
Violent preheating in inflation with nonminimal coupling

Ryusuke Jinno (IBS-CTPU)



Based on

RJ Ph.D.Thesis

arXiv:1609.05209 with Y.Ema, K.Mukaida and K.Nakayama

Violent preheating in Higgs inflation

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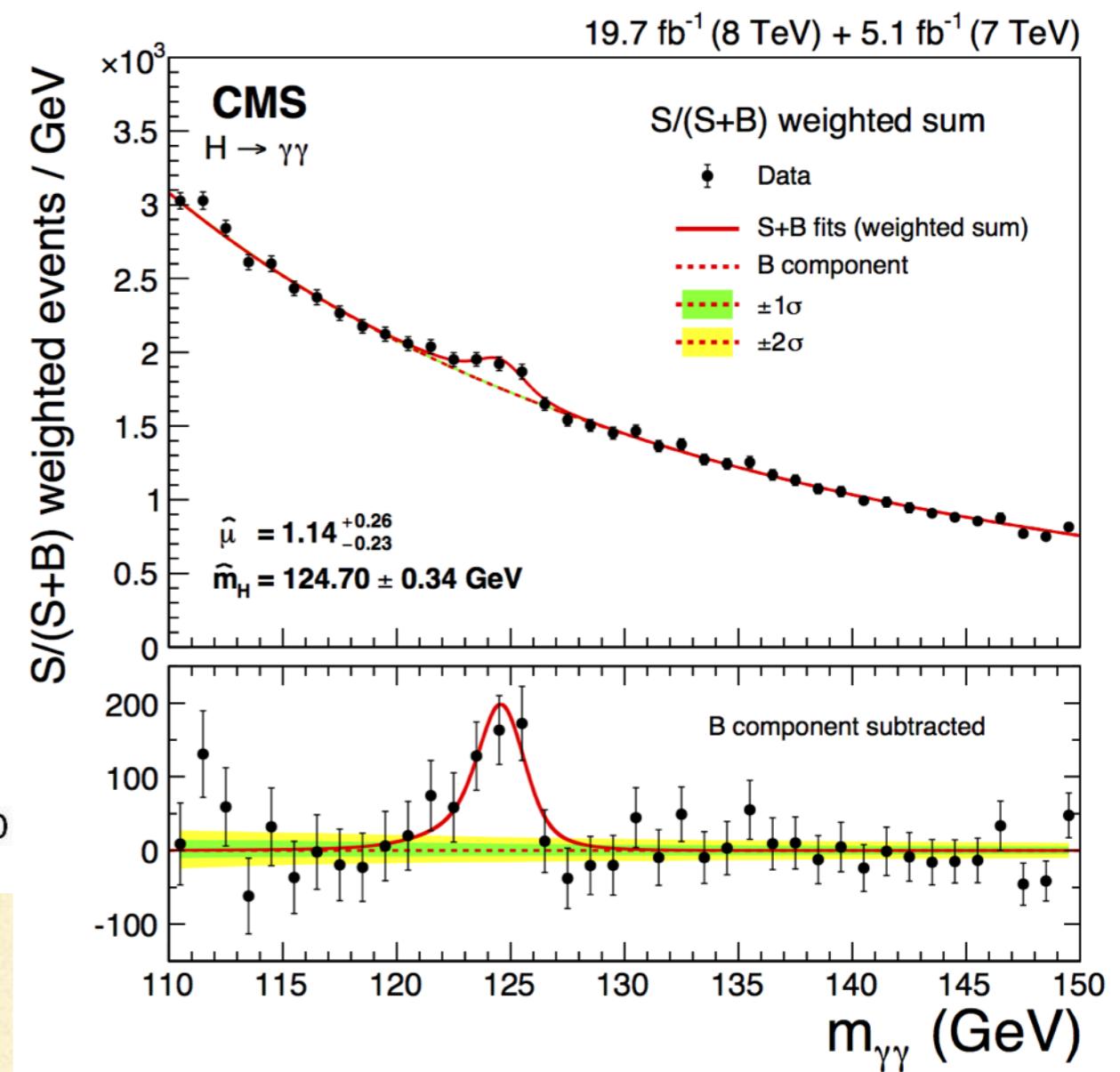
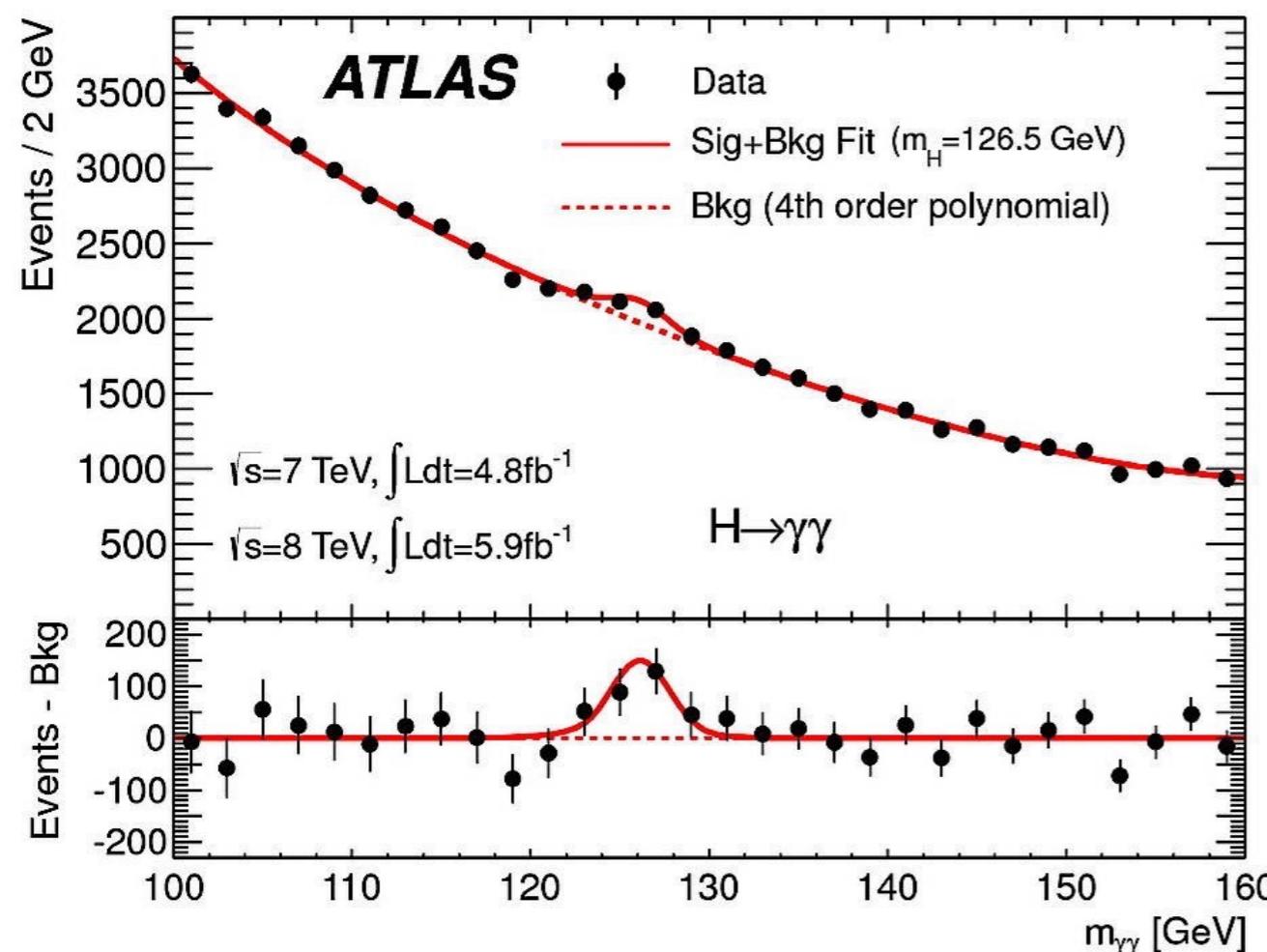


