Observing Cosmological Anisotropies with LSST

Large Synoptic Survey Telescope

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Dark Energy in 2 slides

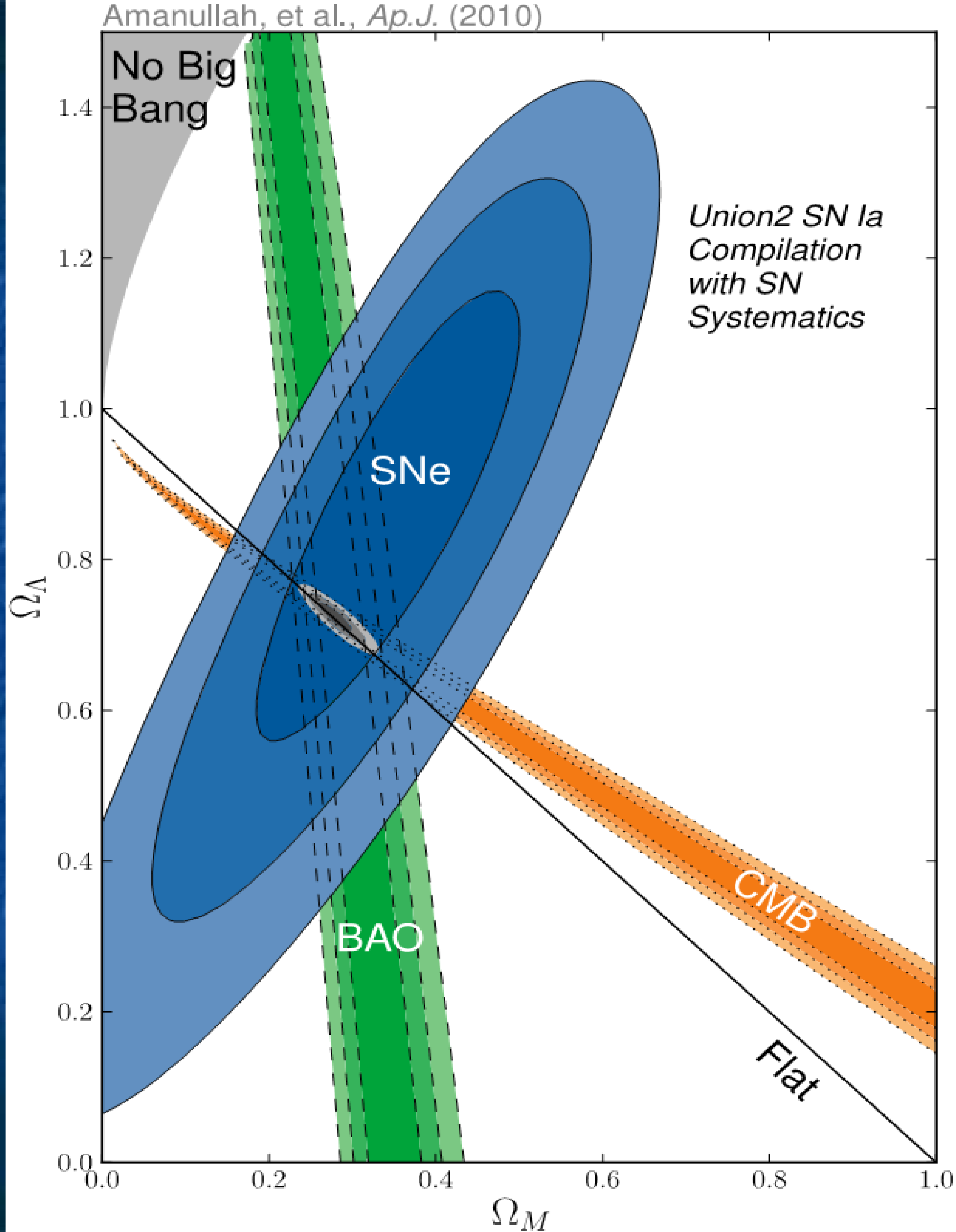
- Observational evidence for dark energy:
  - Cosmic Background Radiation (CMB) → *Nobel Prize 2006*
  - Supernovae → *Nobel Prize 2011*
  - Matter power spectrum in large scale structure
  - Age of the Universe > age of oldest stars
  - Baryon Acoustic Oscillations

- A flat universe with only standard model particles + dark matter cannot explain *any* of the above!

Dark Energy in 2 slides

$$\Omega_m + \Omega_\Lambda = 1 - \Omega_k$$

- N.B.: BAO → Baryon Acoustic Oscillations ↔ matter power spectrum



Homogeneity and Isotropy

- The most basic (and old) tenets of cosmology
- Friedmann (Lemaître) Robertson Walker (FRW) metric:
  - most general homogeneous and isotropic metric
  - overwhelmingly successful at describing the universe in large-scales
  - *Consistent* with all current observations

$$\mathrm{d}s^2 = -\mathrm{d}t^2 + \frac{a^2(t)}{1-kr^2}\mathrm{d}r^2 + a^2(t)\mathrm{d}\Omega^2$$

- Hard to probe directly → *lightcone* vs. *const. time* slices:
  - Possibility → more exotic models may also be *consistent* with data
    - e.g.: void models; anisotropic curvature models

Homogeneity?

- LTB metric (spher. symmetric, inhomogeneous) → Gpc Void models

$$\mathrm{d}s^2 = -\mathrm{d}t^2 + \frac{[R'(t,r)]^2}{1-k(r)}\mathrm{d}r^2 + R^2(t,r)\mathrm{d}\Omega^2$$

  - Surprinsingly successful as an accelerating model without Dark Energy;
  - Can fit all observations on the light cone SNe, BAO & CMB
  - But may fail for observations inside the light cone (kSZ, redshift drift & CMB blackbody spectrum)

Marra, Notari 1102.1015 (CQG) *Quartin, Amendola 0909.4954 (PRD)*

Zhang, Stebbins 1009.3967 (PRL) *Caldwell, Stebbins 0711.3459 (PRL)*

Isotropy?

- People usually consider 2 possibilities
  - Shear
  - Vorticity
- But there is a 3rd type of anisotropy: (spatial) curvature anisotropy
  - Basically: the 3-curvature can be different in different directions
  - There exists aniso. curv. models which are
    - Homogenous
    - Irrotational
    - Shear-free

Koivisto, Mota, Quartin, Zlosnik 1006.3321 (PRD)

- Are we taking supposed symmetries too seriously???

