A Journey Through the "Clumpy" Universe

Devdeep Sarkar
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In collaboration with:
Scott Sullivan (UCI/UCLA), Shahab Joudaki (UCI), Alexandre Amblard (UCI), Paolo Serra (UCI), Kiyotomo Ichiki (Tokyo), Daniel Baumann (Princeton/MIT), Daniel Holz (Los Alamos), Asantha Cooray (UCI).

Carnegie Mellon McWilliams Center for Cosmology Lunch Seminar November 21, '08

Dark Energy & Primordial non-Gaussianity with Future Generation Surveys: Weak Lensing on the Way

with a sneak-peek to

Detecting Gravity Waves with Weak Gravitational Lensing

Agenda

Dark Energy

- Constraining the EOS
- To Bin or Not to Bin
- SNe Ia ++
- Lensing of SNe
- Other Worries

Non-Gaussianity

- Beyond Gaussianity
- CMB Bispectrum
- Lensing of CMB
- Lensed Bispectrum
- S/N Reduction & Bias

Gravity Waves via Weak Gravitational Lensing

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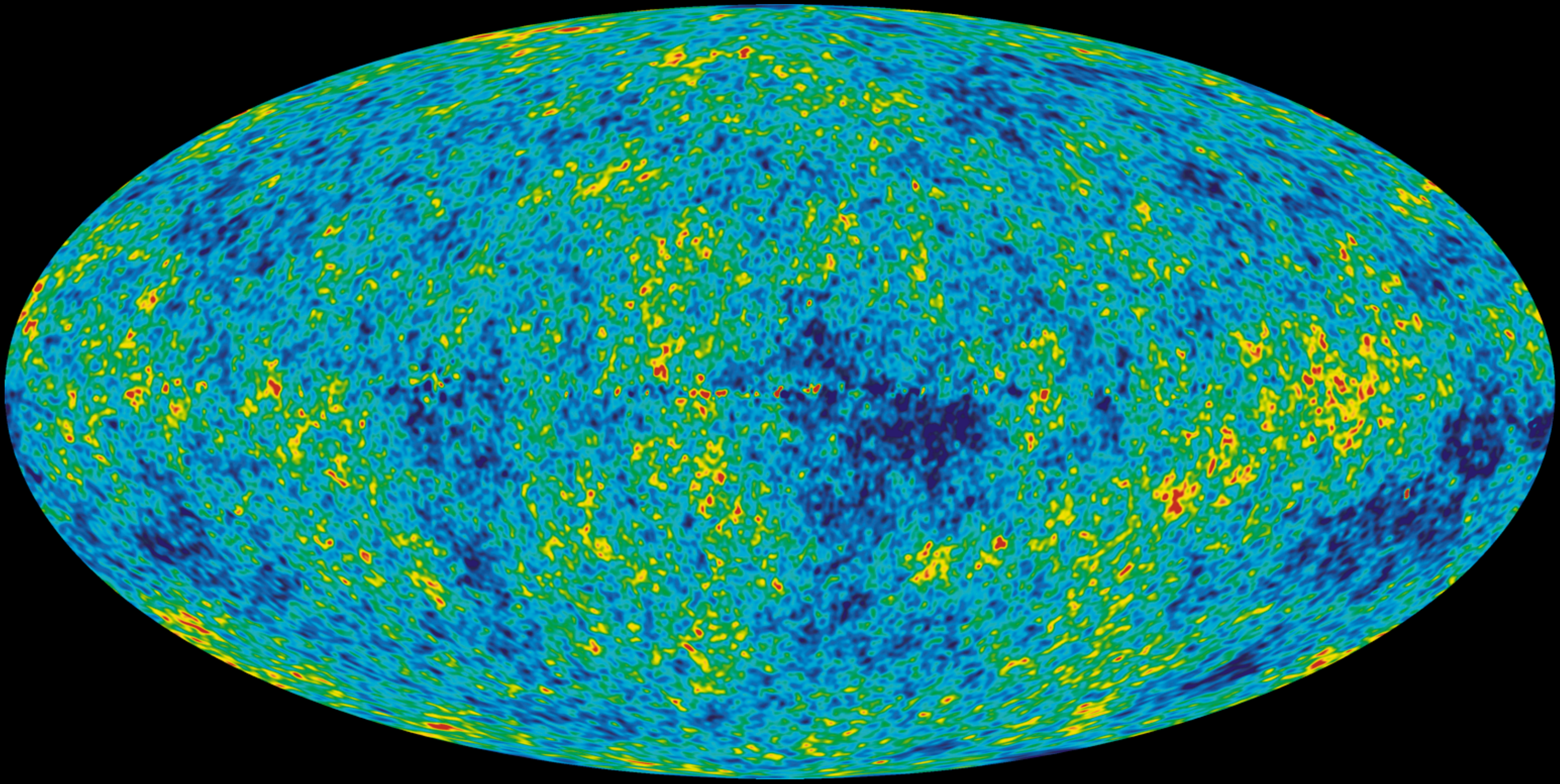
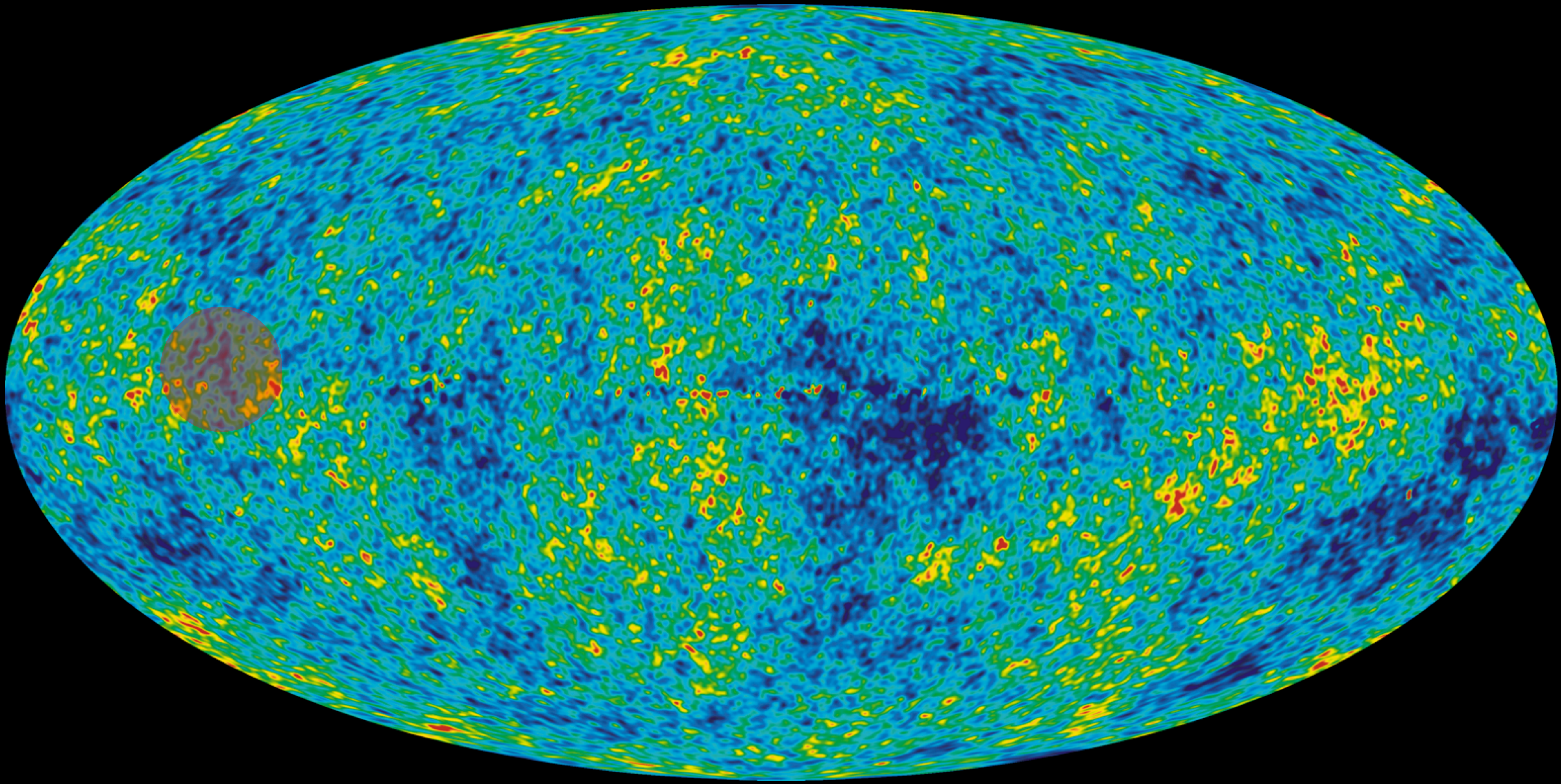
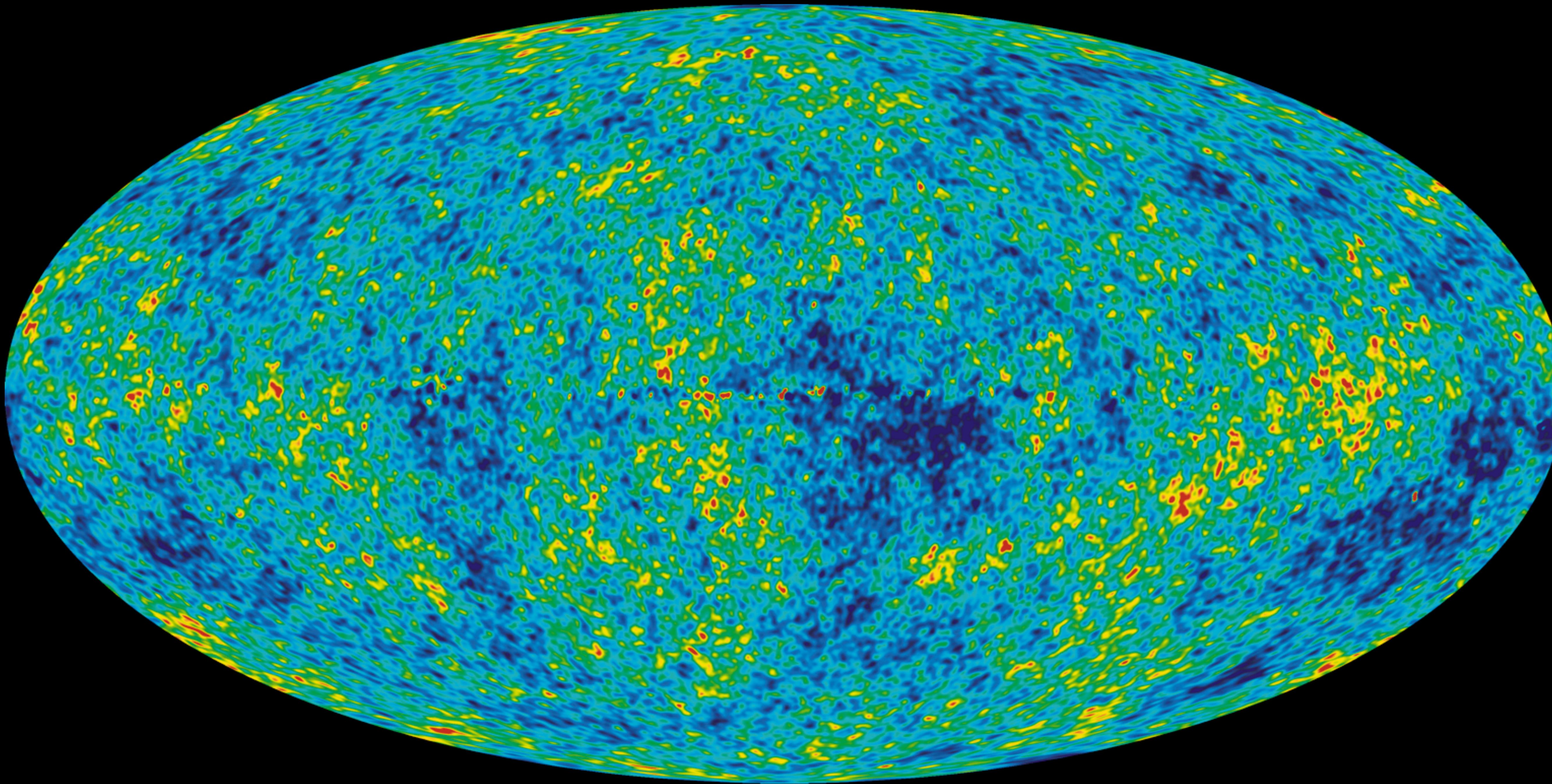
Gravity Waves via Weak Gravitational Lensing



Credit: NASA/WMAP Science Team



Credit: NASA/WMAP Science Team



Credit: NASA/WMAP Science Team

THE ASTRONOMICAL JOURNAL, 116:1009–1038, 1998 September

OBSERVATIONAL EVIDENCE FROM SUPERNOVAE FOR AN ACCELERATING UNIVERSE AND A COSMOLOGICAL CONSTANT

ADAM G. RIESS,[1] ALEXEI V. FILIPPENKO,[1] PETER CHALLIS,[2] ALEJANDRO CLOCCHIATTI,[3] ALAN DIERCKS,[4] PETER M. GARNAVICH,[2] RON L. GILLILAND,[5] CRAIG J. HOGAN,[4] SAURABH JHA,[2] ROBERT P. KIRSHNER,[2] B. LEIBUNDGUT,[6] M. M. PHILLIPS,[7] DAVID REISS,[4] BRIAN P. SCHMIDT,[8,9] ROBERT A. SCHOMMER,[7] R. CHRIS SMITH,[7,10] J. SPYROMILIO,[6] CHRISTOPHER STUBBS,[4] NICHOLAS B. SUNTZEFF,[7] AND JOHN TONRY[11]
Received 1998 March 13; revised 1998 May 6

Illustration: John Kascht

THE ASTROPHYSICAL JOURNAL, 517:565–586, 1999 June 1

MEASUREMENTS OF Ω AND Λ FROM 42 HIGH-REDSHIFT SUPERNOVAE

S. PERLMUTTER,[1] G. ALDERING, G. GOLDHABER,[1] R. A. KNOP, P. NUGENT, P. G. CASTRO,[2] S. DEUSTUA, S. FABBRO,[3]
A. GOOBAR,[4] D. E. GROOM, I. M. HOOK,[5] A. G. KIM,[1,6] M. Y. KIM, J. C. LEE,[7] N. J. NUNES,[2] R. PAIN,[3]
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(THE SUPERNOVA COSMOLOGY PROJECT)

Received 1998 September 8; accepted 1998 December 17

THE ASTROPHYSICAL JOURNAL, 607:665–687, 2004 June 1

Ⓔ

TYPE Ia SUPERNOVA DISCOVERIES AT $z > 1$ FROM THE *HUBBLE SPACE TELESCOPE*: EVIDENCE FOR PAST DECELERATION AND CONSTRAINTS ON DARK ENERGY EVOLUTION[1]

ADAM G. RIESS,[2] LOUIS-GREGORY STROLGER,[2] JOHN TONRY,[3] STEFANO CASERTANO,[2] HENRY C. FERGUSON,[2] BAHRAM MOBASHER,[2]
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Received 2004 January 20; accepted 2004 February 16

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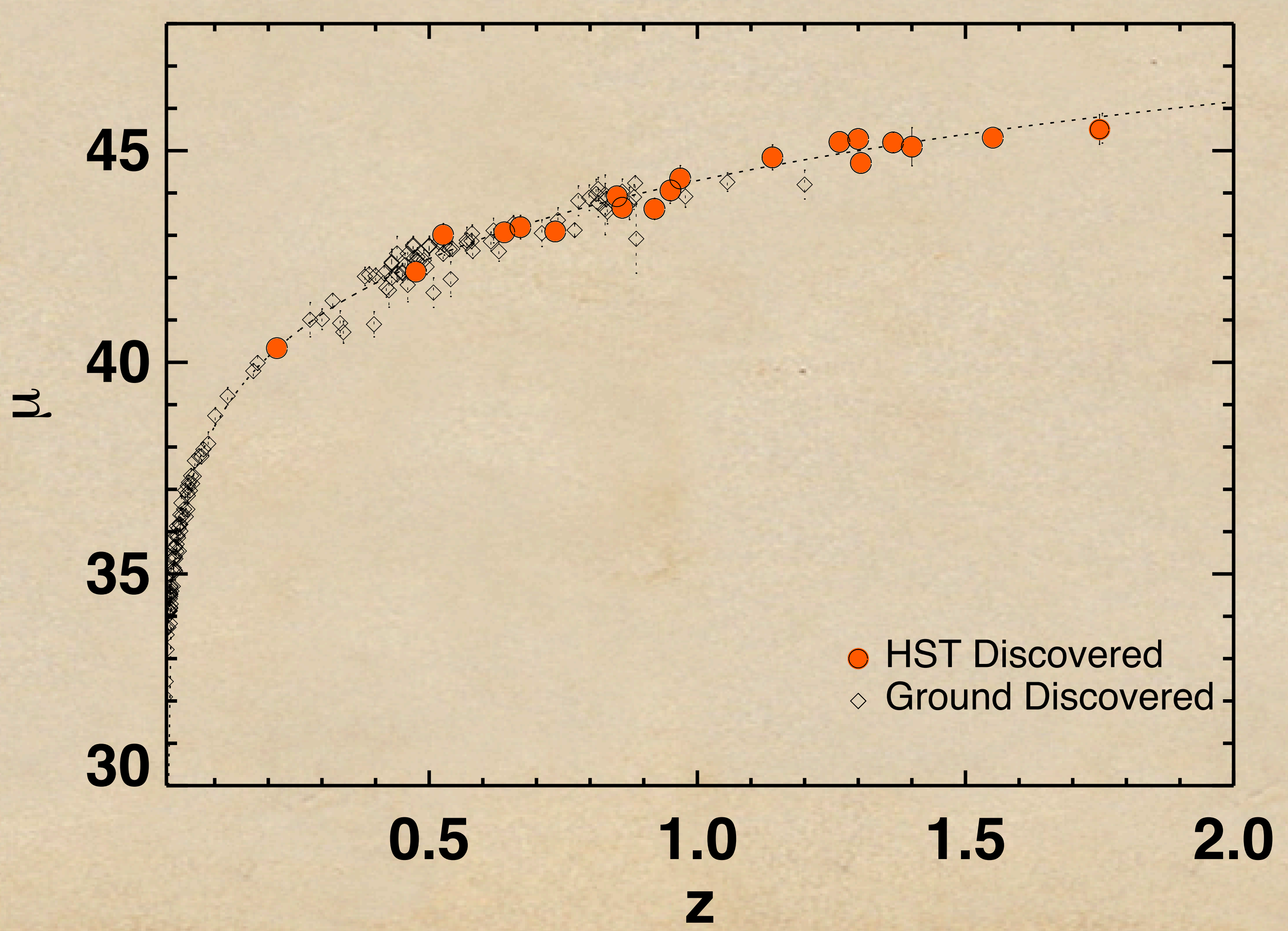

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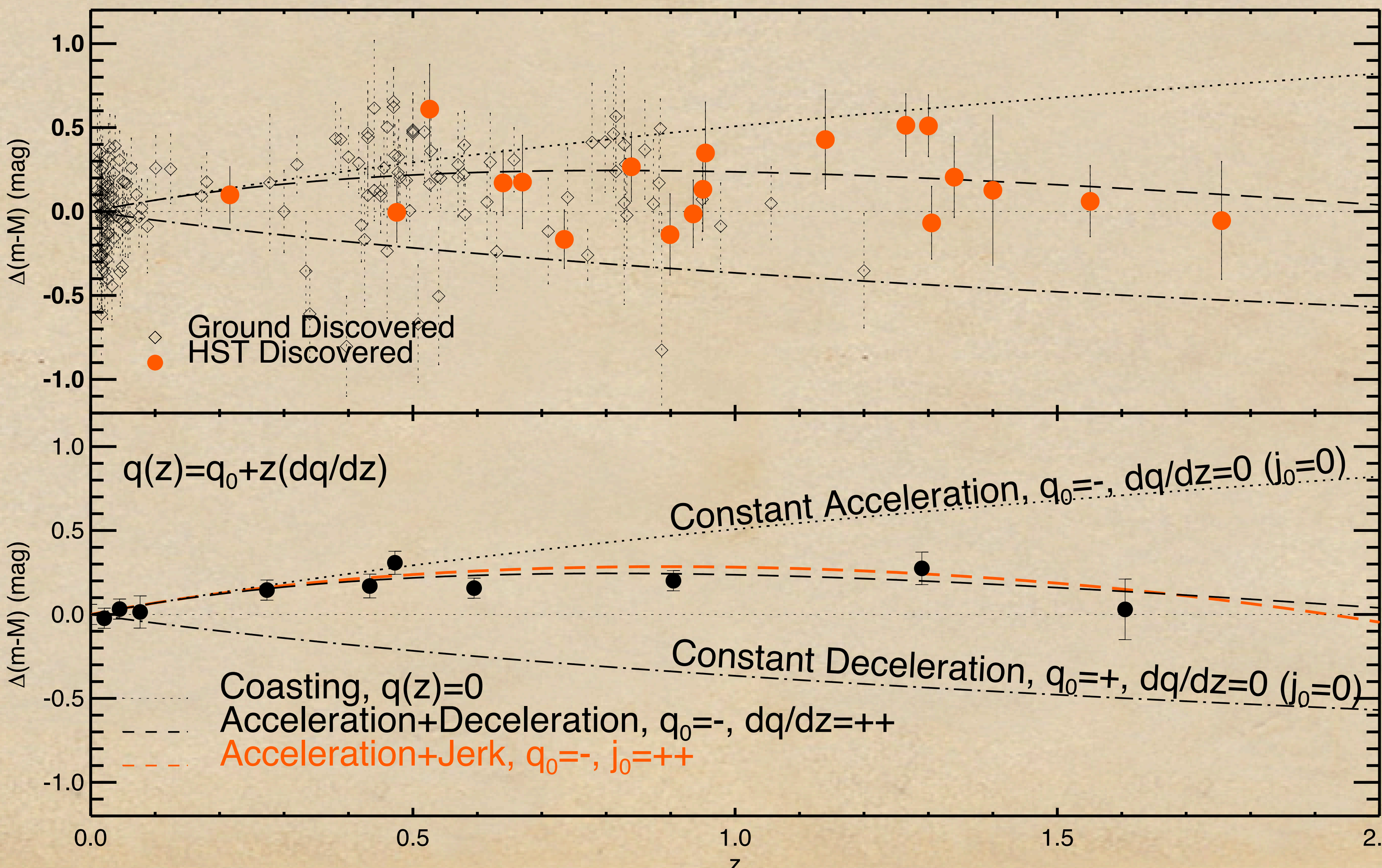


Cosmic Acceleration

Modified Gravity ↔ Cosmic Acceleration ↔ Dark Energy

$$H^2 - \frac{H}{r_c} = \frac{8\pi G}{3}(\rho + \rho_V)$$

Modification of Friedmann equation (5D Gravity)

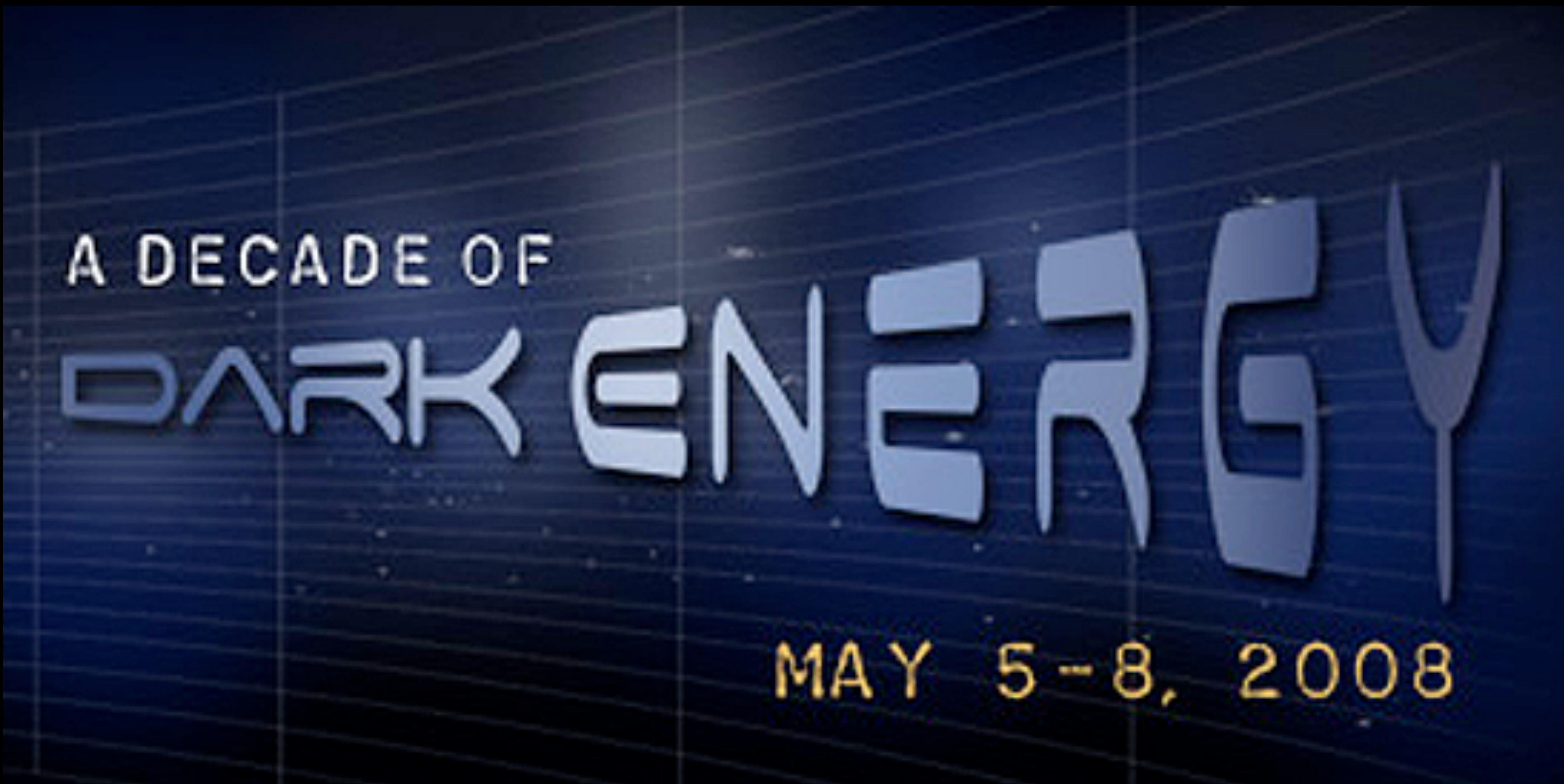
Phenomenological modification to the GR Lagrangian

Vacuum Energy (Cosmological Constant)

Scalar Fields
Evolving Equation of State

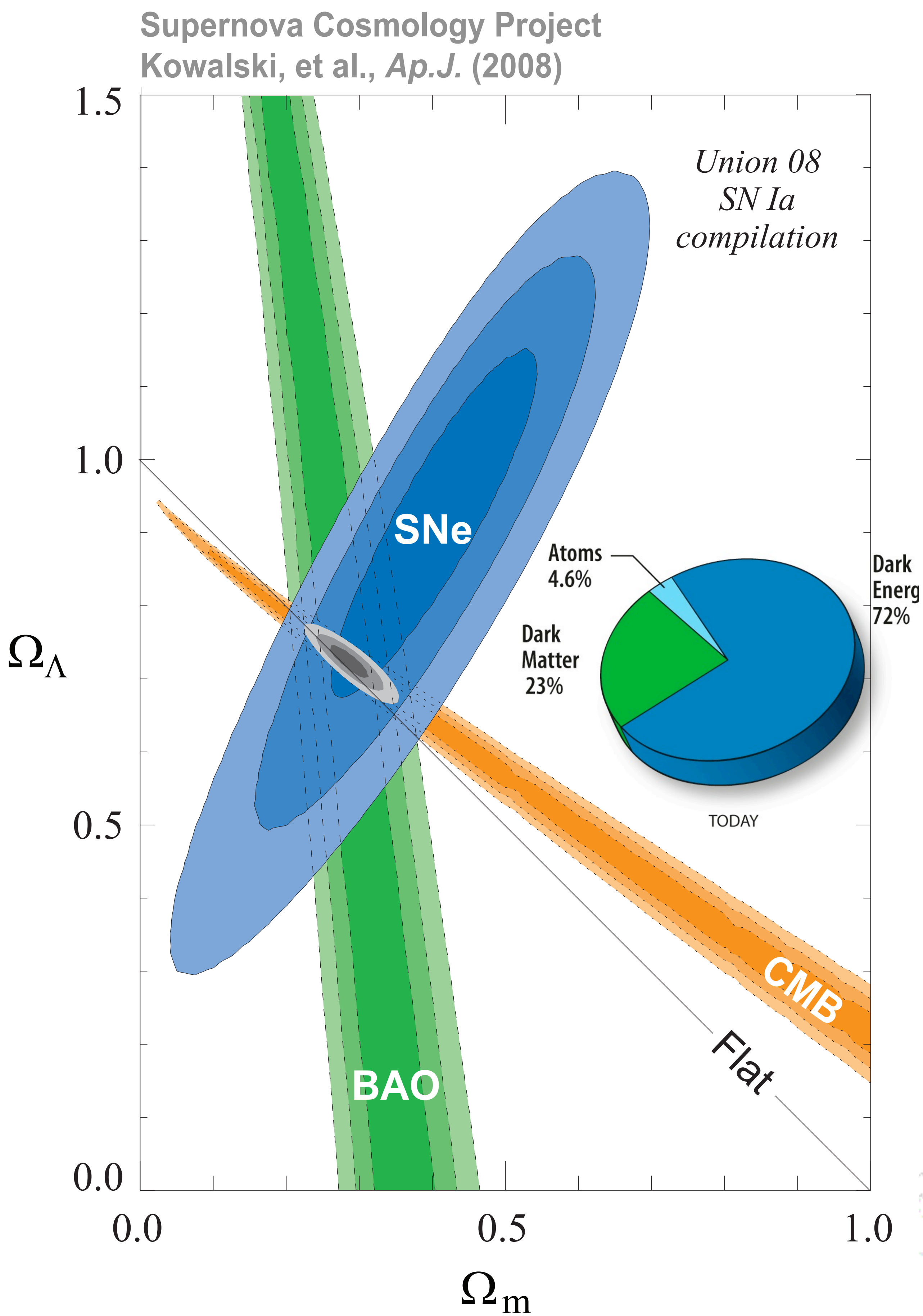
New Physics/Surprises?

