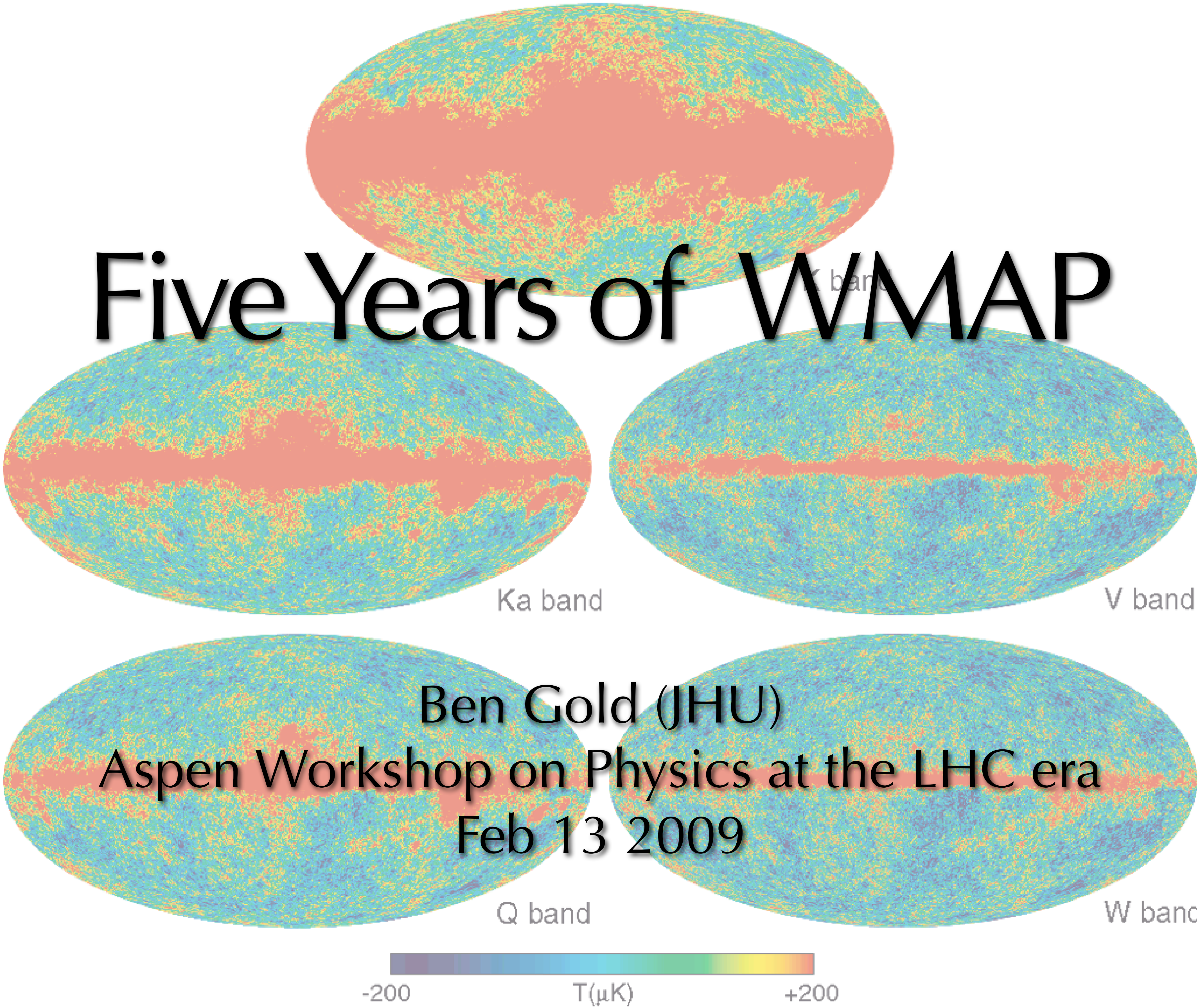
# Five Years of WMAP

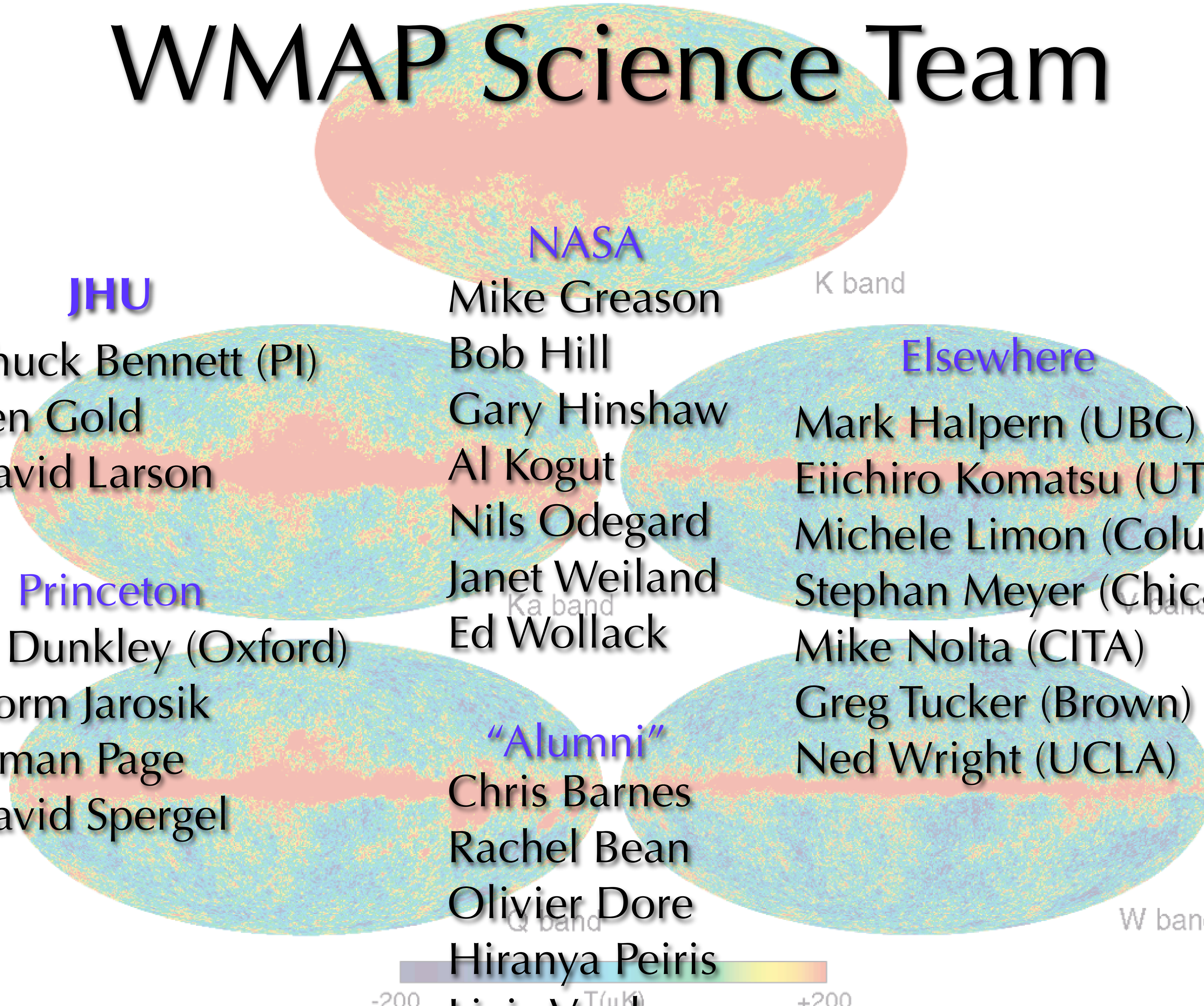



Ben Gold (JHU)

