# Violent preheating in Higgs inflation

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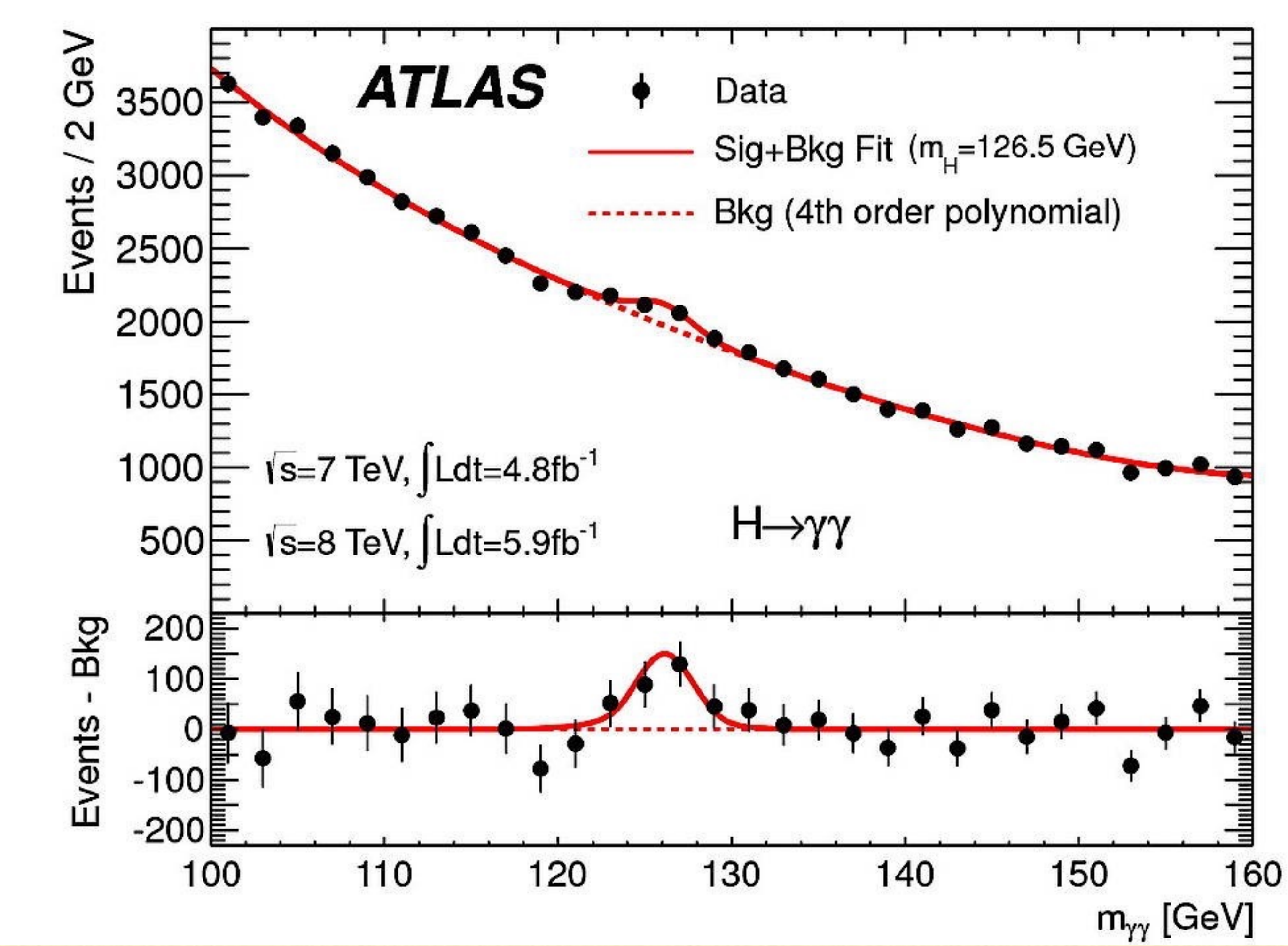
Based on
RJ Ph.D. Thesis
arXiv:1609.05209 with Y.Ema, K.Mukaida and K.Nakayama

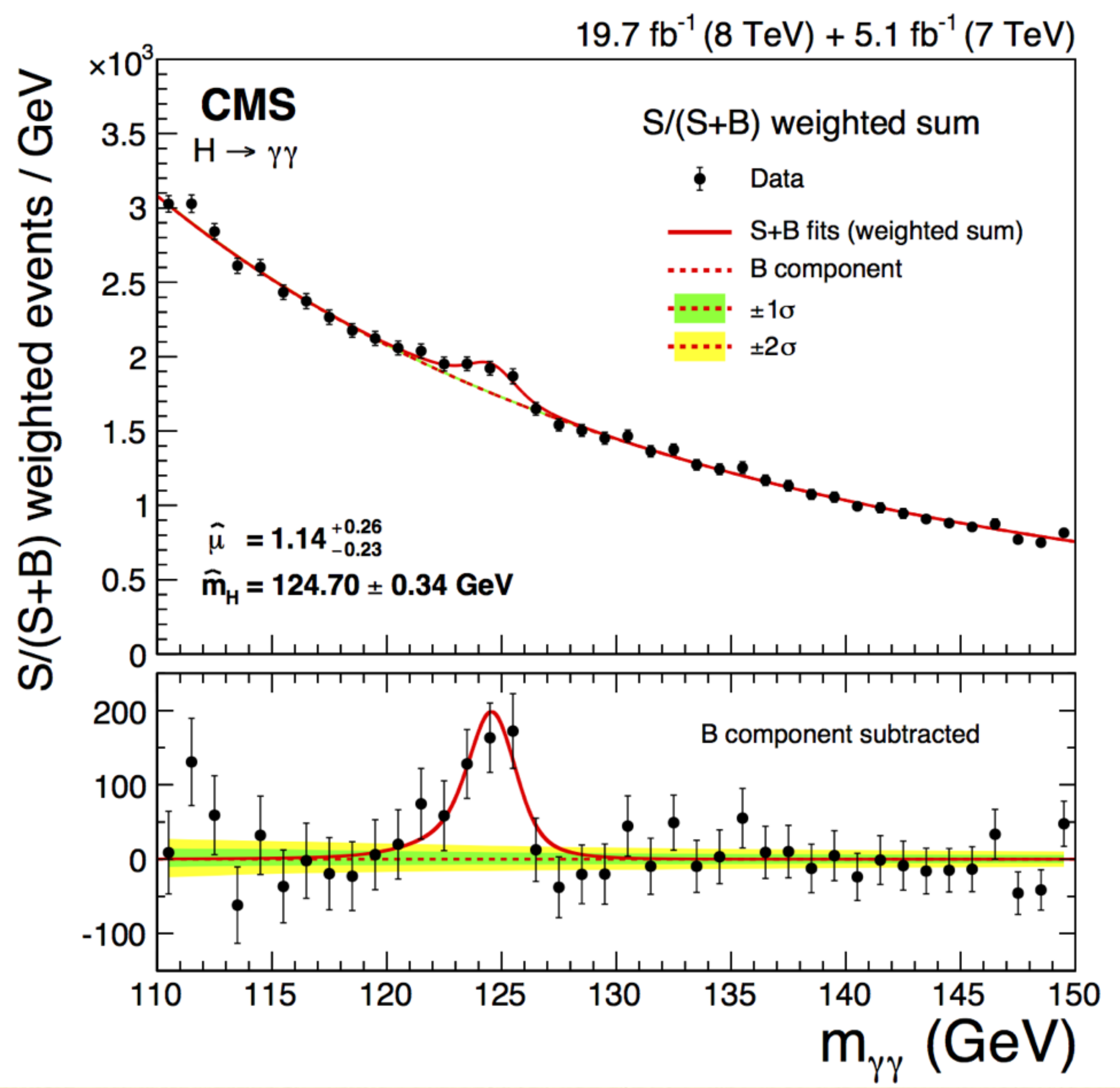
# MESSAGE

***Transverse and Longitudinal gauge bosons***

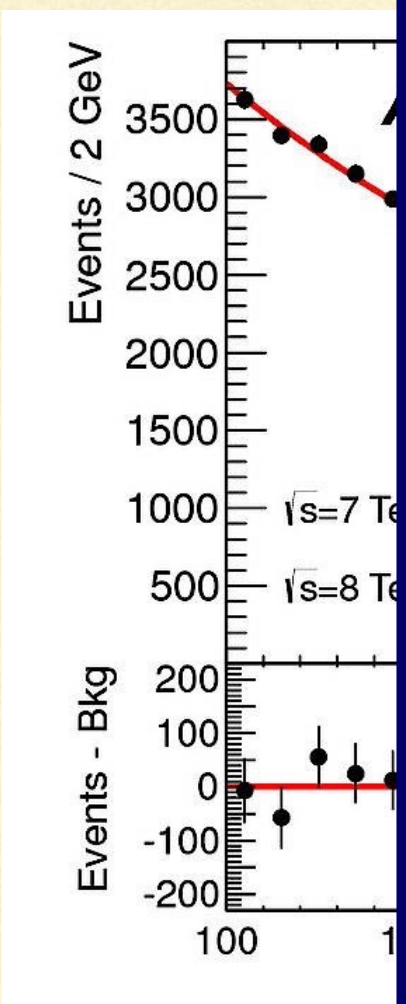
***behave differently in the early Universe***