Where Do We Stand?
After...



Space Telescope Science Institute, Baltimore, MD

$$\Omega_\Lambda = 0.713^{+0.027}_{-0.029}(\text{stat})^{+0.036}_{-0.039}(\text{sys})$$



What is Dark Energy?

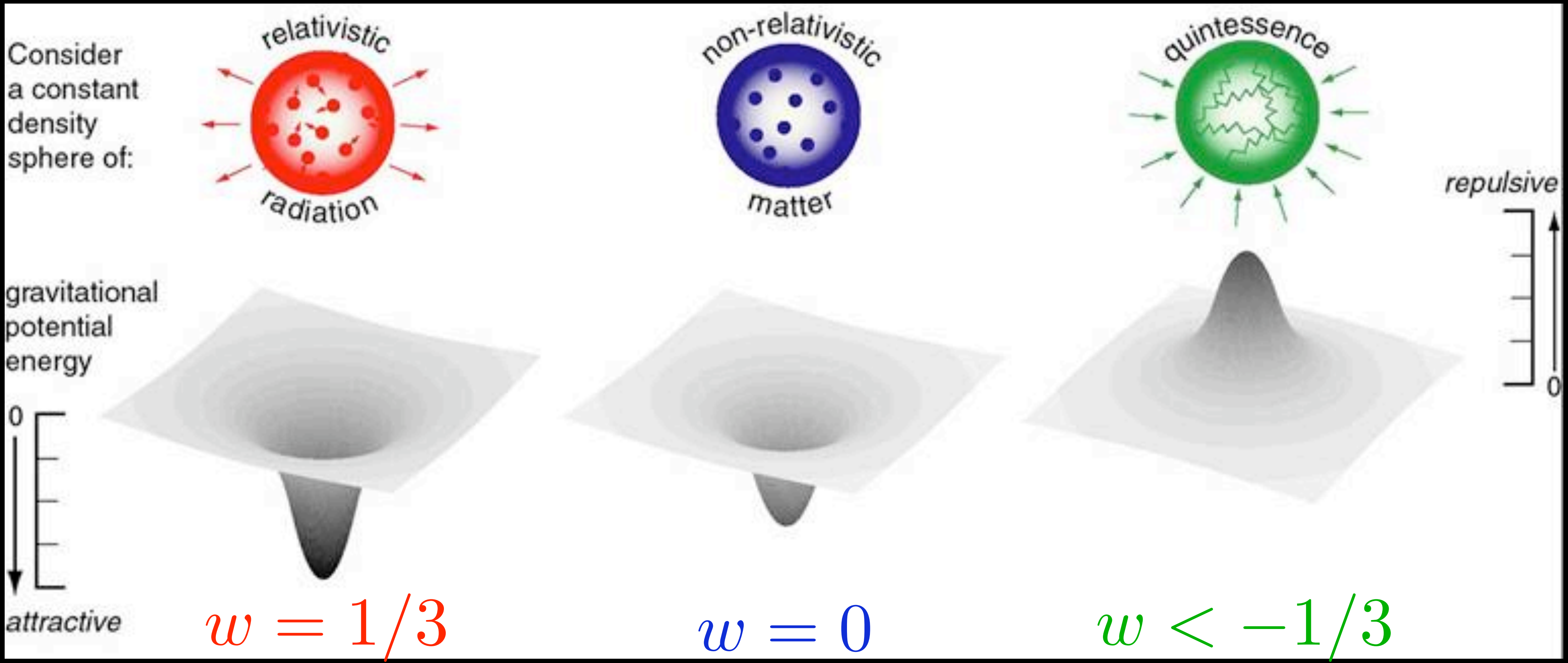
What is Dark Energy?

"Dark Energy is made from an exclusive blend of vital L-amino acids, beneficial vitamins and bionutrients that allows faster and greater ion penetration of the cell walls, visibly enhancing the rate of growth"

GrowLightSource.com

Dark Energy Equation Of State

$$T^{\nu}_{\mu} = diag(\rho, -p, -p, -p) \qquad p = w\rho$$



For Cosmological Constant... $w = -1$

"Seeing" The Dark Energy

...via its effect on the expansion of the Universe

$$H(z) = H_0 \left[\Omega_m(1+z)^3 + \Omega_k(1+z)^2 + (1 - \Omega_k - \Omega_m)F(z)\right]^{1/2}$$

"Seeing" The Dark Energy

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$$H(z) = H_0 \left[\Omega_m (1+z)^3 + \Omega_k (1+z)^2 + (1 - \Omega_k - \Omega_m) F(z)\right]^{1/2}$$

$$F(z) = \exp\left(3 \int_0^z dz' \frac{1+w(z')}{1+z'}\right)$$

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Approaches...

- Standard Candles: Luminosity Distance of SNe
- Standard Rulers:
  - Angular Diameter Distance via BAO
  - Distance to the Last Scattering Surface
- Weak Lensing Tomography

DE EOS Revisited: Different Approaches...

(A) Parameterize w(z) [Adopted by the DETF]

$$w(a) = w_0 + (1-a)w_a$$

Chevallier & Polarski (2001)
(Linder 2003)

DE EOS Revisited: Different Approaches...

(A) Parameterize w(z) [Adopted by the DETF]

$$w(z) = w_0 + w_a z/(1+z)$$

Chevallier & Polarski (2001)
(Linder 2003)

DE EOS Revisited: Different Approaches...

(A) Parameterize w(z) [Adopted by the DETF]

$$w(z) = w_0 + w_a z/(1+z)$$

Chevallier & Polarski (2001)
(Linder 2003)

(B) Non-Parametric w(z)

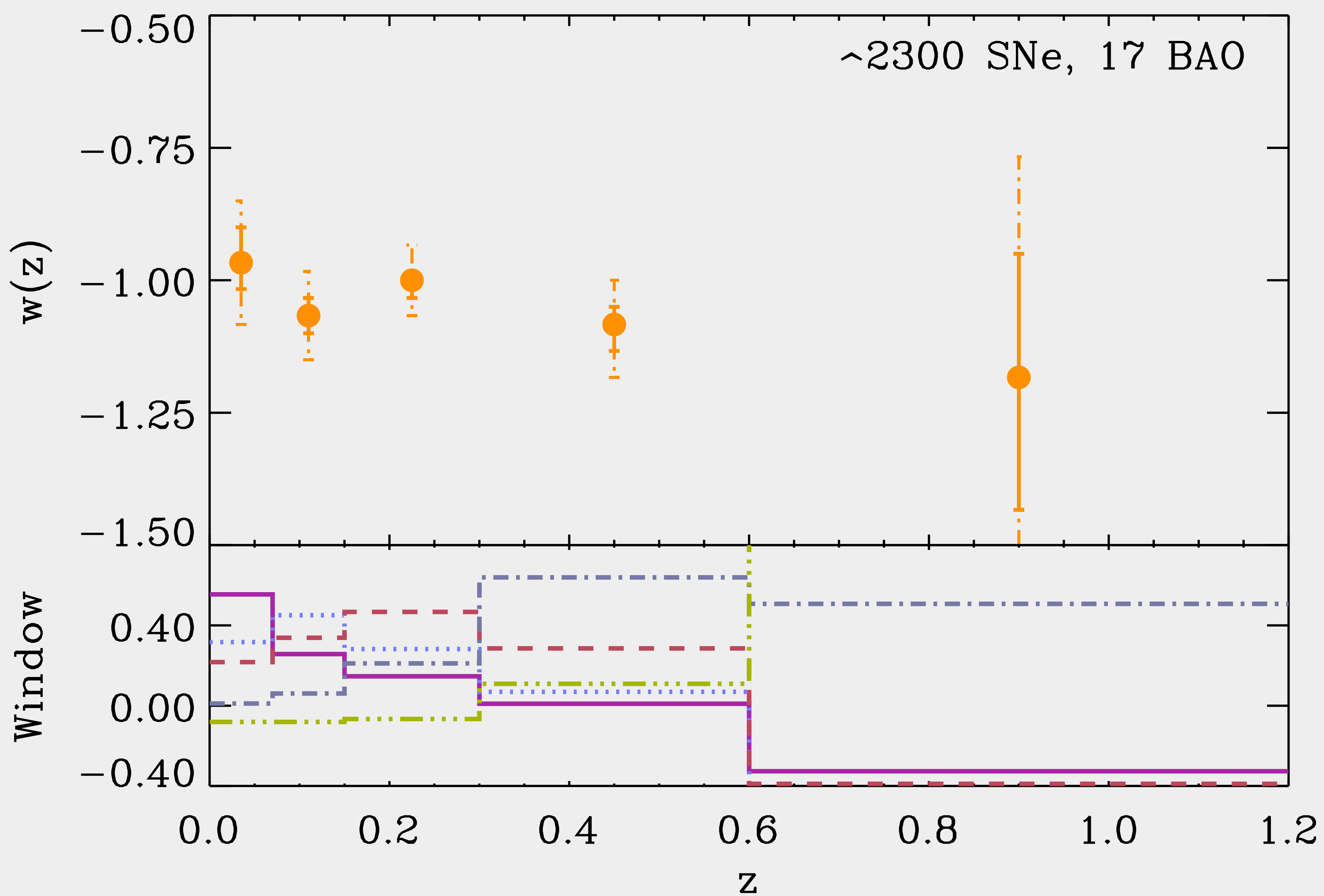
✓ Unbiased Estimate of DE Density (Wang & Lovelace 2001)
✓ Principal Component Approach (Huterer & Starkman 2003)
✓ Uncorrelated Estimates (Huterer & Cooray 2005)

✓ ...

For a review: Please see Sahni and Starobinsky (2006) [arXiv:astro-ph/0610026]

Binned Estimates: Future

$$F(z_n > z > z_{n-1}) = (1+z)^{3(1+w_n)} \prod_{i=0}^{n-1} (1+z_i)^{3(w_i - w_{i+1})}$$



w_1	0-.07
w_2	.07-.15
w_3	0.15-.3
w_4	0.3-0.6
w_5	0.6-1.2
w_6	1.2-2.0

D.S., S. Sullivan, S. Joudaki, A. Amblard, D. Holz, A. Cooray; PRL, 100, 241302 (2008)

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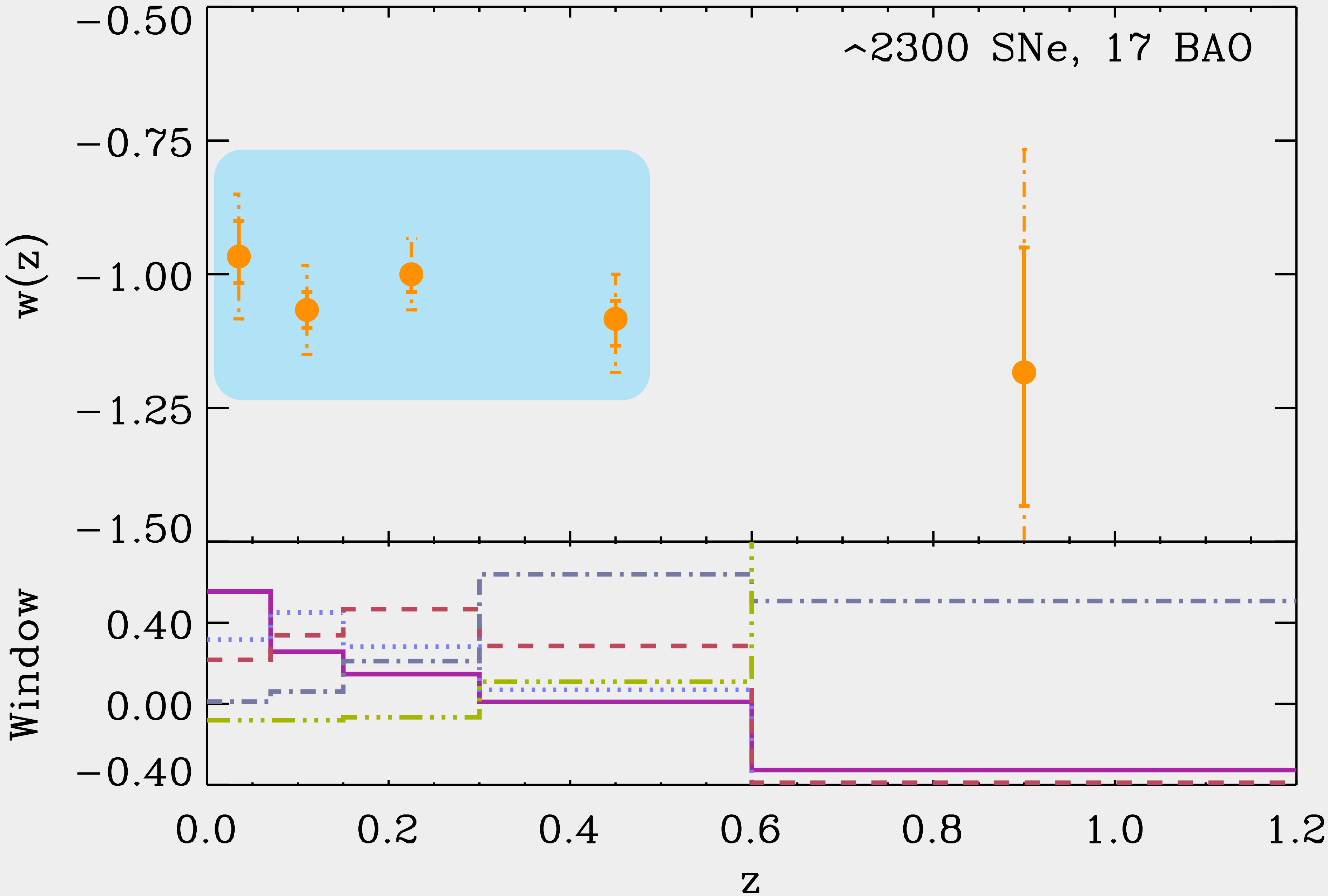

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File Edit View History Bookmarks Window Help Mon 12:26 AM

Codes

http://dsarkar.org/code.html

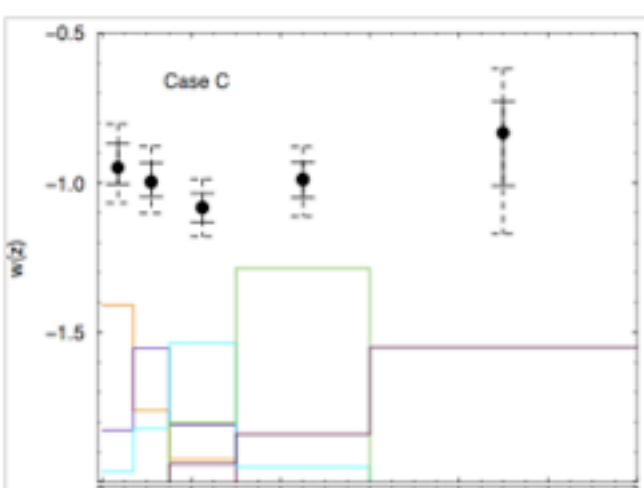
DevdeepSarkar

center for cosmology, uc irvine

› Abode › Research › Publications › Codes › Awards › Talks › Teaching › CV › Personal › Travel

wzBinned Code

wzBinned is a numerical code to extract uncorrelated binned estimates of the dark energy equation of state, w(z), using Type Ia supernovae distance-redshift data and other cosmological probes and priors. It is written in C programming language and based on Markov chain Monte Carlo method. For further details please refer to Sarkar et al., Phys. Rev. Lett. 100 241302 (2008), and Sullivan et al., JCAP 09 004 (2007).



Other Resources

- COSMOMC
- CMBFAST
- IDL Astro

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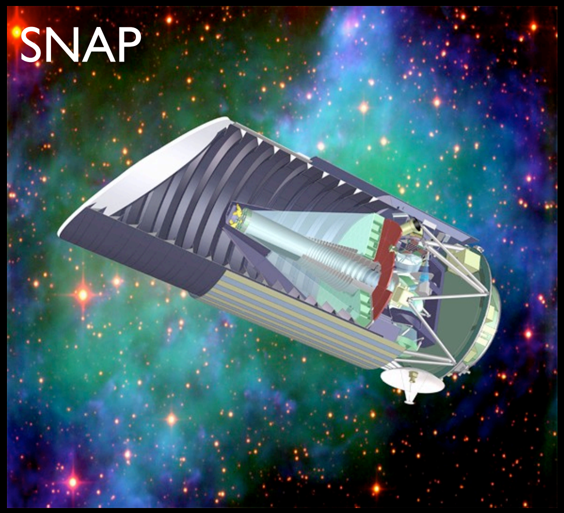
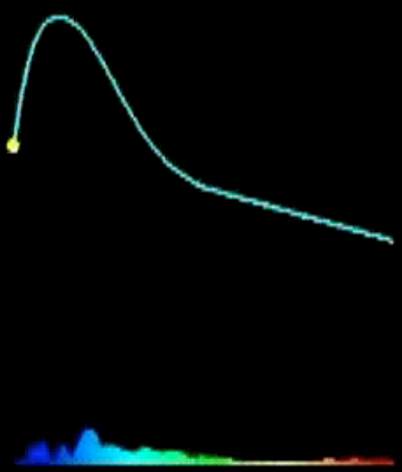
Gravity Waves via Weak Gravitational Lensing

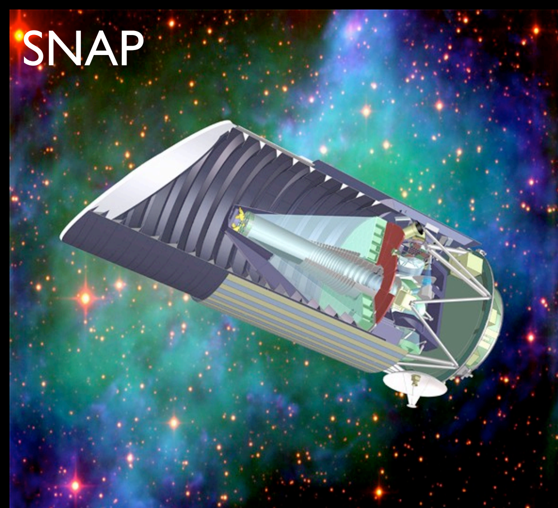
Cosmology with SNe Ia: Revisited

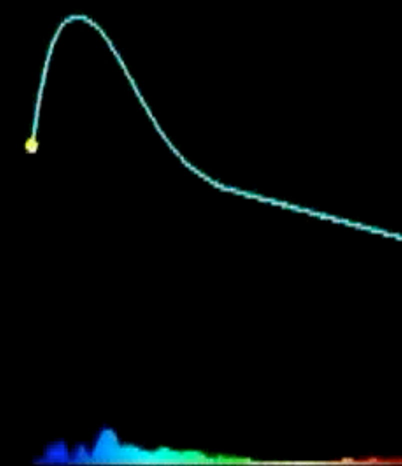




Credit: This clip was prepared by the Supernova Cosmology Project (P. Nugent: spectral sequence; A. Conley: image sequence) with the help of Lawrence Berkeley National Laboratory's Computer Visualization Laboratory (N. Johnston: animation) at the National Energy Research Scientific Computing Center.

Cosmology with SNe Ia: Revisited





Advantages

- ✓ Direct measure of accl.
- ✓ Small dispersion
- ✓ Single objects (easier!)
- ✓ Can be observed over wide z
- ✓ Not cosmic variance limited
- ✓ Straightforward tests of sys.

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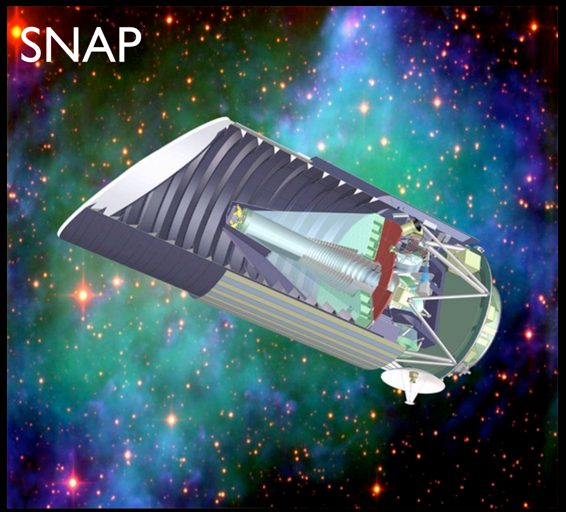


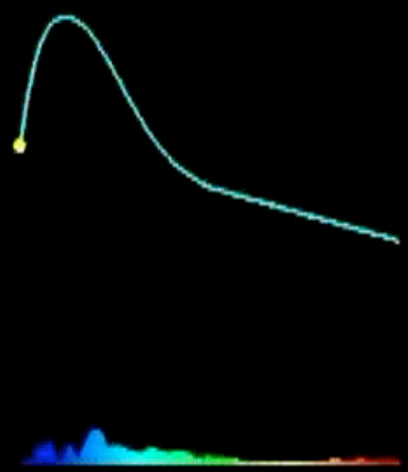


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Challenges

- Dust extinction
- Photometric calibration (Vega)
- Malmquist bias
- K-corrections
- Evolution, chemical comp.
- Population bias + Grav. Lensing

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Challenges: Systematic Uncertainties

source of uncertainty	common (mag)	sample-dep.(mag)	treatment
Extinction	0.013	-	Multi-band photometry including near-IR
Calibration	0.021	0.021	Calibration of standard stars (optical thru near-IR) to <1%
Malmquist	-	0.020	High S/N lightcurves & spectra; requirement of pre-rise data
Lightcurve	0.028	-	SN spectra with broad λ, temporal coverage
Evolution	0.015	-	High-resolution spectroscopy

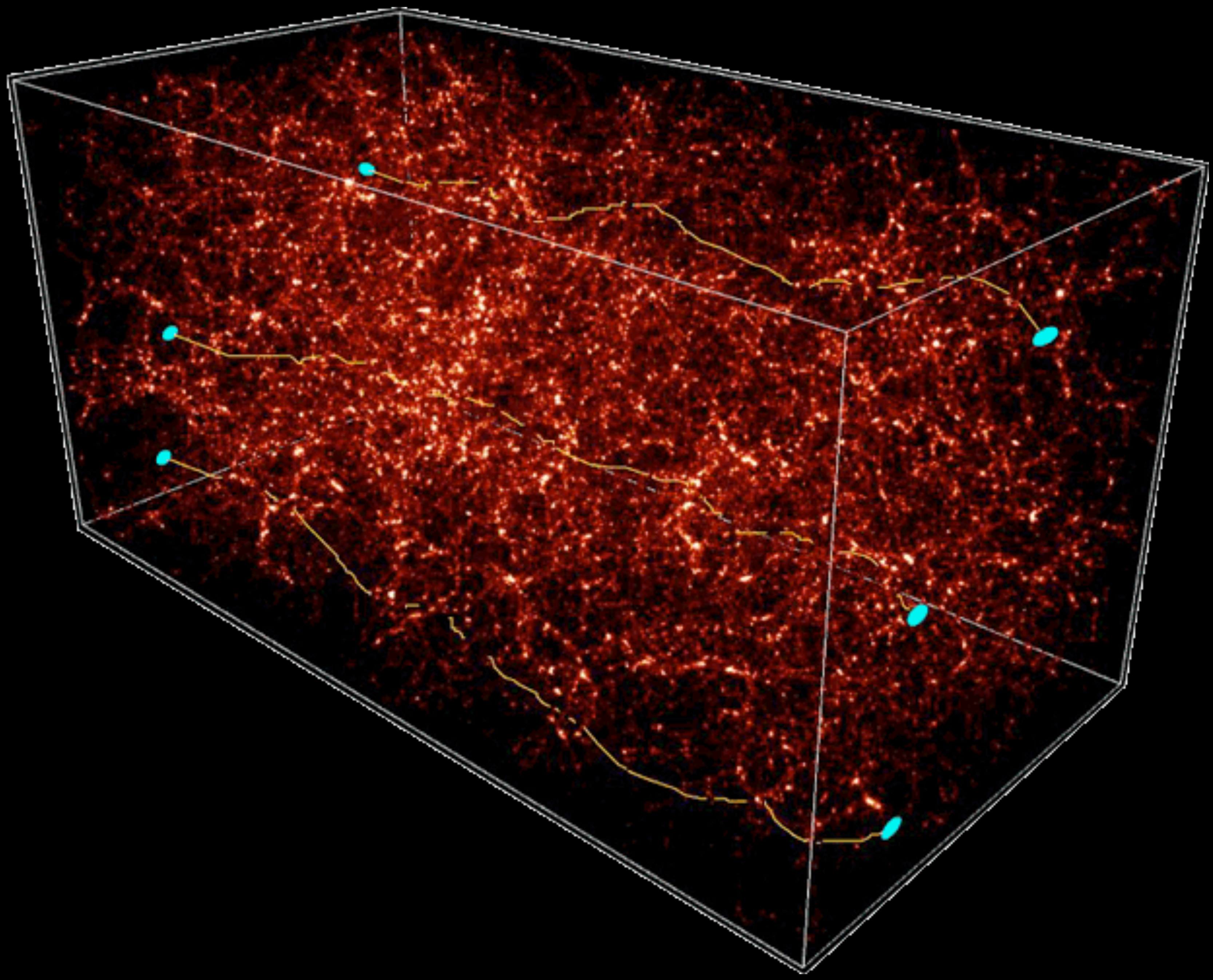
Kowalski et al. (2008), Carnegie Supernova Project: W. Freedman

Lensing	
2-Population	

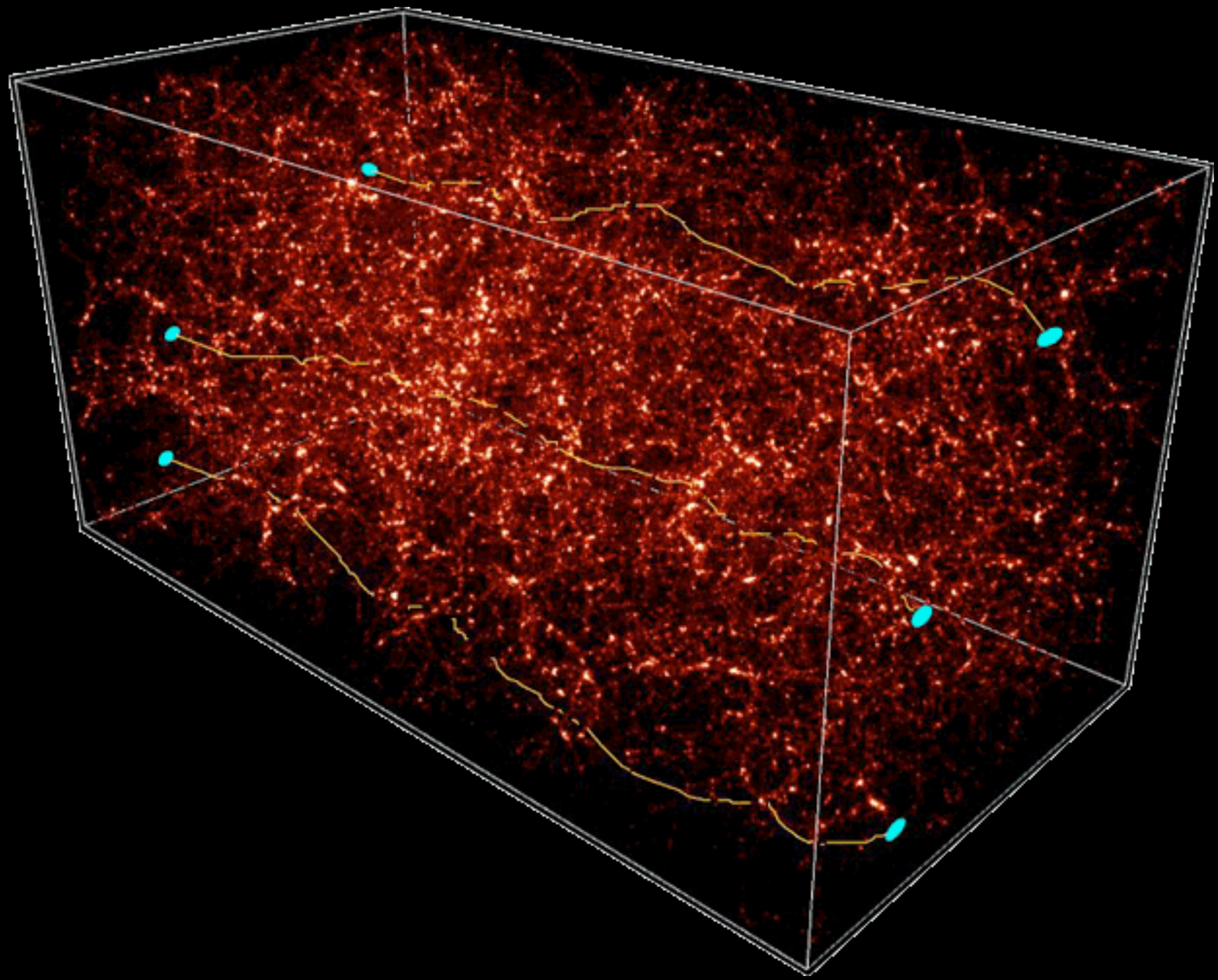
Influence of Gravitational Lensing?

