Relativistic D-brane Dynamics

Based on work by T.B. and Liam McAllister

Q: What are the dynamics of relativistic D-brane scattering?

Consider $\mathrm{D3}/\mathrm{D3}(\overline{\mathrm{D3}})$ scattering in $\mathcal{M}_{10} = \mathcal{M}_4 \times \mathcal{M}_6$.

Take-home Message:

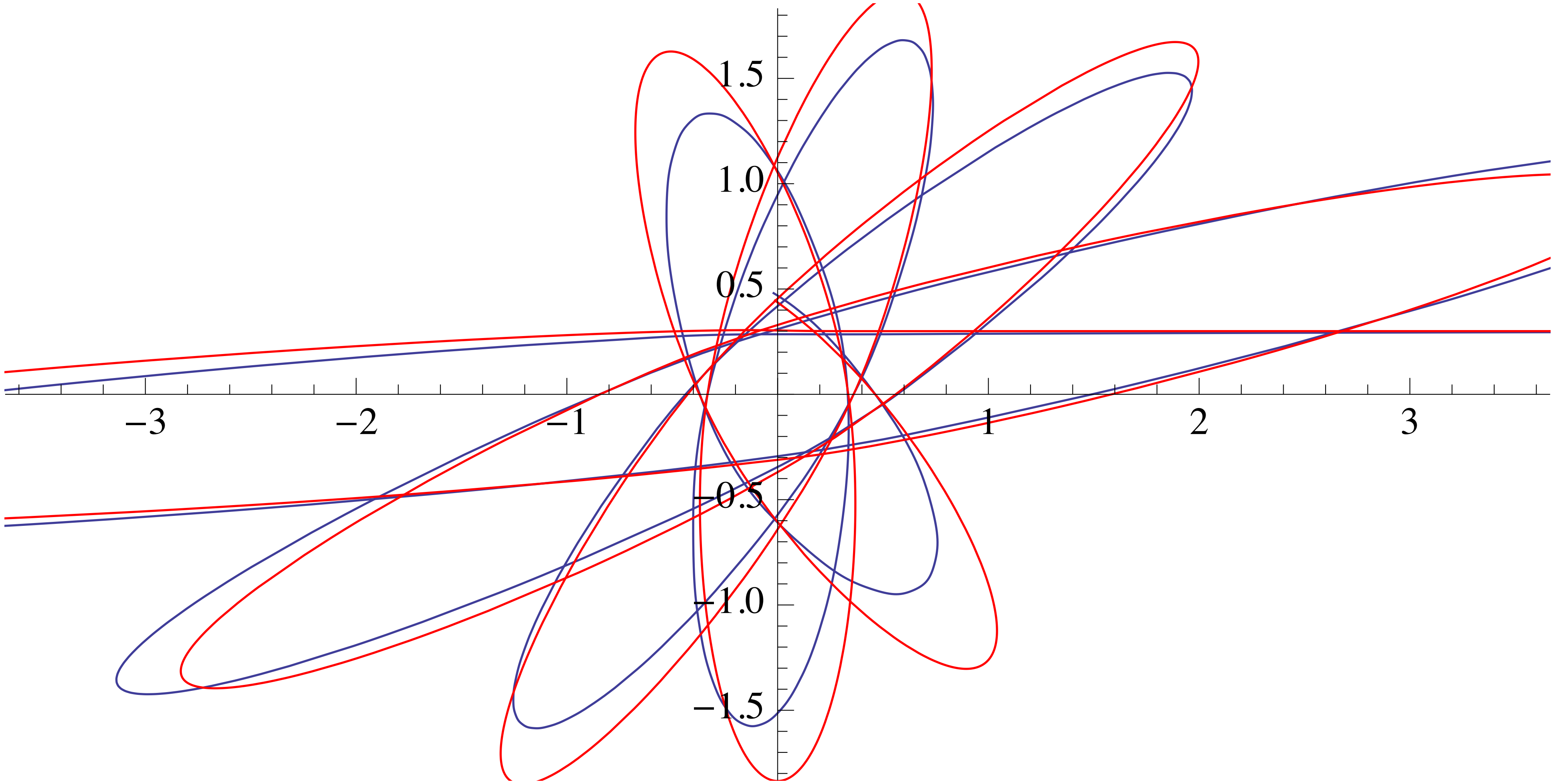
Relativistic D-brane interactions probe energies above the string scale

Energy loss is dominated by closed string emission

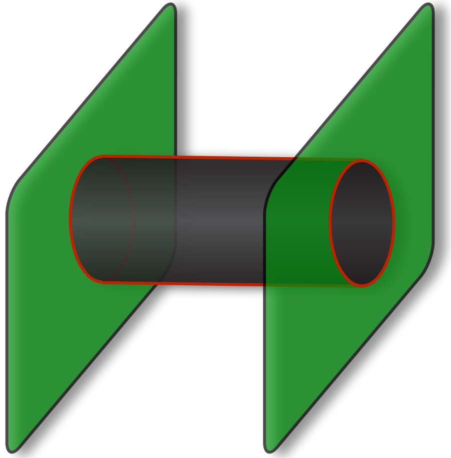
Low Velocity Limit

Non-relativistic limit is well known: (hep-th/0403001)
On-shell open string production leads to trapping from massless string production:

$$\mathcal{L} = \frac{1}{2}\partial_\mu\phi\partial^\mu\bar{\phi} + \frac{1}{2}\partial_\mu\chi\partial^\mu\chi - \frac{g^2}{2}|\phi|^2\chi^2 \, .$$



Building Blocks

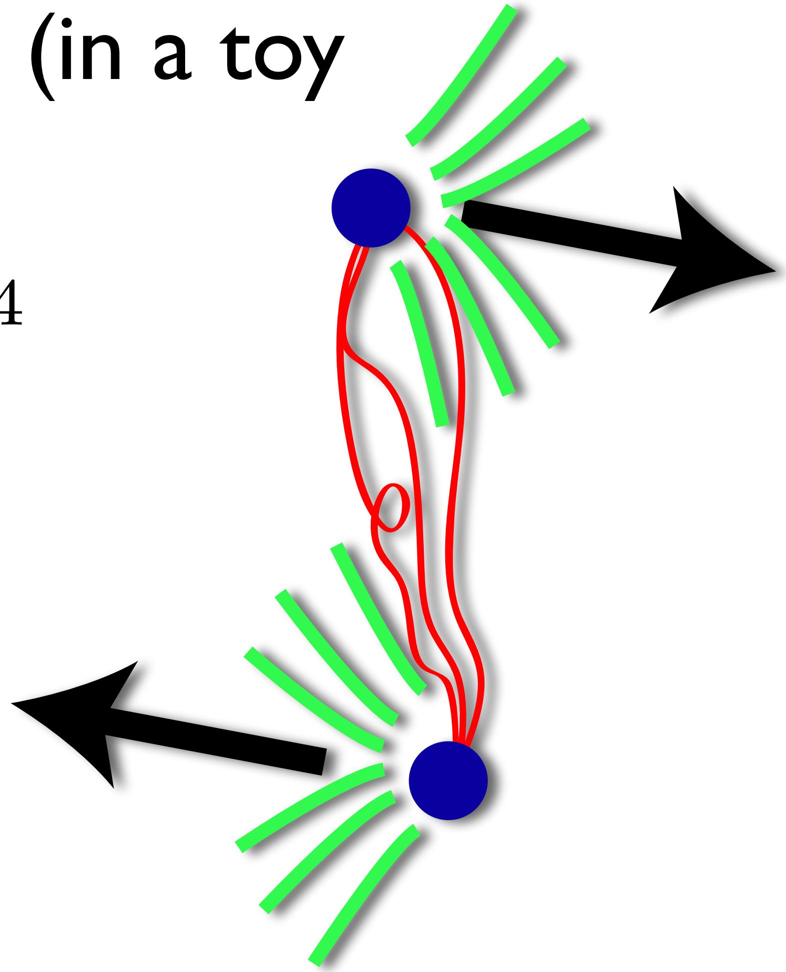


1.) $\mathrm{Im}(\quad) \propto \#$ of produced strings

$\rightarrow$ Instantaneous production rate $\Gamma(\vec{d},\vec{v})$

2.) Power loss due to graviton emission in D=6 (in a toy model):

$$\frac{P_{\mathrm{rad}}}{\mathrm{Vol}} = \frac{G_{\mathrm{N}}\lambda^{k}_{\mathrm{closed}}T^{2}_{\mathrm{D}k}}{24\pi^{2}}\gamma^{12}a^{4}$$

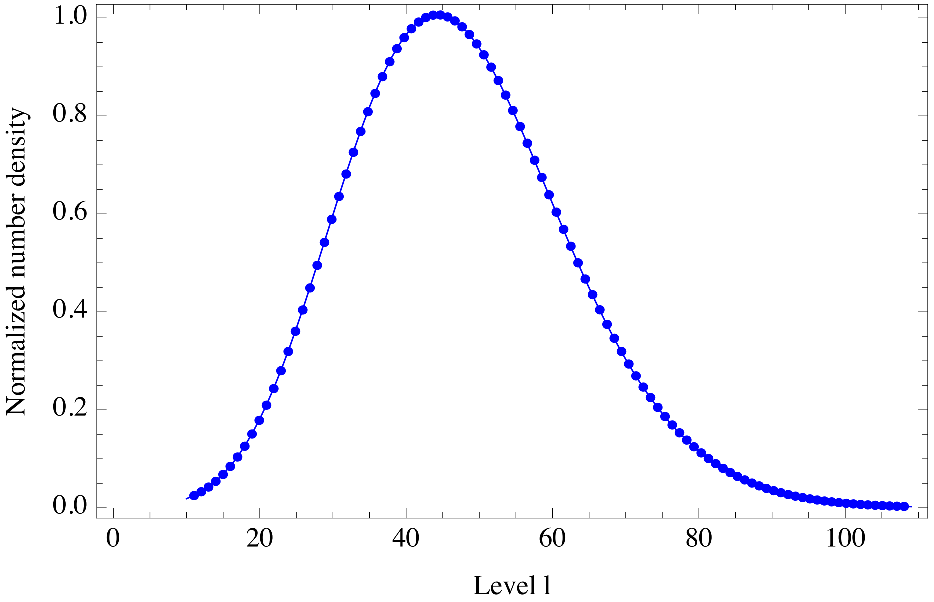


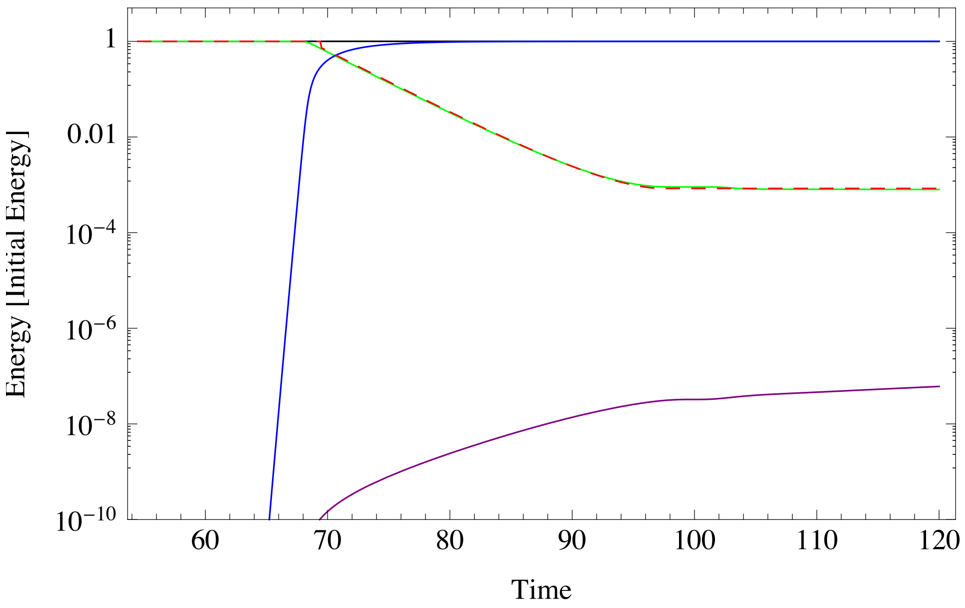
Results

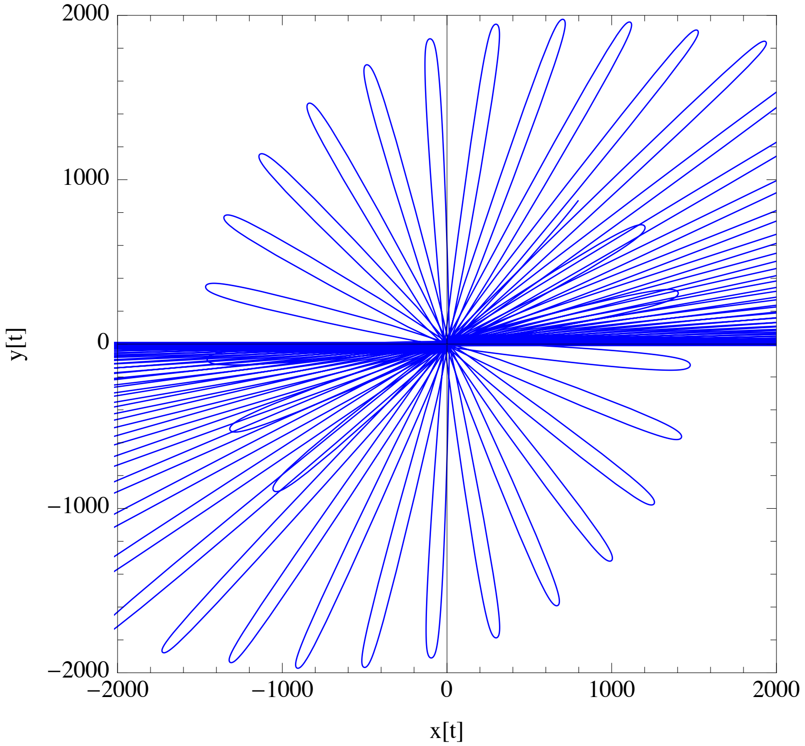
Trapping Radius $\propto \log(\gamma)$

$\#$ of open strings $\propto 1/\gamma^{7/4}$

$v \ll 1$ when $b \lesssim \sqrt{15}\log\gamma$







Note: $\omega_{\rm c} \sim \gamma^5/l_{\rm s} \rightarrow$ massive closed string emission?