LRS Metrics

- We focus on this Locally Rotationally Symmetric (LRS) *axi-symmetric* and *homogeneous* class of metrics

$$\mathrm{d}s^2 = -\mathrm{d}t^2 + a^2(t)\,\mathrm{d}y^2 + b^2(t)\left[\mathrm{d}\xi^2 + \frac{1}{|k|}S^2(\sqrt{|k|}\xi)\mathrm{d}\phi^2\right]$$

$$S(x) \equiv \{sin(x), x, sinh(x)\} \;\; \text{for} \;\; \{k > 0, k = 0, k < 0\}$$

  - k > 0: Kantowski-Sachs metric (R^2 x S^2) *S^2: 2-sphere*
  - k = 0: Bianchi I metric (R^2 x R^2)
  - k < 0: Bianchi III metric (R^2 x H^2) *H^2: 2-hyperboloid*

LRS Metrics (2)

- These models exhibit a preferred direction
  - E.g.: k > 0 → (R^2 x S^2) → R (time) x (R x S^2)
- For simplicity, we assume $a(t) = b(t)$
  - No shear!
  - We can then write:

$$\mathrm{d}s^2 = -\mathrm{d}t^2 + a^2(t)\left[\mathrm{d}\chi^2 + \chi^2\mathrm{d}\theta^2 + \frac{1}{|k|}S^2\left(\sqrt{|k|}\,\chi sin\theta\right)\mathrm{d}\phi^2\right]$$

$$S(x) \equiv \{sin(x), x, sinh(x)\} \text{ for } \{k>0, k=0, k<0\}$$

The "SIGA" Condition

- ∃ anisotropic models with an isotropic expansion
  - Imperfect fluid

Mimoso & Crawford
CQG 10 (1993) 315

$$\pi_{ab} = 2E_{ab}$$

anisotropic stress

electric part of the Weyl tensor

- SIGA → SIG + A = Shearless Irrotational Geodesic (SIG) models with Anisotropy

Particular Examples

- There are "simple" models that achieve the SIGA cond.
  - a canonical 2-form B_{ab} (a Kalb–Ramond field)
  - a min-coupled, inhomogeneous massless scalar field
    - preliminary results → SIGA condition is stable

Koivisto, Mota, Quartin, Zlosnik
1006.3321 (PRD)

Carneiro & Mena Marúgan
gr-qc/0109039 (PRD)

- More interesting → phenomenology of anisotropic curv.
  - In general → not too much model dependent

Observational Effects
(*i.e.* "So what?")

- LRS metrics → spatial sections contain both flat and curved surfaces

- SIGA condition → isotropic expansion + aniso. curvature
  - $H(t)$, redshift z & comoving distances → isotropic
  - Angular diameter & luminosity dist. → anisotropic
  - N.B.: there are 2 types of angular diameter distances
    - 1-D: d_{1A} ≡ length / angle
    - 2-D: d_{2A} ≡ area / solid angle

d_{2A} is related to d_L by the Reciprocity Theorem

Angular diameter dist. d_{2A}

- d_{2A} ≡ area / solid angle

$$d_{2A}(\theta)^2 = \frac{a^2(t)\,\chi}{H_0\sqrt{2\,|\Omega_{k0}|}}\,\frac{S\left(H_0\sqrt{2\,|\Omega_{k0}|}\,\chi\, sin\theta\right)}{sin\theta}$$

- Compare with the FRW one:

$$\left[d_A^{\mathrm{FRW}}\right]^2 = \frac{a^2(t)}{{H_0}^2\,|\Omega_{k0}|}\,S^2\left(H_0\sqrt{|\Omega_{k0}|}\,\chi\right)$$

$$S(x) \equiv \{sin(x), x, sinh(x)\}$$

Observational Effects – Summary

- The CMB is isotropic at the background level
- CMB is therefore sensitive only to perturbations
  - Full perturb. equations recently derived in LRS metrics

    Tom Zlosnik 1107.0389

  - Correlations between $\ell \leftrightarrow \ell+2$ in the $a_{\ell m}$'s

    Graham, Harnik, Rajendran 1003.0236 (PRD)

- BAO: 2 kinds of BAO: radial & transversal
  - Radial → measure comoving dist. (isotropic)
  - Transversal → measure ang. diam. dist. (anisotropic)
- SNe, weak-lensing, and more???

Observational Effects – SNe

- The angular diameter distance has an angular dependence → so will SNe magnitudes!
- SNe data → Look for a preferred direction
- Currently: ~10^3 SNe measured
  - Near future: ~10^4 SNe → DESurvey + SN Factory + SN Legacy Survey + Pan-STARRS + PAU + J-PAS ...
  - Around 2020: ~10^5 SNe / year → **LSST alone**
    - Effective # depend on contamination / photo-z / etc.
- But... error bars are already dominated by **systematics**
  - Huge efforts needed to understand / control systematics!

Review of SNe: Howell, 1011.0441 (Nature Comm.)

SNe Systematics

Systematic	SNLS3[143]	CfA[27]/ESSENCE[44]	SDSS-II[26]	SCP[28]
Best fit w (assuming flatness)	...	-0.987	-0.96	-0.997
Statistical error	...	0.067	0.06	0.052
Total stat+systematic error	...	0.13	0.13	0.08
Systematic error breakdown				
Flux reference	0.053	0.02	0.02	0.042
Experiment zero points	0.01	0.04	0.030	0.037
Low-z photometry	0.02	0.005	...	...
Landolt bandpasses	0.01	...	0.008	...
Local flows	0.014	...	0.03	...
Experiment bandpasses	0.01	...	0.016	...
Malmquist bias model	0.01	0.02	...	0.026
Dust/Color-luminosity (β)	0.02	0.08	0.013	0.026
SN Ia Evolution	...	0.02	...	...
Restframe U band	...	...	0.104	0.010
Contamination	...	...	...	0.021
Galactic Extinction	...	...	0.022	0.012

Table 1: **Best-fit values of $\langle w \rangle$ and error estimates.** For the CfA3/ESSENCE colum

N.B. girl youngest ever to discover a supernova

BY TOBI COHEN, POSTMEDIA NEWS JANUARY 4, 2011 COMMENTS (16)

SN2010lt

STORY | PHOTOS (1) | VIDEO (1)

cope.

andout

Kathryn Aurora Gray is taking her new celebrity in stride after becoming the youngest person ever to discover a supernova.

