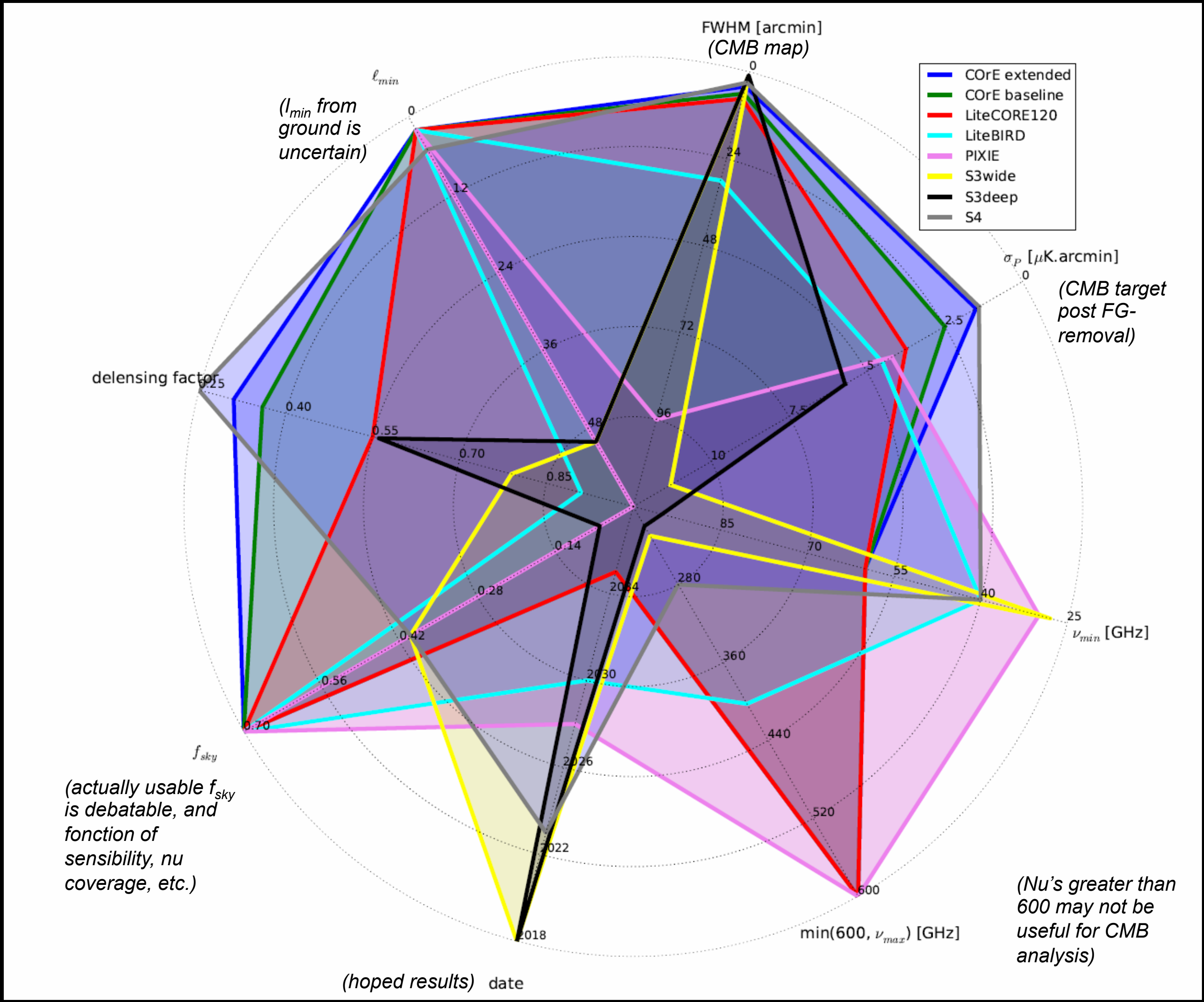
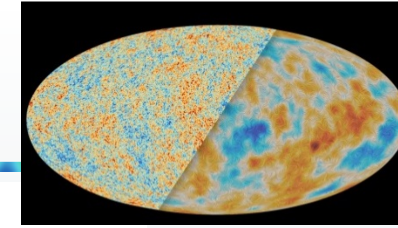
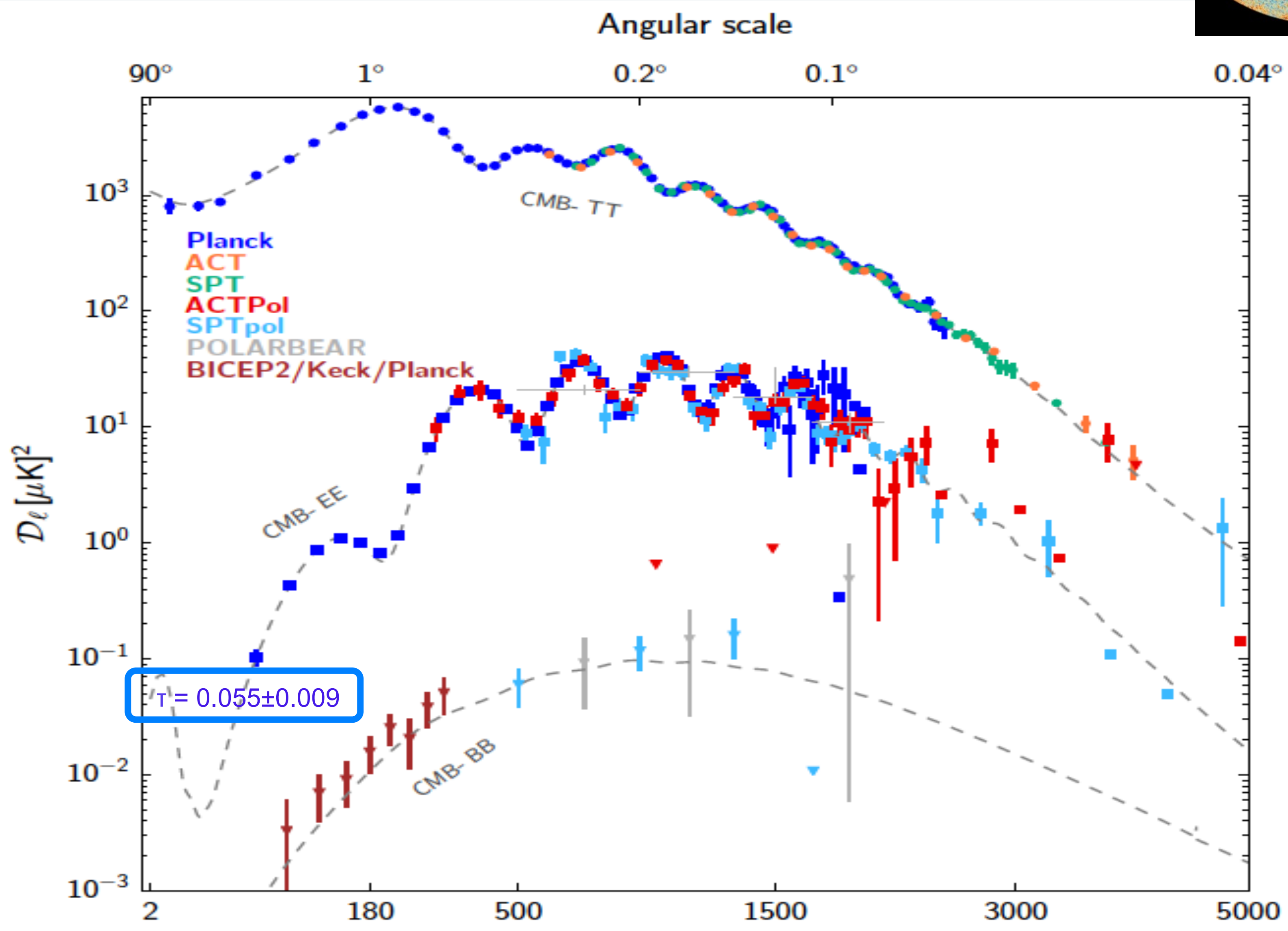
Scientific objectives of space CMB probes?



