Cosmic Frontiers:
The Big Questions

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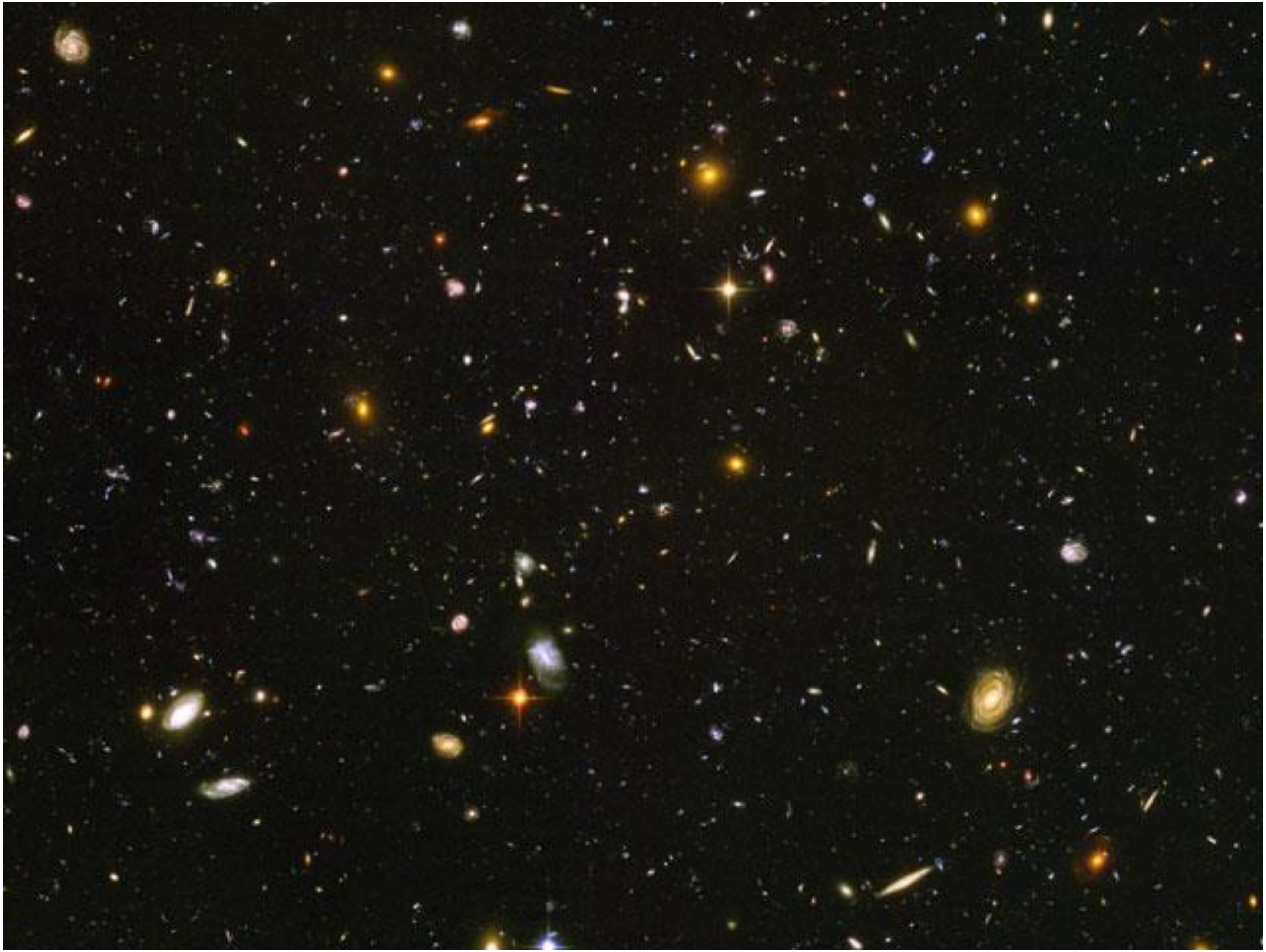
The questions

- dark matter?
- dark energy?
- Inflation?

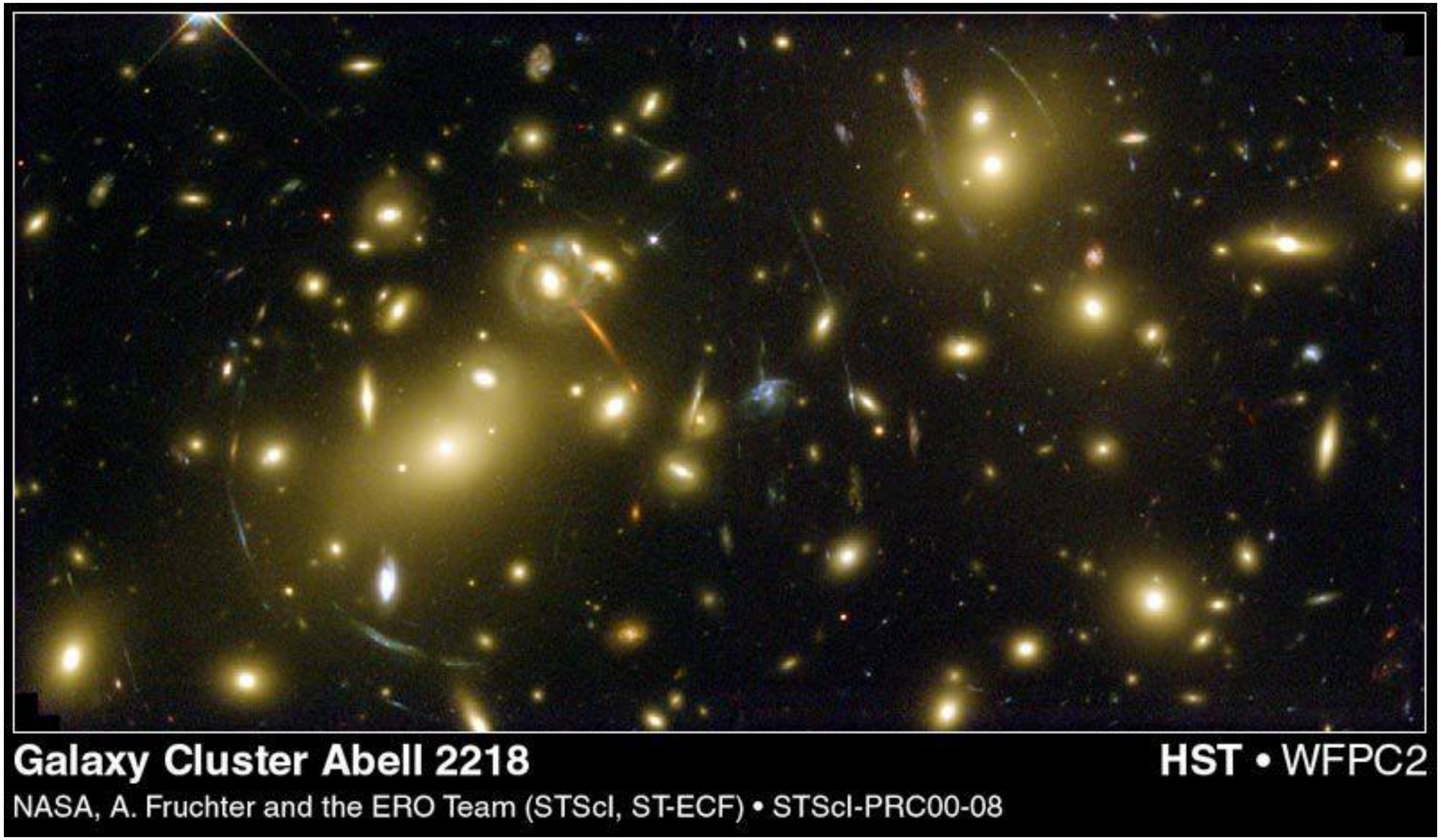
Dark matter basics

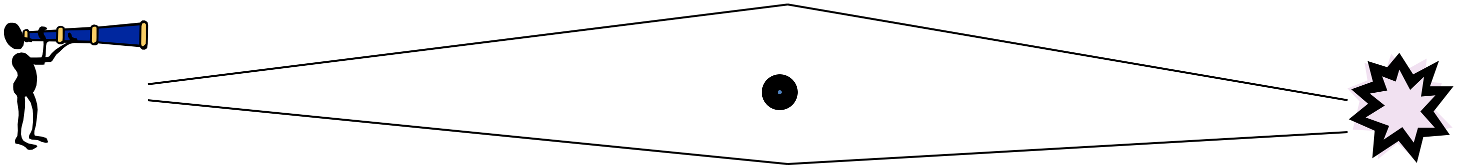
D'Amico, MK, Sigurdson, 0907.1912 [short]

Jungman, MK, Griest, Phys Rep 267, 195 (1996) [long]



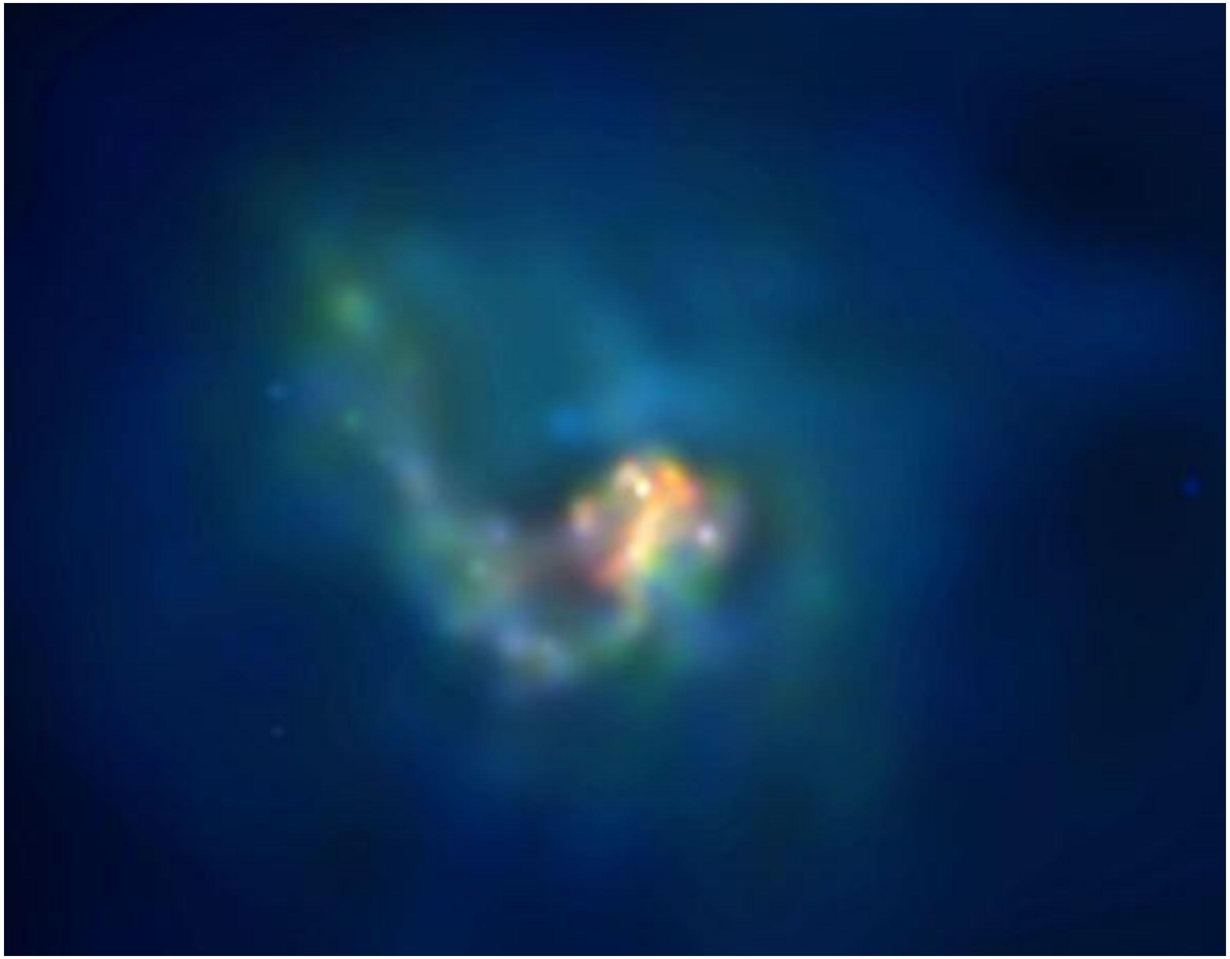
Lensing effect of dark matter





X-ray clusters: Gas in hydrostatic eq

$$dP/dr = -G\rho_{\rm tot}(r) m_b(r)/r^2$$



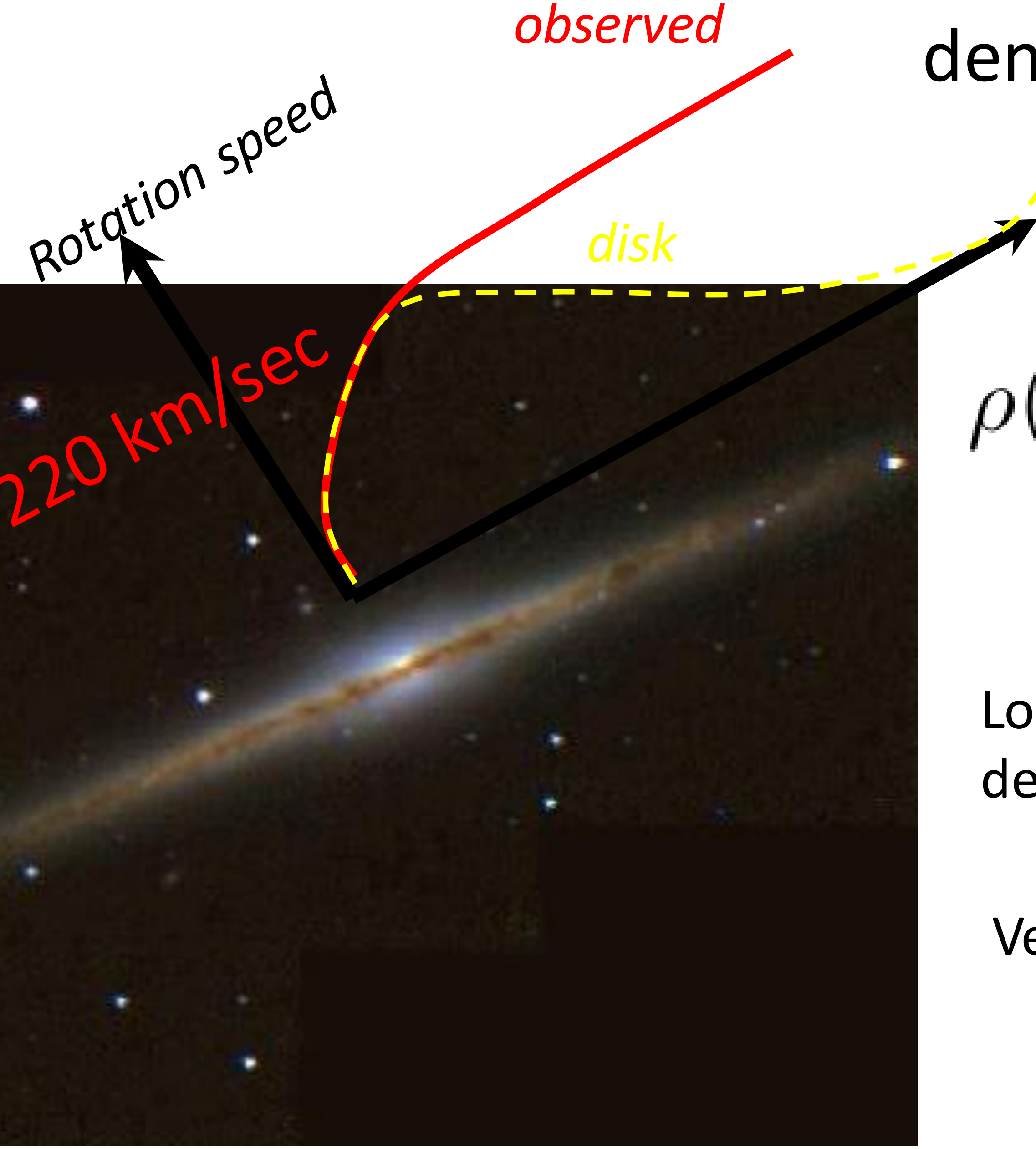
$$M_{\rm total} \gg M_{\rm baryons} \quad \text{in clusters}$$

13 years of CMB experiments

(see Thurs talk)

Collisionless matter outweighs baryons by factor of ~6

Not just in the “Universe”; in our own Galaxy!



Dark-matter density profile:

3-5 kpc

$$\rho(r) = \rho_0 \frac{R^2 + a^2}{r^2 + R^2}$$

8.5 kpc

Local dark-matter density: ~0.4 GeV/cm^3

Velocity dispersion:
v ~ 300 km/sec

Dark matter properties:

- Must have no (or no more than very weak) coupling to photons
- Cross section for self-scattering must be $<10^{-24}$ cm^2
- Interactions with baryons must be very weak

Only SM particle that fits the bill is neutrino

Could dark matter be neutrino?

No!

Quantum mechanics:

$$\Delta x \Delta p > \hbar$$

$$\Delta x \sim n_\nu^{-1/3} \sim (\rho_0/m_\nu)^{-1/3}$$

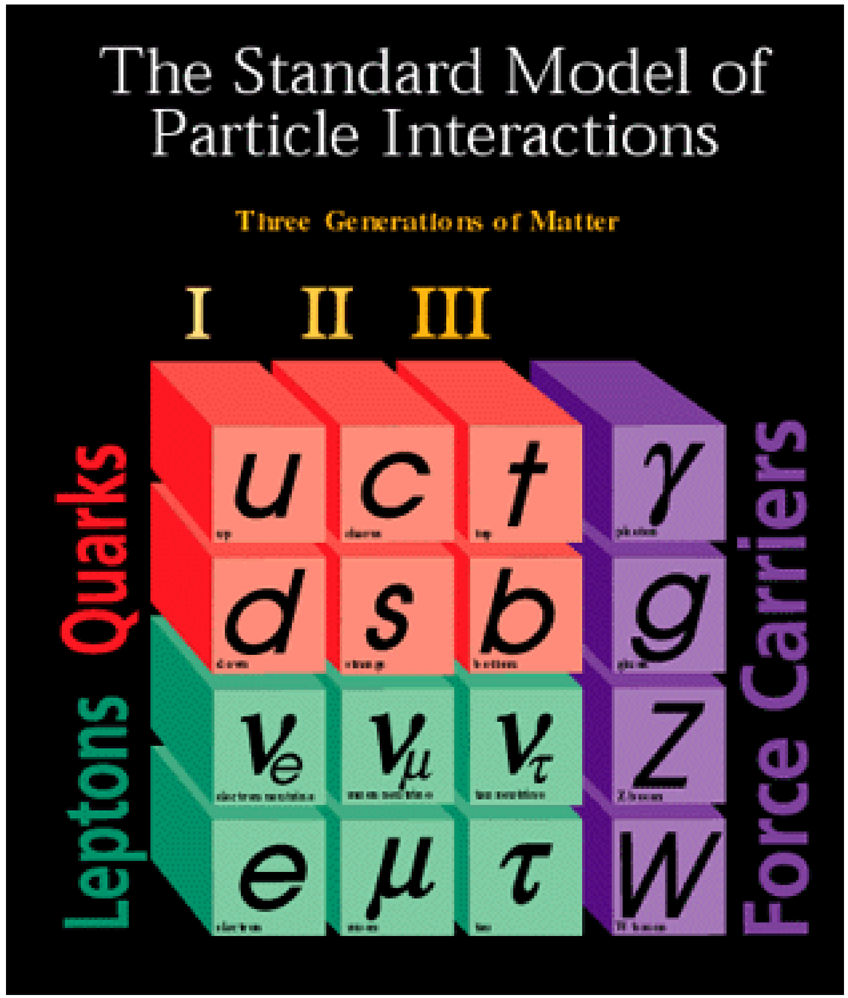
$$\Delta p \sim m_\nu v \quad (v \sim 300\,\mathrm{km/sec})$$

$$\rightarrow m_\nu > 50\,\mathrm{eV}$$

But

$$m_\nu < 10\,\mathrm{eV} \ \text{ if } \ \Omega_\nu h^2 < 0.1$$

Elementary-particle physics



Unfinished business

- Why three generations?
- Why the quark/lepton masses?
- Why no strong-CP violation?
- Why weak CP violation?
- Strong + Electroweak = grand unified theory?
- Gravity?

New Electroweak Physics:

- Technicolor, two Higgs-doublet models, left-right symmetric models, universal extra dimensions ……Supersymmetry
- Often results in stable neutral particle with weak interactions (i.e., couple to Z^0 and $W^\pm$ bosons, like neutrinos)

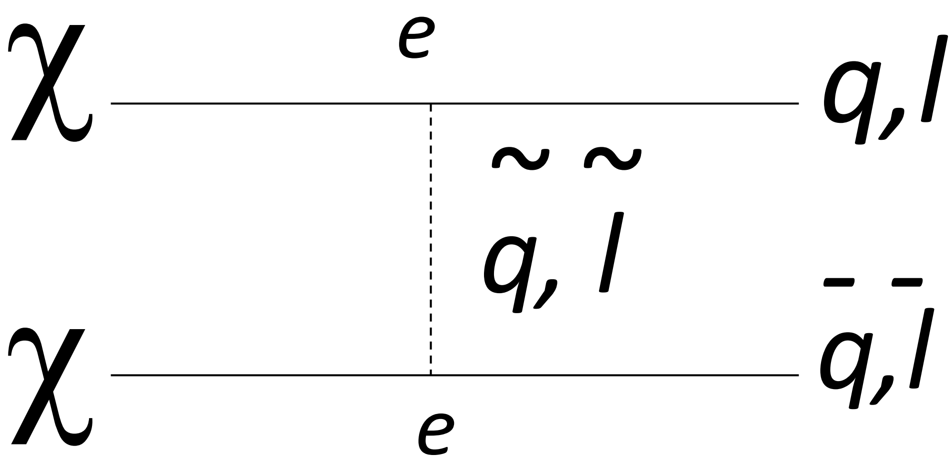
Supersymmetric models:

WIMP (weakly-interacting massive particle) is
neutralino = (photino + Z-ino + higgsino)

$$\tilde{\chi} = \xi_\gamma \tilde{\gamma} + \xi_Z \tilde{Z} + \xi_h \tilde{h}$$

Mass m_χ ~ 10s - 1000s GeV
Spin=1/2 (Majorana fermion)

WIMP interactions:



$$\alpha \sim \frac{1}{137}$$

$$m_{\tilde{q}} \sim 100\,\mathrm{GeV}$$

Cross Section:

$$\sigma \sim \frac{\alpha^2}{m_{\tilde{q}}^2} \sim 10^{-8}\,\mathrm{GeV}^{-2} \sim 10^{-36}\,\mathrm{cm}^2$$

WIMP Freezeout

Annihilation Rate

$$\Gamma(\chi\chi \leftrightarrow q\bar{q}, l\bar{l}, \cdots) = n_\chi \langle \sigma |v| \rangle$$

Expansion Rate

$$H = \left(\frac{8\pi G\rho}{3}\right)^{1/2} \propto T^2$$

Early Times:

$$k_B T \gg m_\chi c^2$$

$$n_\chi \propto T^3$$

$$\Gamma \gg H$$

Equilibrium Holds

Late Times:

$$k_B T \ll m_\chi c^2$$

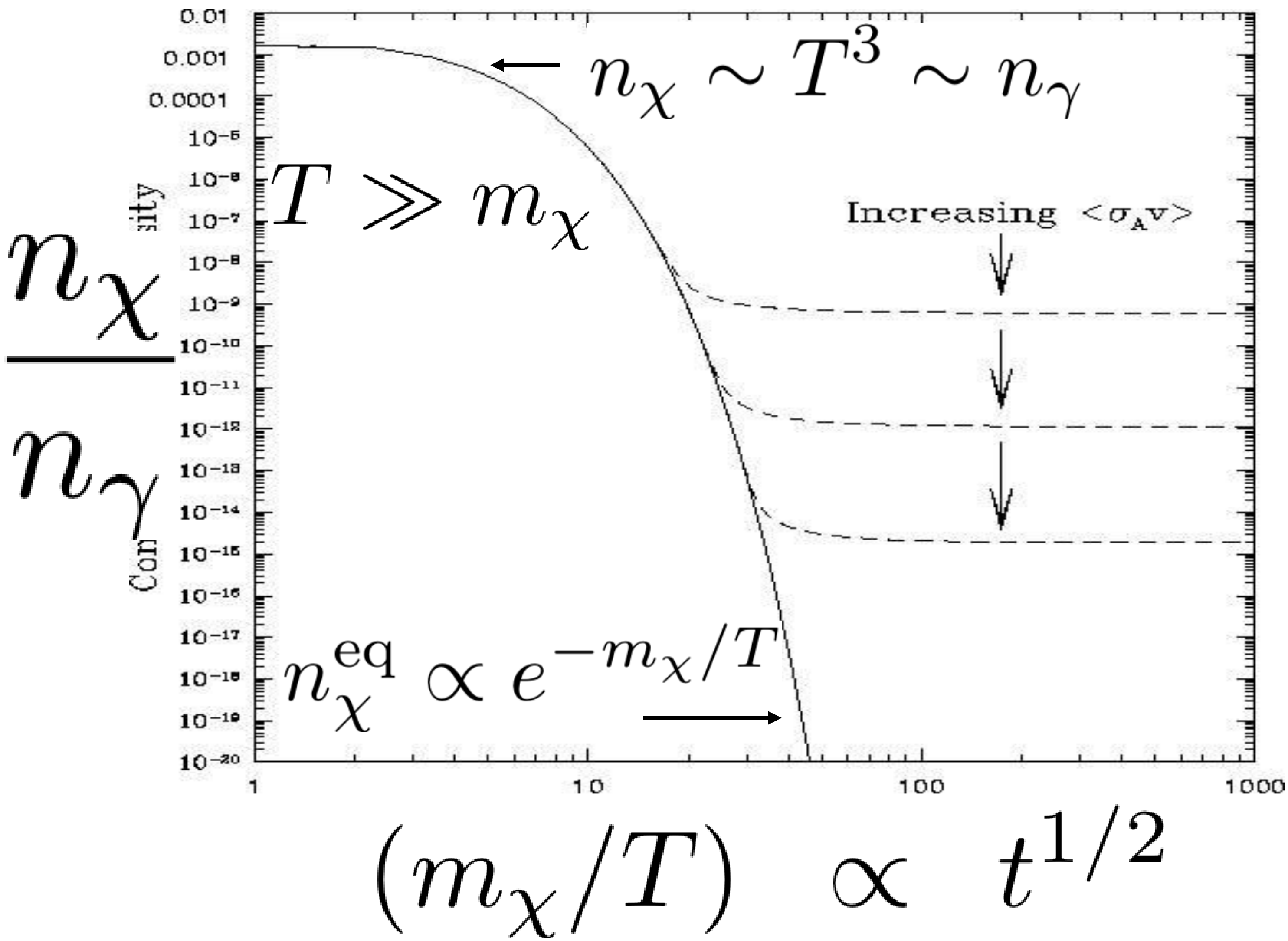
$$n_\chi^{\mathrm{eq}} \propto e^{-m_\chi/T}$$

$$\Gamma \ll H$$

Annihilations can not occur

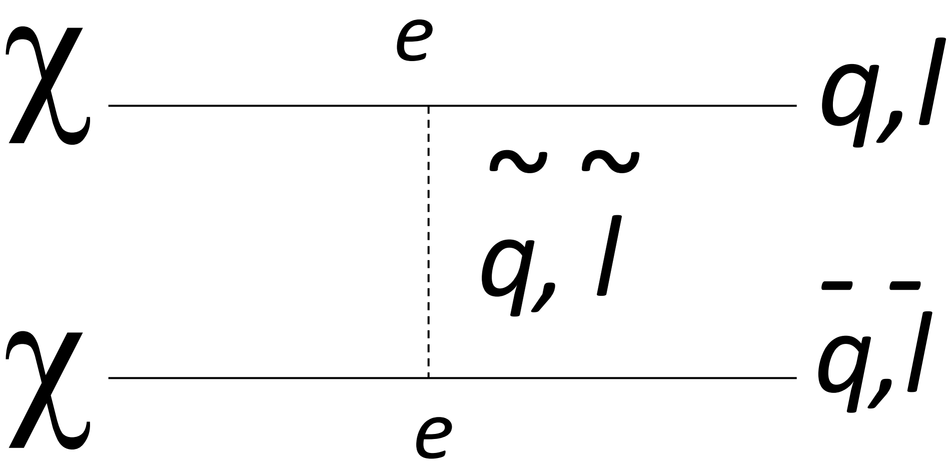
"Freezeout" at $$\Gamma(T_f) = H(T_f)$$

Afterwards, comoving WIMP # constant



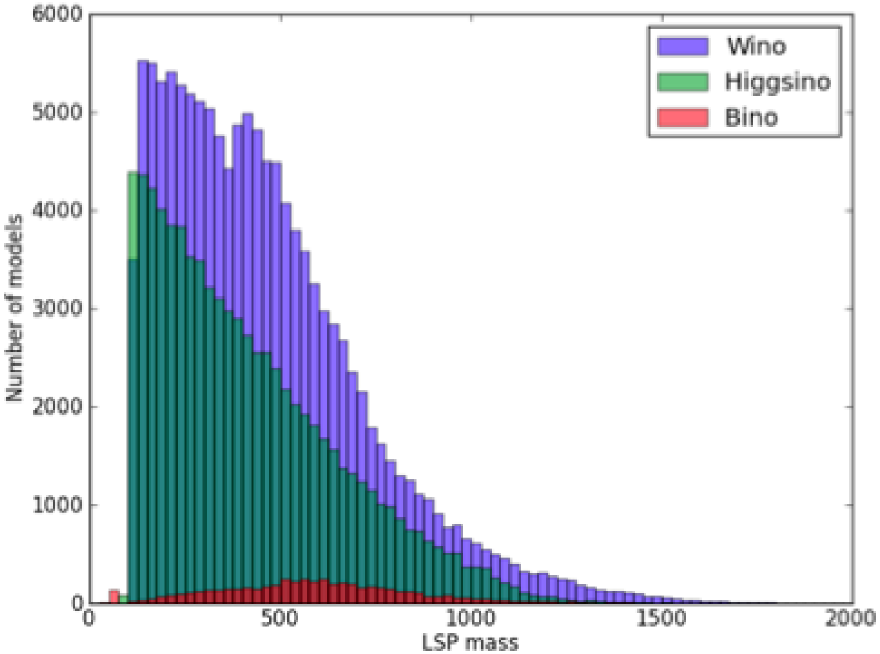
Freezeout Calculation:

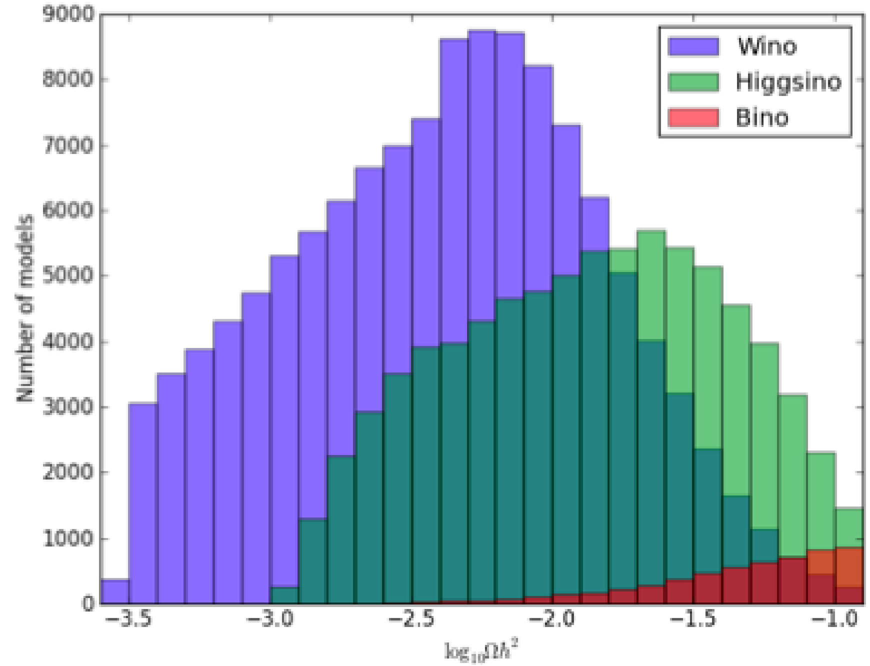
$$\Omega_\chi h^2 \simeq 0.1 \left(\frac{\langle \sigma v \rangle}{3\times 10^{-26}\,\mathrm{cm}^3\,\mathrm{sec}^{-1}} \right)^{-1}$$



$$\sigma \sim \frac{\alpha^2}{m_\chi^2}$$

Number of models

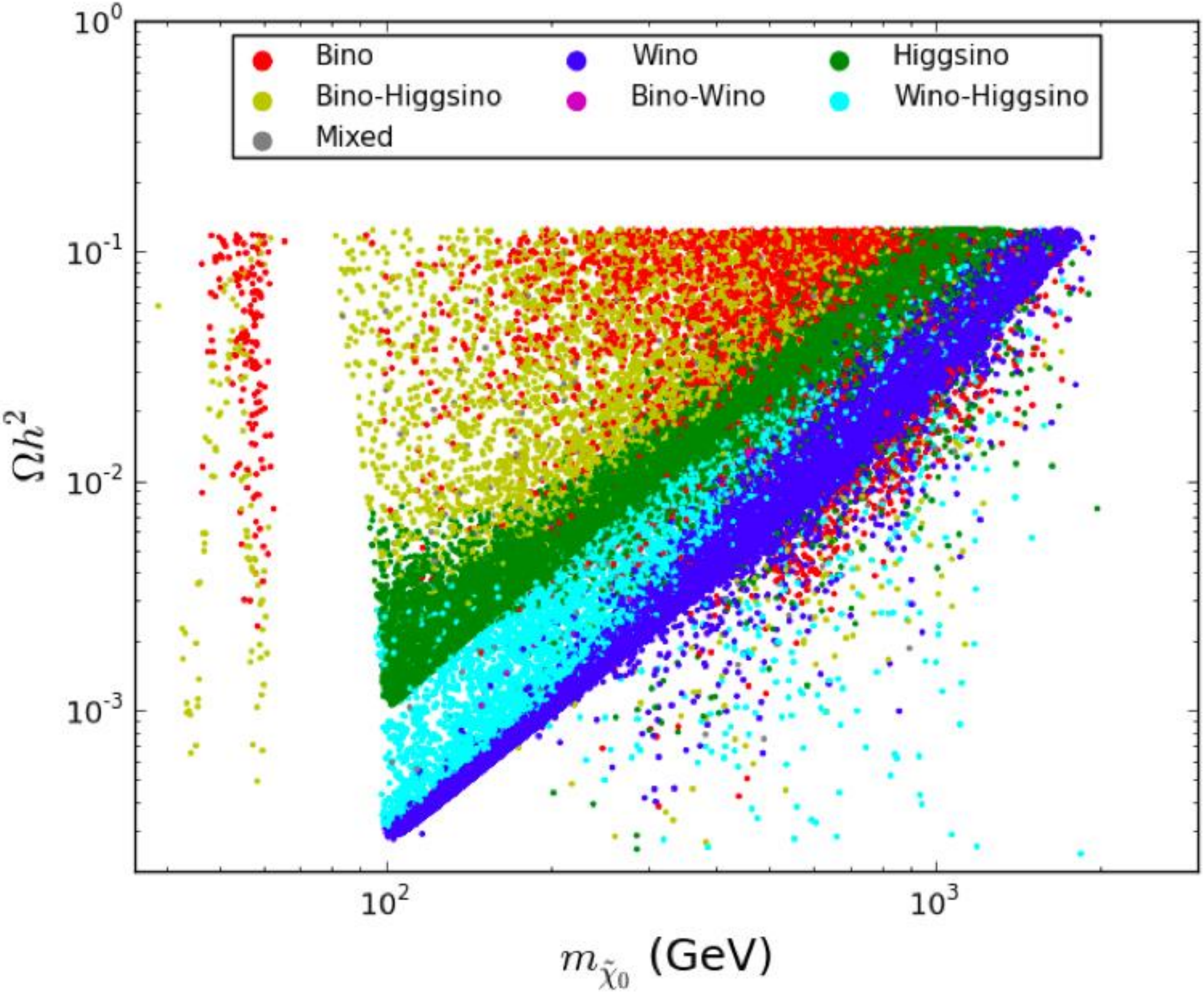




LSP Mass

Relic density

Survey of MSSM (Cahill-Rowley et al. 1305.6921



Bino
Wino
Higgsino
Bino-Higgsino
Bino-Wino
Wino-Higgsino
Mixed
10^0
10^{-1}
10^{-2}
10^{-3}
Ωh^2
10^2
10^3
$m_{\tilde{\chi}_0}$ (GeV)

$$\Omega_\chi h^2 \sim m_\chi^2 \quad \text{from} \quad \langle \sigma v \rangle \sim m_\chi^{-2}$$

In fact, partial-wave unitarity,

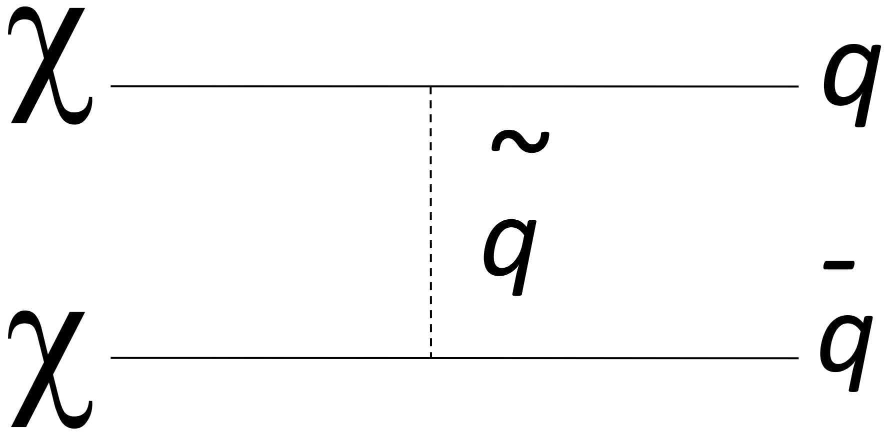
$$\langle \sigma v \rangle \lesssim m_\chi^{-2} \quad \text{with} \quad \Omega_\chi h^2 \lesssim 0.1$$

leads to WIMP-mass limit,

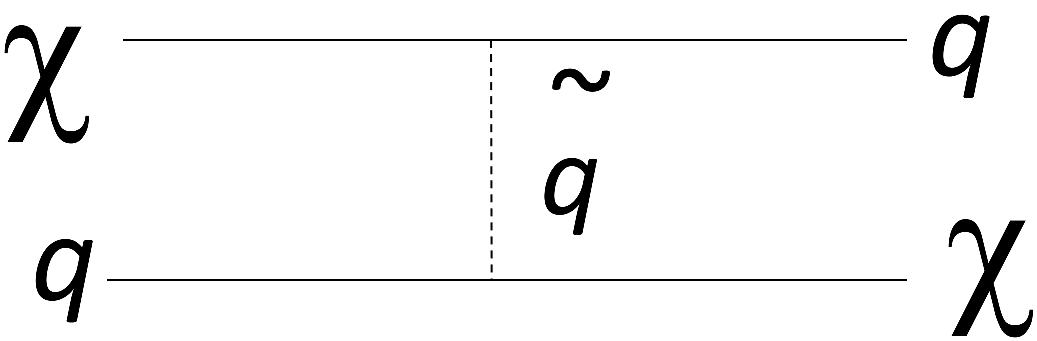
$$m_\chi \lesssim 100\,\mathrm{TeV}$$

Griest&MK 1991

WIMP Detection: Crossing Symmetry



for $\Omega_\chi h^2 \sim 0.1$



WIMP-quark scattering with similar cross section

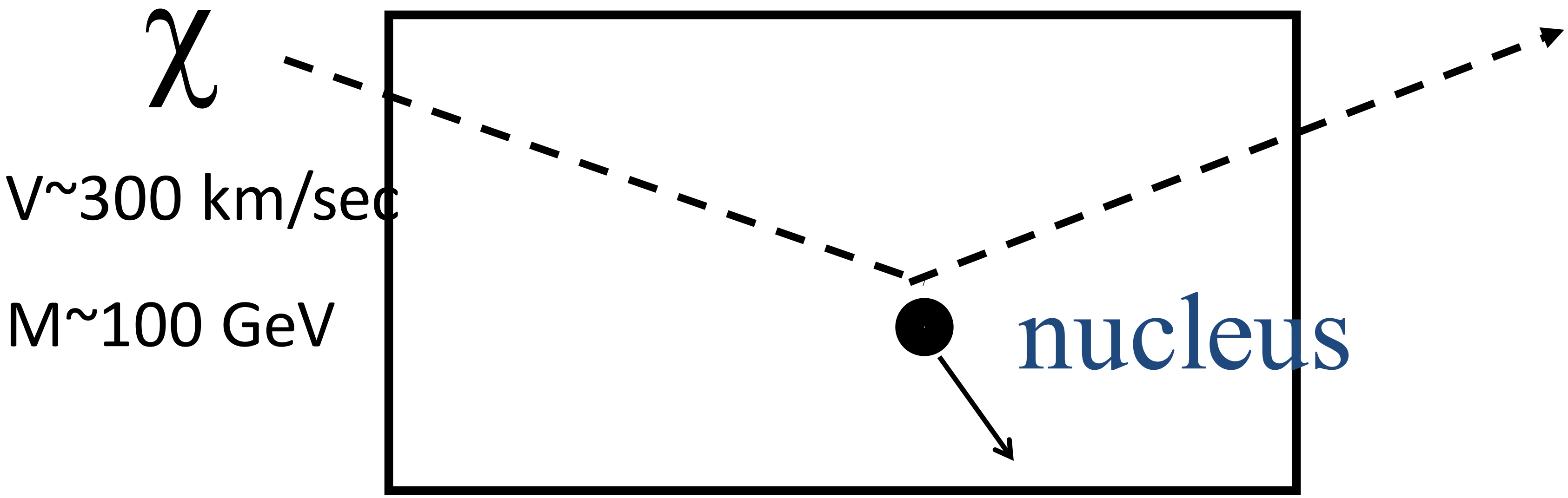
Direct detection:

QCD nuclear physics

$$\chi q \longrightarrow \chi n \longrightarrow \chi N$$

$$\sigma_{\mathrm{WIMP-nucleus}} \sim 10^{-36}\,\mathrm{cm}^2$$

E.g., Ge or Xe detector



$E_{recoil} \sim (1/2)mv^2 \sim 50$ keV

Rate:

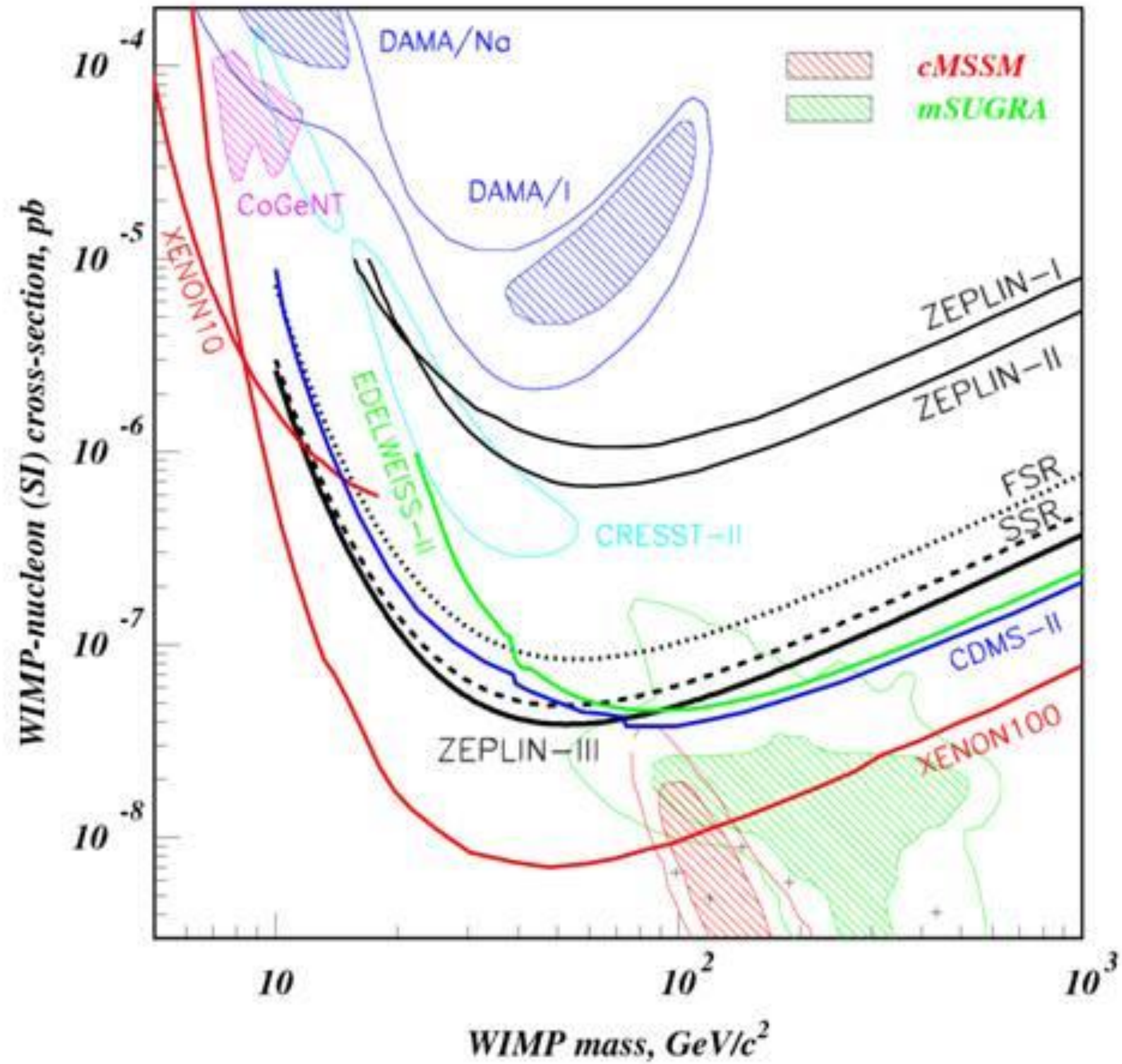
$$n\sigma v N_{\rm nuclei} \sim (10^{-36}\,{\rm cm}^2)\left(\frac{0.4\,{\rm GeV/cm}^3}{100\,{\rm GeV}}\right)(3\times 10^7\,{\rm cm/sec})\left(\frac{6\times 10^{23}\,{\rm kg}^{-1}}{A}\right)$$

$$\sim \text{few kg}^{-1}\ \text{yr}^{-1}$$

Wimp can have several types of interactions with nuclei; e.g.,

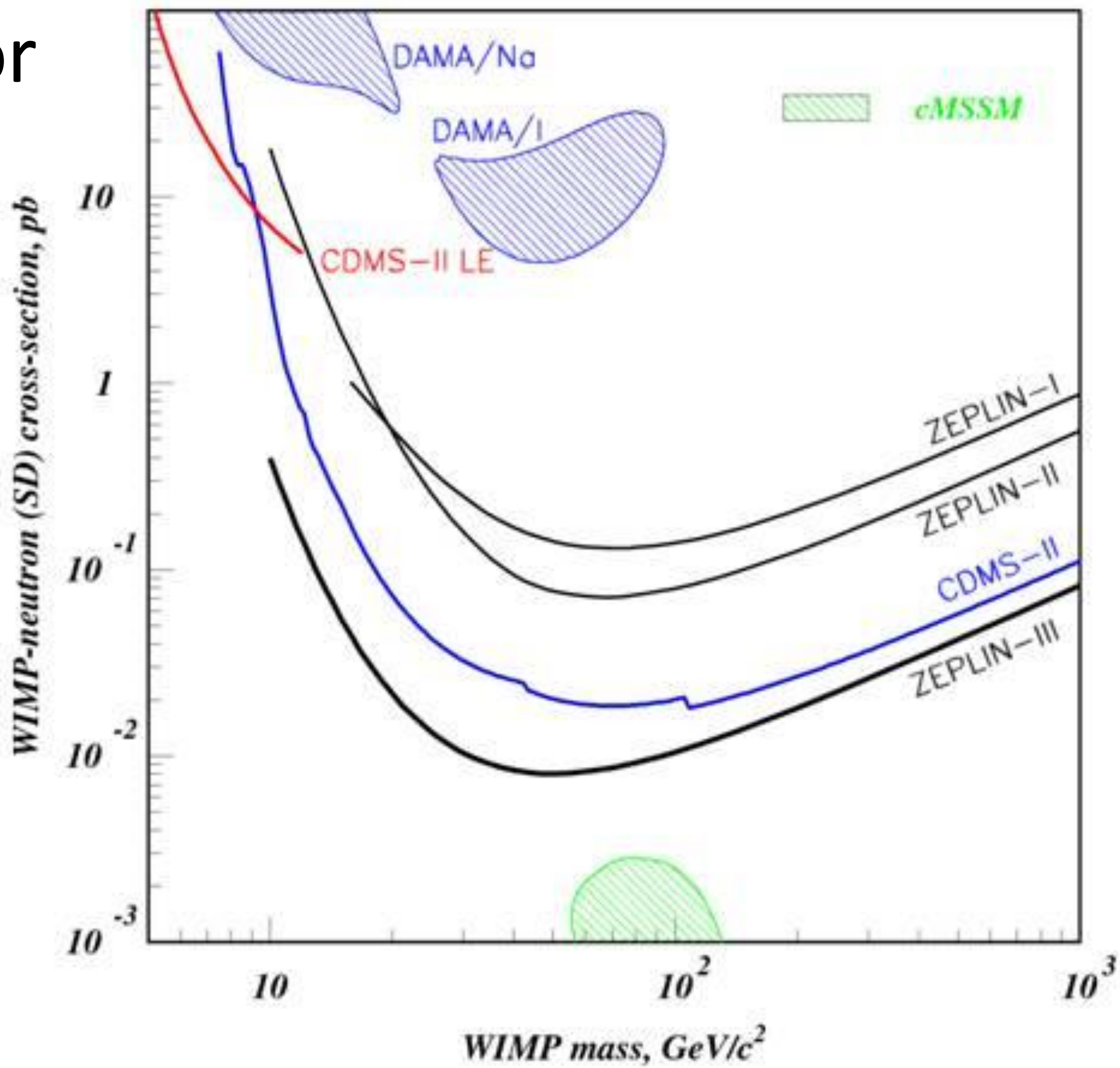
- Scalar interaction (or spin-independent)
  - $$\mathcal{L} \sim \bar{\chi}\chi\bar{q}q$$
  - Couples to *mass* of nucleus
- Axial-vector (or spin-dependent)
  - $$\mathcal{L} \sim \bar{\chi}\gamma^{\mu}\gamma_5\chi\bar{q}\gamma_{\mu}\gamma_5 q$$
  - Couples to *spin* of nucleus
    (actually, more like spin of unpaired neutron or proton)

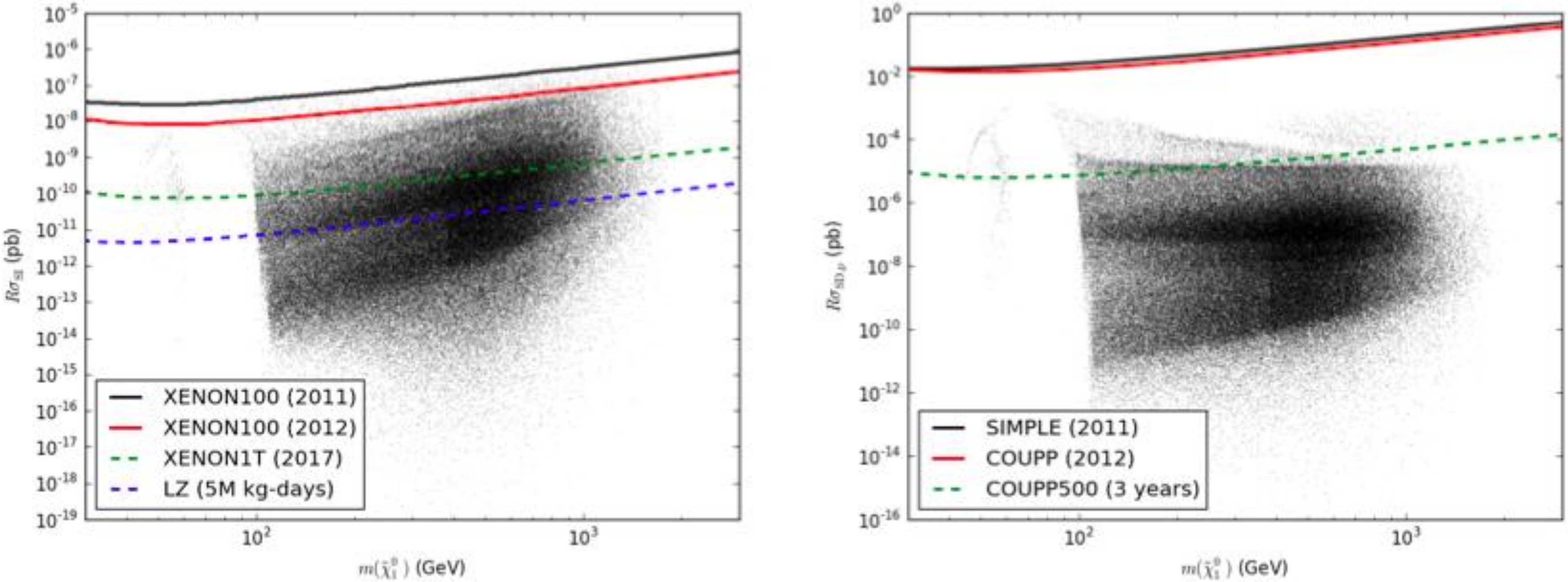
scalar



DAMA/Na
cMSSM
mSUGRA
DAMA/I
CoGeNT
XENON10
ZEPLIN-I
ZEPLIN-II
EDELWEISS-II
FSR
SSR
CRESST-II
CDMS-II
XENON100
ZEPLIN-III
WIMP-nucleon (SI) cross-section, pb
WIMP mass, GeV/c^2
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10
10^2
10^3

Axial-vector





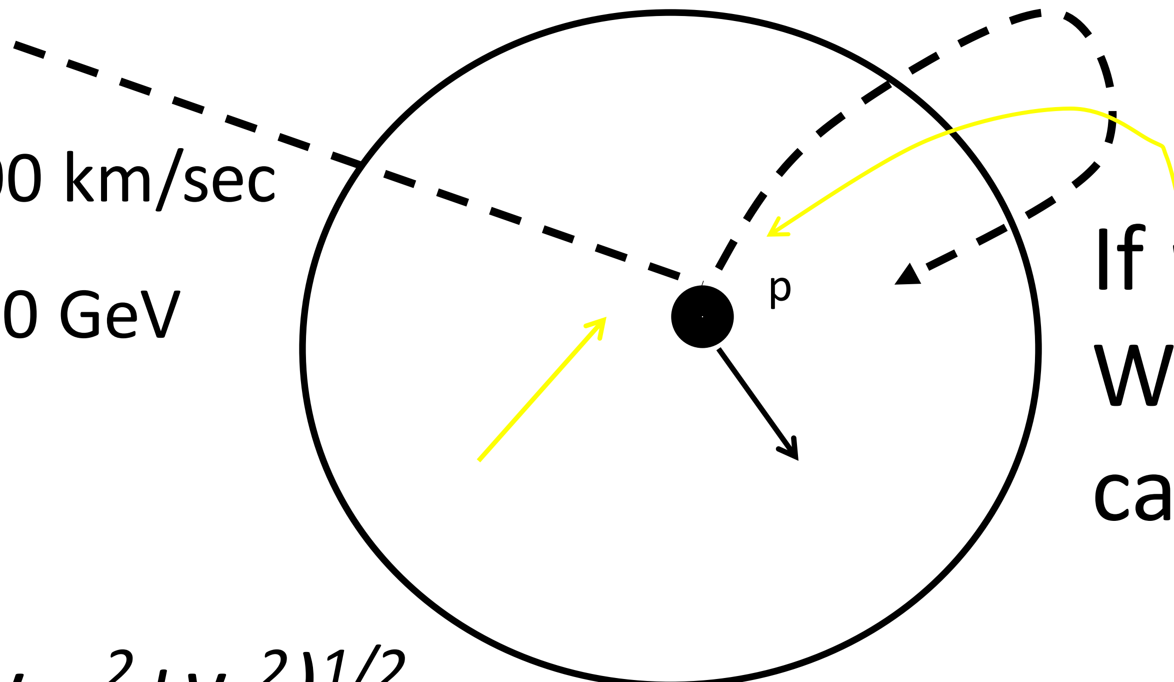
XENON100 (2011)
XENON100 (2012)
XENON1T (2017)
LZ (5M kg-days)
$R\sigma_{SI}$ (pb)
$m(\tilde{\chi}_1^0)$ (GeV)
SIMPLE (2011)
COUPP (2012)
COUPP500 (3 years)
$R\sigma_{SDp}$ (pb)
$m(\tilde{\chi}_1^0)$ (GeV)

Indirect Detection: Energetic neutrinos from WIMP annihilation in Sun/Earth

χ

V_0~300 km/sec

M~100 GeV



If $v<v_{esc}$, WIMP captured

$$v=(v_{esc}^2+v_0^2)^{1/2}$$

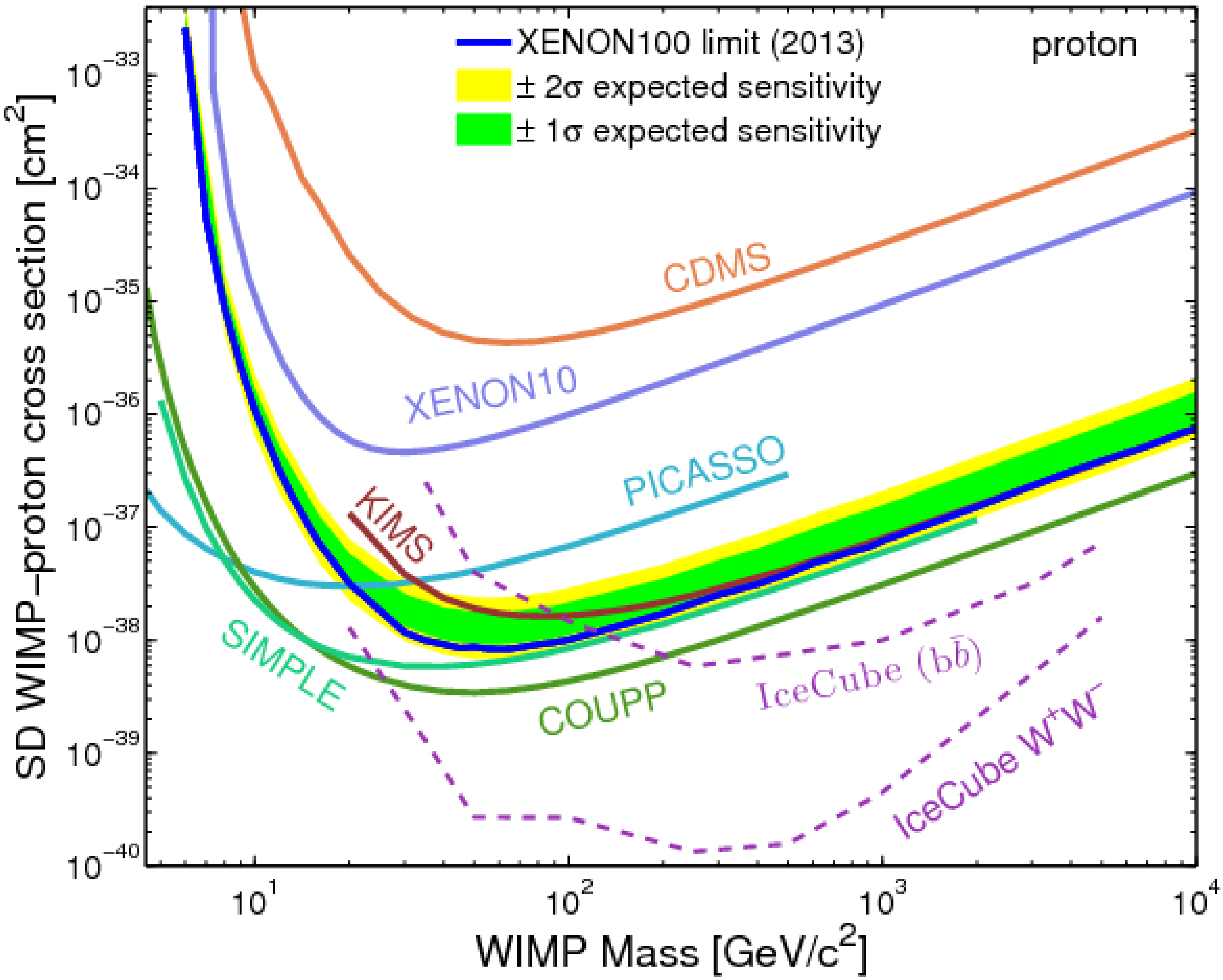
Inside Sun and/or Earth:

$$\chi\chi \to (W^+W^-, Z^0Z^0, q\bar{q}, l\bar{l}, \cdots) \to \nu\bar{\nu}$$

$$E_\nu \sim (1/10 - 1/2)m_\chi \sim 10 - 1000s\,\mathrm{GeV}$$

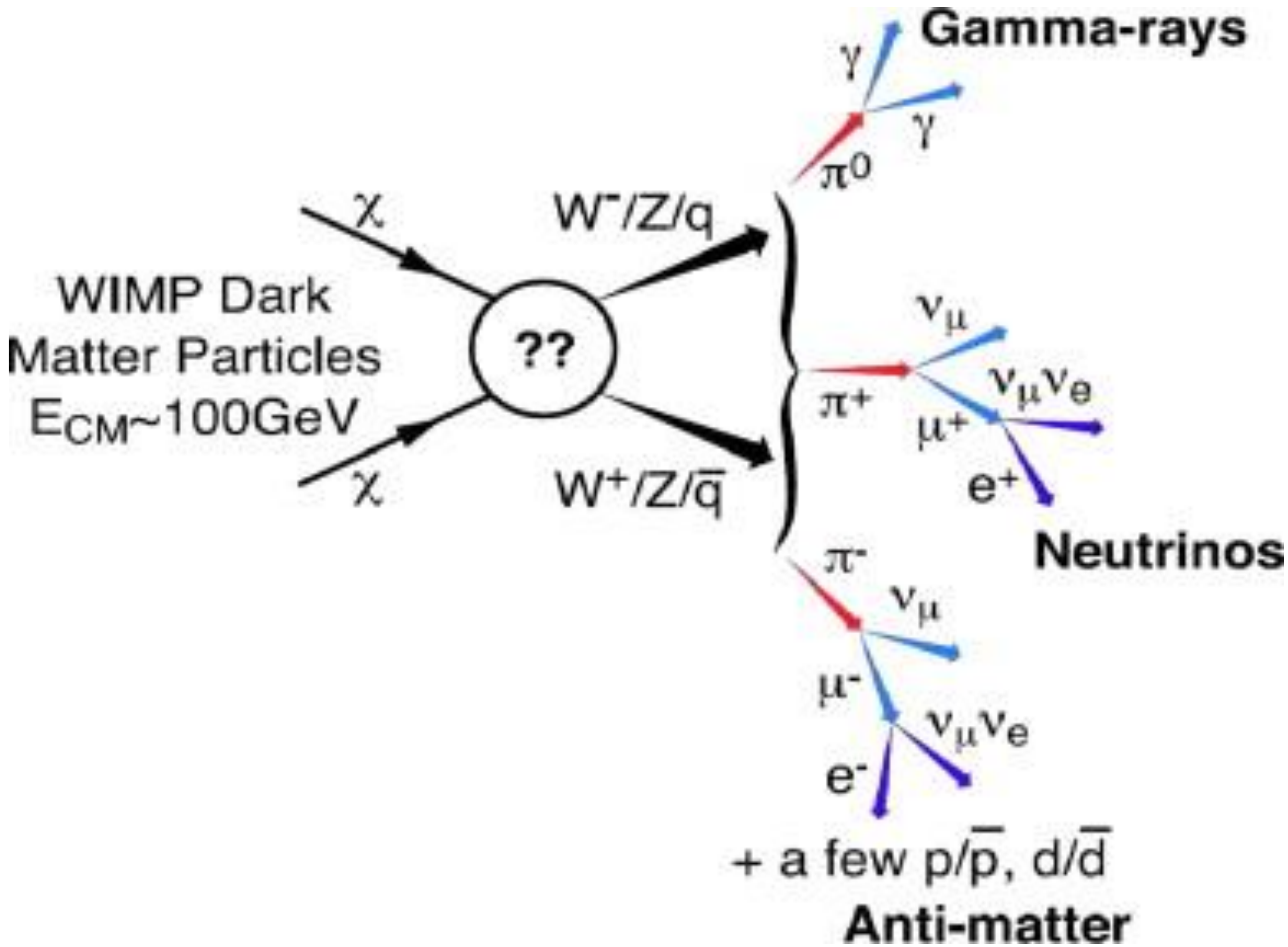
Neutrinos sought in, e.g., MACRO, IMB, Super-Kamiokande, IceCube…..

WIMPs that couple to nuclear spin may be effectively sought through energetic neutrinos from the Sun

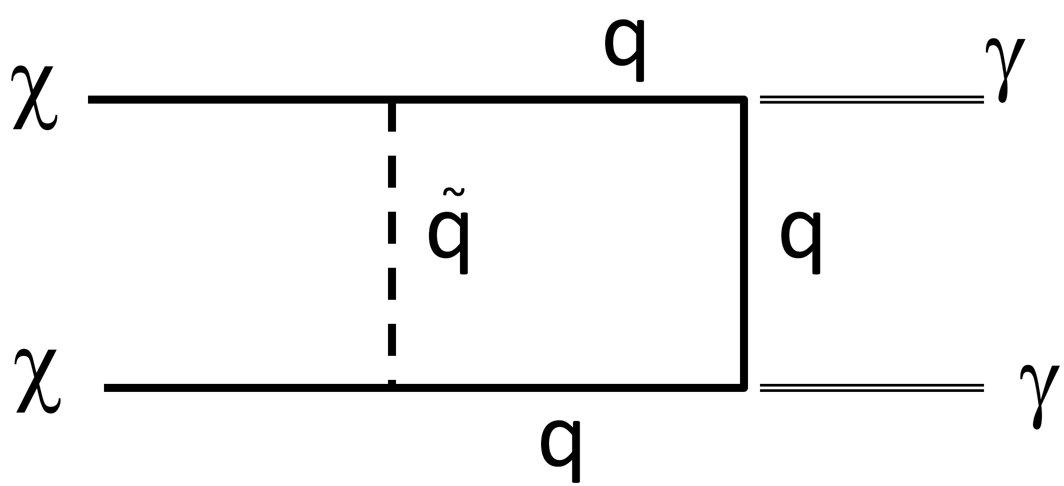


Ullio, MK, Vogel (2001)

Indirect detection: Exotic cosmic rays from WIMP annihilation in Galactic halo

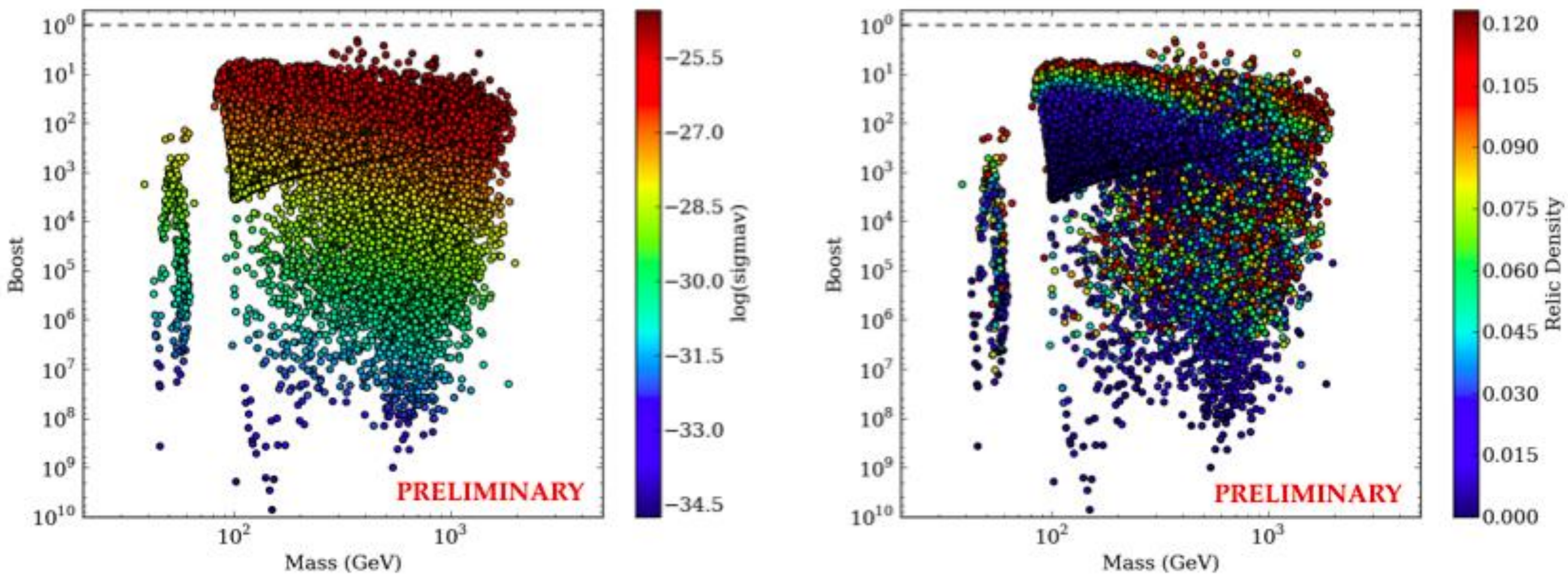


Indirect Detection: Gamma-rays from WIMP annihilation in Galactic halo

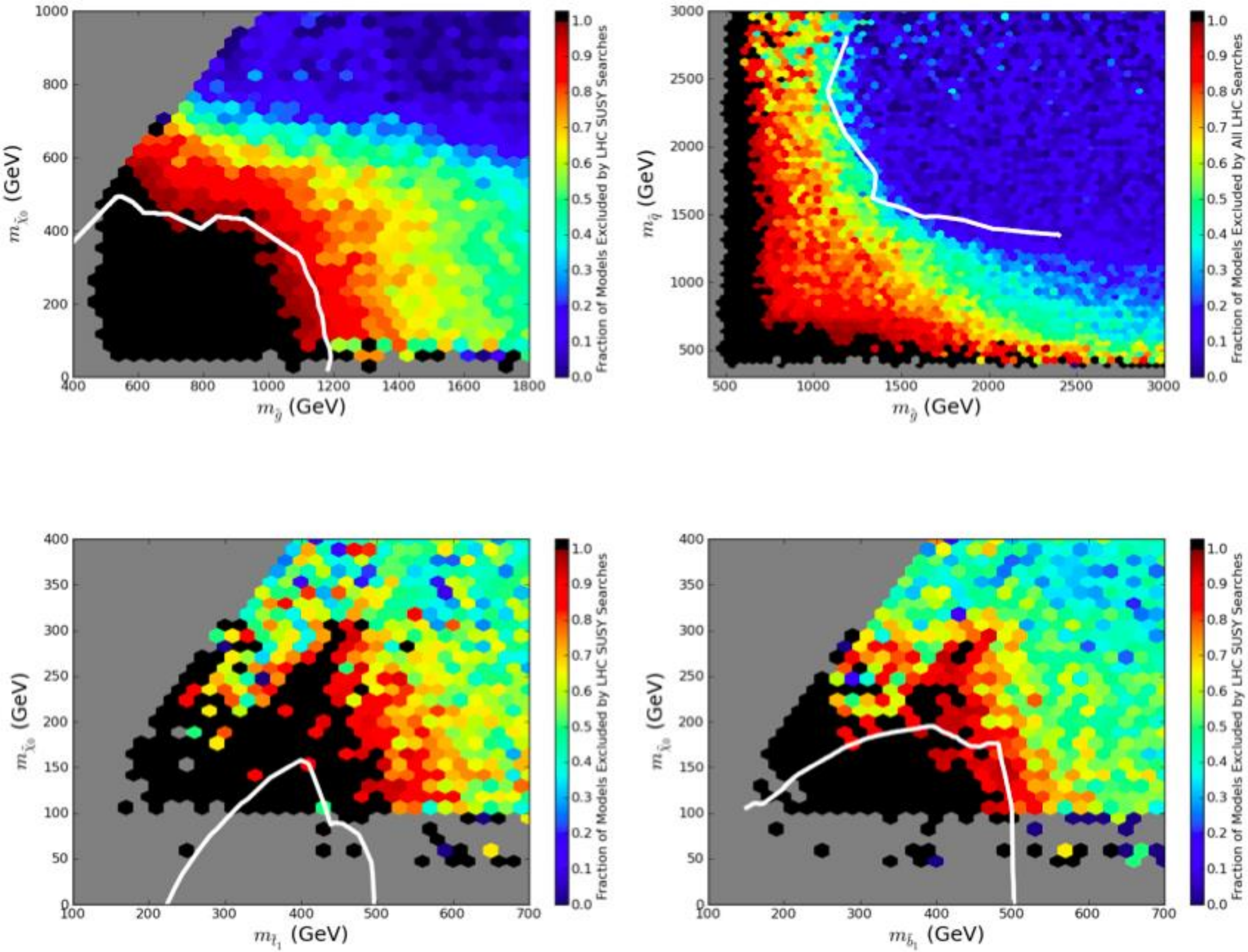


$$E_\gamma = m_\chi$$

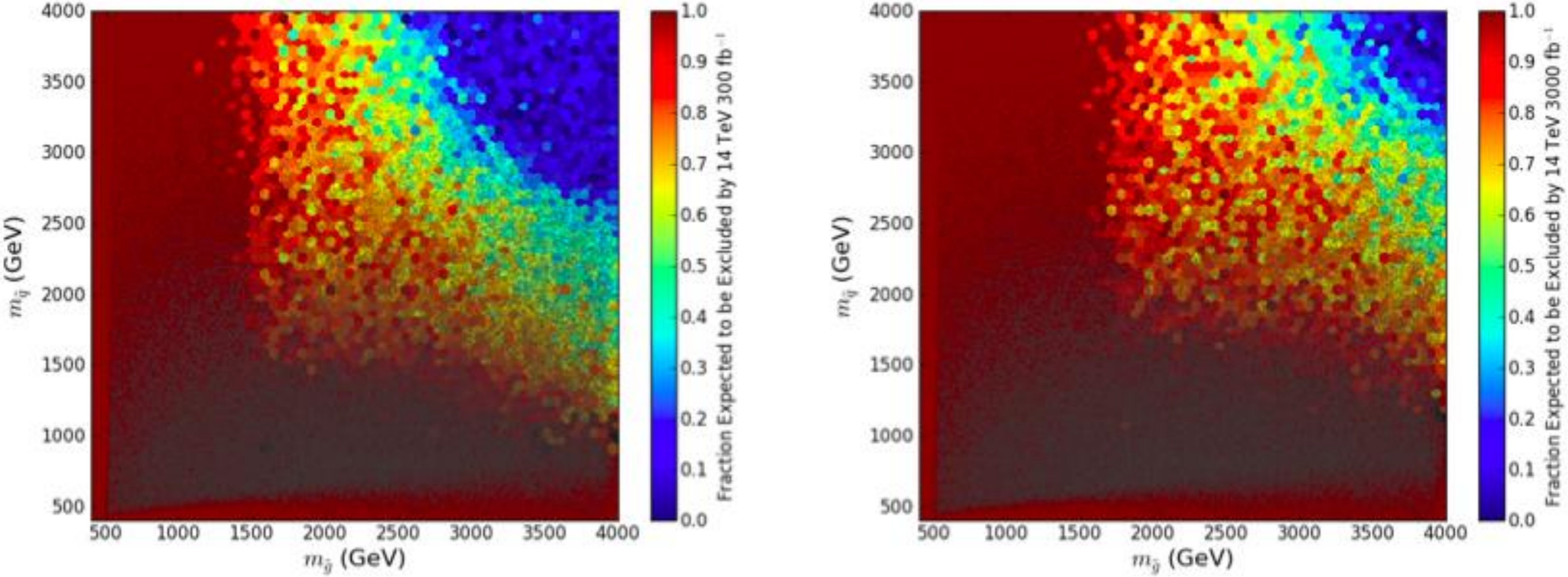
Can be sought in Fermi, air Cherenkov telescopes (e.g, CTA)



Boost
Mass (GeV)
log(sigmav)
−25.5
−27.0
−28.5
−30.0
−31.5
−33.0
−34.5
PRELIMINARY
Relic Density
0.120
0.105
0.090
0.075
0.060
0.045
0.030
0.015
0.000
PRELIMINARY



$m_{\tilde{\chi}^0}$ (GeV)
$m_{\tilde{g}}$ (GeV)
Fraction of Models Excluded by LHC SUSY Searches
$m_{\tilde{q}}$ (GeV)
$m_{\tilde{g}}$ (GeV)
Fraction of Models Excluded by All LHC Searches
$m_{\tilde{\chi}^0}$ (GeV)
$m_{\tilde{t}_1}$ (GeV)
Fraction of Models Excluded by LHC SUSY Searches
$m_{\tilde{\chi}^0}$ (GeV)
$m_{\tilde{b}_1}$ (GeV)
Fraction of Models Excluded by LHC SUSY Searches



$m_{\tilde{q}}$ (GeV)
$m_{\tilde{g}}$ (GeV)
Fraction Expected to be Excluded by 14 TeV 300 fb^{-1}
$m_{\tilde{q}}$ (GeV)
$m_{\tilde{g}}$ (GeV)
Fraction Expected to be Excluded by 14 TeV 3000 fb^{-1}

Cahill-Rowley conclusions:

- LSP may exist/detectable, even if not DM
- If its DM, most likely (co-annihilating) B-ino
- SI direct detection, CTA, LHC most important tools
- Different avenues are complementary

Variations/Questions/extensions/etc

- Gravitino
  - Must exist
  - May be LSP
    - May be DM, but relic density not set by WIMP miracle
  - If light, may lead to interesting LHC signatures (e.g., displaced vertices, Feng, Lee, MK 2011)

Variations/Questions/extensions/etc

- Gamma-ray/cosmic-ray anomalies
  - Are *lots*
  - None explained by canonical WIMP
  - Boosts required for Galactic annihilation rate
    - Explained by clumping of DM?
    - Explained by Sommerfeld enhancement?
      - Requires extension of WIMP scenario to include additional light particle

Variations/Questions/extensions/etc

- Self-interacting DM?
  - Empirical window very narrow
  - May appear in models that introduce Sommerfeld

Variations/Questions/extensions/etc

- Fifth force, EP violation
  - Postulated to solve problems (?) with LSS
  - Tightly constrained by tidal tails of Sgr dwarf (Kesden, MK 2006)

Variations/Questions/extensions/etc

- Inelastic DM
  - Motivated (in part) to explain DAMA
- New DM-baryon interactions beyond scalar/axial-vector (e.g., dipole, Sigurdson et al. 2004; Kurylov, MK 2004)

Variations/Questions/extensions/etc

- Asymmetric dark matter (Kaplan, Luty, Zurek, 2009)
  - Accounts for coincidence between DM,baryon densities
  - Lots of current interest

AXIONS

The Strong CP Problem

$$\mathcal{L}_{\rm QCD} = \cdots + \theta \frac{g^2}{32\pi^2} G^a_{\mu\nu} \tilde{G}^{a\,\mu\nu}$$

From constraints to the neutron EDM,,

. $\theta \leq 10^{-10}$

Why is θ so small?