The 10-year-old Fredericton girl's phone has been ringing off the hook

The 10-year old

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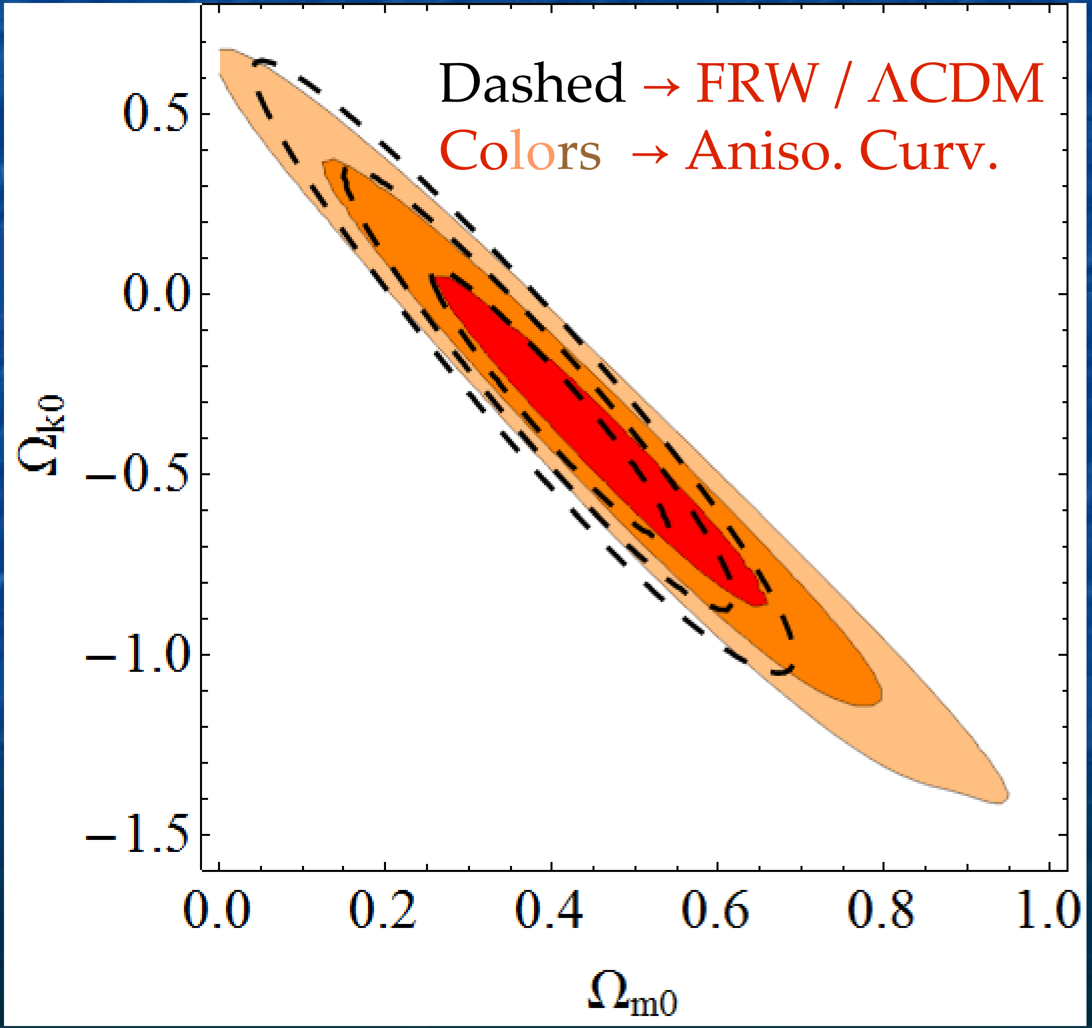
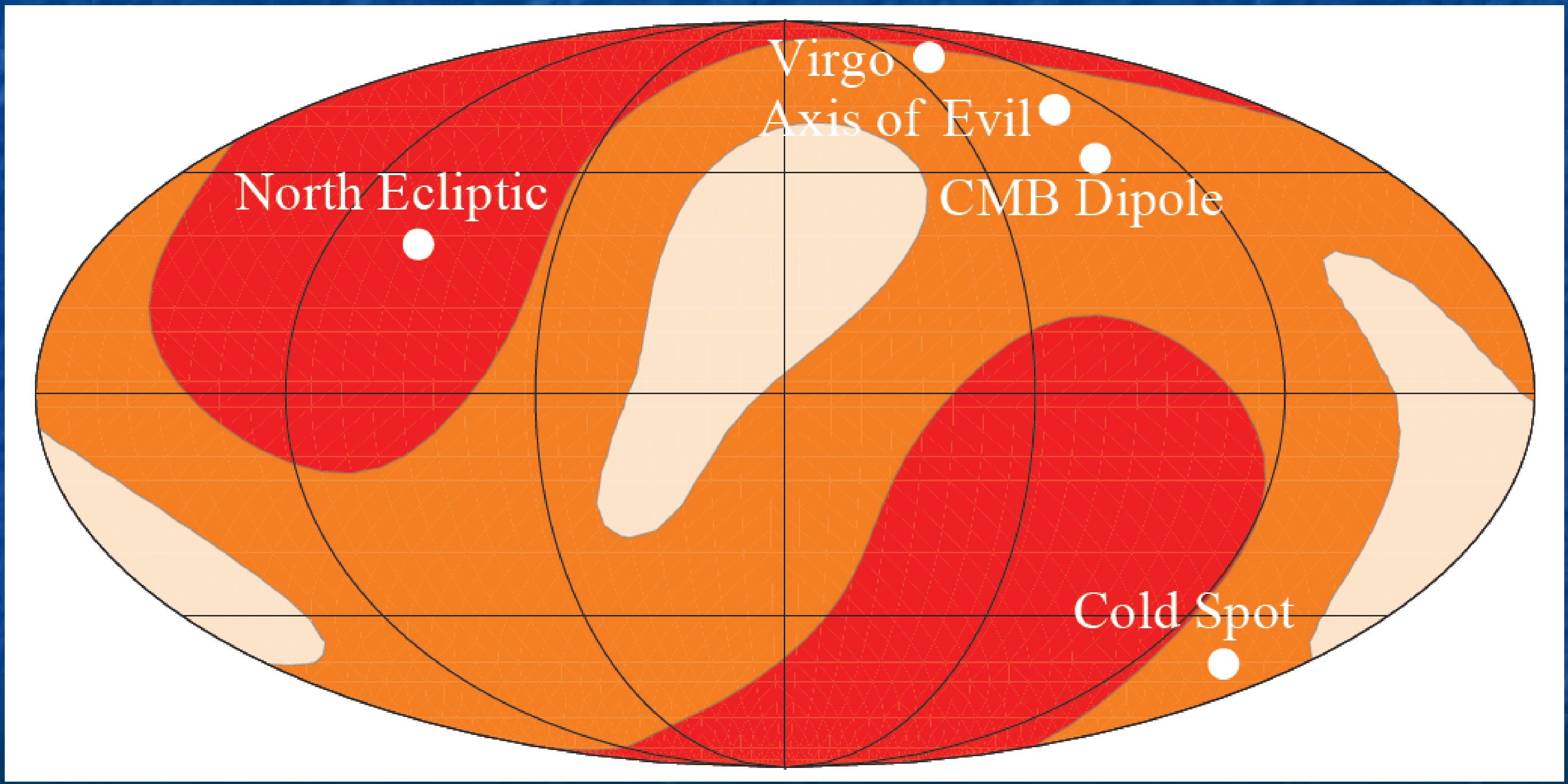
SNe Results ("SALT2")

- Results depend on fiducial metric!



