Gauge-field inflation and the origin of the matter-antimatter asymmetry

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PRL: 108,261302 (2012), with M. Wyman
PRD: 88, 021302 (2013), with E. Martinec & M. Wyman
JHEP: 09, 087 (2013), with E. Martinec & M. Wyman
JHEP: 12, 137 (2016), with E. Martinec, E. Sfakianakis & M. Wyman
JHEP: 08, 130 (2017), with E. Sfakianakis
PRD: 98, 043525 (2018), with A. Long and E. Sfakianakis

Invitation

- Another model of inflation - why do I care?

  -Rather than a new model, a new class

  Replace: $\eta_V = M_{\rm Pl}^2 \frac{V''}{V} \ll 1$

  With: $M_{\rm Pl}^2 \frac{V''}{V} \sim 1$ and (e.g.) $f(F_{\mu\nu}, \tilde{F}_{\mu\nu})$

- Definite (potentially) testable predictions!

  e.g. Parity violation (EB, TB correlations), large-amplitude chiral gravitational waves, large tensor non-Gaussianities, gravitational leptogenesis

- Important to understand implications of potential B-mode measurements

$$\Lambda_{\rm inf} \sim \sqrt{H M_{\rm Pl}} \stackrel{?}{=} 1.04 \times 10^{16} {\rm GeV} \left(\frac{r}{0.01}\right)^{1/4}$$

Scalar-field Inflation—parametrization of ignorance

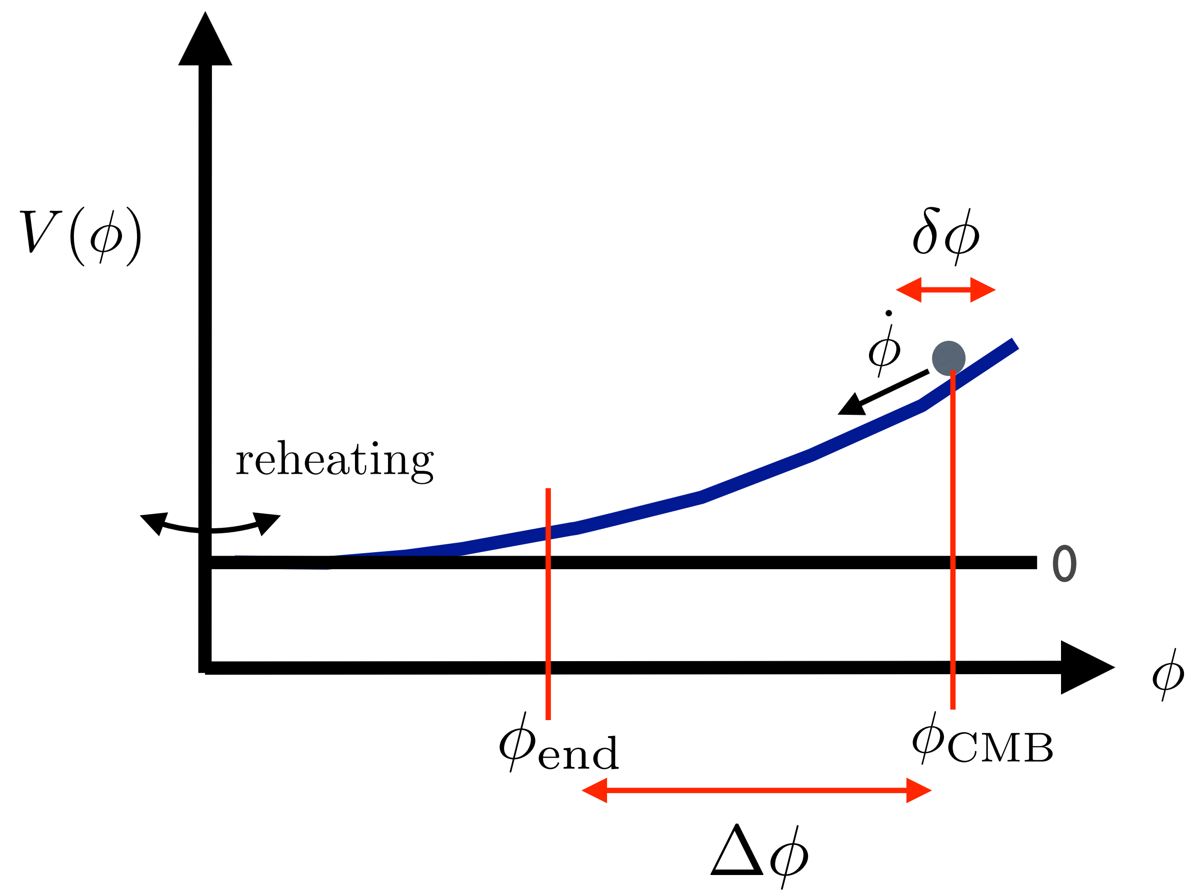
- Potential of a slowly-rolling scalar drives inflation

$$\mathcal{L} = \sqrt{-g}\left[\frac{M_{\rm Pl}^2}{2}R - \frac{(\partial\phi)^2}{2} - V(\Phi)\right]$$

- Requires a flat potential

$$\epsilon = \frac{M_{\rm Pl}^2}{2}\left(\frac{V'}{V}\right)^2 \ll 1$$

$$\eta = M_{\rm Pl}^2 \frac{V''}{V} \ll 1$$



- Fluctuation spectra

$$\Delta_{\mathcal{R}}^2 = \frac{1}{24\pi^2 M_{\rm Pl}^2}\frac{V}{\epsilon} \sim 10^{-10}$$

$$\Delta_h^2 = \frac{2}{3\pi^2 M_{\rm Pl}^2} V \sim ?$$

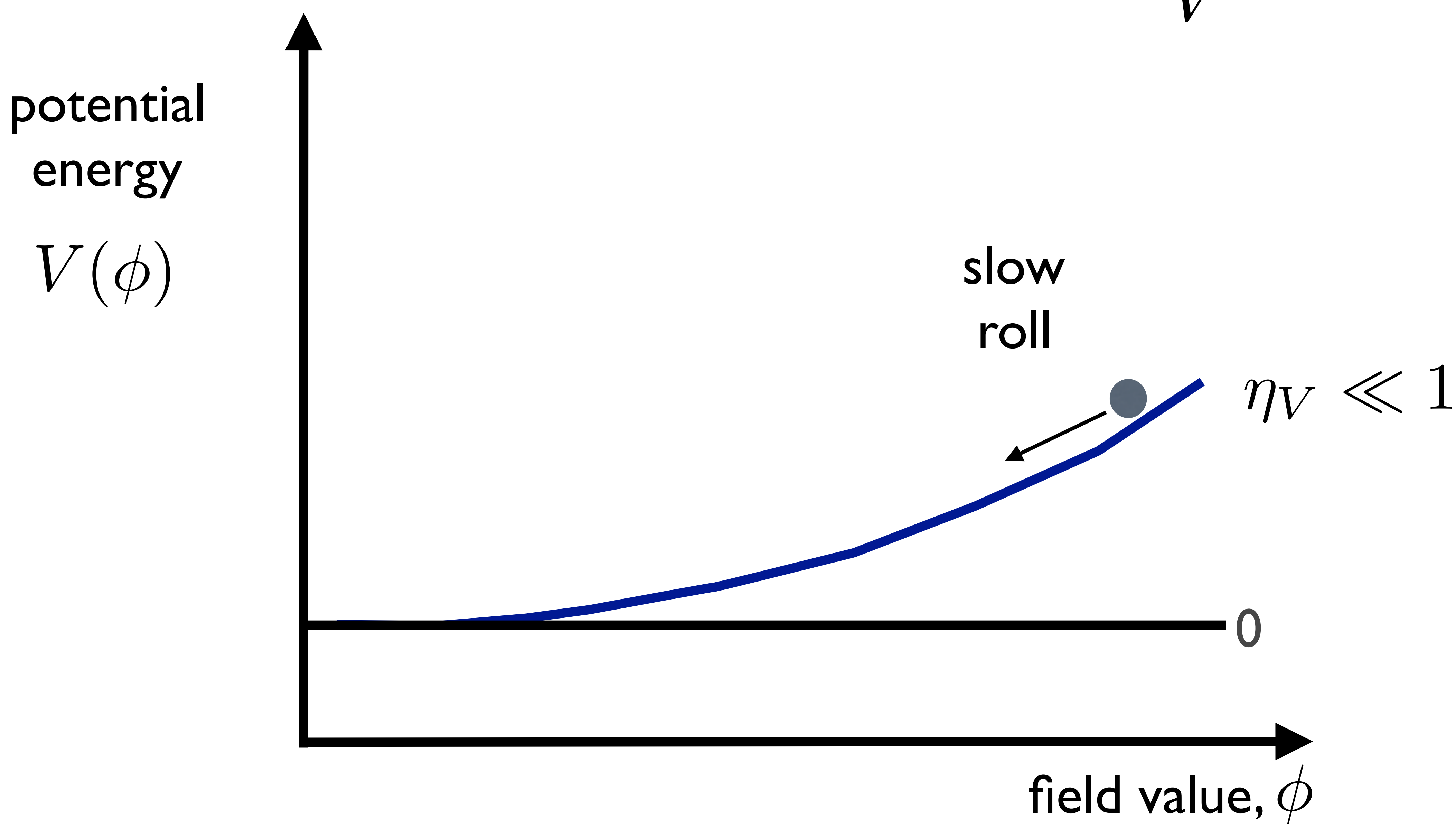
- Tensor-to-scalar ratio

$$r = \frac{\Delta_h^2}{\Delta_{\mathcal{R}}^2} = 16\epsilon$$

The ‘eta’ problem

We need a flat potential to sustain slow roll.

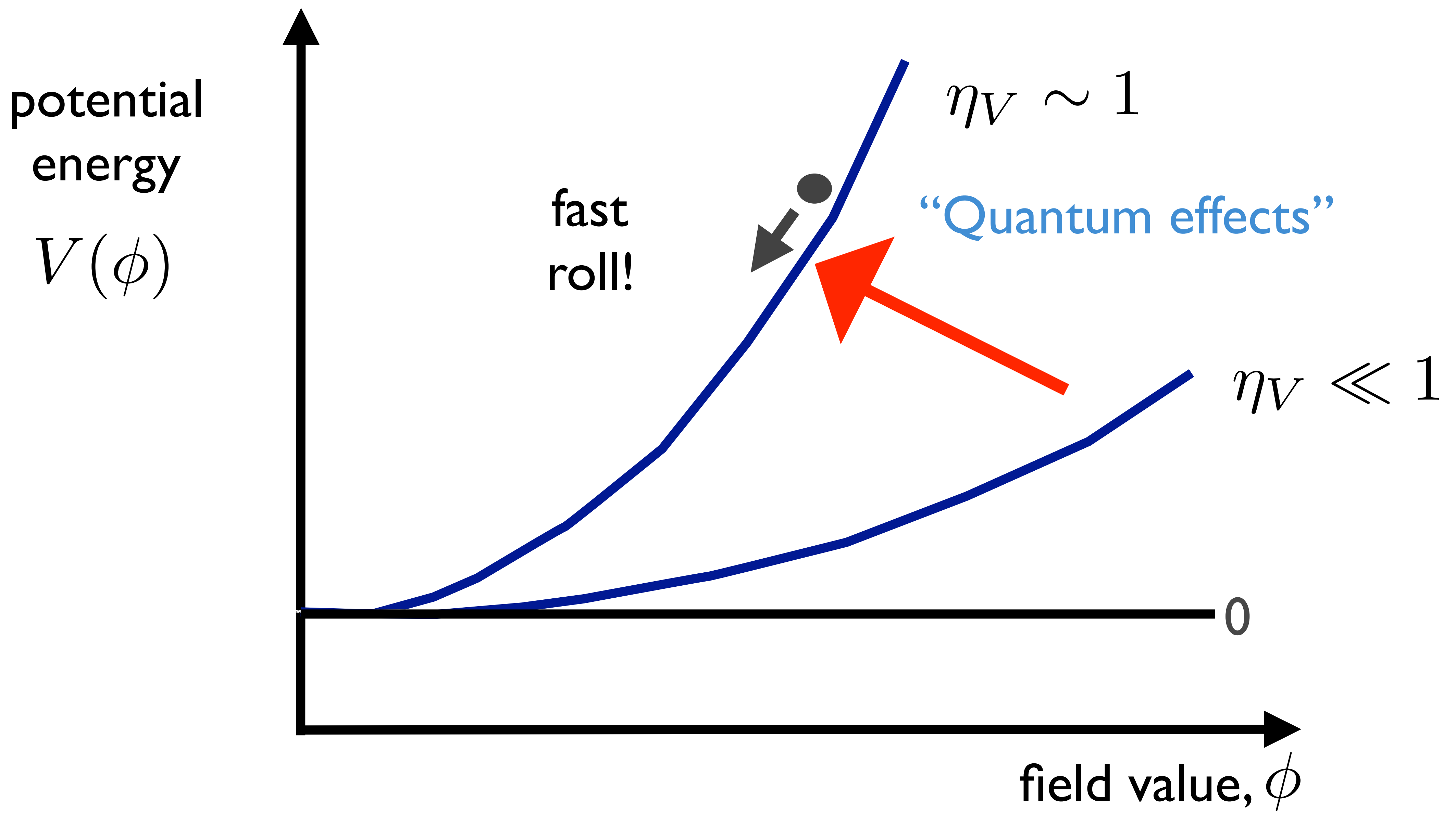
$$\eta_V \equiv M_{\rm Pl}^2 \frac{V''}{V} \ll 1$$



