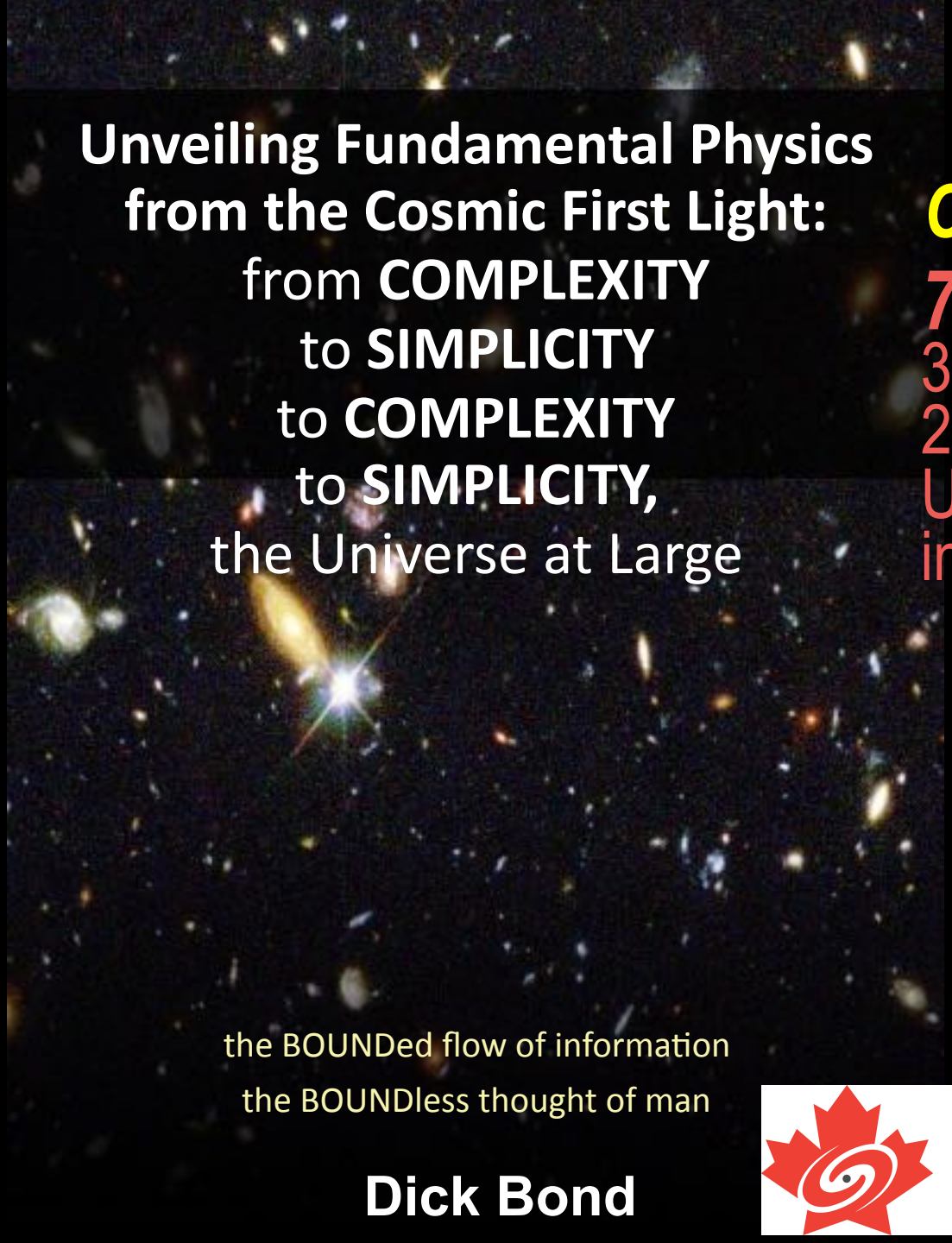

Unveiling Fundamental Physics from the Cosmic First Light:

from **COMPLEXITY**
to **SIMPLICITY**
to **COMPLEXITY**
to **SIMPLICITY,**
the Universe at Large

CMB@51

7^{+} numbers
3 densities,
2+1 early-Universe inflation

the BOUNDed flow of information
the BOUNDless thought of man

Dick Bond

CIFAR
CANADIAN INSTITUTE FOR ADVANCED RESEARCH

CITA ICAT
Canadian Institute for Theoretical Astrophysics
L'institut Canadien d'astrophysique théorique

Dick Bond CITA *the summary talk*

CMB@50 THEN & NOW & THEN
a celebration *Princeton June 2015*

CMB prediction
Alpher, Gamow Herman 1950s Tcmb ~5K
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COBE 1989 launch
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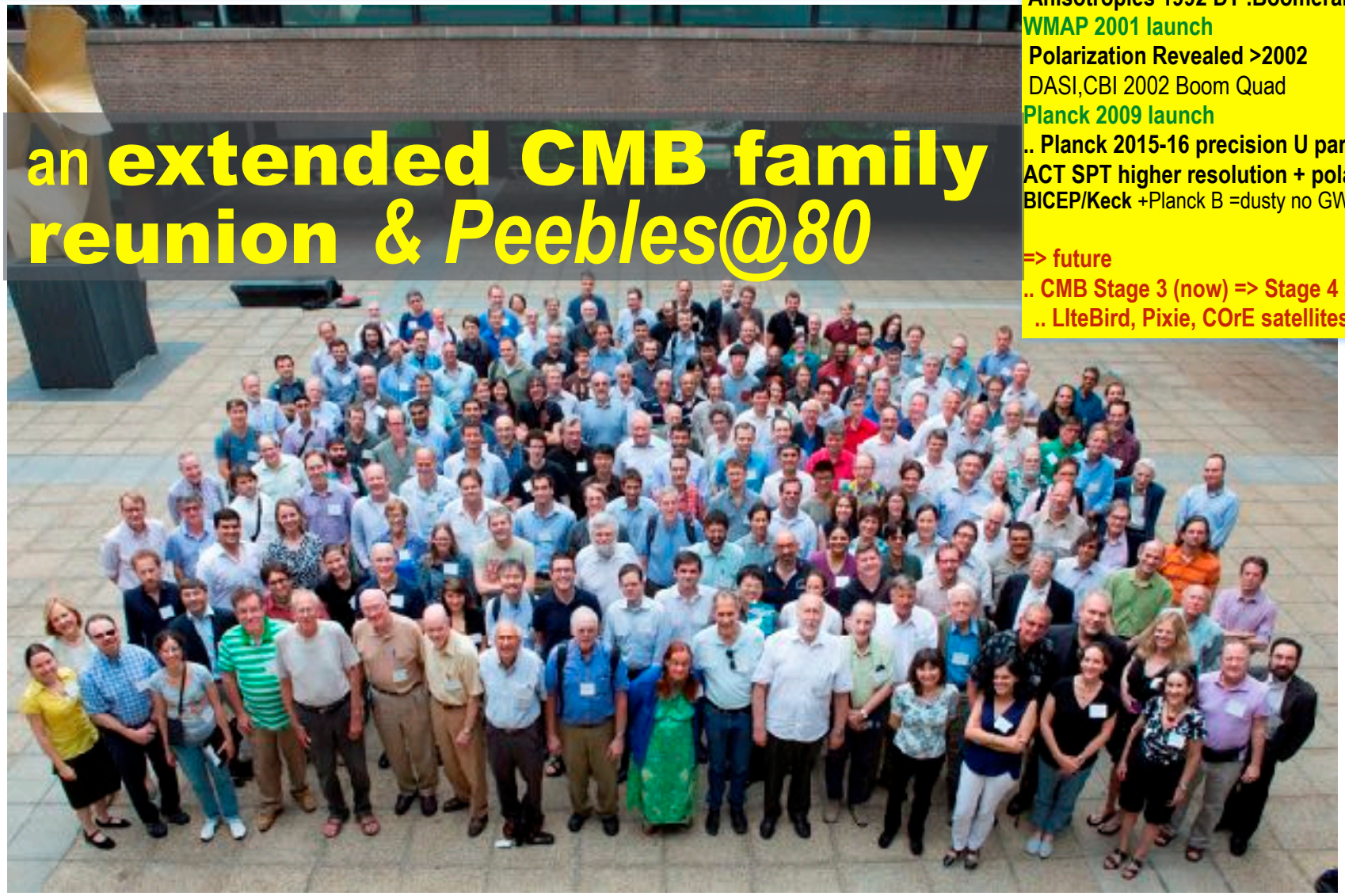
.. Planck 2015-16 precision U parameters
ACT SPT higher resolution + polarization
BICEP/Keck +Planck B =dusty no GW Spider

=> future
.. CMB Stage 3 (now) => Stage 4 > 2022
.. LIteBird, Pixie, COrE satellites ??

an extended CMB family reunion & *Peebles@80*



CMB@51:

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Dick Bond

on cosmic Photons cosmic microwave background radiation 1st light 412 /cm^3 0.005%

on cosmic Baryons Ordinary Matter air ~amu /nm^3 O_2 N ; U 5.0% H,He ~0.055 amu /cm^3

on cosmic Dark Matter ~amu /m^3 27.0 ± 0.9% compressed in MilkyWay ~0.3 amu /cm^3 ; for LHC@CERN-type relics ~ 1 every 10 cm *or axions or … ?*

on cosmic Dark Energy ~ vacuum potential density ~ 3 amu /m^3 68.0 ± 0.9% late-inflaton KE/PE?

on cosmic Neutrinos number density ~ cosmic photons Energy fraction > 0.47% ~stars

THE LIGHT

on cosmic Phonons ~ isotropic Strain Deformations

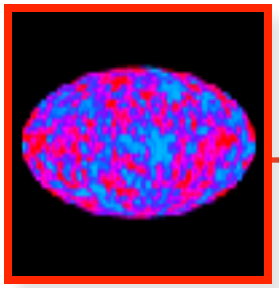
on cosmic Inflatons - source the phonons

on cosmic Gravitons ~ anisotropic Strain (Transverse Traceless) <<< photons / neutrinos

on cosmic Isocons transverse degrees of freedom to the inflaton on the potential surface

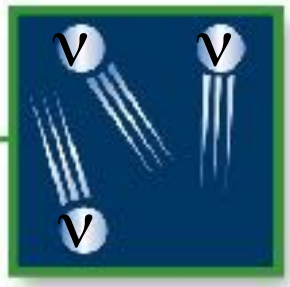
SMpp = Standard Model of particle physics electroweak + strong interactions
=> *BSMpp = Beyond the SMpp* neutrino masses, Dark Matter, Dark Energy, Gravity, SUSY …

SMc = Standard Model of cosmology tilted Gaussian LCDM model, B+DM+DE+photons+neutrinos
=> *BSMc = Beyond the SMc* neutrino masses, dynamical coupled Dark Energy, modified Gravity …



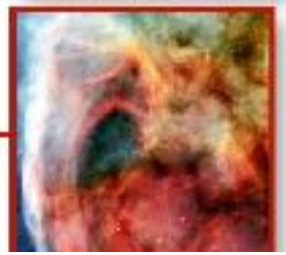
Radiation:
0.005%

Chemical Elements:
(other than H & He) 0.025%

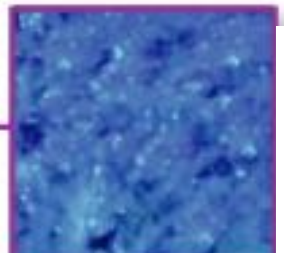


Neutrinos:
> 0.47%

Stars:
0.5%



Free
H & He:
4.3%

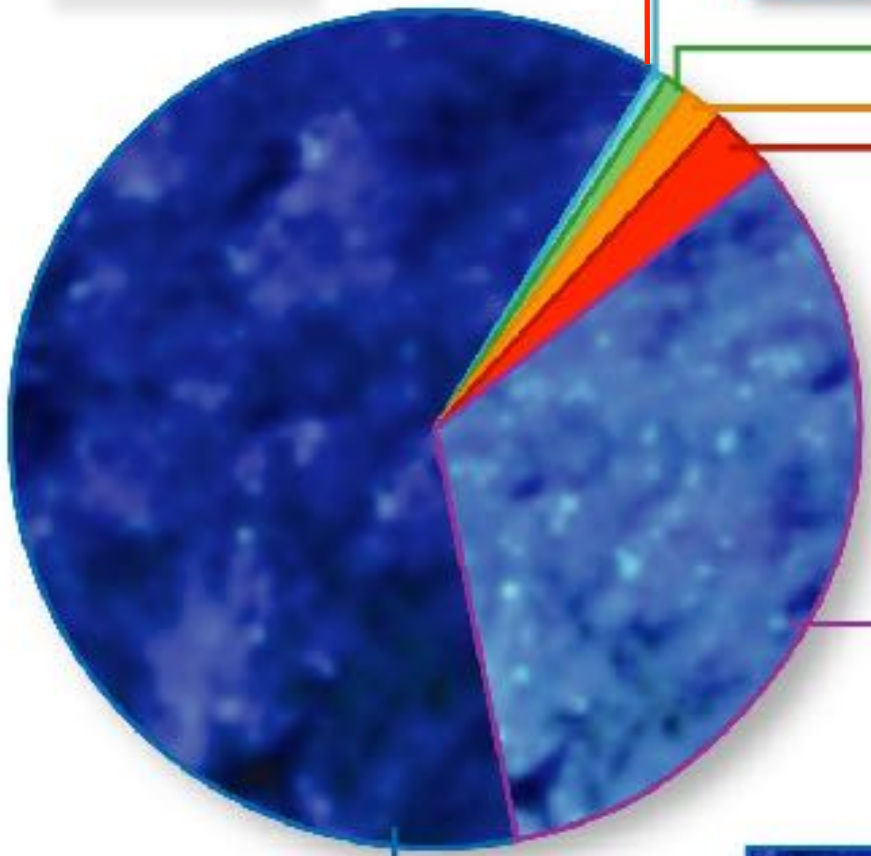


Dark Matter:

$\Omega_{dm} = 26.8 \pm 0.9\%$

Dark Energy:

$\Omega_{de} = 68.8 \pm 0.9\%$



$\Omega_{total} = 1$

Gravity Waves

Ω_{GW} ~10^{-14} - 10^{-10} LIGO

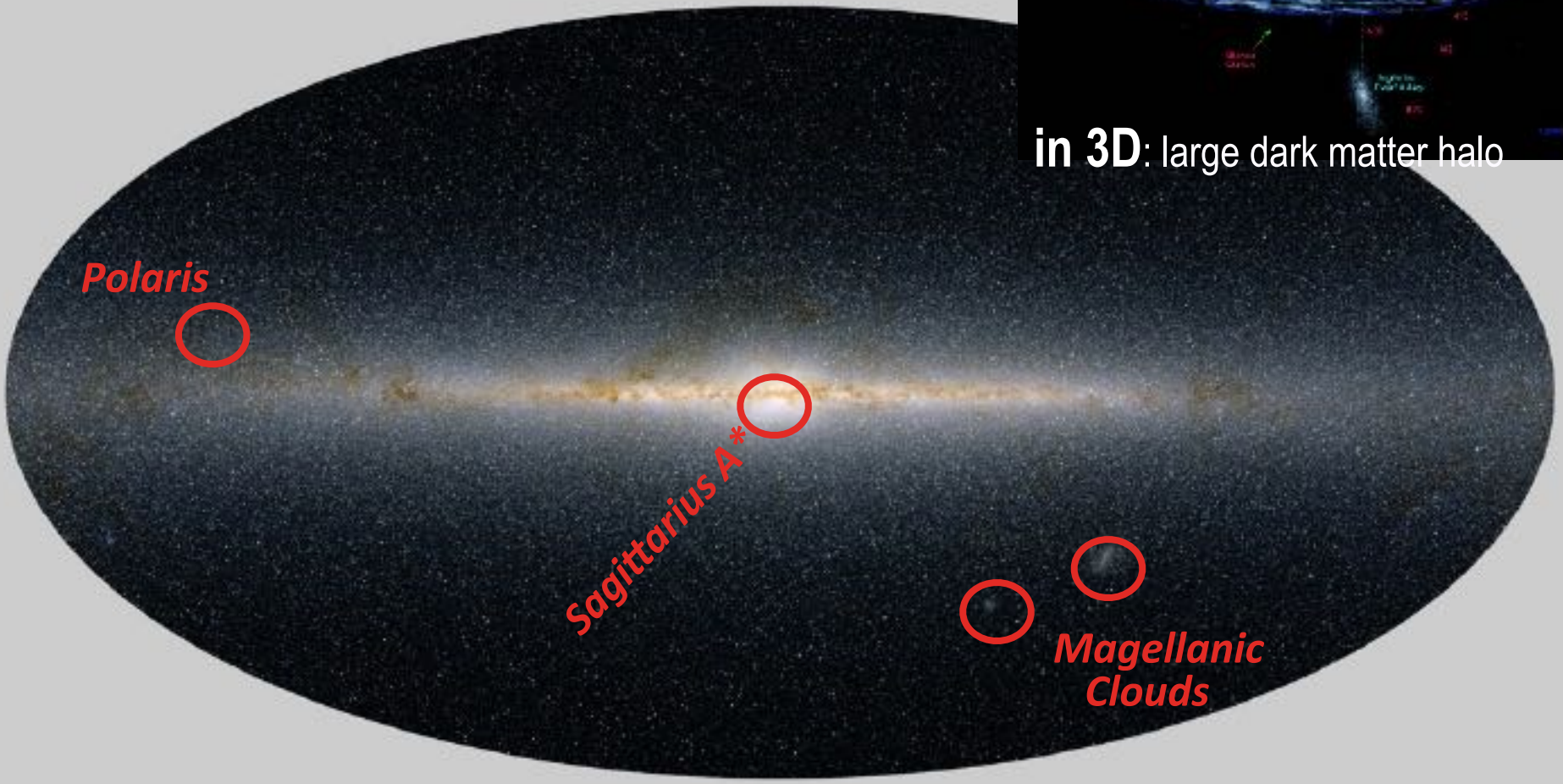
$\Omega_{BlackHoles}$ ~10^{-7}

\

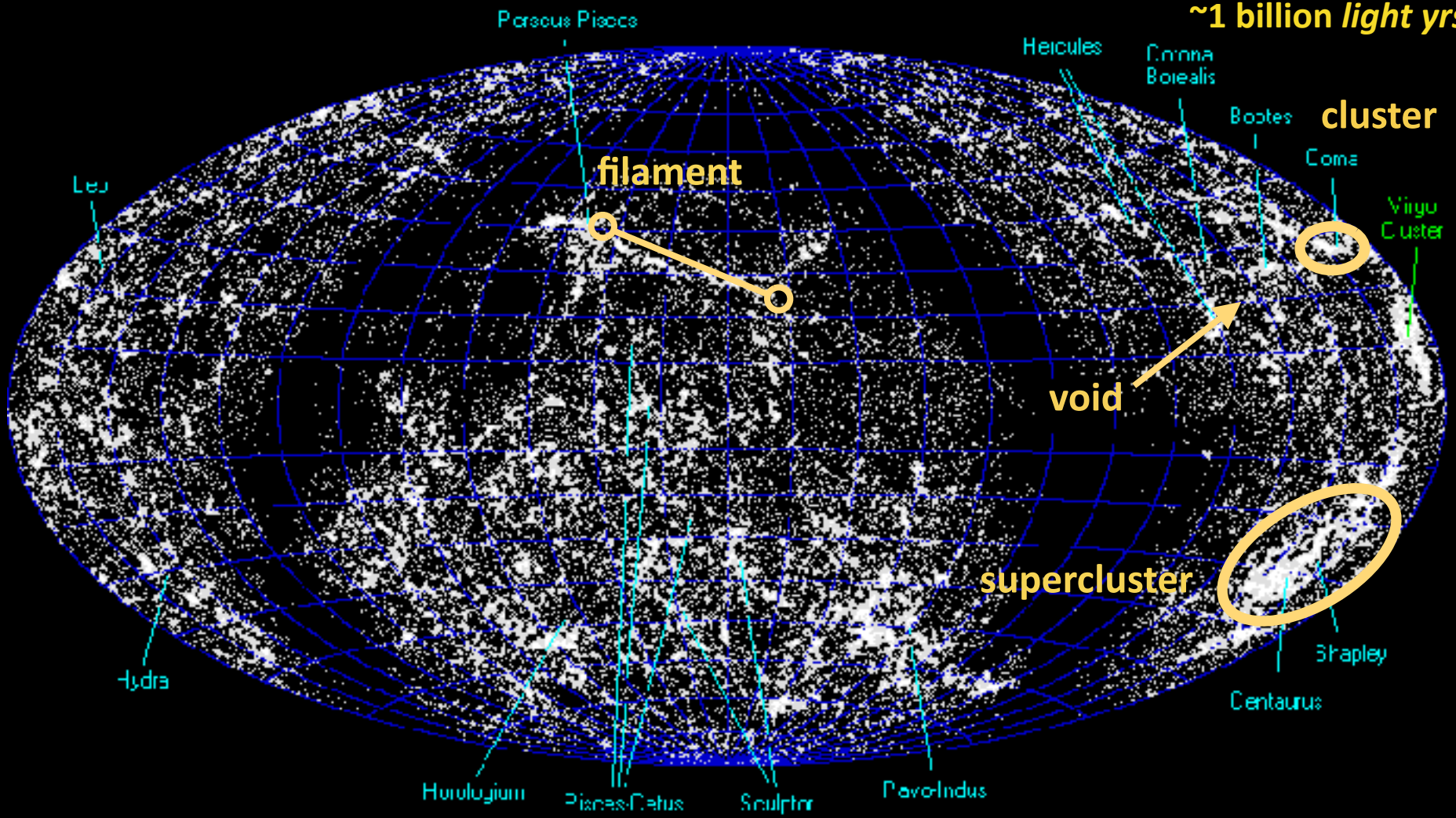
Milky Way in infra-red:

half a billion stars, a disk galaxy

in 3D: large dark matter halo

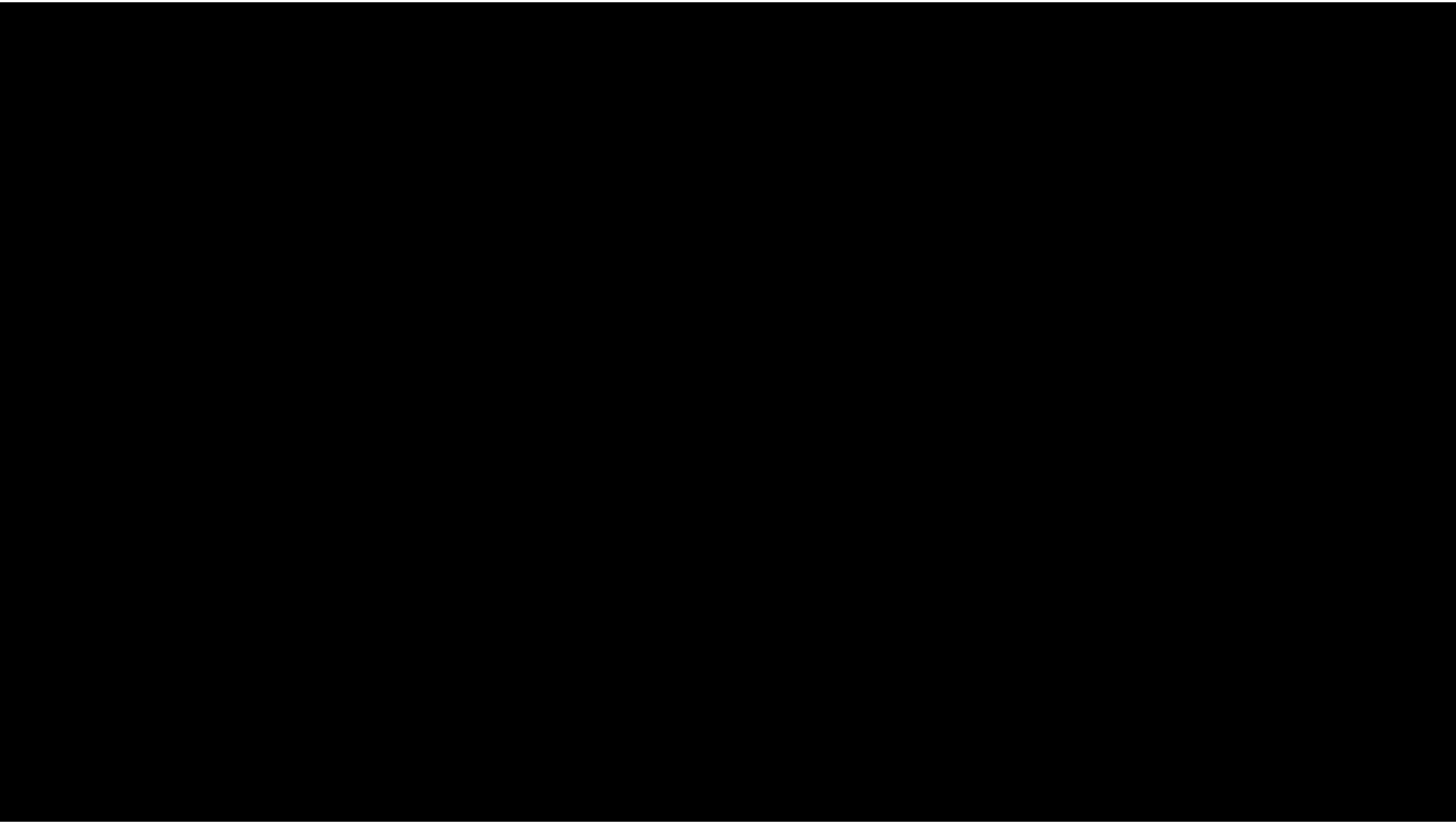


Cosmic Web of 60,000 nearby galaxies: exhibits "local" **COMPLEXITY**



hard won observational emergence of the web. 79-81 sparse info, e.g., of Coma supercluster. So what Arnold, Shandarin and Zeldovich knew was very very much less, ie speculative theory

SDSS main galaxy survey BOSS



Sloan Digital Sky Survey DR9 ~ 400,000 galaxies in this animation redshift range z=0.01-0.1. $a \sim e^{-0.1} = 1/1.1$. far side of the survey (z=0.1) is ~ 400 Mpc (1.3 billion light years).