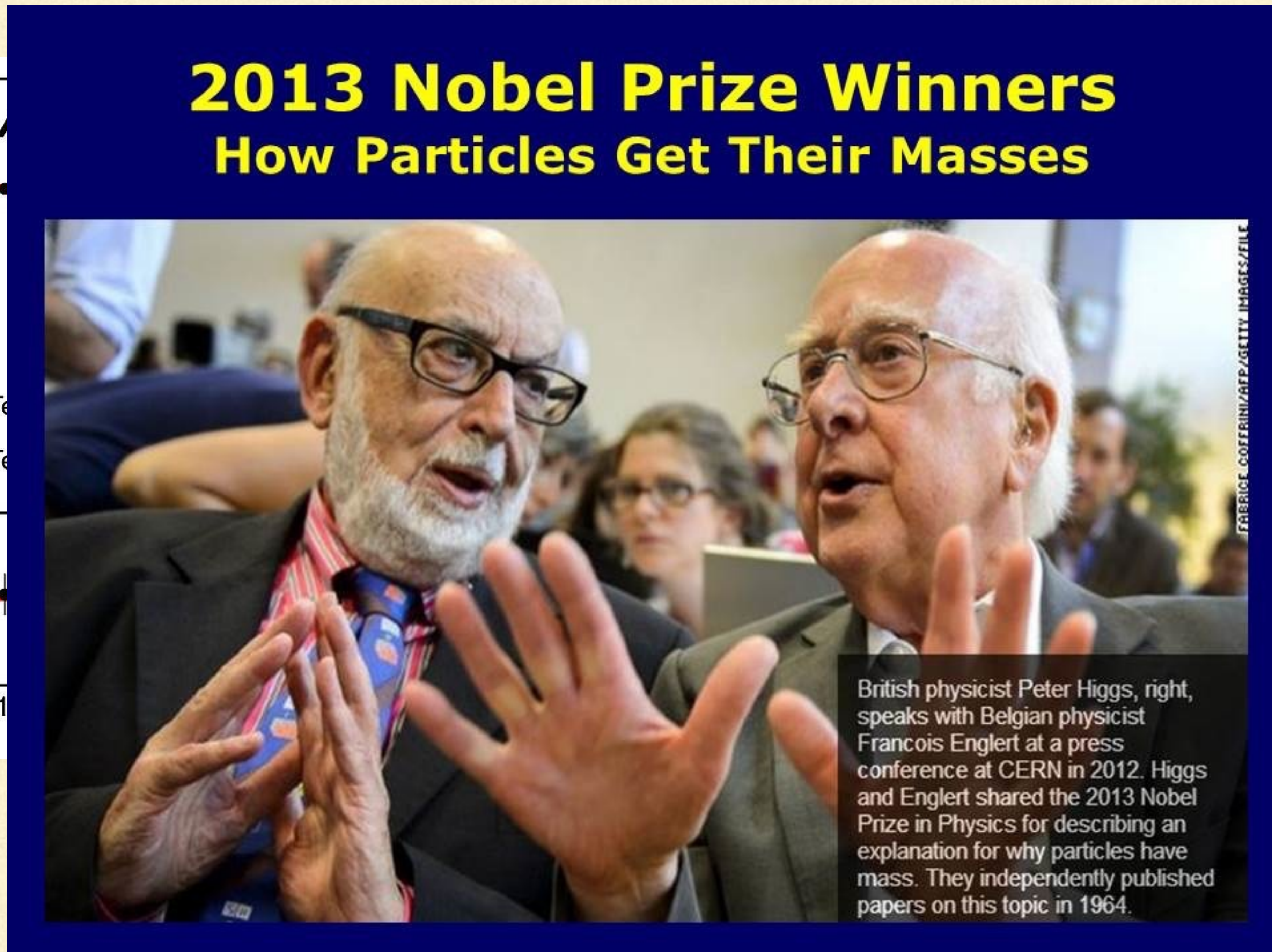
# HIGGS DISCOVERY

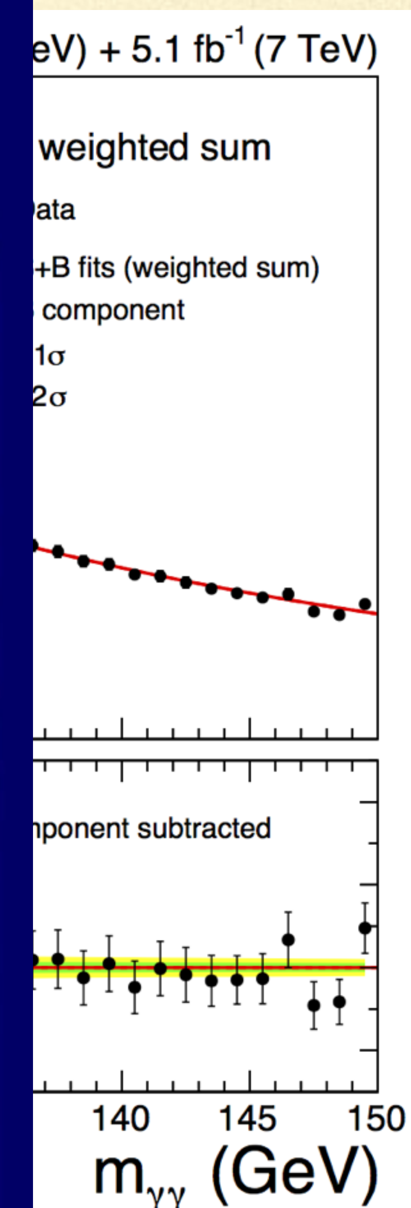


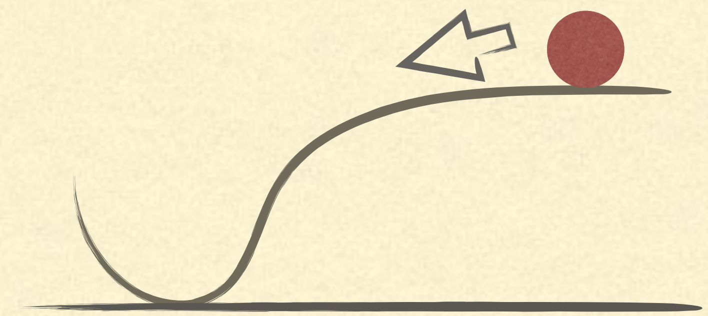
# HIGGS DISCOVERY

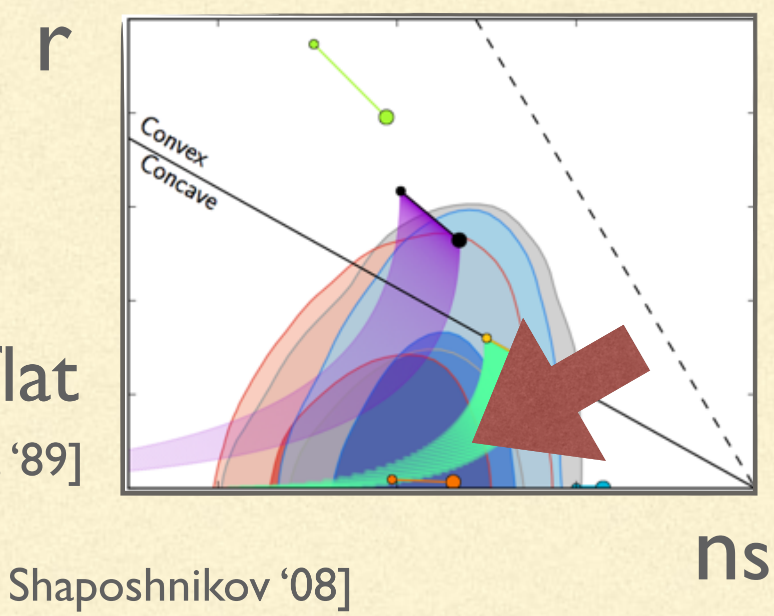


# HIGGS AS THE INFLATON






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

  - Nonminimal coupling $\xi\phi^2 R$ makes the potential flat [Futamase & Maeda '89]

