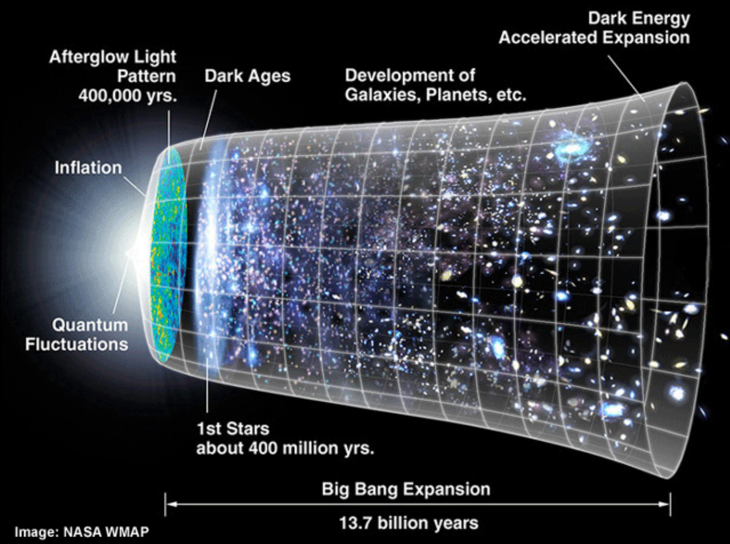
Observational Constraints on Pre-Inflationary Relics

Based on:
AF, Itzhaki, Kovetz (JCAP 2010)
Rathaus, **AF**, Itzhaki (JCAP 2011)



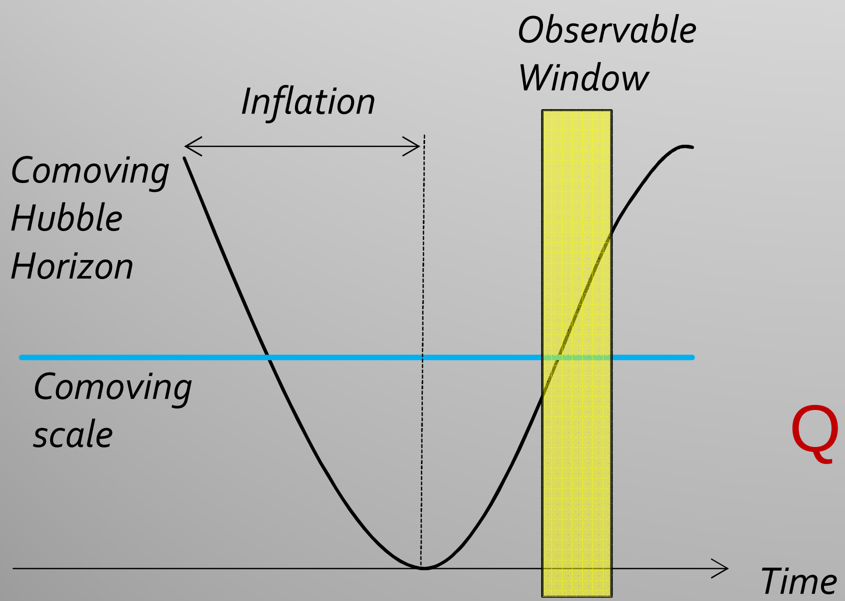
Credit: WMAP team

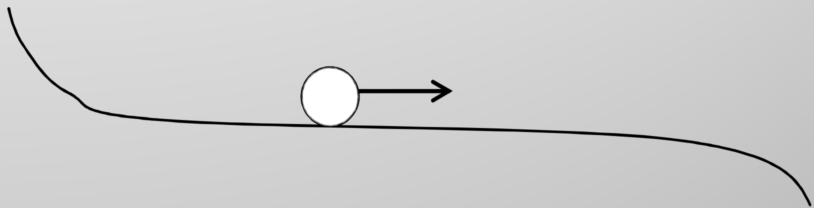
Anastasia Fialkov
Tel Aviv University
MPIK 29.10.2012

The Standard Picture of Inflation

- Inflation is a period of ~ exponential expansion.
- Simplest model:

scalar field (inflaton, ϕ) slowly rolls down a ~ flat potential





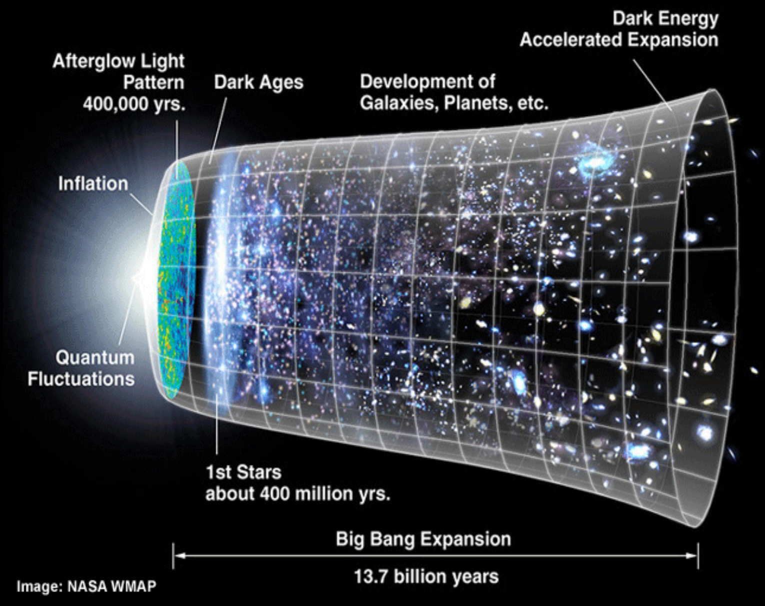
Initial Conditions
for structure formation:
Quantum fluctuations $\rightarrow$ classical

Standard Picture of Structure Formation

Image: Loeb, Scientific American 2006

Inflation
CMB
Structure Formation

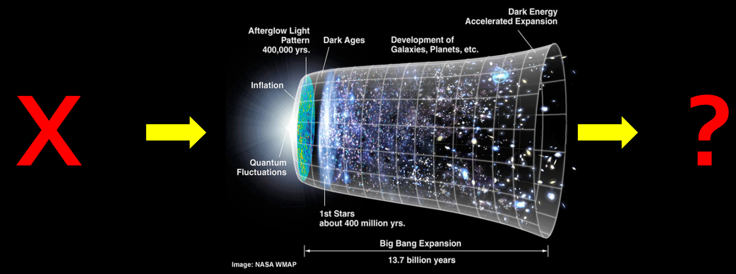
The Standard Picture of Inflation + a Pre - Inflationary Relic

X →  → ?

Relics: massive particle, domain wall, string etc.

What is the impact on the observable universe?

Motivation



Credit: WMAP team

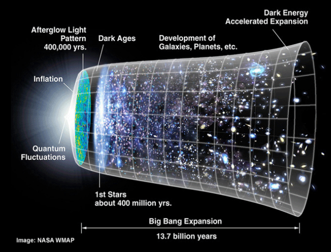
1) Particle production (thermally) before and during inflation

2) From string theory: particles, domain walls, strings

3) Cosmic anomalies

Can one of these expected relics explain (some of) the observed anomalies?

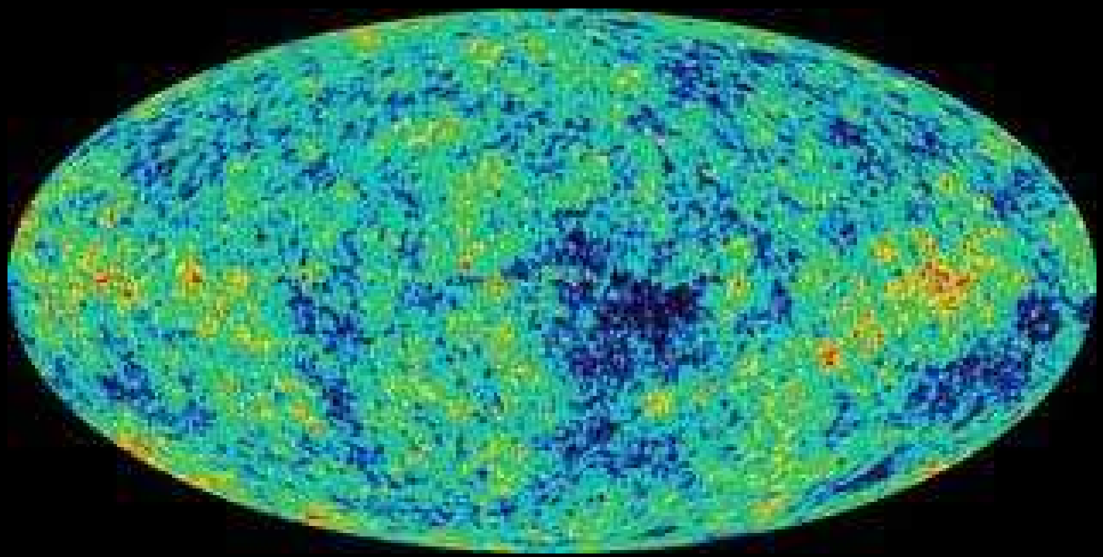
Outline

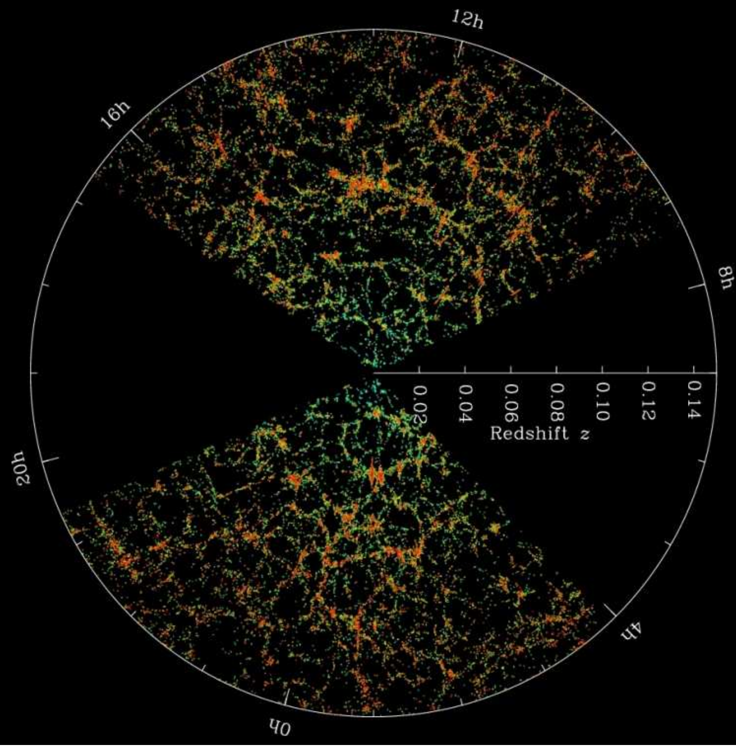
X →  → ?

- Review of relevant cosmic anomalies
- Intro: pre-inflationary point particle (PIP)
- Cosmological signature of PIP. Can we explain the anomalies?

Part I: Anomalies (In Cosmology > 2σ)
Ongoing Debate!

WMAP team

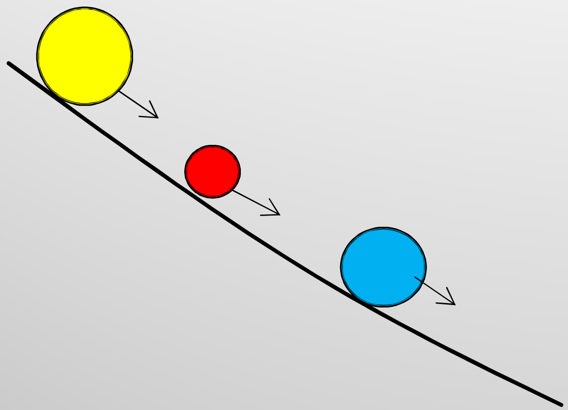


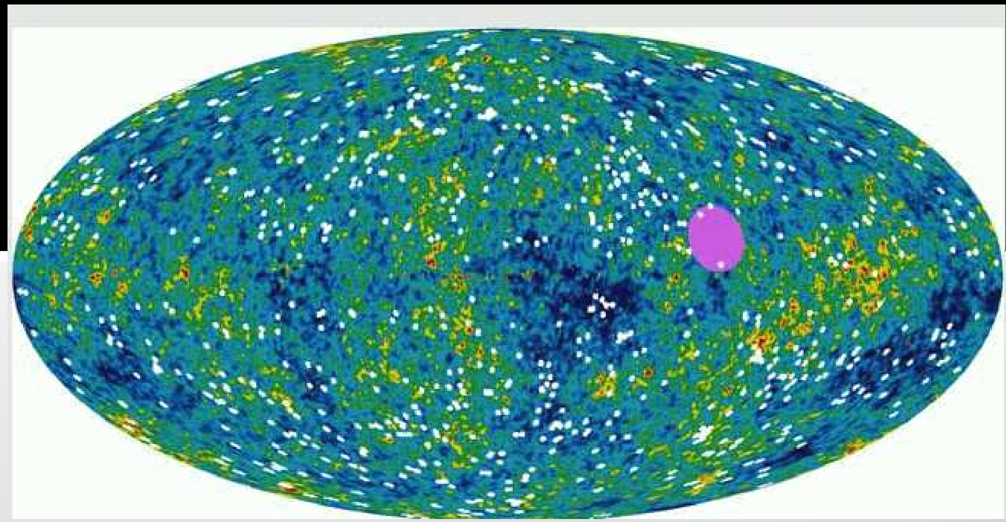


SDSS webpage

- In large scale structure
- In the CMB

The Bulk Flow





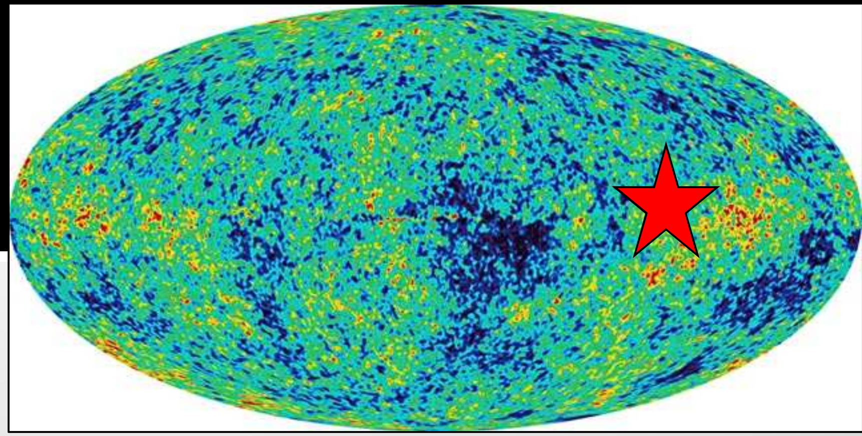
Observed coherent motion
on top of the Hubble expansion

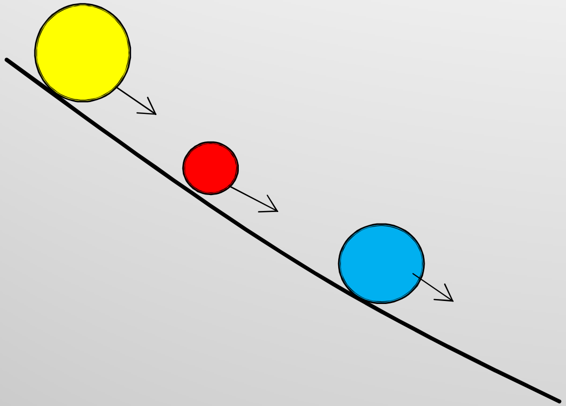
- Large scale structure surveys: Pike, Hudson 2005; Feldman, Watkins 2008; Watkins, Feldman, Hudson 2009; Lavaux, Tully, Mohayaee, Colombi 2010; ……..