Lensing Galaxy

Influence of Gravitational Lensing?

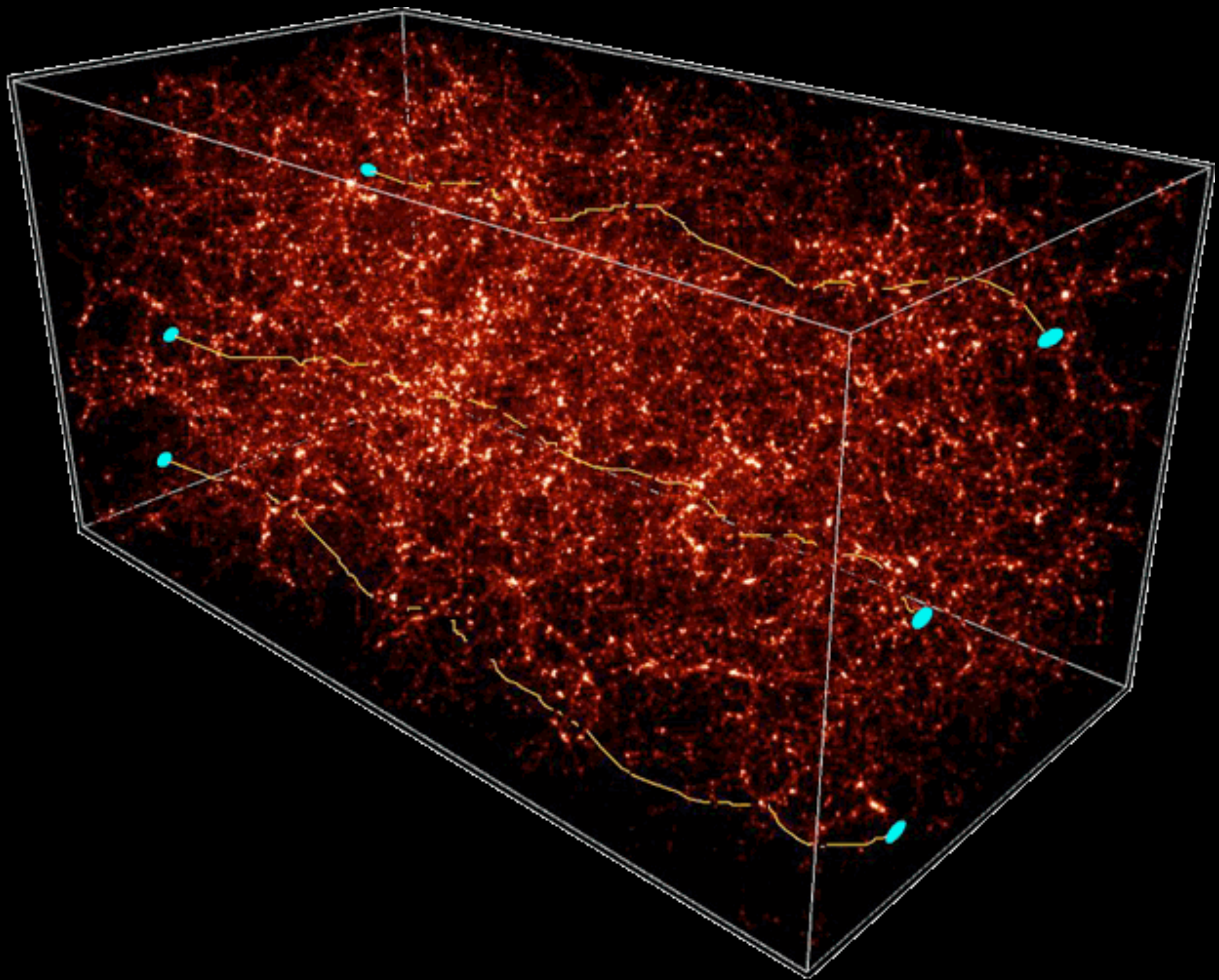


Influence of Gravitational Lensing?



$$\mathcal{F}^{\rm obs,lensed}(z,\hat{\mathbf{n}}) = \mu(z,\hat{\mathbf{n}})\mathcal{F}^{\rm obs,true}(z)$$

Influence of Gravitational Lensing?



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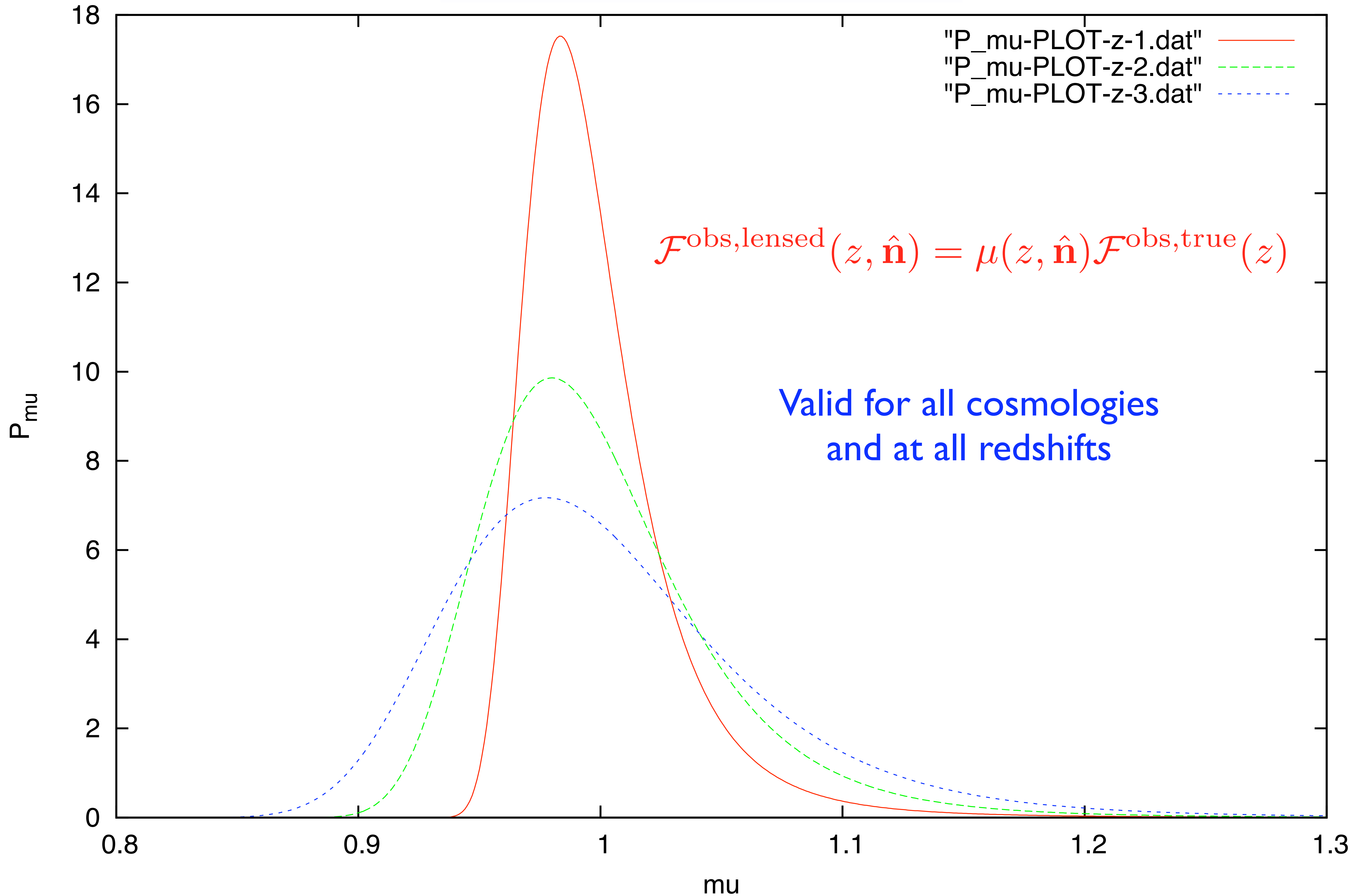
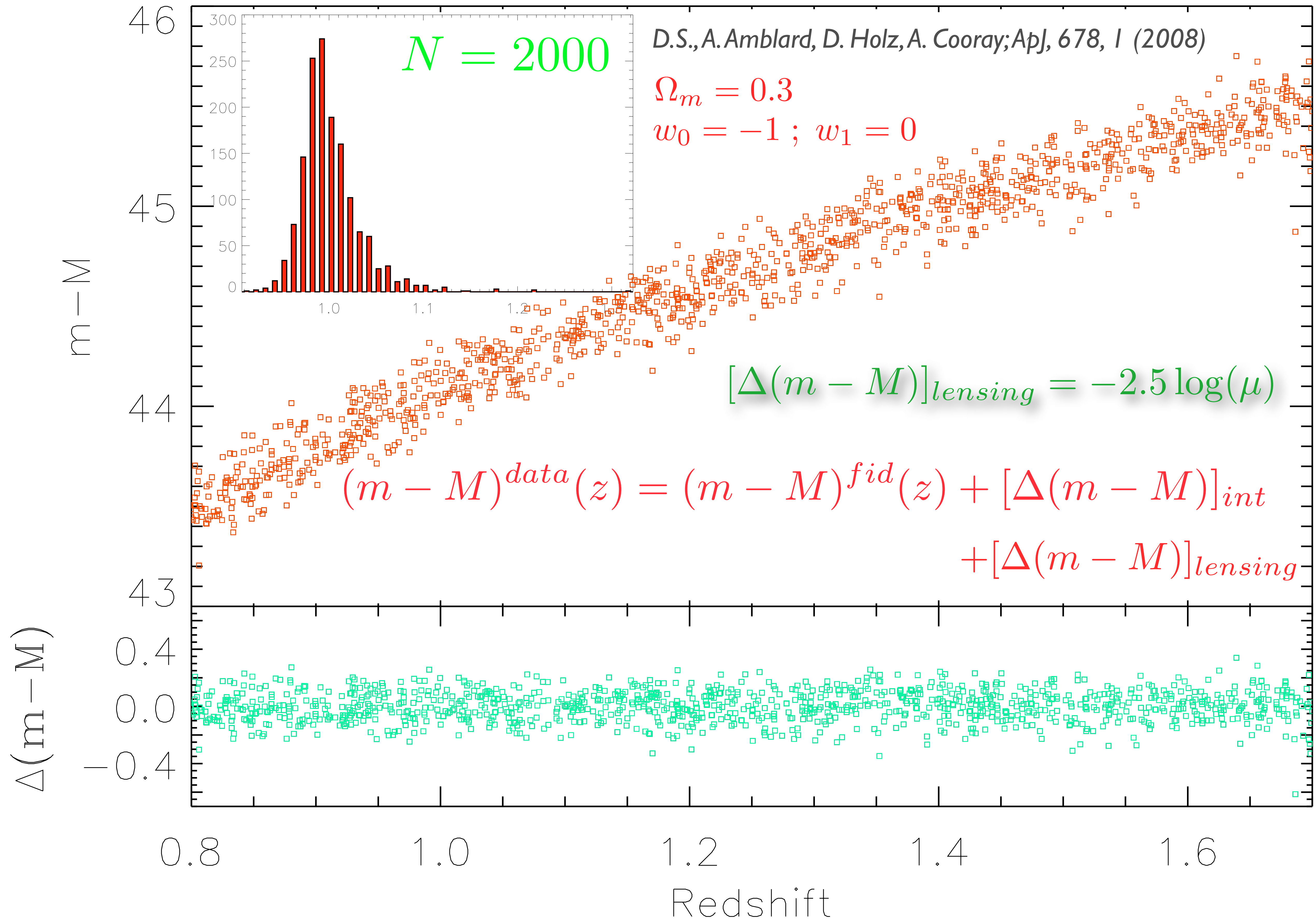
Weak lensing can modify the SNa flux & bias estimates of w

Amplification Probability Distribution

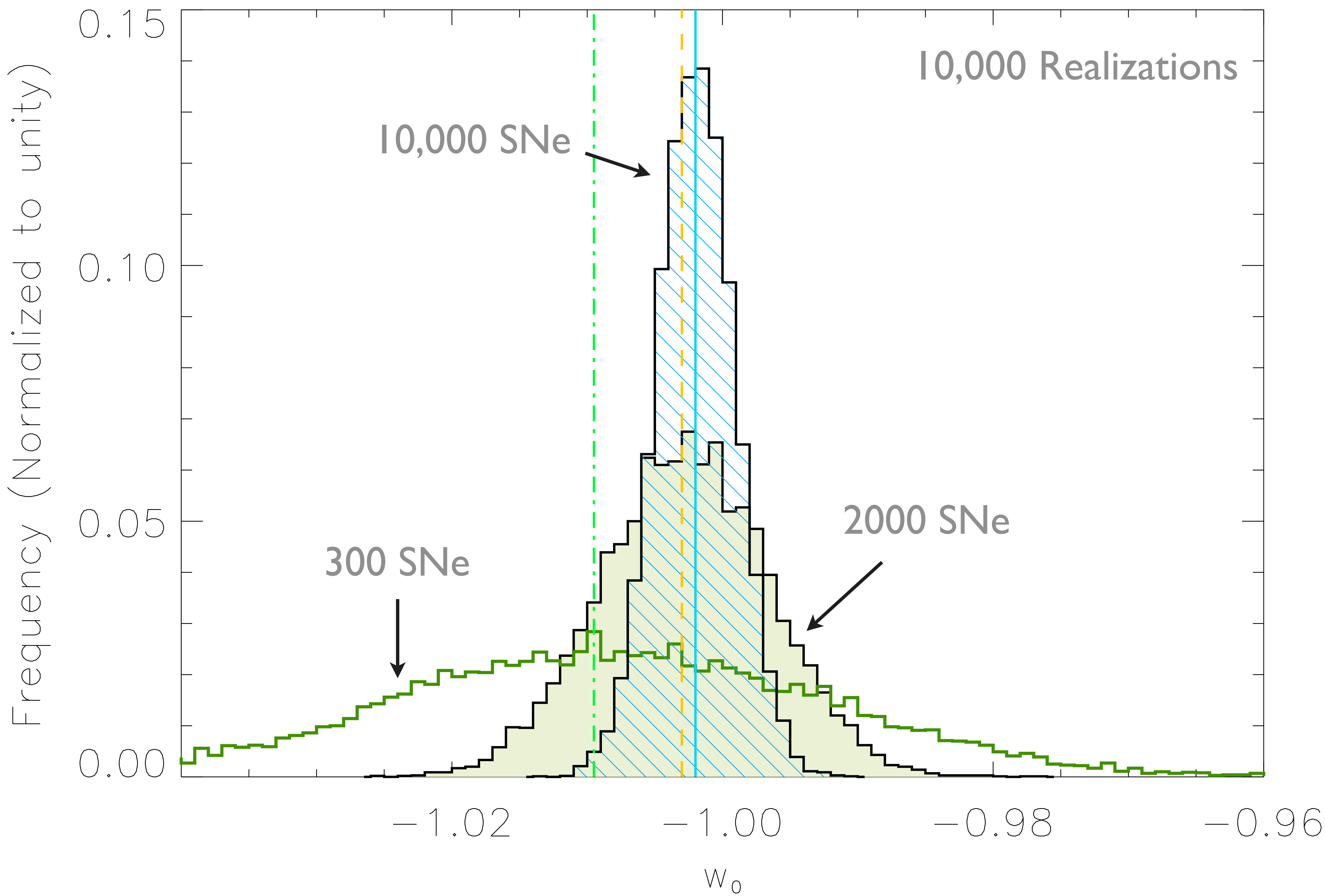


*Wang, Y., Holz, D. E., & Munshi, D., 2002, ApJ, **572**, L15*

Our Analysis with Mock Catalogs

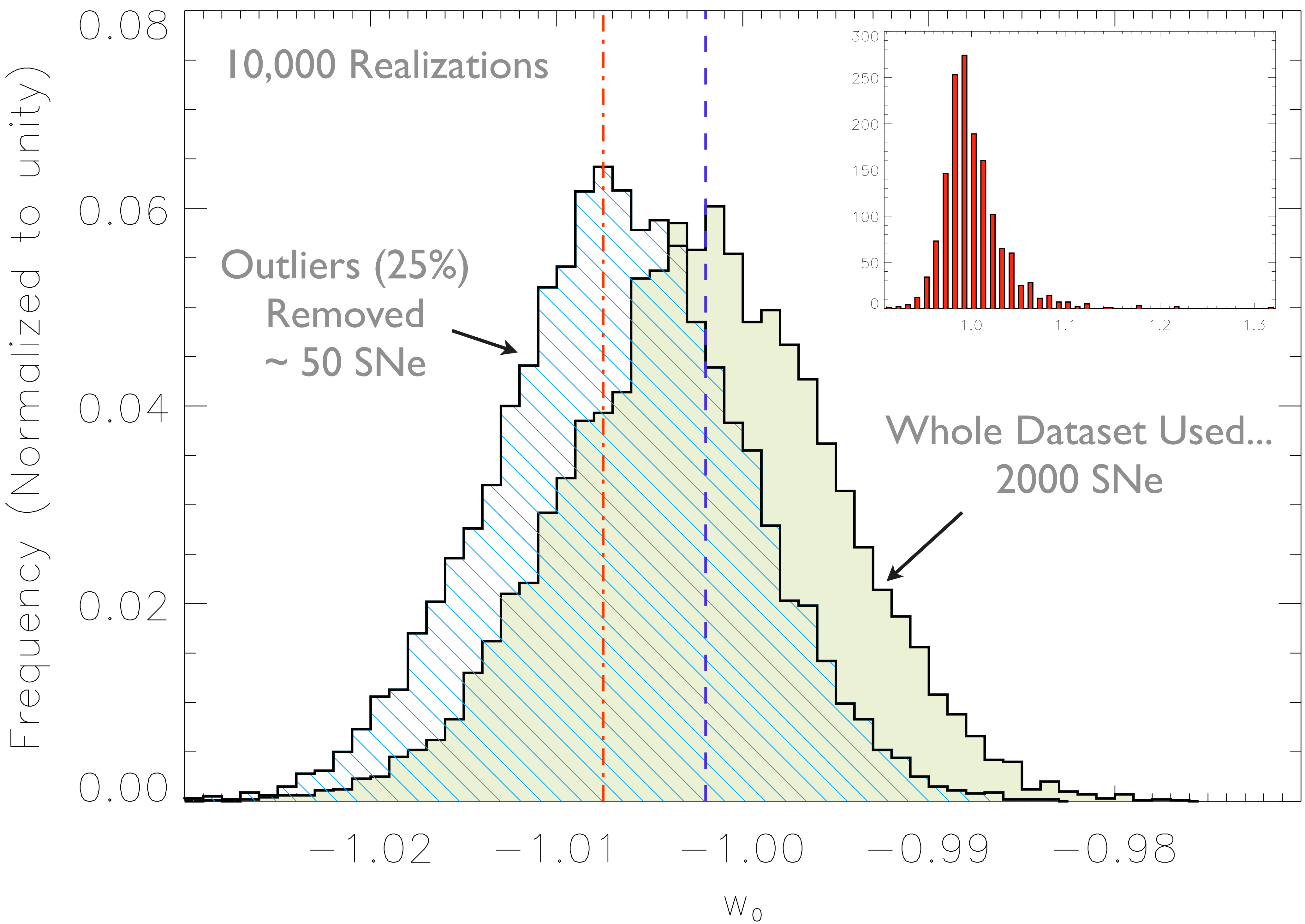


Effect of Weak Lensing on Estimates of "w"



D.S., A. Amblard, D. Holz, A. Cooray; ApJ, 678, 1 (2008)

Effect of Removing the Outliers



D.S., A. Amblard, D. Holz, A. Cooray; ApJ, 678, 1 (2008)

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Lightcurve	0.028	-	SN spectra with broad λ, temporal coverage
Evolution	0.015	-	High-resolution spectroscopy

Kowalski et al. (2008), Carnegie Supernova Project: W. Freedman

Lensing	Need a large # of SNe per redshift bin to keep bias < 1%
2-Population	

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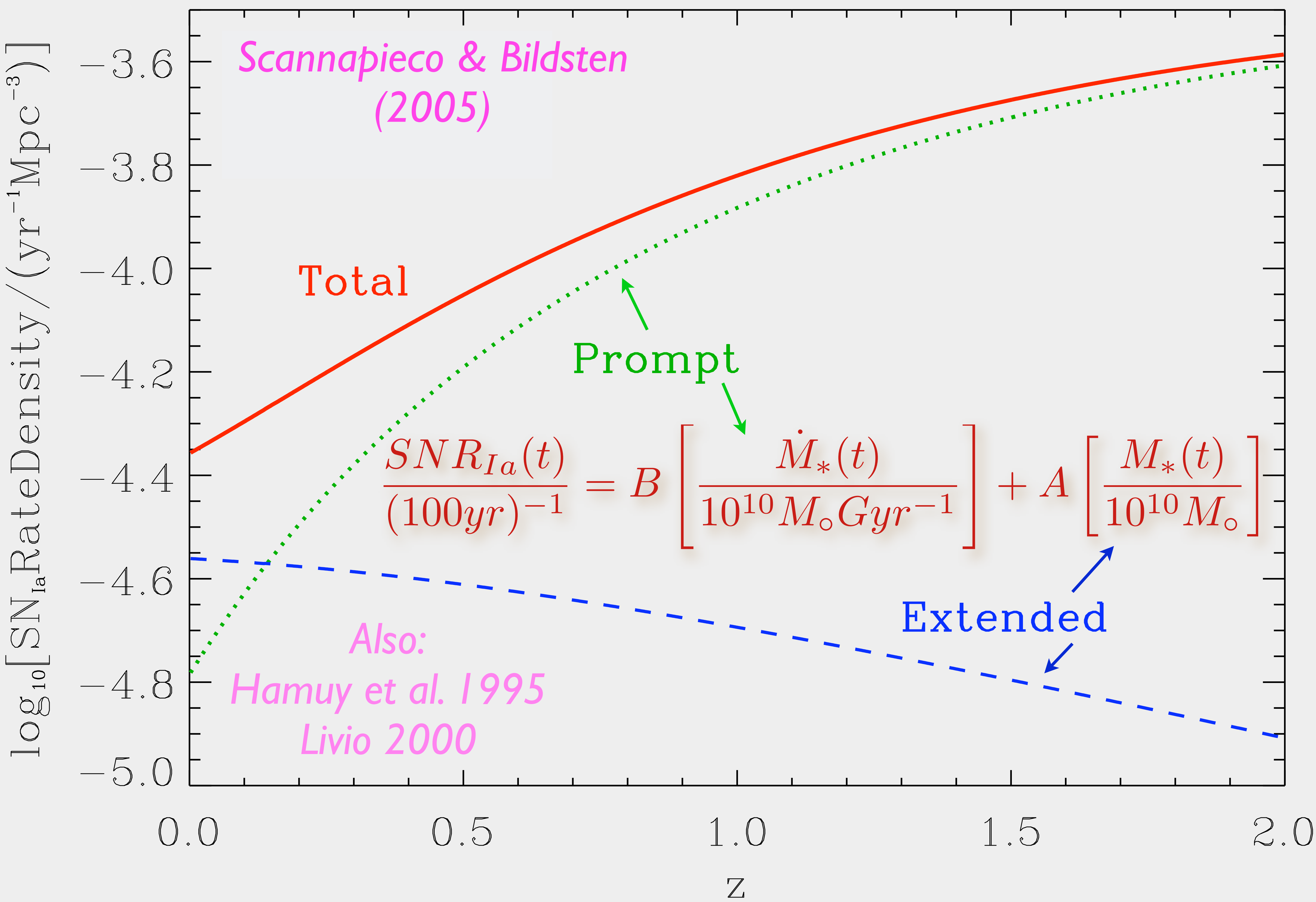
Evolution based on Two SN Populations



