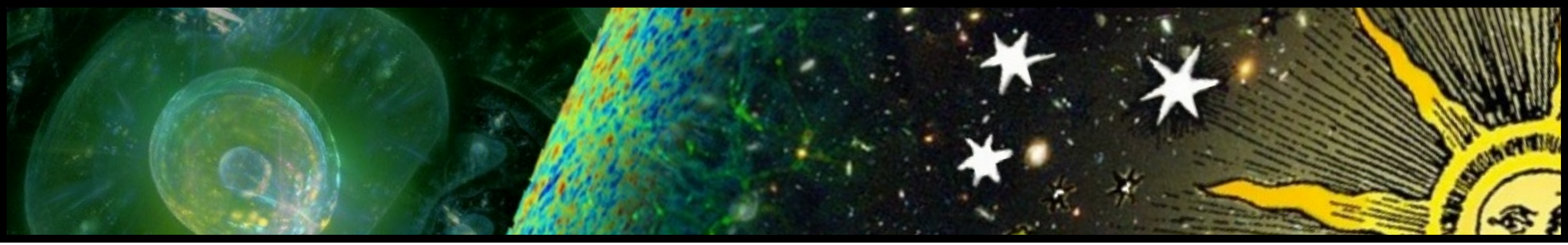

Considerations in the Interpretation of Cosmological Anomalies

Hiranya V. Peiris
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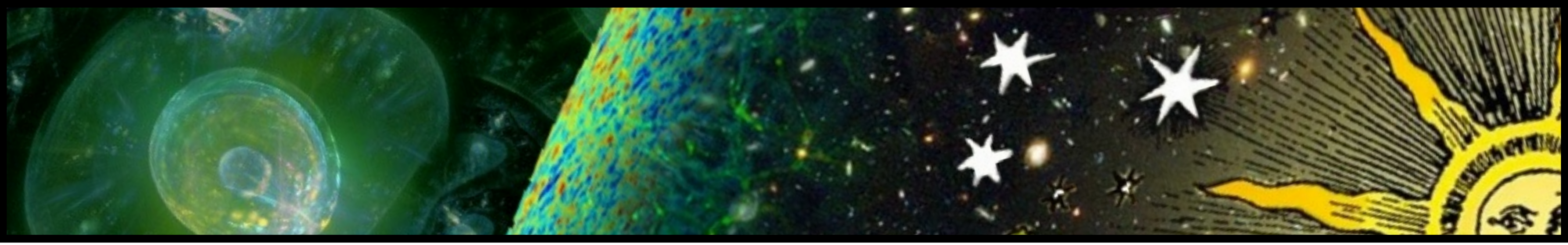
European Research Council
Established by the European Commission

IDEAS



"No one trusts a model except the person who wrote it; everyone trusts an observation, except the person who made it".

paraphrasing H. Shapley

Reference: arXiv:1410.3837 (Proc. IAU Symposium 306)

Experimental landscape in 2024

- ***CMB:*** *ground-based (BICEP++,ACTpol, SPT3G, PolarBear,...), balloon-borne (EBEX, SPIDER,...), mission proposal for 4th generation satellite (CMBPol, EPIC, CoRE, LiteBird...), spectroscopy (PIXIE, PRISM proposal...)*

- ***LSS:*** *photometric (DES, PanSTARRS, LSST...), spectroscopic (HSC, HETDEX, DESI,...), space-based (Euclid,WFIRST...)*

- ***21cm:*** *SKA and pathfinders...*

- ***GW:*** *Advanced LIGO, NGO pathfinder...*

Science goals tie early/late universe together; multi-goal; Cross-talk of data-types and probes critical for success

Modelling in the next decade

- ***"Big Data" era***
  Very large datasets: data compression, filtering, sampling, inference

- ***Small SNR***
  frontier research inevitably involves small signal-to-noise

- ***Large model space***

- ***Cosmic variance***
  a single realisation of an inherently random cosmological model
  (cf. quantum fluctuations)

Modelling

Mechanistic (physical) models

- *Based on physics, forward modelling feasible*
- *Types of analyses: parameter estimation, model comparison...*
- *Used to test theoretical predictions*

Empirical (data-driven) models

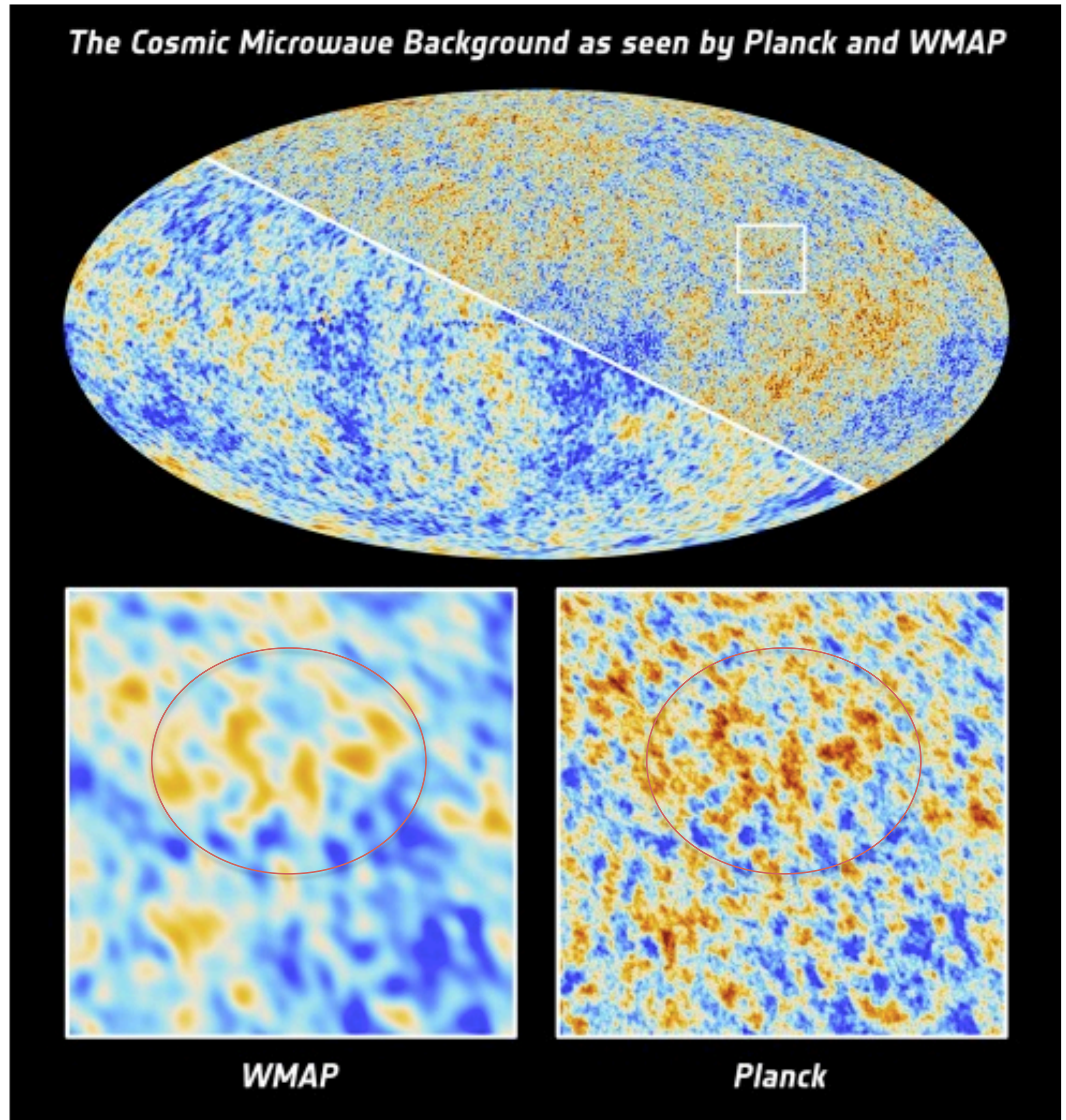
- *Characterise relationships in data*
- *Not quantitatively based on physics / qualitatively motivated by physics but forward-modelling infeasible*
- *May be used to postulate new theories / generate statistical predictions for new observables.*

Anomalies

- *Anomalies: unusual data configurations*
- *Deviations from expectations*
  outliers / unusual concentration of data points / sudden behaviour changes….
- *May rise from:*
  - *chance configurations due to random fluctuations*
  - *systematics (unmodelled astrophysics; instrument/detector artefacts; data processing artefacts)*
  - *genuinely new discoveries*

Caution: Pareidolia

- Humans have evolved to see patterns in data



Anomalies: new physics?

- In cosmology, anomalies often discovered using *a posteriori* estimators: spuriously enhances detection significance
- Often cannot account for "look-elsewhere effect" and / or formulate model priors to compare with standard model

In absence of alternative theory, how to judge if given anomaly represents new physics?

Case studies

- **Assessing anomalies**
  accounting for the look-elsewhere effect

- **"Just-so" models**
  designer theories that stand-in for "best possible" explanations

- **Data-driven models**
  predictions for new data

- **Blind analysis**
  experimental design to minimize false detections due to experimenter's bias

Case studies

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Assessing anomalies: two aspects

- **Search:** finding the anomalies
  measures of irregularity, unexpectedness, unusualness, etc

- **Inference:** chance vs mechanism
  need to allow for the particle physicists' "look elsewhere" effect

The mysterious case of the CMB Cold Spot

- Cruz et al (Science, 2007): CMB "Cold Spot" is likely a texture (type of spatially-localised cosmic defect).

- Based on analysis of single feature at particular location; (incomplete) attempt to correct *a posteriori* selection.

- *accounts for expected sky fraction covered by textures in a patch*

- *doesn't account for fact that each texture could be anywhere on sky*

- *considers only cold spots*

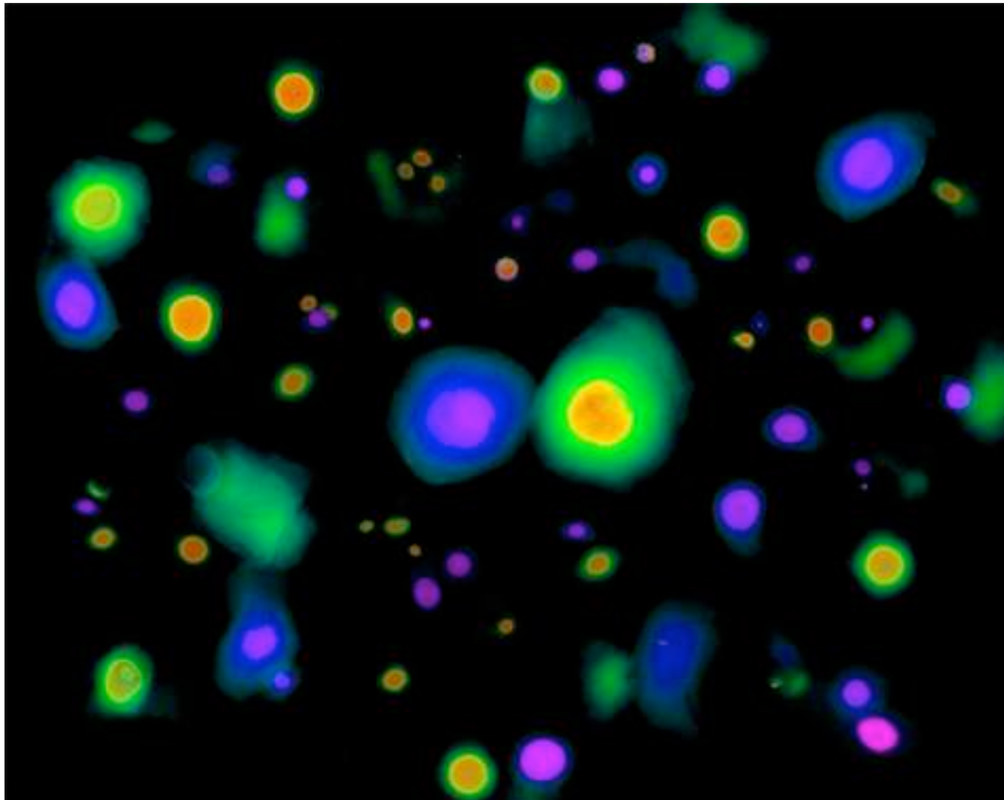

Figure: N. Turok

Testing the texture hypothesis

Texture model formulated as a hierarchical Bayesian model.

- **Population level:**
  expected number of textures per CMB sky, symmetry breaking scale

- **Source level:**
  template size, location, whether hot or cold

To obtain posterior probability of population-level parameters, must marginalise over source parameters:

Expected # of textures per CMB sky < 5.2 (95% CL).

