Violent preheating in inflation with nonminimal coupling

Ryusuke Jinno (KEK→IBS)

Based on

RJ Ph.D. Thesis

arXiv:1609.05209 w/ Yohei Ema, Kyohei Mukaida and Kazunori Nakayama

Joint KEK Theory Fermilab Theory Meeting @ Fermilab, 26th, Sep., 2016

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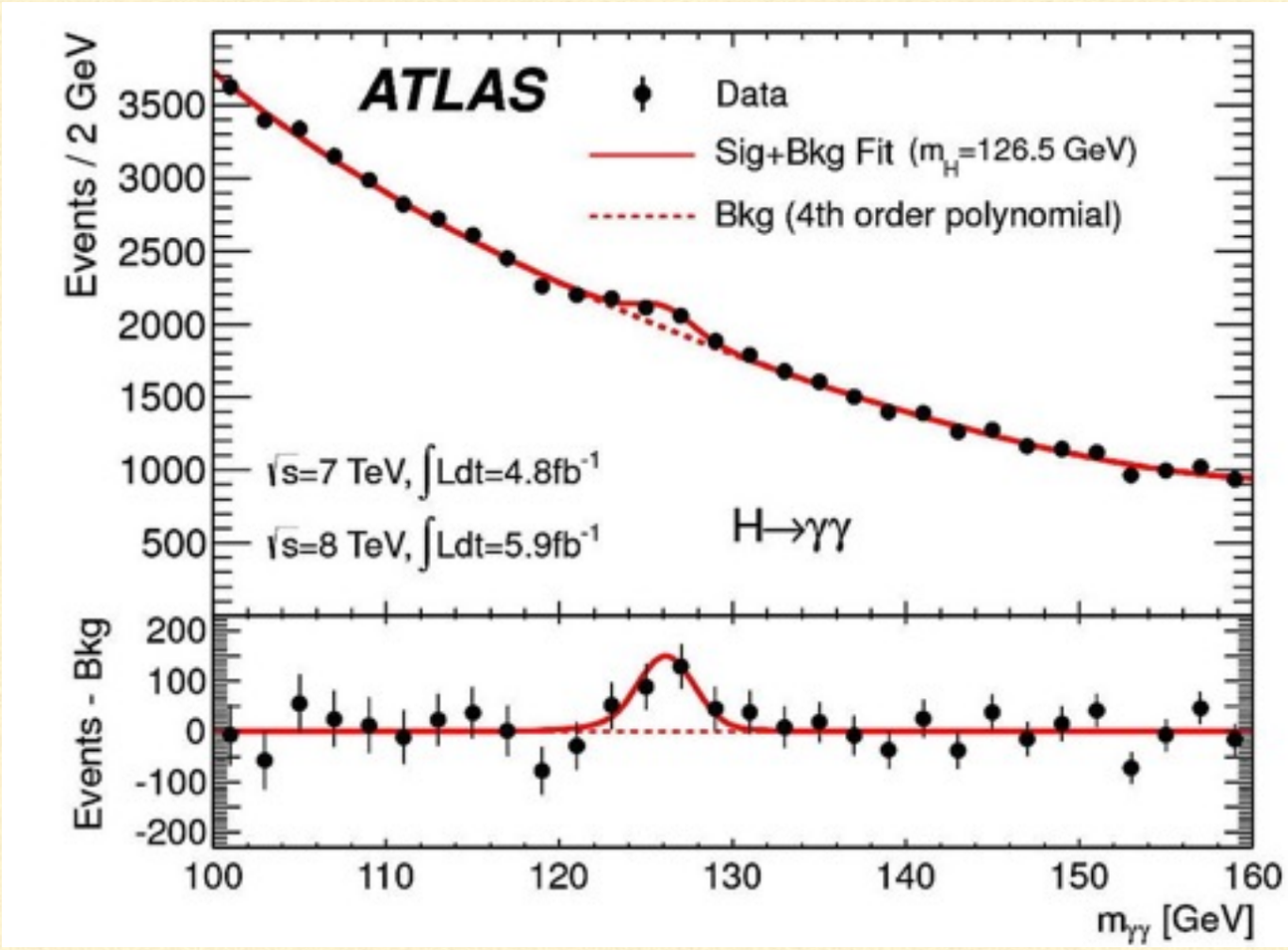
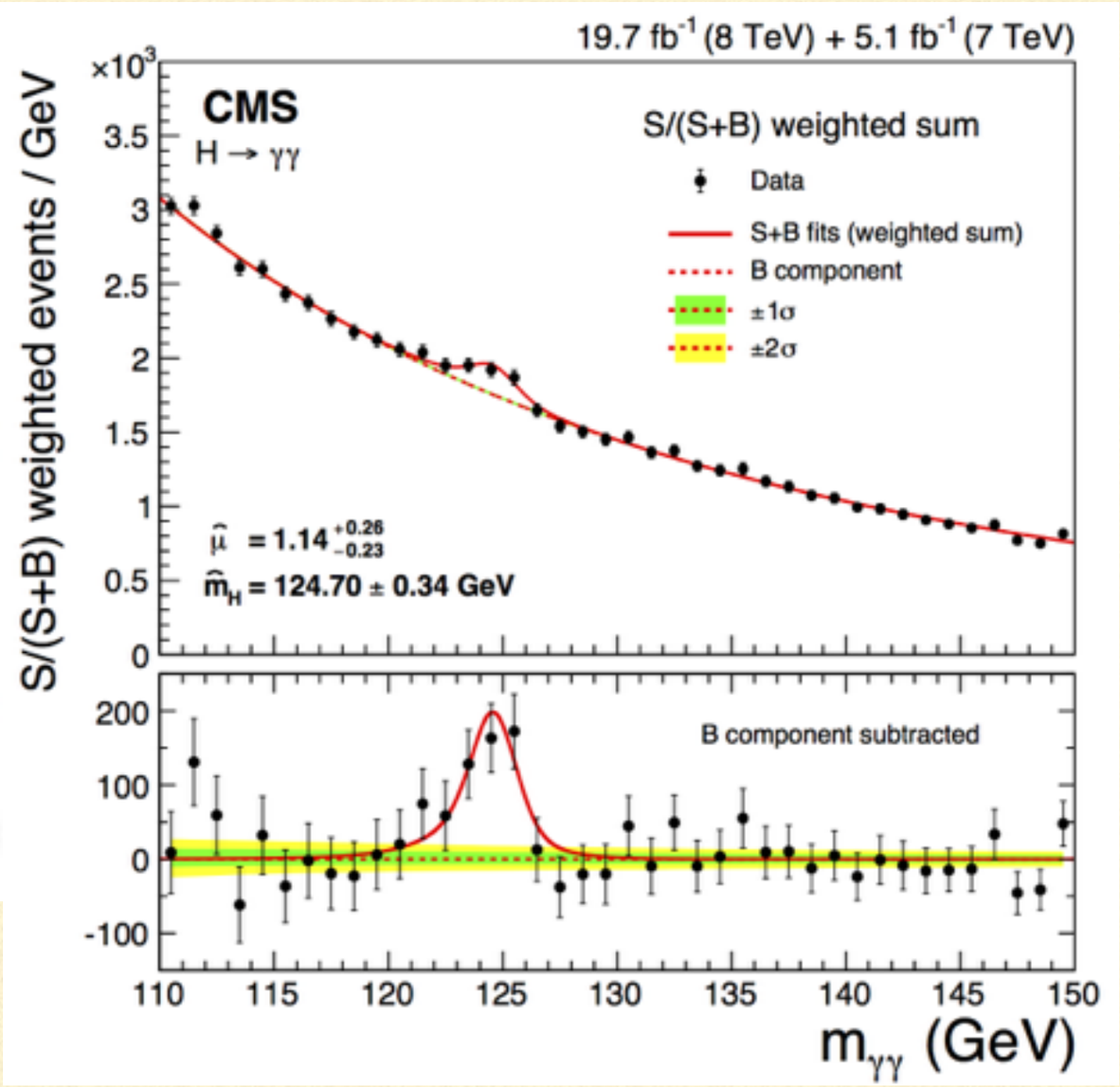
HIGGS DISCOVERY