SNe Results (2)

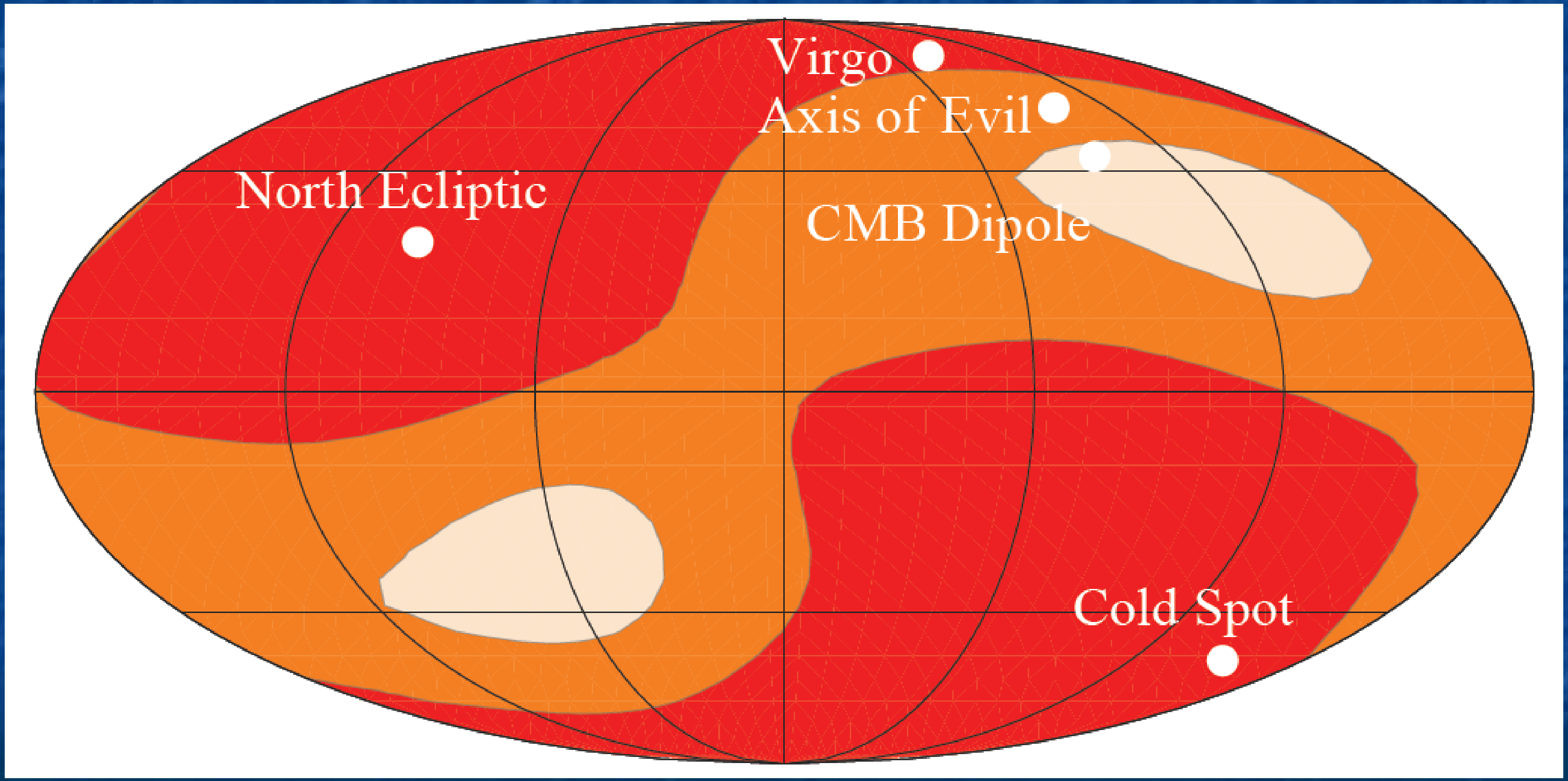
- Any preferred direction in the Union catalog? (300 SNe)



- Interpretation not straightforward!

SNe Results (3)

- Any preferred direction in the Union2 catalog? (500 SNe)



- Interpretation not straightforward!

SNe Forecasts

- We generated some SNe mock catalogs
- Two goals:
  - How many SNe are needed to detect a preferred direction
  - Better interpret current results

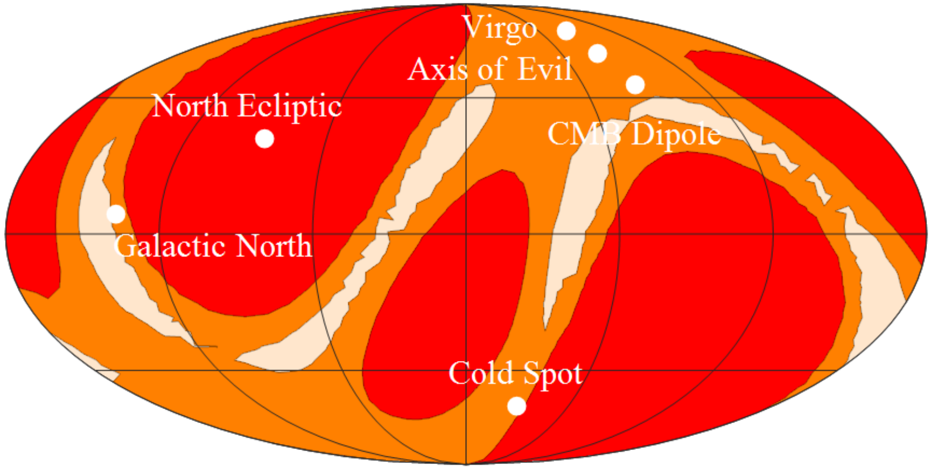
$$\mu_{\rm LRS} - \mu_{\rm FRW} \approx -0.4\, H_0^2\, \chi^2(z)\, \Omega_{k0}\, \cos^2\theta + \mathcal{O}({\Omega_{k0}}^2)$$

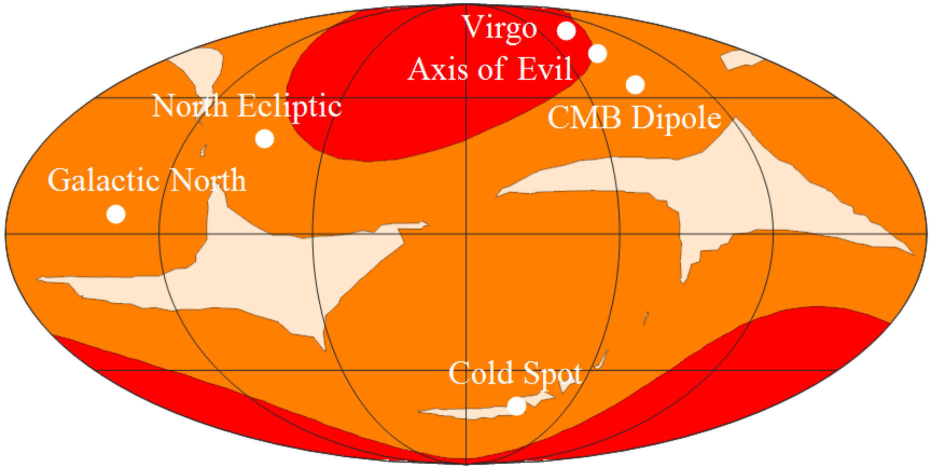
$$\frac{\rm Signal}{\rm Noise} \sim 0.6\, \Omega_{k0} \sqrt{N_{\rm SNe}}$$

