteed)

Maldacena 2003 $f_{nl} \sim n_s - 1 \sim 0.02$ with Planck $n_s = 0.98$..

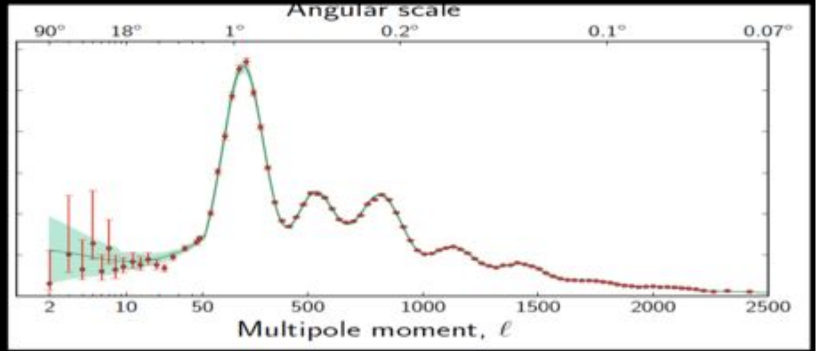
simple inflation already is strongly constrained by the failure to detect gravitational waves in the cosmic microwave background

we need to improve on Planck precision by 100 or more!

Microwave background probes N~$10^6$ independent samples

to l~1000

2D limiting accuracy $N^{-1/2}$ ~ 0.1%

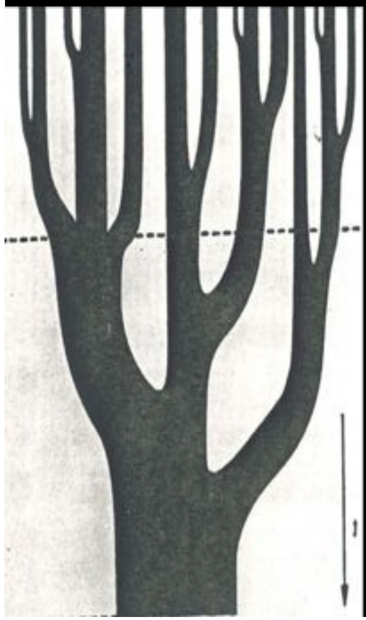



# How do we increase N?

galaxy surveys? 3D probe allow

N~ $10^9$ but galaxies are biased probes

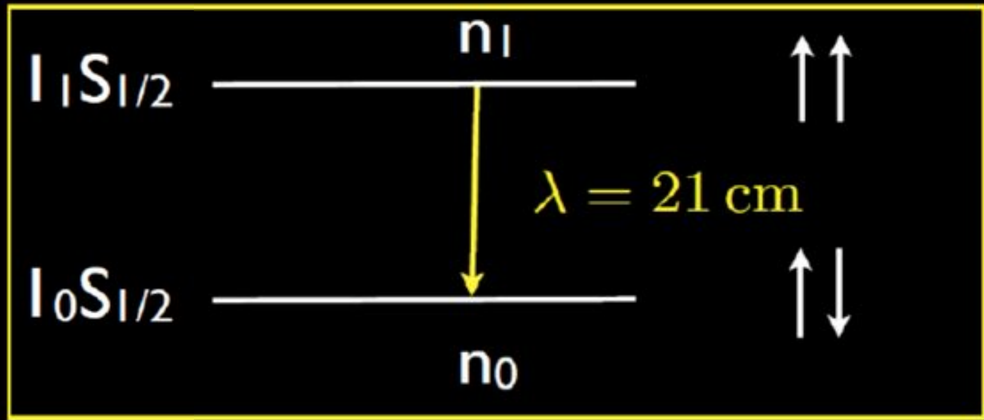
Need to go to dark ages to use HI gas clouds, allows N > > $10^{10}$ in 3D