COSMOLOGICAL UV/IR DIVERGENCES

Wei XUE
McGill University

Work with R. Brandenberger
and K. Dasgupta

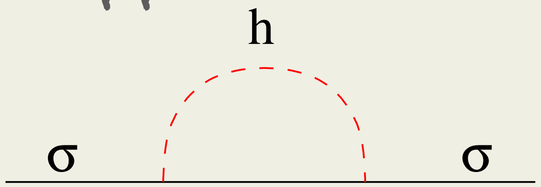
Phys.Rev. D83 (2011) 083520

Why loops?

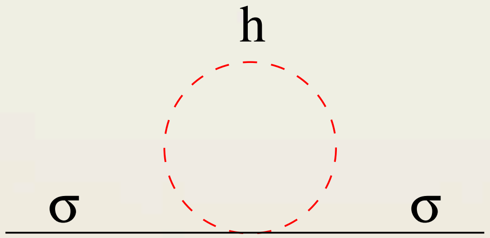
- Interactions: Non-Gaussianity
- UV divergences : GR is nonrenormalizable
- I R divergences (Stochastic $\log(a) \sim Ht$)
- de Sitter and Inflationary perturbations
- Back reaction
- Debates on $\log(k/\mu)$, $\log(H/\mu)$
  (S. Weinberg hep-th/0506236;
  Senatore and Zaldarriaga arxiv:0912.2734)

Result

- The different schemes will not change the physical result. Brute-cutoff, Dimensional Regularization and Pauli-Villars
- Physical cutoff and comoving cutoff



h (δσ) (δσ)



h h (δσ) (δσ)

- Inflation power spectrum is not exactly flat

$$<\Phi(x,t)^2> \sim \int d^3k\, H^2/k^3 \sim H^2 \log(\Lambda_{IR})$$

$$<\Phi(x,t)^2> \sim \int d^3k\, H^2/k^3 \sim H^2 (\Lambda_{IR})^{-\varepsilon}/\varepsilon$$

Discussion

- Using three regularization method, we get the same result for the loop corrections to two-point functions
- The result depends on whether the cutoff is physical or comoving.
- Inflationary IR divergence is different from de Sitter
- Linde's problem in Thermal Field Theory
  (perturbation theory breaks down because of the IR loops of thermal gluons)

Uplifting AdS/CFT to Cosmology

Xi Dong

SITP and SLAC, Stanford University

July 26, 2011

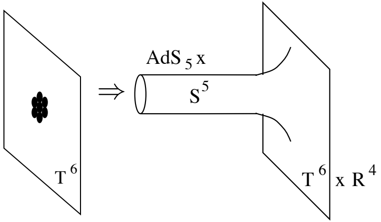
- AdS/CFT provides a complete description of quantum gravity in AdS.
- What about cosmological spacetimes such as dS or FRW?

Based on

- XD, Bart Horn, Eva Silverstein, Gonzalo Torroba arXiv:1005.5403 [hep-th]
- XD, Bart Horn, Shunji Matsuura, Eva Silverstein, Gonzalo Torroba arXiv:1108.???? [hep-th]

Warped compactification and the dS/dS correspondence

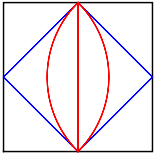
AdS/CFT with a UV brane
or compactification manifold
⇒ Randall-Sundrum
or warped compactification.

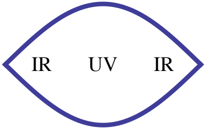


De Sitter space is naturally
a warped compactification:

$$ds^2_{dS_d} = dw^2 + \sin^2 \frac{w}{R_{dS}} ds^2_{dS_{d-1}}$$

$$0 \leq w \leq \pi R_{dS}$$





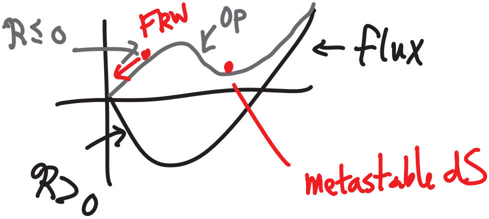
dS/dS correspondence: quantum gravity on dS$_d$ = two QFTs living on dS$_{d-1}$, corresponding to the IR regions of the warped throats, plus $(d-1)$-dimensional gravity, corresponding to the zero mode of the d-dimensional graviton. $M_{d-1}^{d-3} \sim M_d^{d-2} R_{dS}$.
Alishahiha, Karch, Silverstein, Tong [hep-th/0407125v2]

A brane construction for the dS/dS correspondence

Uplift known AdS/CFT examples:
e.g. $AdS_3 \times S^3 \times T^4 \Rightarrow dS_3/dS_2, \quad AdS_4 \times \mathbb{CP}^3 \Rightarrow dS_4/dS_3$.

Effective potential for AdS:

$$U(g) = ag^2 + cg^4, \quad a < 0, \; c > 0$$



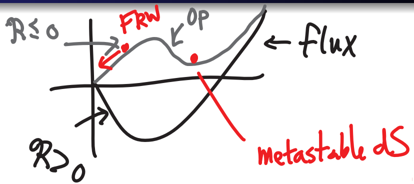
Effective potential for dS:

$$U(g) = ag^2 - bg^3 + cg^4, \qquad a, b, c > 0$$

A concrete example with all moduli stabilized is given in XD, Bart Horn, Eva Silverstein, Gonzalo Torroba [arXiv:1005.5403 [hep-th]].

$$S_{\text{Gibbons-Hawking}} \sim S_{\text{QFT}} \sim \frac{A}{4G_N}$$

A holographic dual of FRW spacetime



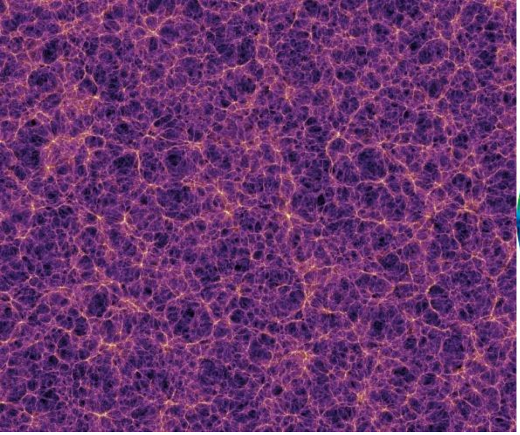
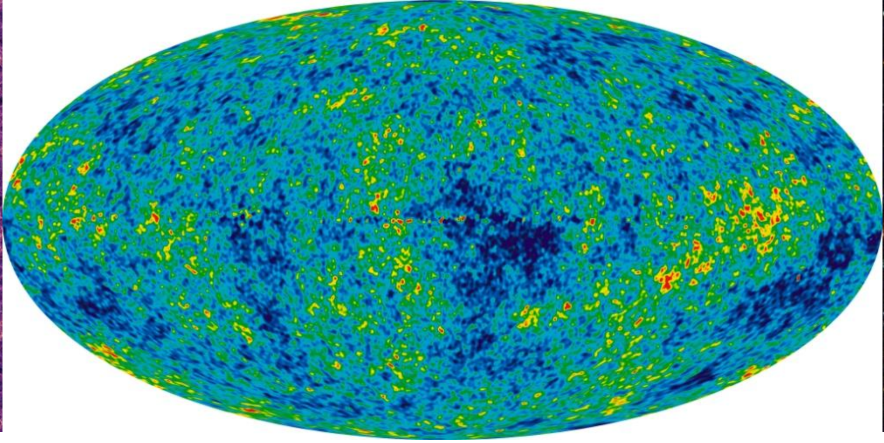
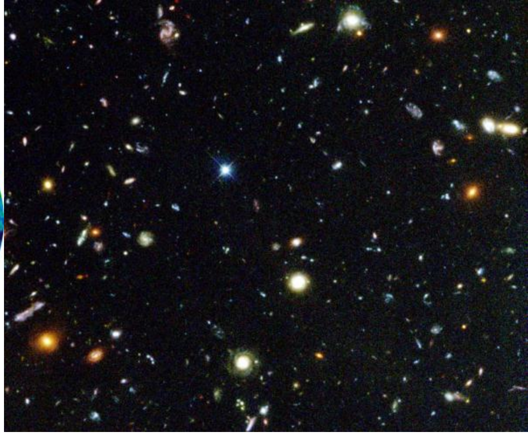
The brane construction for dS eventually decays. One decay channel is through a Coleman–de Luccia bubble
⇒ open FRW universe with a zero cosmological spacetime:

$$ds_d^2 = -dt^2 + (ct)^2 d\mathbb{H}_{d-1}^2, \quad c = \sqrt{3} \quad \text{for} \quad d = 3$$

Brane construction: start with $AdS_3 \times S^3 \times T^4$, put more than 24 (p,q) 7-branes on $\mathbb{CP}^1$ (the base of S^3 as a Hopf fibration). Rewrite the FRW metric as

$$ds_d^2 = c^2(\eta^2 - w^2)^{c-1}(dw^2 - d\eta^2 + \eta^2 d\mathbb{H}_{d-2}^2)$$

This is a (time-dependent) warped metric. $w = 0$ is the UV and the $w = \eta$ is the IR. Can the dual QFT be UV complete and decouple from $(d-1)$-dimensional gravity? $M_{d-1}^{d-3} \sim t$.

Adiabaticity and Non-Gaussianity

Joel Meyers
University of Texas at Austin

PITP 2011
Institute for Advanced Study
July 26, 2011

arXiv:1011.4934 and 1104.5238 w/Navin Sivanandam

Non-Gaussianity

- Contains information beyond power spectrum

$$f_{NL}^{\mathrm{local}} = 32 \pm 21 \ (68\% \ \mathrm{CL})$$

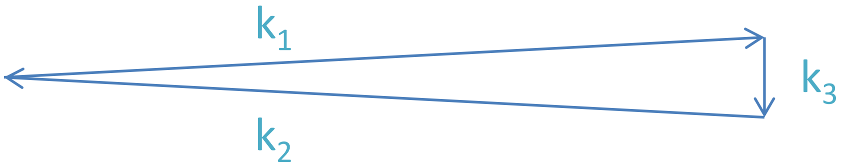
WMAP 7

- Single field inflation models predict small f_{NL}^{local}

$$f_{NL}^{\mathrm{local}} = \frac{5}{12}(1 - n_s)$$

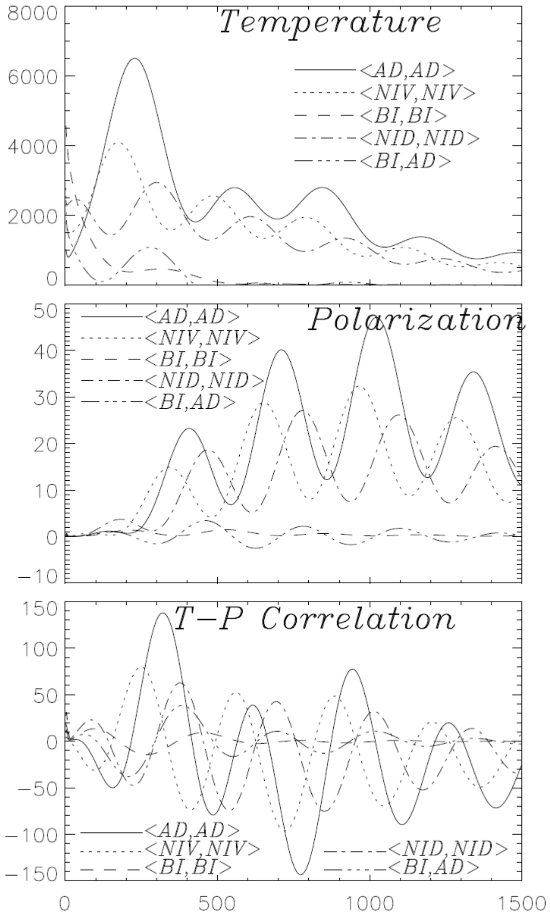
Maldacena (2002)
Creminelli, Zaldarriaga (2004)
Ganc, Komatsu (2010)

- A convincing detection of f_{NL}^{local} would rule out *ALL* models of single field inflation



Adiabaticity

- Non-adiabatic modes:
  - Are generically present in multiple field models
  - Lead to superhorizon evolution of ζ
  - Can be detected in the CMB
- There are at least two ways to achieve adiabaticity:
  - Effectively single field inflation
  - Local Thermal Equilibrium



Weinberg (2004), (2008a), (2008b); JM (2011)

Bucher, Moodley, Turok (2001)

Model and Results

- Two-field inflation with potentials of the form:

$$W(\phi, \chi) = F[U(\phi) + V(\chi)]$$

- After passing through a short phase of effectively single field inflation we find:

$$f_{NL}^{\rm local} \sim \mathcal{O}(\varepsilon_*)$$

JM, Sivanandam (2010)

- Similarly for local n-point functions we find:

$$F_{\rm NL,\it i}^{(n)} \sim \mathcal{O}(\varepsilon_*)$$

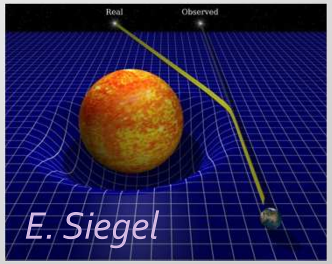
JM, Sivanandam (2011)

How sensitive is the CMB to a Local Lens.