- Xrays & kSZE: Kashlinsky, Atrio-Barandela, Ebeling, Edge, Kocevski 2010; …..

The Bulk Flow

(Feldman *et al* 2010)



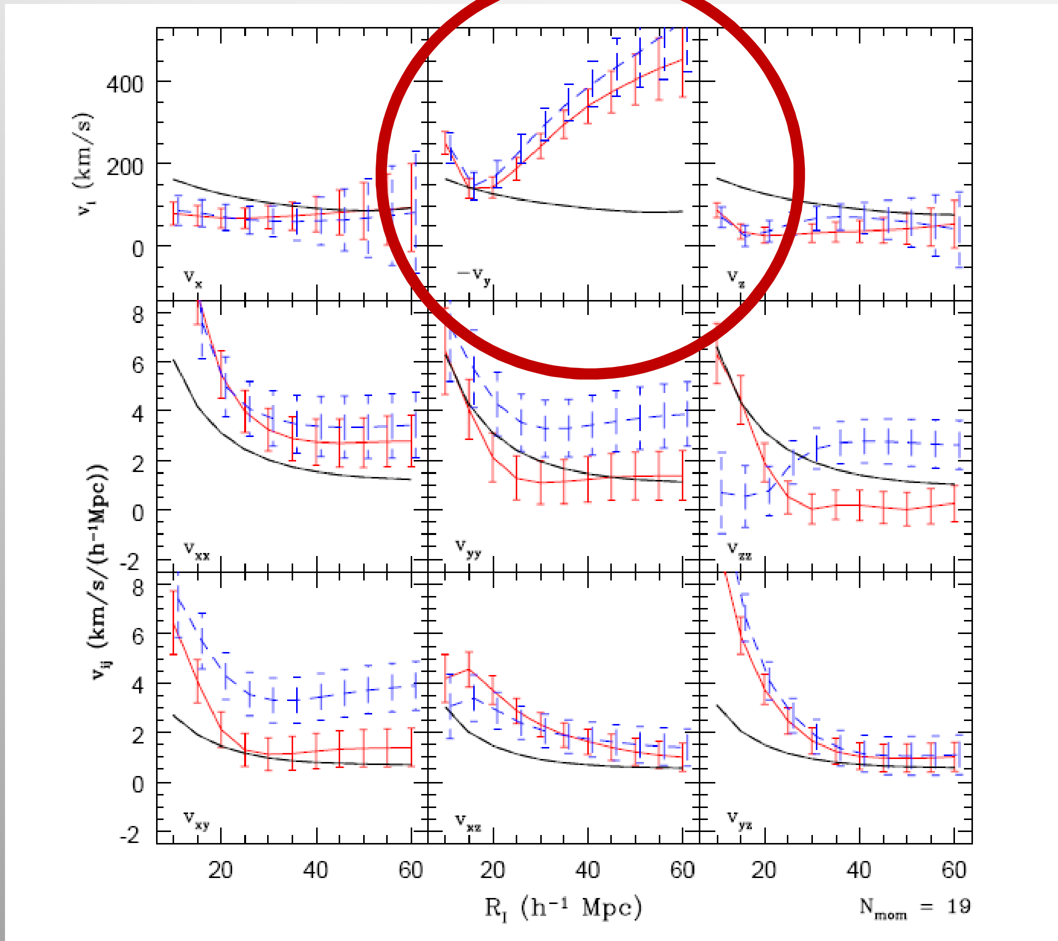


Observed coherent motion on top of the Hubble expansion

- Coherence scale of 100 h^{-1}Mpc ($z \leq 0.03$)
- ~3σ inconsistent with ΛCDM
- Flow of ~ 400 km/s toward (l = 282°, b = 6°)

Dipolar Motion at 100 h^{-1}Mpc scales

(Feldman *et al* 2010)

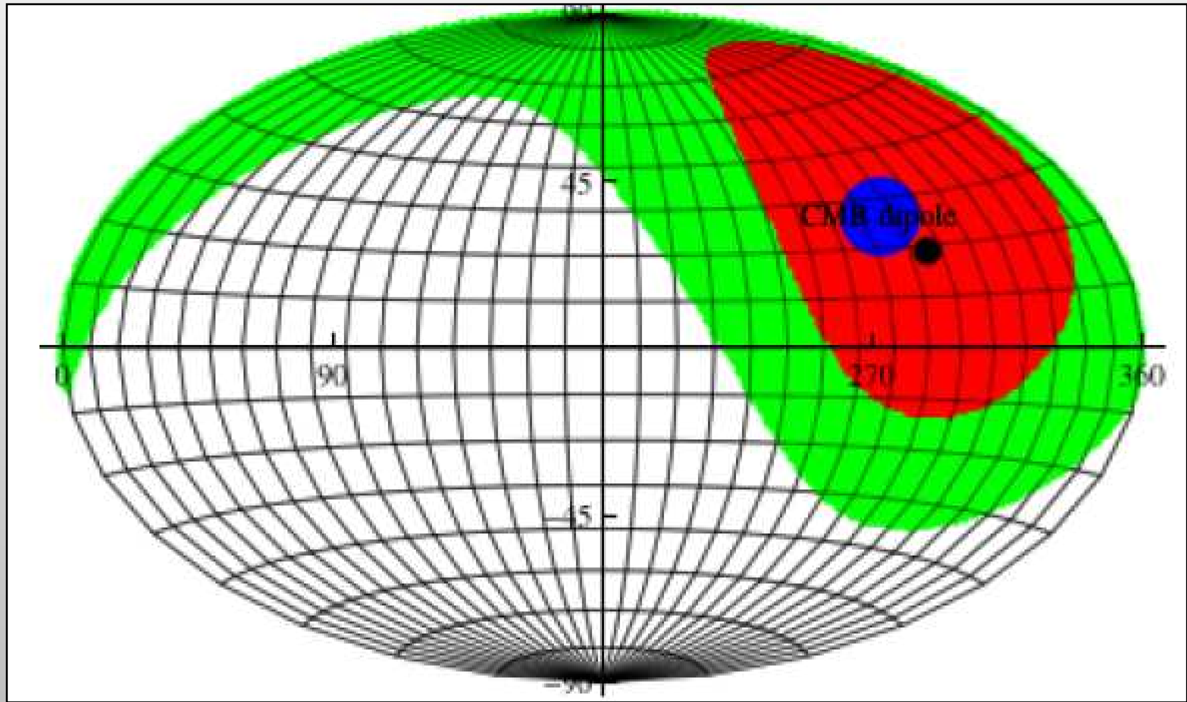


Only dipole is inconsistent with ΛCDM

"COMPOSITE" compilation.
Peculiar velocity surveys

All sample is moving → attractor is far (≥ 300 h^{-1}Mpc)

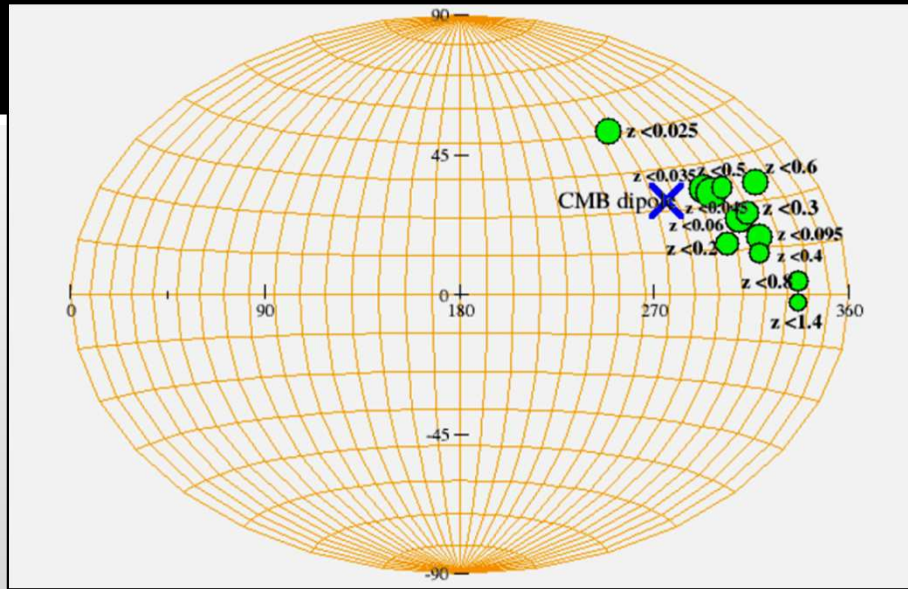
Dipole in SNe Data



Schwarz, Weinhorst 2007; Antoniou, Perivolaropoulos 2010; Colin, Mohayaee, Sarkar, Shafieloo 2011; Campanelli, Cea, Fogli, Marrone 2011; ……………..

Dipole in SNe Data

(Colin *et al* 2010)



The cumulative dipole direction in shells of increasing radii. Colin, Mohayaee, Sarkar, Shafieloo 2011) Union2 compilation (557 SNe) .

- SNe probe the Hubble flow at high redshifts ($z < 0.15$)
- The data is ~ 2σ inconsistent with ΛCDM at $z < 0.05$
- The data confirms the bulk flow at low redshifts

Latest Disagreements

ABSTRACT

Peculiar velocities are one of the only probes of very large-scale mass density fluctuations in the nearby Universe. We present new "minimal variance" bulk flow measurements based upon the "First Amendment" compilation of 245 Type Ia supernovae (SNe) peculiar velocities and find a bulk flow of 249 ± 76 km s^{-1} in the direction $l = 319^\circ \pm 18^\circ$, $b = 7^\circ \pm 14^\circ$. The SNe bulk flow is consistent with the expectations of ΛCDM. However, it is also marginally consistent with the bulk flow of a larger compilation of non-SNe peculiar velocities (Watkins, Feldman, & Hudson 2009). By comparing the SNe peculiar velocities to predictions of the IRAS Point Source Catalog Redshift survey (PSCz) galaxy density field, we find $\Omega_m^{0.55}\sigma_{8,\mathrm{lin}} = 0.40 \pm 0.07$, which is in agreement with ΛCDM. However, we also show that the PSCz density field fails to account for 150 ± 43 km s^{-1} of the SNe bulk motion.

" The SNe bulk flow is consistent with the expectations of LCDM"

Turnbull, Hudson, Feldman, Hicken, Kirshner, Watkins 2011

" Our findings are consistent with the LCDM model"

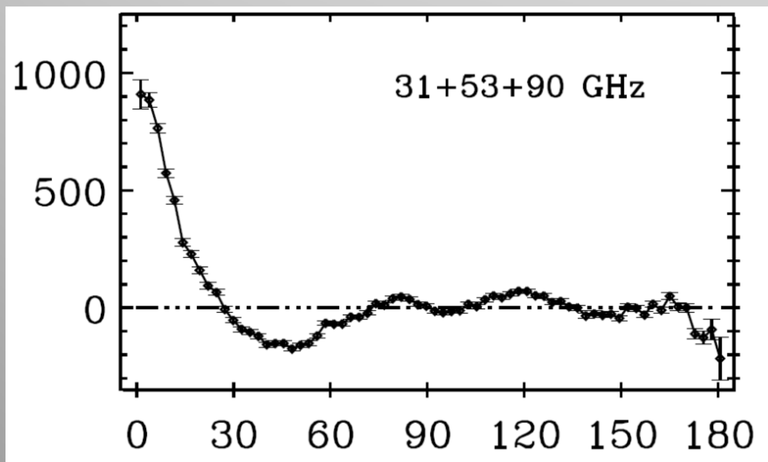
Nusser, Davis 2011

Lack of Large Scale Correlation

(Copi *et al* 2010; Bennett *et al* 2011)

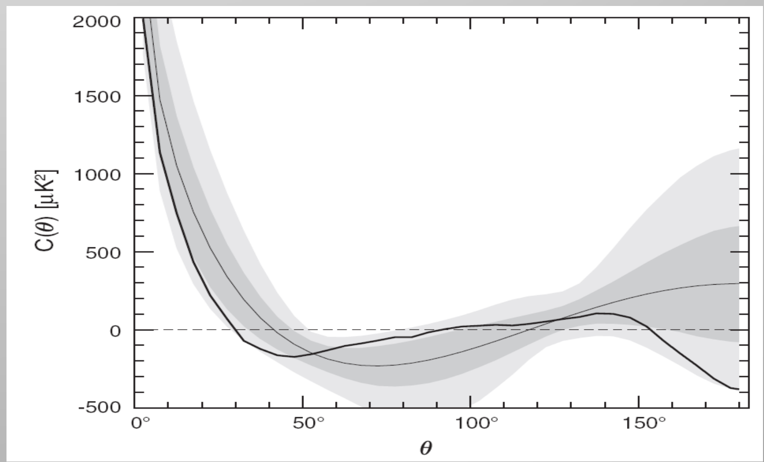
- Two-point angular correlation function of the CMB vanishes at large angles
- This is anomalous at 99.9% level (>3σ)
- Also in COBE data $\rightarrow$ not a systematic!

COBE:



Hinshaw *et al* 1996

WMAP:



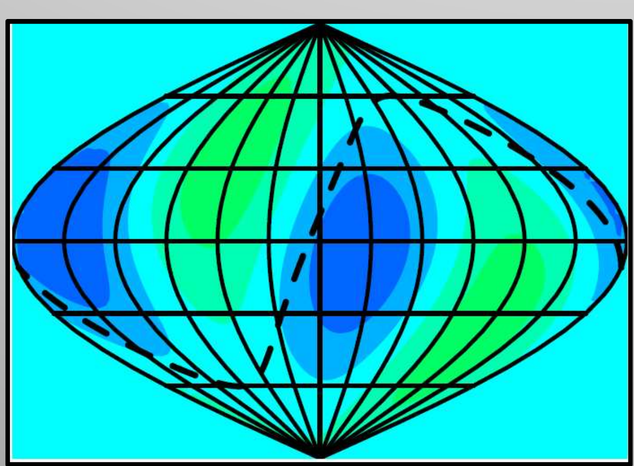
Bennett et al 2011

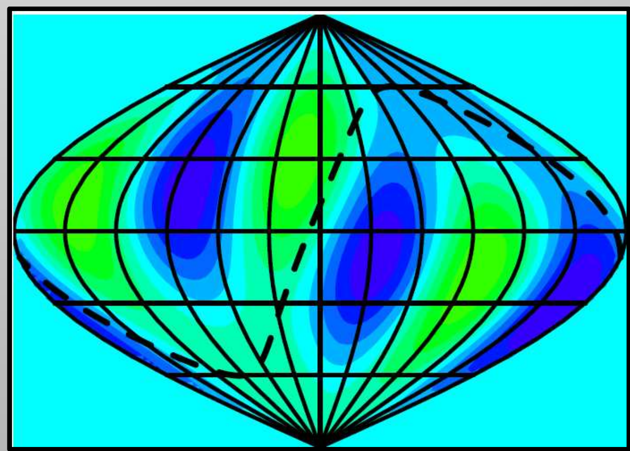
Planarity and Alignment

(Copi *et al* 2010; Bennett *et al 2011*)

- ✓ Octopole is planar: power is suppressed along an axis
- ✓ Quadrupole and octopole planes are aligned.