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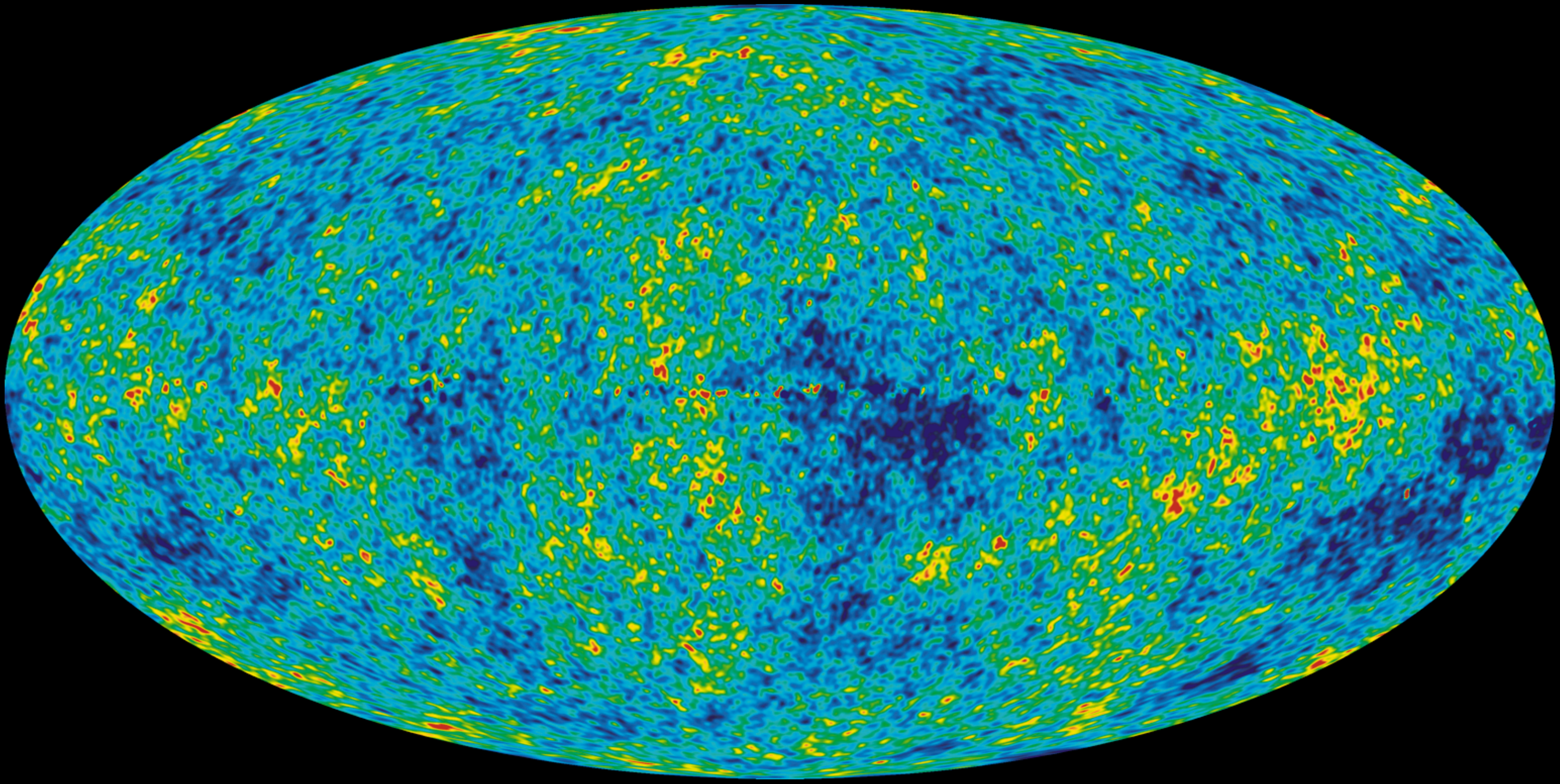
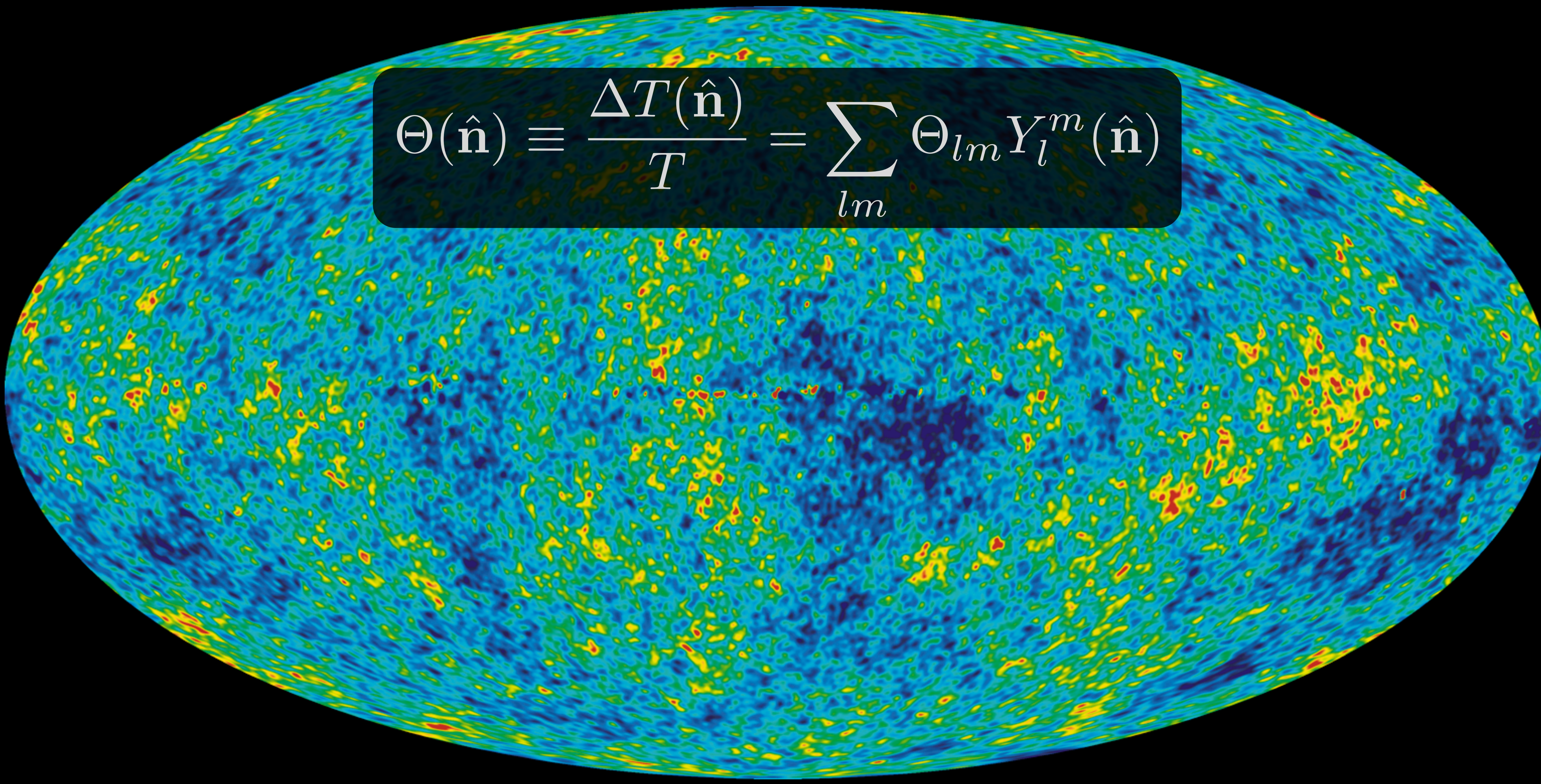
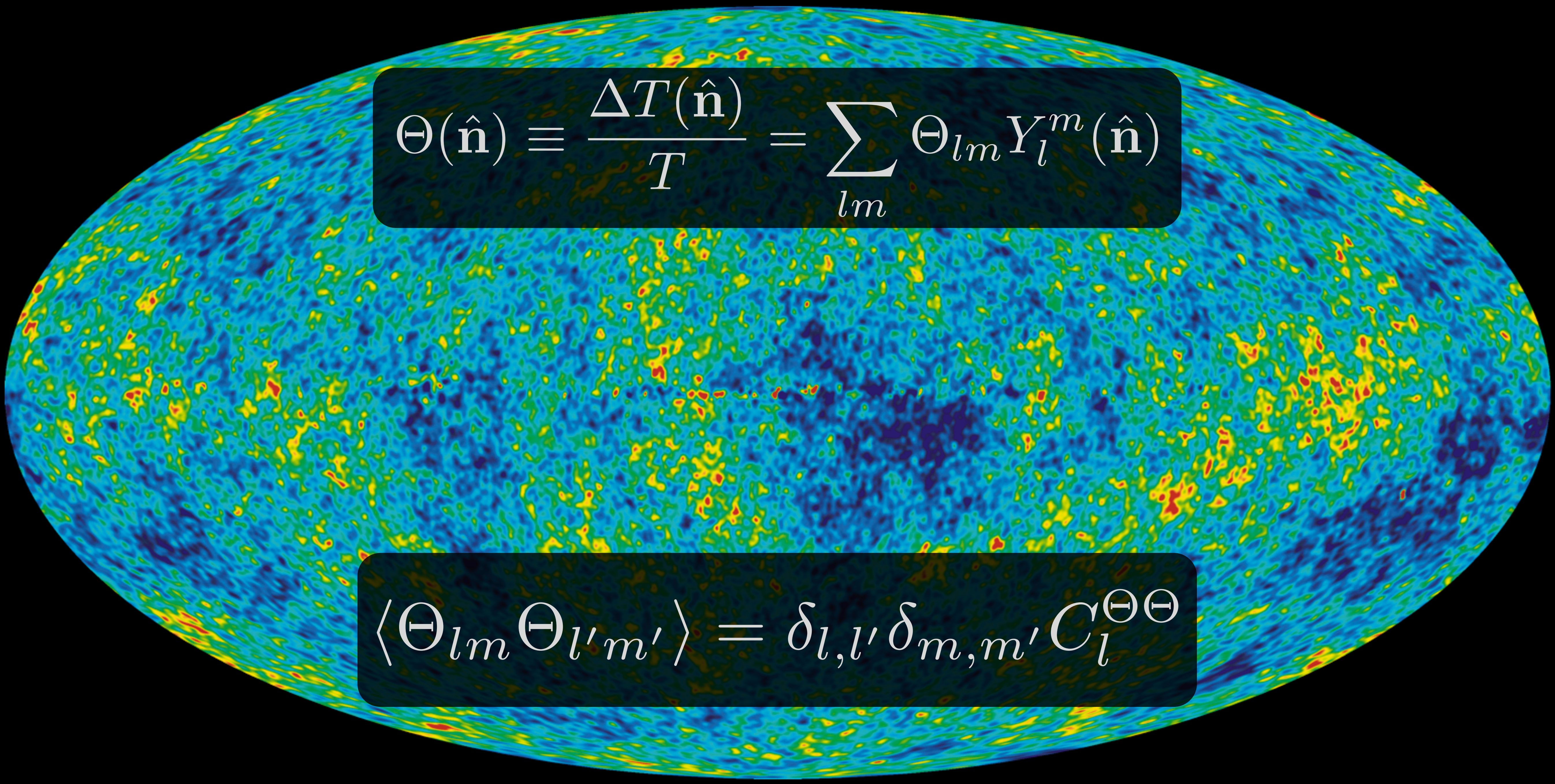


Credit: NASA/WMAP Science Team

$$\Theta(\hat{\mathbf{n}}) \equiv \frac{\Delta T(\hat{\mathbf{n}})}{T} = \sum_{lm} \Theta_{lm} Y_l^m(\hat{\mathbf{n}})$$



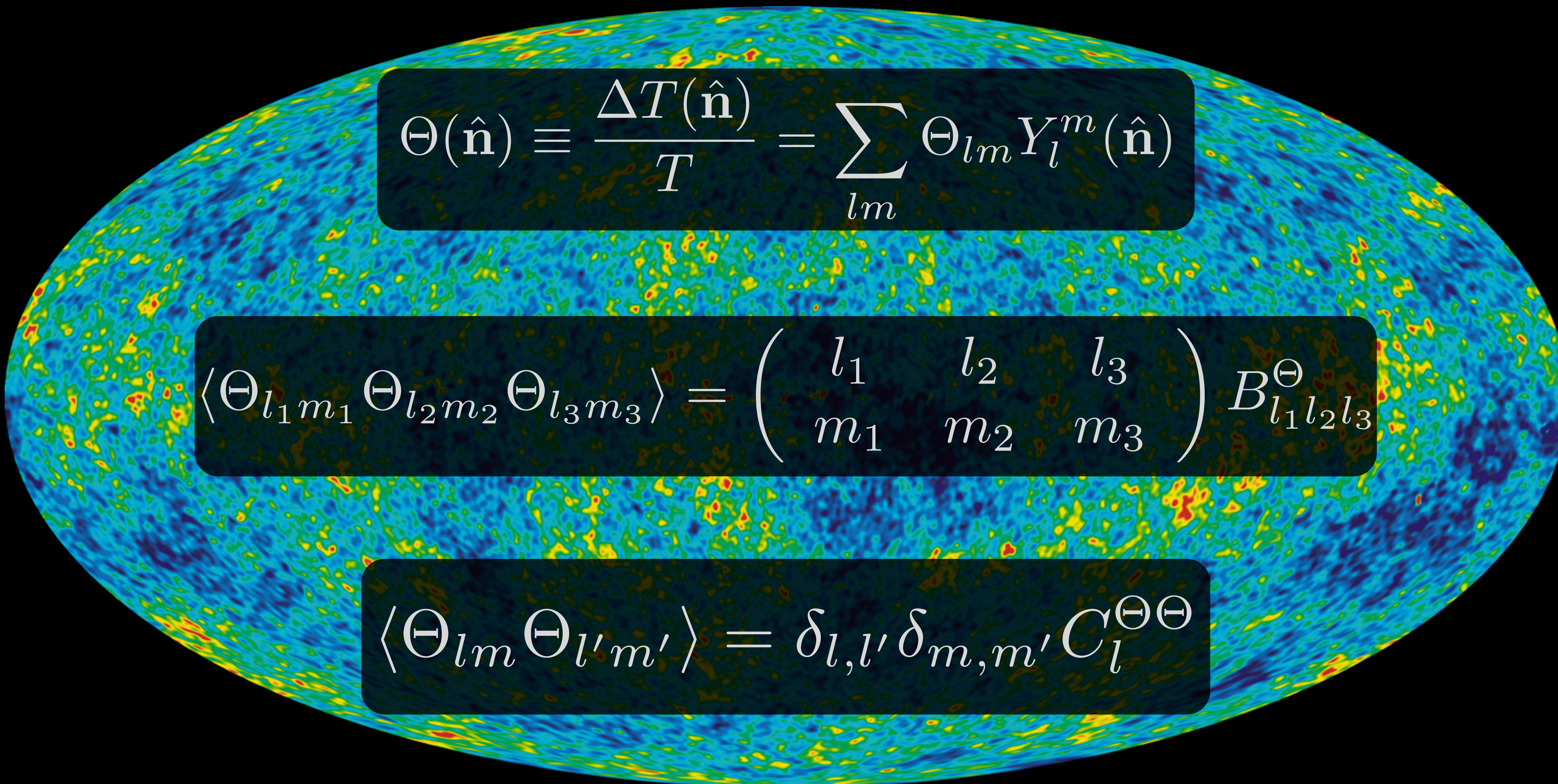
Credit: NASA/WMAP Science Team



$$\Theta(\hat{\mathbf{n}}) \equiv \frac{\Delta T(\hat{\mathbf{n}})}{T} = \sum_{lm} \Theta_{lm} Y_l^m(\hat{\mathbf{n}})$$

$$\langle \Theta_{lm} \Theta_{l'm'} \rangle = \delta_{l,l'} \delta_{m,m'} C_l^{\Theta\Theta}$$

Credit: NASA/WMAP Science Team



$$\Theta(\hat{\mathbf{n}}) \equiv \frac{\Delta T(\hat{\mathbf{n}})}{T} = \sum_{lm} \Theta_{lm} Y_l^m(\hat{\mathbf{n}})$$

$$\langle \Theta_{l_1 m_1} \Theta_{l_2 m_2} \Theta_{l_3 m_3} \rangle = \begin{pmatrix} l_1 & l_2 & l_3 \\ m_1 & m_2 & m_3 \end{pmatrix} B^{\Theta}_{l_1 l_2 l_3}$$

$$\langle \Theta_{lm} \Theta_{l'm'} \rangle = \delta_{l,l'} \delta_{m,m'} C_l^{\Theta\Theta}$$

Credit: NASA/WMAP Science Team

Primordial non-Gaussianity

Primary CMB Bispectrum

$$\frac{\Delta T(\mathbf{x})}{T} \sim \Phi(\mathbf{x})$$

$$\Phi(\mathbf{x}) = \Phi_L(\mathbf{x}) + f_{NL}\left[\Phi_L^2(\mathbf{x}) - \langle\Phi_L^2(\mathbf{x})\rangle\right]$$

Non-Linear Coupling Parameter

Measurement of non-Gaussian CMB anisotropies can potentially constrain non-linearity, “slow-rollness”, and “adiabaticity” in inflation.

Primordial non-Gaussianity

Primary CMB Bispectrum

Non-Gaussianity from the simplest inflation model is very small:

$$f_{NL} \sim 0.01 - 1$$

Much higher level of primordial non-Gaussianity is predicted by:

- Models with Multiple Scalar Fields
- Non-Adiabatic Fluctuations
- Features in the Inflation Potential
- Non-Canonical Kinetic Terms
- ...

Review: N. Bartolo, E. Komatsu, S. Matarrese, and A. Riotto, Phys. Rep. 402, 103 (2004)

Evidence of Primordial Non-Gaussianity ($f_{\rm NL}$) in the Wilkinson Microwave Anisotropy Probe 3-Year Data at 2.8σ

Amit P. S. Yadav[1] and Benjamin D. Wandelt[1,2]

[1]*Department of Astronomy, University of Illinois at Urbana-Champaign, 1002 W. Green Street, Urbana, Illinois 61801, USA*

[2]*Department of Physics, University of Illinois at Urbana-Champaign, 1110 W. Green Street, Urbana, Illinois 61801, USA*

(Received 7 December 2007; revised manuscript received 6 March 2008; published 7 May 2008)

We present evidence for primordial non-Gaussianity of the local type ($f_{\rm NL}$) in the temperature anisotropy of the cosmic microwave background. Analyzing the bispectrum of the Wilkinson Microwave Anisotropy Probe 3-year data up to $\ell_{\rm max} = 750$ we find $27 < f_{\rm NL} < 147$ (95% C.L.). This amounts to a rejection of $f_{\rm NL} = 0$ at 2.8σ, disfavoring canonical single-field slow-roll inflation. The signal is robust to variations in $l_{\rm max}$, frequency and masks. No known foreground, instrument systematic, or secondary anisotropy explains it. We explore the impact of several analysis choices on the quoted significance and find 2.5σ to be conservative.

FIVE-YEAR WILKINSON MICROWAVE ANISOTROPY PROBE (WMAP[1]) OBSERVATIONS: COSMOLOGICAL INTERPRETATION

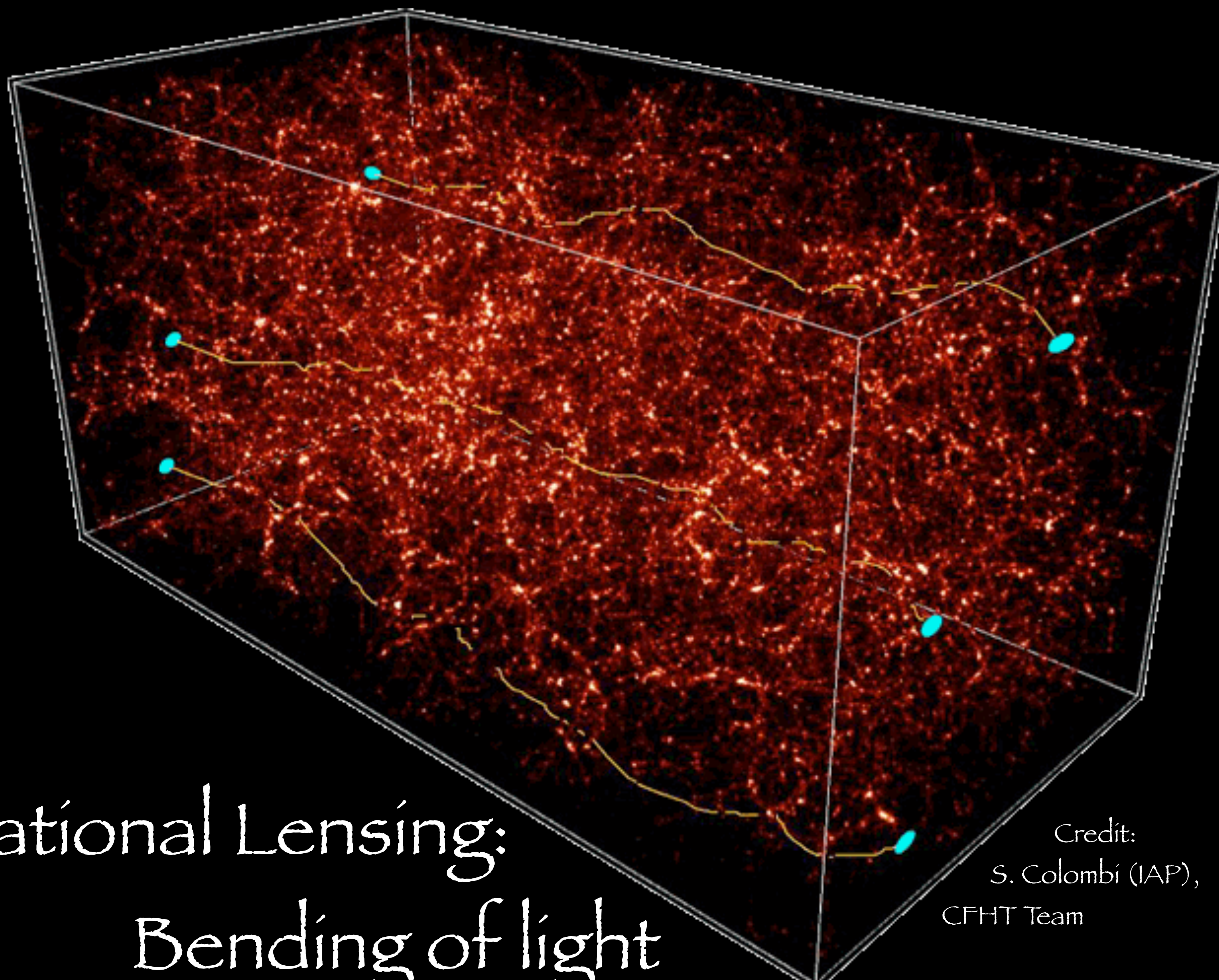
E. Komatsu [1], J. Dunkley [2,3,4], M. R. Nolta [5], C. L. Bennett [6], B. Gold [6], G. Hinshaw [7], N. Jarosik [2], D. Larson [6], M. Limon [8] L. Page [2], D. N. Spergel [3,9], M. Halpern [10], R. S. Hill [11], A. Kogut [7], S. S. Meyer [12], G. S. Tucker [13], J. L. Weiland [10], E. Wollack [7], and E. L. Wright [14]

Submitted to the Astrophysical Journal Supplement Series

ABSTRACT

$$-9 < f_{NL}^{local} < 111 \text{ and } -151 < f_{NL}^{equil} < 253 (95\% \, CL)$$

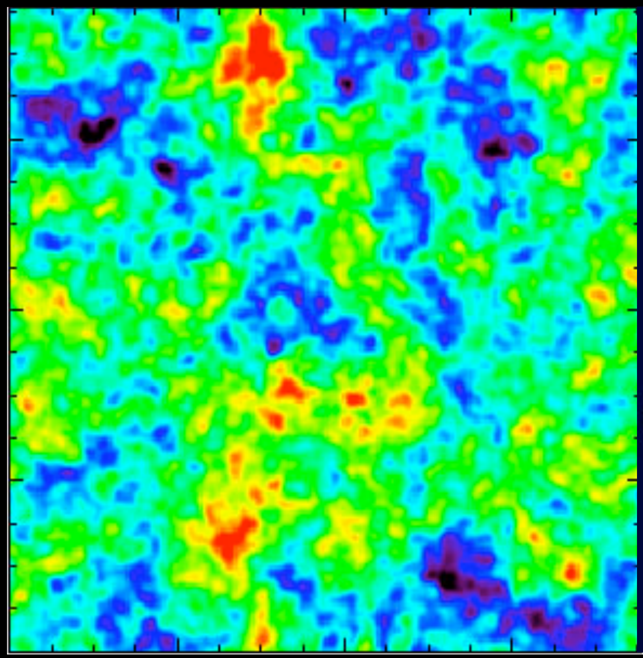
Journey Through the "Clumpy" Universe



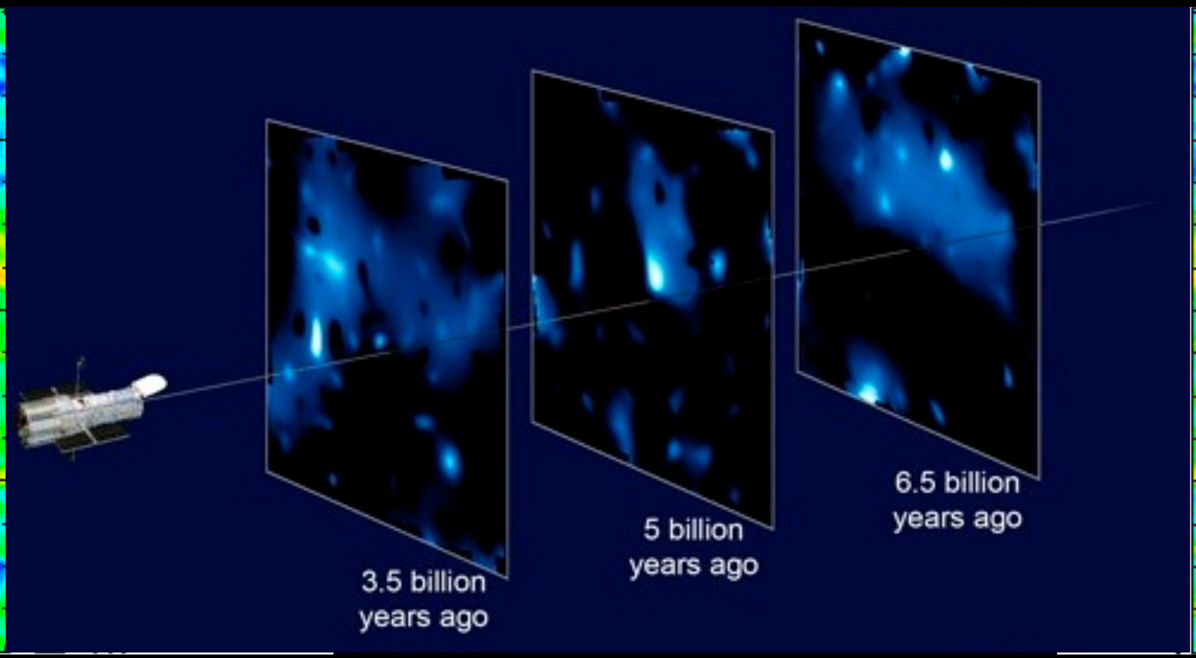
Weak
Gravitational Lensing:
Bending of light

Credit:
S. Colombi (IAP),
CFHT Team

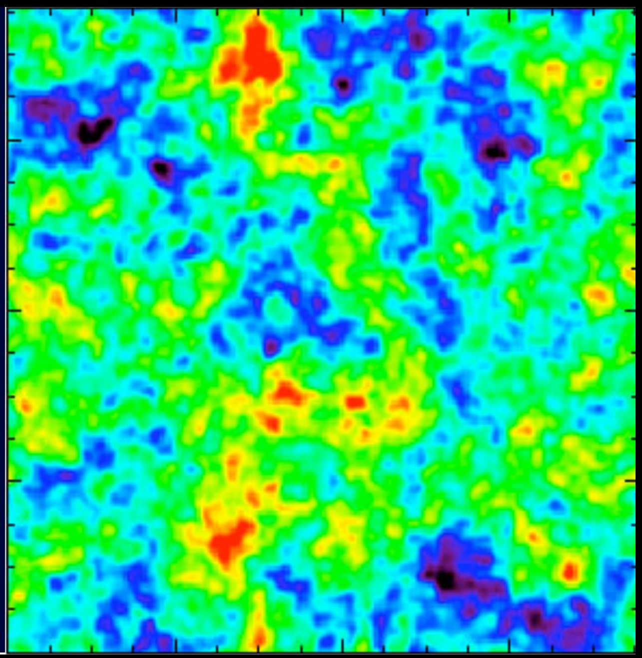
Weak Lensing of the Primary Bispectrum



Credit: Vale, Amblard, White (2004)



NASA, ESA, and R. Massey (CalTech)



Credit: Vale, Amblard, White (2004)

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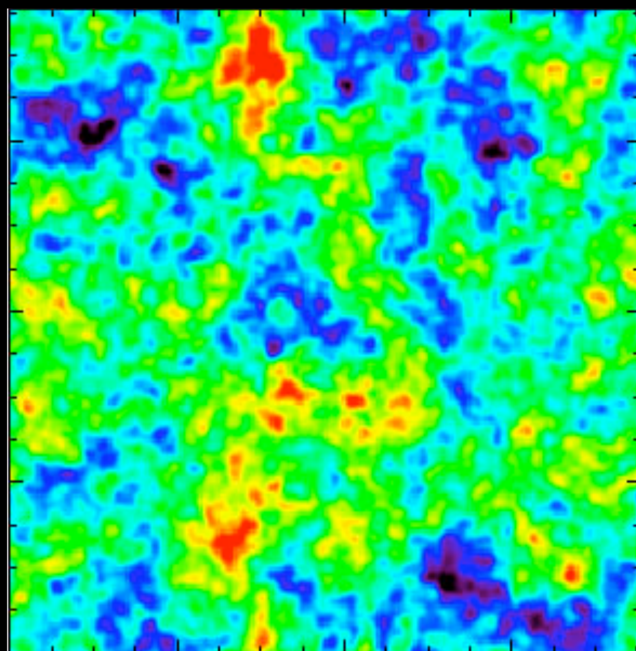
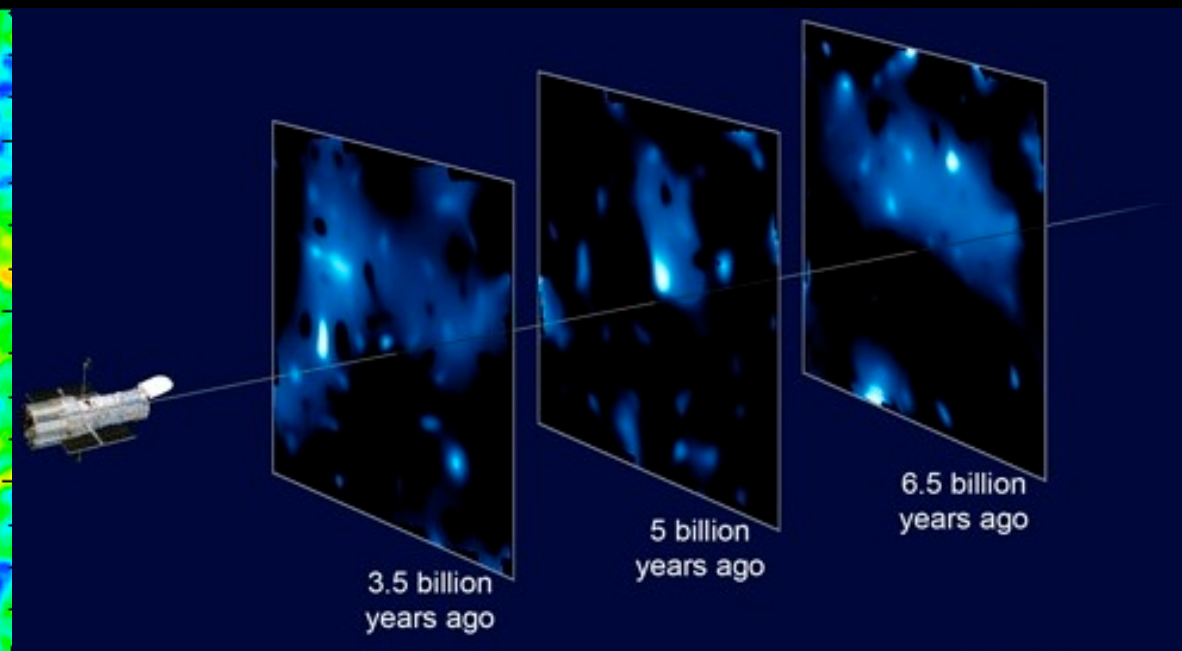