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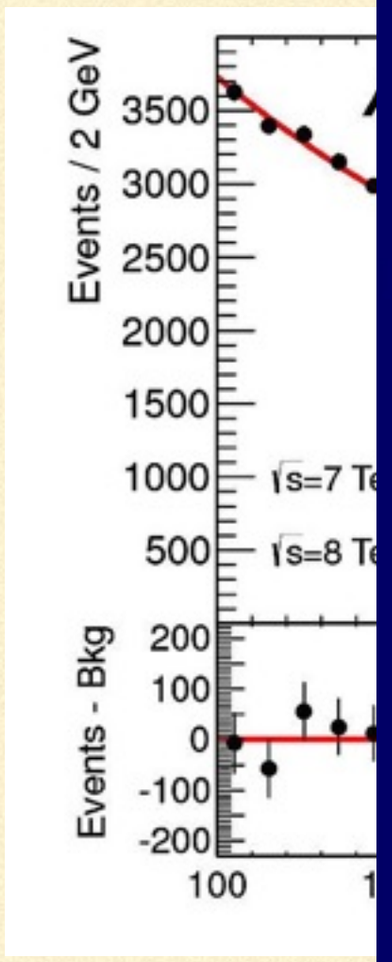
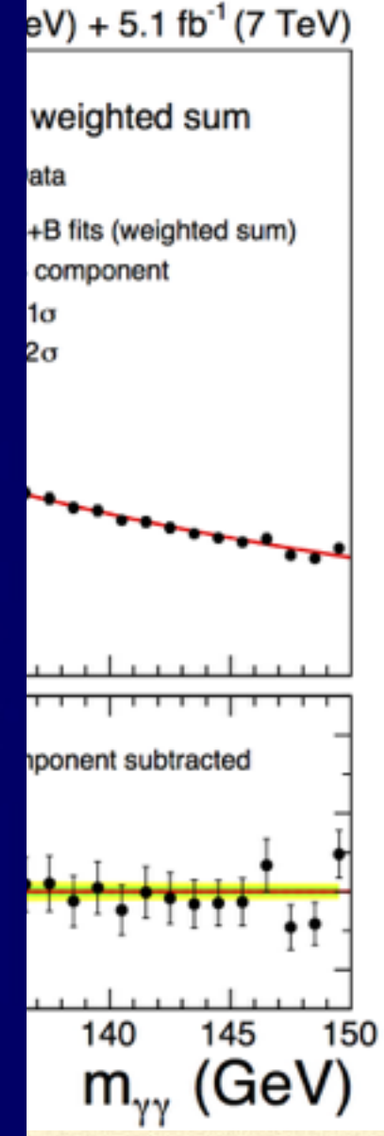


2013 Nobel Prize Winners

How Particles Get Their Masses

FABRICE COFFRINI/AFP/GETTY IMAGES/FILE

British physicist Peter Higgs, right, speaks with Belgian physicist Francois Englert at a press conference at CERN in 2012. Higgs and Englert shared the 2013 Nobel Prize in Physics for describing an explanation for why particles have mass. They independently published papers on this topic in 1964.

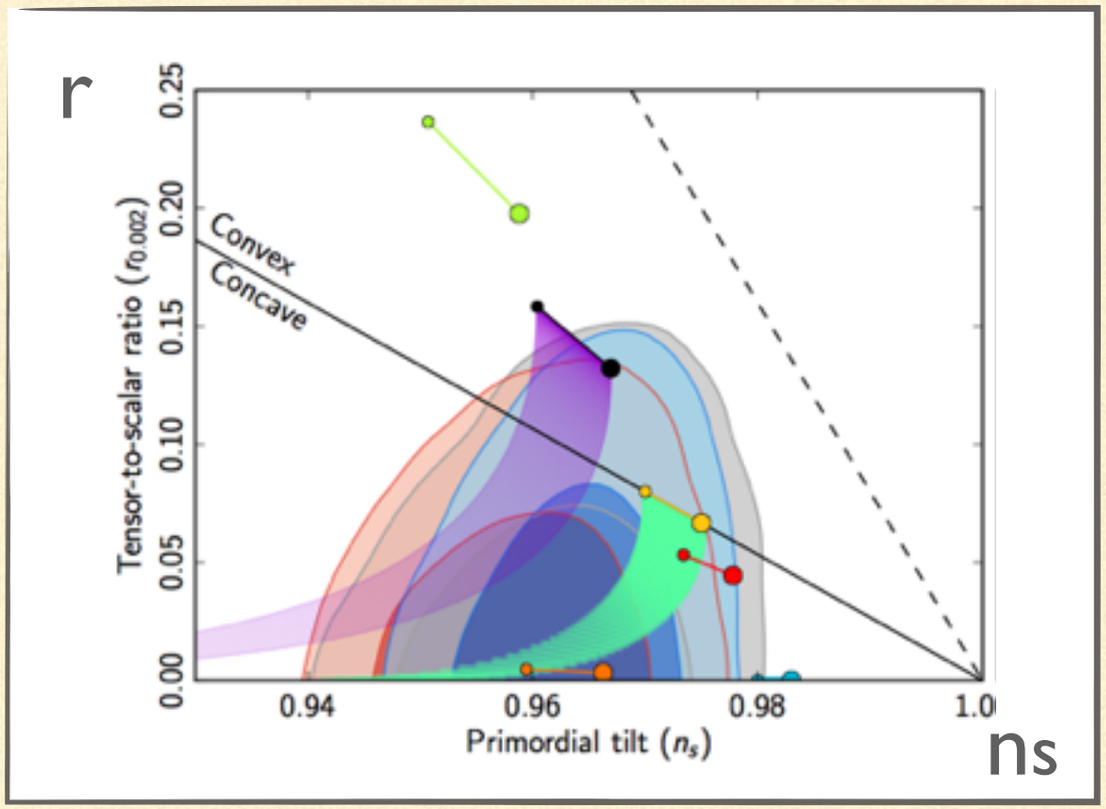


HIGGS AS THE INFLATON

- Inflation : accelerated expansion triggered by "inflaton"