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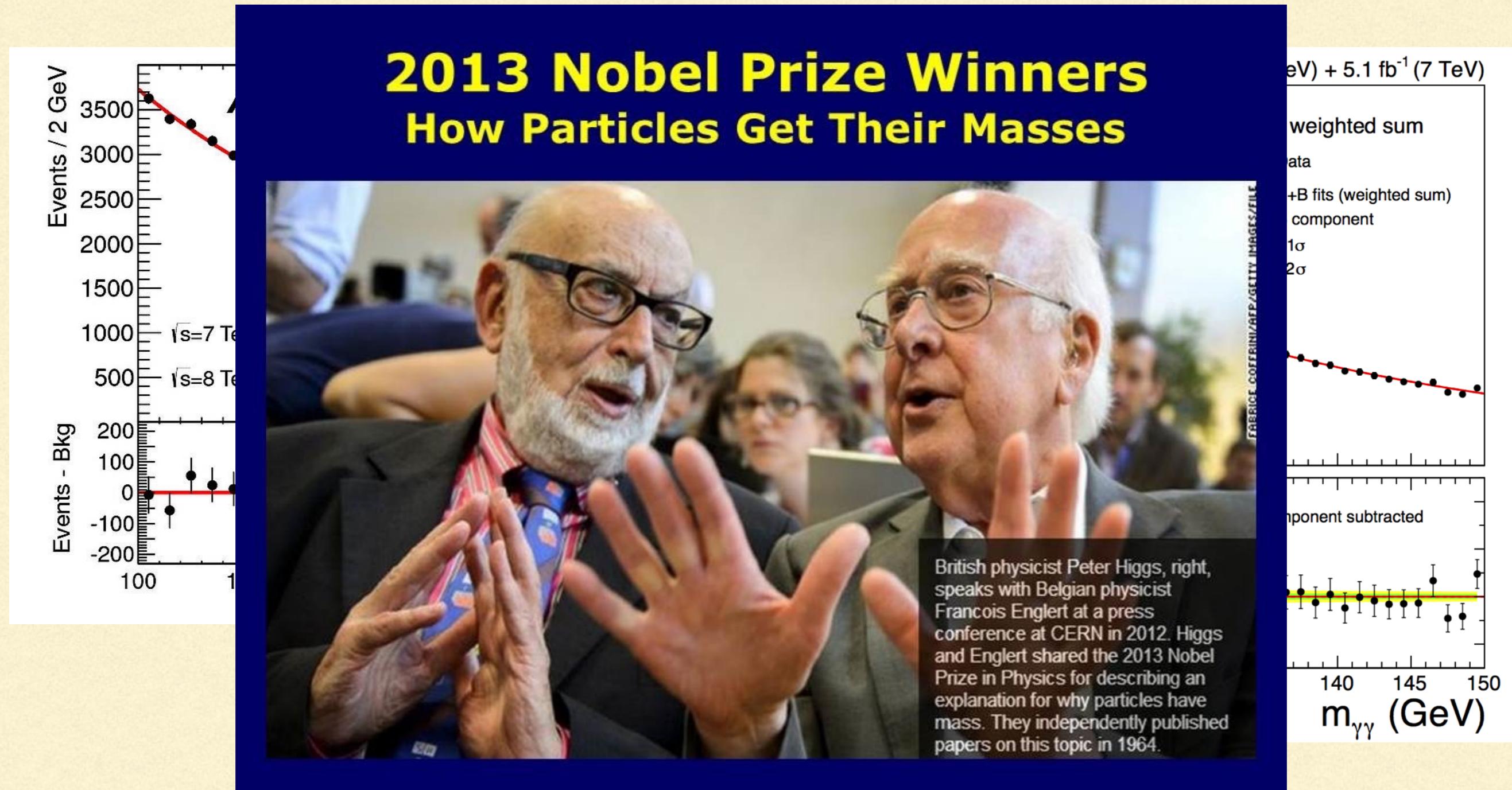
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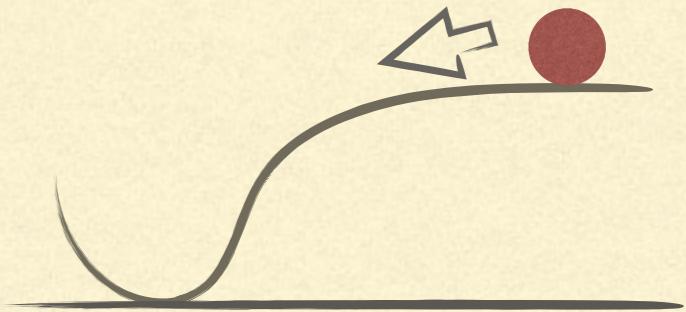
HIGGS DISCOVERY



HIGGS DISCOVERY



HIGGS AS THE INFLATON

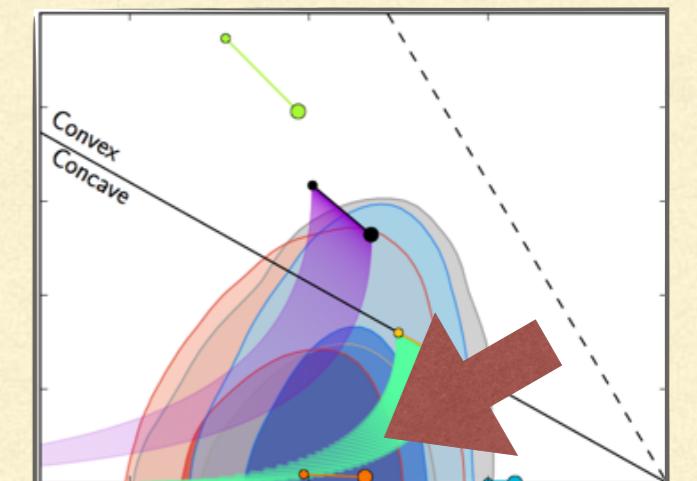


- Inflaton = Higgs ? [Cervantes-Cota & Dehnen '95]

- Nonminimal coupling $\xi\phi^2 R$ makes the potential flat

[Futamase & Maeda '89]

→ Excellent agreement with observations [Bezrukov & Shaposhnikov '08]

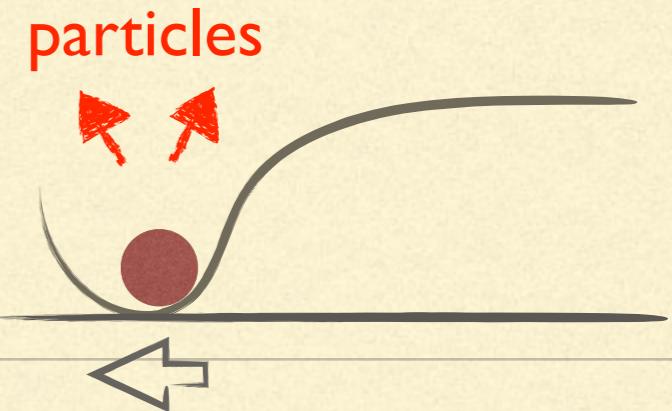


- Several advantages

1. Economical : no need to add new fields

2. Predictable : the whole history is (in principle) calculable

PREHEATING



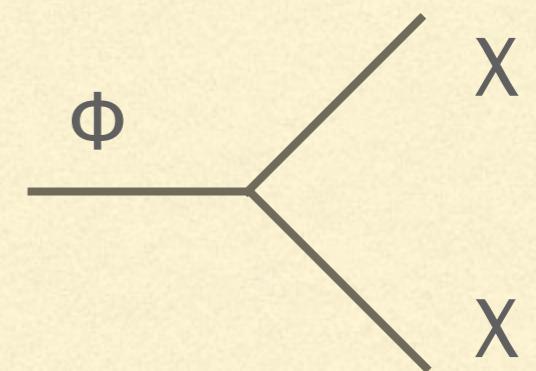
- Inflation is just the beginning of the story

Inflation

(P)reheating :

{ Energy transfer from inflaton to light particles
&
Thermalization of these particles

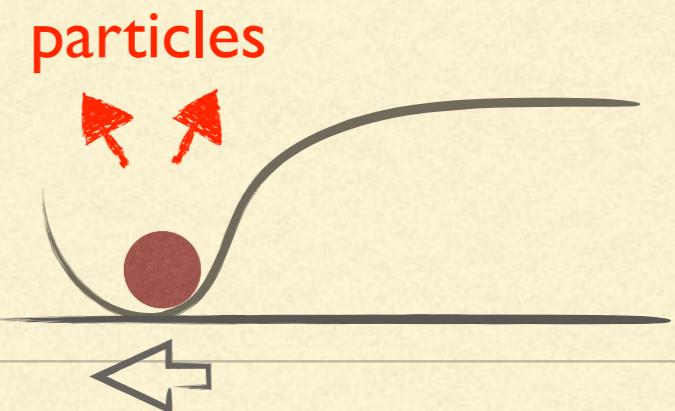
[Bezrukov, Gorbunov, Shaposhnikov '09,
Garcia-Bellido, Figueroa, Rubio '09, ...]