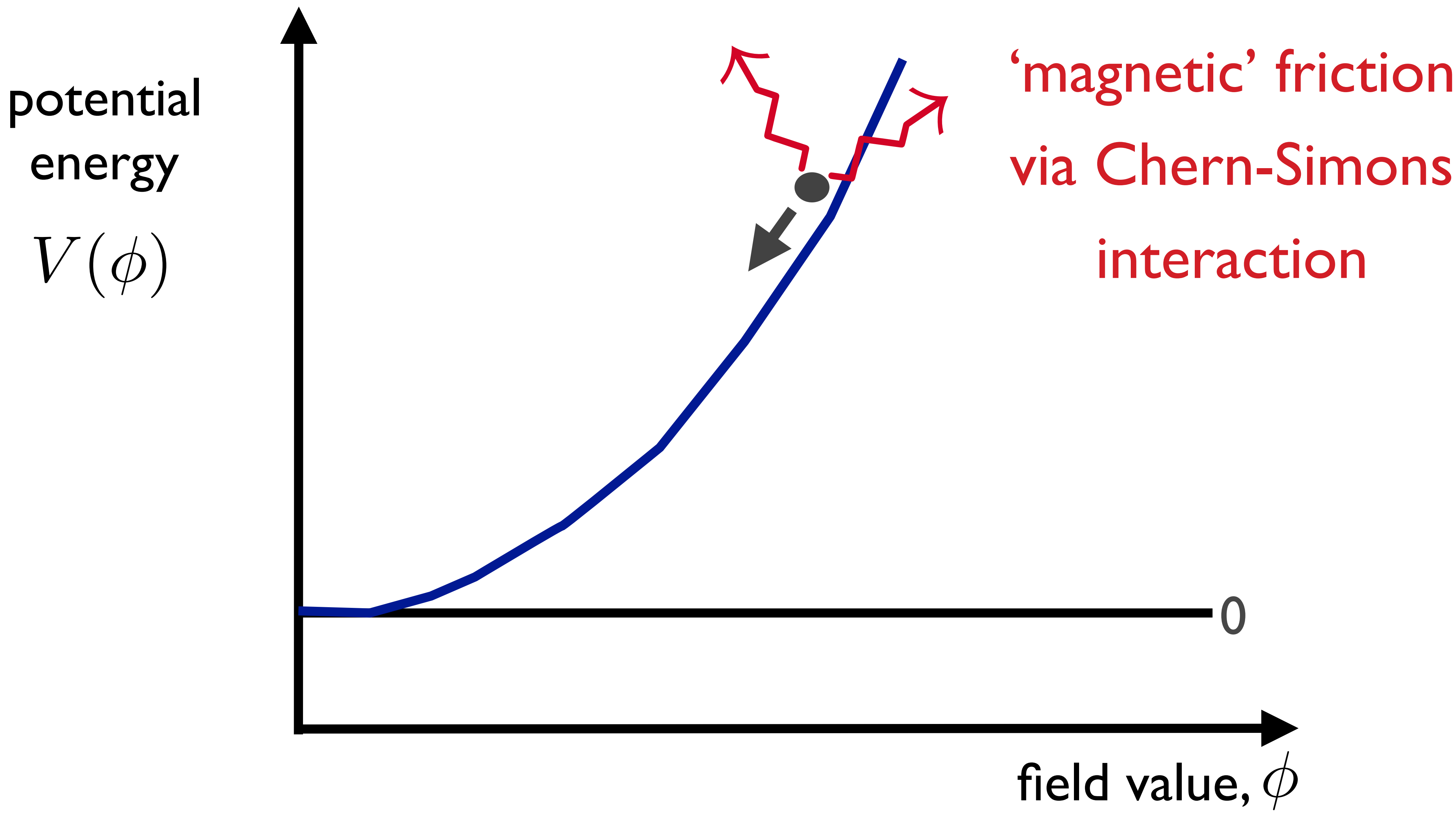
Linde; Steinhardt & Albrecht (1982)

But this introduces an *inflationary* hierarchy problem.

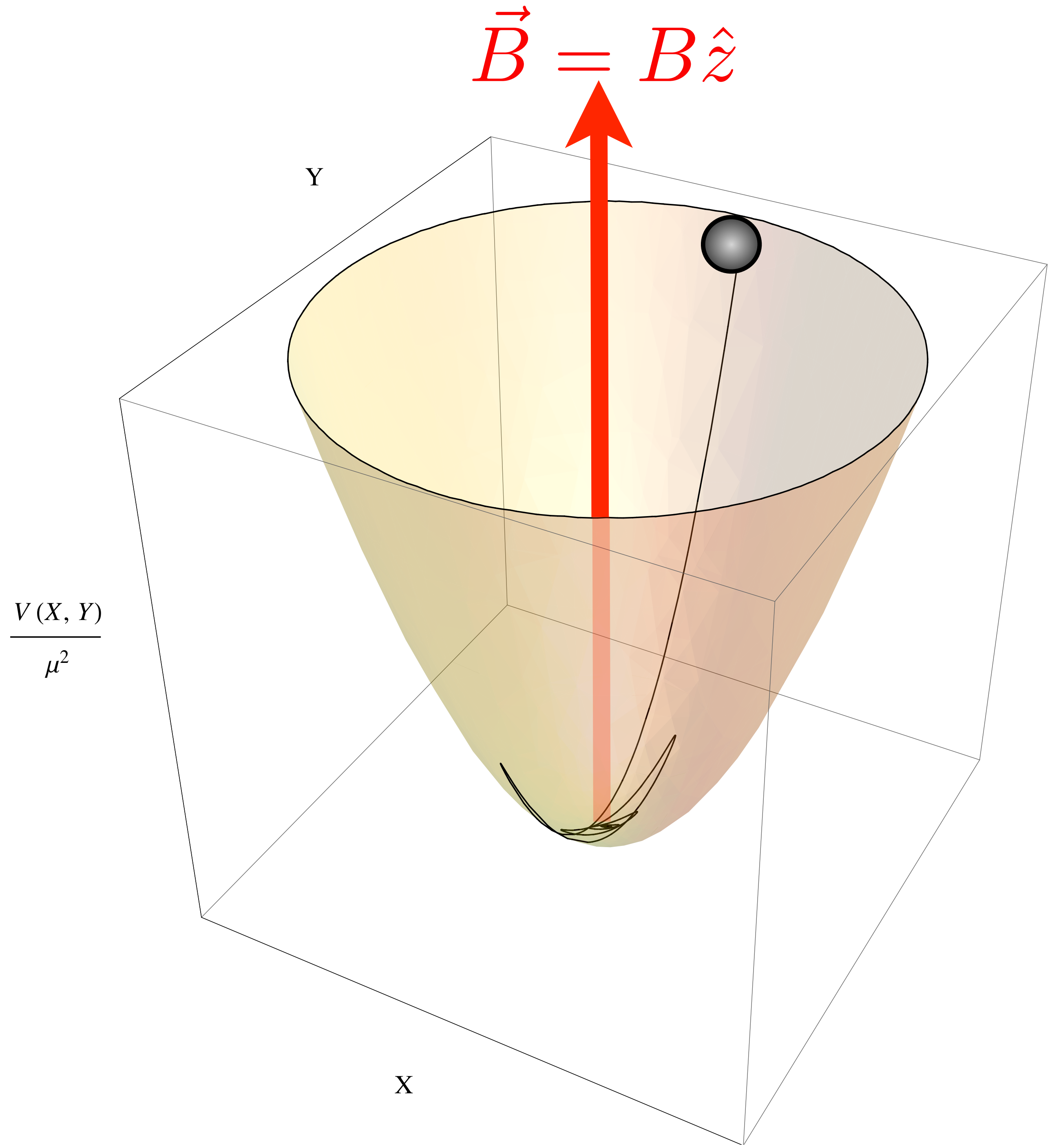
The eta problem: $\eta_V \equiv M_{\rm Pl}^2 \frac{V''}{V} \ll 1$



Today, a way to avoid this hierarchy problem.



The new physics is analogous to the Lorentz force:



potential force

$$\ddot{X} + H\dot{X} + \mu^2 X = B\dot{Y}$$
$$\ddot{Y} + H\dot{Y} + \mu^2 Y = -B\dot{X}$$

ordinary friction

magnetic force

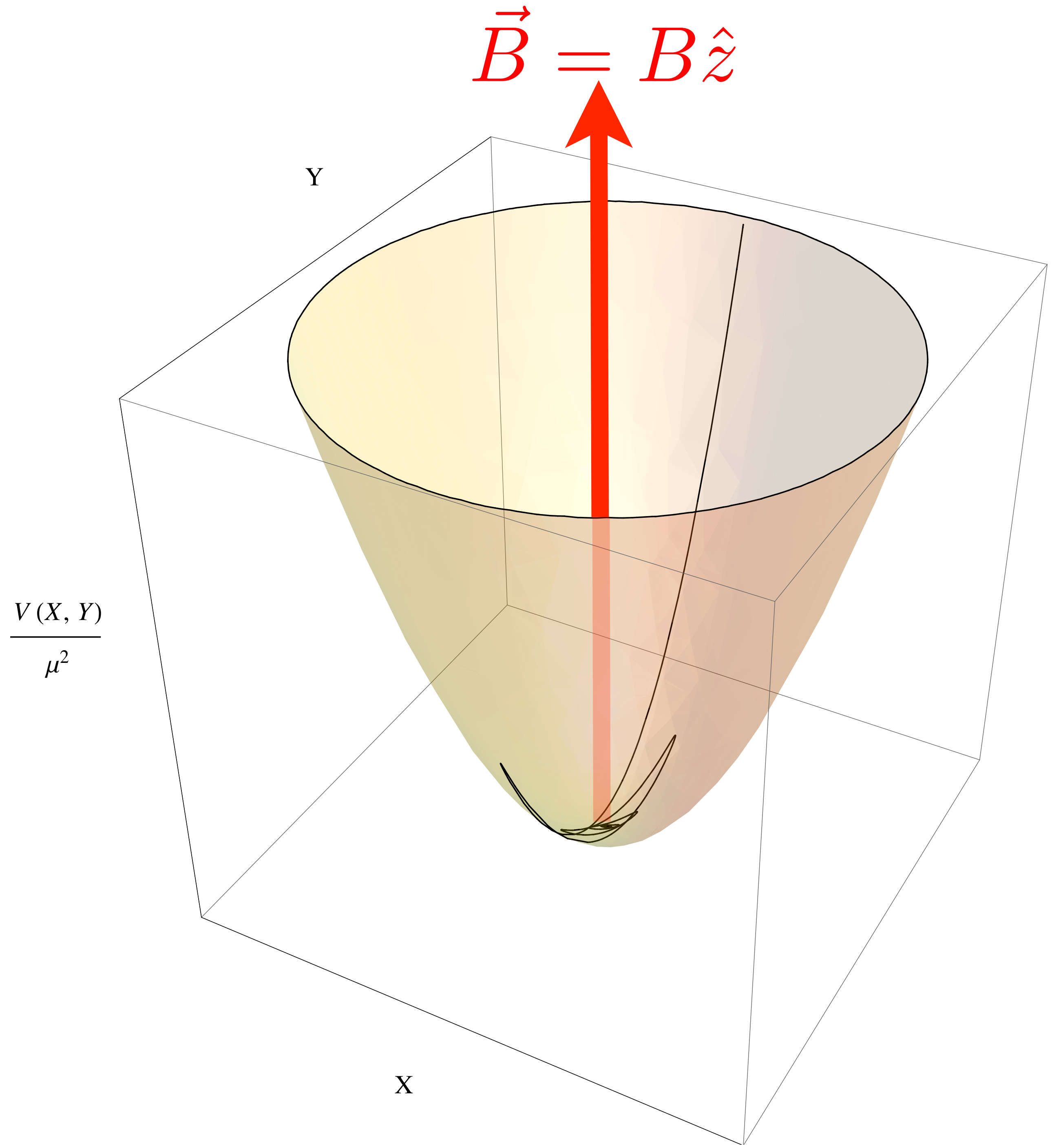
Analysis: Normal modes

- 2-mode characterized by orientation of angular momentum relative to magnetic field:

$\vec{B} \parallel -\vec{L}$	$\vec{B} \parallel \vec{L}$
$\vec{v} \times \vec{B} \approx -\frac{v^2}{r}\hat{r}$	$\vec{v} \times \vec{B} \approx -\nabla V$
	$Bv_+ \approx \mu^2 r_+$
$\omega_- \sim B$	$\omega_+ \approx \mu^2/B$

$$(v \sim r\omega)$$

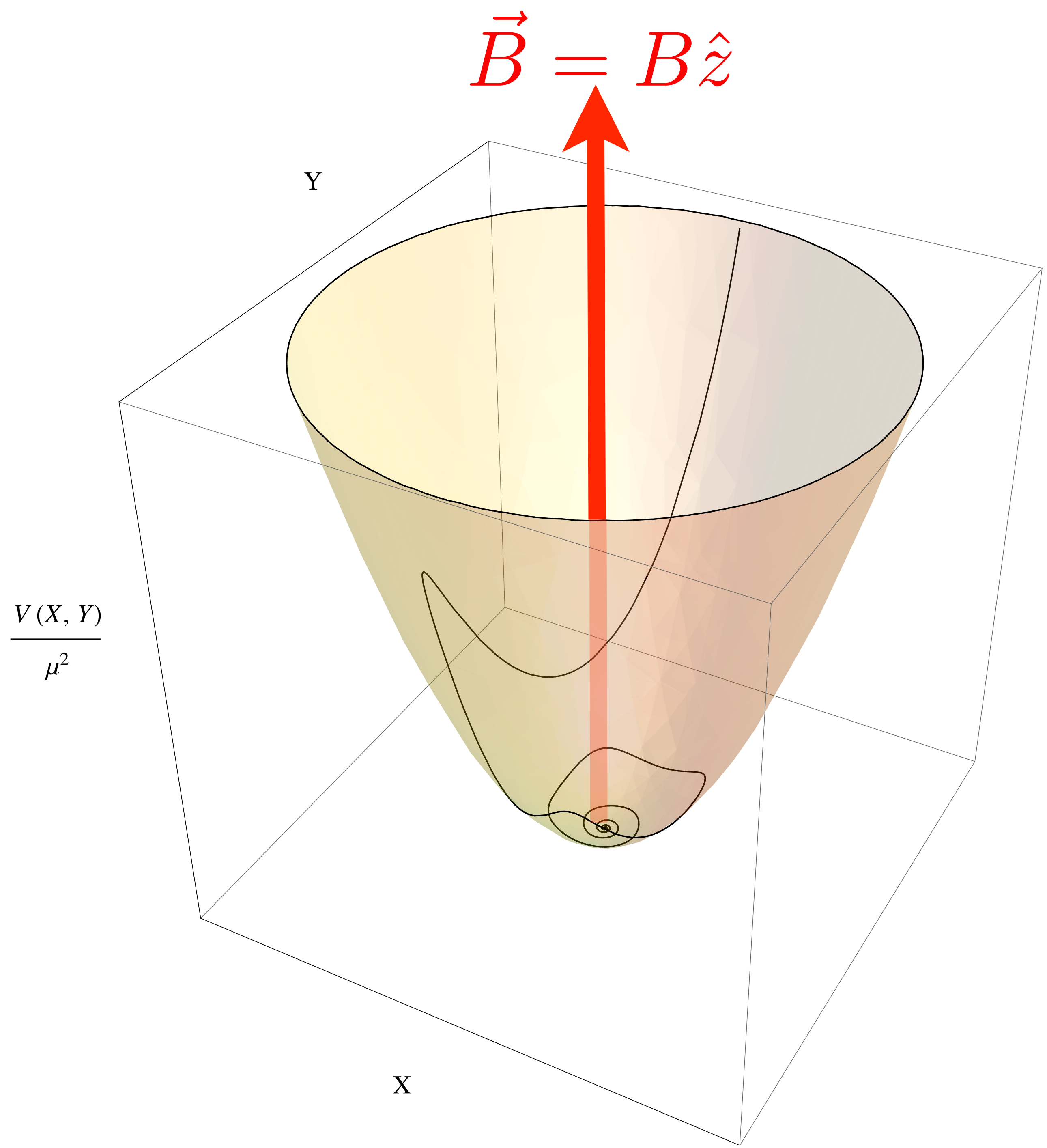
At low B field strength...



$$B = 0.1\mu$$

$$H = \frac{\mu^2}{\sqrt{3}}$$

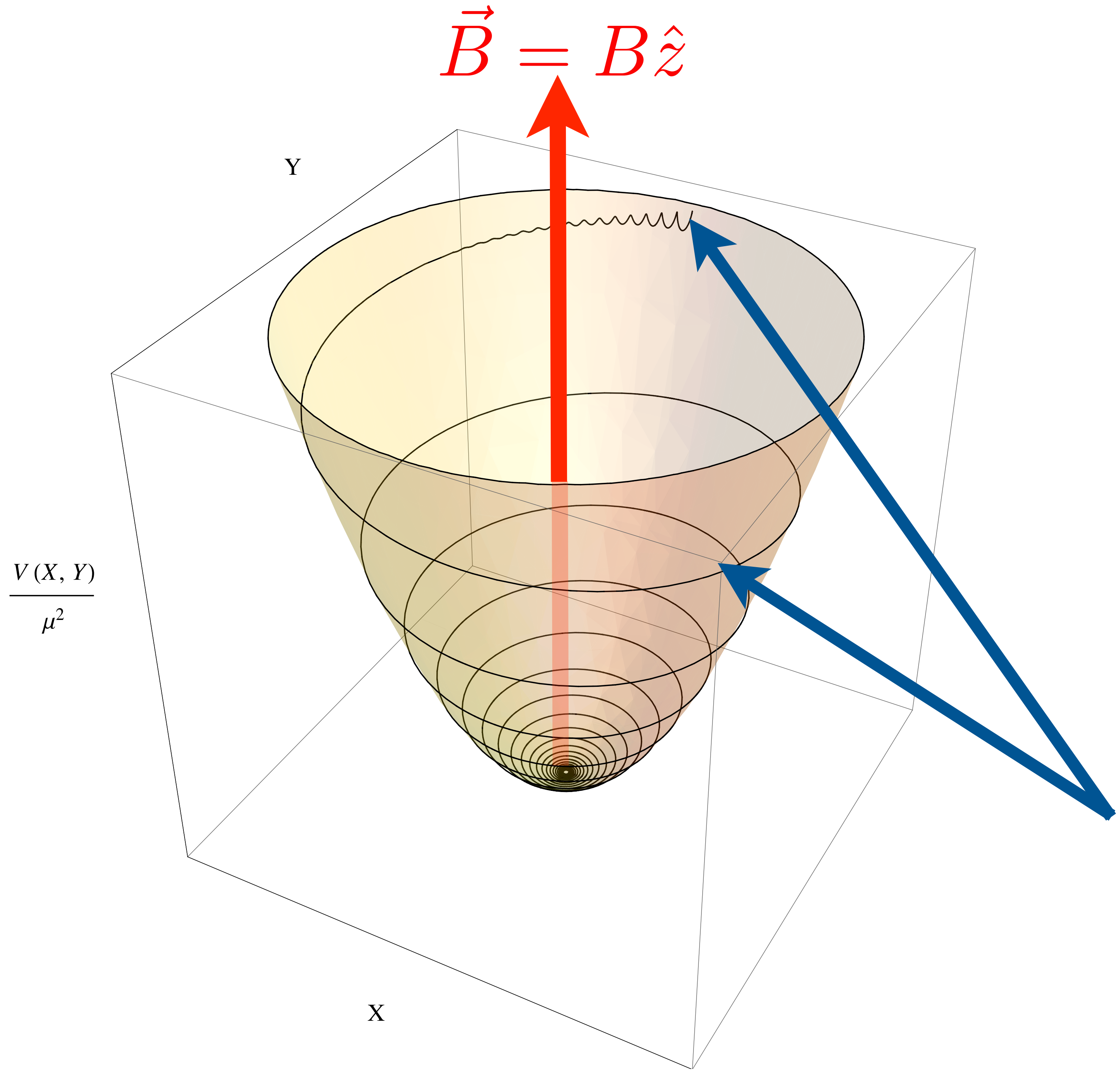
Turning up the B-field



$$B = \mu$$

$$H = \frac{\mu^2}{\sqrt{3}}$$

This is magnetic drift.



$$B = 10\mu$$

$$H = \frac{\mu^2}{\sqrt{3}}$$

Fast mode rapidly damped leaving slow magnetic drift mode.

Long **slow** spiral down the potential!

Magnetic Friction

$$\ddot{X} + H\dot{X} + \frac{\partial \mathcal{V}(X,Y)}{\partial X} = B\dot{Y}$$
$$\ddot{Y} + H\dot{Y} + \frac{\partial \mathcal{V}(X,Y)}{\partial Y} = -B\dot{X}$$

- In the slow roll limit, diagonalize velocities

$$(H^2 + B^2)\dot{X} = H\mathcal{V}_{,X} - B\mathcal{V}_{,Y}$$
$$(H^2 + B^2)\dot{Y} = B\mathcal{V}_{,X} + H\mathcal{V}_{,Y}$$

Magnetic Friction

- In magnetic drift limit B >> H, gradient flow balanced by magnetic friction

Building a new theory:

$$\mathcal{L} = \sqrt{-g}\left[\frac{R}{2} - \frac{1}{2}(\partial\mathcal{X})^2 - V(\mathcal{X}) - \frac{1}{2}\mathrm{Tr}\left[F^{\mu\nu}F_{\mu\nu}\right] - \frac{\lambda}{4f}\mathcal{X}\frac{\epsilon^{\mu\nu\alpha\beta}}{\sqrt{-g}}\mathrm{Tr}\left[F_{\mu\nu}F_{\alpha\beta}\right]\right]$$

Start with the basics...

$$\mathcal{L} = \sqrt{-g}\left[\underline{\frac{R}{2} - \frac{1}{2}(\partial\mathcal{X})^2 - V(\mathcal{X})} - \frac{1}{2}\mathrm{Tr}\left[F^{\mu\nu}F_{\mu\nu}\right] - \frac{\lambda}{4f}\mathcal{X}\frac{\epsilon^{\mu\nu\alpha\beta}}{\sqrt{-g}}\mathrm{Tr}\left[F_{\mu\nu}F_{\alpha\beta}\right]\right]$$

Usual inflationary action.