Miguel Aragon (JHU), Mark Subbarao (Adler) & Alex Szalay (JHU)

a scale of the Universe

strained photons redshift

=1/ (1+redshift)

now = **1** when we **observe** the **1st light**

then = **1/1100** when the **1st light** was **released from matter**, billion X denser

galaxies forming ~ 1/4

there were **no galaxies** when a < 1/20

mean (isotropic) number of e-foldings of scale ≡ $\langle \ln a \rangle$

a scale of the Universe

$\langle \alpha \rangle$

0

now = **1** when we **observe** the **1st light**

then = **1/1100** when the **1st light** was **released from matter**, billion X denser **7**

galaxies forming ~ 1/4 **1 ⇓ 2**

there were **no galaxies** when a < 1/20 **3**

light nuclei

Dark Matter **21 ⇓ 35**

Heat: matter & **radiation** **67**

quantum **noise** **67 ⇓ 127**

esa

planck

cnes

agenzia spaziale italiana

NASA

cnrs

DTU Space
National Space Institute

Science & Technology Facilities Council

INAF ISTITUTO NAZIONALE DI ASTROFISICA

CSIC
Consejo Superior de Investigaciones Científicas

National Research Council of Italy

GOBIERNO DE ESPAÑA
MINISTERIO DE CIENCIA E INNOVACIÓN

CSA ASC

DLR Deutsches Zentrum für Luft- und Raumfahrt e.V.

UK SPACE AGENCY

MAX-PLANCK-GESELLSCHAFT

PLANCK LFI

HFI PLANCK
a look back to the birth of Universe

IAS orsay

IAP

INAF - IASF BO
ISTITUTO NAZIONALE DI ASTROFISICA
ISTITUTO DI ASTROFISICA SPAZIALE E FISICA COSMICA DI BOLOGNA

Aalto University

ioa

KICC

Cavendish Astrophysics

University of Cambridge

Cardiff University
Prifysgol Caerdydd

irfu
cea
saclay

CEFCA

CESR

CITA–ICAT

IASF

cnrs INSU
Observer & comprendre

cnrs IN2P3
Les deux infinis

ipac

Helsinki Institute of Physics

IFCA
Instituto de Física de Cantabria

Imperial College London

Università degli Studi di Milano

NÉEL institut

IPAG
Institut de Planétologie et d'Astrophysique de Grenoble

ISDC
Data Centre for Astrophysics

JPL

LAC
Laboratoire de l'Accélérateur Linéaire

l'Observatoire de Paris — LERMA

LPSC Grenoble
Laboratoire de Physique Subatomique et de Cosmologie

The University of Manchester

MilliLab

Max-Planck-Institut für Astrophysik

NUI Maynooth

INAF Osservatorio Astronomico di Padova

University of Oxford

Dipartimento di Fisica Sapienza Università di Roma

Science & Technology Facilities Council
Rutherford Appleton Laboratory

Università Tor Vergata

Osservatorio Astronomico di Trieste

UBC

UC Universidad de Cantabria

UCSB

SISSA

ALMA

ESO

University of Sussex

Haverford

esa

University of Helsinki

Université de Genève

University of Toronto

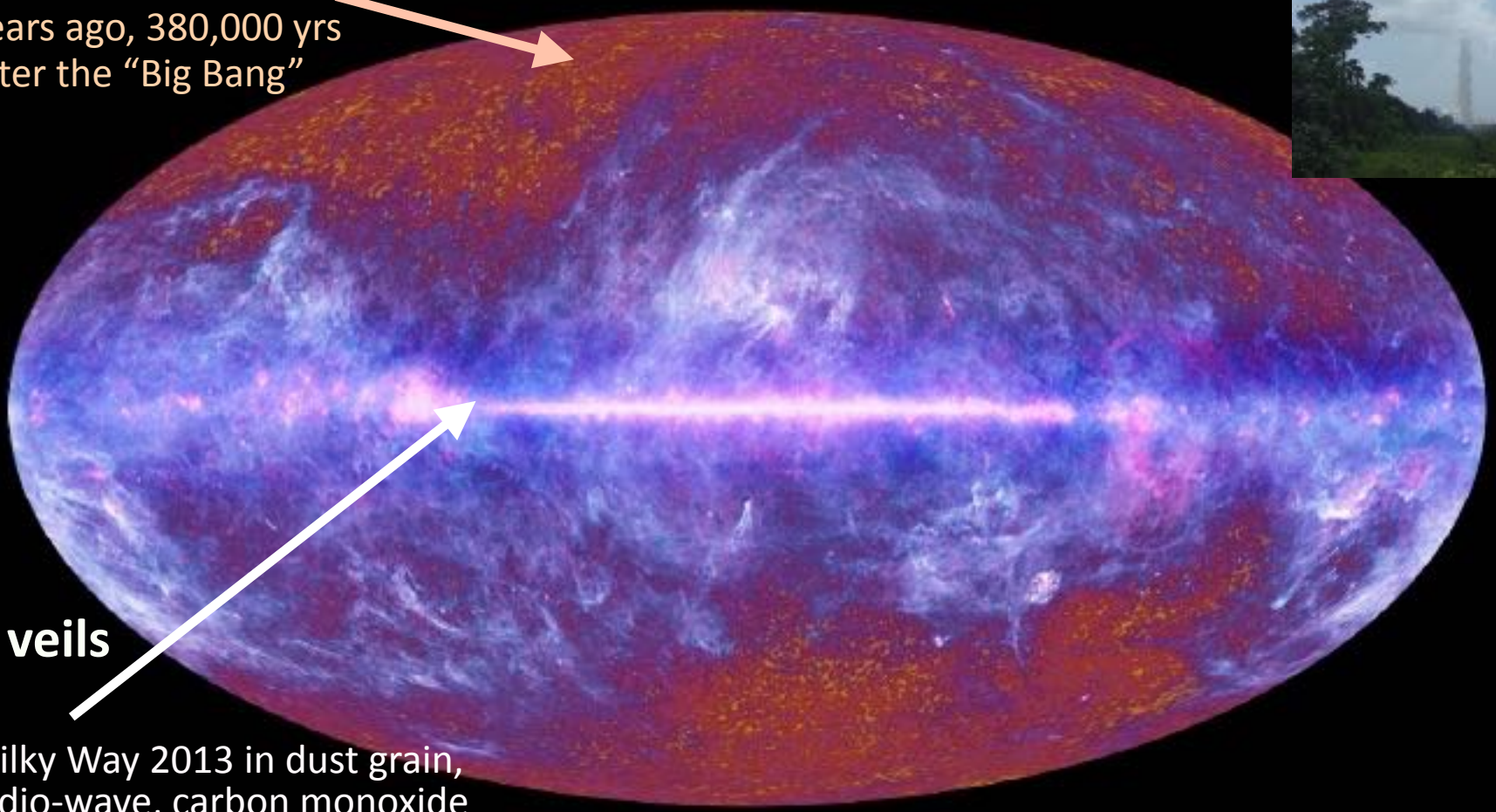
Université de Paris-Sud XI

asdc
ASI Science Data Center

Bond since 1993, Canada since 2001, 1st CSA pre-launch contract 2002-09, post-launch 2010-11, 2011-16

COMPLEXITY of here & now

the primordial light, released 13.8 billion years ago, 380,000 yrs after the "Big Bang"



7 veils

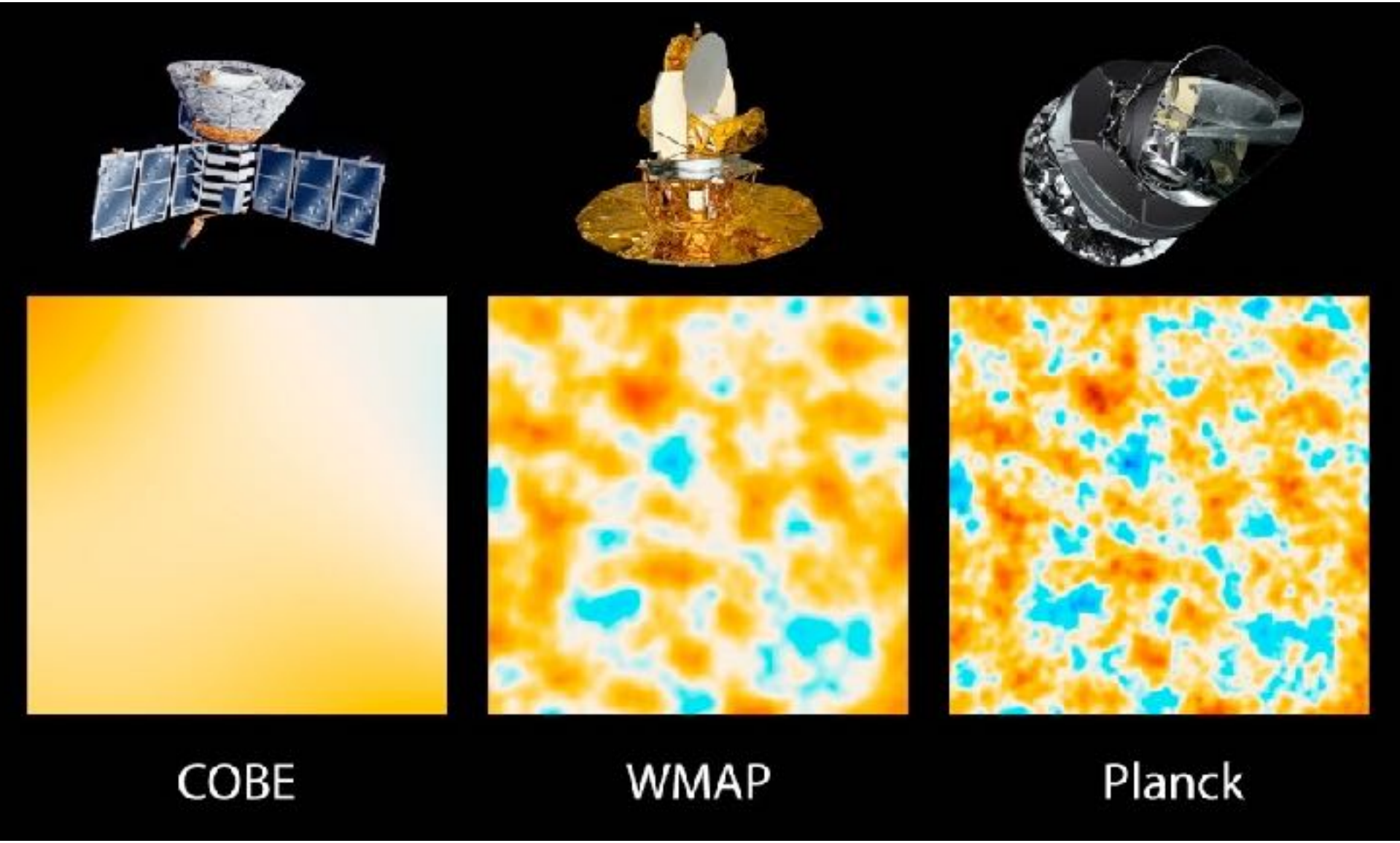
Milky Way 2013 in dust grain, radio-wave, carbon monoxide emissions; plus stellar, X-ray, gamma ray, cosmic ray emissions ...