If a $\mathrm{U}_{\mathrm{PQ}}(1)$ symmetry is assumed,

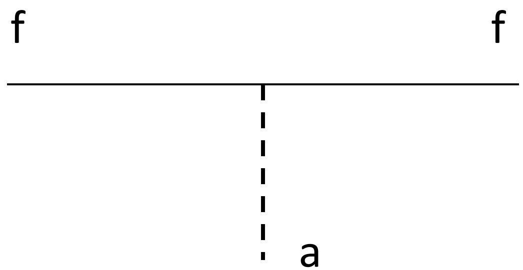
$$\mathcal{L}_{\mathrm{QCD}} = \cdots + \frac{\varphi}{f_a}\frac{g^2}{32\pi^2}G^a_{\mu\nu}\tilde{G}^{a\,\mu\nu} + \frac{1}{2}(\partial_\mu\varphi)(\partial^\mu\varphi)$$

$\theta = \dfrac{\varphi}{f_a}$ relaxes to zero,

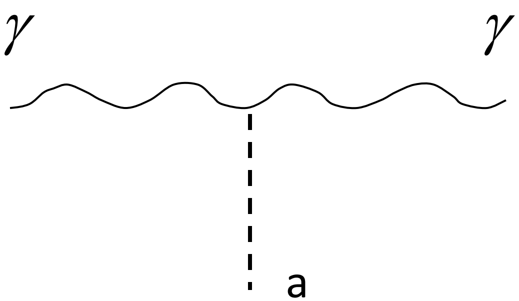
Axion = quantum of φ, a PNGB

(Sikivie)

$$m_a \;\square\; 6\ \text{eV}\ \frac{10^6\ \text{GeV}}{f_a}$$



$$L_{a\bar{f}f} = i\, g_f \,\frac{\varphi}{f_a}\ \overline{f}\ \gamma_5\ f$$



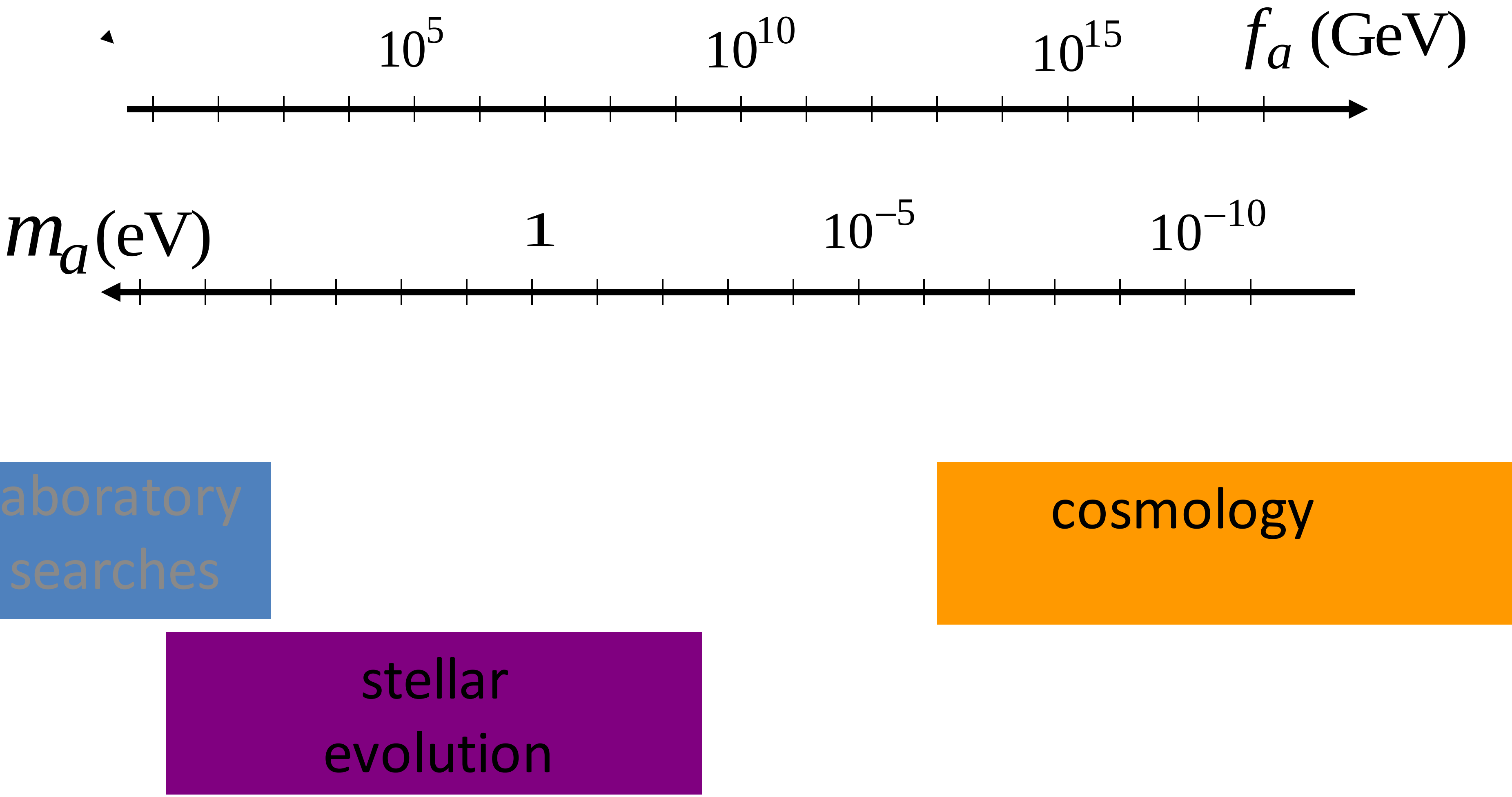
$$L_{a\gamma\gamma} = g_\gamma\ \frac{\alpha}{\pi}\ \frac{\varphi}{f_a}\ \vec{E}\cdot\vec{B}$$

g_γ = 0.97 in KSVZ model

0.36 in DFSZ model

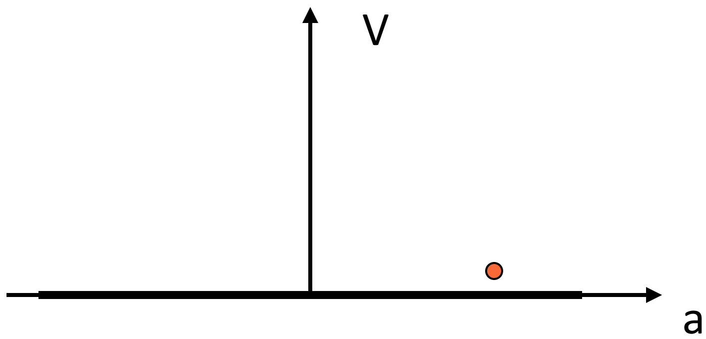
The remaining axion window

(Sikivie)

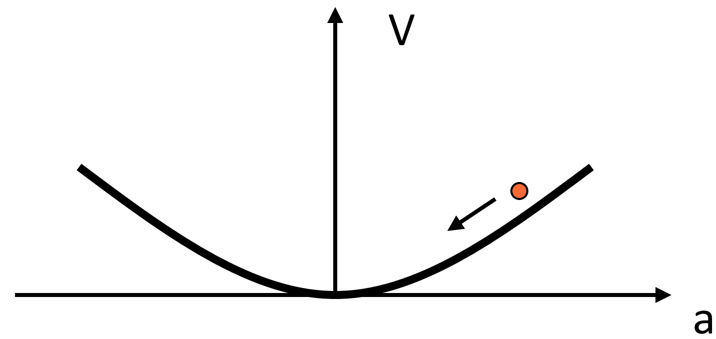


(Sikivie)

Axion production by vacuum realignment



$T \geq 1\,\mathrm{GeV}$



$T \leq 1\,\mathrm{GeV}$

$$n_a(t_1) \approx \frac{1}{2} m_a(t_1)\, \varphi(t_1)^2 \approx \frac{1}{2t_1} f_a^{\,2}\, \theta(t_1)^2$$

initial misalignment angle

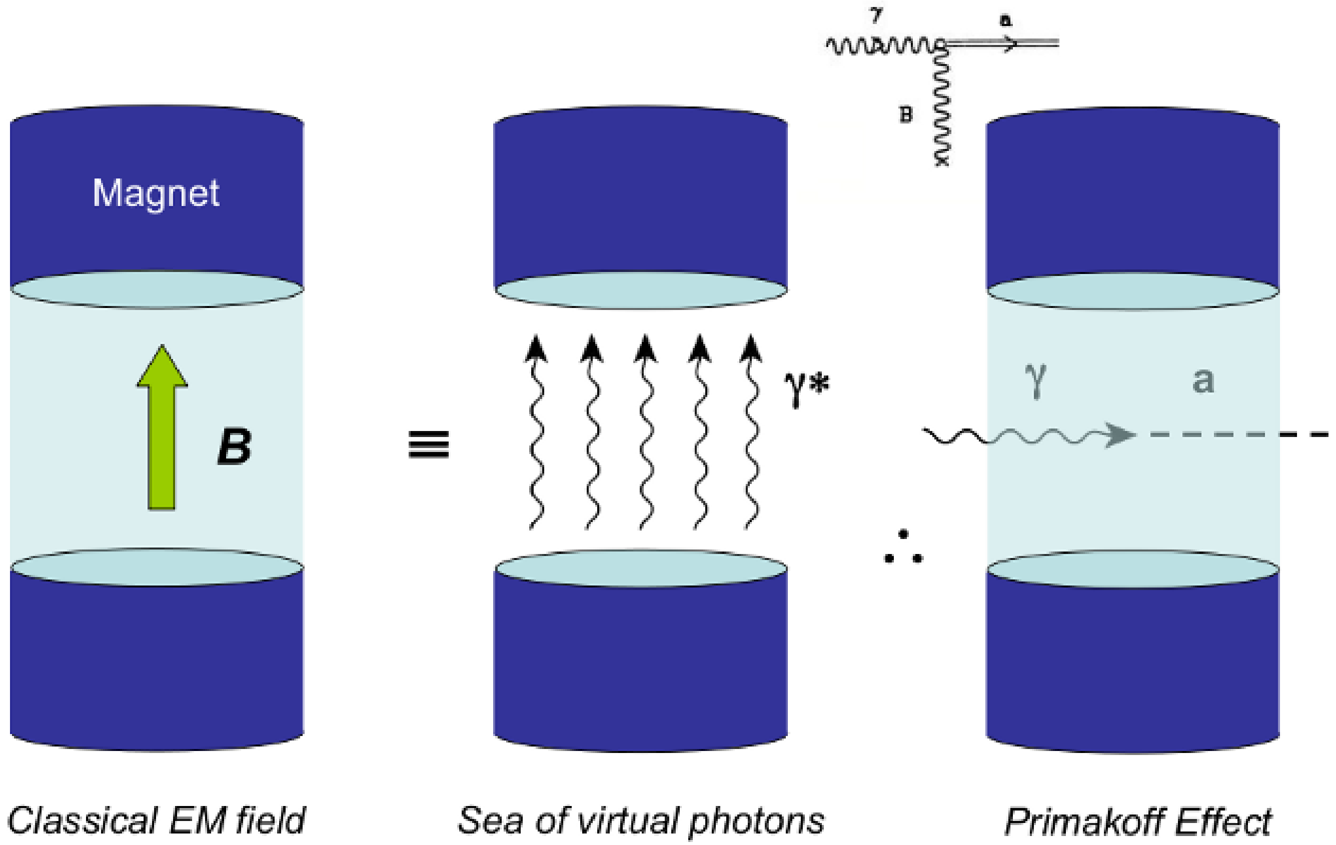
$$\rho_a(t_0) \approx m_a\, n_a(t_1) \left(\frac{a_1}{a_0}\right)^3 \propto m_a^{-\frac{7}{6}}$$

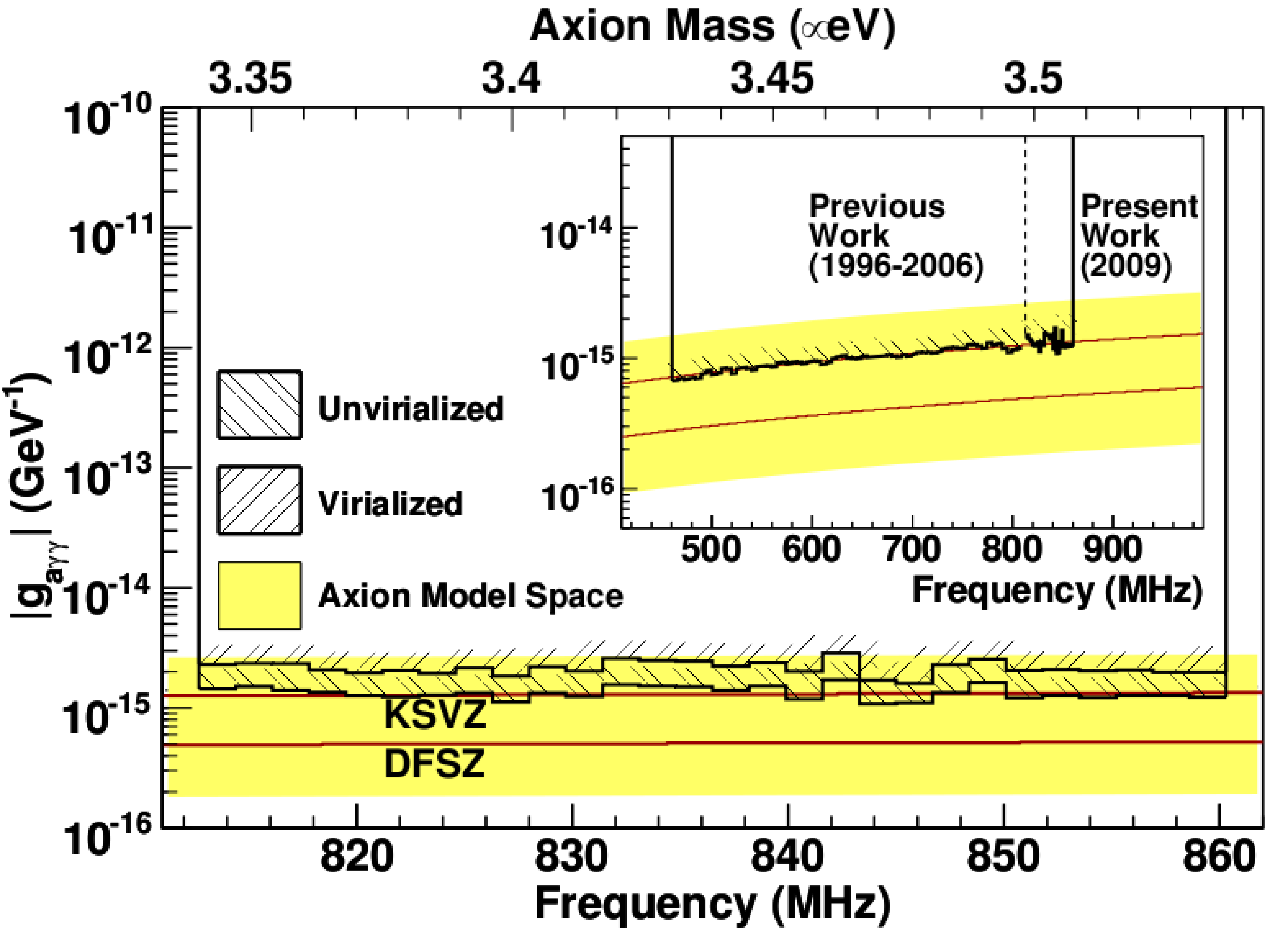
Axion relic density

$$\Omega_a \simeq 0.15 \left(\frac{f_a}{10^{12}\,\mathrm{GeV}} \right)^{7/6} \theta_1^2$$

Detection of axions (e.g., ADMX expt)

- Through Primakoff effect (axion-photon-phonton production)





Axion Mass (μeV)
3.35
3.4
3.45
3.5
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-14}
10^{-15}
10^{-16}
$|g_{a\gamma\gamma}|$ (GeV^{-1})
Unvirialized
Virialized
Axion Model Space
KSVZ
DFSZ
820
830
840
850
860
Frequency (MHz)
Previous Work (1996-2006)
Present Work (2009)
500
600
700
800
900
Frequency (MHz)

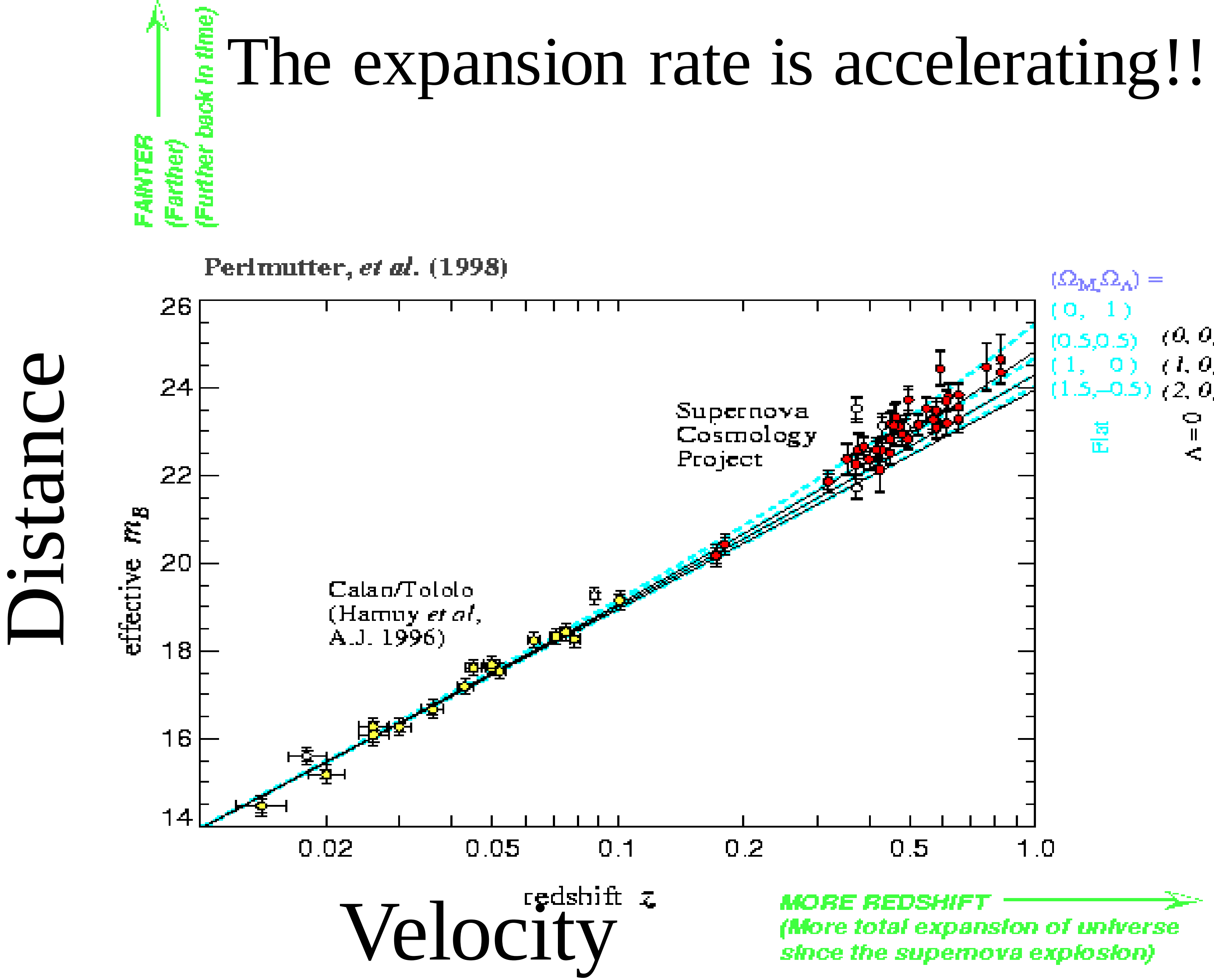

Dark Energy

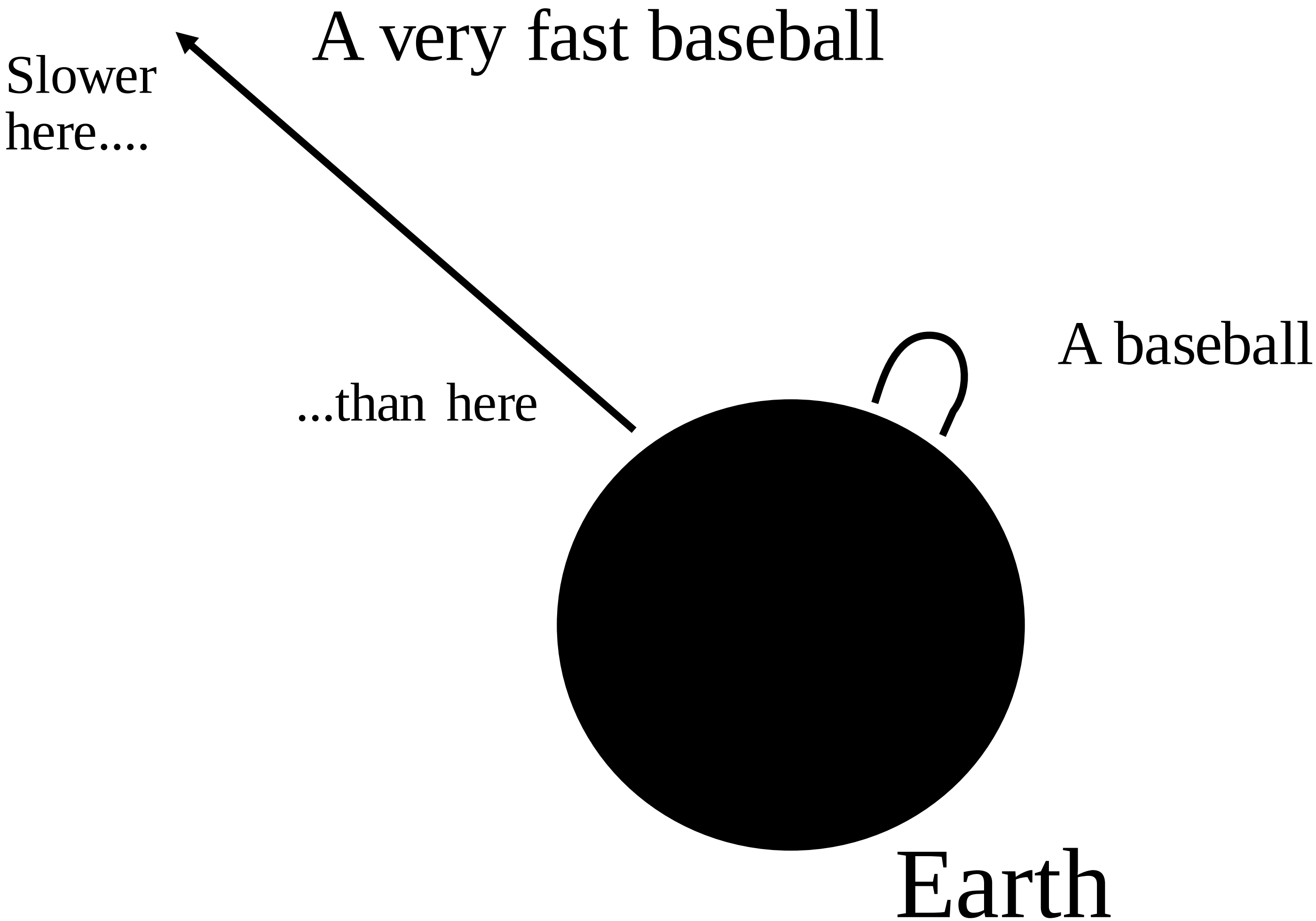
The Physics of Cosmic Acceleration

Based on Caldwell, MK ARNP 59, 397 (2009) [arXiv:0903.0866]


You are here

The expansion rate is accelerating!!!!





Gravity is attractive


Anti-gravitating
"cosmological
constant",
"quintessence"
or "dark energy"

How can this be explained?

Newtonian gravity:

$$\nabla^2 \Phi = 4\pi G \rho$$

How can this be explained?

Relativistic gravity (general relativity):

$$\nabla^2 \Phi = 4\pi G(\rho + 3p)$$

i.e., pressure also sources gravitational field

If $w = \dfrac{p}{\rho} < -\dfrac{1}{3}$, then gravity repulsive

THE PHYSICS OF COSMIC ACCELERATION

Basics: FRW metric

scale factor

$$ds^2 = -dt^2 + a^2(t)[dr^2 + r^2 d\theta^2]$$

redshift $z \equiv (a_0/a) - 1 \quad \sim t$

$a_0 \equiv a(t_0)$ (today)

Expansion rate $H \equiv \dot{a}/a$

$H_0 \simeq 70$ km/sec/Mpc today

Deceleration parameter

$$q \equiv -(\ddot{a}/a)/H^2 = (1+z)\frac{H'(z)}{H(z)} - 1$$

Luminosity Distance

$$d_L \equiv \left(\frac{L}{4\pi F}\right)^{1/2} = (1+z)c\int_0^z \frac{dz'}{H(z')}$$

Time interval: $dt = \frac{dz}{H(z)(1+z)}$

Angular-diameter distance:

$$d_A(z) \equiv \frac{l_{prop}}{\theta} = \frac{d_L(z)}{(1+z)^2}$$

Expanding about $z=0$,

$$H_0 d_L(z) = cz\left[1+\frac{1}{2}(1-q_0)z+\cdots\right]$$

supernovae 1998 $\Rightarrow q_0 < 1$

Dynamics

$$H^2 = \left(\frac{\dot a}{a}\right)^2 = \frac{8\pi G}{3}\sum_i \rho_i$$

$$\frac{\ddot a}{a} = -\frac{4\pi G}{3}\sum_i (\rho_i + 3p_i)$$

$$\equiv -\frac{4\pi G}{3}\sum_i \rho_i(1+3w_i)$$

EoS parameter (w_i)

e.g.,

$$w = \begin{cases} 0 & \text{NR matter} \\ 1/3 & \text{radiation} \\ -1 & \text{cosm const} \end{cases}$$

acceleration ($\ddot{a} > 0$) requires

$$w_i < -1/3$$

Expansion History

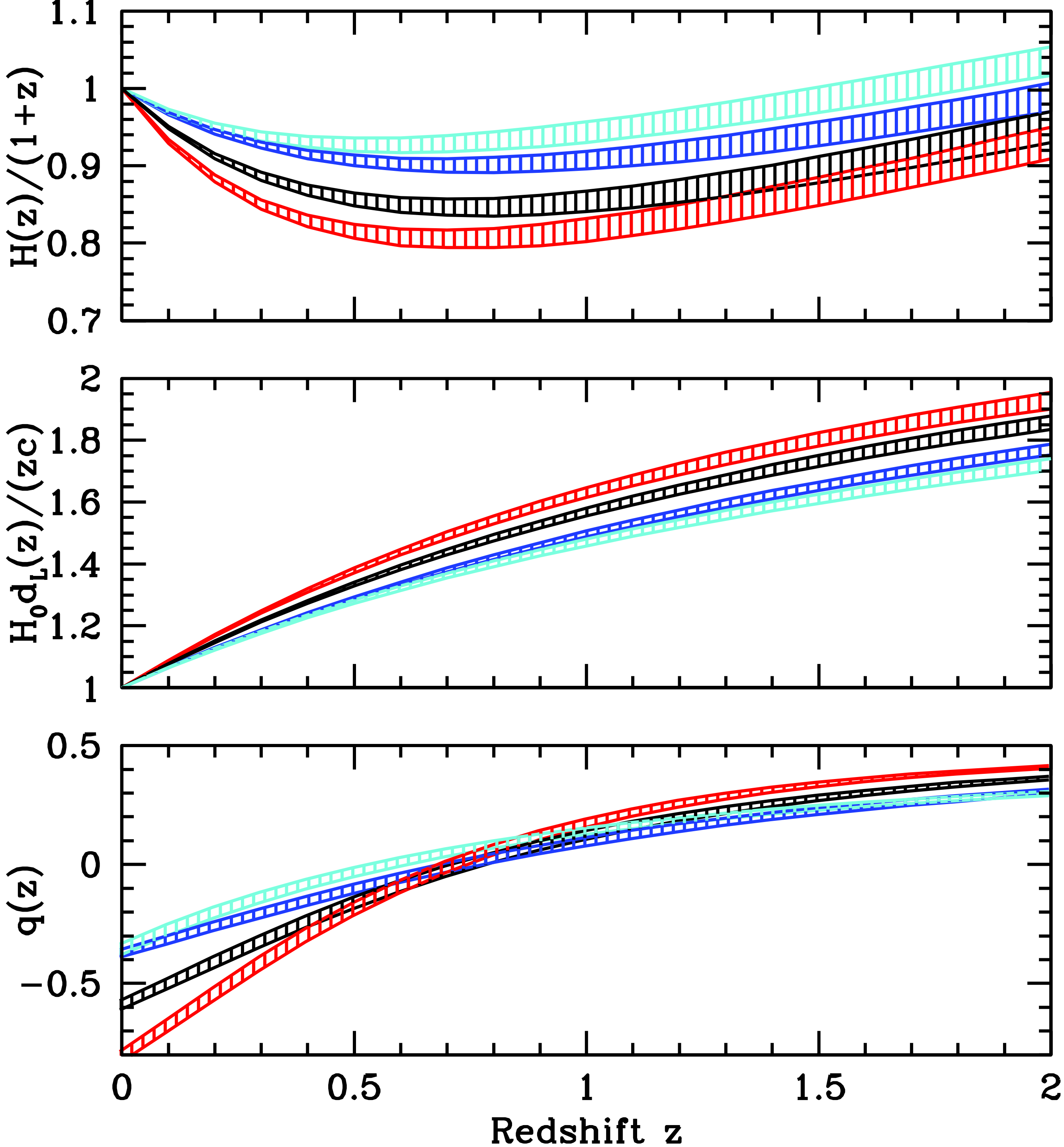
$$H(z) \longleftrightarrow d_L(z) \longleftrightarrow q(z)$$

If $U \subset$ matter + "dark energy"

(with $w = w_Q < -1/3$),

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

$$q_0 = (1 + 3 w_Q \Omega_Q)/2$$



1.1
1
0.9
0.8
0.7
H(z)/(1+z)
2
1.8
1.6
1.4
1.2
1
H0dL(z)/(zc)
0.5
0
−0.5
q(z)
0
0.5
1
1.5
2
Redshift z

There is no reason for w_Q to be constant!

Popular parametrization:

$$w_Q = w_0 + w_a(1 - a/a_0)$$

Growth of Structure

Amplitude $\delta_m(t)$ of fractional density perturbation satisfies

$$\ddot{\delta}_m + 2H\dot{\delta}_m - (3/2)\Omega_m H^2 \delta_m = 0$$

Growing-mode sol'n $\delta(z) \propto D(z)$.

$D(z)$ depends on $H(z)$

Measurements/Constraints

supernovae: $\sim q_0 = (1+3w_Q\Omega_Q)/2$

$\simeq -0.7 \pm 0.1$

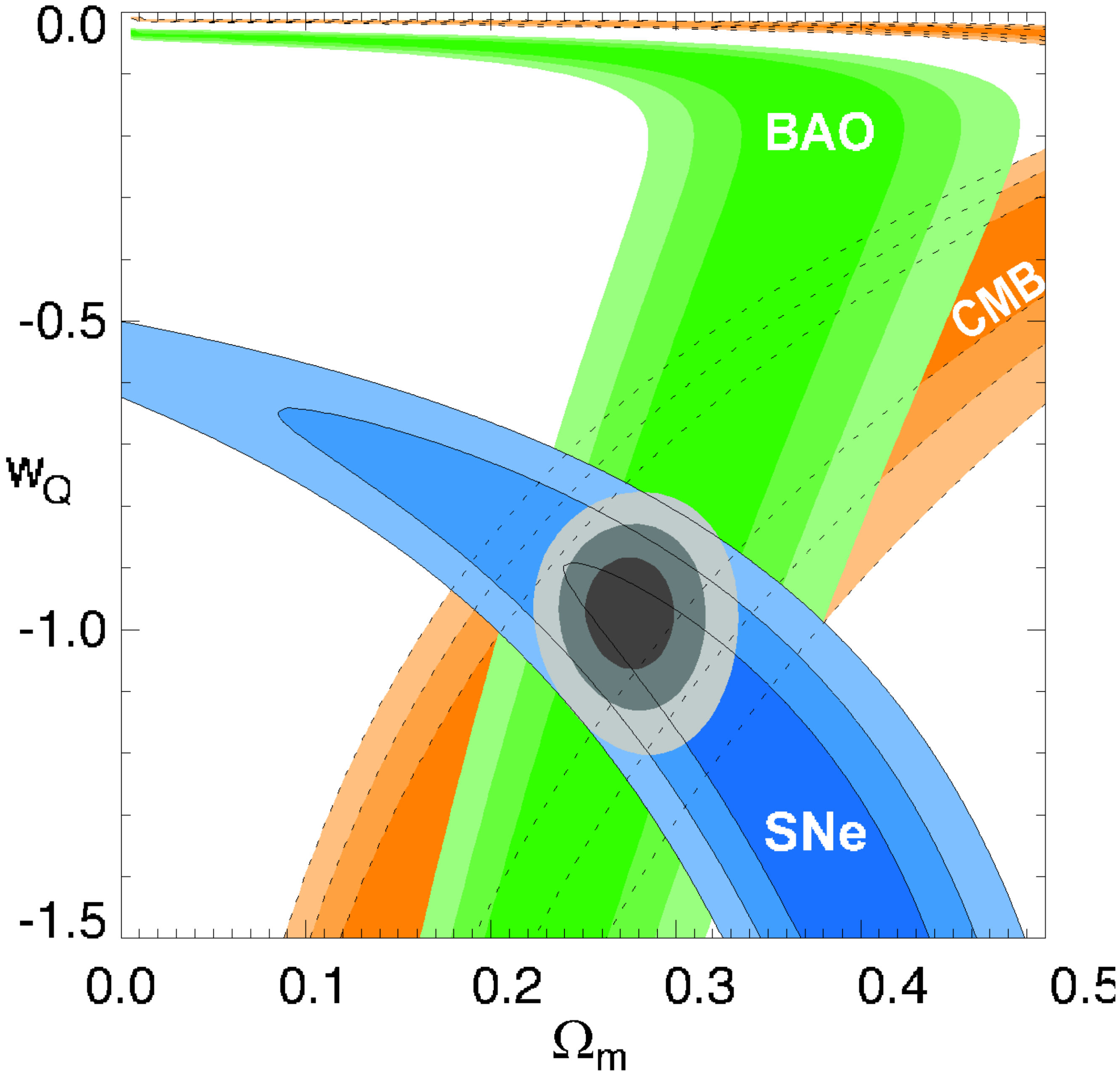
CMB: $d_L(z \simeq 1100)$ (Thurs)

Baryon acoustic oscillations (BAO):

$\sim \Omega_m$

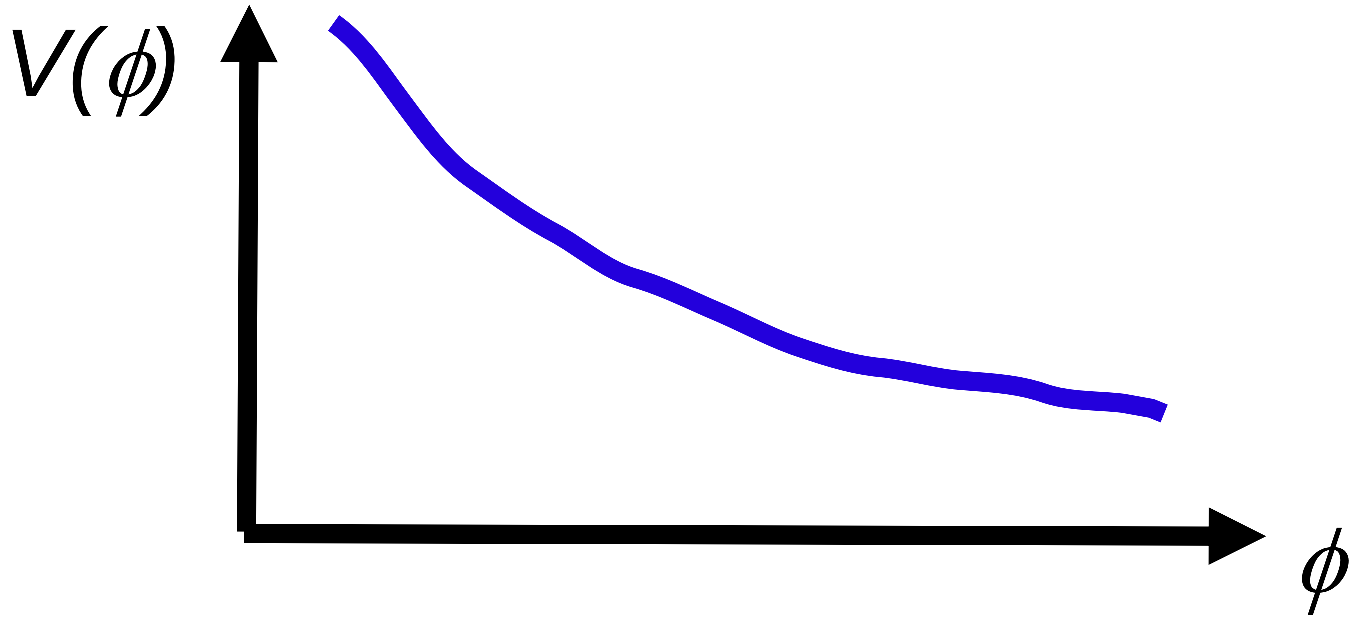
$\Rightarrow \Omega_Q \simeq 0.7$

$w_Q \simeq -1 \pm 0.1$



0.0
-0.5
-1.0
-1.5
0.0
0.1
0.2
0.3
0.4
0.5
w_Q
Ω_m
BAO
CMB
SNe

Quintessence! slowly-rolling scalar field:



$$p = (1/2)\dot{\phi}^2 - V(\phi)$$

Pressure

$$\rho = (1/2)\dot{\phi}^2 + V(\phi)$$

Energy density

Theory: I. Quintessence

Postulate scalar field Q with potential $V(Q)$

$$S = \int d^4x \sqrt{-g} \left(\frac{R}{16\pi G} + \mathcal{L}_{sm} + \mathcal{L}_Q \right)$$

$$\mathcal{L}_Q = -\frac{1}{2}(\nabla_\mu Q)(\nabla^\mu Q) - V(Q)$$

EoM: $\ddot{Q} + 3H\dot{Q} + \partial V/\partial Q = 0$

$\rho_Q = \frac{1}{2}\dot{Q}^2 + V(Q) \quad p = \frac{1}{2}\dot{Q}^2 - V(Q)$

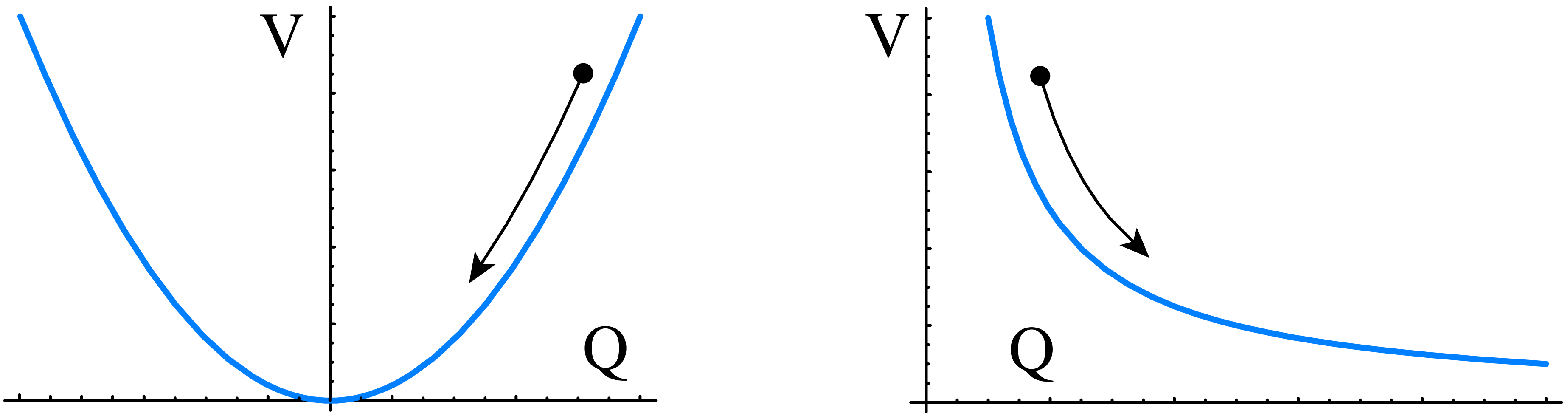
$w_Q < -1/3$ when $\dot{Q}^2 < V$

E.g., if $V(Q) = \frac{1}{2}m^2 Q^2$

and $m \ll H \Rightarrow \ddot{Q} \ll H\dot{Q}, V'$

$\Rightarrow 3H\dot{Q} \simeq -m^2 Q \, , \; \dot{Q}^2 \ll V$

More generally, $m_Q \equiv \sqrt{\partial^2 V/\partial Q^2} \ll H$


V
Q
V
Q

What is special about Quintessence:

perturbations satisfy

$$\delta\ddot{Q} + 3H\delta\dot{Q} + \left(\partial^2 V/\partial Q^2 - \frac{1}{a^2}\nabla^2\right)\delta Q$$
$$= \dot{\delta}_m \dot{Q}$$

As $W_Q \to -1$ $\dot{Q} \to 0$.

$$\frac{\partial^2 V}{\partial Q^2} = \frac{-3}{2}(1-W_Q)\left[\dot{H} - \frac{3}{2}(1+W_Q)H^2\right]$$

$$\sim H^2 \quad \ll \frac{1}{a^2}\nabla^2$$

on $\lambda \ll H^{-1}$

$\therefore$ Perturbations to Q are stable!

i.e., $W = \frac{p}{\rho} \neq c_s^2 = \left(\frac{\partial p}{\partial \rho}\right)$

so $W < -1$ with $c_s^2 > 0$

Models/Variations

PNGB:

$V = \mu^4 (1 + \cos \frac{Q}{f})$

(flatness protected)

Tracker fields:

$V \propto Q^{-n} \quad n > 0$

$V \propto \exp[-\lambda Q / m_{pl}]$

$\rho_Q \sim \rho_{m,R}$ at early times

Spintessence:

$Q = R e^{i\Theta}$

spins with

$\dot{\Theta} \gg H$

(unstable to perts)

Oscillescence:

field oscillates in

$V(Q) \propto |Q|^n$

with $n < 1$

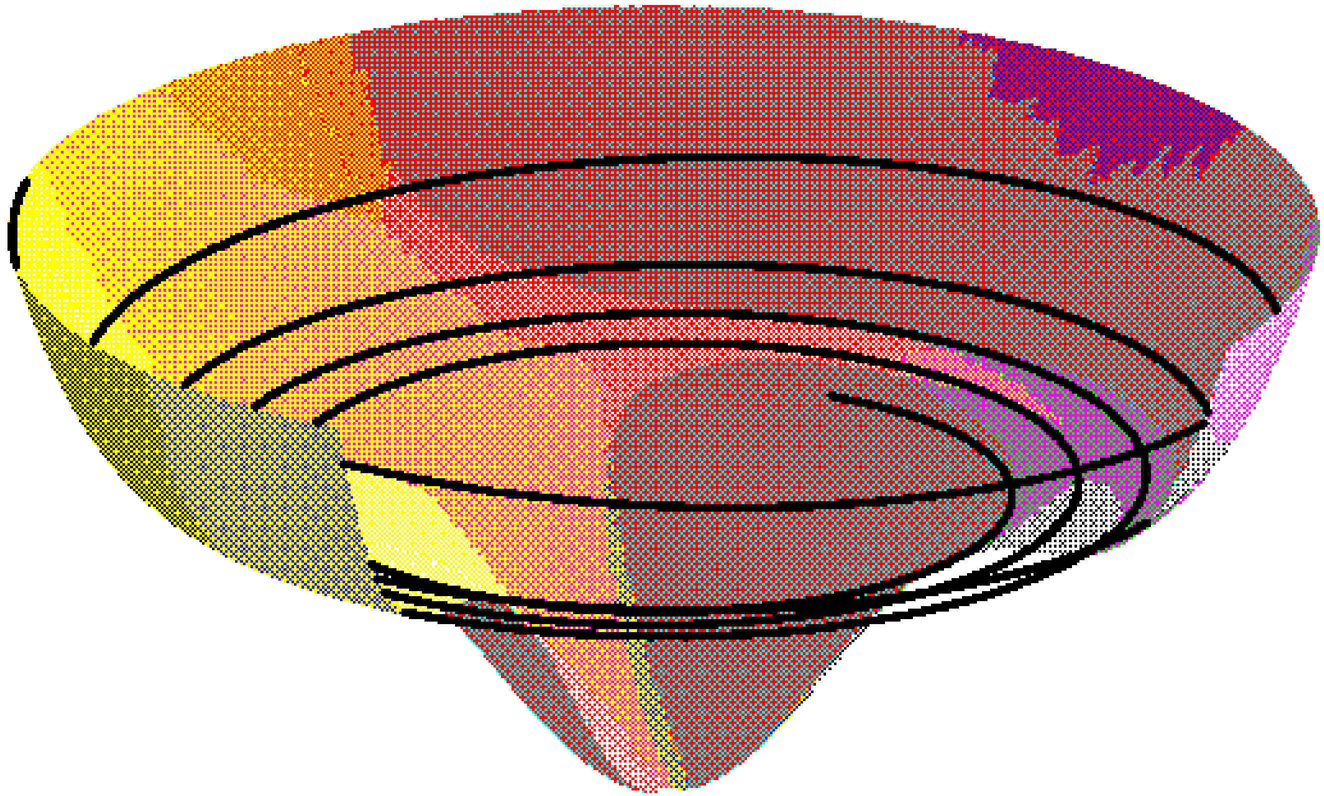
(unstable)

