Title: Connecting inflation to diverse observables: leptons, baryons and cosmological magnetic fields

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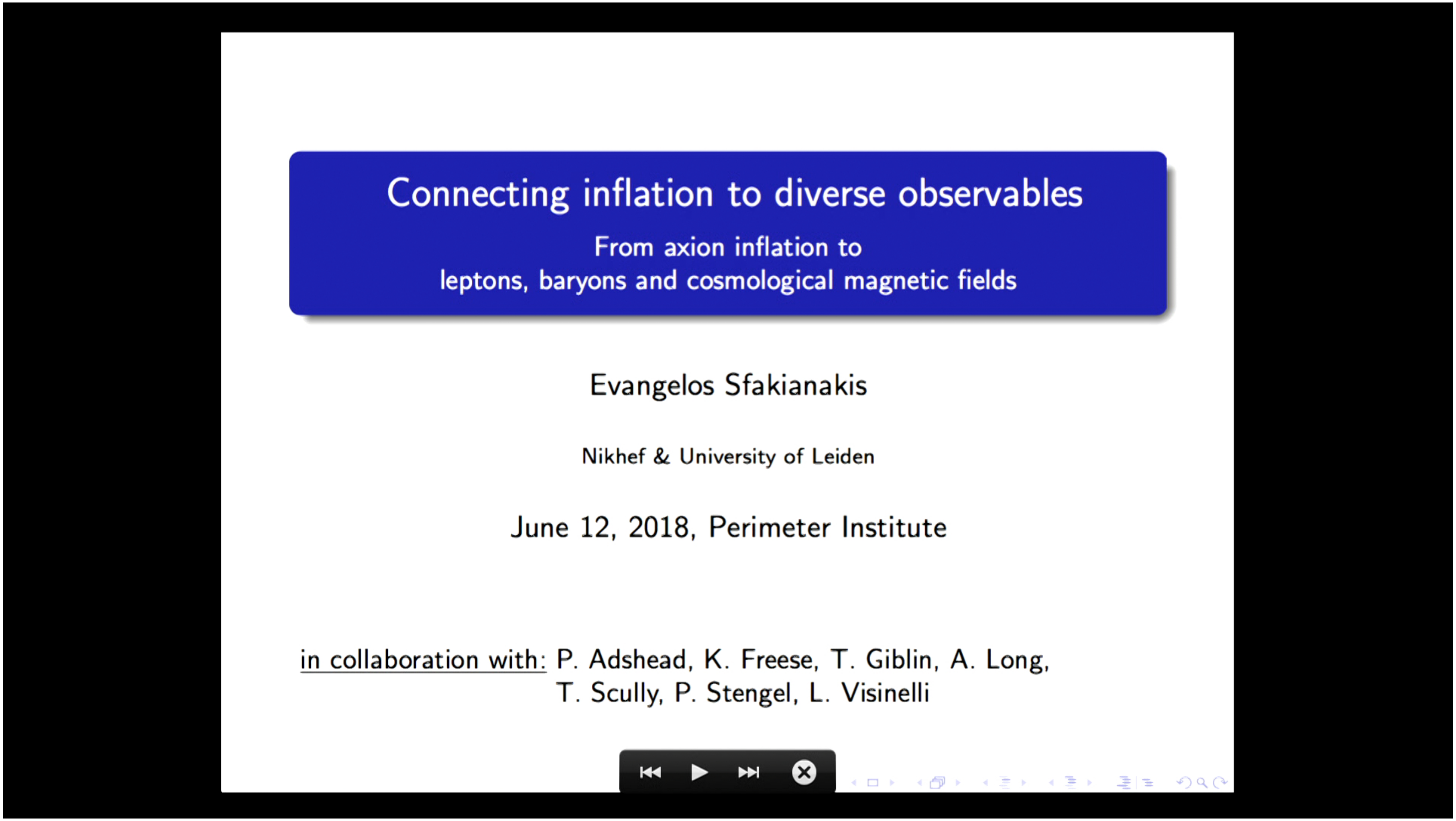
Abstract: <p>Axions are attractive candidates for theories of large-field inflation that are capable of generating observable primordial gravitational wave backgrounds. These fields enjoy shift-symmetries that protect their role as inflatons from being spoiled by coupling to unknown UV physics. This symmetry also restricts the couplings of these axion fields to other matter fields. At lowest order, the only allowed interactions are derivative couplings to gauge fields and fermions. These derivative couplings lead to the biased production of fermion and gauge-boson helicity states during and after inflation. I will discuss preheating in axion-inflation models that are derivatively coupled to Abelian gauge-fields and fermion axial-currents.</p>

<p>For an axion coupled to U(1) gauge fields preheating is efficient for a wide range of parameters. In certain cases the inflaton is seen to transfer all its energy to the gauge fields within a few oscillations. Identifying the gauge field as the hypercharge sector of the Standard Model can lead to the generation of cosmologically relevant magnetic fields.</p>

<p>Coupling the inflaton-axion to Majorana fermions leads to the biased production of fermion helicity-states which can have interesting phenomenological implications for leptogenesis.</p>



# Connecting inflation to diverse observables

## From axion inflation to leptons, baryons and cosmological magnetic fields

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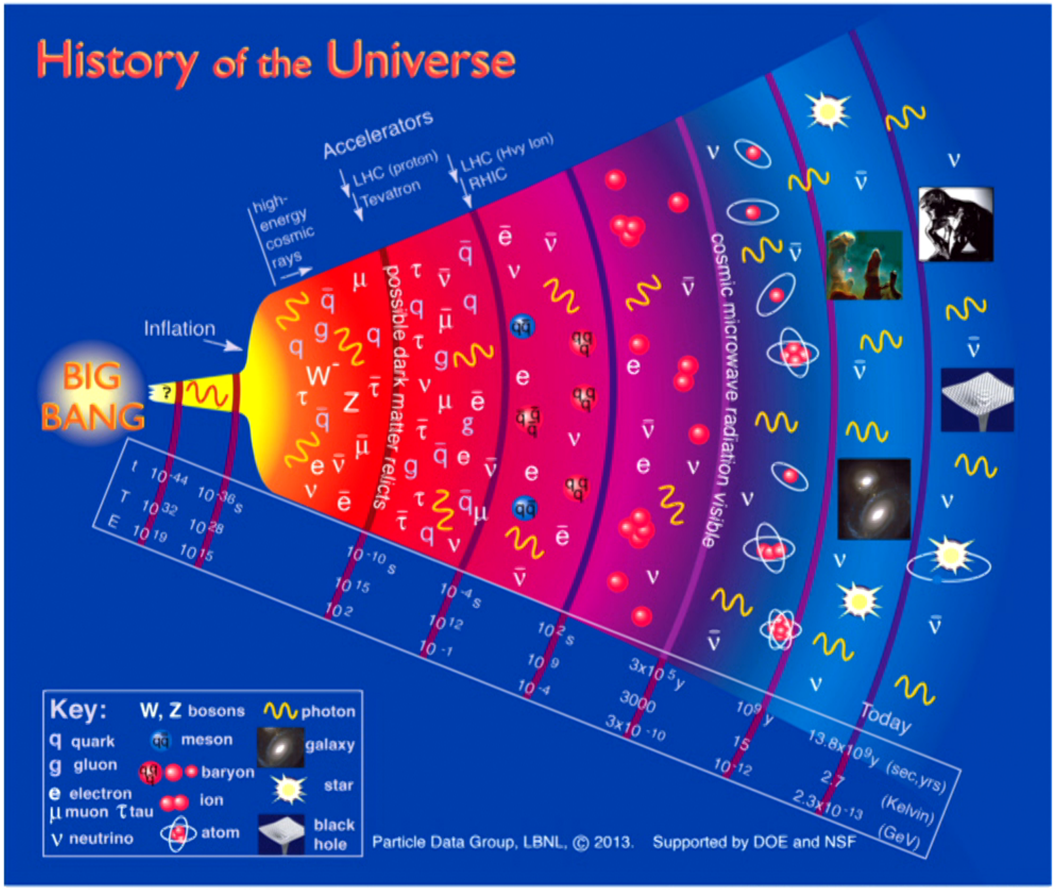
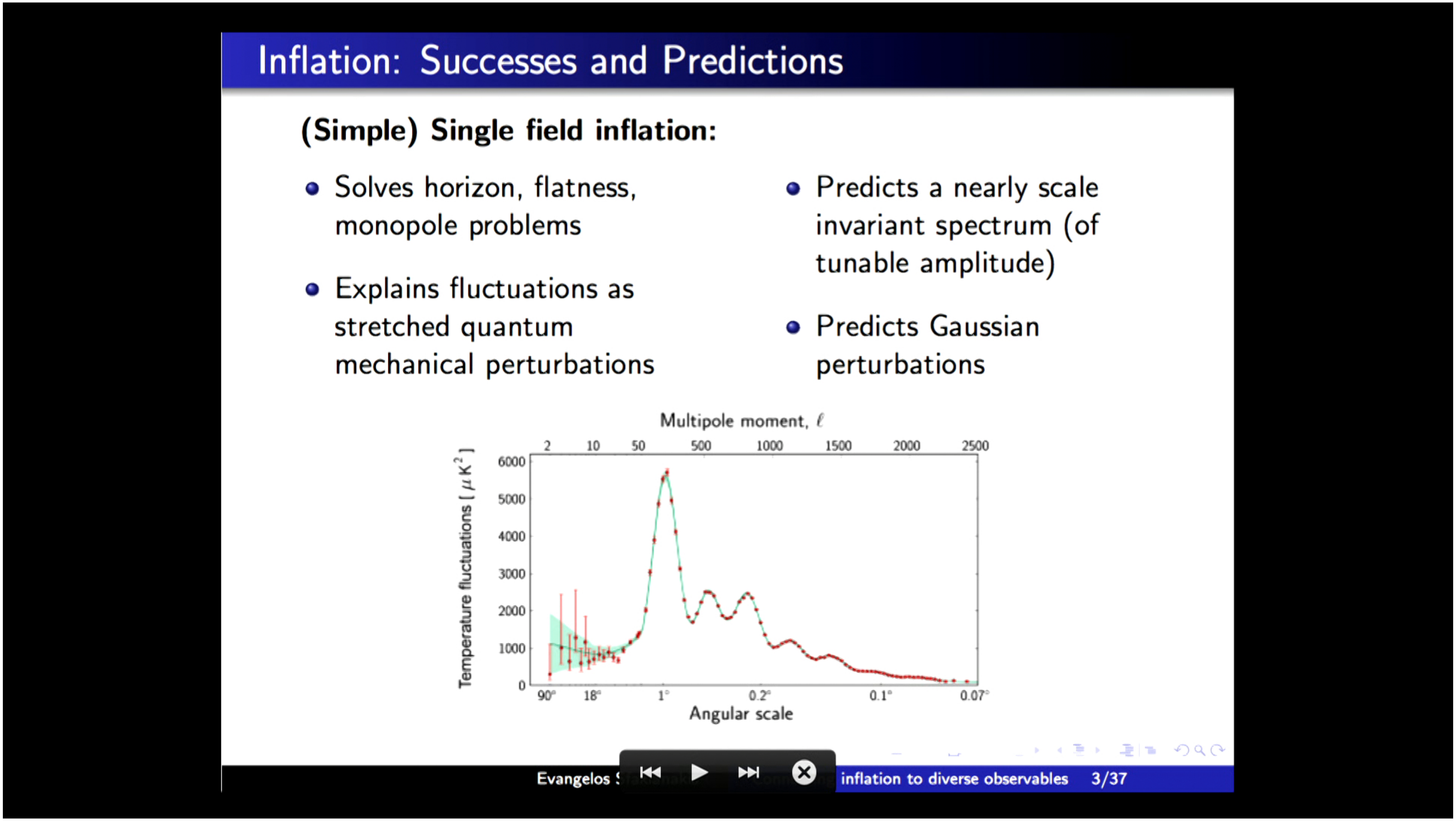
June 12, 2018, Perimeter Institute

in collaboration with: P. Adshead, K. Freese, T. Giblin, A. Long,
T. Scully, P. Stengel, L. Visinelli

# ~~The~~ Our universe



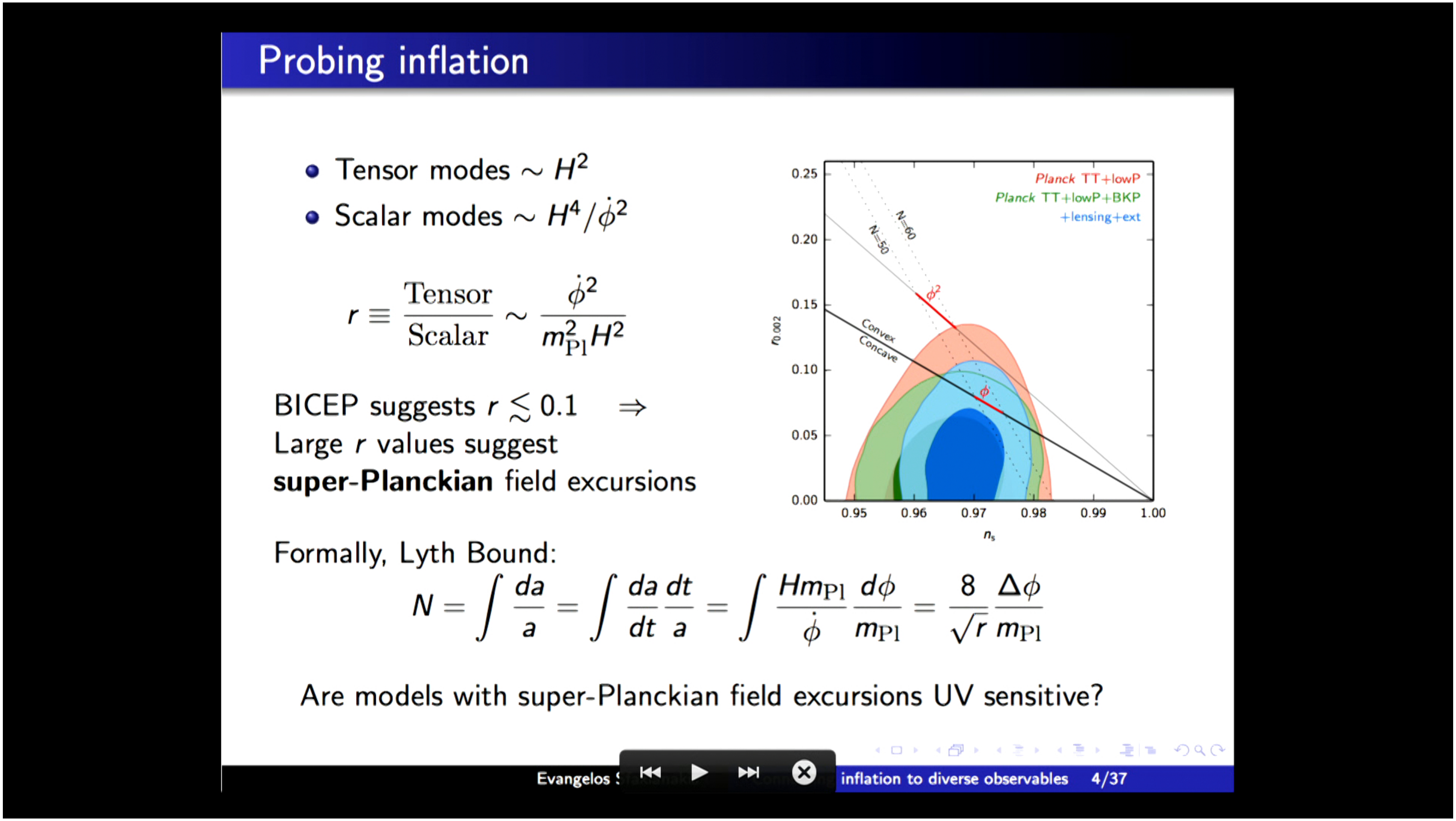
Particle Data Group, LBNL, © 2013. Supported by DOE and NSF



# Inflation: Successes and Predictions

**(Simple) Single field inflation:**

- Solves horizon, flatness, monopole problems
- Explains fluctuations as stretched quantum mechanical perturbations
- Predicts a nearly scale invariant spectrum (of tunable amplitude)
- Predicts Gaussian perturbations



# Probing inflation

- Tensor modes $\sim H^2$
- Scalar modes $\sim H^4/\dot{\phi}^2$

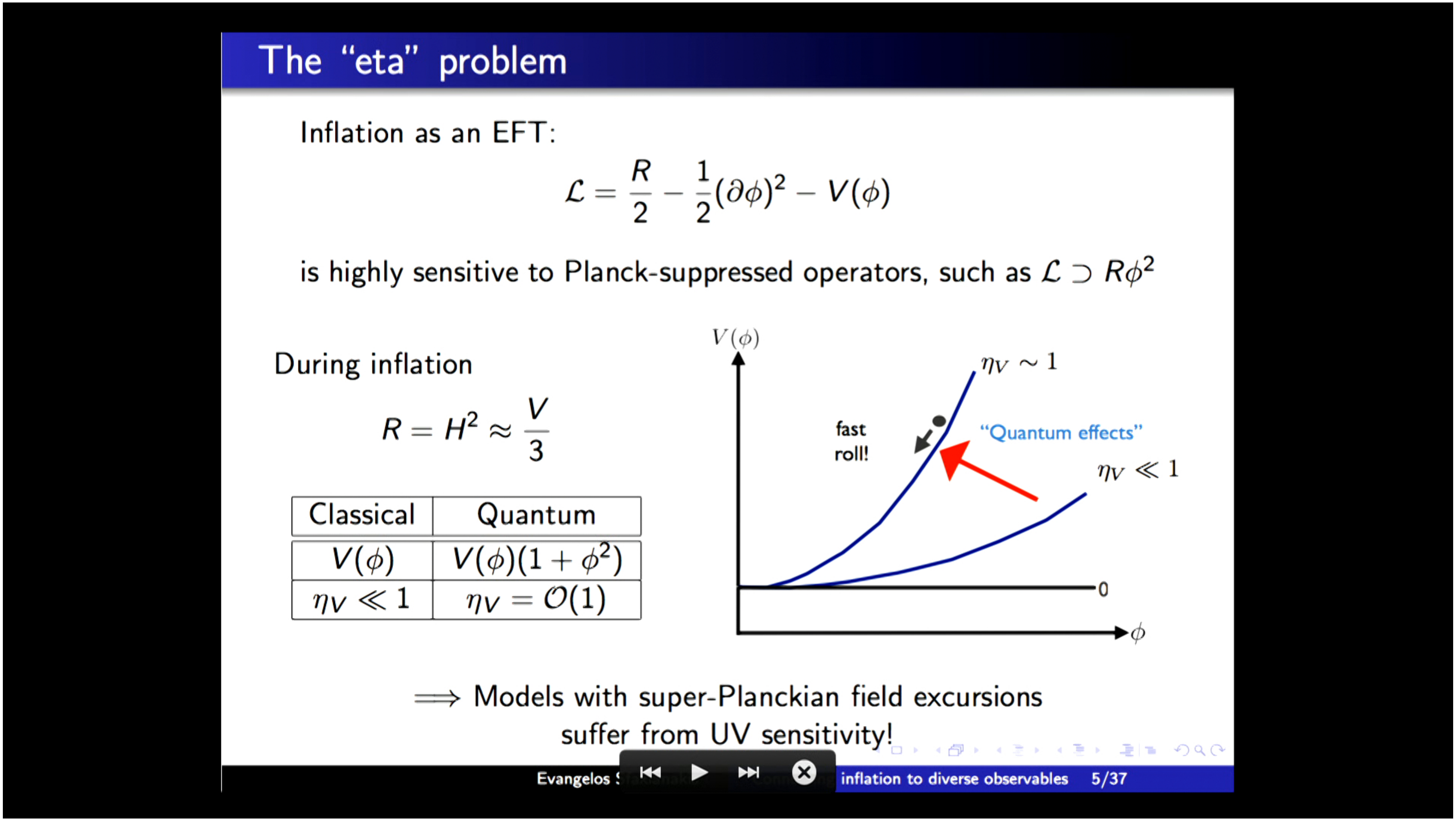
$$r \equiv \frac{\text{Tensor}}{\text{Scalar}} \sim \frac{\dot{\phi}^2}{m_{\rm Pl}^2 H^2}$$

BICEP suggests $r \lesssim 0.1 \quad \Rightarrow$
Large $r$ values suggest
**super-Planckian** field excursions

Formally, Lyth Bound:

$$N = \int \frac{da}{a} = \int \frac{da}{dt}\frac{dt}{a} = \int \frac{H m_{\rm Pl}}{\dot{\phi}}\frac{d\phi}{m_{\rm Pl}} = \frac{8}{\sqrt{r}}\frac{\Delta\phi}{m_{\rm Pl}}$$

Are models with super-Planckian field excursions UV sensitive?