TT, EE, BB – mid 2015 status



Only keeping points w. sufficiently small error bars, Fig. calabrese



1 114 000 Modes measured with TT,

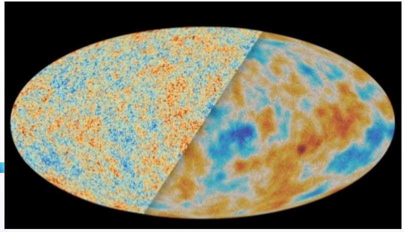
60 000 with TE

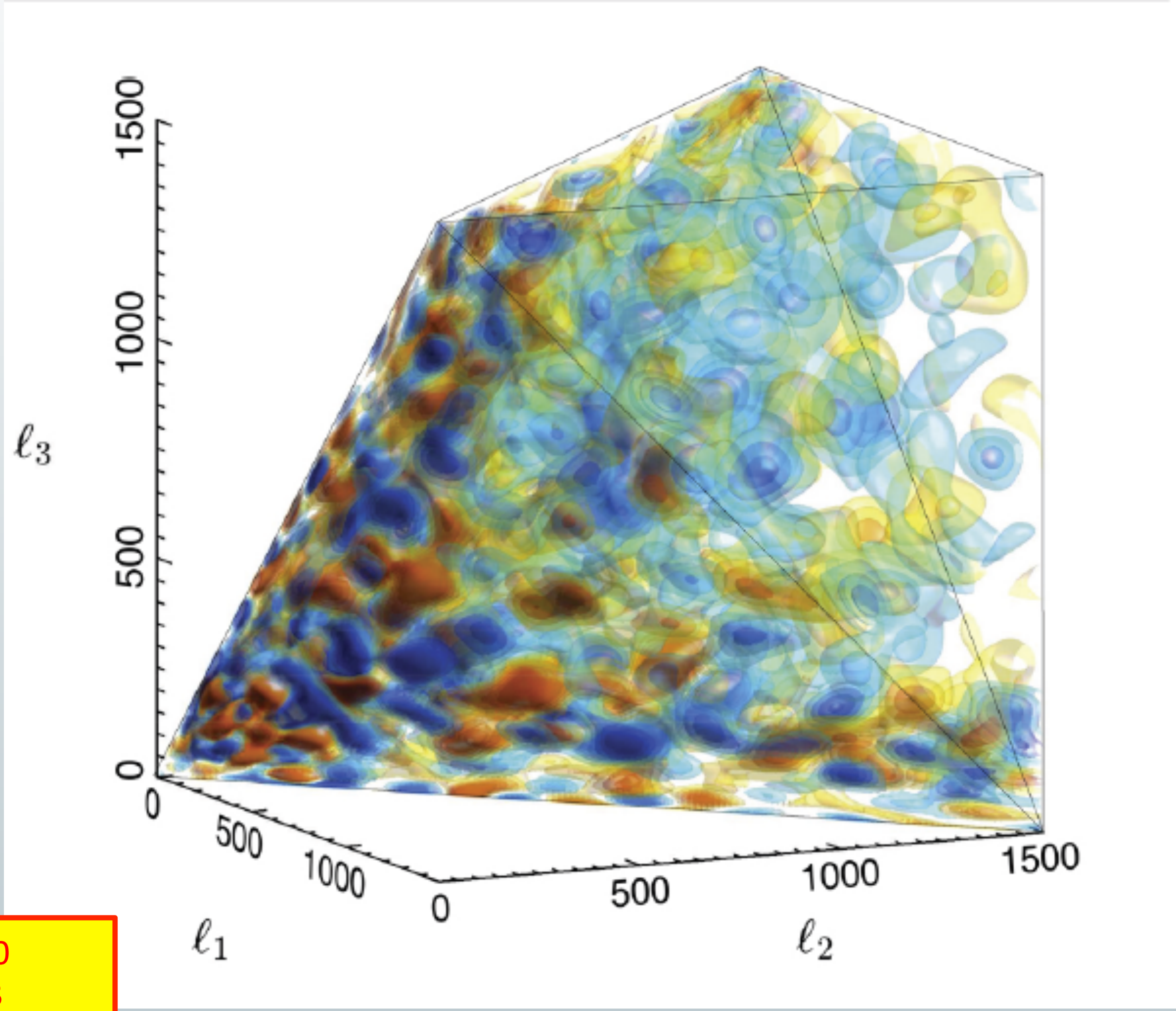
96 000 with EE

… and 10's in BB

+ weak constraints with TB and EB

Planck 2015 TTT – 2001 modes





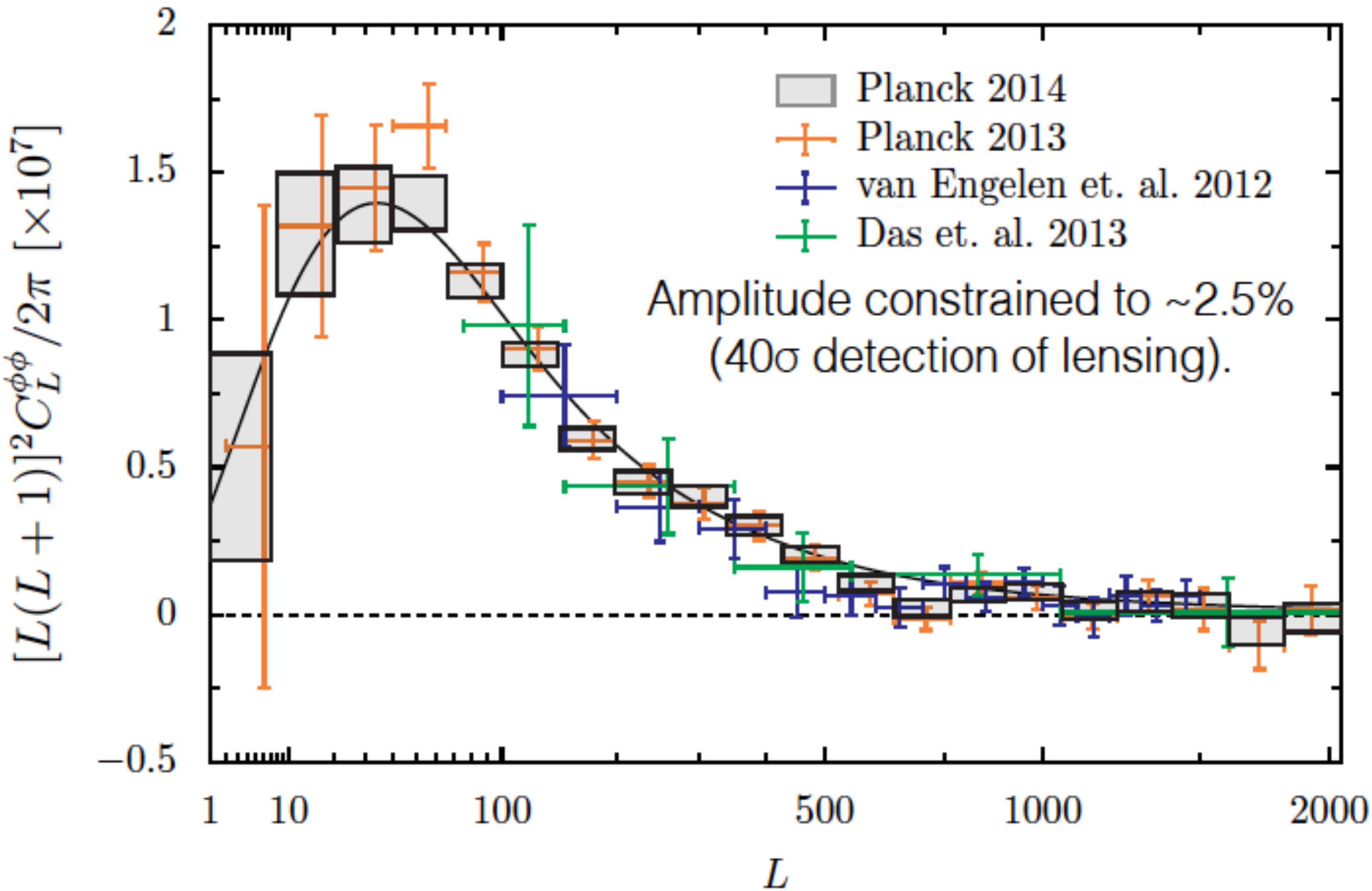
f^{local}_{NL} = 0.8 ± 5.0
f^{equil}_{NL} = - 4 ± 43
f^{ortho}_{NL} =-26 ± 21

$|f_{NL}^{Loc}| <$

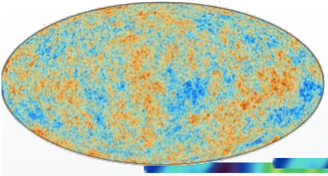
10^3 (Maxima 2001),
10^2 (WMAP7),
10 (Planck15)

A hundred-fold improvement in 14 years

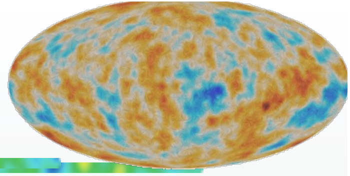
Lensing power spectrum



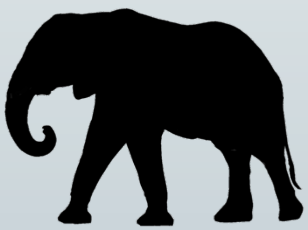
Planck for the first time measured the lensing power spectrum with higher accuracy than it is predicted by the base CDM model that fits the temperature data



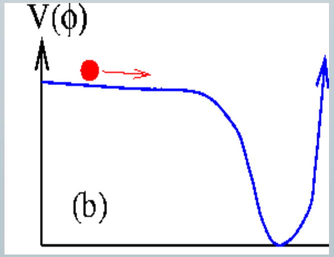
Summary: Basic ΛCDM fits



- CMB + LSS provide a consistent picture within LCDM. Content known with percent accuracy.
- Primordial fluctuations are, to a very good approximation:
  - *Isotropic*
  - *Gaussian*
  - *Adiabatic* *(fluctuations in pressure α to the density)*
  - *Coherent* *(fluctuations start @same time, harm. osc)*
  - *Close to Scale invariant*
  - *but not exactly* *(n_s =1 is excluded at more than 5σ)*
- With minimal cosmological content,
  - *Flat spatial geometry* *(is a very good approximation)*
  - *Matter is mostly dark* *(and cold)*
  - *"Dark energy" consistent with Λ* *(w=-1)*
  - *Small fraction of baryon, consistent with BBN*