Feeney, Johnson, McEwen, Mortlock, Peiris (Phys. Rev. Lett. 2012, Phys. Rev. D 2013)

Case studies

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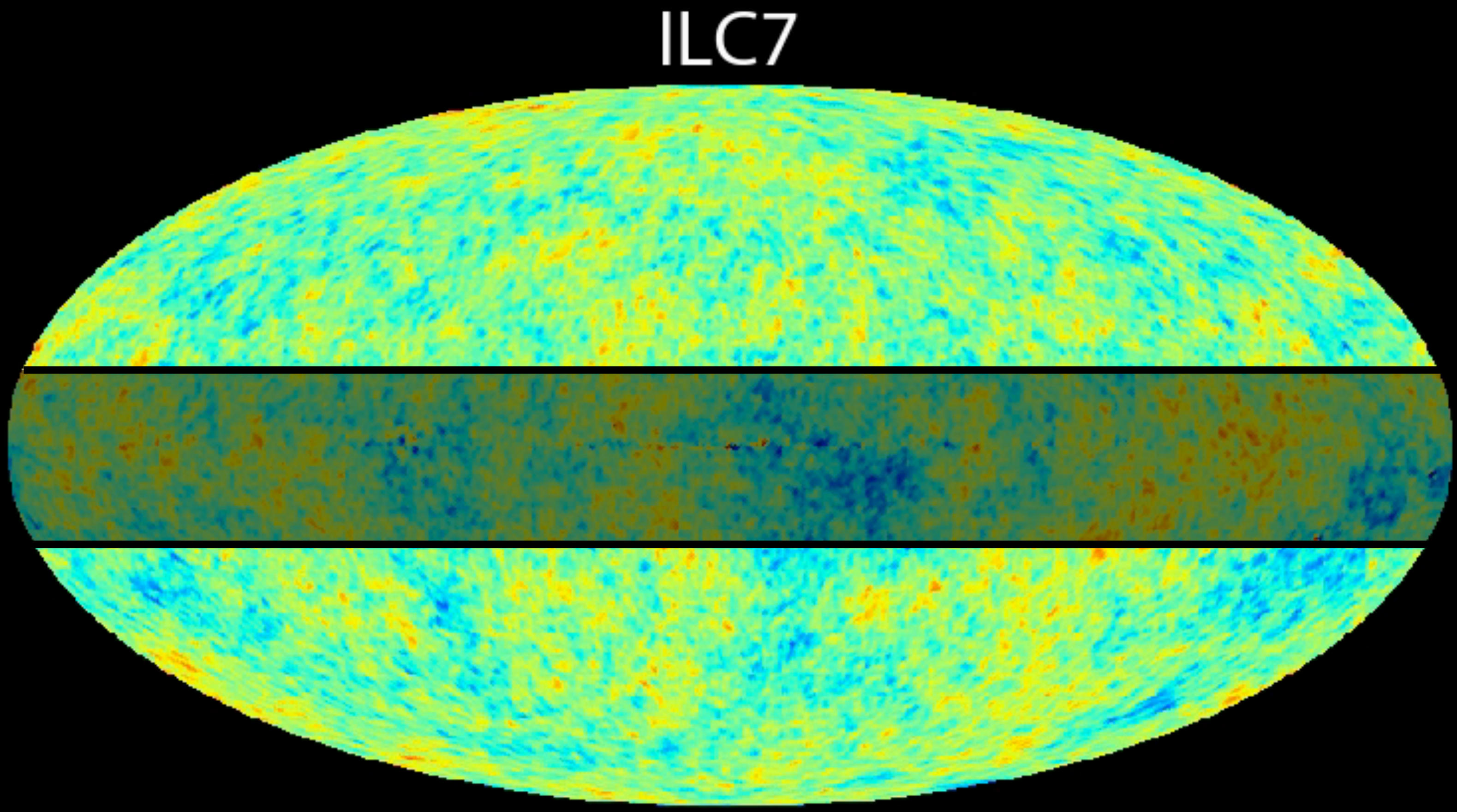
Does given anomaly represent new physics?
A proposal

1. Find designer theory ("just-so" model in statistics) which maximizes likelihood of anomaly

2. Determine available likelihood gain wrt standard model

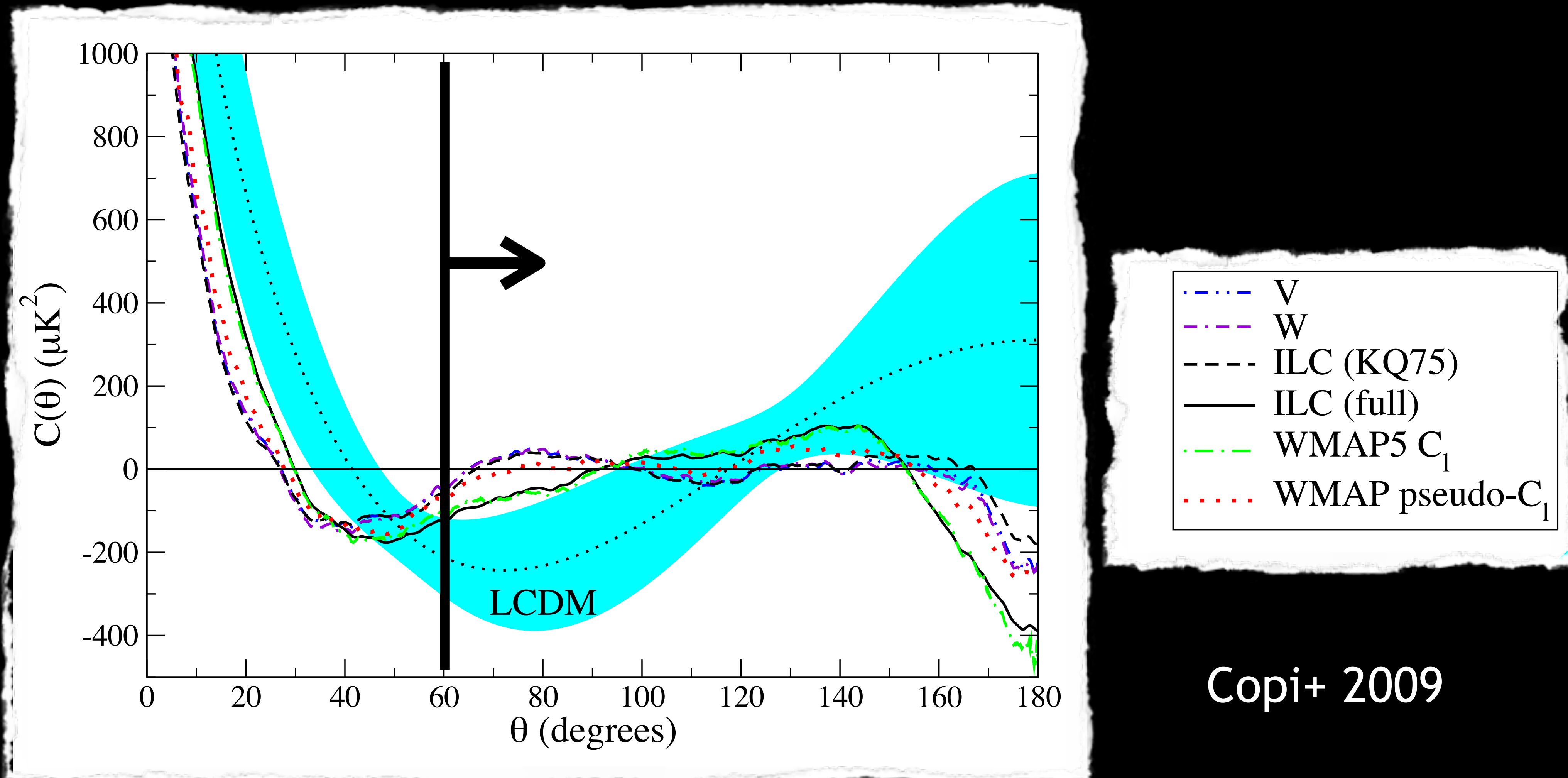
3. Judge if this is compelling compared to model baroqueness

$$C(\theta) = \overline{T_1 T_2}$$



$$S_{1/2} = \int_{60^\circ}^{180^\circ} C(\theta)^2 \cos\theta \, d\theta$$

(Spergel+ 2003)



Copi+ 2009

$$S_{1/2} = \int_{60^\circ}^{180^\circ} C(\theta)^2 \cos\theta \, d\theta$$

(Spergel+ 2003)

$S_{1/2}^{cut} \sim 1000\ \mu K^4$

$\langle S_{1/2}^{cut} \rangle_{\Lambda CDM} \sim 94{,}000\ \mu K^4$

$p_{\Lambda CDM}(\leq S_{1/2}^{cut}) \sim 0.03\%$

$$\mathcal{C}(\theta) = \frac{1}{4\pi}\sum_\ell (2\ell+1)\mathcal{C}_\ell P_\ell(\cos\theta)$$

$C(\theta) \longleftrightarrow C_l$ p ~ 5%

$C^{cut}(\theta) \longleftrightarrow C^{PCL}{}_l$ p ~ 0.03%

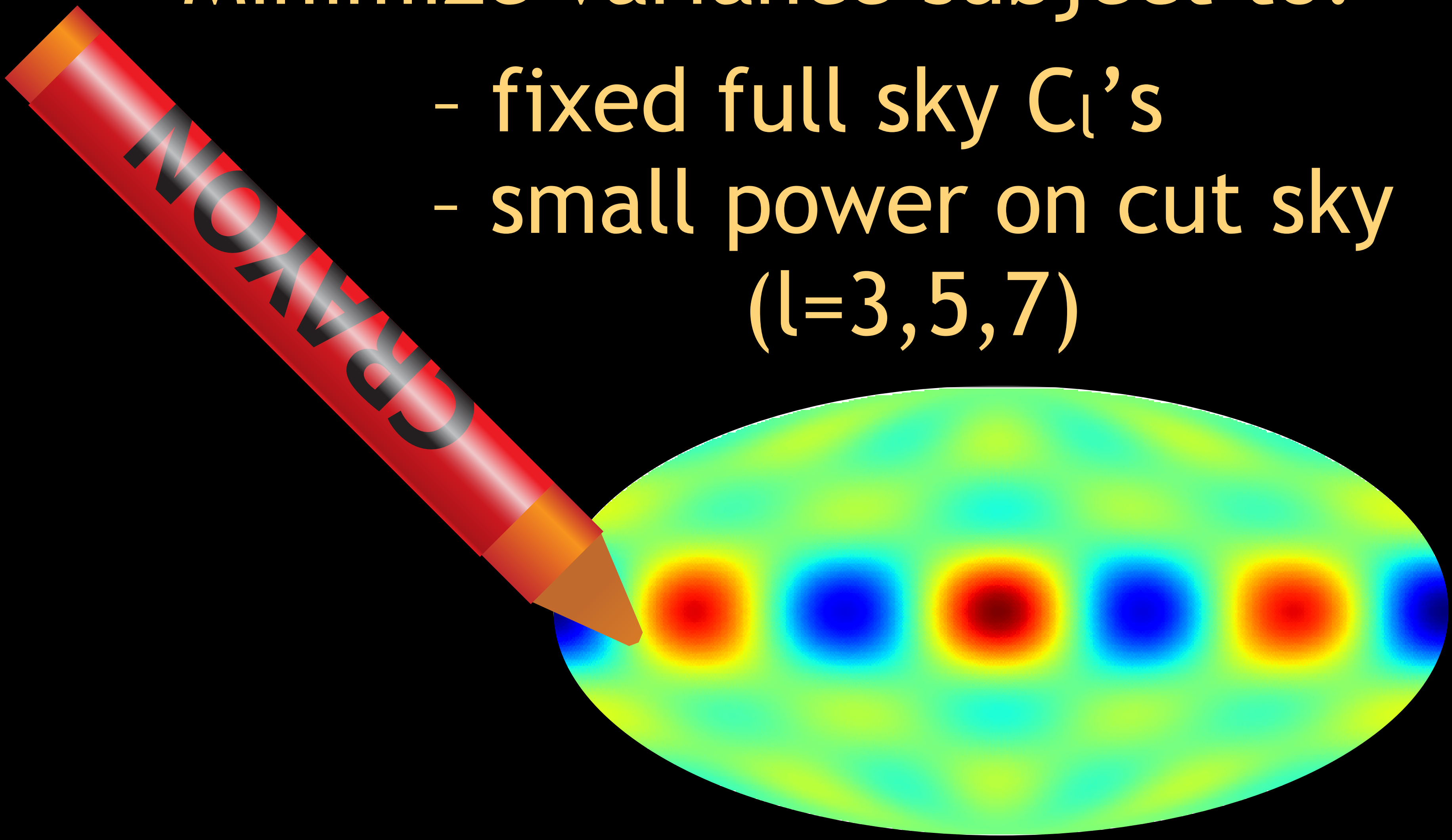
$C^{MLE}(\theta) \longleftrightarrow C^{MLE}{}_l$ p ~ 5%

This is a *p*-value, NOT the probability of LCDM being correct!

$$S_{1/2}^{cut} = \int_{60^\circ}^{180^\circ} C^{cut}(\theta)^2 \cos\theta \, d\theta = \sum s_{ll'} C^{PCL}{}_l \, C^{PCL}{}_{l'}$$