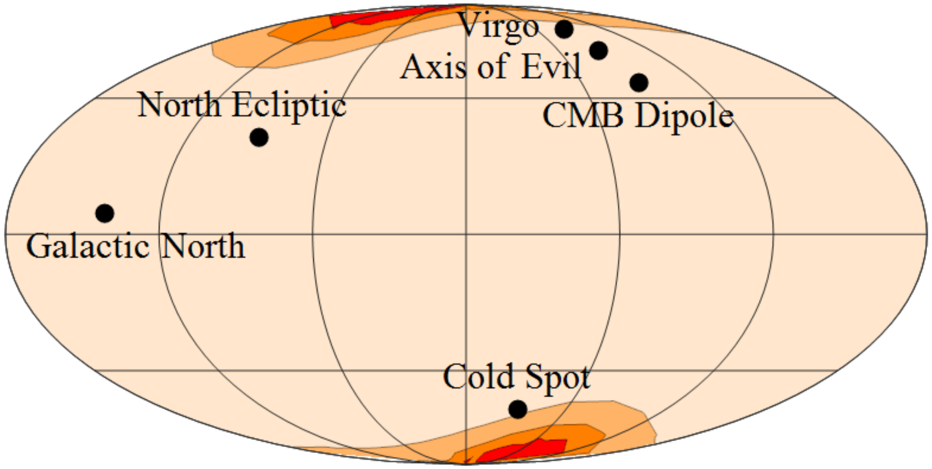
- S/N > 3 → $N_{\rm SNe} \gtrsim \frac{20}{{\Omega_{k0}}^2}$

SNe Forecasts

- Assumptions:
  - Only statistical errors considered
  - Fiducial $\Omega_{k0} = -0.1$
  - All-sky coverage
- Top: 1000 SNe
- Middle: 3000 SNe
- Bottom: 10000 SNe







Ongoing work

- Separate the observable effects of aniso. curv. & shear
- Study BAO → In principle very useful here:
  - But: need to re-derive BAO in LRS metrics
- CMB peak-positions anisotropy
- Weak-lensing → intrinsic ellipticity
- (maybe...) explore full perturbation equations

Nunes, Quartin, Zlosnik (in prep)

Precision Cosmology
vs.
Accurate Cosmology

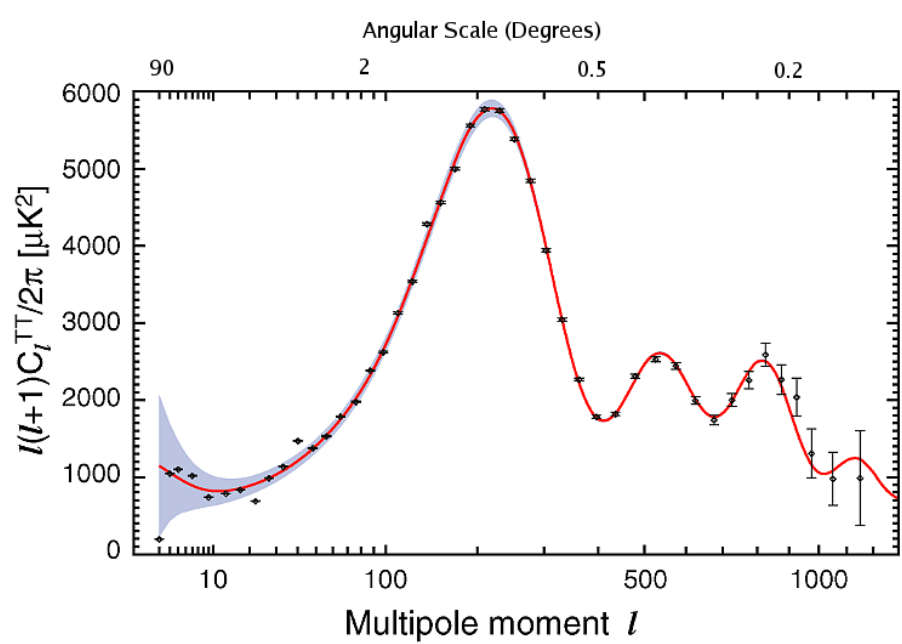
1%

The CMB Dipole

- CMB Temperature: $T_{\rm CMB} = 2.725\,K \left[1 + \frac{\Delta T(\theta,\phi)}{T}\right]$
- Spherical Harmonics decomposition:

$$\frac{\Delta T(\theta,\phi)}{T} = \sum_{\ell} \sum_{m=-\ell}^{\ell} a_{\ell m} Y_{\ell m}$$

- $\ell = 0 \rightarrow$ monopole
- $\ell = 1 \rightarrow$ dipole: $\sim 10^{-3}$
- $\ell = 2 \rightarrow$ quadrupole: $\sim 10^{-5}$
- $\ell > 2 \rightarrow$ all $\sim 10^{-5}$



The CMB Dipole (2)