- with something like

$$V(\mathcal{X}) = \mu^4\left(1 + \cos\left(\frac{\mathcal{X}}{f}\right)\right)$$

"Natural Inflation" - Freese, Frieman and Olinto '90

add gauge fields,

$$\mathcal{L} = \sqrt{-g}\left[\frac{R}{2} - \frac{1}{2}(\partial\mathcal{X})^2 - V(\mathcal{X}) - \underline{\frac{1}{2}\mathrm{Tr}\left[F^{\mu\nu}F_{\mu\nu}\right]} - \frac{\lambda}{4f}\mathcal{X}\frac{\epsilon^{\mu\nu\alpha\beta}}{\sqrt{-g}}\mathrm{Tr}\left[F_{\mu\nu}F_{\alpha\beta}\right]\right]$$

Action for a vector (gauge) field theory.

e.g. Maxwell's E&M: U(1)
Weak: $SU(2)_L$
QCD: SU(3)

and let them interact.

$$\mathcal{L} = \sqrt{-g}\left[\frac{R}{2} - \frac{1}{2}(\partial\mathcal{X})^2 - V(\mathcal{X}) - \frac{1}{2}\mathrm{Tr}\left[F^{\mu\nu}F_{\mu\nu}\right] - \underline{\frac{\lambda}{4f}\mathcal{X}\frac{\epsilon^{\mu\nu\alpha\beta}}{\sqrt{-g}}\mathrm{Tr}\left[F_{\mu\nu}F_{\alpha\beta}\right]}\right]$$

Interaction

$$\mathcal{X}\epsilon^{\mu\nu\alpha\beta}\mathrm{Tr}\left[F_{\mu\nu}F_{\alpha\beta}\right] = \mathcal{X}\mathrm{Tr}\left[\vec{E}\cdot\vec{B}\right]$$

- Dimension 5 operator
- Chern-Simons term
- Topological

Key: a single time derivative.

- Chern-Simons terms are total derivatives,

$$\mathcal{X}\epsilon^{\alpha\beta\mu\nu}\mathrm{Tr}\left[F_{\alpha\beta}F_{\mu\nu}\right] = \mathcal{X}\epsilon^{\alpha\beta\mu\nu}\mathrm{Tr}\left[\partial_\alpha\left(A_\beta\partial_\mu A_\nu + \frac{1}{2}A_\beta A_\mu A_\nu\right)\right]$$

integrate action by parts

$$\mathcal{L} \supset \dot{\mathcal{X}}\epsilon^{ijk}\mathrm{Tr}\left[\left(A_i\partial_j A_k + \frac{1}{2}A_i A_j A_k\right)\right]$$

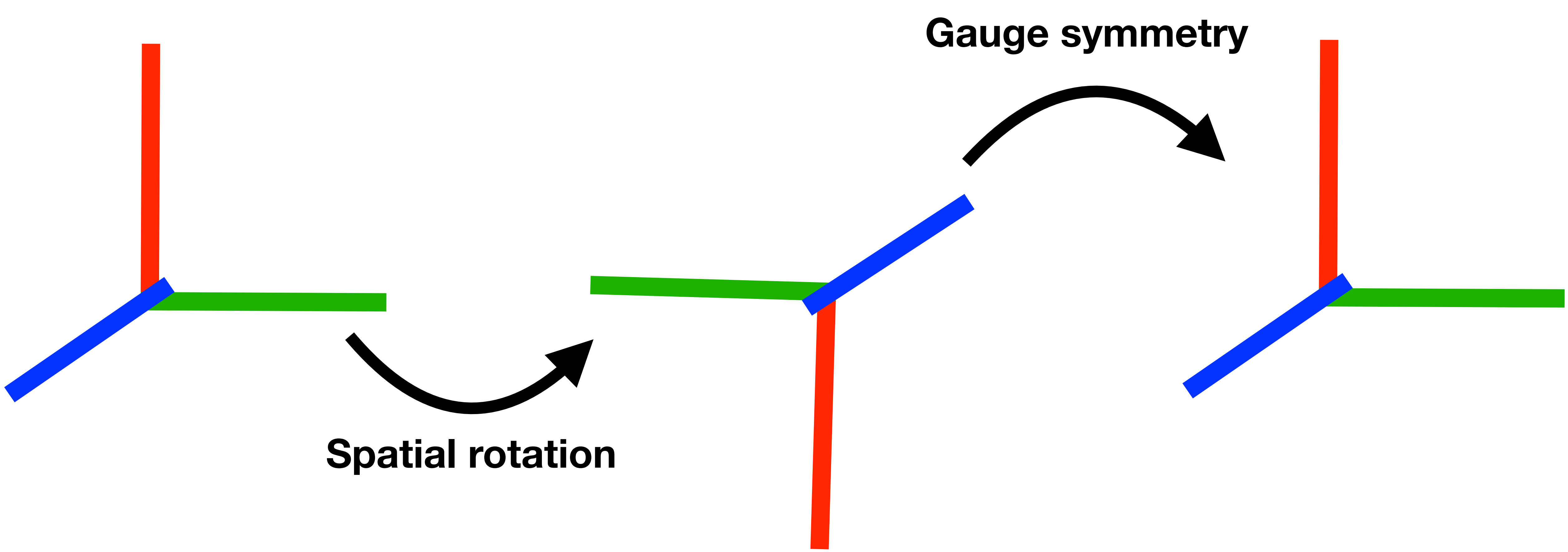
Like Lorentz force! $(\dot{x} \times B)$

Cosmological Gauge fields

- Homogeneity and isotropy of FRW at first appear to prohibit cosmological vector fields

- On second thought, need at least three fields with an additional (gauge) symmetry

- Rotations map to gauge-equivalent configurations



Isotropic, homogeneous vector fields?

- Flavor-space locked configuration:

$$A_0^a = 0, \quad A_i^a = a(t)\psi(t)\delta_i^a \qquad \psi \sim 10^{-2} M_{\rm Pl}$$

- How can a classical vector field be consistent with the symmetries of FRW?

    - Under rotations:

$$A_i^a \to R_{ij}(\vec{\theta})A_j^a = (\delta_{ij} + \epsilon_{ijk}\theta^k)A_j^a$$

    - Residual (large) gauge transformations

$$A_i^a \to (U(\lambda)A_i U^{-1}(\lambda))^a = (\delta_b^a + \epsilon_{bc}^a \lambda^c)A_j^b$$

- Rotations map to gauge-equivalent configurations

We call this Chromo-Natural Inflation.

potential force

- Equations of motion:

$$\ddot{\mathcal{X}} + 3H\dot{\mathcal{X}} + V'(\mathcal{X}) = \boxed{-3\tilde{g}\frac{\lambda}{f}\psi^2(\dot{\psi} + H\psi)}$$

ordinary friction

magnetic force

$$\ddot{\psi} + 3H\dot{\psi} + (\dot{H} + 2H^2)\psi + 2\tilde{g}^2\psi^3 = \tilde{g}\frac{\lambda}{f}\psi^2\dot{\mathcal{X}},$$

PA and M. Wyman, PRL: 108,261302 (2012), PRD 86, 043530 (2012)

Magnetic drift leads to slow roll.

- In the slow-roll, large λ limit, system simplifies.

$$\frac{\dot{\mathcal{X}}}{H} = \frac{2f}{\lambda}\left(\frac{g\psi}{H} + \frac{H}{g\psi}\right)$$

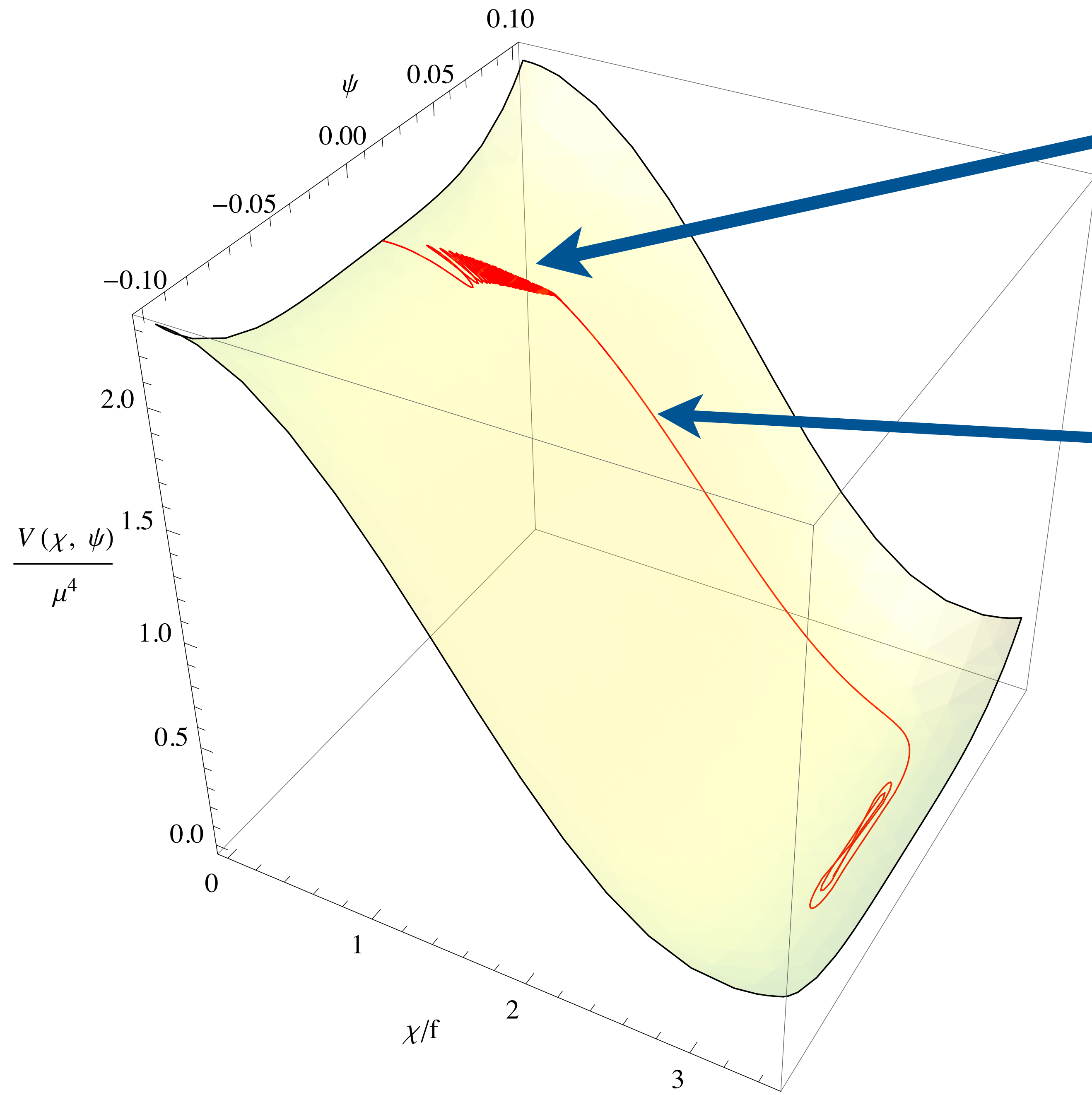
$$\dot{\psi} = -H\psi + \frac{f}{3g\lambda}\frac{V'(\mathcal{X})}{\psi^2}$$

- Axion equation of motion independent of V'!
- Gauge field evolves to (approximate) fixed-point

$$\frac{\dot{\psi}}{H\psi} \ll 1 \qquad\qquad \psi \approx \left(\frac{fV'(\mathcal{X})}{3g\lambda H}\right)^{1/3}$$

- Axion drives slow-roll inflation independent of V
- Inflation duration: $N \propto \lambda \Rightarrow \lambda \gtrsim \mathcal{O}(10^2 - 10^3)$

Chromo-Natural Drift



Fast `Larmor' oscillations

Magnetic drift

$$\text{“}B\text{”} = \frac{\lambda}{f} g \psi^2$$

The axion is not required….