- The alignment is 99.6% (~3σ) anomalous
- Strange 95.9 % (> 2 σ) alignment with solar system features
- No systematics found

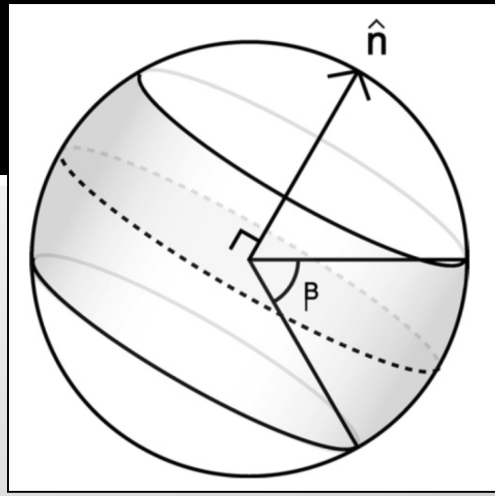




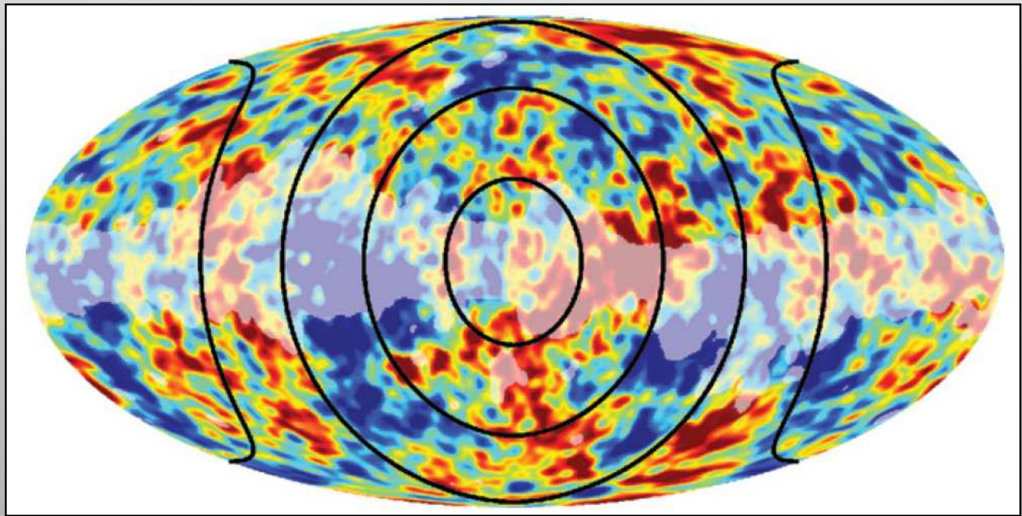
Schwartz *et al* 2004

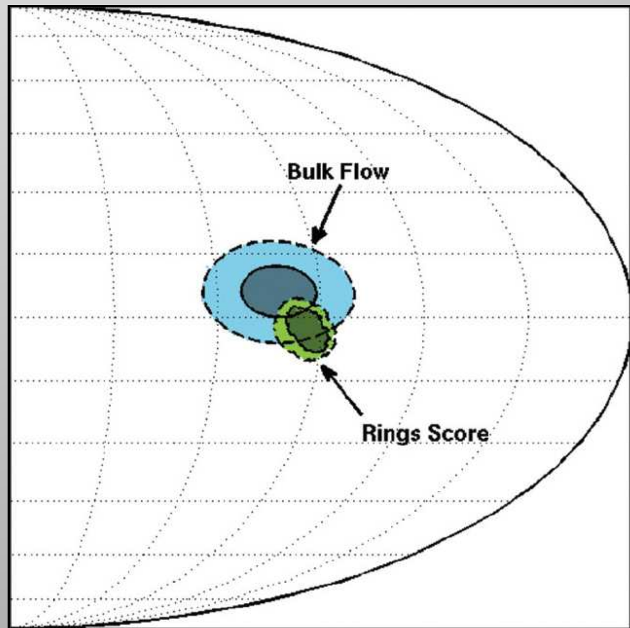
Giant Rings in the CMB

(Kovetz, Ben-David, Itzhaki *2011*)



- Significance 3σ
- Alignment with the bulk flow 2.5σ



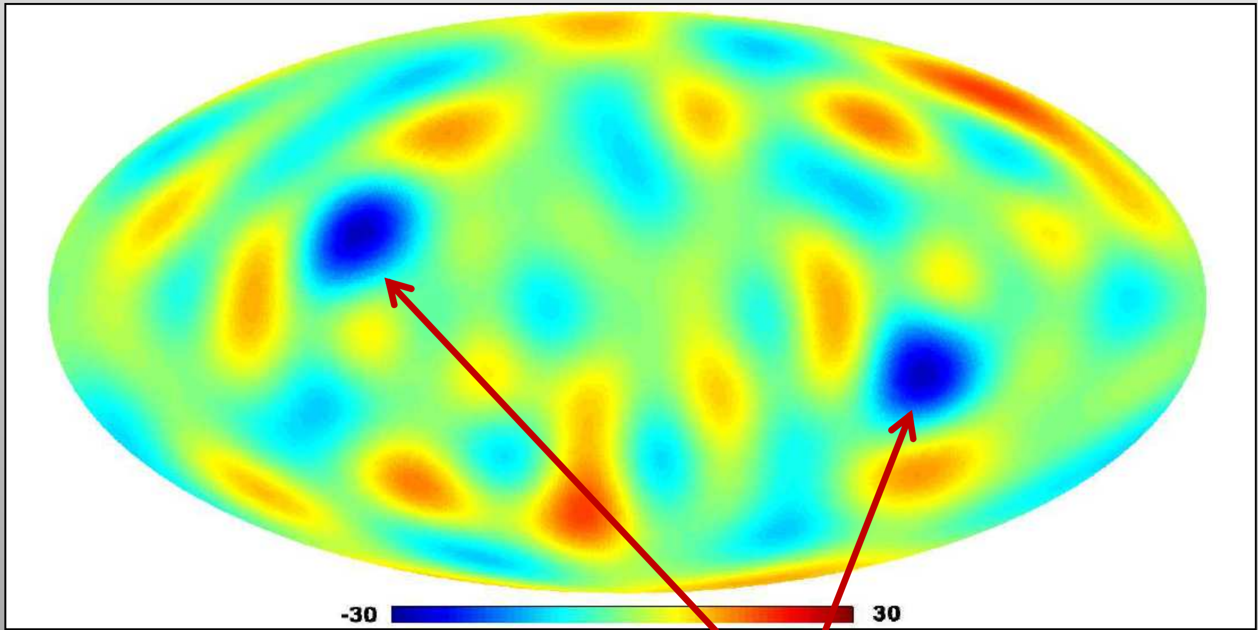


Can be generated by the same physical phenomenon?

Parity in the CMB

(Ben-David, Kovetz, Itzhaki *2011*)

- Reflection through a plane
- Compare power in even and odd *l+m* multipoles (low *l*)



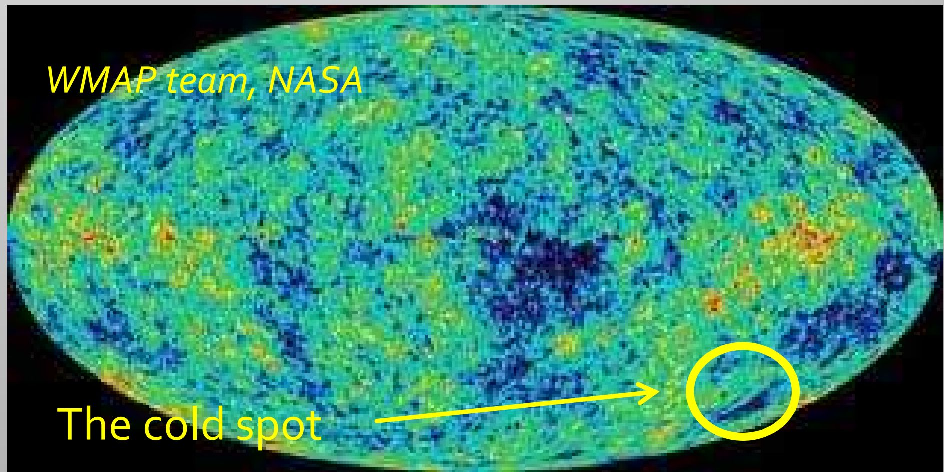
Score map of directions with maximal even and odd parity

The space is ODD! 3.6σ significance

Other Large Scale Anomalies in the CMB

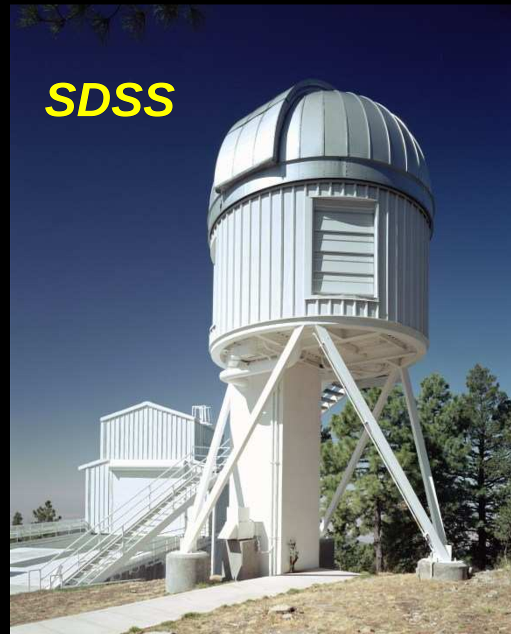
(Bennett *et al 2011*)

- Hemispherical power asymmetry
  - Low significance (~2σ)
  - Possible: beam asymmetry
- The cold spot
  - The coldest spot on the sky (-170 μK)
  - Significance ~2.4 σ



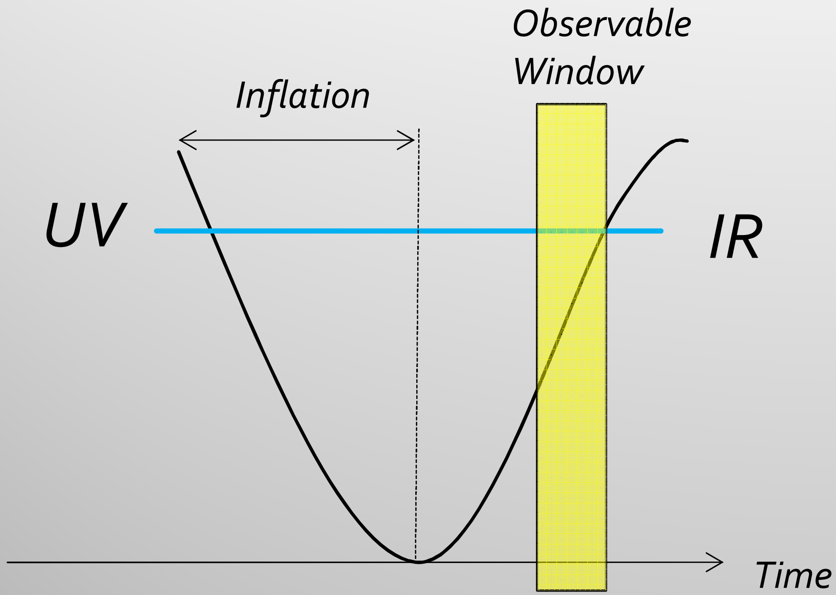
Future Probes

CMB
Galaxy surveys
21-cm



Are there any real anomalies?

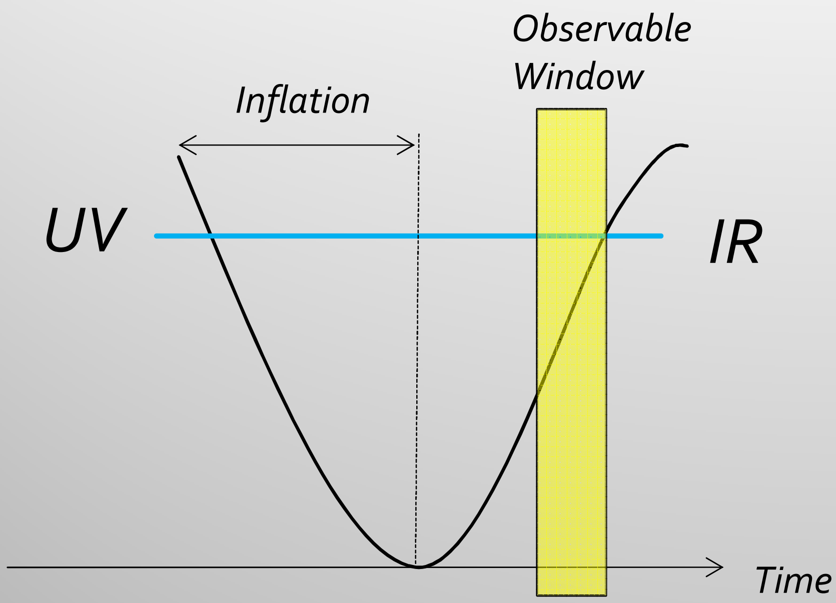
Large Scale Anomalies: Probe UV with IR



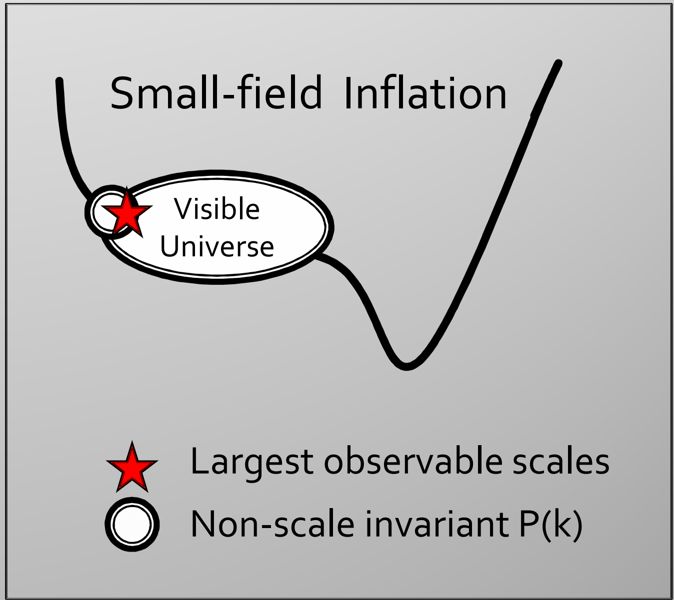
Short inflation:

- ✓ Large scales (beginning of inflation)

Large Scale Anomalies: Probe UV with IR



$$P(k) \propto \frac{V^3}{V_{,\varphi}^{\ 2}}$$



Short inflation:

- ✓ Large scales (beginning of inflation)
- ✓ Lack of large angular correlations

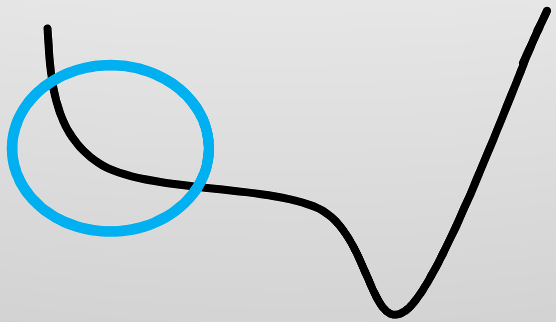
Part II:
Pre-Inflationary Relics

- We study slow roll inflation + add-ons:
  - Non-dynamical massive particle (PIP)
  - Massless particle
  - Cosmic string
  - Domain wall
- What are the cosmological imprints?