Credit: Vale, Amblard, White (2004)



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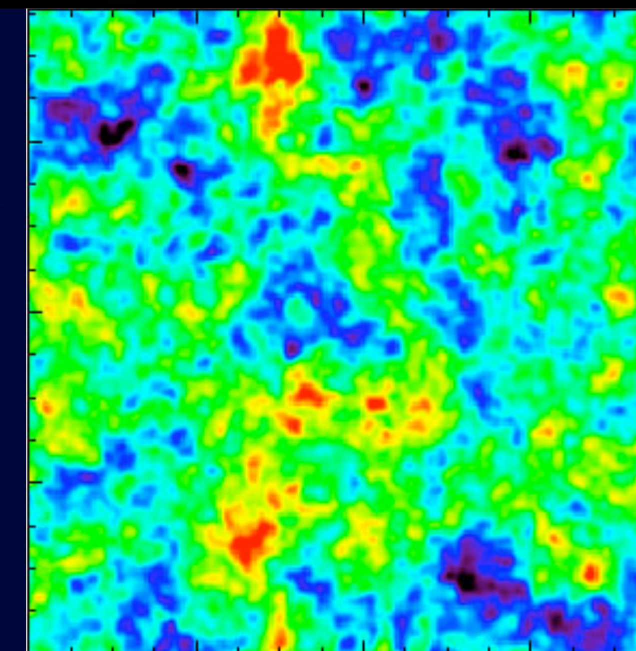
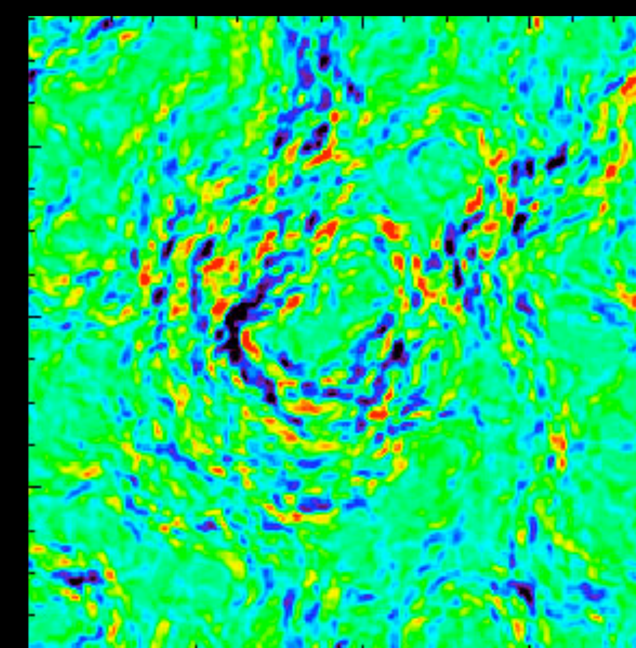
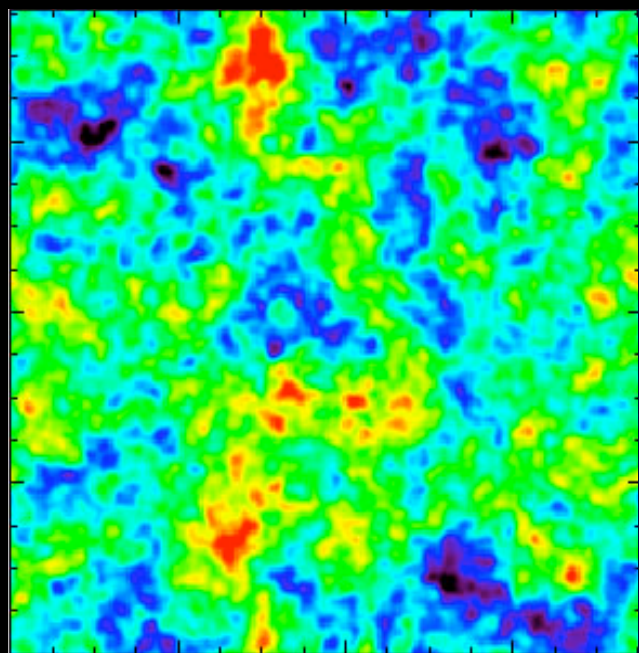


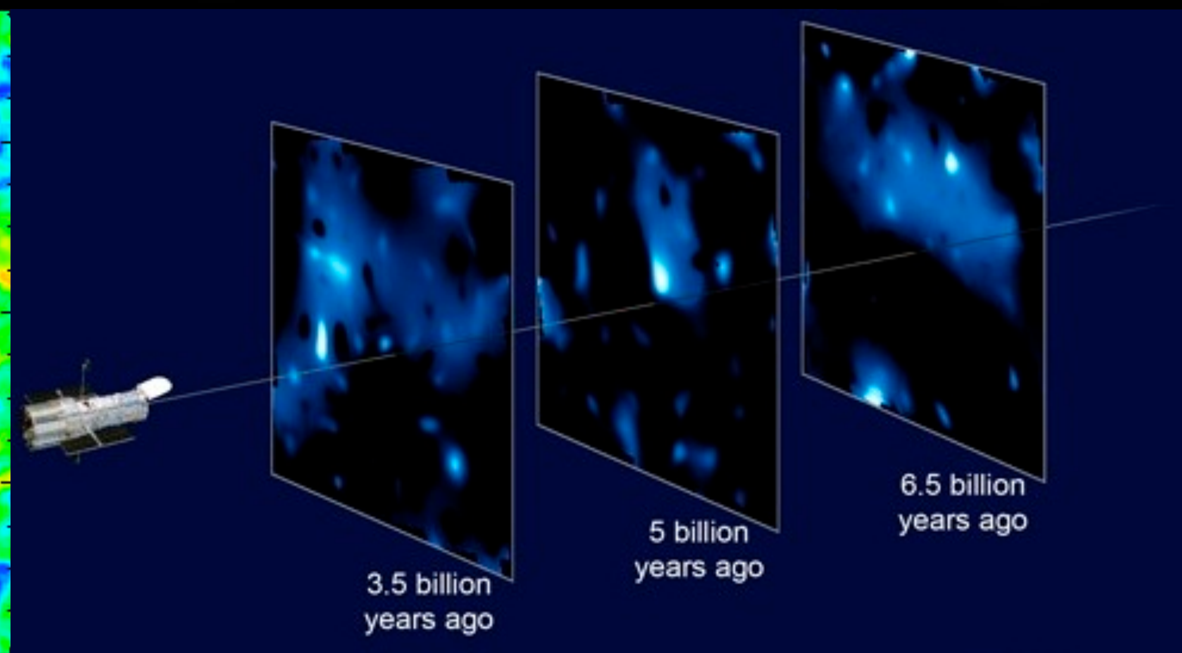
Credit: Vale, Amblard, White (2004)



Weak Lensing of the Primary Bispectrum



Credit: Vale, Amblard, White (2004)



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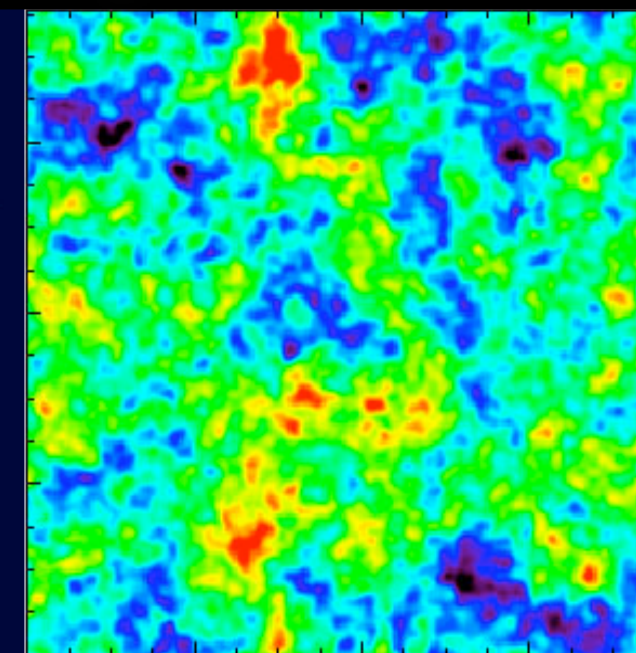
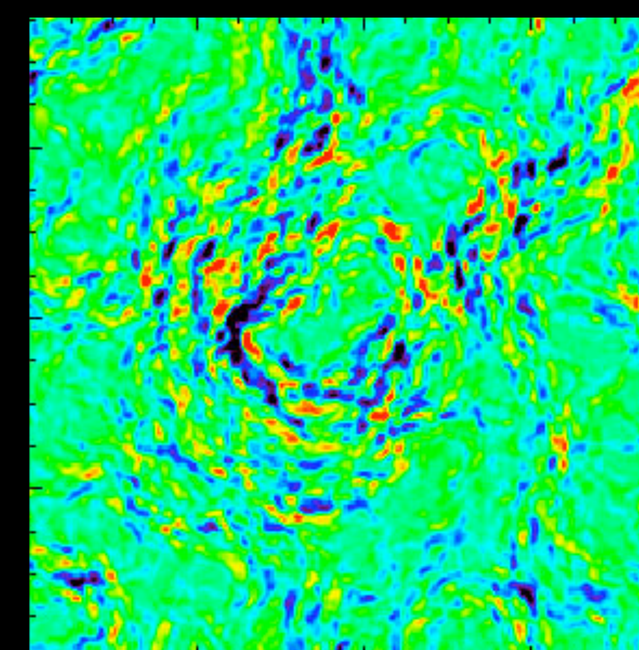
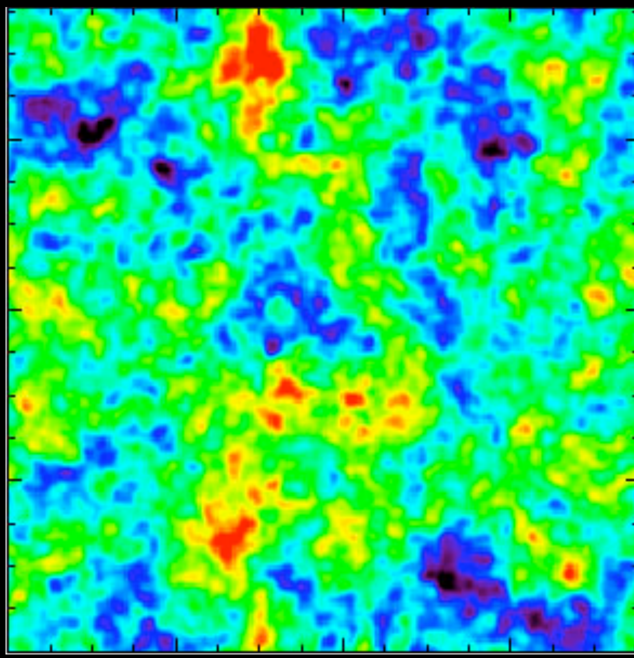


Credit: Vale, Amblard, White (2004)

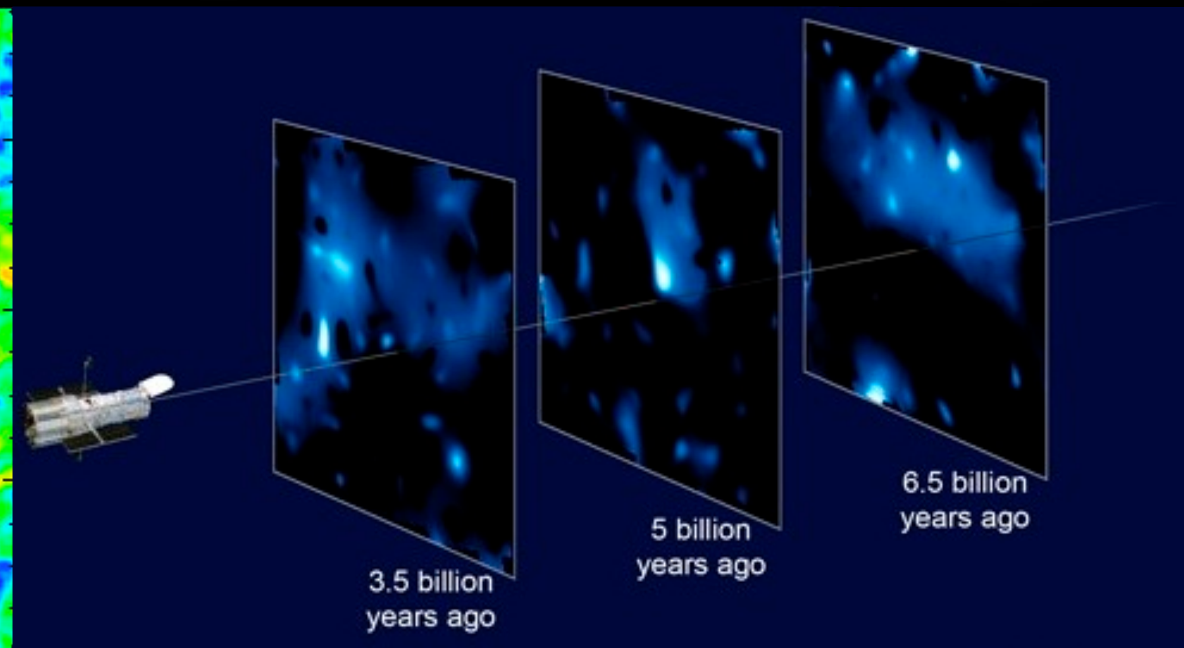
$$\tilde{\Theta}(\hat{\mathbf{n}}) = \Theta\left[\hat{\mathbf{n}} + \hat{\alpha}\right]$$



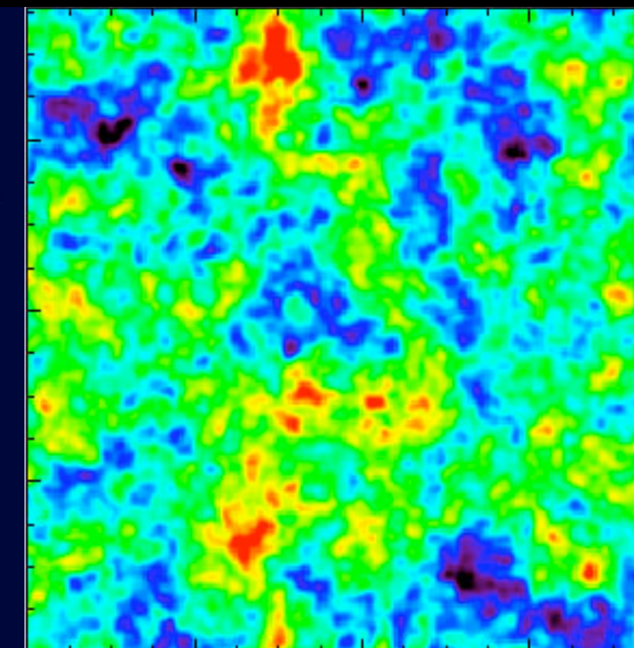
Weak Lensing of the Primary Bispectrum



Credit: Vale, Amblard, White (2004)



NASA, ESA, and R. Massey (CalTech)



Credit: Vale, Amblard, White (2004)

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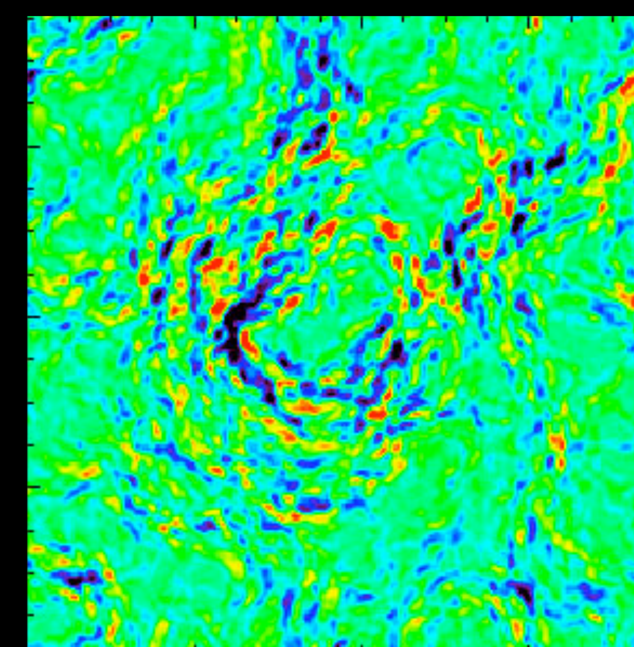
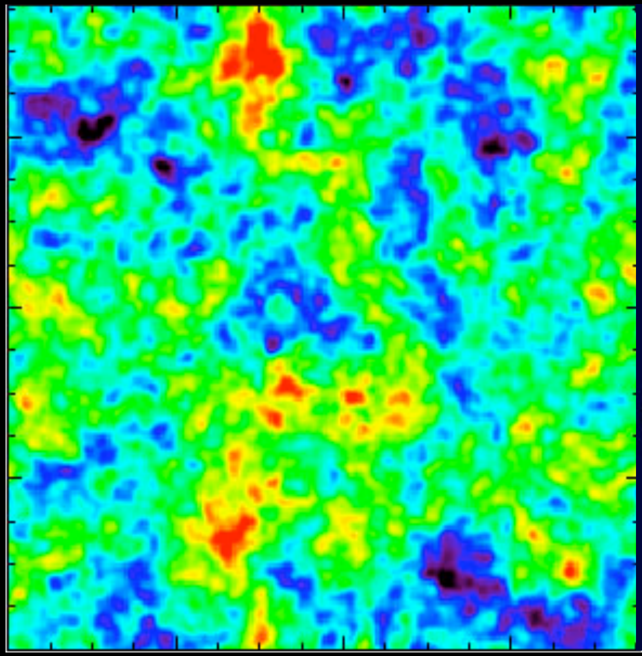
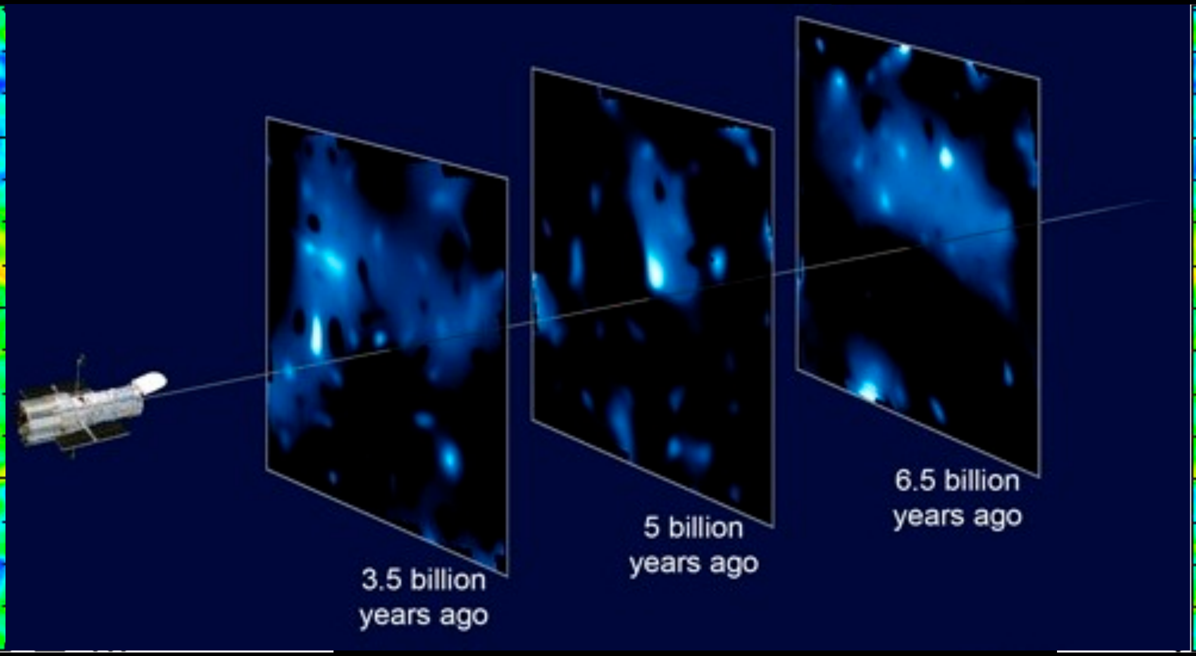


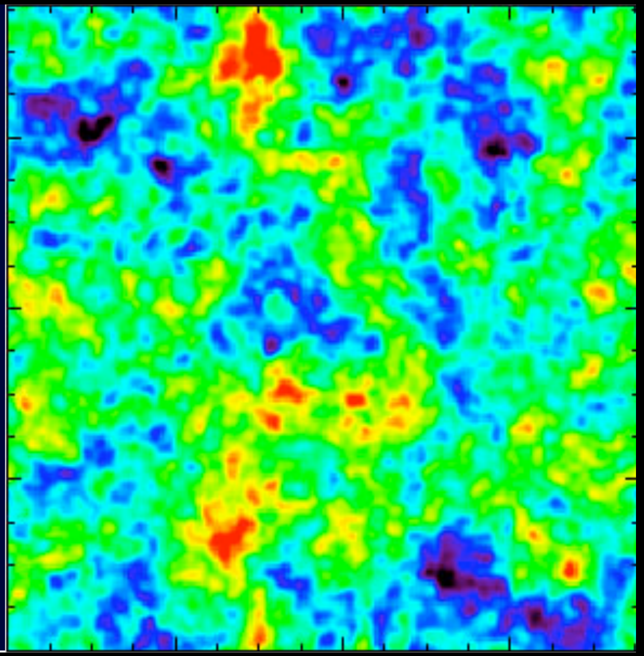
Weak Lensing of the Primary Bispectrum



Credit: Vale, Amblard, White (2004)



NASA, ESA, and R. Massey (CalTech)



Credit: Vale, Amblard, White (2004)

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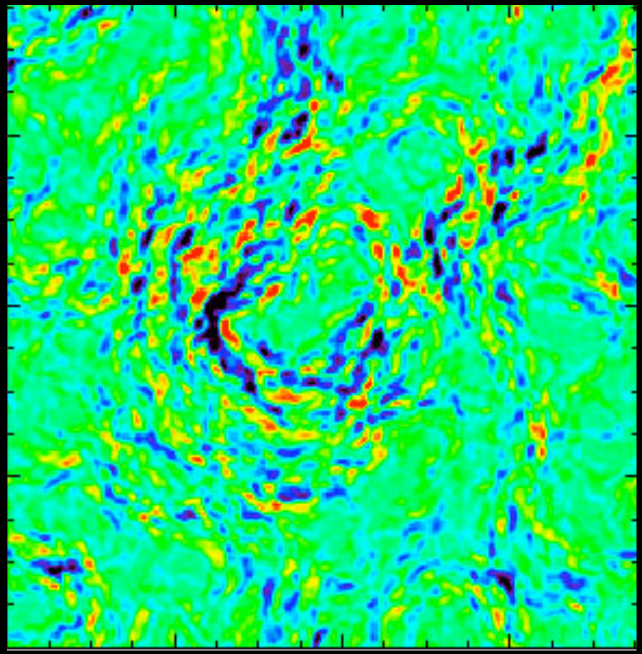
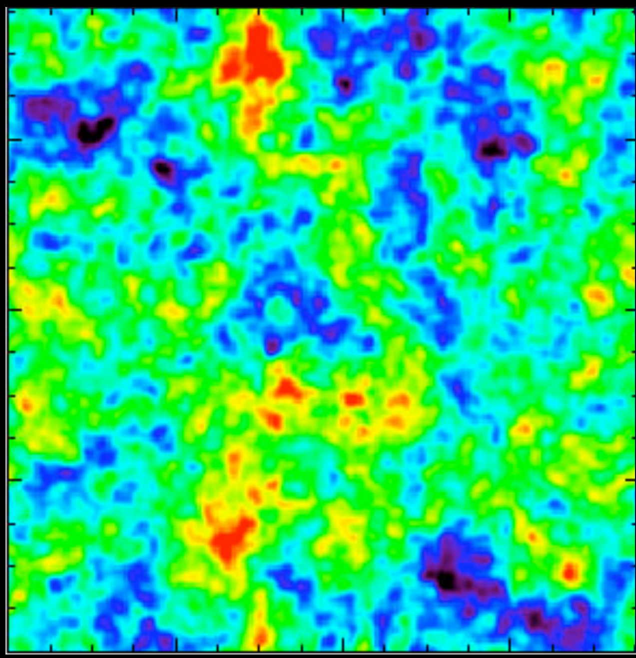
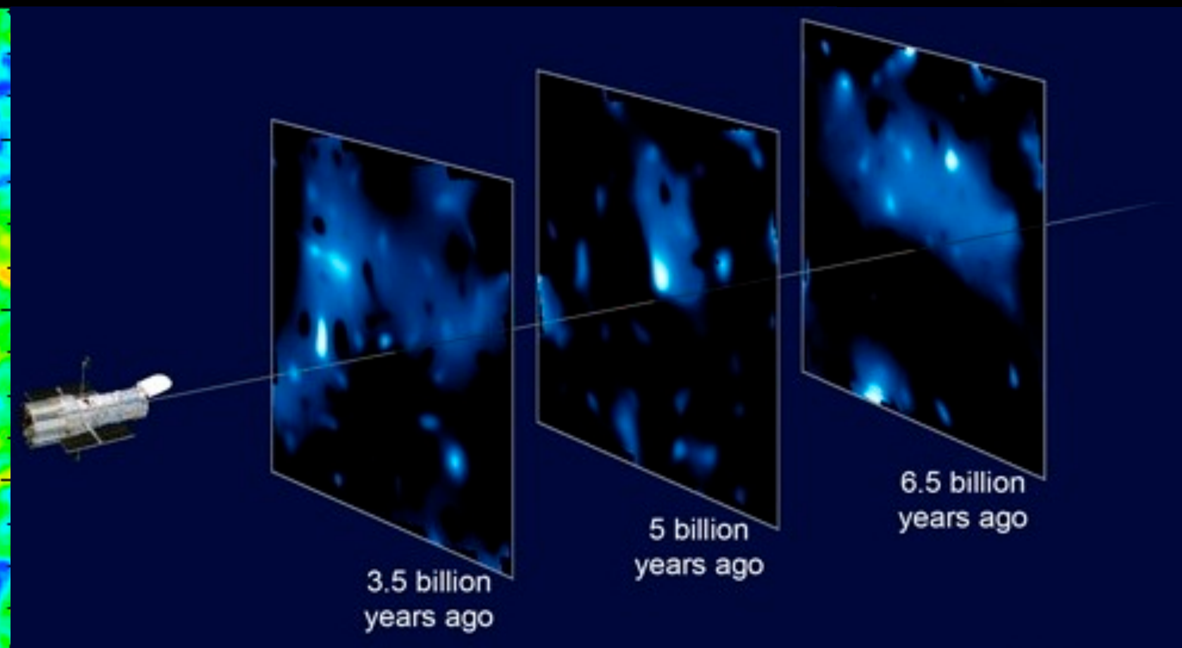


Weak Lensing of the Primary Bispectrum



Credit: Vale, Amblard, White (2004)



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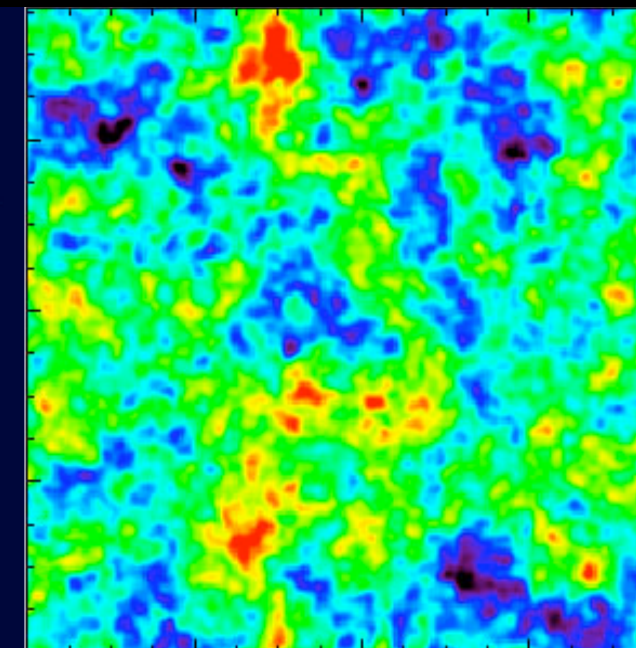