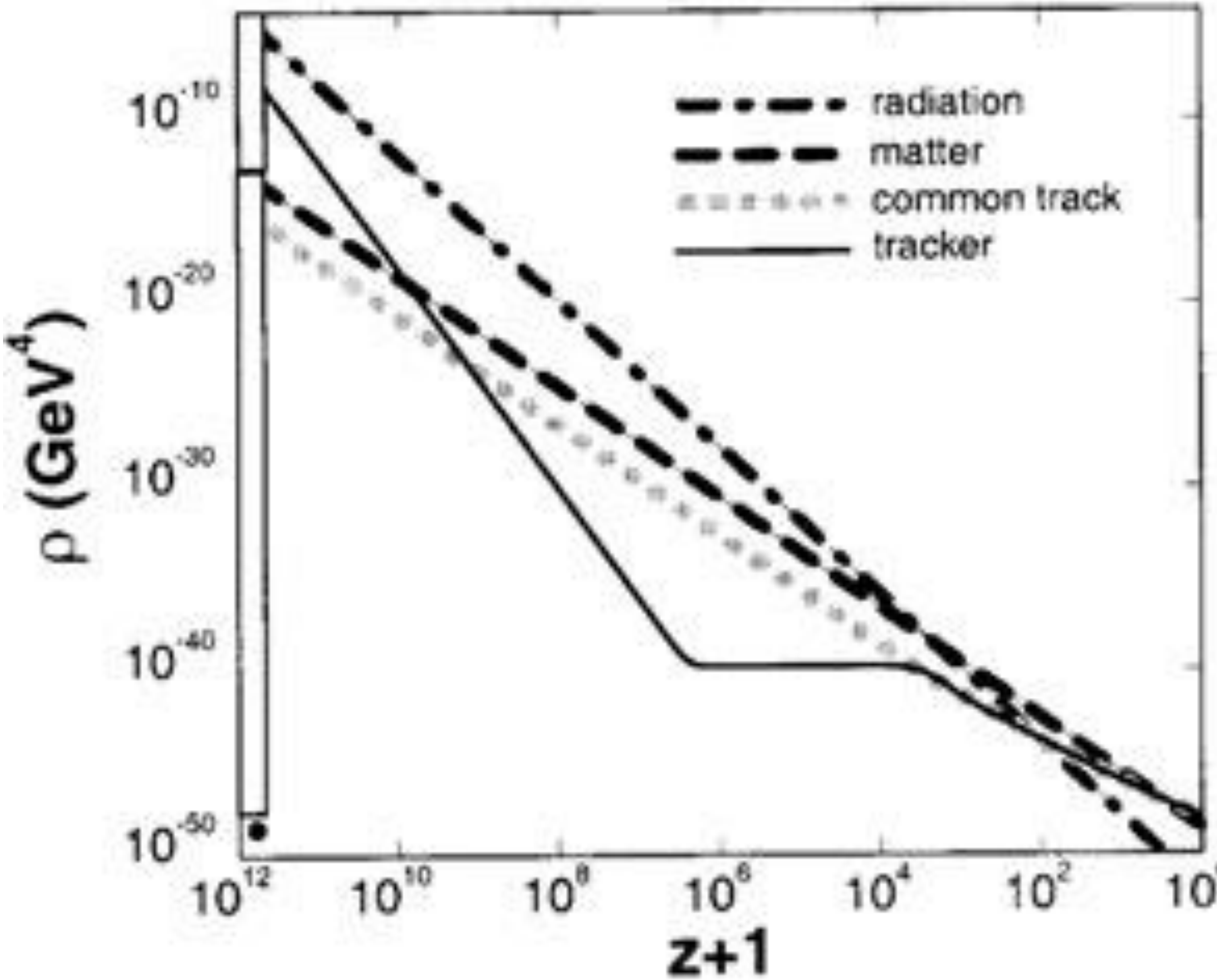
K-essence:

non-canonical kinetic term

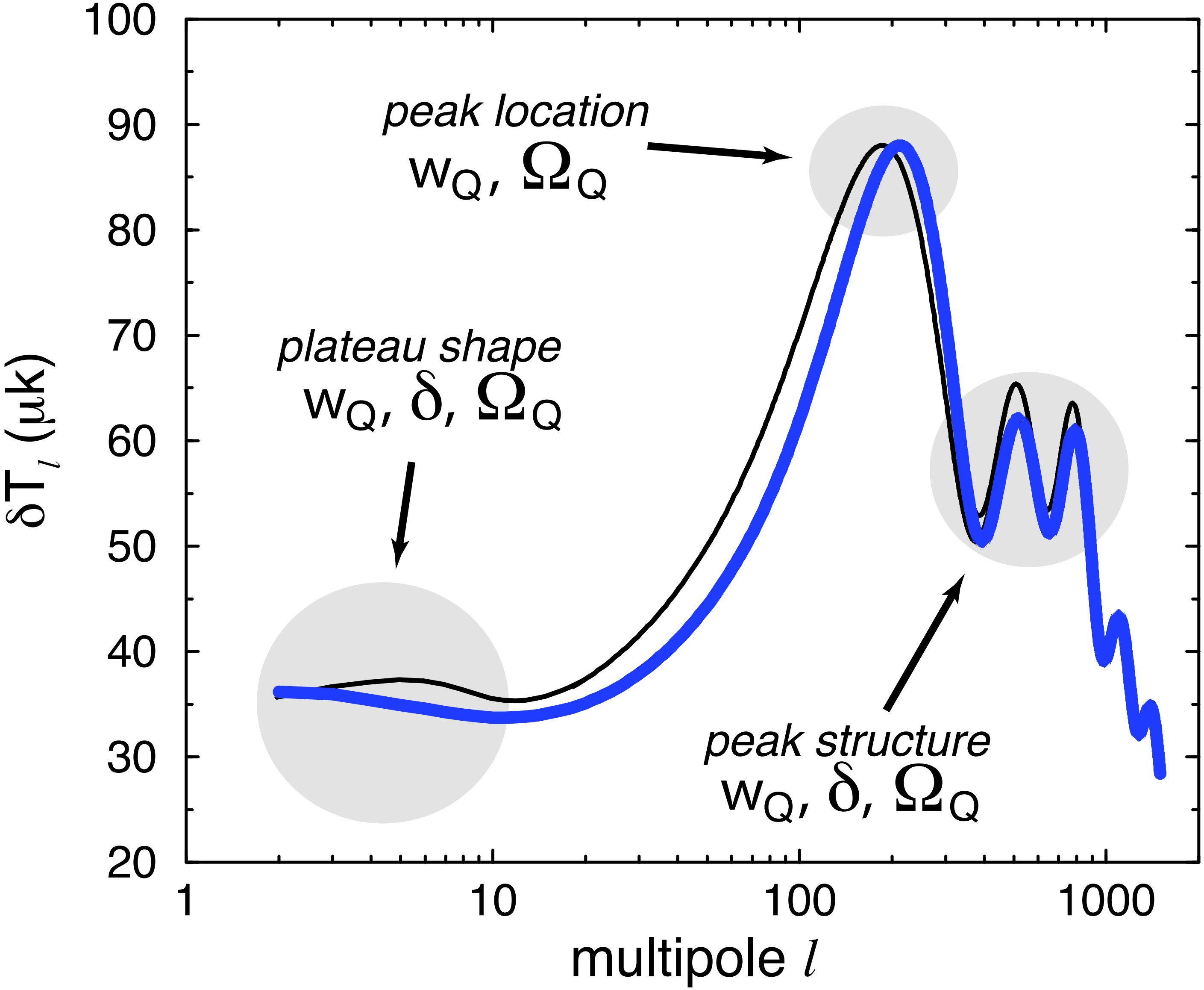
Ghost condensates

higher-order derivatives





radiation
matter
common track
tracker
ρ (GeV^4)
10^{-10}
10^{-20}
10^{-30}
10^{-40}
10^{-50}
10^{12}
10^{10}
10^{8}
10^{6}
10^{4}
10^{2}
10^{0}
z+1



100
90
80
70
60
50
40
30
20
1
10
100
1000
δT$_l$ (μk)
multipole l
peak location
w$_Q$, Ω$_Q$
plateau shape
w$_Q$, δ, Ω$_Q$
peak structure
w$_Q$, δ, Ω$_Q$

Quintessence coupling to SM?

e.g., <u>Cosmic Birefringence</u>

$$\mathcal{L}_{EM} = \frac{1}{4} F_{\mu\nu} F^{\mu\nu} - \frac{1}{4}\frac{\phi}{M} F_{\mu\nu}\tilde{F}^{\mu\nu}$$

$$\tilde{F}_{\mu\nu} = \frac{1}{2}\epsilon_{\mu\nu\rho\sigma}F^{\rho\sigma}$$

<u>Maxwell eqns:</u>

$$\vec{\nabla}\cdot\vec{D} = \rho \qquad \vec{\nabla}\times\vec{H} - \frac{\partial\vec{D}}{\partial t} = \vec{J}$$

with
$$\vec{D} = \vec{E} + \frac{\phi}{M}\vec{B}$$
$$\vec{H} = \vec{B} - \frac{\phi}{M}\vec{E}$$

If $\phi(\vec{x},t) = \phi(t)$

$$\vec{\nabla}\cdot\vec{E} = \rho \qquad \vec{\nabla}\cdot\vec{B} = 0$$

$$\vec{\nabla}\times\vec{B} - \frac{\partial\vec{E}}{\partial t} = \vec{J} + \frac{\dot{\phi}}{M}\vec{B}$$

$$\vec{\nabla}\times\vec{E} + \frac{\partial\vec{B}}{\partial t} = 0$$

In vacuum,

$$\Box\vec{E} = -\frac{\dot{\phi}}{M}\frac{\partial\vec{B}}{\partial t} \qquad \Box\vec{B} = \frac{\dot{\phi}}{M}\frac{\partial\vec{E}}{\partial t}$$

For plane wave $\vec{P}_{\pm} = \vec{E} \pm i\vec{B}$

with $\vec{P}(\vec{x},t) \propto e^{i\omega t - i\vec{k}\cdot\vec{x}}$,

$$\omega^2 = k^2 \pm \frac{\dot{\phi}}{M}\omega$$

$$\Longrightarrow \quad c_+ - c_- = \dot{\phi}/M$$

leads to CB rotation of linear polarization by $(\Delta\phi/2M)d$ over distance d

Mass-varying neutrinos (MaVaNs)

scalar field determines mass of ν

$$\rho_{dark} = m_\nu n_\nu + \rho_a(m_\nu)$$

field value minimizes ρ_{dark}:

$$\frac{\partial \rho_{dark}}{\partial m_\nu} = n_\nu + \frac{\partial \rho_a}{\partial m_\nu} = 0$$

with $\qquad \dot{\rho}_{dark} = -3H(\rho_{dark} + p_{dark})$

$$\Rightarrow \quad w = \frac{p_{dark}}{\rho_{dark}} = -1 + \frac{m_\nu n_\nu}{m_\nu n_\nu + \rho_a}$$

but perts are unstable

Phantom Energy

$w_\varphi < -1$ $\quad$ $\rho_{DE} \uparrow$ with time

(violates null energy condition)

soln to $H^2 = \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G\rho}{3}$

$\Longrightarrow$ $a(t) \longrightarrow \infty$

in finite time!

Big Rip!

(requires very strange physics)

Scalar-Tensor Theories:

(~ variable-G gravity)

$$S = \int d^4x \sqrt{-g} \Big[b(\lambda) R - \frac{1}{2} h(\lambda) g^{\mu\nu} (\partial_\mu \lambda)(\partial_\nu \lambda) - U(\lambda) + \mathcal{L}_M (g_{\mu\nu}, \psi_i) \Big]$$

"Einstein" Eqn:

$$G_{\mu\nu} = b^{-1} \Big[\frac{1}{2} T^{(M)}_{\mu\nu} + \frac{1}{2} T^{(\lambda)}_{\mu\nu} + \nabla_\mu \nabla_\nu b - g_{\mu\nu} \Box b \Big]$$

$$T^{(\lambda)}_{\mu\nu} = h(\lambda)(\nabla_\mu \lambda)(\nabla_\nu \lambda) - g_{\mu\nu} \Big[\frac{1}{2} h(\lambda) \times g^{\rho\sigma} (\nabla_\rho \lambda)(\nabla_\sigma \lambda) + U(\lambda) \Big]$$

$$h \Box \lambda + \frac{1}{2} h' g^{\mu\nu} (\nabla_\mu \lambda)(\nabla_\nu \lambda) - U' + b' R = 0$$

Friedmann eqn:

$$H^2 \equiv \left(\frac{\dot{a}}{a}\right)^2 = \frac{\rho}{6b} + \frac{h\dot{\lambda}^2}{6b} - H\frac{\dot{b}}{b} + U/6b$$

$$\ddot{\lambda} + 3H\dot{\lambda} = 3\frac{b'}{h}(\dot{H} + 2H^2) - \frac{h'\dot{\lambda}^2}{2h} - \frac{1}{2}U'/h$$

__Brans__-__Dicke__ __Theory__:

$$b = \frac{\lambda}{16\pi G} \quad h = \frac{\omega}{8\pi\lambda G} \quad U(\lambda) = 0$$

PPN parameter $\gamma = \frac{\omega+1}{\omega+2}$

measured by time delay

$$\gamma = 1 \pm 10^{-5} \Rightarrow \omega \gtrsim 5\times 10^4$$

Must be __very__ $\simeq$ GR!

f(R) gravity

$$S = \frac{1}{16\pi G}\int d^4x \sqrt{-g}\, f(R) + S_{matter}$$

(i.e., $R \longrightarrow f(R)$)

But consider then

$$S = \frac{1}{16\pi G}\int d^4x \sqrt{-g}\, [f(\lambda) + f'(\lambda)(R-\lambda)] + S_{matter}$$

$$\frac{\partial S}{\partial \lambda} = 0 \Rightarrow \lambda = R$$

$\Rightarrow$ f(R) = scalar-tensor

with $b(\lambda) = f'(\lambda)$,

$U(\lambda) = -f(\lambda) + \lambda f'(\lambda)$, $h(\lambda) = 0$

$\hookrightarrow$ $\gamma = \frac{1}{2}$

Important Lesson!

GR is special!

$\exists$ only <u>two</u> propagating dofs in metric
(2 polarizations +, x, of GWs)

"Modifications" of GR generically bring scalar dof in metric to life, and so very tricky to perturb around GR

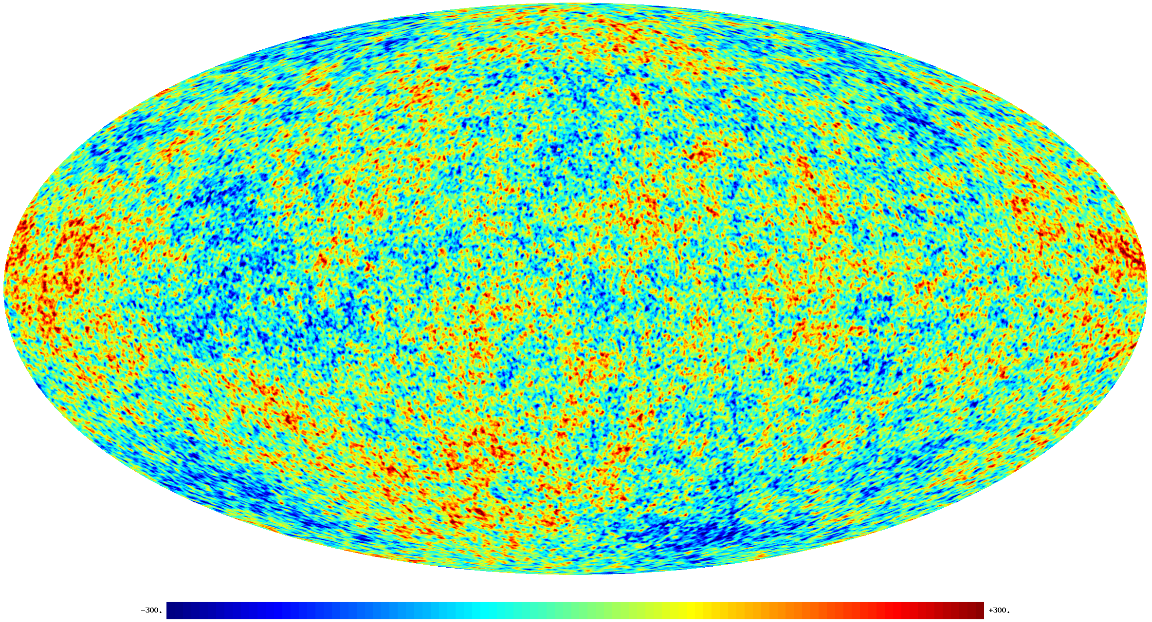
Massive gravity (+ DGP, braneworlds, degravitation, ...)

If $m_g \neq 0$, gravity weaker at $r \gtrsim m_g^{-1}$

If $m_g \sim H$, may explain cosmic acceleration

But things get difficult!

[cf. previous slide]



The Cosmic Microwave Background

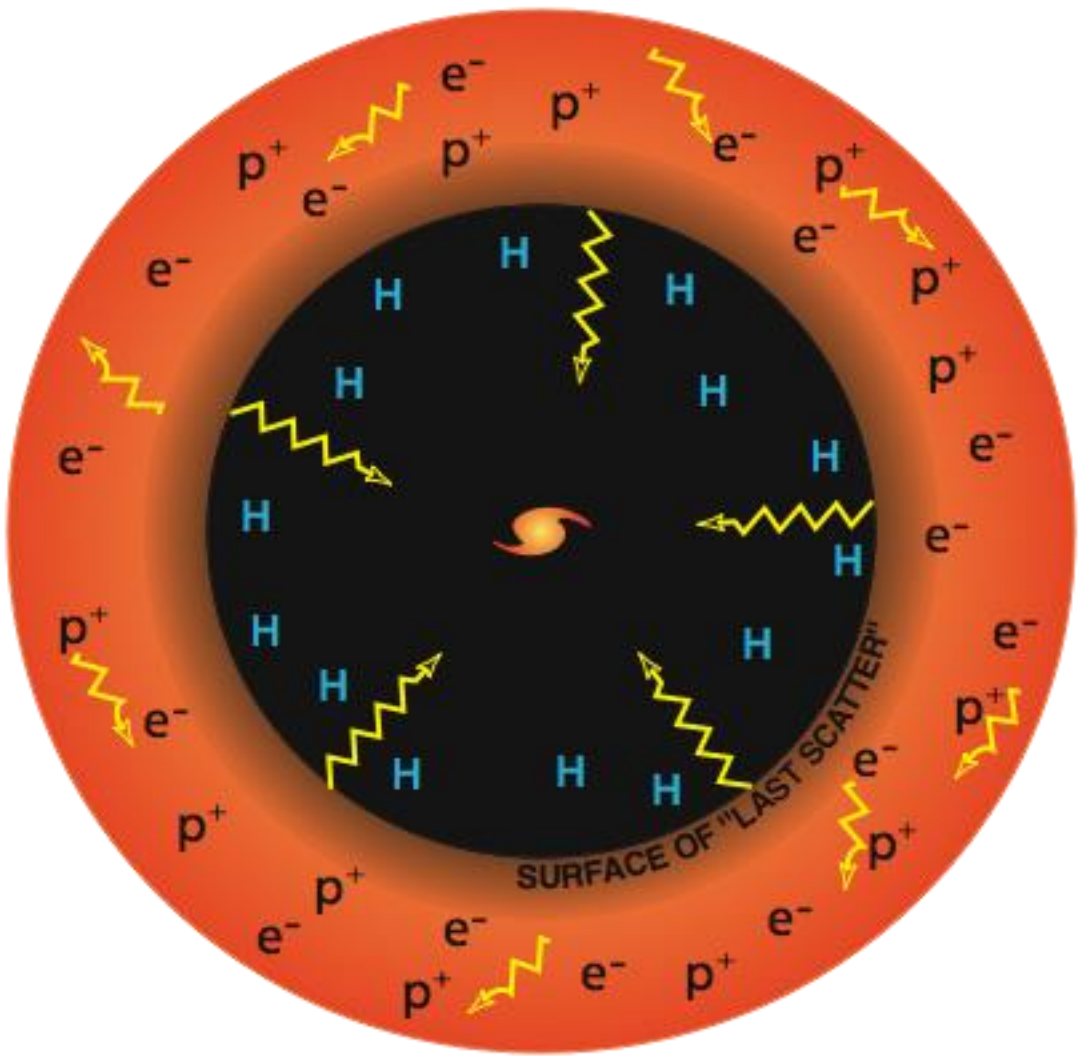
Marc Kamionkowski
(Johns Hopkins University)

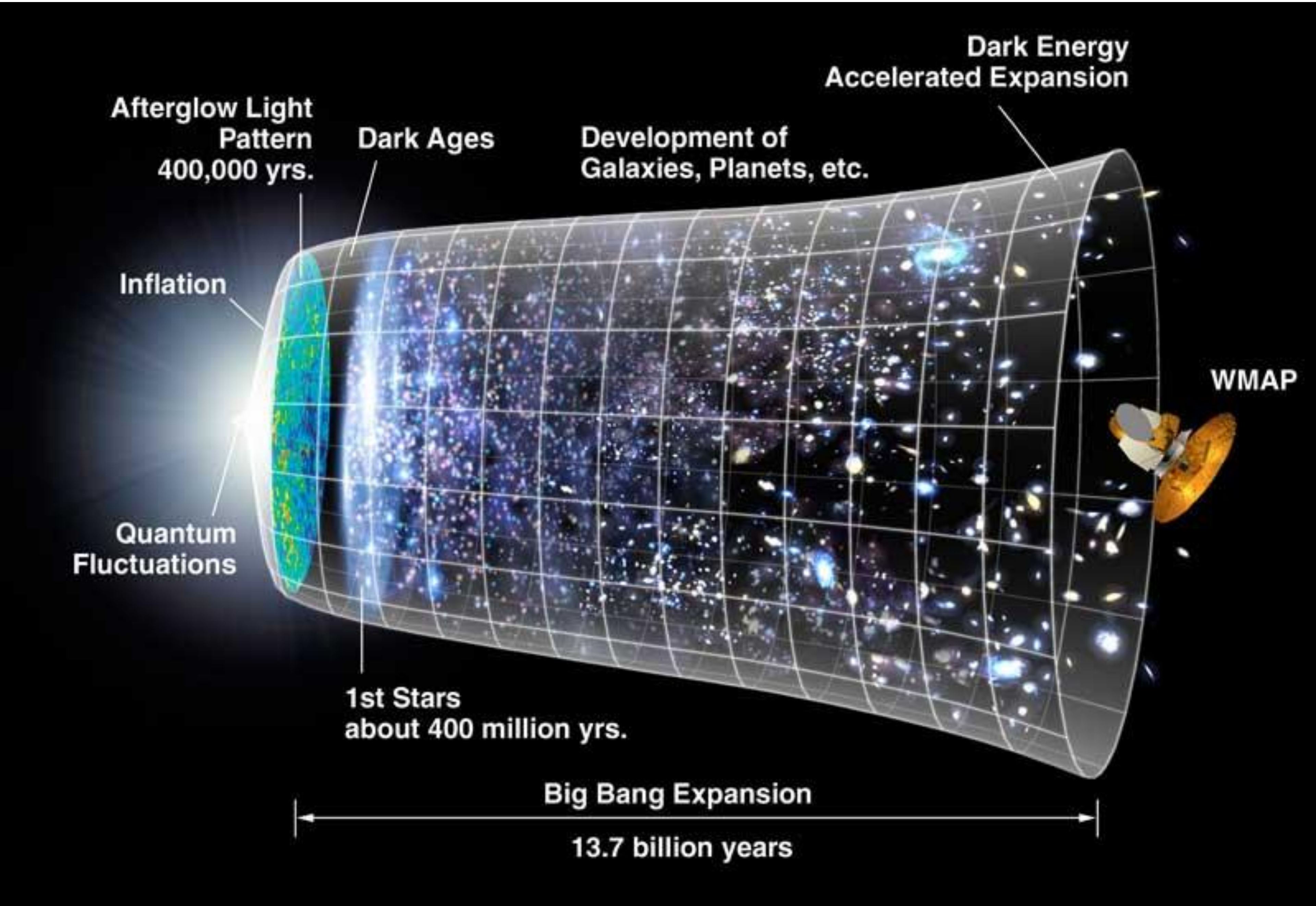
What you’re about to hear

- What we usually do with a CMB map (power spectrum)
- What we have inferred from such maps
- A bunch of new things you can do with the CMB (bipolar spherical harmonics)
- Musings on the power asymmetry

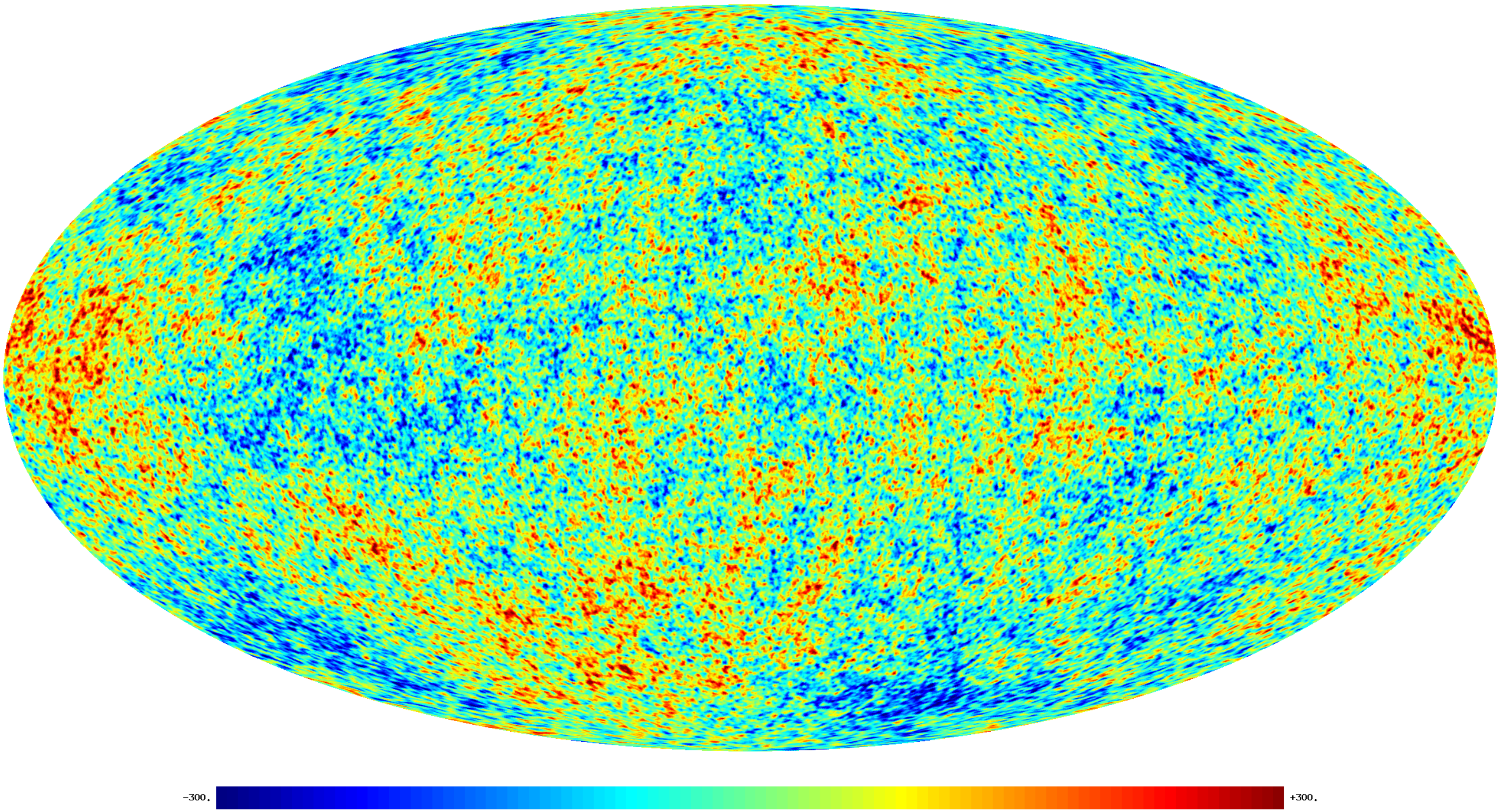
- Today, E_{CMB}~meV
- At z>1000, E_{CMB}>eV
- Universe ionized at z>1000 and neutral afterwards
- CMB photons last scattered at z~1000
- Snapshot of spherical surface of R=13.8 billion lt-yrs 380,000 years after Big Bang

The origin of the CMB




Dark Energy
Accelerated Expansion
Afterglow Light
Pattern
400,000 yrs.
Dark Ages
Development of
Galaxies, Planets, etc.
Inflation
WMAP
Quantum
Fluctuations
1st Stars
about 400 million yrs.
Big Bang Expansion
13.7 billion years

And this is what we see:



$$T(\hat{n})$$

Here's how we quantify it:

$$a_{lm} = \int d^2\hat{n}\, T(\hat{n})\, Y^*_{lm}(\hat{n})$$

depends on coordinate system.

Power spectrum

$$C_l = \sum_m \frac{|a_{lm}|^2}{2l+1}$$

is rotational invariant.

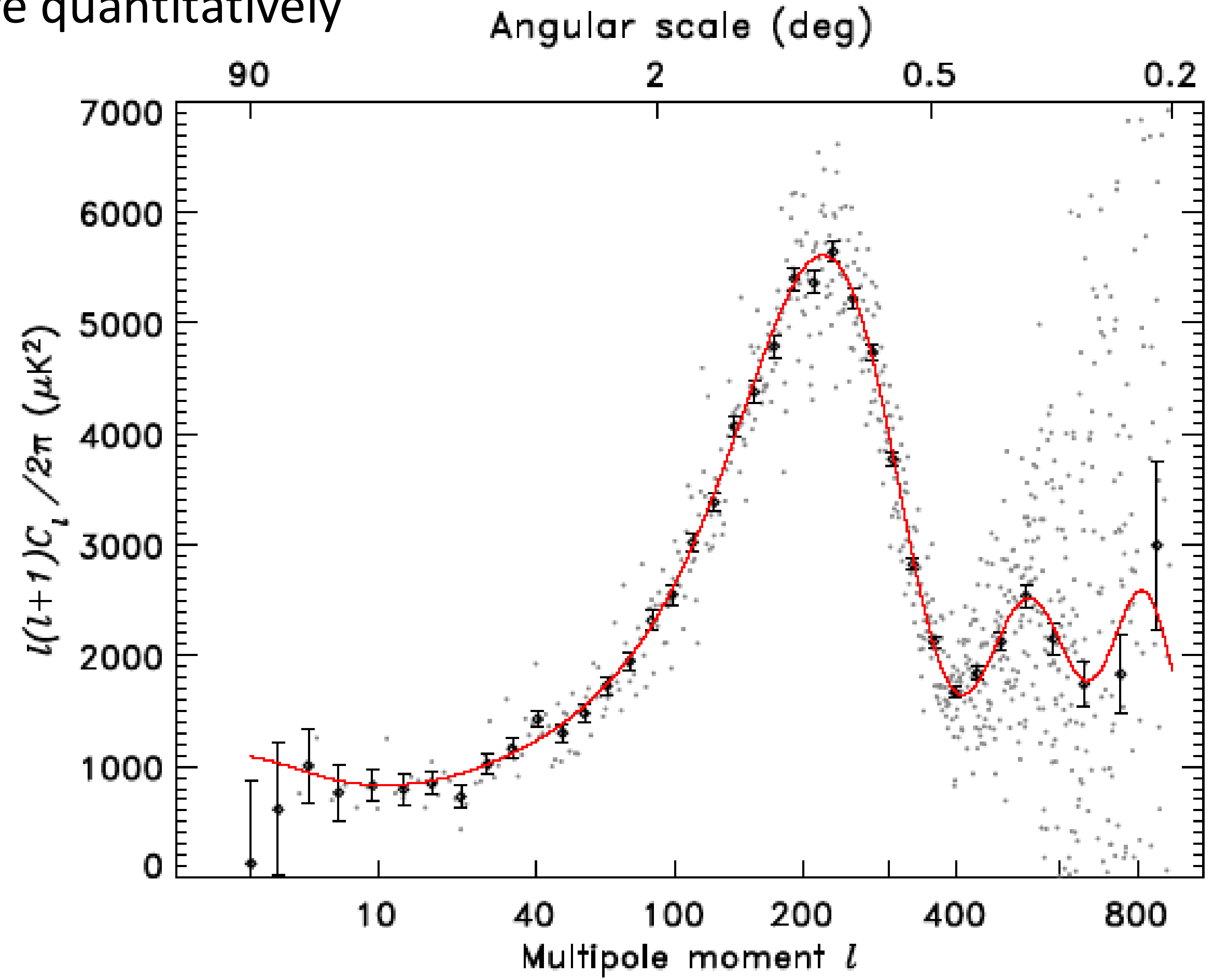
Variance of temperature distribution is

$$\langle (\Delta T)^2 \rangle = \sum_l \frac{2l+1}{4\pi} C_l$$

How to measure it

$$\widehat{C_l} = \frac{1}{2l+1} \sum_{m=-l}^{l} |a_{lm}|^2$$

More quantitatively

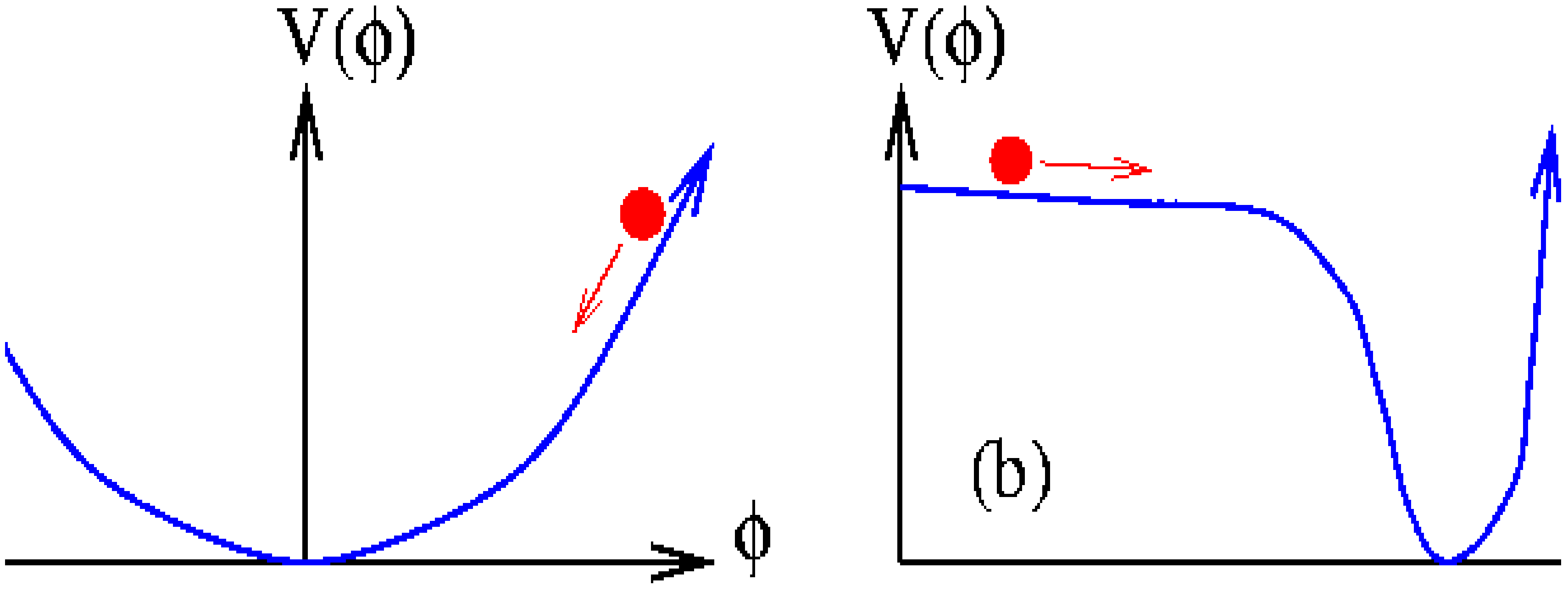


Fourier amplitude

wavenumber l~1/θ

Interpretation: Temperature fluctuations from primordial density perturbations from inflation

The mechanism: Vacuum energy associated with new ultra-high-energy physics (e.g., grand unification, strings, supersymmetry, extra dimensions….)