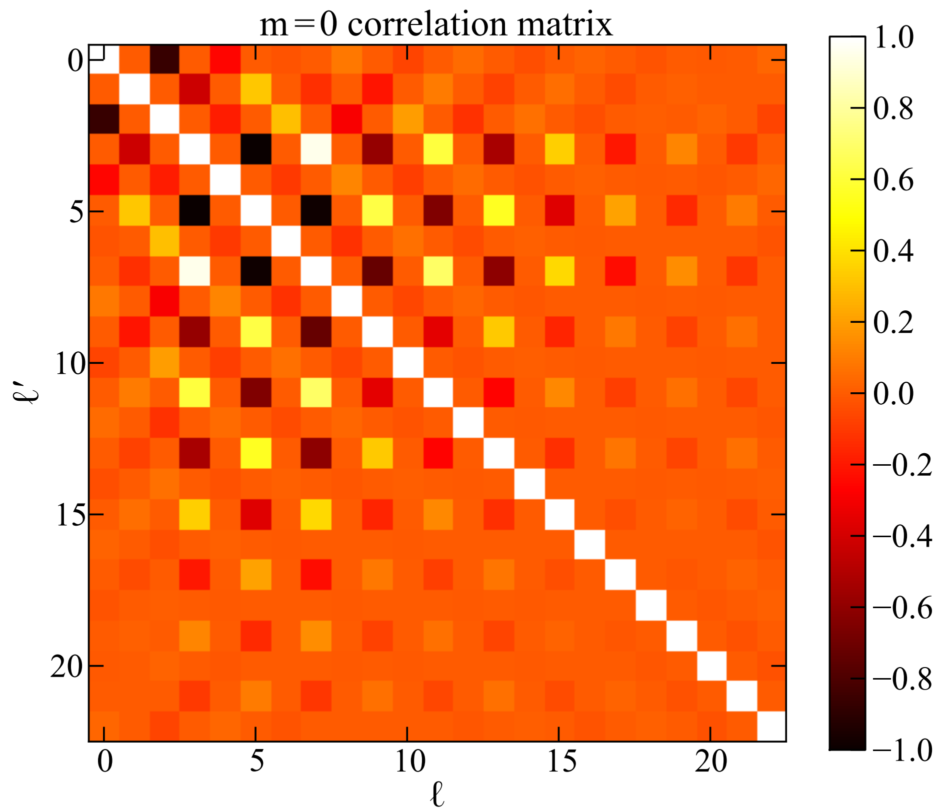
Minimize variance subject to:

- fixed full sky C_l's
- small power on cut sky (l=3,5,7)



Pontzen & Peiris (1004.2706, PRD, 2010)

Verdict for C(θ) anomaly



- Maximize likelihood of cut sky S statistic over all anisotropic* Gaussian models with zero mean.

- Designer model (~ 6900 dof) improves likelihood over LCDM (8 dof) by *ln* $\mathscr{L}$ ~ 5.

*Covariance matrix of alms can be arbitrarily correlated, as long as it's positive-definite.

Pontzen & Peiris (1004.2706, PRD, 2010)

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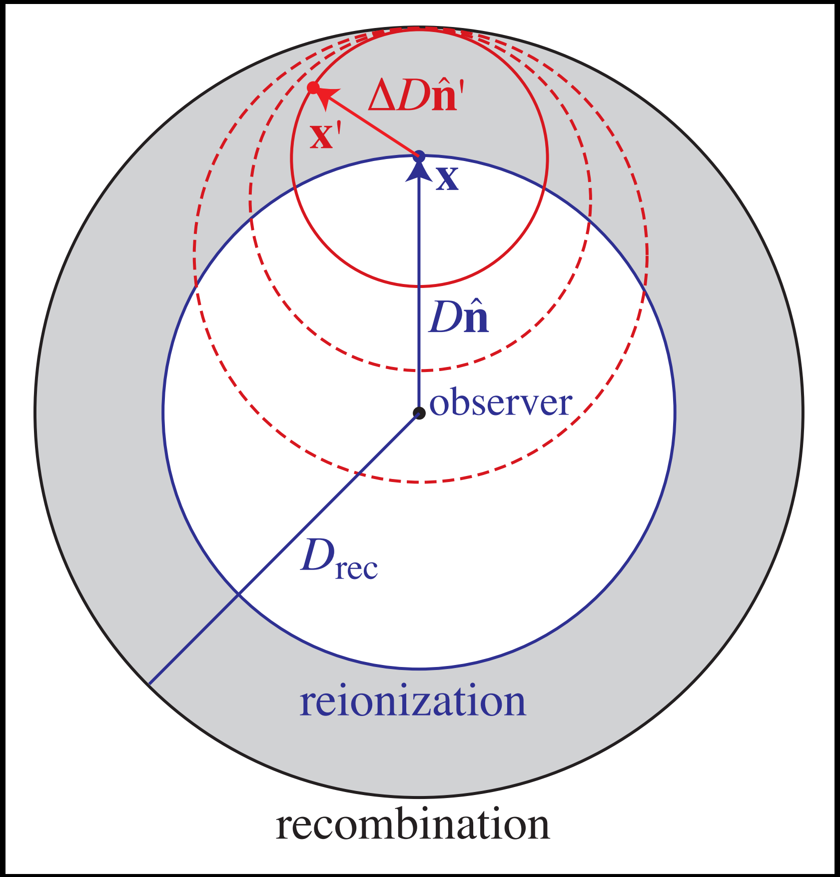
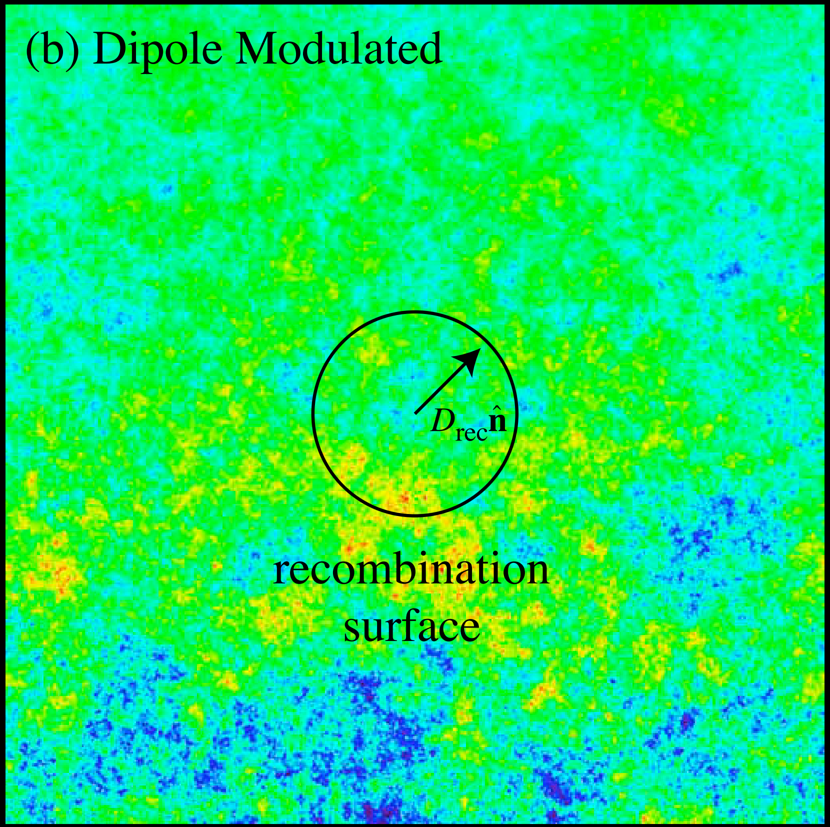
CMB Polarization: Testing Statistical Isotropy

- Isotropy "anomalies" identified in WMAP temperature field (e.g. hemispherical asymmetry, quadrupole-octupole alignment)

- Any physical model of temperature anomalies provides testable predictions for statistics of polarization field; goes beyond *a posteriori* inferences.





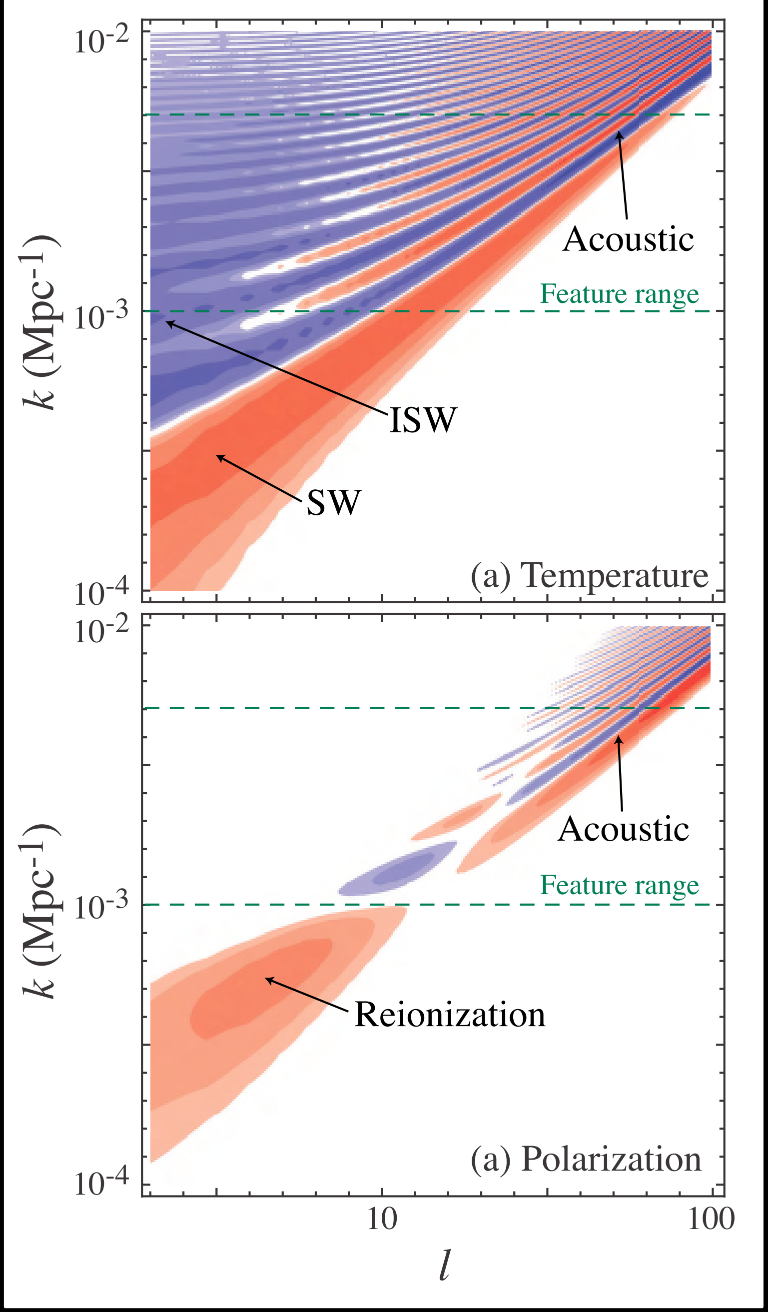
Dvorkin, Peiris & Hu (astro-ph/0711.2321)

CMB Polarization: Is Power Spectrum Smooth?

- “Glitches” in WMAP TT spectrum at large scales: statistics, systematics, or new physics?

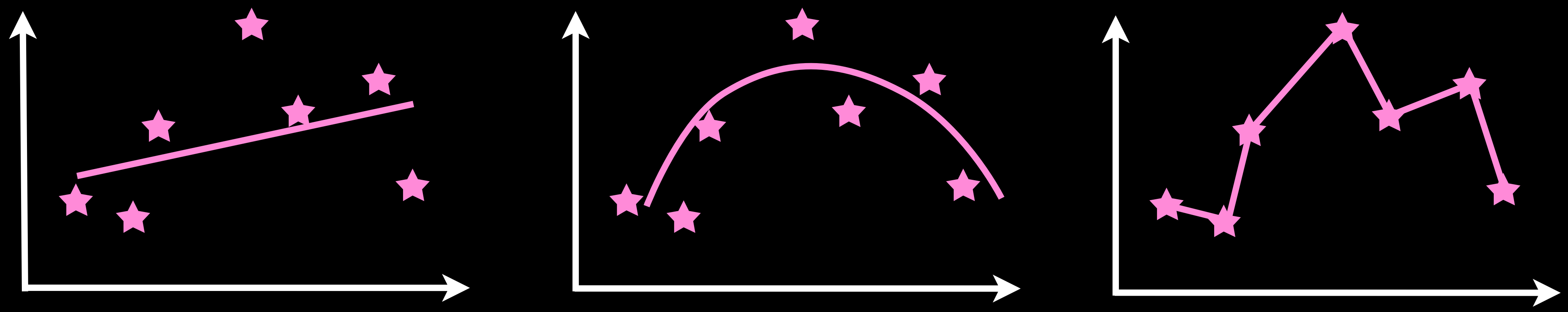
- Features in inflationary power spectrum?

- Test: polarization transfer function narrower than temperature one.