Anastasia Fialkov, Tel Aviv University

PiTP 2011

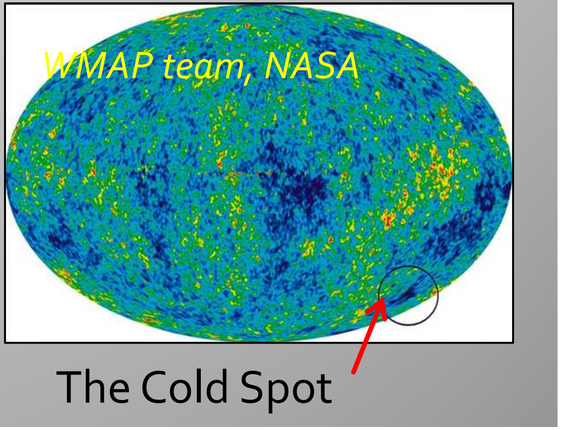
- Aim: Weak lensing of the CMB by a single lens that breaks statistical isotropy



E. Siegel

- Motivation:
    - High energy theories
    - Some of the cosmic "anomalies" at large scales
- Single Lens Examples:
    - Texture (Turok & Spergel 1990)
    - Giant Void (Inoue & Silk 2007)
    - Traces of a Pre-Inflationary Point particle (Itzhaki 2008, Fialkov *et al* 2010)
- Previous works in this field study lensing by a giant void and a texture. Motivated by the WMAP cold spot.

  (Masina & Notari 2009, 2010; Das & Spergel 2009)



WMAP team, NASA

The Cold Spot

The Upper Bound for the Detection.
The Signal to Noise from an Ideal Experiment.

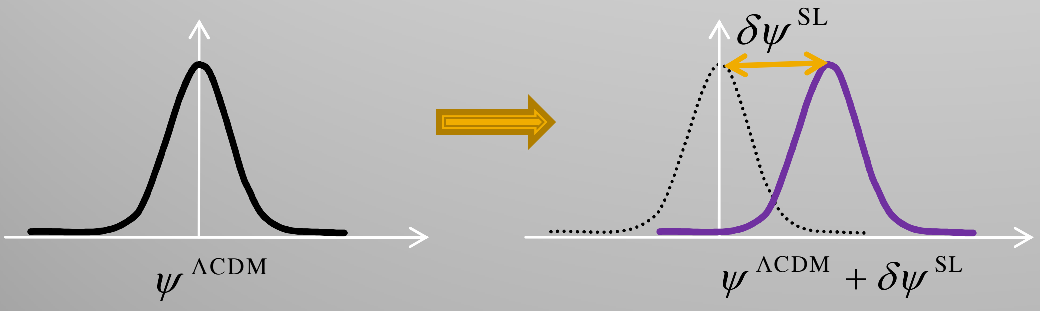
- Complete reconstruction of the deflection potential

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

random

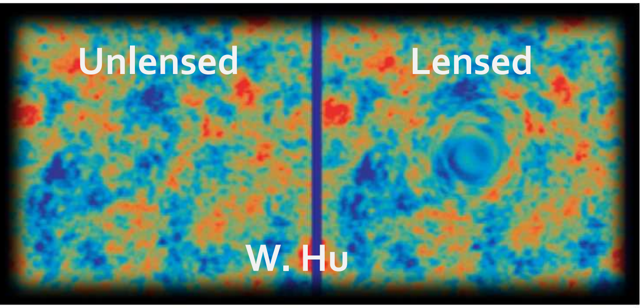
non-random

- The single lens adds a 1-point function to the deflection field



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

The Realistic Signal to Noise.

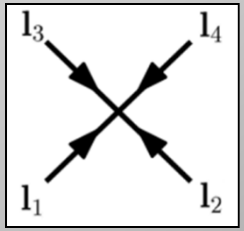


- Effect of lensing is to re-map the CMB sky

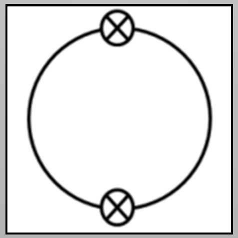
$$\tilde{T}(\theta)=T\left(\theta+\nabla\delta\psi^{\mathrm{SL}}\right) \xrightarrow[\textit{Weak lensing}]{} \tilde{T}(\theta)=T(\theta)+\nabla\delta\psi^{\mathrm{SL}}\nabla T(\theta)$$

$$+$$

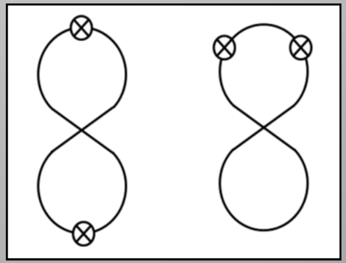
- Include Non-Gaussianity from LCDM weak lensing



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



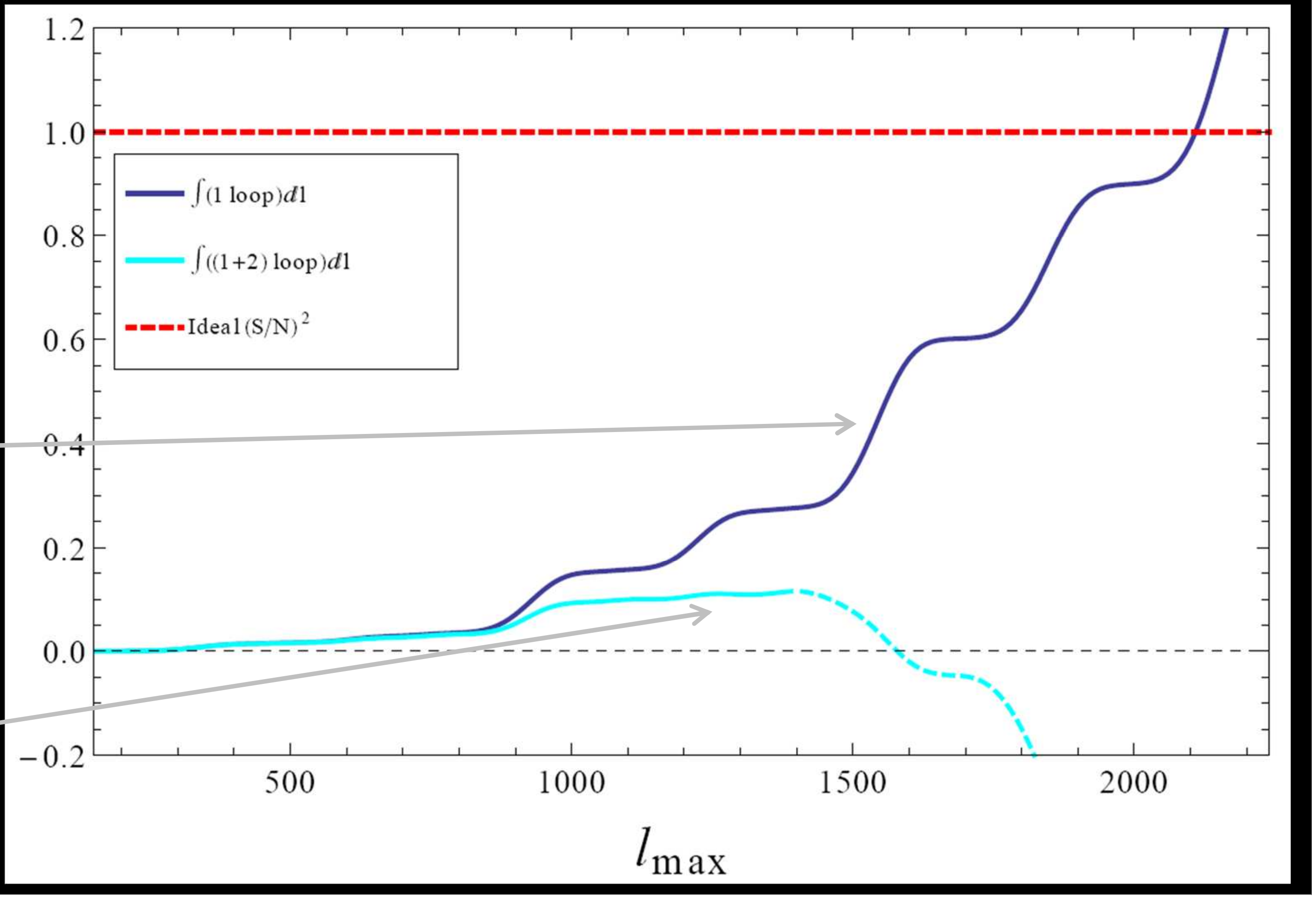
$$+$$



Accumulated SN² vs. the resolution of a CMB experiment

$$\left(\frac{S}{N}\right)^2_{\text{1LOOP}} \Big/ \left(\frac{S}{N}\right)^2_{\text{IDEAL}}$$

$$\left(\frac{S}{N}\right)^2_{\text{1+2LOOP}} \Big/ \left(\frac{S}{N}\right)^2_{\text{IDEAL}}$$



- The NG correction becomes important at l=900.
- At l = 1400 the accumulated SN^2_{OBS} starts to drop. Higher order terms in loop expansion should be added to fix it.
- Plateau at 1000<l<1400. The true SN from T is: $\left(S/N\right)_{\text{OBS}} \sim \frac{1}{3}\left(S/N\right)_{\text{IDEAL}}$

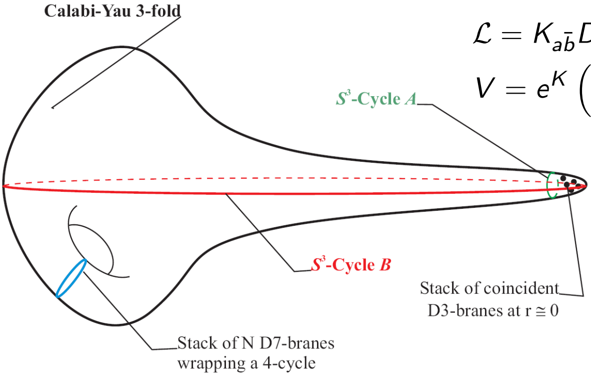
A sufficient Condition for de Sitter Vacua in type IIB String Theory

Markus Rummel
University of Hamburg

arXiv:1107.2115 [hep-th] with Alexander Westphal

PiTP at the Institute for Advanced Study, Princeton
July 26, 2011

Goal: More general parametric understanding of the existence of dS vacua in type IIB string theory



$$\mathcal{L} = K_{a\bar{b}} D_\mu \phi^a D^\mu \phi^{\bar{b}} - V + \ldots,$$

$$V = e^K \left(K^{a\bar{b}} D_a W \overline{D_b W} - 3|W|^2 \right)$$

[GKP '01]
[KKLT '03]

- Moduli ϕ^a: Kähler T_i, complex structure U_i and dilaton S
- $K = -2\ln\left(\hat{\mathcal{V}}(T_i) + \alpha'^3 \hat{\xi}(S)\right)$, $W = W_0(S, U_i) + \sum_i A_i\, e^{-a_i T_i}$

A sufficient Condition for dS vacua

Expand potential for

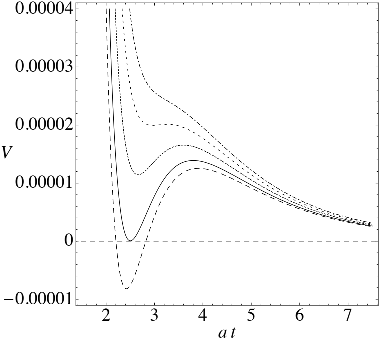
- $\hat{\mathcal{V}} \gg \hat{\xi}$ $\Rightarrow$ Large Volume $\hat{\mathcal{V}} \simeq \gamma t^{3/2} \sim \mathcal{O}(100 \ldots 1000)$
- $|W_0| \gg Ae^{-at}$ $\Rightarrow$ Non-perturbative effects are small

$\Rightarrow$ Obtain simple 2-term potential in $\hat{\mathcal{V}}$: $\mathbf{V \simeq C_1 \frac{\hat{\xi}}{\hat{\mathcal{V}}^3} - C_2 \frac{Ae^{-at}}{\hat{\mathcal{V}}^2}}$

$\Rightarrow$ Sufficient for metastable dS:

$$\mathbf{12.2 \lesssim \frac{W_0 \hat{\xi} a^{3/2}}{\gamma A} \lesssim 13.1}$$

Other moduli are stabilized supersymmetrically at $D_i W = 0$



Further Results:

- Arbitrary number of Kähler and complex structure moduli can be included explicitly ⇒ Works for a whole class of Calabi-Yau threefolds! ('swiss cheese type')
- SUSY breaking well controlled by F-terms only ⇒ Do not need extra sector or uplifting mechanism!
- Sufficient condition is on geometric properties of the Calabi-Yau and fluxes W_0 ⇒ F-theory data!
- Small cosmological constant can be achieved by tuning of $\#U \simeq \mathcal{O}(100)$ background fluxes! [Bousso, Polchinski '00]

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Thank you for your attention!

Reheating, Baryon Asymmetry, Dark Matter: All You Need is Neutrino Decays

Kai Schmitz

Deutsches Elektronen-Synchrotron

DESY, Hamburg, Germany

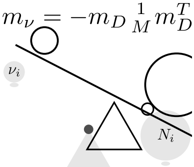
Based on arXiv:1008.2355 [hep-ph] and arXiv:1104.2750 [hep-ph].
In collaboration with Wilfried Buchmüller and Gilles Vertongen.

