the limits of cosmology

UKHEP FORUM

28 November 2017

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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?

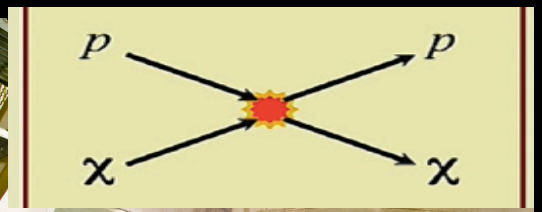
Dark matter many predictions, no success yet

Dark energy no prediction of deviations from Λ

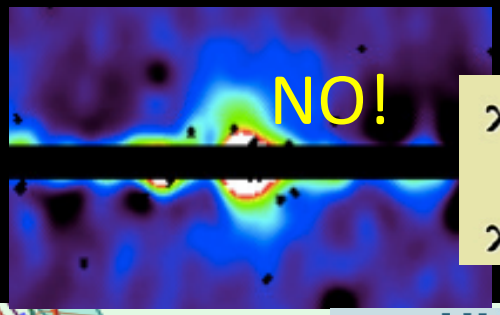
Where do we come from?

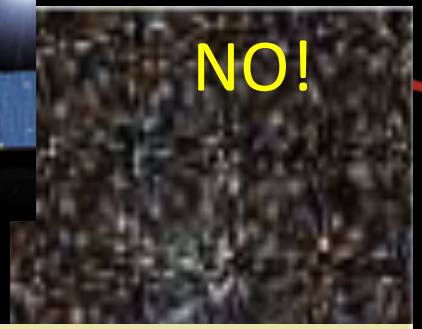
Inflation? best theory so far but needs confirmation!

DARK MATTER


p
p
χ
χ


NO!


NO!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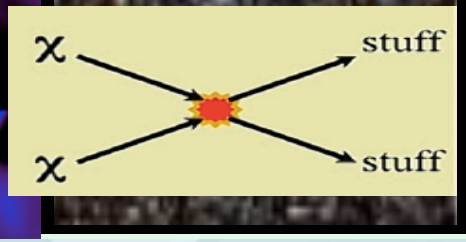
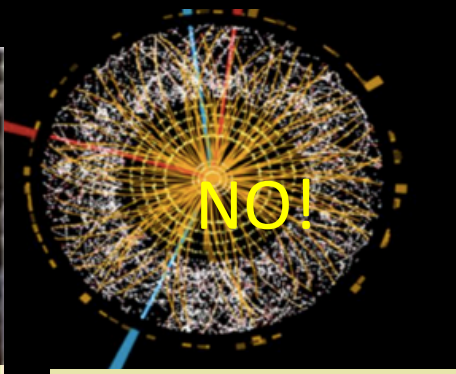
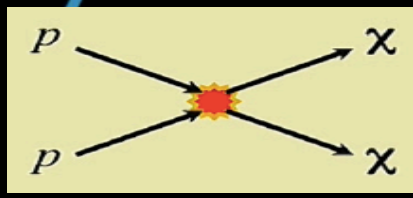

χ
χ
stuff
stuff


NO!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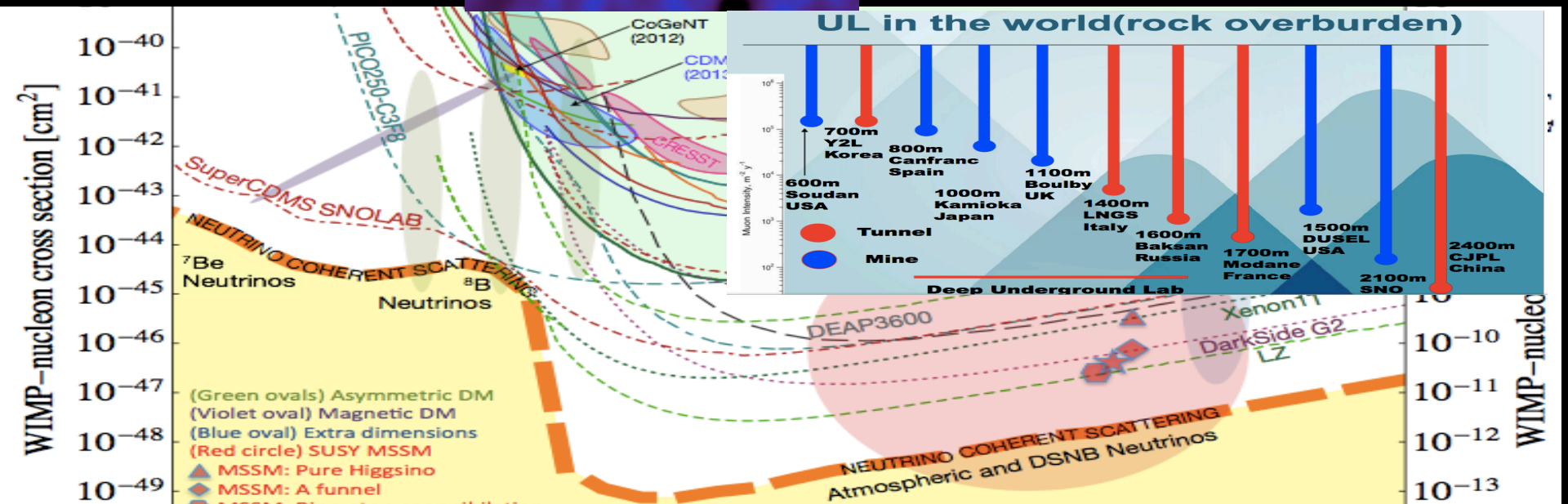
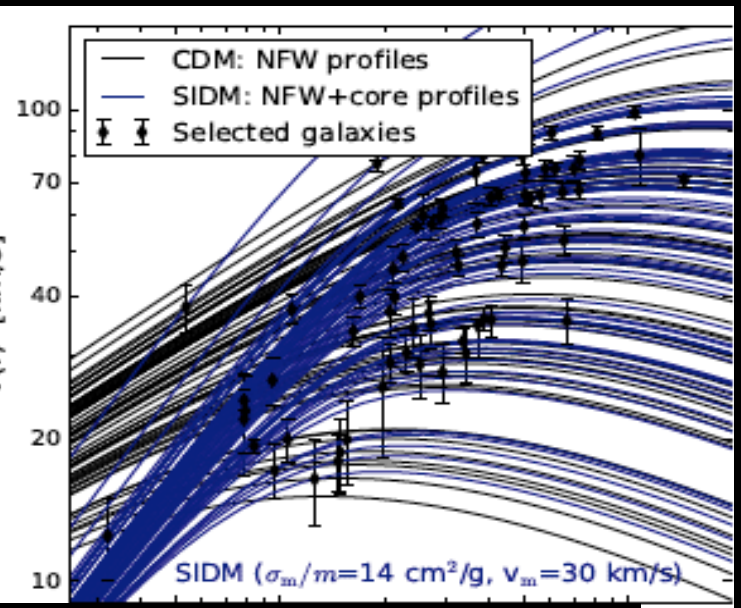
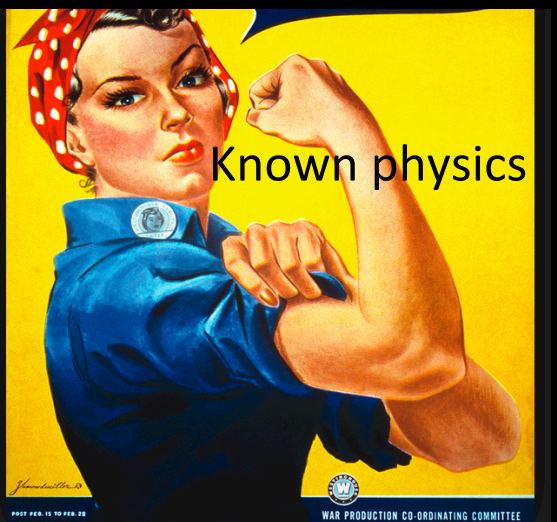

WIMP–nucleon cross section [cm²]
10⁻⁴⁰
10⁻⁴¹
10⁻⁴²
10⁻⁴³
10⁻⁴⁴
10⁻⁴⁵
10⁻⁴⁶
10⁻⁴⁷
10⁻⁴⁸
10⁻⁴⁹
CoGeNT (2012)
CDM
CRESST
PICO250-C3F8
SuperCDMS SNOLAB
NEUTRINO COHERENT SCATTERING
⁷Be Neutrinos
⁸B Neutrinos
DEAP3600
Xenon1T
DarkSide G2
LZ
(Green ovals) Asymmetric DM
(Violet oval) Magnetic DM
(Blue oval) Extra dimensions
(Red circle) SUSY MSSM
MSSM: Pure Higgsino
MSSM: A funnel
NEUTRINO COHERENT SCATTERING
Atmospheric and DSNB Neutrinos
UL in the world(rock overburden)
600m Soudan USA
700m Y2L Korea
800m Canfranc Spain
1000m Kamioka Japan
1100m Boulby UK
1400m LNGS Italy
1600m Baksan Russia
1700m Modane France
1500m DUSEL USA
2100m SNO
2400m CJPL China
Tunnel
Mine
Deep Underground Lab
WIMP–nucleo
10⁻¹⁰
10⁻¹¹
10⁻¹²
10⁻¹³

SIDM?