The Planck one-year all-sky survey

esa

Comparison of CMB Space Experiments: Resolution, 420', 12.5', ~5-7'

COBE 89 launch *WMAP 01 launch* *Planck 09 launch*

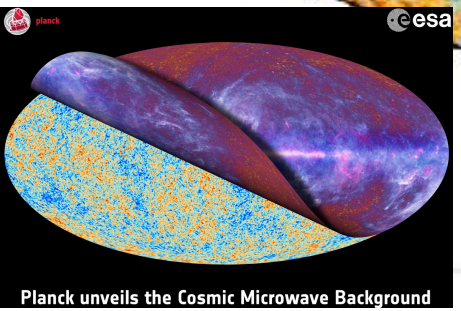


goal: high enough resolution to plumb all cosmic parameter information. but high L foregrounds, extragalactic sources => higher L expts ACT (1.4'), SPT (1') = PlanckEXT to nail the "nuisance"

Planck's primordial light unveiled, *Mar 2013 =>* **Feb 2015** *=> pre-2016 => march 2017 final*

reveals the SIMPLICITY of primordial cosmic structure

7+ numbers, 3 densities, 2+1 early-Universe inflation



300 200 100 0 100 200 300

μK_{cmb}

Temperature changes in micro-degrees

Planck+Herschel Launch May14 09 French Guiana

1.5m telescope,

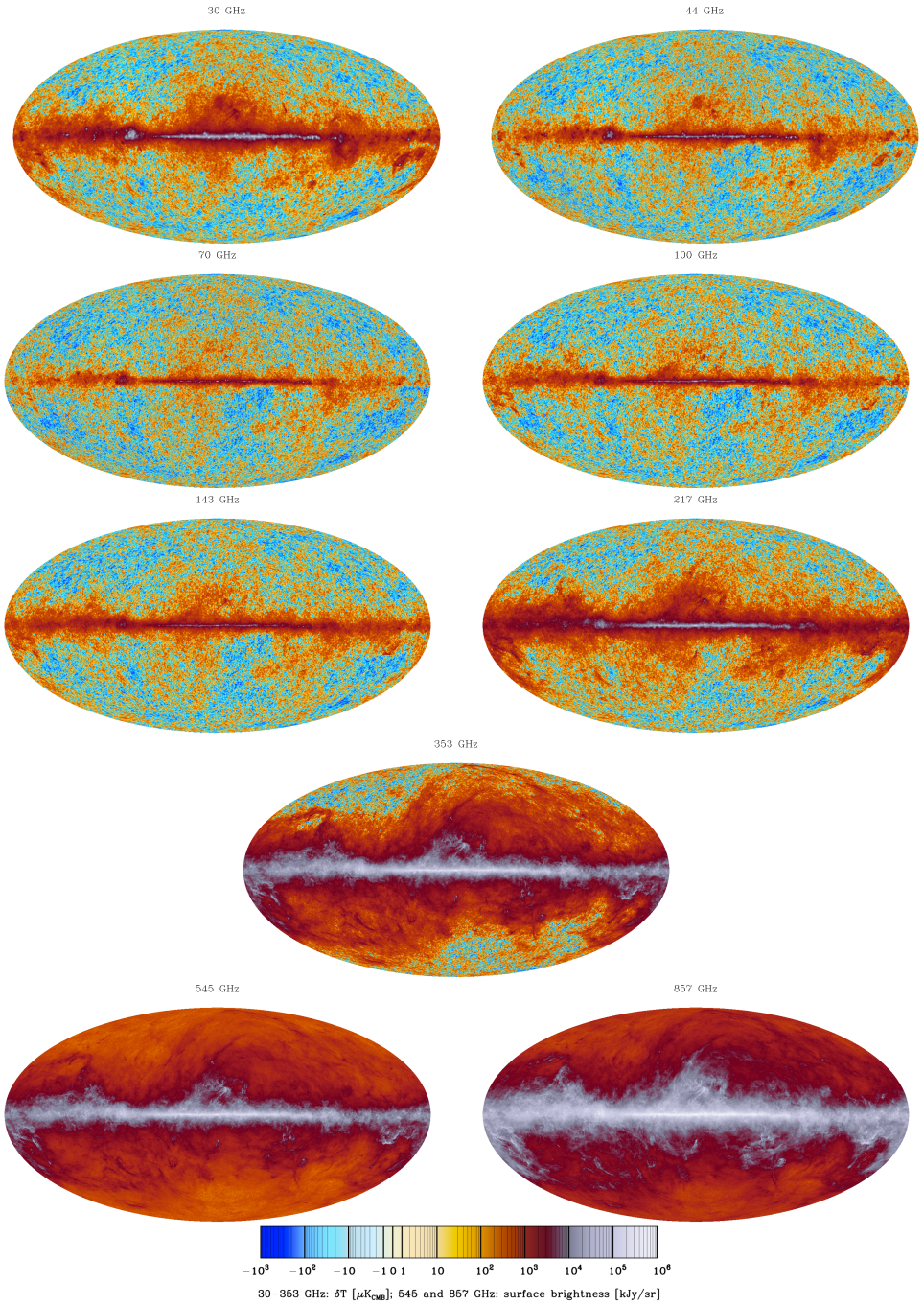
~60 HFI bolometers @6freq <100mK,

LFI HEMTs@3freq,

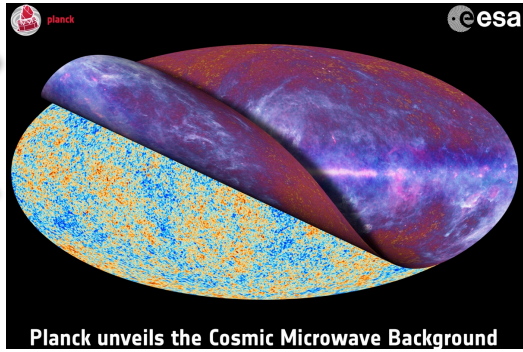
some bolometers & all HEMTS are polarization sensitive

- Left earth at ~10 km/s, 1.5 million km in 45 days, cooling on the way (20K, 4K, 1.6K, 0.1K 4 stage). @L2 on July 2 09; Survey started on Aug 13 09
- spun@1 rpm, 40-50 minutes on the same circle, covered all-sky in ~6 month
- kicked out of L2 Oct13
- 5 HFI all-sky surveys (to Jan 2012) 29 months
- 8 LFI surveys 48 months
- 2015 T some Q,U all-data, low L polarization May2016 refined final set Mar 2017

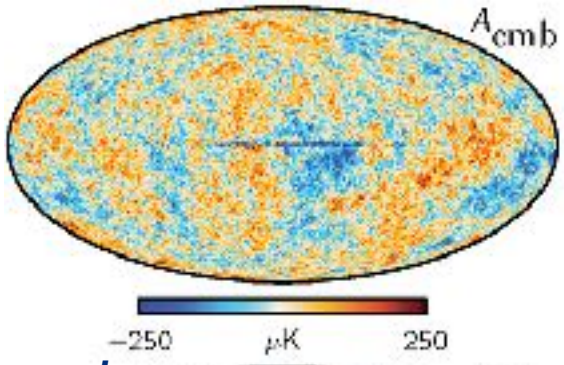
Planck 2013 Frequency Maps Mar13

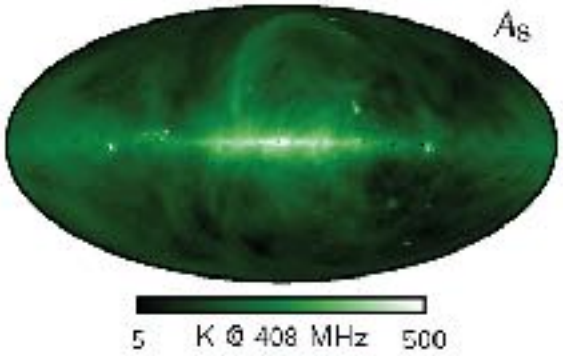


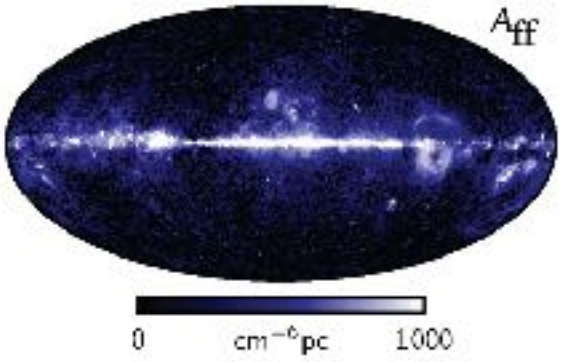
Feb 2015 Planck Component Separated Temperature Maps