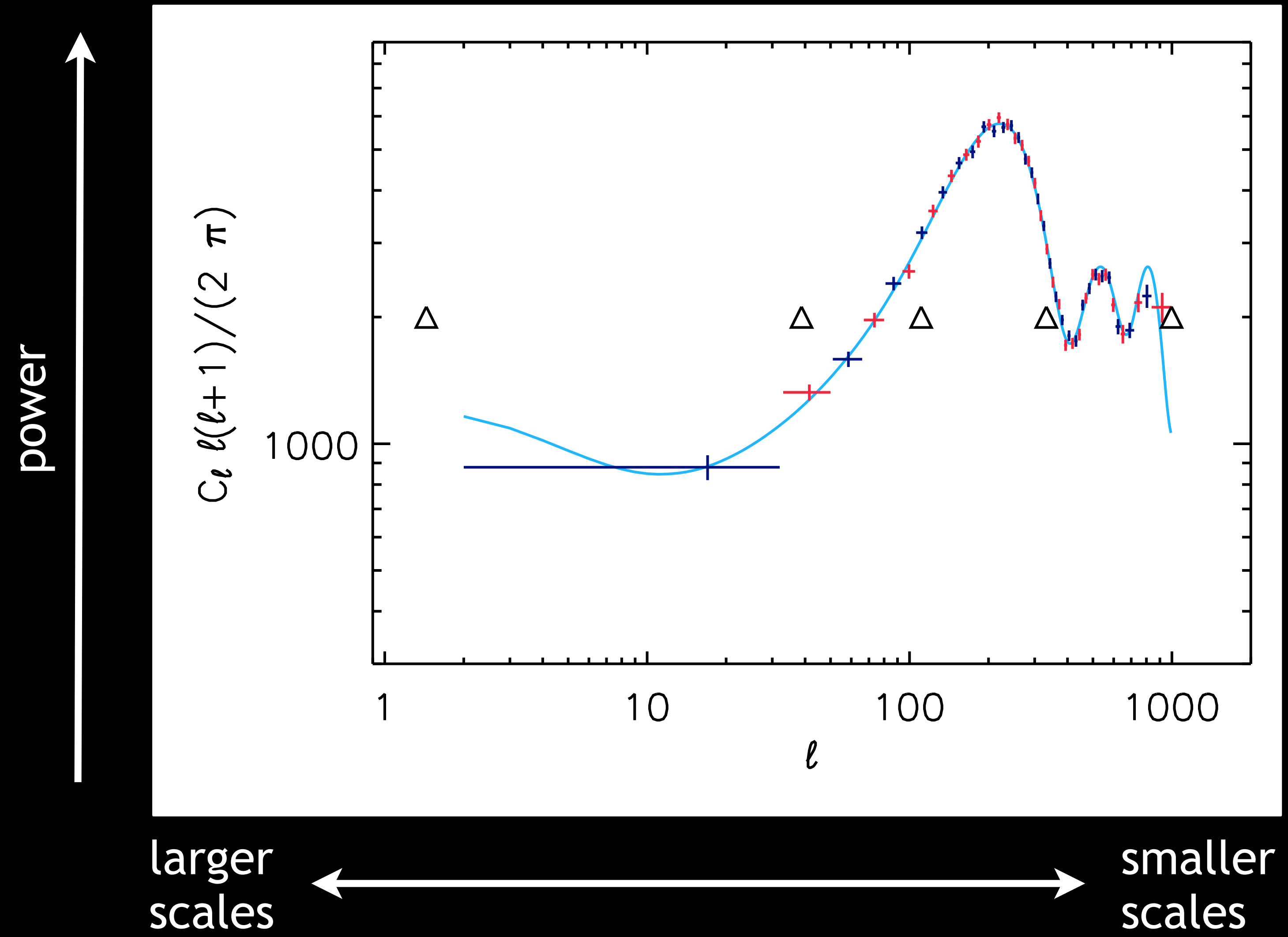
Mortonson, Dvorkin, Peiris & Hu (0903.4920)

Which is best?



How well are you going to predict future data drawn from the same distribution?

2-fold cross-validation

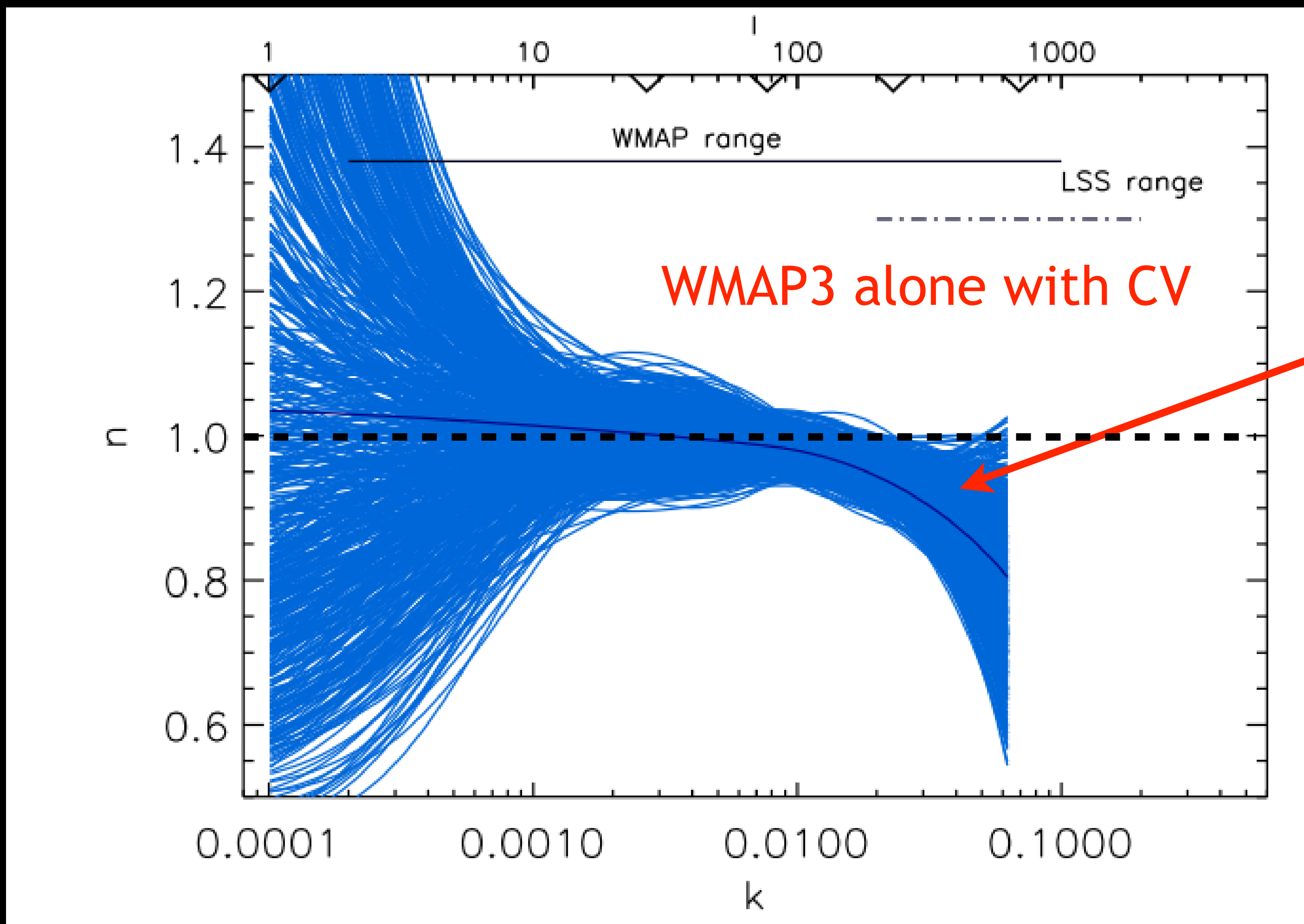


How well do a fit to the blue points (training set) predict the red points (validation set), and vice versa? (CV score)

Power spectrum reconstruction results for WMAP3

- Good way to identify systematics in datasets.

scale dependence of spectral index



point sources? beams?

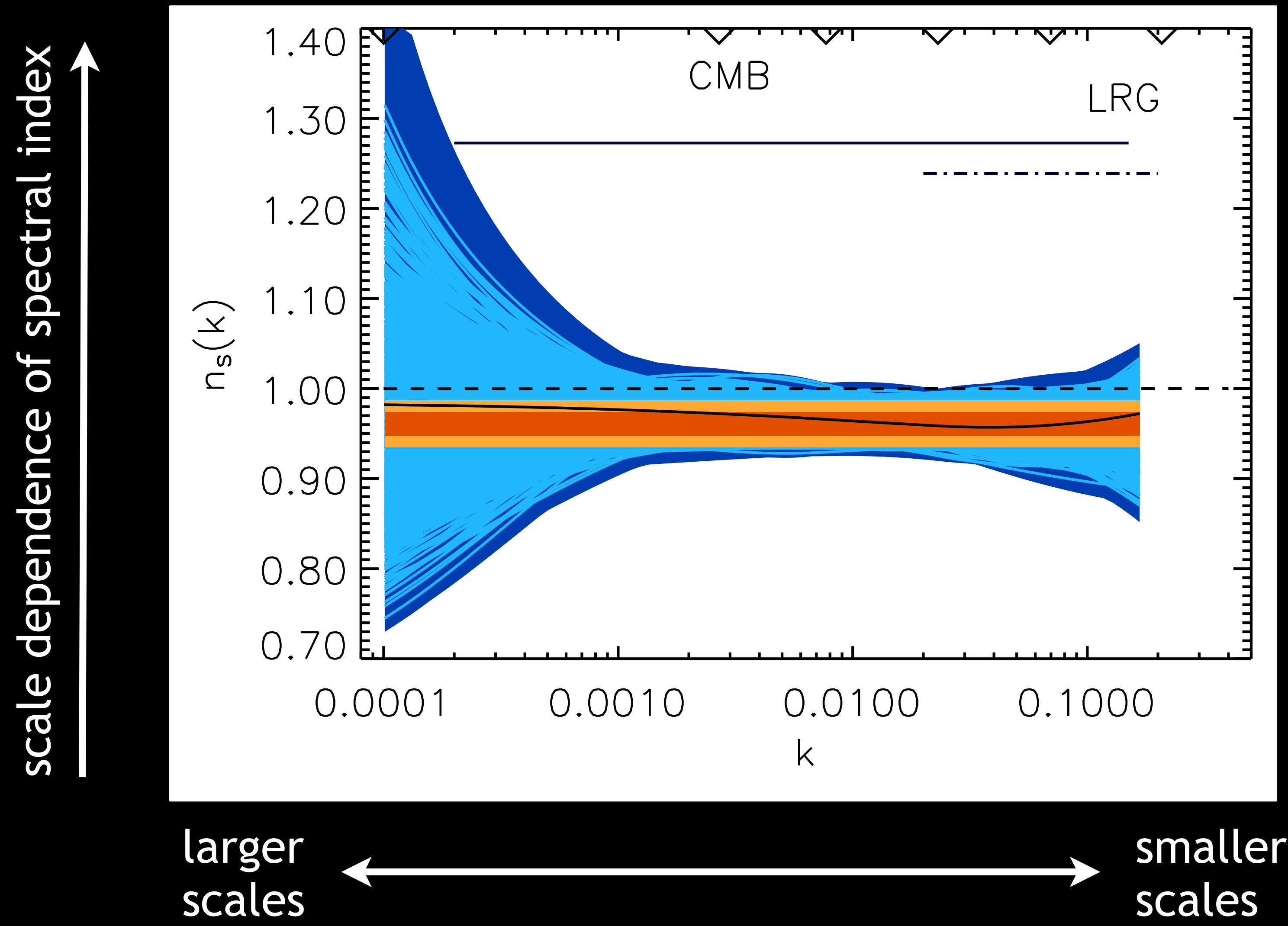
Huffenberger et al. 07, Reichardt et al 08

larger scales

smaller scales

Verde & Peiris (arxiv:0802.1219)

Power spectrum reconstruction results for WMAP5



Peiris and Verde (arxiv:0912:0268)

Case studies

- **Assessing anomalies:** accounting for the look-elsewhere effect
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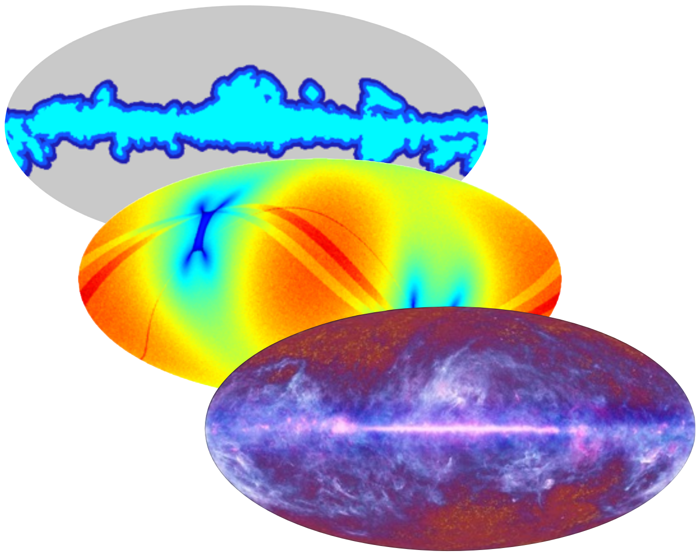
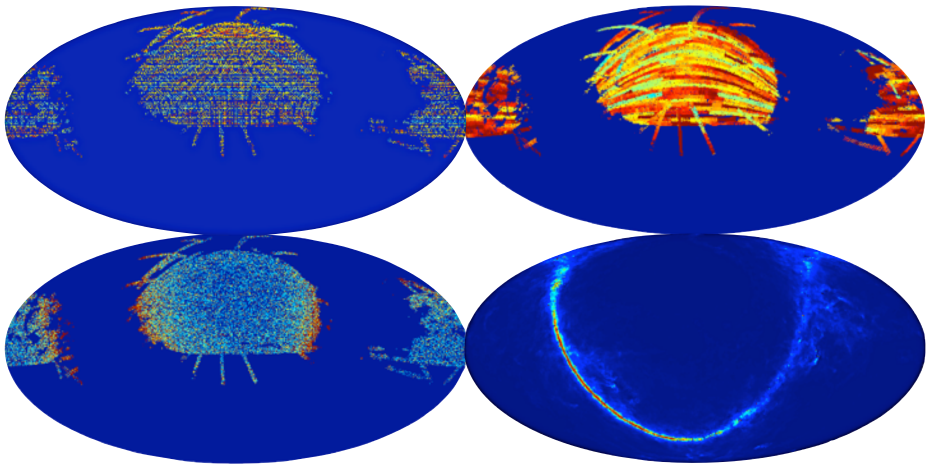
Data analysis

Challenges

Need thorough understanding of data & systematics for convincing detections.