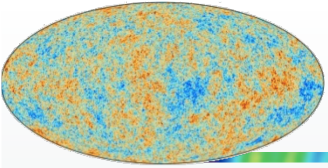


- No gravitational waves (10 percent level)
- Large scale power, with TT versus TE anti-correlation ($5^o > \vartheta > 1^o$):
  - *apparently a-causal physics, calling for a period of accelerated expansion*

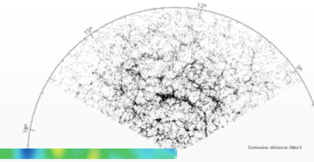


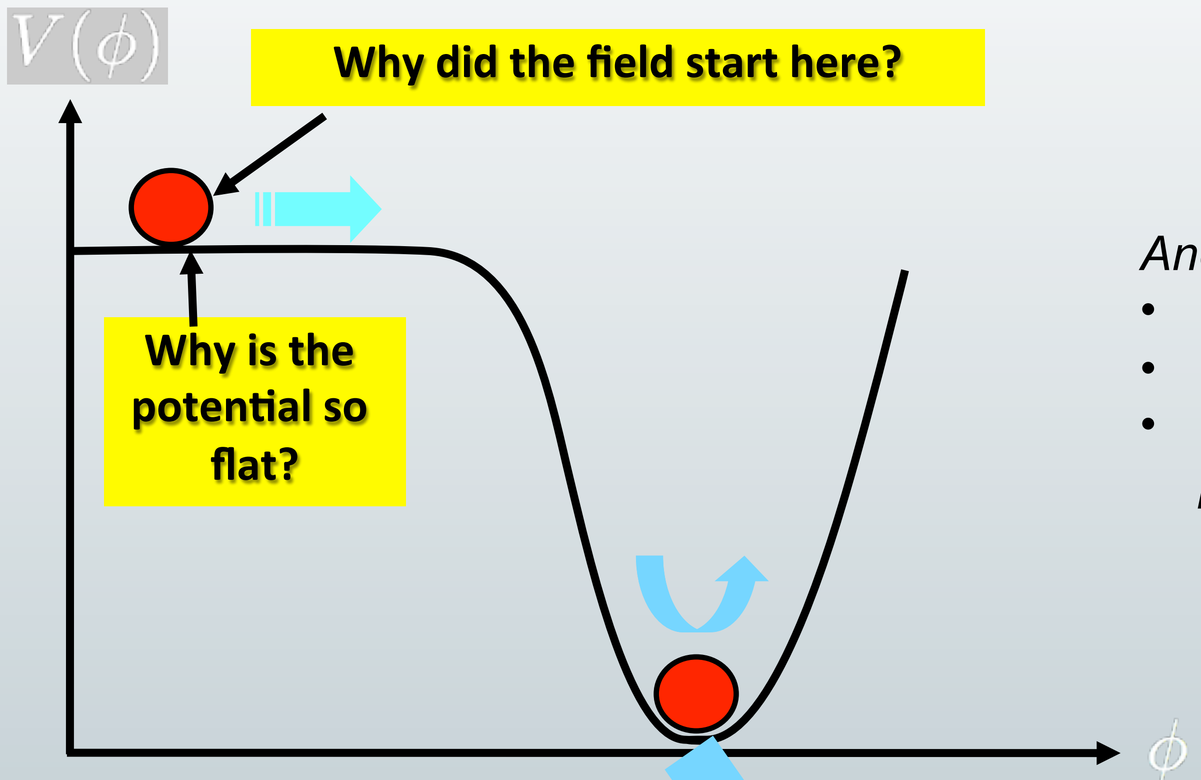
➔ I.e. all consistent within the generic inflationary framework, completing the standard model of cosmology (w. Hot Big Bang phase).

➔ "Anomalies" are present at tantalizing levels, but at large scales.



But what is the physics of inflation?





Why did the field start here?

Where did this function come from?

Why is the potential so flat?

And what are:

- *Dark Matter*
- *Lambda/DE*
- *Neutrinos properties …*

Is there a completely different paradigm to explain the measurements?

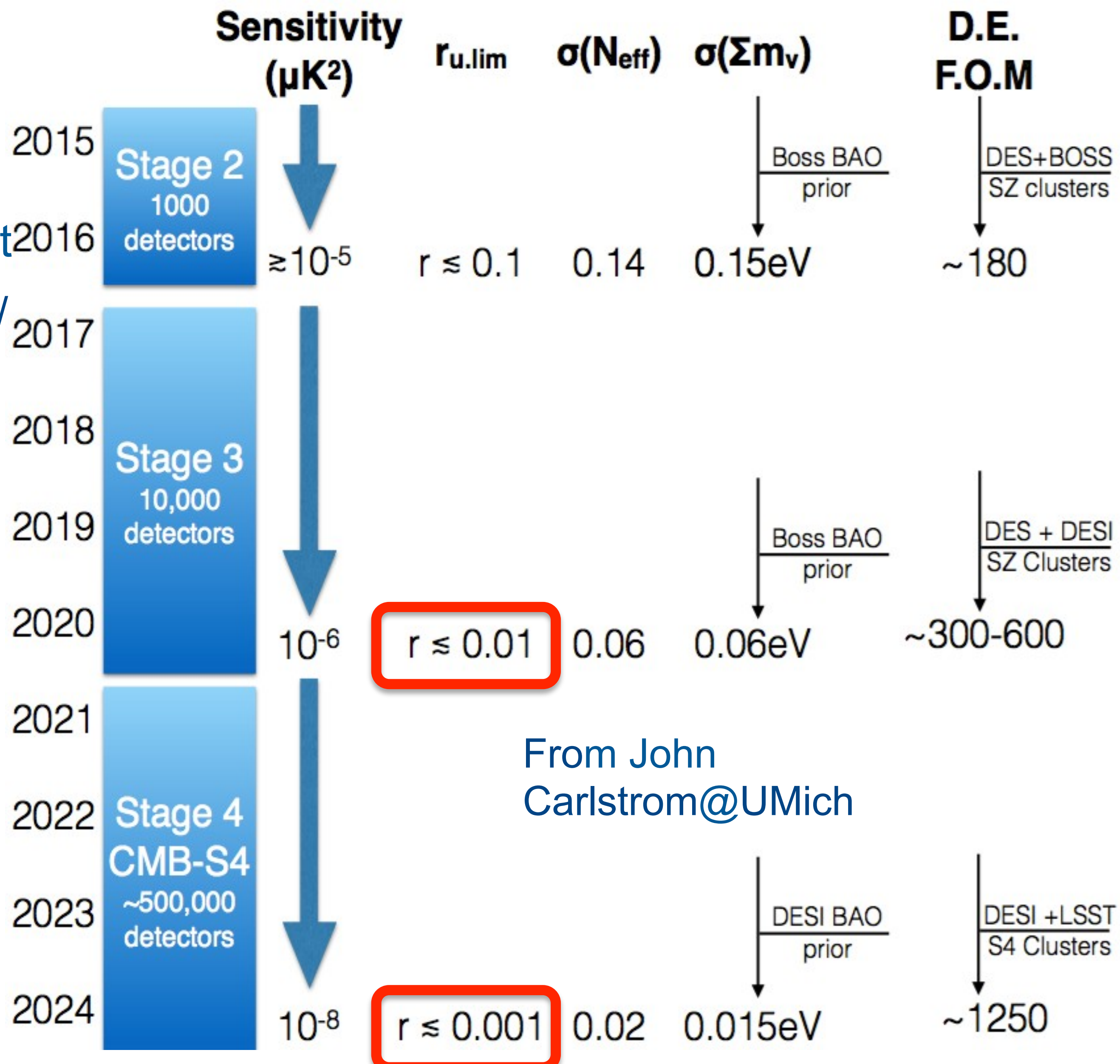
How do we convert the field energy completely into particles?

CMB will continue uniquely helping!

- Planck has about exhausted (as promised back in 1996) the information content of the temperature anisotropies. But only a few per cent of the more tenuous CMB polarisation modes are known with S/N >1.
- CMB polarisation is a *unique* source of still unknown cosmological information: globality (ensemble of parameters, some of which are quasi-inaccessible otherwise (e.g., r, f_{NL}), complementarity with temperature (an independent probe), with other probes of large scale structures (LSS) and particle physics experiments (eg Neutrinos Phys.), nature (quasi-linearity).
- We now want to map as much of the sky as possible with exacting, but achievable, requirements of sensitivity and control of systematics, both instrumental and astrophysical in nature (to measure millions of CMB polarisation modes with S/N > 1), in synergy between ground, sub-orbital and space.
- The CMB polarisation requirements insures great ancillary science.
- Spectral distortion have not been revisited since FIRAS... Lots there too!