Based on:
Itzhaki, Kovetz 2007; Itzhaki 2008 & **AF**, Itzhaki, Kovetz 2010

Assumptions

1. PIPs exist at the beginning of inflation.



2. One PIP in the observable universe

3. Mass of PIP can be inflaton-dependent $m_{PIP}(\varphi)$.

4. PIP has a perturbative effect on cosmology.

PIP Modifies EoM of the Inflaton

- The action of the inflaton (φ) + PIP:

$$S_{\varphi} + S_{\mathrm{PIP}} = \int d^4x\sqrt{-g}\left[\frac{1}{2}\partial_\mu\varphi\,\partial^\mu\varphi - V(\varphi)\right] - \int d\eta\, m_{\mathrm{PIP}}(\varphi)$$

- PIP is a perturbation $\rightarrow$ same background eom for φ

$$\ddot{\varphi} + 3H\dot{\varphi} + V_{,\varphi} = 0$$

- EoM for $\delta\varphi$:

$$\delta\ddot{\varphi} + 3H\delta\dot{\varphi} - \frac{1}{a^2}\nabla^2\delta\varphi + \cancel{V_{,\varphi\varphi}} + \left(\frac{\partial m_{\mathrm{PIP}}}{\partial\varphi} - \frac{1}{2}\frac{V_{,\varphi}}{V}\frac{m_{\mathrm{PIP}}}{m_{\mathrm{PL}}}\right)\frac{\delta^3(x)}{a^3} = 0$$

Slow roll

Only 1 New Parameter

PIP adds a source term to the eom of δφ

$$\delta\ddot{\varphi} + 3H\,\delta\dot{\varphi} - \frac{1}{a^2}\nabla^2\delta\varphi = -\underbrace{\left(\frac{\partial m_{\mathrm{PIP}}}{\partial\varphi} - \sqrt{\frac{\varepsilon}{2}}\,\frac{m_{\mathrm{PIP}}}{m_{\mathrm{PL}}}\right)}_{\equiv\,\lambda}\frac{\delta^3(x)}{a^3}$$

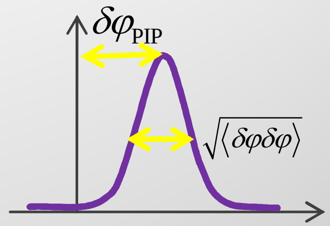
$$\lambda = \frac{\partial m_{\mathrm{PIP}}}{\partial\varphi} - \sqrt{\frac{\varepsilon}{2}}\,\frac{m_{\mathrm{PIP}}}{m_{\mathrm{PL}}}$$

The leading term: direct coupling to the inflaton

Suppressed term: coupling via gravity

Solution for the EoM

$$\delta\ddot{\varphi} + 3H\delta\dot{\varphi} - \frac{1}{a^2}\nabla^2\delta\varphi = -\lambda\frac{\delta^3(x)}{a^3}$$



- The solution is:

Homogenous

+

Particular Inhomogenous

Describes the random fluctuations in the inflaton field with:

$$\left\langle \delta\varphi_{\mathrm{k}} \right\rangle = 0$$

$$\left\langle \delta\varphi_{\mathrm{k}}\delta\varphi_{\mathrm{k'}} \right\rangle = \frac{H^2}{2k^3}\delta\left(k + k'\right)$$

Adds 1pf to the field:

$$\delta\varphi_{\mathrm{PIP,k}} = -\frac{\lambda}{k^3}\frac{H}{\sqrt{32\pi}}$$

In total: quantum perturbations with non-vanishing 1pf

Range for λ

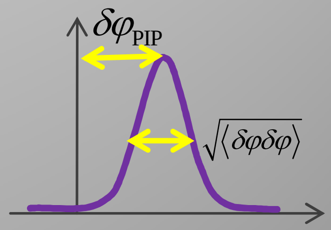
$$\lambda = \frac{\partial m_{\mathrm{PIP}}}{\partial \varphi} - \sqrt{\frac{\varepsilon}{2}} \frac{m_{\mathrm{PIP}}}{m_{\mathrm{PL}}}$$

- PIP is a perturbation if we can ignore it in the background EoM: $\ddot{\varphi} + 3H\dot{\varphi} + V_{,\varphi} = 0$

$$\frac{\nabla^2 \delta\varphi_{\mathrm{PIP}}}{a^2} << V' \longrightarrow |\lambda| < 10^5$$

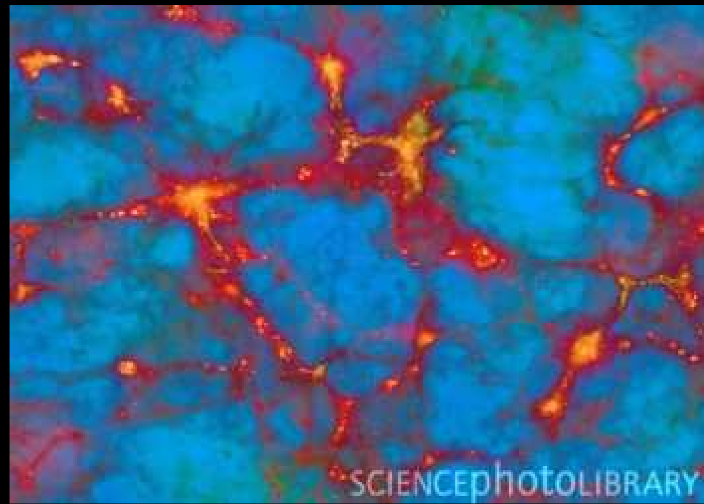
- PIP can be detected in principle:

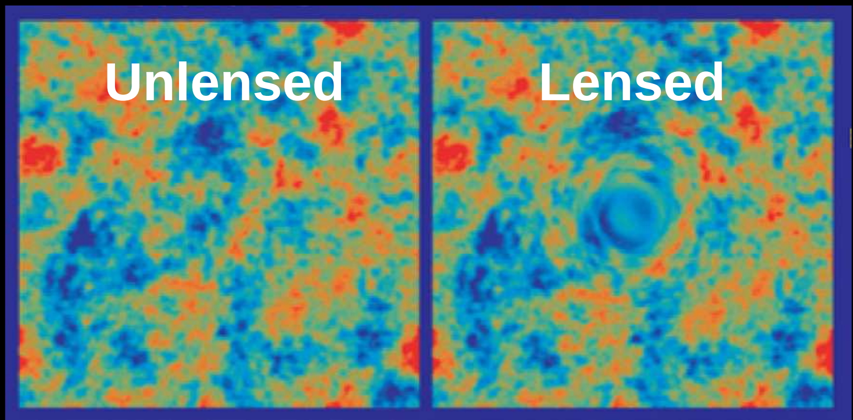
$$\frac{\langle \delta\varphi_{\mathrm{PIP}} \rangle}{\sqrt{\langle \delta\varphi\delta\varphi \rangle}} = 1 \longrightarrow |\lambda| = O(1)$$



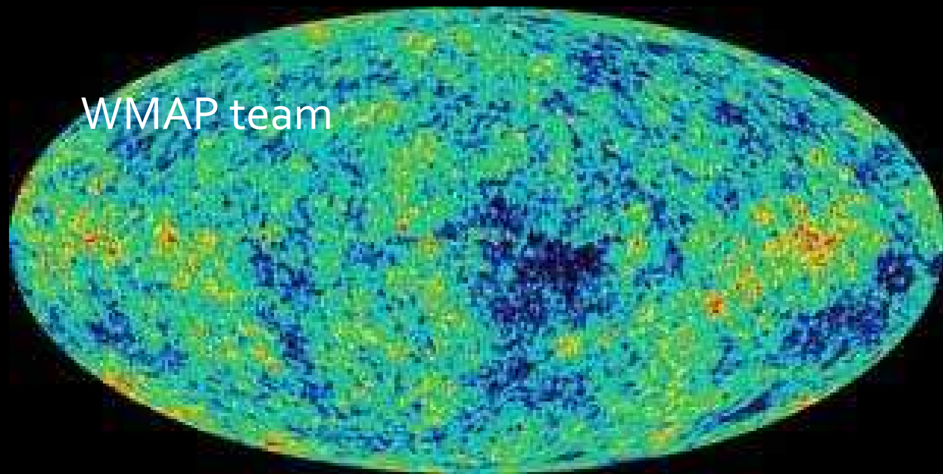
Part III: Cosmological Signature

- The large scale structure
- Signature in the CMB
- Gravitational lensing

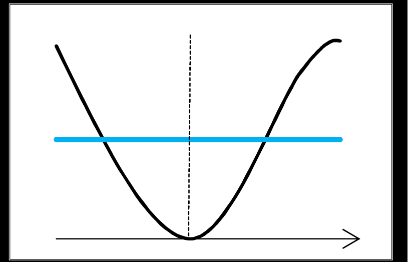




Wayne Hu



Initial Conditions for Structure Formation



- We evolve the perturbation through the horizon in the usual way: ξ is conserved on superhorizon scales

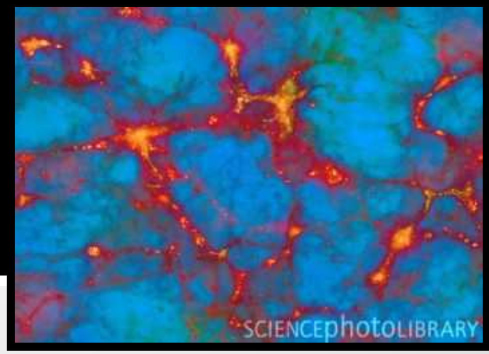
$$\xi = -\frac{H}{\dot{\varphi}}\delta\varphi \quad \Rightarrow \quad \Phi_0 = -\frac{2}{3}\xi$$

Initial conditions for structure formation

- After inflation ends:

$$\Phi(k,z) = \frac{9}{10}\Phi_0(k)T(k)D_1(z)(1+z)$$

Structure is Formed

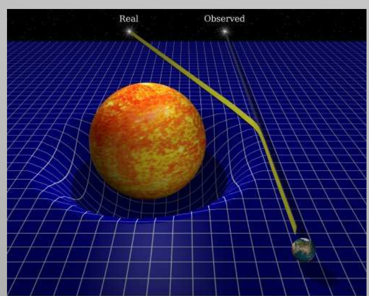


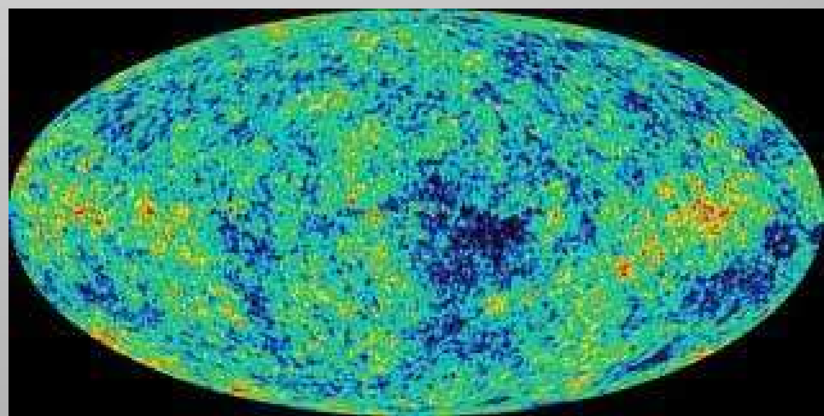
- We use Φ(k,z) to calculate

$$\frac{\delta\rho}{\rho}(r) \propto \nabla^2\Phi(r, z=0)$$ Energy density profile

$$\vec{\mathrm{v}}(r) \propto \vec{\nabla}\Phi(r, z)$$ Peculiar velocity field

- Gravitational redshift effects: anisotropy in the CMB, gravitational lensing etc.





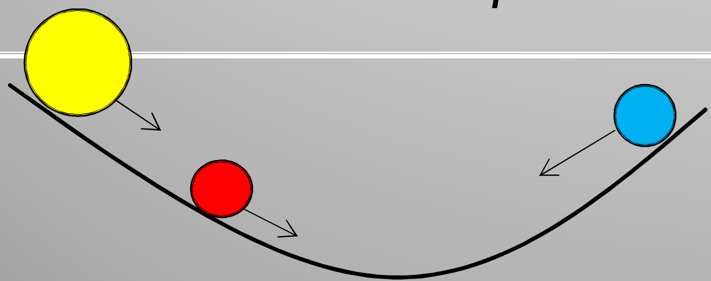
Large Scale Structure from Pre-Inflationary Particle

PIP-SOURCED STRUCTURE

$$\Phi(r) \cong \frac{\lambda}{10^5} \log\left(r / 100\,\mathrm{Mpc} \right)$$

$$\delta(r) \cong 233 \frac{\lambda}{r^2}$$

$$\mathrm{v}(r) / c \cong 0.04 \frac{\lambda}{r}$$



Potential well

PROPERTIES

- Spherically symmetric giant structure
- Characteristic scale of ~100 Mpc
- Decays log-slowly with the distance
- Is an overdense region if λ>0

Large Scale Structure: Comparison

PIP-SOURCED STRUCTURE

$$\Phi(r) \cong \frac{\lambda}{10^5} \log\left(r \big/ 100\,\mathrm{Mpc} \right)$$

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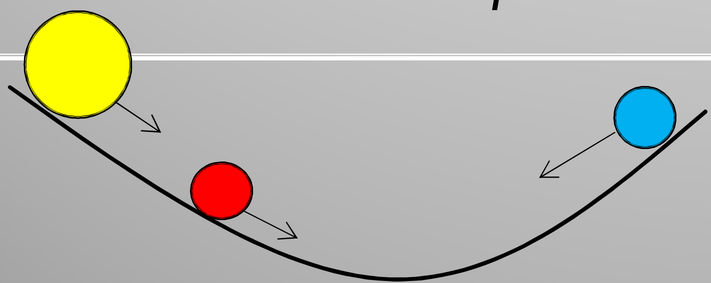


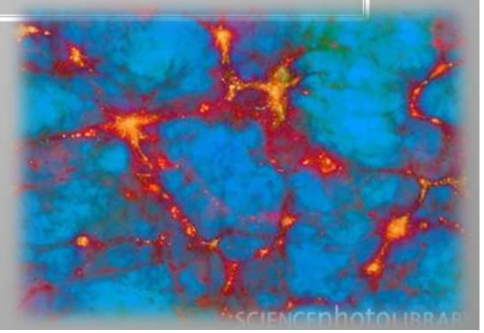
Potential well

ΛCDM STRUCTURE

$$\Phi(r) \cong 1 \big/ r \qquad \delta(r) \cong 1 \big/ r^3$$

$$\frac{\mathrm{v}}{c}(r) \cong 1 \big/ r^2$$

Decays faster and on smaller scales (< 10 Mpc)



Large Scale Structure: Comparison

PIP-SOURCED STRUCTURE

$$\Phi(r) \cong \frac{\lambda}{10^5}\log\left(r/100\,\mathrm{Mpc} \right)$$

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$$\mathrm{v}(r)/c \cong 0.04\frac{\lambda}{r}$$