# The “eta” problem

Inflation as an EFT:

$$\mathcal{L} = \frac{R}{2} - \frac{1}{2}(\partial\phi)^2 - V(\phi)$$

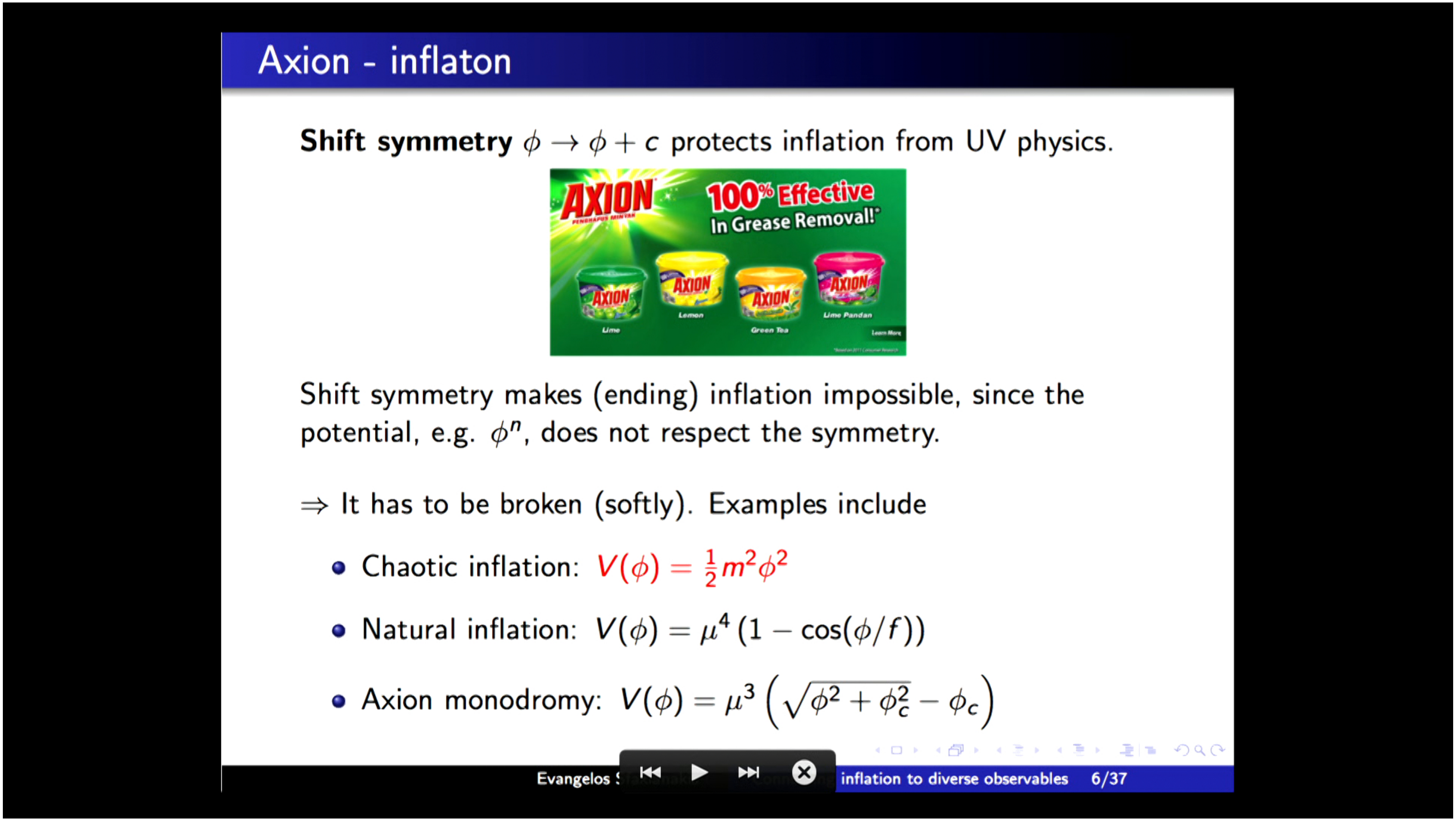
is highly sensitive to Planck-suppressed operators, such as $\mathcal{L} \supset R\phi^2$

During inflation

$$R = H^2 \approx \frac{V}{3}$$

| Classical | Quantum |
|---|---|
| $V(\phi)$ | $V(\phi)(1+\phi^2)$ |
| $\eta_V \ll 1$ | $\eta_V = \mathcal{O}(1)$ |

$\Longrightarrow$ Models with super-Planckian field excursions suffer from UV sensitivity!



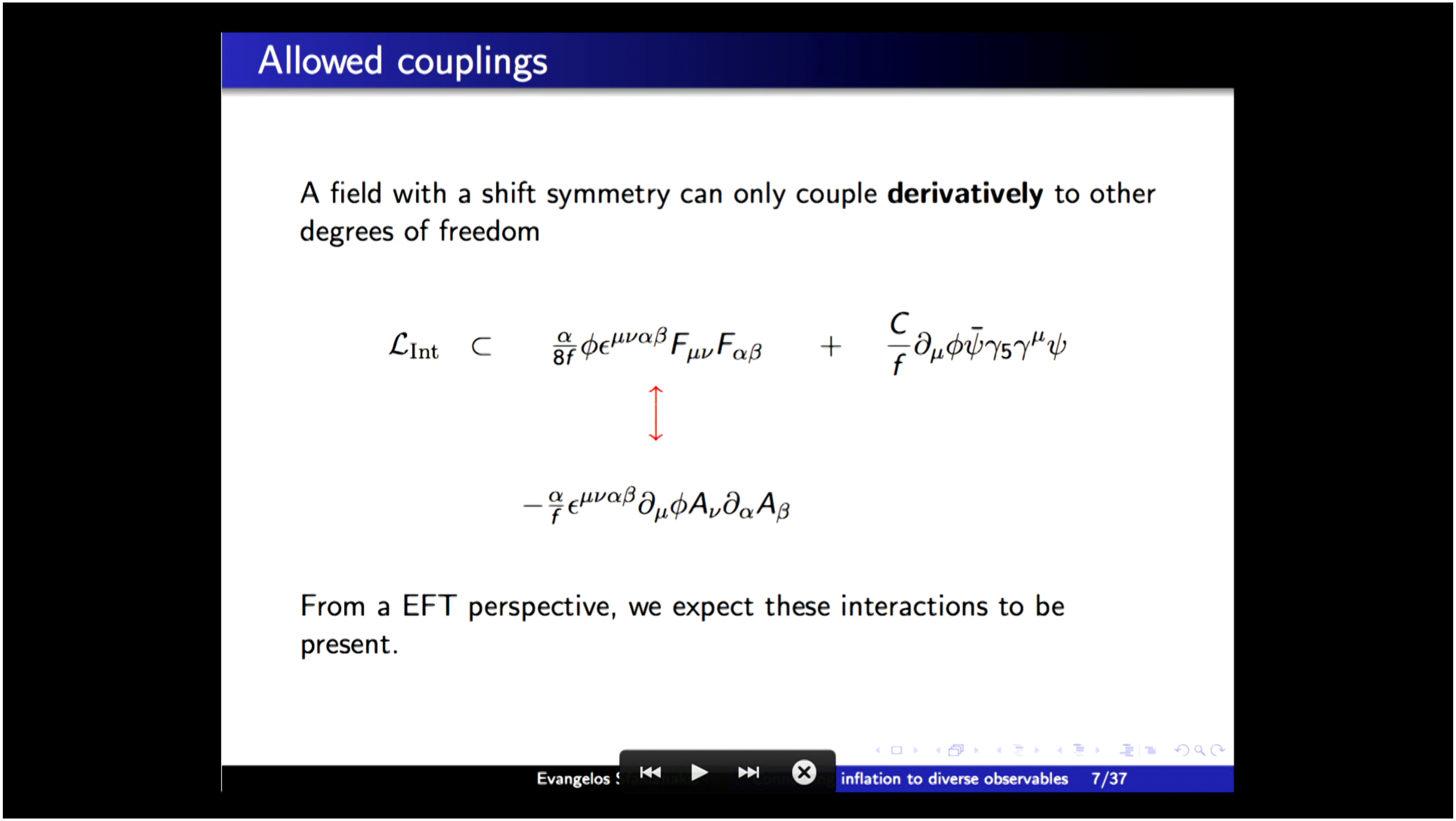
## Axion - inflaton

**Shift symmetry** $\phi \to \phi + c$ protects inflation from UV physics.

Shift symmetry makes (ending) inflation impossible, since the potential, e.g. $\phi^n$, does not respect the symmetry.

$\Rightarrow$ It has to be broken (softly). Examples include

- Chaotic inflation: $V(\phi) = \frac{1}{2} m^2 \phi^2$
- Natural inflation: $V(\phi) = \mu^4 \left(1 - \cos(\phi/f)\right)$
- Axion monodromy: $V(\phi) = \mu^3 \left(\sqrt{\phi^2 + \phi_c^2} - \phi_c\right)$



# Allowed couplings

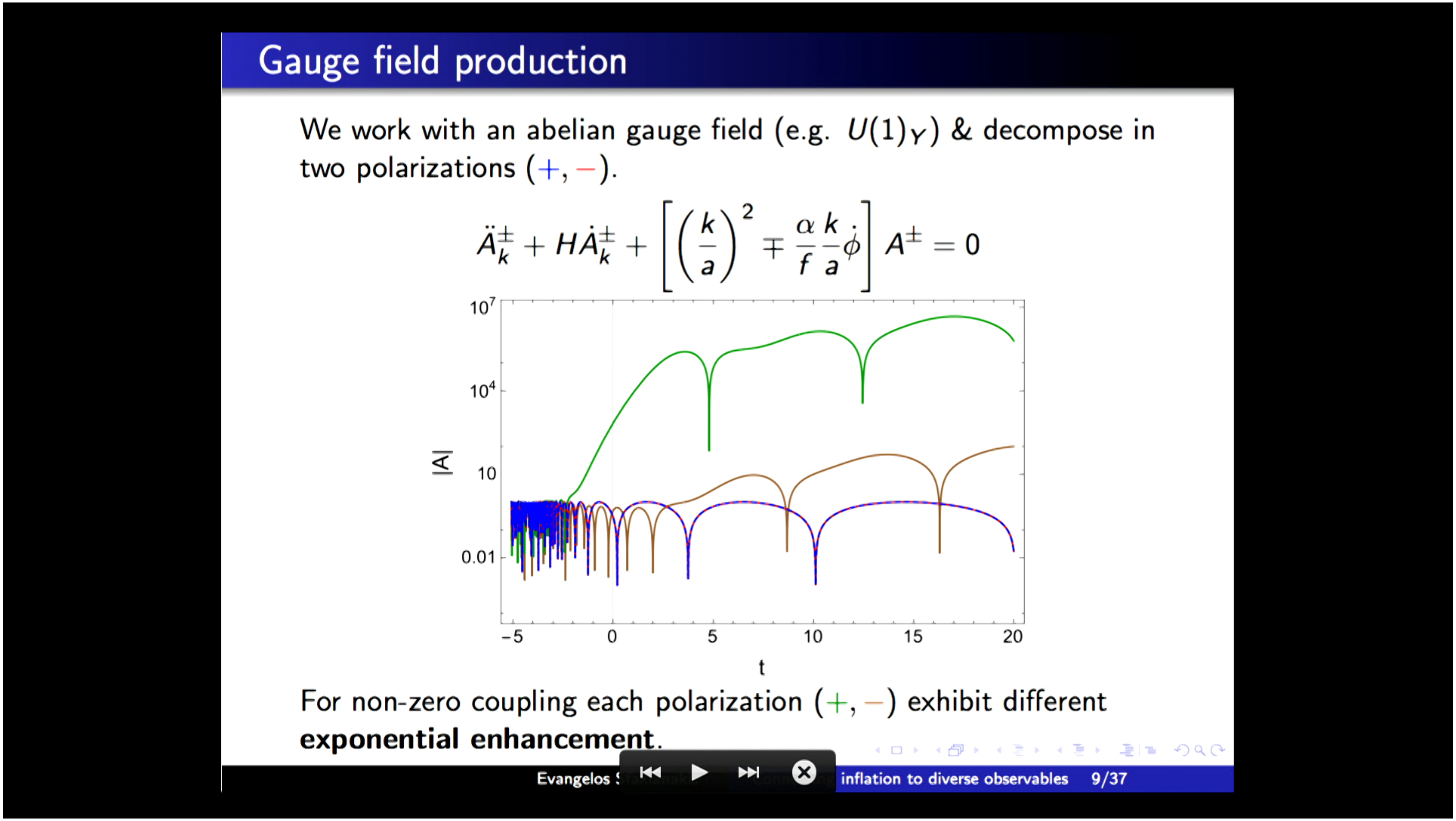
A field with a shift symmetry can only couple **derivatively** to other degrees of freedom

$$\mathcal{L}_{\rm Int} \subset \frac{\alpha}{8f}\phi\epsilon^{\mu\nu\alpha\beta}F_{\mu\nu}F_{\alpha\beta} + \frac{C}{f}\partial_\mu\phi\bar{\psi}\gamma_5\gamma^\mu\psi$$

$$\updownarrow$$

$$-\frac{\alpha}{f}\epsilon^{\mu\nu\alpha\beta}\partial_\mu\phi A_\nu\partial_\alpha A_\beta$$

From a EFT perspective, we expect these interactions to be present.

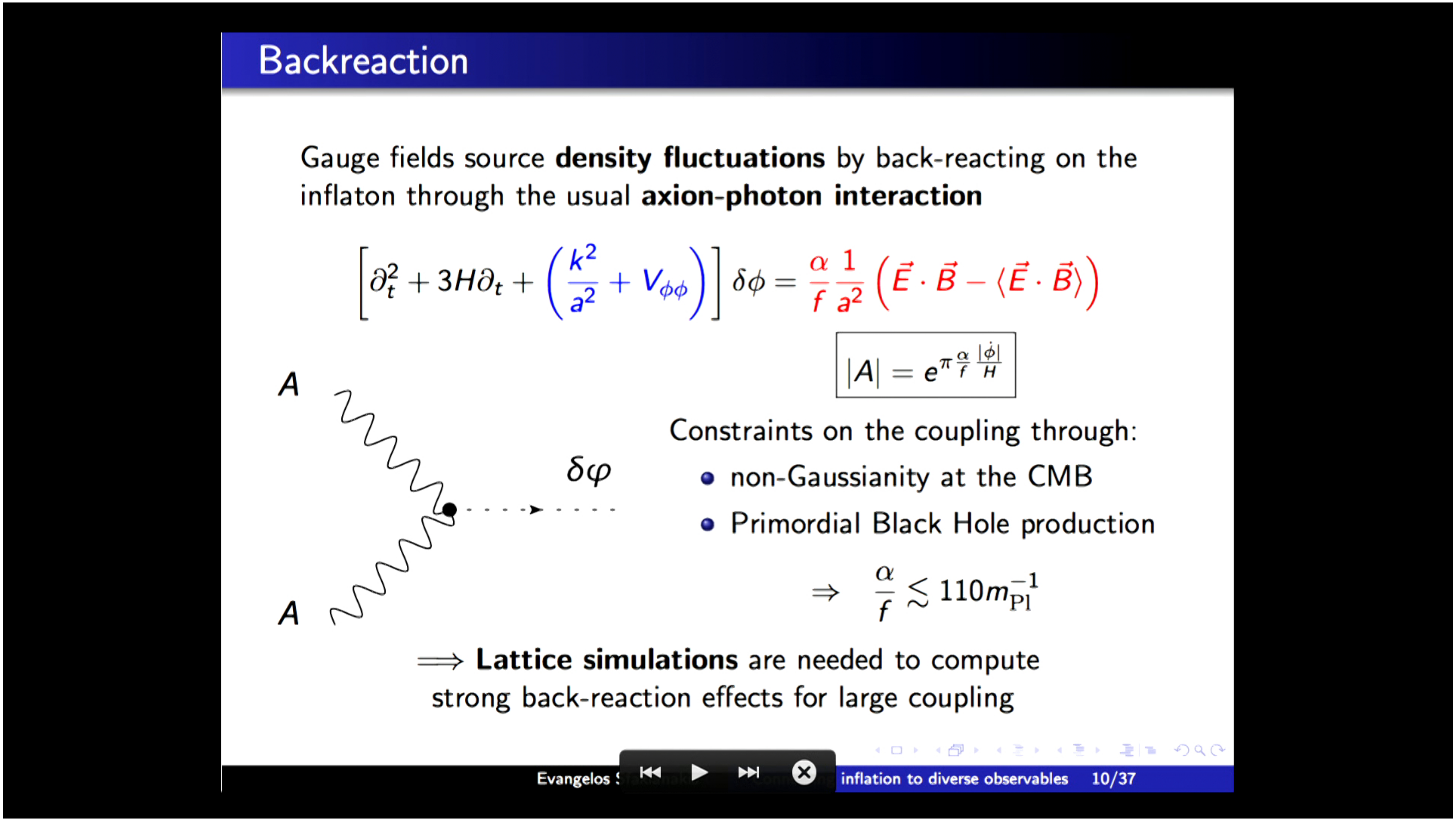


# Gauge field production

We work with an abelian gauge field (e.g. $U(1)_Y$) & decompose in two polarizations $(+, -)$.

$$\ddot{A}^{\pm}_k + H\dot{A}^{\pm}_k + \left[\left(\frac{k}{a}\right)^2 \mp \frac{\alpha}{f}\frac{k}{a}\dot{\phi}\right]A^{\pm} = 0$$

For non-zero coupling each polarization $(+, -)$ exhibit different **exponential enhancement**.