CMB-S4 « Roadmap »

- Ground-based is building on S2 & S3
- Complementary, but not dependant on balloons/ satellites (to be demonstrated for very low r)
- US universities DOE, Natl. Labs, HEP comm.
  - International is encouraged (S4 is not funded yet)



From John Carlstrom@UMich


GRAVITATIONAL
WAVES

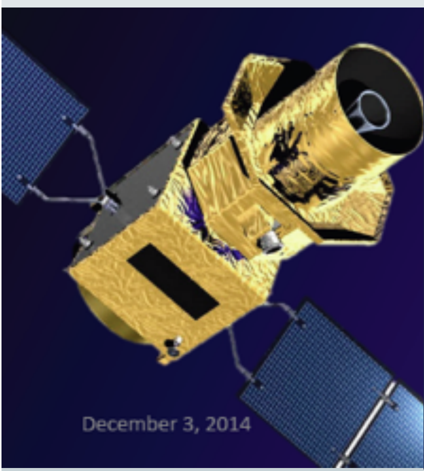
Planned CMB space missions

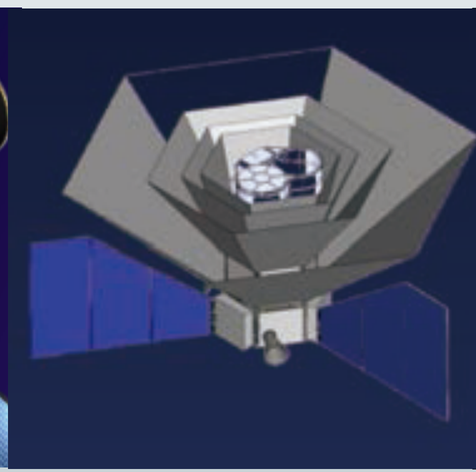
Each with rather different trade-offs/synergies/objectives…

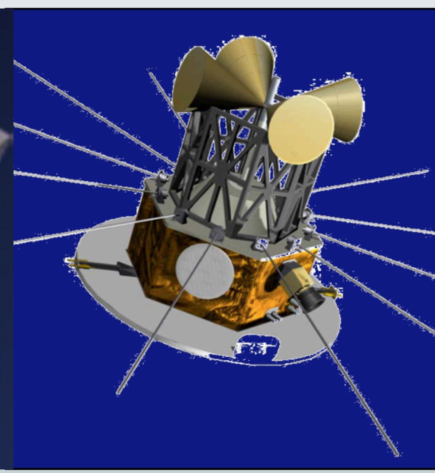
PIXIE, DARE, EPIC+? (NASA)

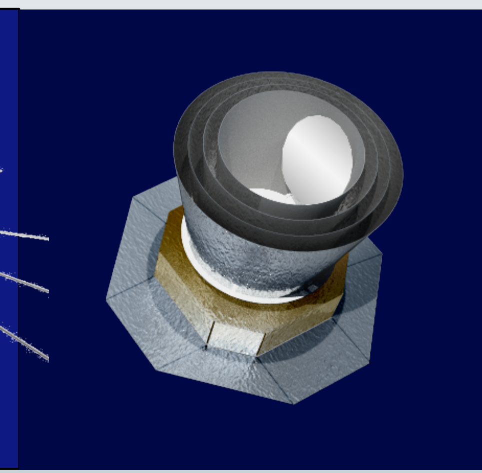
(BPOL, CORE, PRISM, CORE+) LiteCORE? (ESA-M2/M3/L2/M4/M5!)

LiteBird (JAXA) down selected to a list of 3, 6 June 2015. Passed last week in A1









….

LiteBIRD (JAXA)
30-60’ 2 uK/arcmin
+PhyA NASA
Launch 2025

PIXIE (NASA)
Next Prop 12/2016

Launch 2023

DARE (NASA)
Prop 12/2016

ESA/M5 (LiteCore?)
Prop ~10/2016
(AO 04/2016)
Launch 2026-30?

Science reach of sats?

How do different CMB projects compare on parameter estimation within LCDM?
What is the gain with more capable experiments/satellites,

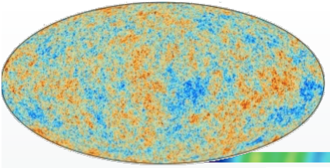
- on r (n_t), if r is as « large » as $r=10^{-2}$?
- on r (n_t), if $r<=10^{-3}$ (when "delensing" becomes an important factor)?
- on standard LCDM paramters?
- on neutrinos physics?
- On checks of LCDM extensions and serendipitous discovery?

➔ Might be useful to have an homogeneous comparison for various fiducial cases for space sats alone, various ground options, and their combinations

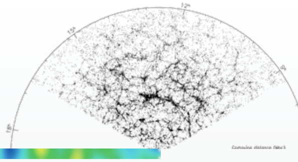
Here follows a potentially useful series of plots, in view of the M5 proposal to be submitted, from a simplistic analysis comparing PIXIE, LiteBird, LiteCORE120, CORE-M4 baseline, CORE-M4 extended, S3d, S3w, S4, looking only at the withdrawable information content in the CMB, i.e. specs are compressed to

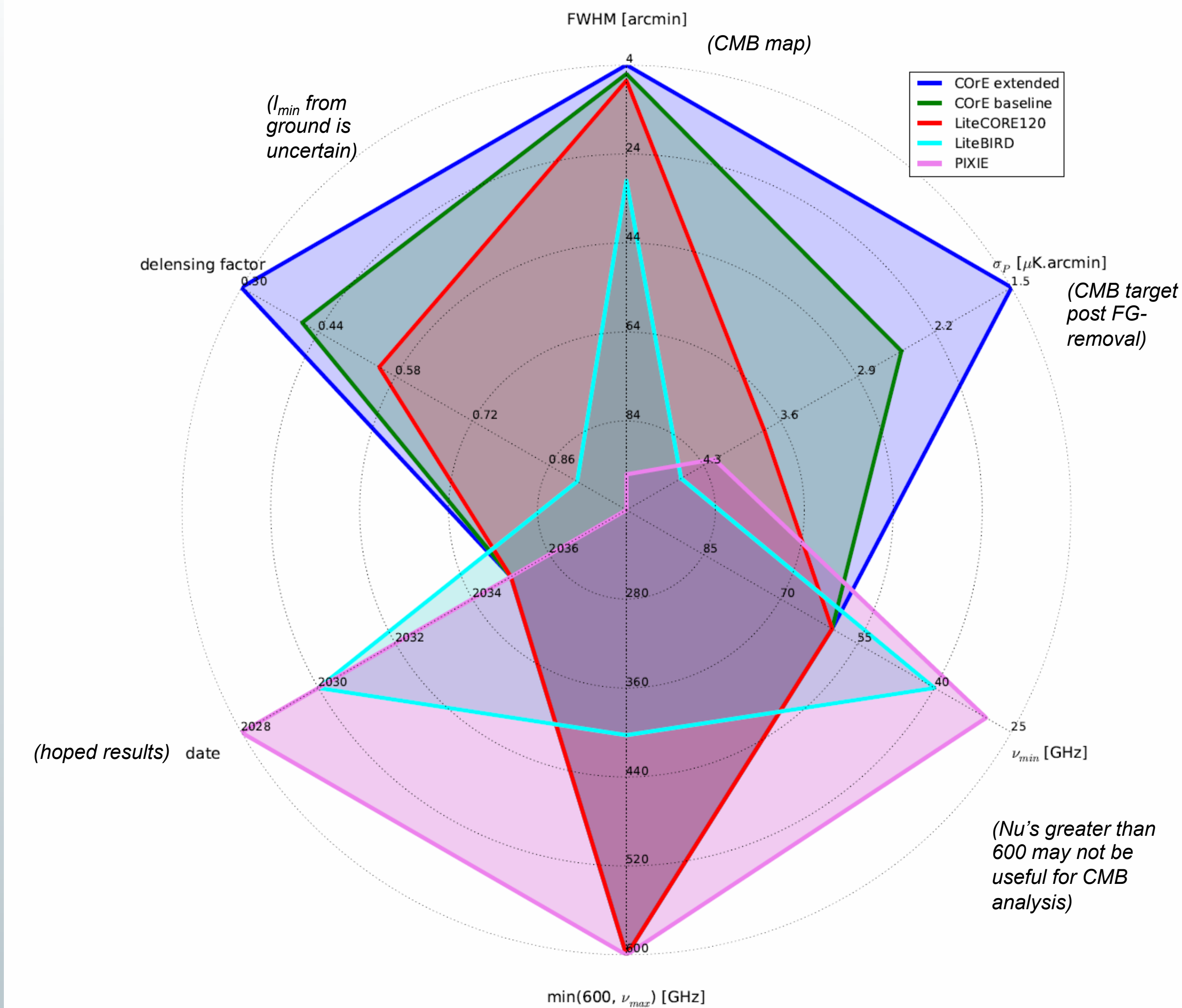
- σ_p
- FWHM
- F_{sky}

without worrying about actual foreground taming capabilities.
(but looking at biasing effect of unaccounted residuals easy to do, + ala JE)