***CMB**: complex sky mask, coloured / inhomogeneous noise, foregrounds...*



***LSS**: seeing, sky brightness, stellar contamination, dust obscuration, spatially-varying selection function, Poisson noise, photo-z errors etc...*

Solutions

Known-unknowns: Propagate with robust **Bayesian** statistical techniques.

Unknown-unknowns: Mitigate with **blind analysis** algorithms.

(cf. particle physics)

Blind analysis

The value of a measurement does not contain any information about its correctness.

- Knowing value of measurement therefore of no use in performing the analysis itself.

- *Blind analysis:* final result & individual data on which it is based kept hidden from analyst till analysis essentially complete.

See reviews by Roodman (2003), Harrison (2002)

Why blind analysis?

To avoid experimenter's (subconscious) bias:

Data collection / analysis / inference involves human stage.

Represents unquantifiable systematic uncertainty

Why blind analysis?

To avoid experimenter's (subconscious) bias

- Looking for bugs when result doesn't conform to expectation (and not looking for them when it does).

- Looking for additional sources of systematic uncertainty when a result does not conform.

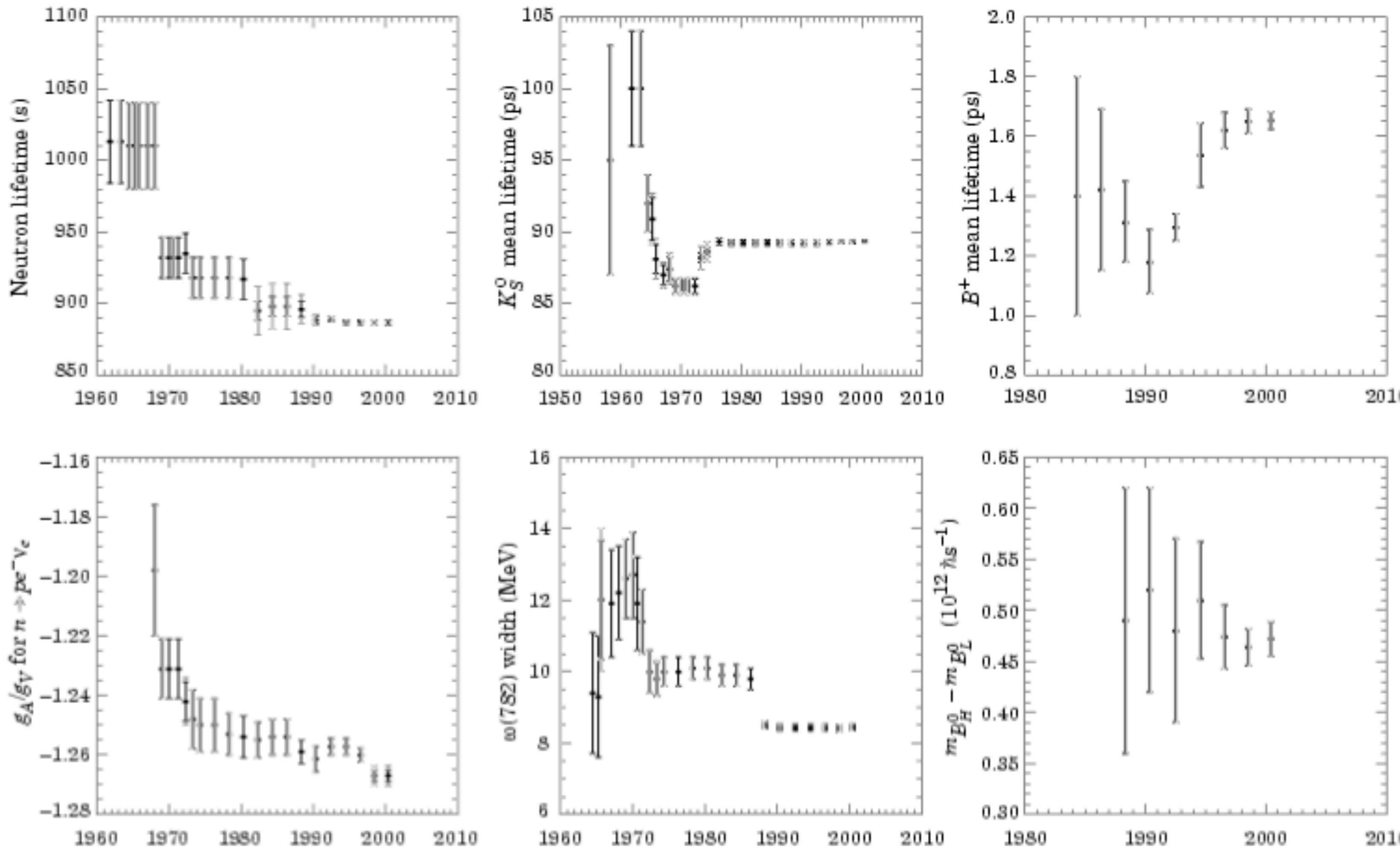
- Deciding whether to publish, or wait for more data.

- Choosing cuts while looking at the data.

- Preferentially keeping / dropping outlier data.

Represents unquantifiable systematic uncertainty

Some measurements as a function of time



periods of surprisingly small variation, followed by jumps of several standard deviations

D.E. Groom et al. Eur. Phys. J. C15 (2000) 1 via Harrison (2002)

What isn't a blind analysis?

- ***Double-unblind:*** doing two analyses in parallel
- ***"Mock data"*** analysis
- ***Semi-blind:*** use fraction of the data; freeze analysis

What is a blind analysis?

- "***Encrypt***" science result: e.g., *add non-changing random number to numerical result or transform a variable.*
    - Do NOT blind how result changes due to changes in analysis.
    - Do NOT blind calibration data, etc.

- "***Hide***" signal region. [difficult for many cosmological data types?]

- Searching for rare events: ***blind injection*** of signals into data *(cf. gravitational wave detection)*

- *Mix in* unknown fraction of simulated data during calibration etc.

- Analysts can define checks they will do after unblinding.

Just thinking about how to blind can lead to greater understanding of analysis & pitfalls.

Examples of blind analyses in cosmology

- Cosmic shear analysis of CFHTlenS
  Heymans et al 2012, Fu et al 2014

- CMB B-mode polarisation of POLARBEAR
  Ade et al 2014

- Supernovae cosmology
  Conley et al 2006

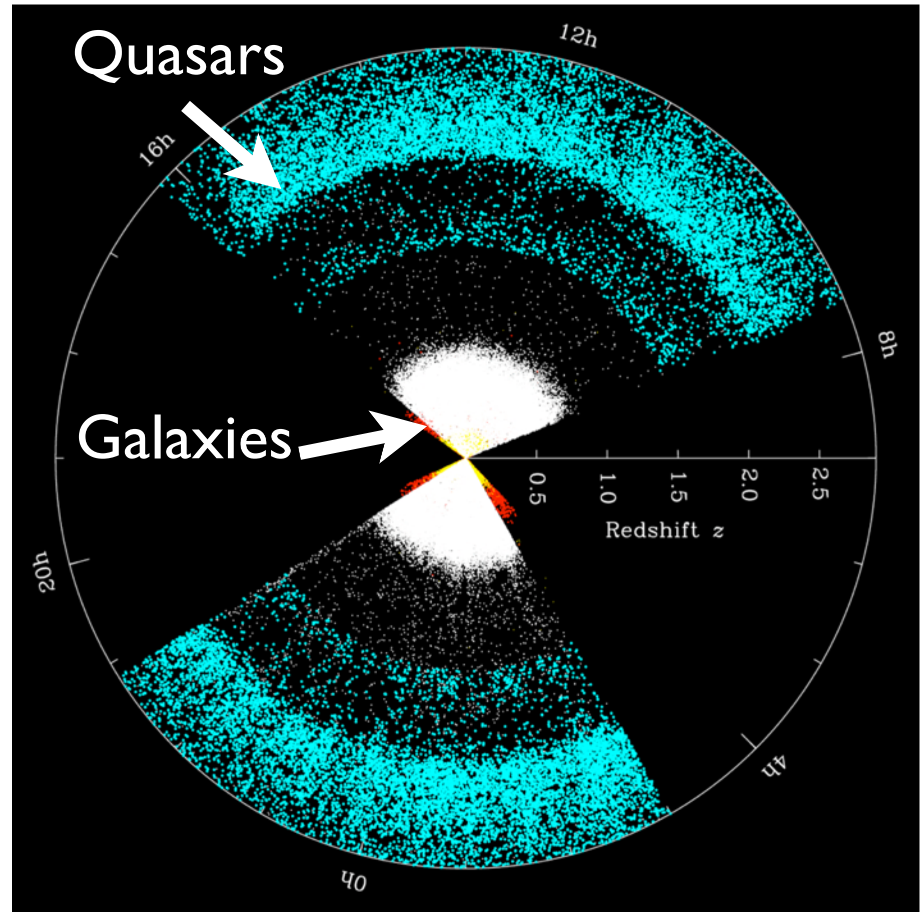
Blind mitigation of systematics in quasar surveys

XDQSOz: 1.6 million QSO candidates from SDSS DR8 spanning z ~ 0.5-3.5 (800,000 QSOs after basic masking).

(Bovy et al.)

Boris Leistedt

Nina Roth

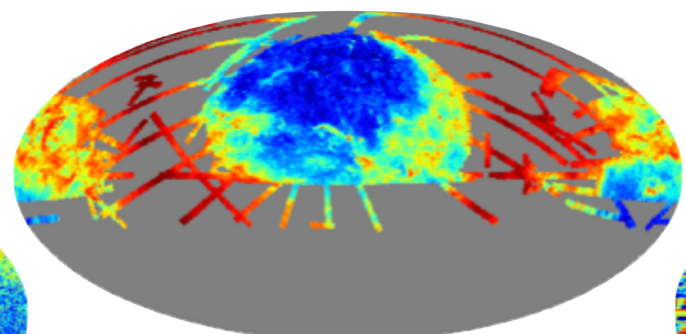


Leistedt & Peiris+ (MNRAS 2013, 1404.6530)
Leistedt, Peiris & Roth (Phys. Rev. Lett. 2014, 1405.4315)

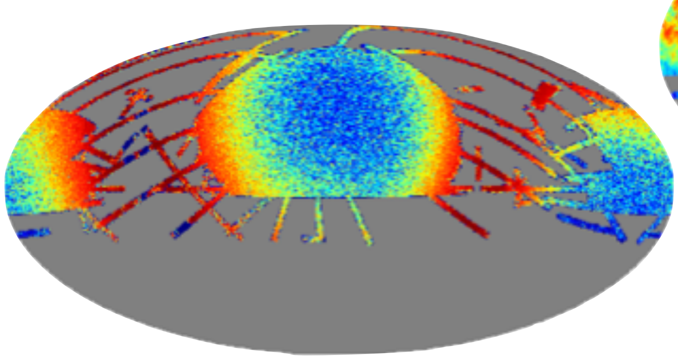
Systematics in quasar surveys

- Anything that affects point sources or colours
  seeing, sky brightness, stellar contamination, dust obscuration, calibration etc..
- Create spatially varying depth & stellar contamination

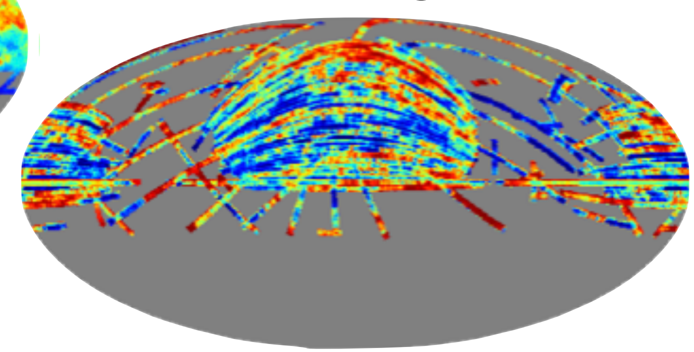
dust



stars



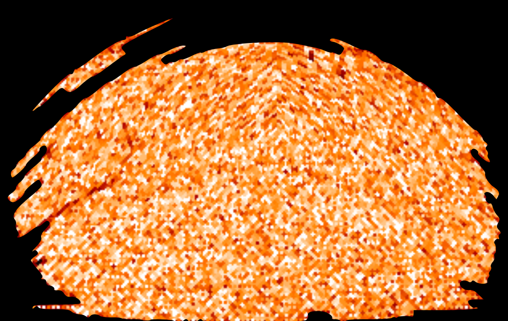
seeing



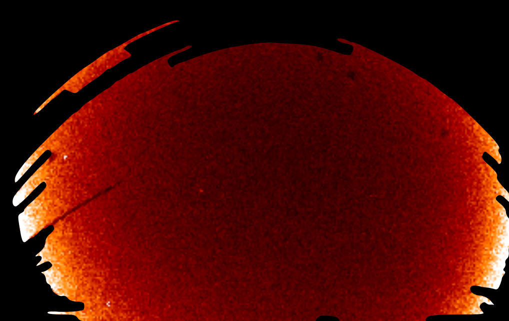
Systematics and mode projection

- Mode projection: marginalises over linear contamination models, using systematics templates $\vec{c}_k$