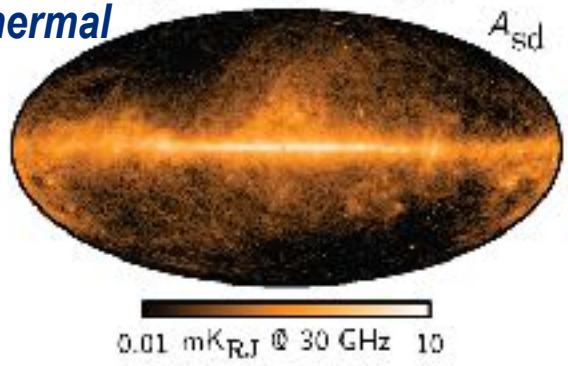
LF Synchrotron + bremsstrahlung

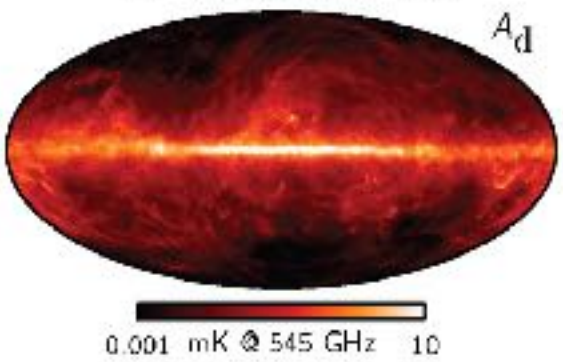


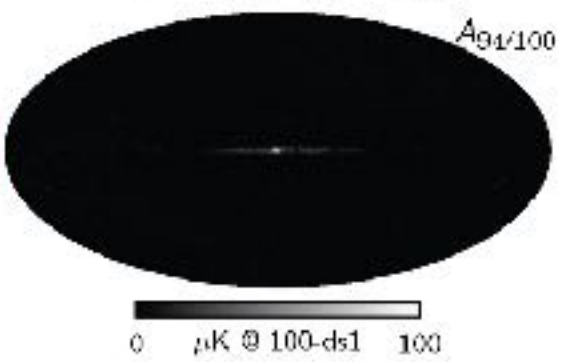




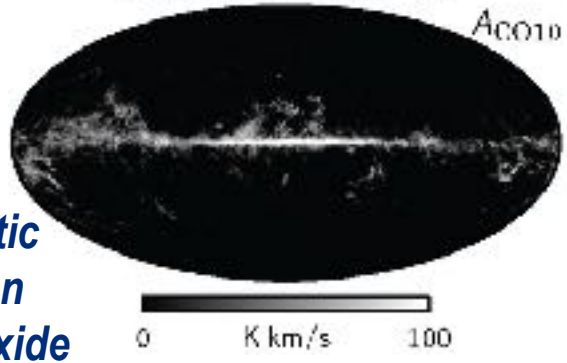
HF Thermal Dust

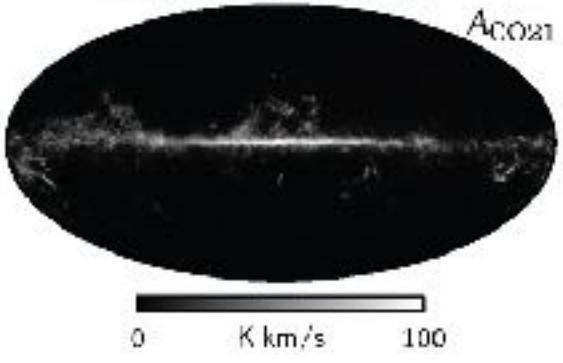


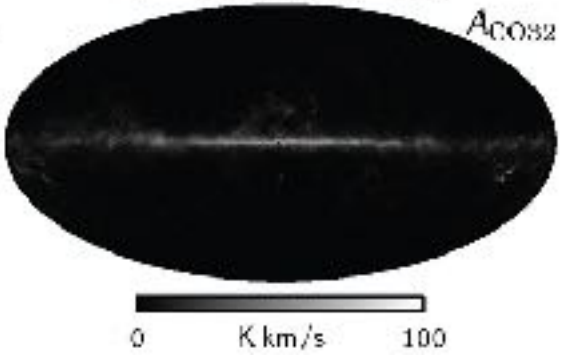




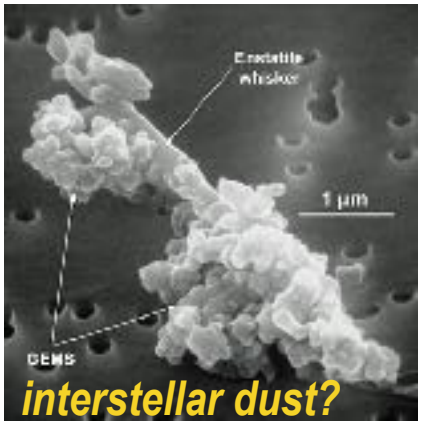
Galactic Carbon Monoxide





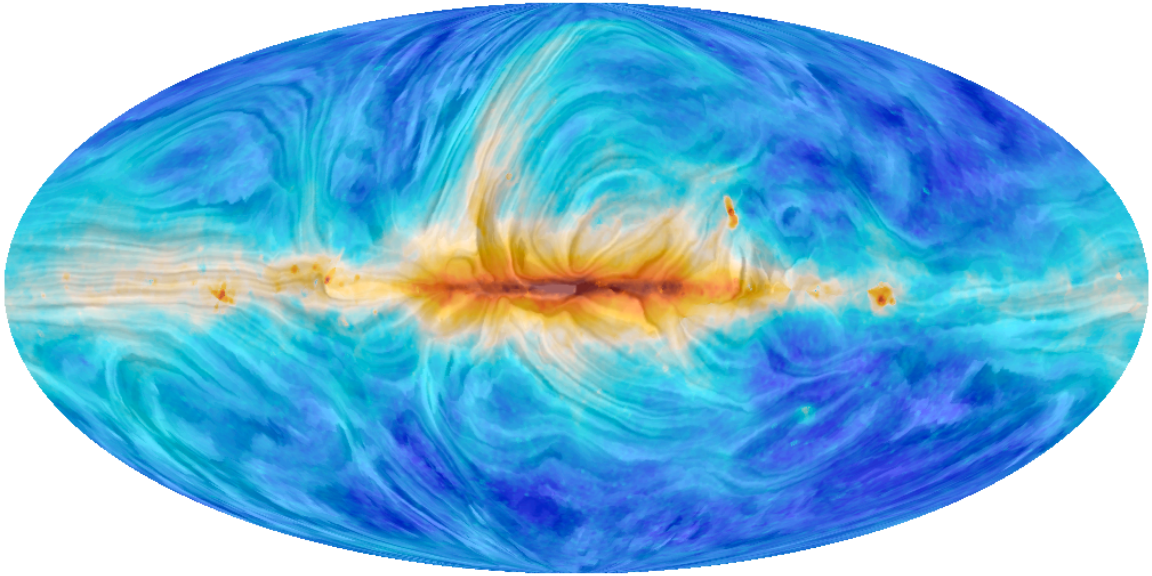


the gritty face of the CMB - foreground challenges



interstellar dust?

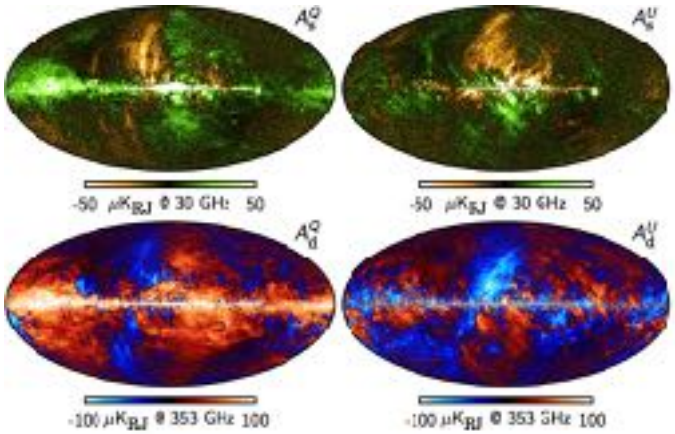
30 GHz LFI Synchrotron



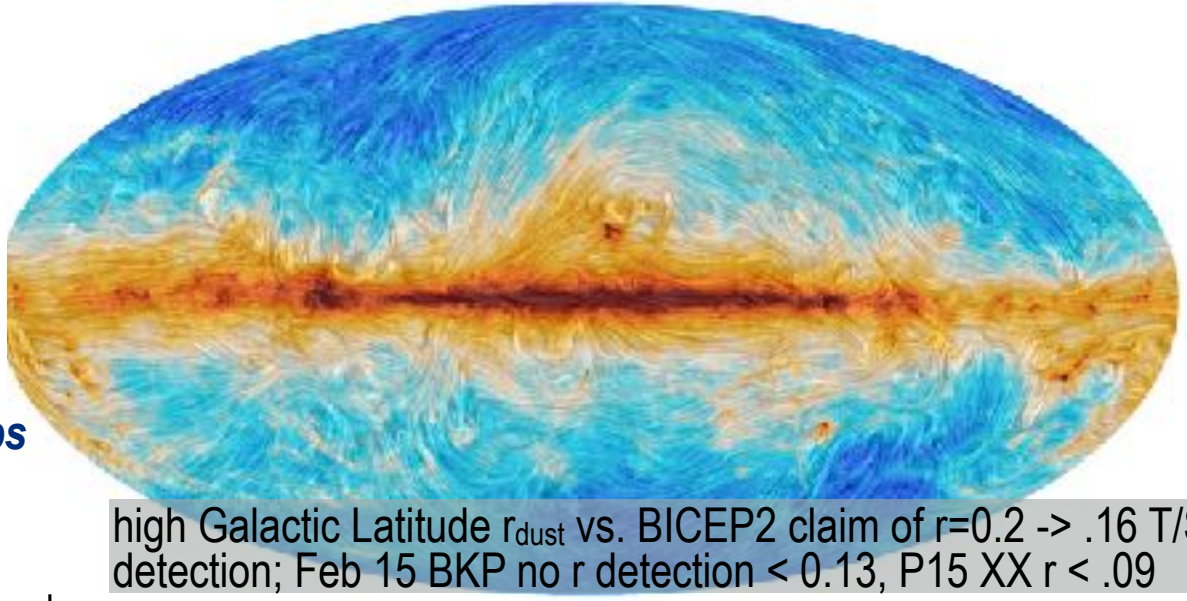
our dusty pol dilemma

dust is complex, will be multi-Temp

& .. => the more channels the better



353 GHz HFI Thermal Dust



Planck T/P Combined van Gogh Maps

Polarization used to follow B field
using Line Integral Convolution
a directional "flow" miville deschenes for Planck

high Galactic Latitude r_{dust} vs. BICEP2 claim of r=0.2 -> .16 T/S detection; Feb 15 BKP no r detection < 0.13, P15 XX r < .09

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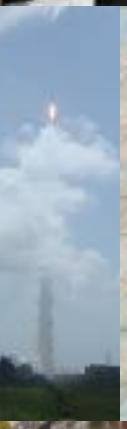
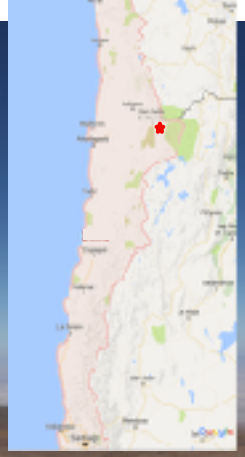
.. Planck 2015-16 precision U parameters
ACT SPT higher resolution + polarization
BICEP/Keck +Planck B =dusty no GW Spider

=> future
.. CMB Stage 3 (now) => Stage 4 > 2022
.. LIteBird, Pixie, COrE satellites ??

an extended CMB family reunion & *Peebles@80*


Atacama

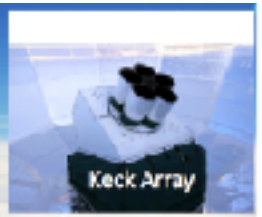


California+
South Africa
C-BASS 5 GHz

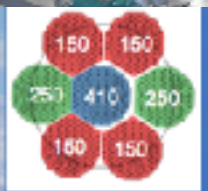
Tenerife (+South Africa?)
(2015/16 - 30, 40 GHz)

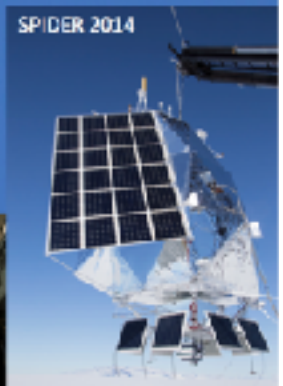
California

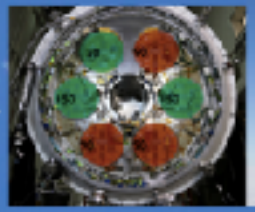
South Pole



=>>>> Simons Observatory => CMB Stage 4







Antarctic balloons

& futures S4, more ballooning, back into space

& futures S4, more ballooning, back into space

managing the CMB

on to Stage IV CMB

Advanced ACTPol

boomerang ~40/paper

planck

~250/paper, ~100 institutions

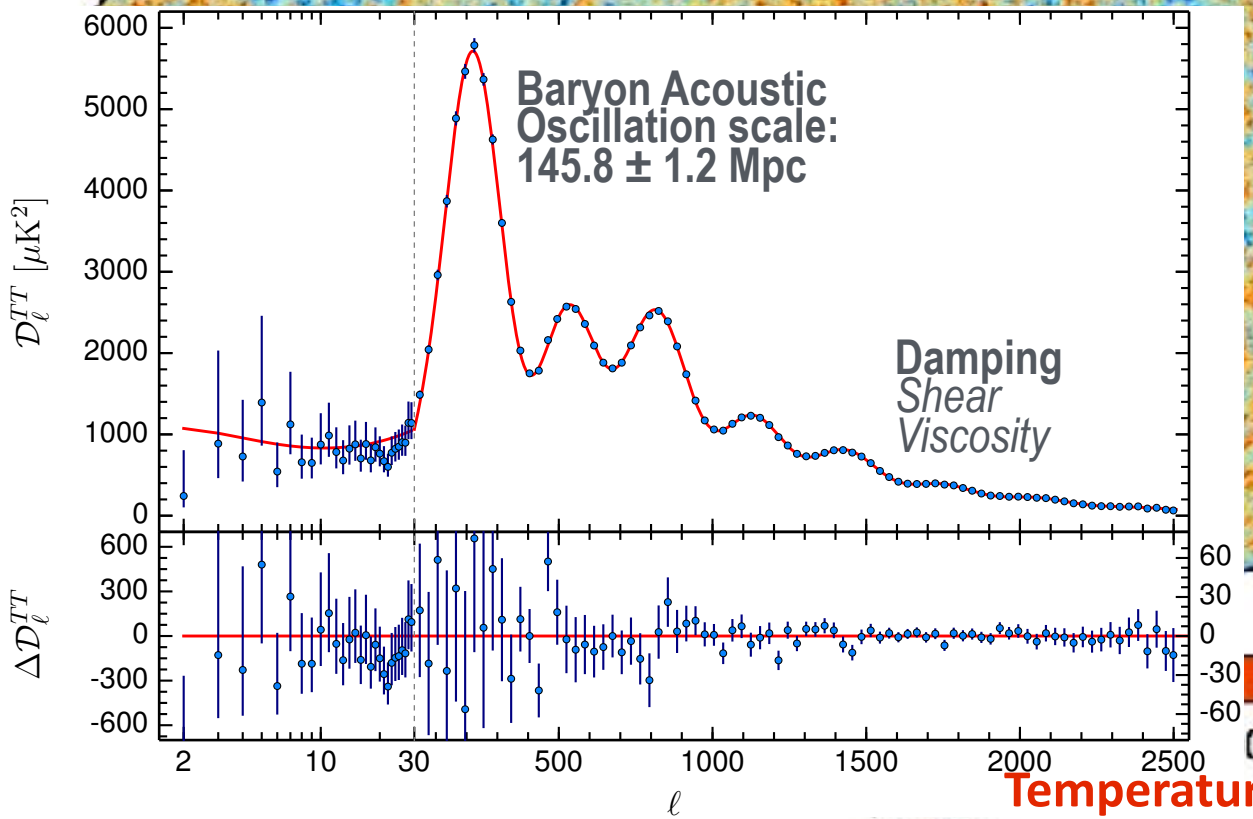
SPIDER

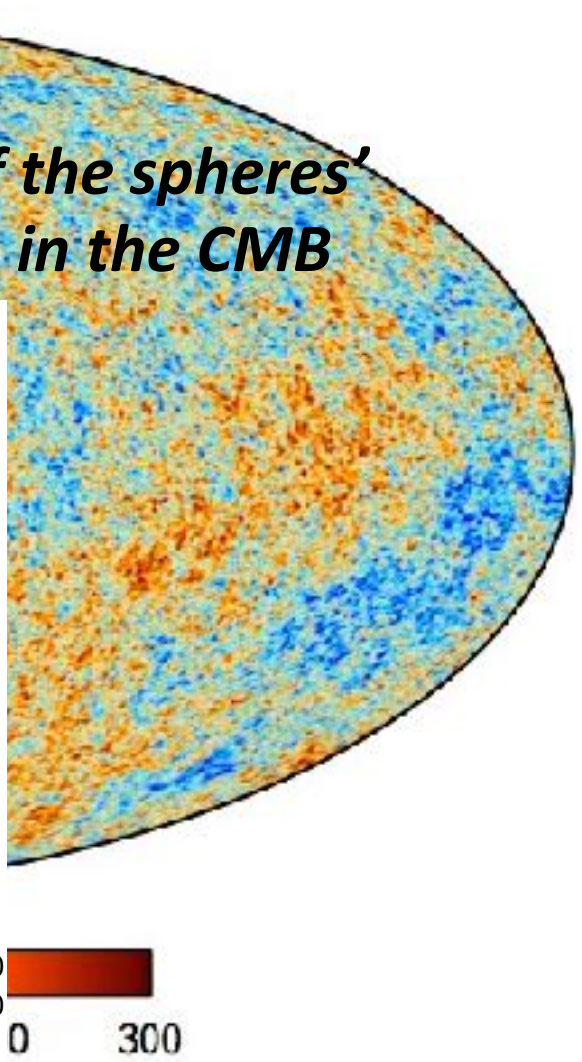
Planck's primordial light unveiled, *Mar 2013 =>* **Feb 2015** *=> pre-2016 => march 2017 final*

reveals the SIMPLICITY of primordial cosmic structure

7⁺ numbers, 3 densities, 2+1 early-Universe inflation

harmonic analysis of the *'music of the spheres'*
=> inharmonious, coloured noise in the CMB