  - solves horizon, flatness etc. problems + generates seeds for galaxies

  - gives predictions on CMB observation



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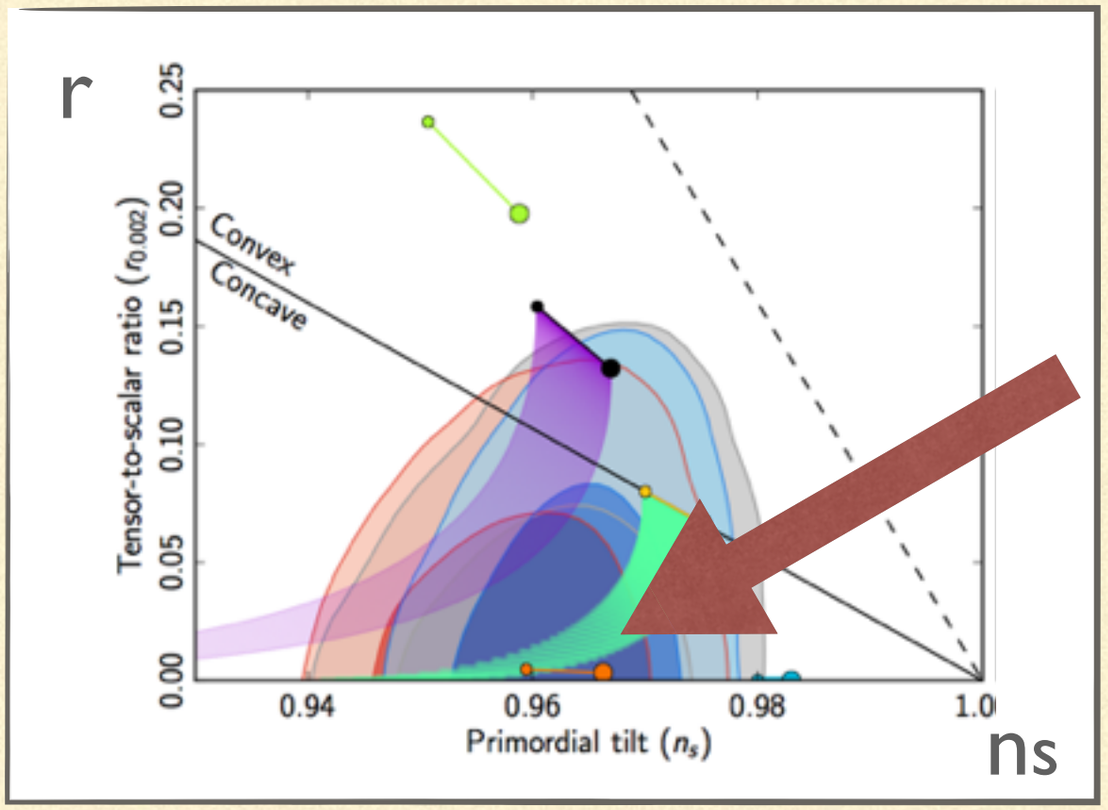


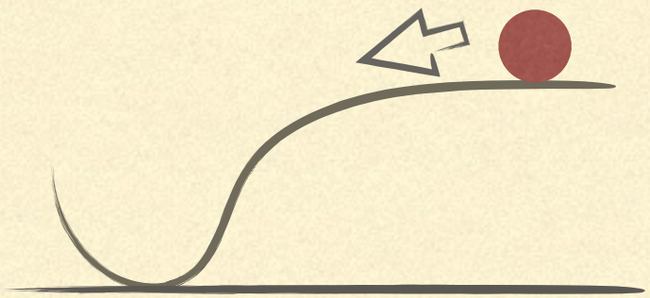
Starobinsky inflation

$$\mathcal{L} \sim R + R^2$$

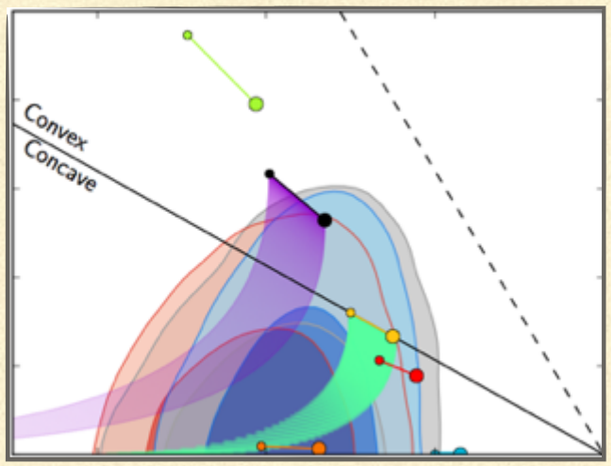
Higgs inflation

$$\mathcal{L} \sim R + \phi^2 R + \cdots$$

HIGGS AS THE INFLATON



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



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

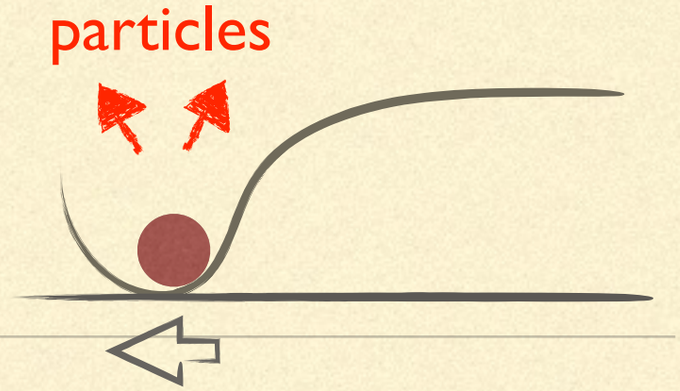
→ Excellent agreement w/ observation [Bezrukov & Shaposhnikov '08]

- Sevaral advantages

1. Economical : no need to add new field

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

PREHEATING

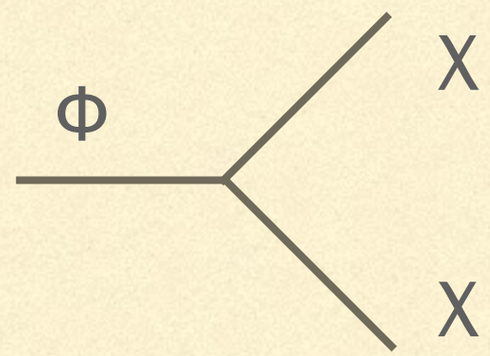


- Inflation is only the beginning of the story

Inflation

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

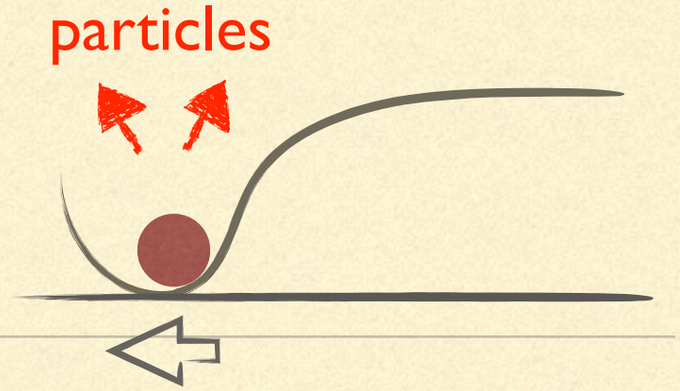
[Bezrukov, Gorbunov, Shaposhnikov '09
Garcia-Bellido, Figueroa, Rubio '09
and subsequent works]



BBN, CMB, ...

t

PREHEATING



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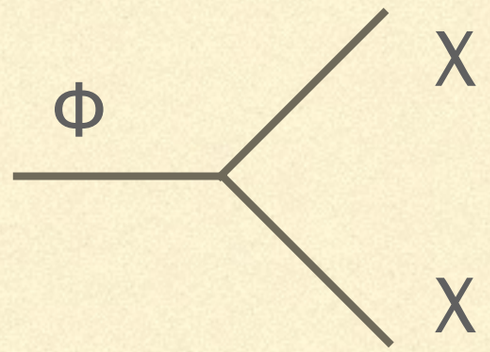
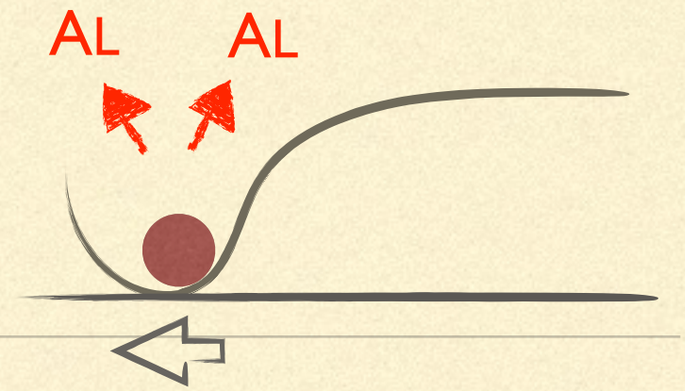


BBN, CMB, ...

t

SUMMARY



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

Longitudinal gauge boson

- These G.B.s have momentum ~ $\lambda^{1/2}$ Mp (λ : 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 production of longitudinal G.B.