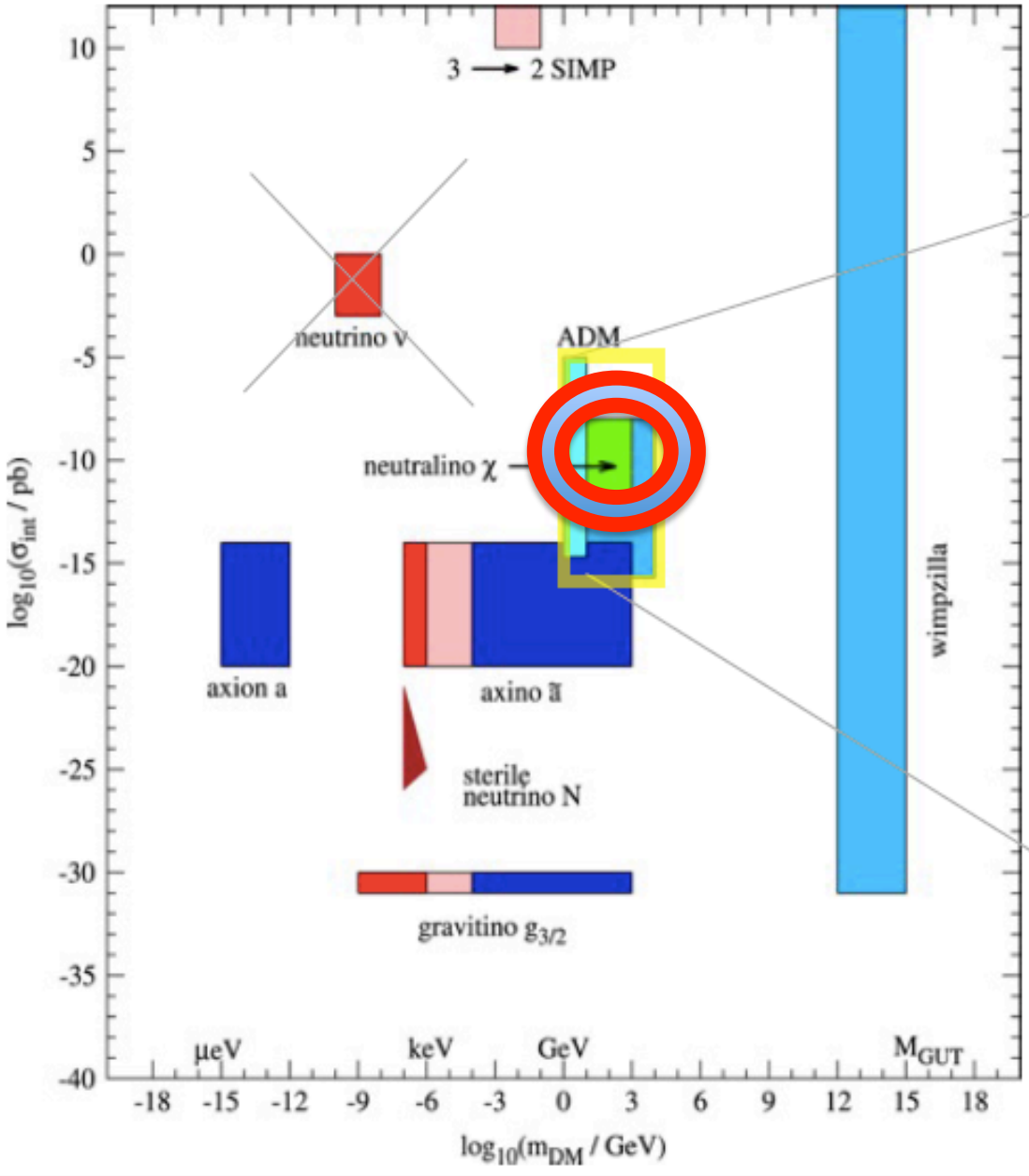
Dwarf galaxy anomalies



PBH can do it!



Searching for the promised land



DARK ENERGY

Cosmological constant: Einstein invented it but Lemaitre interpreted it

EVOLUTION OF THE EXPANDING UNIVERSE

By G. Lemaitre

University of Louvain

Read before the Academy, Monday, November 20, 1933

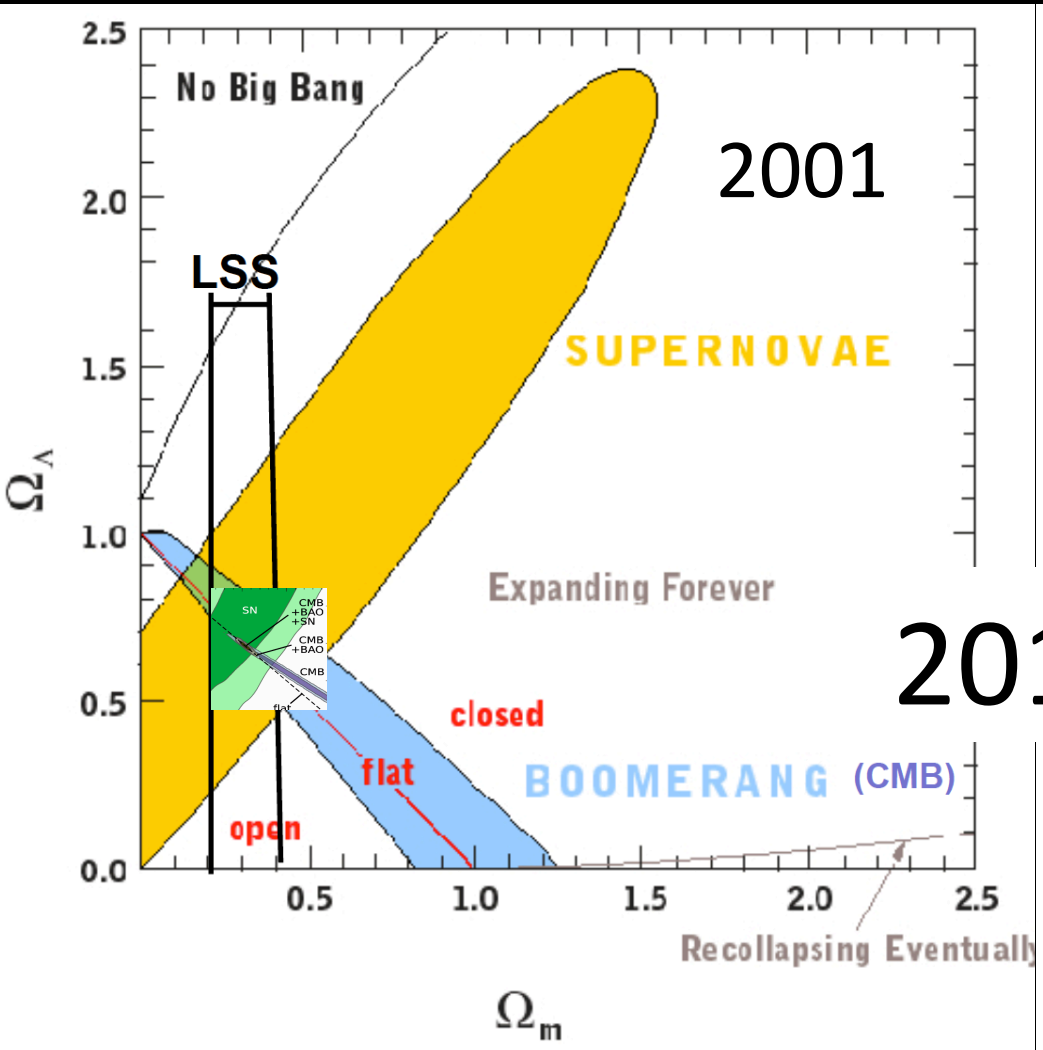
The problem of the universe is essentially an application of the law of gravitation to a region of extremely low density. The mean density of matter up to a distance of some ten millions of light years from us is of the order of 10^{-30} gr./cm.^{3}; if all the atoms of the stars were equally distributed through space there would be about one atom per cubic yard, or the total energy would be that of an equilibrium radiation at the temperature of liquid hydrogen. The theory of relativity points out the possibility of a modification of the law of gravitation under conditions. It suggests that, when we identify gravitatio energy, we have to introduce a constant. Everything happ the energy *in vacuo* would be different from zero. In order motion, i.e., motion relative to vacuum, may not be dete associate a pressure $p = -\rho c^2$ to the density of energy ρ This is essentially the meaning of the cosmical constant λ sponds to a negative density of vacuum ρ_0 according to