BBN, CMB, ...

t

PREHEATING



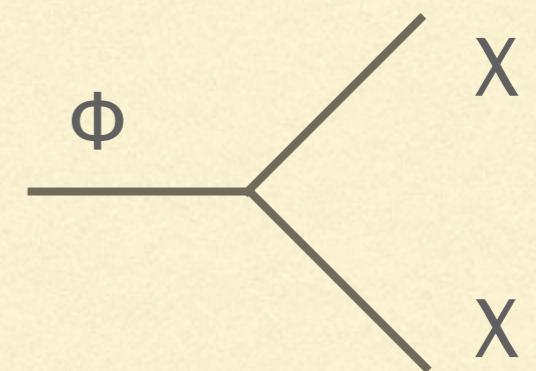
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Inflation

(P)reheating

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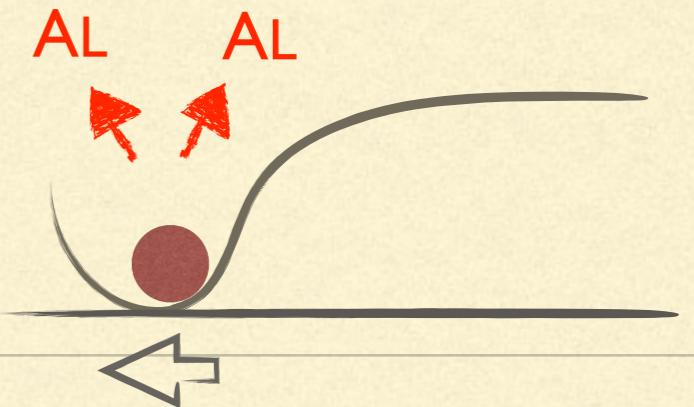
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BBN, CMB, ...

SUMMARY



- Main channel of energy transfer is overlooked in the literature:

Longitudinal gauge boson

- These G.B.s have momentum $\sim \lambda^{1/2} M_P$ (λ : 4-point coupling of Higgs)
- G.B. energy scale exceeds the cutoff scale \rightarrow UV completion required

OUTLINE

0. Introduction

I. Higgs inflation : Standard lore

2. Higgs inflation : Explosive longitudinal G.B. production

Higgs inflation : Standard lore

ACTION

- Consider REAL inflaton for the moment, for simplicity

Free parameter

$$\xi \sim 50000\sqrt{\lambda} \gg 1$$

$$S = \int d^4x \sqrt{-g_J} \left[\left(\frac{M_P^2}{2} + \frac{\xi}{2} \phi_J^2 \right) R_J - \frac{1}{2} (\partial \phi_J)^2 - V_J(\phi_J) \right]$$

Real inflaton

Ricci scalar

Potential $\frac{\lambda}{4} \phi_J^4$

$$\lambda \sim 0.01$$

Jordan frame :

ϕ_J and R_J are nonminimally coupled ($\xi \phi_J^2 R$)

INFLATION IN EINSTIEN FRAME

Note : conformal factor

$$\Omega^2 = 1 + \frac{\xi\phi_J^2}{M_P^2}$$

- Nonminimal coupling is eliminated as

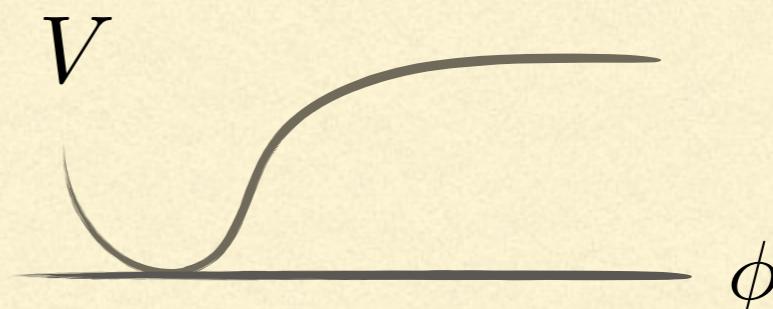
$$S = \int d^4x \sqrt{-g} \left[\frac{M_P^2}{2} R - \frac{1}{2} (\partial\phi)^2 - V(\phi) \right]$$

by conformal trans.: $g_{\mu\nu} \equiv \Omega^2 g_{J\mu\nu}$, which gives $R_J = \Omega^2 R + \dots$

inflaton redefinition : $\frac{d\phi}{d\phi_J} \equiv \begin{pmatrix} \text{some complicated} \\ \text{func. of } \phi_J \end{pmatrix}$ & $V(\phi) \equiv \frac{V_J(\phi_J)}{\Omega^4}$

Einstein frame :

No nonminimal coupling



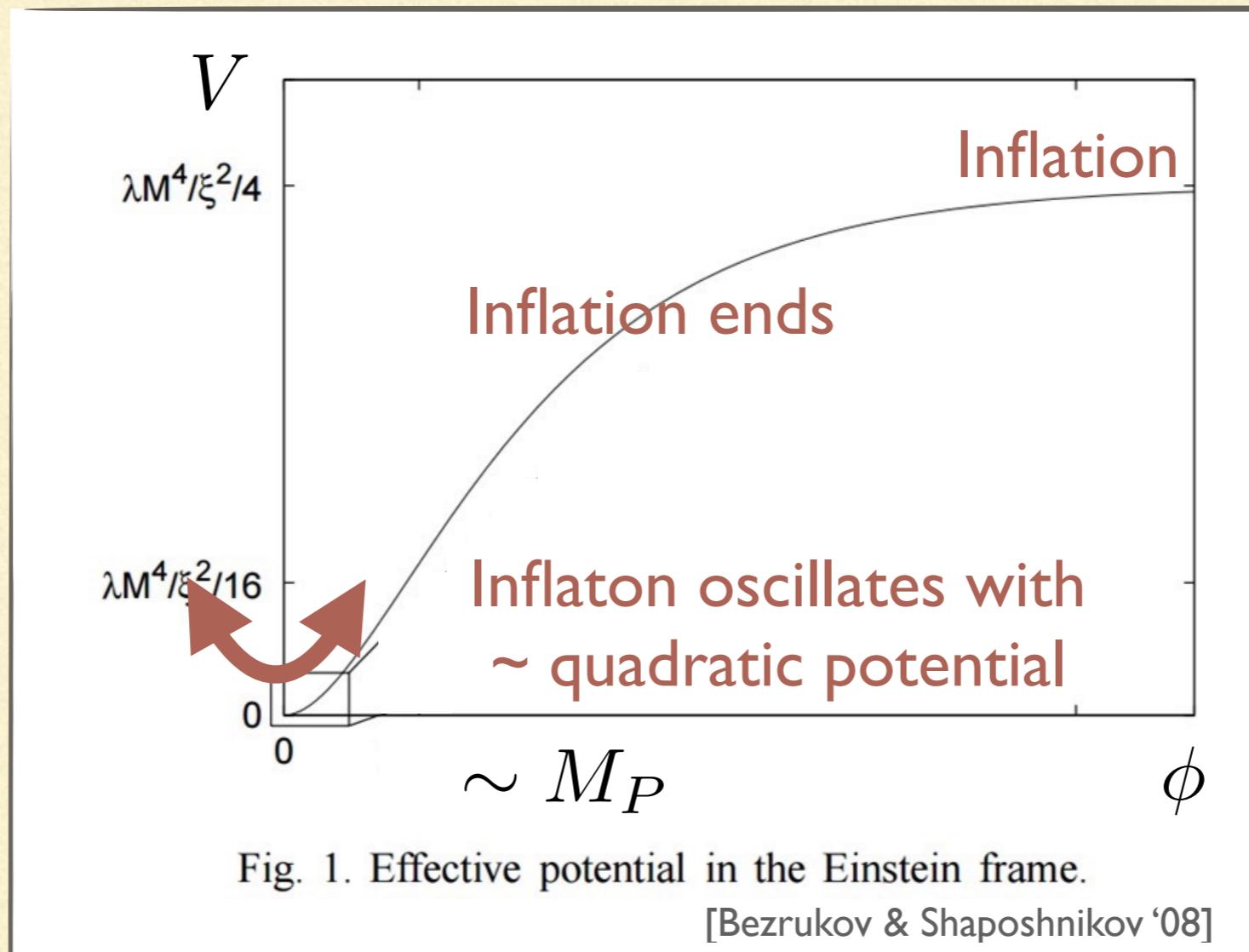
INFLATION IN EINSTEIN FRAME

Note :

$$\xi \sim 50000\sqrt{\lambda} \gg 1$$

from CMB normalization

■ Potential in the Einstein frame



(P)REHEATING

- Let's make inflaton to be SM Higgs Φ_J

Terms in SM Lagrangian
(Gauge boson etc.)