Long ago

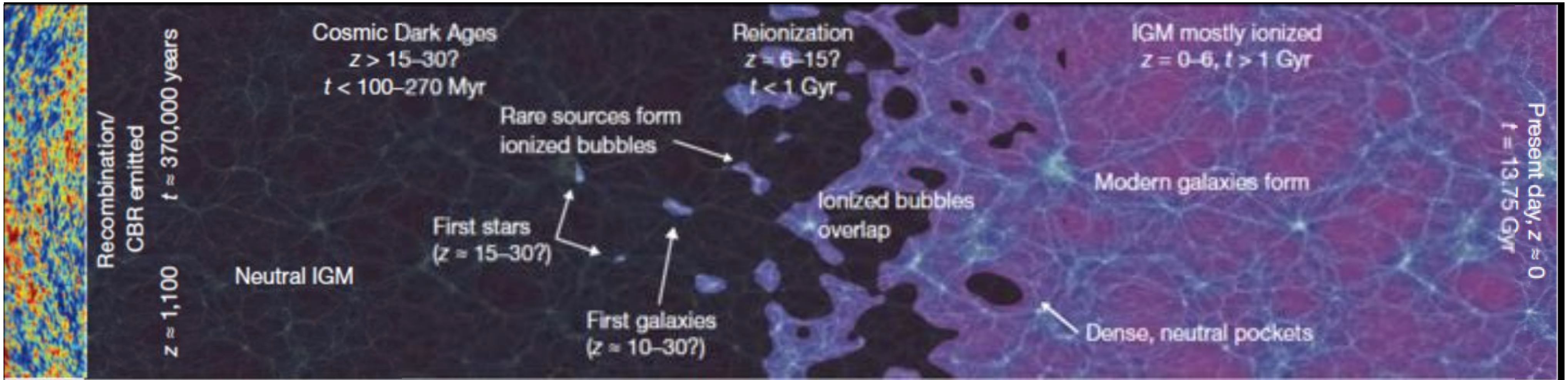
NOW

$$\nu_{21cm} = 1,420,405,751.768 \pm 0.001\ \mathrm{Hz}$$

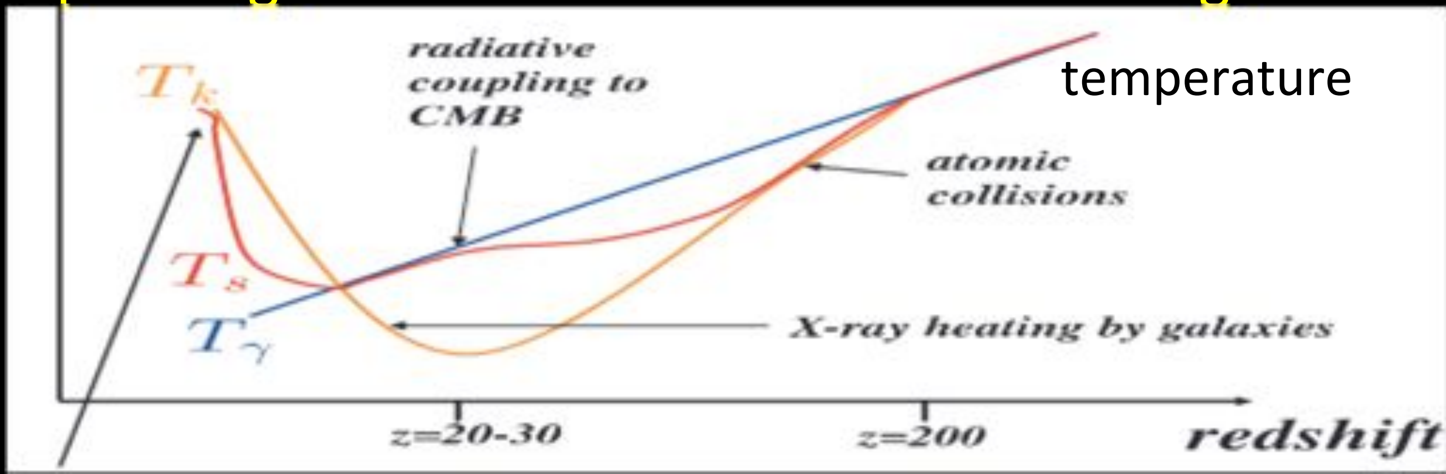



Spin temperature describes relative occupation of levels

Hyperfine transition of neutral hydrogen




Detectable in absorption against the cosmic microwave background




Highly redshifted from a wavelength of 21 cm or a very precise frequency 1420.40575177 GHz

a very challenging experiment!