$$\rho_0 = \frac{\lambda c^2}{4\pi G} \cong 10^{-27} \text{ gr./cm.}^3$$

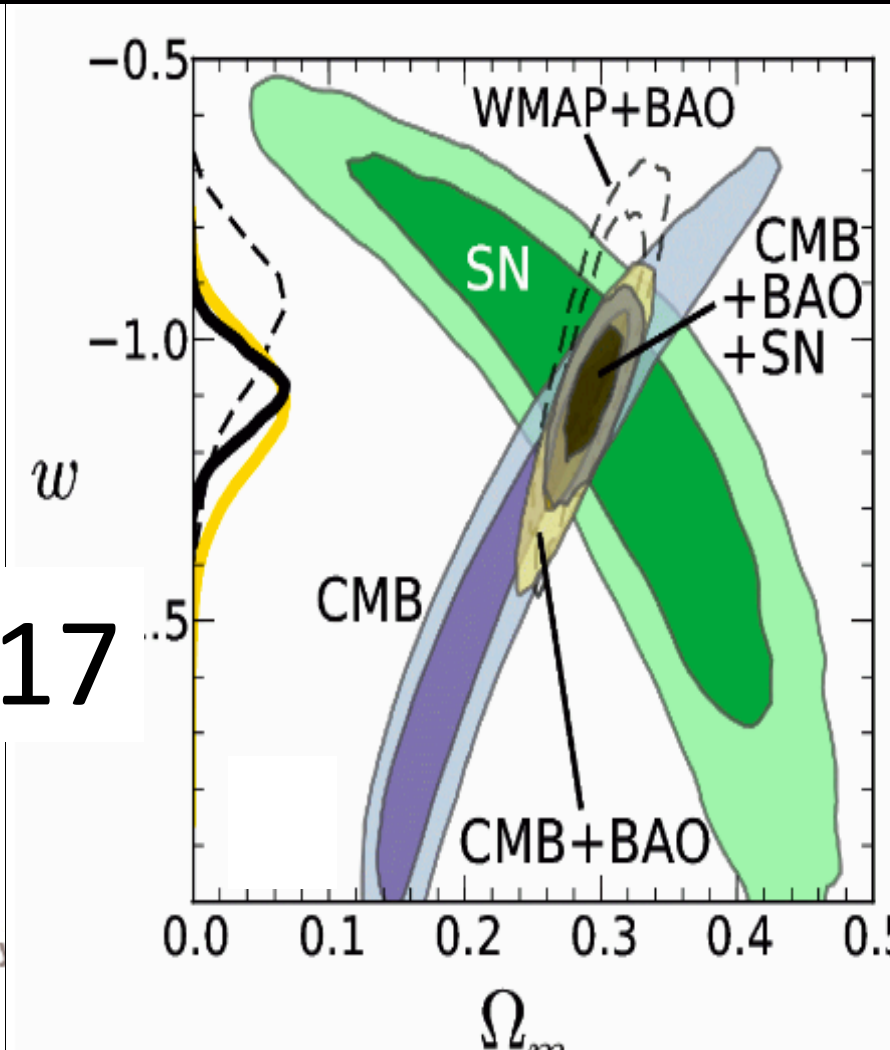
Distant type Ia supernovae are too faint

Where next in cosmology

- Dark energy? no prediction for $p \neq -\rho$



2017



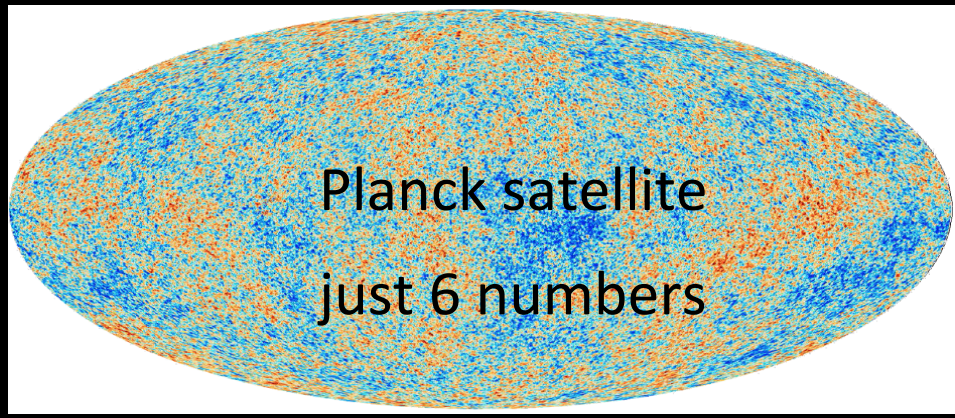
INFLATION

the ultimate goal

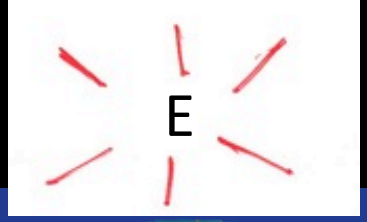
- Dark matter? no detection in sight
- Dark energy? no prediction for w ≠ -1
- Testing inflation via the CMB

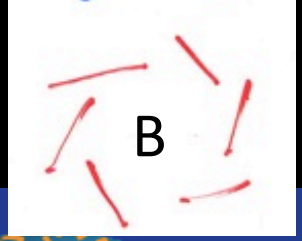
gravity wave background
T/S < 0.08 B mode polarisation

non-gaussianity of fluctuations
f_{NL} $\delta T/T$< 0.01% measured limits

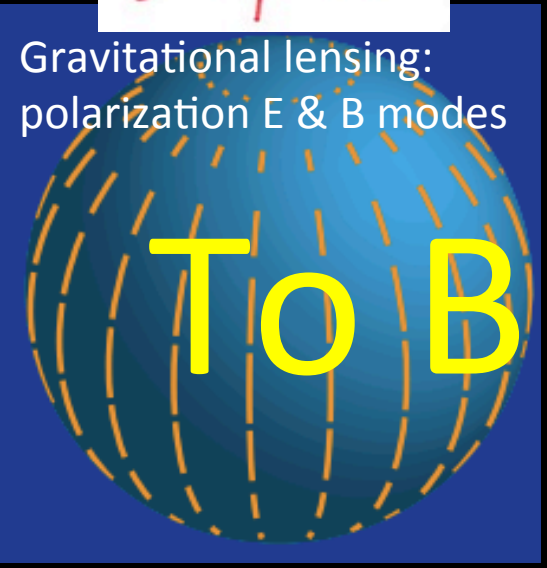


CMB

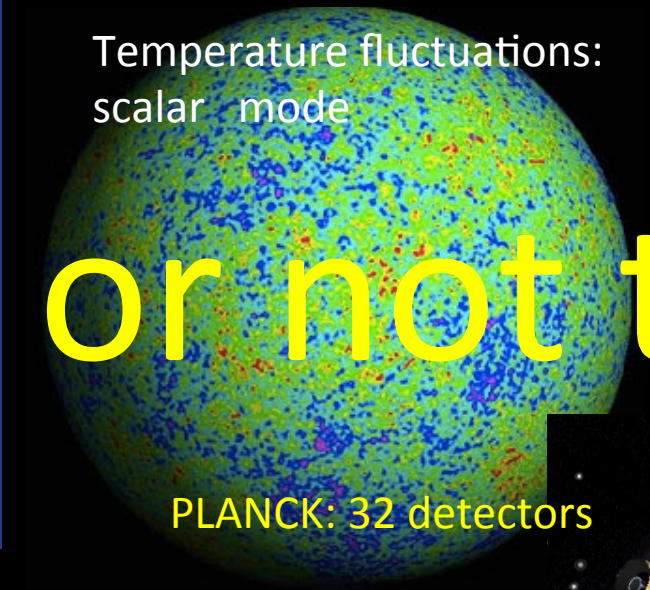




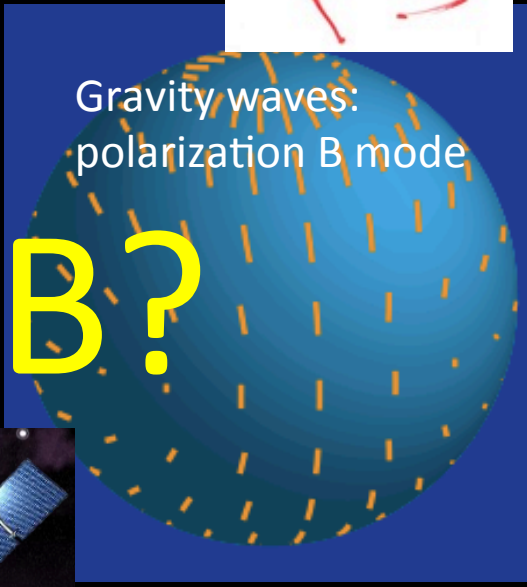
Gravitational lensing:
polarization E & B modes



Temperature fluctuations:
scalar mode



Gravity waves:
polarization B mode



To B or not to B?

