Title: Infrared Challenges for Inflation

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Abstract: I will review some recent work on infrared issues for scalar fields in exact and quasi de Sitter space. Renewed interest in this topic has been driven by the observational potential for a more accurate determination of statistics of the primordial curvature perturbations, especially non-Gaussianity. Interestingly, the resulting questions are not only relevant for mapping inflationary models to observation but also link directly to more fundamental questions about the initial state, eternal inflation, and the long time dynamics of interacting quantum fields in curved space. Infrared questions provide a precisely calculable way to put pressure on inflation as a rigorous and consistent framework, ready to confront future observations.

Infrared Challenges for Inflation

Sarah Shandera
Perimeter Institute

with C.P. Burgess, R. Holman, L. Leblond (0912.1608; 1005.3551)
with T. Galvez Ghersi, G. Gheshnizjani, F. Piazza (1103.0783)

Reminder: de Sitter IR

Massive field: $\delta = M^2/3H^2$

$\langle \phi(x)^2 \rangle =$

Massless field:

A. Linde, hep-th/0503203

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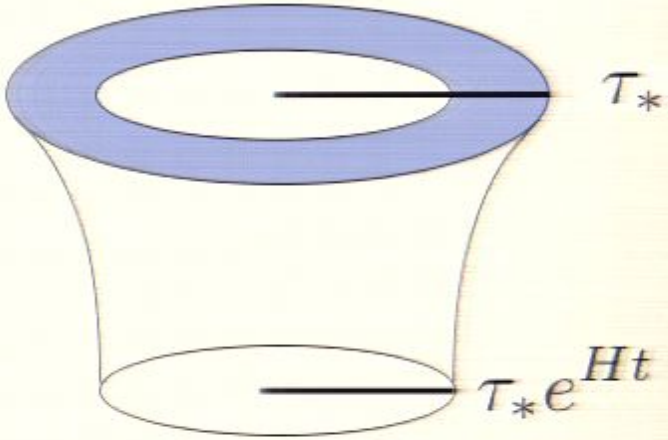

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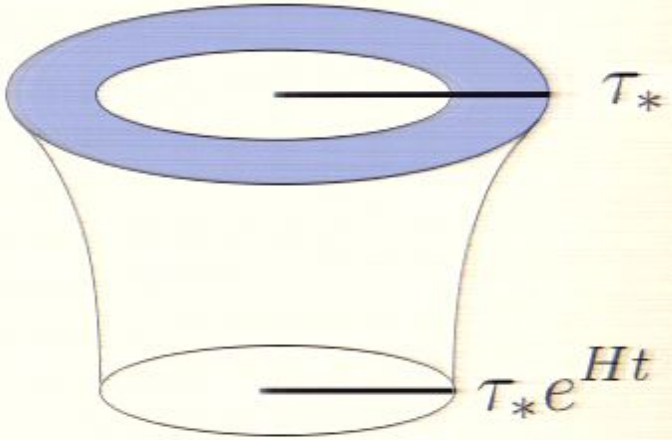

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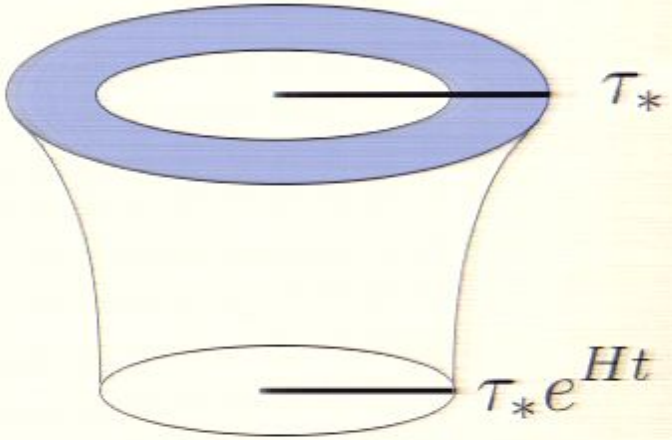

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Infra-Red? Again?

INFRA-RED? AGAIN?

DATA!

- non-Gaussianity (Planck, Large Scale Structure surveys)
- Interactions: $\langle \zeta^n \rangle \quad n > 2$ (ζ *curvature*)
  - Gravitational
  - Everything Else
- Expect patterns

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  - Gravitational
  - Everything Else
- Expect patterns
- Matching a scenario → Testing the Idea

(MODERN) NATURAL INFLATION

$$\mathcal{L}_0 = -\frac{1}{2}(\partial\varphi)^2 - \frac{1}{4f}\varphi G^a\tilde{G}^a - \frac{\alpha}{4f}\varphi F\tilde{F} + \sum_{n=1}^{\infty} c_n \frac{(\partial\varphi)^{2n+2}}{f^{4n}} + \cdots$$
$$+V_{\rm ex}(\varphi) + \mu^4\left[1 - b\cos\left(\frac{\varphi}{f}\right)\right]$$

- Opportunity! Characteristic bispectra; patterns among moments
- Calculational Challenge: Interacting QFT

(Contrast T. Banks' talk)

Freese; Silverstein, Westphal; Barnaby, Peloso; Chen et al; Flauger, Pajer; Lobland, Pajer)

WHAT MATTERS?

(WHAT'S NEW?)