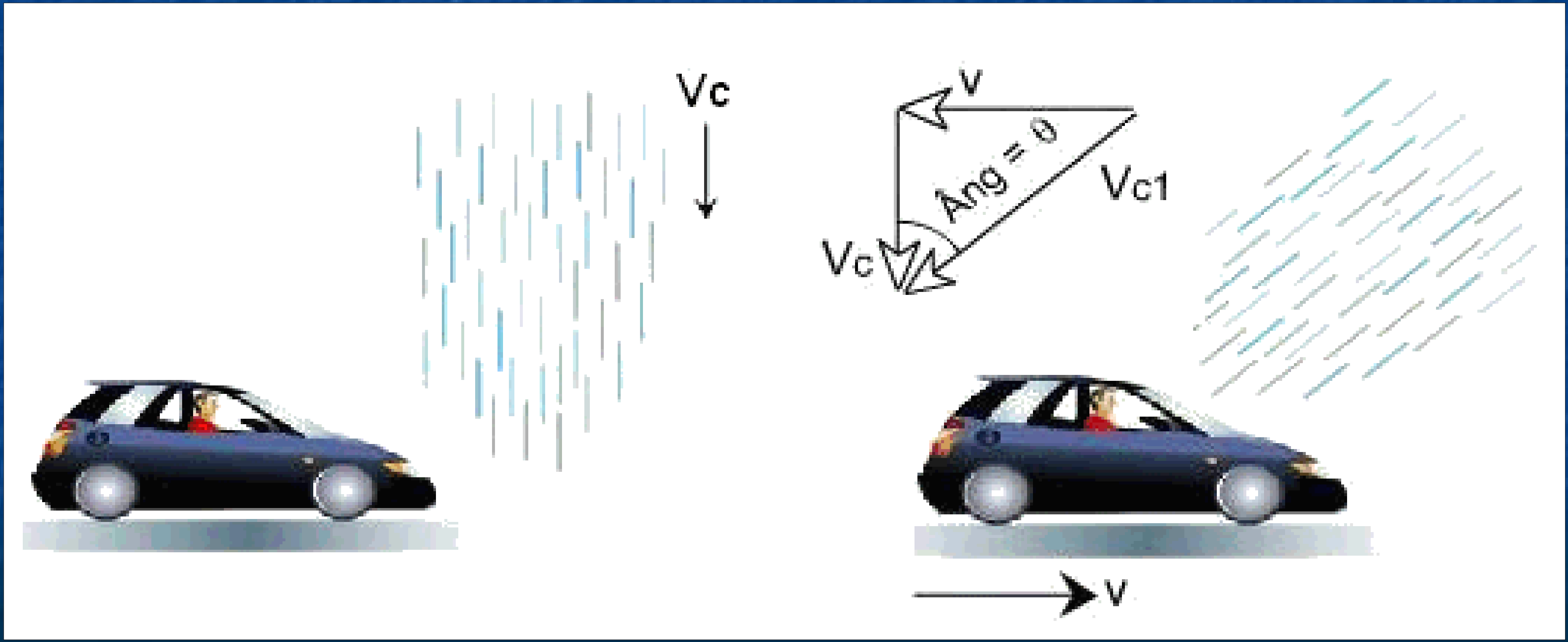
- The CMB dipole ~ 100 times larger than other multipoles
  - Reason: Doppler effect due to our peculiar motion
- CMB dipole → measurement of v_{CMB}
  - $v_{CMB} \approx 370$ km/s → $\beta \equiv v/c = 1.231\ 10^{-3}$
  - direction → $l = 263.99° \pm 0.14°$; $b = 48.26° \pm 0.03°$
- But there might be other contributions to the dipole:
  - Isocurvature CMB dipole; dipolar lensing; etc.
- How to tell these contributions apart?

Doppler & Aberration

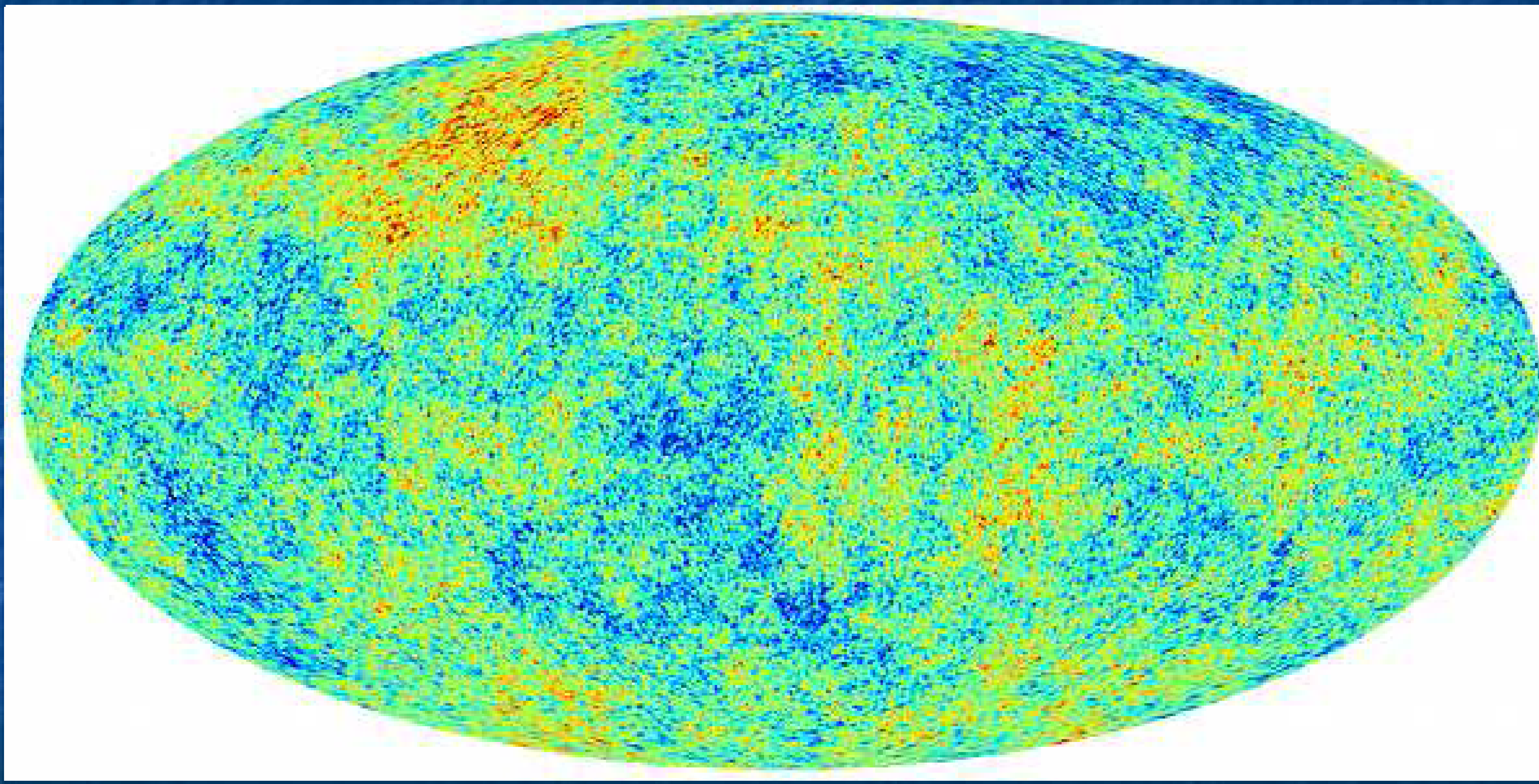
- The CMB dipole $\leftrightarrow$ Doppler effect
- But peculiar motion produces also aberration!