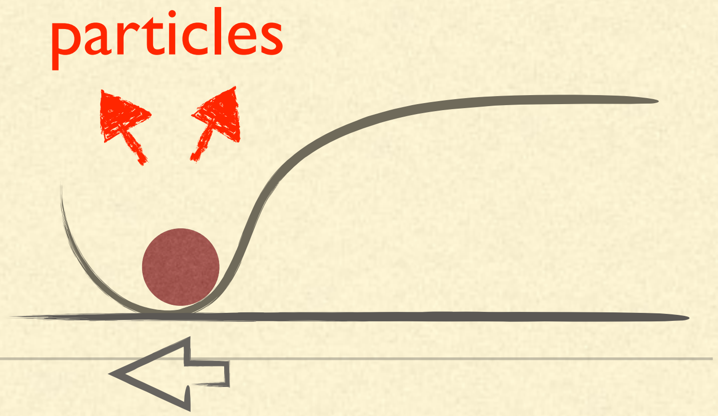
    → Excellent agreement with observations [Bezrukov & Shaposhnikov '08]

  - Sevaral advantages

    1. Economical : no need to add new fields

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

# PREHEATING

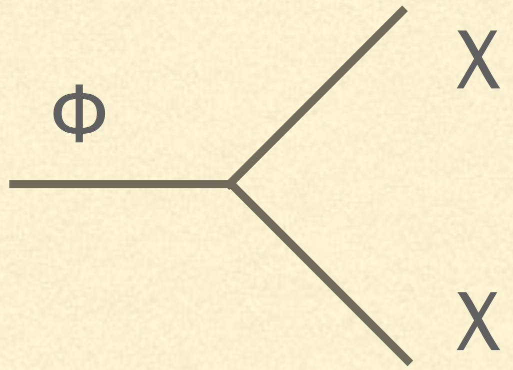



- Inflation is just the beginning of the story

Inflation

(P)reheating : { Energy transfer from inflaton to light particles & Thermalization of these particles

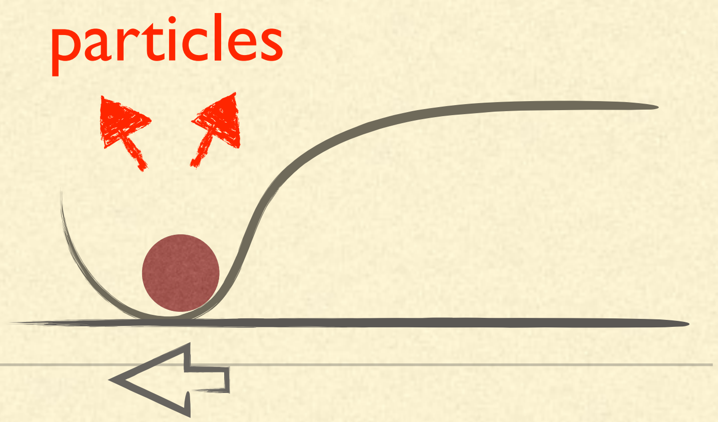
[Bezrukov, Gorbunov, Shaposhnikov ’09, Garcia-Bellido, Figueroa, Rubio ’09, ...]




BBN, CMB, ...

t

# PREHEATING

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Inflation

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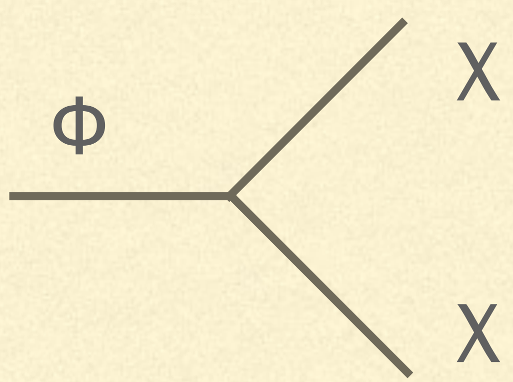
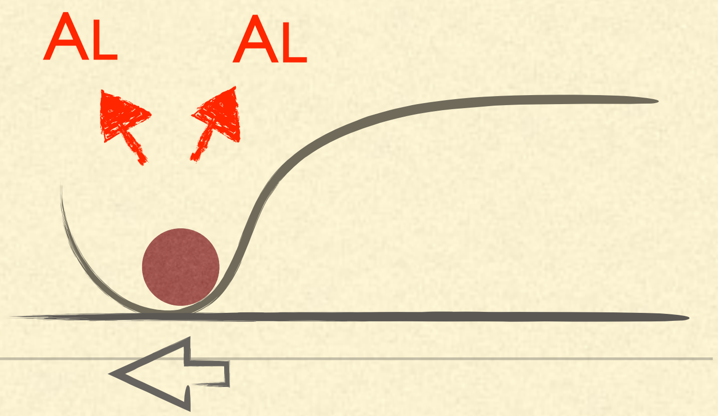


# SUMMARY




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

***Longitudinal gauge boson***

- These G.B.s have momentum ~ $\lambda^{1/2}$ Mp   ($\lambda$ : 4-point coupling of Higgs)

- G.B. energy scale exceeds the cutoff scale → UV completion required

# OUTLINE

0. Introduction

1. 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

Real inflaton

Ricci scalar

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

CMB normalization gives

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

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

$$\lambda \sim 0.01$$

Jordan frame :

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

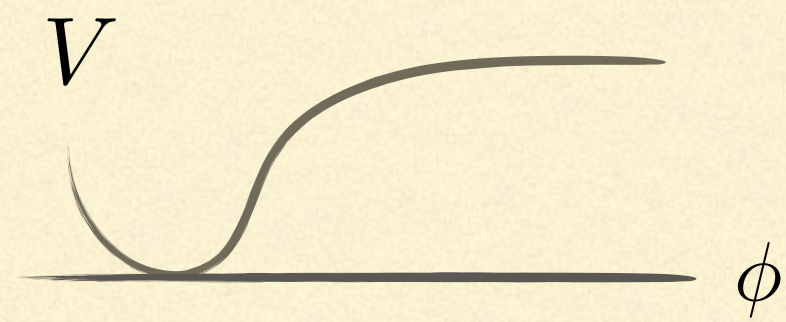
# INFLATION IN EINSTIEN FRAME

Note : conformal factor

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

- Action takes a simple form

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




by conformal transformation & inflaton redifinition

$$g_{\mu\nu} \equiv \Omega^2 g_{J\mu\nu}$$

$$R_J = \Omega^2 R + \cdots$$

$$\phi \;:\; \frac{d\phi}{d\phi_J} \equiv \left( \begin{array}{c} \text{some complicated} \\ \text{func. of } \phi_J \end{array} \right)$$

$$V(\phi) \equiv \frac{V_J(\phi_J)}{\Omega^4}$$

Einstein frame :

No nonminimal coupling

# INFLATION IN EINSTIEN FRAME

Note :