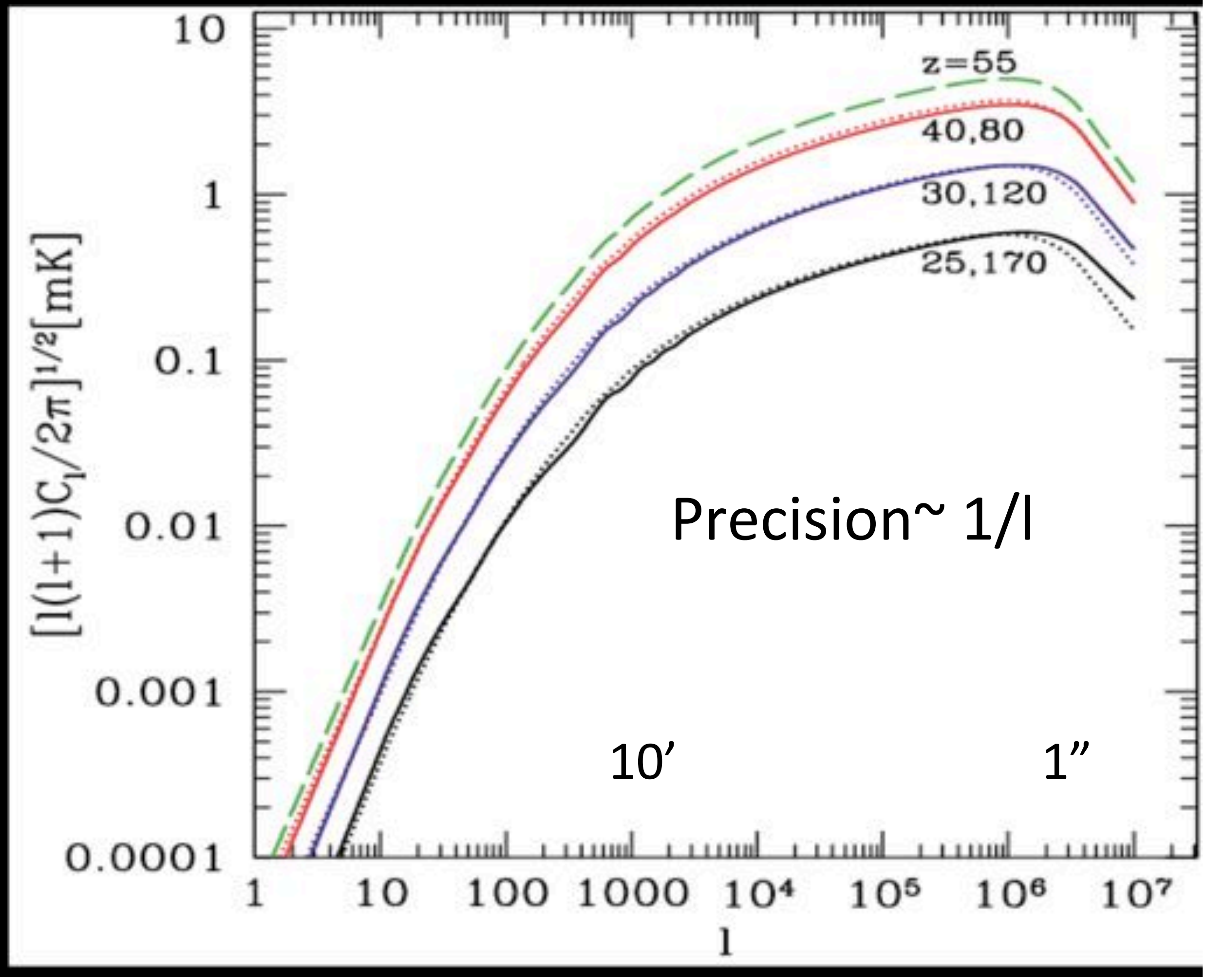
# Sweet spot is at redshift around 50 or a frequency of 35 MHz

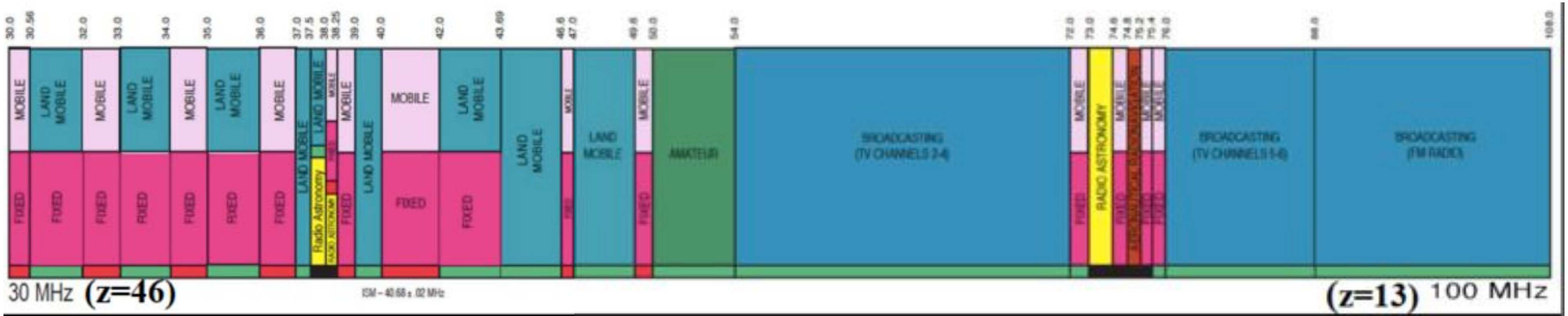
CMB: $\ell \sim 1000$ or $N \sim 10^6$ modes and $f_{nl}\delta\phi < 10^{-3}$ (NB: $f_{nl} < 10$, $\delta\phi \sim 10^{-4}$)