Doppler & Aberration

- But peculiar motion produces also aberration!
  - Aberration → $\ell \leftrightarrow \ell+1$ correlations in the $a_{\ell m}$'s



Doppler & Aberration



$\beta = 0$ $\beta = 0.5$ $\beta = 0.9$

Results: S/N

Notari, Quartin 1112.1400 (JCAP)

Experiment	$f_{\rm sky}$	S/N
WMAP (9 years)	78%	**0.7**
EBEX	1%	**0.9**
Planck (2.5 years)	80%	**5.9**
SPT SZ	6%	**2.0**
SPTPol (3 years)	1.6%	**2.5**
ACTPol (1 year)	10%	**4.4**
ACTPol + (4 years)	40%	**8.8**
COrE (4 years)	80%	**14**
EPIC 4K	80%	**16**
EPIC 30K	80%	**13**
Ideal ($\ell \leq 6000$)	100%	**44**

The SNe Dipole

- CMB dipole → SNe dipole

$$\mu(\theta) - \langle\mu\rangle \approx \frac{5}{\log[10]}\beta \cos\theta \left[1 + \frac{c(1+z)}{\chi(z)H(z)}\right]$$

  - LSST: $z_{SNe} \in [0.1, 0.8]$ → $\mu(\theta) - \langle\mu\rangle \sim 10^{-2}\cos\theta$

$$\frac{\text{Signal}}{\text{Noise}} \sim 5 \times 10^{-2}\sqrt{N_{\text{SNe}}} \approx \begin{cases} 13, \ 10^5\,\text{SNe} \\ 40, \ 10^6\,\text{SNe} \end{cases}$$

Conclusions

- LSST SNe can:
  - Detect anisotropic curvature (SNe only)
    - Unless $|\Omega_{k0}| \ll 0.01$

$$N_{\rm SNe} \gtrsim \frac{20}{{\Omega_{k0}}^2}$$

  - Detect our peculiar velocity
    - SNe → S/N ~ 13 – 40
    - CMB → S/N ~ 6 – 14 (but different z)
    - We can finally measure the intrinsic dipole!
- LSST BAO can also be used to measure anisotropies

More Conclusions

- LSST weak lensing → can also be used → *to do list*
- LSST → anisotropy constraints competitive & complementary with CMB (peak pos. & correlations)
- Inhomogeneity & Anisotropy must be better constrained
  - We want cosmology with both precision & accuracy
  - FLRW less symmetric than static universe
    - Are we taking supposed symmetries too seriously???

Bom Apetite!

Large Synoptic Survey Telescope

Large Synoptic Survey Telescope

CMB Correlations as a Tool

- Statistical isotropy of the CMB is broken for:
  - Anisotropic models produce analogous correlations in the CMB. For example:
    - A preferred direction
    - A preferred "orientation" (an arrow)
  - Models with non gaussianity
- Similar estimators can be built to test these models

Observational Effects – CMB

- The CMB is isotropic at the background level
- CMB is therefore sensitive only to perturbations
  - Full perturb. equations recently derived in LRS metrics

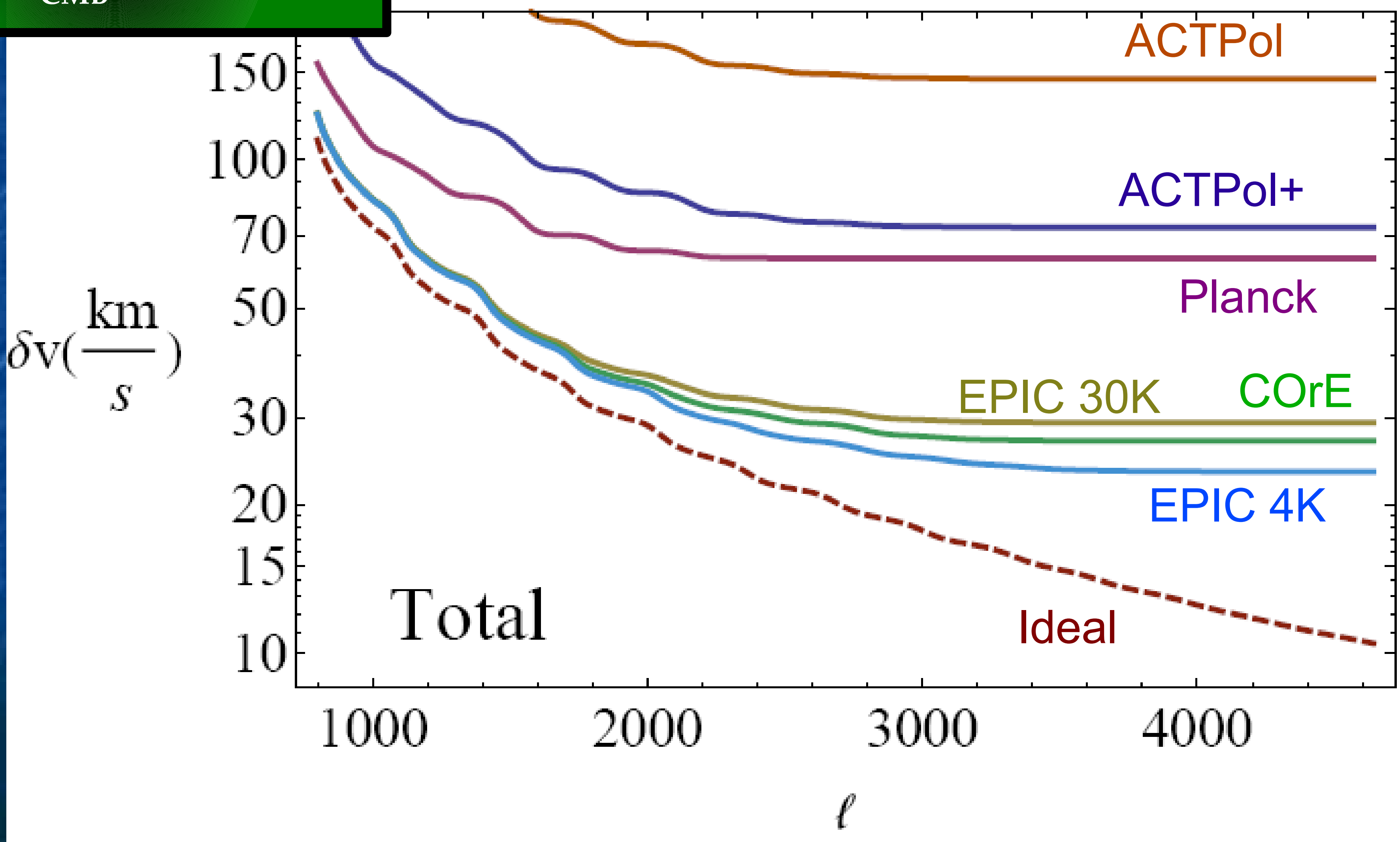
    Tom Zlosnik 1107.0389

  - FRW → harmonic decomposition associated with a 3+1 split of spacetime
    - Scalars, Vectors and Tensors → independent
  - LRS → standard 3+1 leads to mode mixing
    - Better → 2+2 split: $M = R^2 \times S^2$ or $M = R^2 \times H^2$
    - Different modes (polar & axial) but no mixing

Notari, Quartin (1112.1400)

Results: Measuring β

$v_{CMB} \approx 370$ km/s



A Particular Example

- Consider a canonical 2-form B_{ab} (a Kalb–Ramond field) such that

$$S_B = \alpha \int J_{abc} J^{abc} \sqrt{-g}\, d^4x$$

$$J_{abc} \equiv 3! \nabla_{[a} B_{bc]}$$

- We also make the ansatz (only 1 deg. of freedom):

$$J_{abc} = f(t) \epsilon_{adbc} V^d$$

preferred direction

A Particular Example (2)