Aspen Workshop on Physics at the LHC era

Feb 13 2009

# WMAP Science Team

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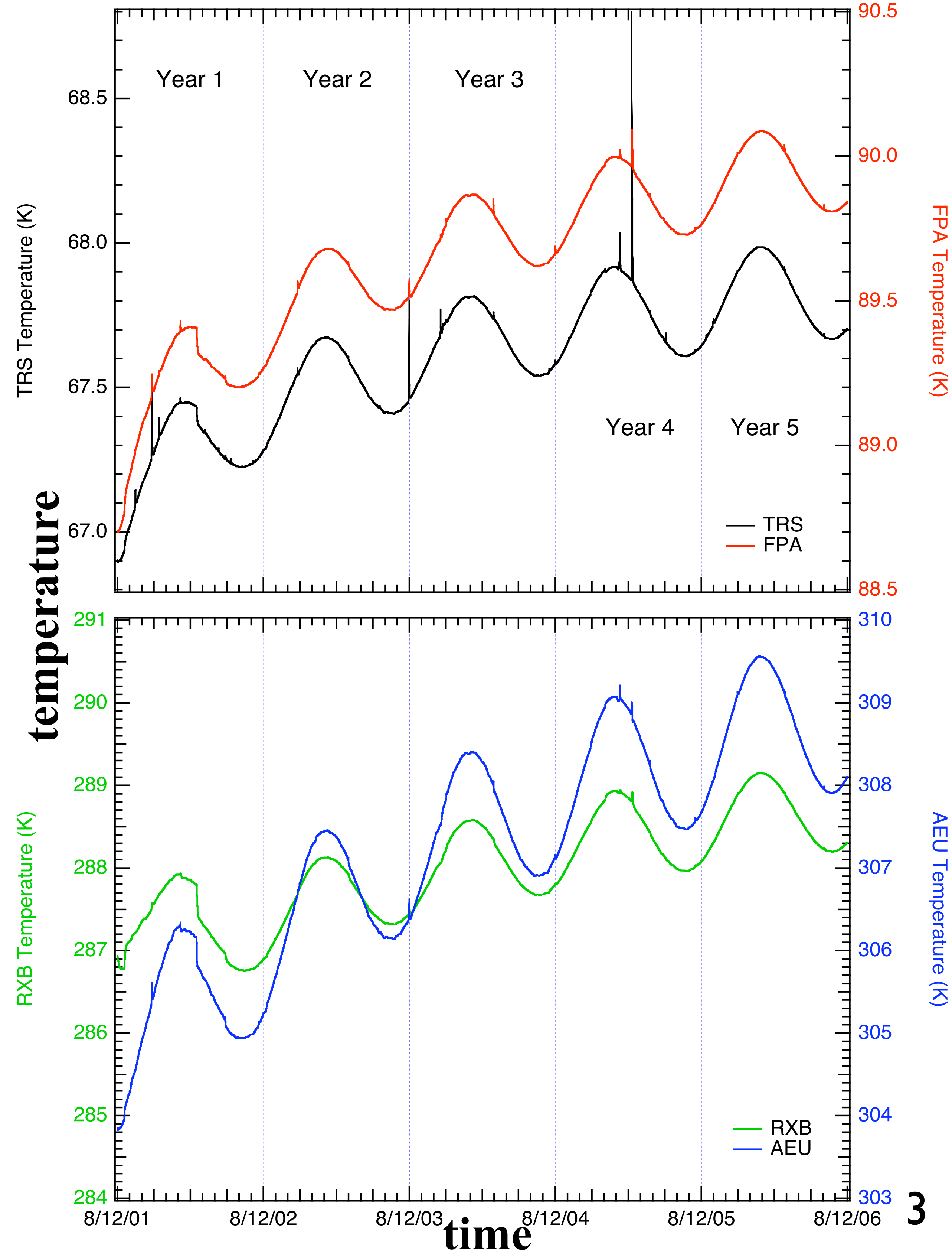
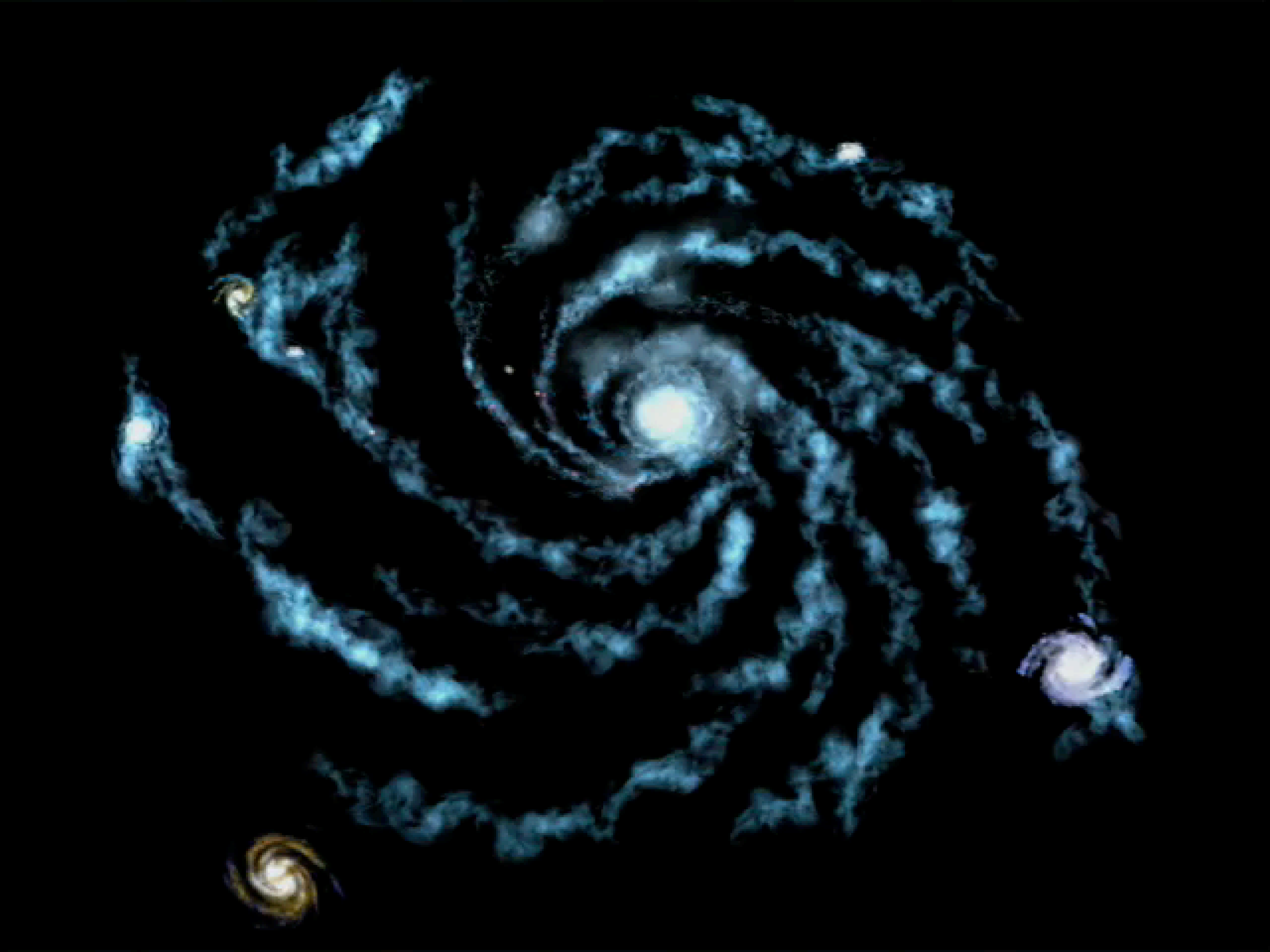
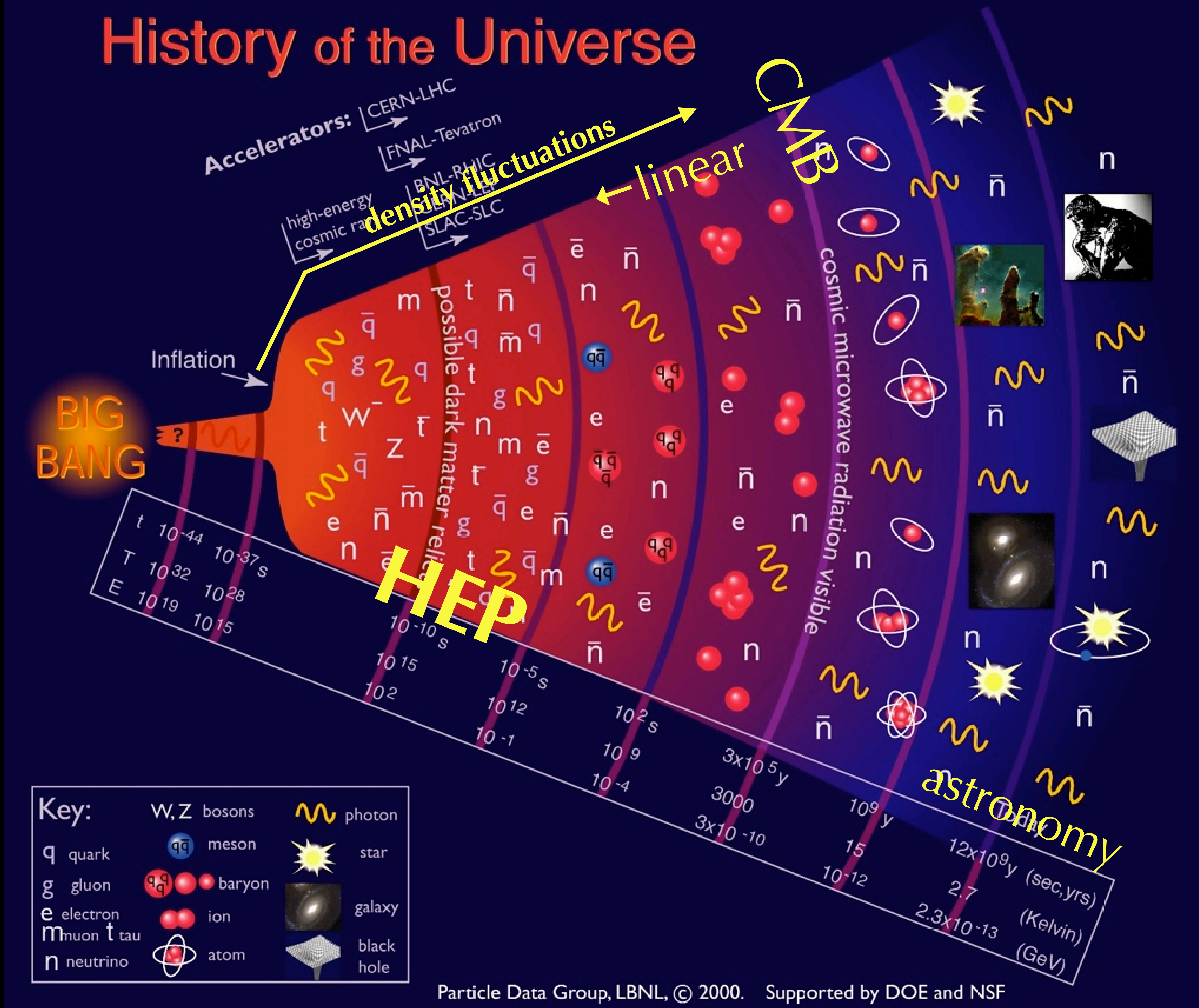
# WMAP status

- Launched June 30th, 2001
- First observations August 2001
- 1-year release February 2003
- 3-year release March 2006
- 5-year release March 2008
- Seven years “in the can”
- > 99% uptime






History of the Universe
Accelerators:
CERN-LHC
FNAL-Tevatron
BNL-RHIC
CERN-LEP
SLAC-SLC
high-energy cosmic rays
density fluctuations
←linear
CMB
Inflation
BIG BANG
possible dark matter relics
cosmic microwave radiation visible
HEP
astronomy
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
10 -12
12x10 9 y (sec,yrs)
2.7 (Kelvin)
2.3x10 -13 (GeV)
Today
Key:
q quark
g gluon
e electron
m muon t tau
n neutrino
W,Z bosons
meson
baryon
ion
atom
photon
star
galaxy
black hole
Particle Data Group, LBNL, © 2000. Supported by DOE and NSF

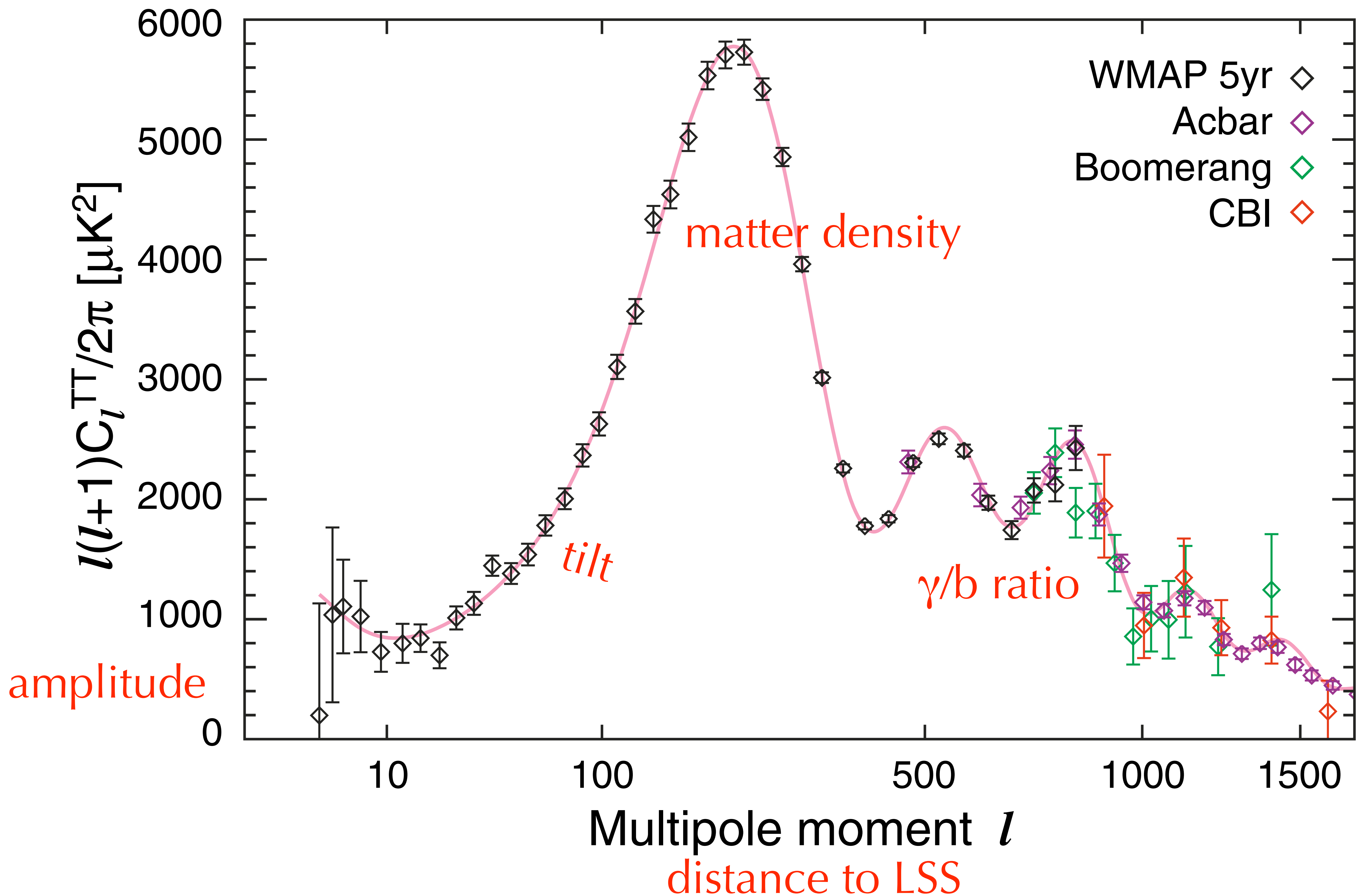
Team

# The ~~Standard~~ Concordance Model

- Six parameter curve fits hundreds of independent data points!
- No need (yet) for other interesting parameters
- 2 inflation params, 2 particle params, 2 astro params, +assumptions

| | Parameter | 5 Year Mean (WMAP only) | |
|---|---|---|---|
| γ/b ratio | $100\Omega_b h^2$ | $2.273 \pm 0.062$ | **~¼ atom per m³** |
| matter density | $\Omega_c h^2$ | $0.1099 \pm 0.0062$ | **~1.2 GeV per m³** |
| distance to LSS | $\Omega_\Lambda$ | $0.742 \pm 0.030$ | **~(1.8 meV)⁴** |
| tilt | $n_s$ | $0.963^{+0.014}_{-0.015}$ | **potential shape** |
| pol'n bump | $\tau$ | $0.087 \pm 0.017$ | **~9% rescattered** |
| amplitude | $\Delta^2_{\mathcal{R}}$ | $(2.41 \pm 0.11) \times 10^{-9}$ | **potential shape** |