$f_{nl}\delta\phi \sim (n_s-1)\,\delta\phi \sim 10^{-6}$ requires $N \sim 10^{12}$ modes

resolve $\ell \sim 10^5$ + 3d tomography: eg $\Delta\nu/\nu \sim 0.01$

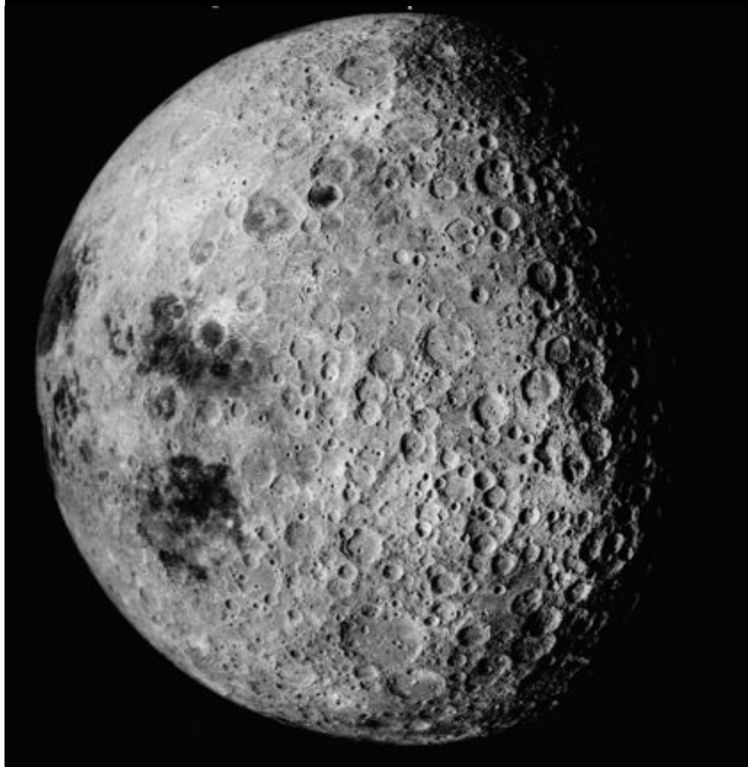
gives $N \sim 10^{10} \times 10^2 \sim 10^{12}$ modes for 21cm experiment






30-40 MHz is a very difficult frequency range to map from the Earth

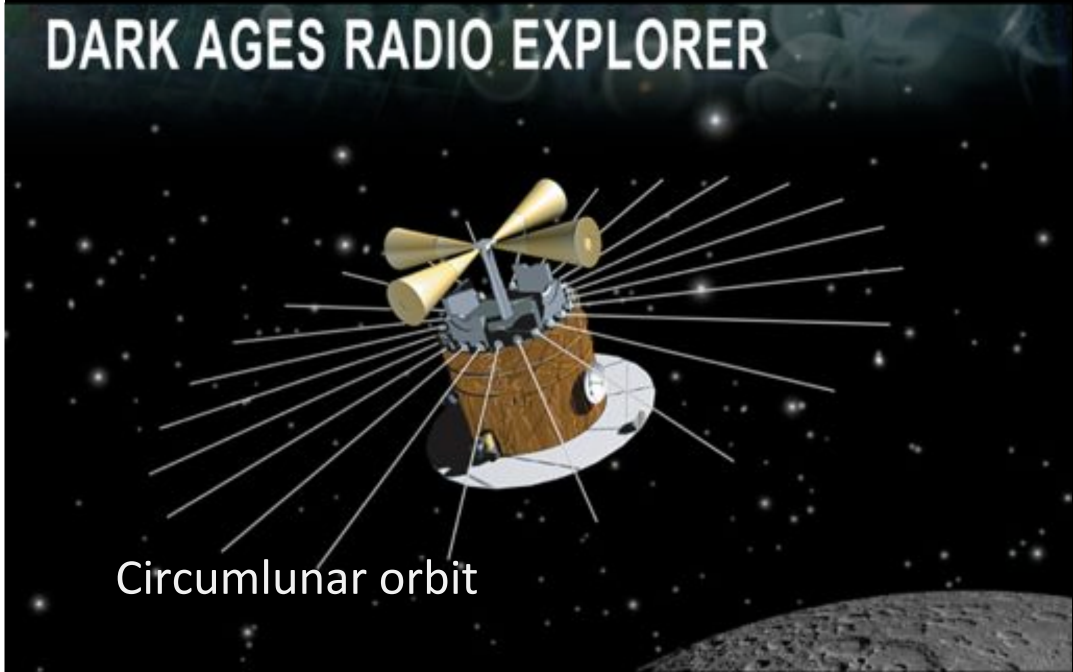
Need to go to far side of MOON for low radio interference



# A vision for the ultimate future of cosmology

far side of the Moon:

first, launch a 30 MHz pathfinder: lunar satellite dipole




Aim: probe reionization epoch z ~ 10

EDGES dipole at MWA site in Western Australia

# STRATEGY

Observe at 30 MHz or $\lambda$=21cm x (1+z)=10m

Need to resolve $\ell \sim 10^5$ or a few arc-seconds

Optimal telescope array size is $\ell\lambda/2\pi$ or a few100 km

Optimal bandwidth L=1 Mpc ($\Delta\nu$/0.1MHz)