ΛCDM STRUCTURE

$$\Phi(r) \cong 1/r \qquad \delta(r) \cong 1/r^3$$

$$\frac{\mathrm{v}}{c}(r) \cong 1/r^2$$

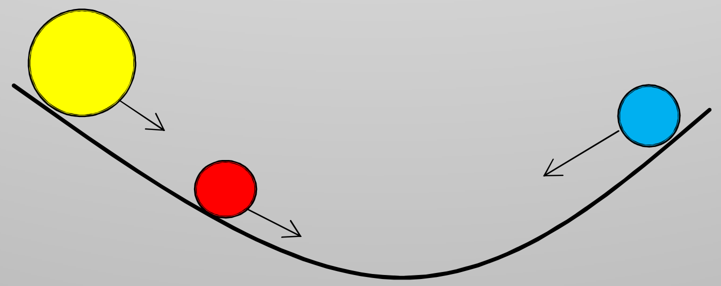
Decays faster and on smaller scales (< 10 Mpc)

TIP: Search for the anomalous structure which breaks statistical isotropy

Anomalous Structure Breaks Statistical Isotropy

- Peculiar velocity flow with slow convergence on very large scales
- Local bulk flow (at the observer)
- Anisotropy in SNIa data

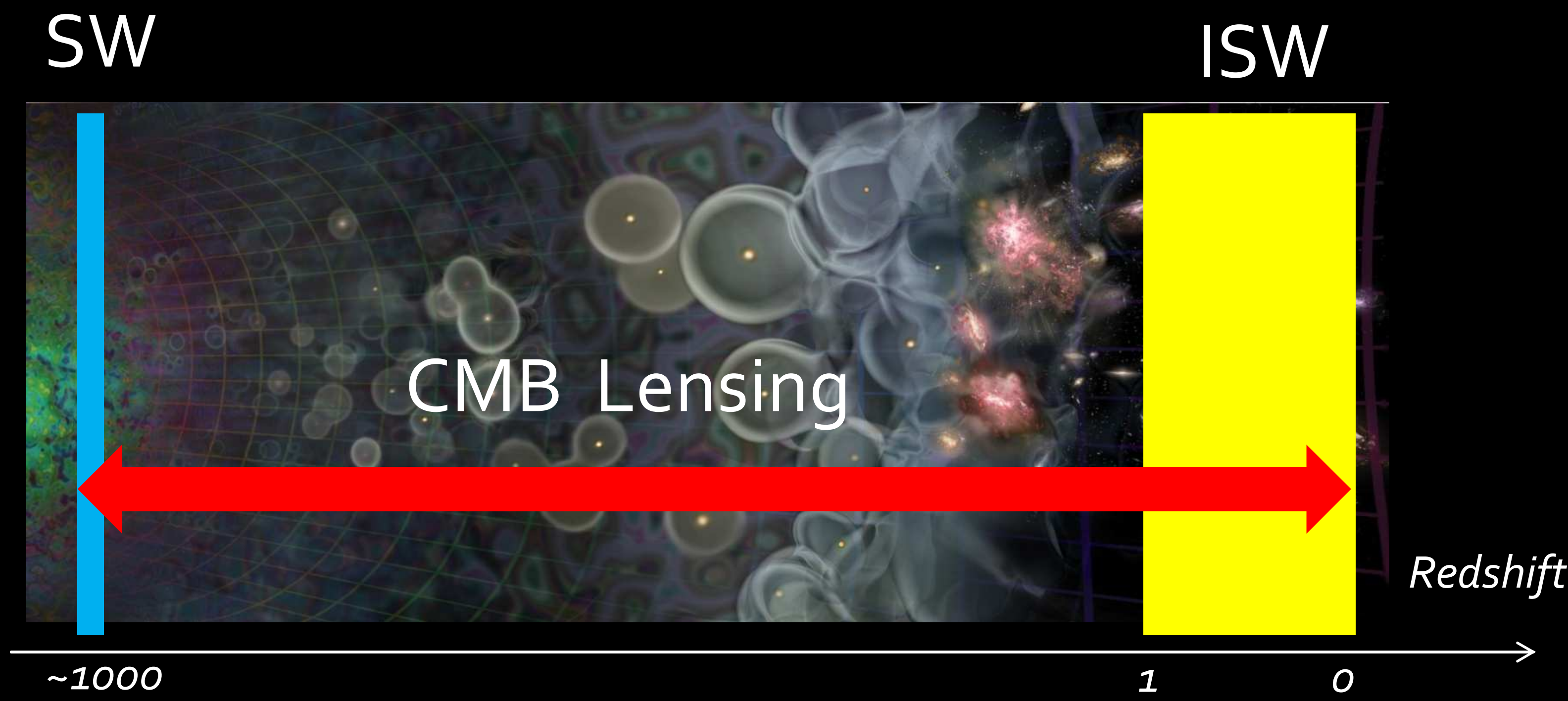
✓ Can explain the bulk flow !



Potential well

Q: What would be the signature in the CMB?

Anisotropies in the CMB



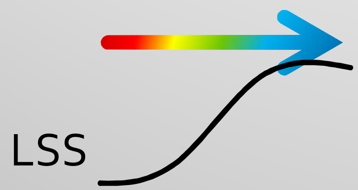
SW probes the last scattering surface
ISW probes the dark energy domain
CMB Lensing is the integral along the geodesics, probes all the redshifts

Anisotropies in the CMB: SW & ISW

- Sachs Wolfe (SW) Effect:

  Photons climb out the potential well at LSS.
  Inhomogeneous potential at LSS.

$$\left\langle \frac{\delta T}{T} \right\rangle^{SW} = \frac{\Phi_{LSS}}{3}$$

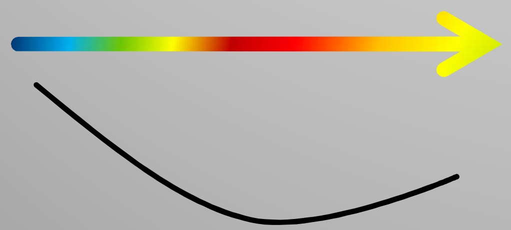


E.g.: overdensity at LSS $\rightarrow$ a cold spot.

- Integrated Sachs Wolfe (ISW):

  Anisotropy due to decay of the potential wells.

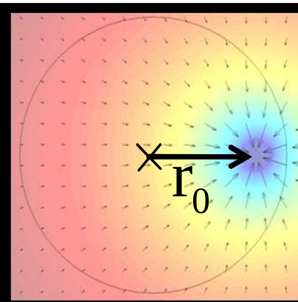
$$\left\langle \frac{\delta T}{T} \right\rangle^{ISW} = 2\int_{LSS}^{\tau_0} d\tau \frac{\partial \Phi}{\partial \tau}$$



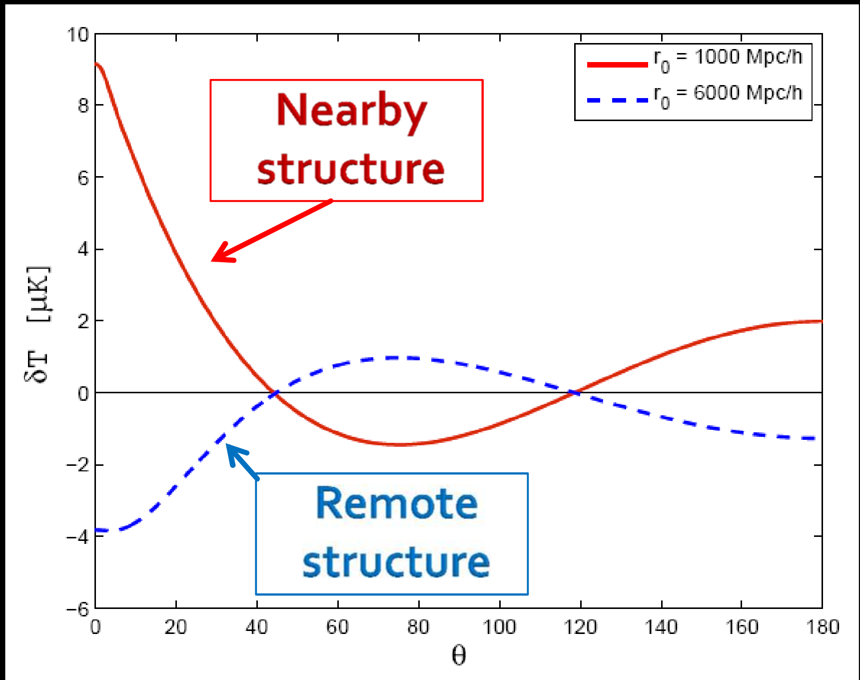
E.g.: decaying overdensity $\rightarrow$ a hot spot.

δT_{SW}^{PIP} & δT_{ISW}^{PIP} change $\langle T_{CMB} \rangle$

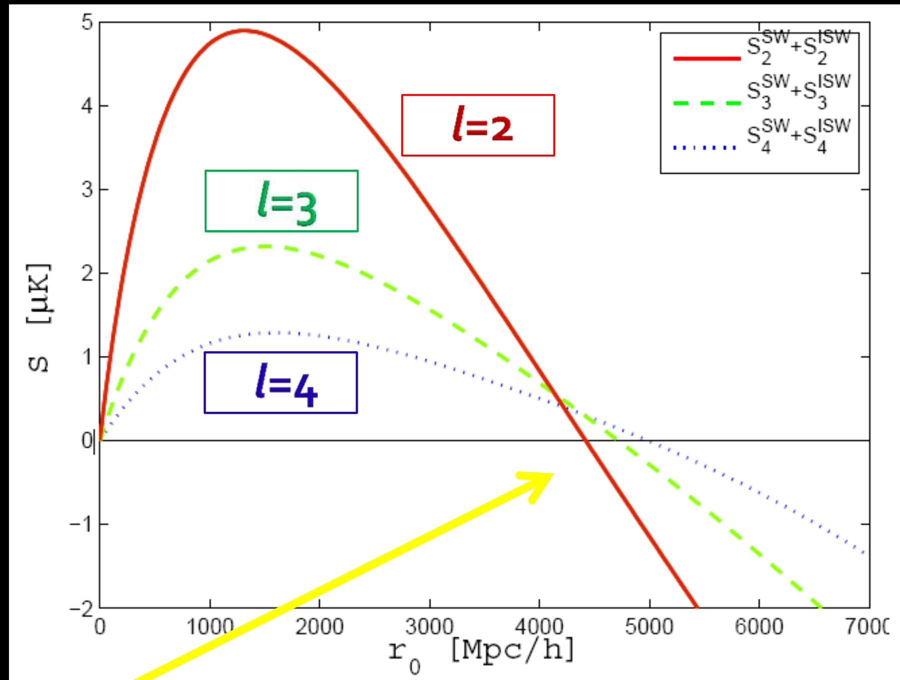
Signature in the CMB: SW + ISW for $\lambda = 1$



$\delta T_{SW}^{PIP} + \delta T_{ISW}^{PIP}$ profile

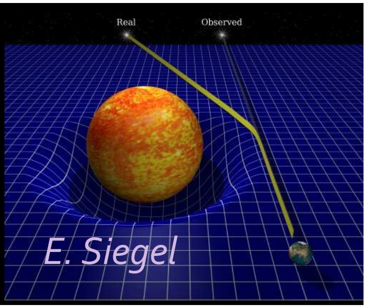


Signal in *l* multipole vs r_0



- Rings in the CMB
- SW-ISW cancelation.
- Signature is dominated by low-multipoles → large spots on the CMB sky.

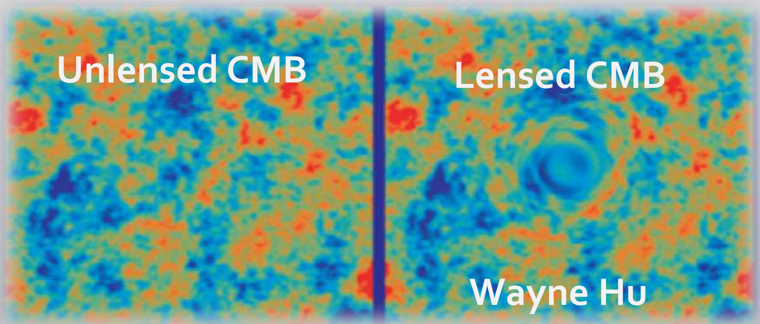
CMB Weak Lensing



- Gravitational lensing is deflection of light by mass

- The temperature is re-mapped $\tilde{T}(\theta) = T(\theta + \nabla\delta\psi)$

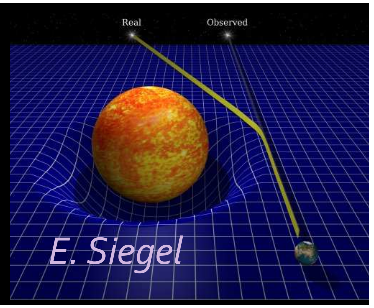
  2-dimensional deflection potential: $\delta\psi = 2\int_{\mathrm{LSS}}^{r_0} dr \frac{r_{\mathrm{LSS}} - r}{r_{\mathrm{LSS}} r} \Phi$



- Weak lensing $\rightarrow$ we can expand the temperature

$$\tilde{T}(\theta) = T(\theta) + \nabla\delta\psi\,\nabla T(\theta) = T(\theta) + \delta T^{\mathrm{GL}}(\theta)$$

CMB Weak Lensing



- Lensing preserves brightness

$$\left\langle \delta T^{\mathrm{GL}} \right\rangle = 0$$

- Generates non-diagonal terms in the covariance (leading order) of the CMB temperature*:

$$\left\langle \tilde{T}_{\mathrm{l}_1} \tilde{T}_{\mathrm{l}_2} \right\rangle = C_{\mathrm{l}} \delta_{\mathrm{l}_1 \mathrm{l}_2} + < \delta\psi > \left[\left(l_2 - l_1 \right) \left(l_2 C_{l_2} - l_1 C_{l_1} \right) \right] + \mathrm{cc}$$

(*) ΛCDM $\rightarrow$ <δψ> = 0 $\rightarrow$ Non-diagonal terms vanishes

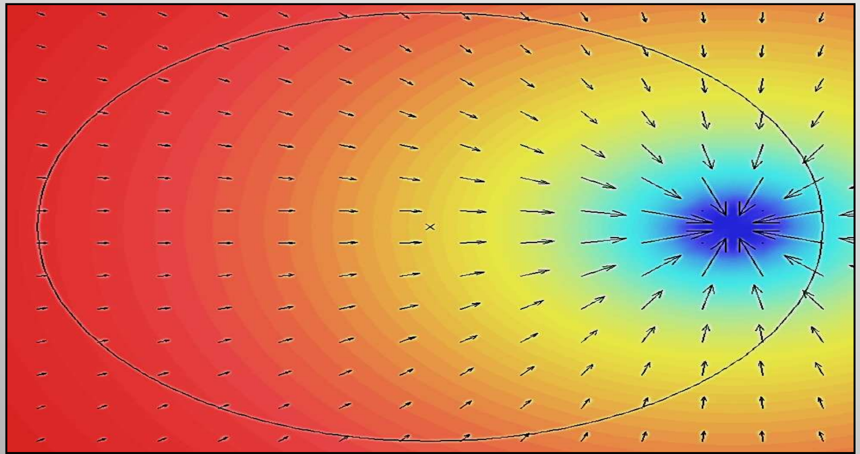
(*) PIP $\rightarrow$ <δψ> ≠ 0 $\rightarrow$ Signal