# Backreaction

Gauge fields source **density fluctuations** by back-reacting on the inflaton through the usual **axion-photon interaction**

$$\left[\partial_t^2 + 3H\partial_t + \left(\frac{k^2}{a^2} + V_{\phi\phi}\right)\right]\delta\phi = \frac{\alpha}{f}\frac{1}{a^2}\left(\vec{E}\cdot\vec{B} - \langle\vec{E}\cdot\vec{B}\rangle\right)$$

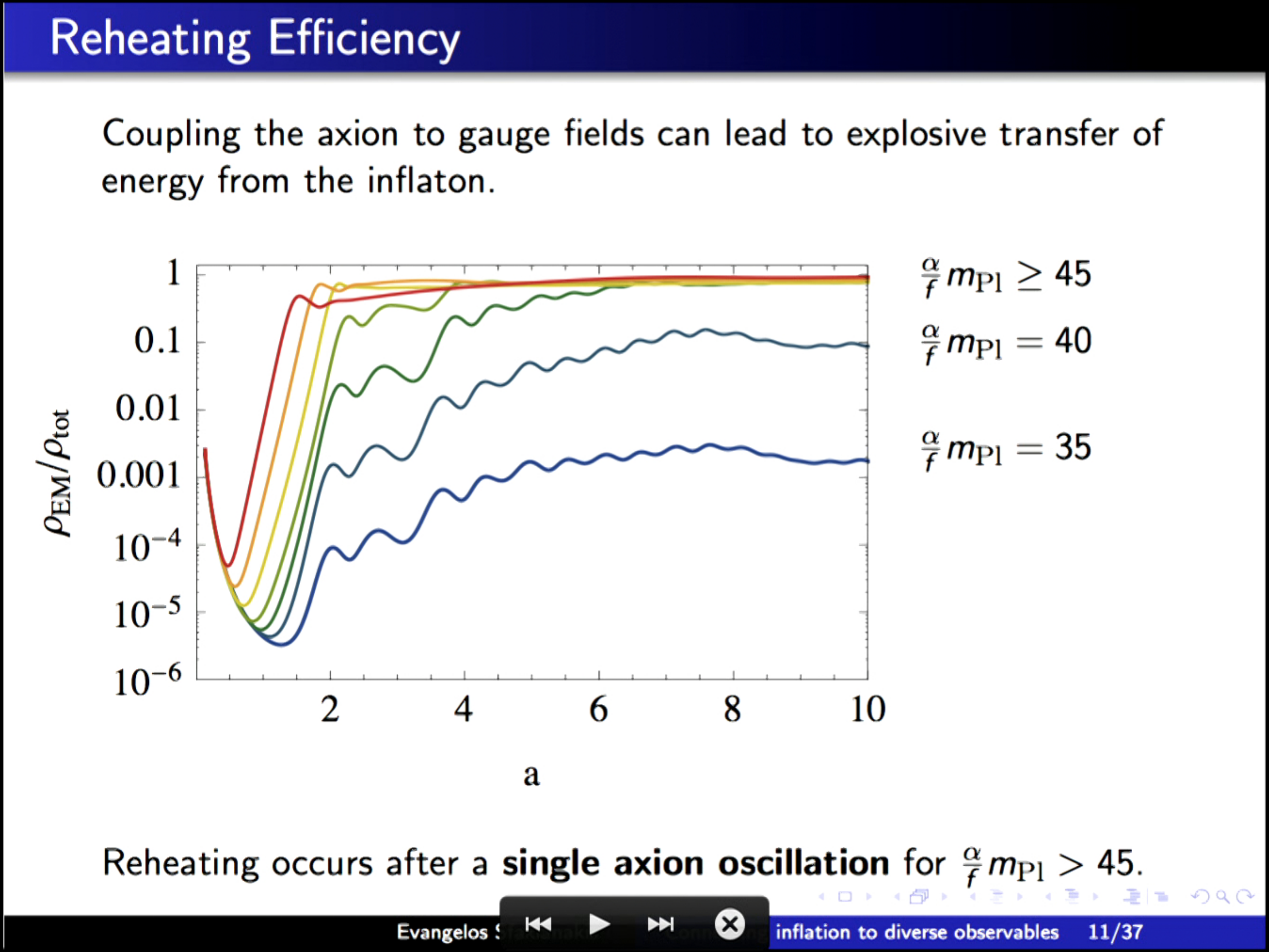
$$\boxed{|A| = e^{\pi\frac{\alpha}{f}\frac{|\dot{\phi}|}{H}}}$$

Constraints on the coupling through:

- non-Gaussianity at the CMB
- Primordial Black Hole production

$$\Rightarrow \quad \frac{\alpha}{f} \lesssim 110 m_{\mathrm{Pl}}^{-1}$$

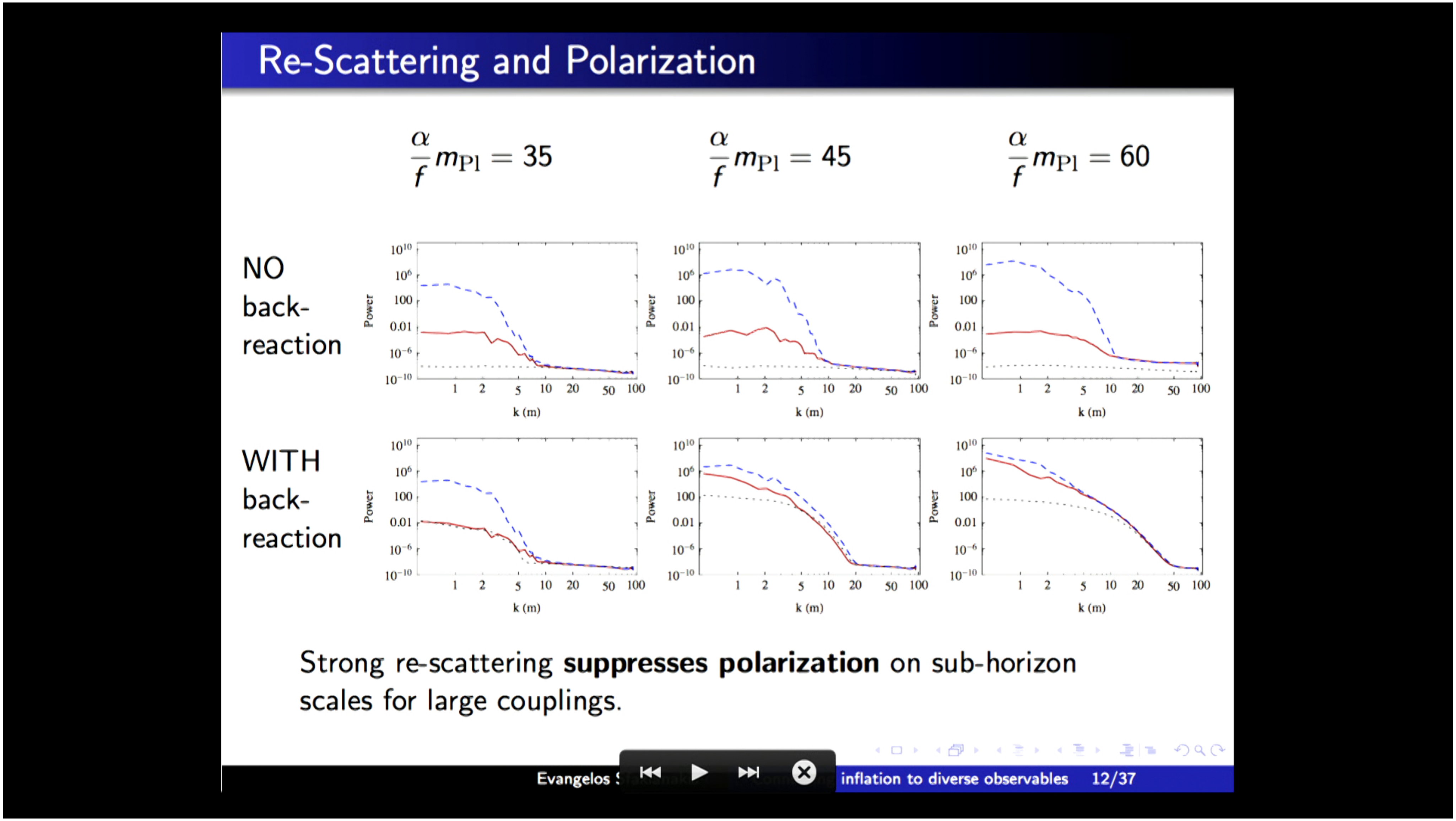
$\Longrightarrow$ **Lattice simulations** are needed to compute strong back-reaction effects for large coupling



## Reheating Efficiency

Coupling the axion to gauge fields can lead to explosive transfer of energy from the inflaton.

Reheating occurs after a **single axion oscillation** for $\frac{\alpha}{f} m_{Pl} > 45$.



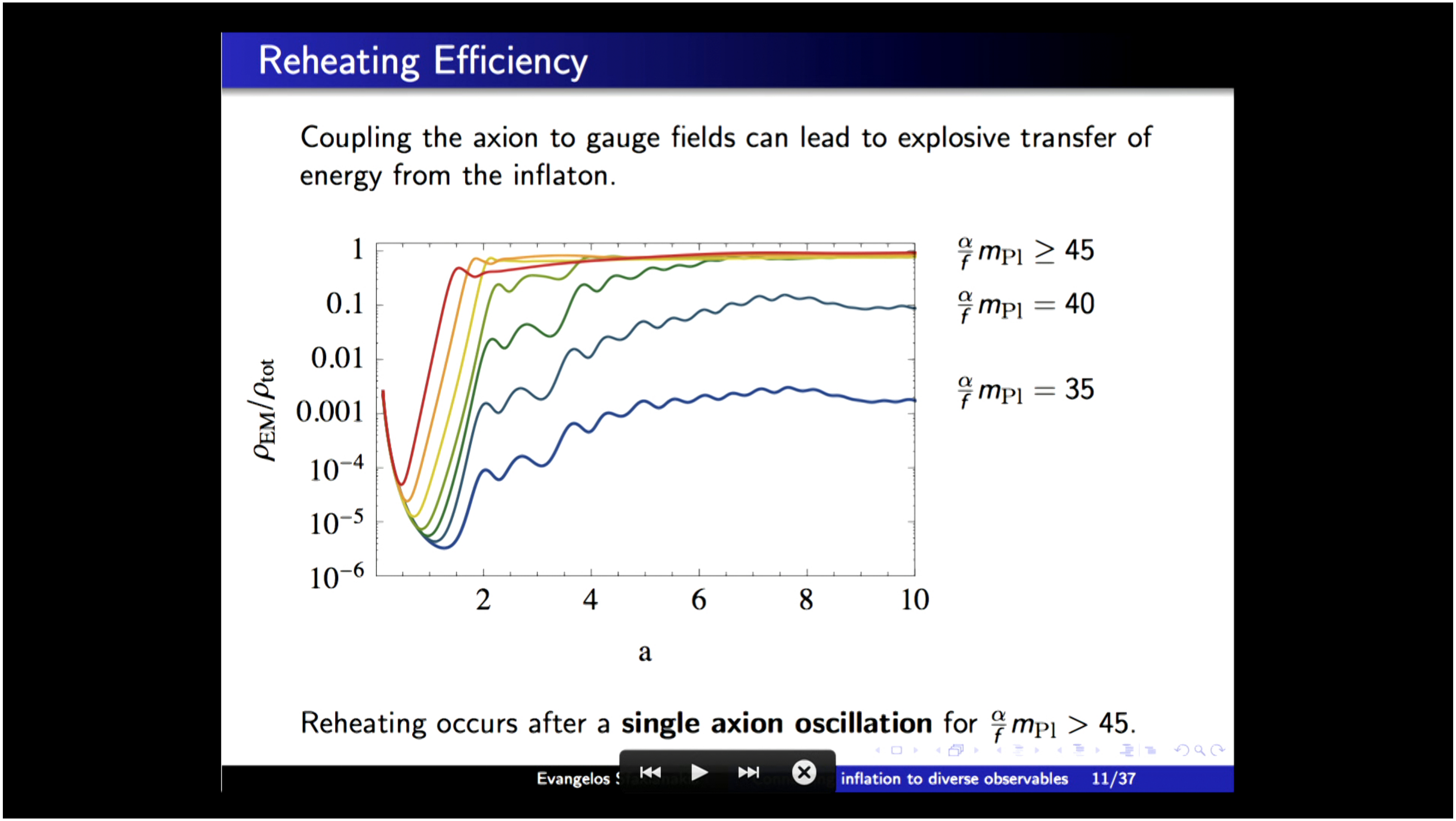
# Re-Scattering and Polarization

$\frac{\alpha}{f} m_{\rm Pl} = 35$ $\frac{\alpha}{f} m_{\rm Pl} = 45$ $\frac{\alpha}{f} m_{\rm Pl} = 60$

NO back-reaction

WITH back-reaction

Strong re-scattering **suppresses polarization** on sub-horizon scales for large couplings.



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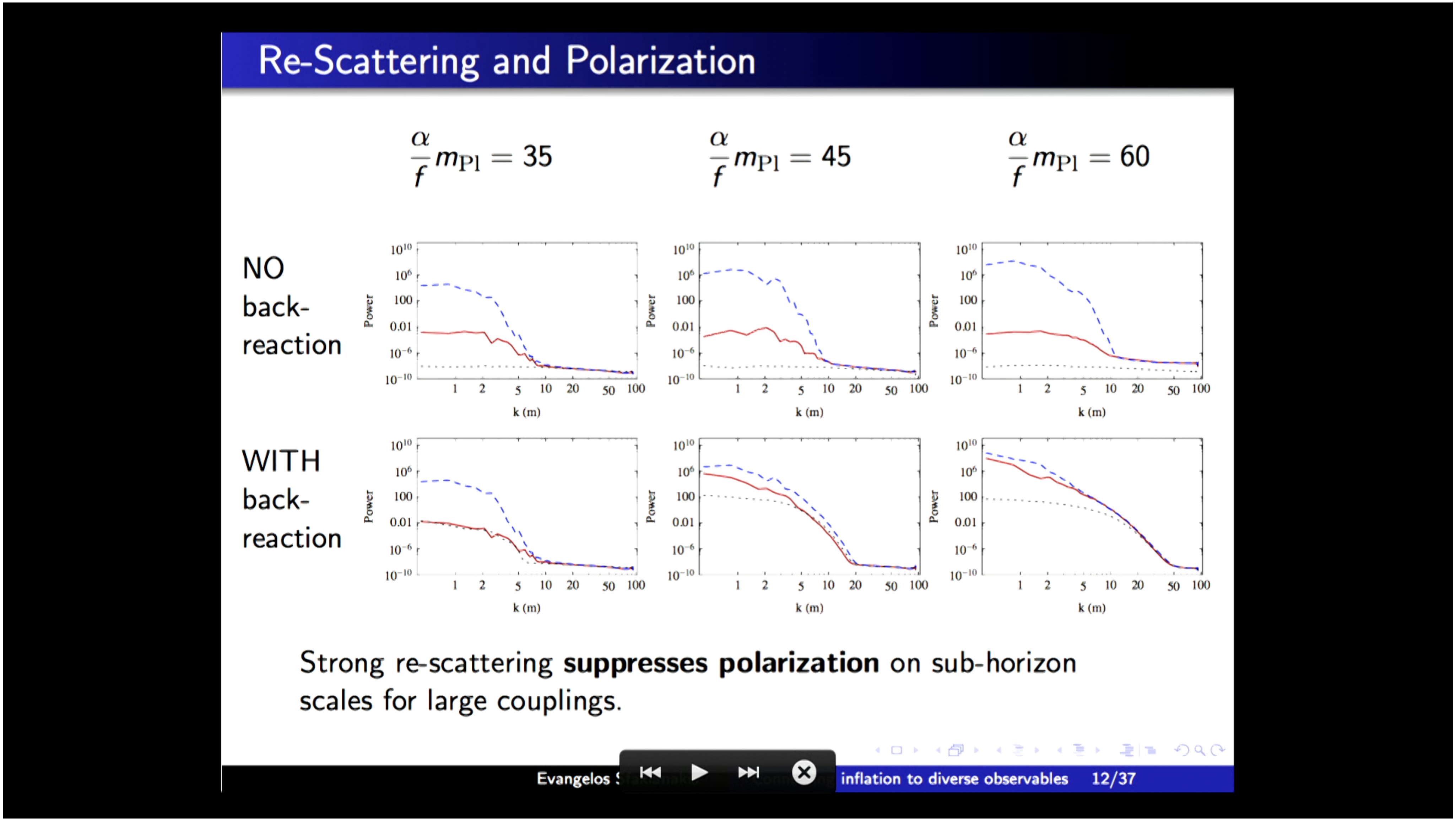