# The Concordance Model

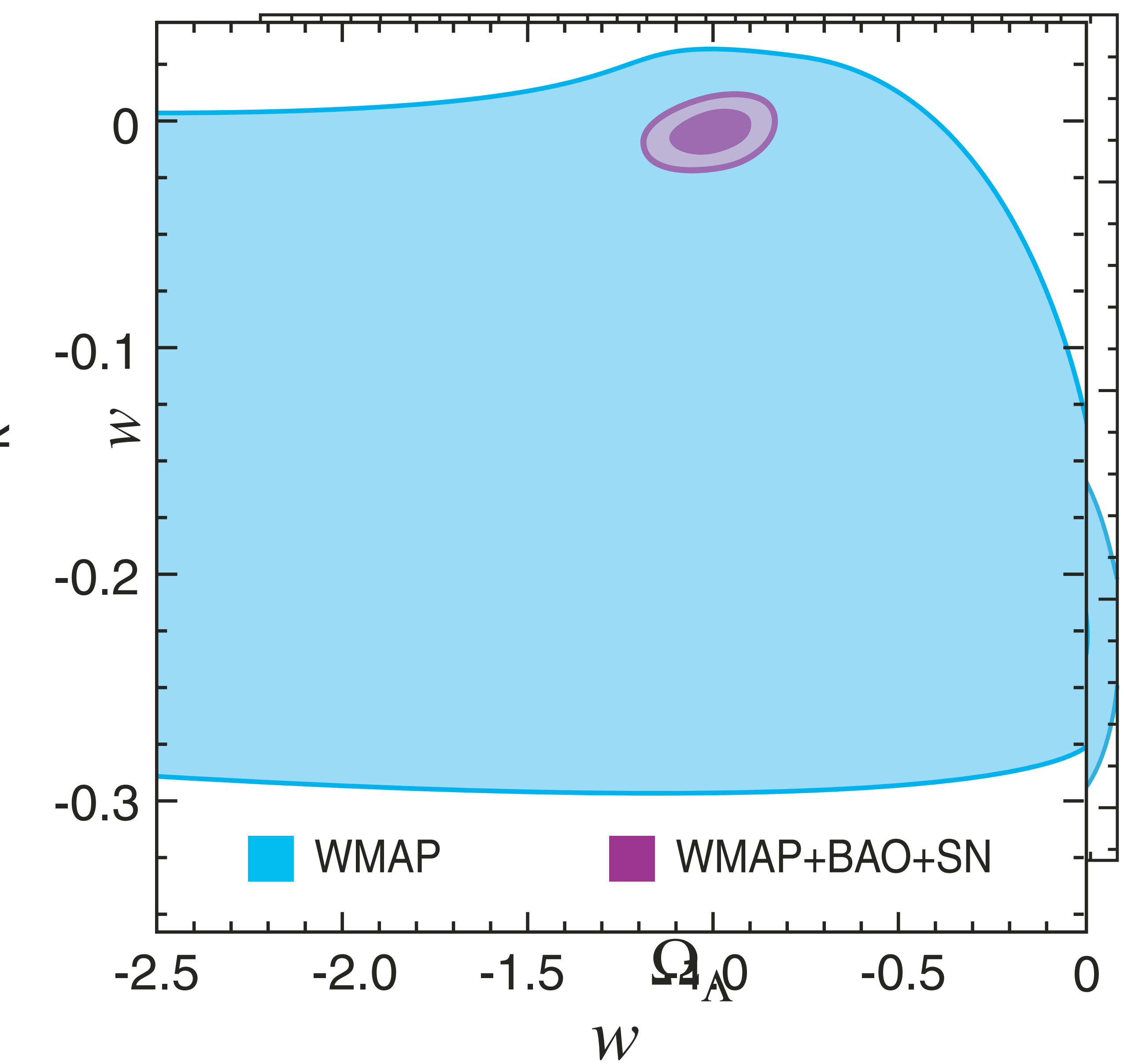


# Beyond the concordance model

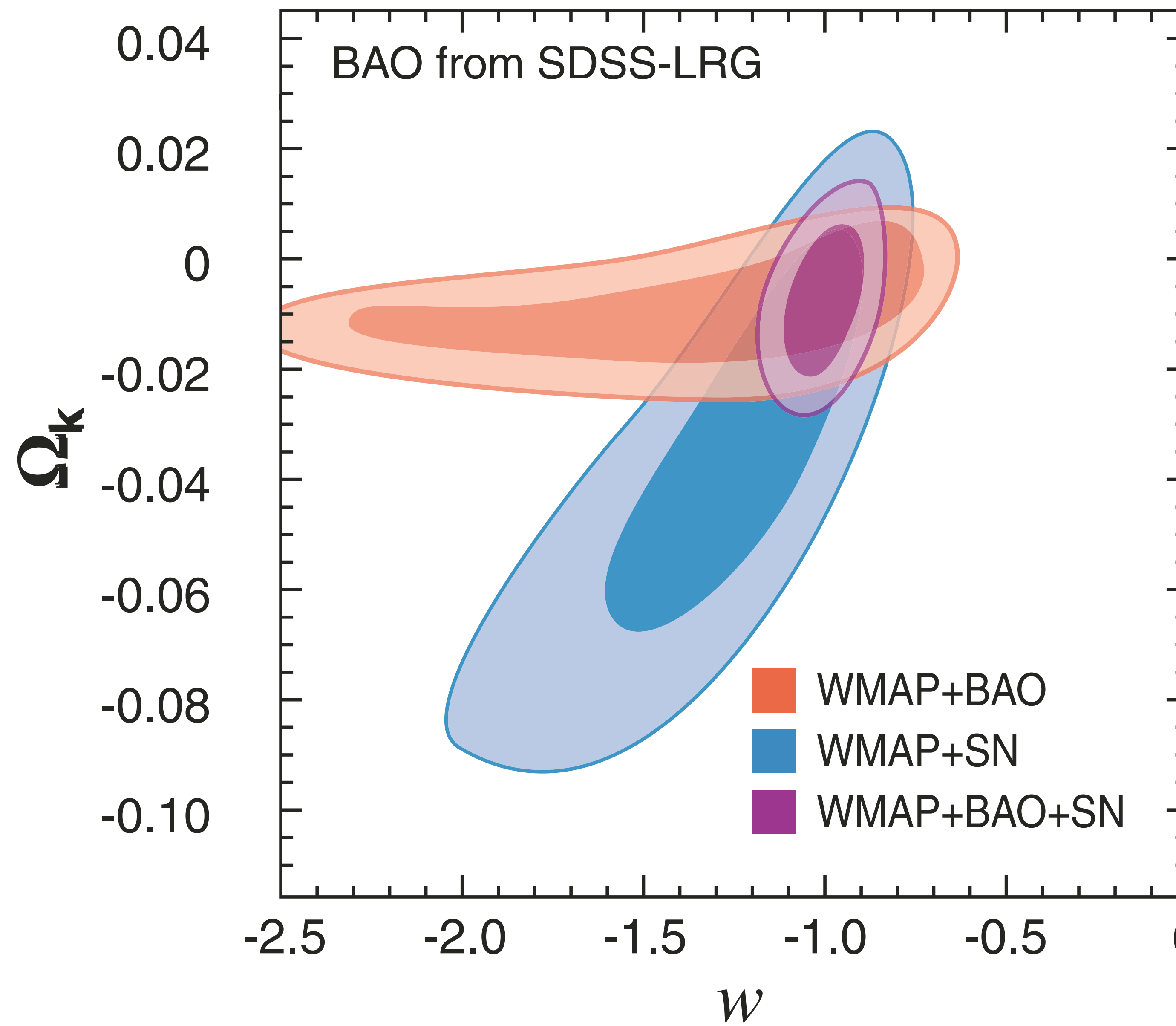
- non-$\Lambda$ dark energy
- tensor (gravitational wave) amplitude
- running of the spectral index
- axionic/other non-inflationary generation of perturbations
- neutrino mass

# Dark energy

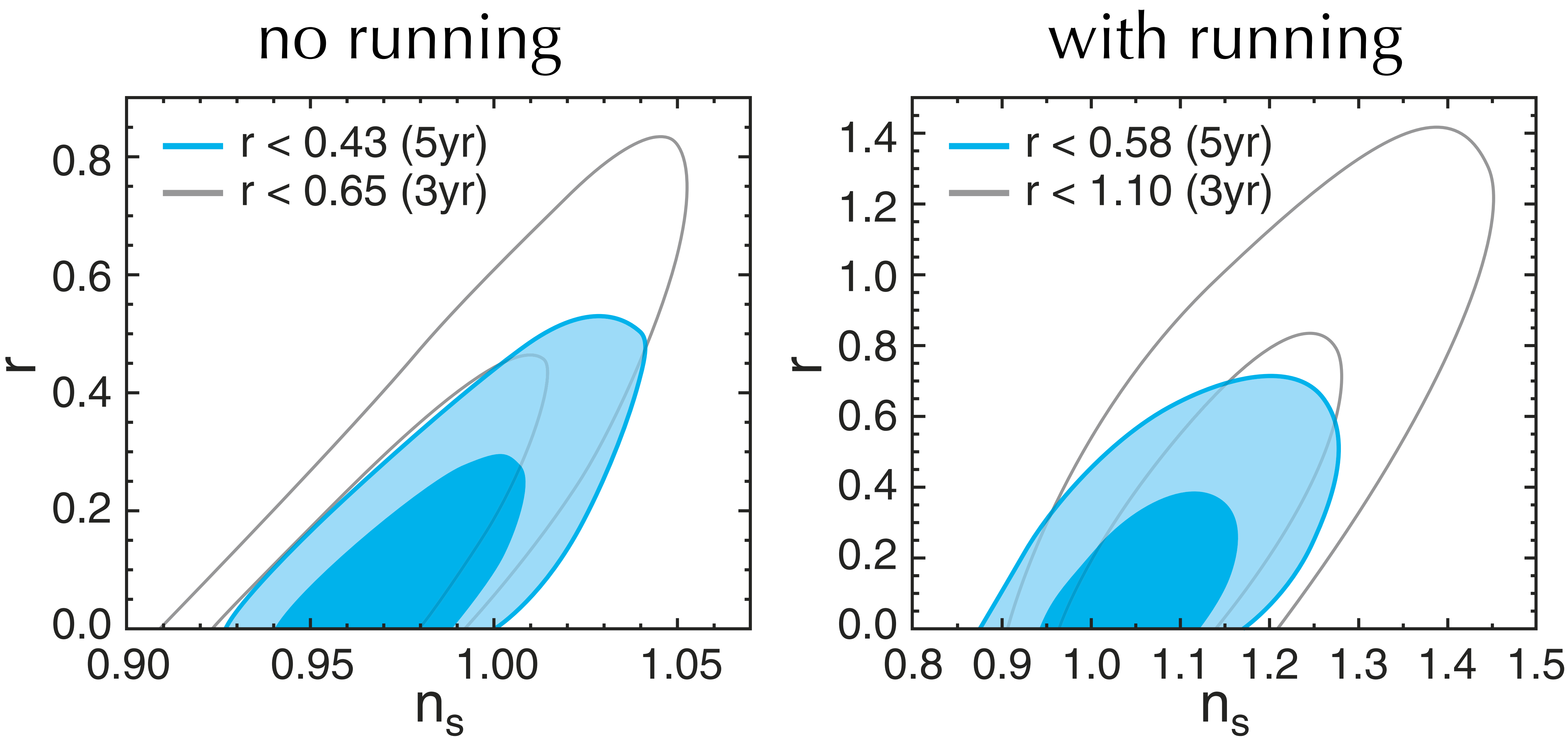
assume flatness




don’t assume flatness



# Inflation parameters

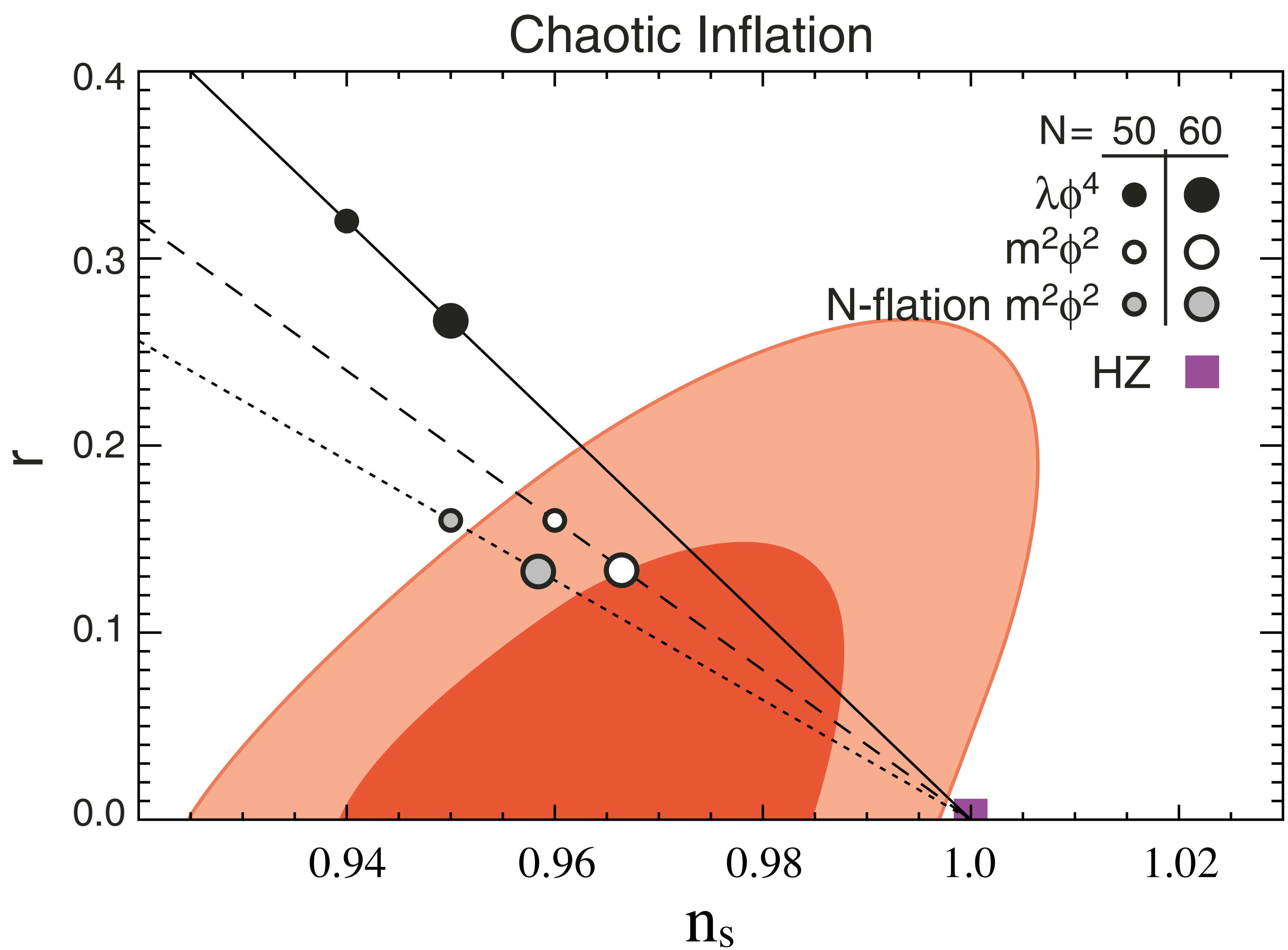



(WMAP only)

3yr to 5yr is not just $\sqrt{t}$!