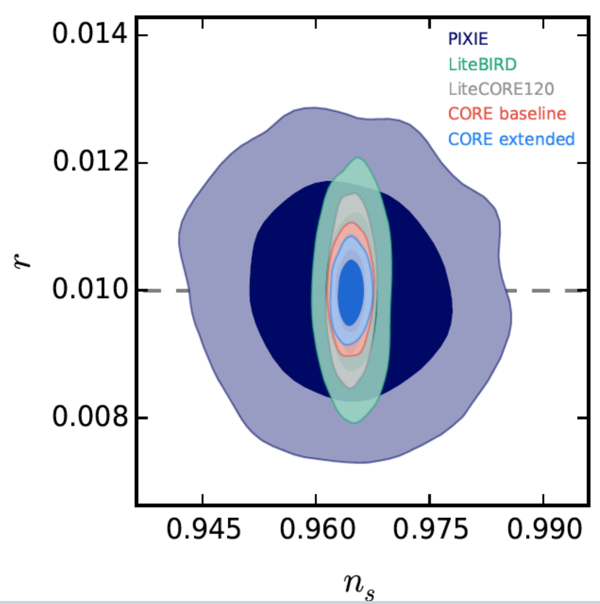
Simplistic Sats summary



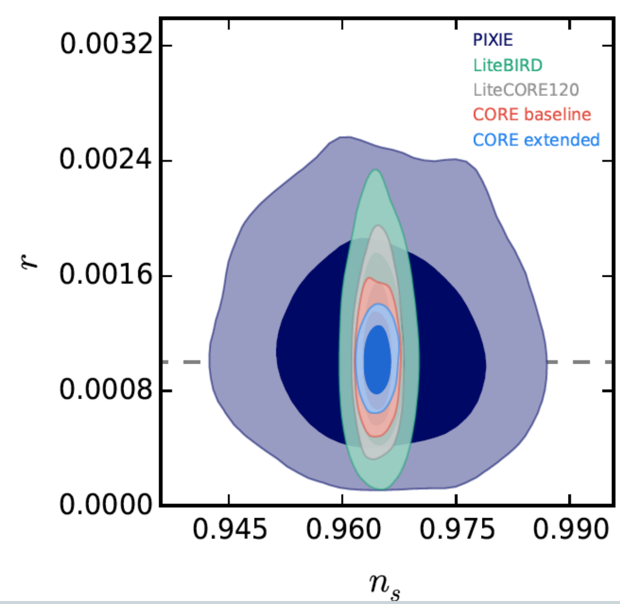


(n_s, r) plane from sats alone

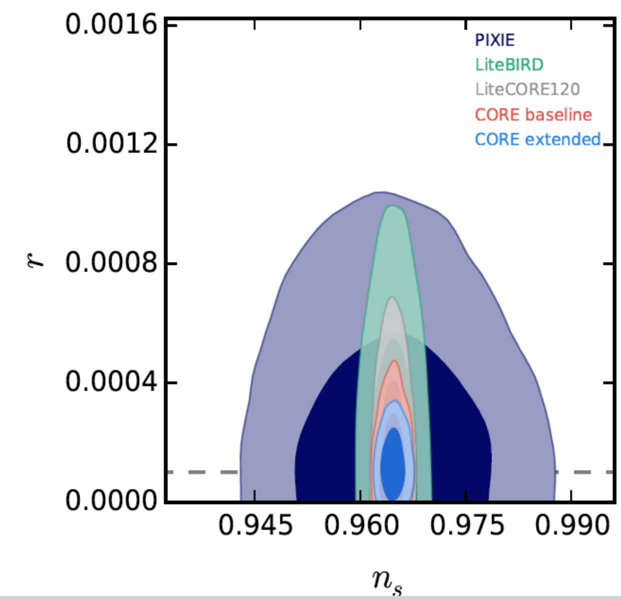
($r_{fid}=10^{-2}$)



($r_{fid}=10^{-3}$)



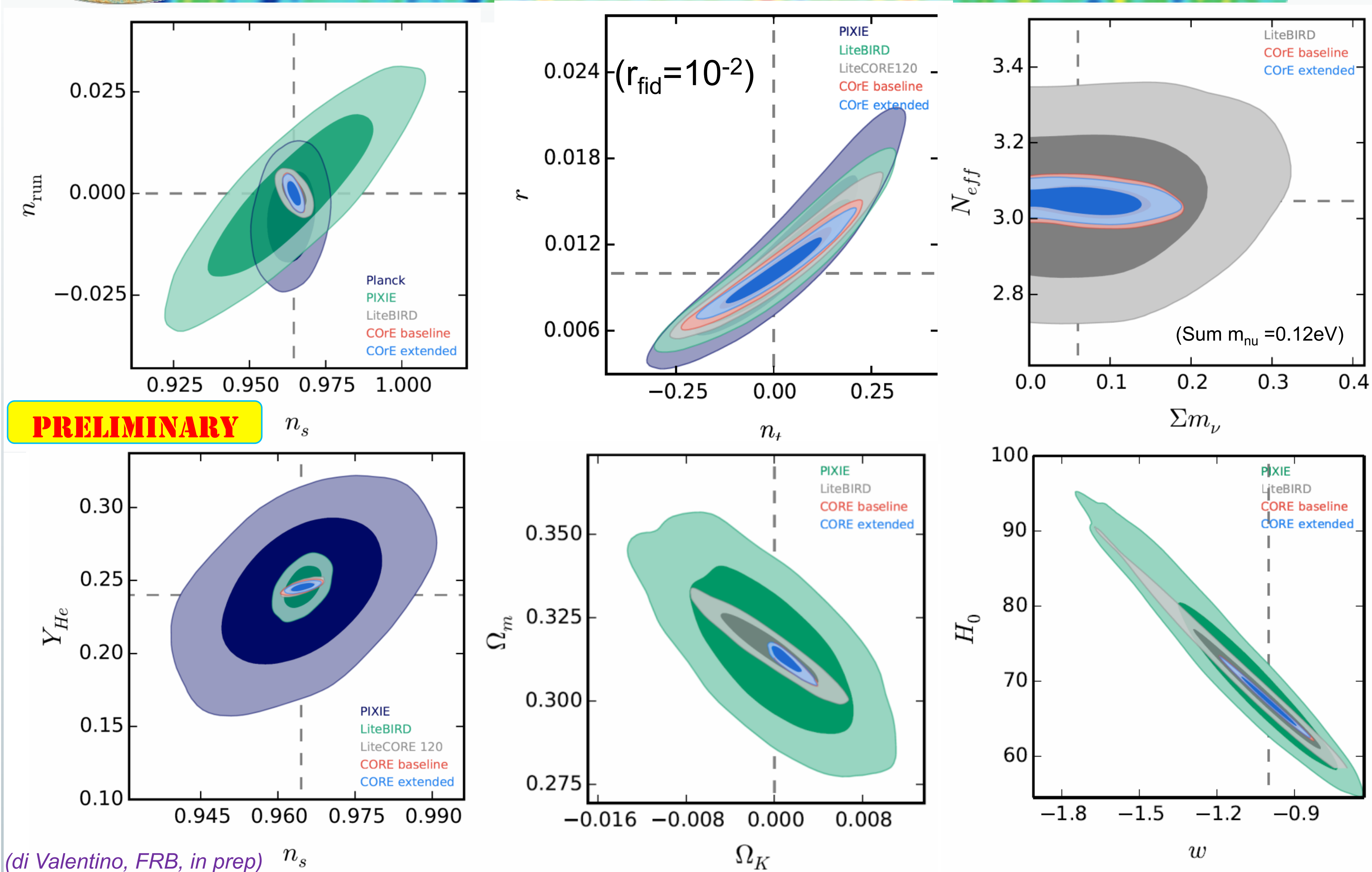
($r_{fid}=10^{-4}$)



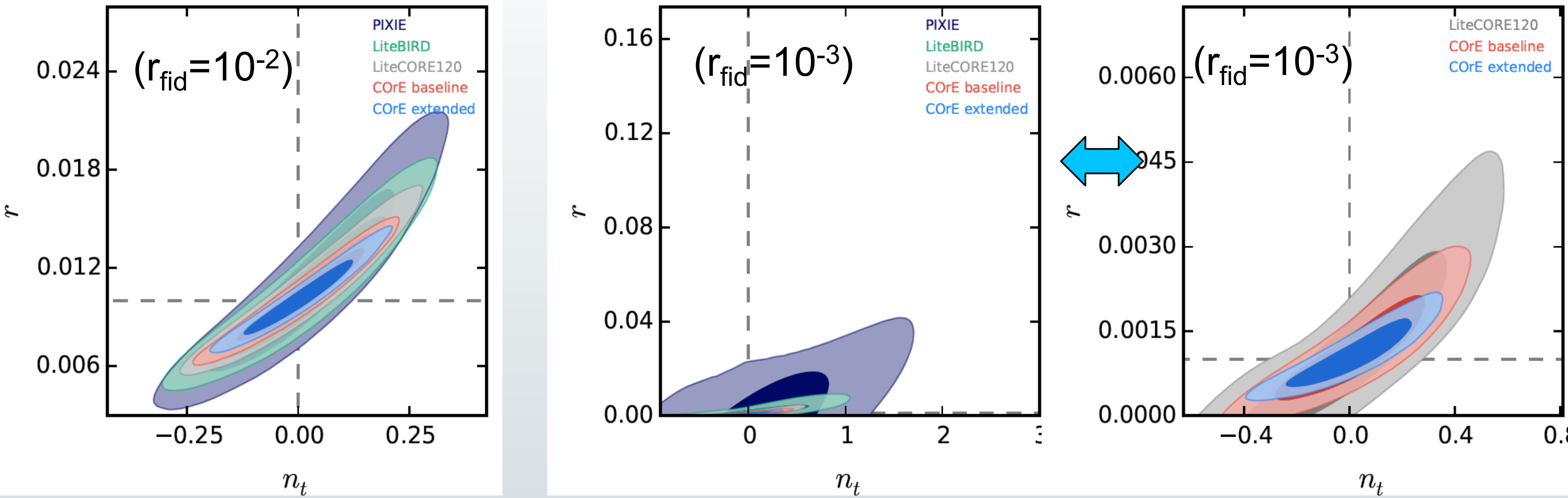
The Core extension is of course mostly useful for low r through delensing capability (nearly a factor of 2)