Higgs inflation : Standard lore

ACTION

- Consider REAL inflaton for the moment, for simplicity

Free parameter

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

Ricci scalar

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

Real inflaton

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

$$\lambda \sim 0.01$$

Jordan frame :

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

WITHOUT NONMINIMAL COUPLING ...

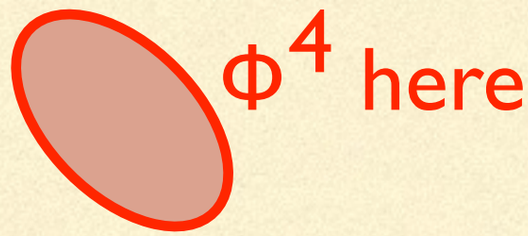
- In the absence of coupling $\xi\phi_J^2 R_J$,

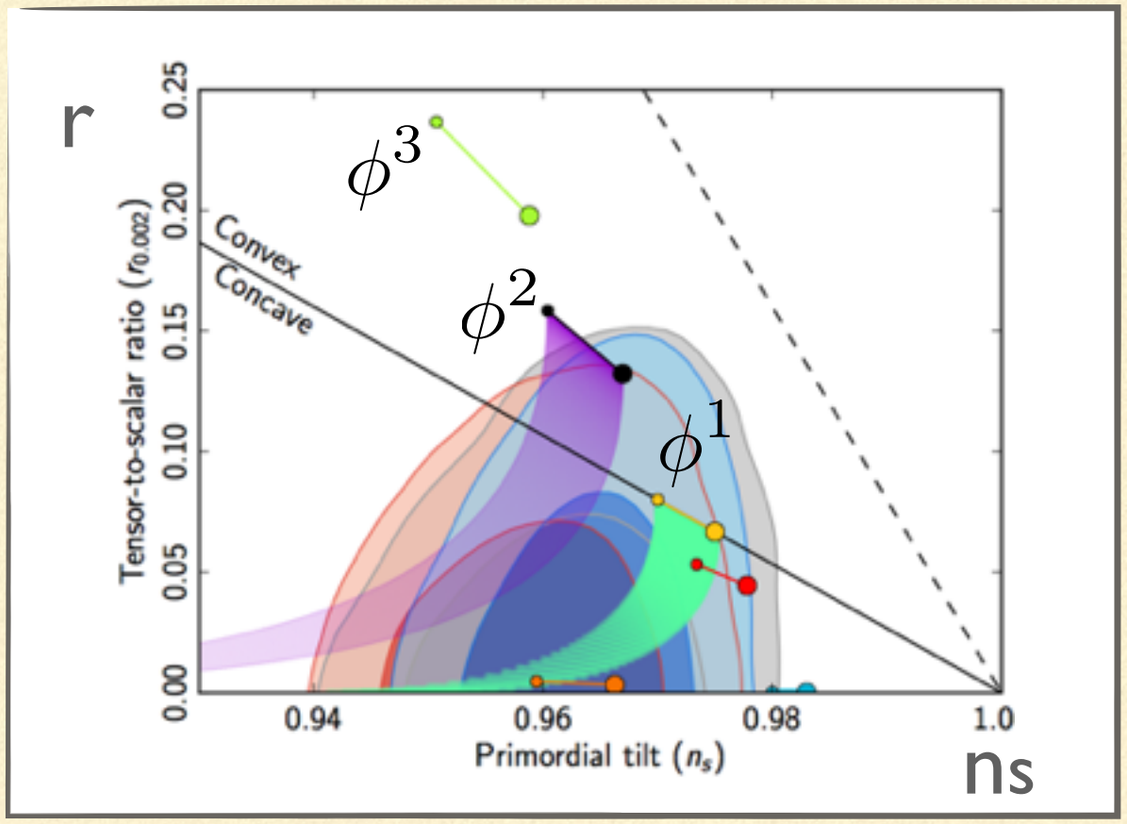
this is just chaotic inflation

with potential $\sim \lambda\phi_J^4$

↓

observationally excluded





WITH NONMINIMAL COUPLING ...

- With coupling $\xi\phi_J^2 R_J$, ... Let's go to the "Einstein frame"

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

  - Ricci scalar transforms as $R_J = \Omega^2 R + \cdots$

  - Action reduces to .. $$S = \int d^4x\sqrt{-g}\left[\frac{M_P^2}{2}R + \cdots\right]$$

Einstein frame :

No nonminimal coupling

w/ $\Omega^2 = 1 + \dfrac{\xi\phi_J^2}{M_P^2}$

INFLATION IN EINSTIEN FRAME

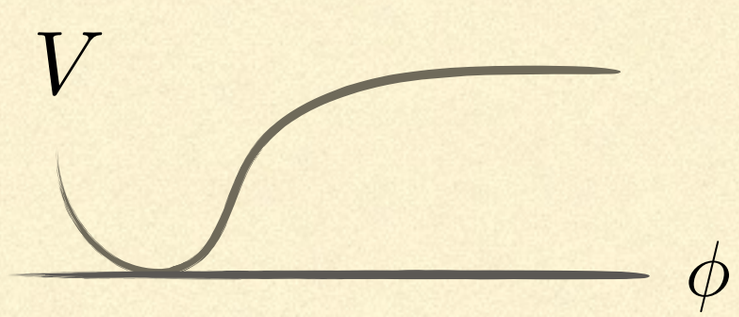
Note : conformal factor

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

- Redefinition of inflaton makes the expression simpler

  - Inflaton redef. : $\frac{d\phi}{d\phi_J} \equiv \frac{1}{\Omega^2}\sqrt{1 + \frac{\xi(1+6\xi)\phi_J^2}{M_P^2}}$

  - Potential redef. : $V(\phi) \equiv \frac{V_J(\phi_J)}{\Omega^4}$



- Action takes the simplest form

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

INFLATION IN EINSTIEN FRAME

Note :