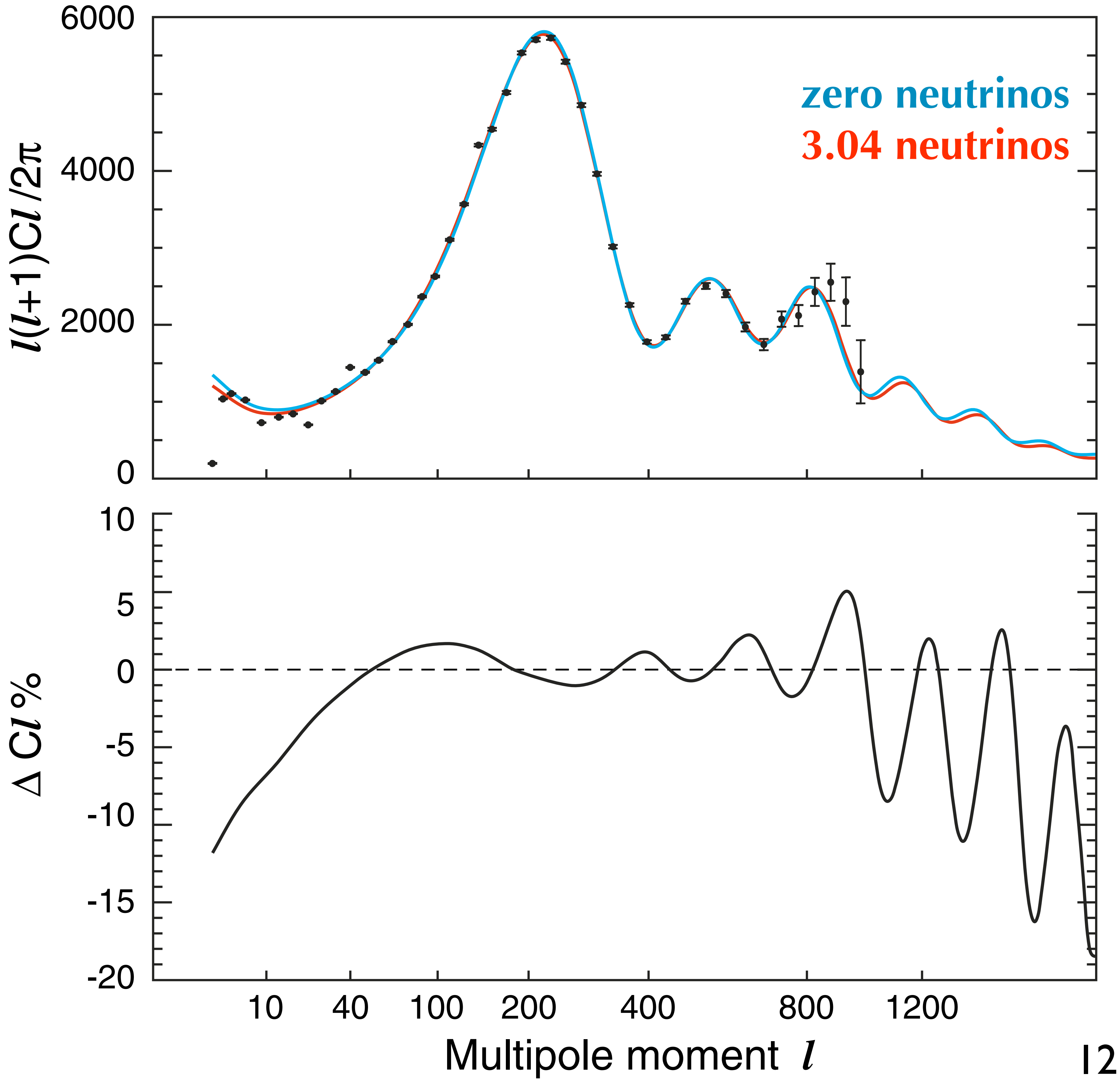
# Inflation parameters

- N < 70 for post-Planck inflation
- $\phi^4$ very disfavored!
- r–$n_S$ combo pushing on theory

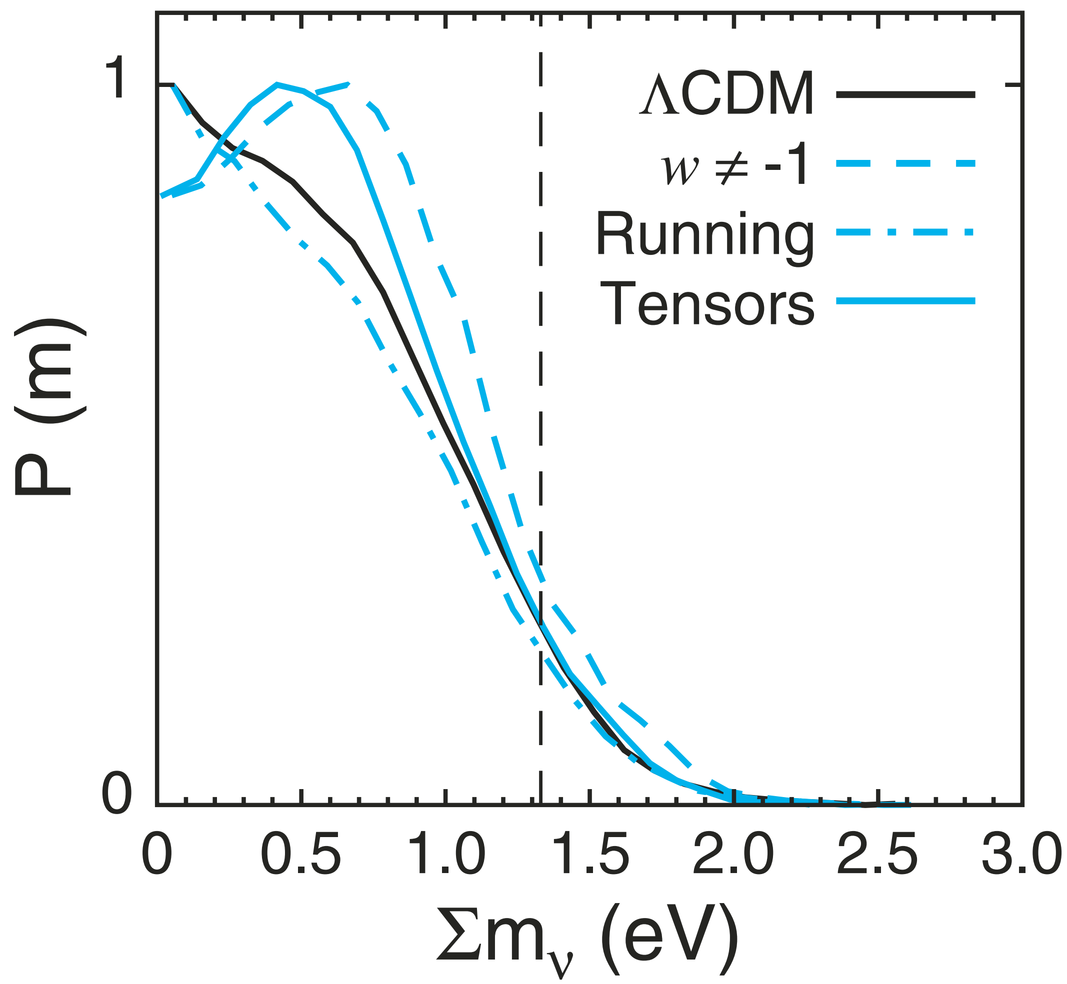


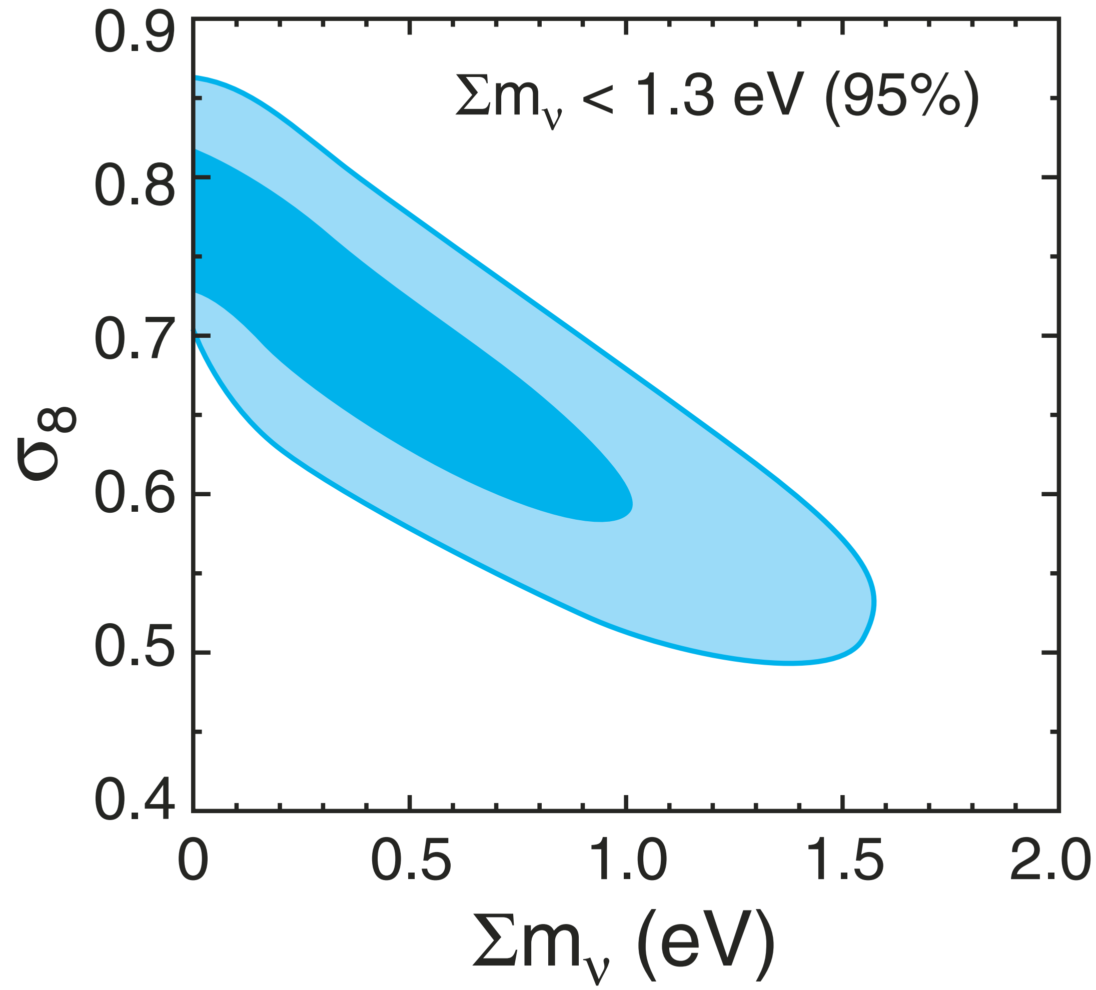
# What if neutrinos weren't there?