- Matter fields are *not spectators* (*semi-classical*)
- Matter fields *interact*
- Background is *not exact, eternal dS*
- Initial state may *not* be *Bunch Davies* vacuum
- Match/predict *observables* post inflation

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* *Techniques should be able to handle all this*

WHY IR ISSUES ARE INTERACTION ISSUES

$$\langle \zeta(k)^2 \rangle \sim \frac{H^2}{k^3} \frac{1}{\epsilon M_p^2}$$

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Observer's two-point function:

$$\langle \zeta(x)\zeta(y) \rangle \sim \int_{L_{IR}^{-1}} \frac{dk}{k} \frac{Sin[k|\vec{x}-\vec{y}|]}{k|\vec{x}-\vec{y}|} e^{-kR}$$

$$\sim \text{Log}\left[\frac{|\vec{x}-\vec{y}|]}{L_{IR}}\right]$$

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WHY IR ISSUES ARE INTERACTION ISSUES

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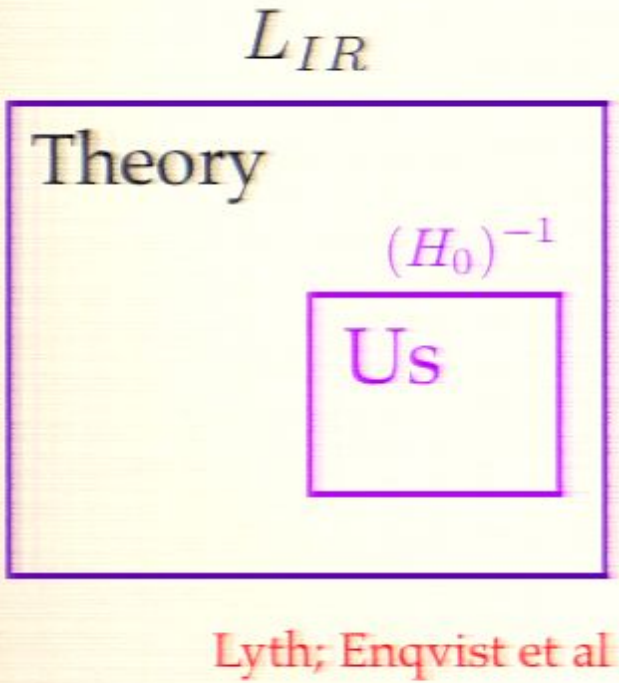
* No IR scale except horizon size (local background sets the "0")

"Curvature in a Box"



Lyth; Enqvist et al

"Curvature in a Box"

L_{IR}

Theory

$(H_0)^{-1}$

Us

Lyth; Enqvist et al

* Add interactions
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- Is $\langle \zeta_k^2 \rangle_0$ actually divergent?
- What regulates the IR?
- Are obs. sensitive to loops?
- Are obs. sensitive to regulator?
- What lessons?

Toy problem:

Spectator scalar with quartic interaction

$$S = -\int \mathrm{d}^4x\,\sqrt{-g}\,\left[\frac{1}{2}\,g^{\mu\nu}\,\partial_\mu\phi\,\partial_\nu\phi + V_0 + \frac{m_0^2}{2}\,\phi^2 + \frac{\lambda_0}{4!}\,\phi^4\right]$$

C.P. Burgess, R. Holman, L. Leblond, S. Shandera
(0912.1608, 1005.3551)

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Other work: Starobinsky, Yokoyama ('94); Riotto, Sloth; van der Meulen, Smit; Petri; Marolf, Morrison; Garbrecht, Rigopoulos

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Mechanics for Evaluating Correlators

$$\langle \mathcal{O}(t) \rangle = \left\langle \text{in} \left| \left[\overline{\text{T}} \exp\left(\text{i} \int_{\text{t}_{\text{in}}}^{\text{t}} \text{dt}' \, \mathcal{H}(\text{t}') \right) \right] \mathcal{O}(\text{t}) \left[\text{T} \exp\left(-\text{i} \int_{\text{t}_{\text{in}}}^{\text{t}} \text{t}' \, \mathcal{H}(\text{t}') \right) \right] \right| \text{in} \right\rangle$$

Double the fields: $\phi \to \{\phi^+, \phi^-\}$

$$G_c = -\frac{i}{2}\left(G^{-+} + G^{+-}\right)$$

$$G_R^0(k, \tau_1, \tau_2) = \theta(\tau_1 - \tau_2)\left(G^{-+} - G^{+-}\right)$$

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Evaluating Diagrams

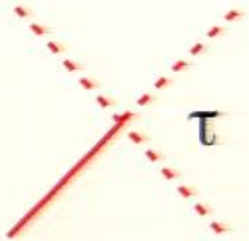
$k\tau \ll 1$

$$G^0_C(k,\tau,\tau) \simeq \frac{H^2}{2k^3}(k\tau)^{2\delta}$$

$$G^0_R(k,\tau_1,\tau_2) \simeq \theta(\tau_1-\tau_2)\frac{H^2}{3}(\tau_1^{3-\delta}\tau_2^{\delta}-\tau_1^{\delta}\tau_2^{3-\delta})$$

Interactions

$-ia^4(\tau)\lambda$



$-ia^4(\tau)\frac{\lambda}{4}$

Use:

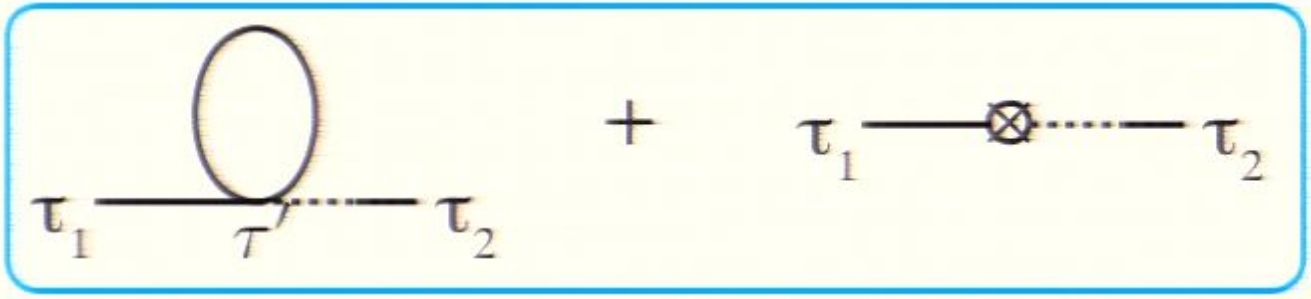
Flat slicing

Bunch Davies

$\delta = M^2/3H^2$

Shandera; PI; July 15, 2011

1-LOOP



- Momentum integral, Time integral

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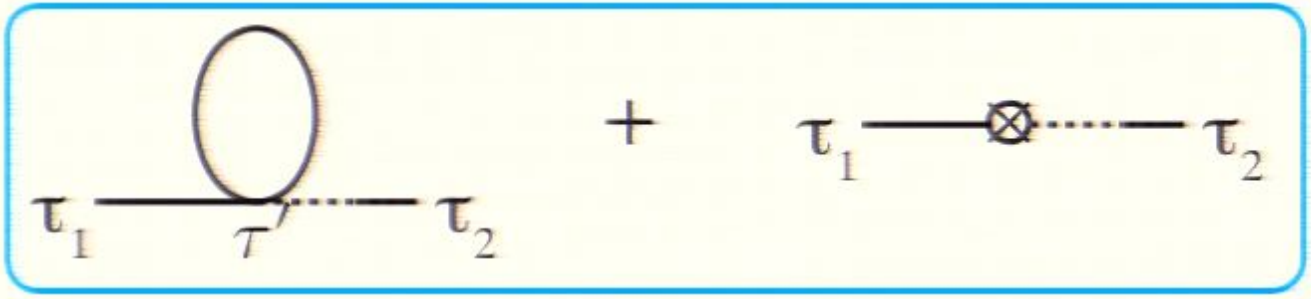

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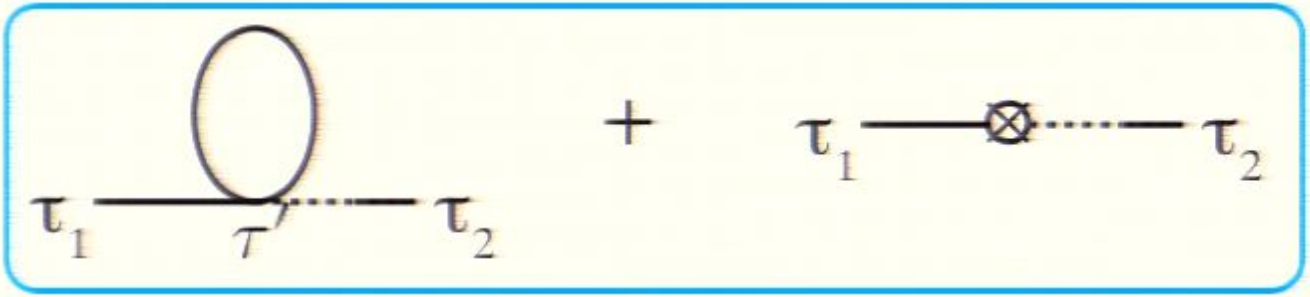
$$\Lambda(\tau) \simeq \frac{H^2}{(2\pi)^2}\int_{a\,\Lambda_{IR}}^{a\,\Lambda_{UV}}\frac{dp}{p}\,(-p\,\tau)^{2\delta} + \text{c.t.} \simeq \frac{H^2}{(2\pi)^2}\int_{a\,\Lambda_{IR}}^{a\,\mu}\frac{dp}{p}\,(-p\,\tau)^{2\delta}$$

$$\simeq \frac{1}{2\delta}\left(\frac{H}{2\pi}\right)^2\left[\left(\frac{\mu}{H}\right)^{2\delta} - \left(\frac{\Lambda_{IR}}{H}\right)^{2\delta}\right]$$

1-LOOP



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Physical scale; *Comoving* scale would introduce $a(\tau')$

1-LOOP, CONT'D

* Momentum integral, Time integral

$$G_c^1(k,\tau,\tau) = -\lambda \left[\frac{1}{2\delta}\left(\frac{H}{2\pi}\right)^2\left(\frac{\mu}{H}\right)^{2\delta}\right]\frac{1}{6k^3}\int_{-1/k}^{\tau}\frac{d\tau'}{\tau'}\left[\left(\frac{\tau}{\tau'}\right)^{3-\delta}-\left(\frac{\tau}{\tau'}\right)^{\delta}\right](k^2\tau'\tau)^{\delta}$$

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- So the full answer:

$$G_C(k,\tau) \simeq \frac{H^2}{2k^3}(-k\tau)^{2\delta}\left[1+\frac{\lambda}{6(2\pi)^2\delta}\left(\frac{\mu}{H}\right)^{2\delta}\ln(-k\tau)+\cdots\right]$$

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* So the full answer:

renormalization scale

secular growing term

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"IR" scale (physical)

SUMMING UP THE LOGS

* Apply "Dynamical Renormalization Group":

(Boyanovsky, de Vega)

$$G_C(k,\tau) \simeq \frac{H^2}{2k^3}(-k\tau)^{2\delta+\Delta_m}$$

$$\Delta_m = \frac{\lambda}{6(2\pi)^2\delta}\left(\frac{\mu}{H}\right)^{2\delta}$$

L.P. Burgess, R. Holman, L. Leblond, S. Shandera

(0912.1608, 1005.3551)