Need millions of ~10m dipole antennas for sensitivity, as it's a weak signal

Far side of the moon is unique site for radio interferometer dipole array

Allows N ~ $10^{10}$ patches on the sky x $10^2$ resolved along line of sigh

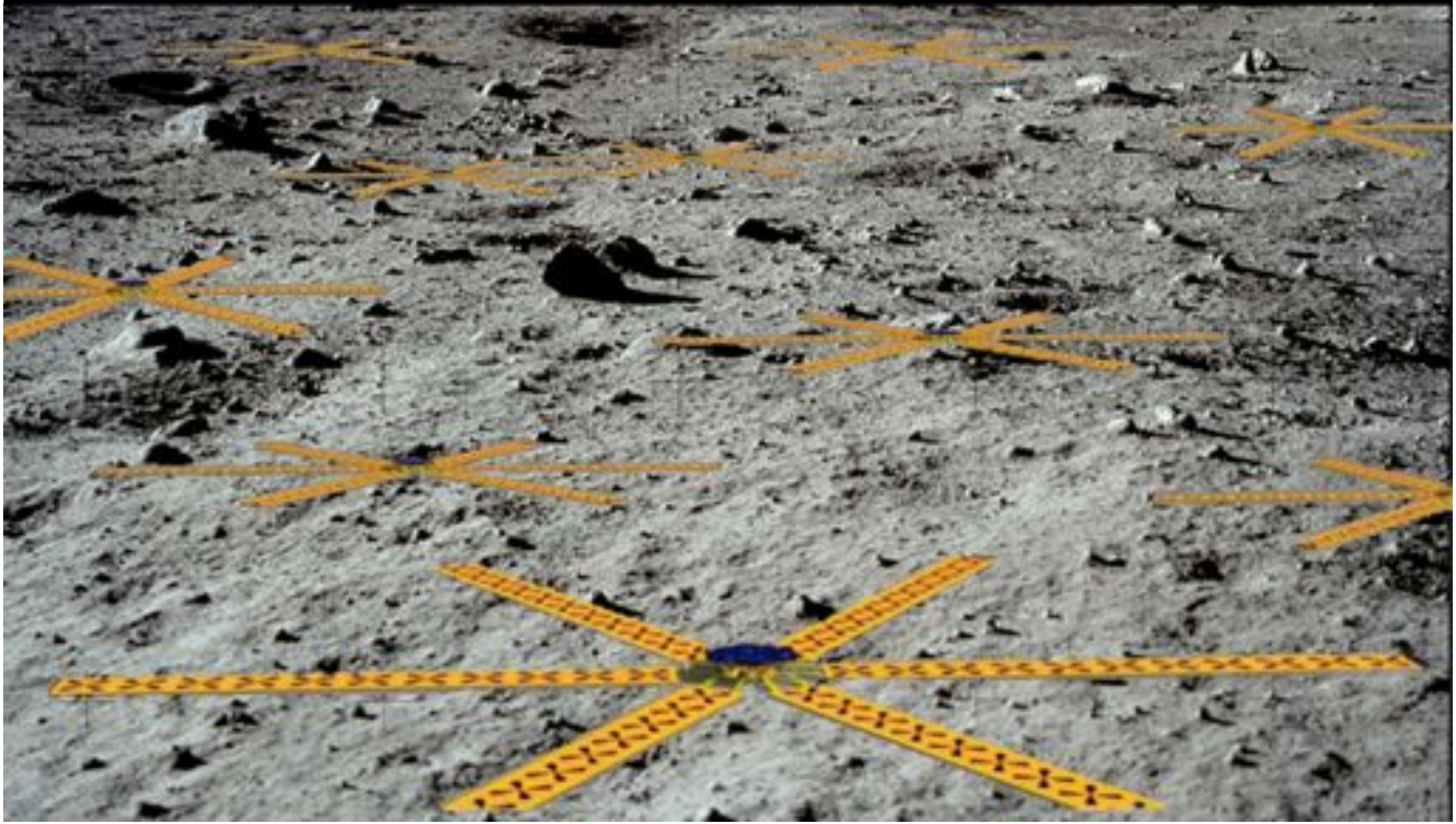
gain up to ~$10^3$ in $N^{1/2}$ relative to CMB