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

to realize observed scalar perturbation

- Potential in the Einstein frame

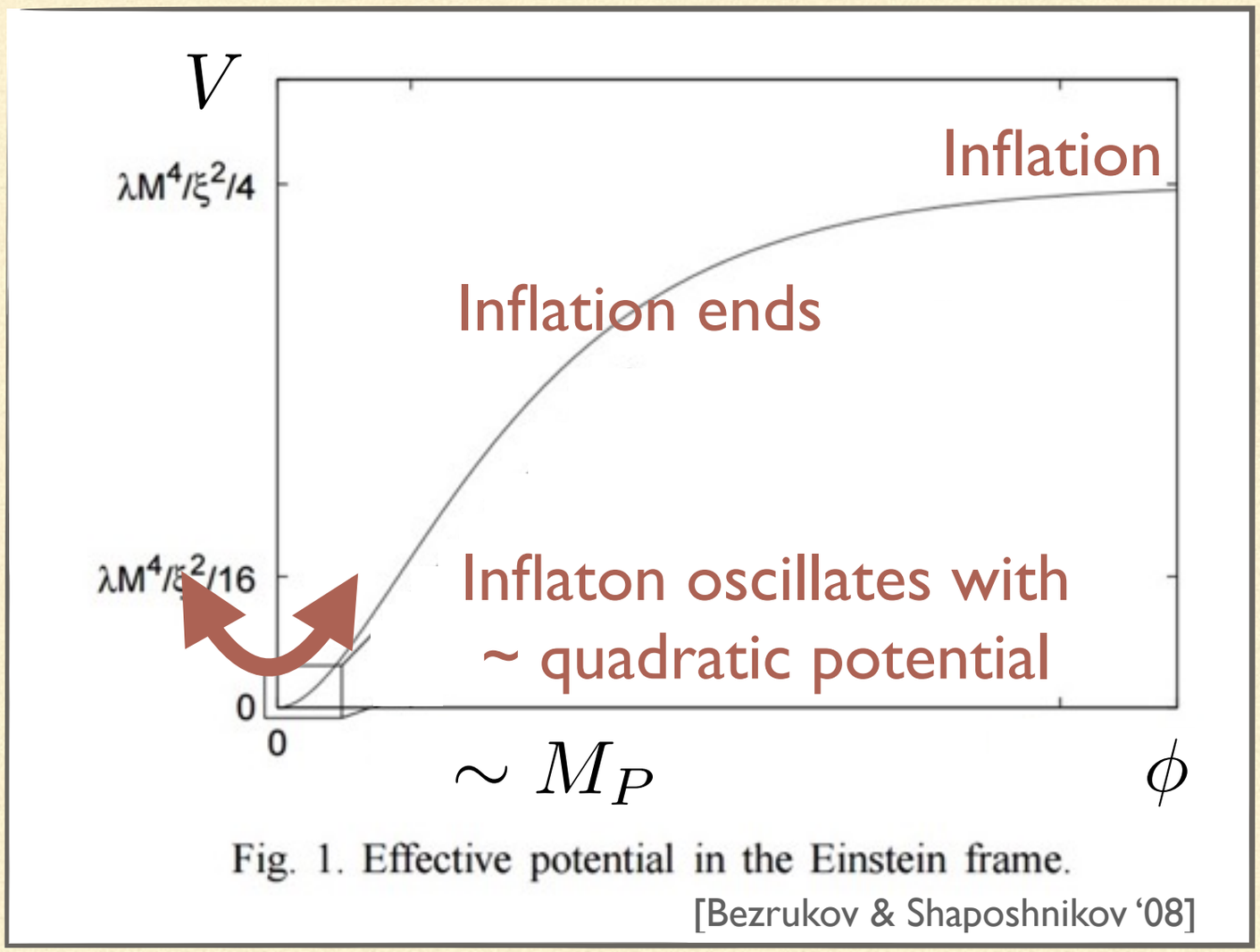


Fig. 1. Effective potential in the Einstein frame.

[Bezrukov & Shaposhnikov '08]

(P)REHEATING

- Let's make inflaton to be SM Higgs Φ_J

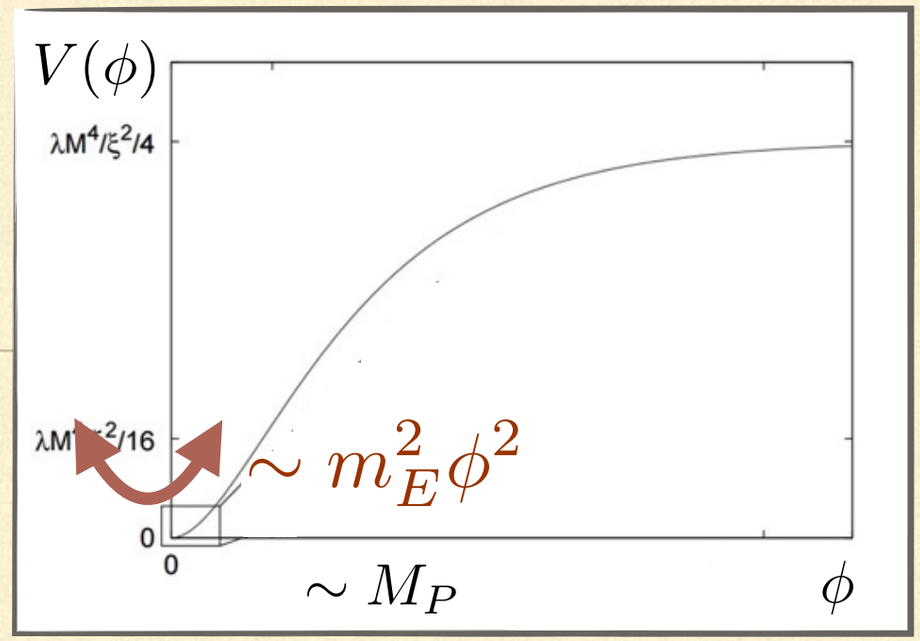
$$S = \int d^4x\sqrt{-g_J}\left[\left(\frac{M_P^2}{2} + \xi|\Phi_J|^2\right)R_J - \overbrace{|D\Phi_J|^2 - V_J(|\Phi_J|) + \cdots}^{\text{Terms in SM Lagrangian (Gauge boson etc.)}}\right]$$

- 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 → oscillation)

  - gauge boson mass oscillates as the inflaton oscillates

(P)REHEATING



- Note : WRONG argument 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

(for first ~ 100 oscillations)

- Parametric resonance of gauge bosons (after first ~ 100 oscillations) ... etc.

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

[Lozanov & Amin '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

- Gauge boson action (after taking unitary gauge $\Phi_J = \phi_J/\sqrt{2}$)

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

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

→ mass of the canonical field $\tilde{A}_L \equiv \sqrt{\frac{m_A}{k^2+m_A^2}}A_L \neq$ mass of A_T

Note : $m_A^2 = \frac{a^2g^2\phi_J^2}{\Omega^2}$, τ : conformal time

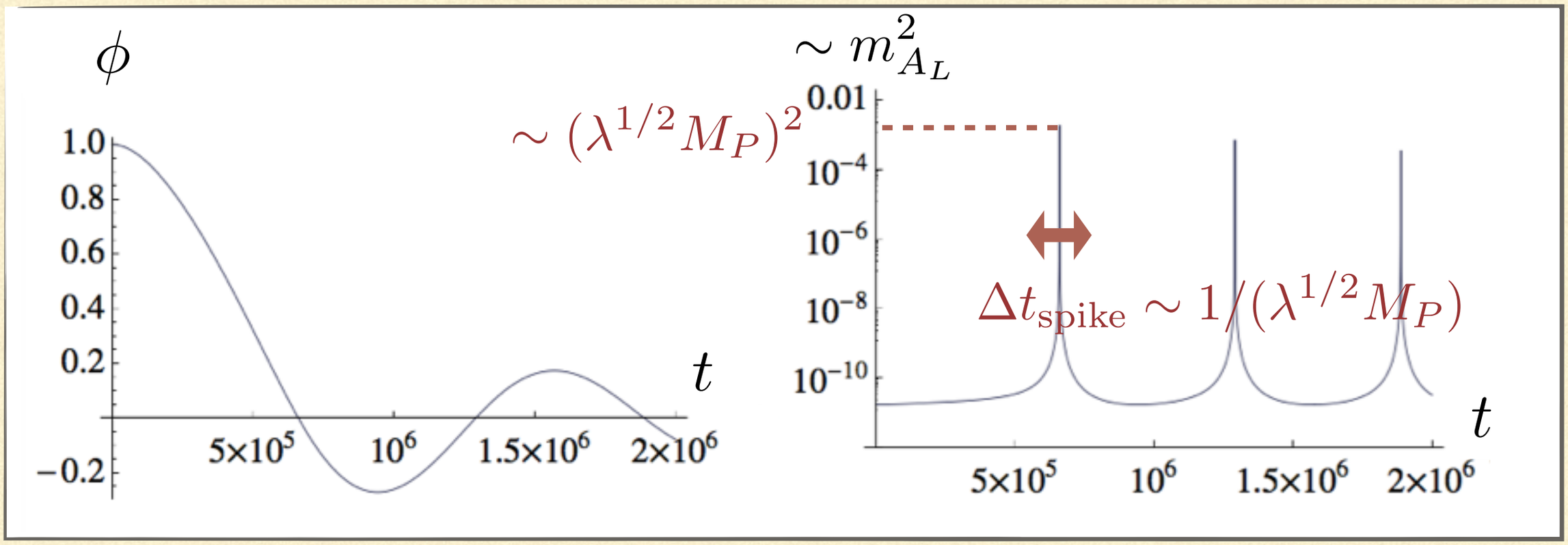
BEHAVIOR OF LONGITUDINAL MASS

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 :