- Neutrino background is cosmologically significant!
- $N_{eff} > 0$ with 99.5% confidence
- Limit comes primarily from the unique effects of a weakly interacting relativistic "fluid"
- Explaining the CMB without neutrinos would push $\chi^2$ up 8.2, push $H_0 >$ 75, and break concordance



# Neutrino mass limits



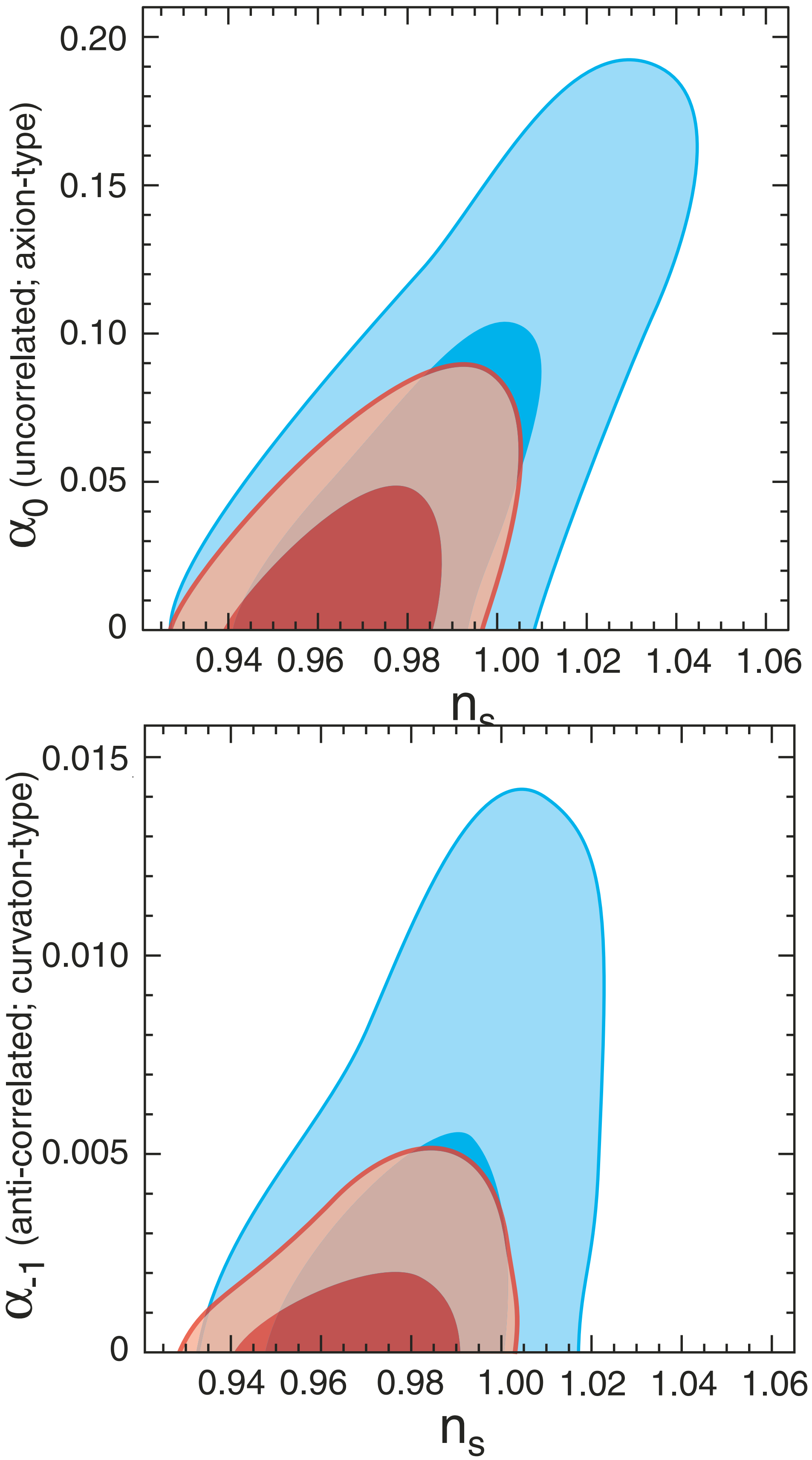

(WMAP only)

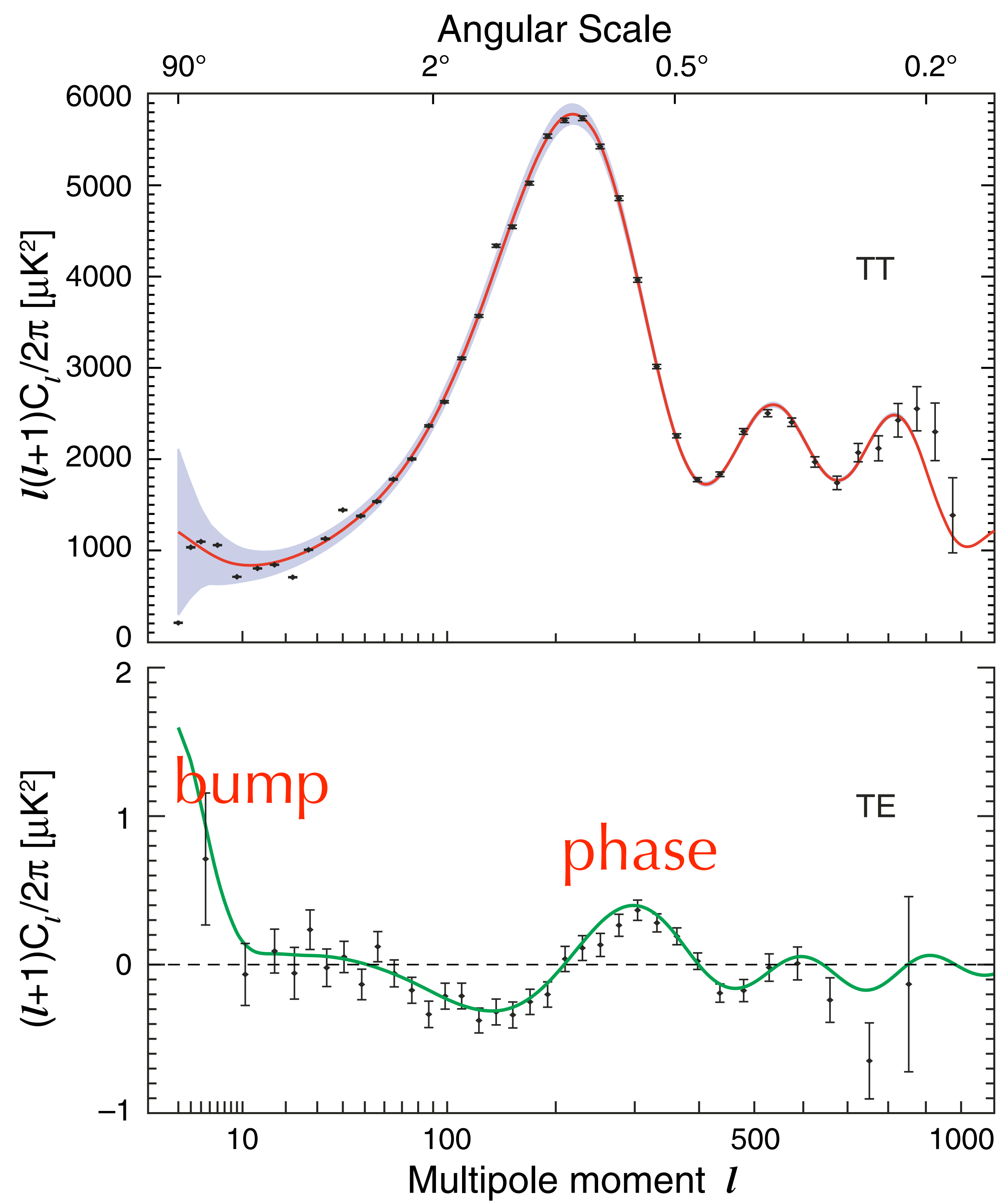
$\Sigma m_\nu < 0.67$ eV (with BAO)

# Alternative dark matter

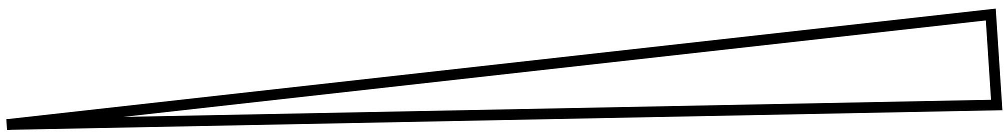
**axion-like**

**curvaton-like**

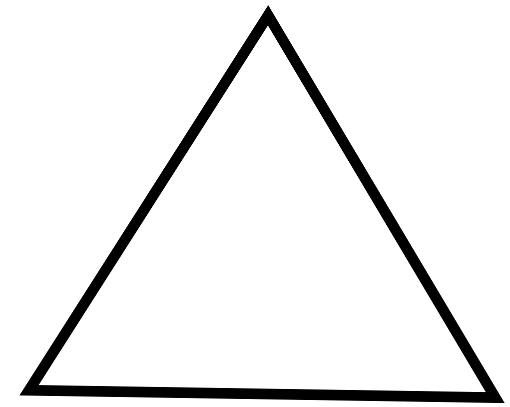


# Non-gaussianity



or



- CMB is a gaussian random field to 0.1%
- -9 < $f_{NL}$ (squeezed) < 111 (95% CL)
- -151 < $f_{NL}$ (equilateral) < 253 (95% CL)
- **27 < $f_{NL}$ (squeezed) < 147 (95% CL) [Yadav & Wandelt 2008]**
- **-18 < $f_{NL}$ (squeezed) < 80 (95% CL) [Curto et al. 2009]**
- limits improve rapidly as noise and foregrounds come down

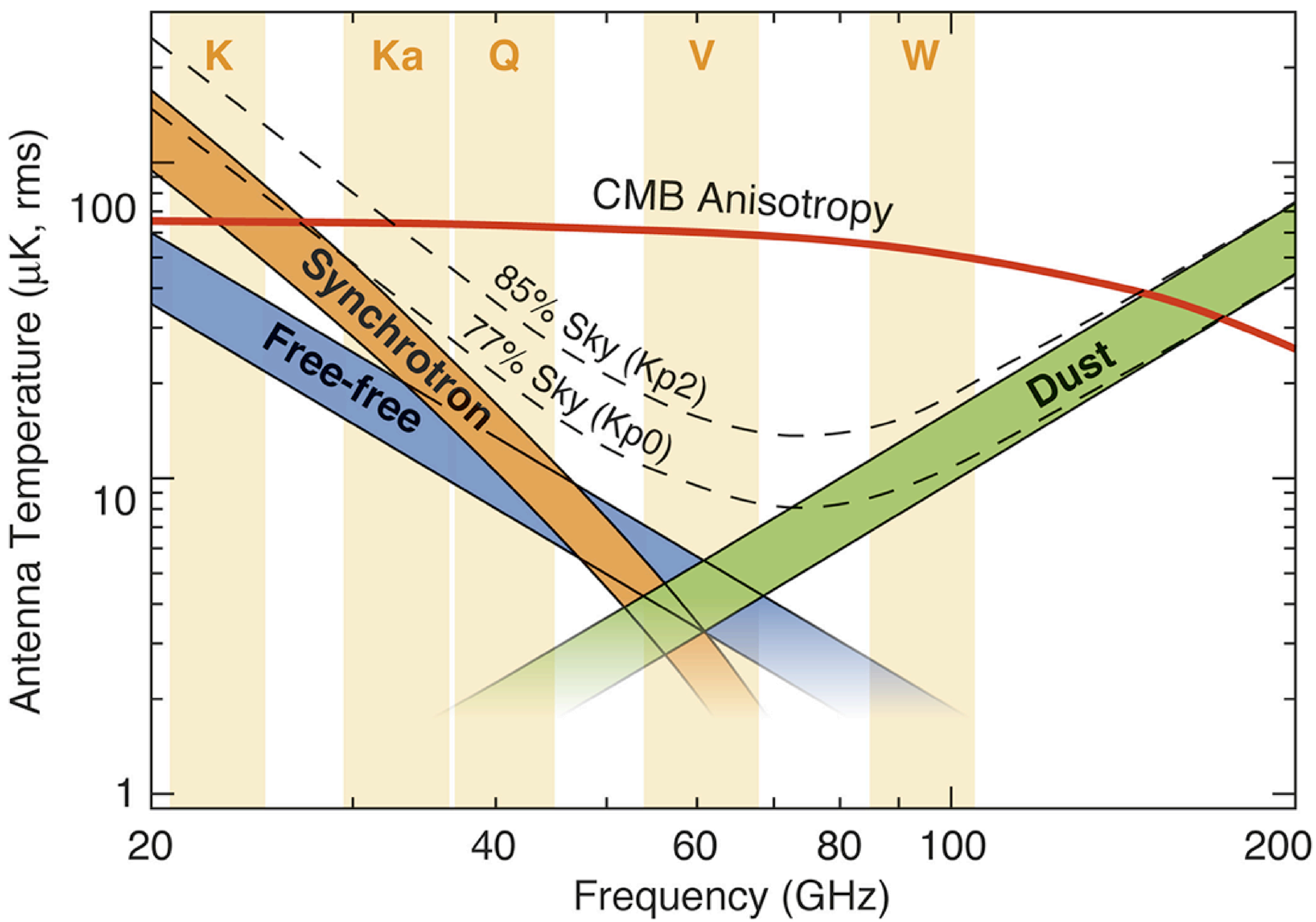
# Foregrounds: why should we care?

Galactic astronomy
is interesting!

Galactic astronomy
is messy!