This enables precision cosmology at a part in a million

NEED lunar satellites to add baselines, download data

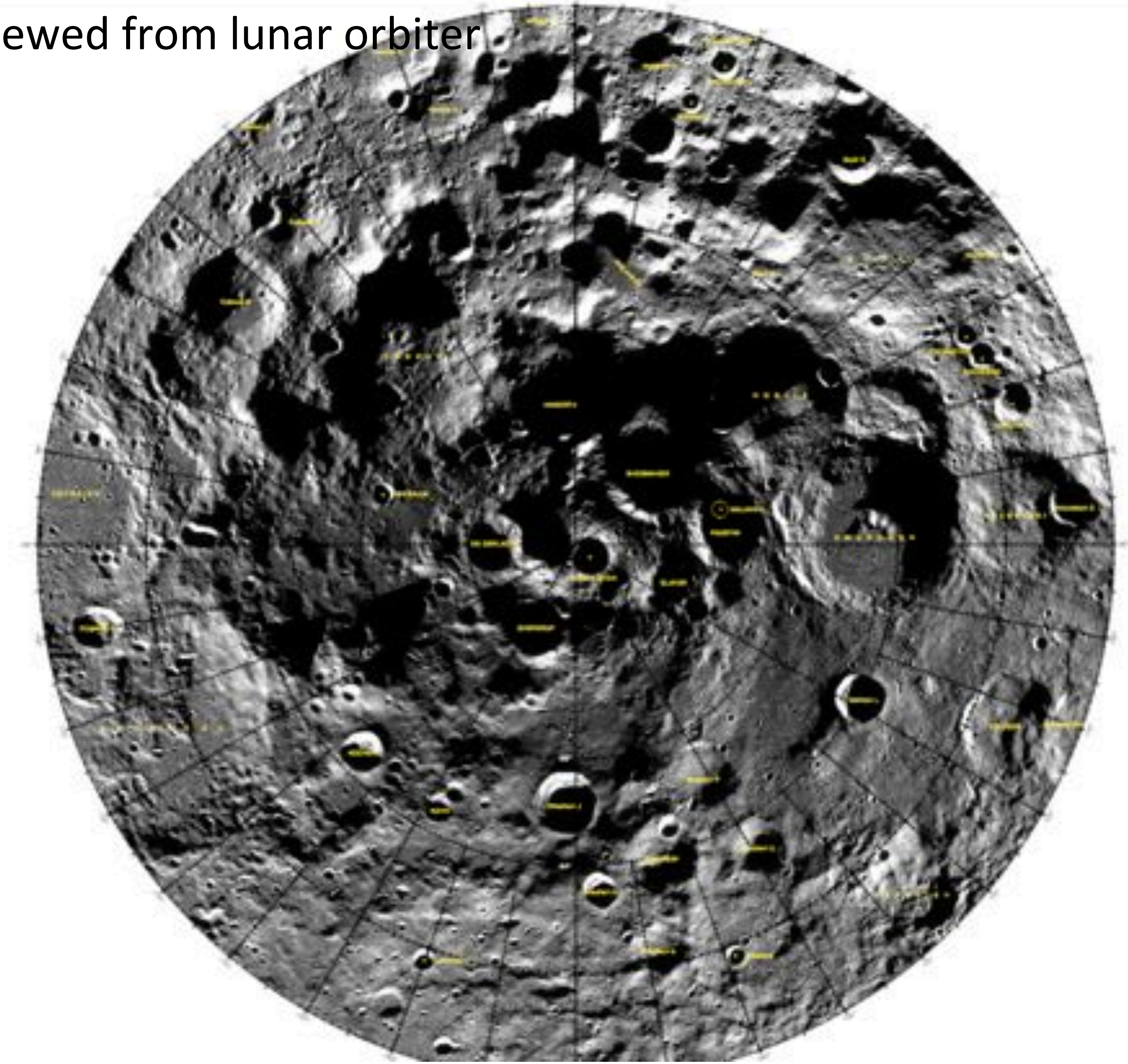