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

from CMB normalization

- Potential in the Einstein frame

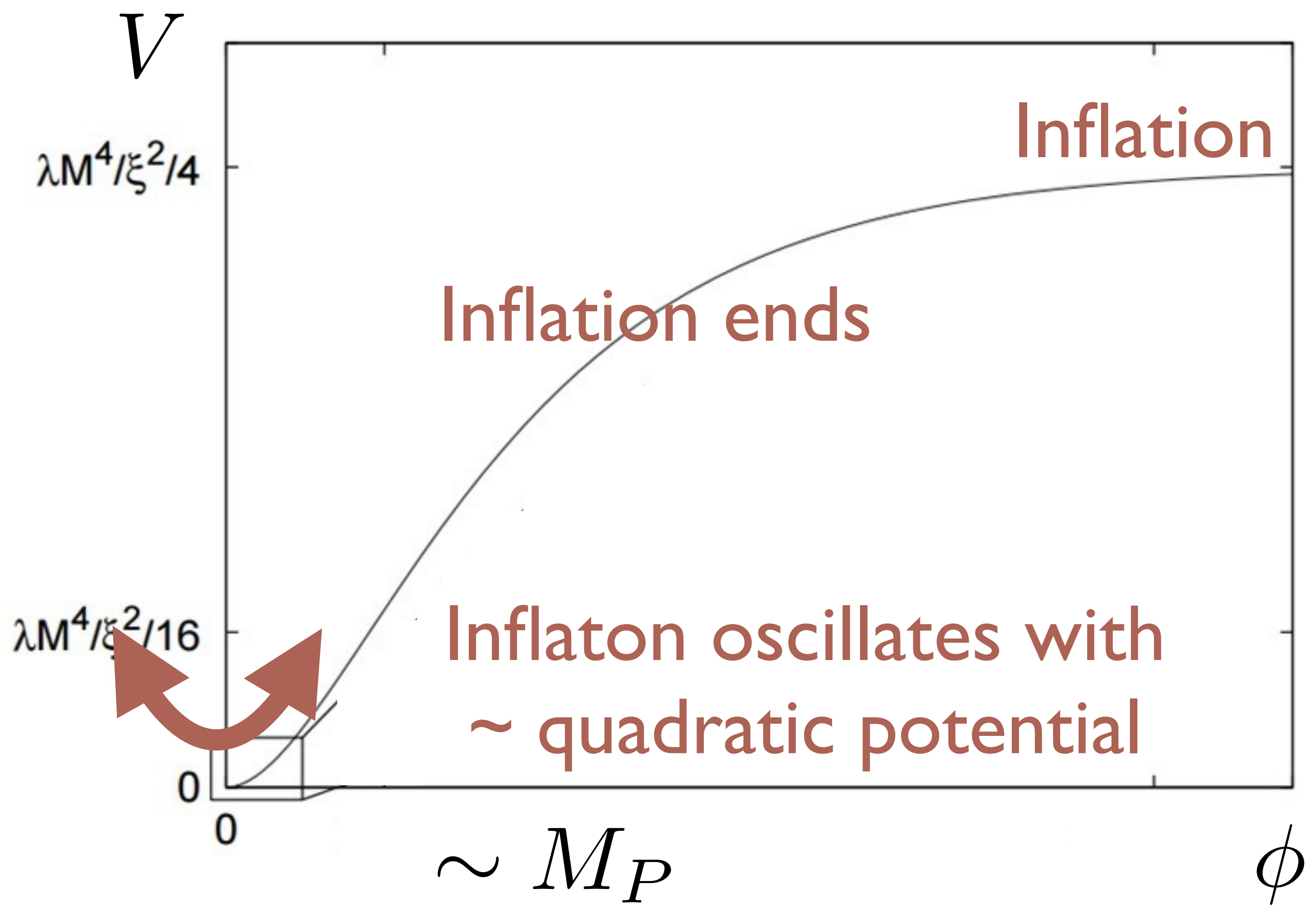



Fig. 1. Effective potential in the Einstein frame.

[Bezrukov & Shaposhnikov '08]

# (P)REHEATING

- Let's make inflaton to be SM Higgs $\Phi_J$

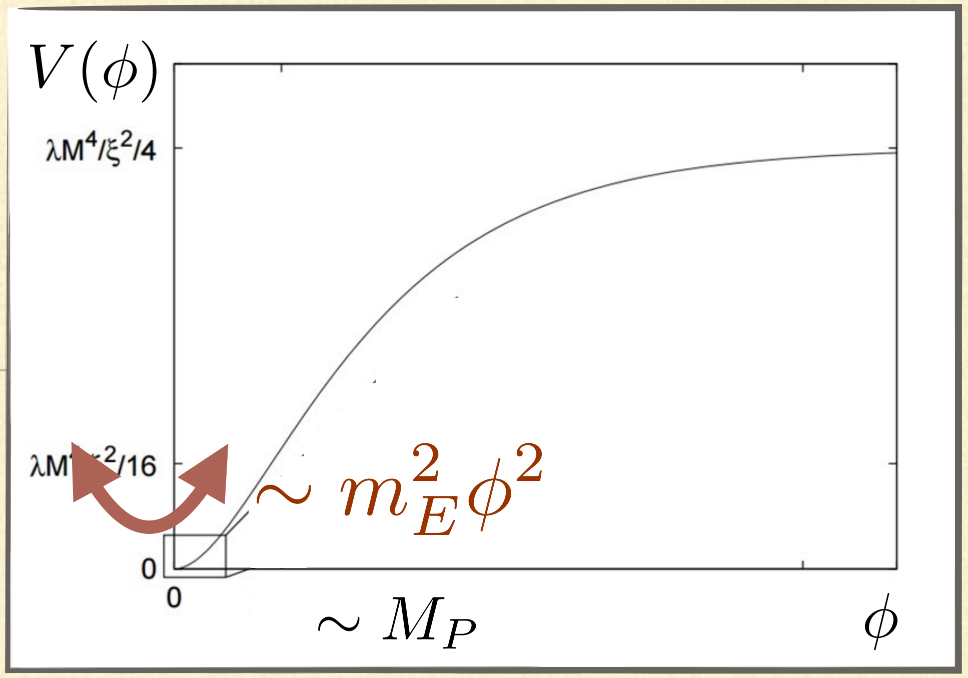
$$S = \int d^4x\sqrt{-g_J}\left[\left(\frac{M_P^2}{2} + \xi|\Phi_J|^2\right)R_J - \overbrace{|D\Phi_J|^2 - V_J(|\Phi_J|) + \cdots}^{\text{SM Lagrangian (Gauge boson etc.)}}\right]$$

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

  - $\phi_J$ dynamics : same as real inflaton ( slow-roll → oscillation )

  - gauge boson mass oscillates as the inflaton oscillates

# (P)REHEATING




- Note : Something is MISSING 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 brings about 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]

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

Note : Both are the same if inflaton is stationary

# MASS SPLITTING OF GAUGE BOSON

Note :

$\tau$ : 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 :

$\tau$ : conformal time

- Gauge boson action

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

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

- 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 ~ $m''_A / m_A$ appears in $\tilde{A}_L$ mass

- In our setup, $m_A \sim g\phi_J$

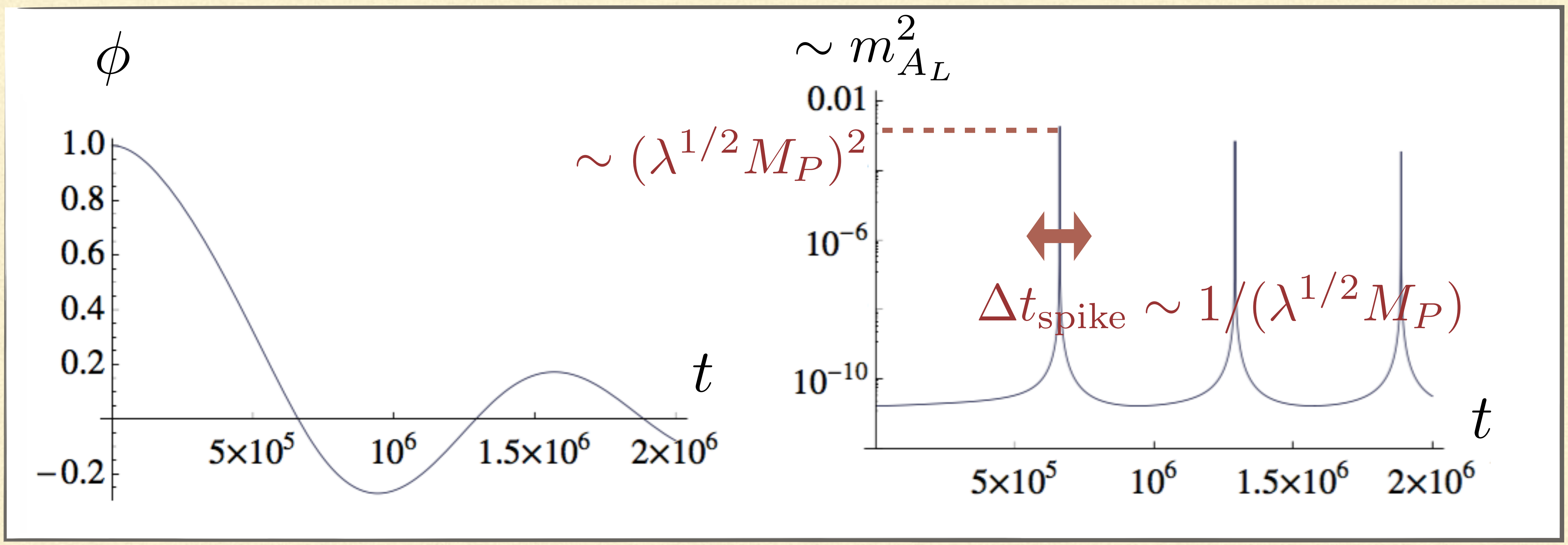
# BEHAVIOR OF LONGITUDINAL MASS

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 Mp = 1 / λ = 0.01 / ξ = 10000

# BEHAVIOR OF LONGITUDINAL MASS

Note :

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

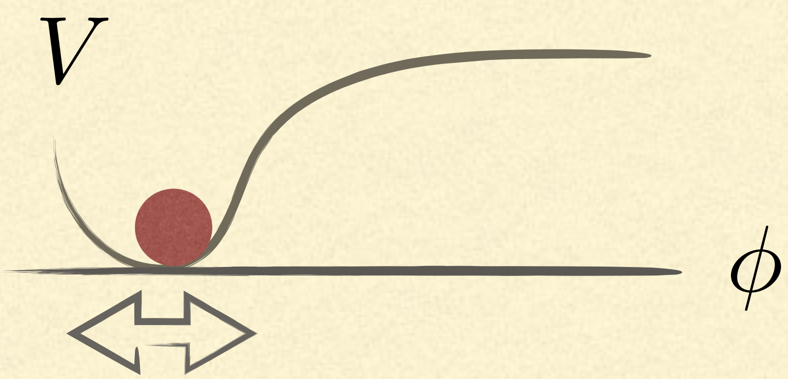
$m_{A_L}^2 \sim m_{A_T}^2 - \dfrac{\ddot{m}_{A_T}}{m_{A_T}}$

- Origin of the spike

  - Mass term contains $\ddot{\phi}_J$, and this shows singular behavior ... Why?