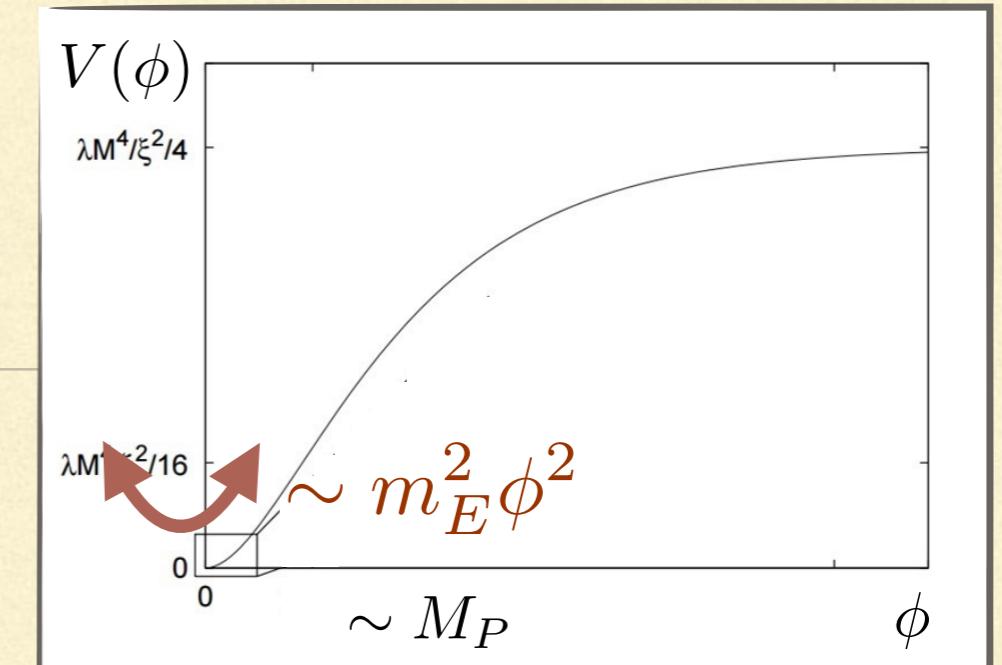
$$S = \int d^4x \sqrt{-g_J} \left[\left(\frac{M_P^2}{2} + \xi |\Phi_J|^2 \right) R_J - \overbrace{|D\Phi_J|^2 - V_J(|\Phi_J|) + \dots}^{\text{(Gauge boson etc.)}} \right]$$

- Taking unitary gauge $\Phi_J = \frac{1}{\sqrt{2}}(0, \phi_J)^T$ (ϕ_J : real),

- ϕ_J dynamics : same as real inflaton (slow-roll \rightarrow oscillation)
- gauge boson mass oscillates as the inflaton oscillates

(P)REHEATING

- Note : Something is **WRONG** below !



- Gauge boson (3 dof) mass oscillates like

$$m_W^2 \sim g^2 \phi_J^2 \sim g^2 \frac{M_P}{\xi} |\phi| \sim |\sin m_E t|$$

- Mass oscillation leads to particle production
- Production of gauge bosons → soon decay into fermions
- After ~100 oscillations, parametric resonance of gauge bosons starts ...

Higgs inflation : Explosive gauge boson production

WHAT'S MISSING IN THE LITERATURE

- Let's take U(1) (not SU(2)) gauged Higgs for simplicity
- What's missing in the literature is ...

Mass splitting btw. transverse & longitudinal gauge bosons

[e.g. Lozanov & Amin '16, Graham et al.'16]

$$m_{A_T}^2 \sim g^2 \phi_J^2$$

$$m_{A_L}^2 \sim m_{A_T}^2 - \frac{\ddot{m}_{A_T}}{\underline{m_{A_T}}}$$

Note : Both are the same if inflaton is stationary

MASS SPLITTING OF GAUGE BOSON

Note :
 τ : conformal time

■ Gauge boson action

$$S_A = \int d^4x \sqrt{-g_J} \left[-\frac{1}{4} F_{\mu\nu} F^{\mu\nu} - \frac{1}{2} m_A^2 A_\mu A^\mu \right]$$

MASS SPLITTING OF GAUGE BOSON

Note :

τ : conformal time

■ Gauge boson action

$$S_{A_T} \sim \int d\tau d^3k \left[|\vec{A}'_T|^2 - (k^2 + m_A^2) |\vec{A}_T|^2 \right]$$

$$S_{A_L} \sim \int d\tau d^3k \underbrace{\frac{m_A^2}{k^2 + m_A^2}}_{\text{red}} \left[|A'_L|^2 - (k^2 + m_A^2) |A_L|^2 \right]$$

- Easiest way to see the difference : use canonical field $\tilde{A}_L \equiv \sqrt{\frac{m_A}{k^2 + m_A^2}} A_L$
- Extra mass term $\sim m''_A/m_A$ appears in \tilde{A}_L mass
- In our setup, $m_A \sim g\phi_J$ (after taking unitary gauge $\Phi_J = \phi_J/\sqrt{2}$)

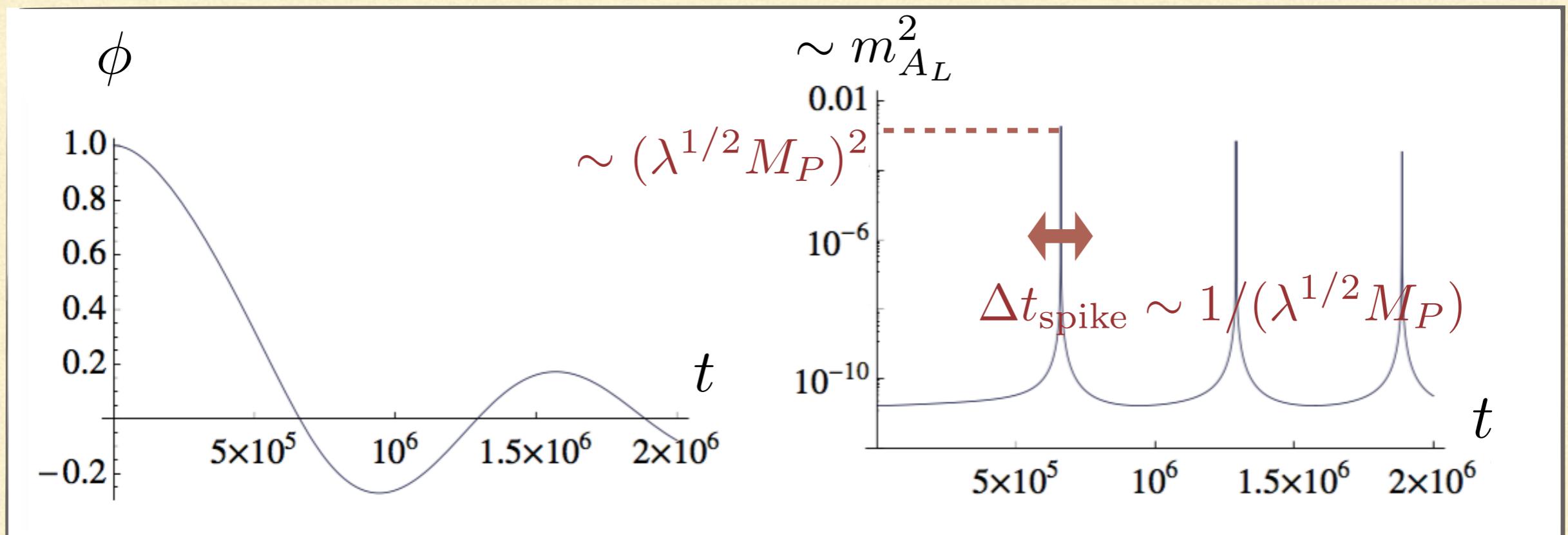
BEHAVIOR OF LONGITUDINAL MASS

Note :

$$m_{A_T}^2 \sim g^2 \phi_J^2$$

$$m_{A_L}^2 \sim m_{A_T}^2 - \frac{\ddot{m}_{A_T}}{m_{A_T}}$$

- Longitudinal gauge boson mass has “spike”



Note : Planck unit $M_P = 1$ / $\lambda = 0.01$ / $\xi = 10000$

BEHAVIOR OF LONGITUDINAL MASS

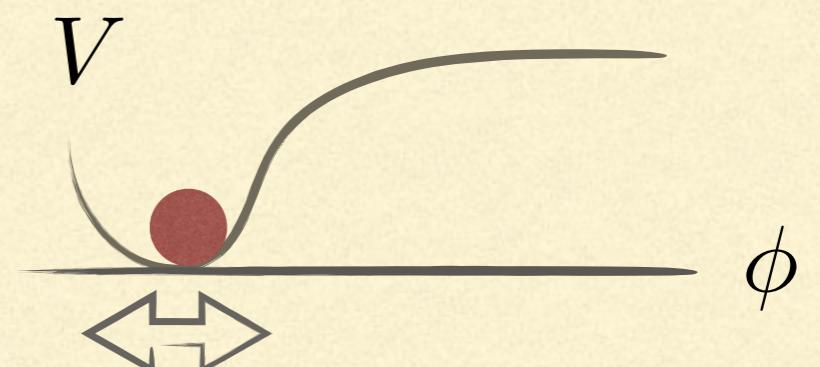
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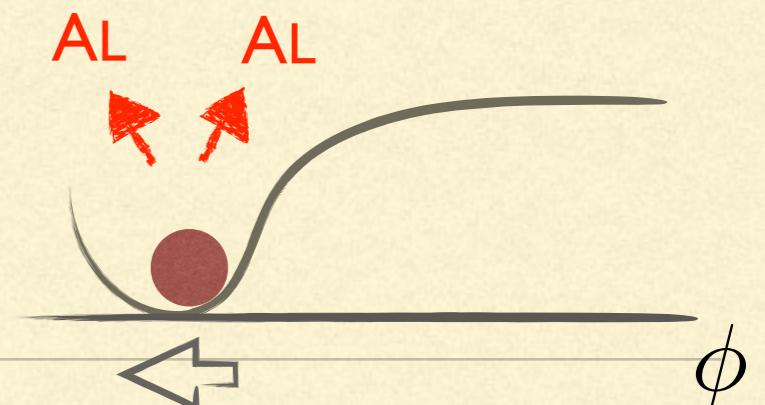
■ Origin of the spike