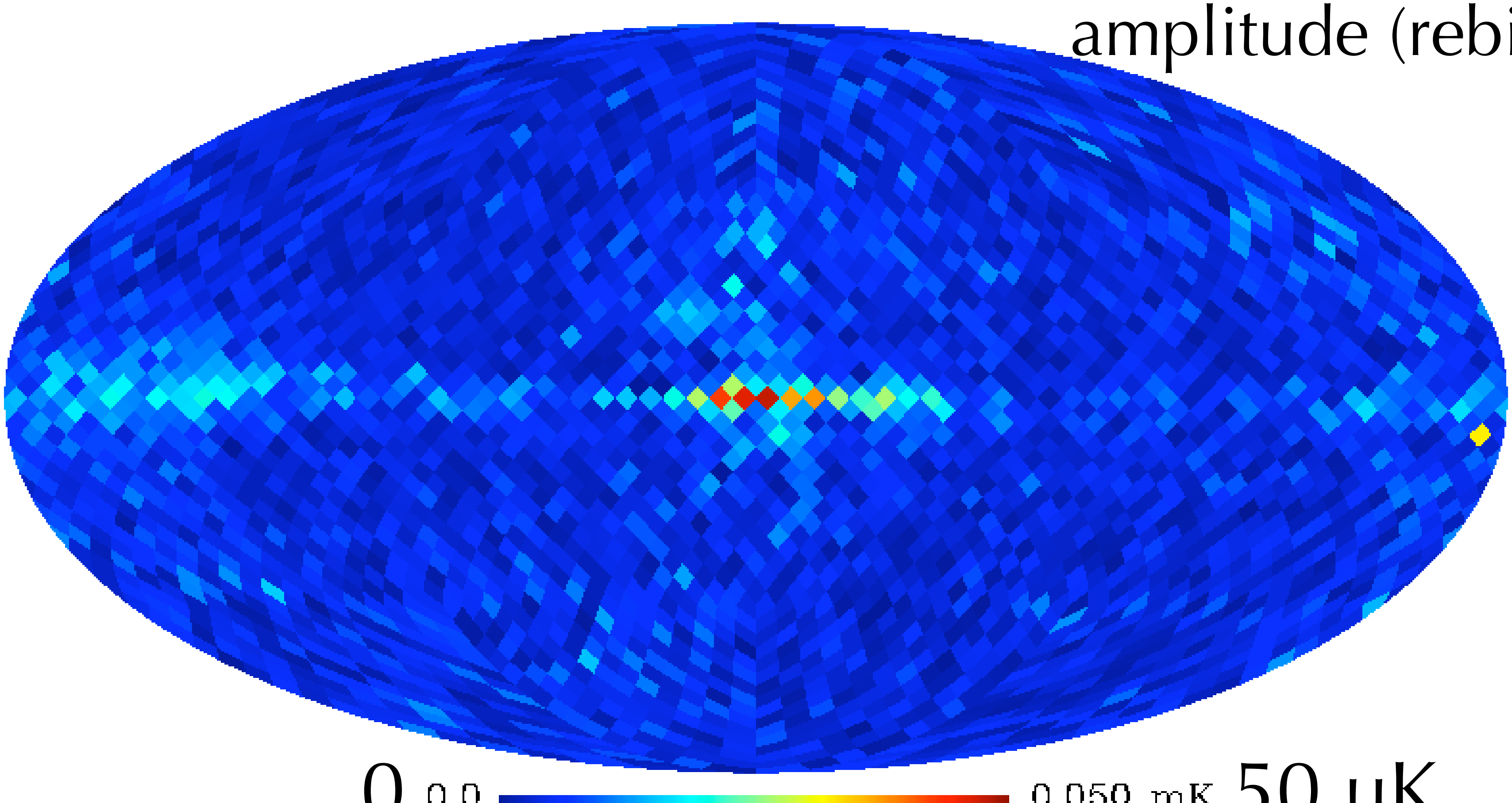
# Foreground levels

- sync is polarized up to 40%
- ff unpolarized
- dust polarized up to 5-10%



# Why we care (polarization)

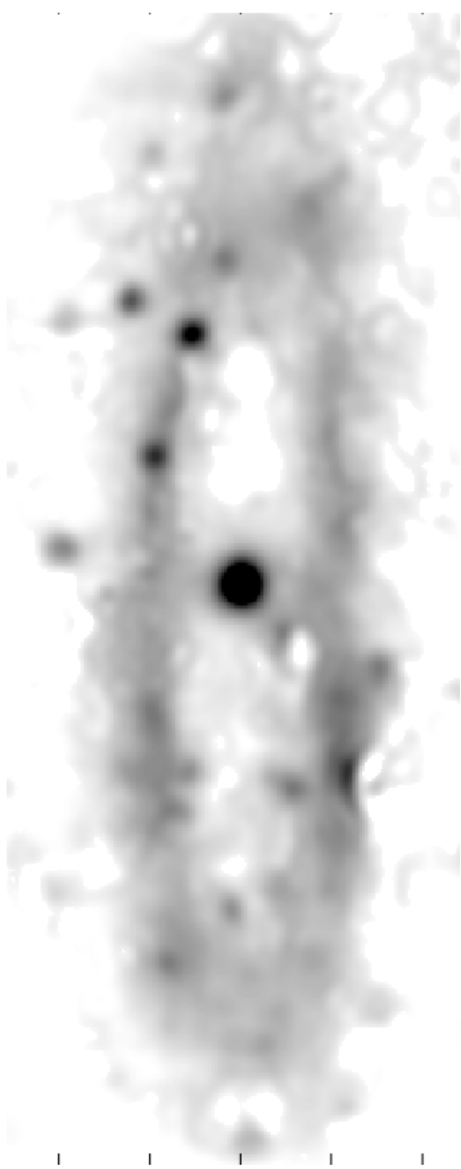
V-band polarization
amplitude (rebinned)




0 … 50 μK

polarization intensity

# synchrotron

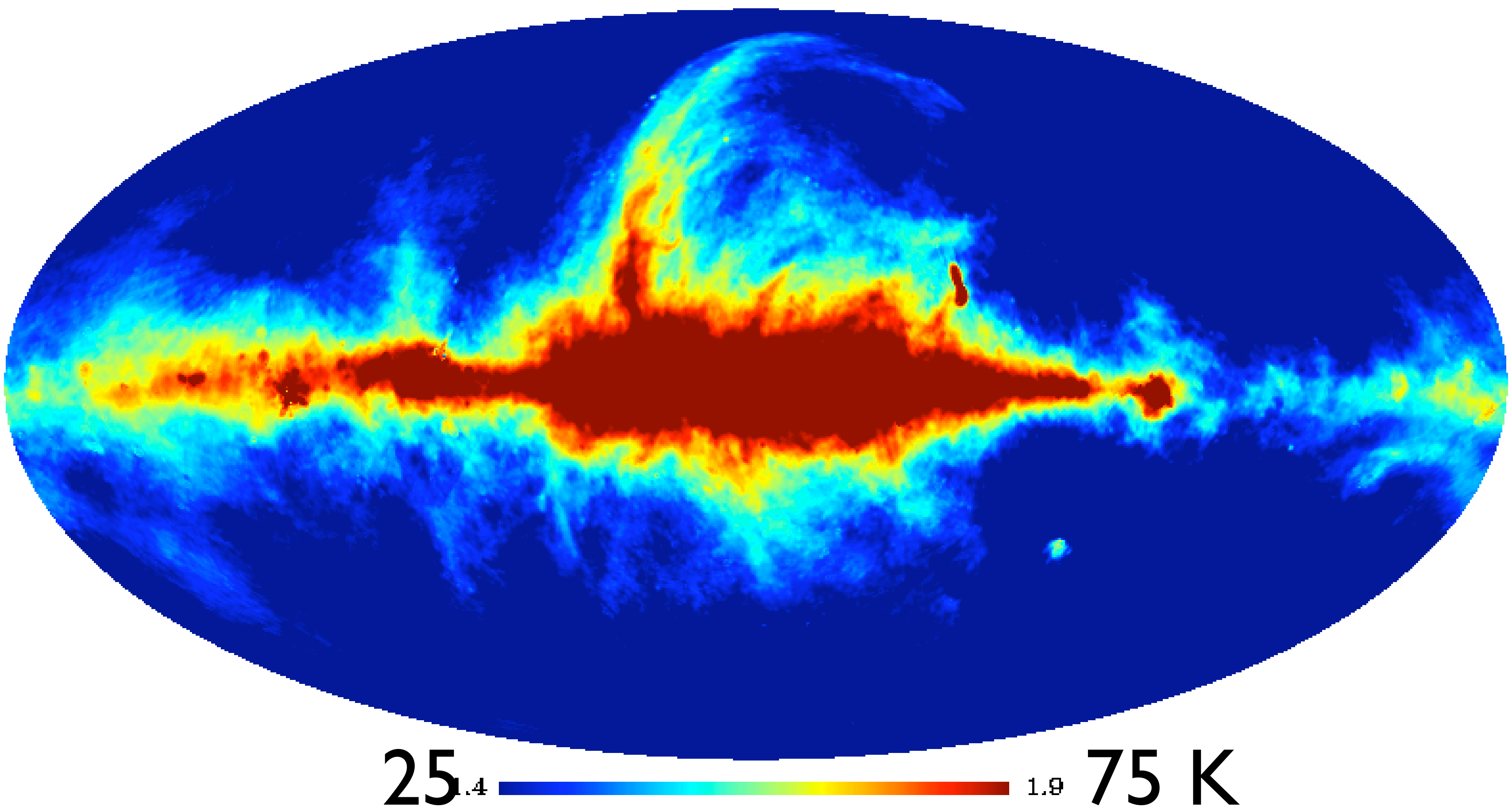


M31 – Berkhuijsen et al. (2002)

- relativistic electrons in magnetic fields
- "halo" but clearly SNR are important
- simple power law $\nu^{-3}$ (no, not really) emission spectrum follows electron energy
- compare with low frequency radio maps
- ideally ~70% polarized

# synchrotron

## 408 MHz

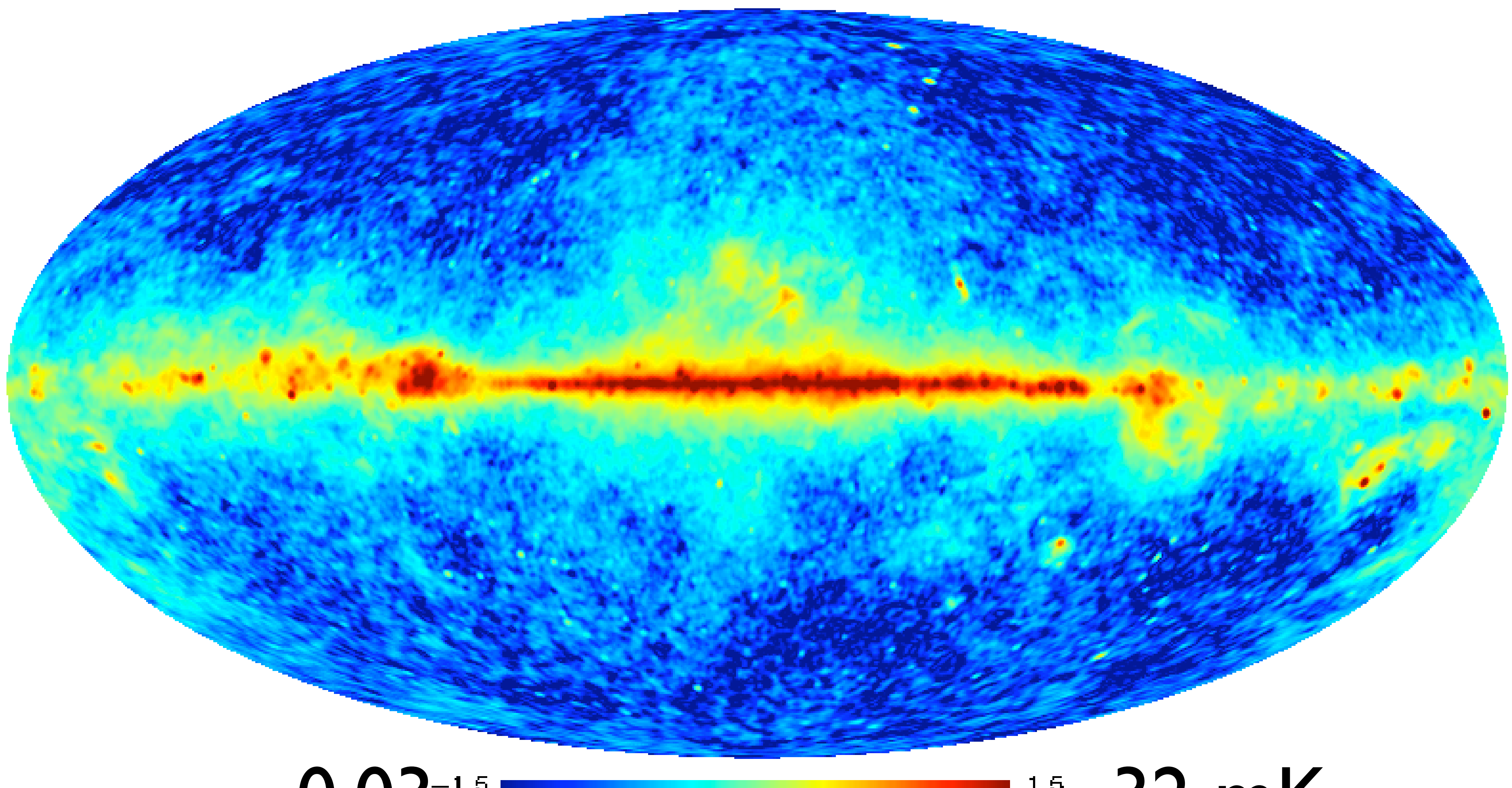



Effelsberg, Jodrell Bank, Parkes

Haslam et al. (1982)