Shandera: PI: July 15, 2011

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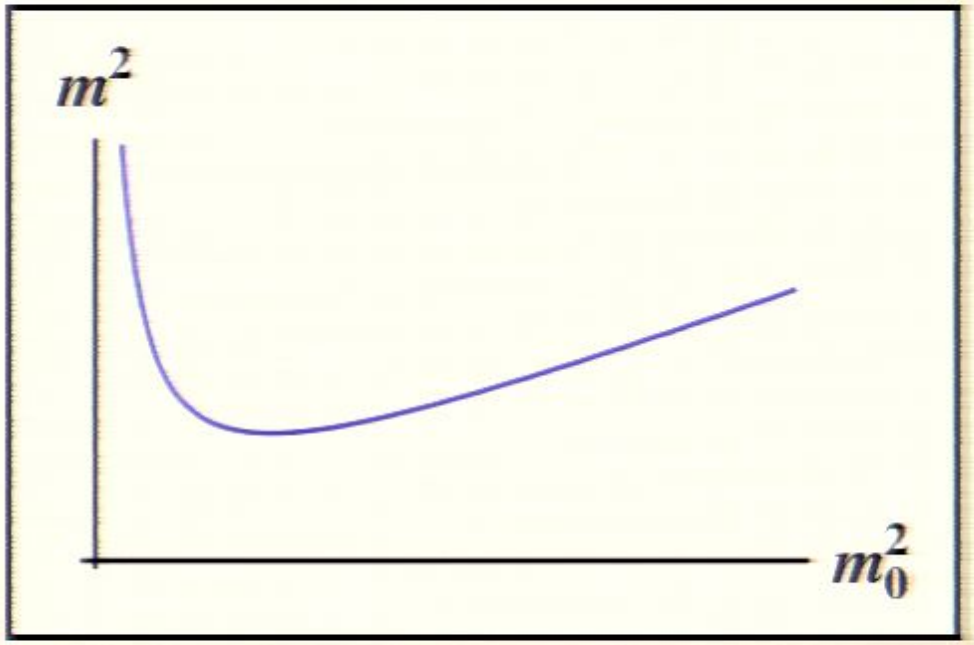
$$m^2 = m_0^2 + \lambda\frac{H^4}{m_0^2}$$



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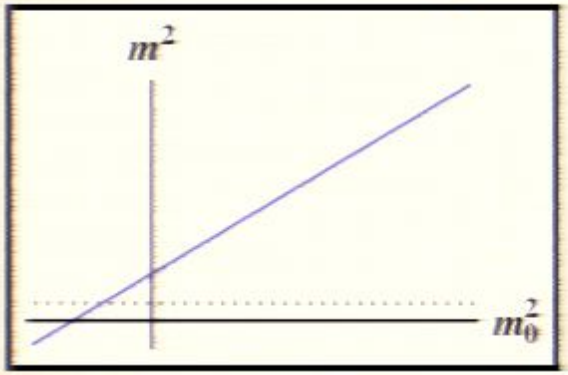
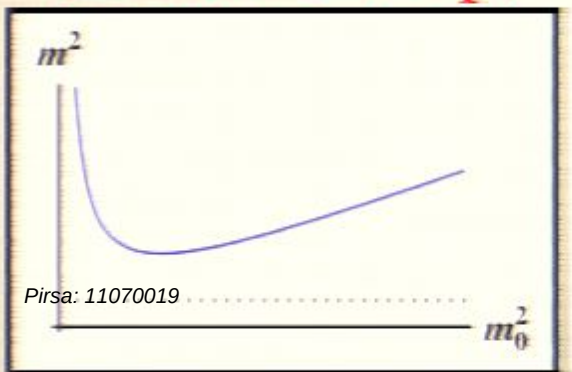
Similar to Thermal FT

Thermal:
(Div. at 2 loops)



dS:
(Div. at 1 loop)



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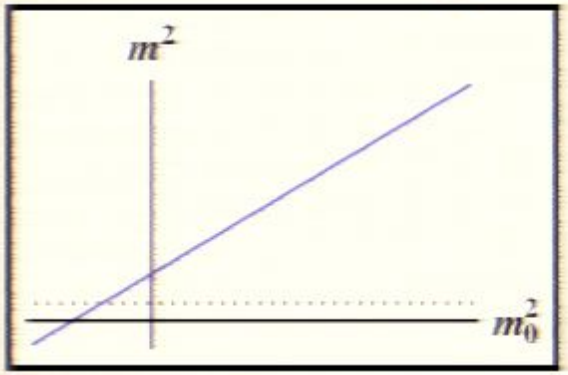

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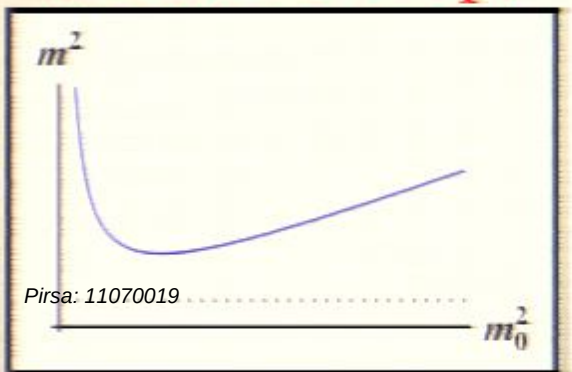

Loop size	$\mathcal{O}(1)$	$\mathcal{O}(\sqrt{\lambda})$	$\mathcal{O}(\lambda)$
	m_C	m_{dyn}	m_{max}
Thermal	λT	$\sqrt{\lambda} T$	T
de Sitter	$\sqrt{\lambda} H$	$\lambda^{1/4} H$	H

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Lessons?

1. Similar, not identical, to *stochastic* result. (Why?)

$$m_{\rm dyn} = A\,\lambda^{1/4} H$$

✱ What range of applicability for stochastic (eg, with sound horizon?)

2. How to count relevant modes (*measure?*)

Back to a massive Scalar:

- How many super-horizon modes matter?