  - Einstein frame inflaton $\phi$ is oscillating

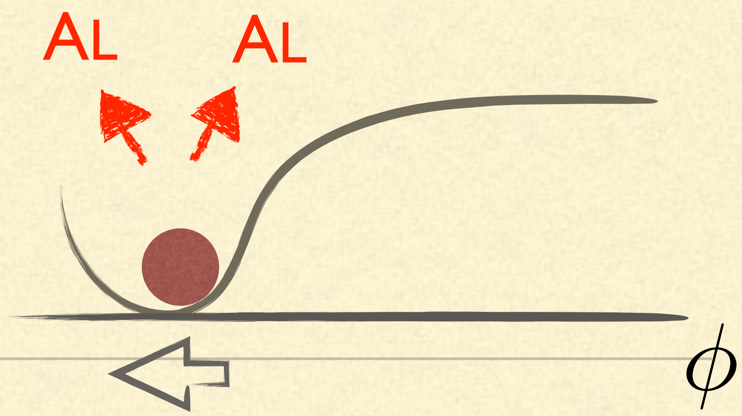
    with ~ quad. potential



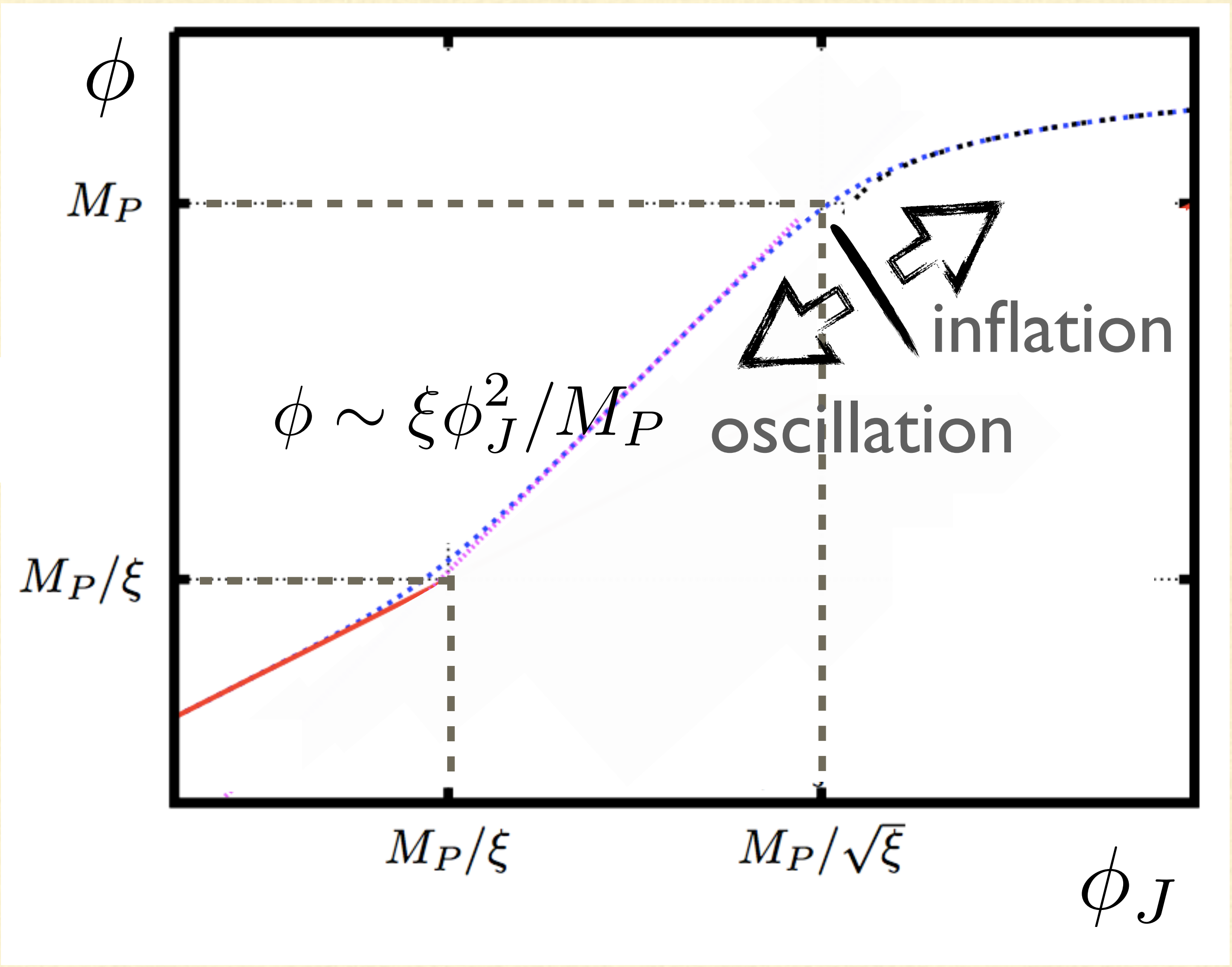

  - However, the map btw. $\phi$ and $\phi_J$ leads to this singular behavior

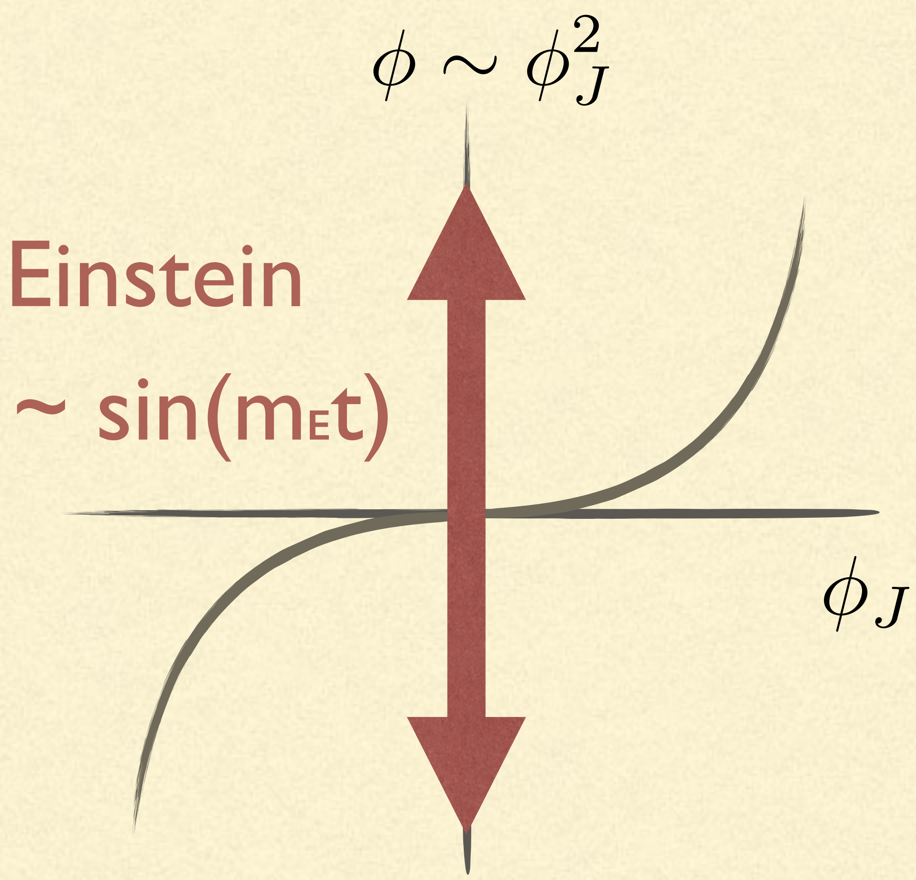
    → next page

# BEHAVIOR OF LONGITUDINAL MASS

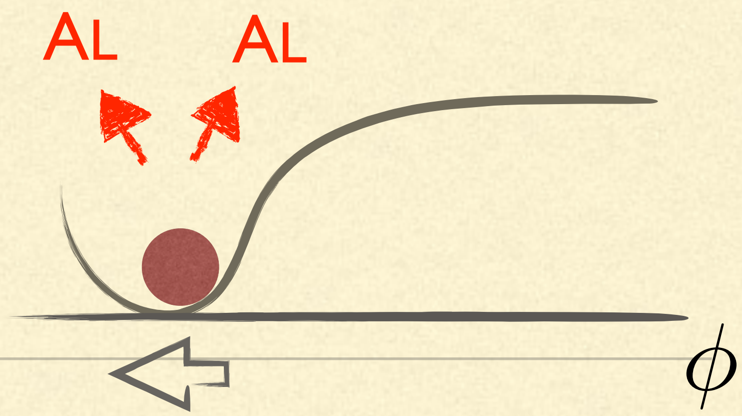



- Map btw. two inflatons (note, log plot)