Prospects in Theoretical Physics,
Institute of Advanced Study | July 26, 2011

A consistent cosmology built upon heavy neutrino decays

Origin of the epoch of radiation domination?

- Seesaw mech.: Add heavy Majorana neutrinos N_i to the SM.
- Assume dominant neutrino energy density after inflation.
- Neutrino decays produce all entropy of the hot early universe.
- $T_{\mathrm{RH}} \propto \sqrt{\Gamma_N} \sim 10^{9\ldots10}\,\mathrm{GeV}$ for typical neutrino parameters.



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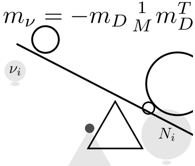
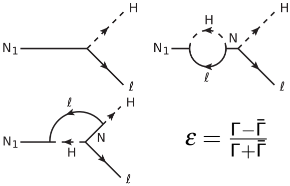




$$\varepsilon = \frac{\Gamma - \bar{\Gamma}}{\Gamma + \bar{\Gamma}}$$

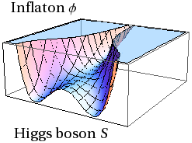
CP-violating out-of-equilibrium neutrino decays to ℓH & $\ell^\dagger H^*$.

By-products: Baryogenesis & dark matter

- Leptogenesis + SM sphaleron processes at T_L.
- Seesaw & neutrino data: $M_1 \sim T_L \sim 10^{9\ldots10}\,\mathrm{GeV}$.
- Thermal production of gravitinos in SUSY QCD.
- If heavy LSP: $\Omega_{\widetilde{G}} h^2 \left(T_{\mathrm{RH}}, m_{\widetilde{G}}, m_{\tilde{g}}\right) \simeq \Omega_{\mathrm{DM}} h^2$.

Non-trivial relation between SUGRA and neutrino parameters! Falsifiable through neutrino observ.

Generating a dominant nonthermal neutrino abundance

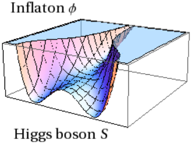


Hybrid infl. $=$
Chaotic infl. $+$ SSB

Tachyonic preheating at the end of hybrid inflation:

- Seesaw mech.: Majorana mass term violates lepton number.
- SSB of local $U(1)_{B-L}$ ends inflation in a waterfall transition.
- Vacuum energy density $\longrightarrow$ $B-L$ Higgs bosons $\longrightarrow$ Neutrinos.

Generating a dominant nonthermal neutrino abundance



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Quantitative numerical analysis:

- Employ Froggatt-Nielson flavor model for GUT multiplets to estimate Yukakwa couplings.
- Solve Boltzmann equations for phase space distr. funcs. & number densities in an expanding FLRW background.
- Scan space of SUGRA and neutrino parameters and calculate T_{RH}, η_B and $\Omega_{\widetilde{G}}h^2$ at each point.

$$\left(\frac{\partial}{\partial t} - Hp\frac{\partial}{\partial p}\right) f = \frac{C}{E}$$

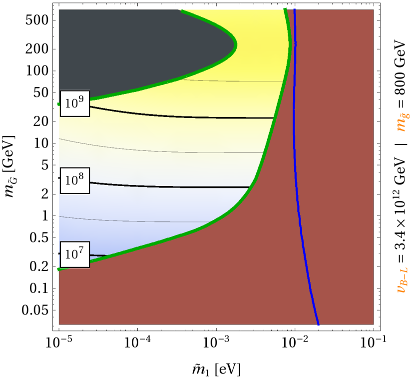
$$aH\frac{d}{da}N = a^3\frac{g}{(2\pi)^3}\int d^3p\,\frac{C}{E}$$

$$H^2 = \frac{8\pi}{3M_P^2}\rho$$

Viable scenario in large region of parameter space.

Connection between SUGRA and neutrino parameters

T_{RH} [GeV] such that $\Omega_{\tilde{G}} h^2 = 0.11$

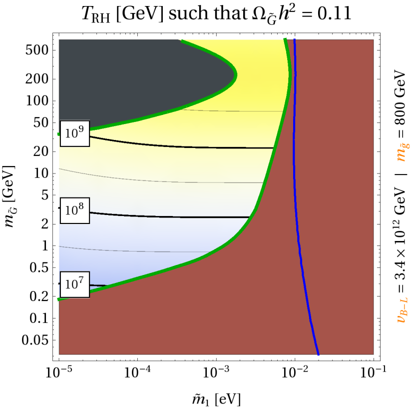


A common origin of entropy, matter and dark matter

- Idea: Neutrino decays produce all entropy of the hot early universe.
- Scenario: Dominant nonthermal neutrino abundance after tachyonic preheating.
- Result: Link between gravitino and neutrino physics that can be probed in collider searches, laboratory exp. and cosmol. obs.

- New bound: T_{RH} as low as $10^7\,\mathrm{GeV}$.
- Effective neutrino mass $\widetilde{m}_1$ constrains gravitino mass $m_{\widetilde{G}}$ and vice versa.

Connection between SUGRA and neutrino parameters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Thank you
for your attention!

Gyromagnetic Factors and Atomic Clock Constraints on the Variation of Fundamental Constants

arXiv: 1107.4154

Feng Luo

collaborated with Keith Olive and Jean-Philippe Uzan

University of Minnesota

July 26, 2011

Motivation

Why study the variation of fundamental constants?

- existence of new d.o.f.
- violation of the Equivalence Principle
  $m_A(\alpha_i) \Rightarrow a = g_N + \delta a_A$, where δa_A depends on $\nabla\alpha_i$ and $\dot{\alpha}_i$

Constraints from atomic clock?

$$\text{e.g.,}\quad \frac{\mathrm{d}}{\mathrm{d}t}\left(\frac{\nu_{\mathrm{Cs}}}{\nu_{\mathrm{H}}}\right) / \left(\frac{\nu_{\mathrm{Cs}}}{\nu_{\mathrm{H}}}\right) = (32 \pm 63) \times 10^{-16}\,\mathrm{yr}^{-1}$$

$$\frac{\nu_{\mathrm{Cs}}}{\nu_{\mathrm{H}}} \propto g_{\mathrm{Cs}}\,\mu\,\alpha^{2.83}$$

where $g_{\mathrm{Cs}} = \frac{7}{9}(10 - g_{\mathrm{p}})$, $g_{\mathrm{p}} = \frac{2\mu_{\mathrm{p}}}{\mu_{\mathrm{N}}}$, $g_{\mathrm{p},exp} = 5.586$, $\mu = \frac{m_{\mathrm{e}}}{m_{\mathrm{p}}}$.

$$\frac{\dot{\nu}_{AB}}{\nu_{AB}} = \lambda_{g_{\mathrm{p}}}\frac{\dot{g}_{\mathrm{p}}}{g_{\mathrm{p}}} + \lambda_{\mu}\frac{\dot{\mu}}{\mu} + \lambda_{\alpha}\frac{\dot{\alpha}}{\alpha}$$

Suppose *only* α vary, then $\dot{\alpha}/\alpha = (11 \pm 22)^{-16}\,\mathrm{yr}^{-1}$.

Is this interpretation correct? Can this limit be stronger or weaker?

In unification theories, various fundamental constants, e.g., α, α_s, h, v, are related. So, $\frac{\dot{\alpha}}{\alpha} = \frac{1}{\lambda_\alpha} \frac{\dot{\nu}_{AB}}{\nu_{AB}}$ becomes $\frac{\dot{\alpha}}{\alpha} = \frac{1}{C_\alpha} \frac{\dot{\nu}_{AB}}{\nu_{AB}}$.

We focus on the dependence of g_p on $m_\mathrm{u,d,s}$ and Λ_QCD.

g_p can be given by

- constituent quark model $g_\mathrm{p,NQM} = 2\left(\frac{8}{9}\frac{m_\mathrm{p}}{M_\mathrm{u}} + \frac{1}{9}\frac{m_\mathrm{p}}{M_\mathrm{d}}\right)$
- chiral perturbation theory $g_{\mathrm{p},\chi\mathrm{PT}}$ depends on $M_{\pi,K,\eta}$, ...
- lattice QCD $g_\mathrm{p,lattice}$, promising, need extrapolation

Discussion

Table: The enhancement factor C_α/λ_α assuming $S = 160$ and $R = 30$ for each of the models for the proton magnetic moment and for the various combinations of clocks discussed in this article.

	Rb-Cs	H-Cs	Hg-Cs	Yb-Cs	Sr-Cs	SF_6-Cs
A	-54.11	1.55	1.26	1.80	1.56	-1.74
B1	0.59	7.53	4.07	10.58	7.67	4.24
B2	-16.77	5.63	3.17	7.79	5.73	2.34
B3	-10.87	6.28	3.48	8.74	6.39	2.99
C	-42.27	2.84	1.86	3.70	2.88	-0.45
HBw/oD	73.57	15.38	7.75	22.09	15.69	12.16
HBwD	-26.70	4.41	2.60	6.00	4.48	1.19
EOMS	11.61	8.60	4.57	12.14	8.76	5.38
χPT+QCD	14.32	8.90	4.71	12.58	9.07	5.68

Finally, similar idea also applies to astrophysical systems through the measurement of transition lines.

PITP Summer School
Jul 26, 2011

Quantum violations of the equivalence principle in scalar-tensor theories

Riccardo Penco
Syracuse University

in collaboration with
Cristian Armendariz-Picon

Action:

vierbein

$$S = \int d^4x \det e \left[\frac{M^2}{2} R - \partial_\mu \varphi \, \partial^\mu \varphi - V(\varphi) \right]$$

$$+ S_M[f(\varphi) e_\mu{}^a, \psi_\alpha]$$

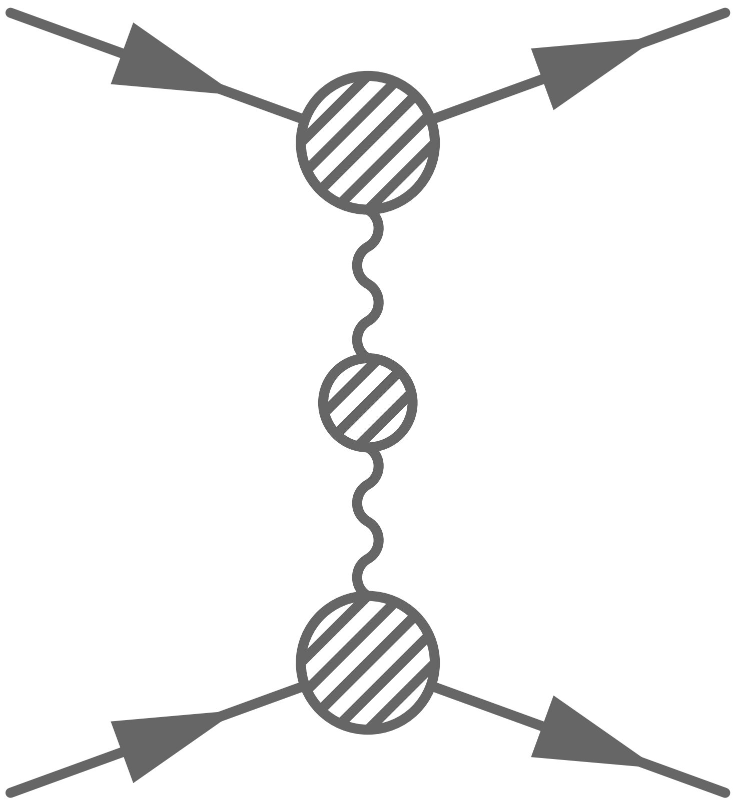
$$f(\varphi) = 1 + \frac{\varphi}{\Lambda} + \cdots$$

Motivation:

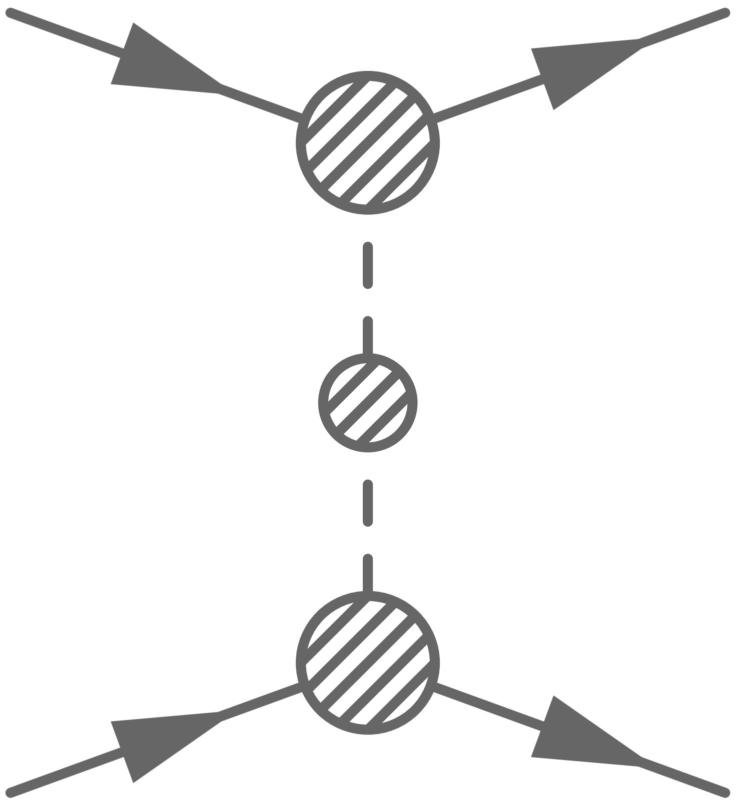
classical action not protected by symmetry