- Can integrate out the axion—get Gauge-flation

$$\mathcal{L} = \sqrt{-g}\left[\frac{M_{\rm Pl}^2}{2}R - \frac{1}{4}{\rm Tr}\left[F_{\mu\nu}F^{\mu\nu}\right] + \frac{\kappa}{192}\left({\rm Tr}\left[F_{\mu\nu}\tilde{F}^{\mu\nu}\right]\right)^2\right]$$

(Maleknejad and Sheikh-Jabbari, 2011)

$$P_{\rm YM} = \frac{1}{3}\rho_{\rm YM} \qquad\qquad P_\kappa = -\rho_\kappa$$

- Inflation requires

$$\rho_{\rm YM} \ll \rho_\kappa$$

Inflation without a scalar field*

***Perturbations sold separately**

Fluctuations

Fluctuations are… complicated

- Gravitation introduces 10 degrees of freedom subject to 8 constraints

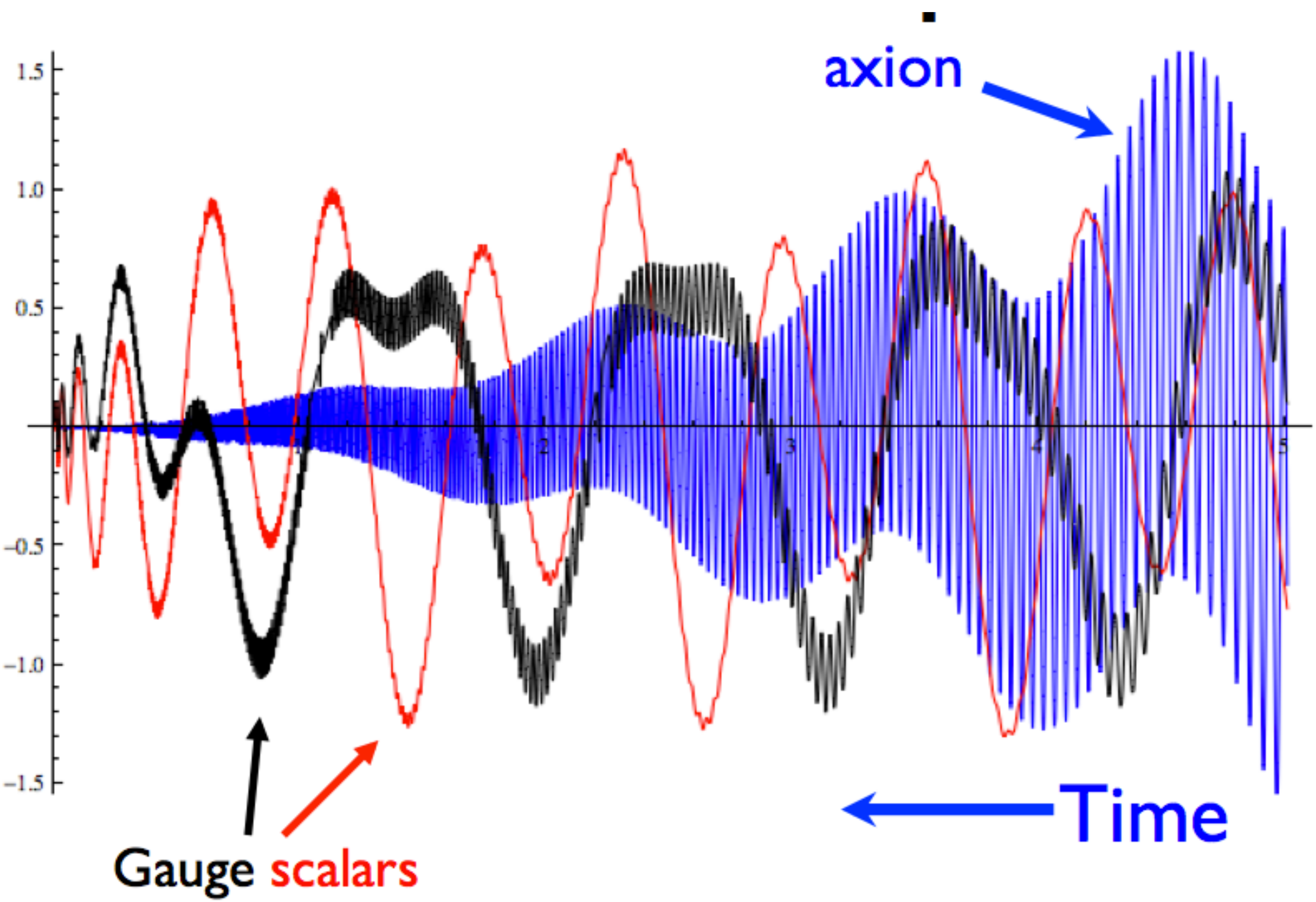
- SU(2) gauge field introduces 12 degrees of freedom subject to 6 constraints

$$\begin{array}{r} \text{10-dof} \\ \text{-8-dof} \\ \text{12-dof} \\ \text{-6-dof} \\ \text{1-dof} \\ \hline \text{9-physical dof} \end{array}$$

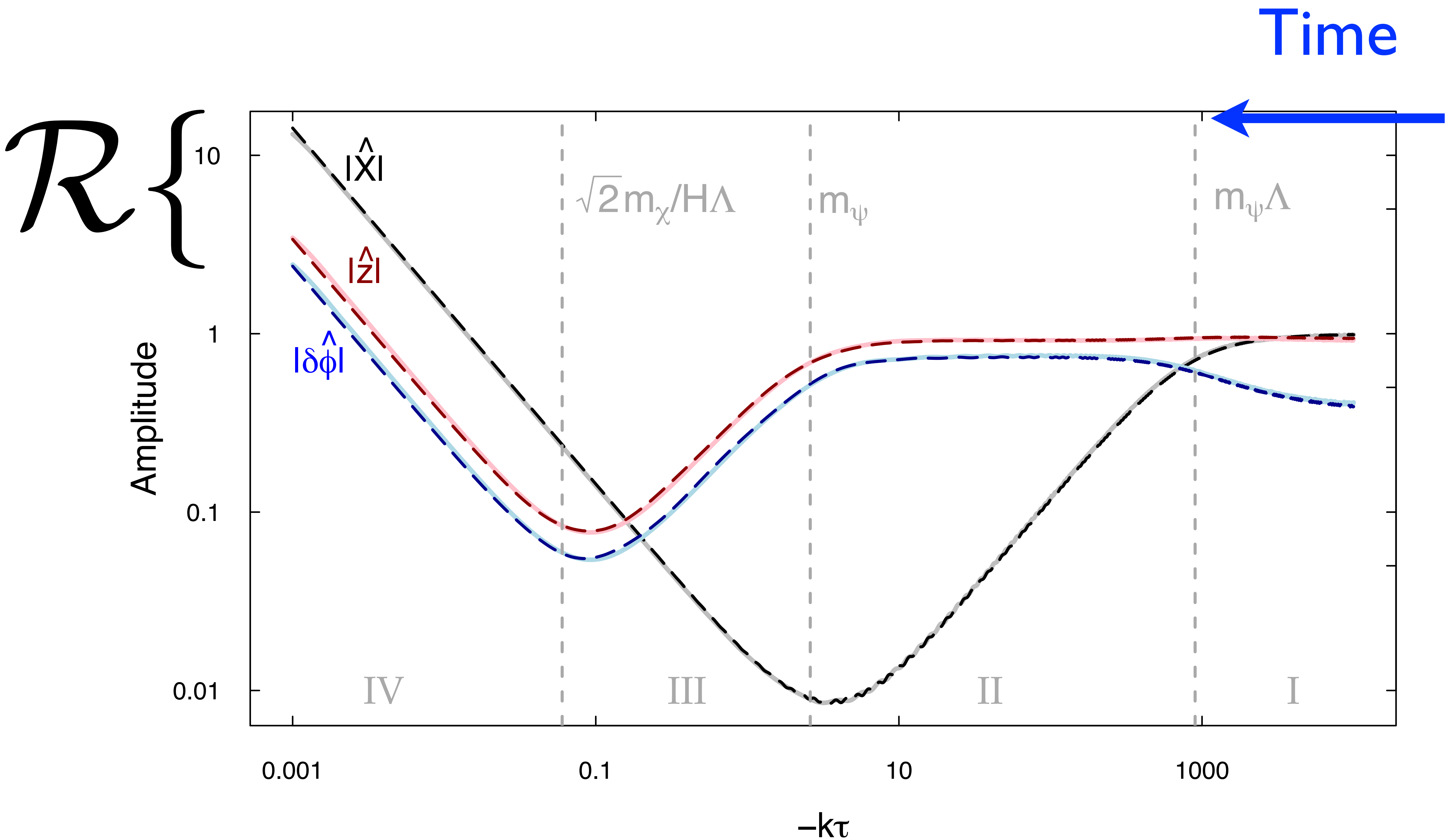
- Physical fluctuations decompose as usual:

3 scalar, 2 vector, 4 tensor

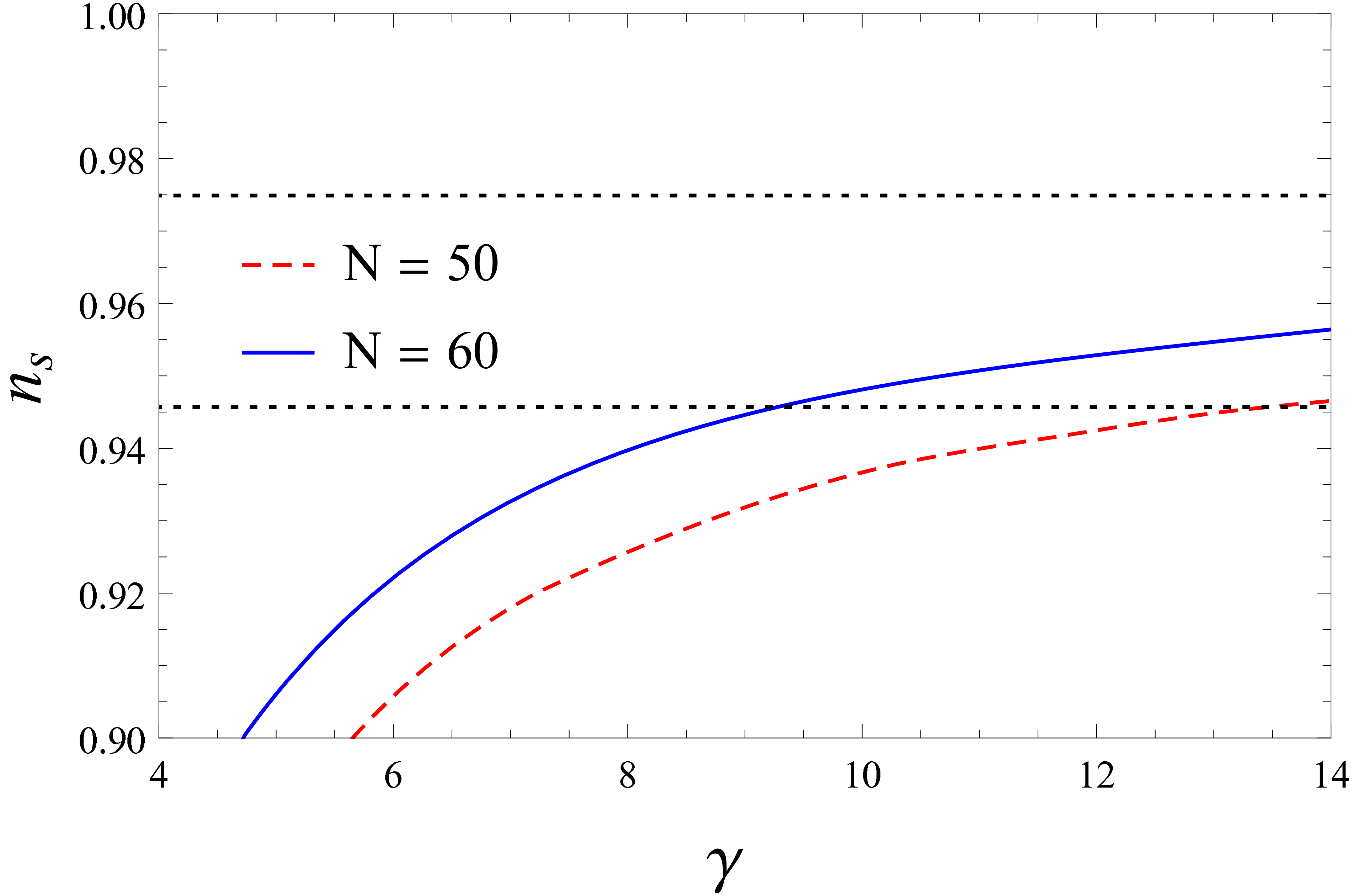
Even though it looks very complicated...