Temperature changes in micro-degrees

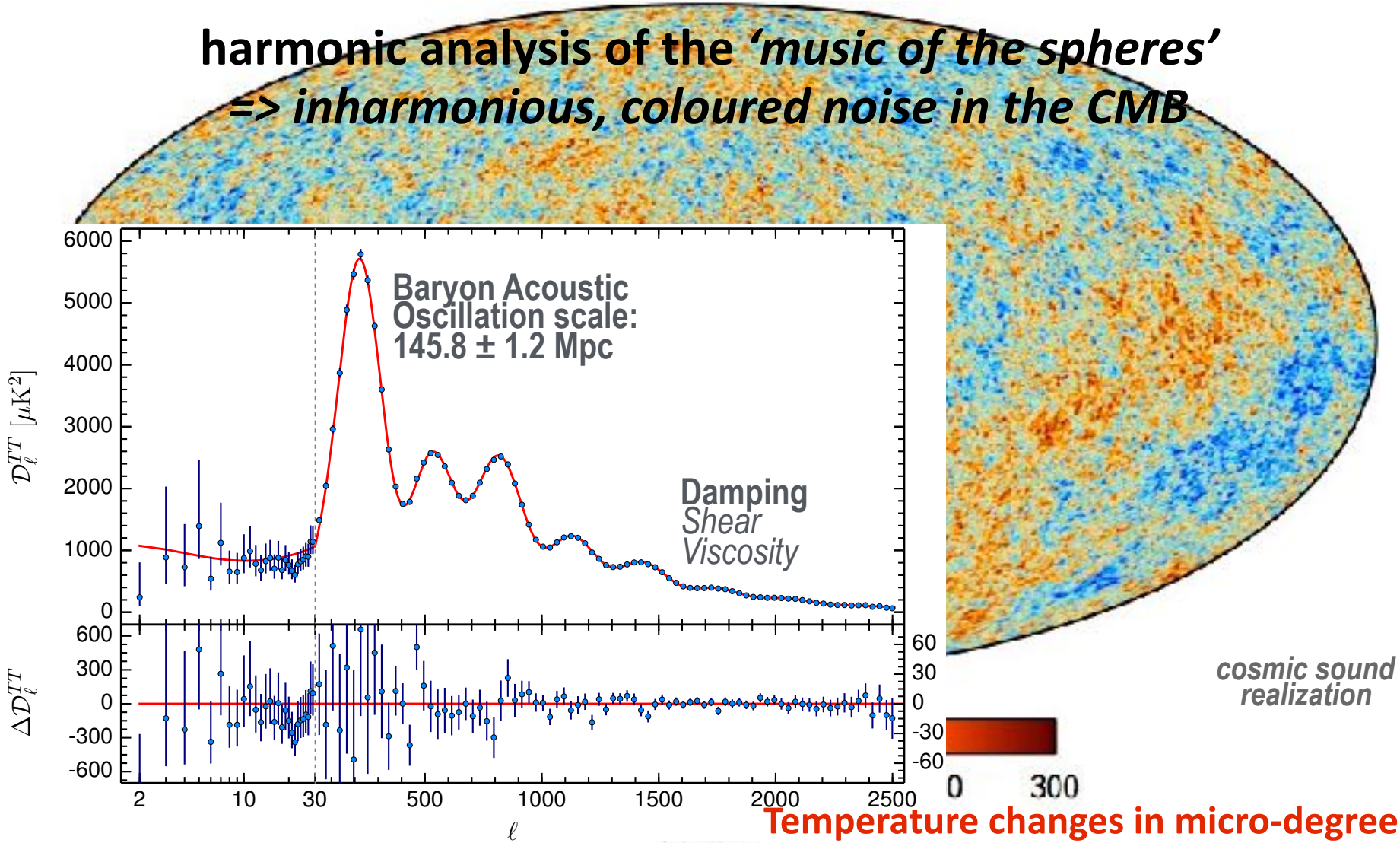
Planck's primordial light unveiled, *Mar 2013 =>* **Feb 2015** *=> pre-2016 => march 2017 final*

reveals the SIMPLICITY of primordial cosmic structure

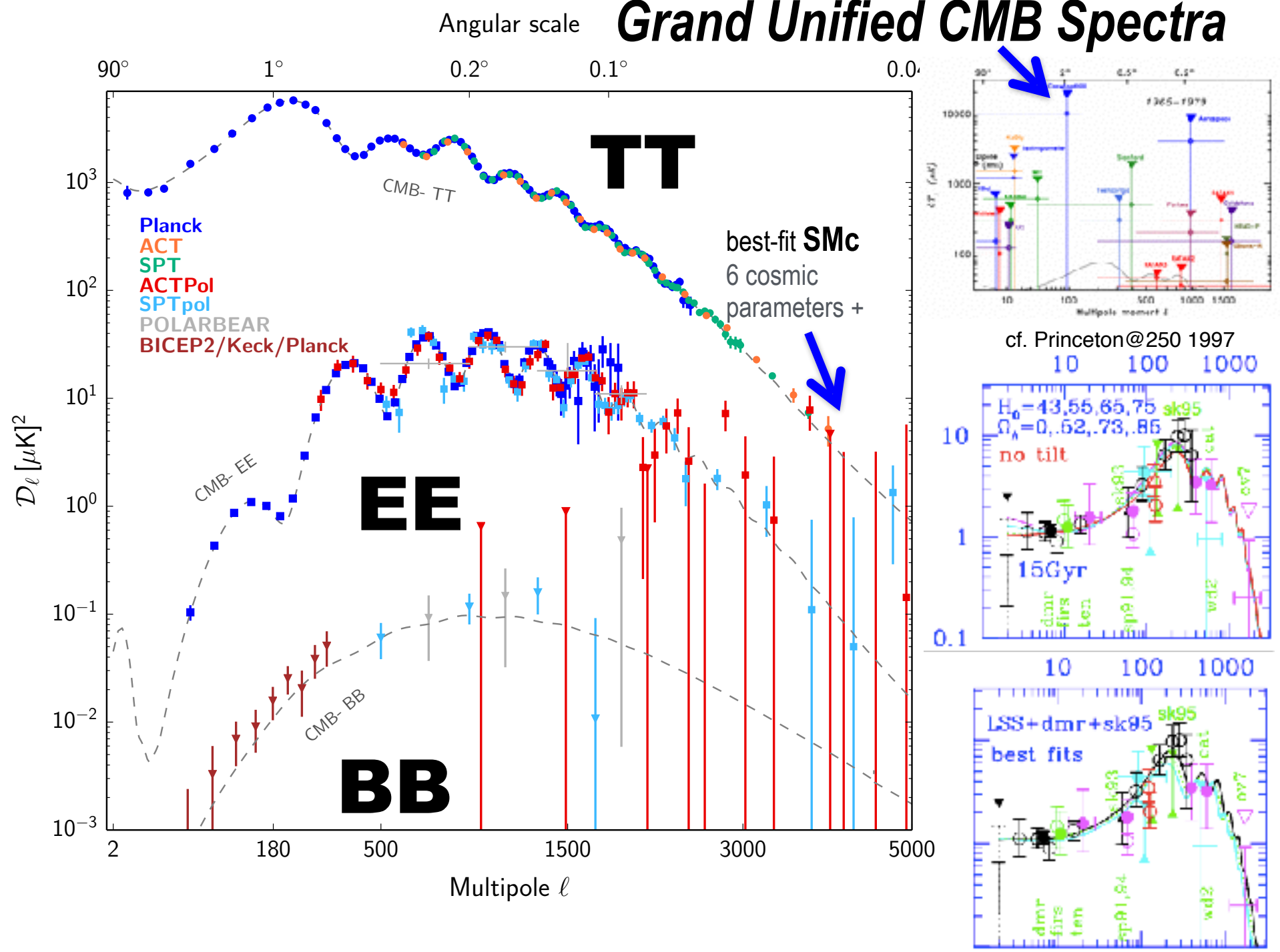
7⁺ numbers, 3 densities, 2+1 early-Universe inflation

harmonic analysis of the *'music of the spheres'*

=> inharmonious, coloured noise in the CMB



Grand Unified CMB Spectra



cf. Princeton@250 1997

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Dick Bond

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on cosmic Dark Energy ~ vacuum potential density ~ 3 amu /m^3 68.0 ± 0.9% late-inflaton KE/PE?

cosmic Neutrinos number density ~ cosmic photons Energy fraction > 0.47% ~stars

THE LIGHT

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on cosmic Inflatons - source the phonons

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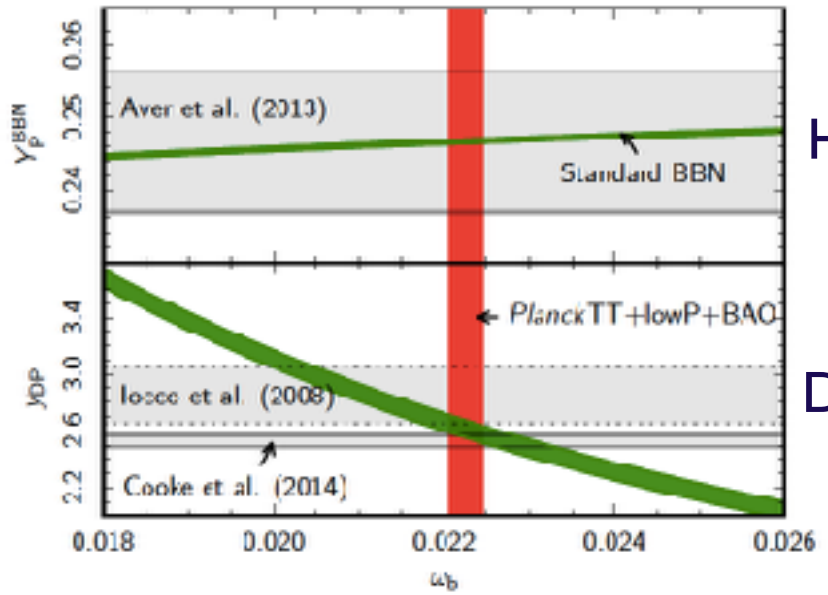
the **accuracy of CMB precision**

CMB@50: we celebrate
baryonic matter from the CMB alone
dark matter from the CMB alone *SDMW 80σ, & EE alone*
dark energy from the "CMB alone"
& the emergence/successes of CMB lensing 40σ

baryons: $\Omega_b h^2 = 0.02225$ +/- 0.00016
(cold) dark matter: $\Omega_c h^2 = 0.1198$ +/- 0.0015
Hubble parameter: $h = 0.673$ +/- 0.007 x 100 km/s/Mpc => age of the Universe