Challenge: field redefinitions

Gravitational interactions



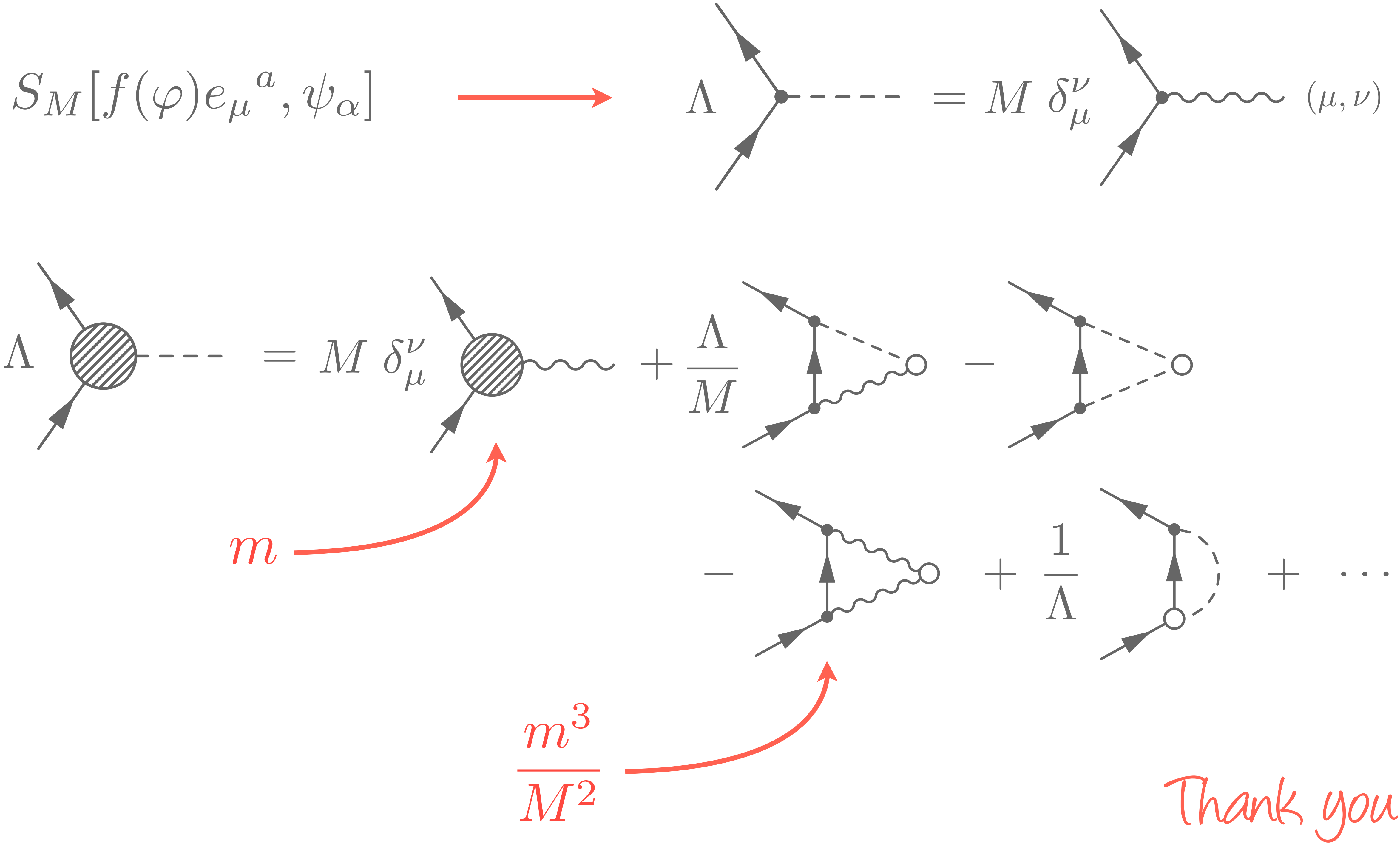
Graviton



Scalar

Interesting limit: long-range, on-shell, non-relativistic.

Scalar interactions



Thank you!

Modified Gravity with Perturbative Constraints

Alan Cooney, Dimitrios Psaltis and, Simon DeDeo

Phys. Rev. D 79, 4 (2009)

- Motivation: Modifications to Gravity in the Infra-Red
- Particular case: f(R) Modifications

$$\mathcal{L}_{\mathrm{Grav}} = R - 2\Lambda + f(R) \qquad \text{say} \qquad f(R) \propto \frac{\mu^4}{R} + \ldots$$

- New Light Scalar
  - New Phenomenology

- What Cosmological Signals = New Scalar Degree of Freedom?

Dynamics

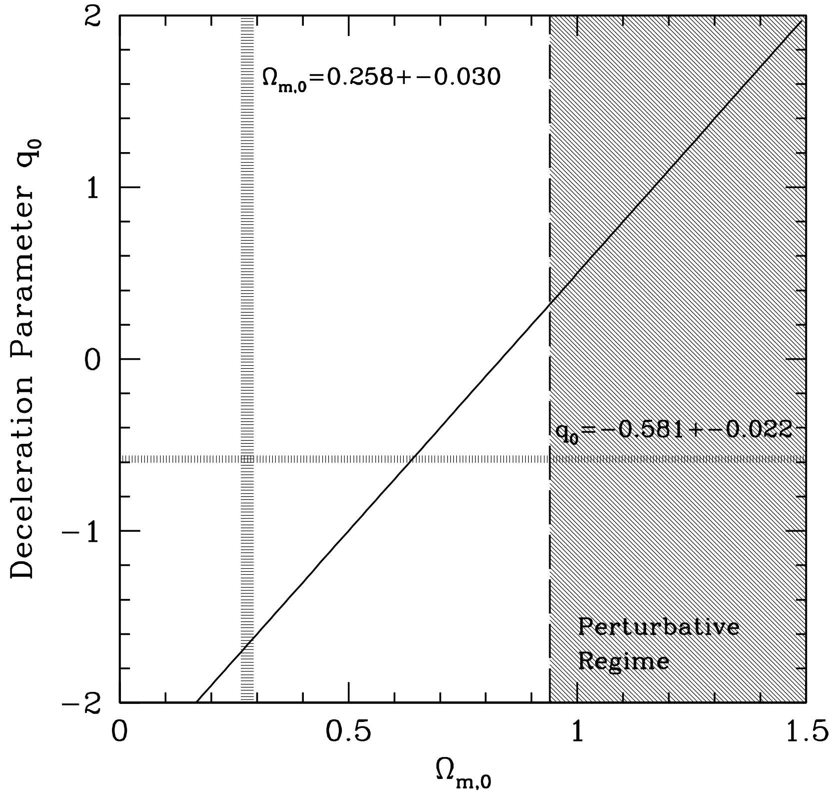
- Spatially Flat FRW metric
- Equations of Motion are 4th Order
- 2 Solutions analytic in μ^4, 2 ill-defined at $\mu^4 = 0$

- Examine behavior of analytic solution by perturbative expansion in μ^4

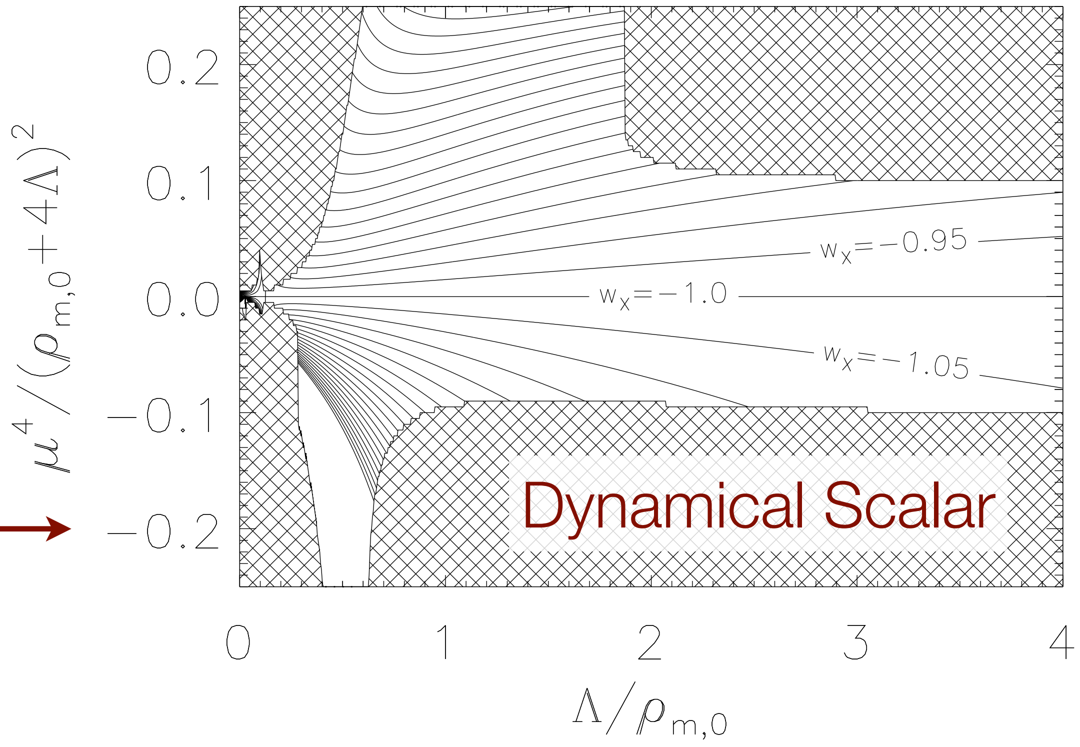
- Dimensionless Expansion parameter $\frac{\mu^4}{R(t_0)^2} = \frac{\mu^4}{(\rho_{m,0} + 4\Lambda)^2}$

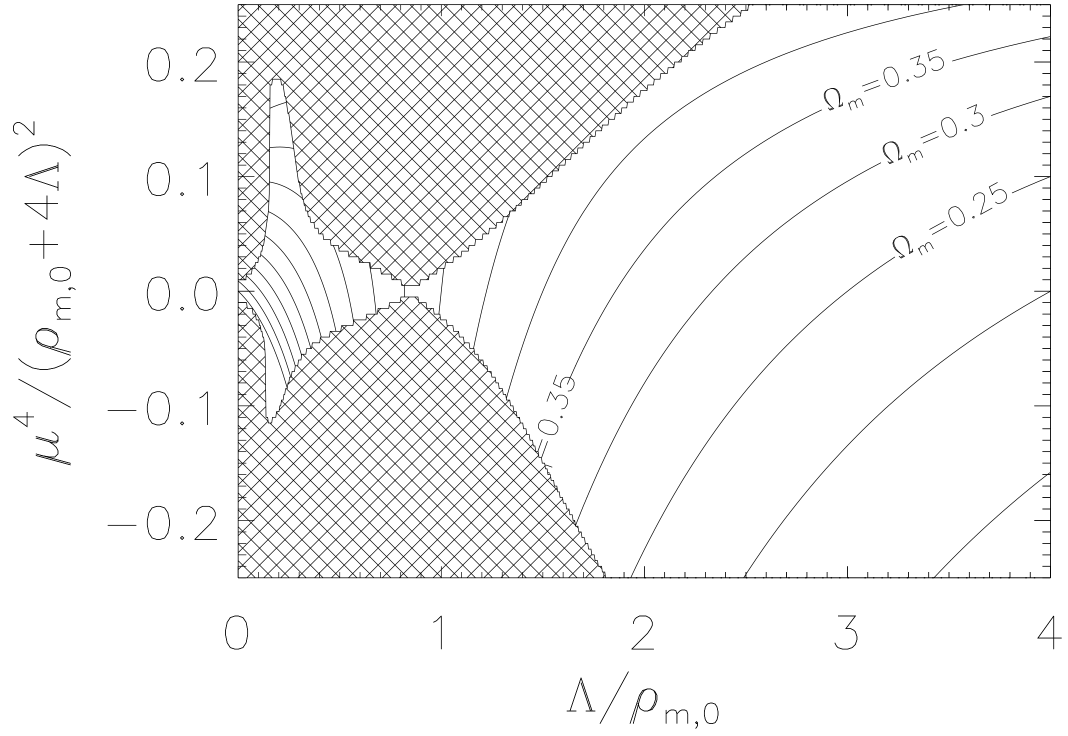
Background Evolution

- Absence of Constant Term:
  - Acceleration = Unambiguous Signal of Dynamical Scalar d.o.f.