- Mass term contains $\ddot{\phi}_J$, and this shows singular behavior ... Why?
- Einstein frame inflaton ϕ is oscillating with \sim quad. potential
- However, the map btw. ϕ and ϕ_J leads to this singular behavior

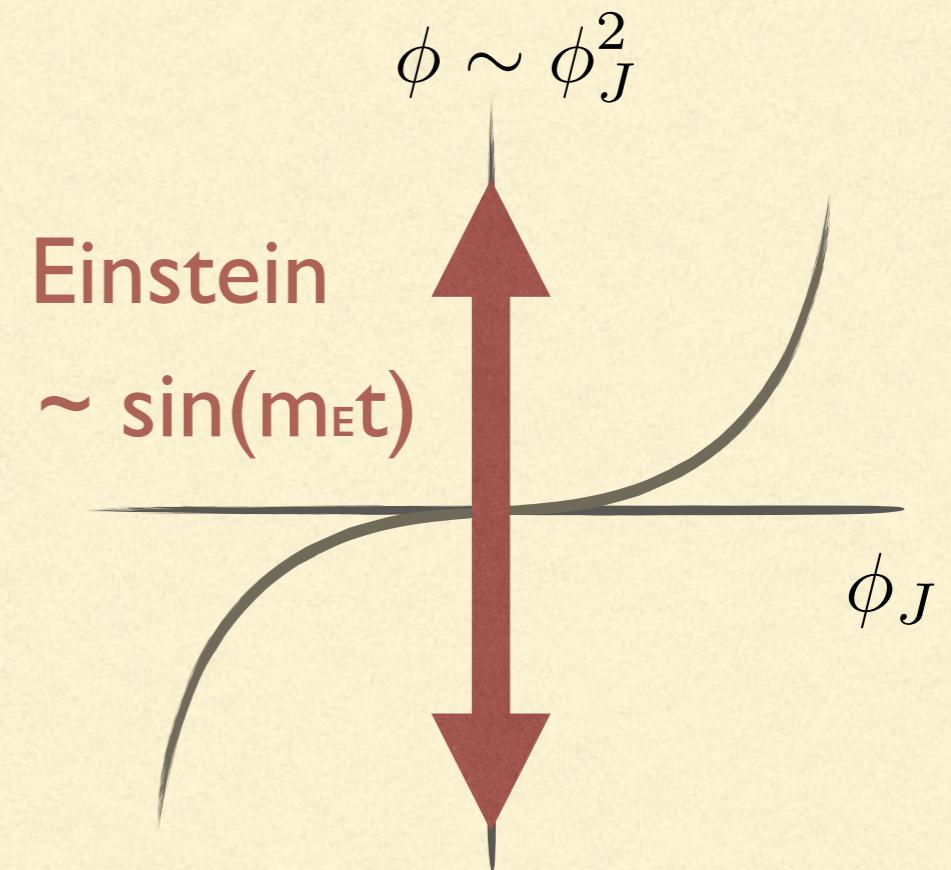
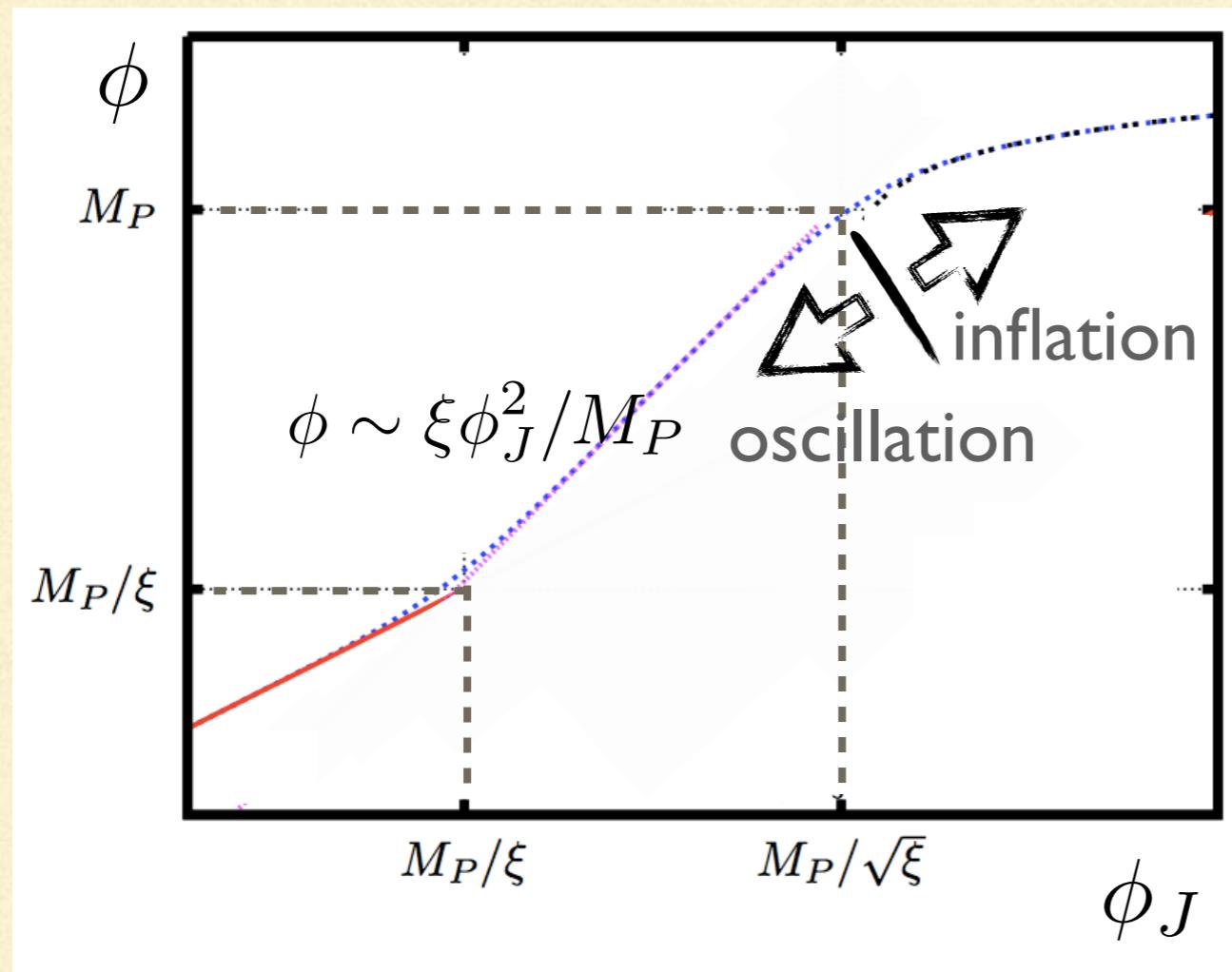


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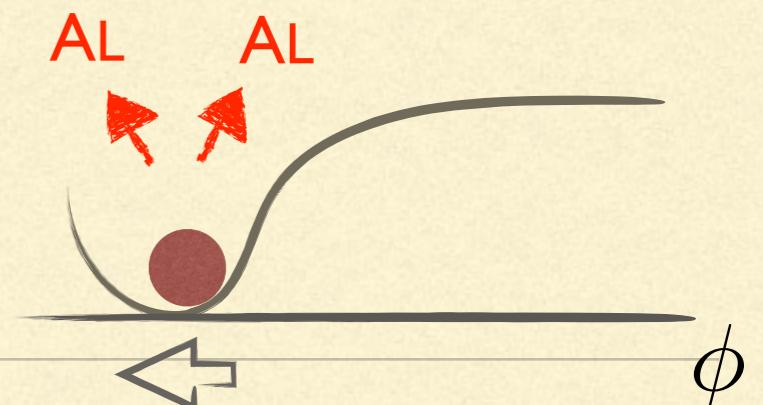
BEHAVIOR OF LONGITUDINAL MASS