(di Valentino, FRB, in prep)

Sats by themselves



Constraints on n_t according to r_{fid}



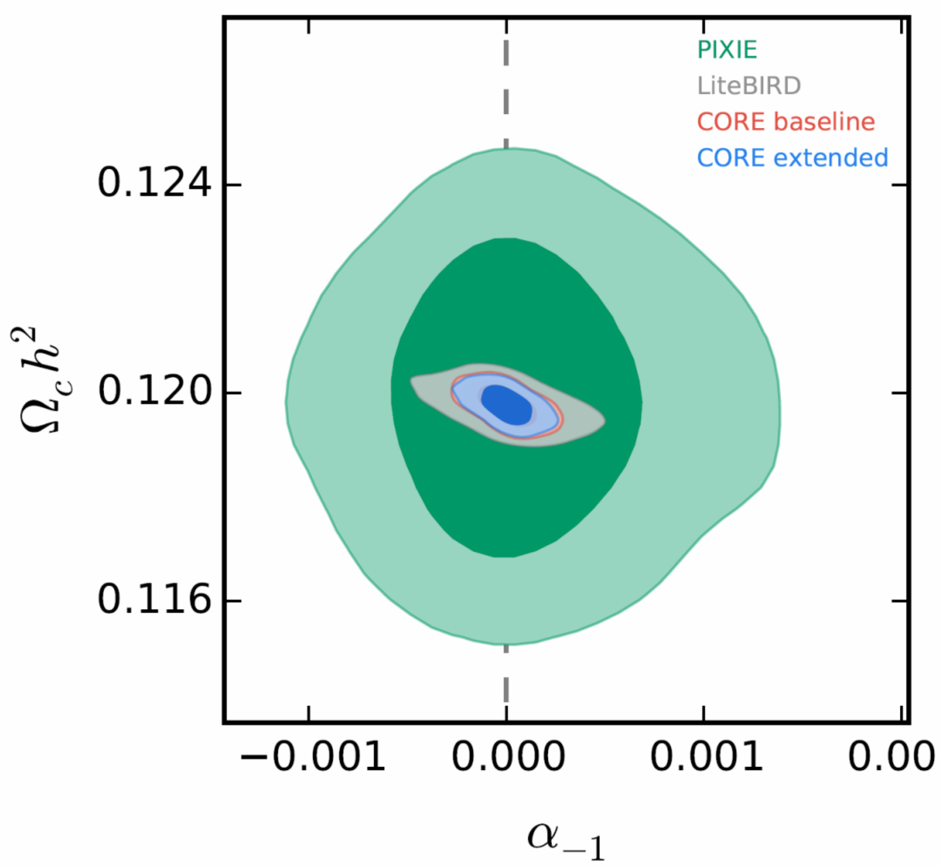
PRELIMINARY

	Model	Tensor power-spectrum	Tensor spectral index		Consistency relation
Background	Standard infl.	$P_T = \frac{8}{M_{pl}^2}\left(\frac{H}{2\pi}\right)^2$	$n_T = -2\epsilon$	red	$r = -8n_T$
	EFT inflation	$P_T = \frac{8}{c_T M_{pl}^2}\left(\frac{H}{2\pi}\right)^2$	$n_T = -2\epsilon + \frac{2}{3}\frac{m_T^2}{H^2}\left(1+\frac{4}{3}\epsilon\right)$	r/b	-
	Gen. G-Infl.	$P_T = \frac{8}{M_{pl}^2}\gamma_T\frac{\mathcal{G}_T^{1/2}}{\mathcal{F}_T^{3/2}}\left(\frac{H}{2\pi}\right)^2$	$n_T = 3 - 2\nu_T$	r/b	-
	Pot.-driv. G-Infl.	$P_T = \frac{8}{M_{pl}^2}\left(\frac{H}{2\pi}\right)^2$	$n_T = -2\epsilon$	r/b	$r \simeq -\frac{32\sqrt{6}}{9}n_T$
Extra background	Particle prod.	$P_T^+ = 8.6\times10^{-7}\frac{4H^2}{M_{pl}^2}\left(\frac{H}{2\pi}\right)^2\frac{e^{4\pi\xi}}{\xi^6}$	-	blue	violation
	Spectator field	$P_T \simeq 3\frac{H^4}{c_S^{18/5}M_{pl}^4}$	$n_T \simeq 2\left(\frac{2m^2}{3H^2}-2\epsilon\right)-\frac{18}{5}\frac{\dot{c}_S}{Hc_S}$	r/b	violation

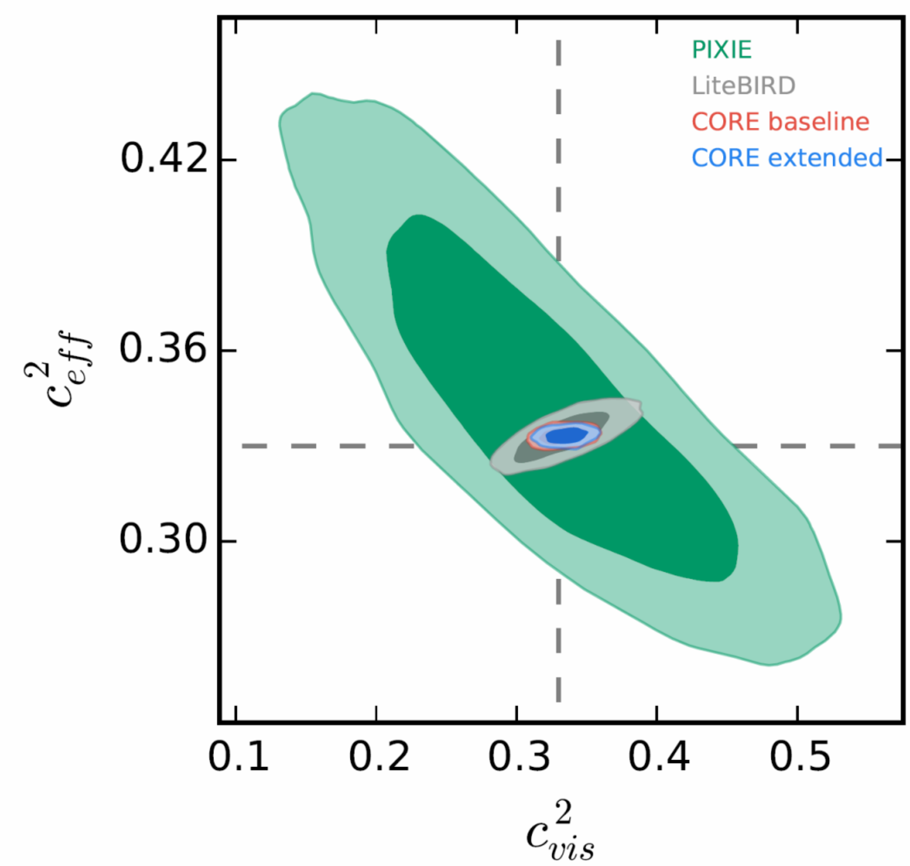
Arxiv/1605.0161

(di Valentino, FRB, in prep)