Big Bang Nucleosynthesis agrees with CMB



Helium

Deuterium

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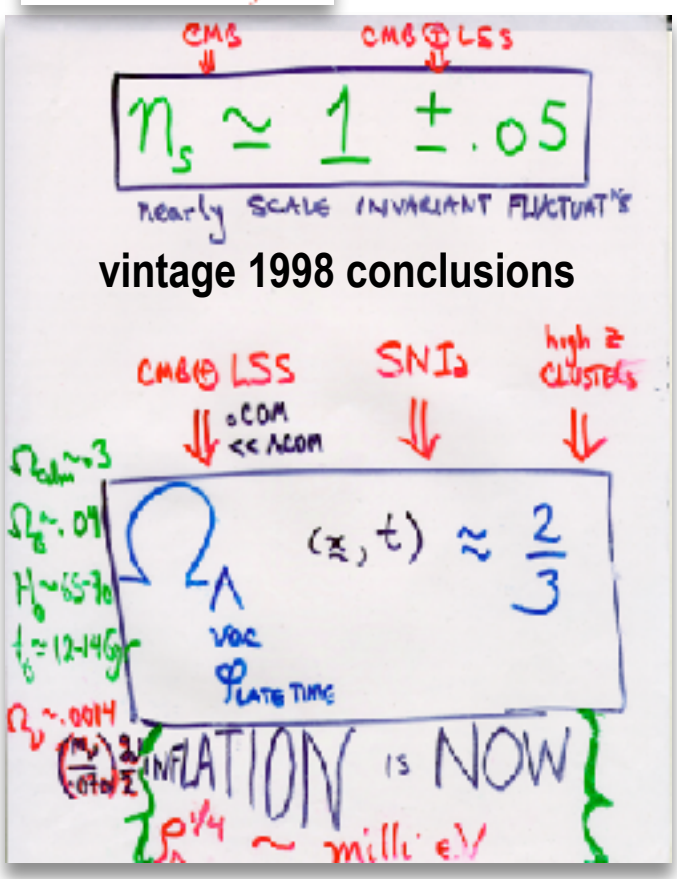
B+Jaffe'96,'98



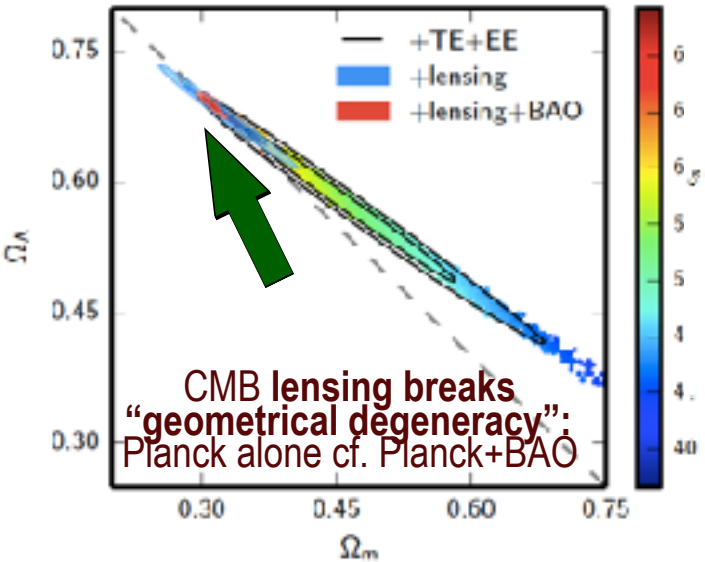
vintage 1998 conclusions

Dark Energy

Ω_Λ : 0.691± 0.006

w_0 : -1.02± 0.08

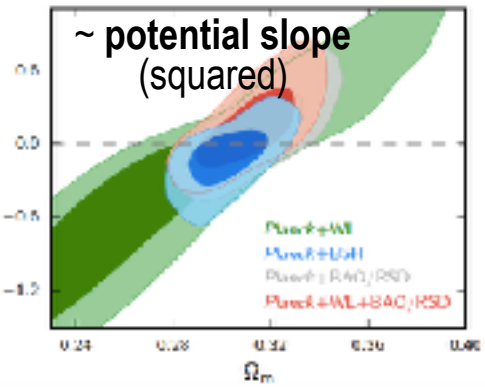
Ω_K : .0008 ± 0.004



CMB **lensing breaks "geometrical degeneracy"**: Planck alone cf. Planck+BAO

also Sherwin+11: ACT

w/ Prof Z. Huang @SYSU



dynamical? maybe coupled to matter?

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SIMPLICITY

at $a\sim e^{-7}\sim 1/1100$ =>

at $a\sim e^{-67-60}\sim 1/10^{30+25}$

Planck2015 early U structure map

reveals primordial ***sound waves*** *in matter*

=> *learn* ***contents*** *&* ***structure*** *at 380000 yr,* $a\sim e^{-7}$

=> *infer the structure far far earlier* $a\sim e^{-67-60}$

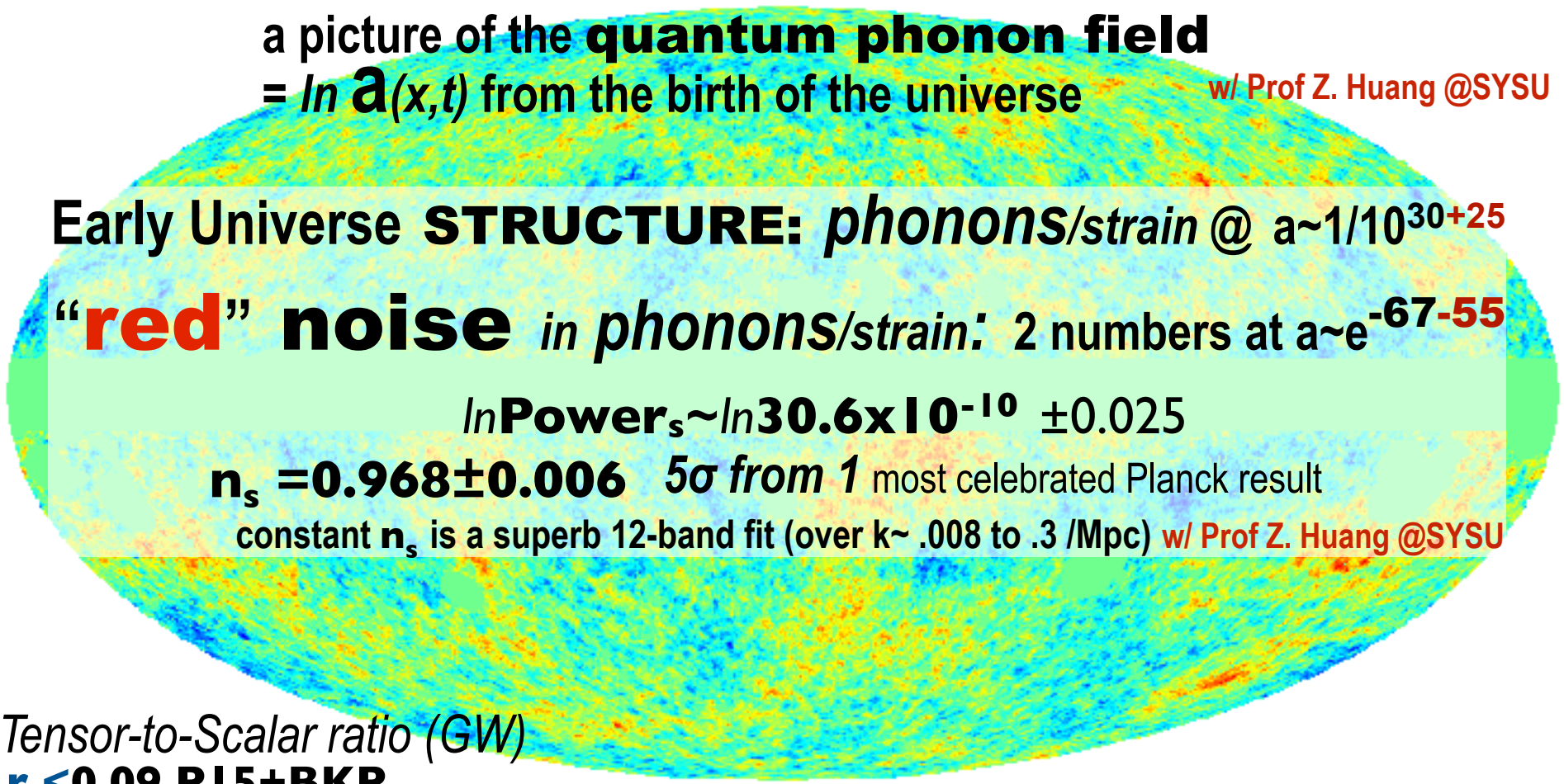
10^5 zeta

2^+ *numbers*

a picture of the **quantum phonon field**

= *ln* $a(x,t)$ from the birth of the universe

w/ Prof Z. Huang @SYSU



Early Universe **STRUCTURE:** ***phonons****/strain @* $a\sim 1/10^{30+25}$

"red" noise *in* ***phonons****/strain:* **2** numbers at $a\sim e^{-67-55}$

$ln\mathbf{Power_s}\sim ln\mathbf{30.6\times10^{-10}}\ \pm0.025$

$\mathbf{n_s = 0.968\pm0.006}$ ***5σ from 1*** most celebrated Planck result

constant $\mathbf{n_s}$ is a superb 12-band fit (over k~ .008 to .3 /Mpc) w/ Prof Z. Huang @SYSU

Tensor-to-Scalar ratio (GW)

r <0.09 P15+BKP

-35.0 +35.0

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$a_J^i(r,t)$ scale-tensor of the Universe

$$dX^i(r,t) = a_J^i(r,t)dr_{eq}^J$$

$$a_J^j \equiv exp(\alpha)_J^j$$

$$\alpha_J^j \equiv \langle ln\ a \rangle \delta_J^j + \varepsilon_J^j$$

ε=strain tensor

$$dV^i(r,t) = H_J^i(r,t)dX^i(r,t)$$

H_J^i=*Hubble aka* ***shear*** $= d\alpha_J^j / dt$

general relativity

Earth under Strain: earthquakes, seismic waves

ε=strain tensor

Universe under Strain: space-quakes = gravity waves

elastic deformation $dx^i = e_J^i\, dr_{eq}^J$ $e_J^i = a_J^i / \langle a \rangle$

anisotropic strain, shear waves ε-Trace(ε)/3

isotropic strain, sound Trace(ε)

scale-deformation a_J^i

anisotropic strain, gravity waves

isotropic strain, sound

linear: **strain** ∝ **tide**

cosmic web *story*

light and gravity are entangled: wavelength stretches under space-strain: ***redshift***

the vacuum is modified under space-strain: inflation theory

general relativity => **a**= *drei*bein, triad, Lagrangian-space metric **g=aa**†

the flow of time => 4D *vier*bein *spacetime-strain* a_b^{β} $b,\beta=0,1,2,3$

Mar 2014: bicep2 GW detection r~0.2 =>BKP Feb 2015 Planck: thou shalt not ignore dust polarization r<0.13 P15+BKP r<.09 95%CL