...we can isolate the adiabatic curvature mode:



Scalar spectral index is a strong function of gauge field effective mass.



$$\gamma = \frac{g^2\psi^2}{H^2}$$

$$A_i^a = a\psi\delta_i^a$$

(Catastrophic) Instability for $\gamma = \frac{g^2\psi^2}{H^2} \leq 2$

The tensor sector has new features.

$$ds^2 = -dt^2 + a^2 e^{\gamma_{ij}} dx^i dx^j$$

$$A_\mu = (0, a(t)\psi(t)\delta_i^a + t_i^a(t, \mathbf{x}))\,\frac{\sigma_a}{2}$$

Gauge and gravity tensors mix

usual equation

$$\boxed{\hat{\gamma}^{\pm\prime\prime} + \left(k^2 - \frac{2}{\tau^2}\right)\hat{\gamma}^{\pm}} = \mathcal{O}(\sqrt{\epsilon})\hat{t}^{\pm}$$

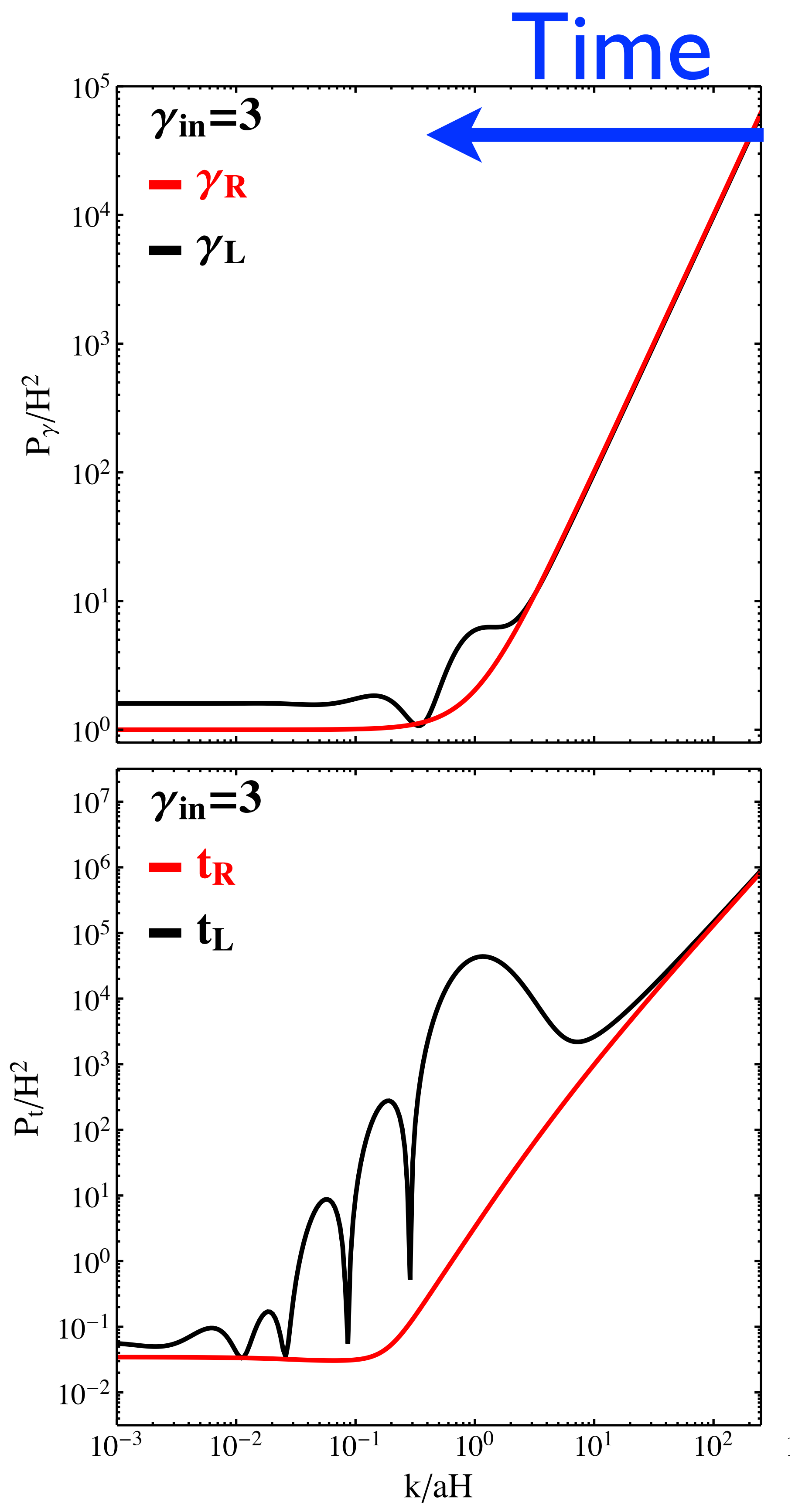
$$\hat{t}^{\pm\prime\prime} + \left(k^2 + \frac{2+2\gamma}{\tau^2}\right)\hat{t}^{\pm} \pm \frac{k}{\tau}\left(\frac{1+2\gamma}{\sqrt{\gamma}}\right)\hat{t}^{\pm} = \mathcal{O}(\sqrt{\epsilon})\gamma^{\pm}$$

Gauge tensors *split;* one is **amplified.**

- Parity is *spontaneously broken* by the background.

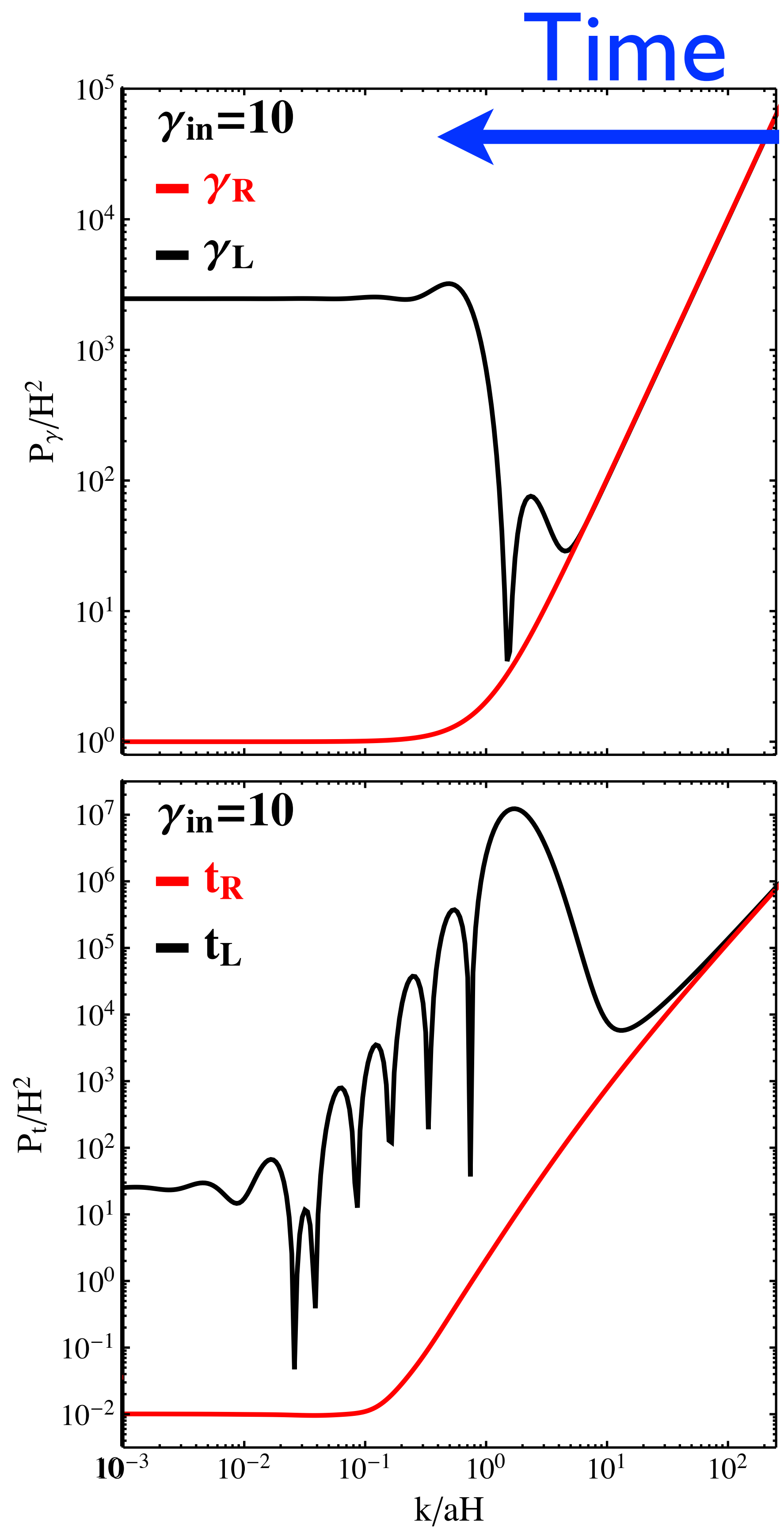
[P.A, E. Martinec, Mark Wyman 2013]

The gauge field sources gravitational waves



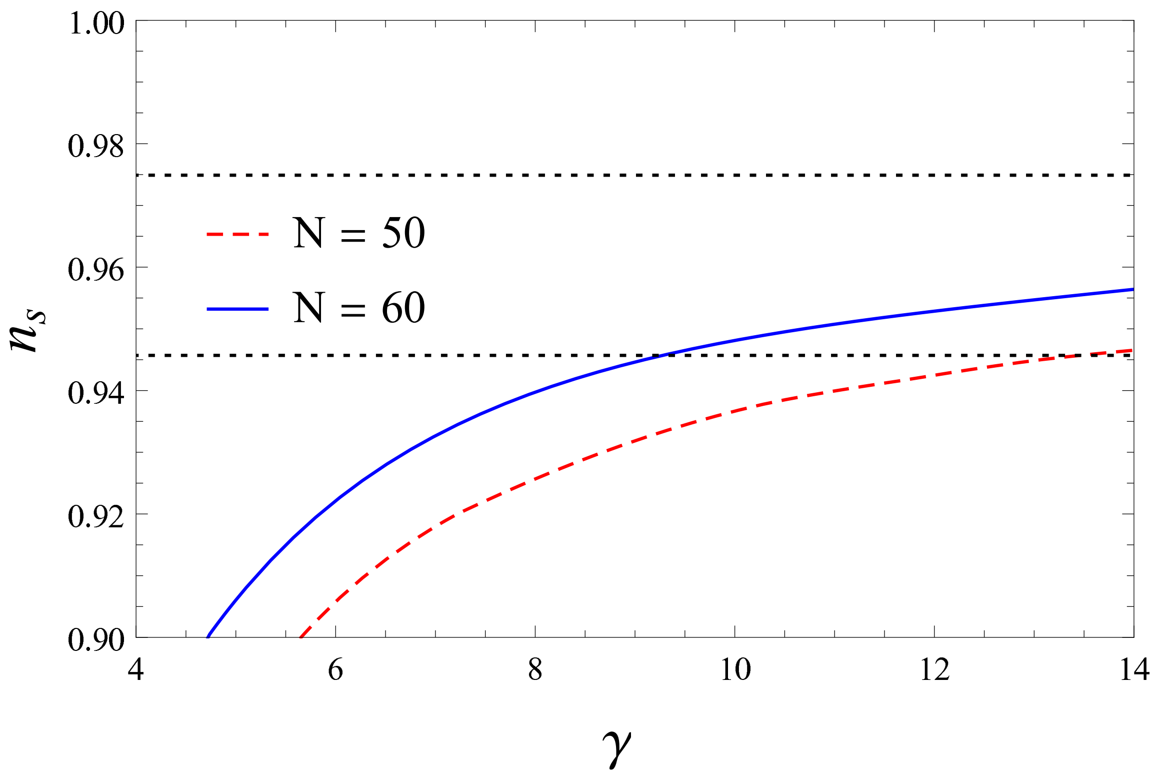
- GWs are chiral, strongly amplified by linear mixing