PLANCK: 32 detectors

Satellite: LiteBIRD (JAXA launch in 2027?)

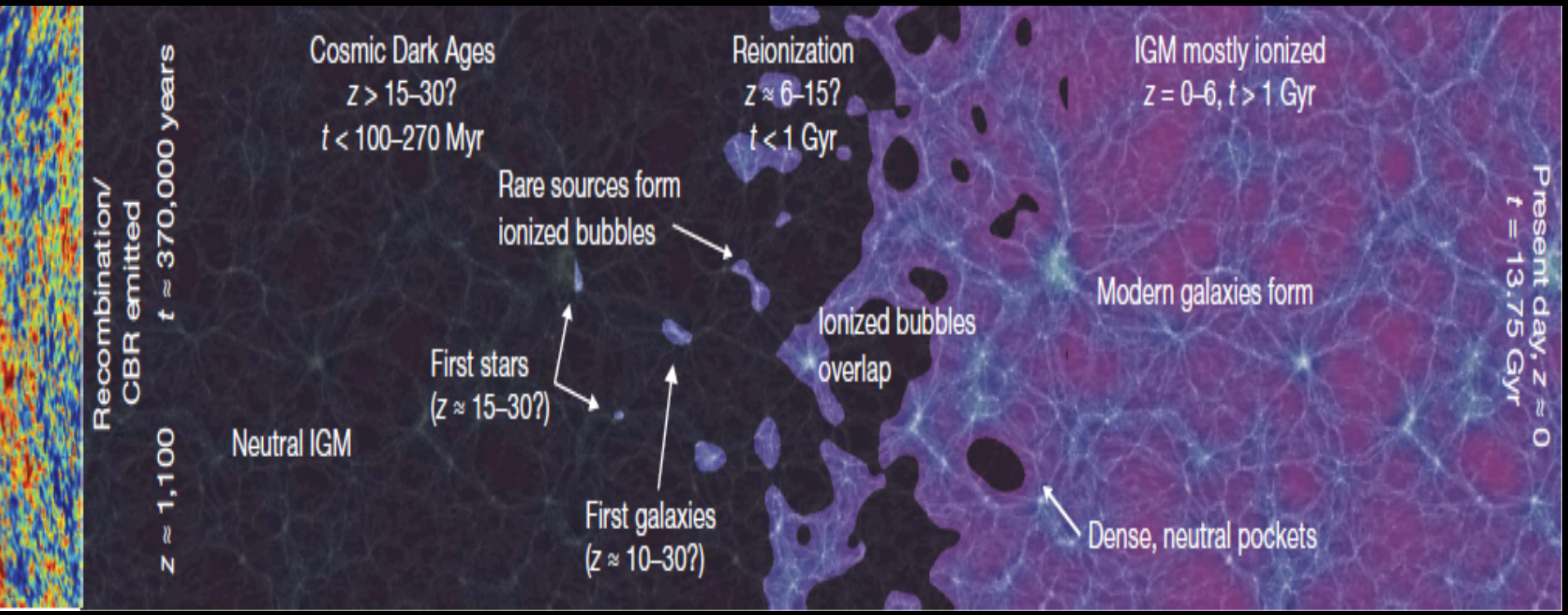
Simons Observatory:
35,000 Detectors – 2TB/day

CMB S4:
500,000 Detectors – 140 TB/day

ground/balloon: CMB-S4, c. 2025

But there is no guarantee of a signal!

DARK AGES


Recombination/
CBR emitted
t ≈ 370,000 years
z ≈ 1,100
Cosmic Dark Ages
z > 15–30?
t < 100–270 Myr
Reionization
z ≈ 6–15?
t < 1 Gyr
IGM mostly ionized
z = 0–6, t > 1 Gyr
Present day, z ≈ 0
t = 13.75 Gyr
Rare sources form
ionized bubbles
First stars
(z ≈ 15–30?)
Neutral IGM
Ionized bubbles
overlap
Modern galaxies form
First galaxies
(z ≈ 10–30?)
Dense, neutral pockets

Another direction in cosmology

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

always some non-gaussianity, since corrections are quadratic

$\delta T/T\ (1+ f_{NL}\ \delta T/T)$

$f_{nl} \sim n_s - 1 \sim 0.03$ with Planck $n_s = 0.96$ is generic

Maldacena 2003

Cabass + 2017: perhaps 0.1 (n_s-1)

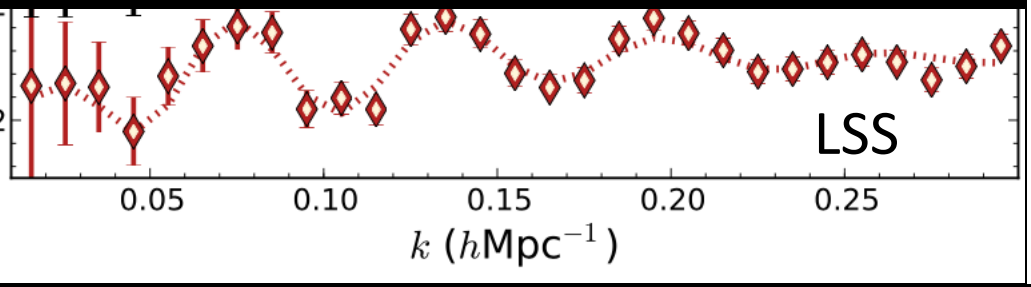
$f_{nl} < 10$ (current limit) vs ~1 (multifield)

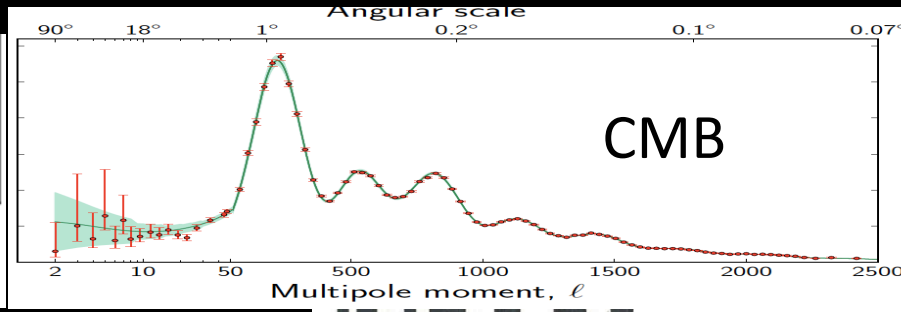
vs ~ 0.01, the ultimate goal

must improve on Planck by 1000!

How to increase number of modes N ?