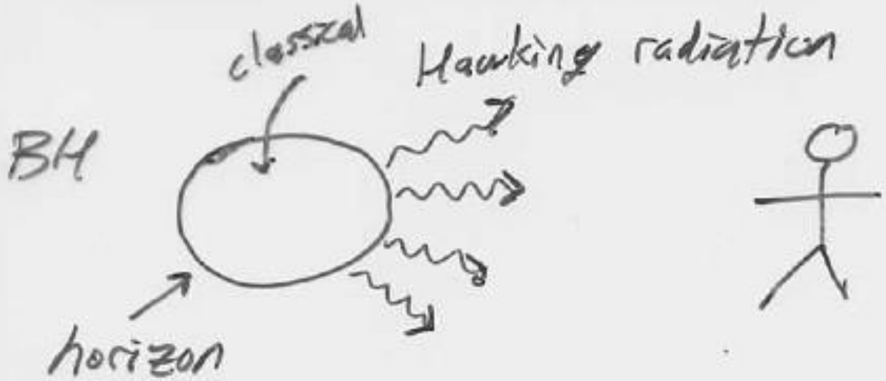
Every Fourier mode of inflaton field satisfies SHO-like equation of motion:

$$\ddot{\phi}_{\vec{k}} + k^2 \phi_{\vec{k}} = 0$$

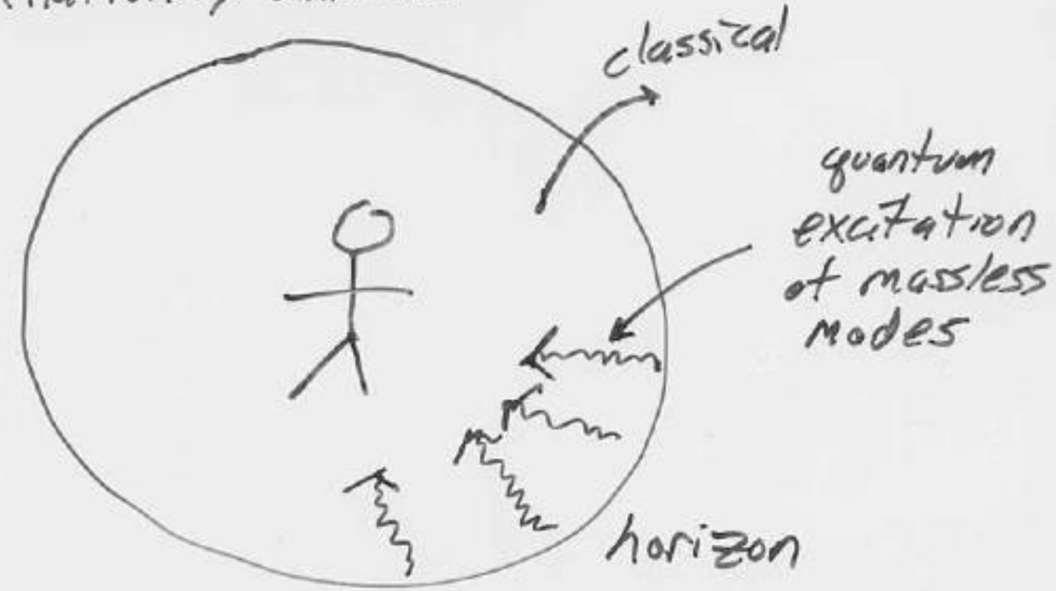
Then imprinted as primordial density perturbations

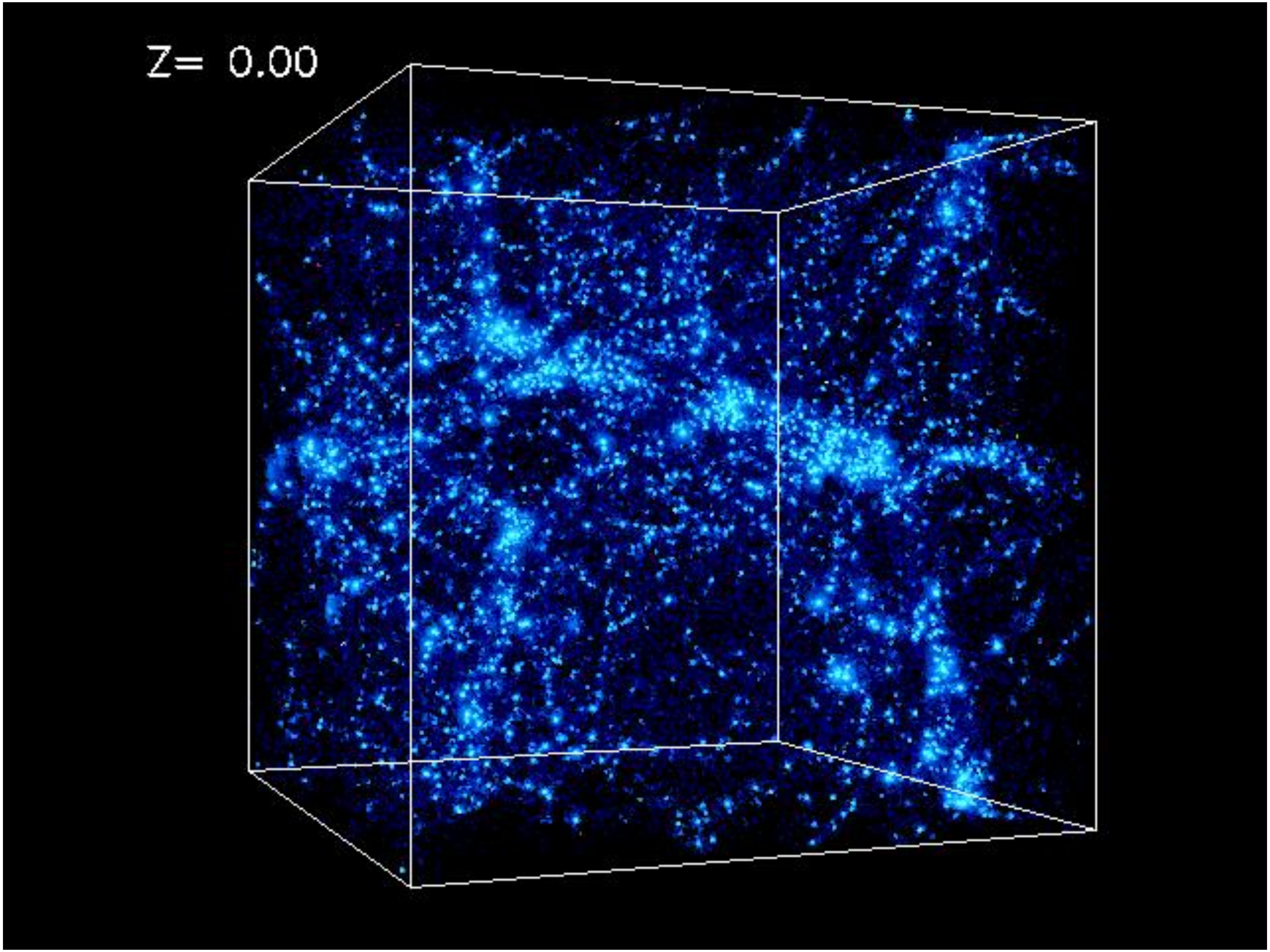
➔ Amplitude of each Fourier mode selected from Gaussian random distribution (the ground-state SHO wave function)

Black-hole analogy



Inflationary Universe




Z= 0.00

Inflation predicts power spectrum

$$P(k) \equiv \left\langle \left(\frac{\delta\rho}{\rho} \right)^2_{\vec{k}} \right\rangle \propto k^{n_s}$$

With

$$n_s = 1 - 2\epsilon + 6\eta$$

$$\epsilon \propto V' \qquad \eta \propto V''$$

i.e.,

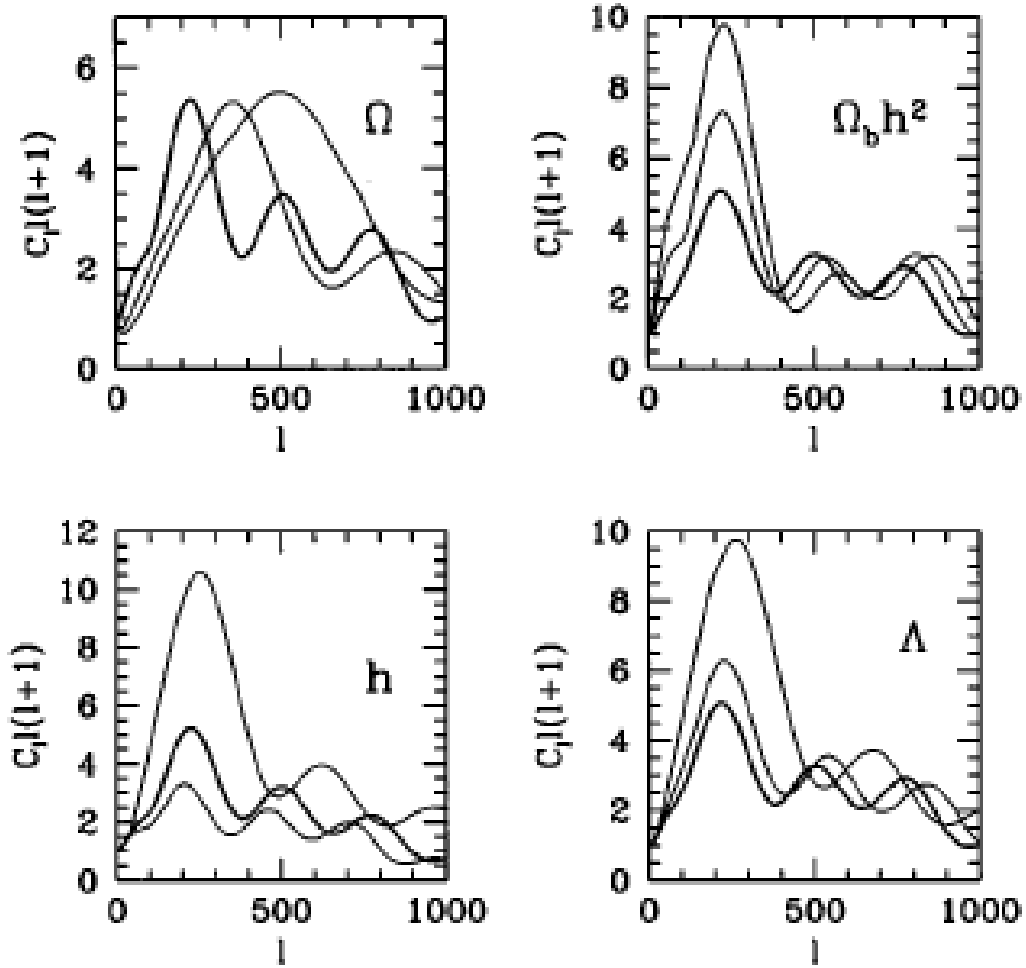
$$V(\phi) \leftrightarrow P(k)$$

Inflationary prediction is that CMB is realization of statistically isotropic Gaussian random field: each a_{lm} is statistically independent and there is no *m* dependence

$$\langle a^*_{lm} a_{l'm'} \rangle = C_l \delta_{ll'} \delta_{mm'}$$

Power-spectrum predictions straightforward given values of cosmological parameters; e.g.,

$$\{\Omega_{\rm m}, \Omega_{\rm de}, w, \Omega_{\rm b}, \Omega_\nu, H_0, \tau_{\rm reion}, n_s, \cdots\}$$



Measurement of power spectrum allows precise determination of cosmological parameters (Jungman, MK, Kosowsky, Spergel, 1996; *including* N_{eff} *!!!)*

As has now been done……

FIVE-YEAR *WILKINSON MICROWAVE ANISOTROPY PROBE** OBSERVATIONS: LIKELIHOODS AND PARAMETERS FROM THE *WMAP* DATA

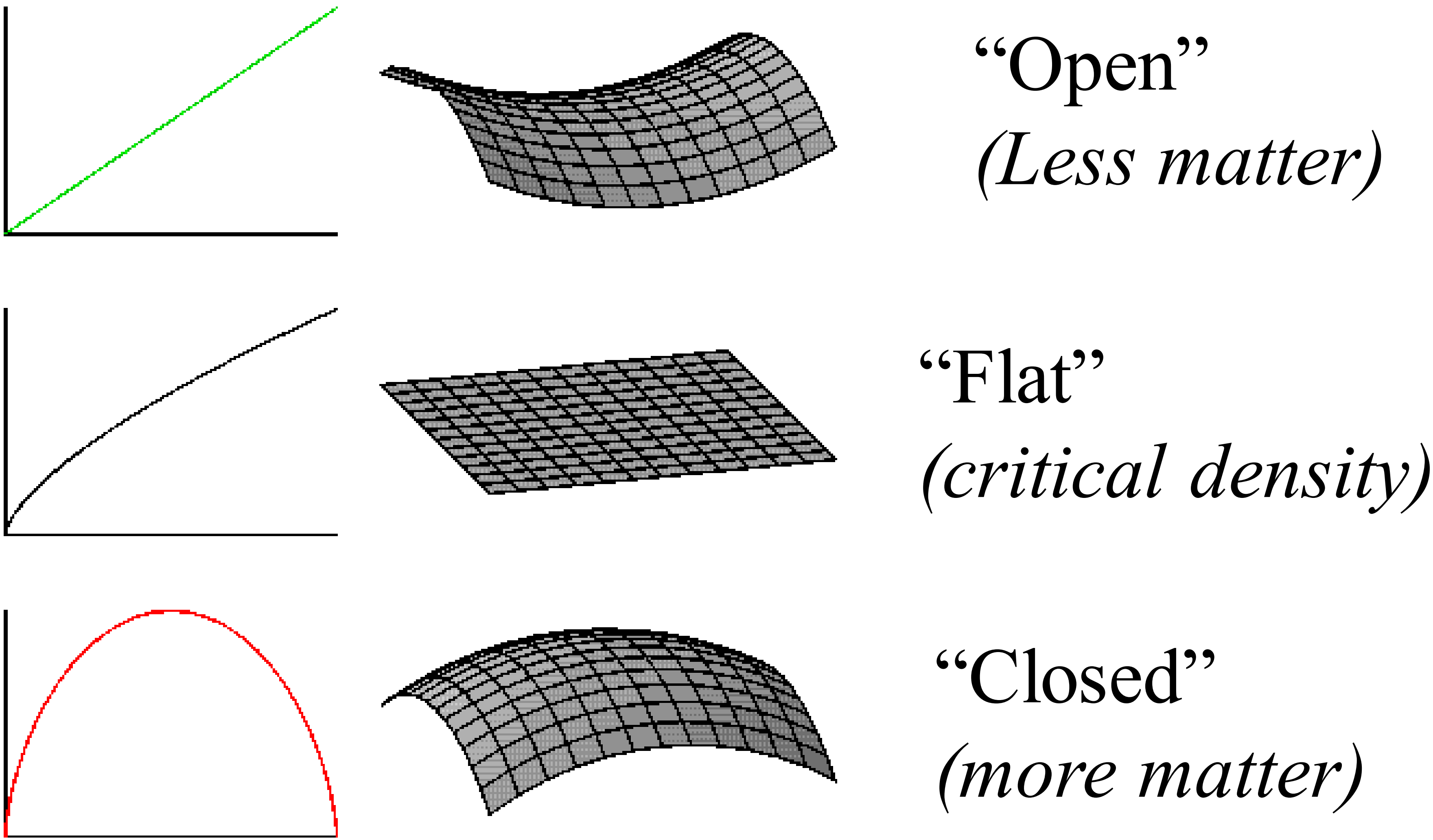
J. DUNKLEY[1,2,3], E. KOMATSU[4], M. R. NOLTA[5], D. N. SPERGEL[2,6], D. LARSON[7], G. HINSHAW[8], L. PAGE[1], C. L. BENNETT[7], B. GOLD[7], N. JAROSIK[1], J. L. WEILAND[9], M. HALPERN[10], R. S. HILL[9], A. KOGUT[8], M. LIMON[11], S. S. MEYER[12], G. S. TUCKER[13], E. WOLLACK[8], AND E. L. WRIGHT[14]

This paper focuses on cosmological constraints derived from analysis of *WMAP* data alone. A simple ΛCDM cosmological model fits the five-year *WMAP* temperature and polarization data. The basic parameters of the model are consistent with the three-year data and now better constrained: $\Omega_b h^2 = 0.02273 \pm 0.00062$, $\Omega_c h^2 = 0.1099 \pm 0.0062$, $\Omega_\Lambda = 0.742 \pm 0.030$, $n_s = 0.963^{+0.014}_{-0.015}$, $\tau = 0.087 \pm 0.017$, and $\sigma_8 = 0.796 \pm 0.036$, with $h = 0.719^{+0.026}_{-0.027}$. With five years of polarization data, we have measured the optical depth to reionization, $\tau > 0$, at 5σ significance. The redshift of an instantaneous reionization is constrained to be $z_{\rm reion} = 11.0 \pm 1.4$ with 68% confidence. The 2σ lower limit is $z_{\rm reion} > 8.2$, and the 3σ limit is $z_{\rm reion} > 6.7$. This excludes a sudden reionization of the universe at $z = 6$ at more than 3.5σ significance, suggesting that reionization was an extended process. Using two methods for polarized foreground cleaning we get consistent estimates for the optical depth, indicating an error due to the foreground treatment of $\tau \sim 0.01$. This cosmological model also fits small-scale cosmic microwave background (CMB) data, and a range of astronomical data measuring the expansion rate and clustering of matter in the universe. We find evidence for the first time in the CMB power spectrum for a nonzero cosmic neutrino background, or a background of relativistic species, with the standard three light neutrino species preferred over the best-fit ΛCDM model with $N_{\rm eff} = 0$ at $> 99.5\%$ confidence, and $N_{\rm eff} > 2.3$ (95% confidence limit (CL)) when varied. The five-year *WMAP* data improve the upper limit on the tensor-to-scalar ratio, $r < 0.43$ (95% CL), for power-law models, and halve the limit on r for models with a running index, $r < 0.58$ (95% CL). With longer integration we find no evidence for a running spectral index, with $dn_s/d\ln k = -0.037 \pm 0.028$, and find improved limits on isocurvature fluctuations. The current *WMAP*-only limit on the sum of the neutrino masses is $\sum m_\nu < 1.3$ eV (95% CL), which is robust, to within 10%, to a varying tensor amplitude, running spectral index, or dark energy equation of state.

E.g., Inflationary prediction of flat Universe

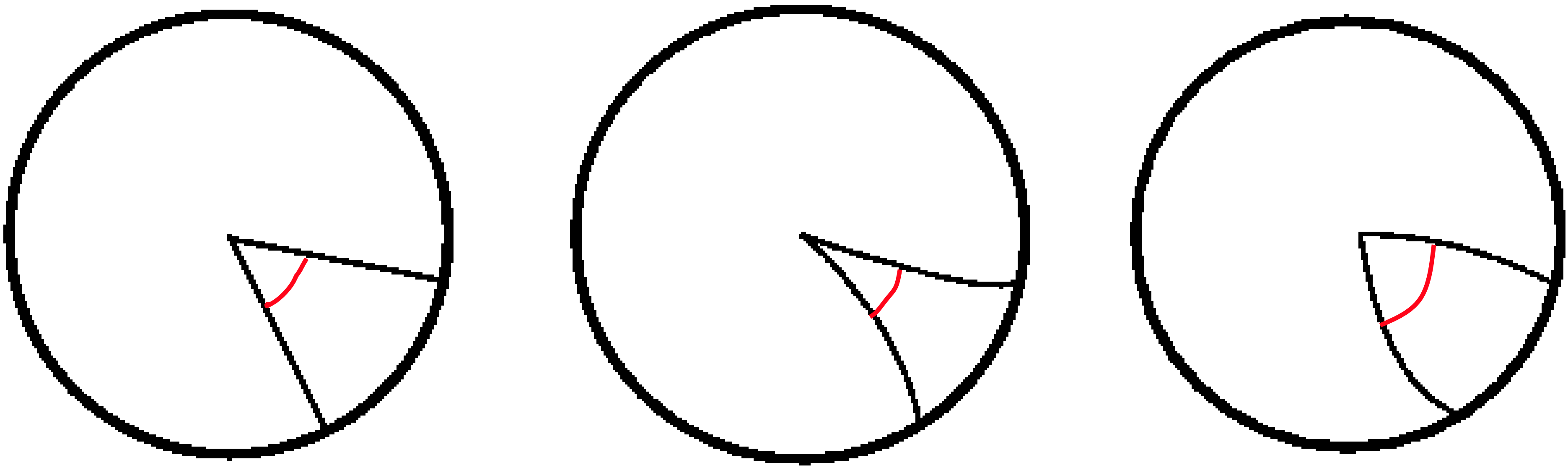
Cosmological geometry: The shape of spacetime

General relativity: Matter warps spacetime



The Geometry of the Universe

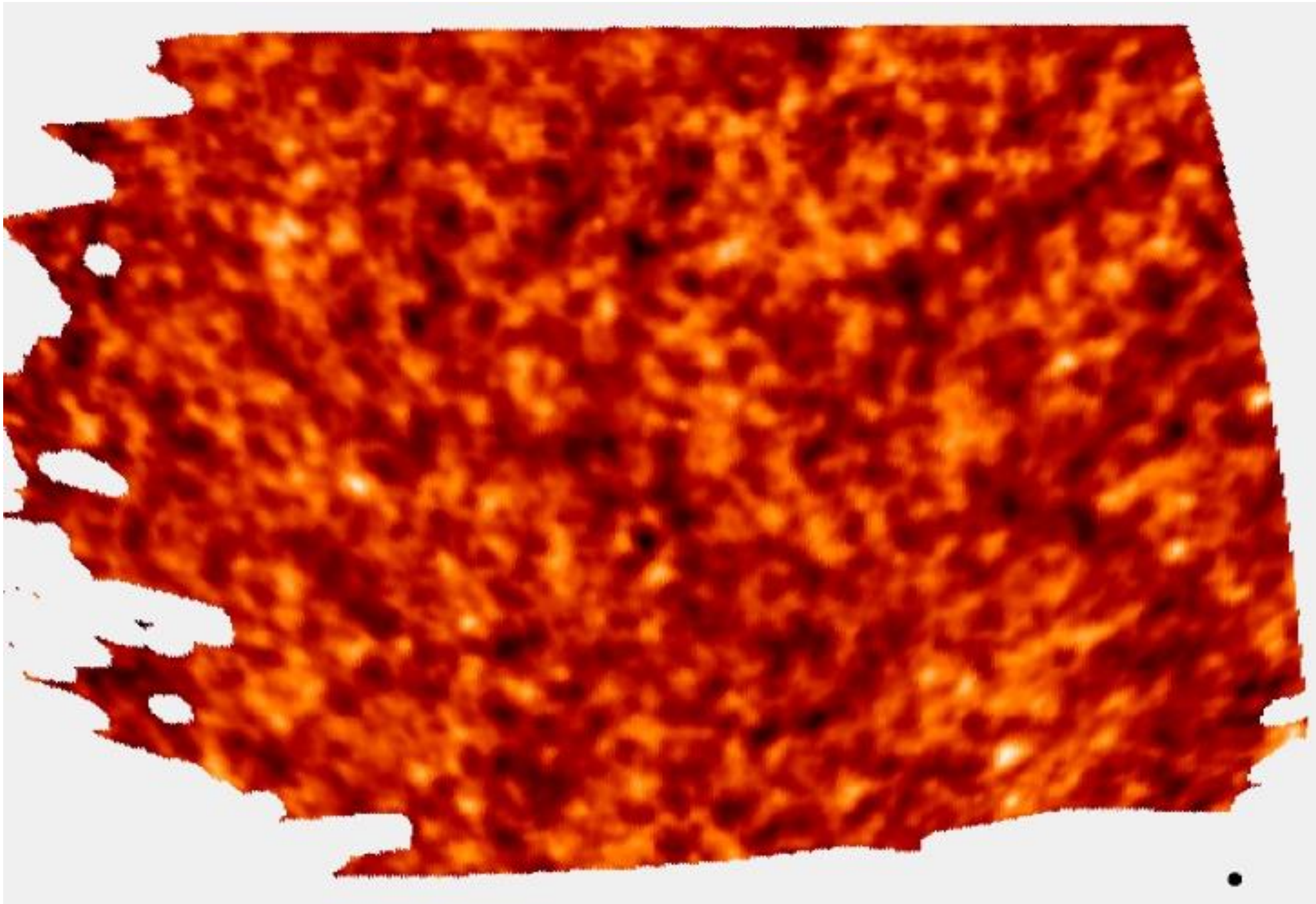
Warped spacetime acts as lens:



“flat” “open” “closed”

(MK, Spergel, Sugiyama 1994)

Map of CMB (Boomerang 2000)



Sizes of hot/cold spots⇒Universe is flat

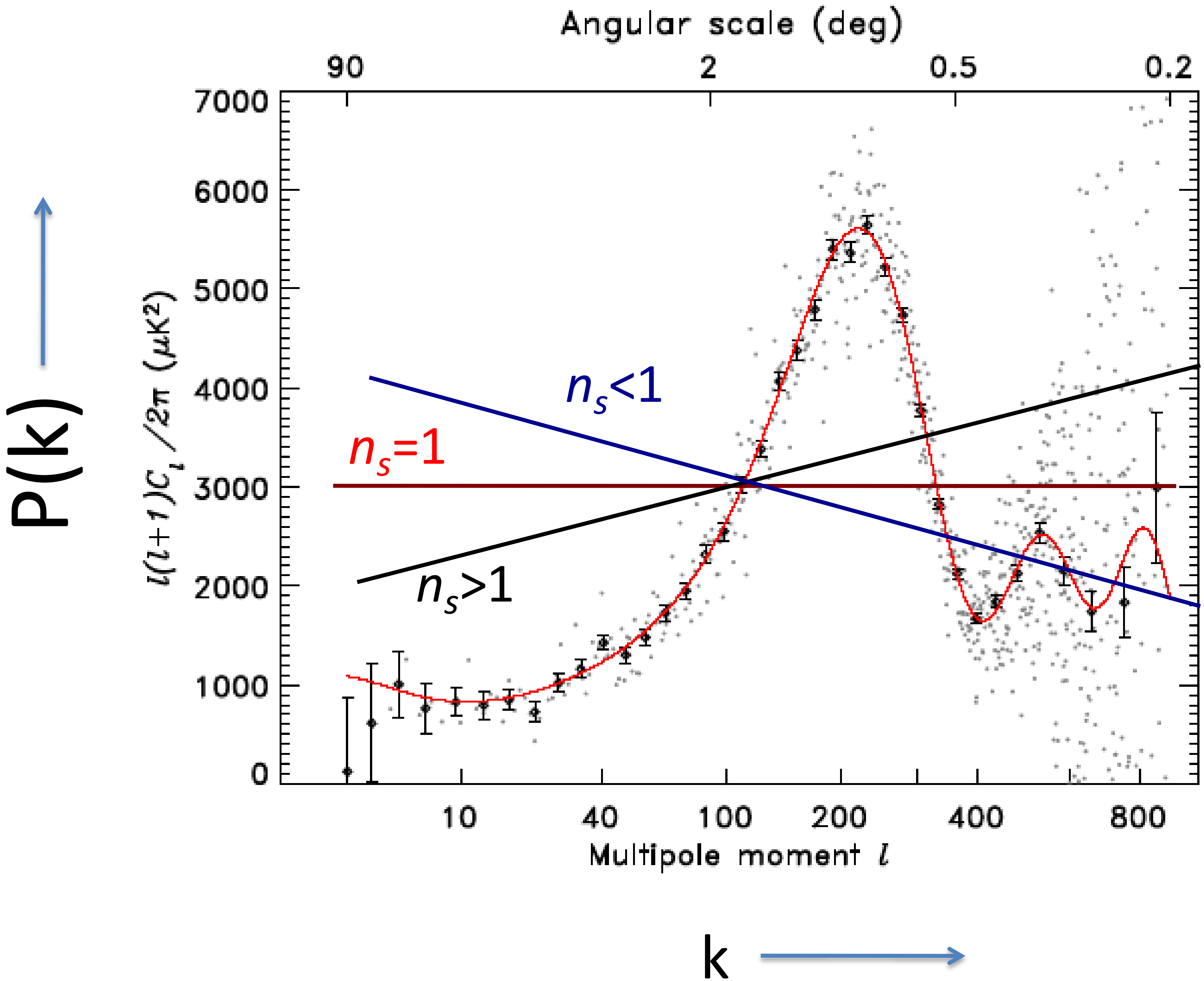
Important recent experimental result:

$$n_s \simeq 0.95$$

$$n_s \neq 1$$

At ~5-sigma level

(as predicted by inflation)



Angular scale (deg)
90
2
0.5
0.2
7000
6000
5000
4000
3000
2000
1000
0
$l(l+1)C_l/2\pi$ (μK^2)
10
40
100
200
400
800
Multipole moment l
$n_s<1$
$n_s=1$
$n_s>1$
P(k)
k

And one final prediction: gaussianity

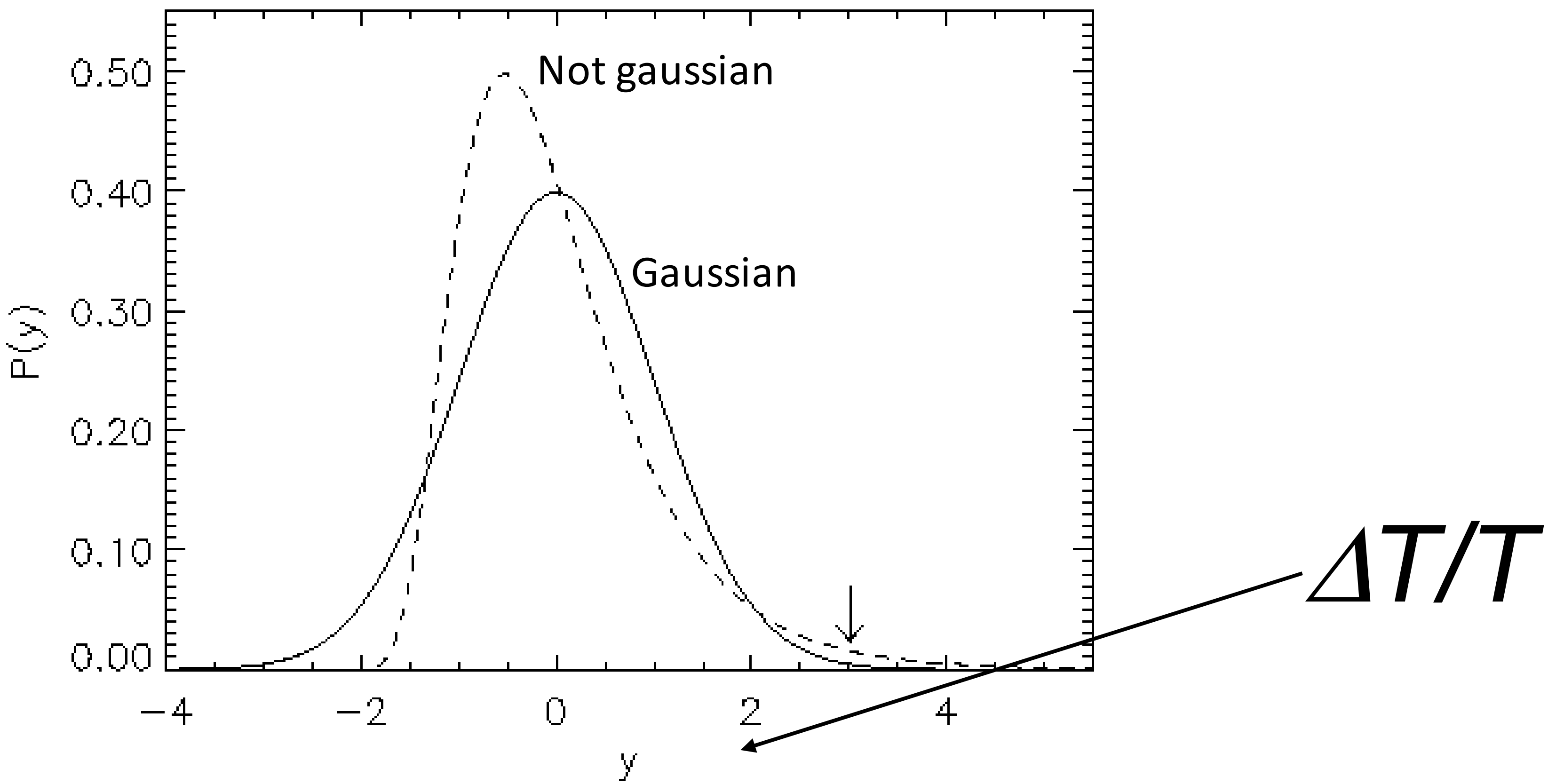
- Gravitational potential (e.g., Verde, Wang, Heavens, MK, 2000)

$$\Phi = \phi + f_{\rm NL}\phi^2$$

Gaussian field

with f_{NL}<1 (e.g., Wang & MK, 2000)

Fractional departure from Gaussianity: $\sim f_{\rm NL}\phi_{\rm rms} \sim 10^{-3}\, f_{\rm NL}$



Current constraints (WMAP5,SDSS):

$|f_{nl}|<100$

We now know:

- Baryon, dark-matter, dark-energy, neutrino densities and Hubble parameter to several significant figures
- that Universe is flat (MK,Spergel, Sugiyama 1994)
- Primordial perturbations are "adiabatic" (i.e., to total density, rather than to DM:baryon:photon ratios), as predicted by inflation
- n_s differs from unity
- Perturbations are Gaussian to ~1 part in 10,000

What else can we do?

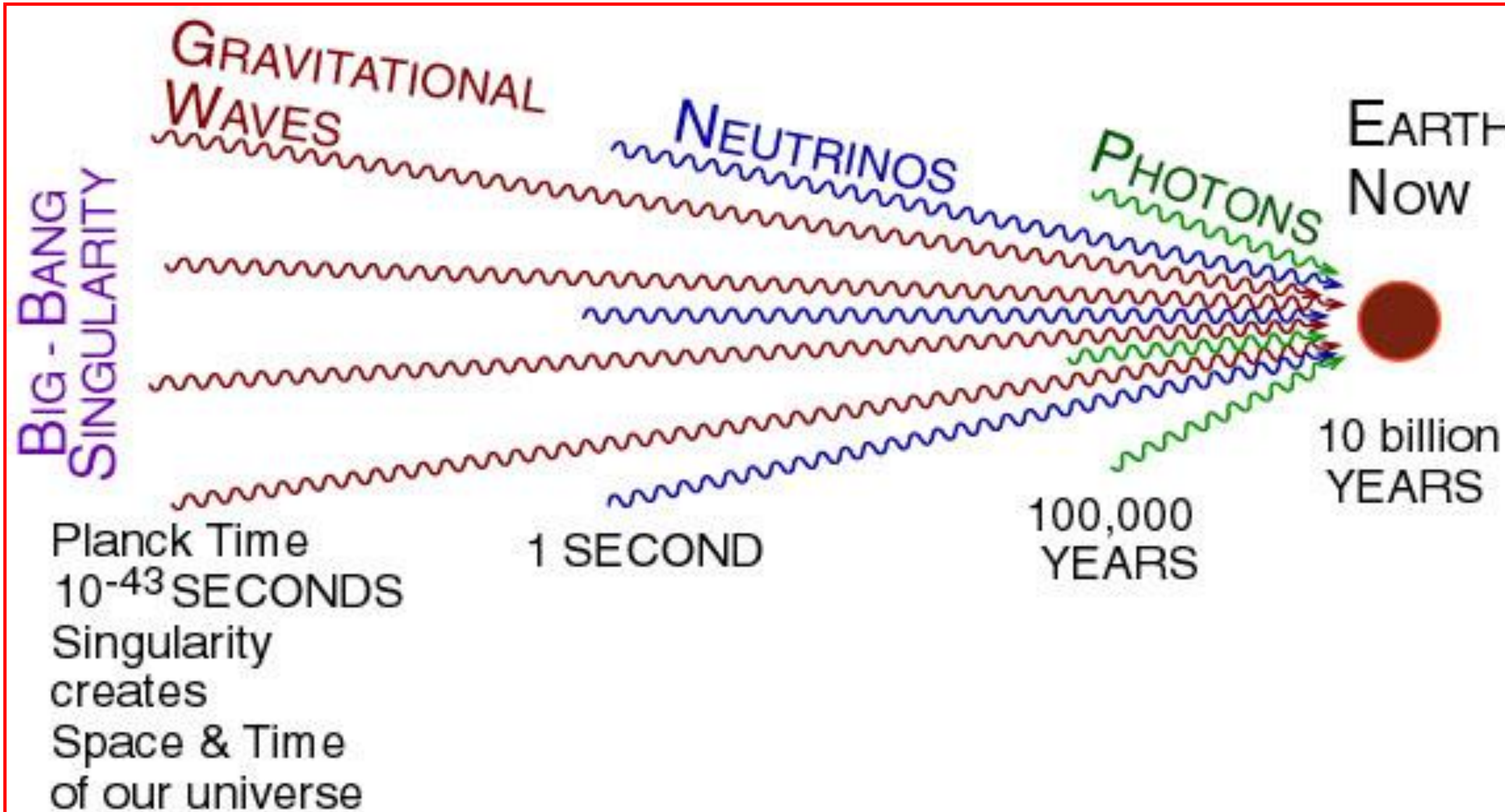
What else can we do?

1. Polarization

What is new physics responsible for inflation?

What is $V(\phi)$??

STOCHASTIC GRAVITATIONAL WAVE BACKGROUND with amplitude $\propto V^{1/2}$



Gravitational Waves
Neutrinos
Photons
Earth Now
Big - Bang Singularity
Planck Time
10-43 SECONDS
Singularity creates Space & Time of our universe
1 SECOND
100,000 YEARS
10 billion YEARS

Detection of gravitational waves with CMB polarization

"E modes" "B modes"

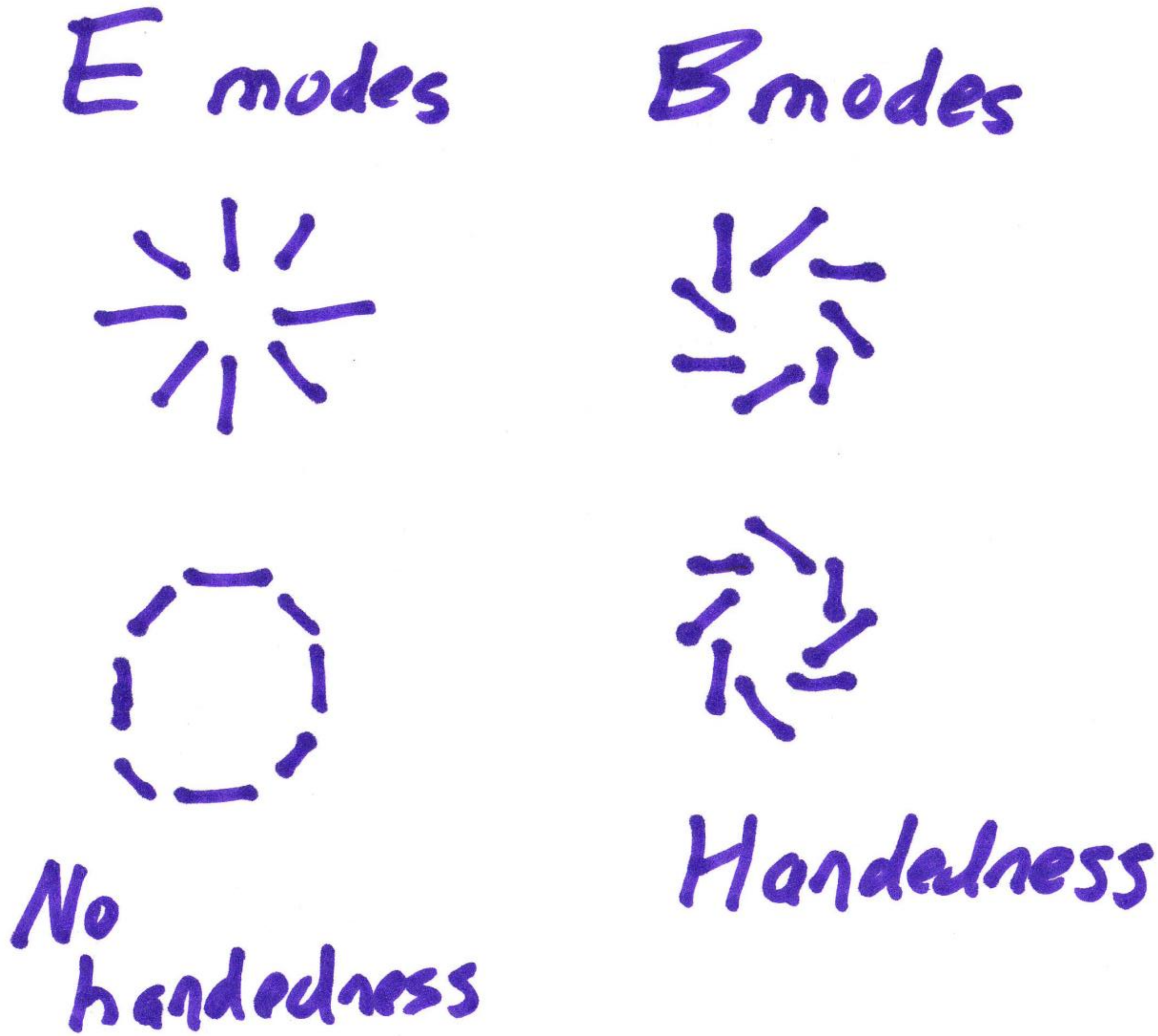
Temperature map: $T(\hat{n})$

Polarization Map: $\vec{P}(\hat{n}) = \vec{\nabla} A + \vec{\nabla} \times \vec{B}$

Density perturbations have no "handedness" so they can*not* produce a polarization with a curl

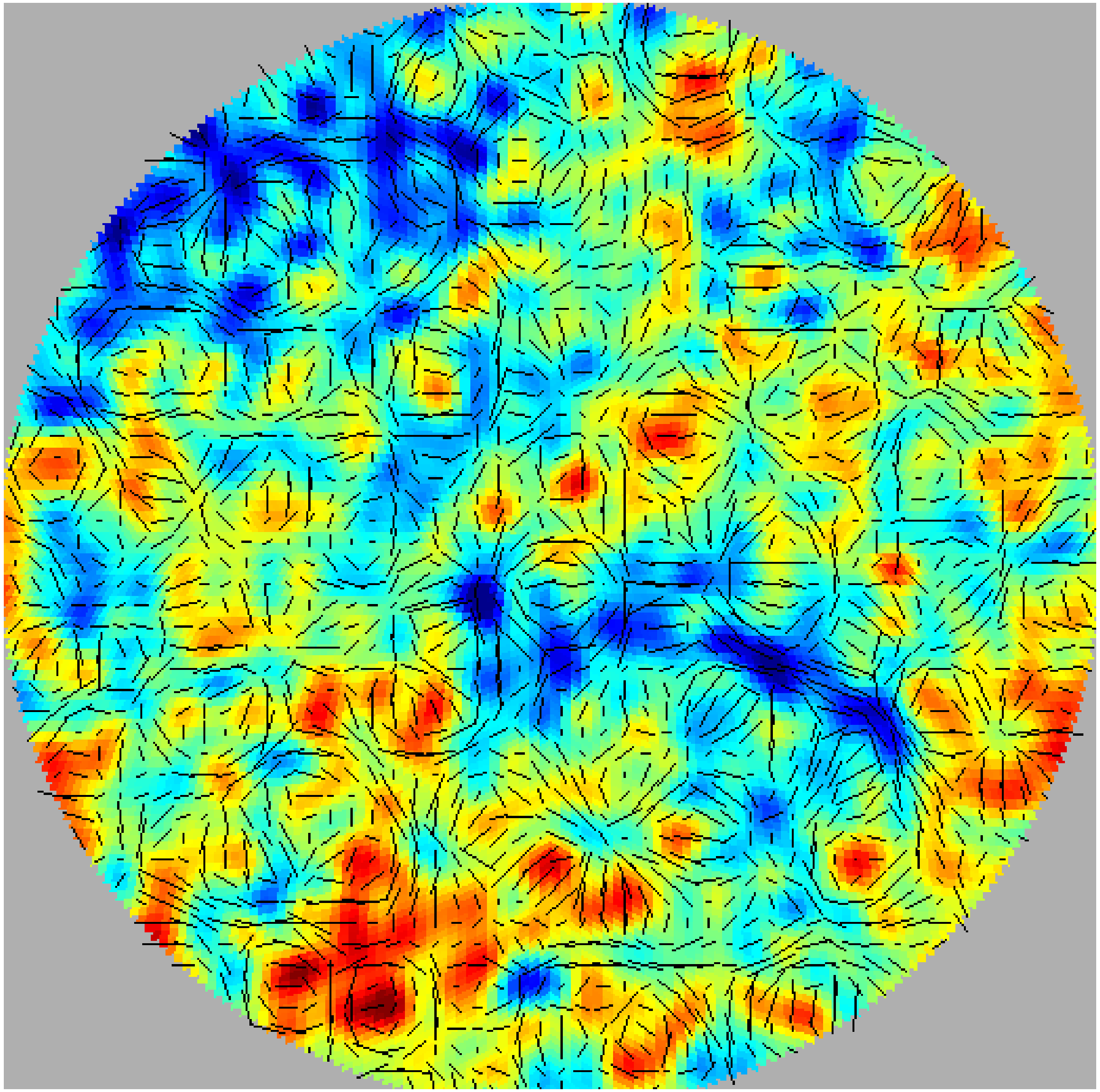
Gravitational waves do have a handedness, so they can (and do) produce a curl

(MK, Kosowsky, Stebbins 1996; Seljak, Zaldarriaga 1996)

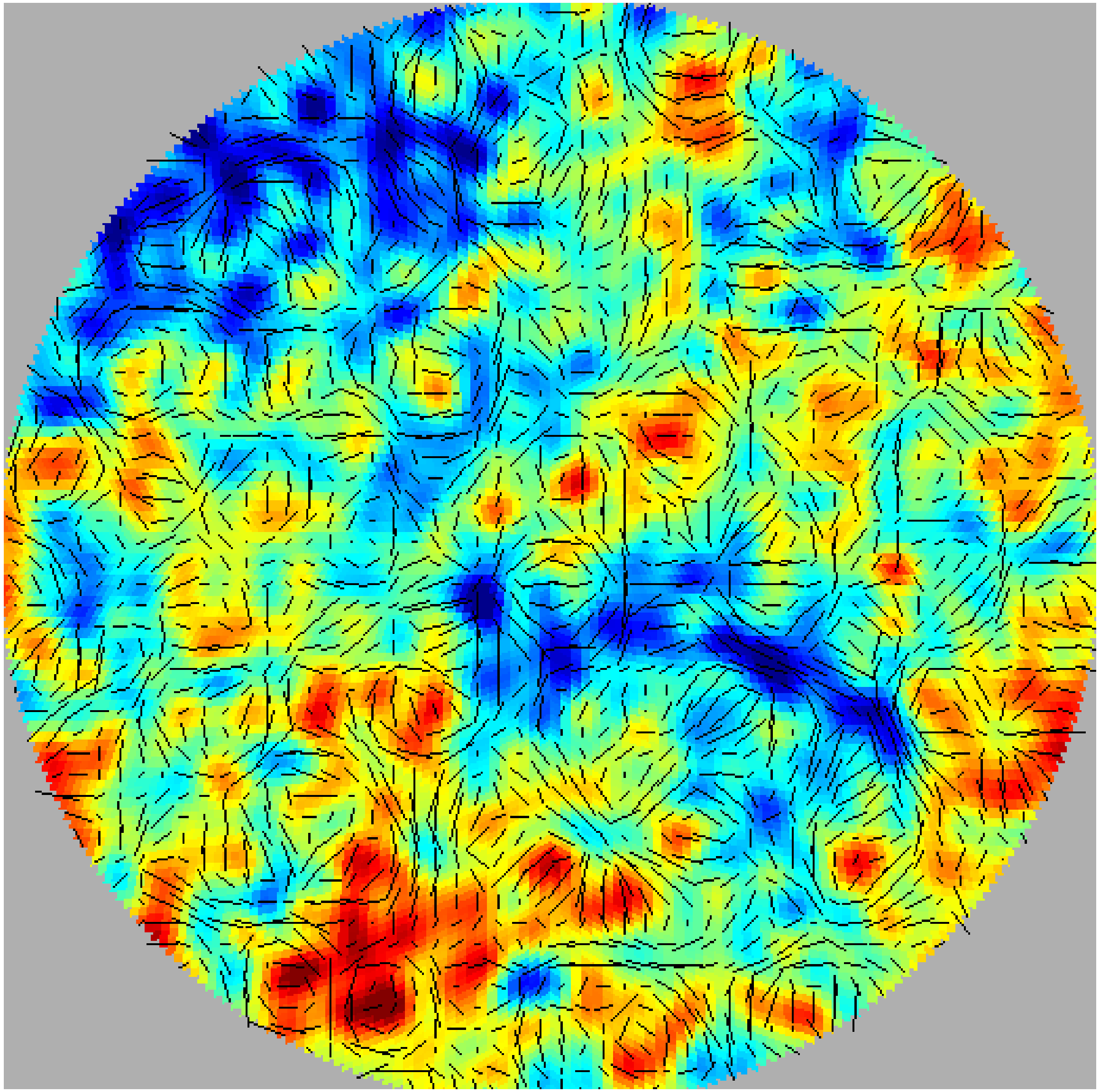


E modes
B modes
No handedness
Handedness

No Gravity Waves



Gravity Waves



Now SIX CMB power spectra

$$C_l^{\mathrm{TT}} \qquad C_l^{\mathrm{EE}} \qquad C_l^{\mathrm{BB}}$$

$$C_l^{\mathrm{TE}} \qquad C_l^{\mathrm{TB}} \qquad C_l^{\mathrm{EB}}$$

(parity breaking)

From three sets of temperature/polarization coefficients:

$$a_{lm}^{\mathrm{T}} \qquad a_{lm}^{\mathrm{E}} \qquad a_{lm}^{\mathrm{B}}$$

Cosmological birefringence

- If some *Φ(t)* couples to E&M through:

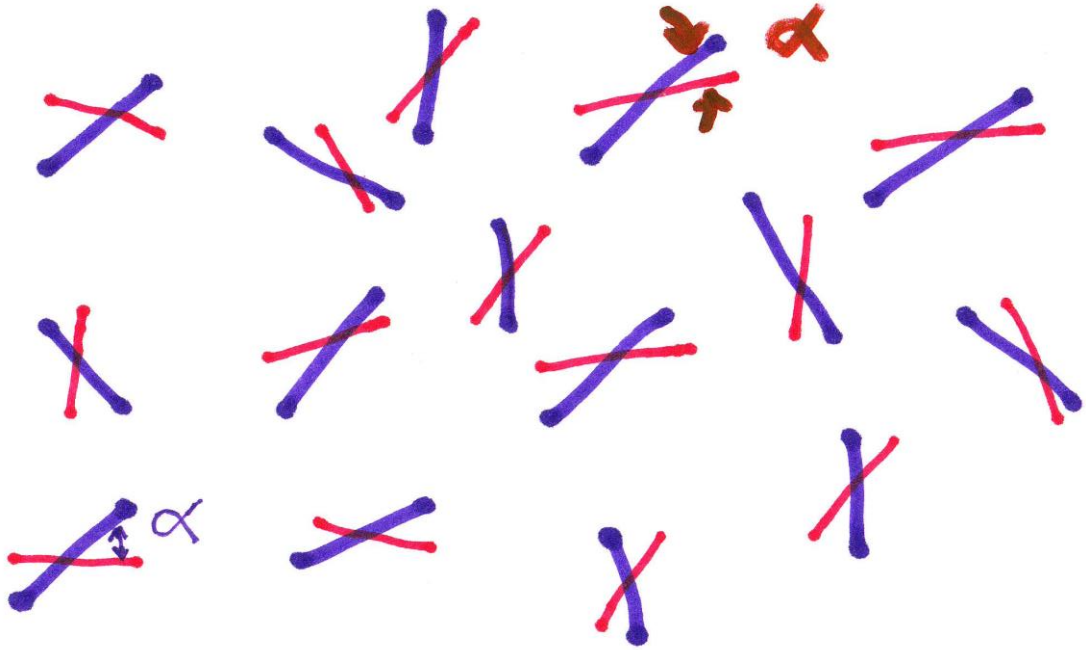
$$\mathcal{L} = \frac{1}{2}(\vec{E}^2 - \vec{B}^2) + \frac{\phi(t)}{M_*}\vec{E}\cdot\vec{B}$$

Φ(t) leads to rotation by $\alpha=\Delta\phi/M_*$, of polarization as photons propagate (Carroll, Field, Jackiw 1998)
Rotation induces EB cross-correlation (Lue, Wang, MK 1999)

CMB searches: $\alpha <$ few degrees (Feng et al., astro-ph/0601095; Komatsu et al. 2008; Wu et al. 2008…..)