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

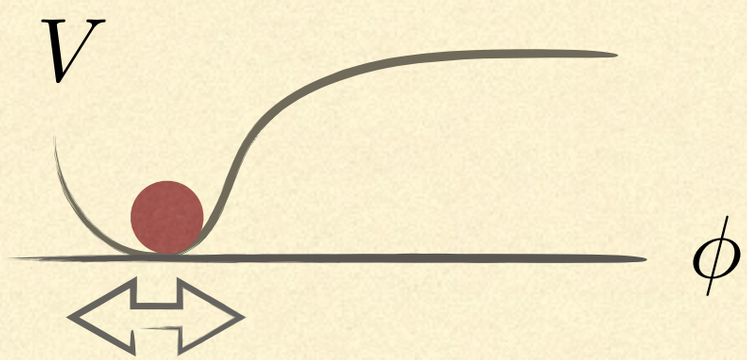
$$m_{A_L}^2 \sim m_{A_T}^2 - \frac{\ddot{m}_{A_T}}{m_{A_T}}$$

- Origin of the spike

  - It contains $\ddot{\phi}_J$, and this shows singular behavior — why?

  - Einstein frame inflaton ϕ is oscillating

    with ~ quad. potential



  - But the map btw. ϕ and ϕ_J suddenly changes around the origin

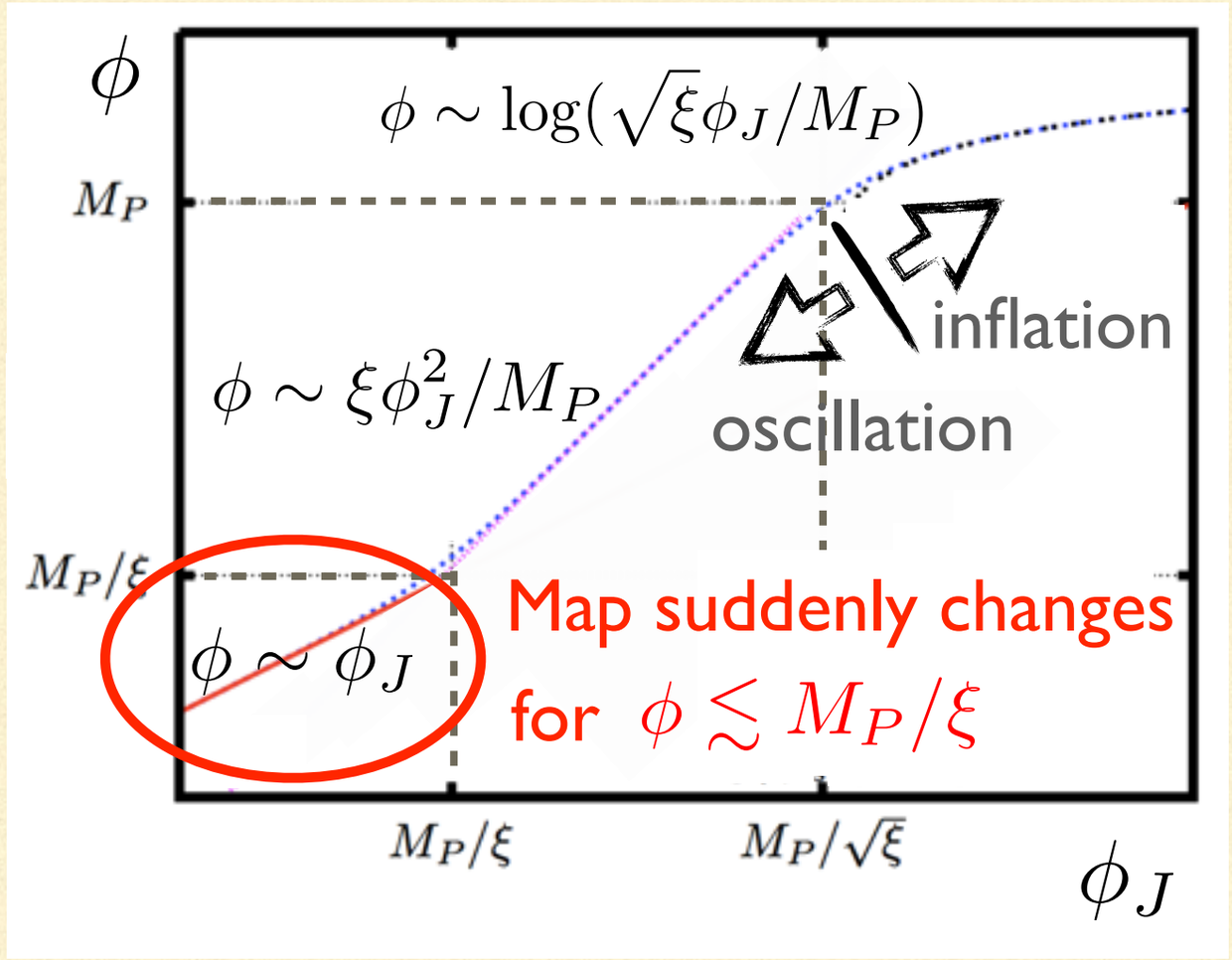
    → next slide

BEHAVIOR OF LONGITUDINAL MASS

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

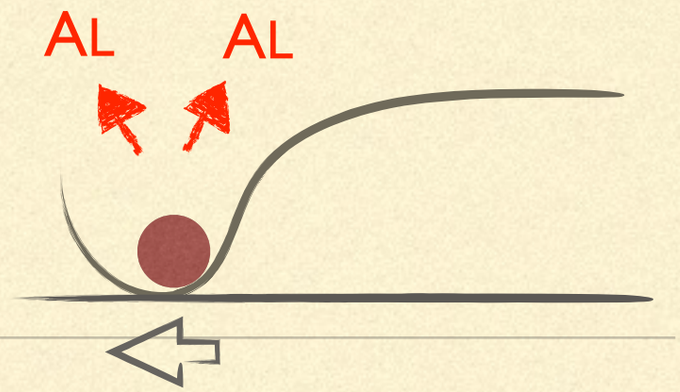
Einstein

~ sin($m_E t$)