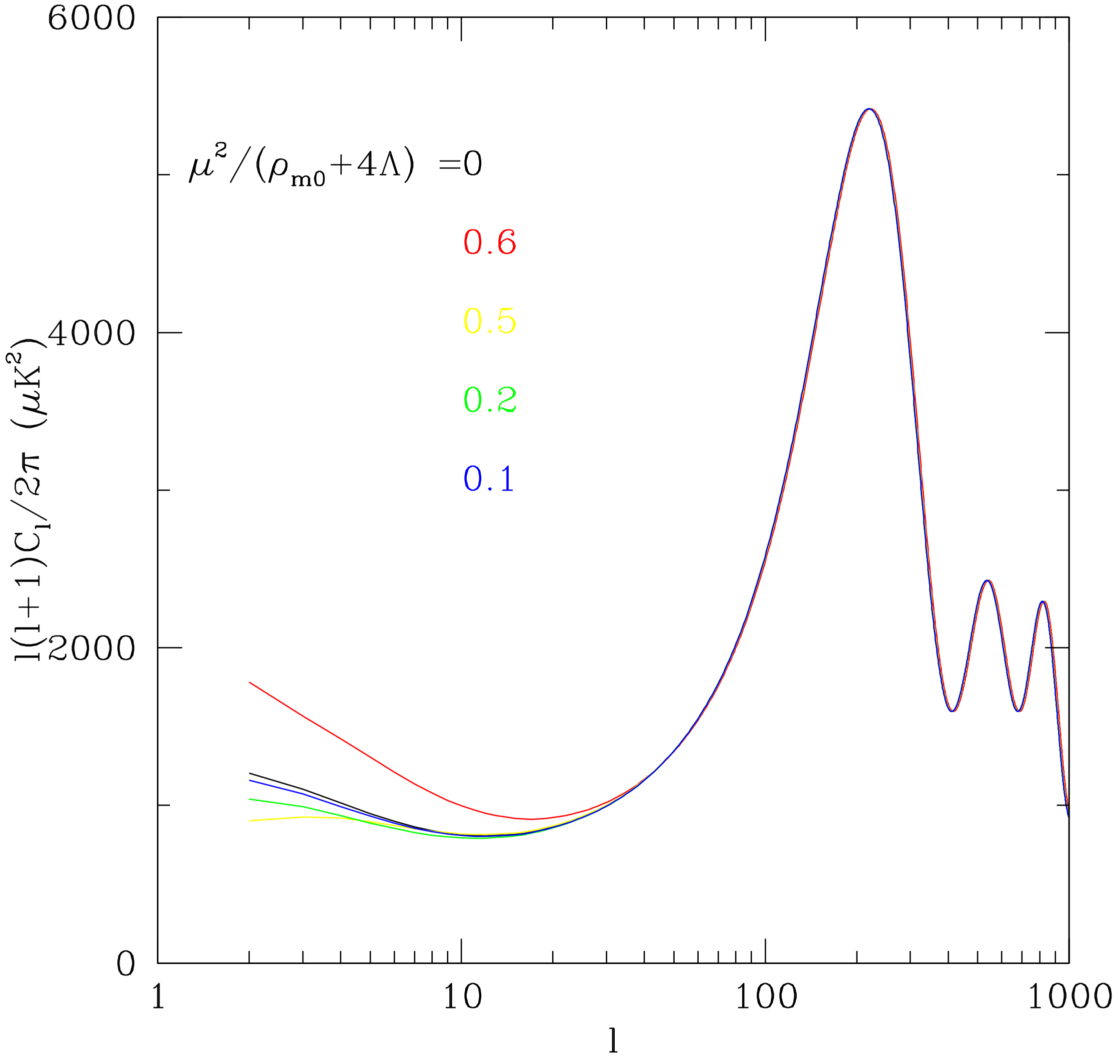
In the presence of a constant, Λ

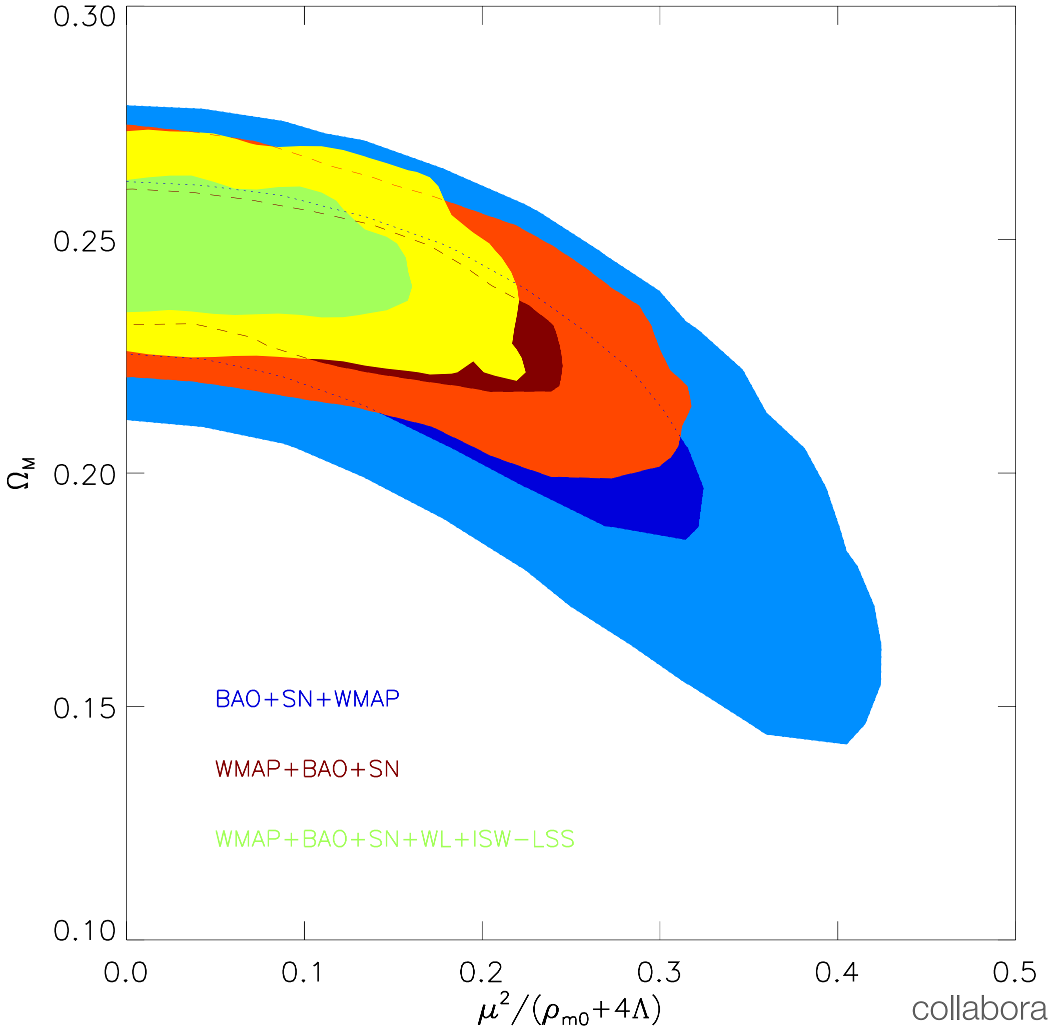




Beyond Background

- Can produce additional power on Large Scales
- Observed deviation to Large Scale features in CMB





collaboration with Rachel Bean.

- Places Limits on what constitutes a Signal of Dynamic Scalar mode

Thank You

Daniel Harlow

Stanford University

Operator Dictionaries and Wave Functions in Ads/CFT and dS/CFT

Generalized Friedmann Equations

BingKan Xue
Princeton University

PiTP 2011

Motivations

FRW metric (homogeneous and isotropic):

$$ds^2 = -dt^2 + a(t)^2\Big(\frac{dr^2}{1-\mathrm{k}\,r^2} + r^2 d\Omega_2^2\Big)$$

Friedmann equations:

$$H^2 = \frac{1}{3}\Big(\rho - \frac{3\mathrm{k}}{a^2}\Big)$$

$$\dot{H} = -\frac{1}{2}(\rho + P) + \frac{\mathrm{k}}{a^2}$$

Motivations

FRW metric (homogeneous and isotropic):

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More general situations (nonflat, inhomogeneous, anisotropic) ?

e.g. beginning of inflation or ekpyrosis, near the bounce ...

Timelike congruence and spatial hypersurface

General metric in ADM form with *lapse* $\mathcal{N}$ and *shift* β^i

$$ds^2 = -\mathcal{N}^2 d\tau^2 + \gamma_{ij}(dx^i + \beta^i d\tau)(dx^j + \beta^j d\tau)$$

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Spatial hypersurfaces of constant time,

$$\text{induced metric } \gamma_{ij} \qquad \Rightarrow \qquad \text{intrinsic curvature } {}^{(3)}R$$

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Timelike unit vector normal to the hypersurface, $n_\mu = (-\mathcal{N}, \vec{0}\,)$

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Kinematic decomposition of the timelike congruence

$$n^{i;j} = \tfrac{1}{3}\theta\gamma^{ij} + \sigma^{ij} - a^i n^j$$

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$$n^{i;j} = \tfrac{1}{3}\theta\gamma^{ij} + \sigma^{ij} - a^i n^j$$

volume expansion $\theta \equiv n^i{}_{;i}$ $\Rightarrow$ local expansion $3H$

shear $\sigma^{ij} \equiv n^{(i;j)} - \tfrac{1}{3}\theta\gamma^{ij}$ $\Rightarrow$ anisotropy $\sigma^2 \equiv \dfrac{1}{2}\sigma^{ij}\sigma_{ij}$

acceleration $a^i \equiv \dot{n}^i \equiv n_\nu n^{i;\nu}$

Local Friedmann equations

Stress-energy tensor of perfect fluid

$$T_{\mu\nu} = (\rho + P)u_\mu u_\nu + P g_{\mu\nu}$$

Energy density measured by the Eulerian observer $E = T_{\mu\nu} n^\mu n^\nu$

Local Friedmann equations

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Dynamics of timelike congruence (equivalent to 3+1 Einstein eqs)

$$\begin{aligned}
(\tfrac{1}{3}\theta)^2 &= \tfrac{1}{3}\big(E - \tfrac{1}{2}{}^{(3)}R + \sigma^2\big) \\
\tfrac{1}{3}\dot{\theta} &= -\tfrac{1}{2}\big(\tfrac{4E-\rho}{3} + P\big) + \tfrac{1}{6}{}^{(3)}R - \sigma^2 + \tfrac{1}{3}a^\mu{}_{;\mu} \\
\tfrac{1}{3}\theta_{|i} &= \tfrac{1}{2}\big(E + P\big)U_i + \tfrac{1}{2}\sigma^j{}_{i|j} \\
\tfrac{D_F}{ds}\sigma^i{}_j &= (E+P)U^i U_j - {}^{(3)}R^i{}_j - \theta\sigma^i{}_j - n^i\sigma_{jk}a^k - \tfrac{1}{3}\theta n^i a_j \\
&\quad + a^i{}_{;j} + a^i a_j + \dot{a}^i n_j - \tfrac{1}{3}\delta^i{}_j(E - \rho - {}^{(3)}R + a^\mu{}_{;\mu})
\end{aligned}$$

Homogeneous case

Recover Friedmann equations

$$H^2 = \tfrac{1}{3}\left(\rho - \tfrac{1}{2}{}^{(3)}R + \sigma^2\right)$$

$$\dot{H} = -\tfrac{1}{2}\left(\rho + P\right) + \tfrac{1}{6}{}^{(3)}R - \sigma^2$$

$$\dot{\sigma}^i{}_j = -3H\sigma^i{}_j - {}^{(3)}R^i{}_j + \tfrac{1}{3}\delta^i{}_j{}^{(3)}R$$

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curvature	${}^{(3)}R \propto \frac{1}{a^2}$	$\Rightarrow$	$w = -\frac{1}{3}$
anisotropy (flat)	$\sigma^2 \propto \frac{1}{a^6}$	$\Rightarrow$	$w = 1$

Homogeneous case

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anisotropy (flat)	$\sigma^2 \propto \frac{1}{a^6}$	$\Rightarrow$	$w = 1$

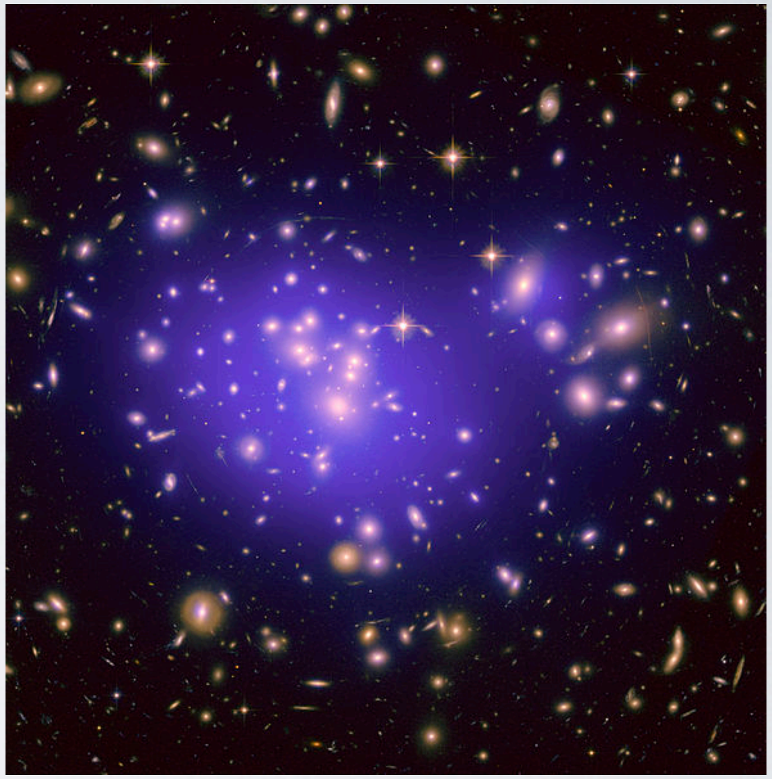
Implication: Inflation $w < -\frac{1}{3}$

Ekpyrotic contraction $w > 1$

OSCILLATING BISPECTRA AND GALAXY CLUSTERING: A NOVEL PROBE OF INFLATIONARY PHYSICS WITH LARGE-SCALE STRUCTURE

Francis-Yan Cyr-Racine, UBC   Fabian Schmidt, Caltech

ArXiv:1106.2806

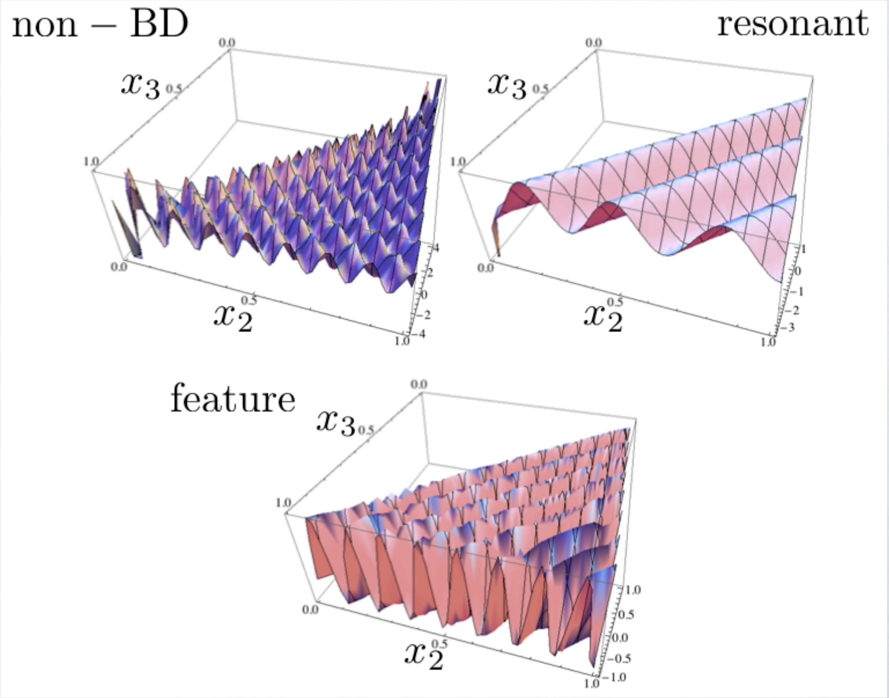


- Primordial Non-Gaussianities induce a scale-dependent bias between the matter and galaxy power spectrum.