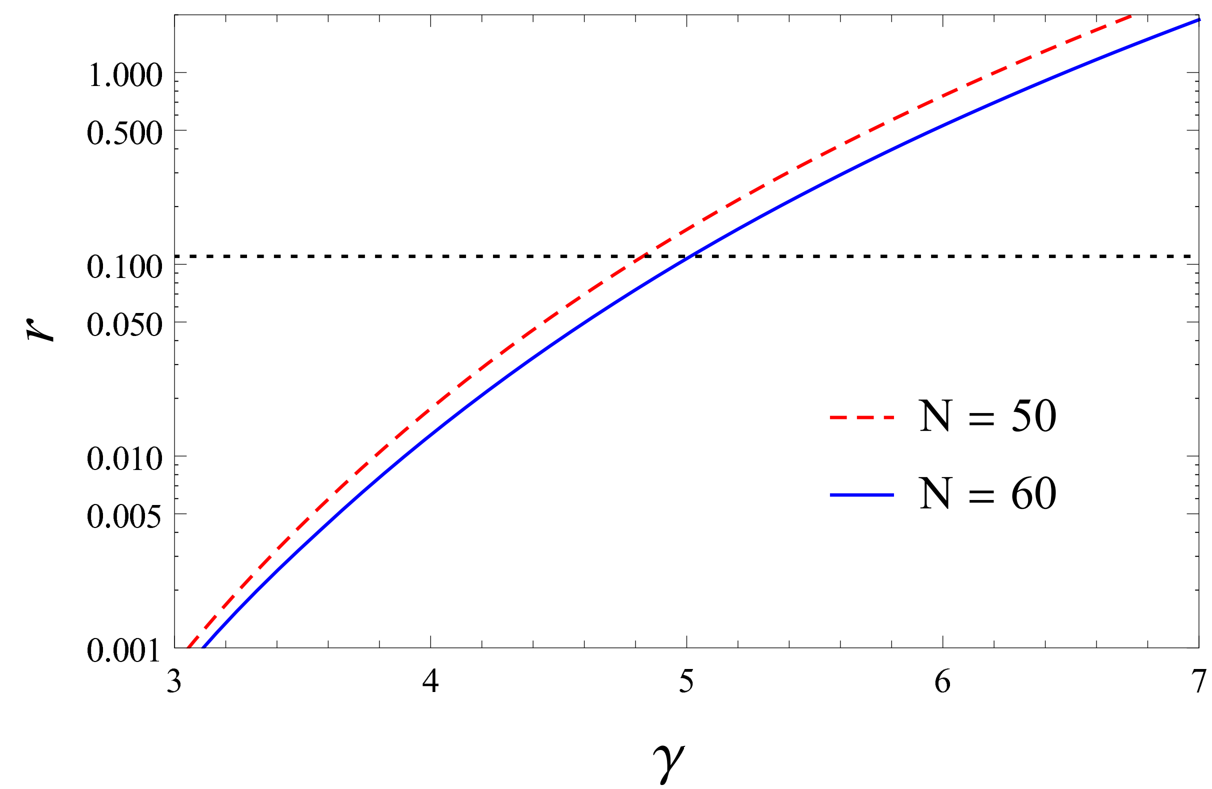
The gauge field sources gravitational waves



- GWs are chiral, strongly amplified by linear mixing

But this is incompatible with the scalars…





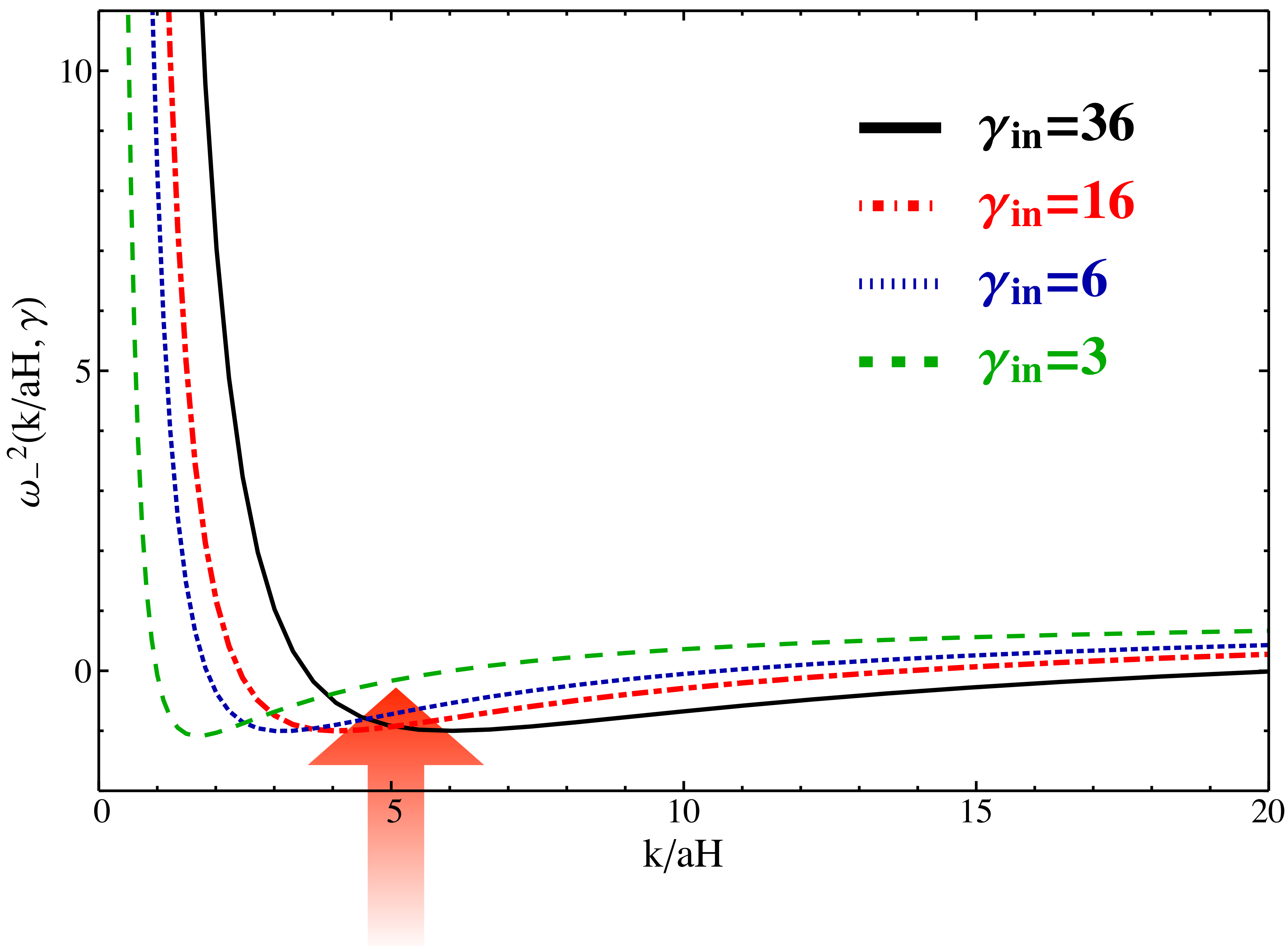
Scalar spectrum reddens due to instability at

GW spectrum grows due to $t^{\pm}$ instability

$$\gamma = \frac{g^2\psi^2}{H^2} \leq 2$$

- CNI is incompatible with data

A positive mass for the gauge field could help...



Higgs mechanism gives positive gauge-field mass!

Massive Gauge-field inflation

- Add a Higgs sector:

$$\mathcal{L}_{\rm Higgs} = -\frac{1}{2}|D_\mu \Phi|^2 - V(\Phi)$$

- Stueckelberg limit:

$$-\frac{1}{2}|D_\mu \Phi|^2 \to -g^2 Z_0^2 {\rm Tr}\left[A_\mu - \frac{i}{g} U^{-1}\partial_\mu U\right]^2$$

$$\rho_{Z_0} = \frac{3}{2} g^2 Z_0^2 \psi^2, \quad p_{Z_0} = -\frac{\rho}{3}$$

- Inflation can occur provided $\rho_{Z_0} \ll M_{\rm Pl}^2 H^2$

$$\epsilon \simeq \frac{\psi^2}{M_{\rm Pl}^2}\left(1 + \gamma + \frac{M^2}{2}\right), \quad \eta \simeq \frac{\psi^2}{M_{\rm Pl}^2}, \quad \gamma = \frac{g^2\psi^2}{H^2}, \quad M = \frac{g Z_0}{H}$$

- Gauge field masses end inflation sooner

Fluctuations are more complicated…

- Goldstone's theorem: 1 massless mode for each broken continuous symmetry

$$\begin{array}{r} \text{9-dof} \\ \text{+3-dof} \\ \hline \text{12 physical dof} \end{array}$$

- Parameterize fluctuations along vacuum manifold:

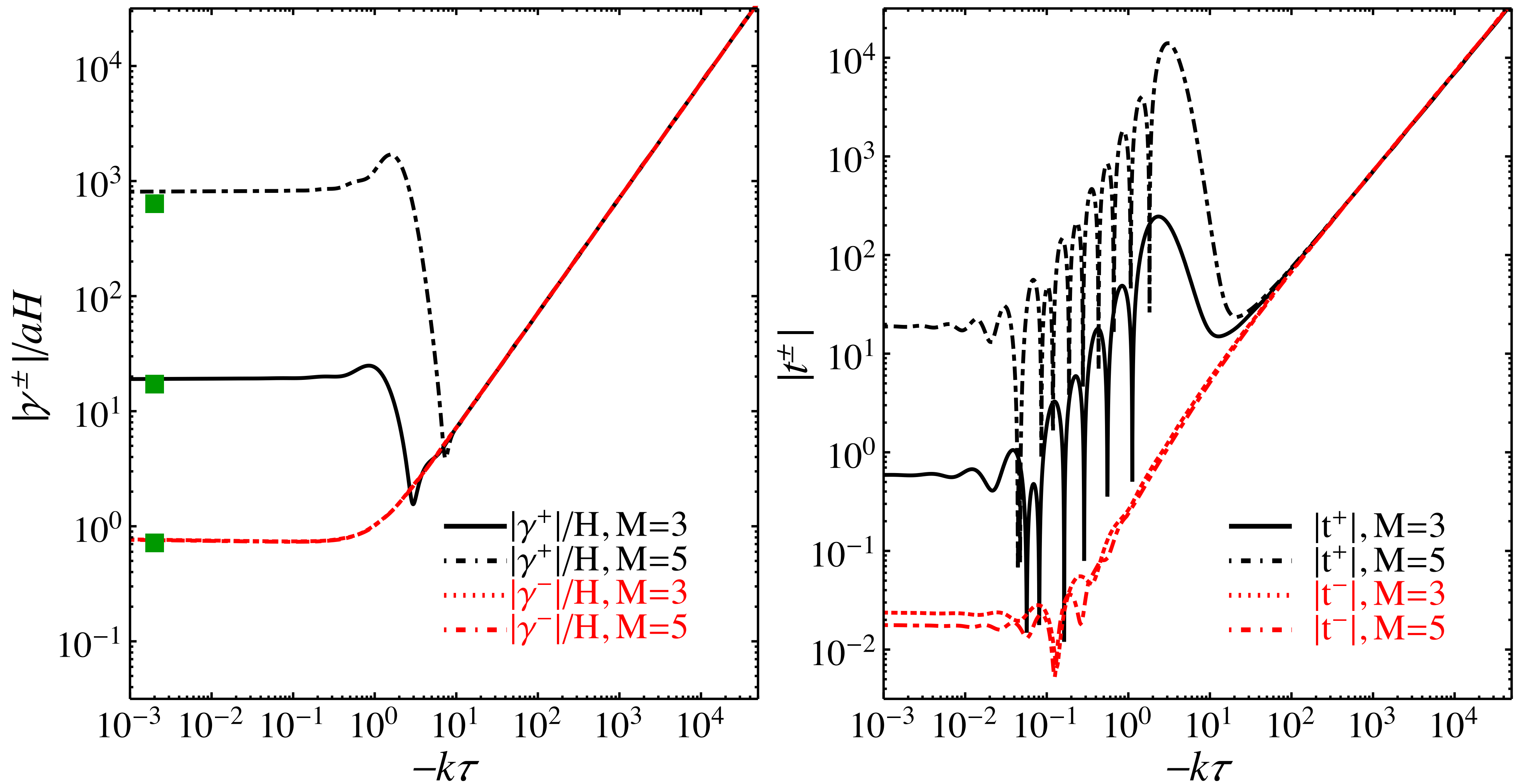
$$U = \exp\left(ig\xi^a \frac{\sigma_a}{2}\right)$$

- Decompose: $\xi^a = \delta^a_i(\partial_i \xi + \xi^i_V)$

- 1 new scalar, 1 new vector mode

The additional mass makes the tensor instability worse

$$\hat{t}^{\pm\prime\prime} + \left(k^2 + \frac{2+2\gamma+M^2}{\tau^2}\right)\hat{t}^{\pm} \pm \frac{k}{\tau}\left(\frac{1+2\gamma+M^2}{\sqrt{\gamma}}\right)\hat{t}^{\pm} = \mathcal{O}(\sqrt{\epsilon})\gamma^{\pm}$$