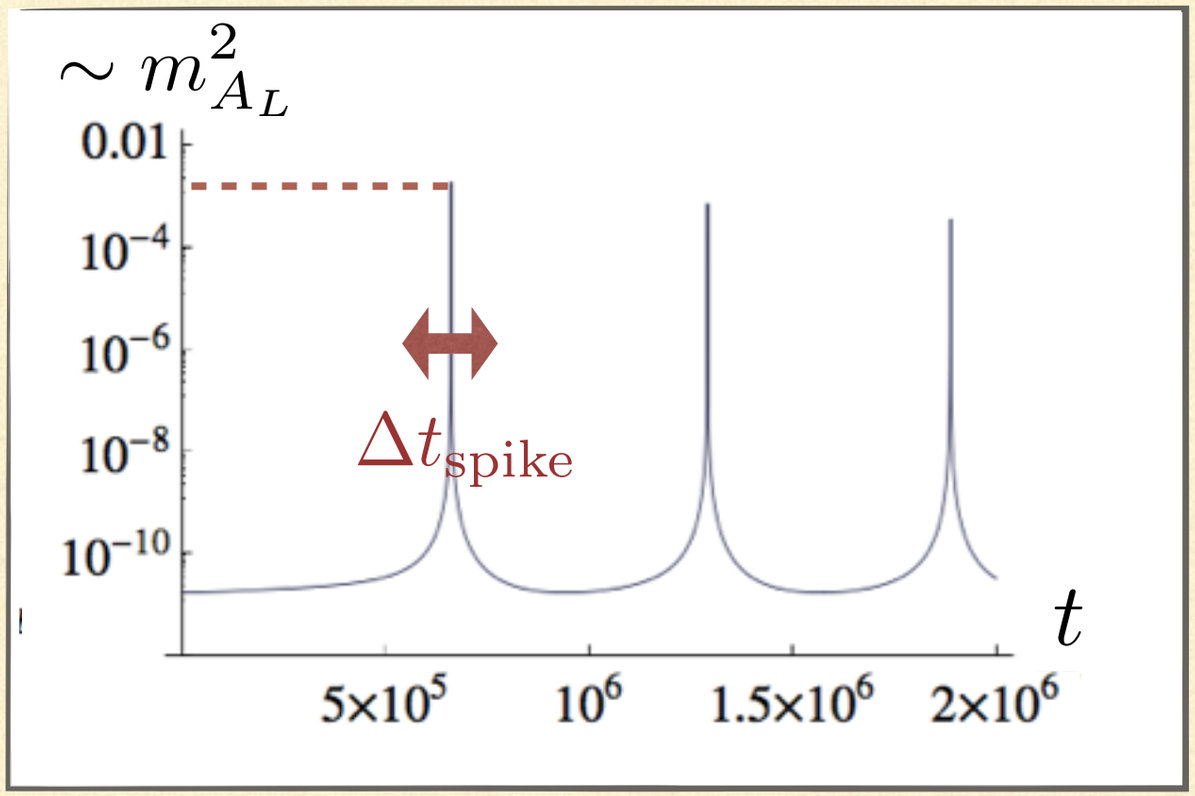
Jordan

BEHAVIOR OF LONGITUDINAL MASS



- "Spike" correponds to the timescale

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

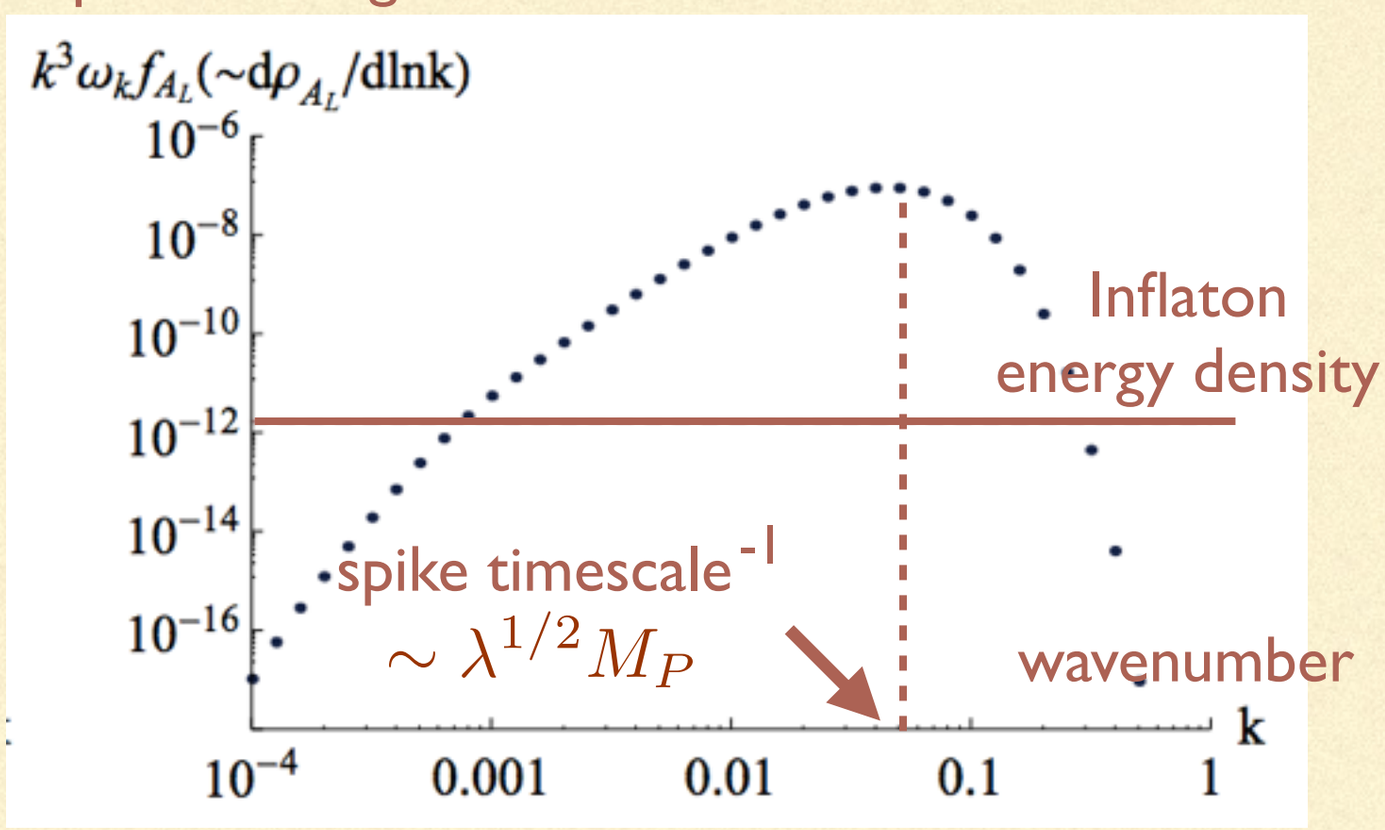


$$\Delta t_{\rm spike} \sim \frac{M_P/\xi}{\dot{\phi}} \sim \frac{1}{\lambda^{1/2} M_P}$$

LONGITUDINAL G.B. PRODUCTION

- Backreaction neglected below

- Energy of longitudinal G.B. exceeds inflaton energy after *only one spike*



BACKREACTION ?