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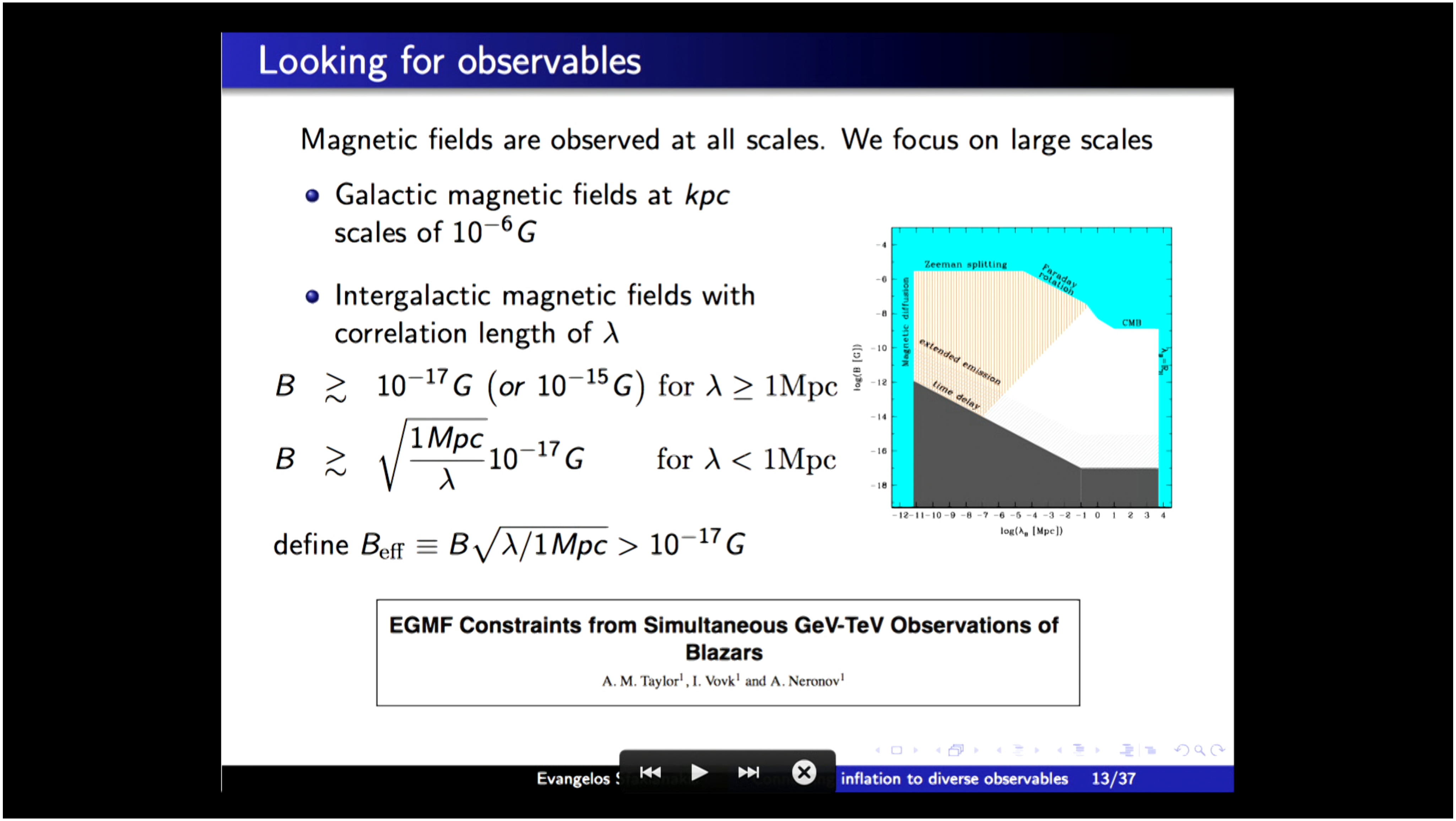


# Looking for observables

Magnetic fields are observed at all scales. We focus on large scales

- Galactic magnetic fields at *kpc* scales of $10^{-6}G$
- Intergalactic magnetic fields with correlation length of $\lambda$

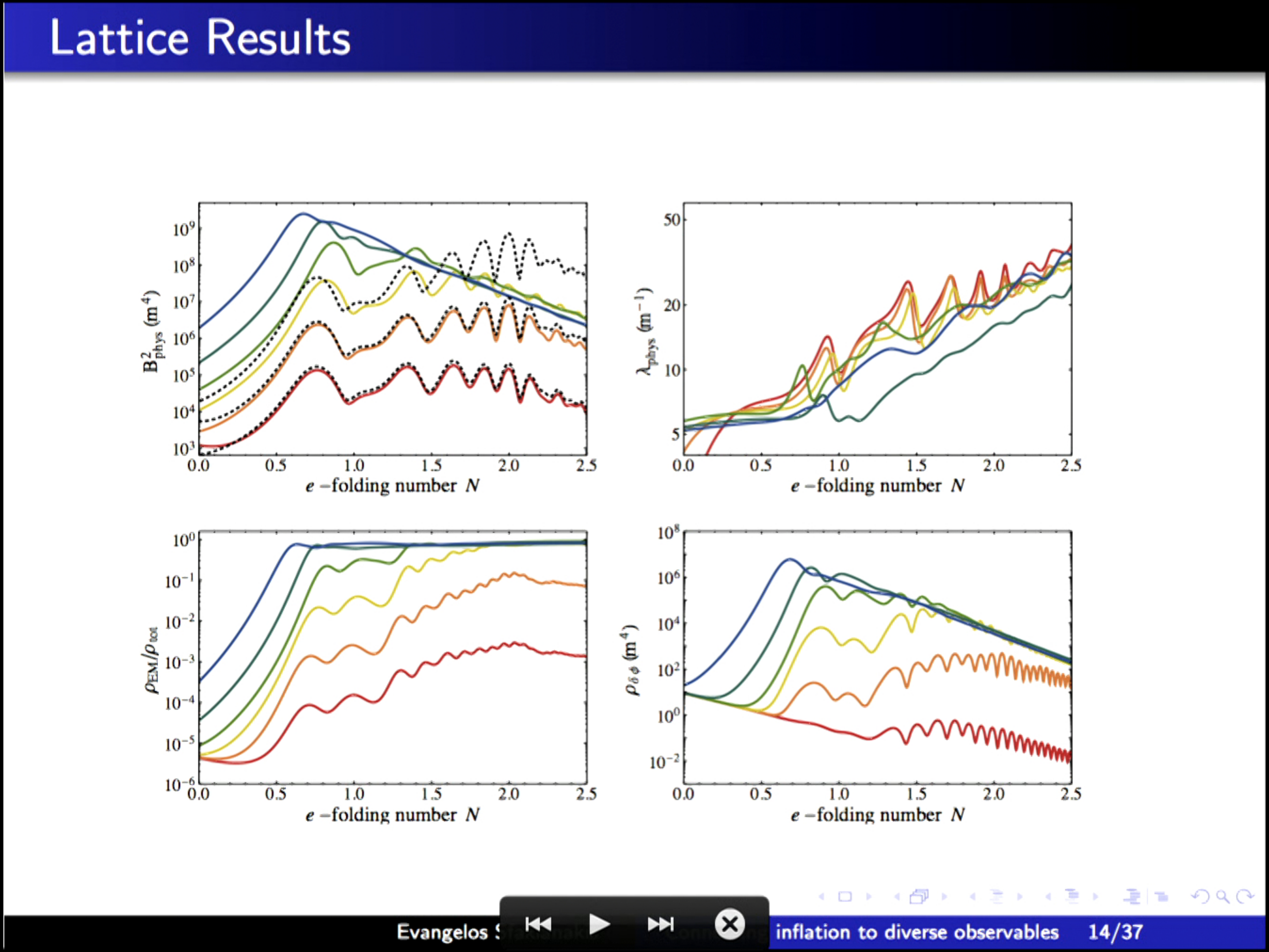
$$B \gtrsim 10^{-17}G \; (or\ 10^{-15}G) \quad \text{for } \lambda \geq 1\text{Mpc}$$

$$B \gtrsim \sqrt{\frac{1Mpc}{\lambda}}\,10^{-17}G \qquad \text{for } \lambda < 1\text{Mpc}$$

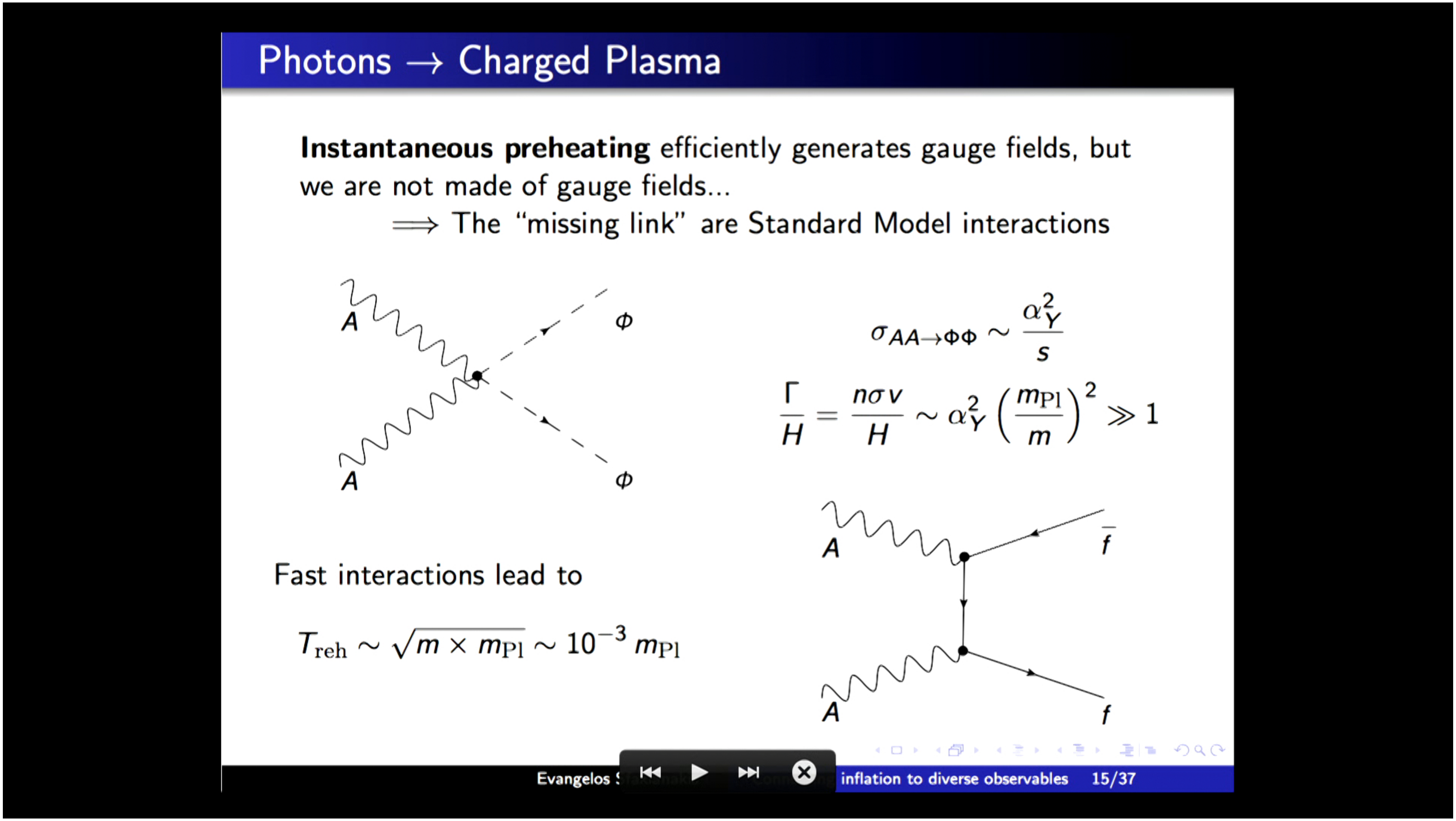
define $B_{\text{eff}} \equiv B\sqrt{\lambda/1Mpc} > 10^{-17}G$

**EGMF Constraints from Simultaneous GeV-TeV Observations of Blazars**

A. M. Taylor[1], I. Vovk[1] and A. Neronov[1]



# Lattice Results



# Photons → Charged Plasma

**Instantaneous preheating** efficiently generates gauge fields, but we are not made of gauge fields...

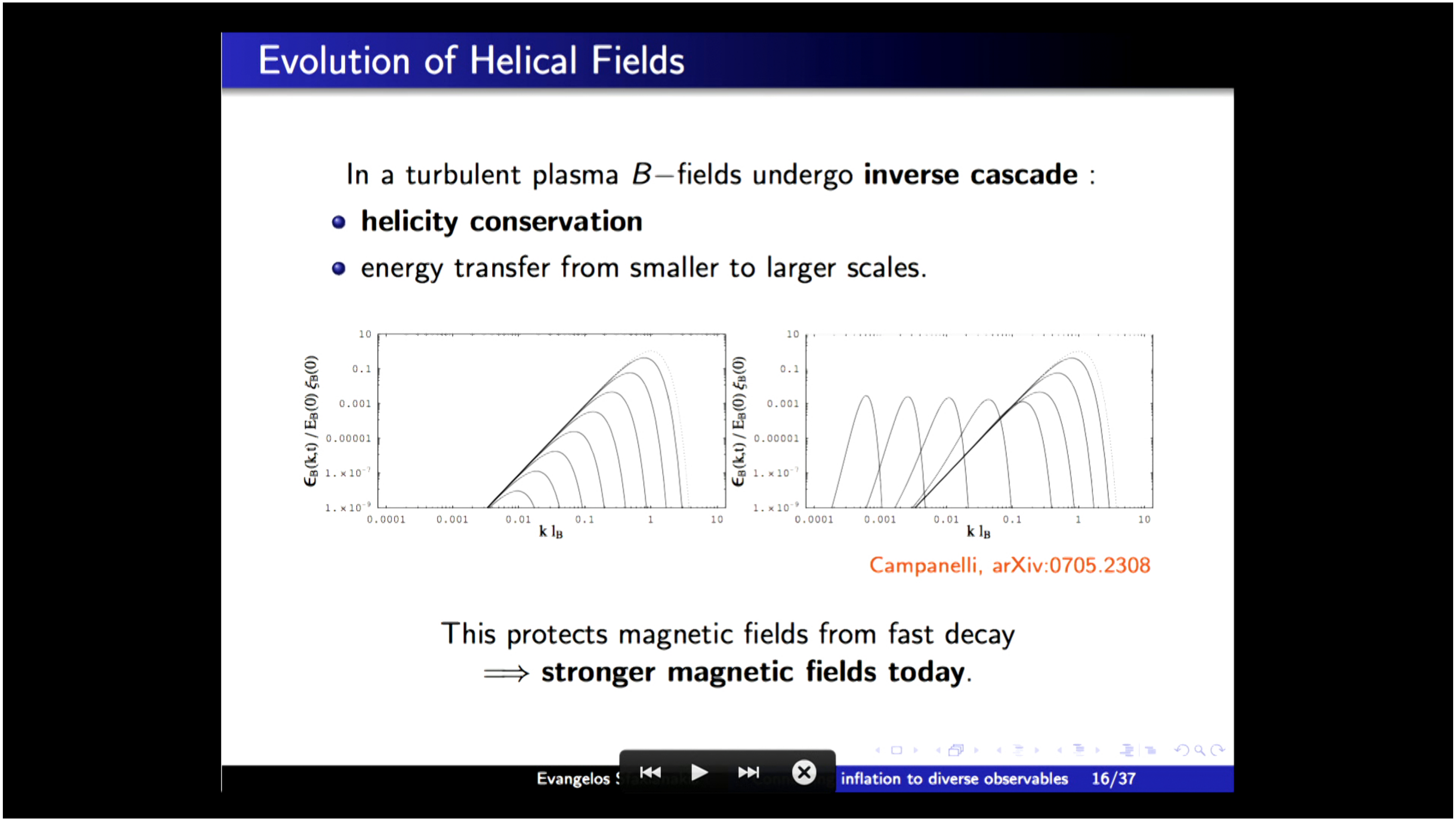
$\Longrightarrow$ The "missing link" are Standard Model interactions

$$\sigma_{AA\to\Phi\Phi} \sim \frac{\alpha_Y^2}{s}$$

$$\frac{\Gamma}{H} = \frac{n\sigma v}{H} \sim \alpha_Y^2 \left(\frac{m_{\rm Pl}}{m}\right)^2 \gg 1$$

Fast interactions lead to

$$T_{\rm reh} \sim \sqrt{m \times m_{\rm Pl}} \sim 10^{-3}\, m_{\rm Pl}$$



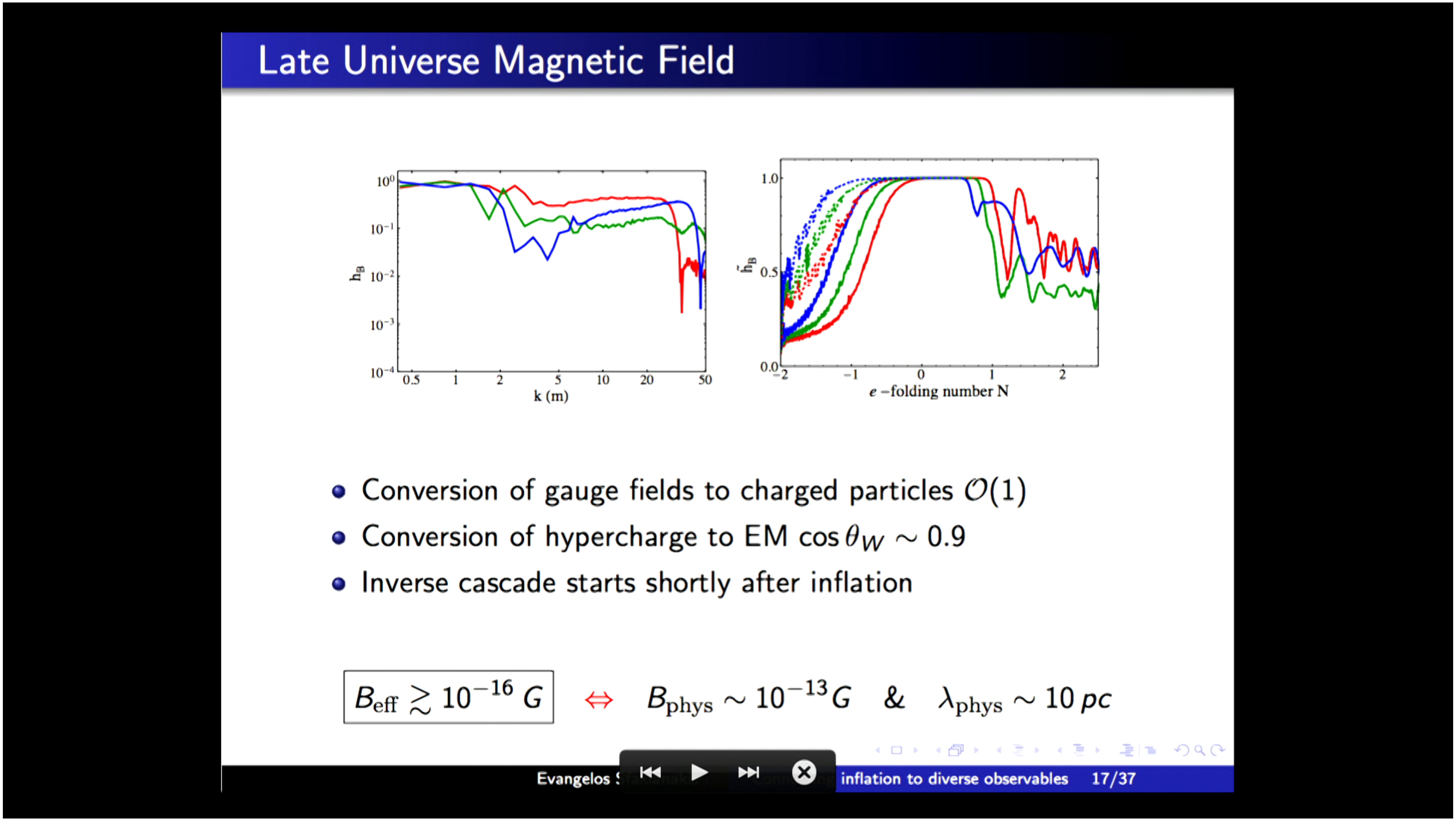
## Evolution of Helical Fields

In a turbulent plasma $B-$fields undergo **inverse cascade** :

- **helicity conservation**
- energy transfer from smaller to larger scales.