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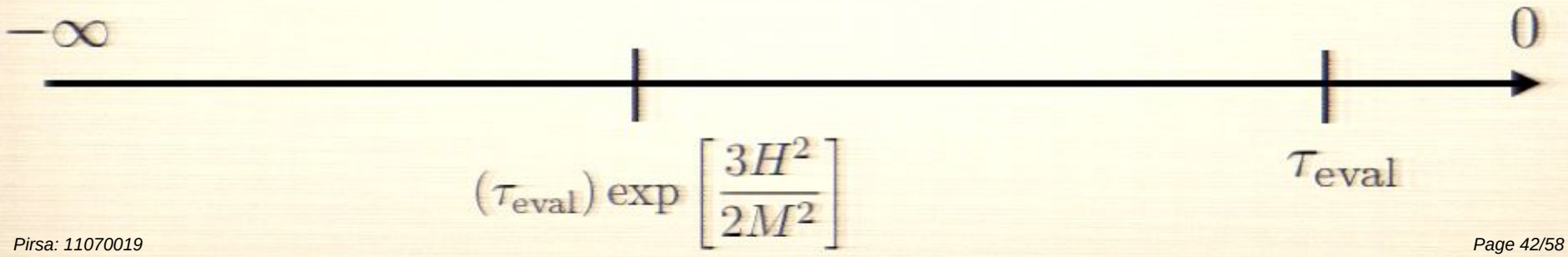

Inflationary Observables

- Use the 'resummed' story to define the background in the Hubble patch...
- what about fluctuations?

$$\langle \zeta_k^2 \rangle = \langle \zeta_k^2 \rangle_0 [1 + \alpha_1 \langle \zeta(x)^2 \rangle_* + \alpha_2 \langle h(x)^2 \rangle_* + \dots]$$

$$\langle h_k^2 \rangle = \langle h_k^2 \rangle_0 [1 + \alpha_3 \langle \zeta(x)^2 \rangle_* + \alpha_4 \langle h(x)^2 \rangle_* + \dots]$$

$$\alpha_1 \, , \alpha_3 \propto n_s - 1$$

$$\alpha_2 \, , \alpha_4 \propto n_t$$

Sloth; Giddings, Sloth;

Shandera; PI; July 15, 2011

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Inflationary Observables, cont'd

$$\langle \zeta(x)^2 \rangle_* \approx \int_{a_i H}^{a_* H} \frac{dk}{k} \frac{H^2}{4\pi^2} \frac{1}{2\epsilon M_p^2} \sim H^3 t$$

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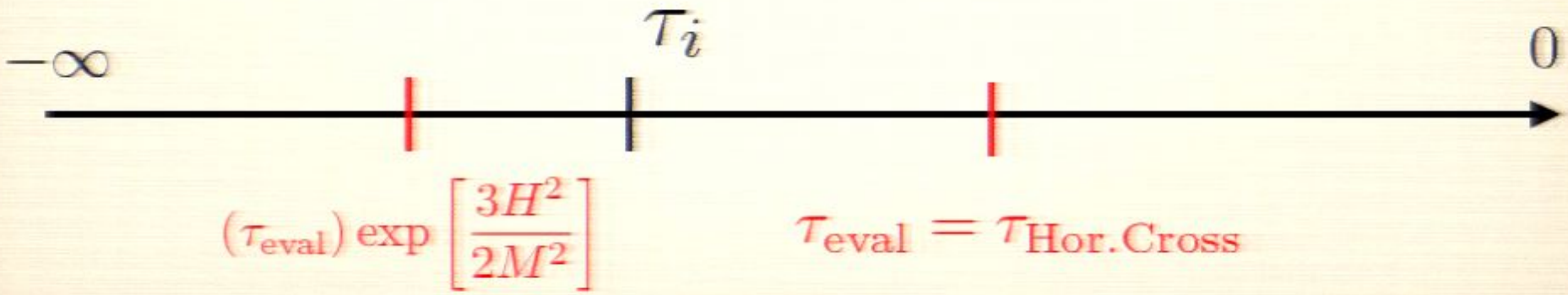
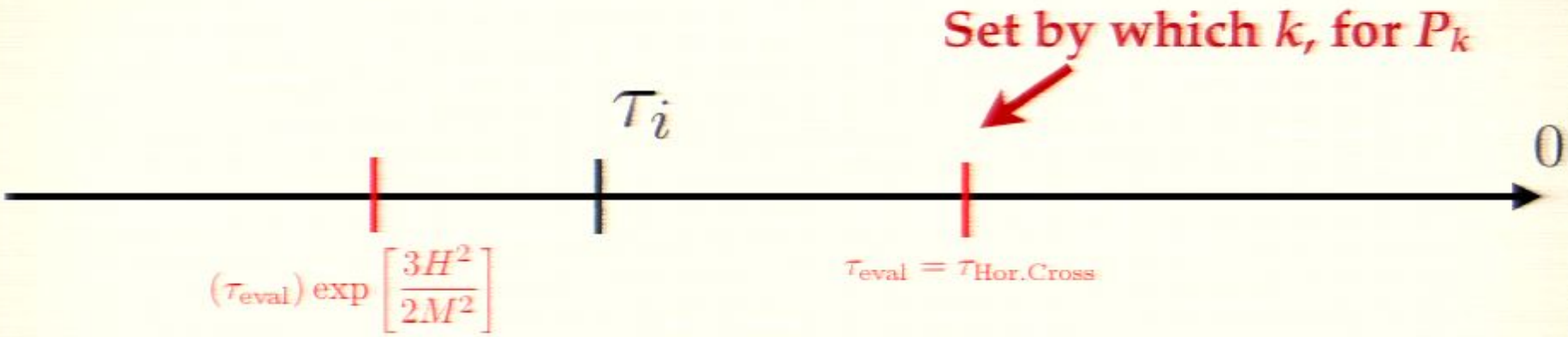
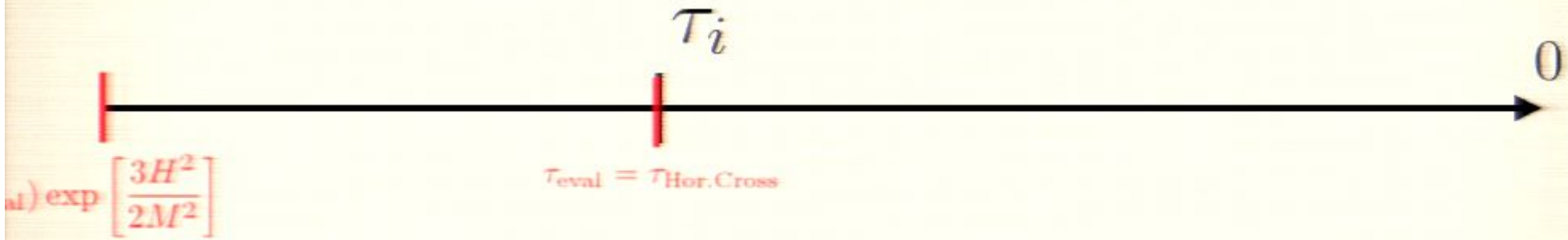
Inflationary Observables, cont'd