=> 1 sigma stage 2 ± 0.03 stage 3 ± 0.006 => stage 4 ± 0.0005

the *ln*a-scape & the CMB

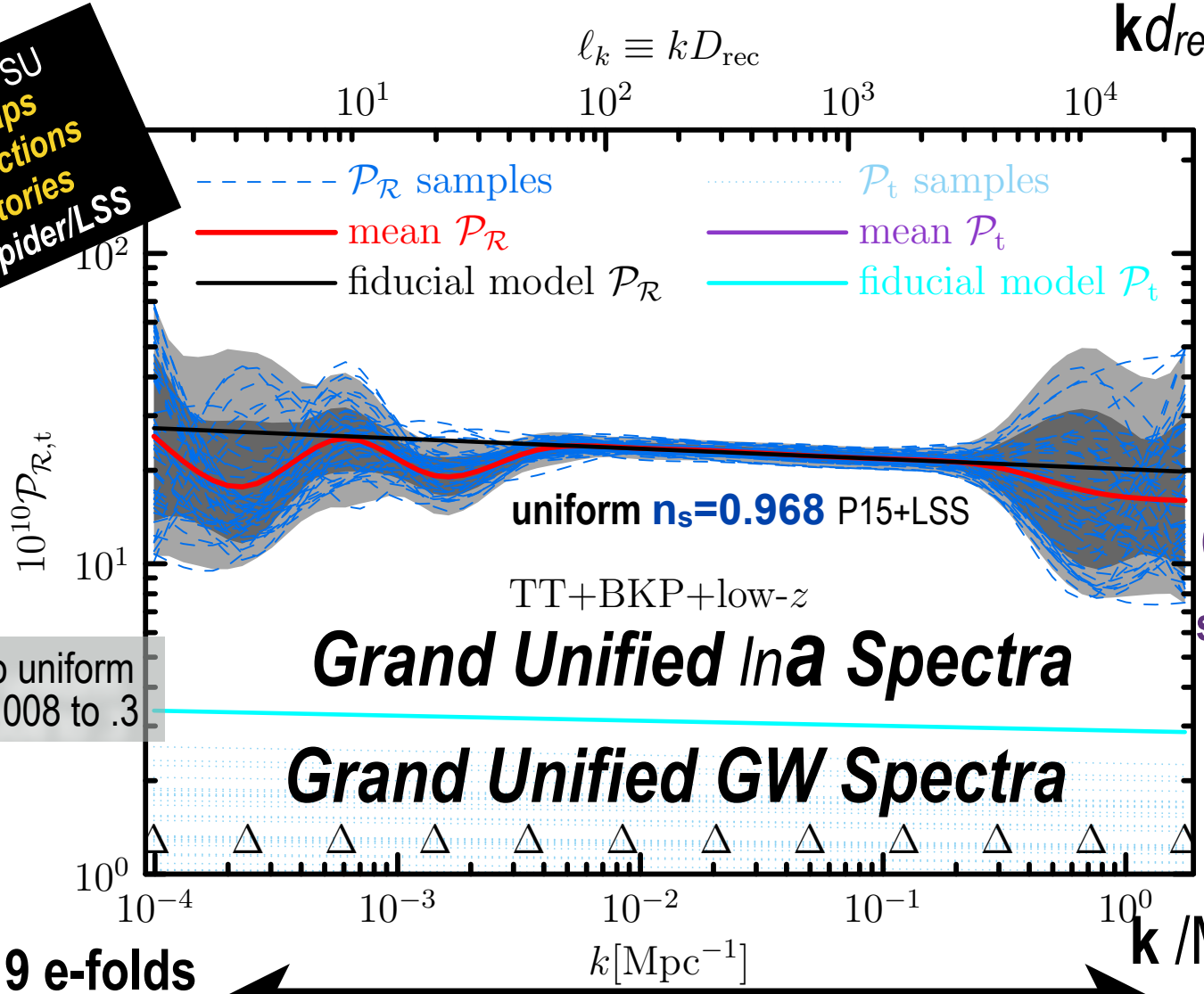
aka mapping early U sound/phonons

multi-band GW: r<.11 95% CL

cf. **r<0.09 uniform n_s** ***=> 1 sigma stage 3 ± 0.006 => stage 4 ± 0.0005***

kd_{rec} ≳L

w/ Prof Z. Huang @SYSU
In a(x,t) early U maps
potential reconstructions
acceleration histories
Planck/AdvACT/Spider/LSS



EE (L>30) looks similar

=> V(ϕ)

superb 12-band fit to uniform n_s=0.968 over k~ .008 to .3

9 e-folds

k /Mpc

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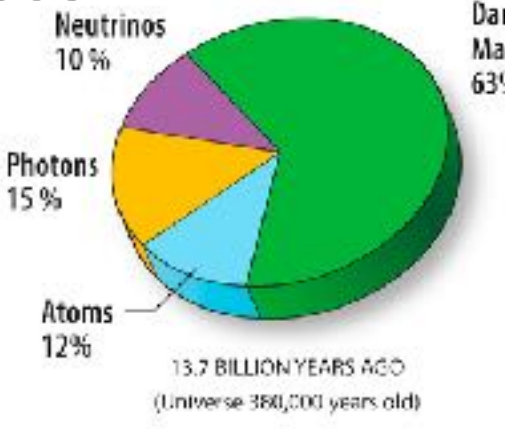
NEUTRINOS: number of species, sum of masses

NEUTRINOS: decouple before Big Bang nucleosynthesis;
effect on BBN a probe of weak interaction / neutrino physics T < 0.5 Mev

$T_\nu = 1.945$ K cf. $T_{cmb} = 2.725$ K

3 known families 113 neutrinos/cm^3/family



energy density in relativistic particles beyond photons & known neutrinos

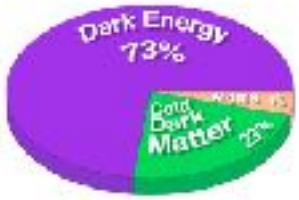
N_{veff} = 3.15 ± 0.23 relativistic dof cf. 3.046 SMc

=> 1 sigma stage 3 ± 0.06 => stage 4 ± 0.027

Nobel Prize 2015 0.06 eV< Σm_ν <2.3 eV (95%cl)

From atmospheric neutrinos at SuperK , ν_{mu} ν_τ

Tritium end point ν_e (Kraus et al., 2005)



mass of neutrinos from effect on large scale cosmic web formation suppress structure formation

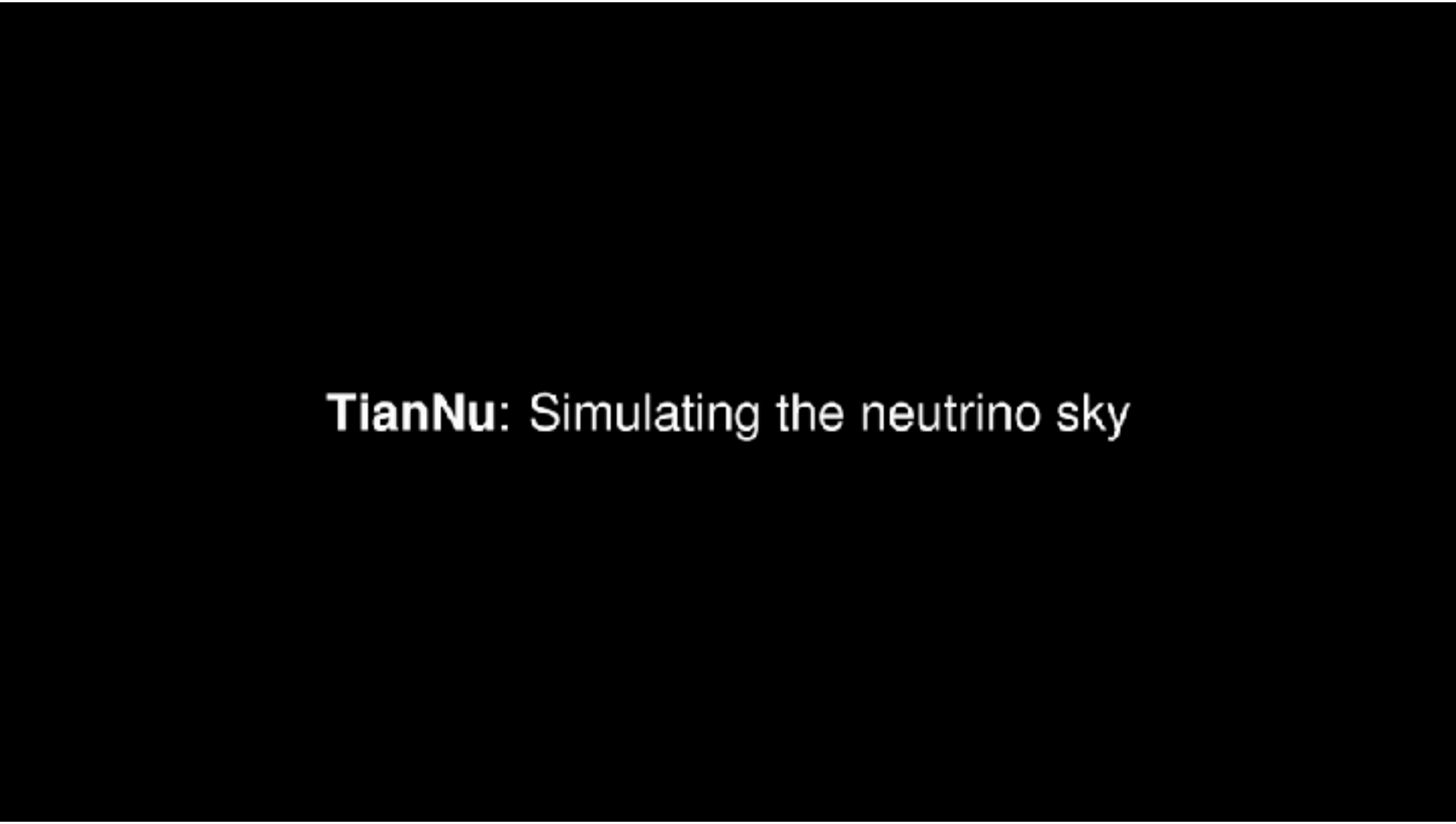
$\sum m_\nu$ < 220 meV 95% => 1 sigma stage 3 ± 60 meV => stage 4 ± 50 meV

P15+Planck(cls)+BAO

$\sum m_\nu$ < 170 meV 95% P15+BAO

TianNu simulation on Tian He@SYSU *neutrinos + cold dark matter, largest sim ever, CITA+China*

Haoran Yu, JD Emberson, D Inman, Ue-Li Pen etal



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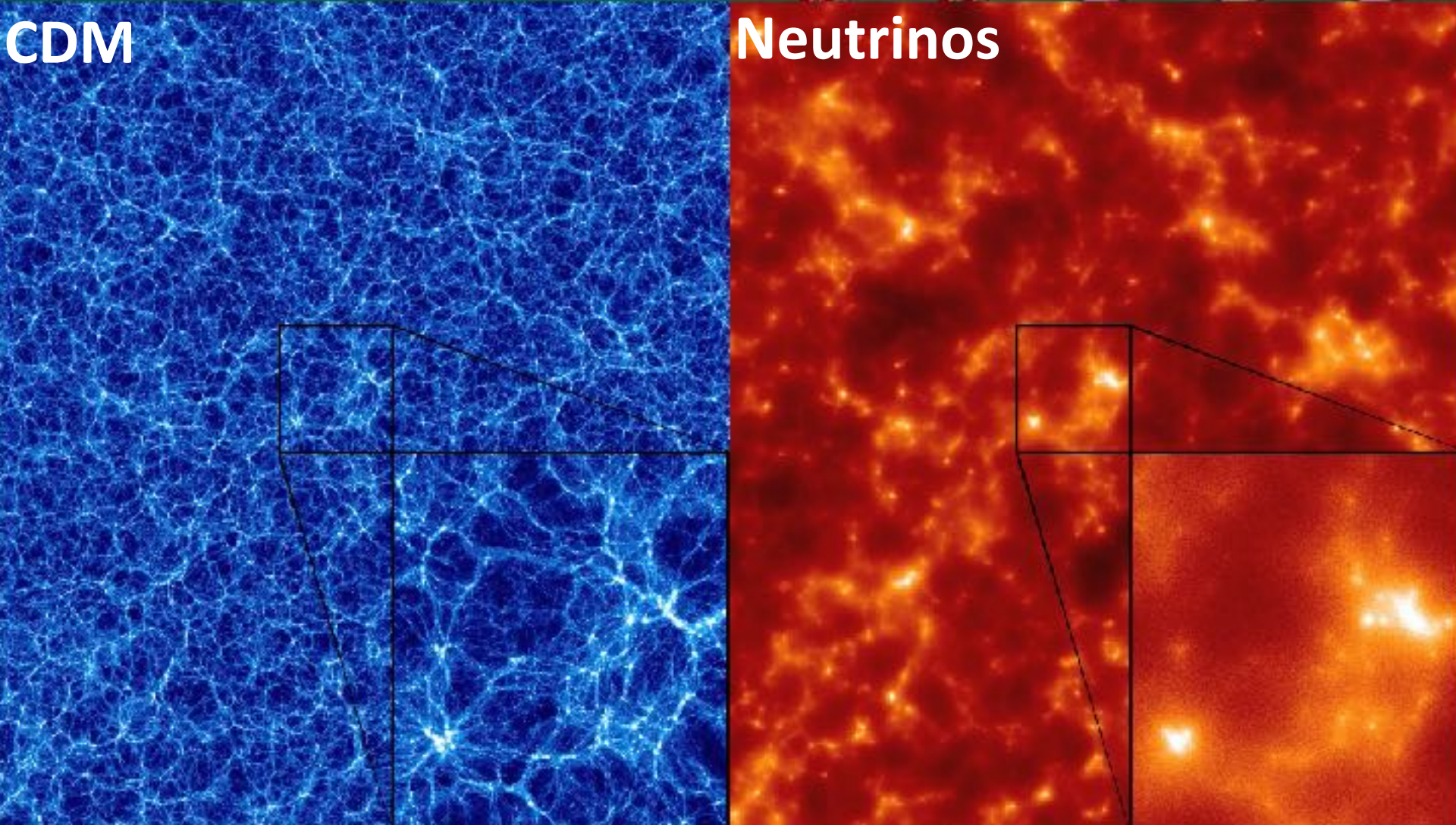

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