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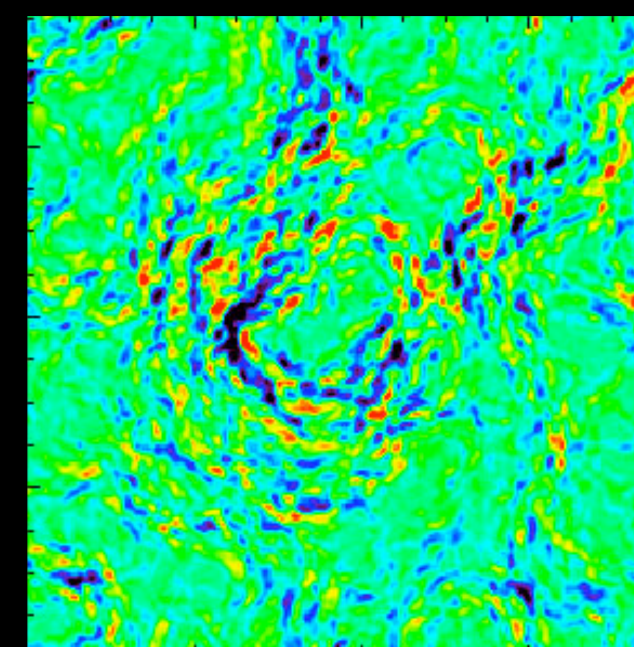
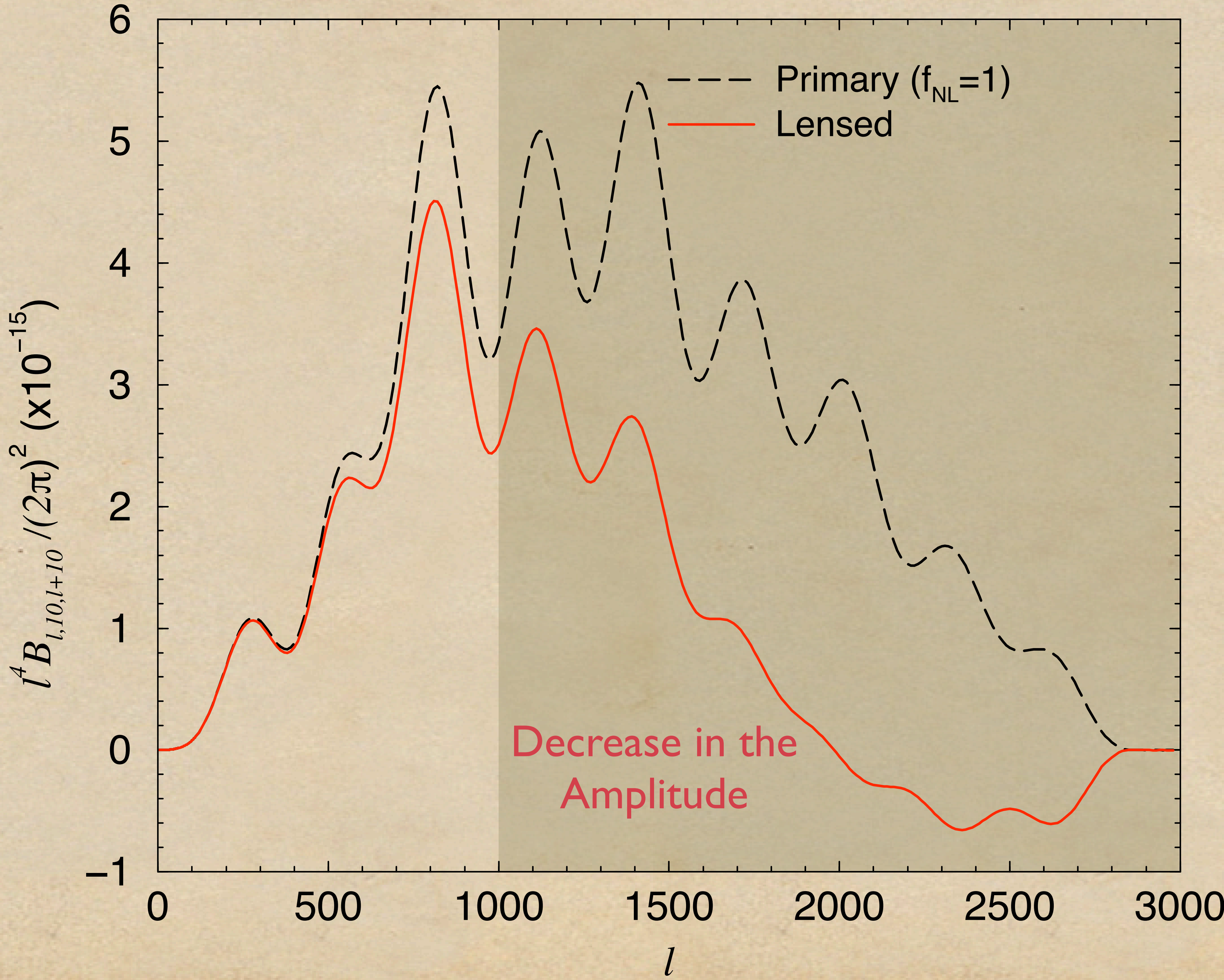


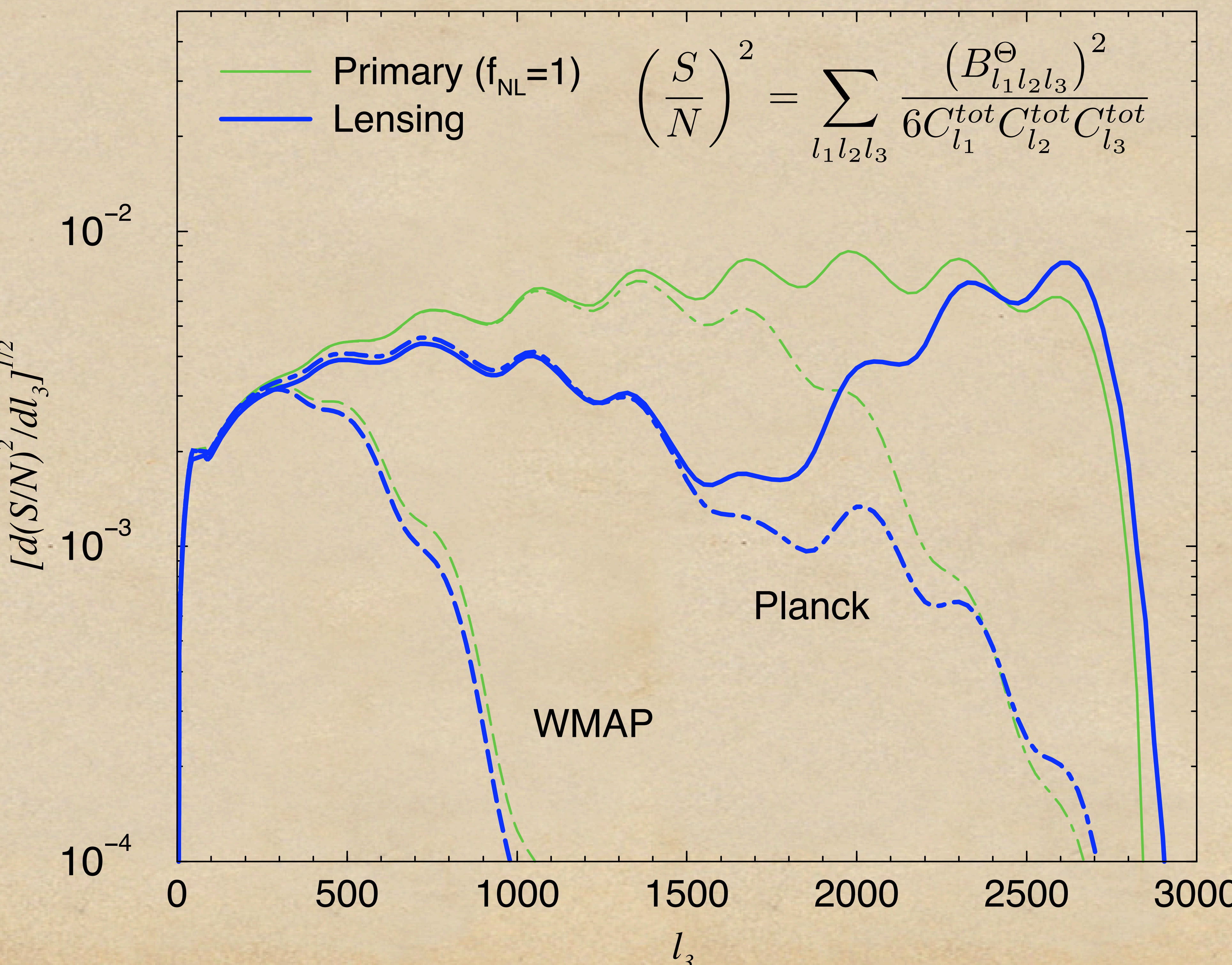
$$\tilde{B}^{\Theta}_{l_1 l_2 l_3} = \sum_{m_1 m_2 m_3} \begin{pmatrix} l_1 & l_2 & l_3 \\ m_1 & m_2 & m_3 \end{pmatrix} \langle \tilde{\Theta}_{l_1 m_1} \tilde{\Theta}_{l_2 m_2} \tilde{\Theta}_{l_3 m_3} \rangle$$

The Effect of Lensing on the Bispectrum



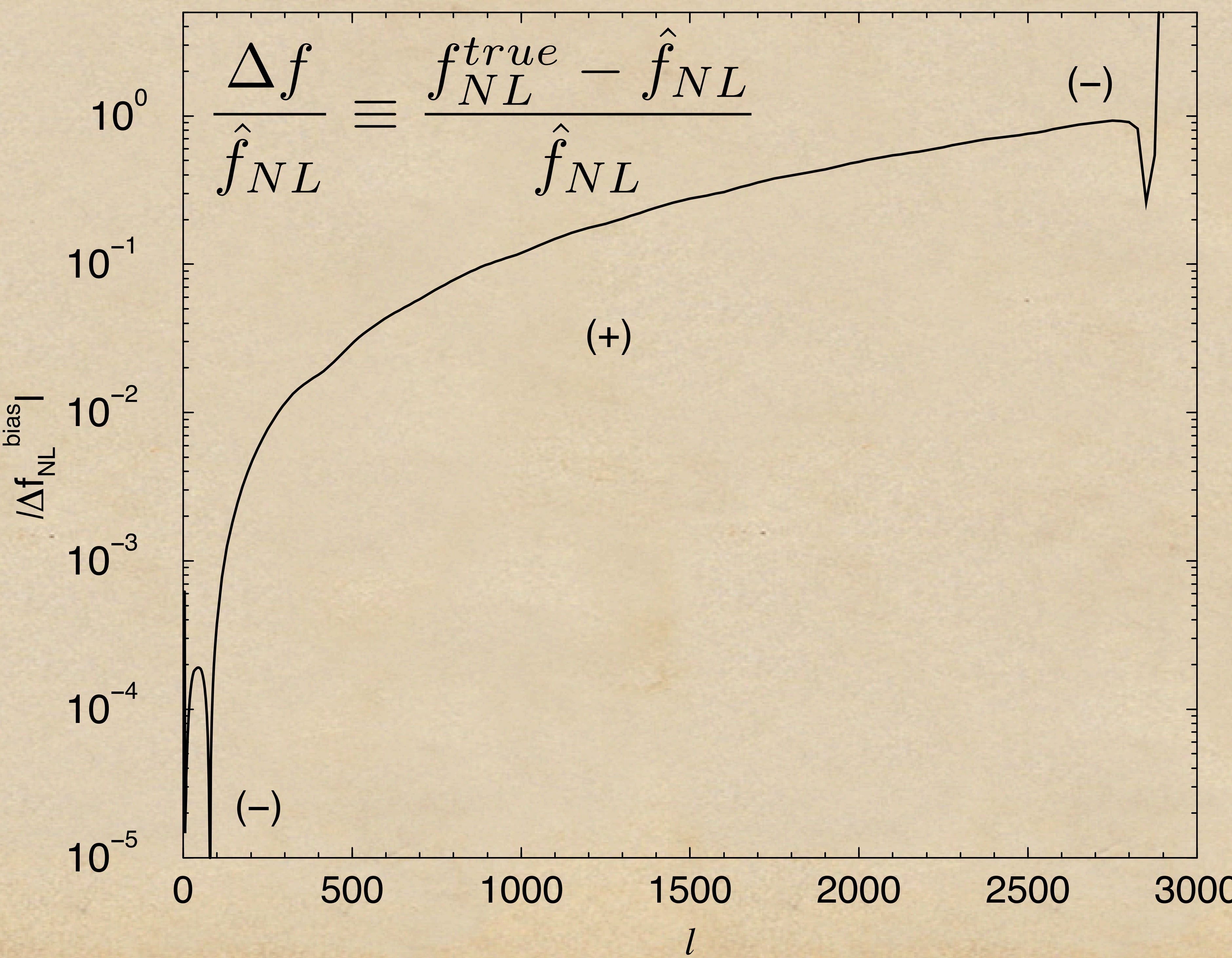
A. Cooray, D. Sarkar, and P. Serra; Phys. Rev. D, 77, 123006 (2008)

Reduction in the S/N due to Lensing



A. Cooray, D. Sarkar, and P. Serra; Phys. Rev. D, 77, 123006 (2008)

Bias in the non-Gaussian Parameter



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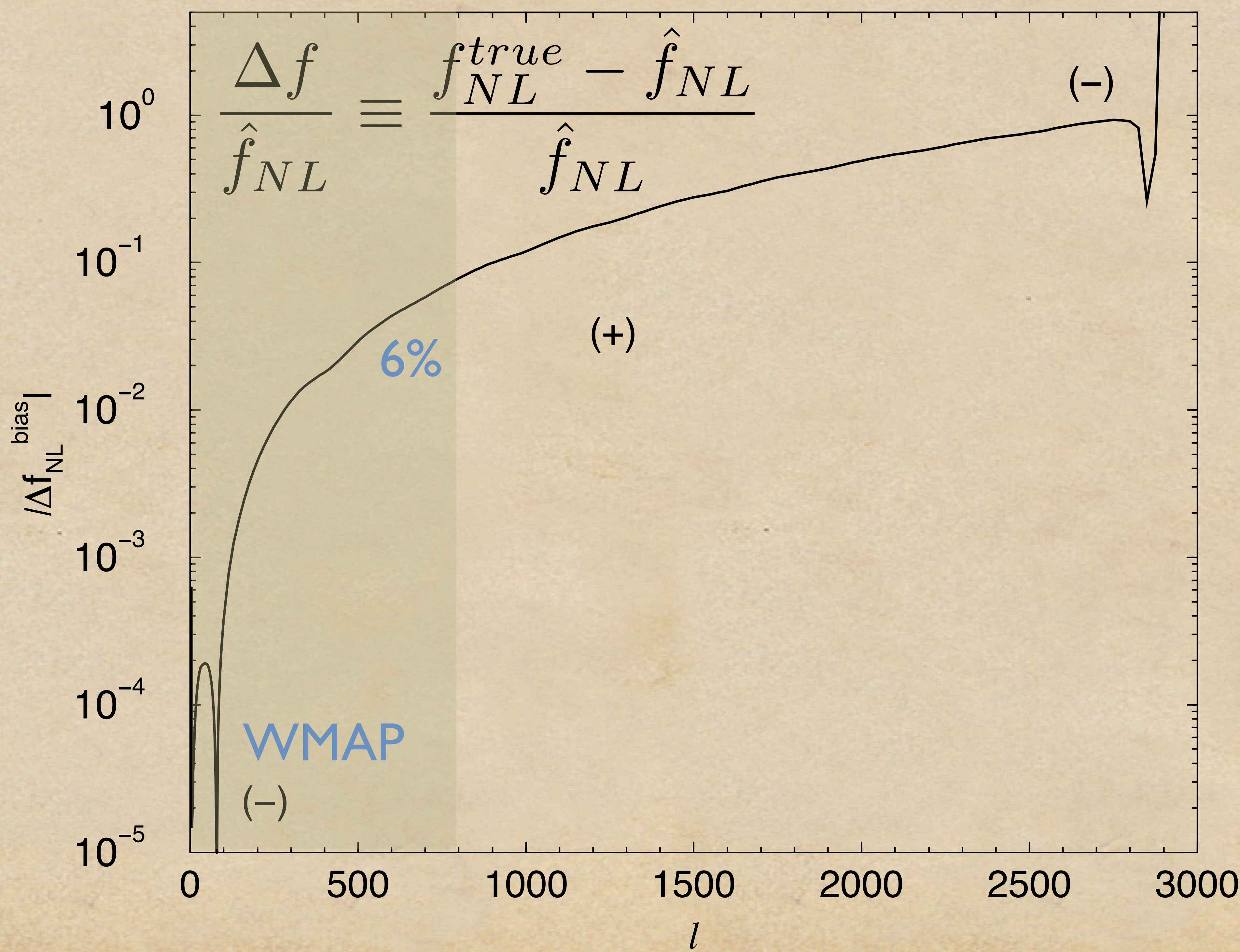

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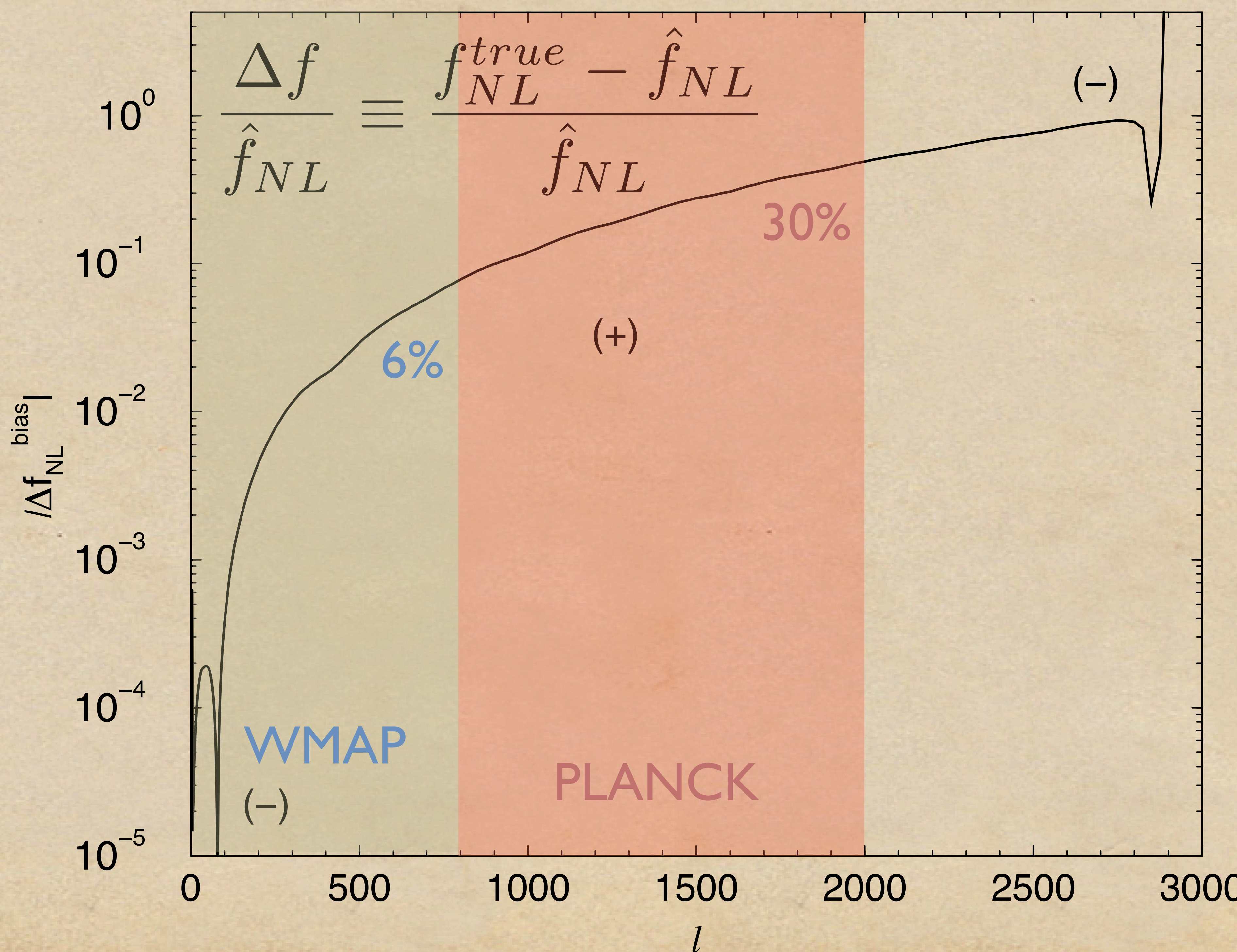

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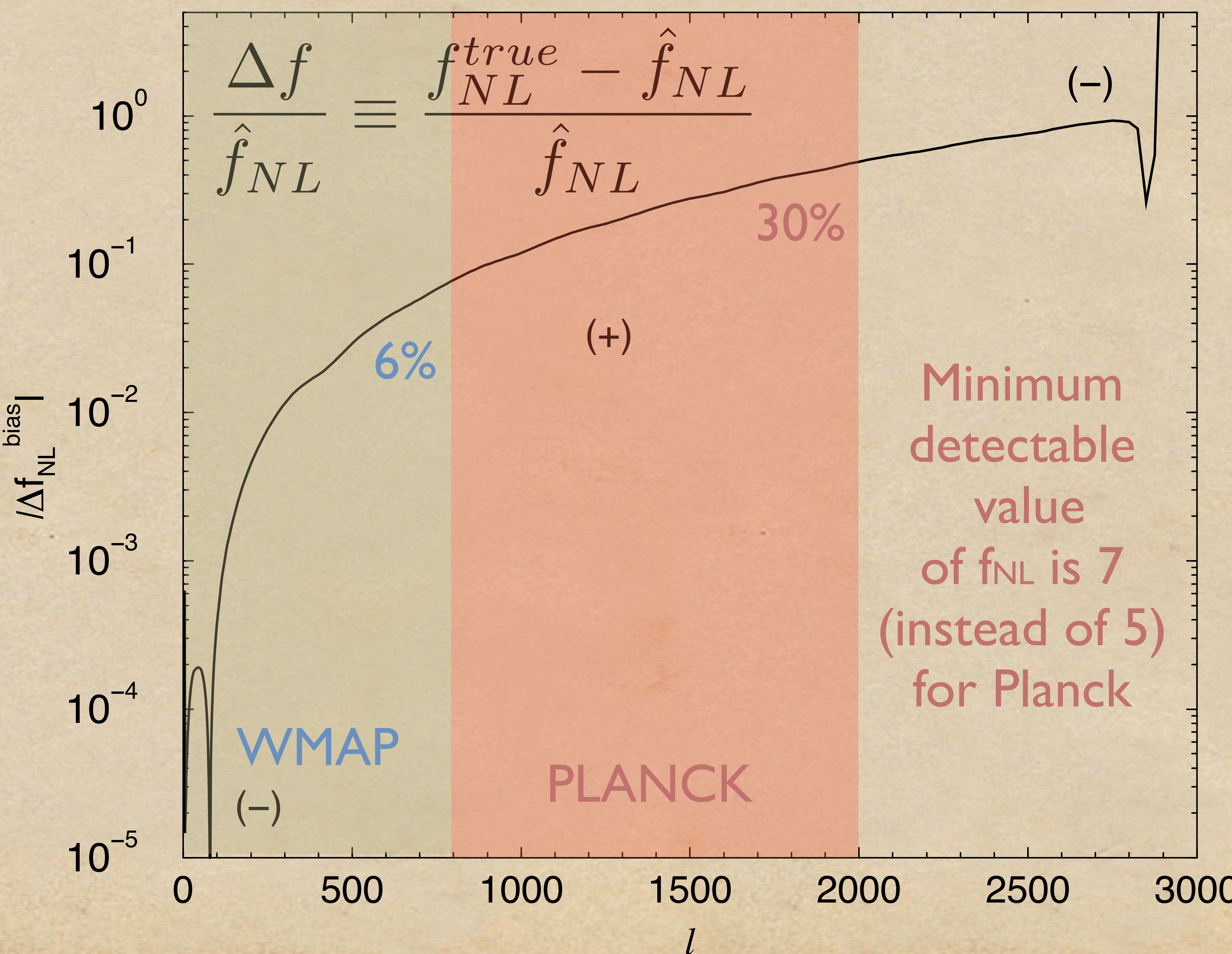

A. Cooray, D. Sarkar, and P. Serra; Phys. Rev. D, 77, 123006 (2008)

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Dark Energy

- Constraining the EOS
- To Bin or Not to Bin
- SNe Ia ++
- Lensing of SNe
- Other Worries

Non-Gaussianity

- Beyond Gaussianity
- CMB Bispectrum
- Lensing of CMB
- Lensed Bispectrum
- S/N Reduction & Bias

Gravity Waves via Weak Gravitational Lensing

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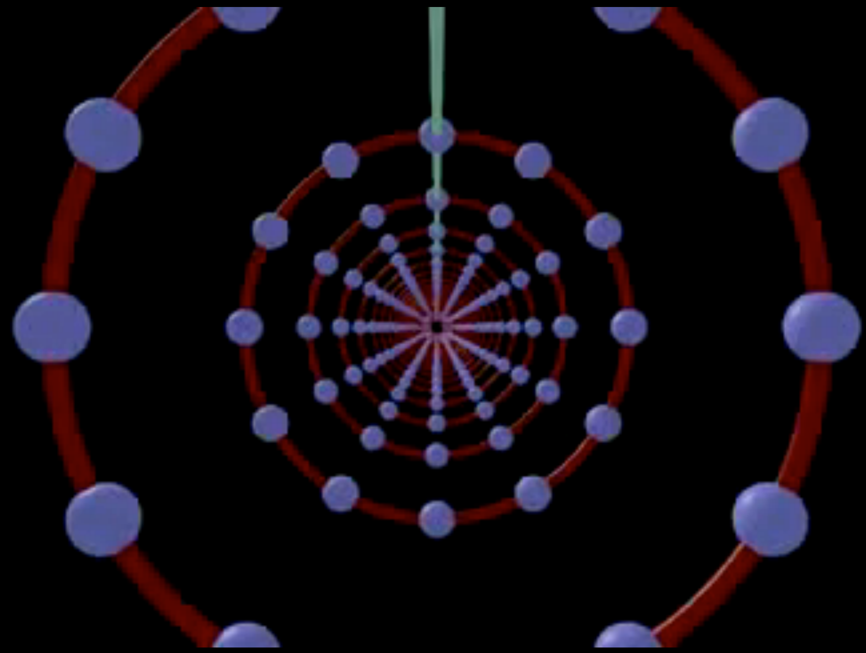
Gravity Waves via Weak Gravitational Lensing