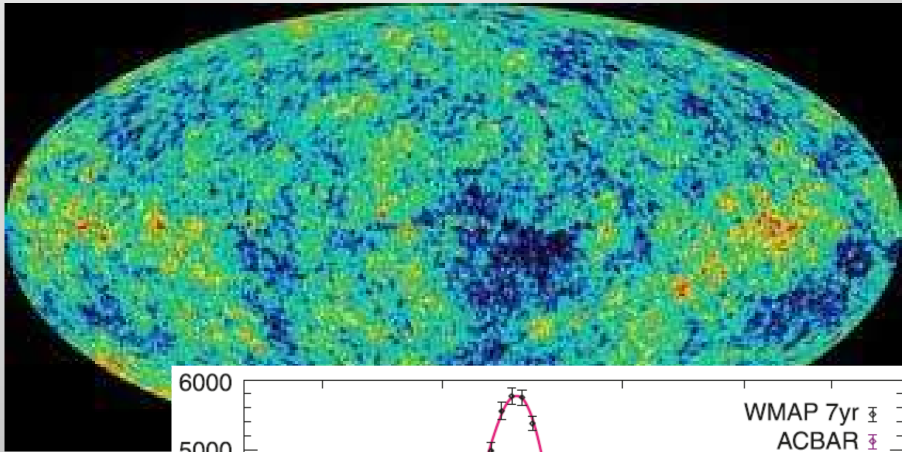
Prospects for Detection

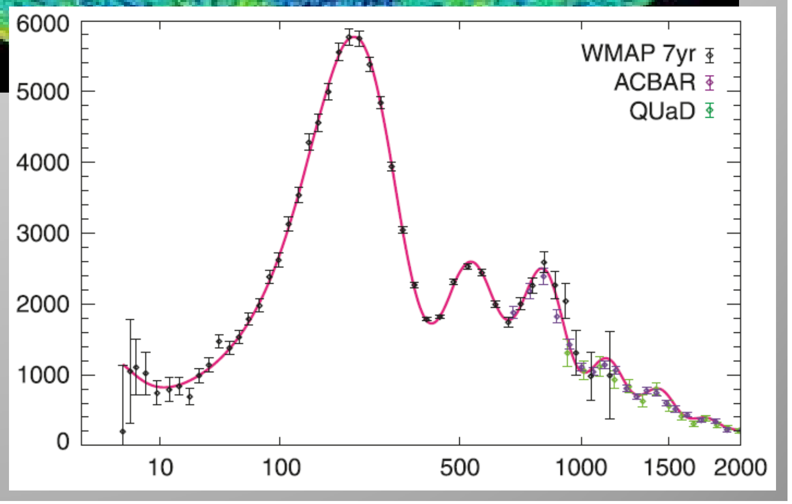
SIGNAL:
SW, ISW, LENSING

~GAUSSIAN NOISE

$$\langle \delta T \rangle = 0, \quad \langle \delta T_{lm} \delta T_{l'm'} \rangle = C_l \delta_{ll',mm'}$$







- SW and ISW change $<T_{CMB}>$
- Lensing modifies $<T_{CMB}\, T_{CMB}>$

Standard Signal to Noise

- Temperature is a Gaussian random field
- The likelihood function:

$$L = \frac{1}{(2\pi)^{n/2}\sqrt{\det C}} \exp\left(-\frac{1}{2} x^{\mathrm{T}} C^{-1} x\right)$$

- The signal to noise:

$$\left(\frac{S}{N}\right)^2 \equiv -2\langle \log L - \log L_0 \rangle$$

Deformed distribution   Original distribution

Deformation of the Mean

- The **1pf** of the distribution is changed

$$x \rightarrow x + b$$

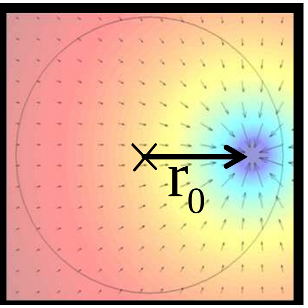
- Signal to Noise:

$$\boxed{\left(\frac{S}{N}\right)^2 = b^{\mathrm{T}} C_0^{-1} b}$$

We want to know:

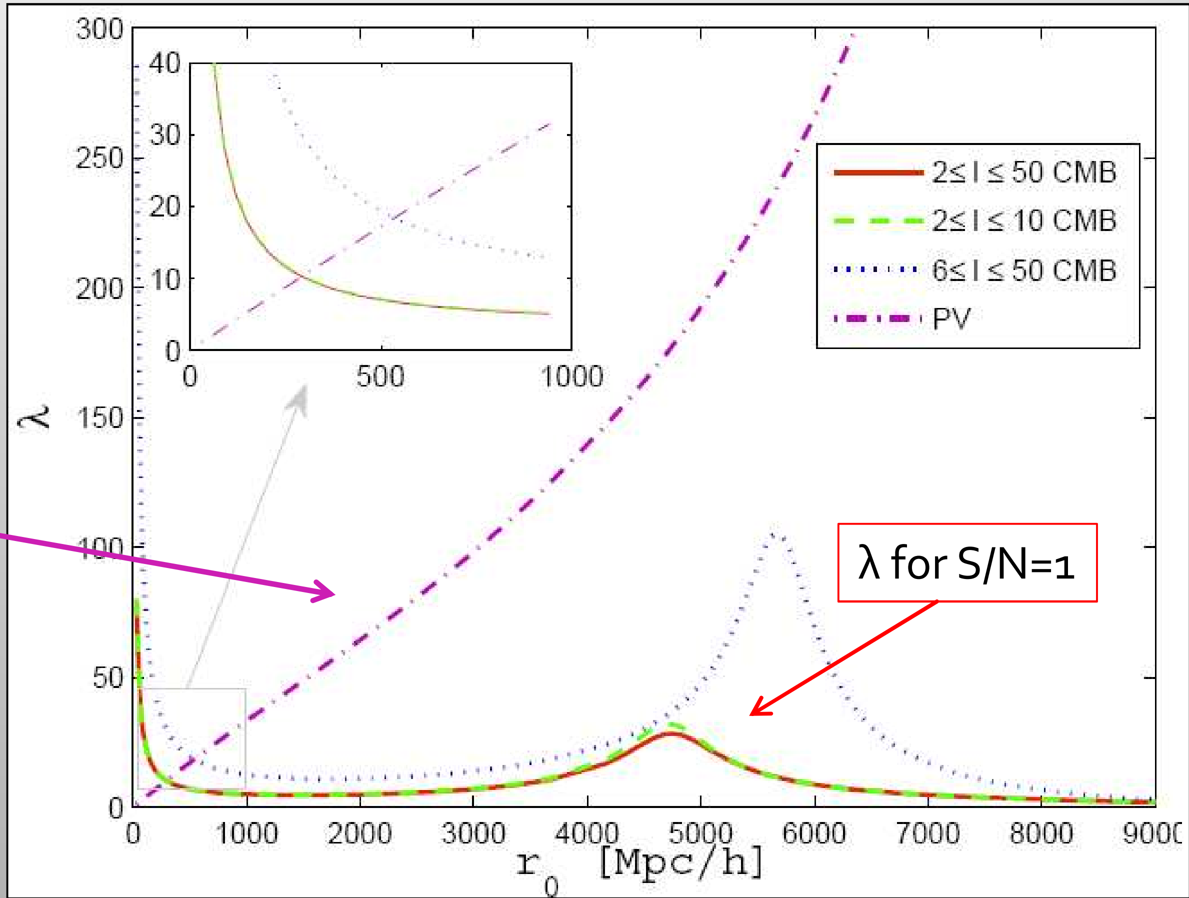
The S/N in T_{CMB} for PIP that creates the bulk flow.

S/N from SW & ISW



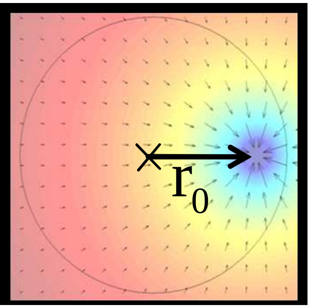
Tune λ at each location r_0 to get the observed bulk flow
→ $\lambda(r_0)$

λ for bulk flow



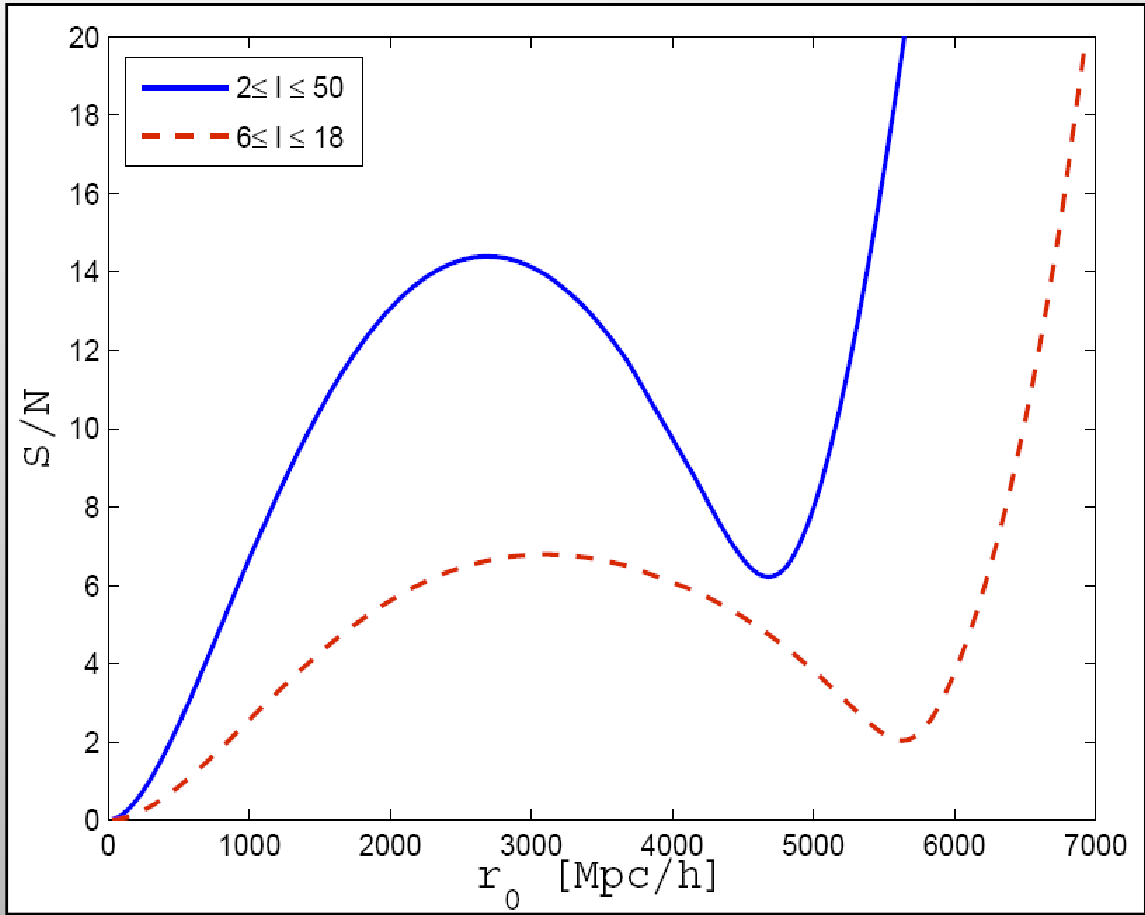
λ for S/N=1

S/N from SW & ISW

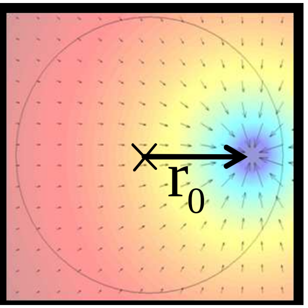


With $\lambda(r_0)$

$$\left(\frac{S}{N}\right)^2 = \sum_l \frac{|a_{l,0}^{\mathrm{SW}} + a_{l,0}^{\mathrm{ISW}}|^2}{C_l}$$

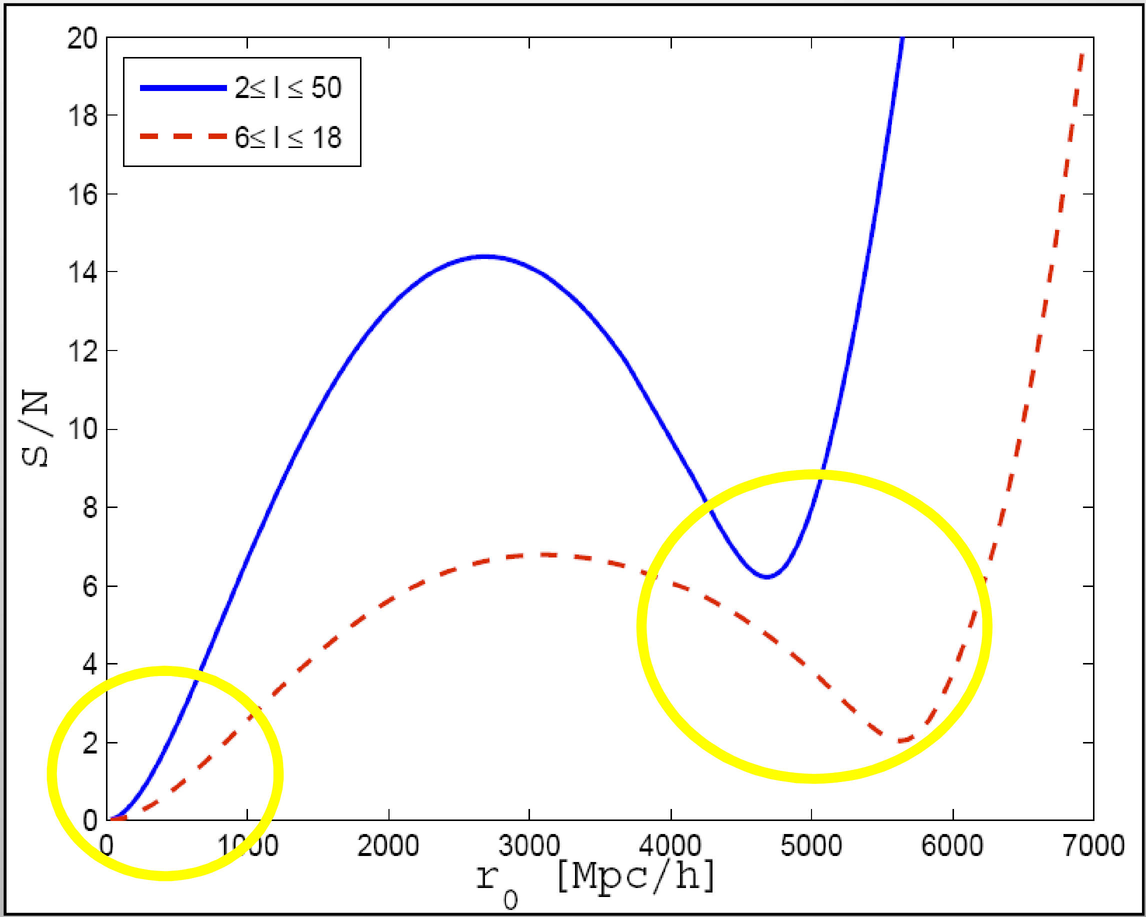


S/N from SW & ISW



With $\lambda(r_0)$

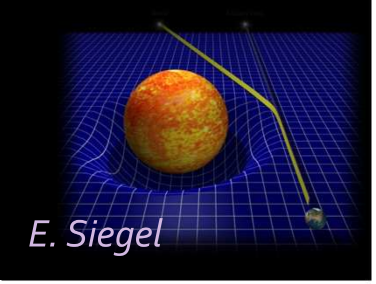
$$\left(\frac{S}{N}\right)^2 = \sum_l \frac{|a_{l,0}^{\mathrm{SW}} + a_{l,0}^{\mathrm{ISW}}|^2}{C_l}$$



Two possible r_0 :

1. Very close to us
2. In the SW - ISW cancellation region

CMB Lensing: Ideal Experiment



- Complete reconstruction of the deflection potential.