# synchrotron (and free-free)

22 GHz

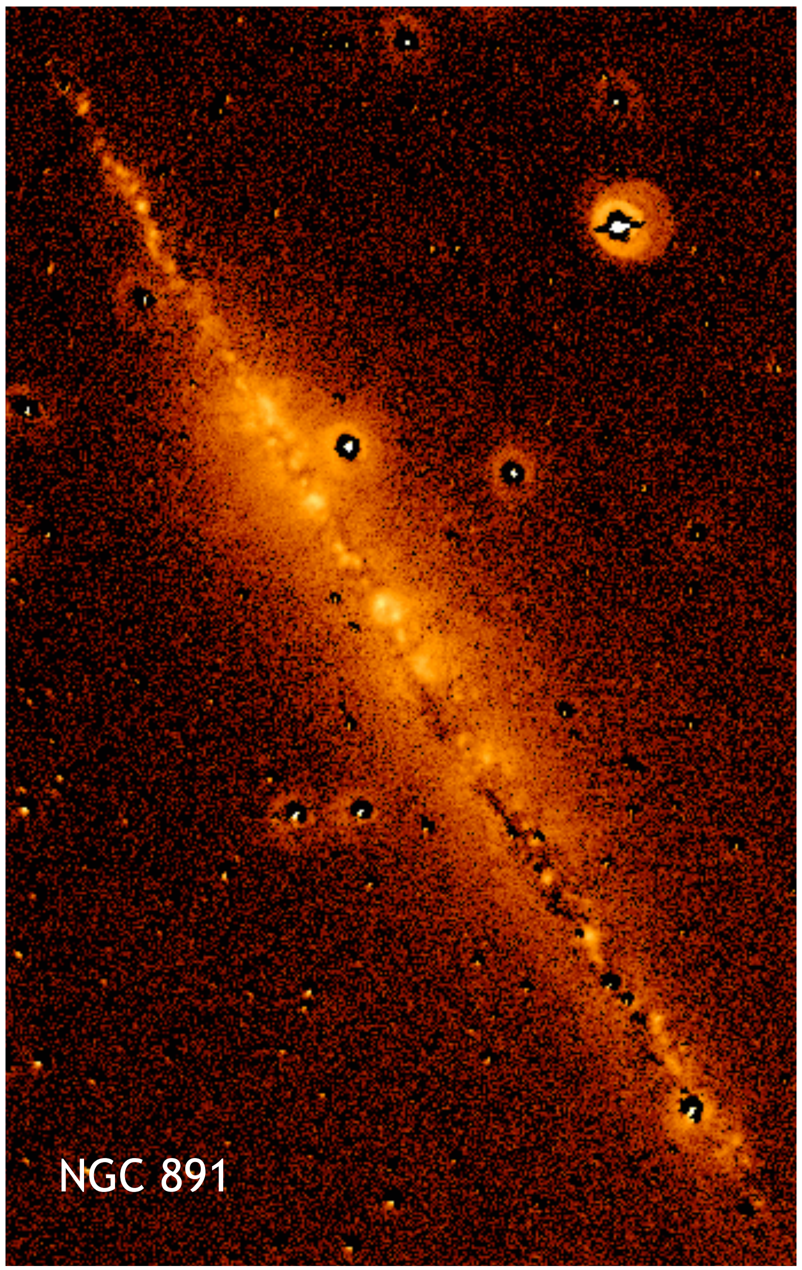



0.03 — 32 mK

WMAP5

# free-free

(aka thermal bremsstrahlung)

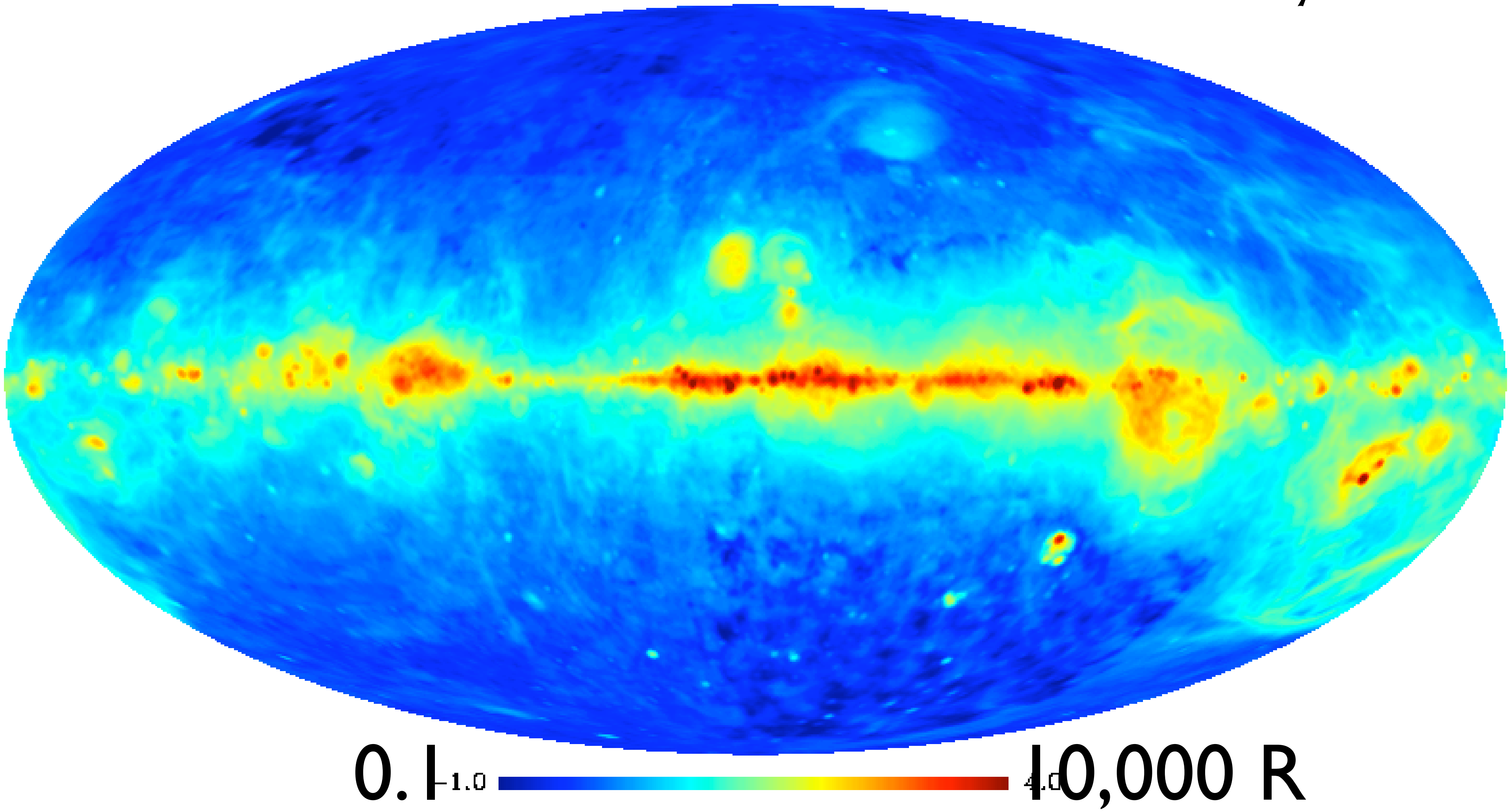



Haffner (2000)

- ionized hydrogen ~7,000 K
- "thick disk", 25-60% WIM, HII regions
- traced by Hα intensity (caveat: depends on temperature)
- physics predicts a very specific radio spectrum
- unpolarized

# free-free

extinction-corrected Hα intensity

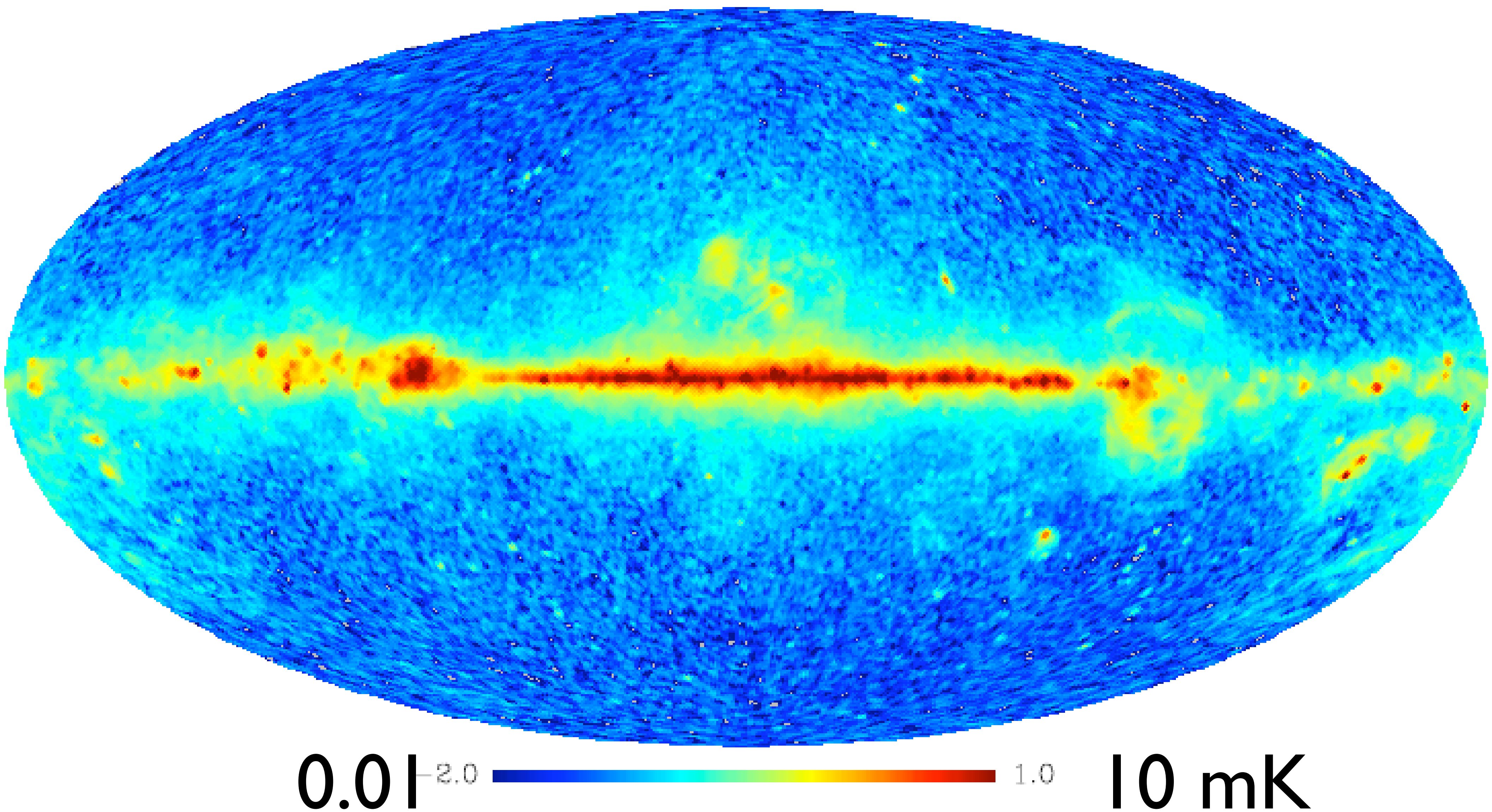



VTSS, SHASSA, WHAM

Schlegel, Finkbeiner & Davis (1998)
Finkbeiner (2003)
Bennett et al. (2003)