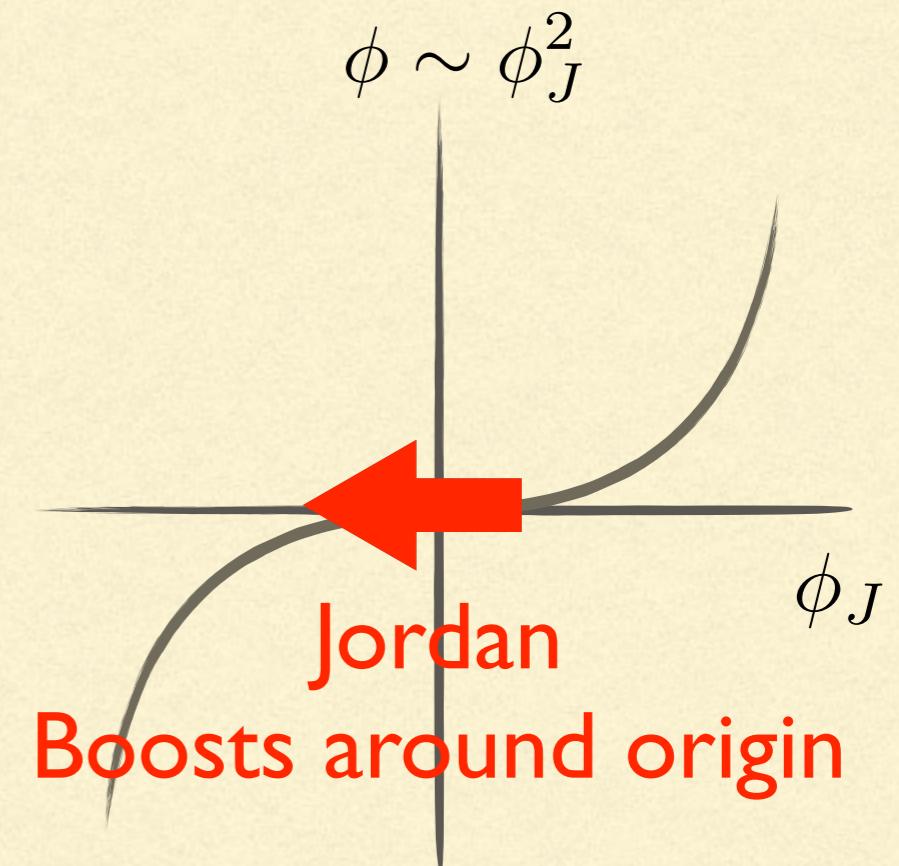
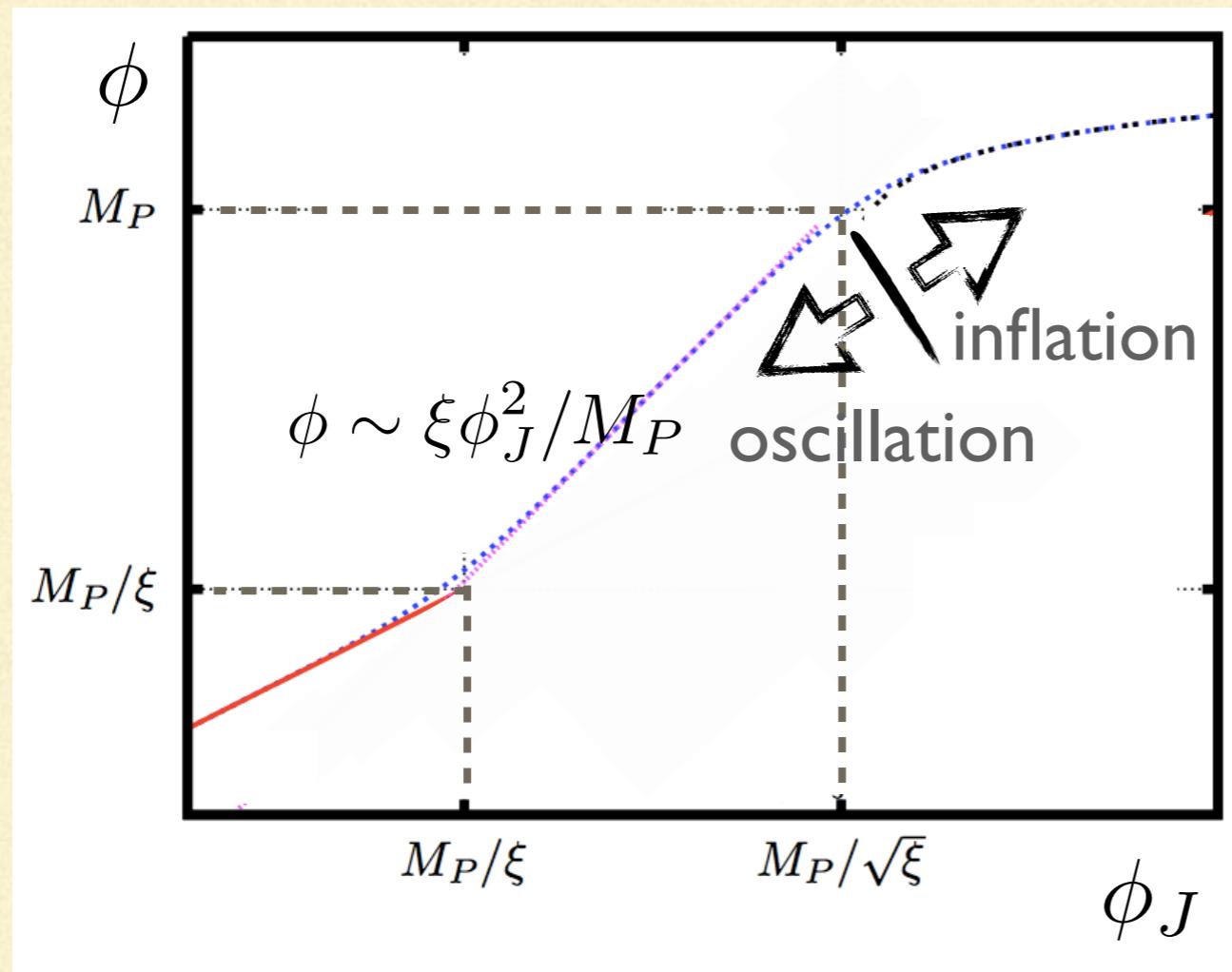
- Map btw. two inflatons (note, log plot)



BEHAVIOR OF LONGITUDINAL MASS



- Map btw. two inflatons (note, log plot)



LONGITUDINAL G.B. PRODUCTION

Note :
Final result is indep. of frames & gauges.
One can check both in
- Unitary/Coulomb gauge
- Jordan/Einstein frame