# Far side of the Moon ~ 2050

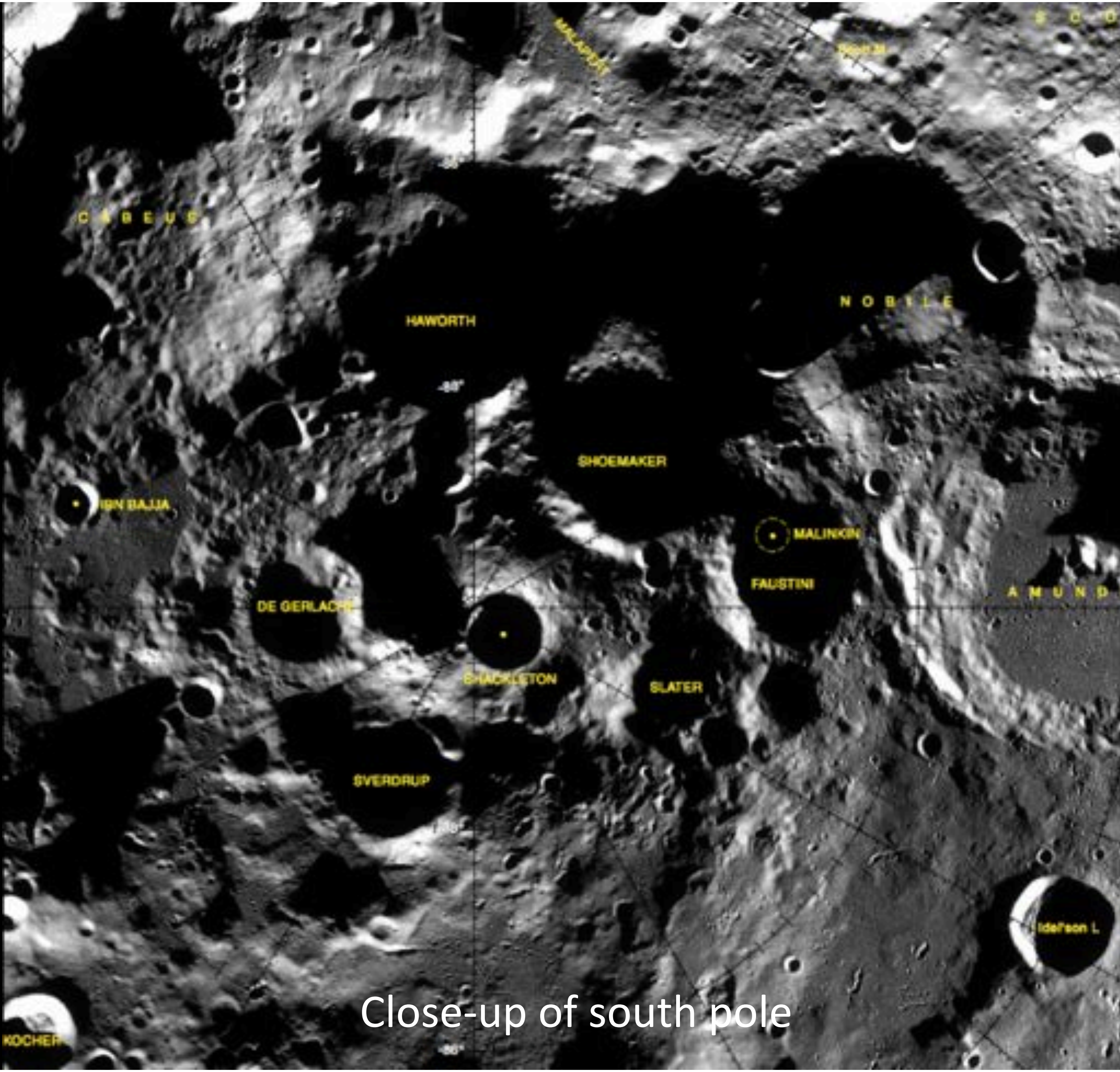
The ultimate dark ages explorer: a lunar dipole array with > $10^6$ dipoles