Right- and left-circularly polarized EM waves propagate with same speed to 10^{-30} !!!

Uniform Rotation α



Primordial Rotated

What else can we do?

2. Departures from Gaussianity and Statistical Isotropy

Inflationary prediction,

$$\langle a_{lm}^* a_{l'm'} \rangle = C_l \delta_{ll'} \delta_{mm'}$$

can be modified by

- late-time effects (e.g., gravitational lensing)
- Inflationary physics beyond vanilla inflation
- Exotica

Any such effects can be parametrized as

$$\langle a_{lm}^* a_{l'm'} \rangle = C_l \delta_{ll'} \delta_{mm'} + \sum_{L \geq 0} \sum_{M=-L}^{L} \mathcal{C}_{lml'm'}^{LM} A_{ll'}^{LM}$$

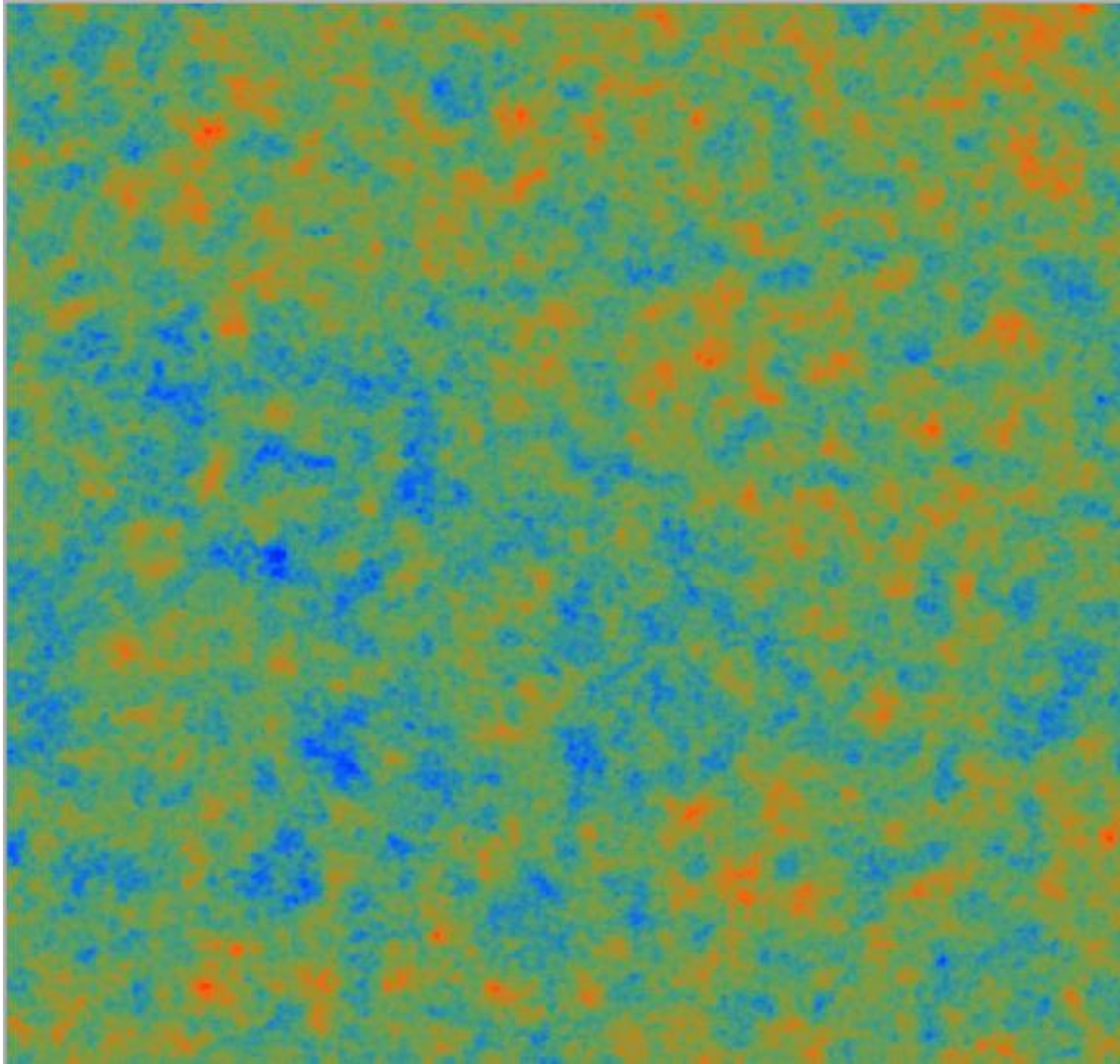
Clebsch-Gordan coefficients

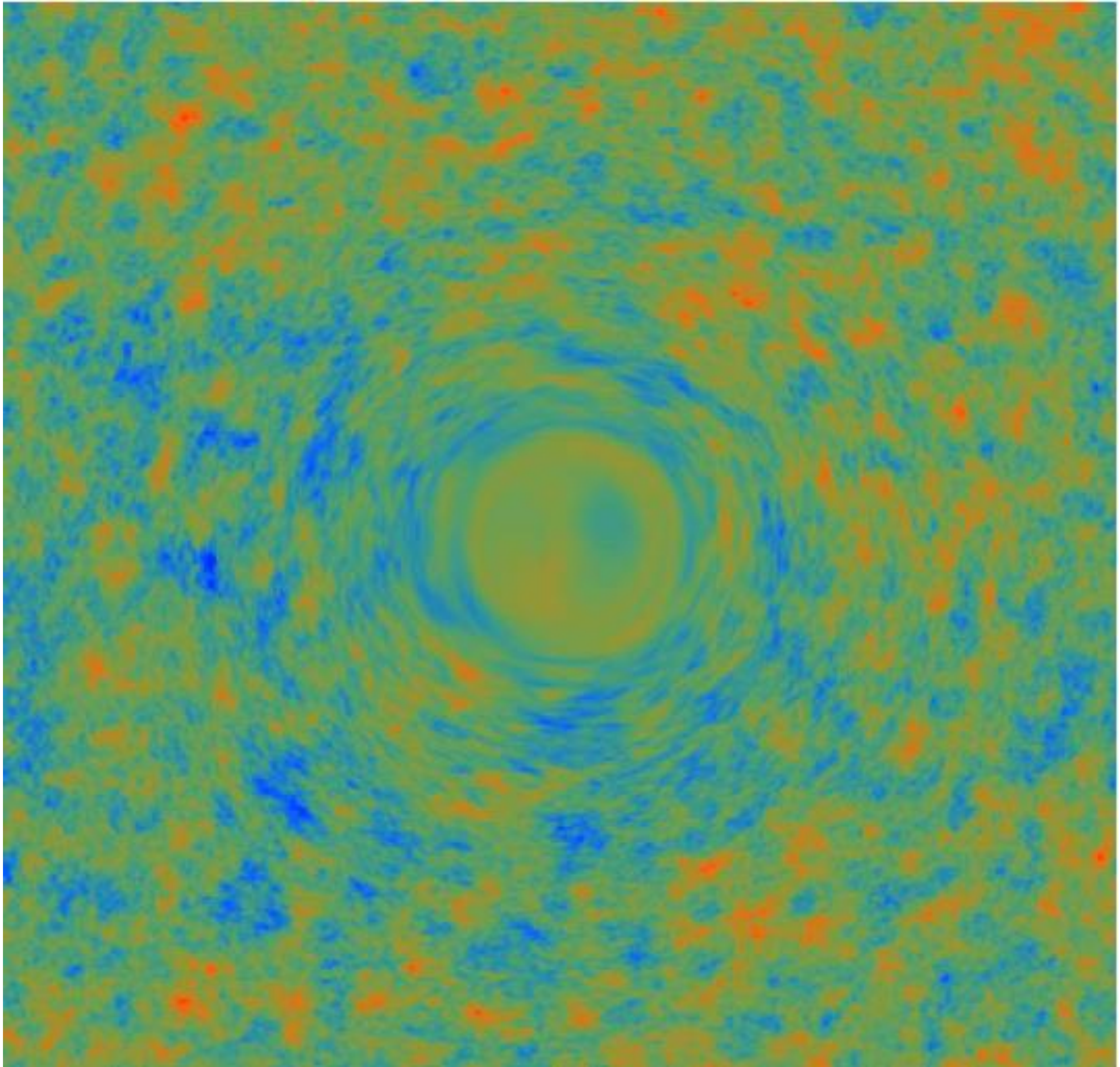
Bipolar spherical harmonics (BiPoSHs)
(Hajian & Souradeep 2004; Book, MK, Souradeep 2011)

Recipe for measuring BiPoSHs (generalizations of power spectrum to direction-dependent fluctuations):

$$\widehat{A_{ll'}^{LM}} = \sum_{lml'm'} \mathcal{C}_{lml'm'}^{LM} a_{lm}^{*} a_{l'm'}$$

Example 1: Weak gravitational lensing of CMB





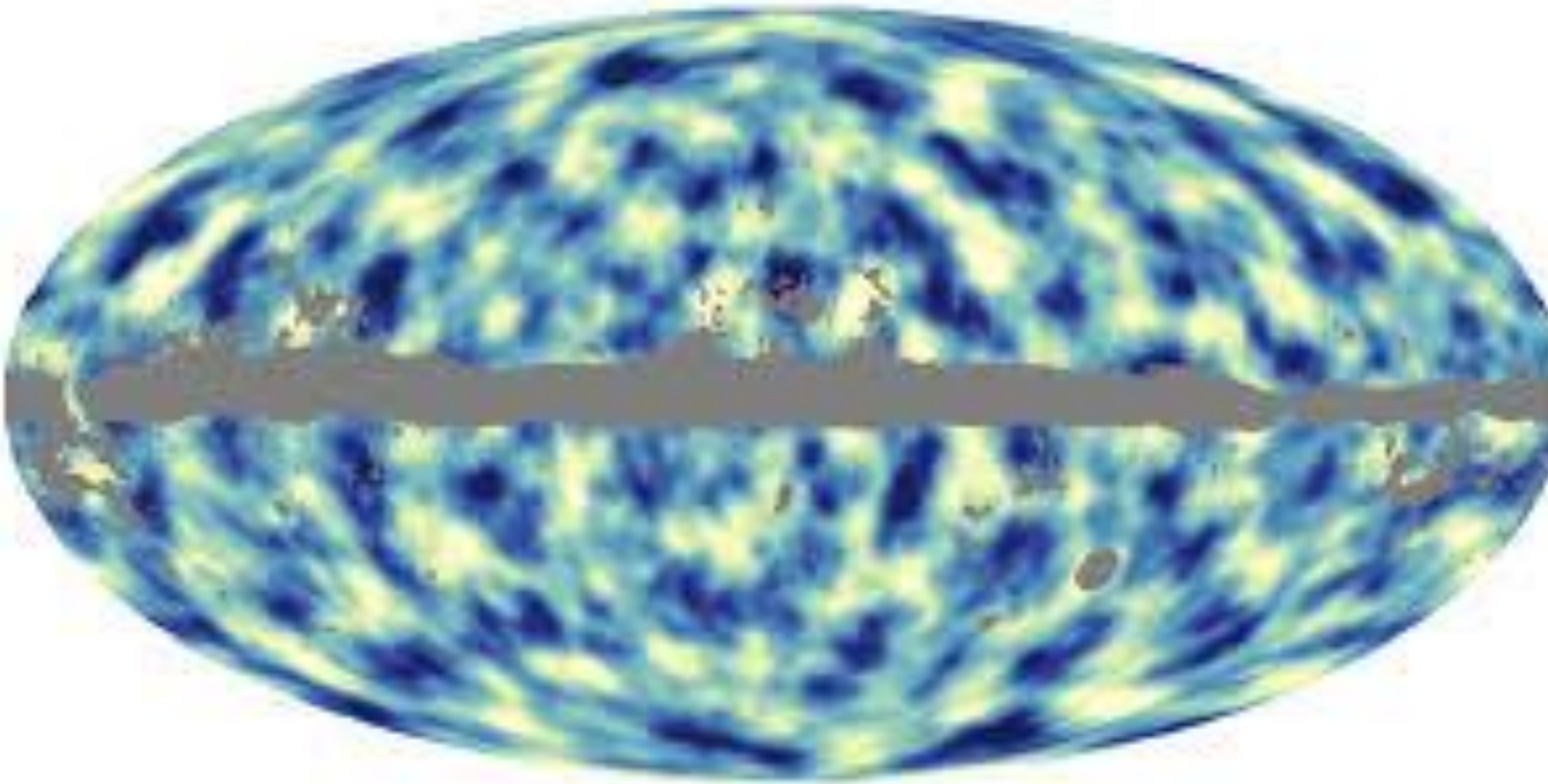
$$A^{\oplus}{}_{ll'}^{LM} = \frac{\phi_{LM}}{\sqrt{2L+1}} \left[\frac{C_l G^L_{l'l}}{\sqrt{l'(l'+1)}} + \frac{C_{l'} G^L_{ll'}}{\sqrt{l(l+1)}} \right] = Q^{\oplus L}_{ll'} \phi_{LM}$$

where deflection angle is $\vec{\alpha} = \vec{\nabla}\phi$

Lensing of CMB detected
through cross-correlation with galaxy surveys

(Smith, Zahn, Dore 2007; Hirata et al. 2008)

And now without galaxies (Das et al. (ACT) 2010;
also now SPT and Planck)

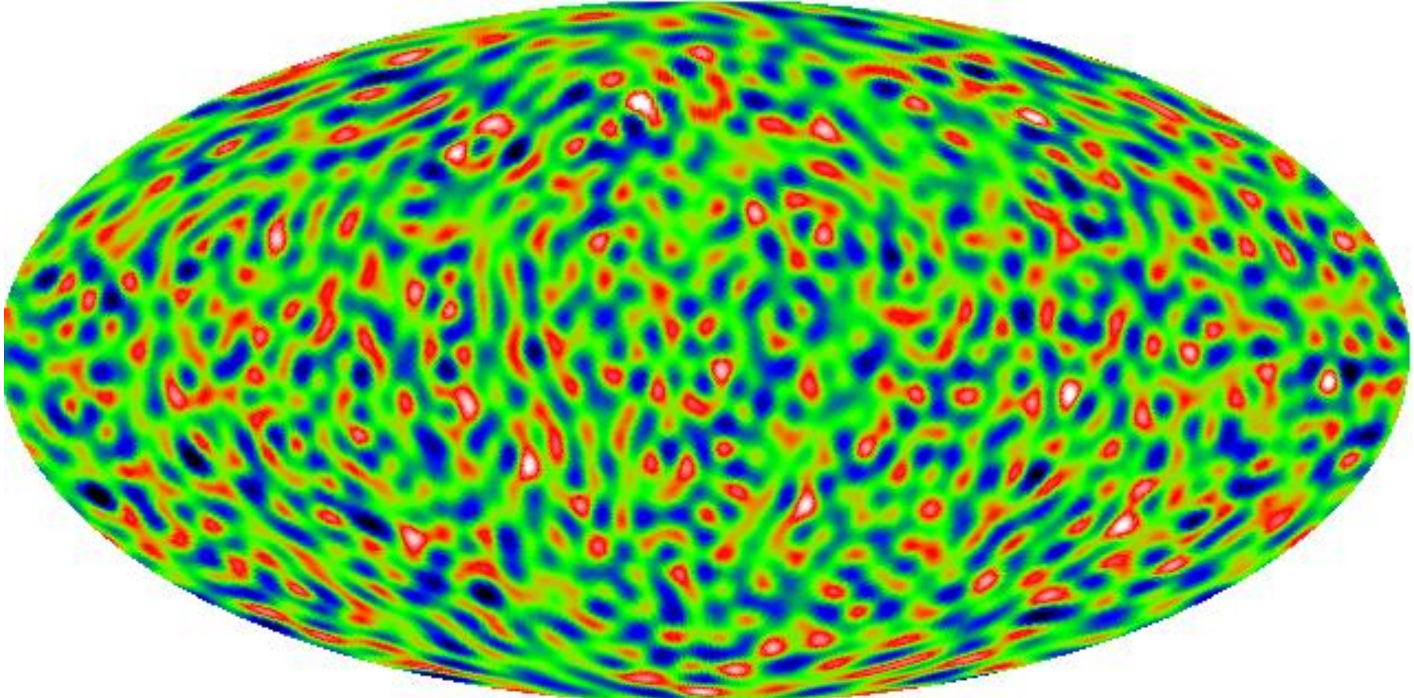


Example II (Exotica): Departures from Statistical Isotropy (Pullen,MK, 2007)

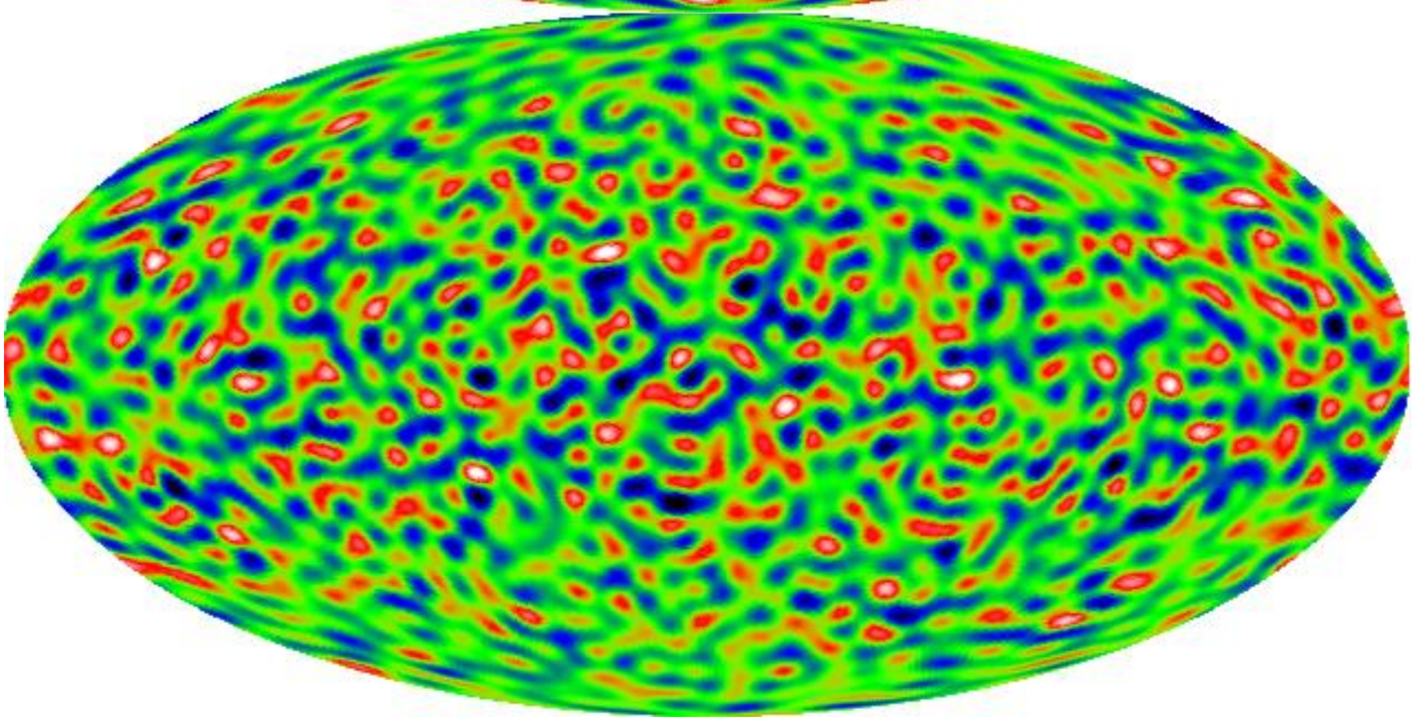
- Inflation: Universe statistically isotropic and homogeneous
- Statistical isotropy: Power spectrum does not depend on direction

To test….

- Require family of models that violate statistical isotropy and/or homogeneity, with departure from SI/SH parametrized by quantity that can be dialed to zero (e.g., inflationary models of Ackerman, Carroll, Wise predict power quadrupole)
- Develop estimators that measure SI/SH-violating parameters from observables

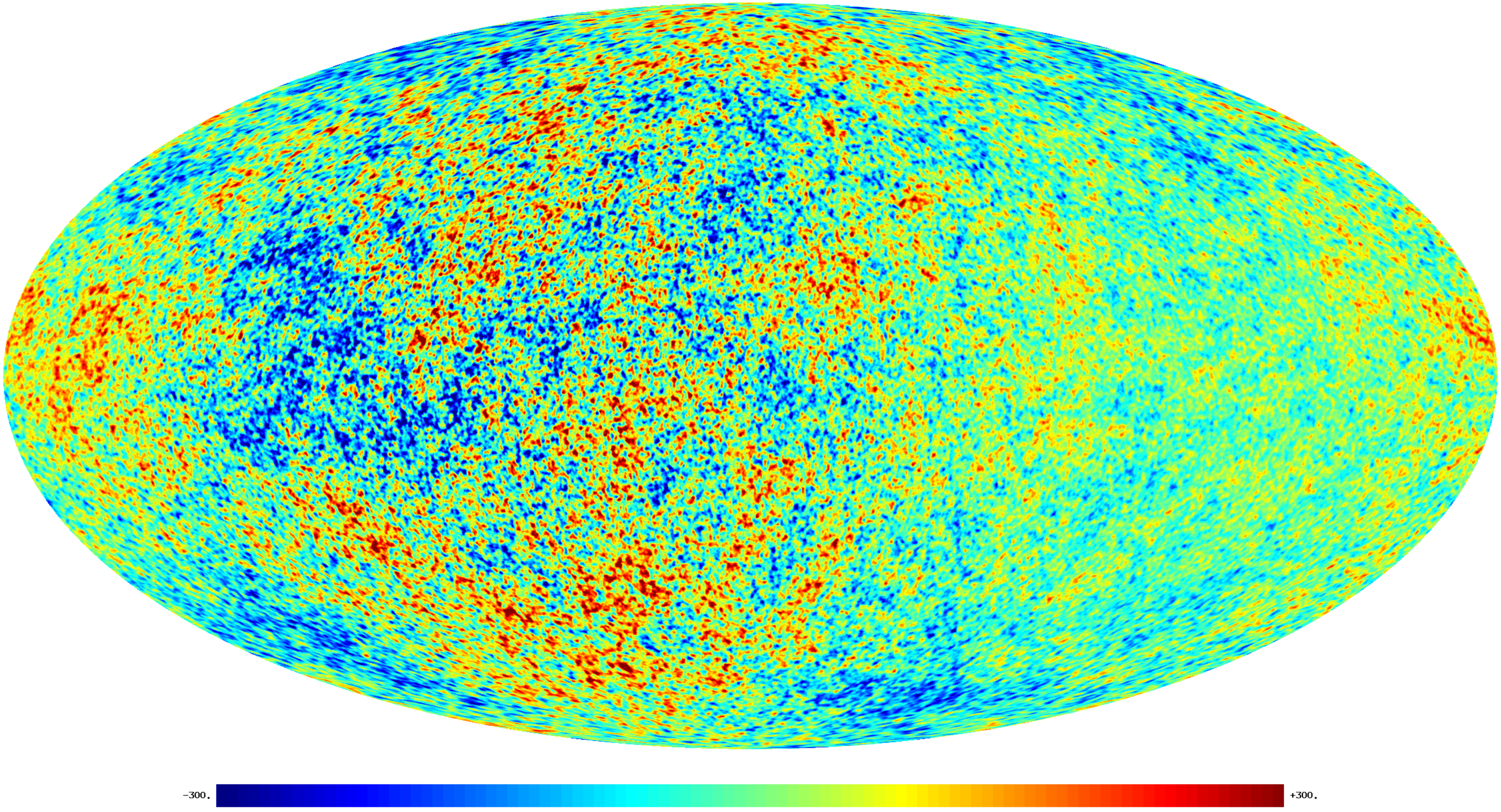


Statistically isotropic



A power quadrupole

A power dipole



Erickcek, MK, Carroll 2008; Erickcek, Carroll, MK 2008; Erickcek, Hirata, MK 2009; Dai, Jeong, MK, Chluba 2013

Hemispherical power asymmetry
(in WMAP, Eriksen et al. 2004, and Planck)

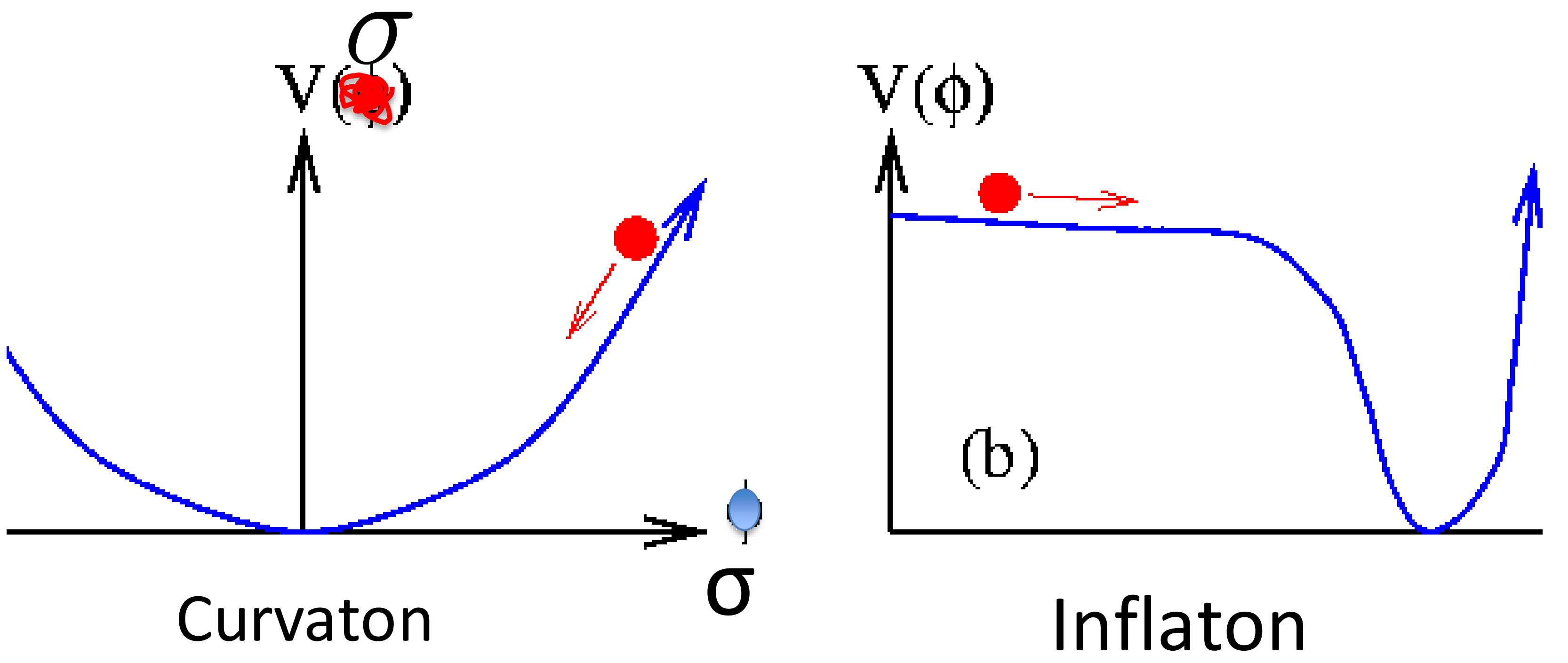
- Has been seen in WMAP and Planck at $l<60$

Problem:

- Inflaton controls density perturbations (which we want to vary across Universe) and the total density (which can*not* vary)
  (Erickcek, MK, Carroll, arXiv:0806.0377; Erickcek, Carroll, MK, arXiv:0808.1570, Zibin-Scott 2008)

Solution

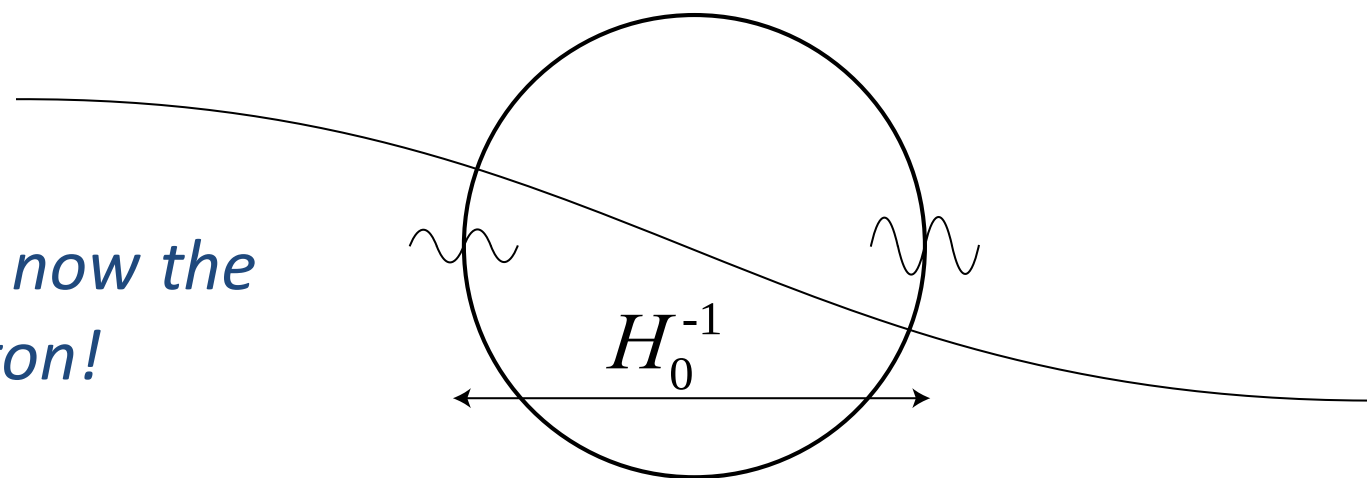
- Add second scalar field (curvaton); energy density generated by one and perturbations generated by other (or both by some combination)



Explaining the power asymmetry

- Postulate long-wavelength curvaton fluctuation $\Delta\sigma$
- Keep inflaton smooth

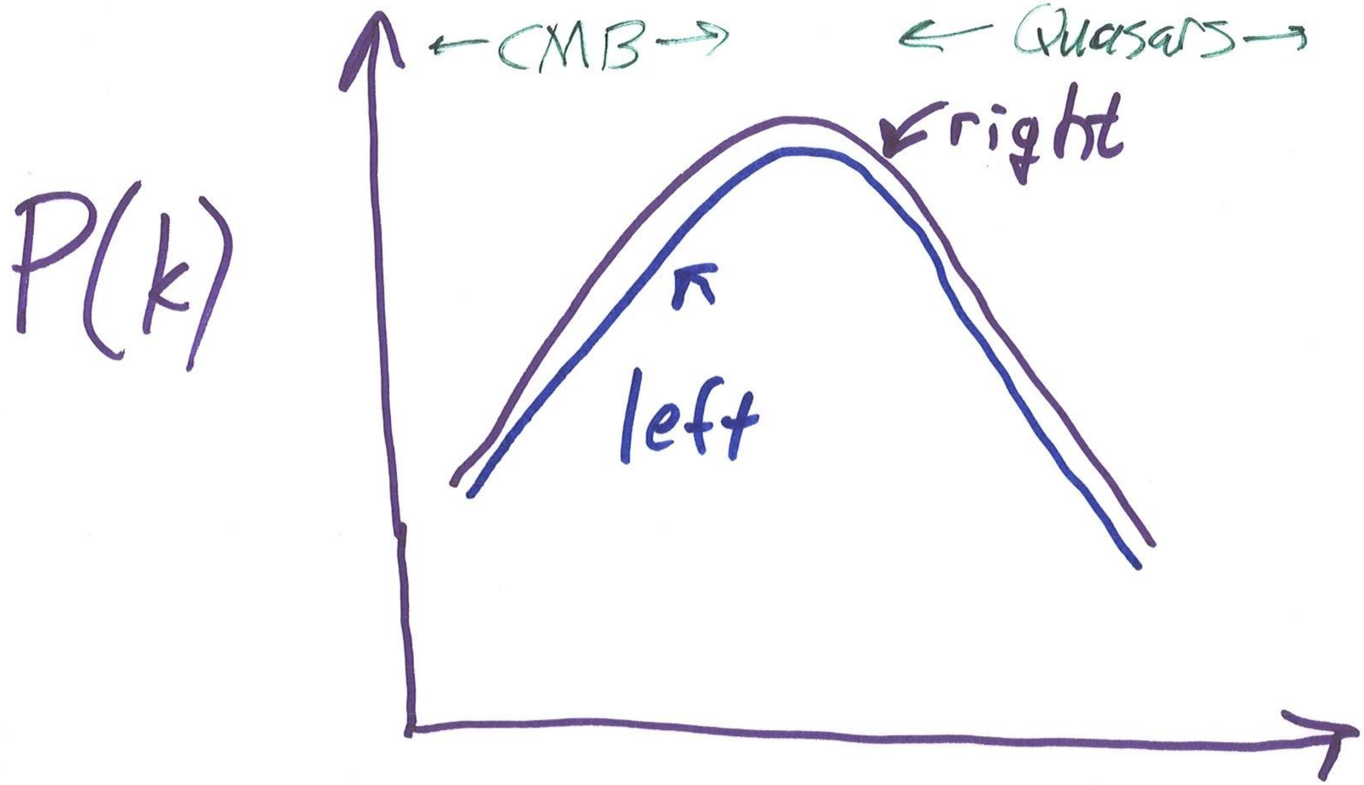
This is now the curvaton!