- We have an imperfect fluid:

$$T_{ab}^{B} = \rho_B U_a U_b + P_B h_{ab} + L_B V_a V_b$$

- The SIGA condition [*a(t) = b(t)*] is written as:

$$\frac{k}{a^2} = -\alpha J_{abc} J^{abc} = 6\,\alpha\,\frac{C^2}{a^2}$$

lagrangian parameter

const. of integration

$a_{\ell m}$ Correlations

Aberration → $a_{\ell m}$ correlations between different ℓ's

$$a_{\ell m}^{X\,[\mathrm{Aberrated}]} = \sum_{\ell'=0}^{\infty} K_{\ell'\,\ell\,m}^{X}\, a_{\ell' m}^{X\,[\mathrm{Primordial}]}$$

$$K_{\ell'\,\ell\,m}^{T} = \int_{-1}^{1} \frac{\mathrm{d}x}{\gamma\,(1-\beta x)}\, \tilde{P}_{\ell'}^{m}(x)\, \tilde{P}_{\ell}^{m}\left(\frac{x-\beta}{1-\beta x}\right)$$

- For E and B polarization the integrals are similar
- These integrals present a numerical challenge!

Chluba 1102.3415 (MNRAS) *Notari, Quartin (1112.1400)*

$a_{\ell m}$ Correlations (2)

- Previous solution for computing $K_{\ell' \ell m}$ → Taylor expansion in β → becomes effectively exp. in $\beta\ell$
  - $a_{\ell m}$ correlations between ℓ and $\ell+n$ are $\mathcal{O}(\beta\ell)^n$
  - Expansion breaks down for $\ell > \sim 800$!

Kosowski & Kahniashvili 1007.4539 (PRL)

Amendola, Catena, Masina, Notari, Quartin, Quercellini 1008.1183 (JCAP)

- We propose 2 better solutions:
  - Very accurate fitting functions for $K_{\ell' \ell m}$
  - An altogether new approach: *pre-deboost* the CMB

Notari, Quartin (1112.1400)

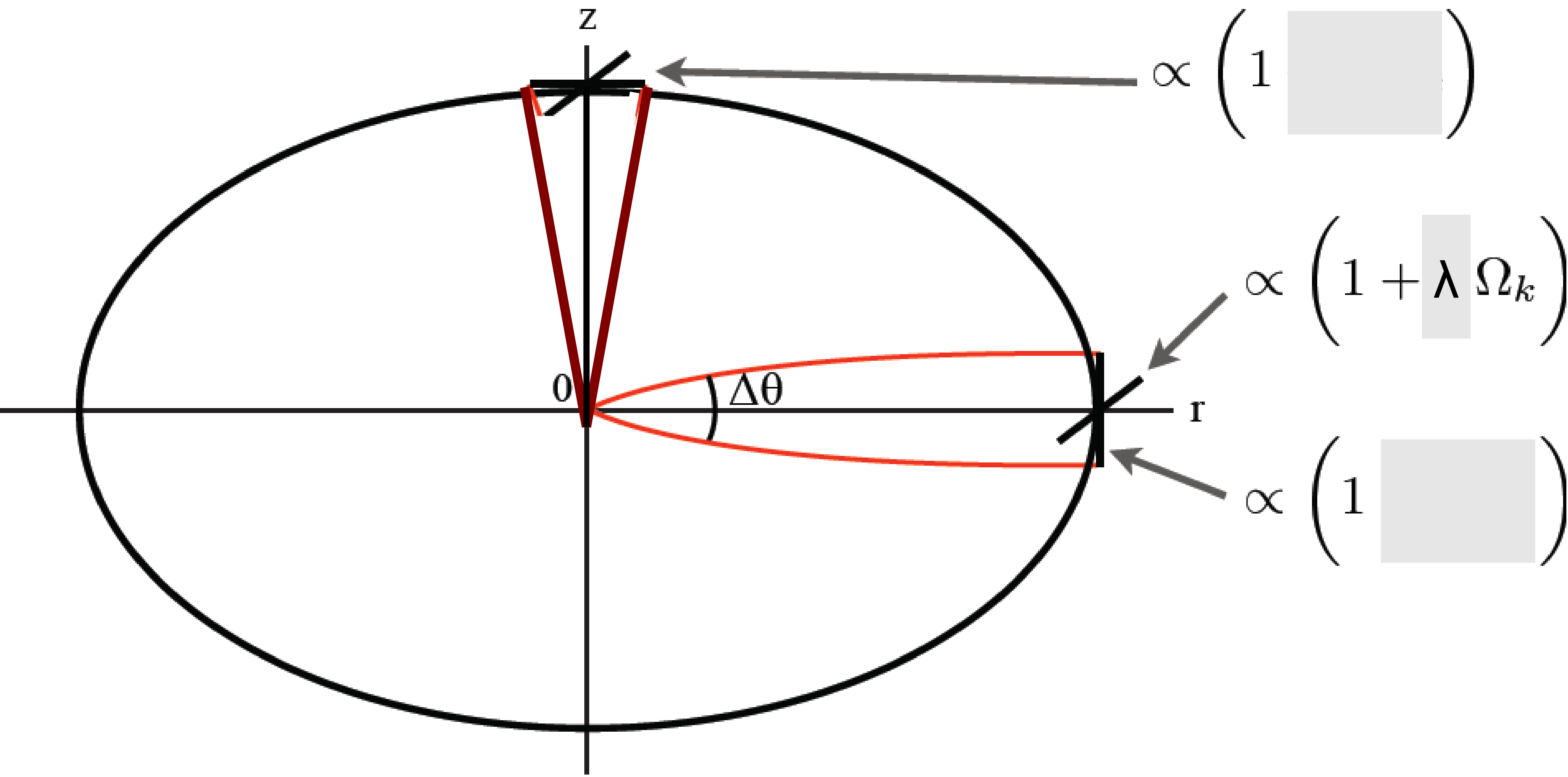
Measuring β

- These predicted correlations
  - Do not affect the angular power spectrum (the C_ℓ's)
  - Break statistical isotropy of the CMB

$$\langle a_{\ell m}\, a_{\ell' m'} \rangle \neq C_\ell\, \delta_{\ell\ell'}\, \delta_{mm'}$$

- We can build an estimator for β
  - Since all ℓ's are affected: more ℓ measured → better S/N
  - Measuring **EE**, **ET**, **TE** and **BB** power spectra → better S/N
  - Better S/N ↔ more accurate measurement of β
  - Planck (30 months): $\ell^T_{max} \sim 2500$; $\ell^{E,B}_{max} \sim 1700$

Geodesics in LRS metrics



Graham, Harnik, Rajendran
1003.0236 (PRD)