Microwave background probes N~10^6 independent samples
to l~1000 limiting 2d accuracy $N^{-1/2}$ ~ 0.1%

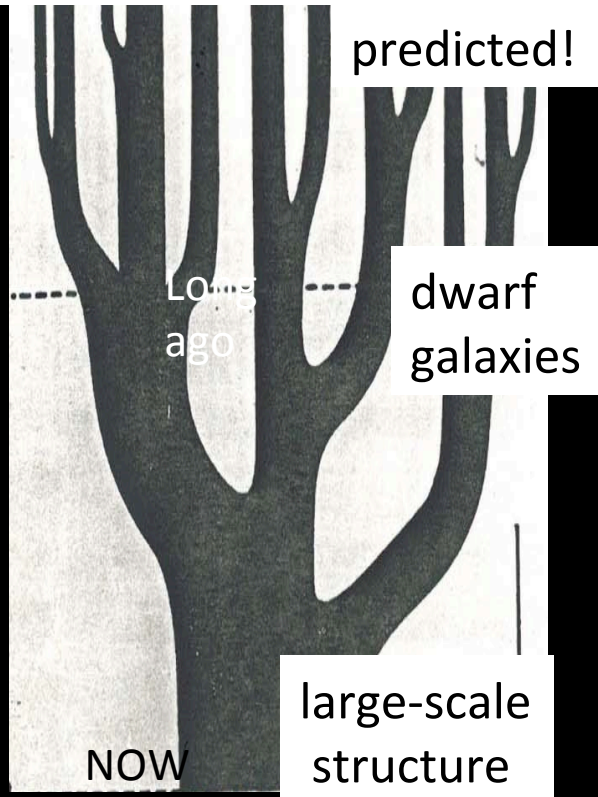




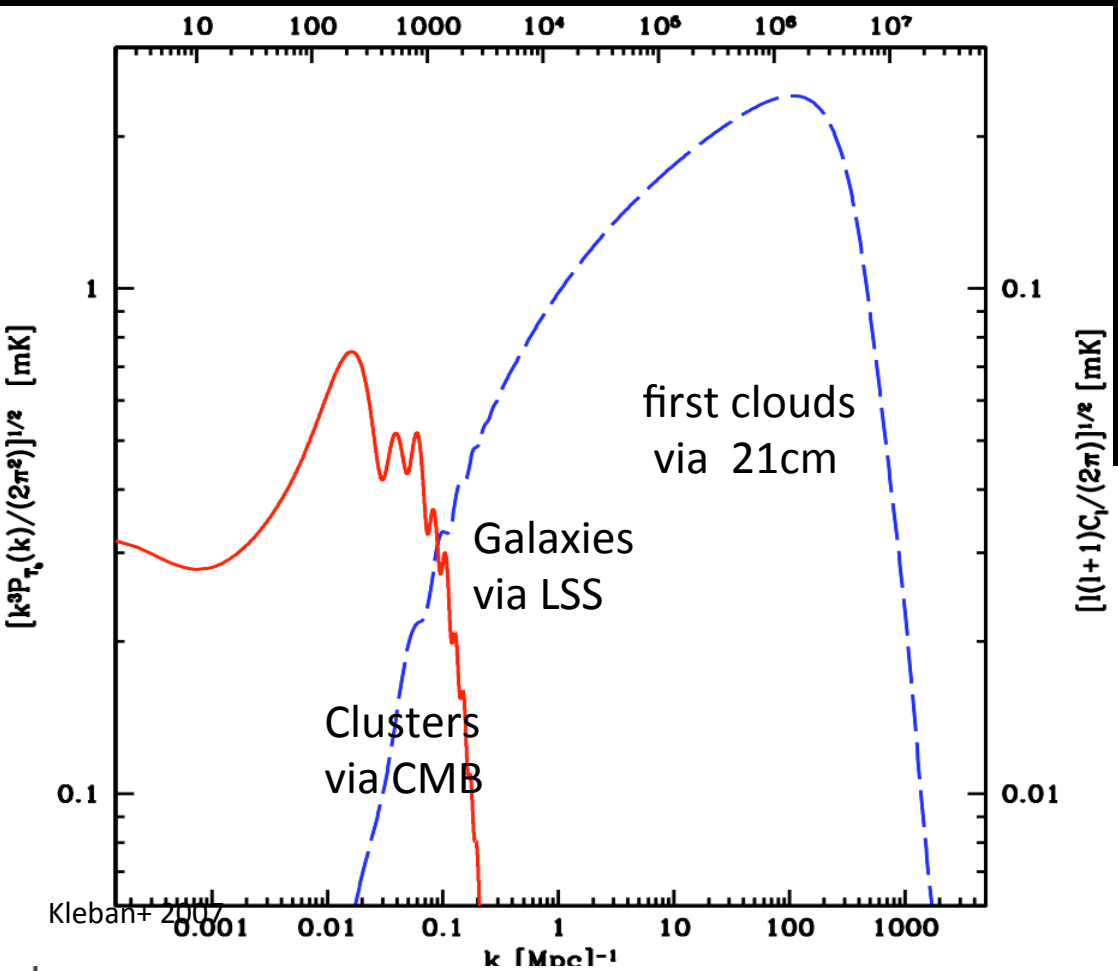
galaxy surveys? 3D probe
allow N~ 10^{10} but galaxies are biased probes
limiting 2d accuracy $N^{-1/2}$ ~ 0.01% for N~10^8

21cm go to early dark ages and use gas clouds, the building blocks of galaxies, allows N > > 10^9

Up to 1000 improvement on Planck, in $N^{-1/2}$!
But its very high redshift

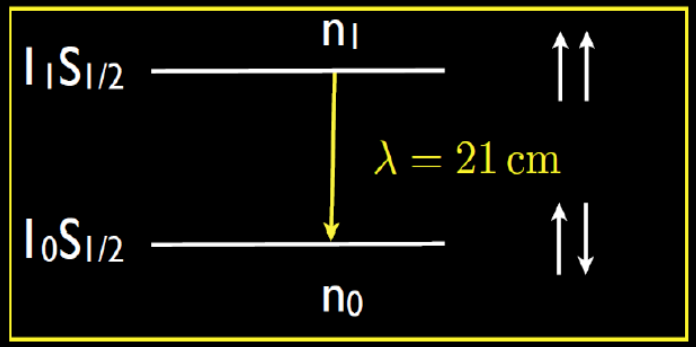


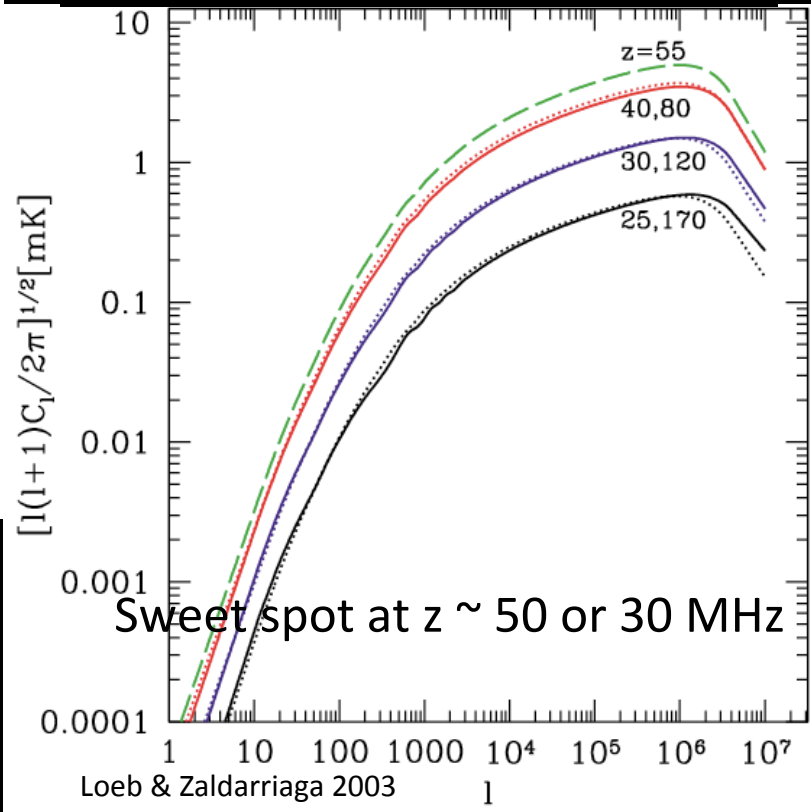
Power spectrum: CMB vs 21cm



Kleban+ 2007

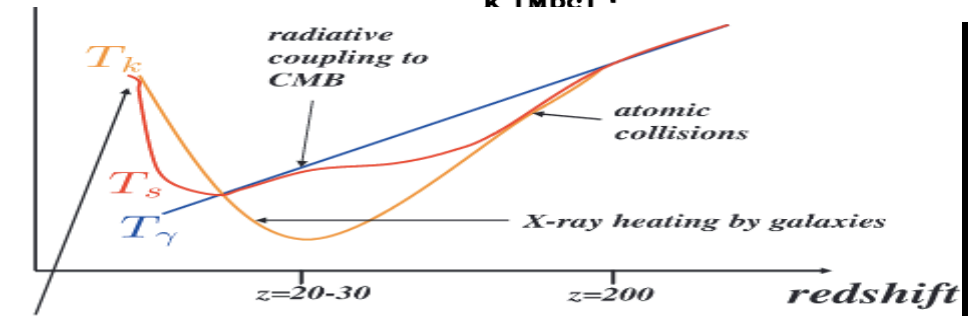
$\nu_{21cm} = 1,420,405,751.768 \pm 0.001\,\mathrm{Hz}$