Campanelli, arXiv:0705.2308

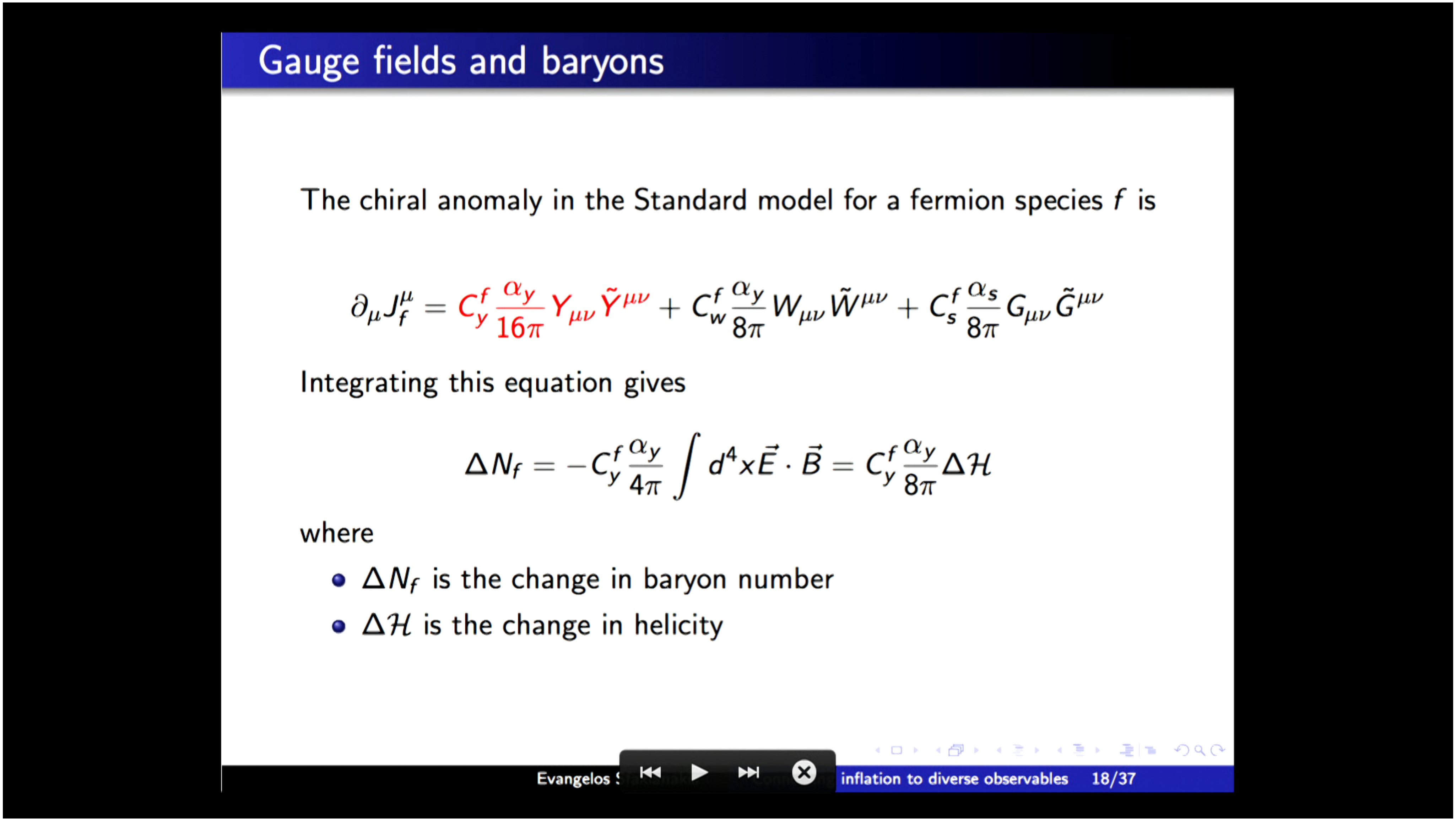
This protects magnetic fields from fast decay
$\Longrightarrow$ **stronger magnetic fields today**.



# Late Universe Magnetic Field

- Conversion of gauge fields to charged particles $\mathcal{O}(1)$
- Conversion of hypercharge to EM $\cos\theta_W \sim 0.9$
- Inverse cascade starts shortly after inflation

$$\boxed{B_{\rm eff} \gtrsim 10^{-16}\, G} \quad \Leftrightarrow \quad B_{\rm phys} \sim 10^{-13} G \quad \& \quad \lambda_{\rm phys} \sim 10\, pc$$



## Gauge fields and baryons

The chiral anomaly in the Standard model for a fermion species $f$ is

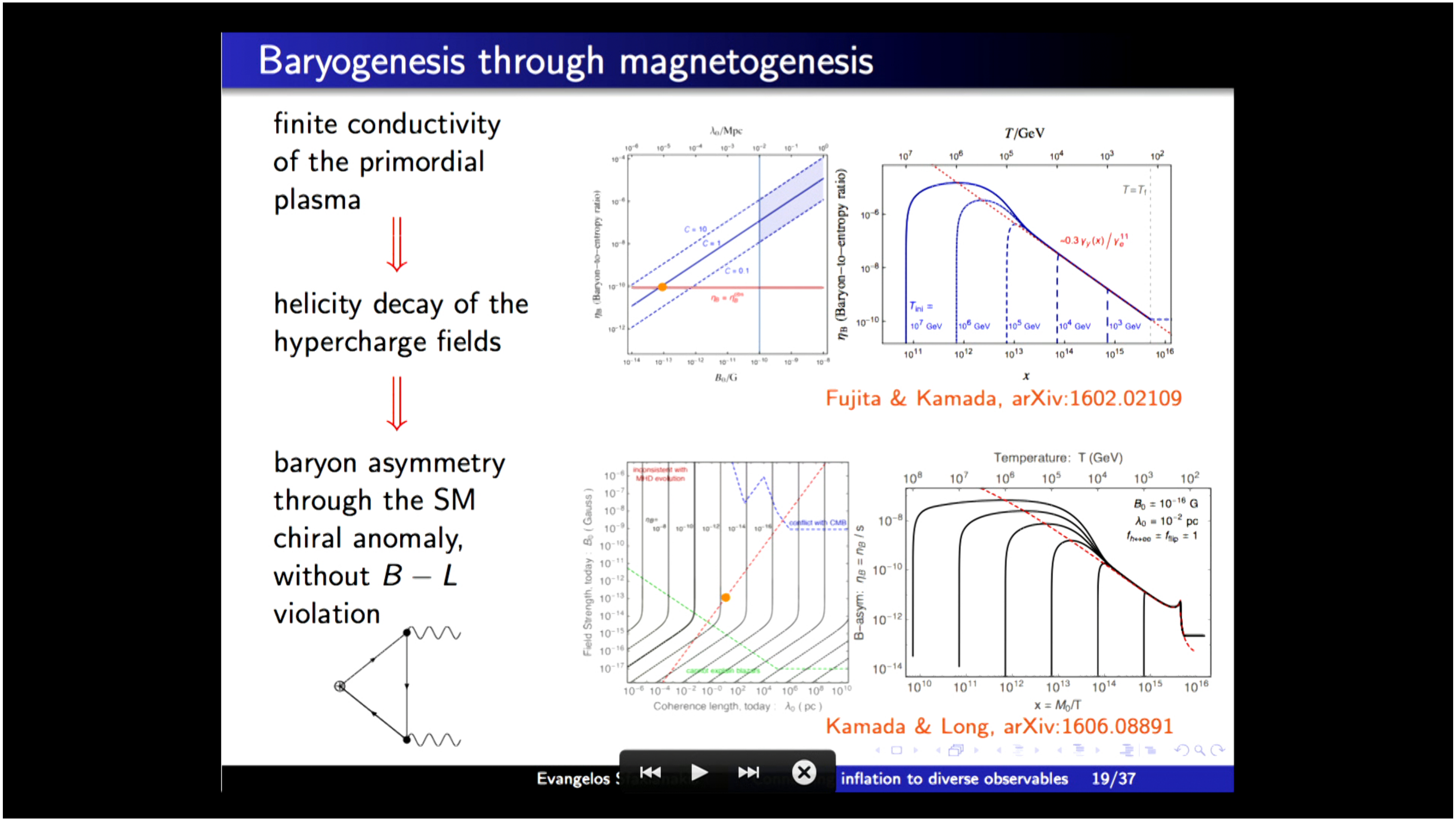
$$\partial_\mu J^\mu_f = C^f_y \frac{\alpha_y}{16\pi} Y_{\mu\nu}\tilde{Y}^{\mu\nu} + C^f_w \frac{\alpha_y}{8\pi} W_{\mu\nu}\tilde{W}^{\mu\nu} + C^f_s \frac{\alpha_s}{8\pi} G_{\mu\nu}\tilde{G}^{\mu\nu}$$

Integrating this equation gives

$$\Delta N_f = -C^f_y \frac{\alpha_y}{4\pi} \int d^4x \vec{E}\cdot\vec{B} = C^f_y \frac{\alpha_y}{8\pi} \Delta\mathcal{H}$$

where

- $\Delta N_f$ is the change in baryon number
- $\Delta\mathcal{H}$ is the change in helicity



# Baryogenesis through magnetogenesis

finite conductivity of the primordial plasma

⇓

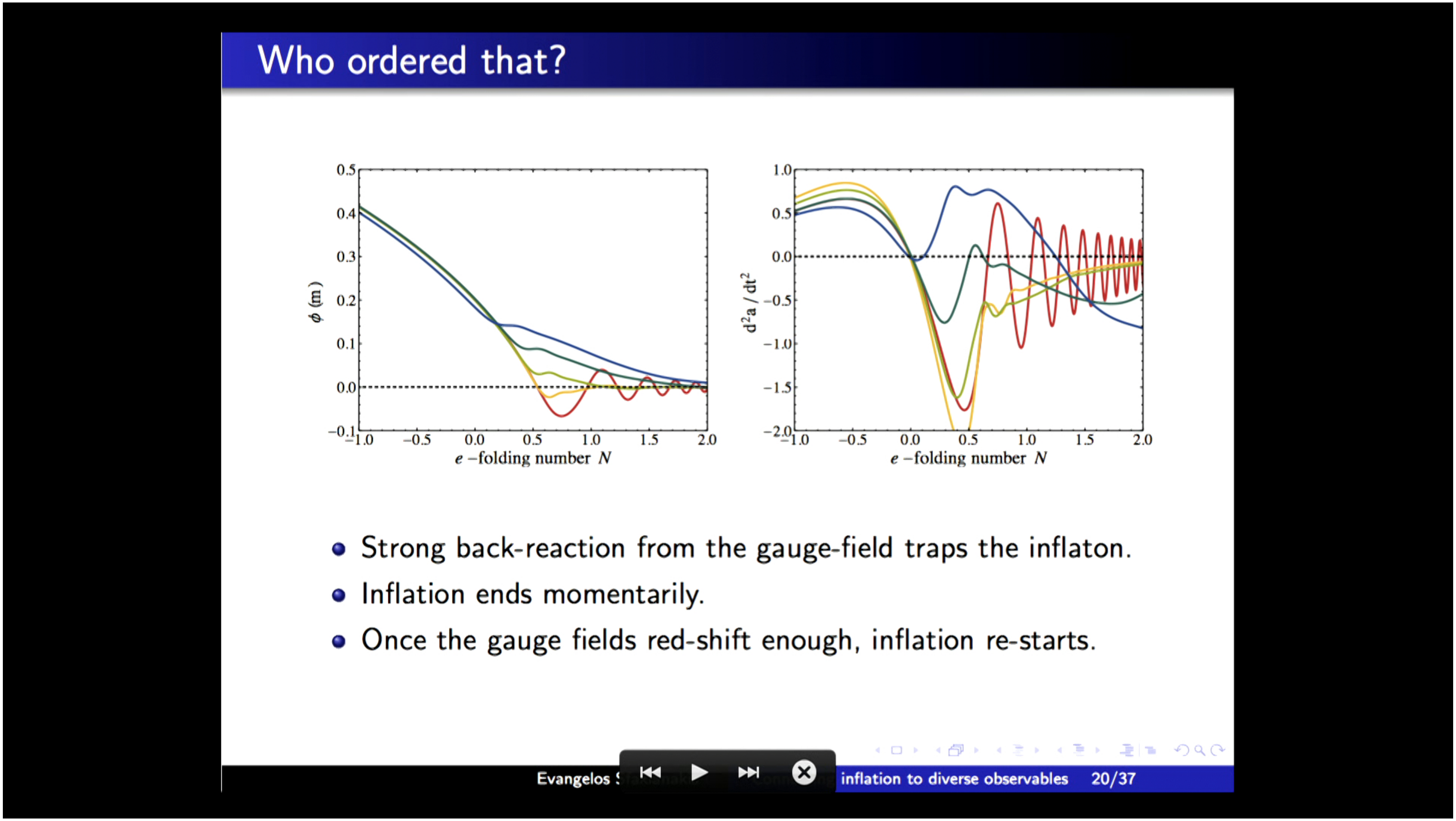
helicity decay of the hypercharge fields

⇓

baryon asymmetry through the SM chiral anomaly, without $B - L$ violation

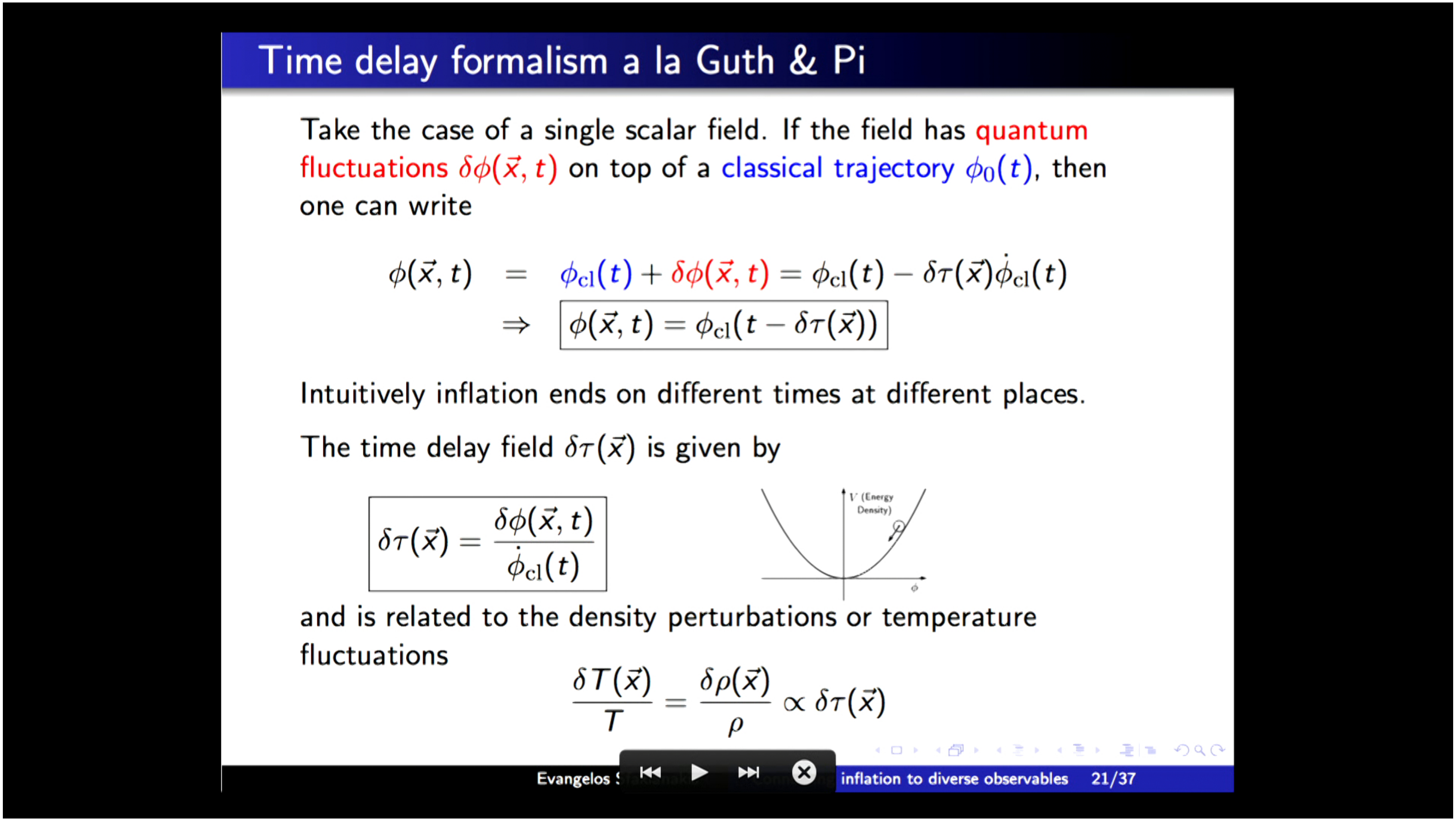
Fujita & Kamada, arXiv:1602.02109

Kamada & Long, arXiv:1606.08891



# Who ordered that?

- Strong back-reaction from the gauge-field traps the inflaton.
- Inflation ends momentarily.
- Once the gauge fields red-shift enough, inflation re-starts.