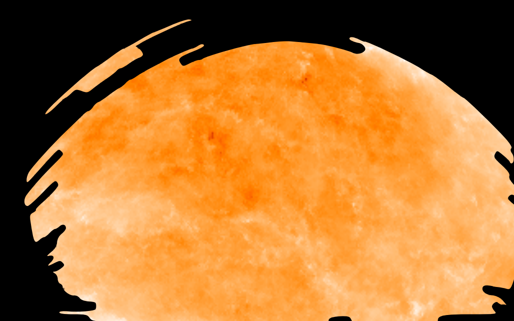
$$\mathbf{C} = \sum_{\ell} \mathcal{C}_\ell \mathbf{P}_\ell + \mathbf{N} + \sum_{k \in \mathrm{sys}} \xi_k \vec{c}_k \vec{c}_k^{\,t} \quad \text{with} \quad \xi_k \to \infty$$



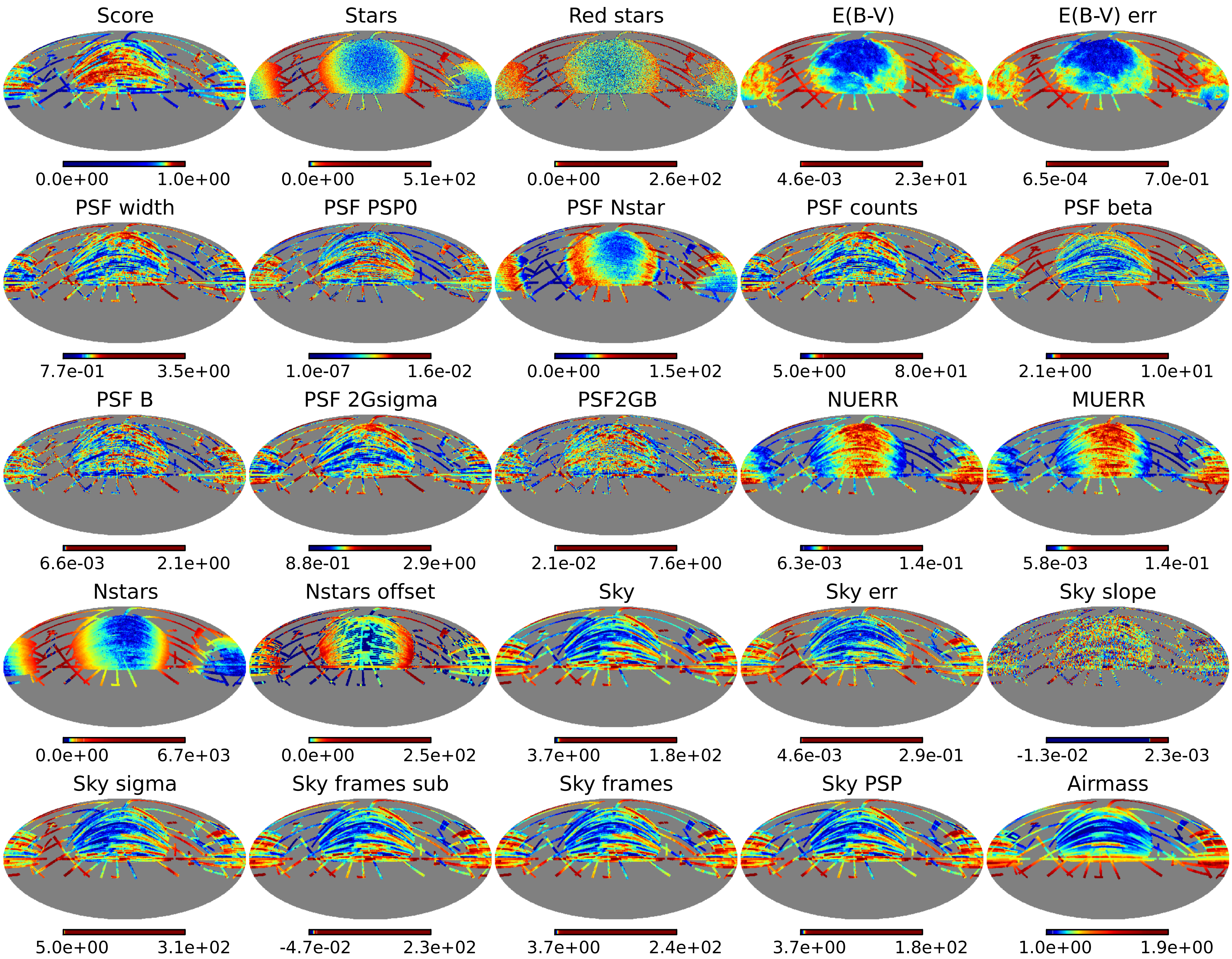
quasar catalogue



stars



dust extinction



Score
0.0e+00
1.0e+00
Stars
0.0e+00
5.1e+02
Red stars
0.0e+00
2.6e+02
E(B-V)
4.6e-03
2.3e+01
E(B-V) err
6.5e-04
7.0e-01
PSF width
7.7e-01
3.5e+00
PSF PSP0
1.0e-07
1.6e-02
PSF Nstar
0.0e+00
1.5e+02
PSF counts
5.0e+00
8.0e+01
PSF beta
2.1e+00
1.0e+01
PSF B
6.6e-03
2.1e+00
PSF 2Gsigma
8.8e-01
2.9e+00
PSF2GB
2.1e-02
7.6e+00
NUERR
6.3e-03
1.4e-01
MUERR
5.8e-03
1.4e-01
Nstars
0.0e+00
6.7e+03
Nstars offset
0.0e+00
2.5e+02
Sky
3.7e+00
1.8e+02
Sky err
4.6e-03
2.9e-01
Sky slope
-1.3e-02
2.3e-03
Sky sigma
5.0e+00
3.1e+02
Sky frames sub
-4.7e-02
2.3e+02
Sky frames
3.7e+00
2.4e+02
Sky PSP
3.7e+00
1.8e+02
Airmass
1.0e+00
1.9e+00

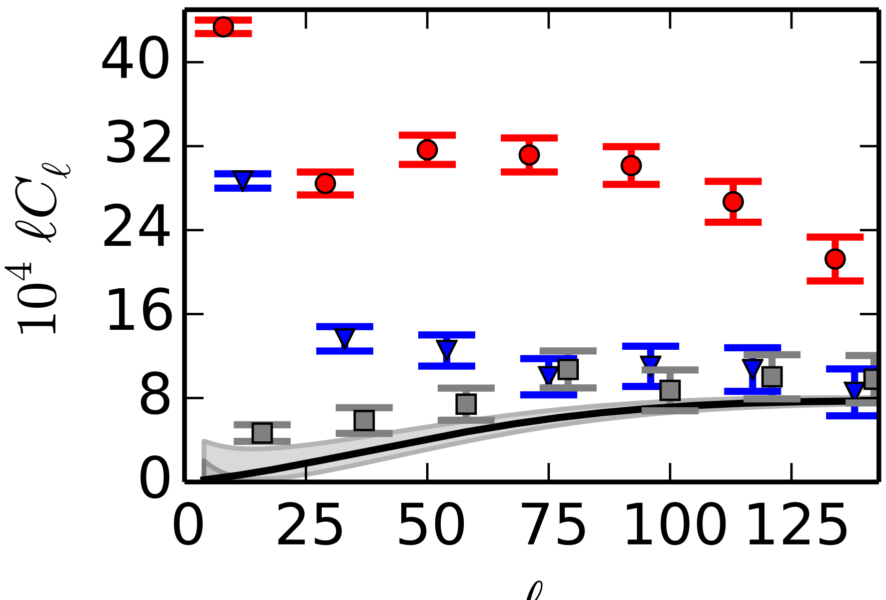
Extended mode projection

- Create set of input systematics
  220 templates + pairs ⇒ >20,000 templates
- Decorrelate systematics
  20,000 templates ⇒ 3,700 uncorrelated modes
- Ignore modes most correlated with data
  3,700 null tests; project out modes with red chi2>1

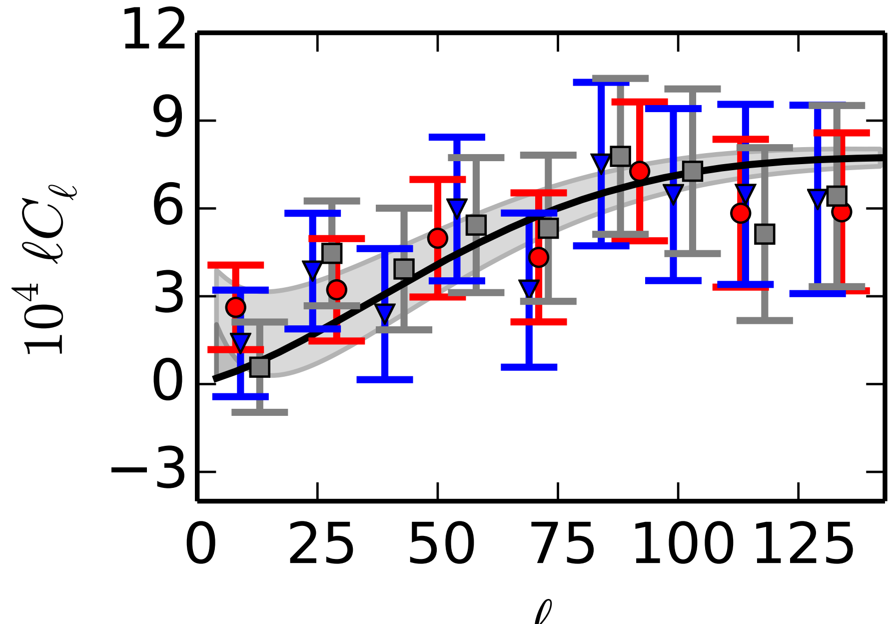
Sacrificing some signal in favour of robustness
⇒ **Blind mitigation of systematics**

Leistedt & Peiris+ (MNRAS 2013, 1404.6530), Leistedt, Peiris & Roth (Phys. Rev. Lett. 2014, 1405.4315)

Blind mitigation of systematics



Raw spectra

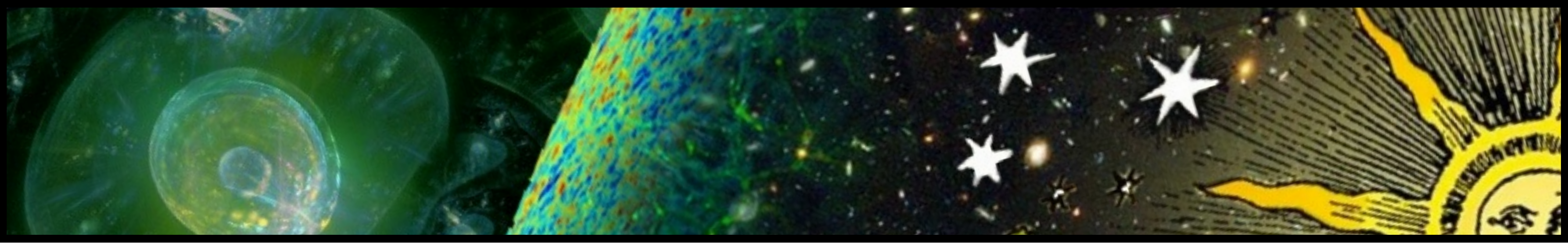


Clean spectra

- Example: one of 10 spectra (auto + cross in four z-bins) in likelihood

- Grey bands: -50 < f_{NL} < 50; colours: basic masking + m.p.