# BEHAVIOR OF LONGITUDINAL MASS

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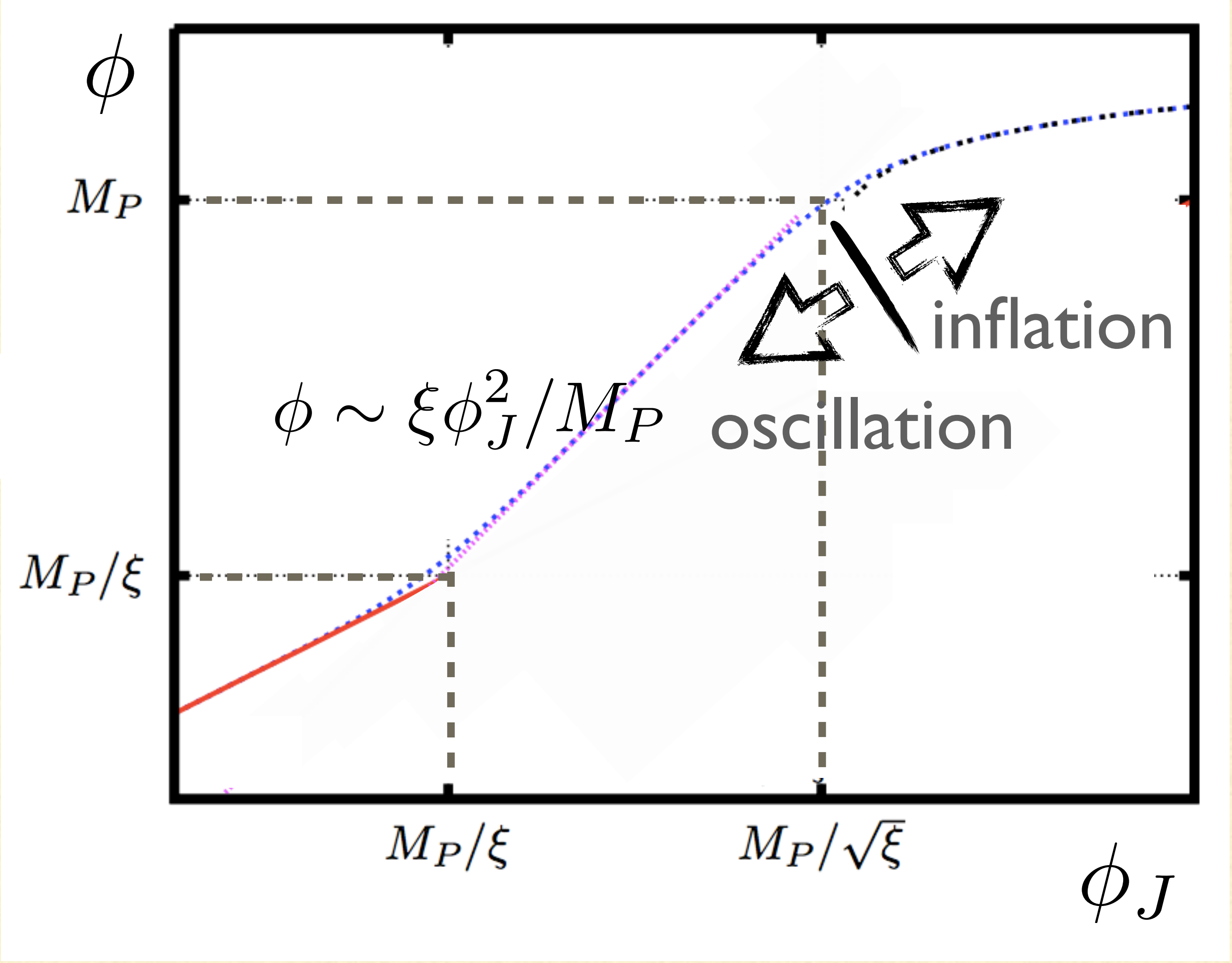
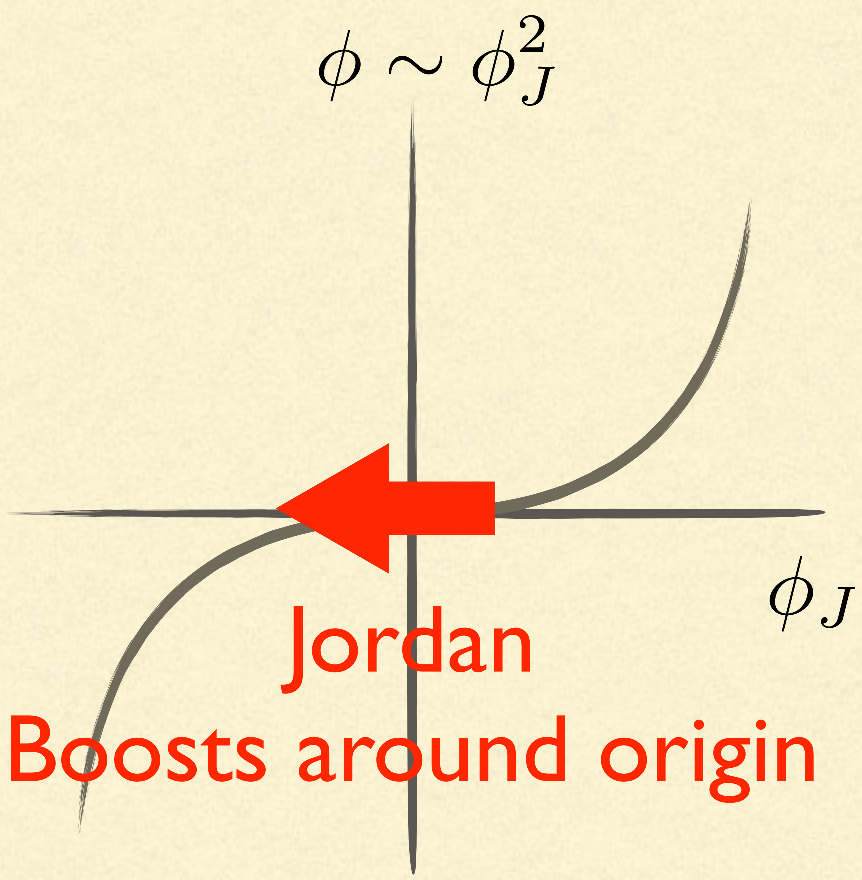