Sats, more fishing for deviations…



Isocurvature modes fraction



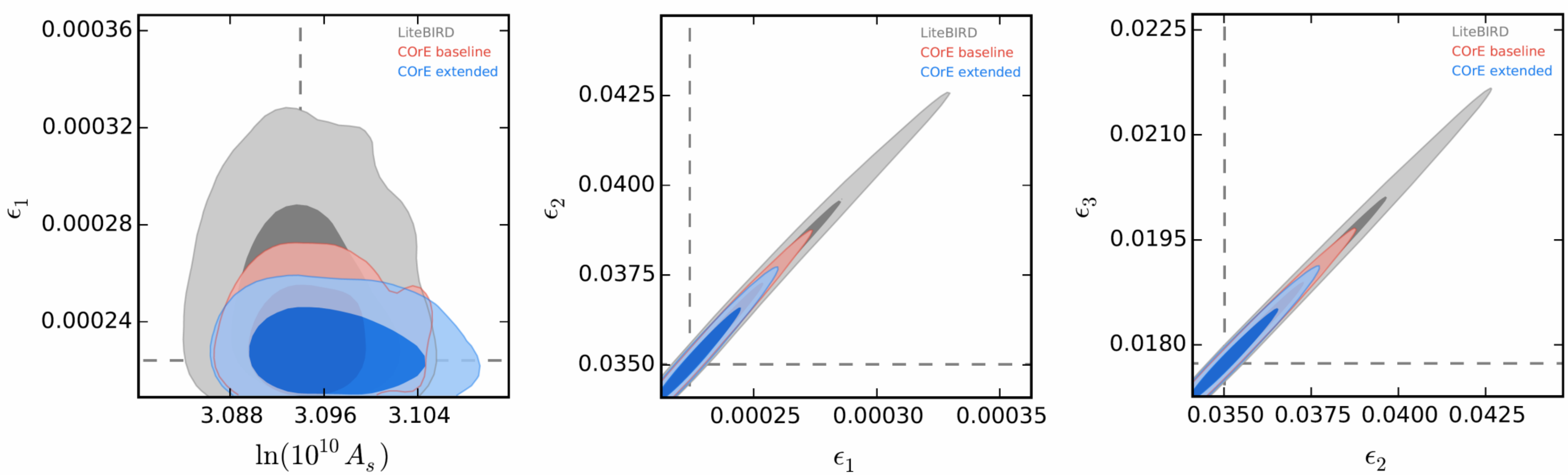
Generalised Dark Matter (1/3, 1/3) for nu’s:

PRELIMINARY

Sats vs S/H inflation model

Slow roll parameters for a Higgs inflation model with $r_{fid}=3.6 \times 10^{-3}$ ($n_s = 0.96$)

$$V(\phi) = M^4 \left(1 - e^{-\sqrt{2/3}\phi/M_{\rm Pl}}\right)^2$$



$$\epsilon_1 \simeq \frac{M_{\rm Pl}^2}{2}\left(\frac{V_\phi}{V}\right)^2,$$

$$\epsilon_2 \simeq 2M_{\rm Pl}^2\left[\left(\frac{V_\phi}{V}\right)^2 - \frac{V_{\phi\phi}}{V}\right],$$

$$\epsilon_2\epsilon_3 \simeq 2M_{\rm Pl}^4\left[\frac{V_{\phi\phi\phi}V_\phi}{V^2} - 3\frac{V_{\phi\phi}}{V}\left(\frac{V_\phi}{V}\right)^2 + 2\left(\frac{V_\phi}{V}\right)^4\right]$$

$$\epsilon_1 = \frac{4}{3}\left(1 - e^{\sqrt{2/3}x}\right)^{-2}, \qquad \epsilon_2 = \frac{2}{3}\left[\sinh\left(\frac{x}{\sqrt{6}}\right)\right]^{-2}$$

$$\epsilon_3 = \frac{2}{3}\left[\coth\left(\frac{x}{\sqrt{6}}\right) - 1\right]\coth\left(\frac{x}{\sqrt{6}}\right).$$

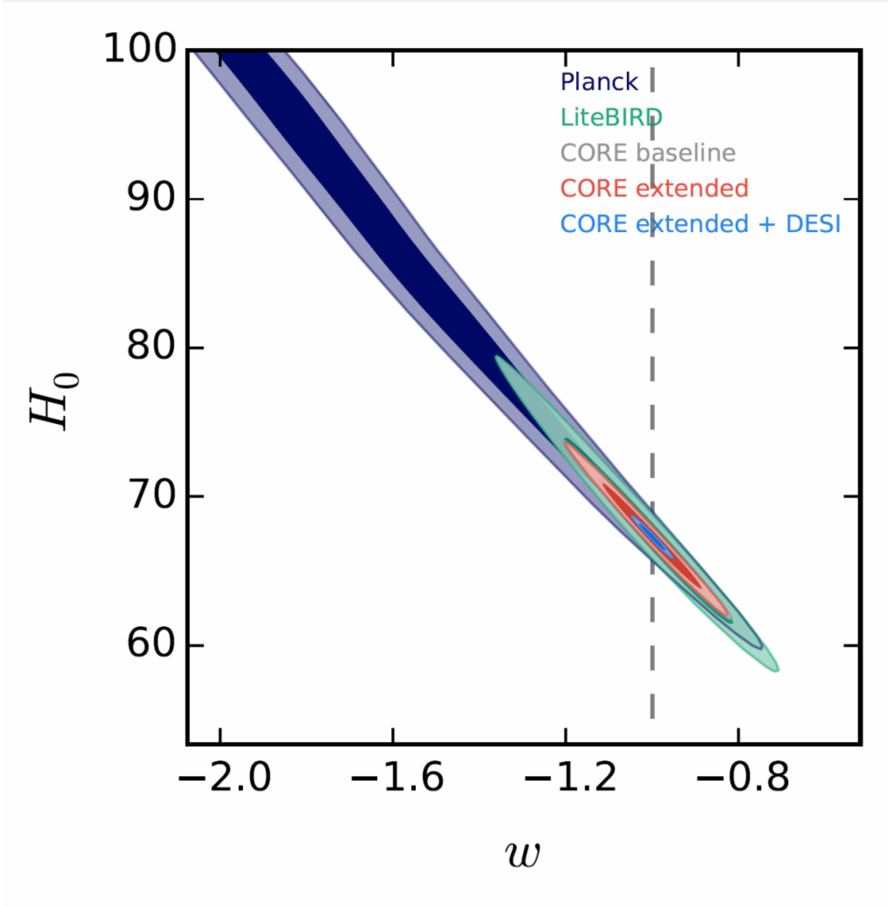
$$x \equiv \phi/M_{\rm Pl}.$$

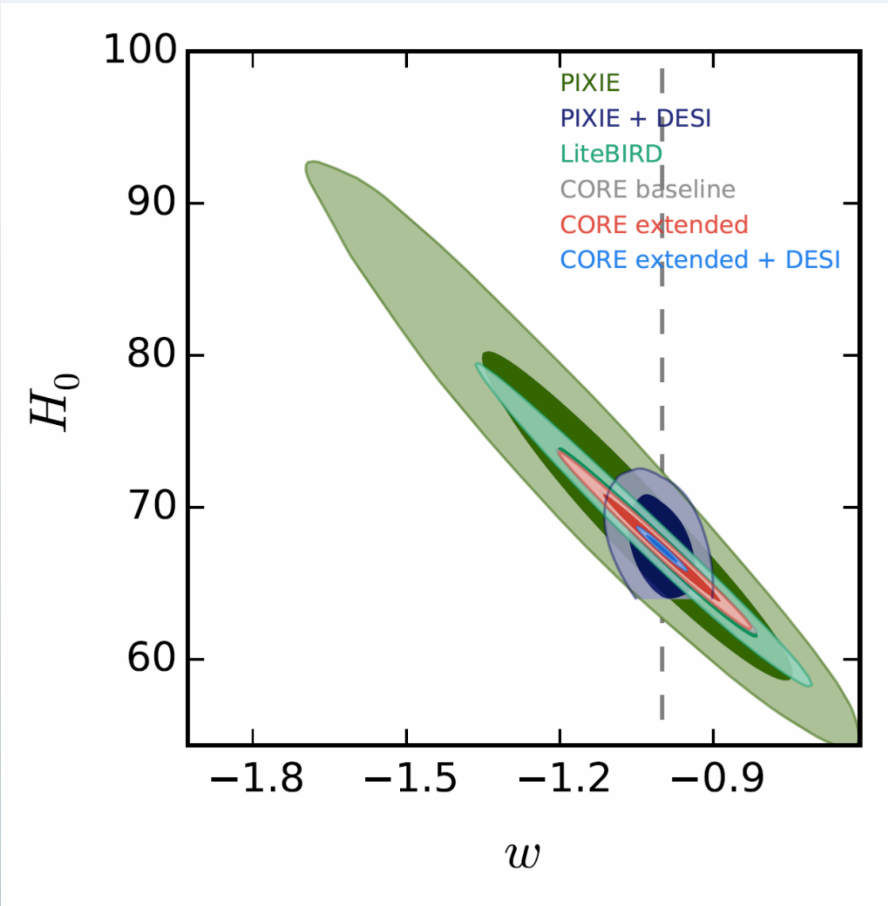
NB: This is computed for internal delensing)

(di Valentino, FRB, in prep)