Gravitational Waves

Credit: Michael
Penn State Schuylkill



Gravitational Waves

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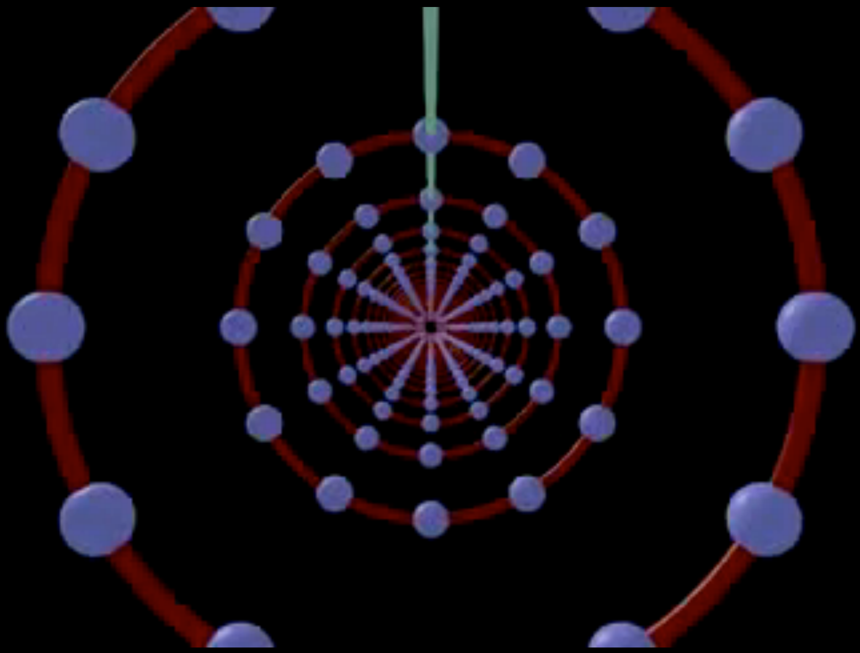
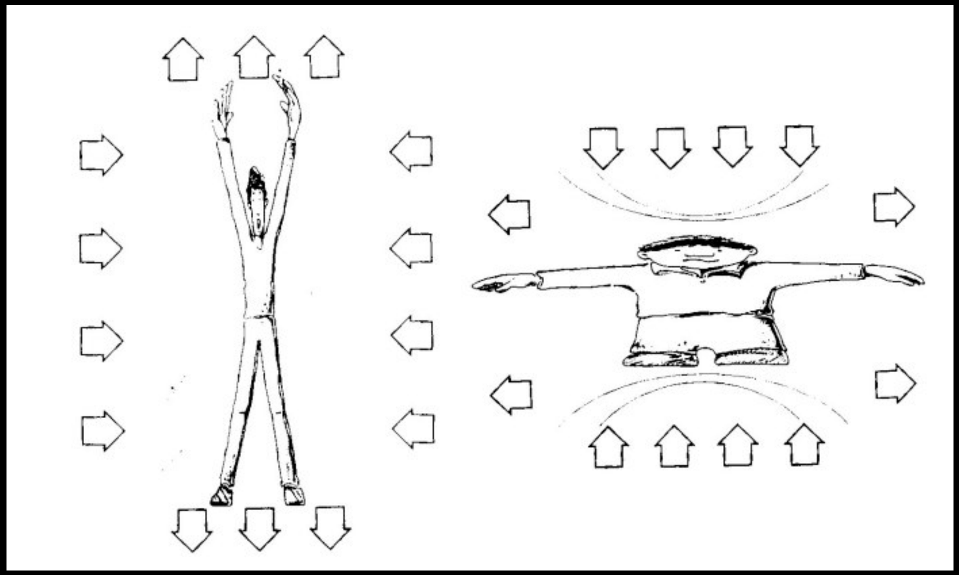
Penn State Schuylkill





credit: http://www.lnl.infn.it/~auriga/

Gravitational Waves

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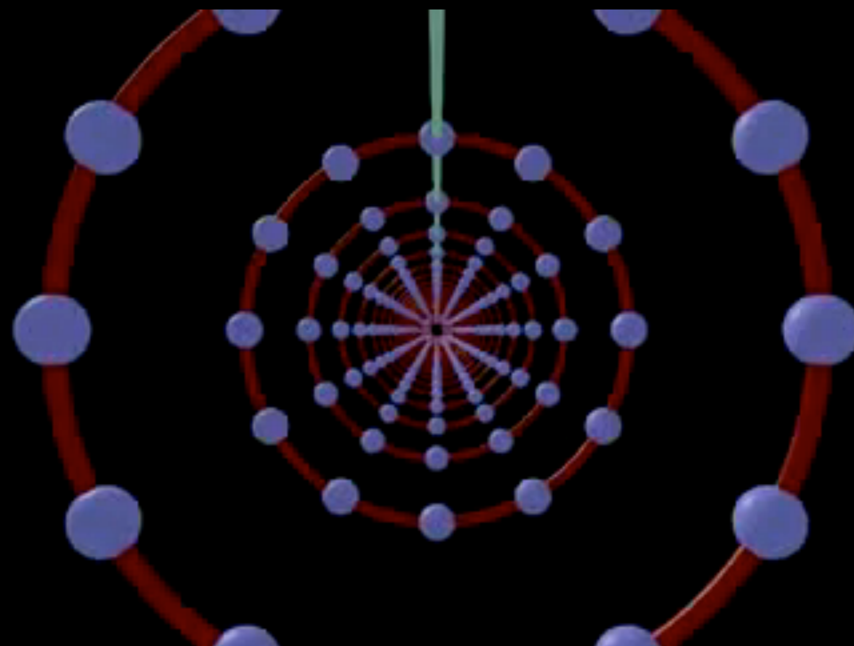

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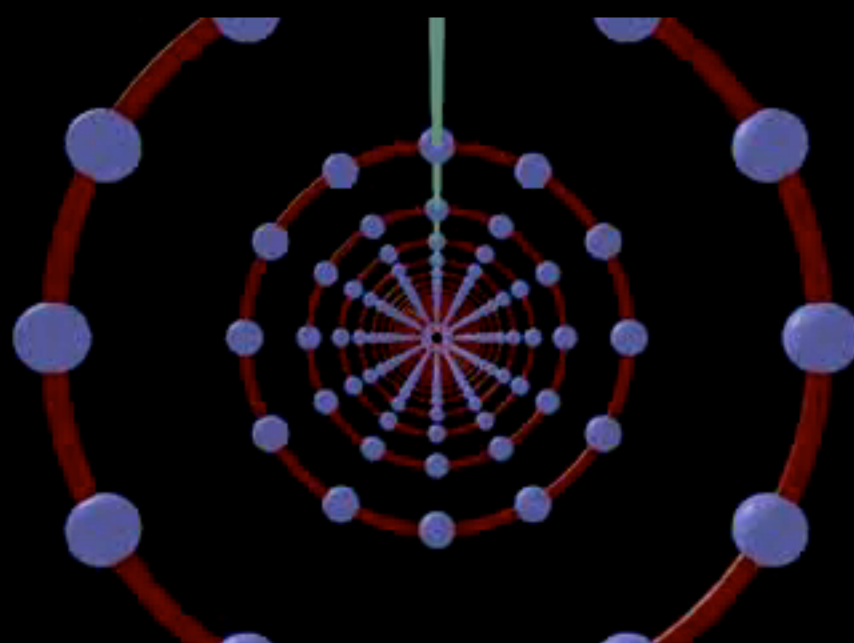

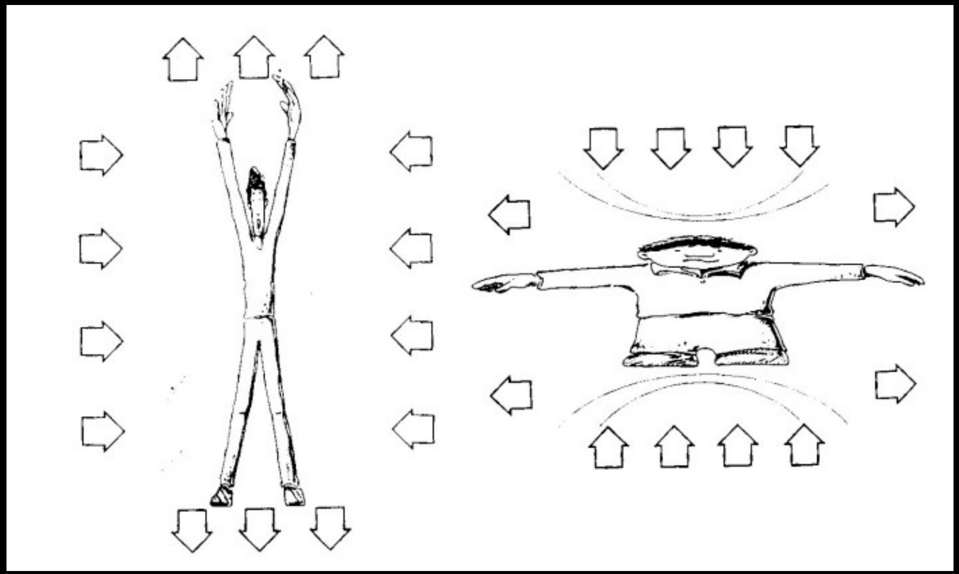

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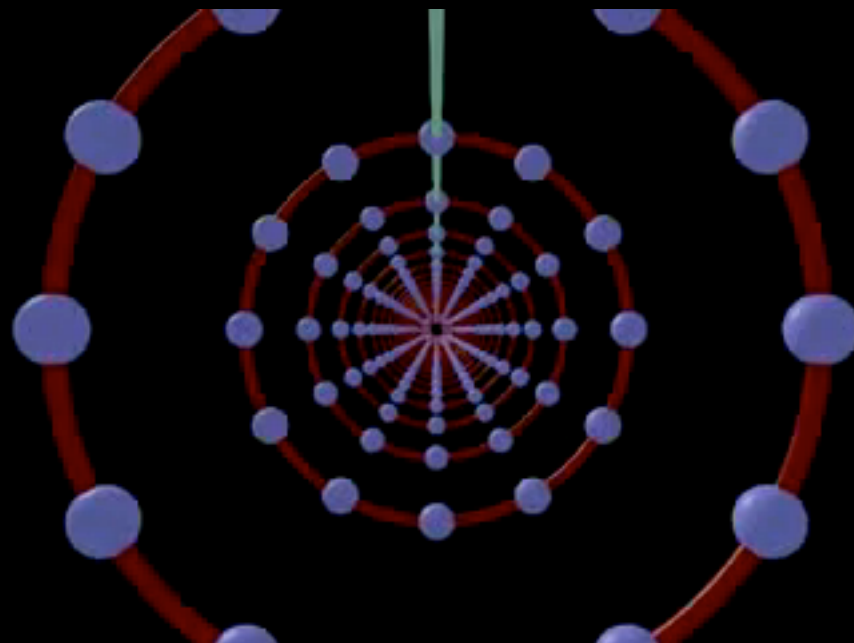
Gravitational Waves



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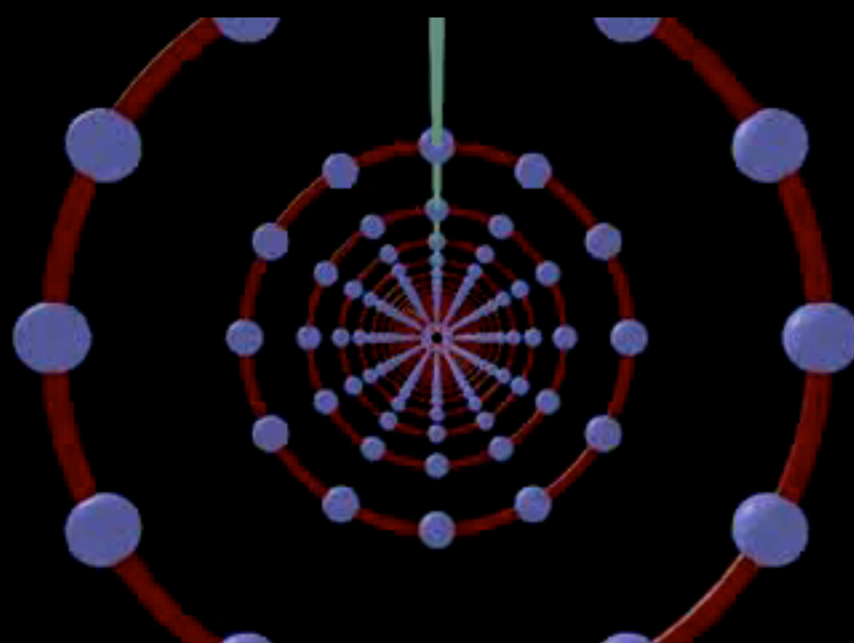

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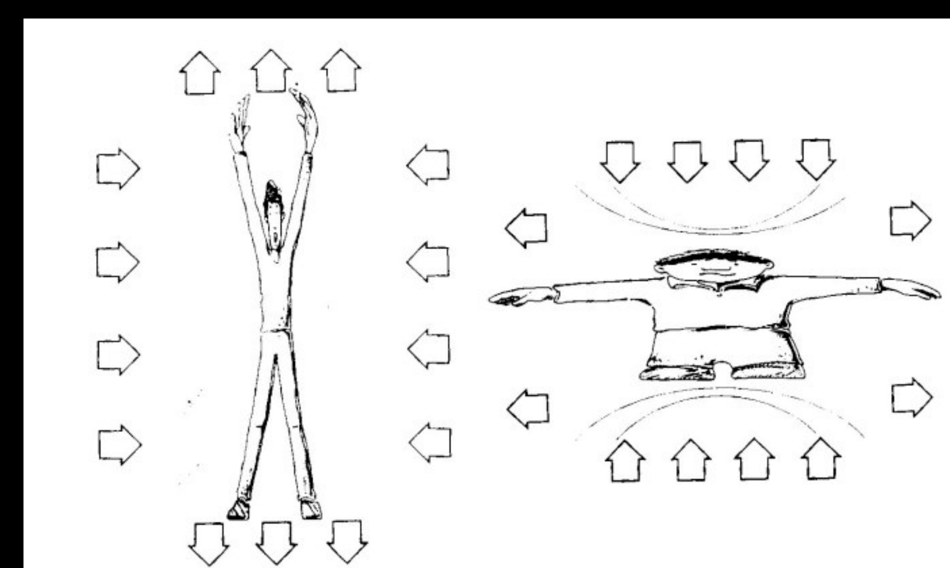
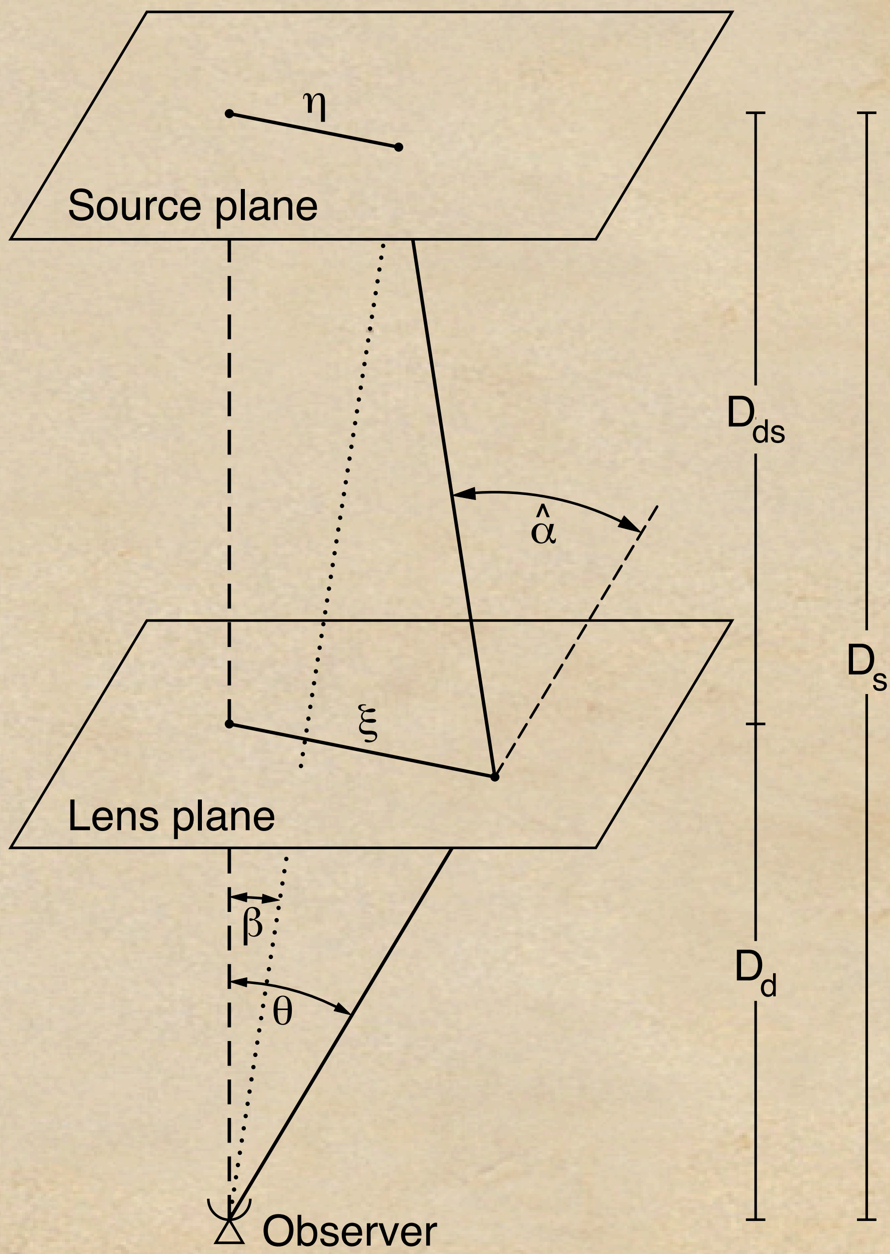


credit: http://www.lnl.infn.it/~auriga/

Gravitational Lensing and GW

The Deflection:

$$\boxed{\vec{\beta} = \vec{\theta} - \vec{\alpha}(\vec{\theta})}$$



Credit: Bartelmann and Schneider 2001

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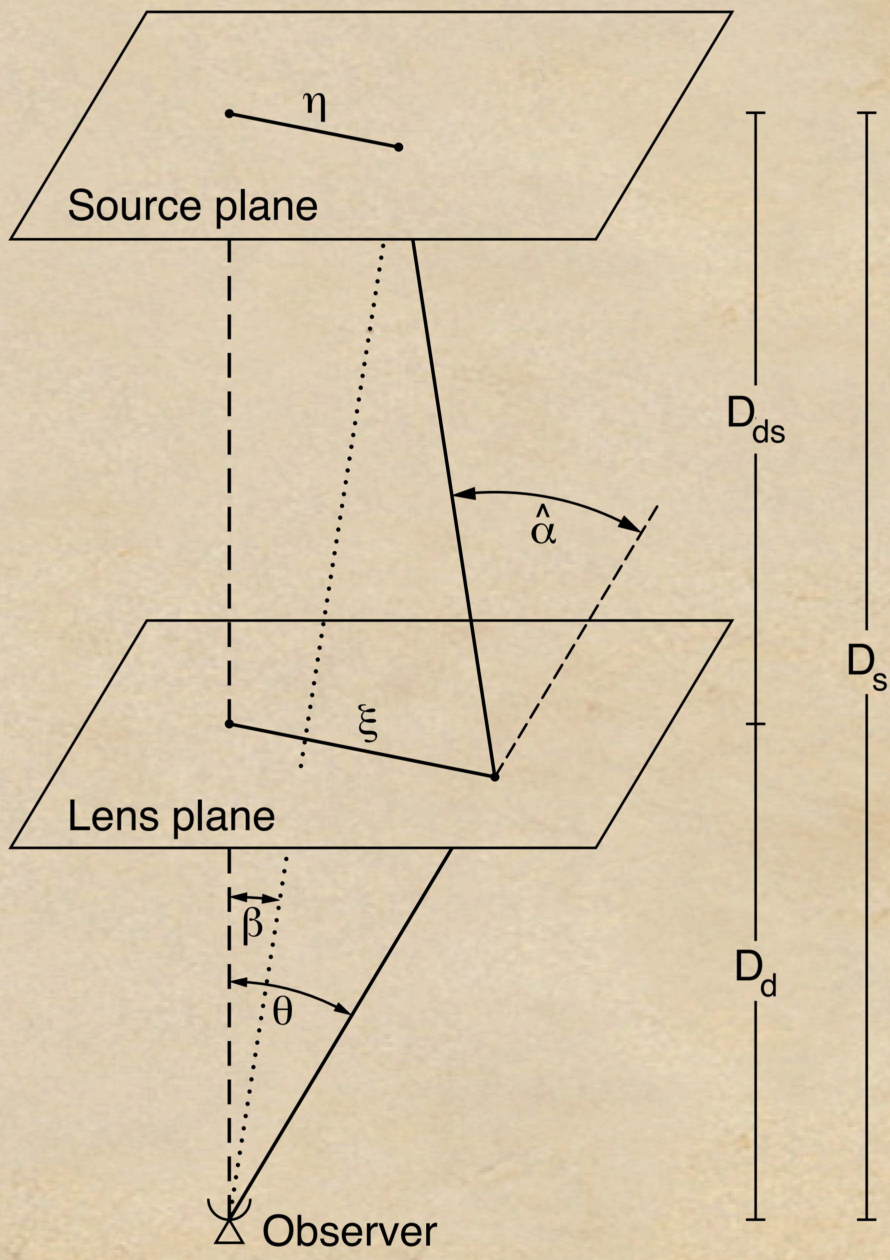

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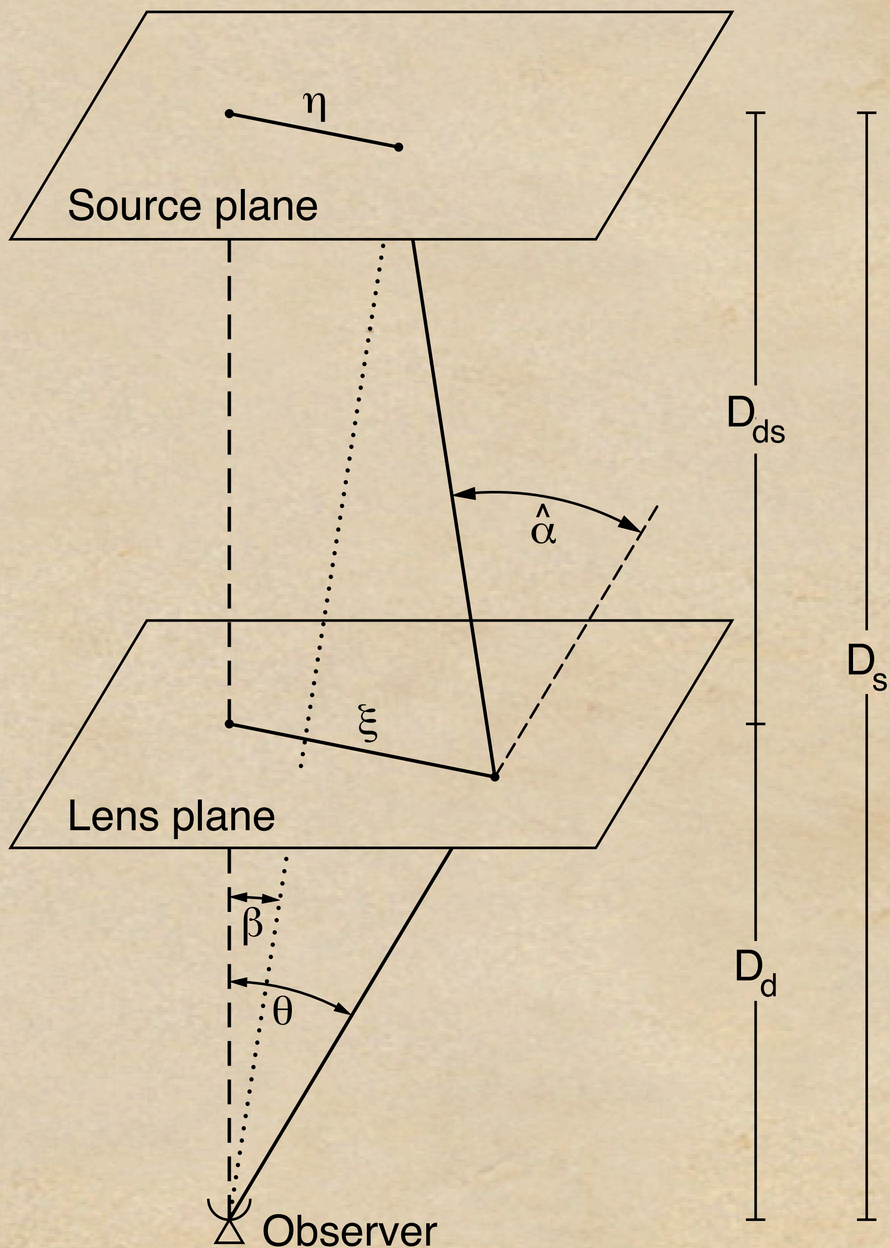
$$\mathcal{A}_{ij} = \frac{\partial x_i^S}{\partial x_j^I}$$



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$$\mathcal{A}_{ij} = \frac{\partial x_i^S}{\partial x_j^I}$$

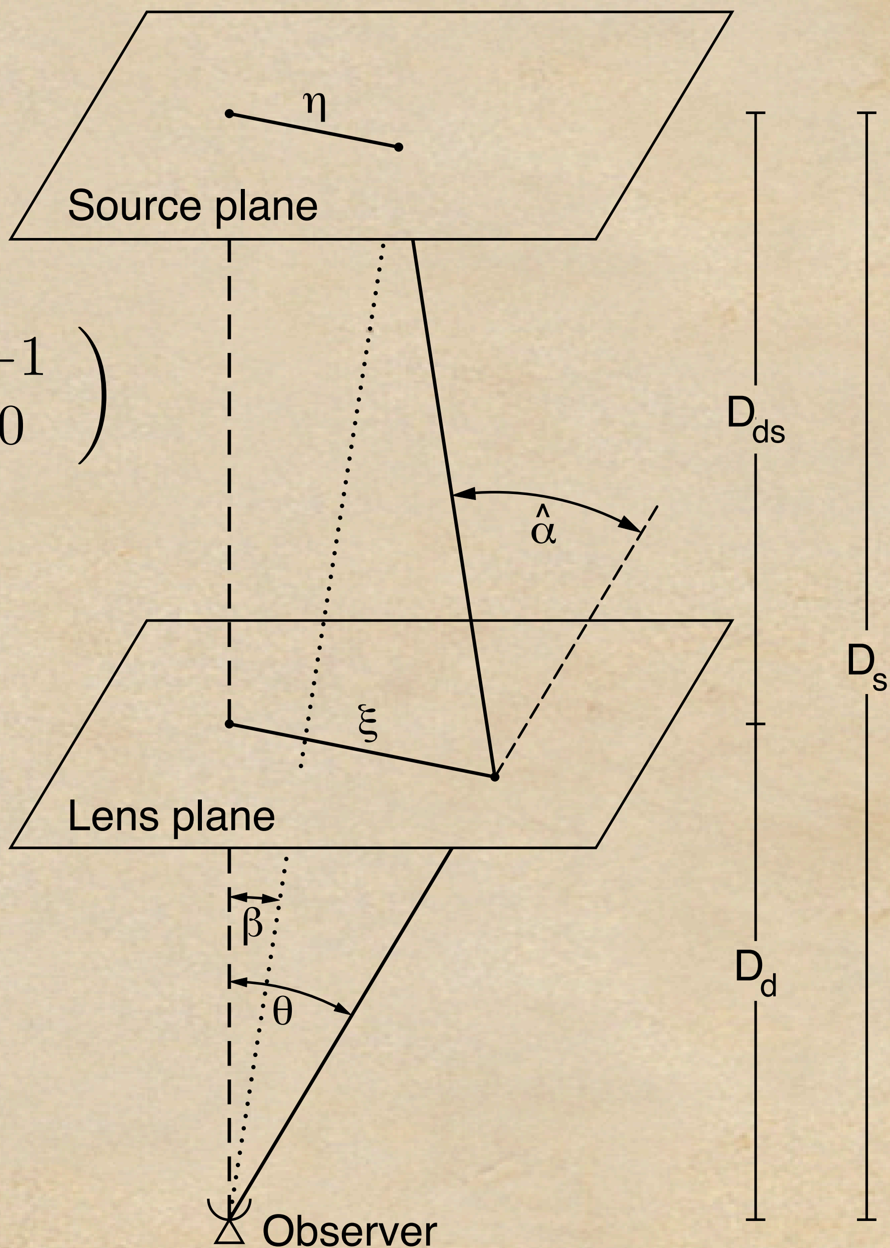
$$= (1-\kappa)\delta_{ij} - \gamma_{ij} + \omega\epsilon_{ij}$$