Moon viewed from earth

Viewed from lunar orbiter



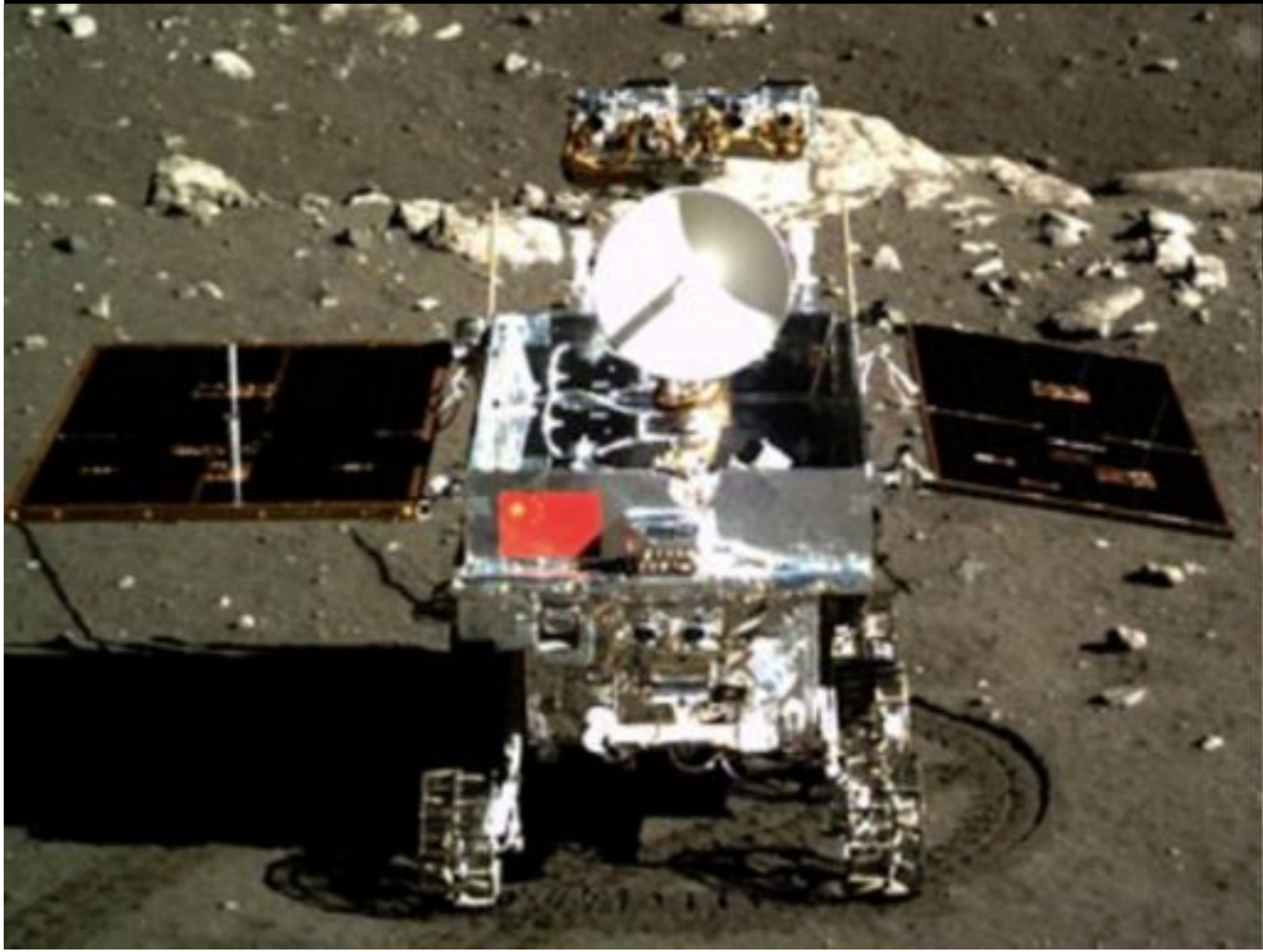


Close-up of south pole

# Thermal image of south pole region

# Chang’e lander  December 2013

Yutu (jade rabbit) moon rover



# ESA concept: Moon Village

# WORKING ON THE MOON

ESA plans include mining Helium-3, tourism…
and why not telescopes ?

**ESA's international moon village concept**

# A non-gaussianity program

CMB: suborbital +space $N \sim 10^6$ $f_{nl} \sim 10$ ($>3\sigma$)

Optical/IR galaxy surveys $N \sim 10^8$ $f_{nl} \sim 1$

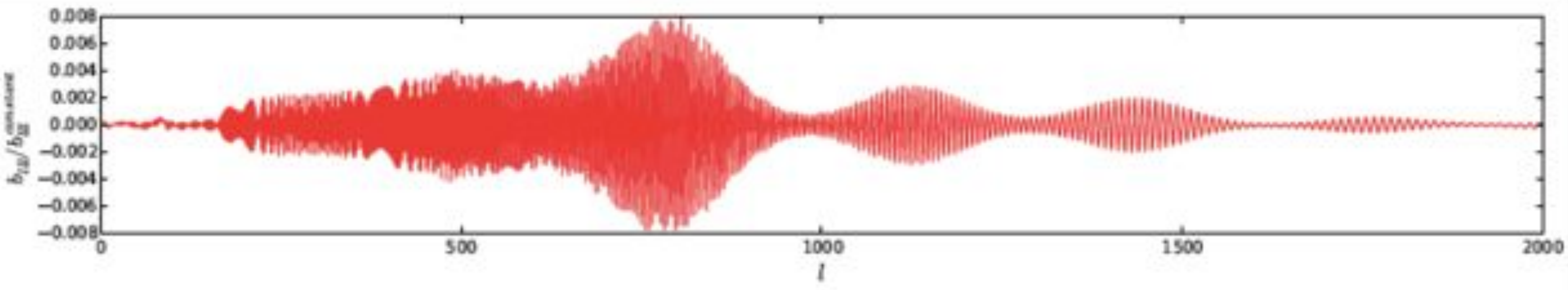
Radio: far side of Moon… $N \sim 10^{10}$ $f_{nl} \sim 0.1$

and eventually $N \sim 10^{12}$ $f_{nl} \sim 0.01$

Foregrounds???

$f_{nl} \sim 1$ is a generic prediction in multifield inflation

Aim: detect pattern of nongaussianity on the sky




Meerburg + 2015

# THE LIMITS OF COSMOLOGY

## Where did we come from?

# The ultimate probe of inflation

## science on the far side of the moon

A radio interferometer will provide at least

- 100 improvement in precision cosmology
- whereas LSST/EUCLID/DESI+ only yields x 10

We'll be able to study the creation of the observable universe via inflation at $10^{-36}$ sec after the Big Bang