$$\langle \zeta(x)^2 \rangle_* \approx \int_{a_i H}^{a_* H} \frac{dk}{k} \frac{H^2}{4\pi^2} \frac{1}{2\epsilon M_p^2} \sim H^3 t$$

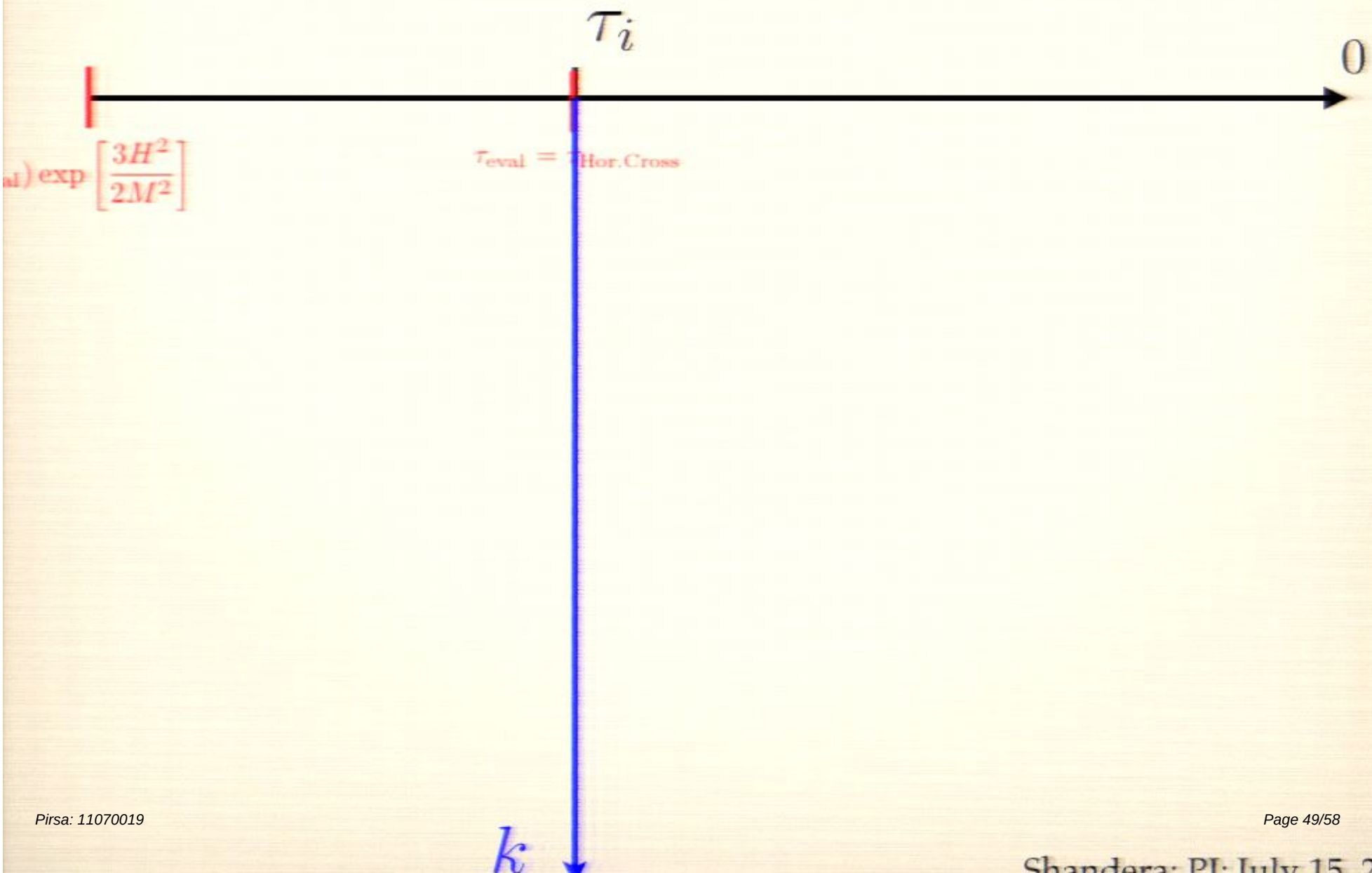
$$\langle h(x)^2 \rangle_* \approx \int_{a_i H}^{a_* H} \frac{dk}{k} \frac{H^2}{4\pi^2} \sim H^3 t$$