# LONGITUDINAL G.B. PRODUCTION

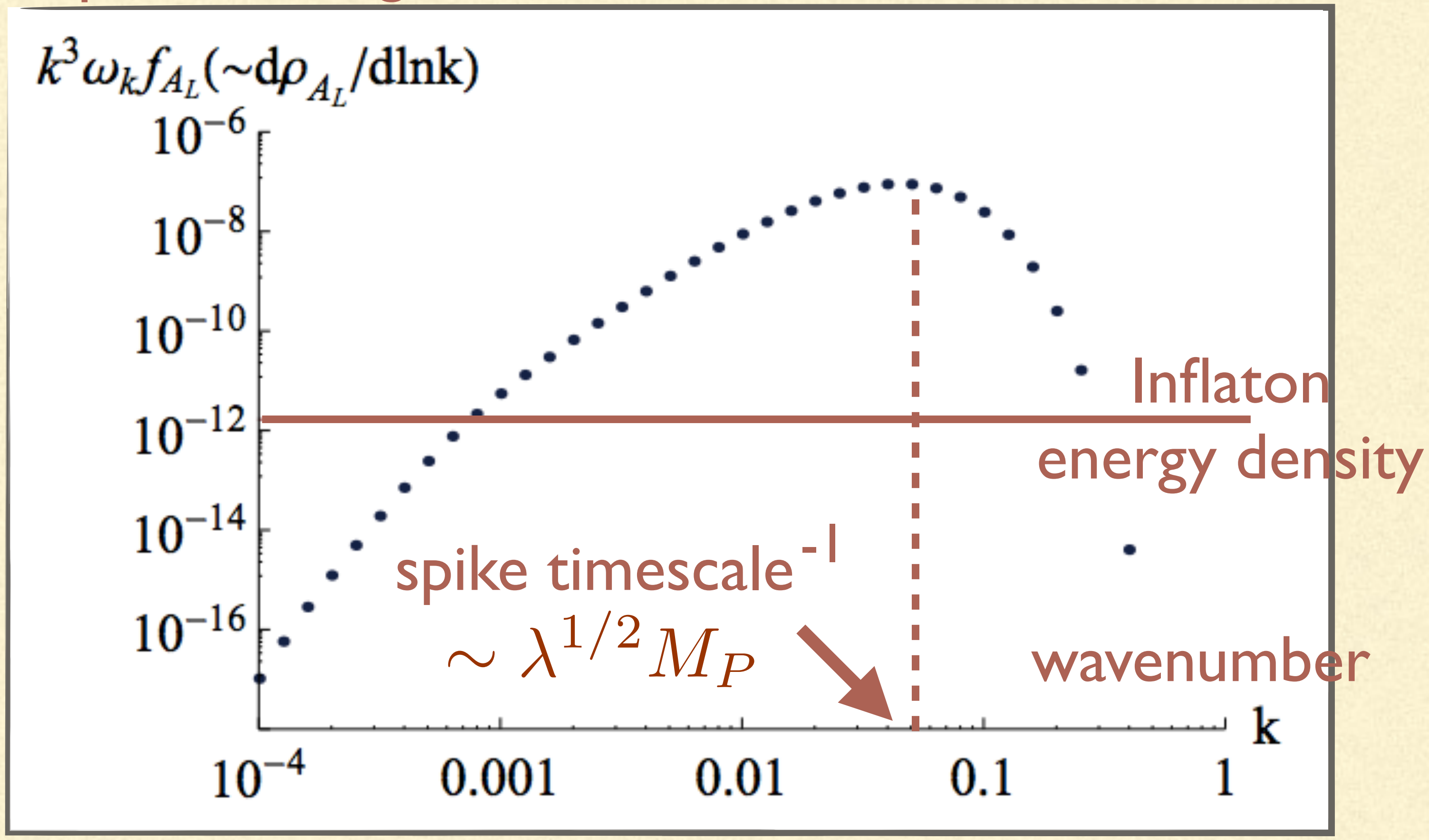
Note :
Final result is indep. of frames & gauges.
One can check in
- Unitary / Coulomb gauge
- Jordan / Einstein frame

- Numerical calculation of longitudinal G.B. production
- Backreaction neglected
- Energy of longitudinal G.B.

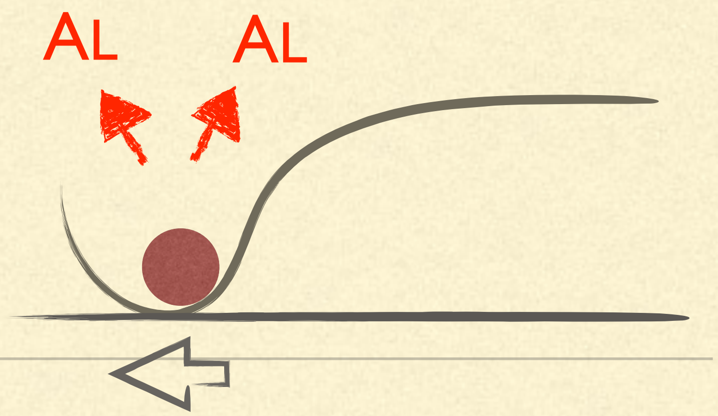
  exceeds inflaton energy

  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***

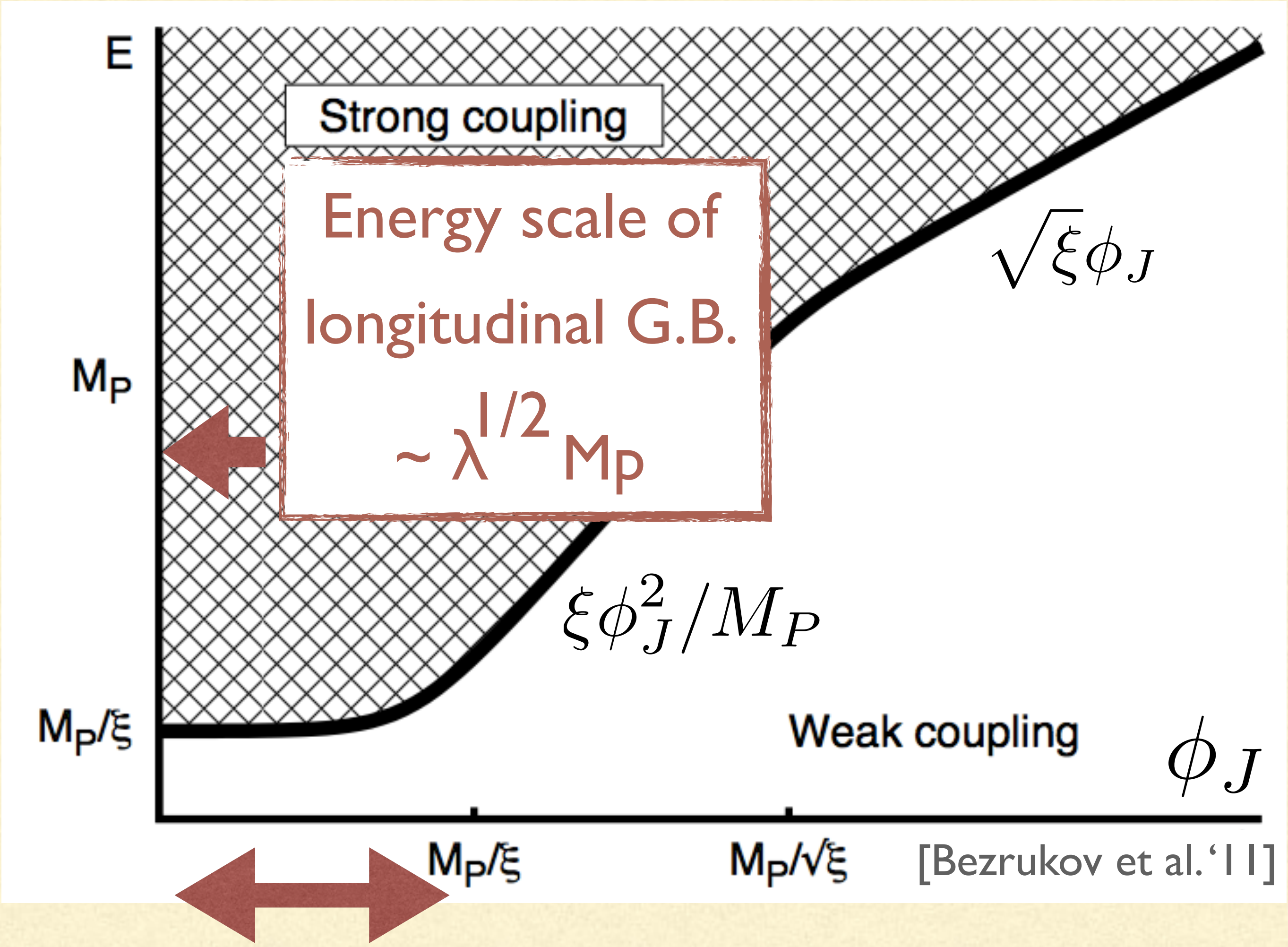
through the "mass spike"

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

# Backup

# UNITARITY VIOLATION

- Longitudinal G.B. energy exceeds the cutoff scale




Longitudinal G.B. produced while $\phi_J$ crosses this region

Note :

Given by the coefficient of scalar$^2$graviton coupling

Note :