- Numerical calculation of longitudinal G.B. production

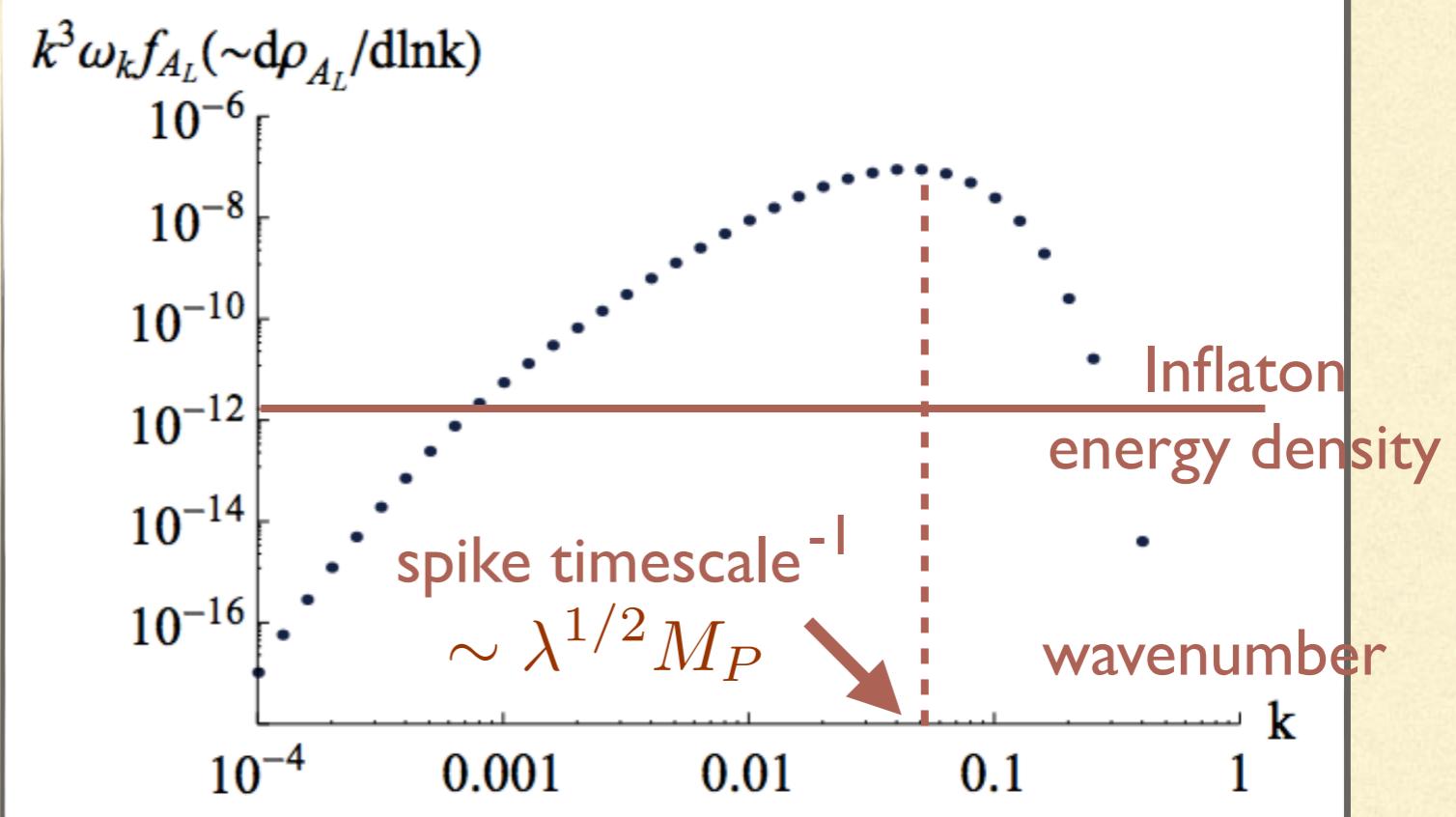
- Backreaction neglected

- Energy of longitudinal G.B.

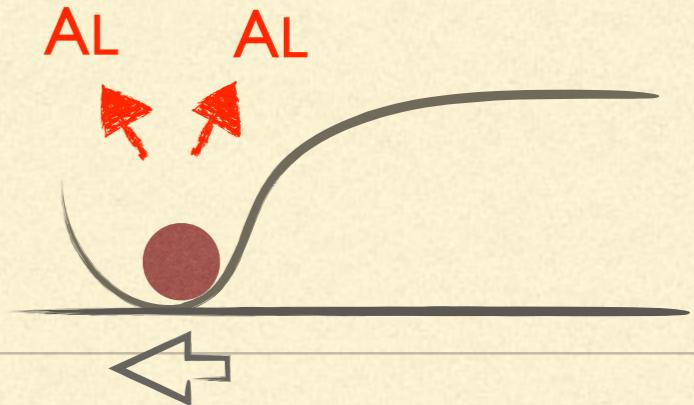
exceeds inflaton energy

after *only one spike*

Longitudinal G.B. energy density
per each log k



SUMMARY



- In Higgs inflation, the main channel of energy transfer is into

Longitudinal gauge boson

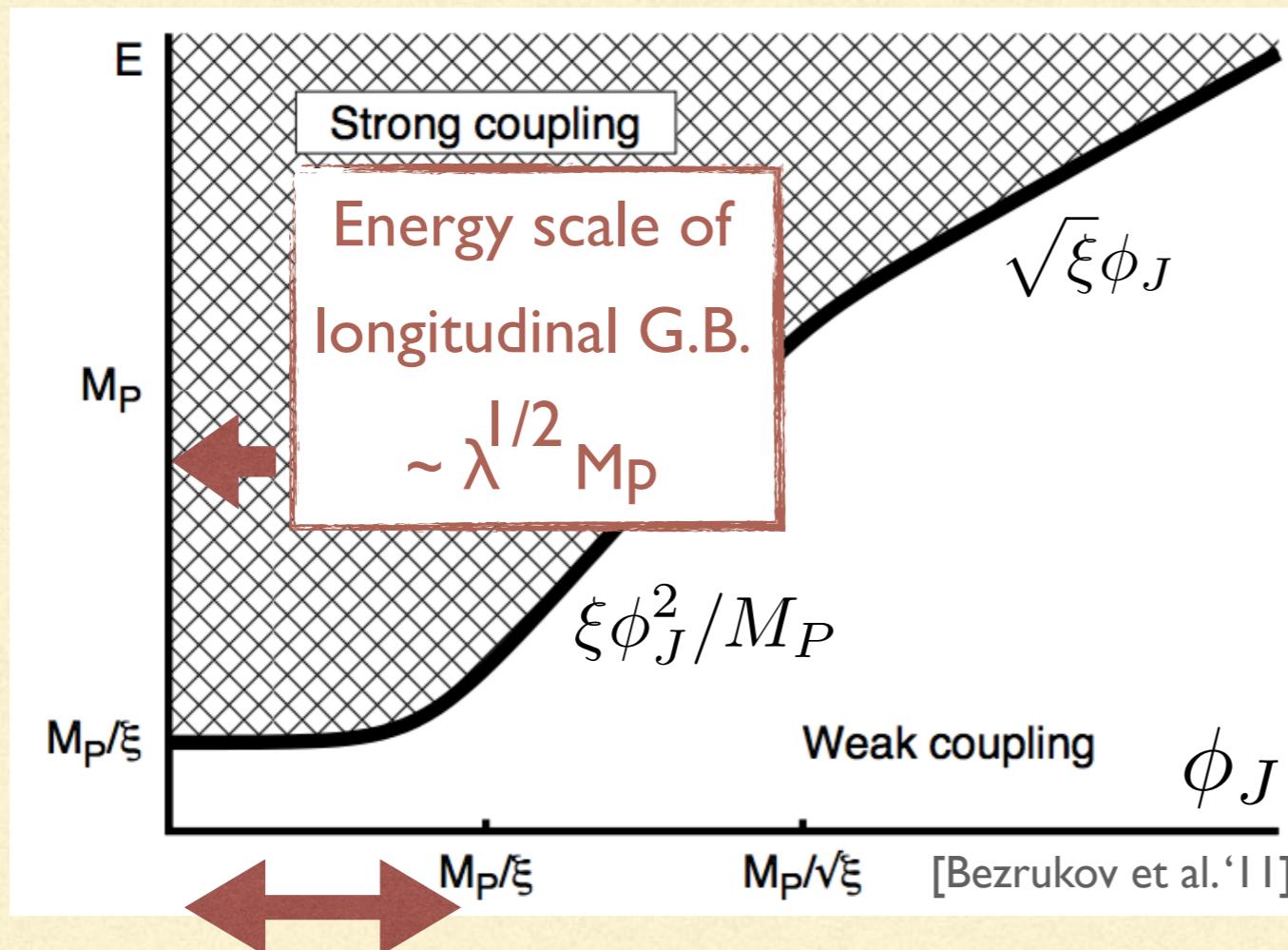
through the “mass spike”

- These G.B.s have momentum $\sim \lambda^{1/2} M_p$ (λ : 4-point coupling of Higgs)
- G.B. energy exceeds the cutoff scale \rightarrow UV completion required

Backup

UNITARITY VIOLATION

- Longitudinal G.B. energy exceeds the cutoff scale



Longitudinal G.B. produced while ϕ_J crosses this region

Note :
Given by the coefficient of scalar² graviton coupling

Note :
Same in Jordan & Einstein

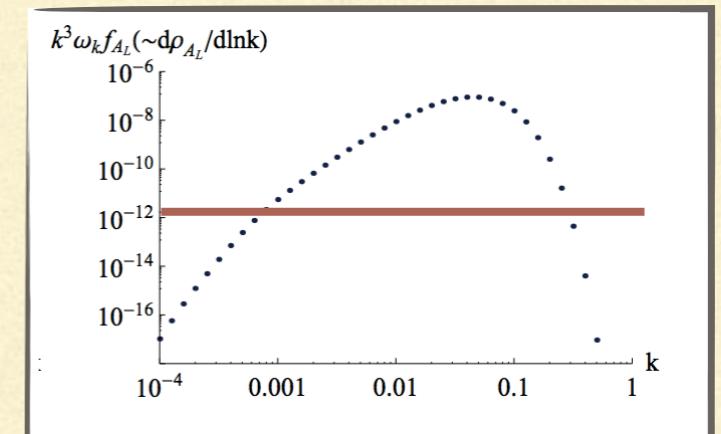
BACKREACTION ?

- Backreaction must be taken into account, in principle
- However, the following statement seems unchanged

“most of the inflaton energy goes into longitudinal G.B.”