## Time delay formalism a la Guth & Pi

Take the case of a single scalar field. If the field has quantum fluctuations $\delta\phi(\vec{x},t)$ on top of a classical trajectory $\phi_0(t)$, then one can write

$$\begin{aligned} \phi(\vec{x},t) &= \phi_{\rm cl}(t) + \delta\phi(\vec{x},t) = \phi_{\rm cl}(t) - \delta\tau(\vec{x})\dot{\phi}_{\rm cl}(t) \\ &\Rightarrow \boxed{\phi(\vec{x},t) = \phi_{\rm cl}(t-\delta\tau(\vec{x}))} \end{aligned}$$

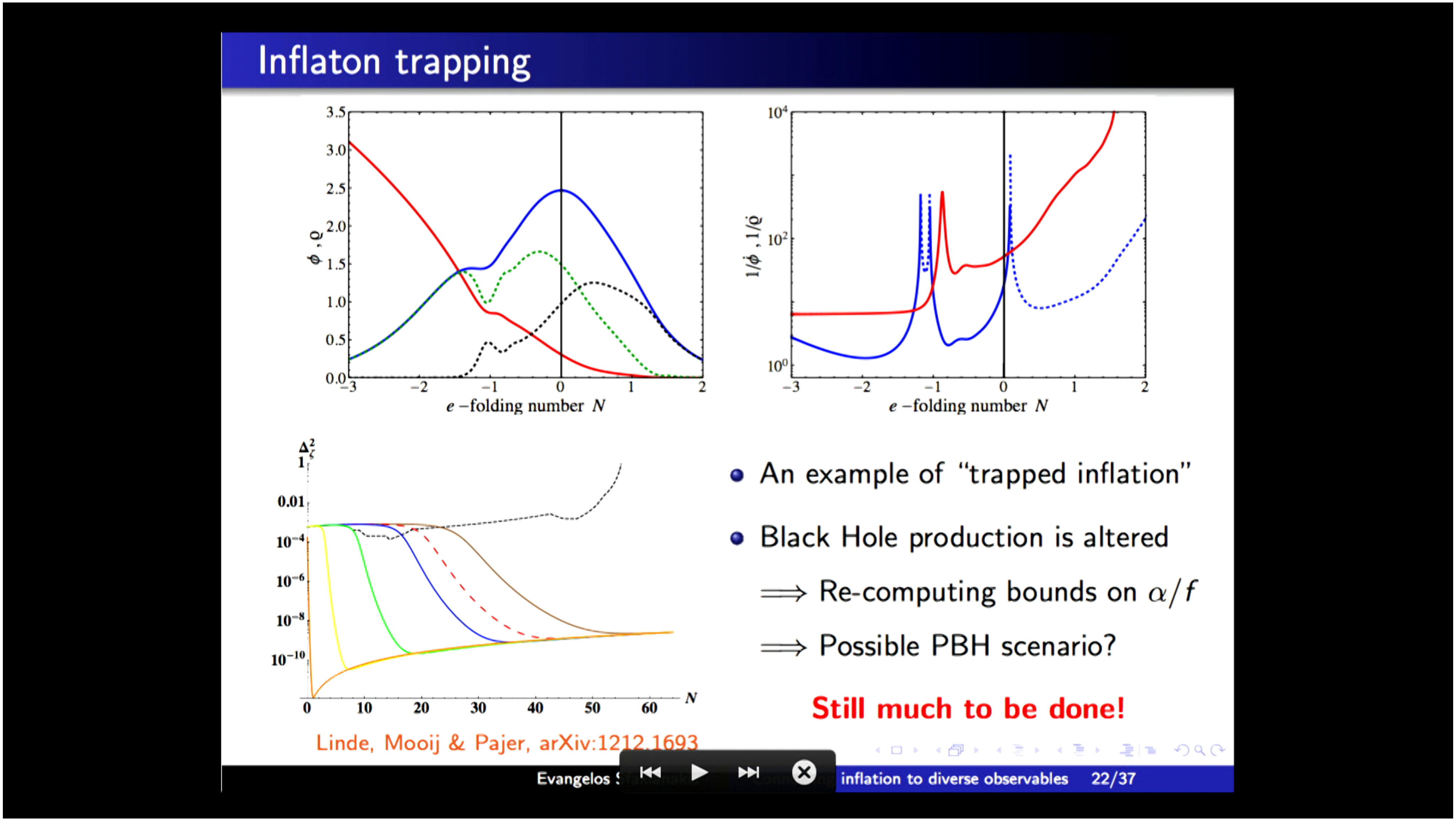
Intuitively inflation ends on different times at different places.

The time delay field $\delta\tau(\vec{x})$ is given by

$$\boxed{\delta\tau(\vec{x}) = \frac{\delta\phi(\vec{x},t)}{\dot{\phi}_{\rm cl}(t)}}$$

and is related to the density perturbations or temperature fluctuations

$$\frac{\delta T(\vec{x})}{T} = \frac{\delta\rho(\vec{x})}{\rho} \propto \delta\tau(\vec{x})$$



# Inflaton trapping

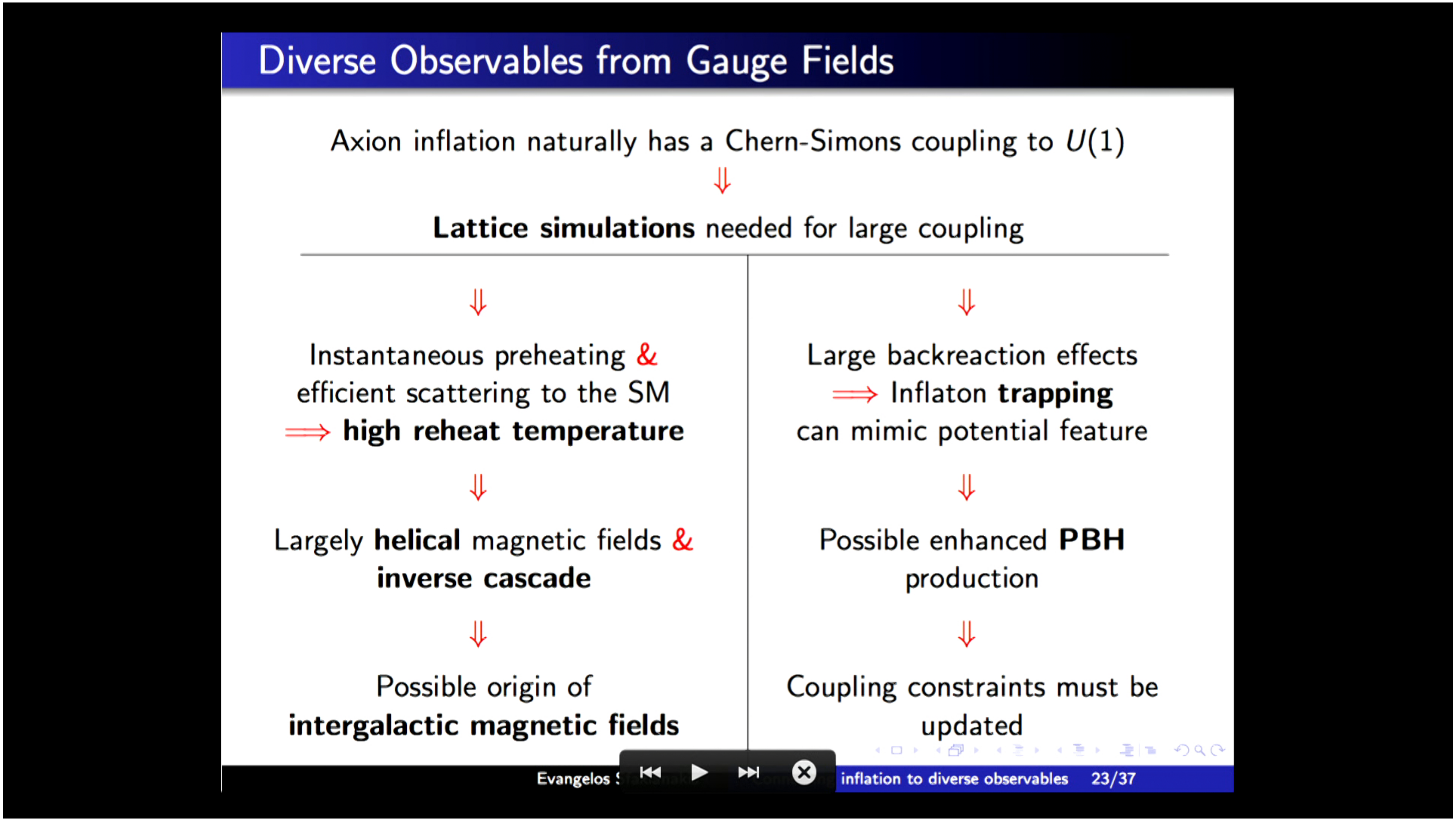
- An example of "trapped inflation"
- Black Hole production is altered

$\Longrightarrow$ Re-computing bounds on $\alpha/f$

$\Longrightarrow$ Possible PBH scenario?

**Still much to be done!**

Linde, Mooij & Pajer, arXiv:1212.1693



# Diverse Observables from Gauge Fields

Axion inflation naturally has a Chern-Simons coupling to $U(1)$

⇓

**Lattice simulations** needed for large coupling

⇓

Instantaneous preheating &
efficient scattering to the SM
⟹ **high reheat temperature**

⇓

Largely **helical** magnetic fields &
**inverse cascade**

⇓

Possible origin of
**intergalactic magnetic fields**

⇓

Large backreaction effects
⟹ Inflaton **trapping**
can mimic potential feature

⇓

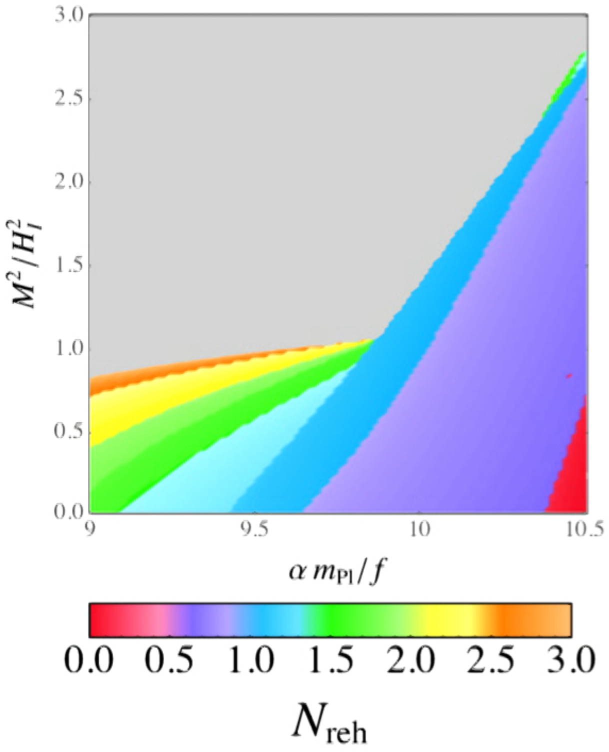
Possible enhanced **PBH**
production

⇓

Coupling constraints must be
updated

# Preheating into massive gauge fields

Gauge field mass term opposes tachyonic / parametric growth



⇒ Preheating is delayed or completely suppressed.

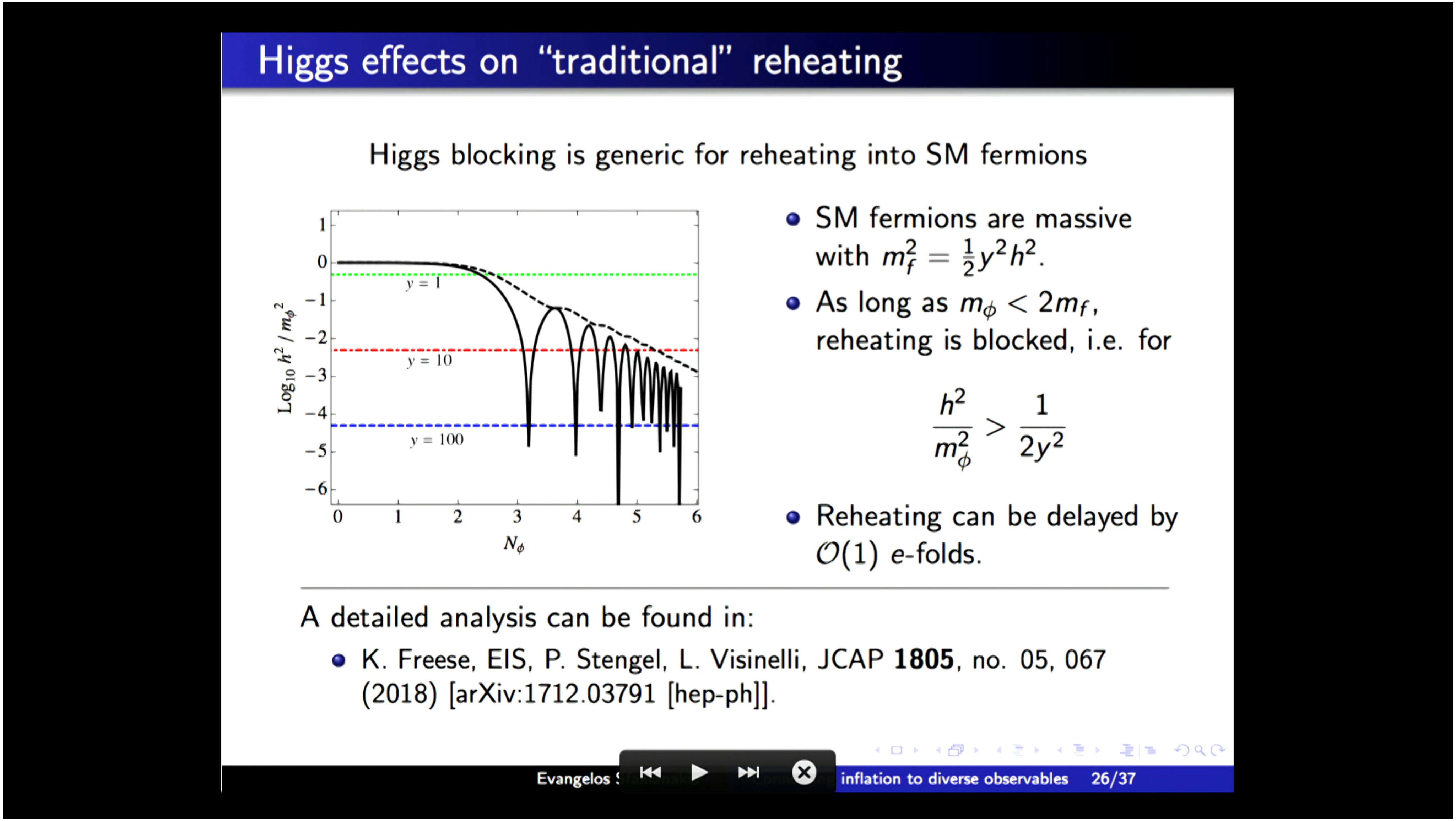
⇕

The Higgs field is a light spectator during inflation, following the PDF

$$f_{\rm eq}(h) \propto \exp\left(-\frac{2\pi^2\lambda_I h^4}{3H_I^4}\right)$$

with

$$\sqrt{\langle h^2\rangle} = 0.36\lambda_I^{-1/4} H_I$$



# Higgs effects on "traditional" reheating

Higgs blocking is generic for reheating into SM fermions

- SM fermions are massive with $m_f^2 = \frac{1}{2} y^2 h^2$.
- As long as $m_\phi < 2 m_f$, reheating is blocked, i.e. for

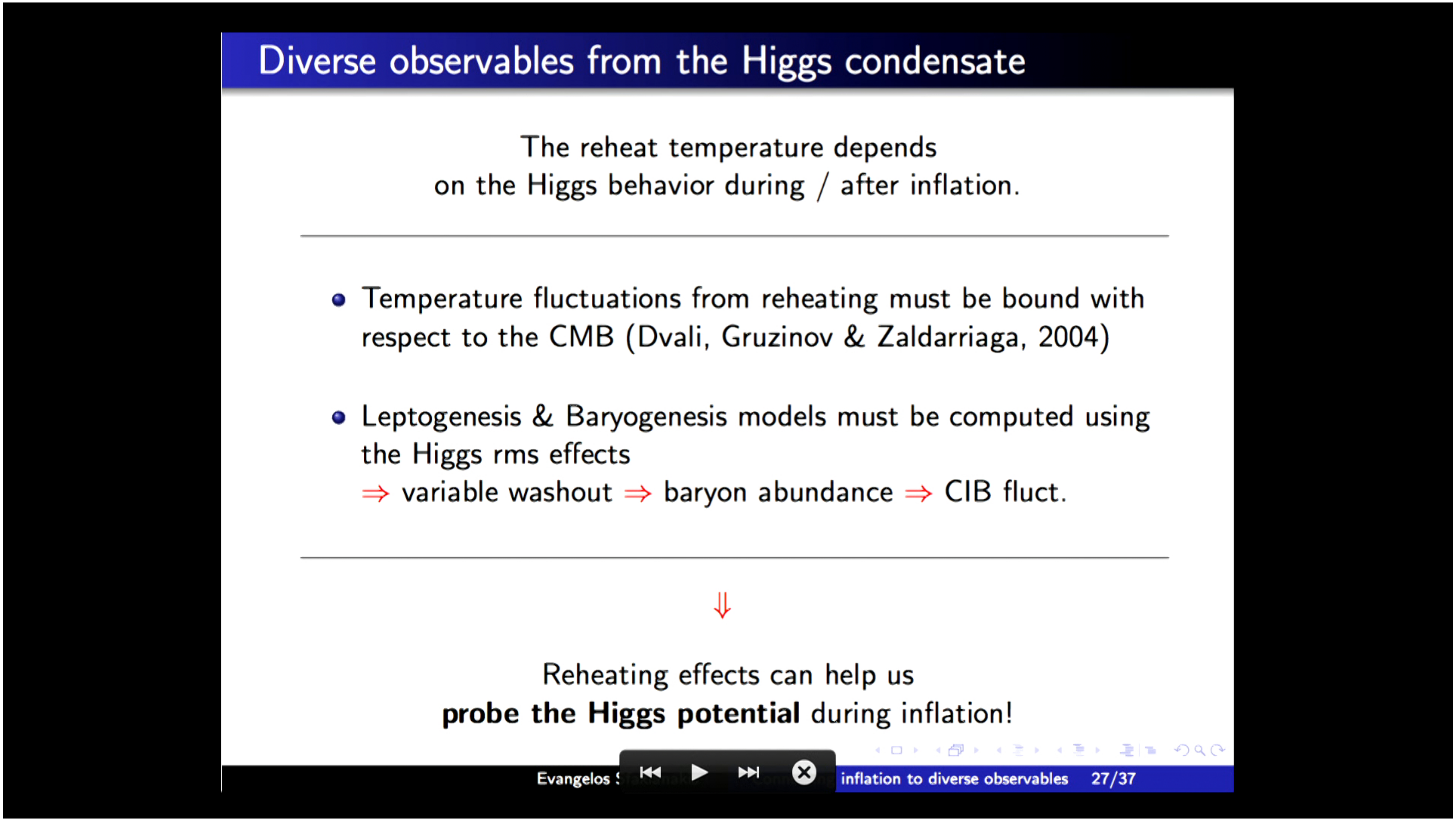
$$\frac{h^2}{m_\phi^2} > \frac{1}{2y^2}$$

- Reheating can be delayed by $\mathcal{O}(1)$ $e$-folds.

---

A detailed analysis can be found in:

- K. Freese, EIS, P. Stengel, L. Visinelli, JCAP **1805**, no. 05, 067 (2018) [arXiv:1712.03791 [hep-ph]].