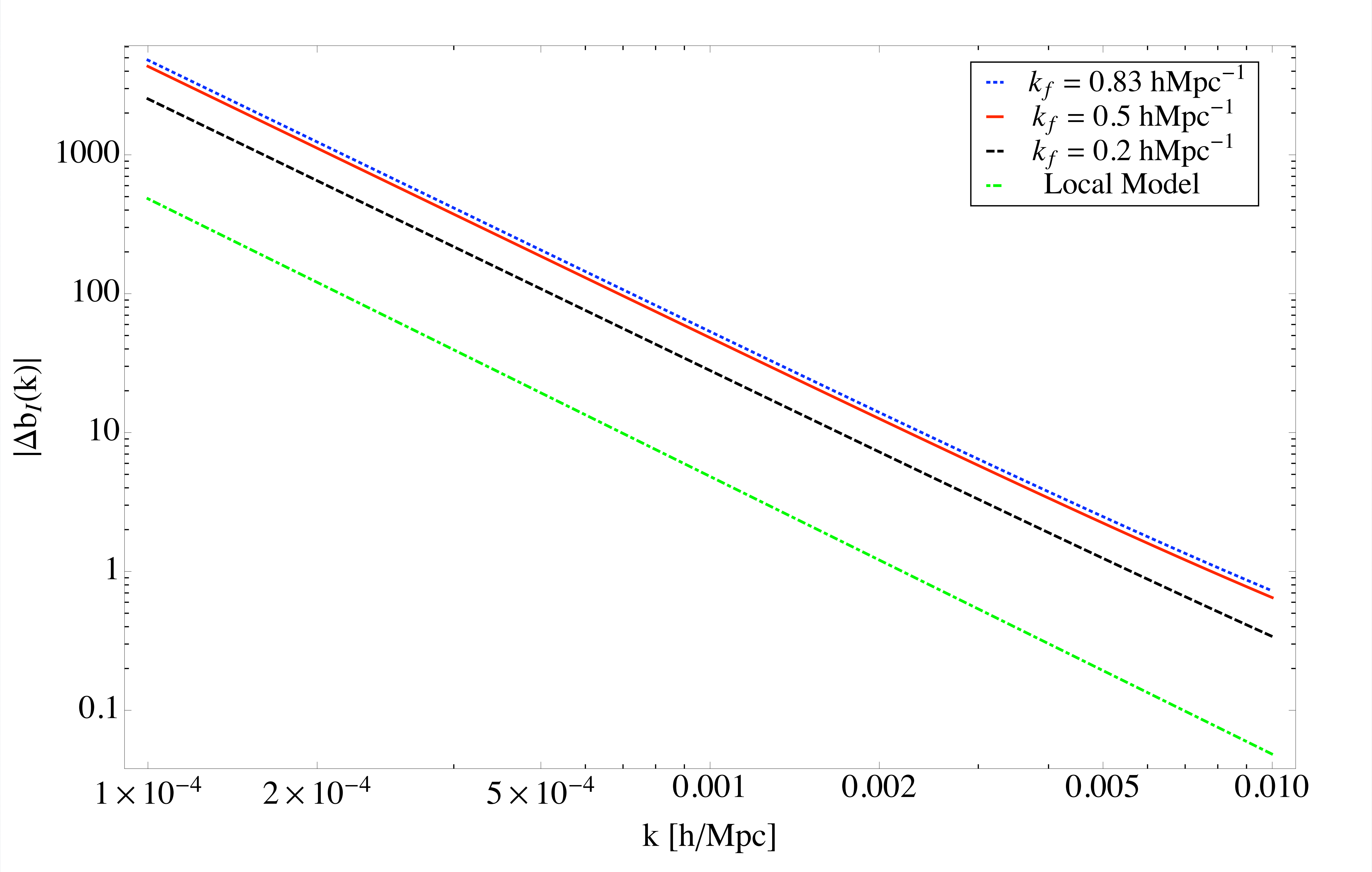
$$P_h(k) = b_I^2 P(k)$$

- We can use the bias to characterize the type of non-Gaussianities arising from Inflation.

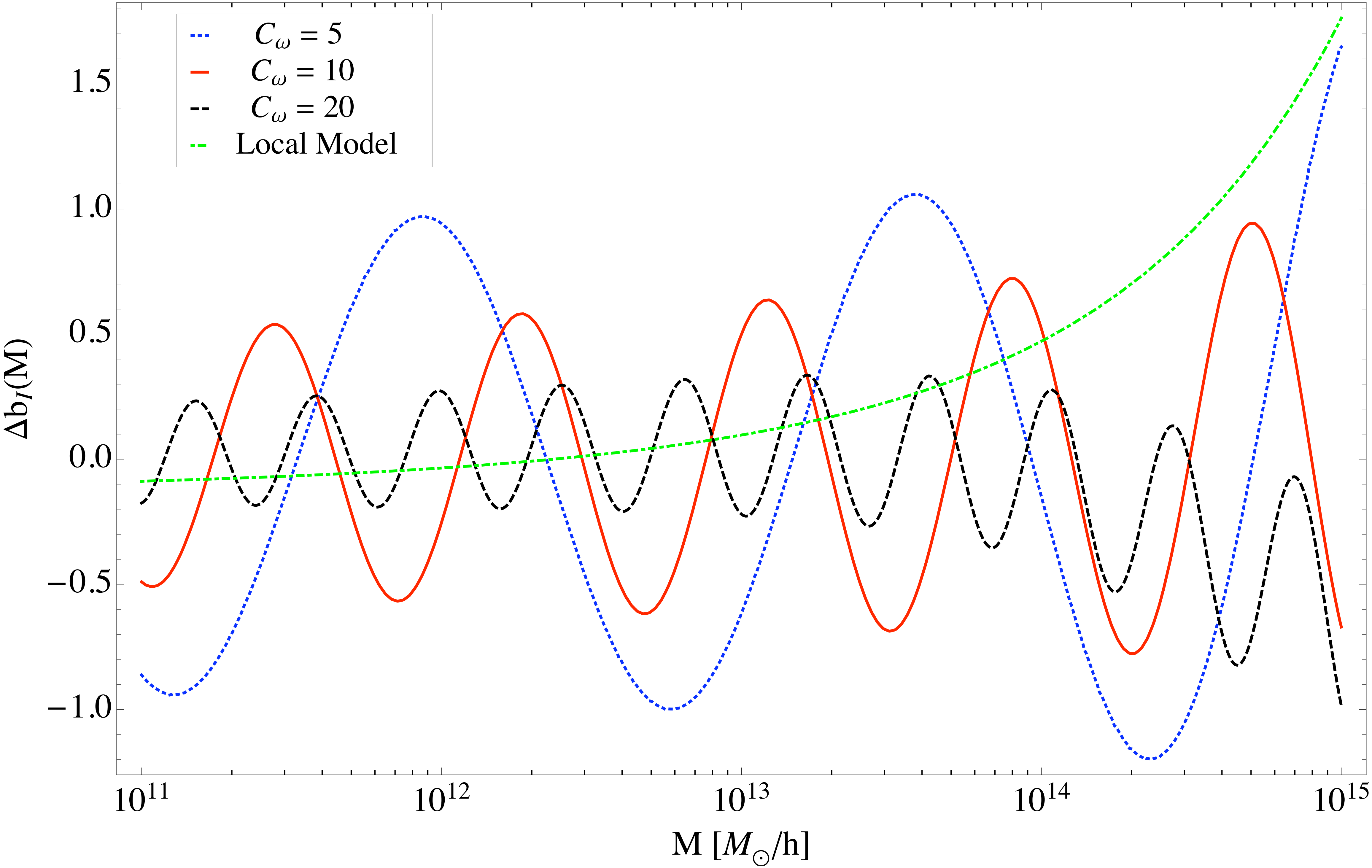
- Focus on oscillatory Bispectra.



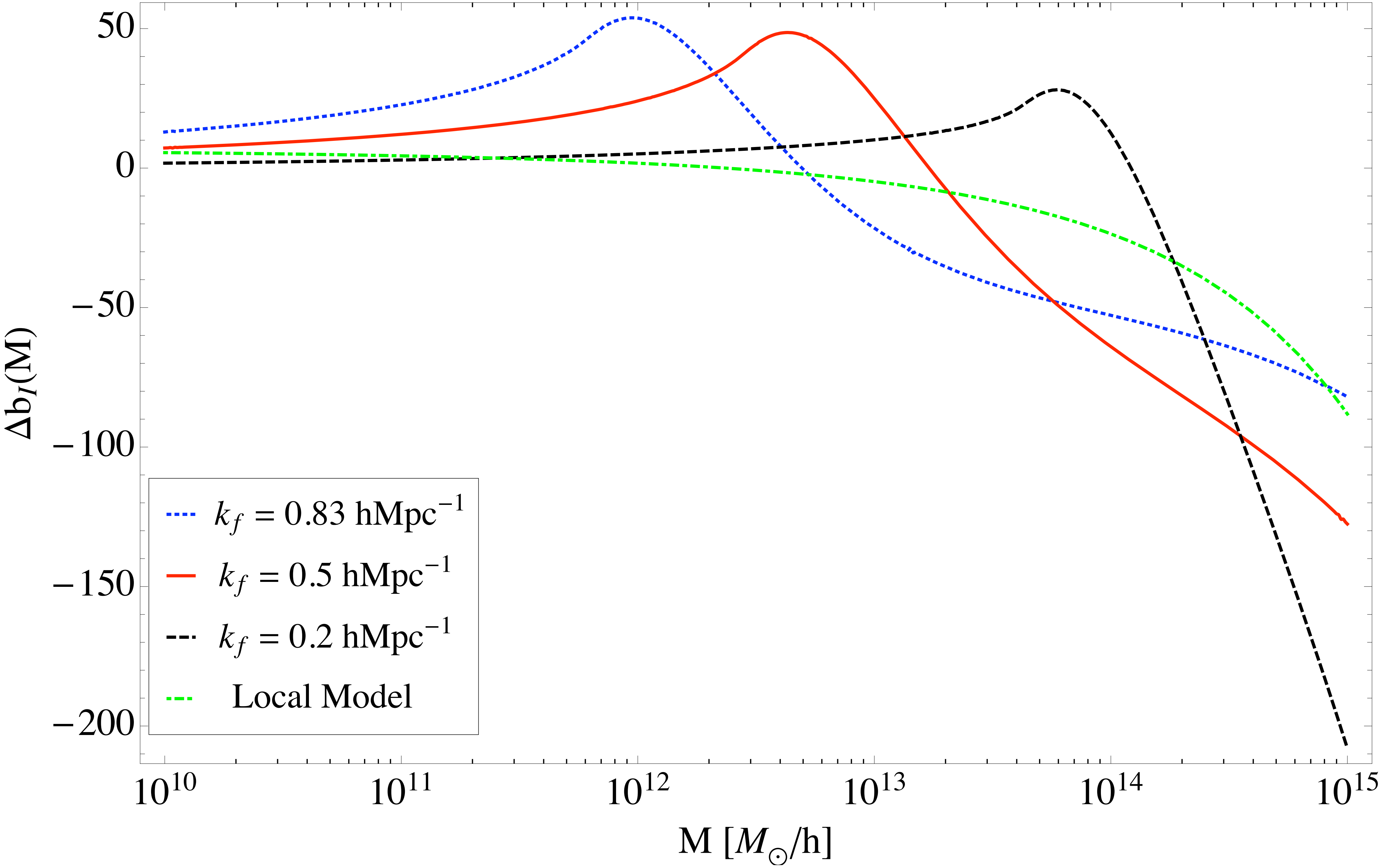
SCALE-DEPENDENT BIAS



RESONANT NON-GAUSSIANITY



FEATURE IN INFLATON POTENTIAL



An Effective Field Theory for Dark Energy

- Low energy descriptions of modifications to GR essentially behave like GR coupled to a scalar field, forming a scalar tensor theory
- Useful to generally parameterize dark energy models involving a scalar field
- Recent work has been performed to construct an effective field theory describing a scalar-tensor theory up to fourth order in derivatives (Weinberg 2008, Creminelli et al 2009, Park et al 2010)
- We extend these models, and in particular address the choice of conformal frame