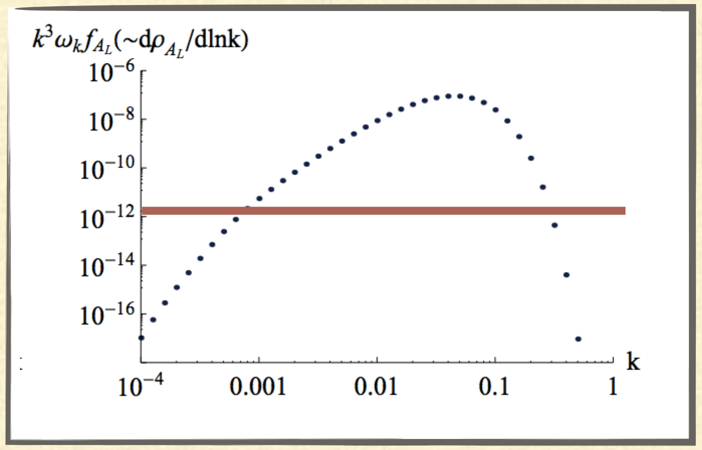
Same in Jordan & Einstein

# 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.”*

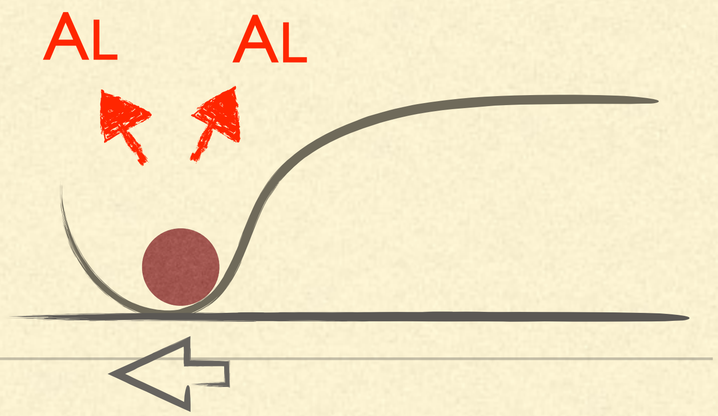
- Why?




- suppose otherwise → background calc. is exact

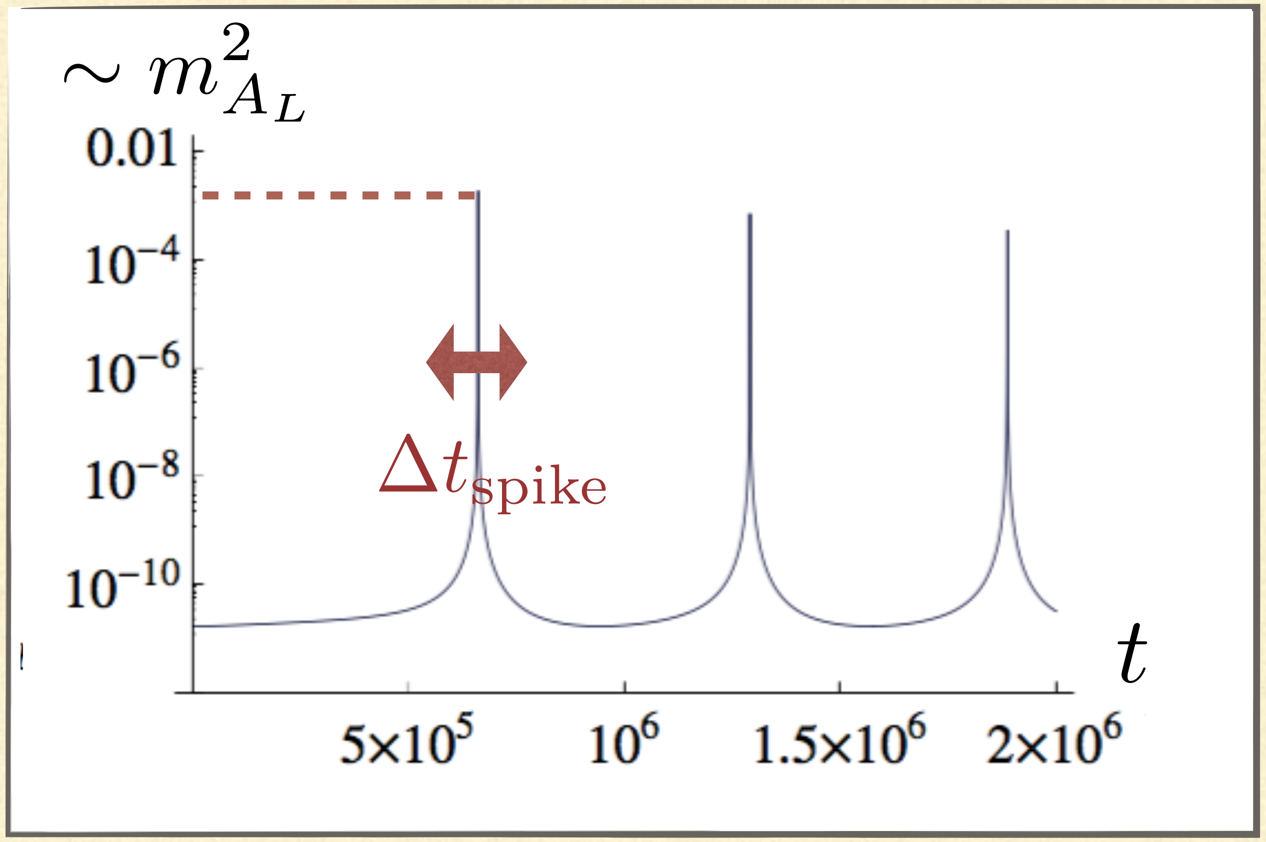
→ long. G.B. is produced this ↗ amount → contradiction

# BEHAVIOR OF LONGITUDINAL MASS



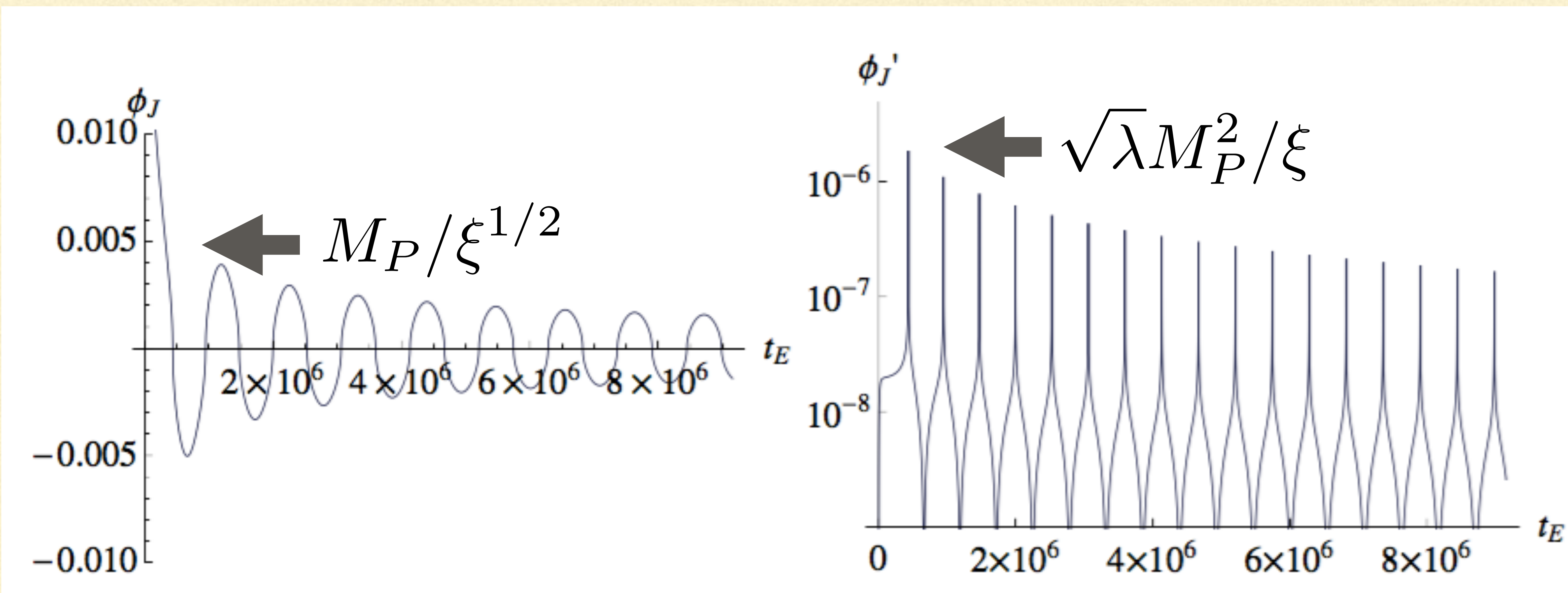

- "Spike" correponds to the timescale

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




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

# BEHAVIOR OF JORDAN INFLATON



# GAUGE BOSON MASSES

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

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

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