PRELIMINARY

Sats + DESI: low-z dynamics

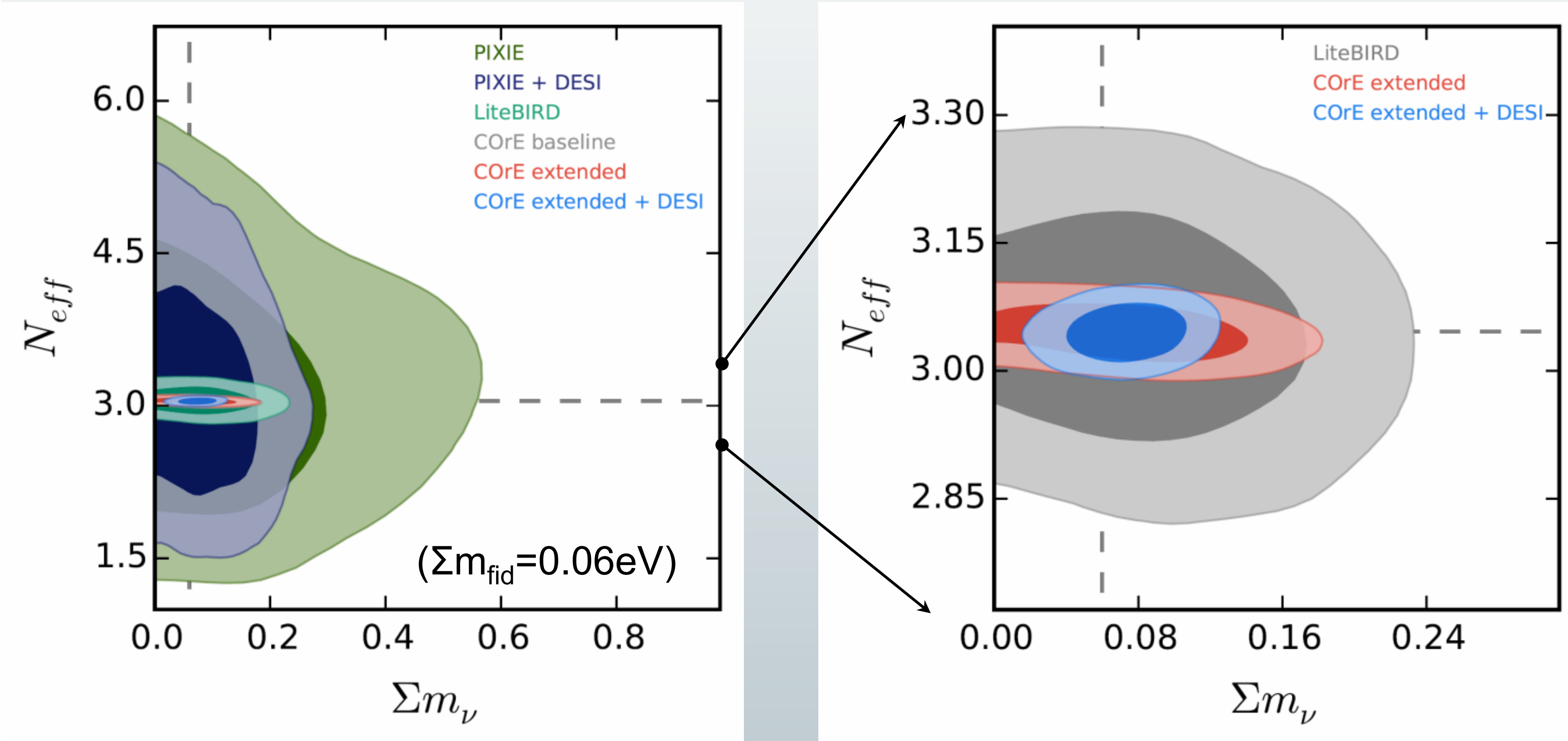




PRELIMINARY

(di Valentino, FRB, in prep)

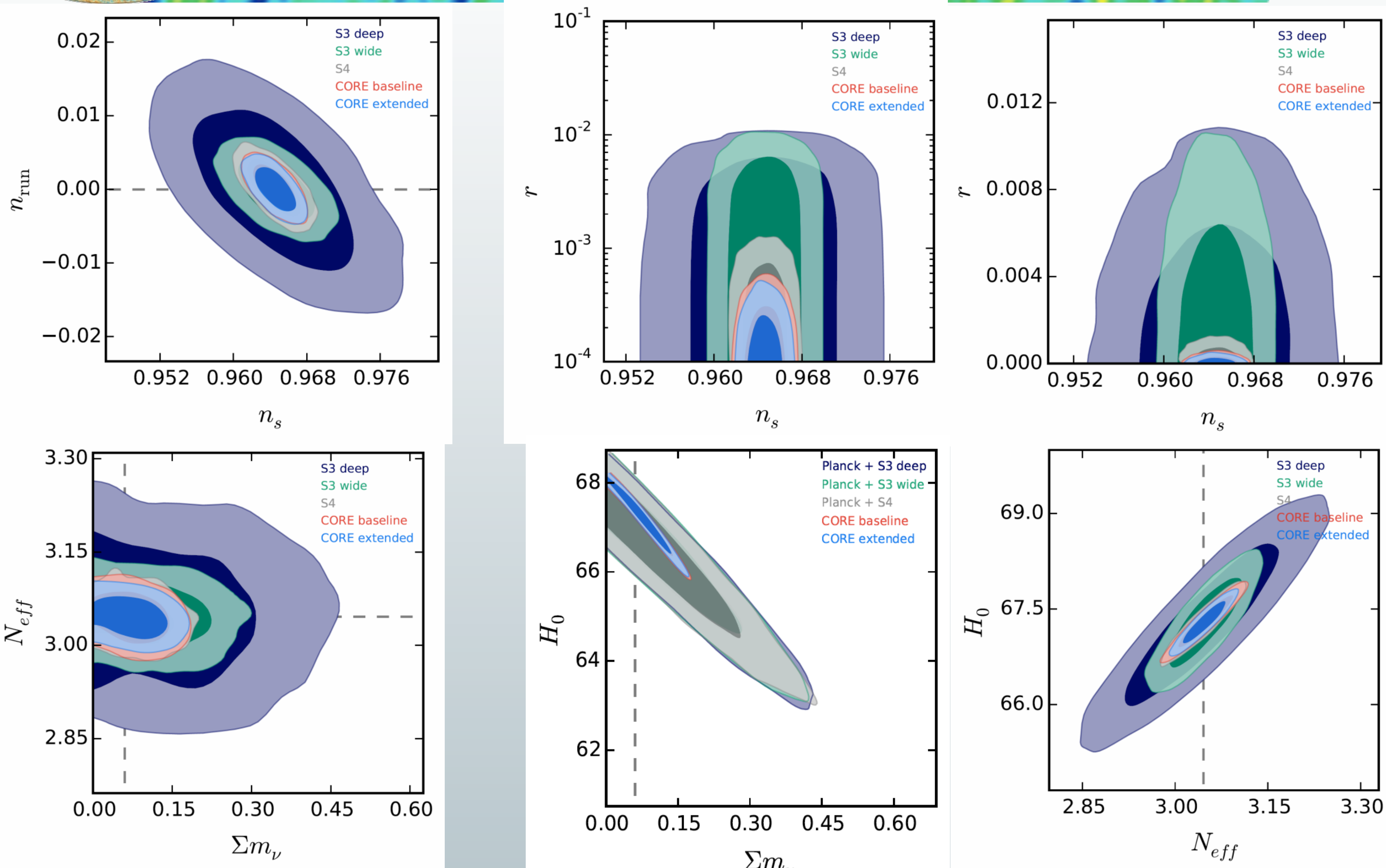
Sats+Desi: Neutrinos



PRELIMINARY

(di Valentino, FRB, in prep)

Ground (w P.tau prior) vs sats

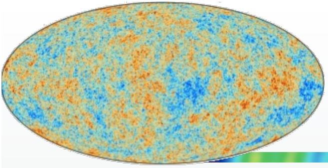


VERY PRELIMINARY

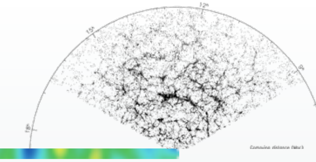
CHALLENGES

- **BEAMS**: in situ measurement of beams, esp. sidelobes (ν & polzn dependence, stability)
- **BANDPASSES:** in situ characterization, matching, polzn dependence, avoiding CO etc
- **GROUND PICKUP**: shielding, sufficient suppression of scan synchronous pickup, stability
- **I → Q/U LEAKAGE**: ν dependence, polarization dependence, stability, spatial dependence
- **SENSITIVITY**: low loading, high optical throughput
- **CALIBRATION**: stability, dynamic range, ν dependence, pointing jitter
- **POLARIZATION ANGLES**: in situ measurement, ν dependence
- **STRIPING**: minimize 1/f with fast modulation

(Staggs, Princeton 06/2015)



+ Data/Analysis challenges



- Extract the most from this expensive data flow
  - *Low level codes not universal, i.e. code share only for high-level analyses*
  - *Moore' s law on cpus unlikely to be enough (smaller final uncertainties tend to increase algorithmic complexity)*
  - ***Simulations** will become more challenging (and so will be the size of the analysis groups?), but needed for precision science (and even more for accurate science).*
- Sharing the data efficiently?
  - *at TOI level? (e.g. to surround pixelization issues); data size*
  - *X-correlations need a lot of detailed knowledge on both sides (e.g. Planck x Bicep/Keck)*
  - *Flexible/efficient formats*
- Overall organisation… (we probably need large integrated teams with varied cultural backgrounds in scattered sites)
- On all those, we gained much experience from Planck!


The
journey
continues!
And we have lots to do