Problems with model

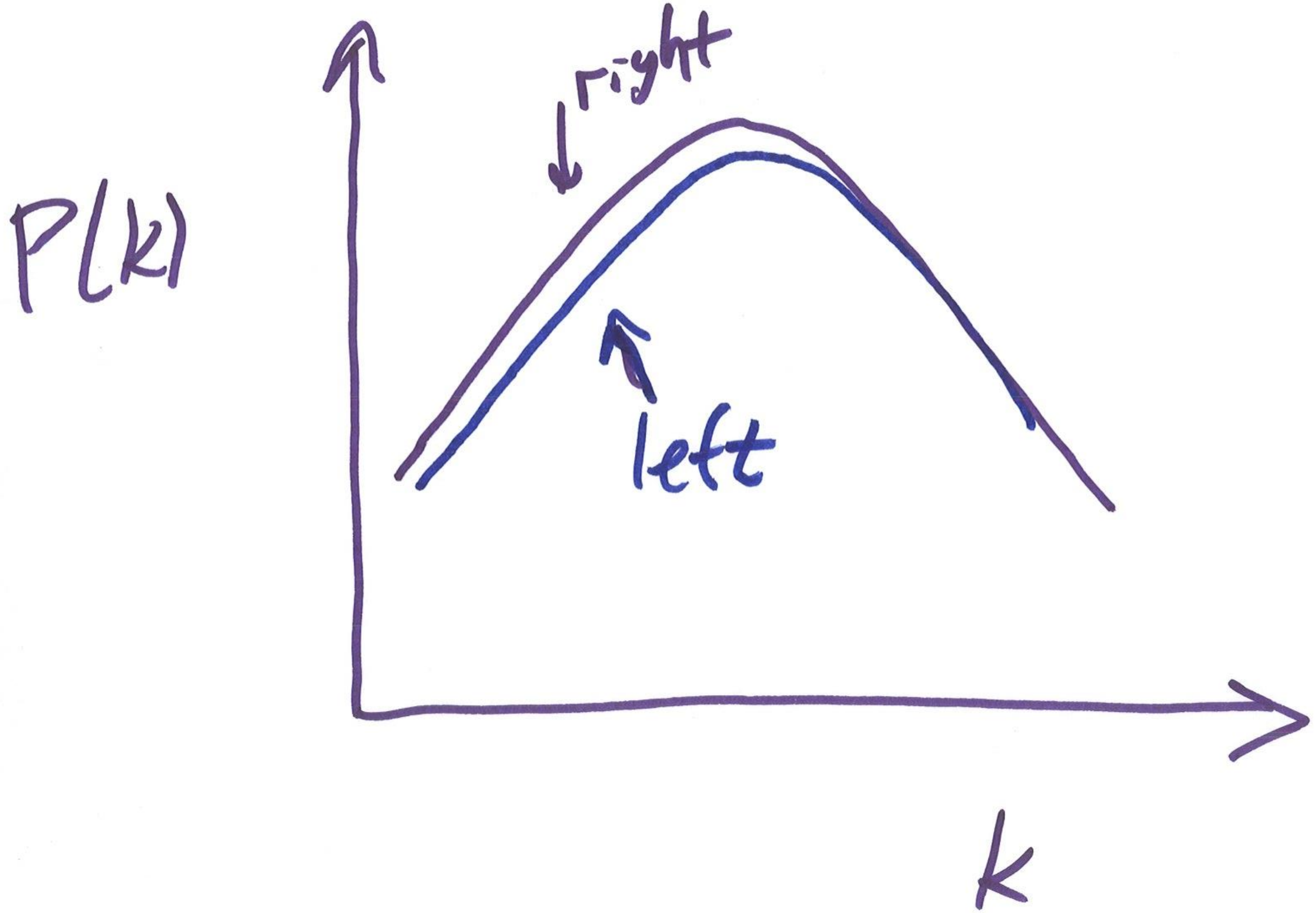
- Predicts $f_{nl}>50$
- SDSS quasar distribution/clustering restricts asymmetry to be small on smaller distance scales (Hirata 2009)

Power Spectrum



Erickcek, MK, Carroll
Prediction

The data

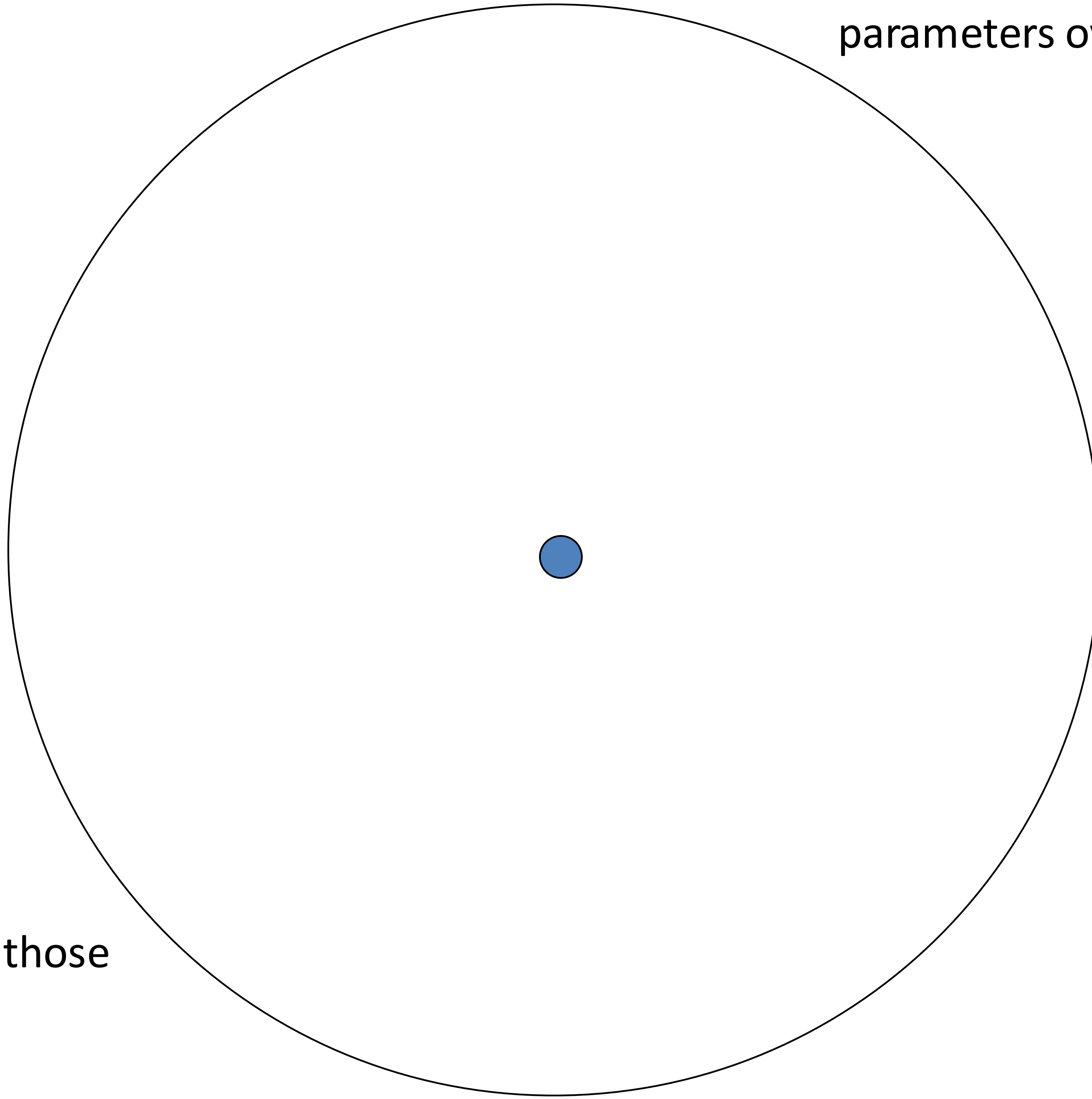


One solution

- “isocurvature” mode from curvaton decay (Erickcek, Hirata, MK 2009)

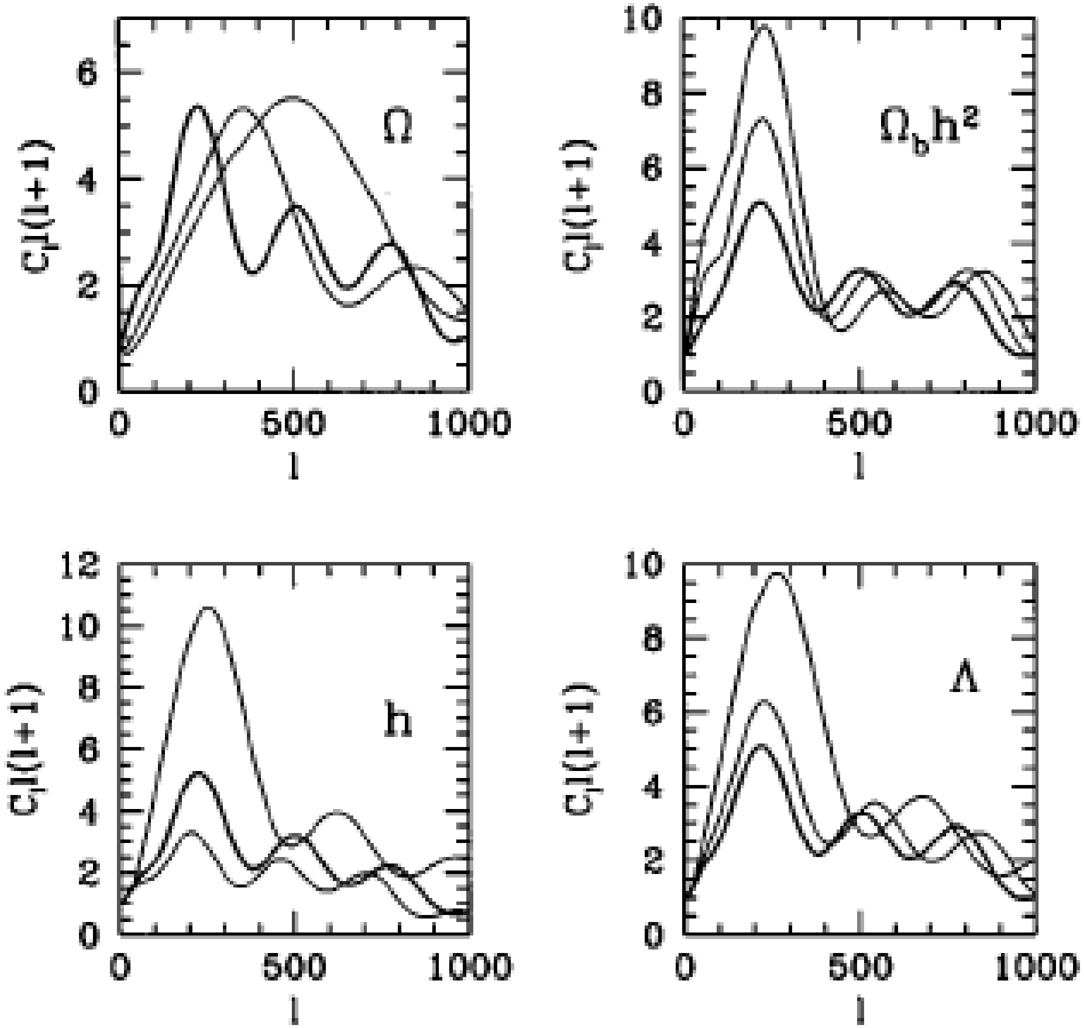
Other solutions: Spatial variation of cosmological parameters that affect CMB without affecting geometry

What if cosmological parameters over here……

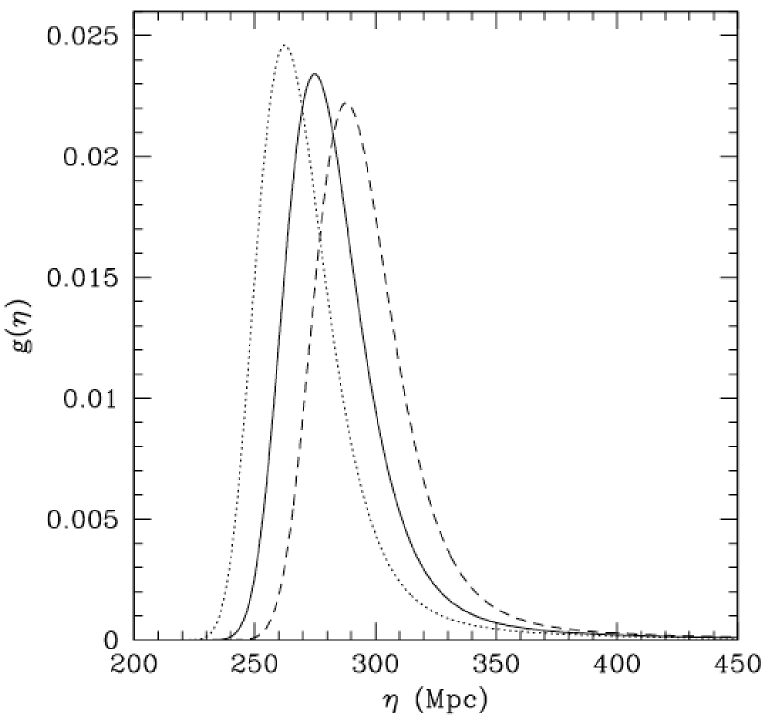


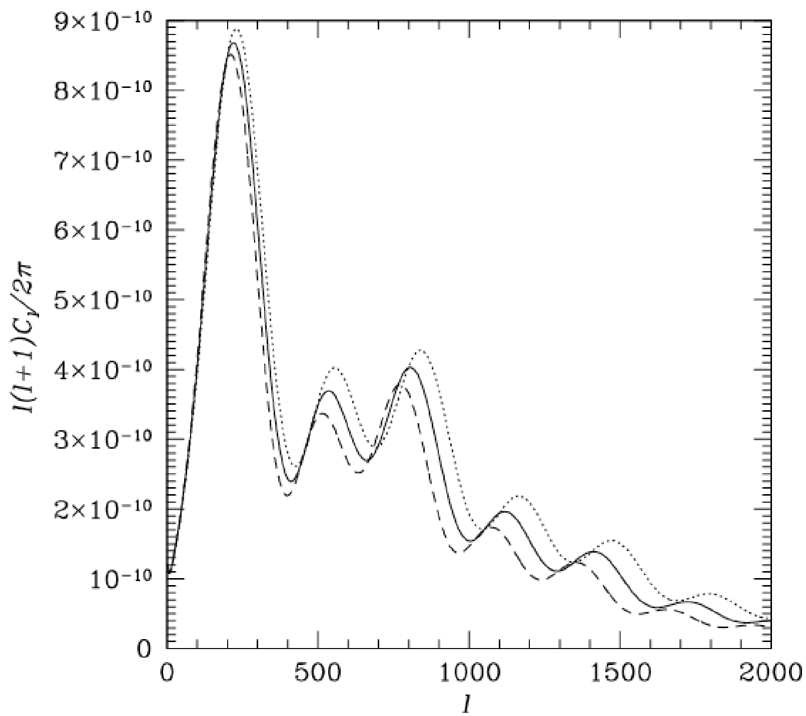
differ from those over here?

Then power spectra will differ from one point on sky to another:



E.g., suppose fine-structure constant varied





Visibility function

Power spectrum

Can be sought with BiPoSHs

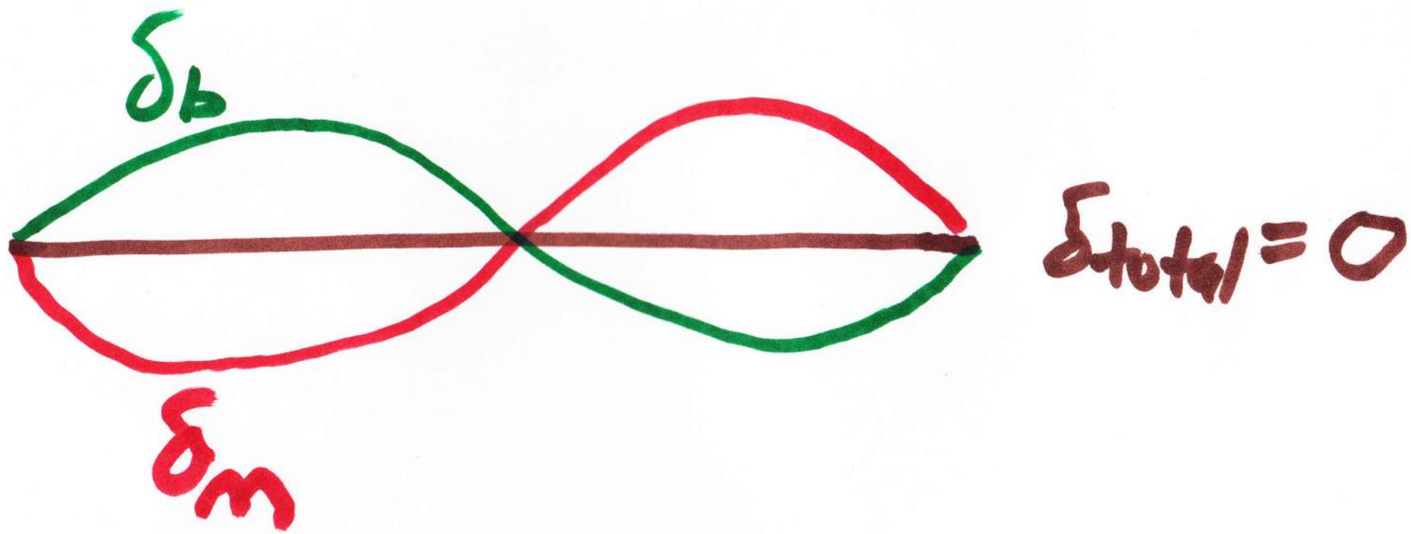
(Sigurdson, MK, Kurylov 2003)

Another example: Compensated isocurvature perturbations

Baryon-density fluctuation compensated by dark-matter fluctuation of equal magnitude (Pritchard and Gordon 2009; Holder, Nollett, van Engelen 2009)

Strongest current constraint, from baryon-DM ratios measured in galaxy clusters: $\lesssim 10\%$

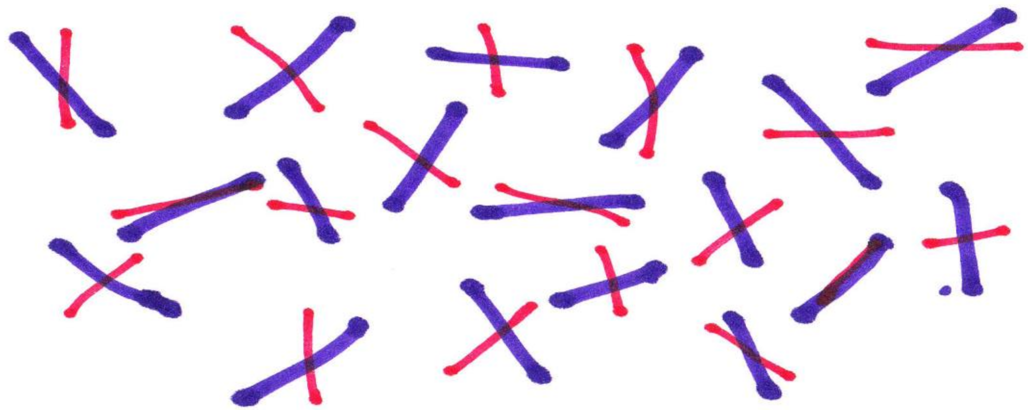
Compensated isocurvature perturbation



Polarization BiPoSHs: Spatially-varying cosmological birefringence (MK, 2008; Gluscevic, MK, Cooray 2009; Yadav et al. 2009; MK 2010; Gluscevic, MK, Caldwell 2011)

- What if CB rotation angle varies from one point on sky to another?? (e.g., Pospelov, Ritz, Skordis 2008; Caldwell et al., in preparation)
- Then observed polarization has nothing to do with primordial polarization!!!
- Develop technique to measure rotation as function of angle, and thus to infer primordial polarization pattern

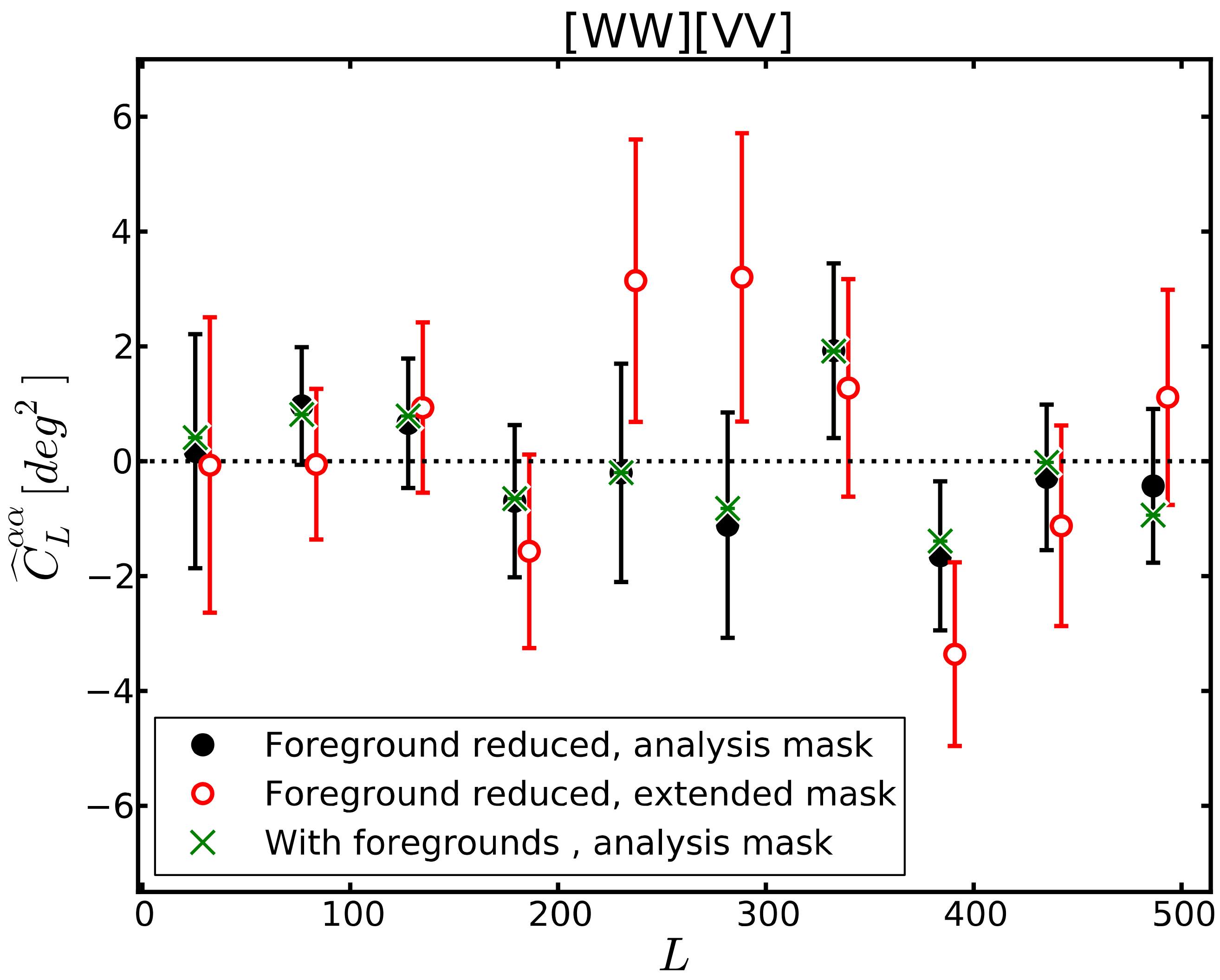
Rotation $\alpha(\hat{n})$ depends on position $\hat{n}$



Primordial Rotated

???

WMAP search (Gluscevic, Hanson, MK, Hirata, 2012)



Odd-Parity BiPoSHs (Book, MK, Souradeep 2011)

- Lensing, SI violations, patchy reionization, variable cosmological parms all induce only BiPoSHs with L+l+l'=even.
- But BiPoSHs can have L+l+l'=odd
- Odd/even split ~ E/B decomposition for CMB polarization
- Odd-parity BiPoSHs may be induced by lensing by GWs or by pointing errors, asymmetric beams, etc.

New probes of parity violation

- Cross-correlation between even- and odd-parity BiPoSHs are parity breaking. May be induced by chiral GW background

Odd-parity bispectrum (MK, Souradeep 2010)

- Three-pt functions from inflation have

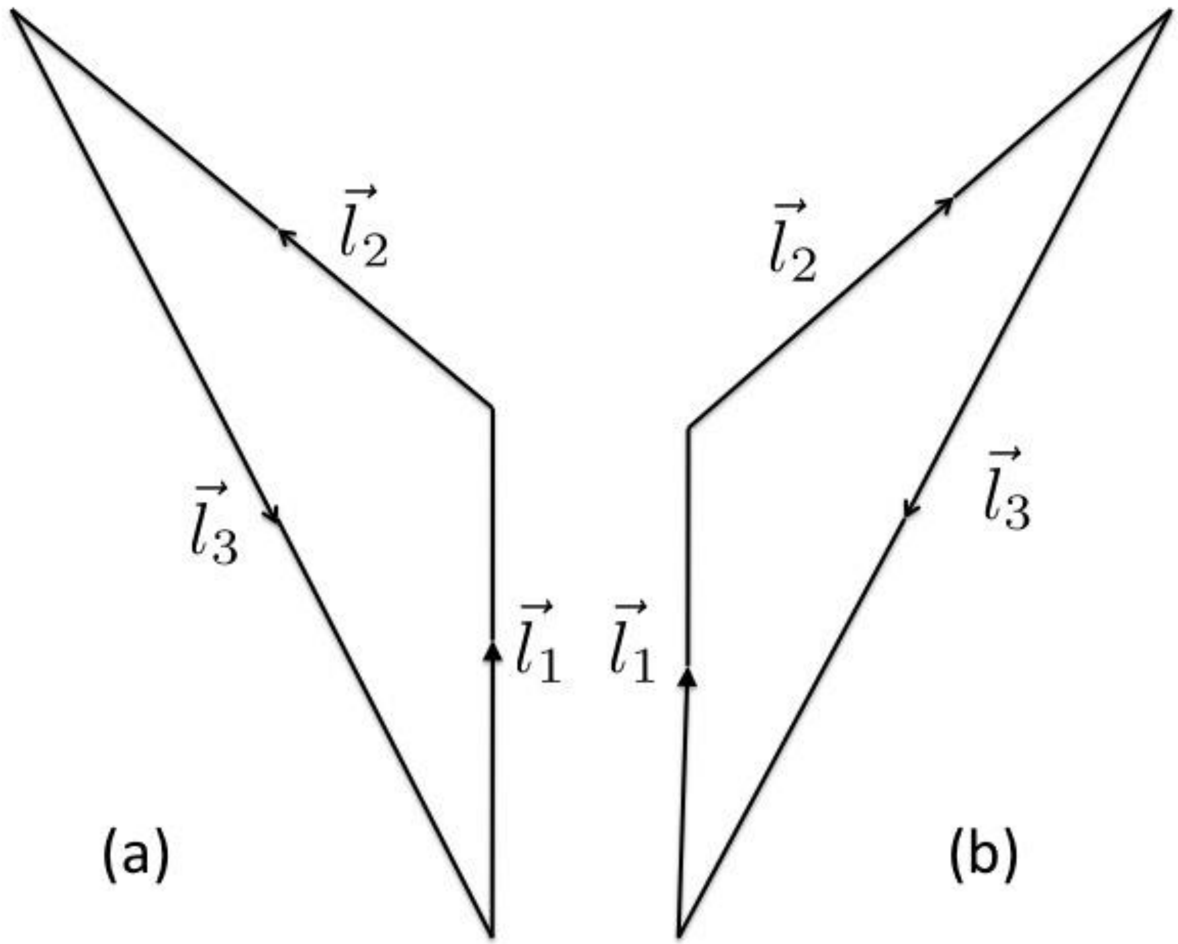
$$\langle a_{l_1 m_1} a_{l_2 m_2} a_{l_3 m_3} \rangle \neq 0 \quad \text{for} \quad l_1 + l_2 + l_3 = \text{even}$$

but odd-parity bispectrum, with

$$l_1 + l_2 + l_3 = \text{odd}$$

is also allowed mathematically and can be measured from data.

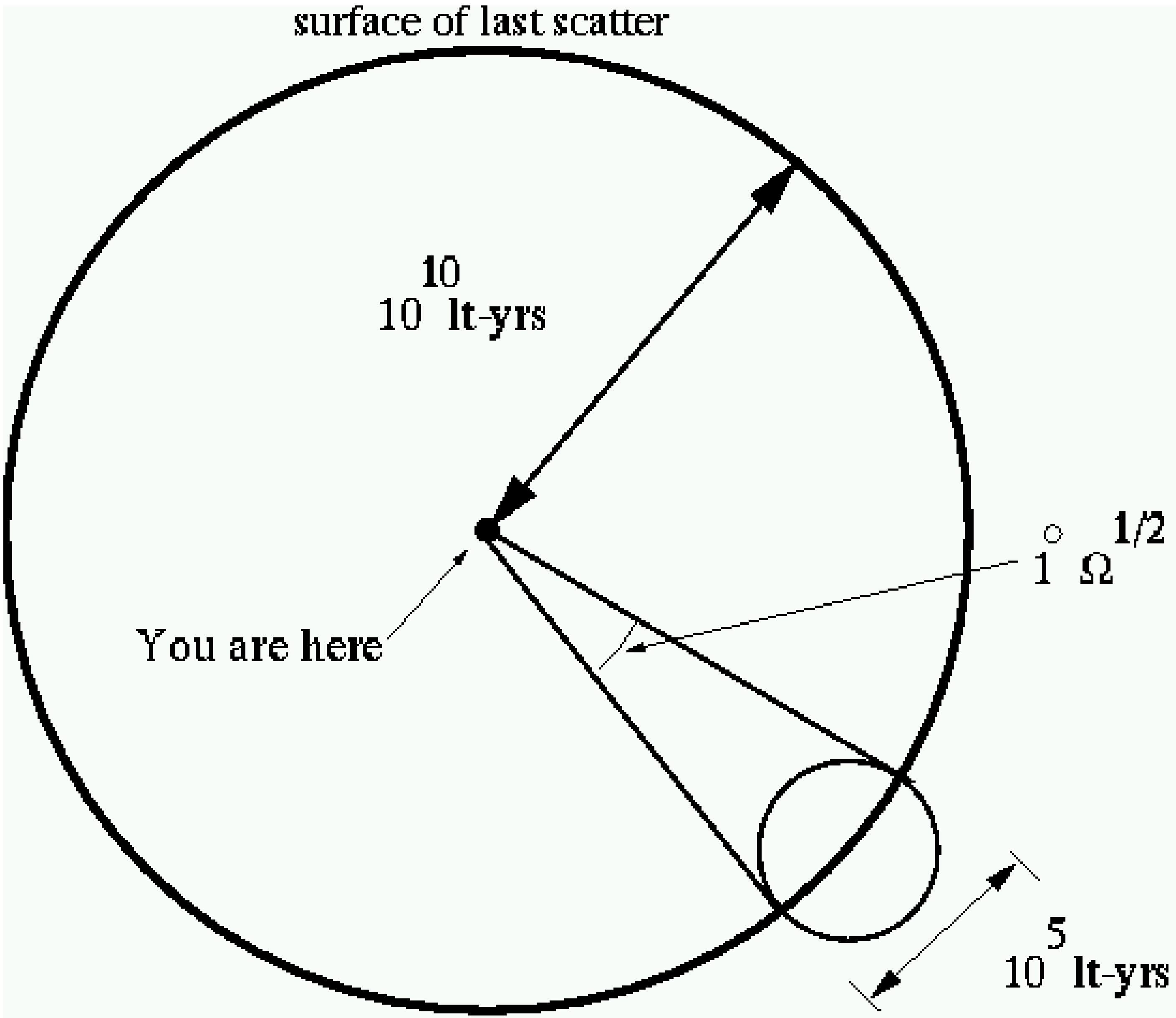
Allows probe of novel parity-breaking early-Universe physics and new set of null tests for systematics in experiments



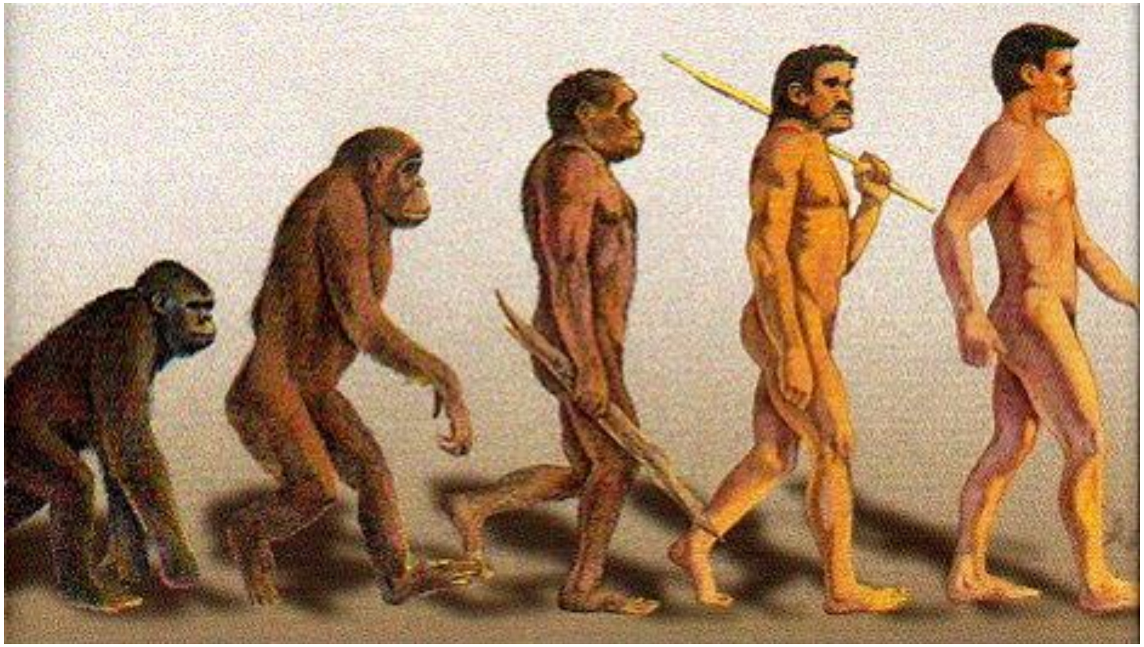
Odd-parity bispectrum differences, rather than sums, contributions from mirror-image triangles

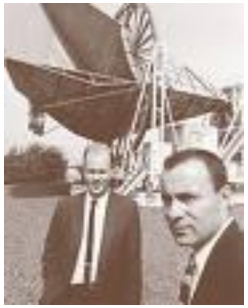
Conclusions

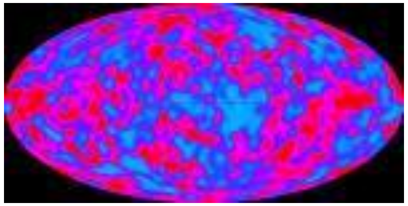
- Current CMB measurements provide precise determination of cosmological parameters and provide strong evidence in support of inflation
- Planck will make these measurements even more precise, and active suborbital search for inflationary gravitational waves under way
- But there is more that can be done with these and future experiments

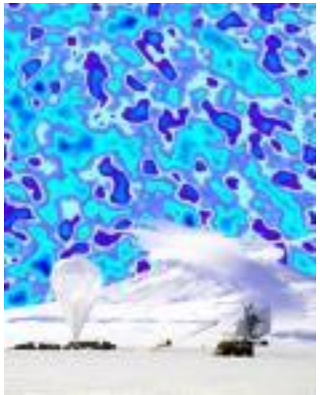


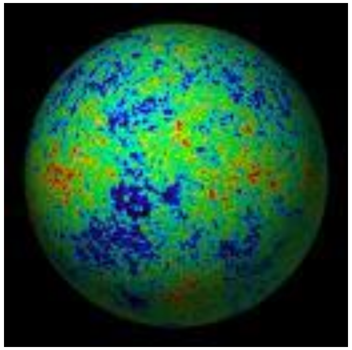
surface of last scatter
10^{10} lt-yrs
$1^{\circ}\ \Omega^{1/2}$
You are here
10^{5} lt-yrs

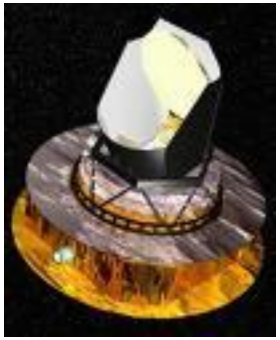












AT&T:
1965

COBE:
1991

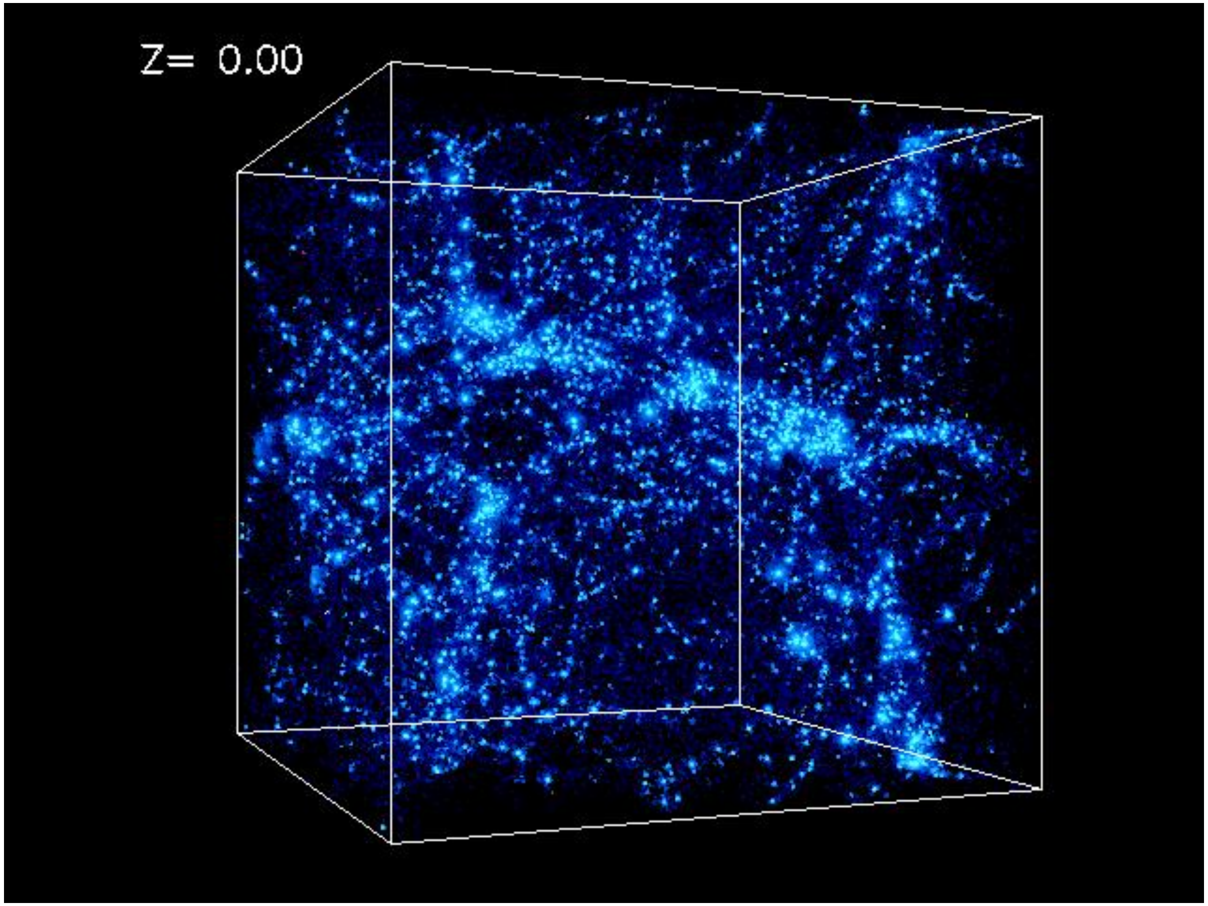
BOOMERanG:
2000

WMAP:
(2003-present)

Planck:
Even better!!
(launched
May 2009)

…and beyond!!

And galaxy surveys! (Ando,MK, PRL 2008; Pullen-Hirata 2010; Kuhlen,MK, in progress)



Do Fourier modes
in x, y, and z directions
have same amplitude?

- Pullen-Hirata (2010): strong constraints to power quadrupole from SDSS

  But how does power anisotropy today compare with primordial anisotropy?