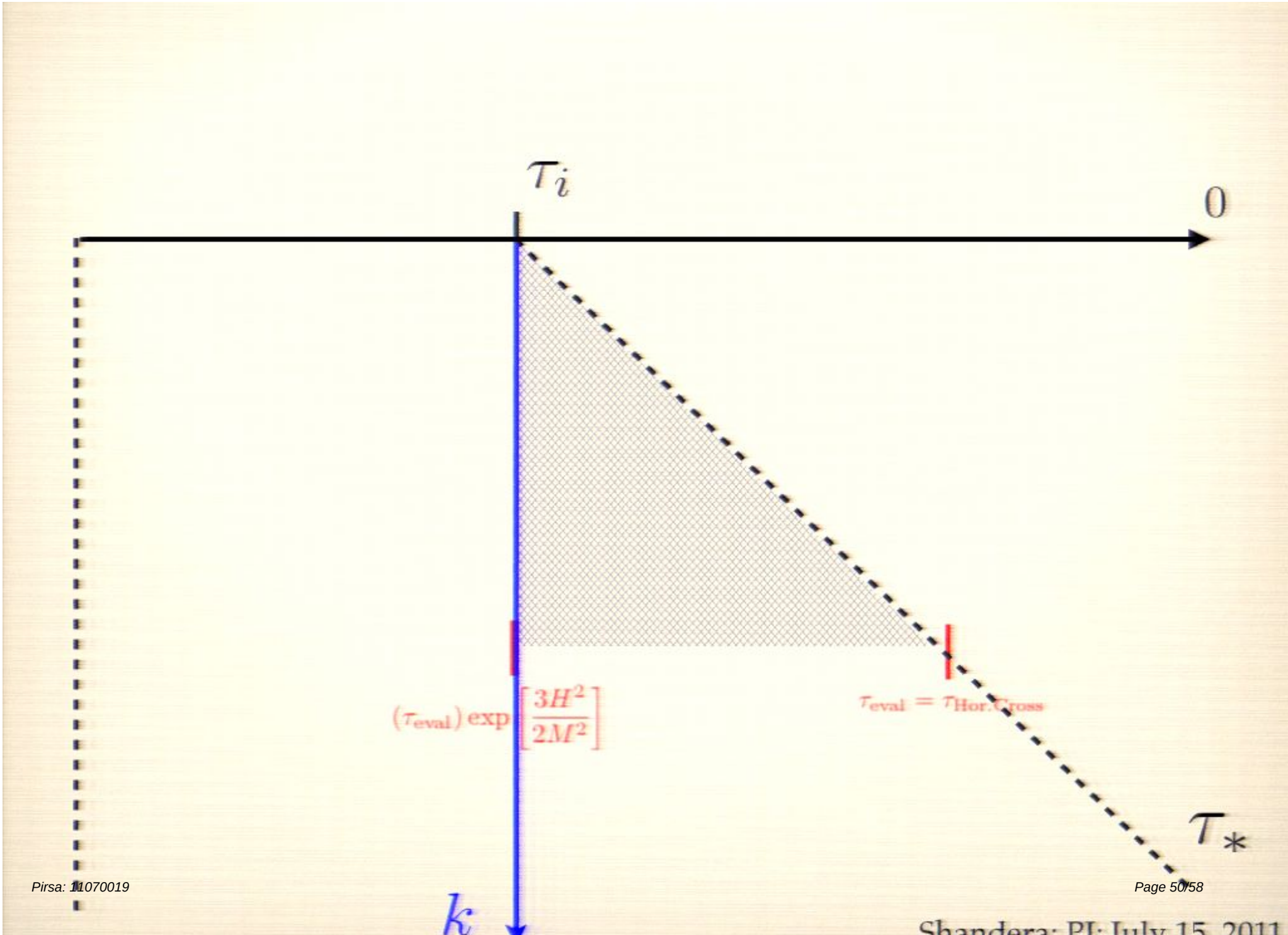

Set by which k, for P_k
τ_i
0
$(\tau_{\rm eval})\exp\left[\frac{3H^2}{2M^2}\right]$
$\tau_{\rm eval} = \tau_{\rm Hor.Cross}$