# Diverse observables from the Higgs condensate

The reheat temperature depends
on the Higgs behavior during / after inflation.

---

- Temperature fluctuations from reheating must be bound with respect to the CMB (Dvali, Gruzinov & Zaldarriaga, 2004)
- Leptogenesis & Baryogenesis models must be computed using the Higgs rms effects
  ⇒ variable washout ⇒ baryon abundance ⇒ CIB fluct.

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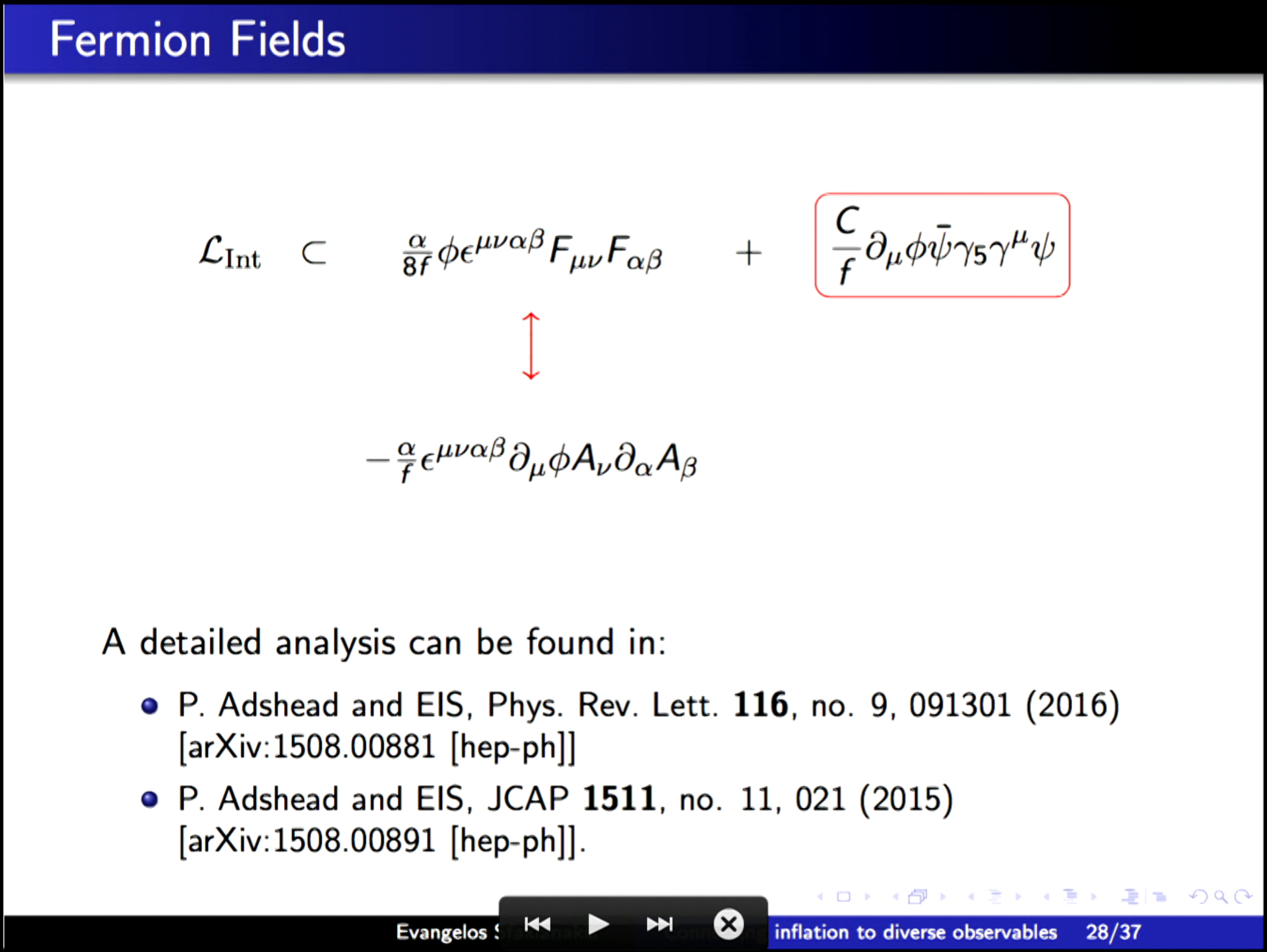
⇓

Reheating effects can help us
**probe the Higgs potential** during inflation!

Evangelos S inflation to diverse observables 27/37



## Fermion Fields

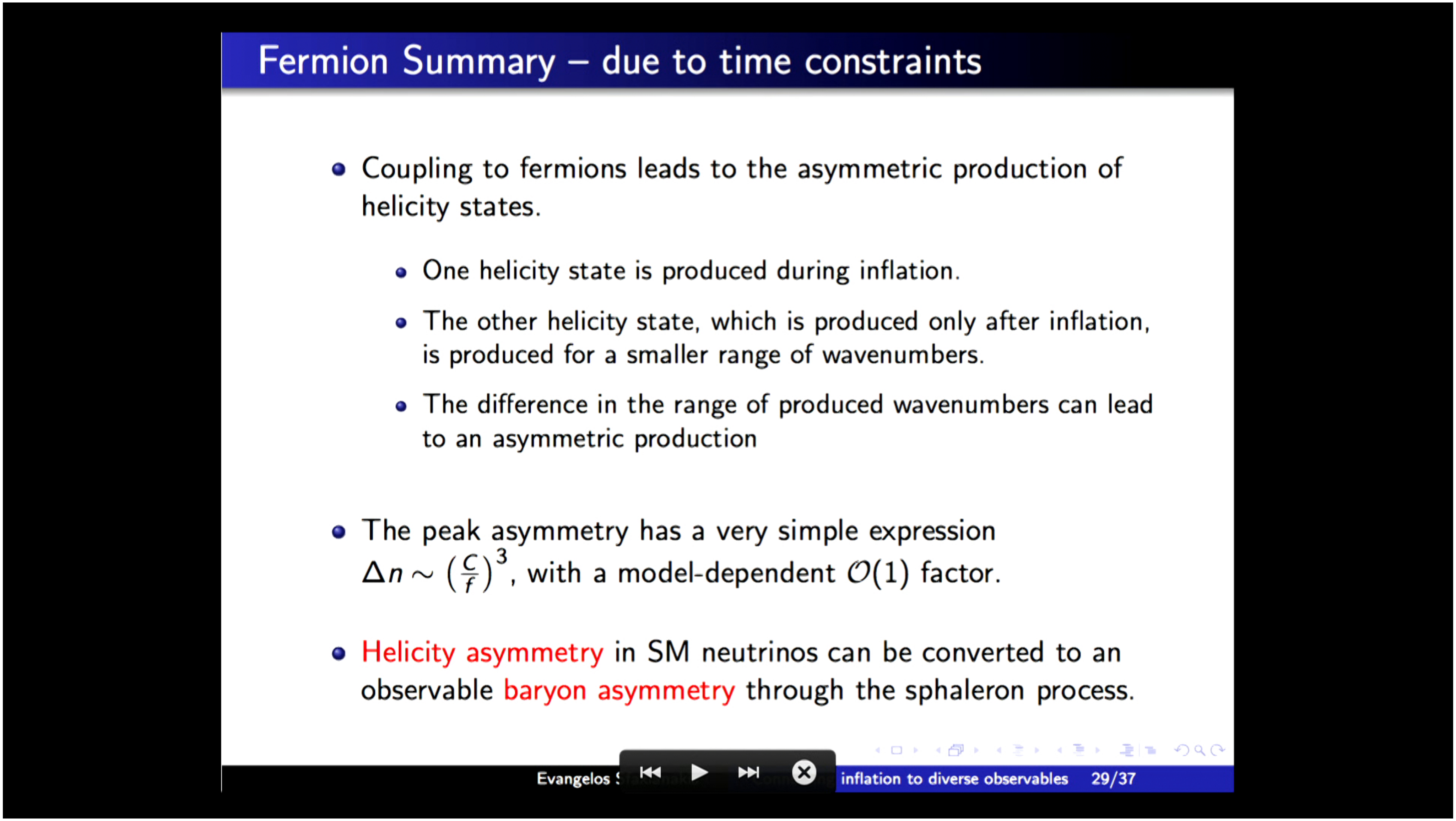
$$\mathcal{L}_{\rm Int} \subset \frac{\alpha}{8f}\phi\epsilon^{\mu\nu\alpha\beta}F_{\mu\nu}F_{\alpha\beta} + \boxed{\frac{C}{f}\partial_\mu\phi\bar{\psi}\gamma_5\gamma^\mu\psi}$$

$$\updownarrow$$

$$-\frac{\alpha}{f}\epsilon^{\mu\nu\alpha\beta}\partial_\mu\phi A_\nu\partial_\alpha A_\beta$$

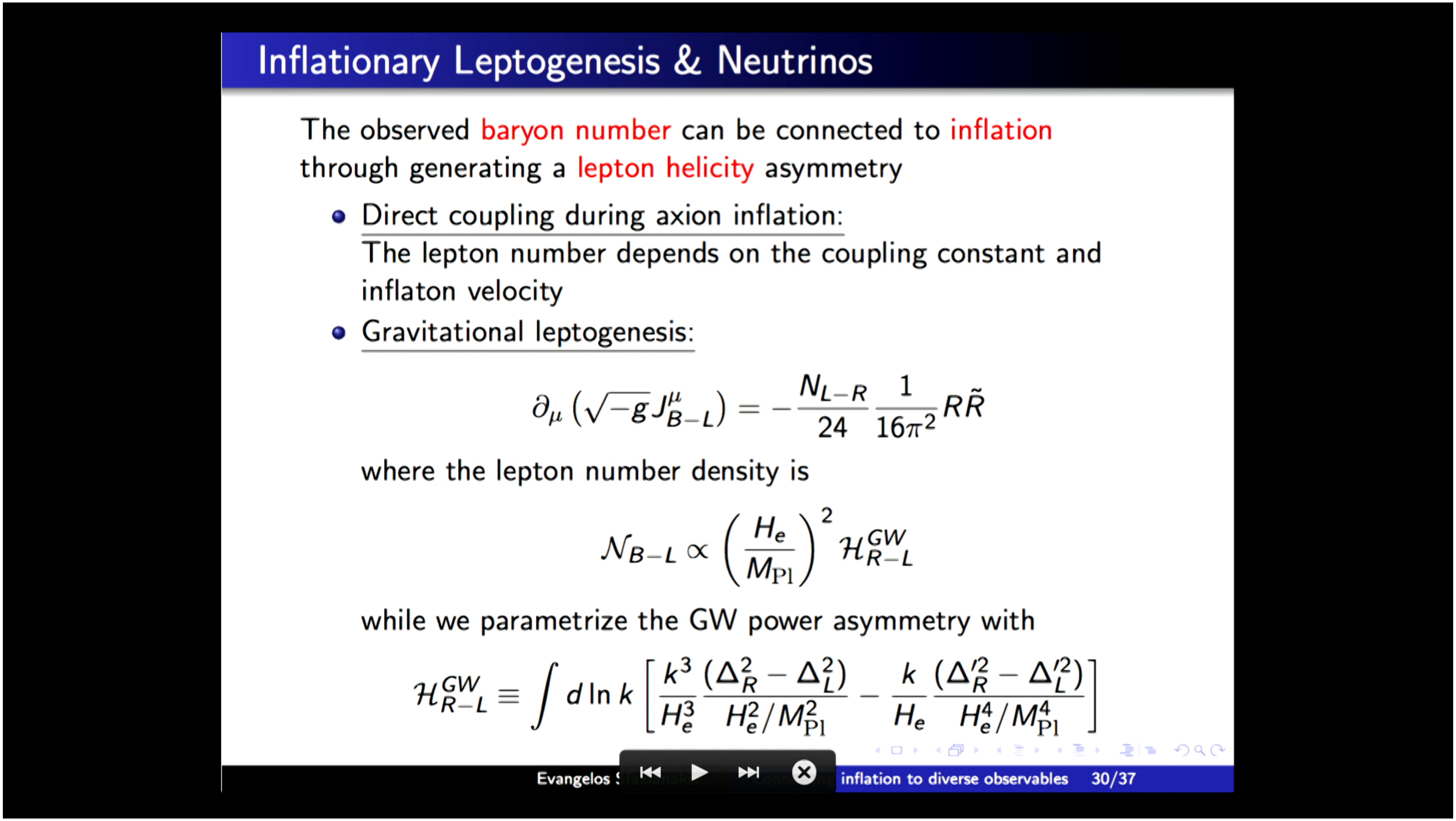
A detailed analysis can be found in:

- P. Adshead and EIS, Phys. Rev. Lett. **116**, no. 9, 091301 (2016) [arXiv:1508.00881 [hep-ph]]
- P. Adshead and EIS, JCAP **1511**, no. 11, 021 (2015) [arXiv:1508.00891 [hep-ph]].



## Fermion Summary – due to time constraints

- Coupling to fermions leads to the asymmetric production of helicity states.
  - One helicity state is produced during inflation.
  - The other helicity state, which is produced only after inflation, is produced for a smaller range of wavenumbers.
  - The difference in the range of produced wavenumbers can lead to an asymmetric production
- The peak asymmetry has a very simple expression $\Delta n \sim \left(\frac{C}{f}\right)^3$, with a model-dependent $\mathcal{O}(1)$ factor.
- Helicity asymmetry in SM neutrinos can be converted to an observable baryon asymmetry through the sphaleron process.



## Inflationary Leptogenesis & Neutrinos

The observed baryon number can be connected to inflation through generating a lepton helicity asymmetry

- Direct coupling during axion inflation:
  The lepton number depends on the coupling constant and inflaton velocity
- Gravitational leptogenesis:

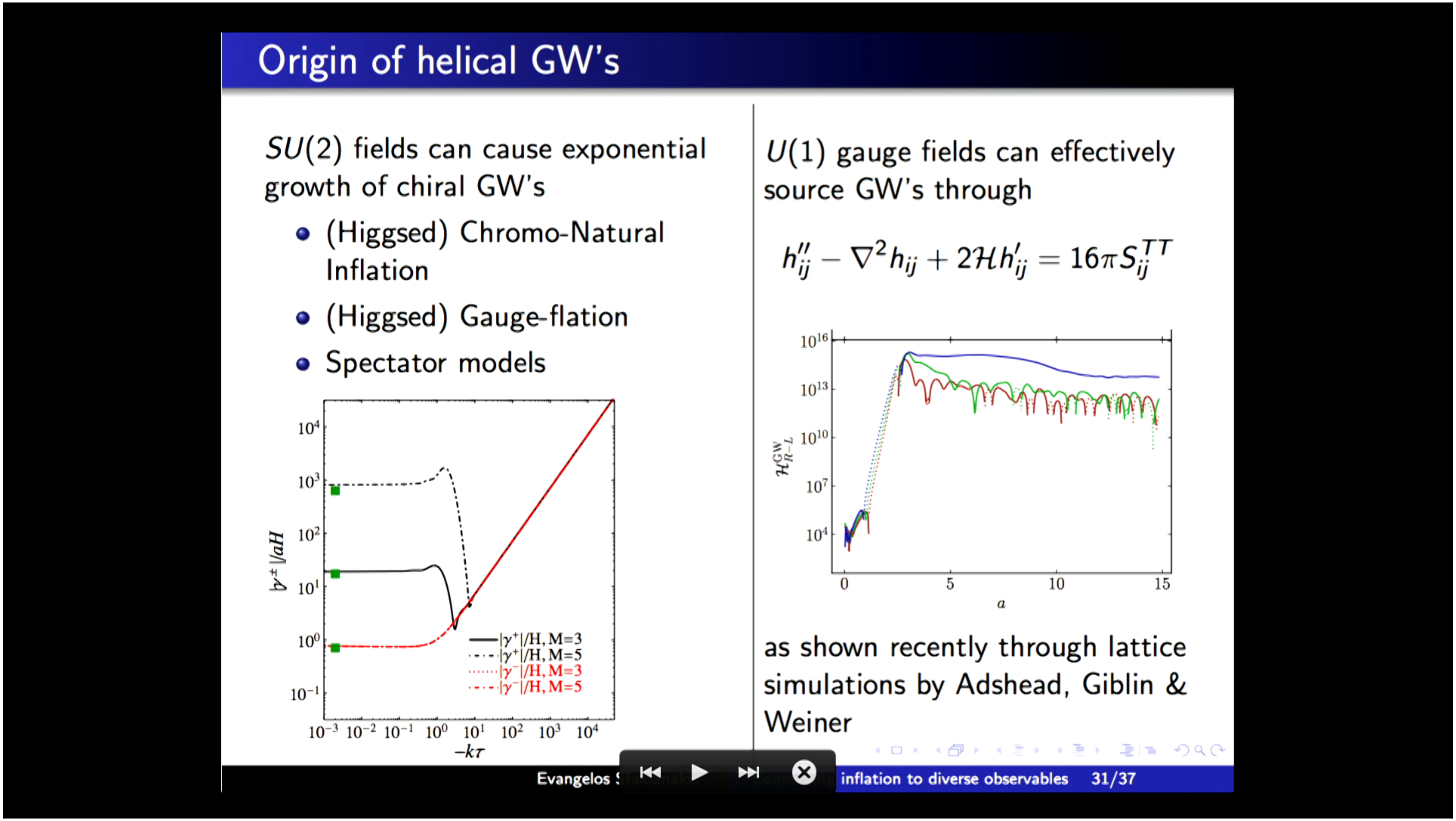
$$\partial_\mu\left(\sqrt{-g}\,J^\mu_{B-L}\right) = -\frac{N_{L-R}}{24}\frac{1}{16\pi^2}R\tilde{R}$$

where the lepton number density is

$$\mathcal{N}_{B-L}\propto\left(\frac{H_e}{M_{\rm Pl}}\right)^2\mathcal{H}^{GW}_{R-L}$$

while we parametrize the GW power asymmetry with

$$\mathcal{H}^{GW}_{R-L}\equiv\int d\ln k\left[\frac{k^3}{H_e^3}\frac{(\Delta_R^2-\Delta_L^2)}{H_e^2/M_{\rm Pl}^2}-\frac{k}{H_e}\frac{(\Delta_R'^2-\Delta_L'^2)}{H_e^4/M_{\rm Pl}^4}\right]$$