Observed: $$\psi^{\Lambda\mathrm{CDM}} + \delta\psi$$

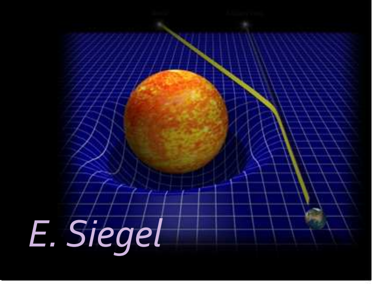
random *non-random*

- For an anomalous lens we can use same S/N

- Gaussian distribution →

$$\left(\frac{S}{N}\right)^2_{\mathrm{IDEAL}} = \sum_{lm} \frac{\left|\delta\psi_{lm}\right|^2}{C_l^{\psi}}$$

CMB Lensing: Ideal Experiment



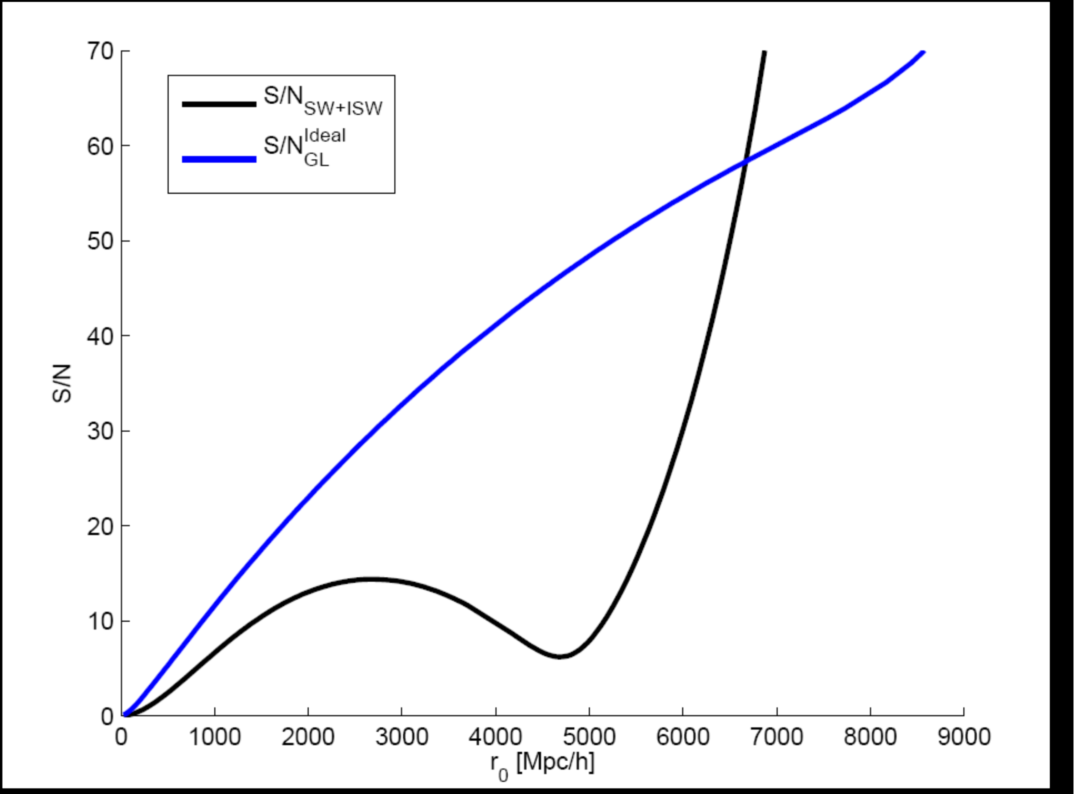
$$\left(\frac{S}{N}\right)^2_{\text{IDEAL}} = \sum_{lm} \frac{\left|\delta\psi_{lm}\right|^2}{C_l^{\psi}}$$

Upper limit of the S/N from lensing.
Any observable S/N should be smaller!

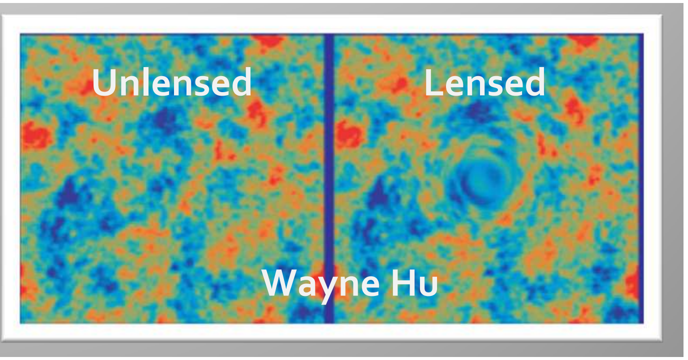
$$\left(\frac{S}{N}\right)^2_{\text{OTHER}} < \left(\frac{S}{N}\right)^2_{\text{IDEAL}}$$

The "Ideal" Signal to Noise from Lensing

A lot of Info in Lensing (Integrated along the geodesics).



How much of it can we see on a real CMB map?



Realistic S/N (Assumes Gaussian T_{CMB}) Deformation of the Covariance

- The covariance matrix is deformed $C_0 \to C$
- S/N: $$\left(\frac{S}{N}\right)^2 = \mathrm{Tr}\left(C_0 C^{-1} - 1\right) + \log\left(\det C / \det C_0\right)$$

Realistic S/N (Assumes Gaussian T_{CMB}) Deformation of the Covariance

- The covariance matrix is deformed $C_0 \to C$
- S/N: $$\left(\frac{S}{N}\right)^2 = \mathrm{Tr}\left(C_0 C^{-1} - 1\right) + \log\left(\det C / \det C_0\right)$$
- Small deformation:

$$C = C_0 + \varepsilon C_1 + \frac{\varepsilon^2}{2} C_2$$

$$\left(\frac{S}{N}\right)^2 = \frac{\varepsilon^2}{2} \sum_{ij} \frac{\left|C_1^{ij}\right|^2}{C_0^{ii} C_0^{jj}}$$

Our Case:

Lets assume Gaussian distribution for the lensed T_{CMB}:

$$\left(\frac{S}{N}\right)^2_{\mathrm{TEMP}} = \frac{1}{2}\sum_{ll'}\frac{\left|\Delta C_{l,l'}\right|^2}{C_l^T C_{l'}^T}$$

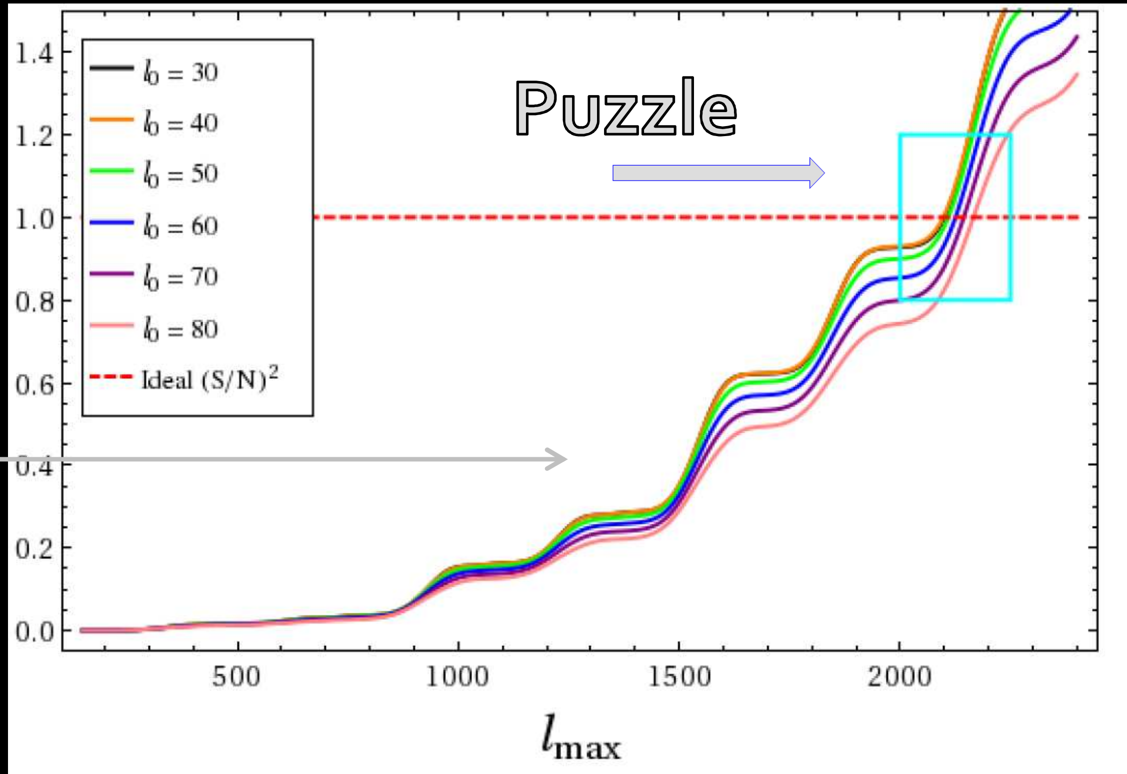
Where:

$$\Delta C_{ll'} = \delta\psi\left[\left(l'-l\right)\left(l'C_{l'} - lC_l\right)\right] + \mathrm{cc}$$

This S/N should be smaller than the Ideal !!!

Toy Example: Single Mode Deflection

$$\left(\frac{S}{N}\right)^2_{TEMP} \Big/ \left(\frac{S}{N}\right)^2_{IDEAL}$$

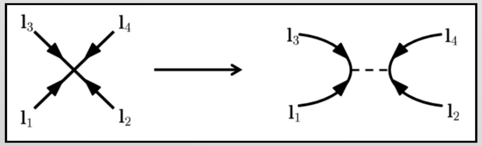


Accumulated SN^2 versus the resolution of a CMB probe

- Wrong behavior at l > 2000.
- Universal: No dependence on the deflecting potential & model parameters

Non-Gaussianity Solves the Puzzle

- We know: LCDM weak lensing adds non-Gaussianity to T_{CMB} via connected **4pf**



(e.g. Lewis & Challinor 2006)

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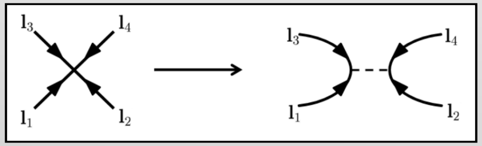
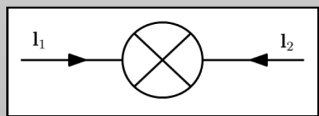


(e.g. Lewis & Challinor 2006)

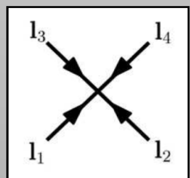
- "Field Theory for Lensing": Feynmann rules

<u>Propagator:</u> T_{CMB} power spectrum

<u>Vertices:</u>



Single lens (by PIP)

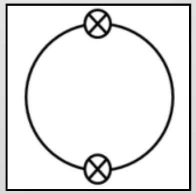


LCDM 4pf (connected)

Correction to the Realistic S/N

- An alternative way to calculate the realistic S/N

$$\left(\frac{S}{N}\right)^2_{\mathrm{TEMP}} = \frac{1}{2}\sum_{ll'}\frac{\left|\Delta C_{l,l'}\right|^2}{C_l^T C_{l'}^T} \quad =$$



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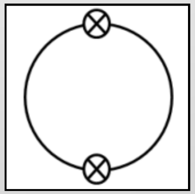
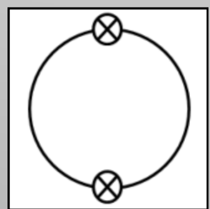
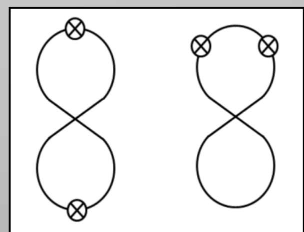


- The 2-loop correction to the S/N (from the non-Gaussianity)

$$\left(\frac{S}{N}\right)^2_{\mathrm{OBS}} =$$

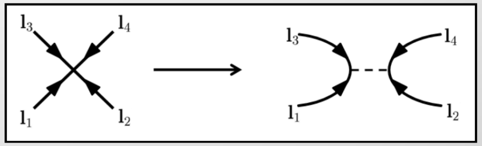


$$+$$

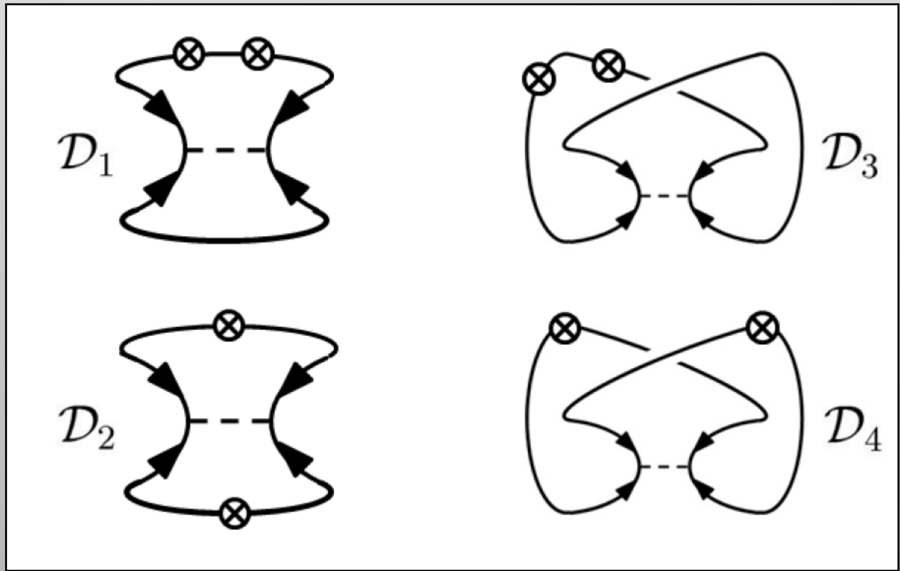


Some Details

- Substructure of the vertex is complicated



- 4 different ways to add the lens and to close loops



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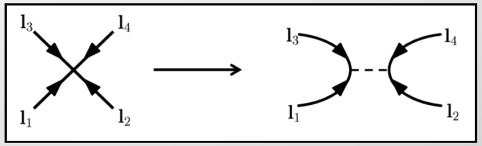
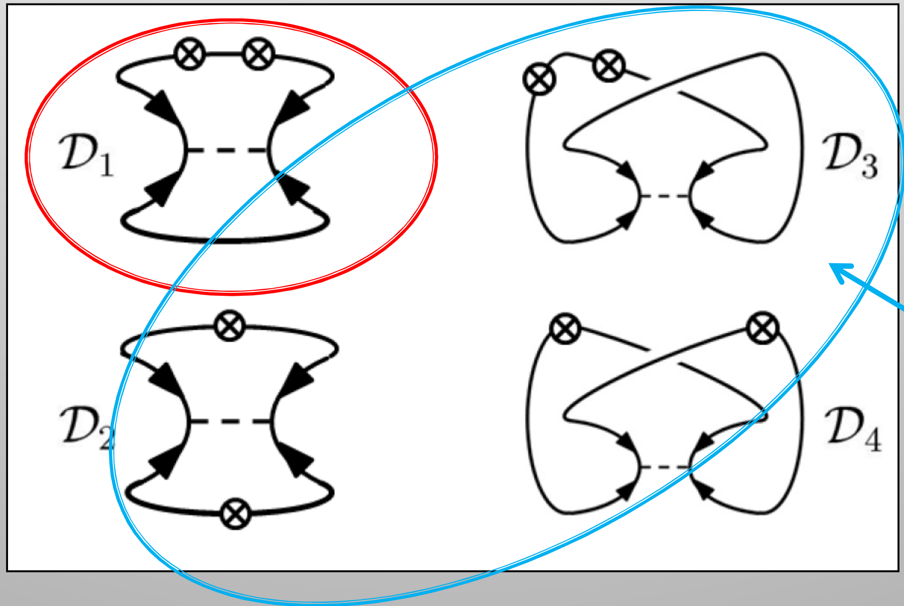