A General Lagrangian to Four Derivatives

$$
\begin{aligned}
S = \int d^4x\sqrt{-g}\Bigg\{ & \frac{m_p^2}{2}\Omega^2(\phi)R - \frac{1}{2}\epsilon M^2 g^{\mu\nu}\partial_\mu\phi\partial_\nu\phi - U(\phi) \\
& + a_1(g^{\mu\nu}\partial_\mu\phi\partial_\nu\phi)^2 + a_2\Box\phi g^{\mu\nu}\partial_\mu\phi\partial_\nu\phi + a_3(\Box\phi)^2 \\
& + \frac{b_1}{\Lambda_m^2}T^{\mu\nu}\partial_\mu\phi\partial_\nu\phi + \frac{b_2}{\Lambda_m^2}Tg^{\mu\nu}\partial_\mu\phi\partial_\nu\phi + \frac{b_3}{\Lambda_m^2}T\Box\phi \\
& + c_1R^{\mu\nu}\partial_\mu\phi\partial_\nu\phi + c_2Rg^{\mu\nu}\partial_\mu\phi\partial_\nu\phi + c_3R\Box\phi \\
& + d_1W^{\mu\nu\lambda\rho}W_{\mu\nu\lambda\rho} + d_2\epsilon^{\mu\nu\lambda\rho}W_{\mu\nu}{}^{\alpha\beta}W_{\lambda\rho\alpha\beta} \\
& + d_3R^{\mu\nu}R_{\mu\nu} + d_4R^2 \\
& + \frac{e_1}{\Lambda_m^4}T^{\mu\nu}T_{\mu\nu} + \frac{e_2}{\Lambda_m^4}T^2 + \frac{e_3}{\Lambda_m^2}R_{\mu\nu}T^{\mu\nu} + \frac{e_4}{\Lambda_m^2}RT\Bigg\} \\
& + S_{\mathrm{matter}}\left[e^{\alpha(\phi)}g_{\mu\nu}\right]
\end{aligned}
$$

Low Energy Effective Action

- Work in Einstein frame for multiple cutoff scales to be well defined
- Reduce terms which introduce new degrees of freedom
- Take limits $M \ll \Lambda_m \ll m_p$

$$S = \int d^4x \sqrt{-g} \left\{ \frac{m_p^2}{2} R - \frac{1}{2} \epsilon M^2 g^{\mu\nu} \partial_\mu \phi \partial_\nu \phi - U(\phi) + a_1 (g^{\mu\nu} \partial_\mu \phi \partial_\nu \phi)^2 \right\}$$

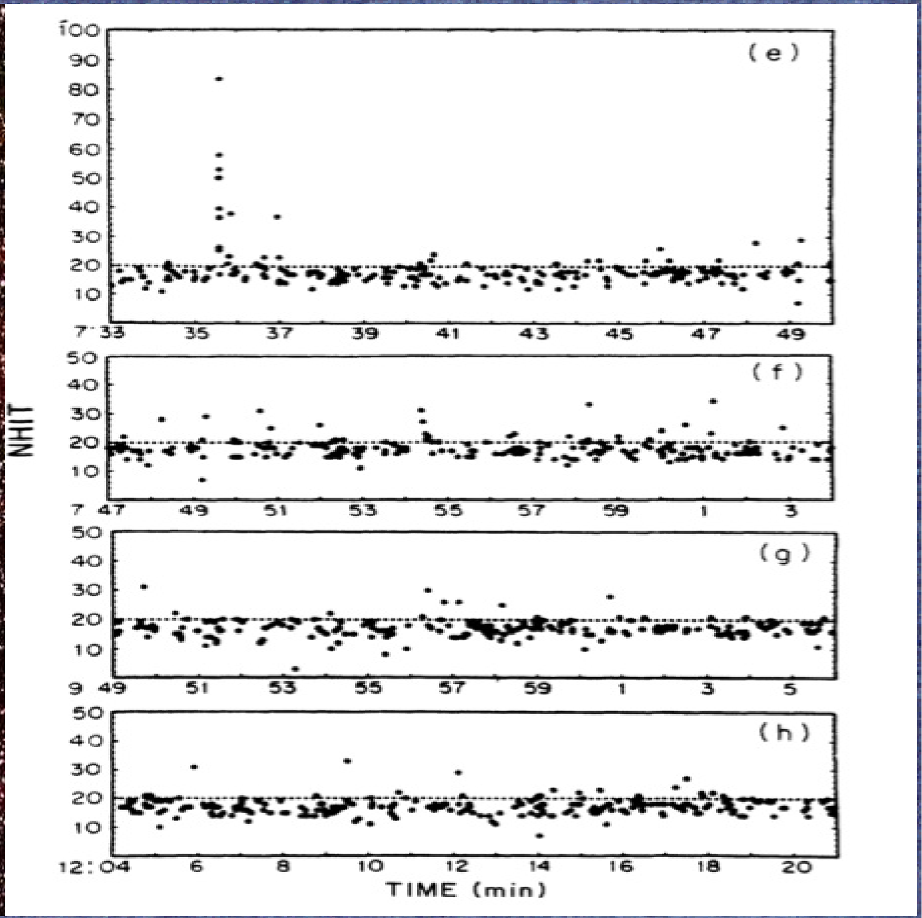
$$+ S_{\text{matter}} \left[e^{\alpha(\phi, (\nabla\phi)^2/\Lambda_m^2)} g_{\mu\nu} + \frac{\beta(\phi)}{\Lambda_m^2} \nabla_\mu \phi \nabla_\nu \phi \right]$$

What can we do with this formalism?

- Construct generic model-independent constraints
- Identify connections with other models
- Motivate searches for new models

Supernova Neutrinos

© Anglo-Australian Observatory



Ranjan Laha
Ohio State University

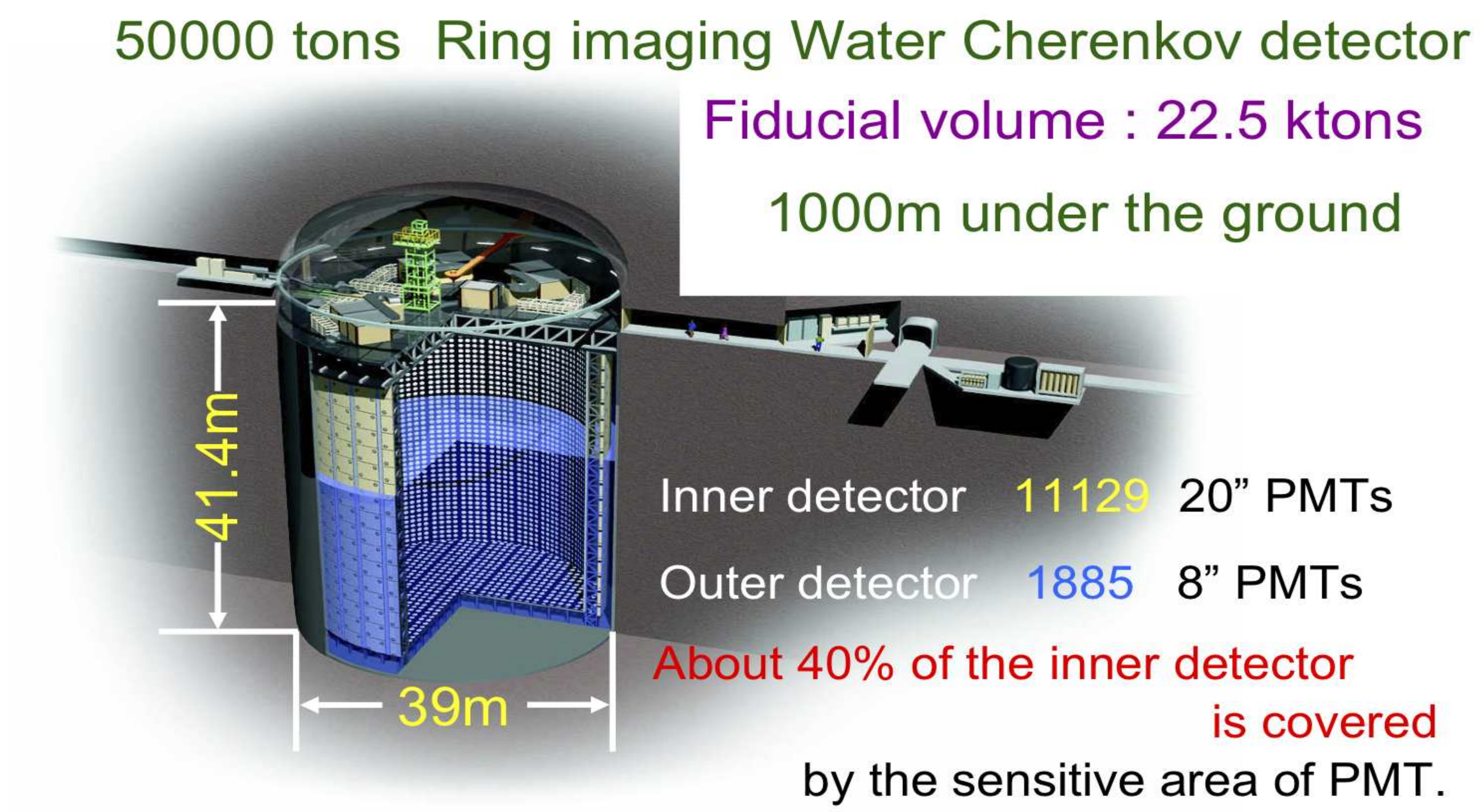
PiTP 2011

Detection reactions

$$\bar{\nu}_e + p \rightarrow e^{+} + n$$

$$\nu + e \rightarrow \nu + e$$

Super Kamiokande



50000 tons Ring imaging Water Cherenkov detector

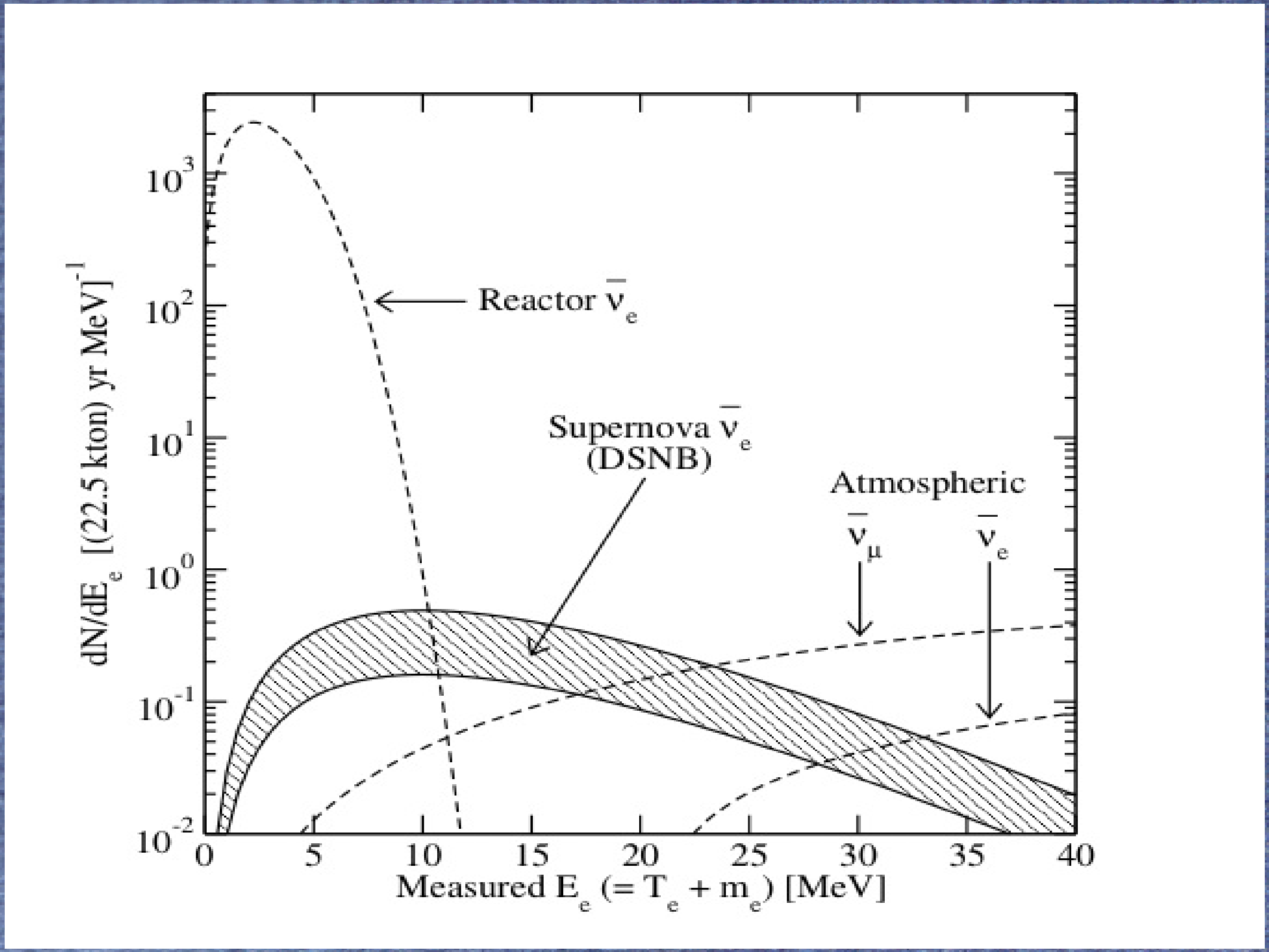
Fiducial volume : 22.5 ktons

1000m under the ground

Inner detector	11129	20” PMTs
Outer detector	1885	8” PMTs

About 40% of the inner detector is covered by the sensitive area of PMT.

Diffuse Supernova Neutrino Background



Add Gd to Super Kamiokande

Beacom and Vagins Phys.Rev.Lett. 93 (2004) 171101
EGADS project