Sweet spot at z ~ 50 or 30 MHz

Loeb & Zaldarriaga 2003



Cosmic microwave background: $\ell \sim 10^3$ $N \sim 10^6$

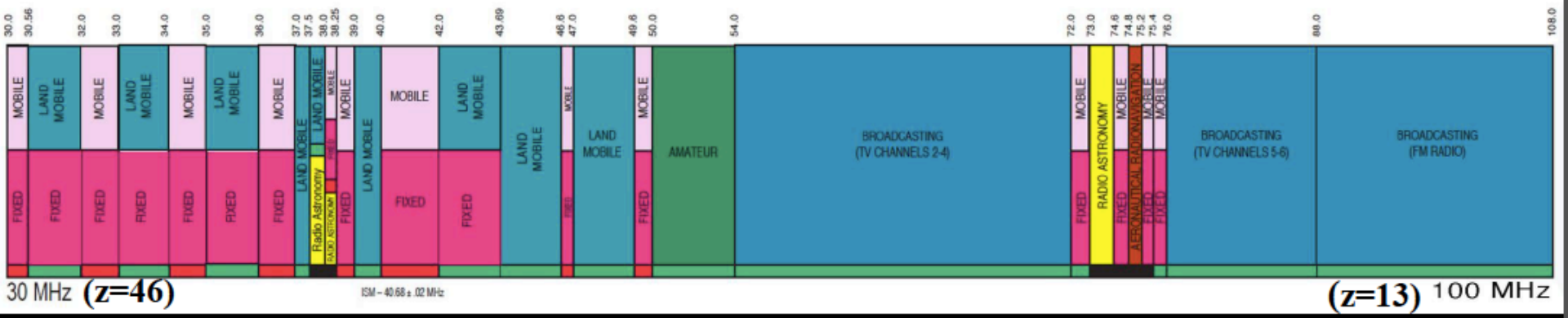
galaxy surveys: LSST to have 10^{10} photo-z $N \sim 10^8$

dark ages 21cm+ tomography: $N \sim 10^{10} \times 10^2$ $N \sim 10^{12}$

gain $N^{1/2}$ precision, 1000 x CMB at 10 arc-sec resolution

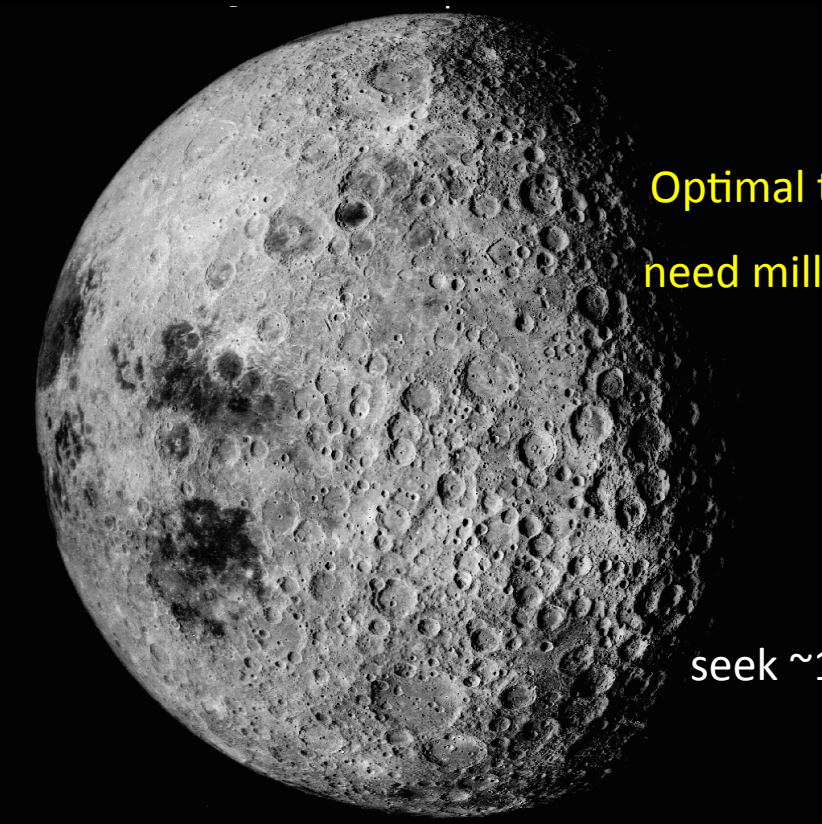
Goal: PNG at z ~ 50-70 or 20-30 MHz

Need to remove non-gaussian foregrounds at level of $x10^5$
with no ionosphere, no mobile phones, no internet…



30-50 MHz is a very difficult frequency range to map from the Earth

Need to go to far side of MOON for most radio-quiet environment in inner solar system



Optimal telescope array is $\ell\lambda/2\pi$ or D ~100 km at λ~ 10 m

need millions of dipoles for weak signal: $\frac{D^2}{4\lambda^2}$ ~10^7

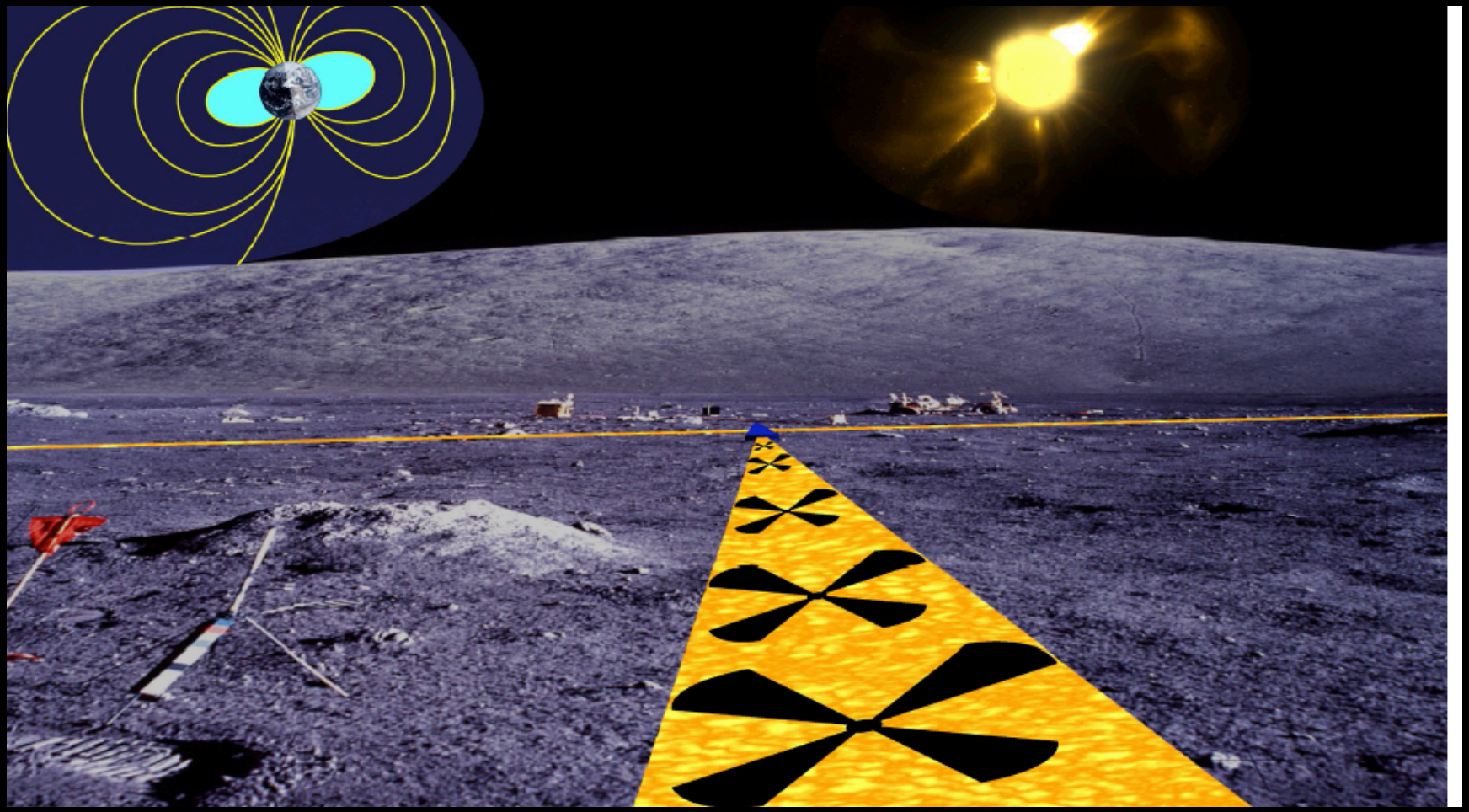
seek ~10mK signal in bright sky foreground T_B~1000K