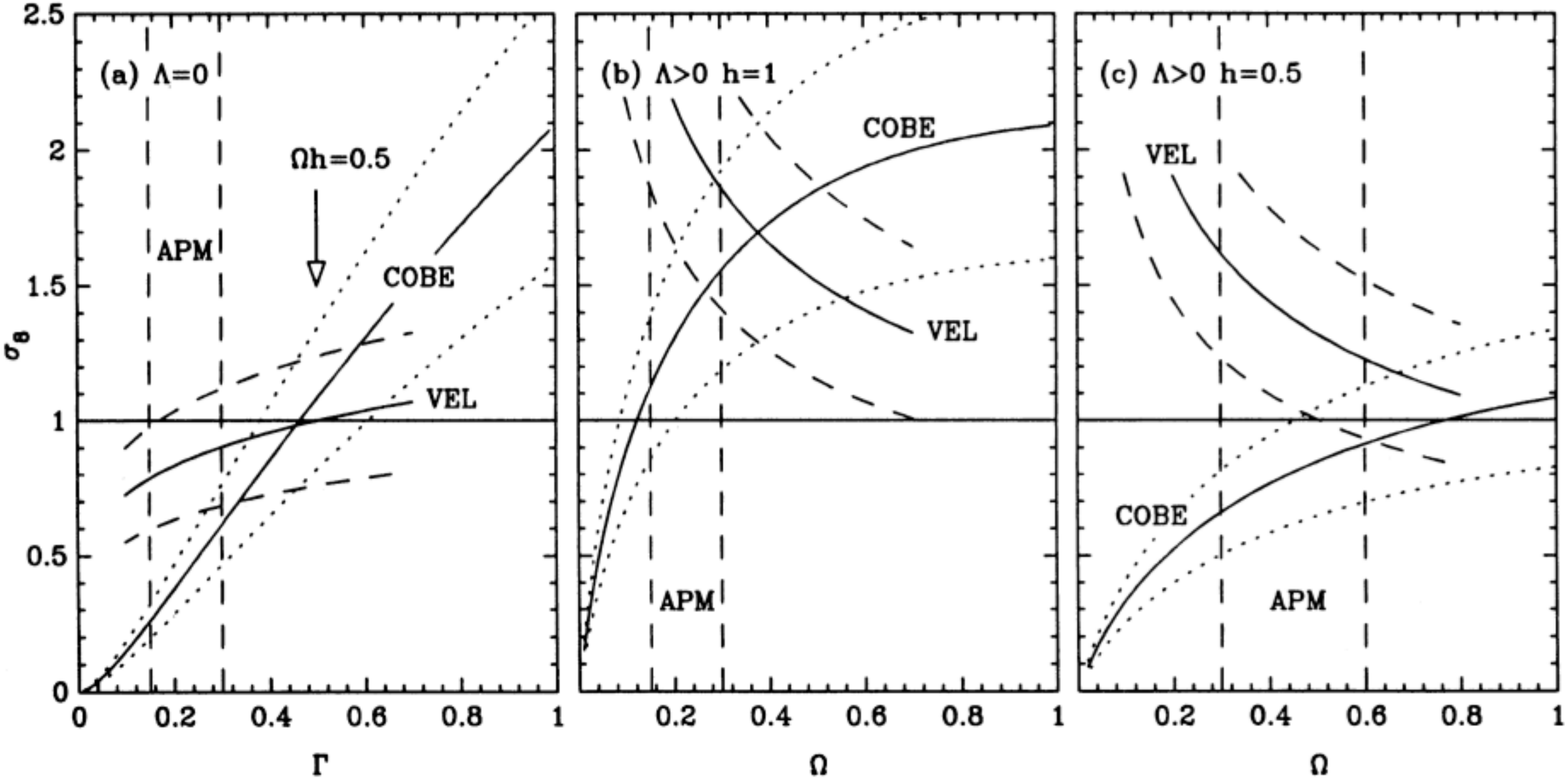
Leistedt & Peiris+ (MNRAS 2013, 1404.6530), Leistedt, Peiris & Roth (Phys. Rev. Lett. 2014, 1405.4315)



*Cosmological anomalies I find intriguing**

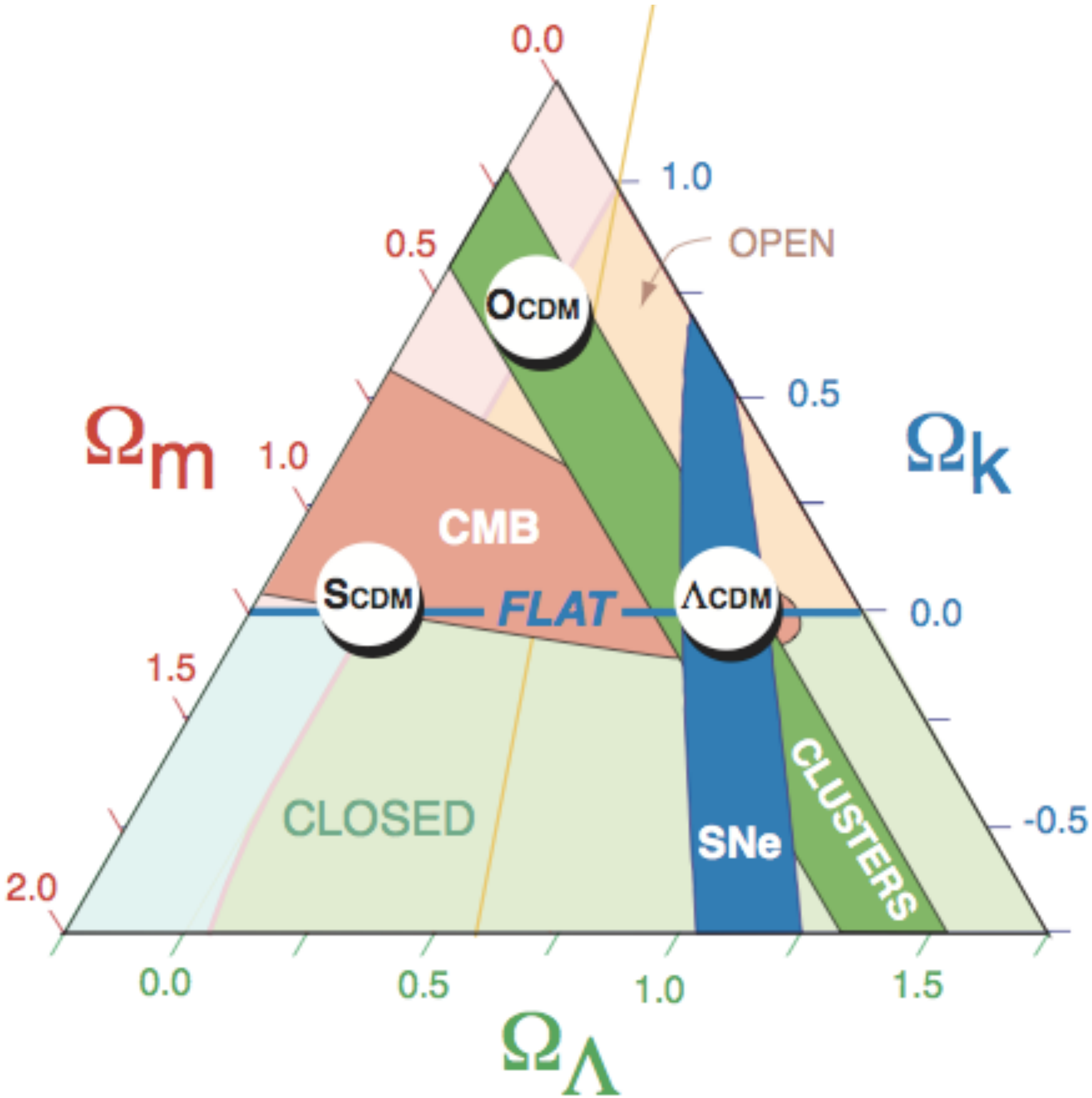
** incomplete; caveat emptor*

Adding parameters for concordance



Efstathiou, Bond, White (1992)

Adding parameters for concordance



Bahcall, Ostriker, Perlmutter, Steinhardt (1999)

Planck/BAO + tension with local H_0

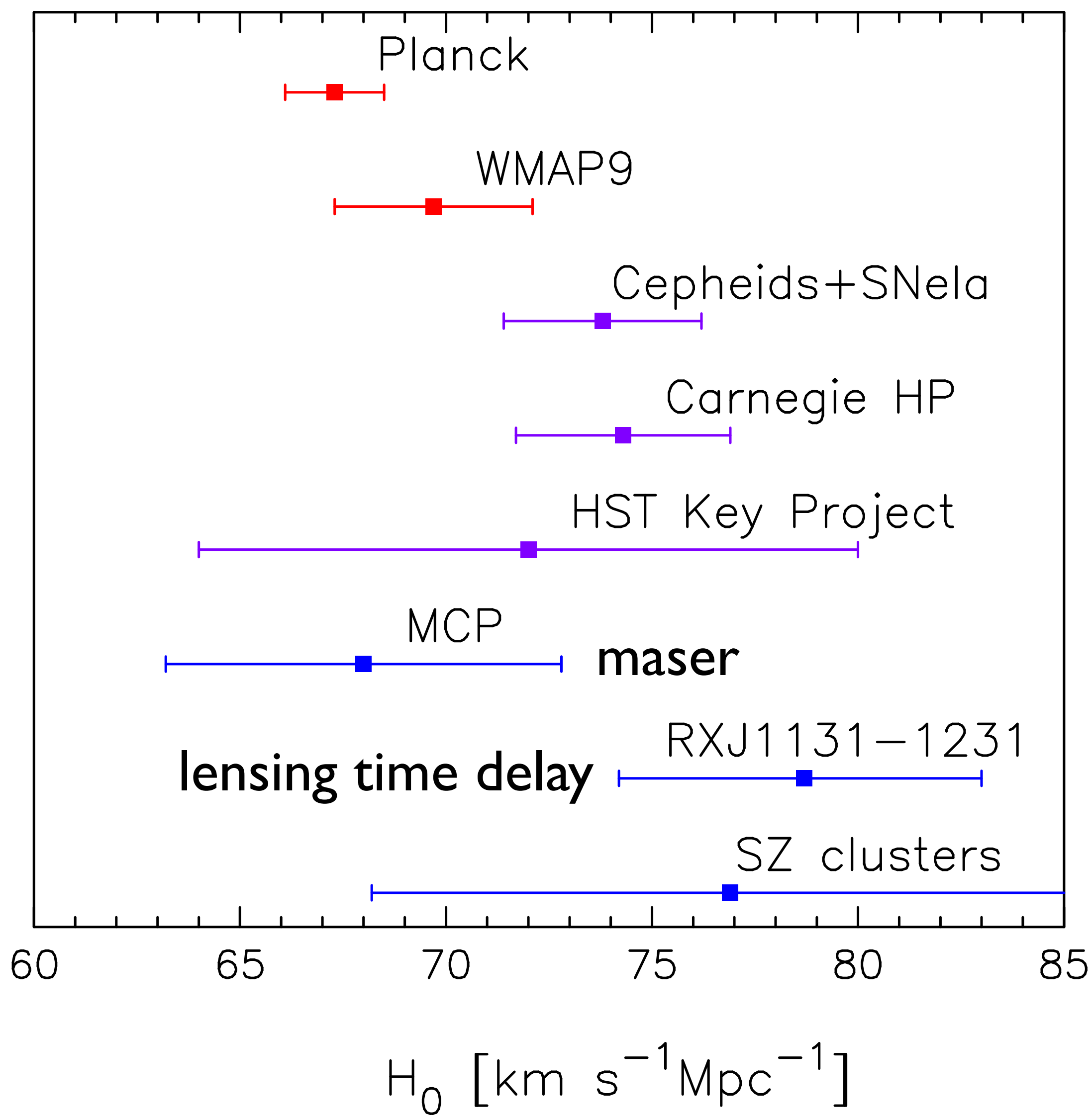
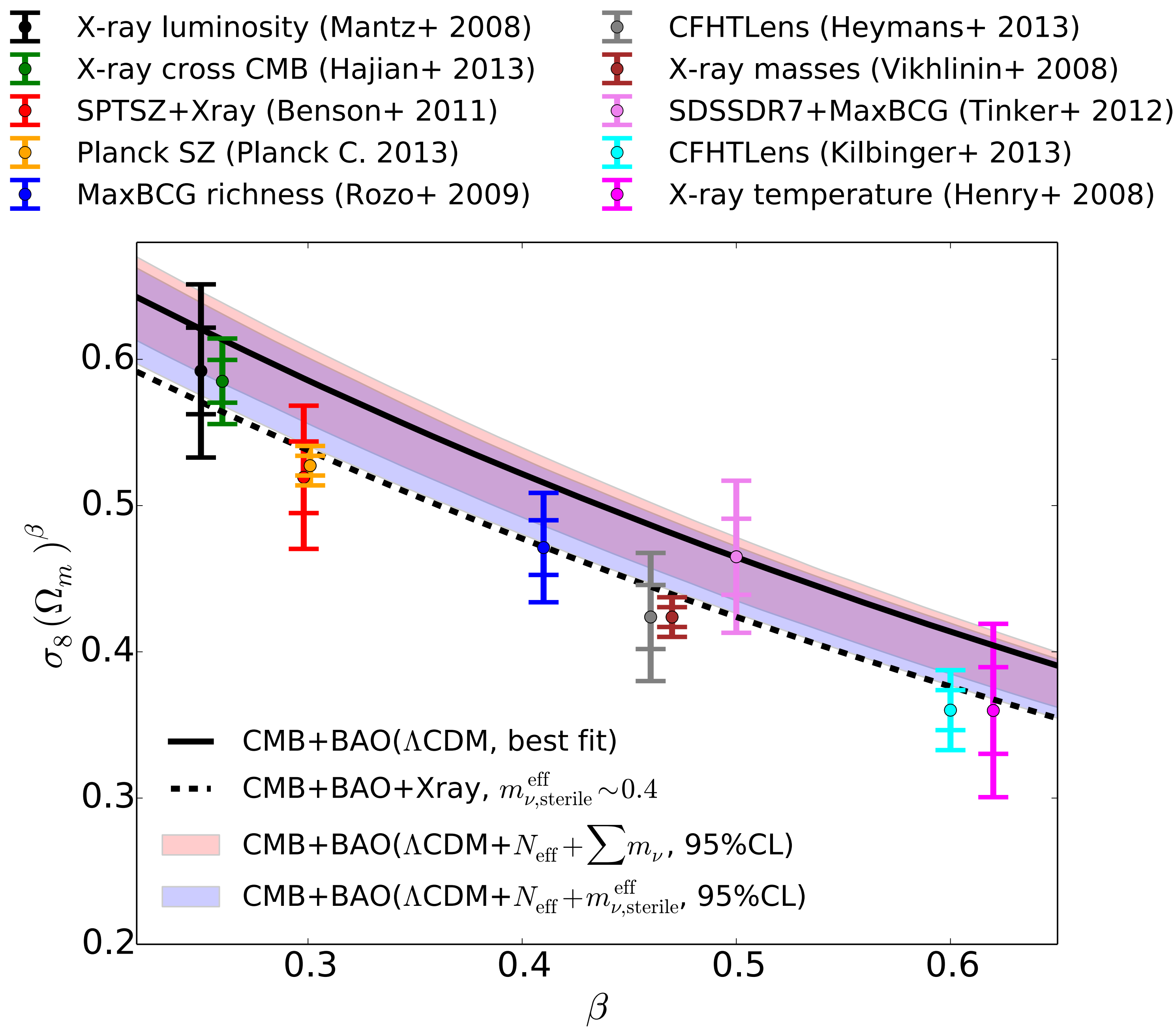