# free-free (and synchrotron)

40 GHz



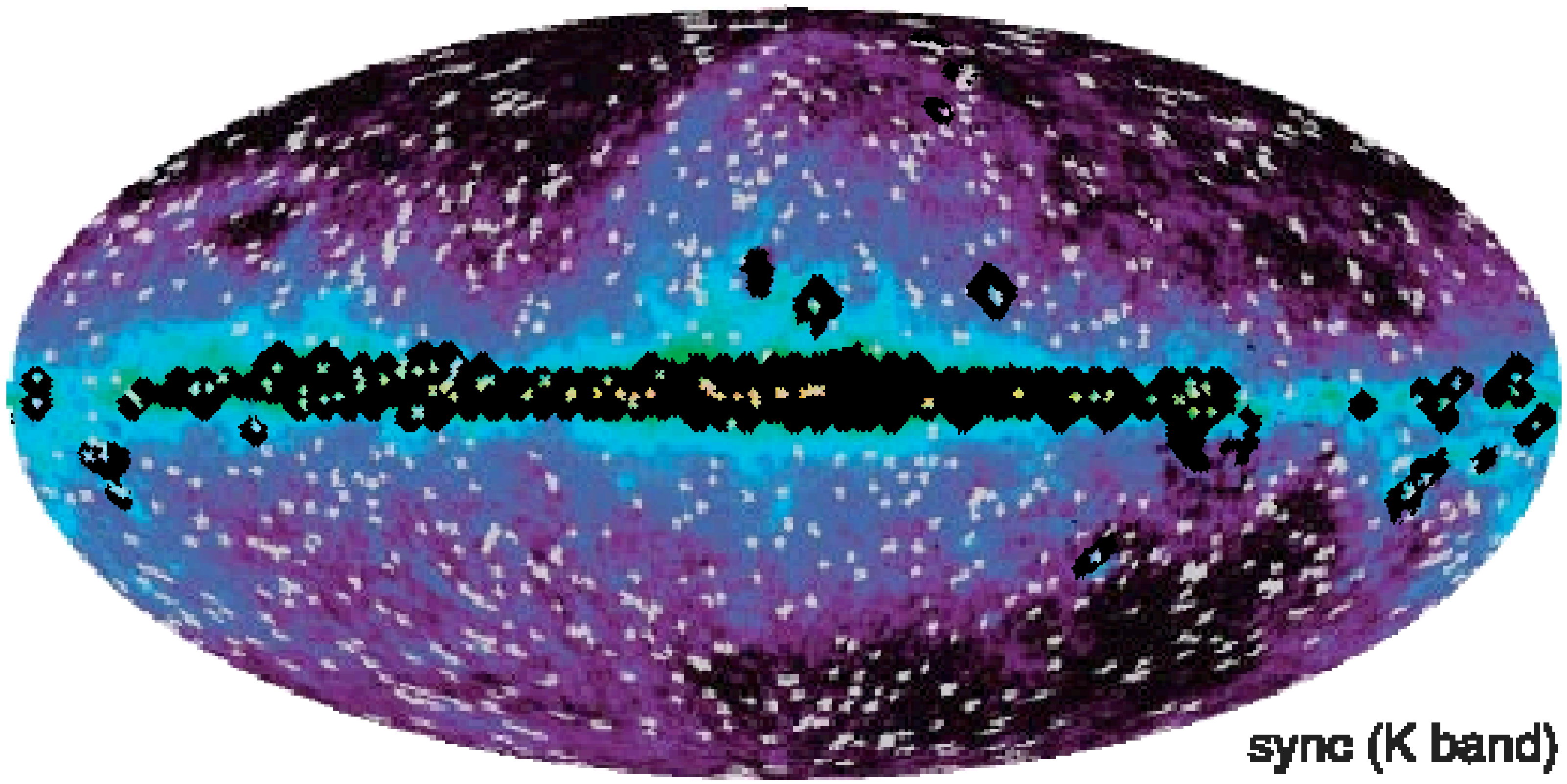

WMAP5

# Foreground fitting/subtraction

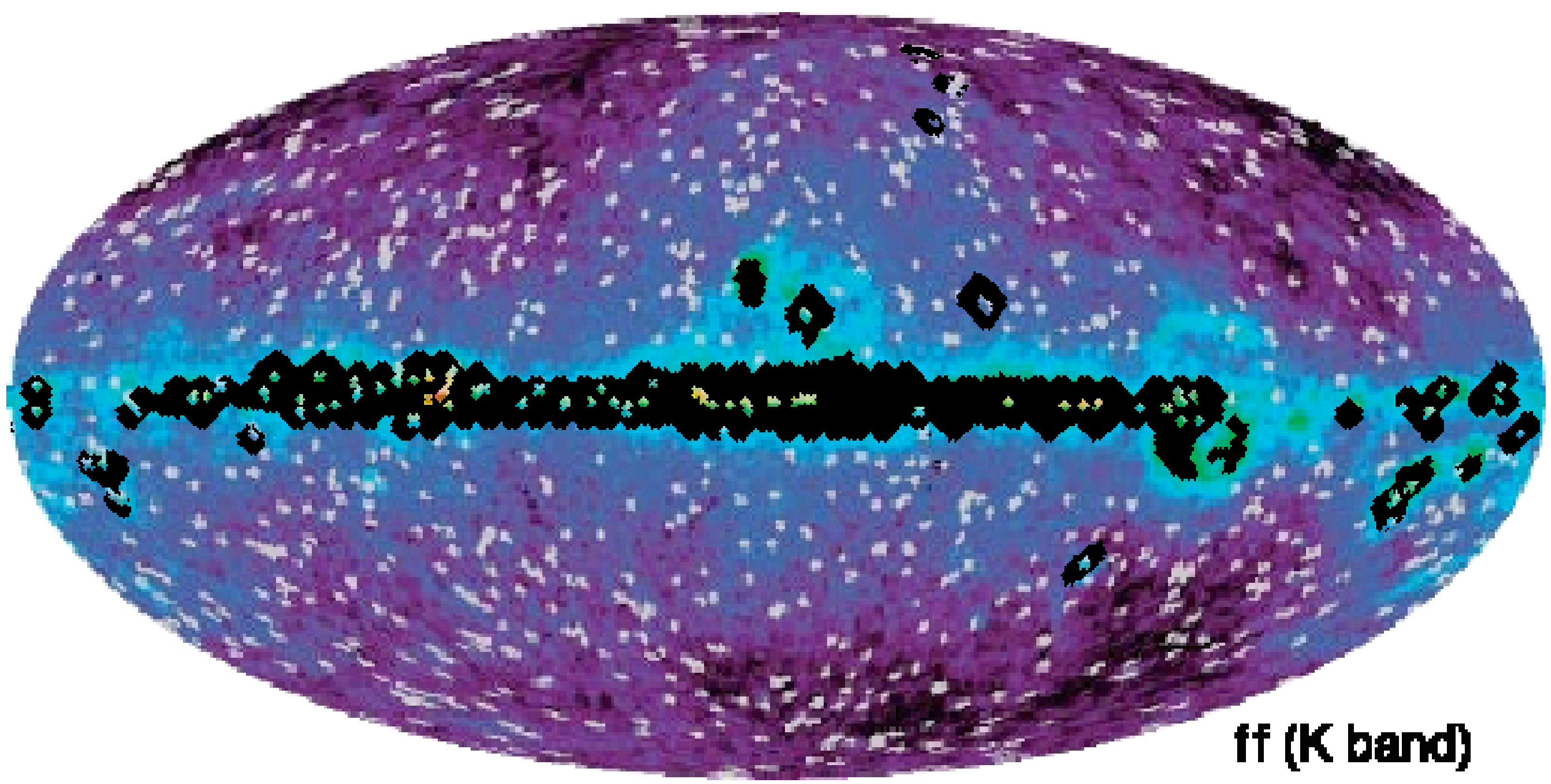
- Masks – ignore the problem and it'll go away
  need to know what to mask!
  still want to assess contamination
- ILC – don't care about fg, want to maximize CMB signal
  learn very little about foregrounds
  noise difficult to assess
- Templates – foregrounds are roughly known, subtract them
  assumes you know what you're doing
- Free fitting – let everything be a "free" parameter in a MCMC fit
  noisiest, but you get error-bars

# MCMC fit

MCMC w/o templates



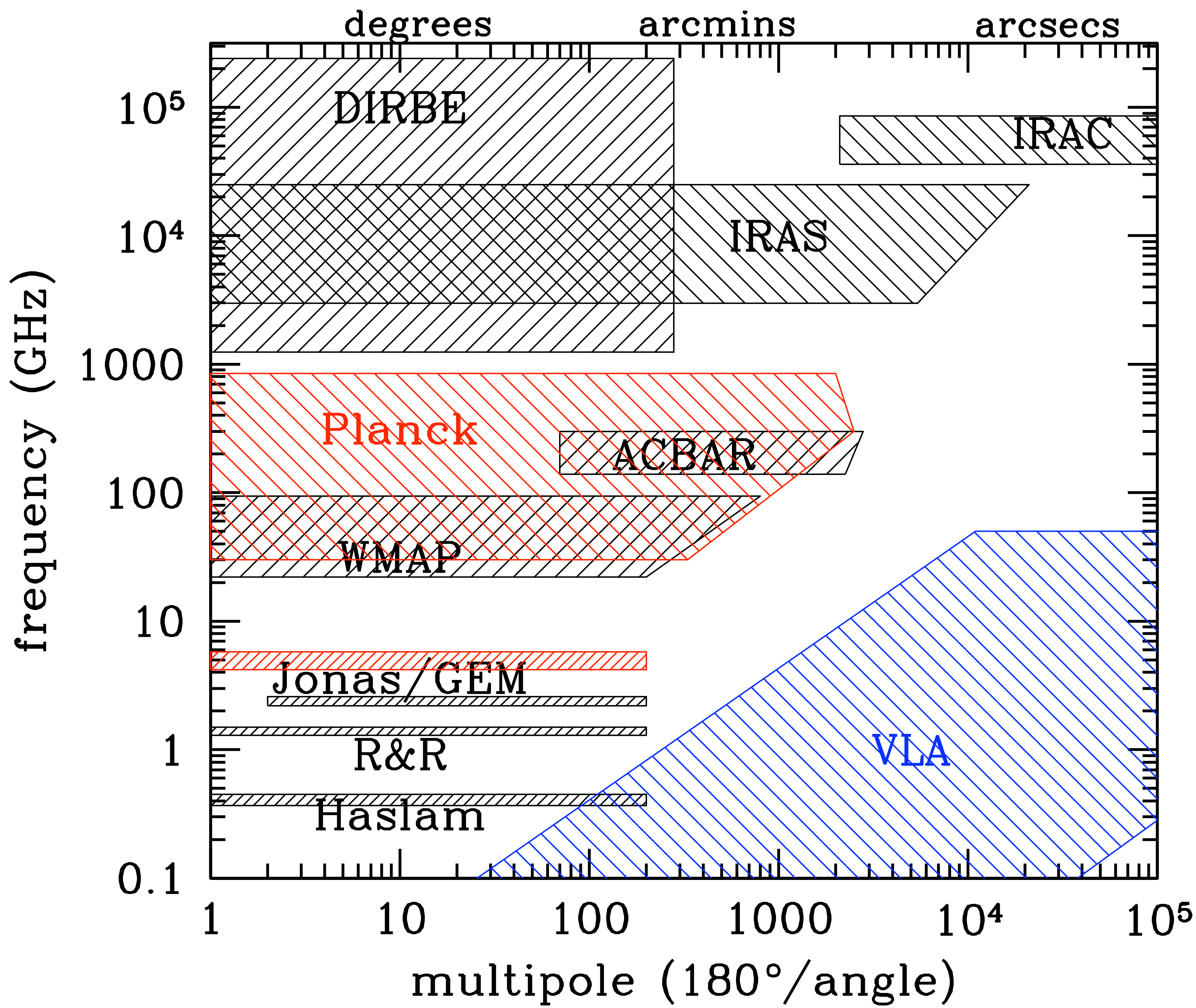

sync




ff

# MCMC fit

| model | # of params | Best-fit $\chi^2_\nu$ [a] outside plane[b] | inside plane[b] | full sky |
|---|---|---|---|---|
| base | 10 | 1.14 | 2.23 | 1.24 |
| base + Haslam | 10 | 1.14 | 2.36 | 1.26 |
| loose priors | 8 | 1.09 | 3.26 | 1.29 |
| steep | 10 | 1.14 | 0.97 | 1.13 |
| exact sd | 9 | 1.21 | 1.63 | 1.25 |
| shifted sd | 9 | 1.24 | 1.00 | 1.22 |
| $\beta_s = -3.2$, $\beta_d = 1.7$ | 8 | 1.16 | 4.33 | 1.45 |
| $\beta_s = -2.6$, $\beta_d = 1.7$ | 8 | 1.30 | 3.42 | 1.50 |
| $\beta_s$ variable, $\beta_d = 1.7$ | 9 | 1.16 | 2.92 | 1.32 |
| $\beta_s$ variable, $\beta_d$ variable | 10 | 1.14 | 2.23 | 1.24 |


degrees
arcmins
arcsecs
DIRBE
IRAC
IRAS
Planck
ACBAR
WMAP
Jonas/GEM
R&R
Haslam
VLA
frequency (GHz)
multipole (180°/angle)
$10^5$
$10^4$
1000
100
10
1
0.1
1
10
100
1000
$10^4$
$10^5$

# WMAP and the future

- Seven years “in the can”
- Observations funded until Summer 2010 (9 years data)
- 6-parameter concordance model
- Constraints on $f_{\rm NL}$ improving rapidly
- Next funding review early 2010
- Planck launches April 16!

# Five-year par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- mological ," **Komatsu** et .0547

Astrophysical Journal Supplement Series 180 (2009), online NOW

# Papers and data available at

`lambda.gsfc.nasa.gov`