$$\begin{pmatrix} 0 & -1 \\ 1 & 0 \end{pmatrix}$$

trace

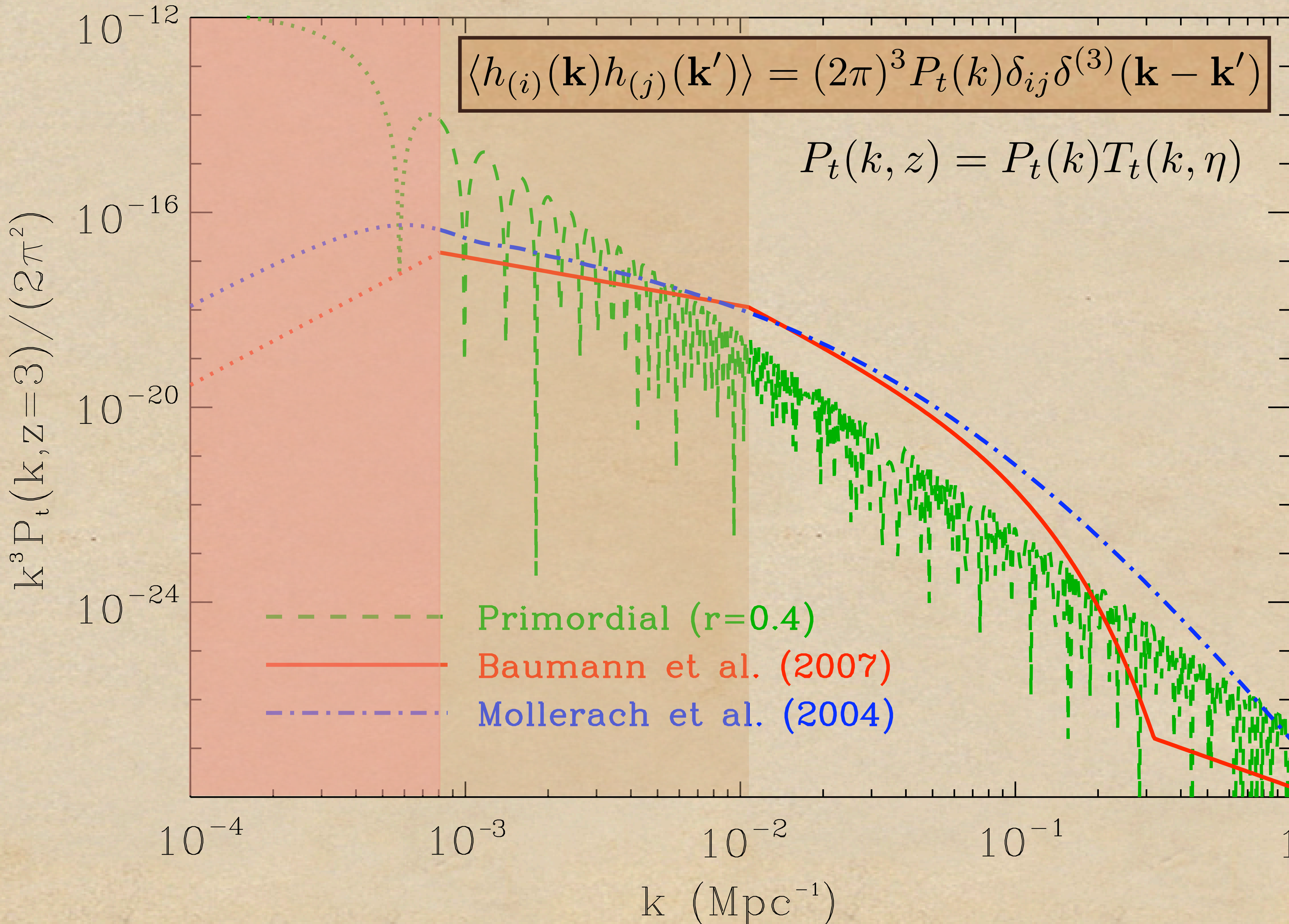
symmetric traceless

antisymmetric rotation



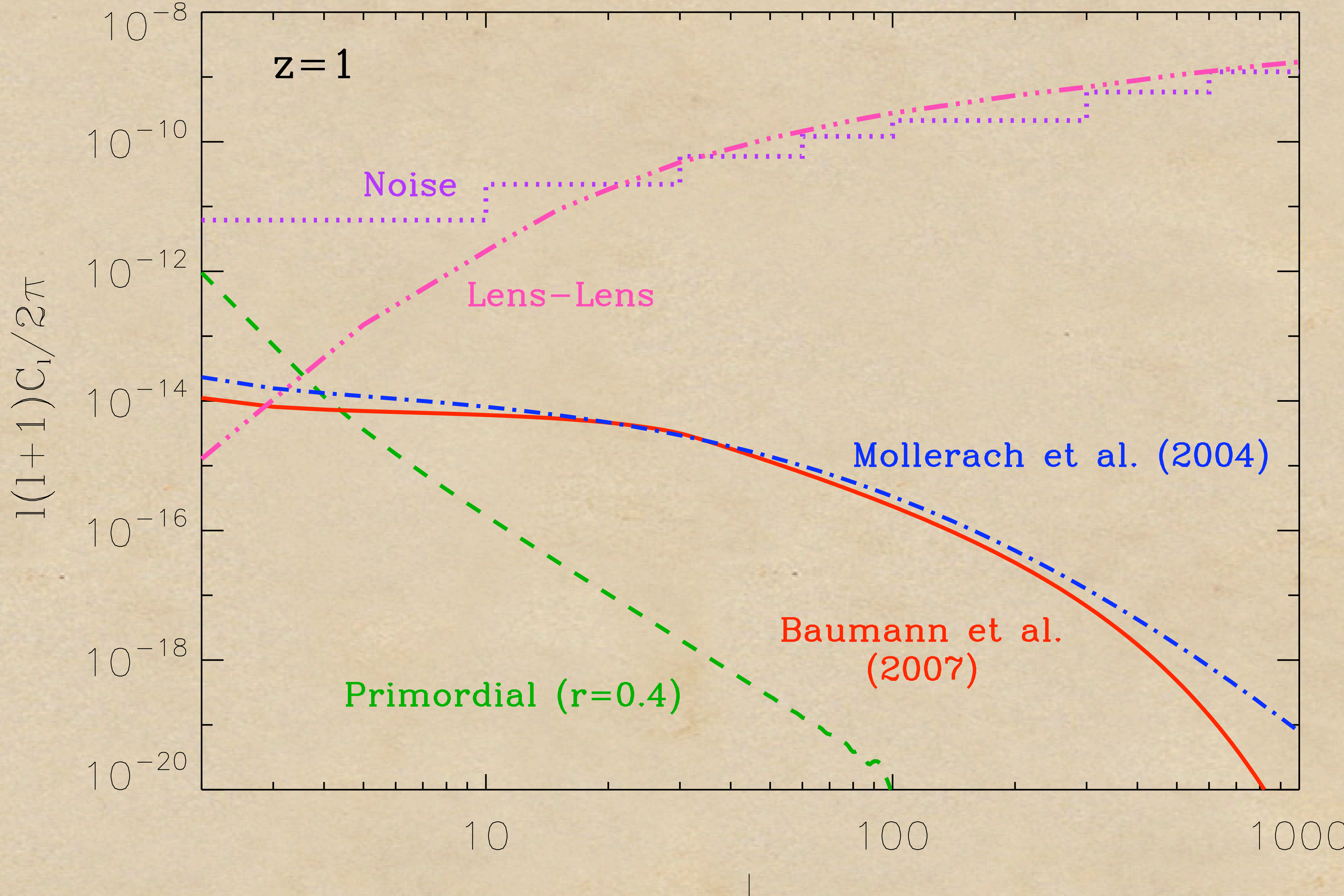
Credit: Bartelmann and Schneider 2001

GW Power Spectra



D.S., P. Serra, A. Cooray, K. Ichiki, D. Baumann,
PRD, 77, 103515 (2008)

Cosmic Shear Curl Mode Power Spectra



D.S., P. Serra, A. Cooray, K. Ichiki, D. Baumann, PRD, *77*, 103515 (2008)

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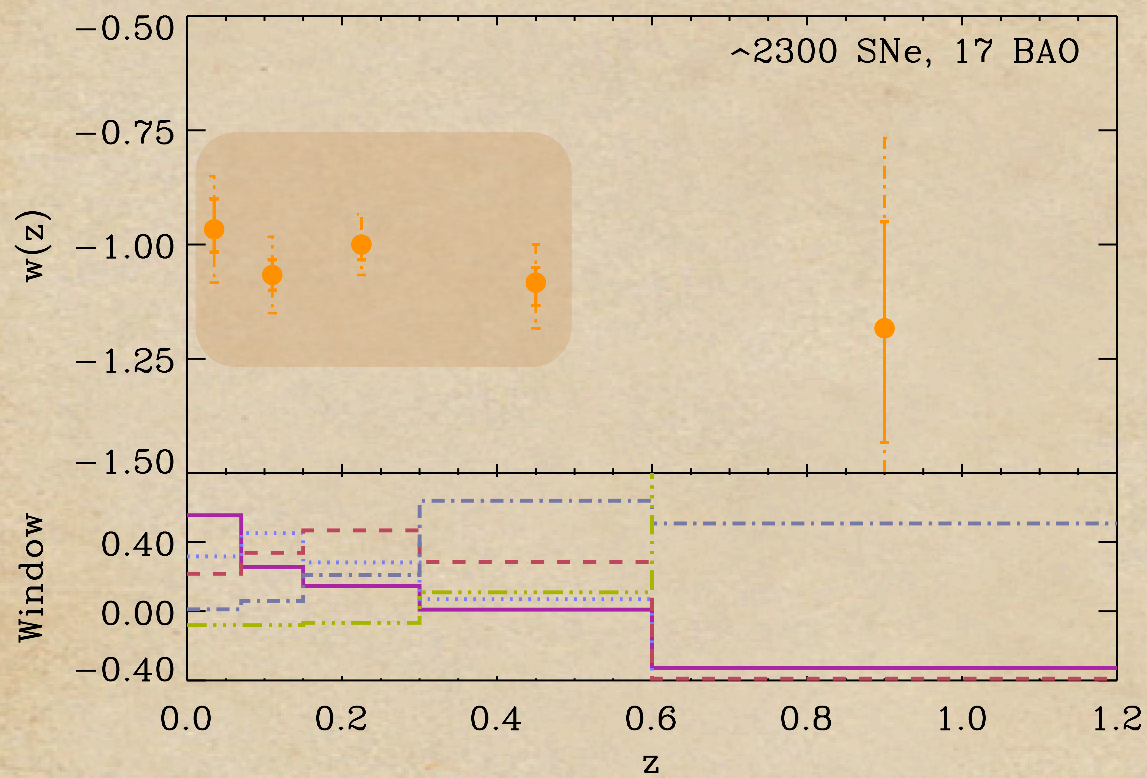
- Lensing of SNe
- Other Worries

Non-Gaussianity

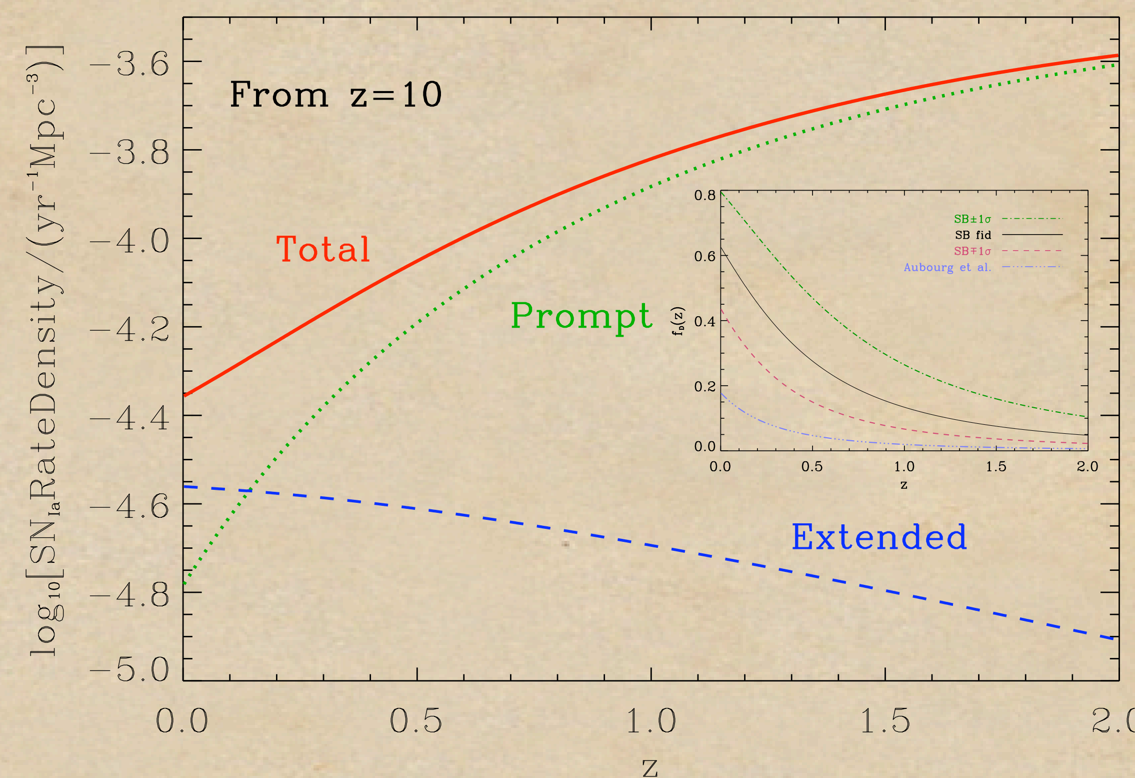
- Beyond Gaussianity
- CMB Bispectrum
- Lensing of CMB
- Lensed Bispectrum
- S/N Reduction & Bias

Gravity Waves via Weak Gravitational Lensing

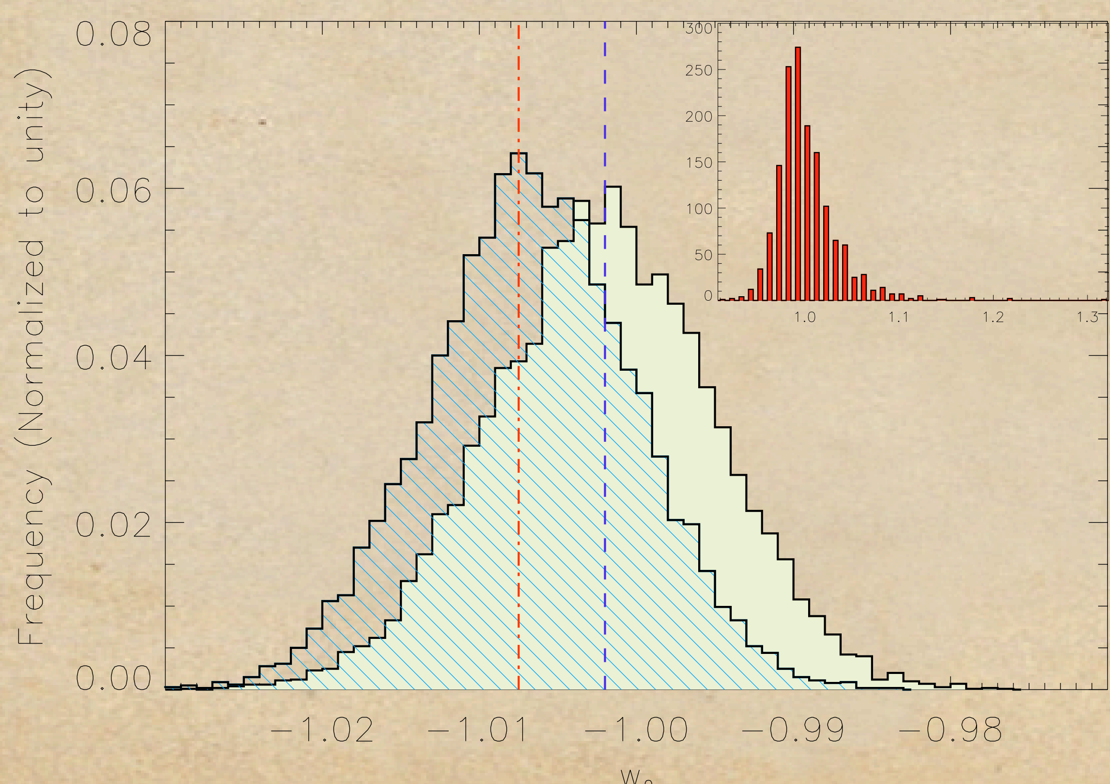
Summary



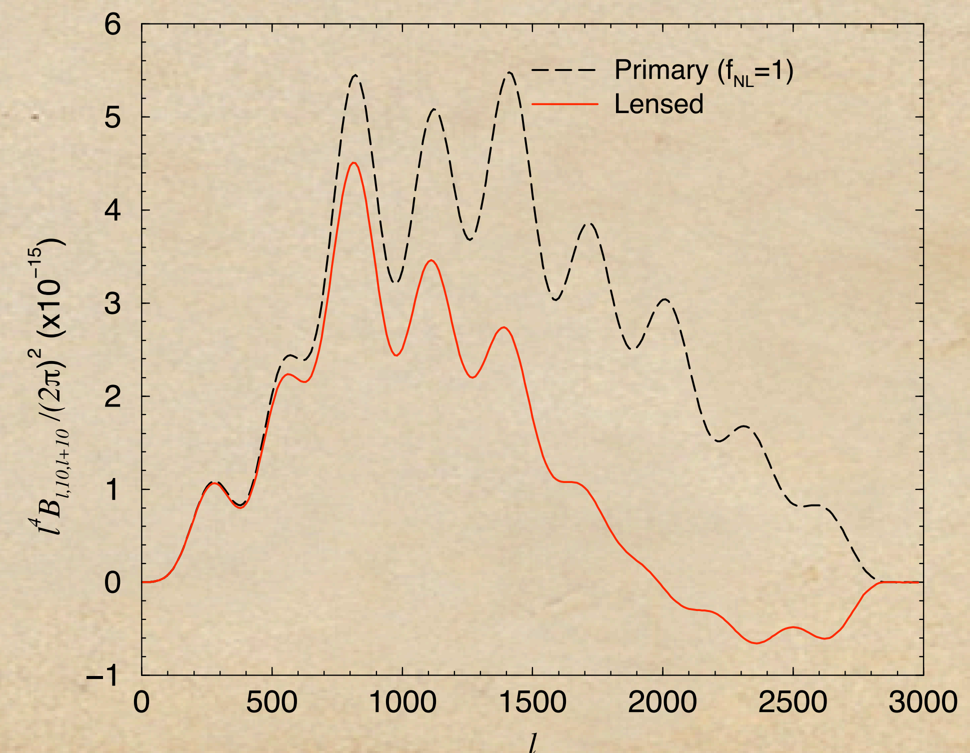
~2300 SNe, 17 BAO
w(z)
Window
z



From z=10
Total
Prompt
Extended
$\log_{10}[\mathrm{SN_{Ia}RateDensity}/(\mathrm{yr^{-1}Mpc^{-3}})]$
z
SB fid
Aubourg et al.



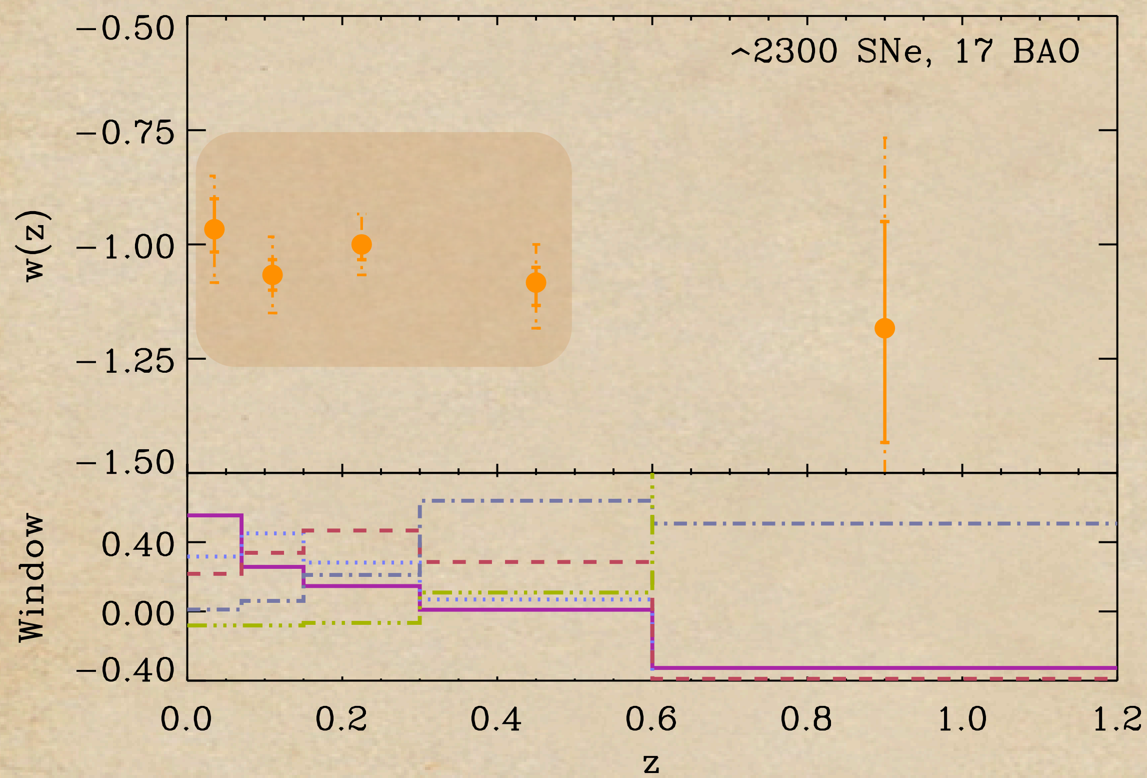
Frequency (Normalized to unity)
w_0

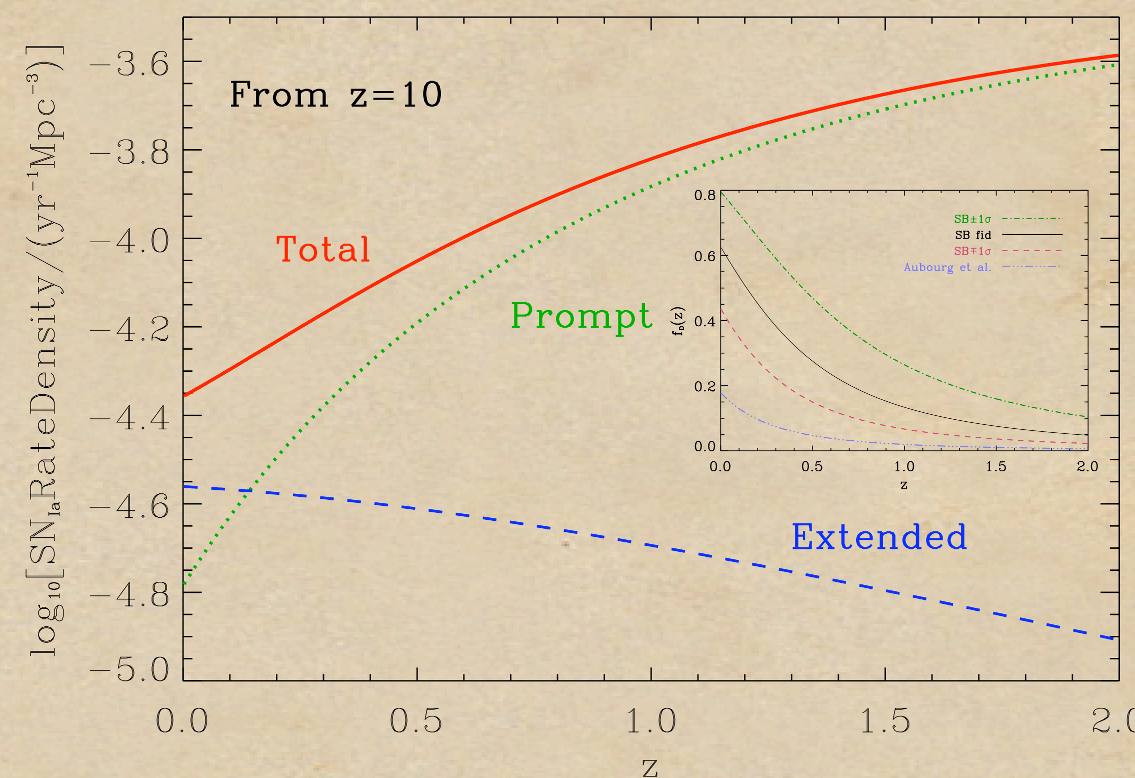


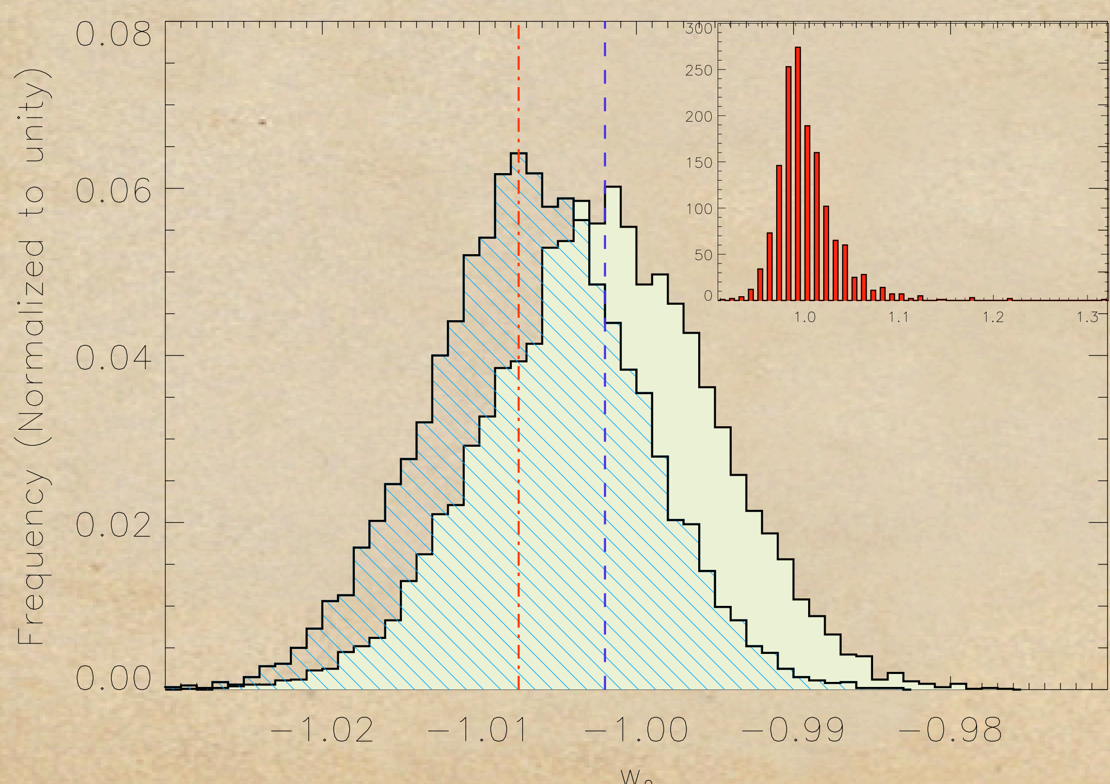
Primary (f_{NL}=1)
Lensed
$l^4 B_{l,10,l+10}/(2\pi)^2\ (\times 10^{-15})$
l

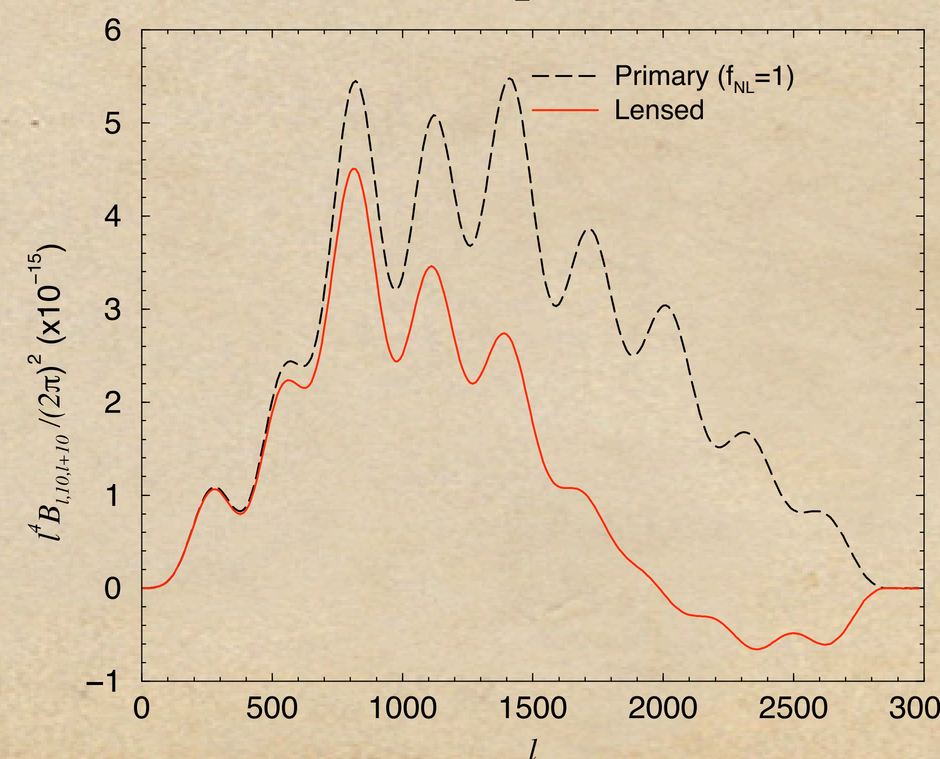
DSARKAR.ORG

Summary


~2300 SNe, 17 BAO
w(z)
Window
z
−0.50
−0.75
−1.00
−1.25
−1.50
0.40
0.00
−0.40
0.0
0.2
0.4
0.6
0.8
1.0
1.2


From z=10
Total
Prompt
Extended
log10[SNIaRateDensity/(yr−1Mpc−3)]
z
−3.6
−3.8
−4.0
−4.2
−4.4
−4.6
−4.8
−5.0
0.0
0.5
1.0
1.5
2.0


Frequency (Normalized to unity)
w0
0.08
0.06
0.04
0.02
0.00
−1.02
−1.01
−1.00
−0.99
−0.98


Primary (fNL=1)
Lensed
l
0
500
1000
1500
2000
2500
3000
6
5
4
3
2
1
0
−1