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

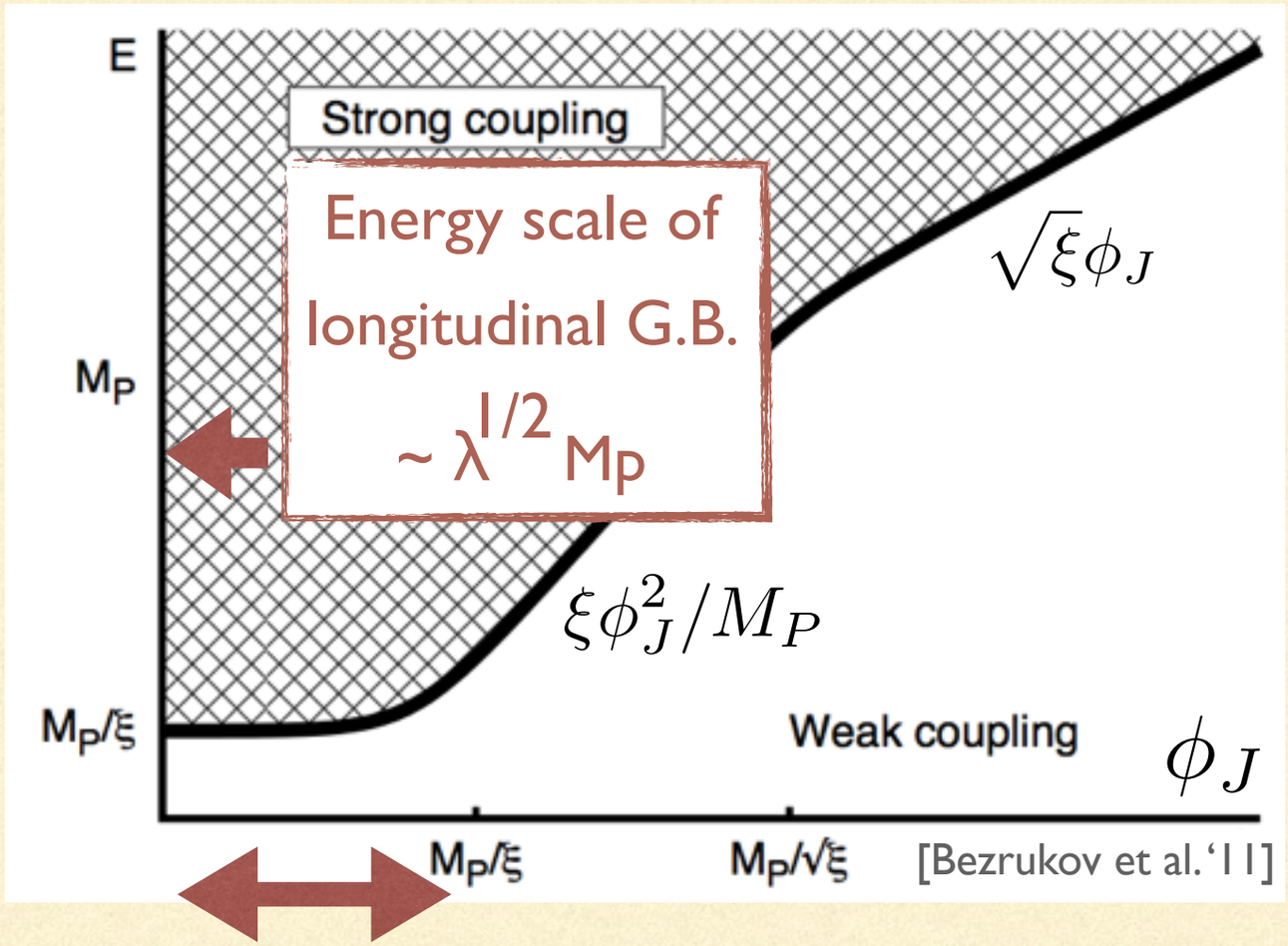
  “most of the inflaton energy goes into longitudinal G.B.”

  though G.B. prod. will cease at some point before exceeding

  the inflaton energy

UNITARITY VIOLATION

- Longitudinal G.B. energy exceeds the cutoff scale



Longitudinal G.B. produced while ϕ_J crosses this region

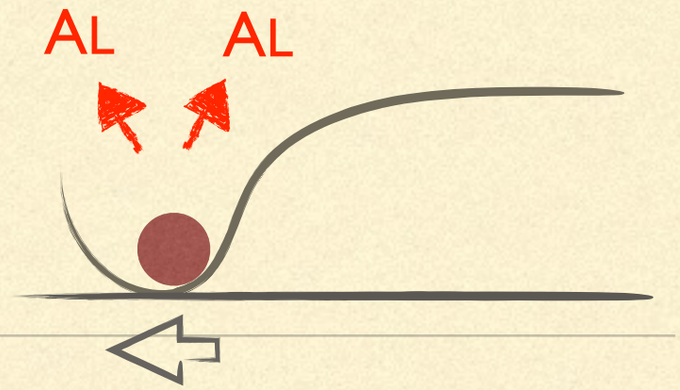
Note :

Given by the coefficient of scalar^{2}graviton coupling

Note :

Same in Jordan & Einstein

SUMMARY



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

Longitudinal gauge boson

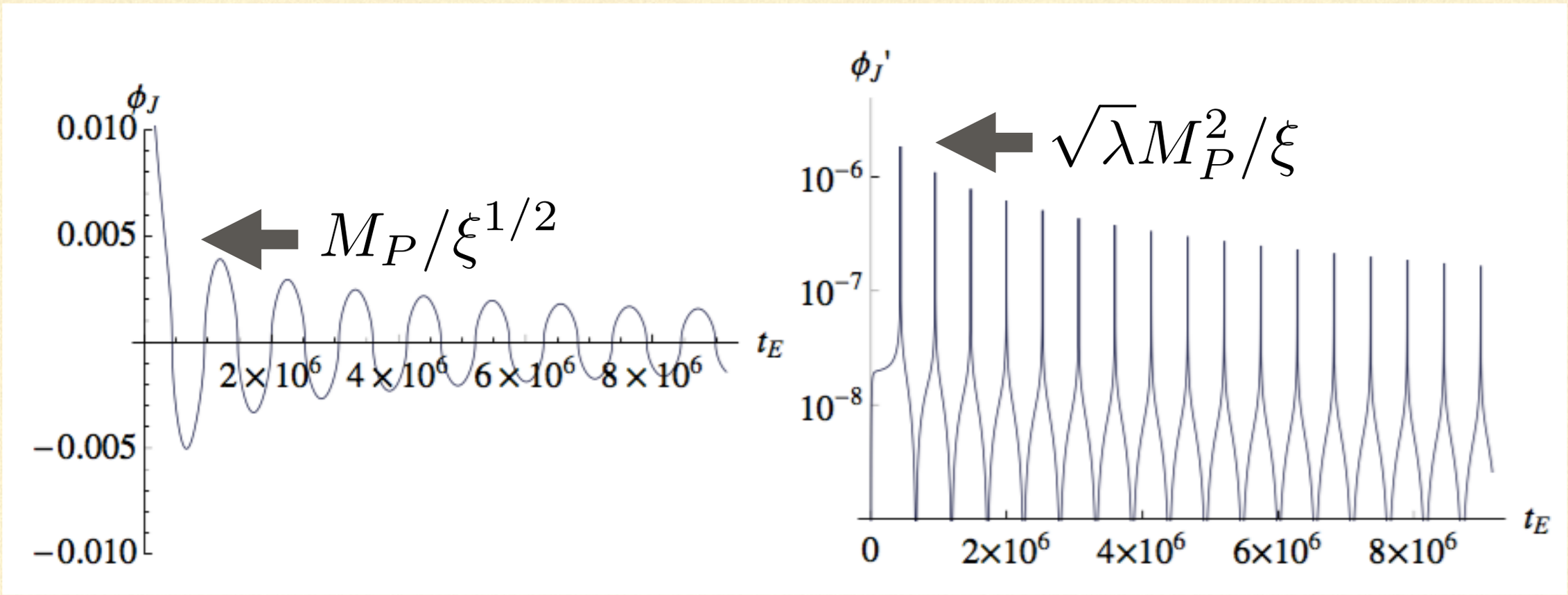
through the "mass spike"

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

- G.B. energy exceeds the cutoff scale

Backup

BEHAVIOR OF JORDAN INFLATON



GAUGE BOSON MASSES

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

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

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