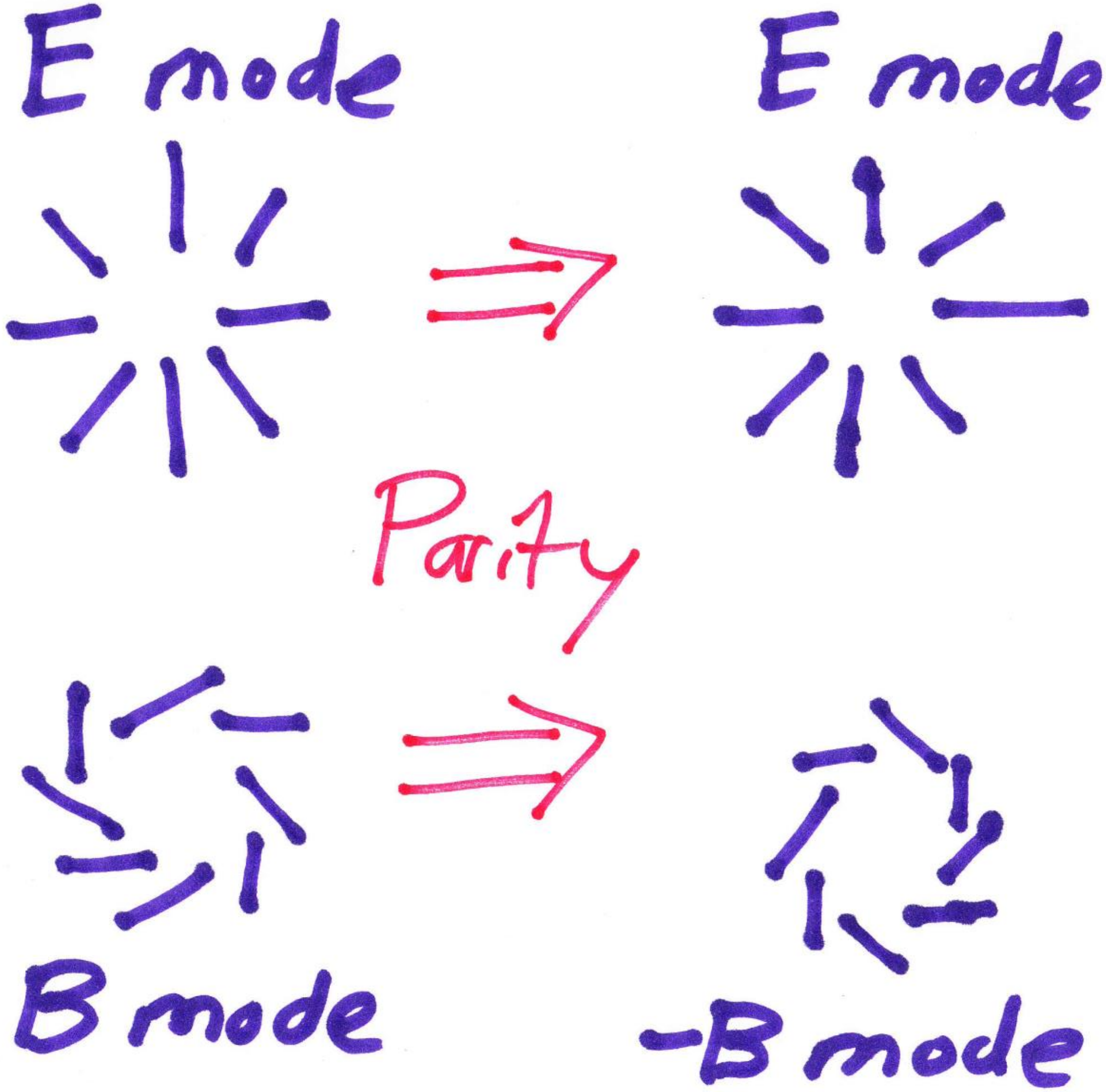
- Ando-MK: Analytic: primordial power quadrupole suppressed, but by <7%, in quasilinear regime

- Current: (with Kuhlen) studying evolution of anisotropic power with simulations

IV. **Cosmological Birefringence**

(Lue, Wang, MK 1999; MK 2008; Gluscevic, MK, Cooray, 2009; MK 2010)

- Is new cosmological physics (e.g., inflation, dark energy) parity violating?
- Polarization E and B modes have opposite parity; EB correlation therefore signature of parity violation


E mode
E mode
Parity
B mode
-B mode

Non-Gaussianity: BiPoSHs from inflation (in progress)

Recap: Every Fourier mode of inflaton field satisfies SHO-like equation of motion:

$$\ddot{\phi}_{\vec{k}} + k^2 \phi_{\vec{k}} = 0$$

These inflaton fluctuations get imprinted as primordial density perturbations

➔ Amplitude of each Fourier mode selected from Gaussian random distribution (the ground-state SHO wave function)

- But that's only to zero-th order
- Many detailed inflation models predict that any two of these SHOs (i.e., Fourier modes) should be (very very weakly) coupled
- May therefore be some (small) three-point correlation:

$$\langle a_{l_1 m_1} a_{l_2 m_2} a_{l_3 m_3} \rangle \propto \mathcal{C}^{l_1 m_1}_{l_2 m_2 l_3 m_3} B_{l_1 l_2 l_3}$$

"Bispectrum"

- 3-pt correlation equivalently cross-correlation between a_{lm} and BiPoSH (quadratic in a_{lm})

Current work (with T. Souradeep)

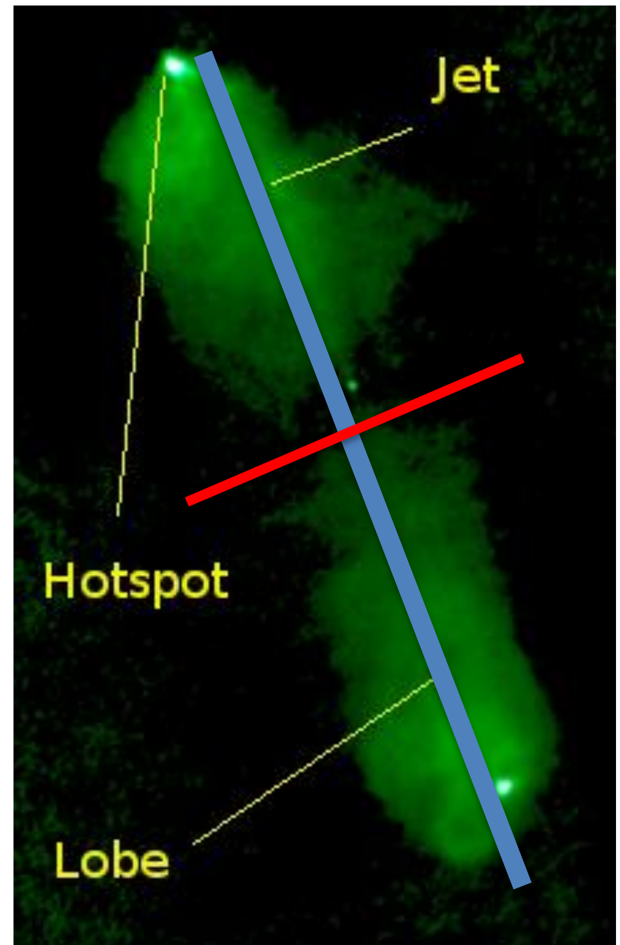
- Are developing and applying parity tests with CMB temperature (alone) and also with weak lensing maps

Cosmological Birefringence with Radio Sources (MK 2010)

If no CB, then on average, polarizations and position angles of a large number of sources should be 90 deg

If there is CB, there should be a mean offset

Data from 100s of sources:
rotation < few degrees



Spatially-varying rotation

- If rotation varies with position on sky:

$$\alpha(\hat{n}) = \sum_{lm} \alpha_{lm} Y^*_{lm}(\hat{n})$$

- Can measure (MK 2010)

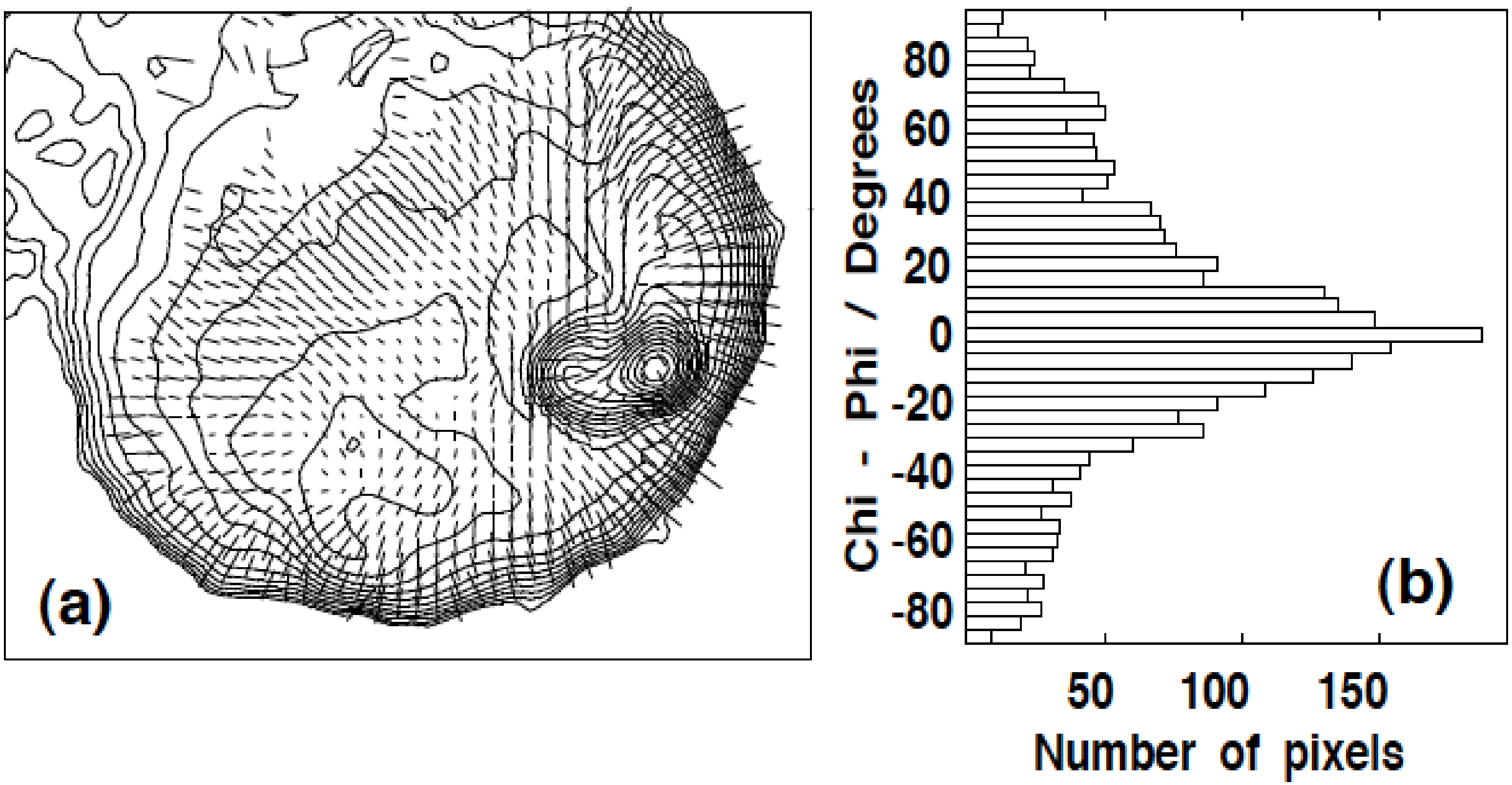
$$\alpha_{lm} \propto \sum_i \alpha_i Y_{lm}(\hat{n}_i)$$

- But even simpler analysis is constraining; variance in α from ~10 sources at z>2 is <few degrees

➔ $$\frac{\alpha_{lm}}{\sqrt{\pi}} \lesssim 4^\circ$$

The best current constraint!

But can do better with high-resolution intensity-polarization maps (Leahy 1997; Wardle, Pearly, Cohen 1997)



And even better (MK 2010; MK, Gluscevic, Sanders, in progress; Battye et al, in progress)

- Use E/B decomposition for polarization
- $\alpha = (EB/EE)/2 = (IB/IE)/2$

Uses full information from polarization-intensity and polarization-polarization correlations to search for rotation

A neutrino analog: cosmological neutrino birefringence! (Ando, MK, Mocioiu 2009)

- What if we have

$$\frac{\partial_\mu \phi}{M_*} \bar{\nu}_\alpha \gamma^\mu (1 - \gamma_5) \nu \quad ???$$

  Leads to MSW-like effects in vacuum; novel, and possibly detectable, effects in atmospheric neutrinos and ultra-high-energy neutrinos
- E.g., M_* up to 10^6 GeV may be accessible with UHE neutrinos if DE-induced mixing is in $\nu_\mu - \nu_\tau$
- Current work: similar effects in kaon mixing

Conclusions

- Will soon have new tests of inflation (B modes; non-Gaussianity, etc.) with forthcoming CMB experiments
- But there may be more we can do with CMB, extragalactic sources, neutrinos, etc. to learn about inflation and dark enery
- Implications of anomalies should be explored---window to new physics?

Evidence for SI violation still tentative, and may be "ugly"

Still……

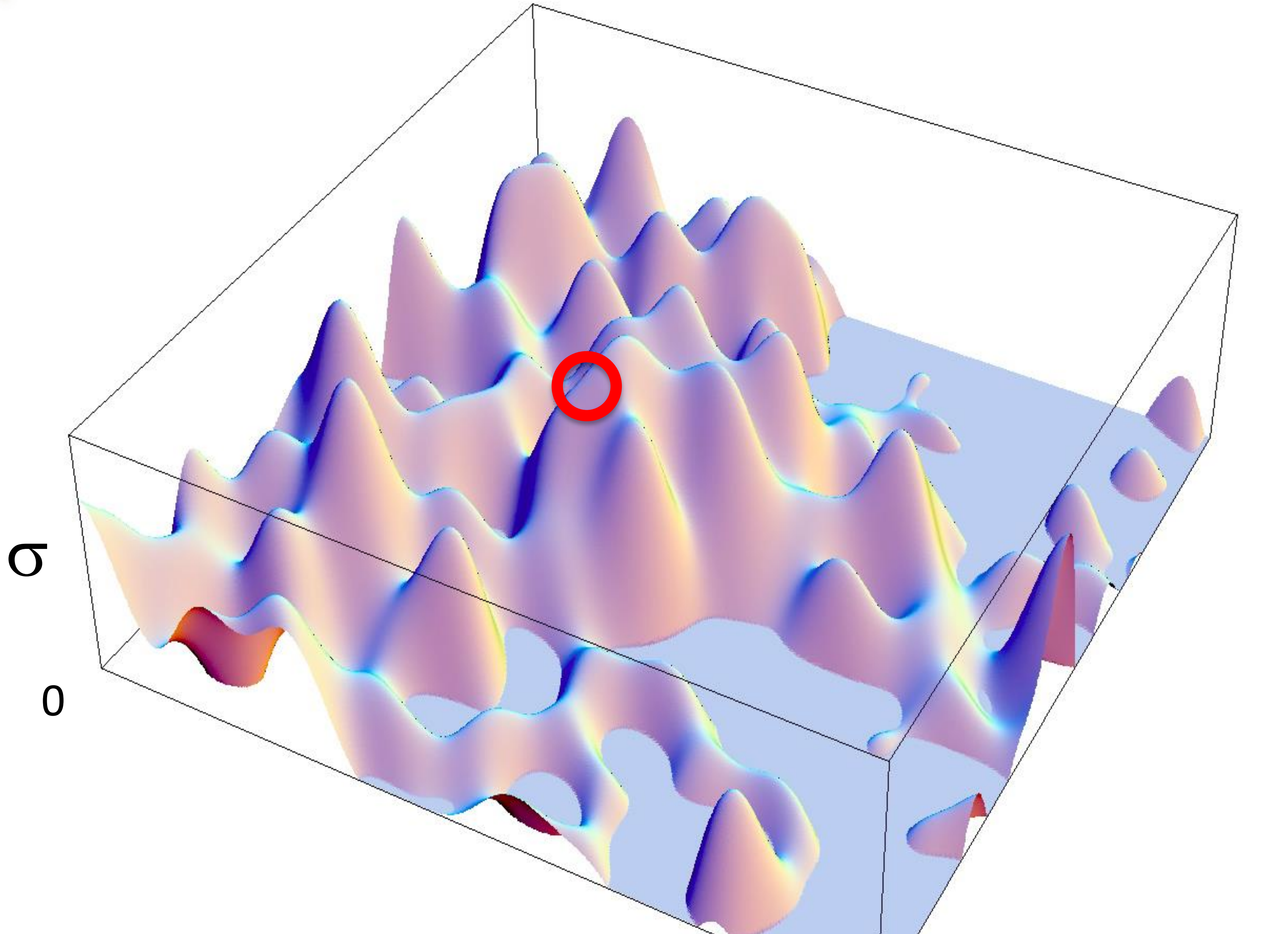
"Frequently nature does not knock with a very loud sound but rather a very soft whisper, and you have to be aware of subtle behavior which may in fact be a sign that there is interesting physics to be had."

---Douglass Osheroff

What more?

- Required curvaton “supermode” probably too big to be QM produced---may have to due with curvaton web (Mukhanov-Linde)? Or pre-inflationary remnant?

Spatial Distribution of the Curvaton Field



So far….

- There is hemispherical power asymmetry in WMAP
- Cannot be accounted for by single-field slow-roll inflation
- Can be explained by curvaton with large-amplitude long-wavelength fluctation
- Model constrained by homogeneity predicts $f_{\mathrm{nl}}>50$

Smallest detectable quadrupole anisotropy

$$\sigma_{g_{2M}} \simeq 7.6/l_{\max}$$

Experiment	σ_T (μK)	σ_P (μK)	$\theta_{\rm fwhm}$	$\sigma^{\rm pmm}_{g_{2M}}$ (TT)	$\sigma^{\rm pmm}_{g_{2M}}$ (EE)	$\sigma^{\rm pmm}_{g_{2M}}$ (total)	$\sigma^{\rm mv}_{g_{2M}}$ (TT)	$\sigma^{\rm mv}_{g_{2M}}$ (EE)	$\sigma^{\rm mv}_{g_{2M}}$ (total)
WMAP	30.0	42.6	$21'$	1.3	11	1.2	0.024	2.4	0.024
Planck	13.1	26.8	$5'$	1.6	0.16	0.16	0.0052	0.033	0.0050
EPIC	0.021	0.068	$52'$	1.2	0.55	0.42	0.016	0.019	0.011
Cosmic variance	0	0	0	1.8	0.014	0.014			

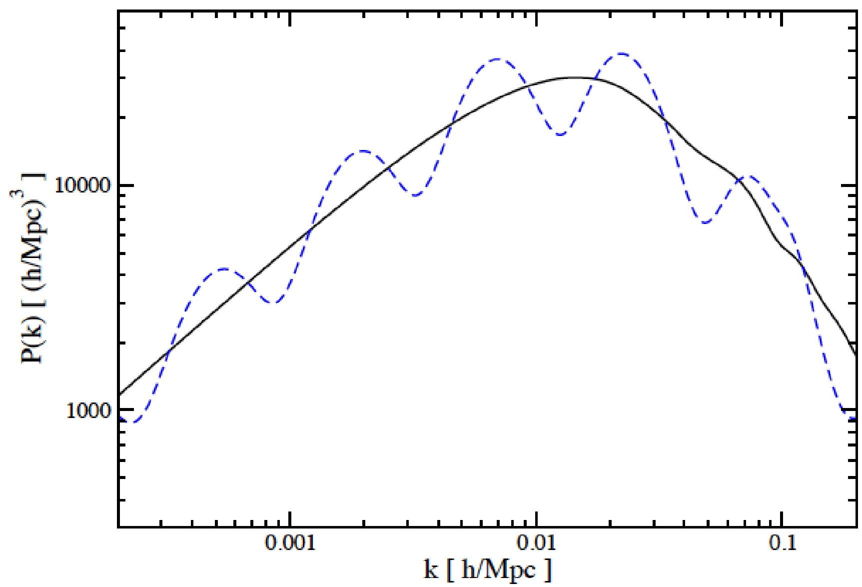
BLE I: The standard error $\sigma_{g_{2M}}$ to the amplitude of a quadrupole anisotropy in the matter power spectrum for different eriments. The instrumental temperature and polarization noises and beam width are listed for each experiment. We show ults for the power multipole moments (pmm)for TT only, EE only, and the full result. We also show in the last three columns $_M$ from the minimum-variance estimator for each experiment, for TT only, EE only, and the full result.

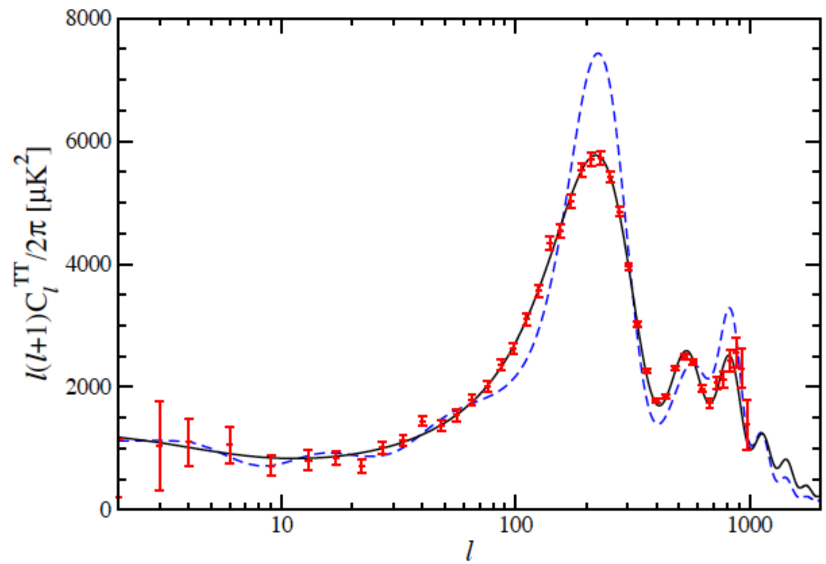
- Have recipe to measure g_{LM}'s from CMB data
- Are minimum-variance estimators: most sensitive possible

Other weird inflation: bumps in the inflaton potential (Pahud, MK, Liddle 2008)

- Suppose inflaton potential:

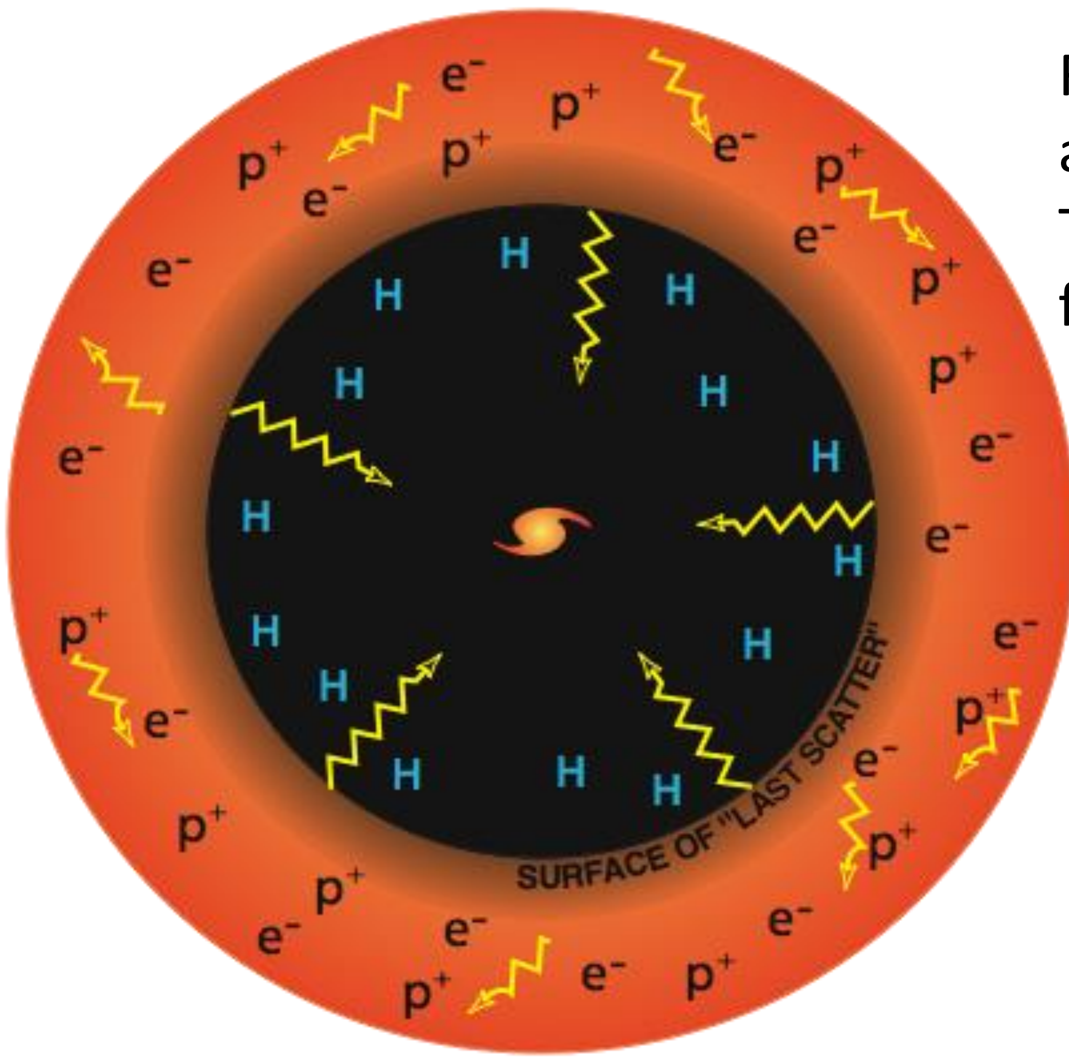
$$V(\phi) = \frac{1}{2}m^2\phi^2 \left[1 + \alpha \sin\left(\frac{\phi}{\beta M_{\rm Pl}} + \delta\right)\right]$$





WMAP: $\alpha \lesssim 3 \times 10^{-5}$

The origin of the CMB

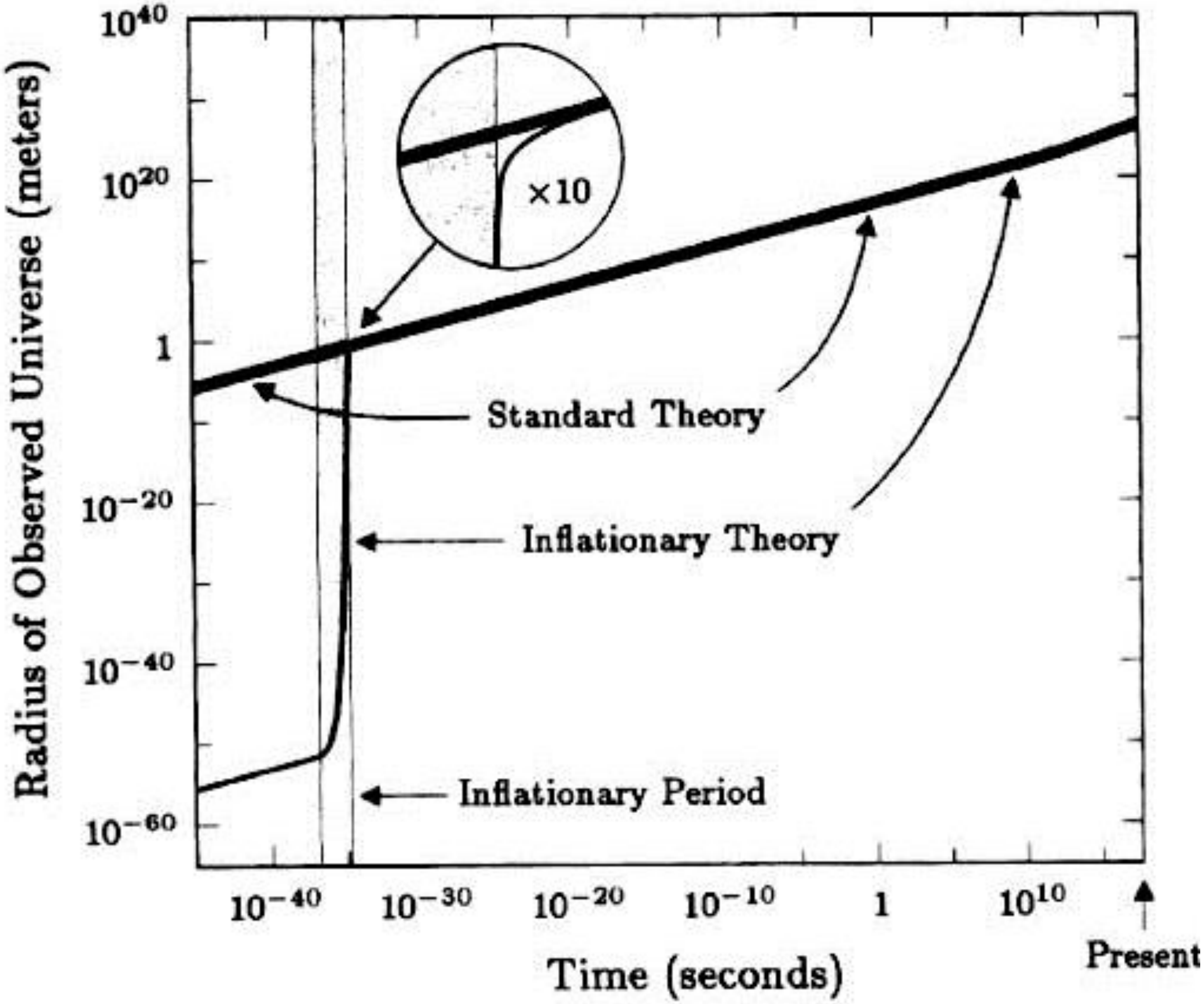


Formed 380,000 yrs after Big Bang, when T~eV and hydrogen forms

An inflationary model

(Ackerman, Carroll, Wise, 2007)

- Spontaneous breaking of Lorentz symmetry during inflation produces nonzero vector field; imprints quadrupole dependence of power on direction



Radius of Observed Universe (meters)
10^{40}
10^{20}
1
10^{-20}
10^{-40}
10^{-60}
×10
Standard Theory
Inflationary Theory
Inflationary Period
10^{-40}
10^{-30}
10^{-20}
10^{-10}
1
10^{10}
Present
Time (seconds)

Statistical isotropy

- Consider models with power spectrum:

$$P(\vec{k}) = A(k)\left[1 + \sum_{LM} g_{LM}(k) Y_{LM}(\hat{\mathbf{k}})\right]$$

- with *L*=2,4,6,…

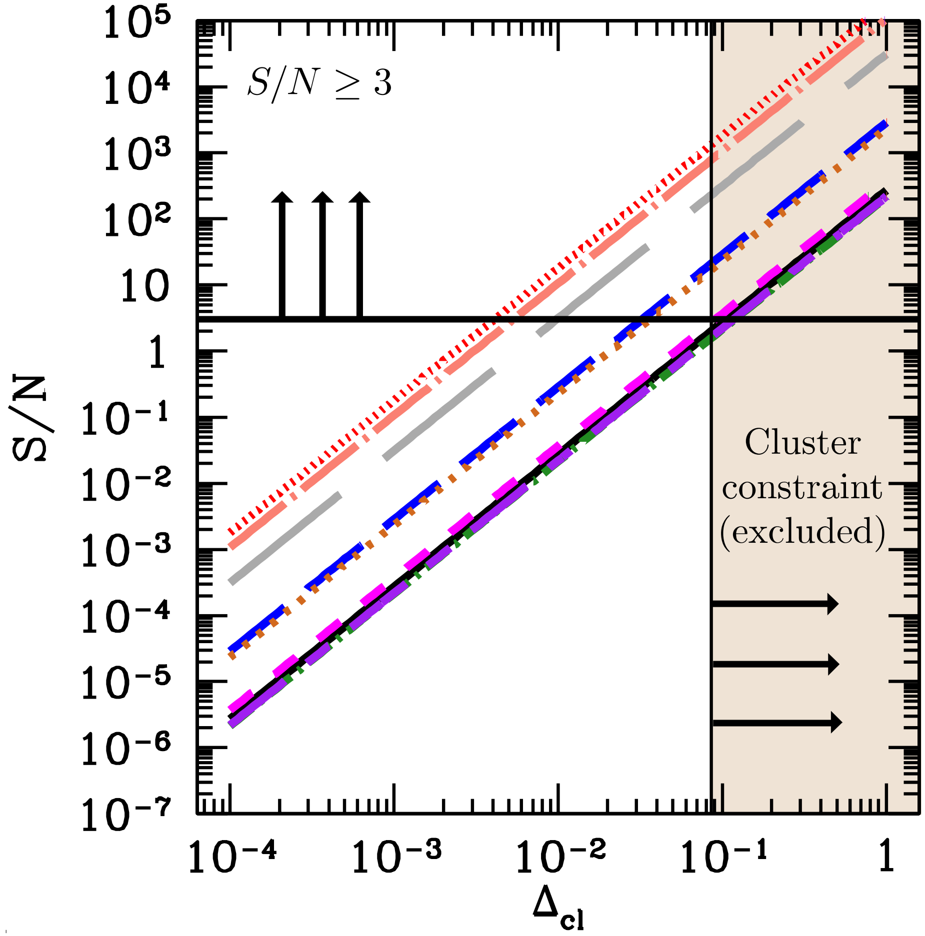
(Note: cannot get dipole from SI violation!!)

- Power asymmetry induces BiPoSHs with appropriate L (e.g., L=2 for quadrupole)
- BiPoSH estimators for, e.g., L=2 (for power quadrupole) can be measured
- Current applications to data find some evidence for quadrupole departures from SI, although likely a systematic artifact

Again, spatial variation in baryon/DM densities

➔ spatial variation in CMB fluctuations

➔ characterized by BiPoSHs



Grin, Dore, MK 2011

Magic? Get more out than you put in?

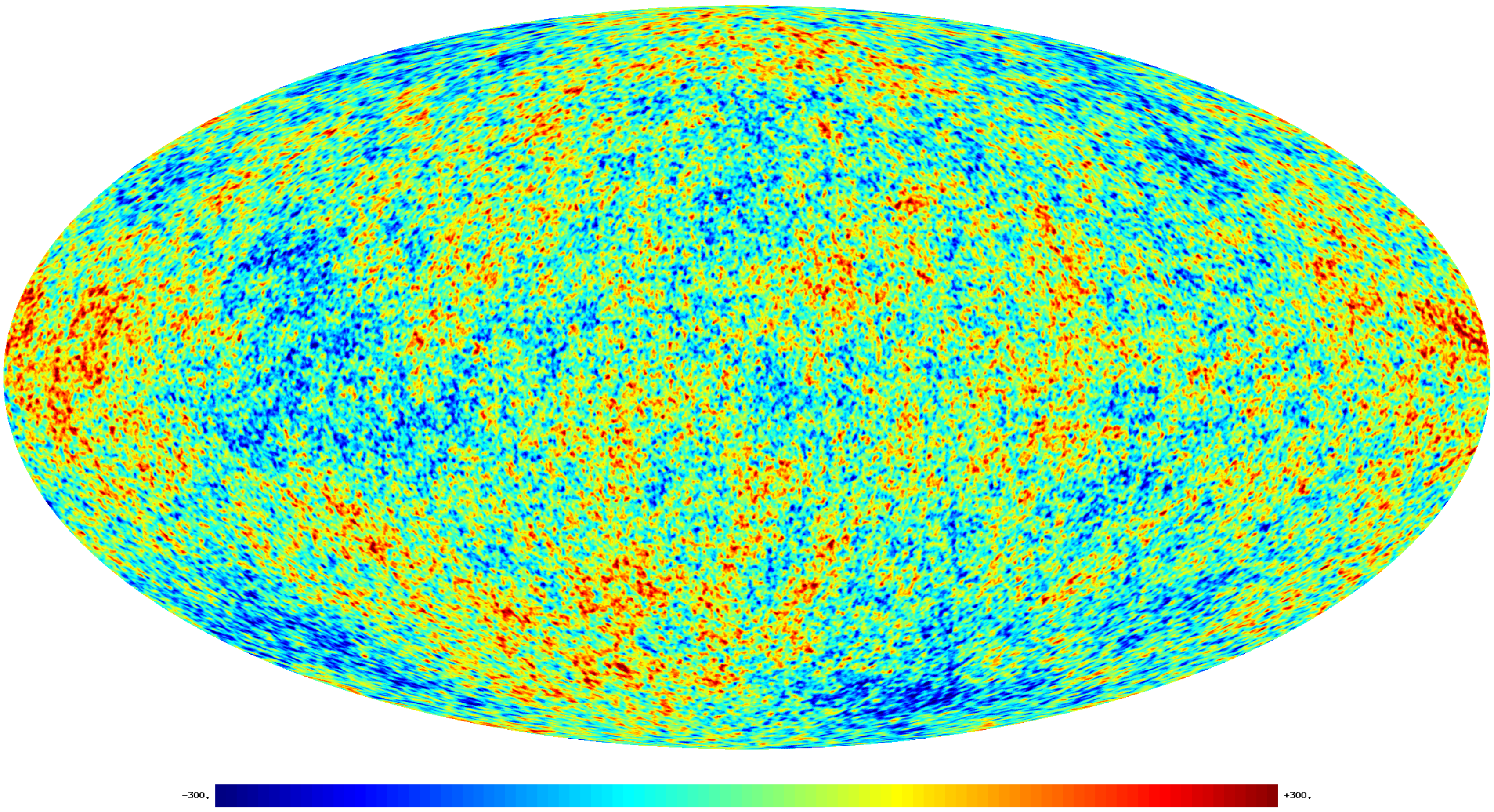
- Measure Stokes parameters Q_{obs} and U_{obs} at each point on sky
- Analysis gives rotation angle α and Q_{prim} and U_{prim} at each point on sky

What about a CMB Power Dipole?

(Erickcek, MK, Carroll, 2008; Erickek, Carroll, MK, 2008; Erickcek, Hirata, MK, 2009)

Eriksen et al. found >3σ evidence for power asymmetry in WMAP1 and WMAP3

Isotropic power

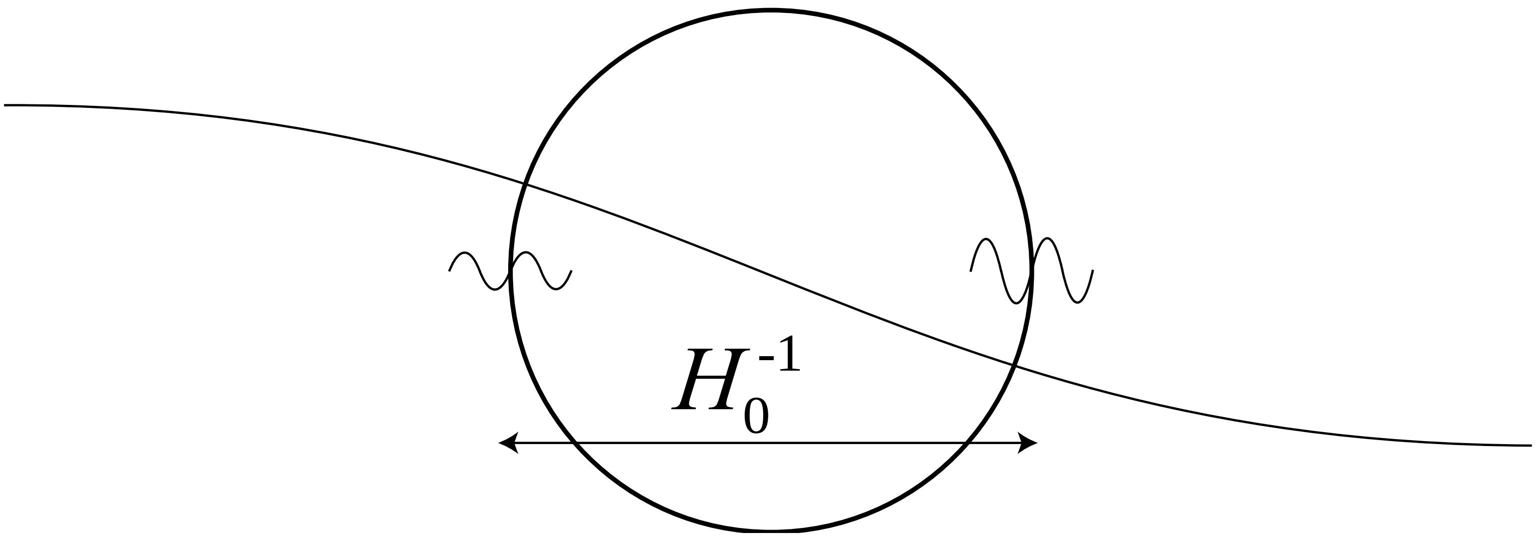


- Recall: Violation of statistical isotropy can*not* produce power dipole.

- Must therefore be violation of statistical *homogeneity*

- …..need spatial modulation of power….

Can it be due to a large-scale inflaton mode?



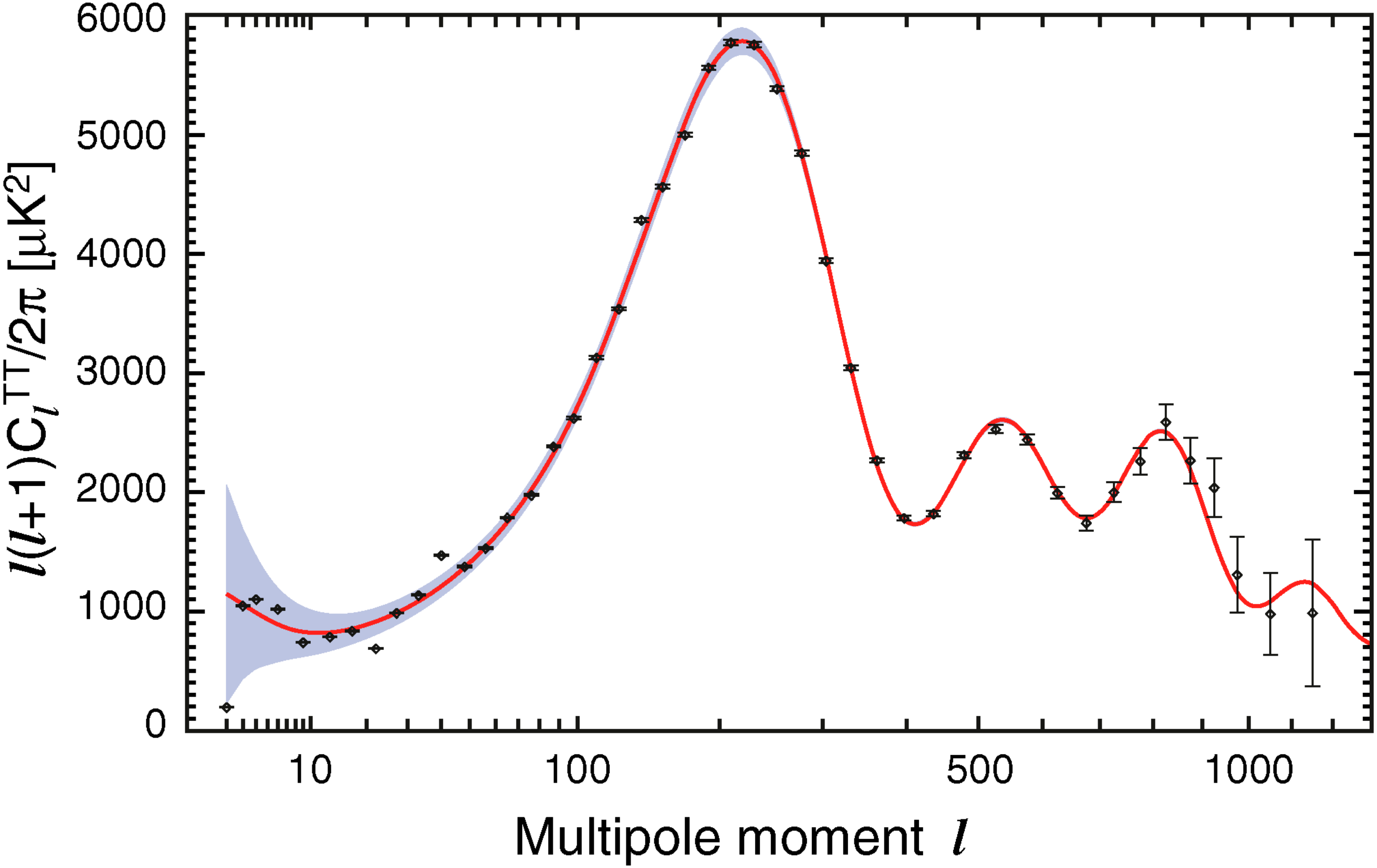
Another cosmological-parameter variation:

Not-so-exotic example: Patchy reionization
(e.g., Smith-Dvorkin 2009)

Reionization at z~8 scatters ~10% of CMB photons reducing T fluctuations by ~10%.

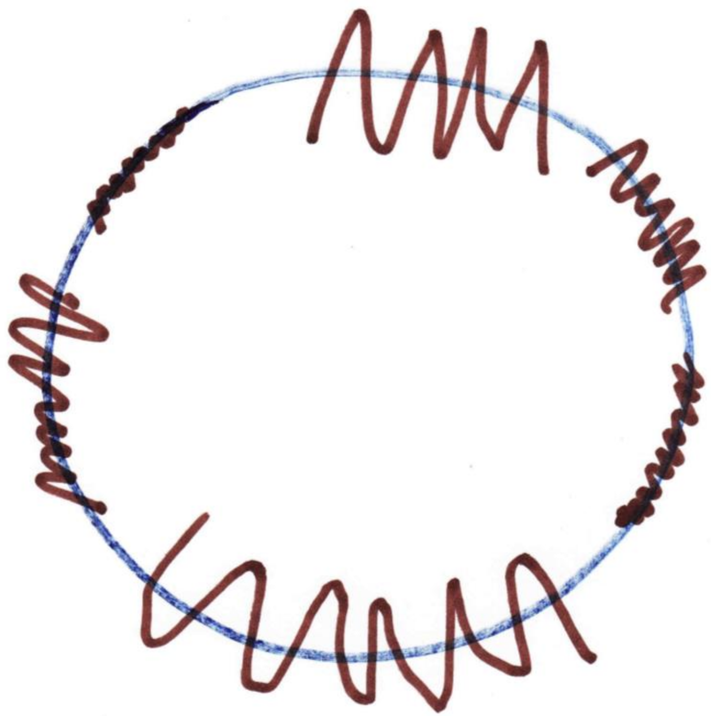
If reionization not perfectly homogeneous, amplitude of T fluctuations will be modulated

Quantified again by BiPoSHs



6000
5000
4000
3000
2000
1000
0
$l(l+1)C_l^{TT}/2\pi$ [μK^2]
10
100
500
1000
Multipole moment l

So T fluctuations may vary across sky……



This is described by BiPoSHs