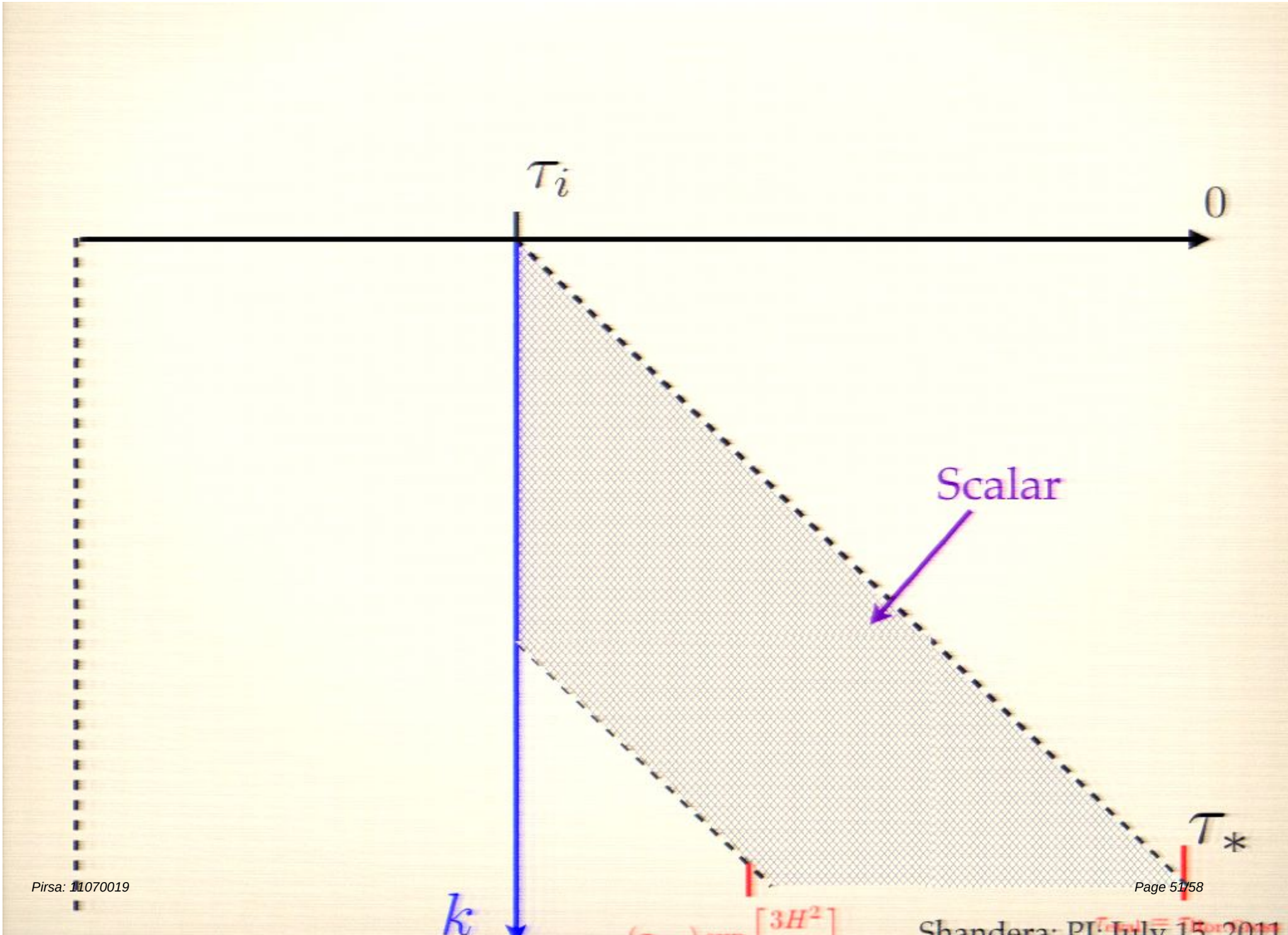


$\left.\text{al}\right) \exp\left[\frac{3H^2}{2M^2}\right]$



Shandera; PI; July 15, 2011


τ_i
0
$(\tau_{\rm eval})\exp\left[\frac{3H^2}{2M^2}\right]$
$\tau_{\rm eval} = \tau_{\rm Hor.Cross}$
τ_*
k


τ_i
0
Scalar
τ_*
k
$[3H^2]$

Future Directions I:
Infrared Puzzle?

$$\langle \zeta_k^2 \rangle = \langle \zeta_k^2 \rangle_0 [1 + \alpha_1 \langle \zeta(x)^2 \rangle_* + \alpha_2 \underbrace{\langle h(x)^2 \rangle_*}_{H^3 t} + \dots]$$

Perturbative breakdown?

$$t > \frac{M_p^2}{H^3} \sim H^{-1} \times \frac{H^{-2}}{G} \sim RS$$

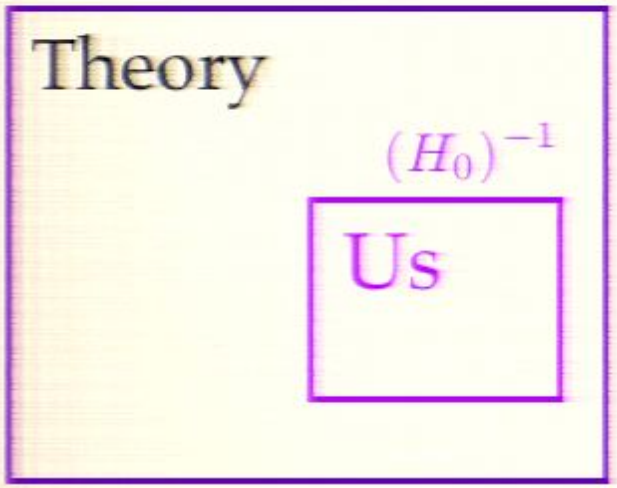
- Stochastic eternal inflation...must have quasi dS
- A sharp analogy to BH information?

kani-Hamed et al; Giddings; Giddings, Sloth;
Leonardo's talk;

Future Directions II:

Matching & Simulating

L_{IR}

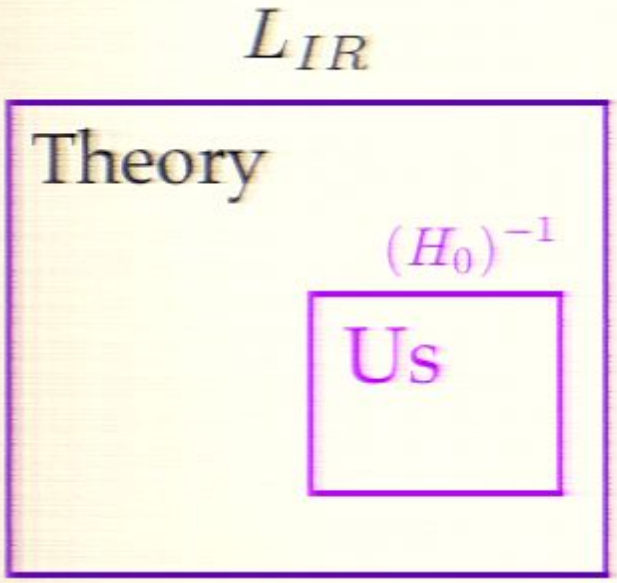


- Two-Point:

$$\langle \zeta_k^2 \rangle \propto A_0 \left(\frac{k}{k_0} \right)^{n_s - 1}$$

Loop-corrections (re)normalize

Future Directions II:
Matching & Simulating



- Two-Point:

$$\langle \zeta_k^2 \rangle \propto A_0 \left(\frac{k}{k_0} \right)^{n_s - 1}$$

Loop-corrections (re)normalize

- Three-Point:

$$\langle \zeta_{k_1} \zeta_{k_2} \zeta_{k_{12}} \rangle \propto AB(k_1, k_2, k_{12})$$

Loop-corrections: change the shape?

Summary

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* Why do we care? Is it observable?

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Present Day Dark Energy