Far side of the Moon ~ 2040

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

Pathfinder concept ROLSS

1-10 MHz, PI: J. Burns



ESA concept: Moon Village

Aims: business and tourism in 2035+

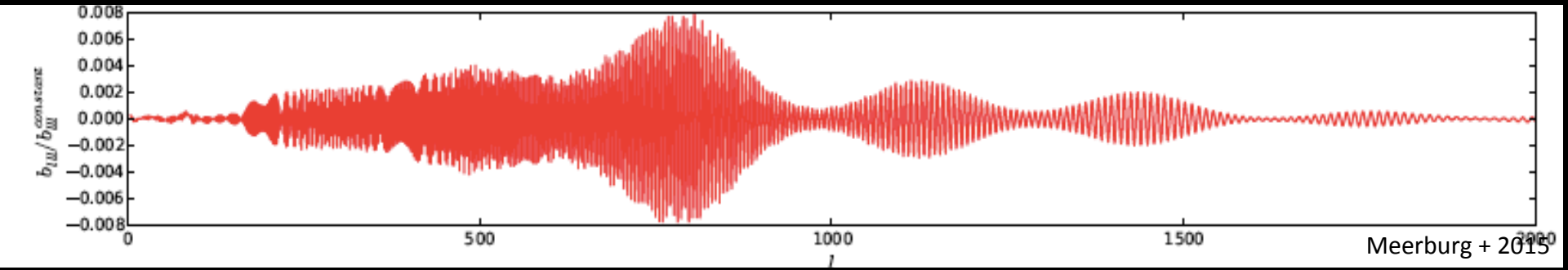
A non-gaussianity program

f_{nl}~0.01 is a generic prediction in multifield inflation

aim: detect patterns of nongaussianity on the sky

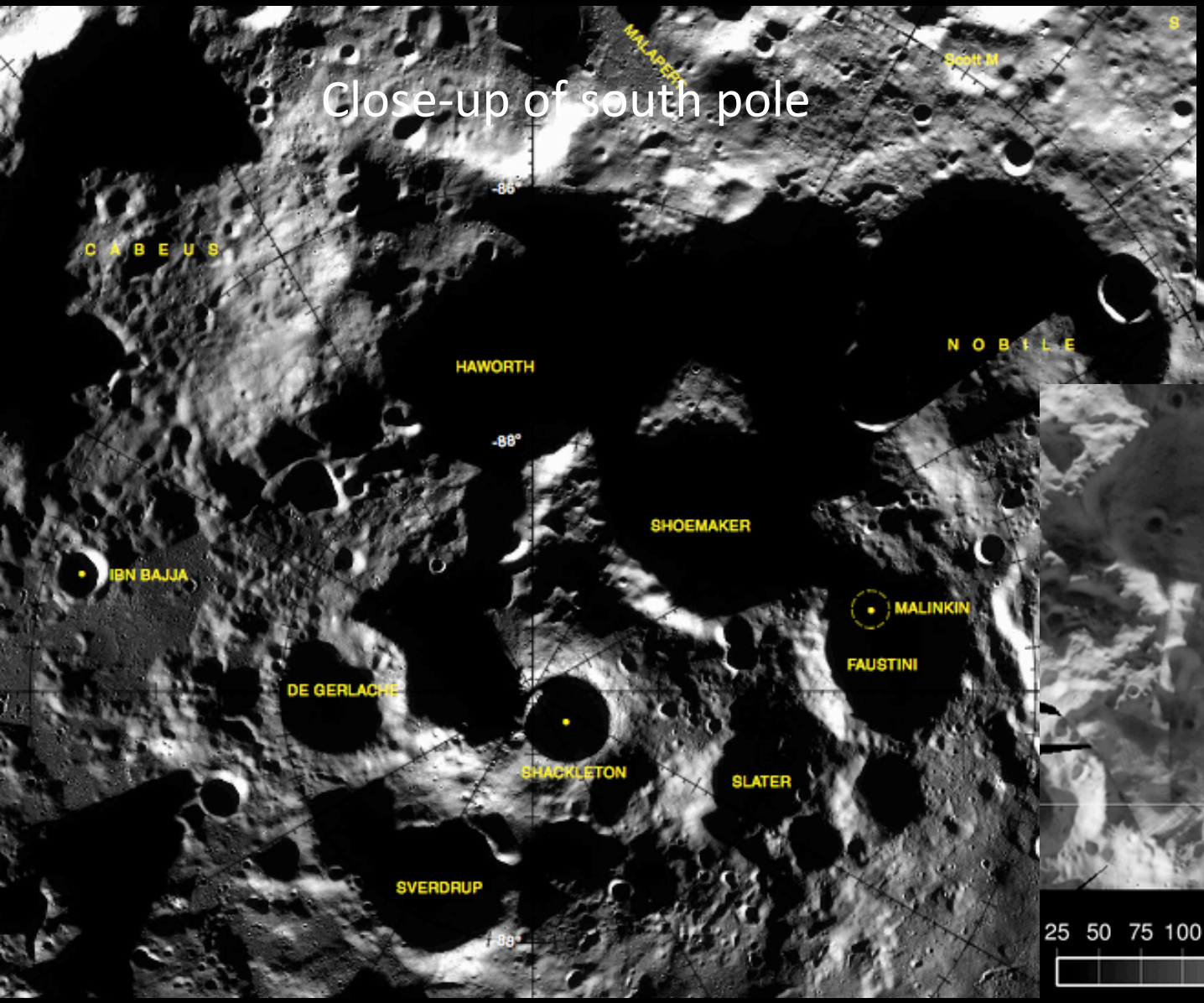
- CMB: suborbital +space N~10^6 f_{nl}~10 (>3σ)
- Optical/IR galaxy surveys N~10^8 f_{nl}~1
- Radio: SKA-Low-2: ~10^6 antennae in 2025
- far side of Moon…N~10^{12} f_{nl}~0.01 by 2035-2040

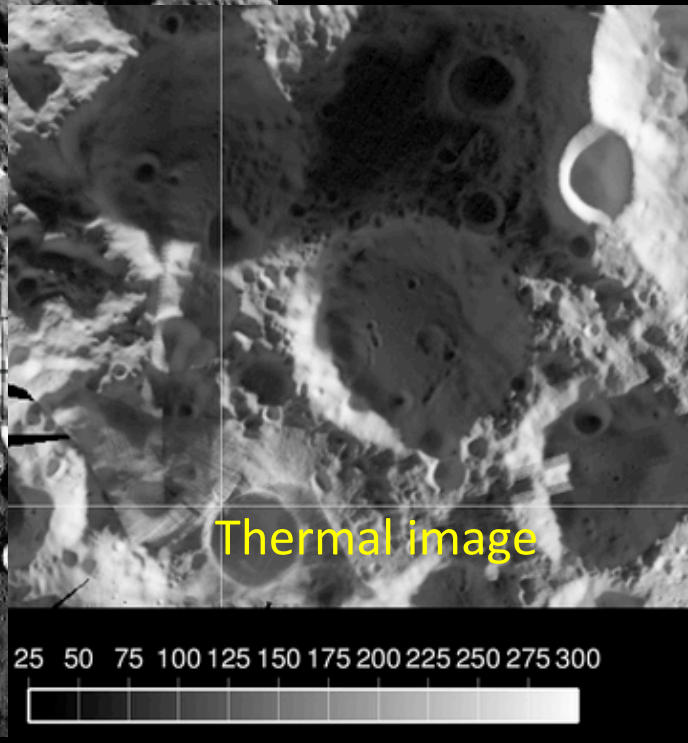
Novel DM probes & only way to falsify inflation