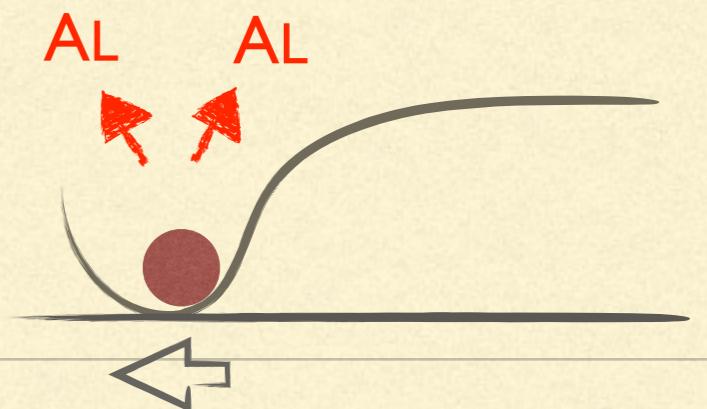
- Why?

- suppose otherwise → background calc. is exact



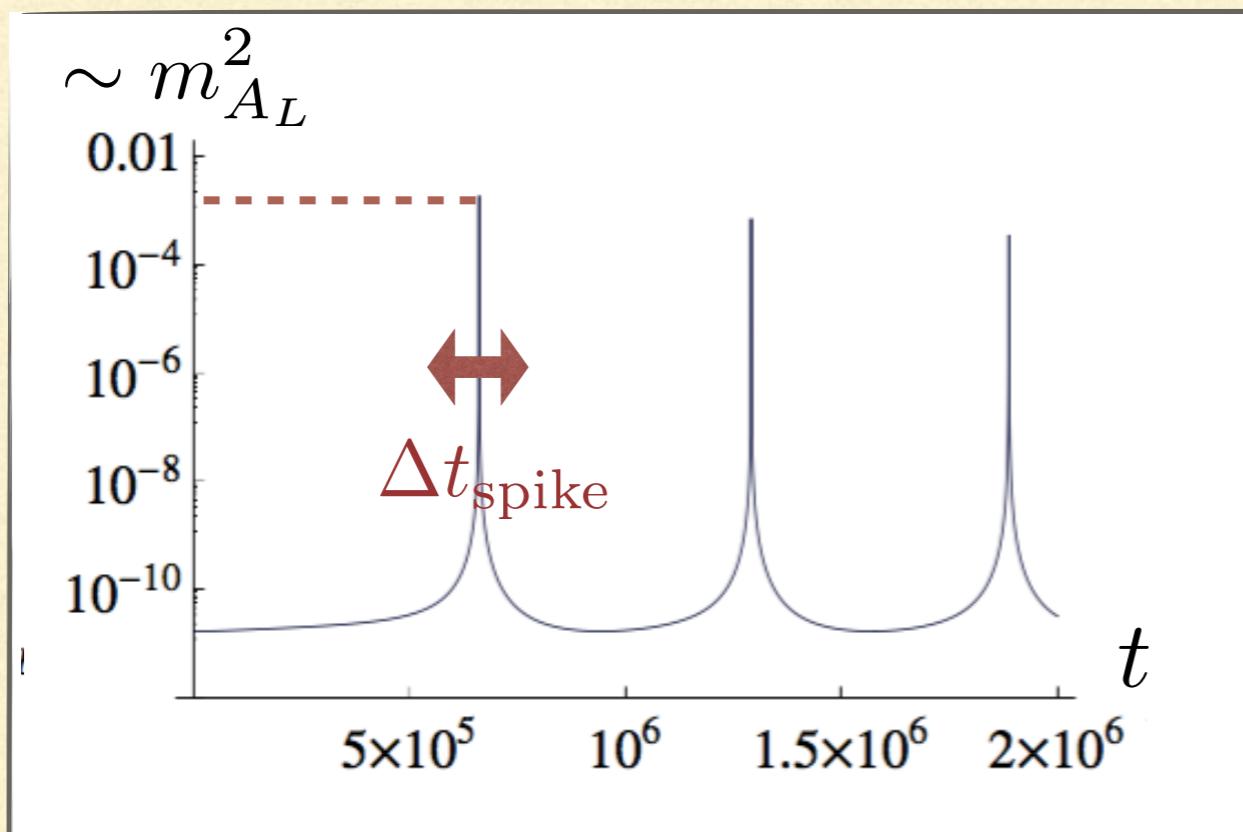
→ long. G.B. is produced this ↑ amount → contradiction

BEHAVIOR OF LONGITUDINAL MASS



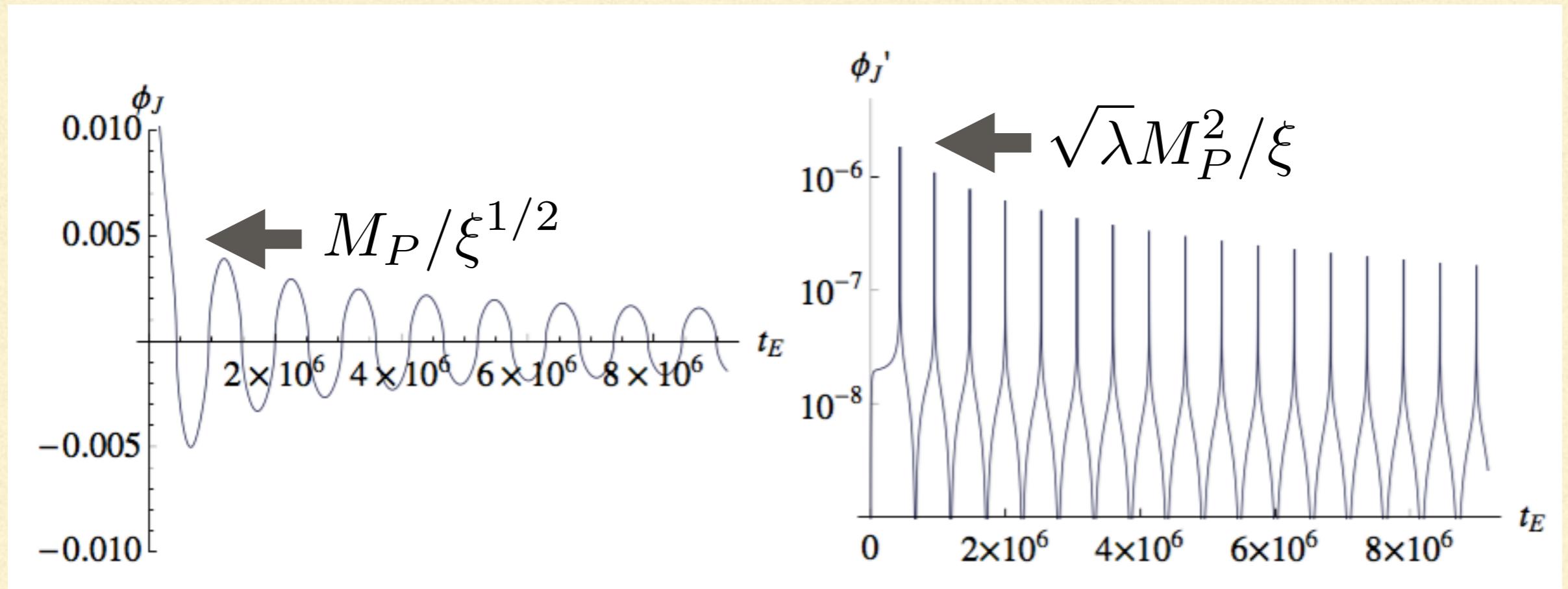
- “Spike” corresponds to the timescale

with which the inflaton passes $\phi \lesssim M_P/\xi$



$$\Delta t_{\text{spike}} \sim \frac{M_P/\xi}{\dot{\phi}} \sim \frac{1}{\lambda^{1/2} M_P}$$

BEHAVIOR OF JORDAN INFLATON



GAUGE BOSON MASSES

$$S_{A_T} = \frac{1}{2} \int \frac{d\tau d^3k}{(2\pi)^3} \left[\left| \vec{A}'_T \right|^2 - (k^2 + m_A^2) \left| \vec{A}_T \right|^2 \right]$$

$$\begin{aligned} S_{A_L} &= \frac{1}{2} \int \frac{d\tau d^3k}{(2\pi)^3} \left[\frac{m_A^2}{k^2 + m_A^2} \left| \tilde{A}'_L \right|^2 - m_A^2 \left| \tilde{A}_L \right|^2 \right] \\ &= \frac{1}{2} \int \frac{d\tau d^3k}{(2\pi)^3} \left[|A'_L|^2 - \left(k^2 + m_A^2 - \frac{k^2}{k^2 + m_A^2} \left(\frac{m''_A}{m_A} - \frac{3m'^2_A}{k^2 + m_A^2} \right) \right) |A_L|^2 \right] \end{aligned}$$

$$A_L \equiv \frac{m_A}{\sqrt{k^2 + m_A^2}} \tilde{A}_L.$$