# Origin of helical GW's

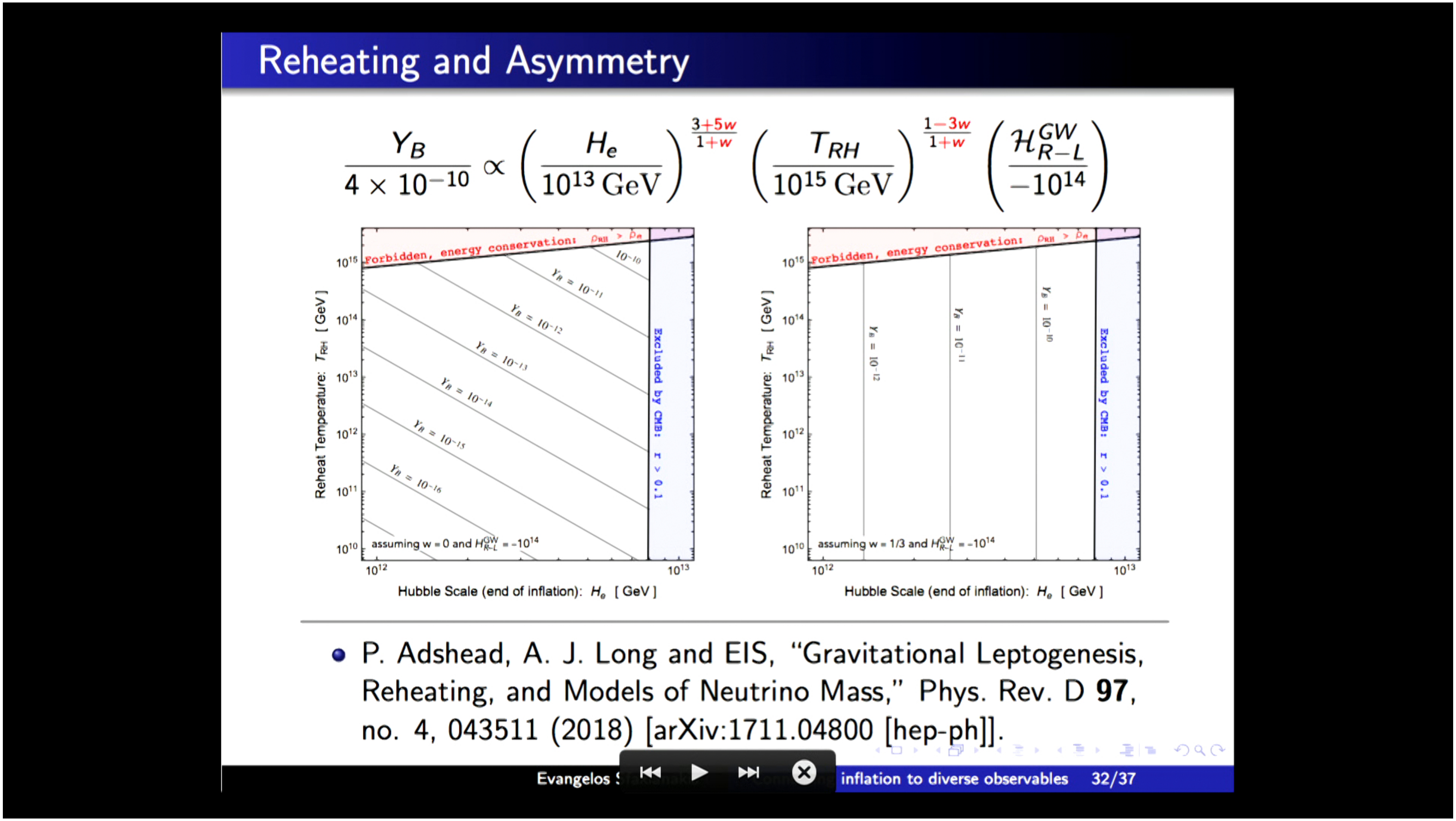
$SU(2)$ fields can cause exponential growth of chiral GW's

- (Higgsed) Chromo-Natural Inflation
- (Higgsed) Gauge-flation
- Spectator models

$U(1)$ gauge fields can effectively source GW's through

$$h''_{ij} - \nabla^2 h_{ij} + 2\mathcal{H} h'_{ij} = 16\pi S^{TT}_{ij}$$

as shown recently through lattice simulations by Adshead, Giblin & Weiner



# Reheating and Asymmetry

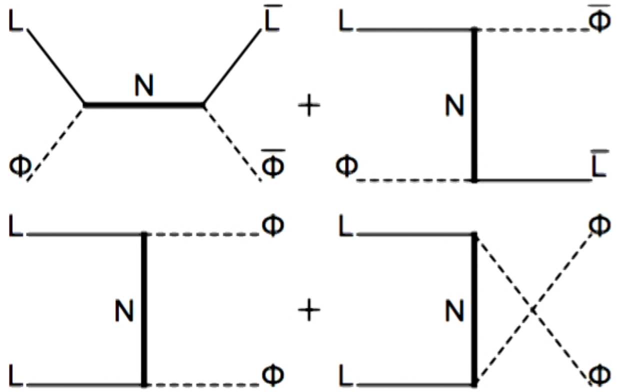
$$\frac{Y_B}{4\times 10^{-10}} \propto \left(\frac{H_e}{10^{13}\,\mathrm{GeV}}\right)^{\frac{3+5w}{1+w}} \left(\frac{T_{RH}}{10^{15}\,\mathrm{GeV}}\right)^{\frac{1-3w}{1+w}} \left(\frac{\mathcal{H}^{GW}_{R-L}}{-10^{14}}\right)$$

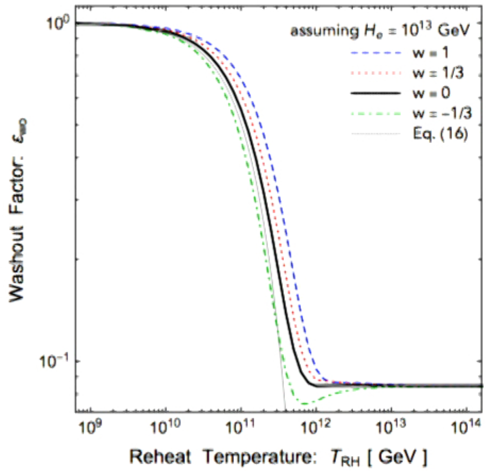
- P. Adshead, A. J. Long and EIS, "Gravitational Leptogenesis, Reheating, and Models of Neutrino Mass," Phys. Rev. D **97**, no. 4, 043511 (2018) [arXiv:1711.04800 [hep-ph]].

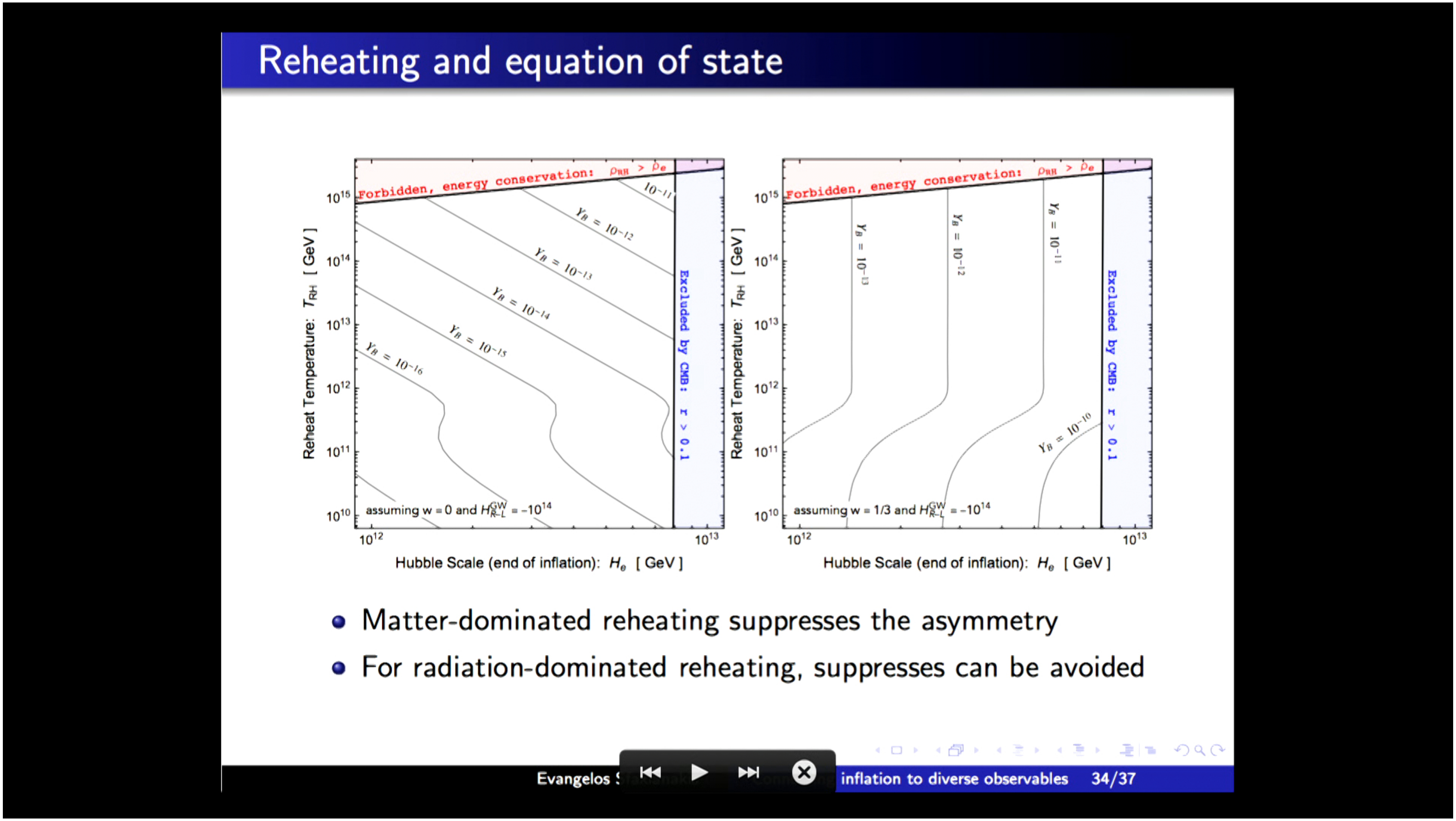
# Reheating and Washout

- Massive Dirac neutrinos: No net lepton number arises, BUT the lepton number of right-handed neutrinos is sequestered from the SM ⇒ effective (axial) SM lepton number with no washout.

- Massive Majorana neutrinos:

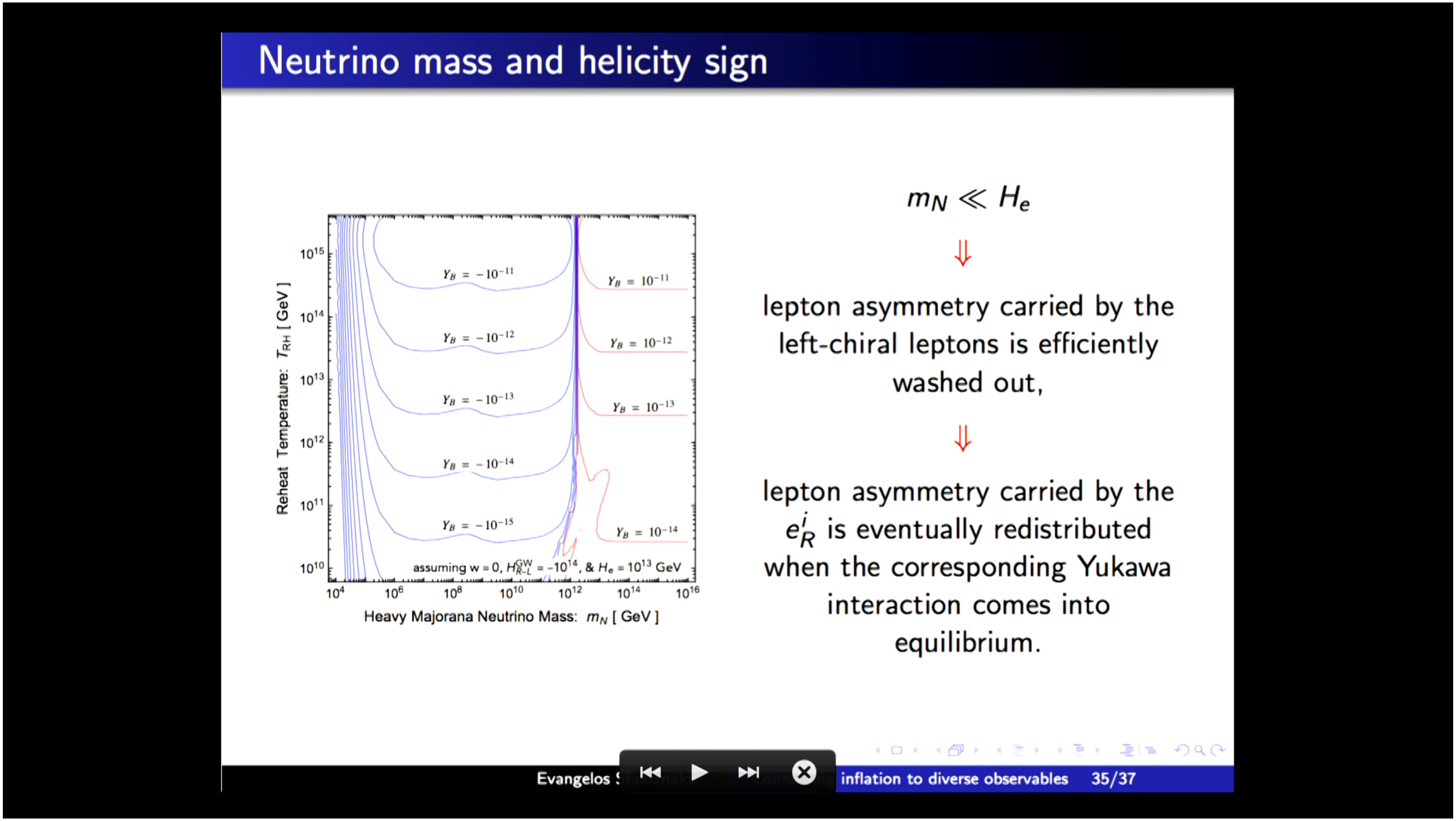






# Reheating and equation of state

- Matter-dominated reheating suppresses the asymmetry
- For radiation-dominated reheating, suppresses can be avoided



# Neutrino mass and helicity sign

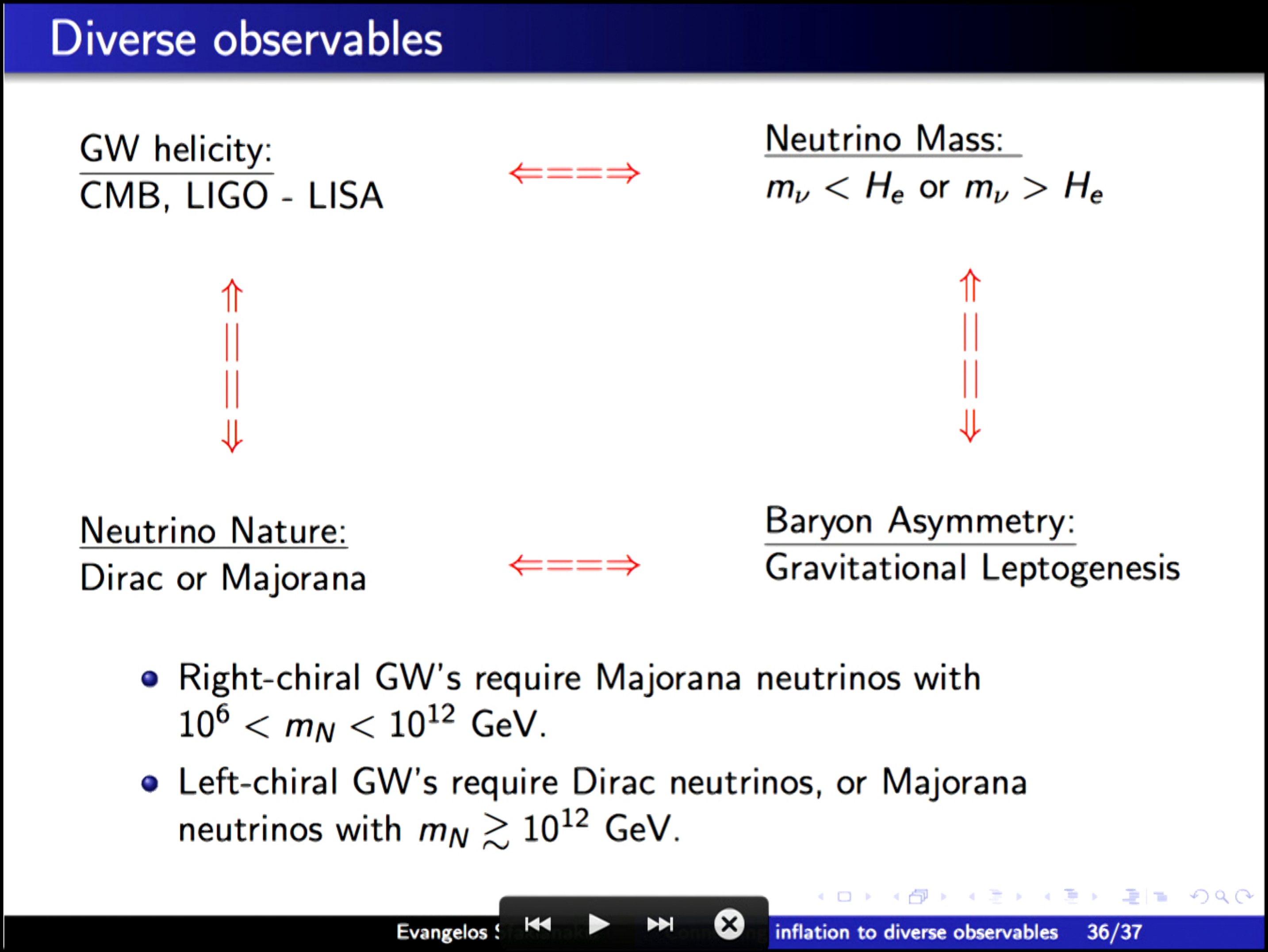
$$m_N \ll H_e$$

$$\Downarrow$$

lepton asymmetry carried by the left-chiral leptons is efficiently washed out,

$$\Downarrow$$

lepton asymmetry carried by the $e_R^i$ is eventually redistributed when the corresponding Yukawa interaction comes into equilibrium.



## Diverse observables

GW helicity:
CMB, LIGO - LISA

$\Longleftarrow\!=\!=\!\Longrightarrow$

Neutrino Mass:
$m_\nu < H_e$ or $m_\nu > H_e$

$\Updownarrow$

Neutrino Nature:
Dirac or Majorana

$\Longleftarrow\!=\!=\!\Longrightarrow$

Baryon Asymmetry:
Gravitational Leptogenesis

- Right-chiral GW's require Majorana neutrinos with $10^6 < m_N < 10^{12}$ GeV.
- Left-chiral GW's require Dirac neutrinos, or Majorana neutrinos with $m_N \gtrsim 10^{12}$ GeV.

# Thank you!