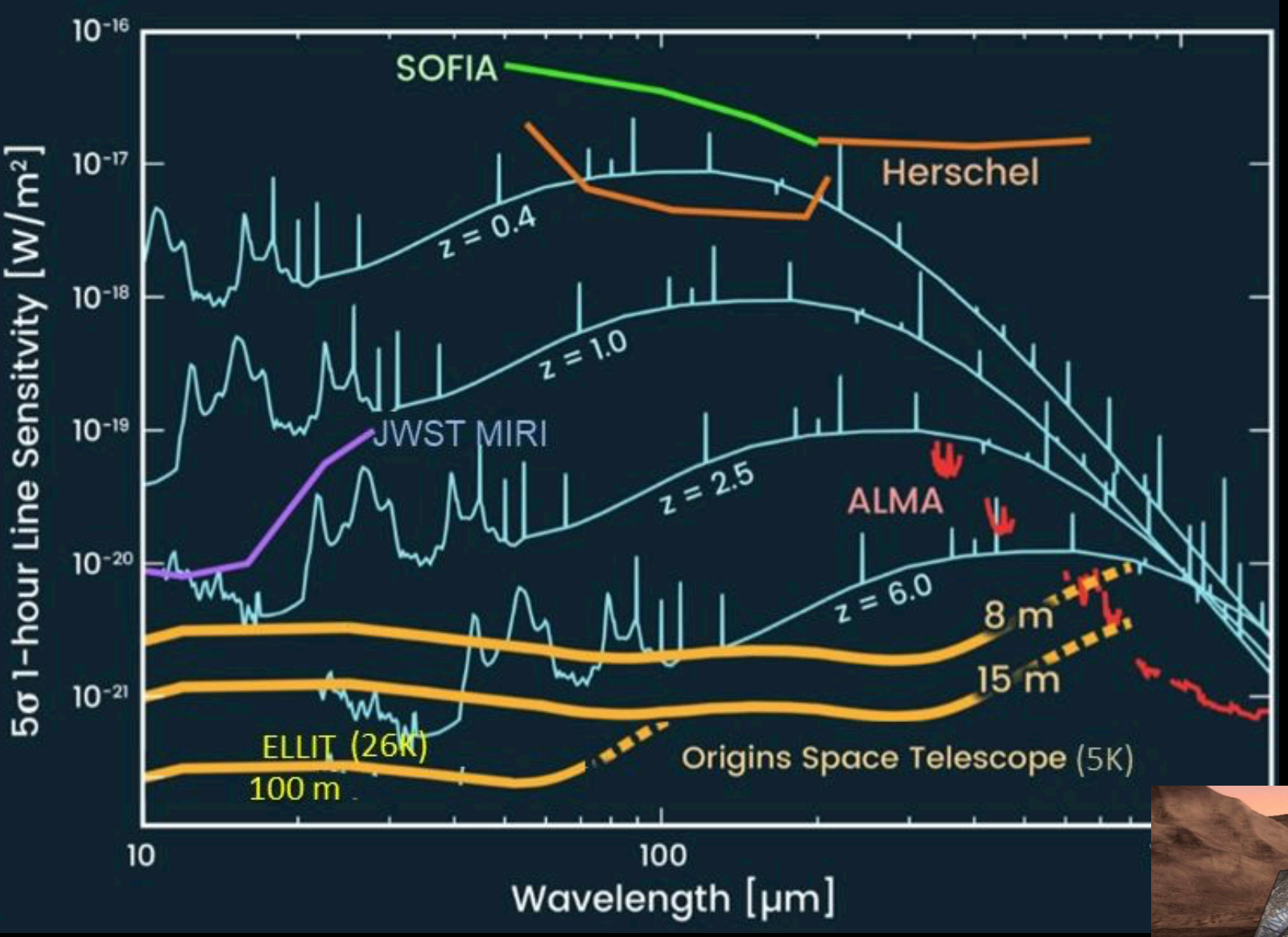


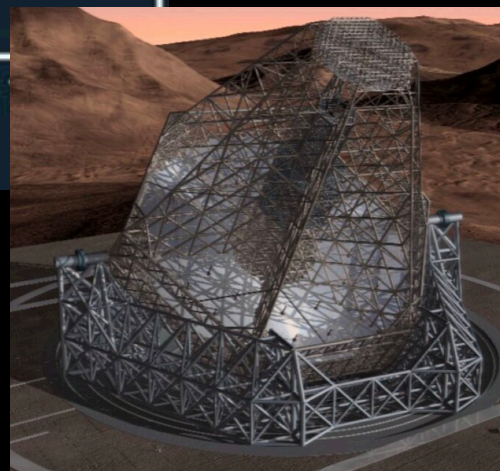
Meerburg + 2015

That's not all! Sites for IR and FIR telescopes





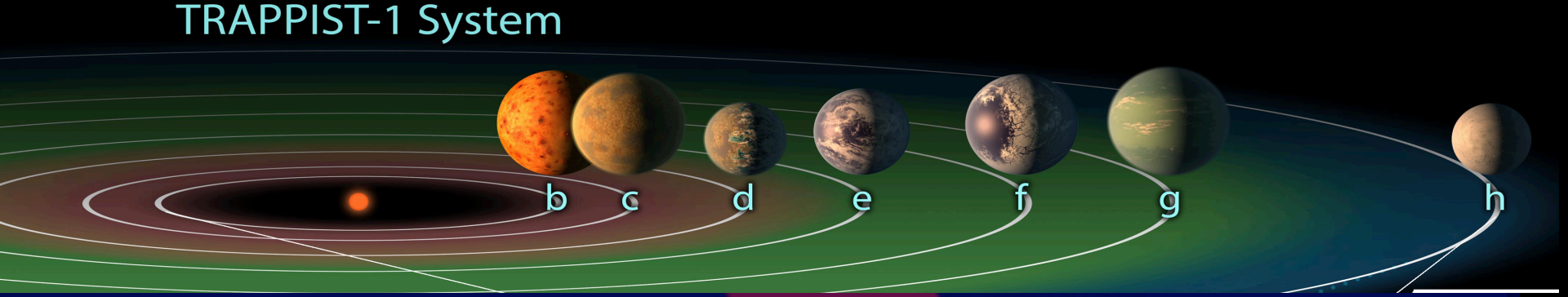


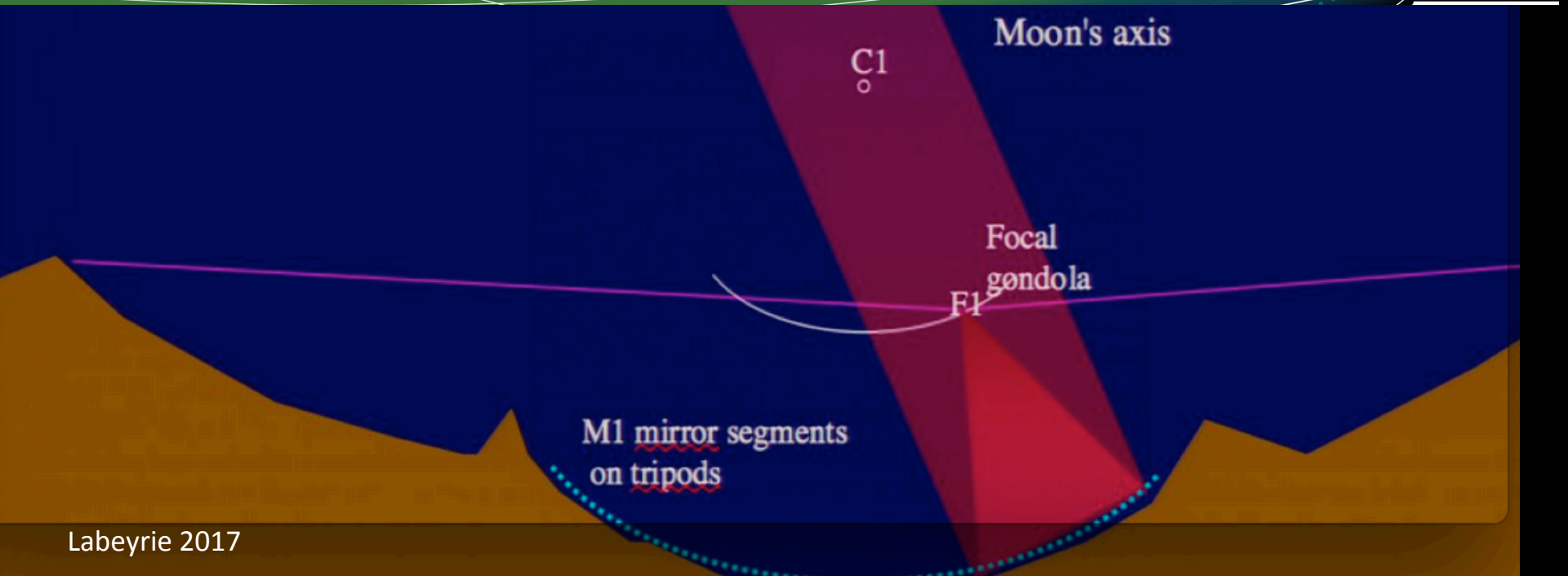


Maillard 2017

10 km NIR hypertelescope

- Fixed segmented primary mirror, 5-10 m size
- Meta-aperture size: 5 km, limited by crater depth





Labeyrie 2017

China is there already!

Where next in cosmology?

- Dark energy? No prediction for $w \neq -1$
- Dark matter? No detection yet!
- Probing inflation via CMB? No lower bound!

- **Back to the moon!**
- primordial nongaussianity
- cosmic recombination
- first stars, galaxies & black holes
- exoplanet atmospheres