Figure: Planck XVI (2013)

Tension with local σ₈

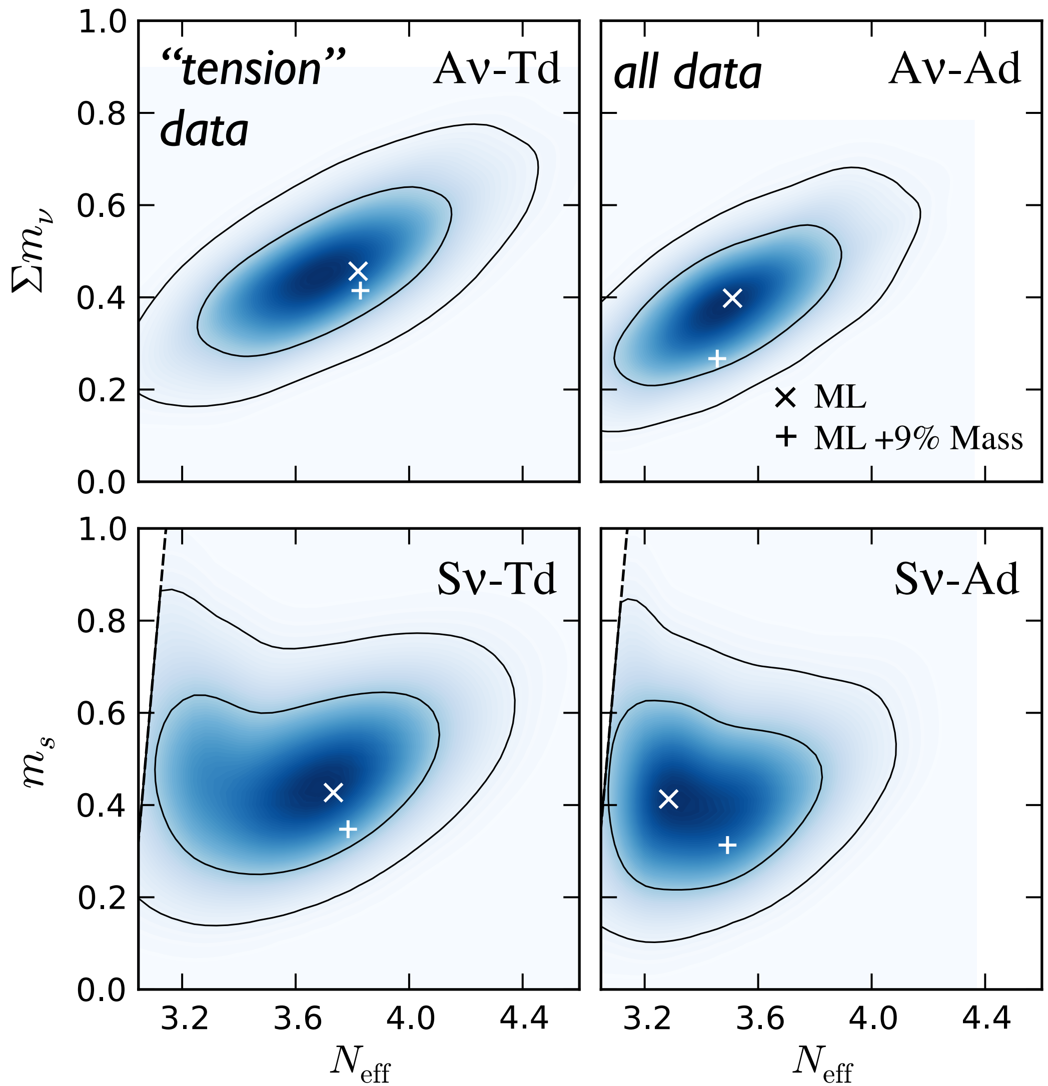


Leistedt, Peiris, Verde (Phys. Rev. Lett. 2014)

Massive sterile neutrinos?!

Recent papers prefer (~3σ) one extra sterile, massive neutrino

Wyman et al. (PRL, 2013), Hamann & Hasenkamp (JCAP, 2013), Battye & Moss (PRL, 2013)



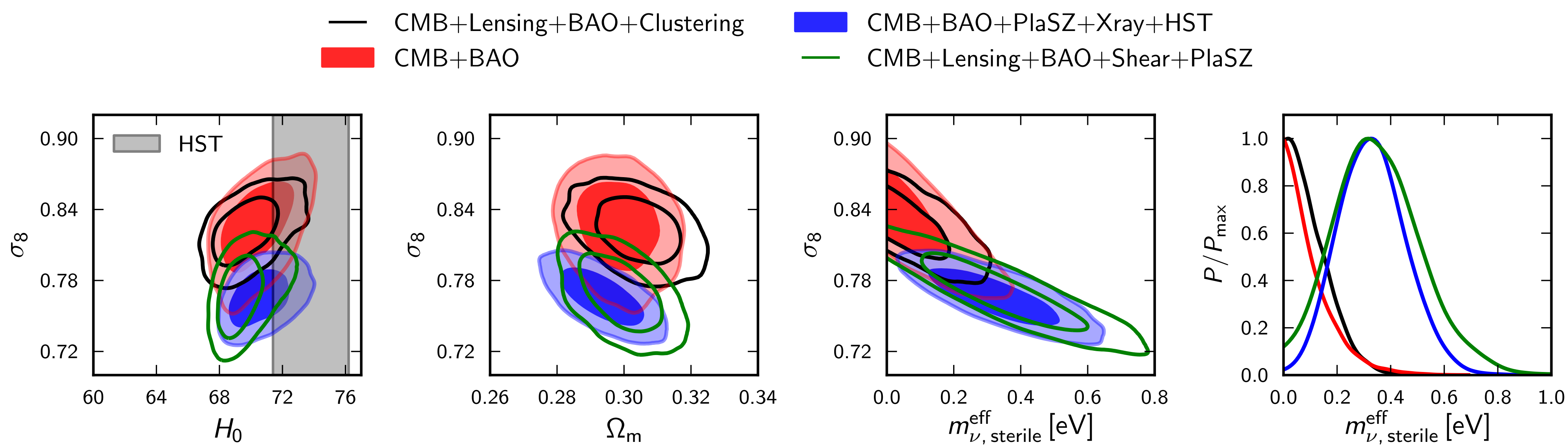
Datasets used (clusters, H_0, cosmic shear) in tension with *Planck*+BAO in ΛCDM.

HST H_0 high: wants high σ_8, low m_ν

Clusters σ_8 low: wants low H_0, high m_ν

Figure: Wyman et al (2013)

A new cosmic concordance?



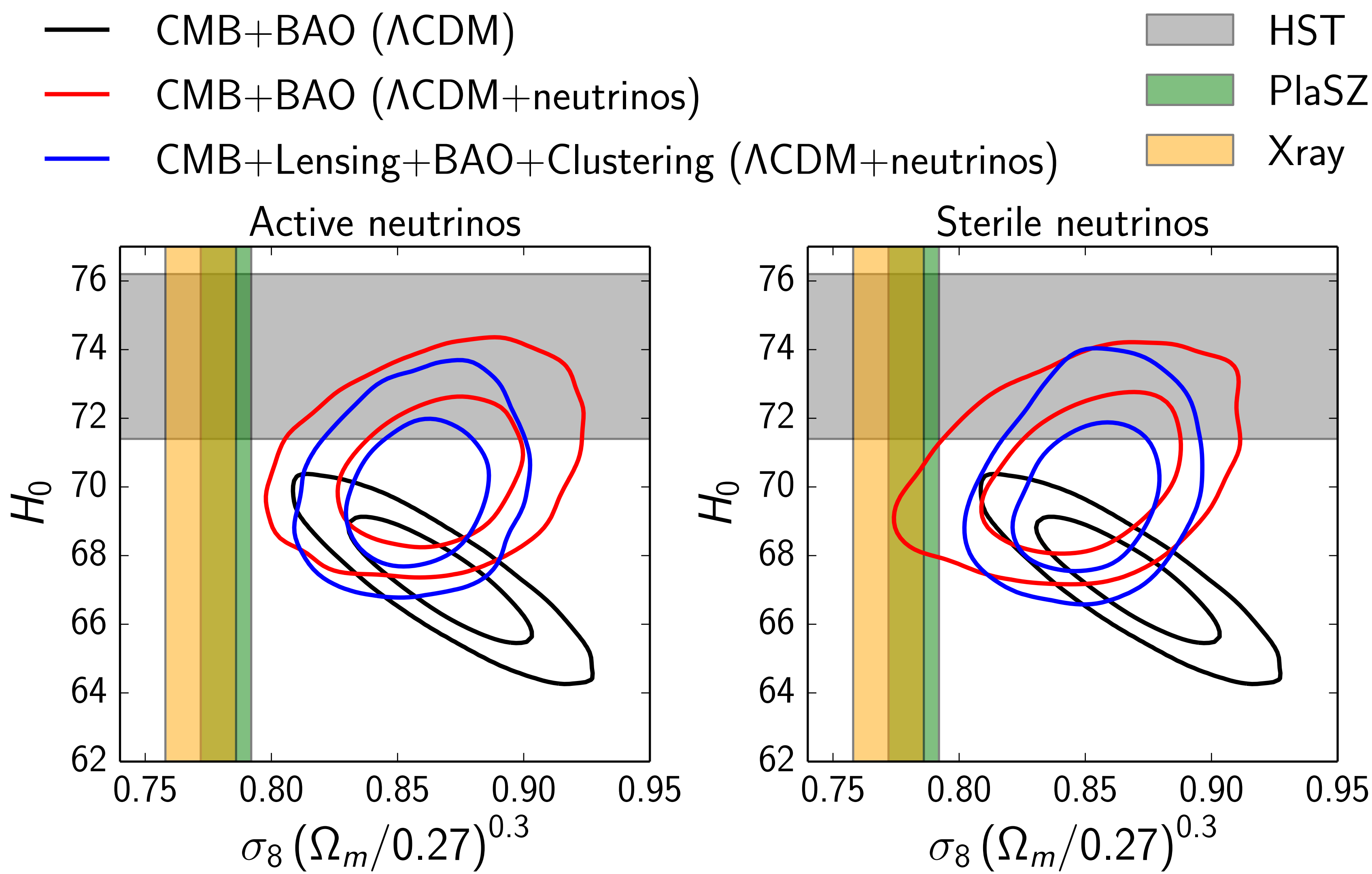
- Non-zero sterile neutrino mass favoured due to:

-tension between CMB and clusters (Planck SZ, X-ray) in σ_8–Ω_m plane

-degeneracy between σ_8 & neutrino mass.

Leistedt, Peiris, Verde (Phys Rev Lett 2014)

A new cosmic concordance?



Bayesian Evidence does not support massive sterile neutrino model even when combining conflicted datasets

Leistedt, Peiris, Verde (Phys. Rev. Lett. 2014)

Conclusions

- Assessing if inconsistencies with LCDM represent new physics requires overcoming pitfalls associated with **multiple testing** and **experimenter's subconscious bias**.

- Case studies illustrate practical strategies: just-so models; data-driven models; blind-analysis

- **Concordance in** combined probes critical; systematics are key.

Life under a "standard model": A balanced portfolio for progress

Standard cosmological model is phenomenological.
GR + broken time-translation invariance+ homogeneity + isotropy + initial conditions

Two paths to a paradigm shift

Nima Arkani-Hamed, quoting John Wheeler

Conservative Radicalism

Give up principles / model assumptions one-by-one and explore consequences. Must be done rigorously - beware epicycles.

Radical Conservatism

Take the model seriously and explore its predictions in hitherto untested regimes. Eventually it will break.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