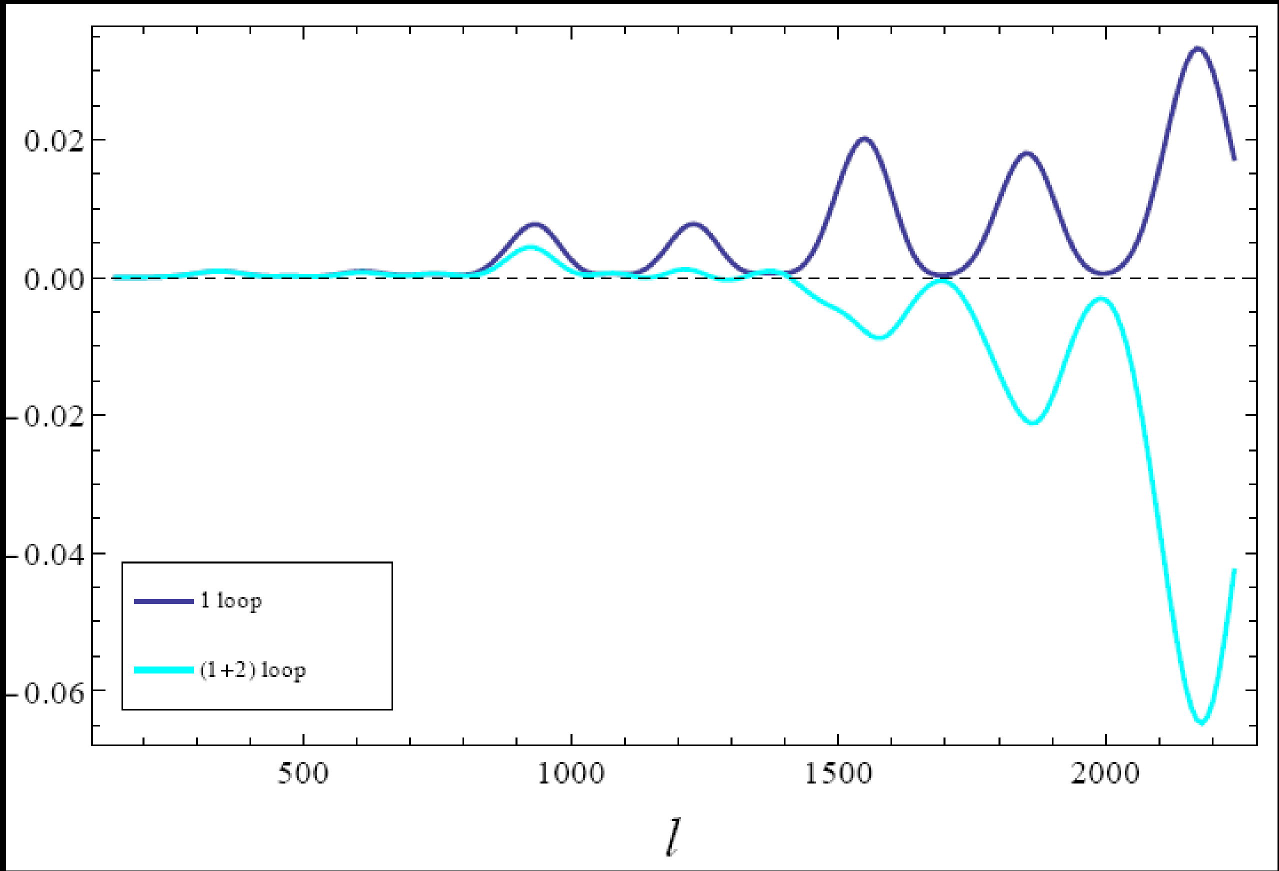
- 4 different ways to add the lens and to close loops

Positive



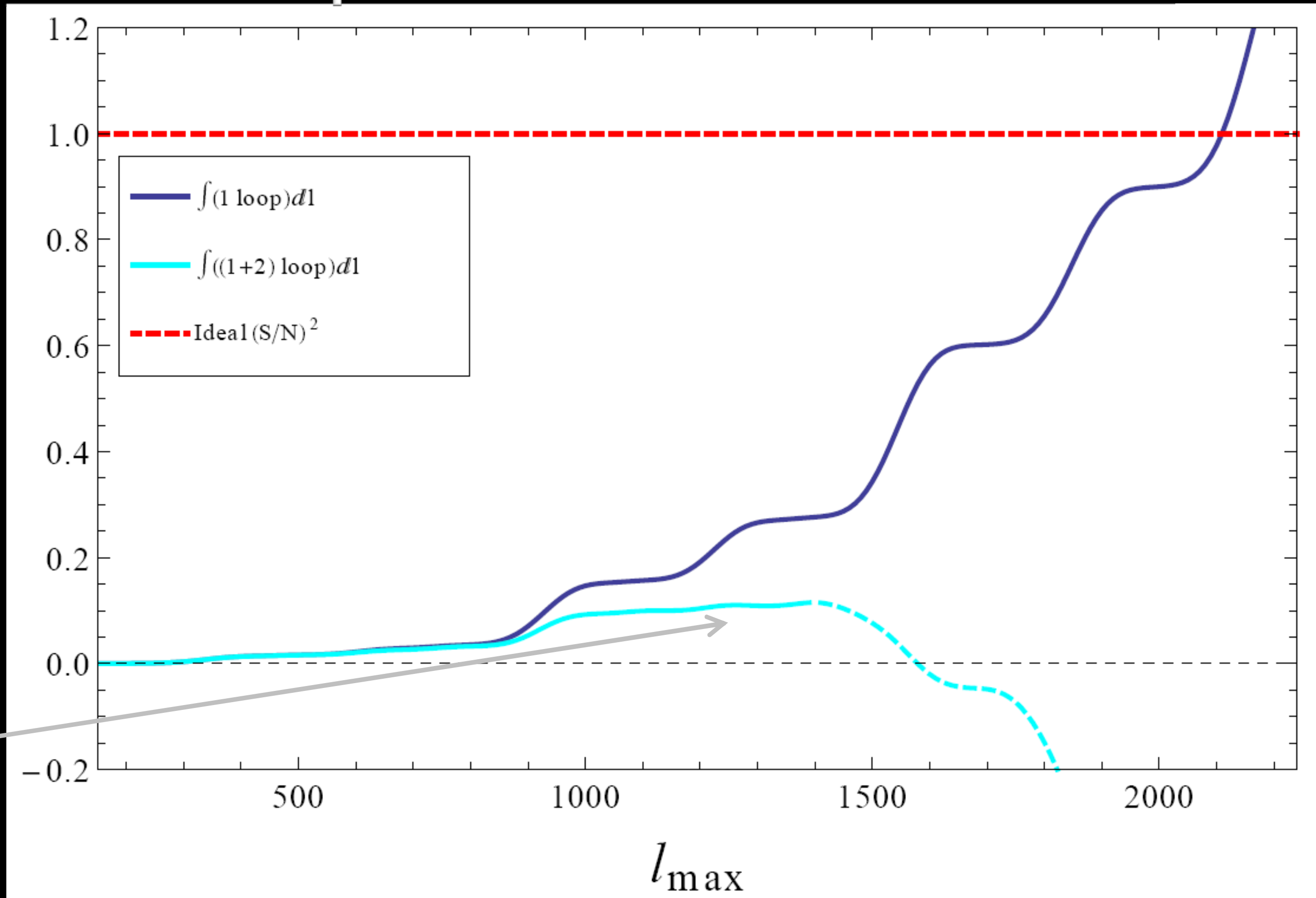
Negative

The SN_l^2 vs Multipole



- The correction contributes at $l > 900$.
- At $l \sim 1400$ the $SN_l^2 < 0$.
  Higher order terms in loop expansion should be added to fix it!

Accumulated SN_l^2 vs the Resolution



$$\left(\frac{S}{N}\right)^2_{OBS} \Big/ \left(\frac{S}{N}\right)^2_{IDEAL}$$

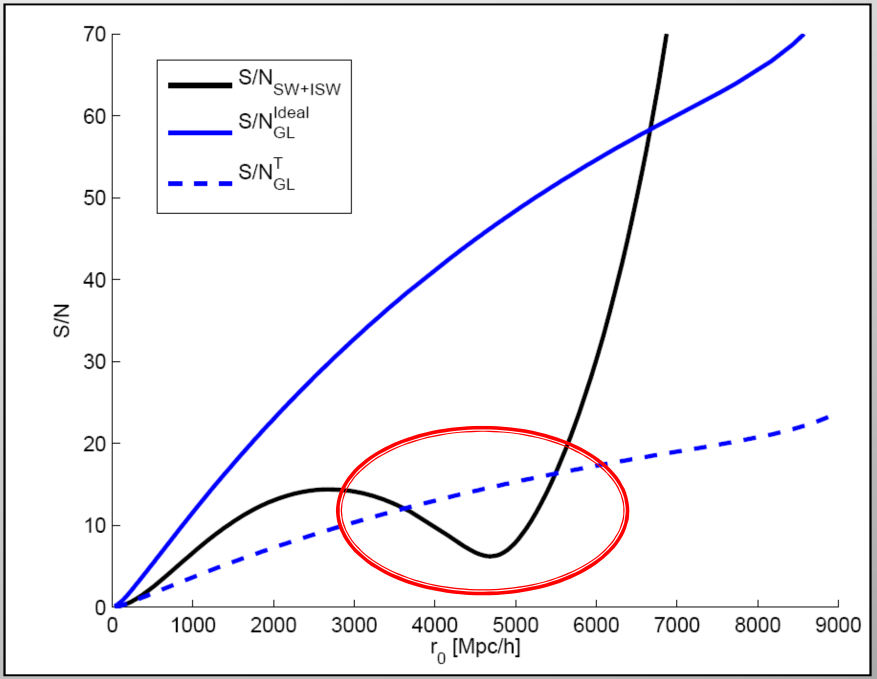
- Plateau at $1000 < l < 1400$!
- The true SN from temperature should be:

$$\left(S/N\right)^2_{OBS} = \frac{1}{10}\left(S/N\right)^2_{IDEAL}$$

For the Pre-Inflationary Relic

- The approximated SN² for a realistic experiment

$$\left(\frac{S}{N}\right)^2_{\mathrm{OBS}} = \frac{1}{10}\left(\frac{S}{N}\right)^2_{\mathrm{IDEAL}}$$



- The “realistic” signal to noise is high in the SW-ISW cancellation region.

A Side Remark on a Single Lens

- Non-gaussianity of T_{CMB} MUST be taken into account.
- Results hold for any “single lens”, which breaks statistical isotropy

- Other examples for a single lens:
  - Texture (Turok & Spergel 1990)
  - Giant Void (Inoue & Silk 2007)
- Previous works: lensing by a giant void and a texture.
- Neither the ideal limit on detection nor the effect of non-Gaussianity considered.

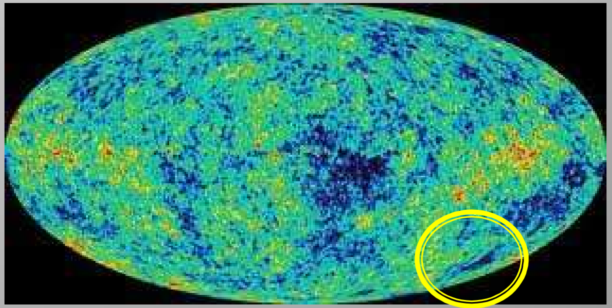
Useful:
Previously Overestimated Void

- In literature:
  A void that creates a cold spot via ISW was thought to have a large SN ~ 100 via weak lensing.

- In practice it is barely observable.

- For a void that gives the cold spot:

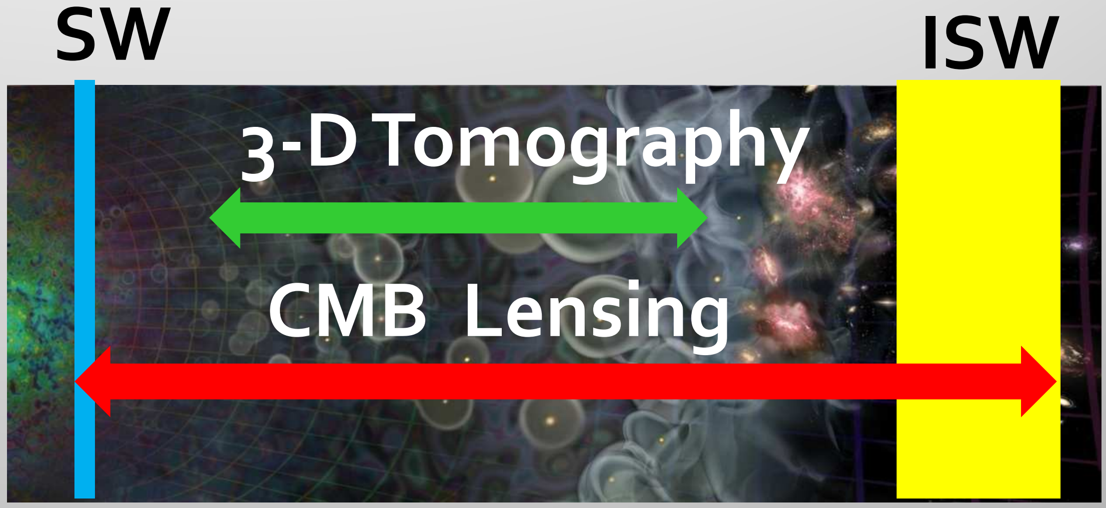
$$\boxed{\left(S/N\right)_{\mathrm{IDEAL}} = 3.9} \Rightarrow \boxed{\left(S/N\right)_{\mathrm{OBS}} = 1.3}$$



Conclusions

- Constrain PIP and explain lack of large angular correlations & dipole in peculiar velocity

- Future probe:
  21-cm



- For any single lens non-Gaussianities must not be overlooked

Thank you!