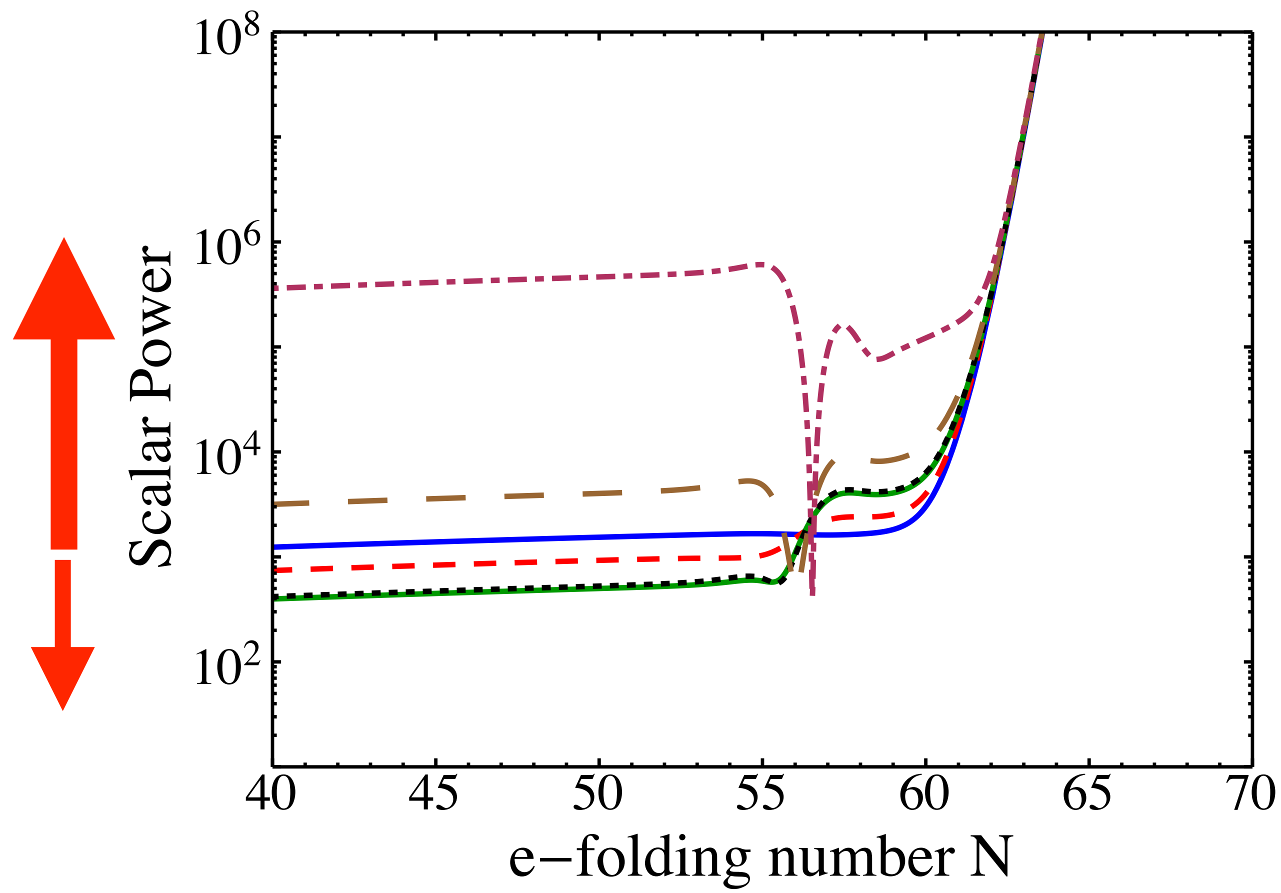


What about the scalar power?

- Goldstone modes contribute additional dof

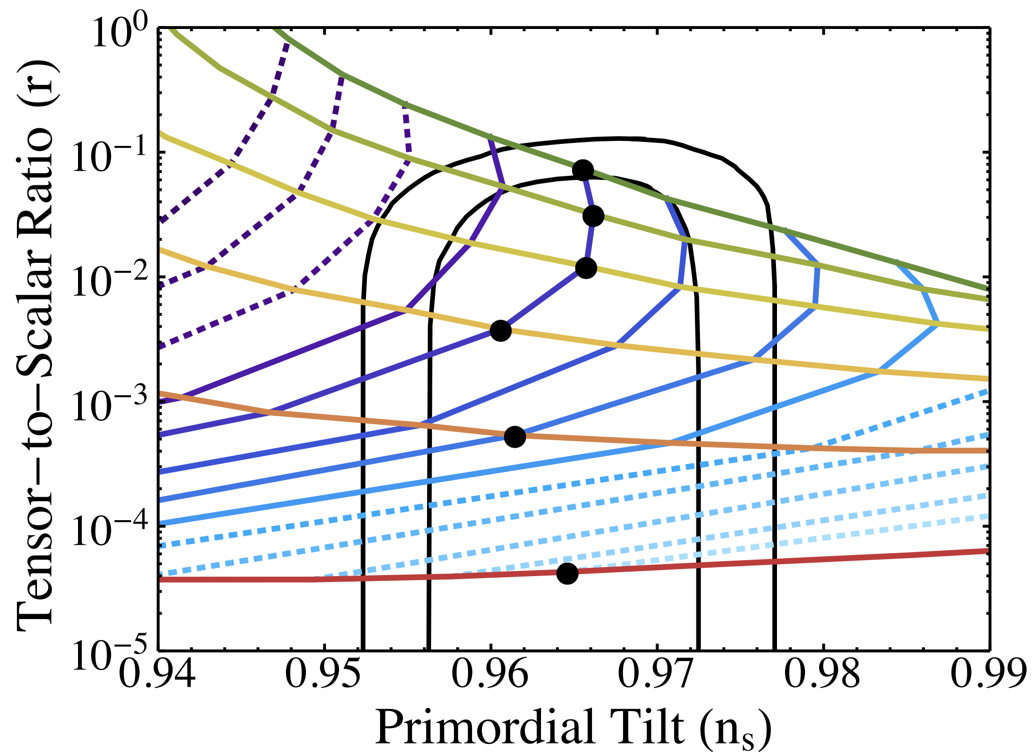
Enhanced for larger M

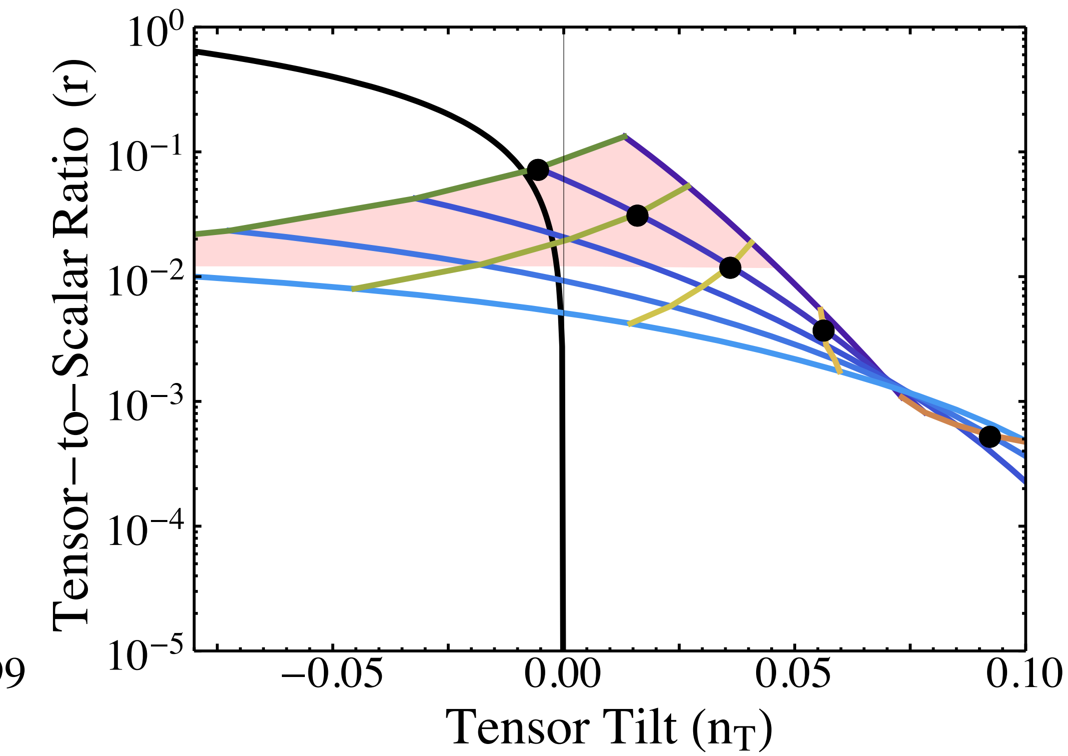
Suppressed for small M



- Dynamics alter the amplitude of scalar power

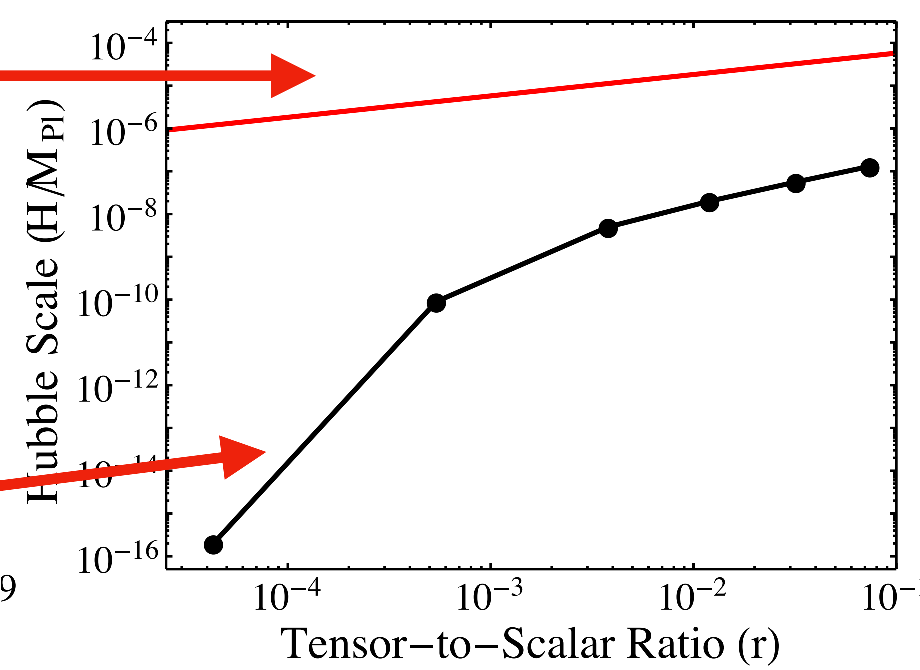
E.g. Massive Gauge-flation





Inferred Hubble rate

$$\frac{H}{M_{\rm Pl}} \sim \frac{(10^{16}{\rm GeV})^2}{M_{\rm Pl}^2}\left(\frac{r}{0.01}\right)^{1/2}$$



Actual Hubble rate

One does not simply read off H from r

(Matteo Fasiello, Nordita ’17)

Implications for B-mode searches

- Observation of B-modes does not imply
  - Inflation happened at the GUT scale
  - The inflaton moved over a Planck sized region in field space
  - Gravity is quantized

GWs and the energy scale of inflation

- The standard arguments are based on the graviton eqn

$$\boxed{\Box h_{ij} = 8\pi G_N \Pi_{ij}}$$

- formal solution:

$$h_{ij}(x) = \underbrace{h_{ij}^{(h)}(x)}_{\text{Homogeneous soln.}} + \underbrace{\int d^4y G_{ij}^{lm}(x-y)\frac{\pi_{lm}(y)}{M_{\rm Pl}^2}}_{\text{Particular soln.}}$$

GWs and the energy scale of inflation

- The standard arguments are based on the graviton eqn

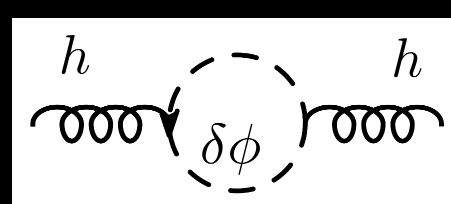
$$\Box h_{ij} = 8\pi G_N \Pi_{ij}$$

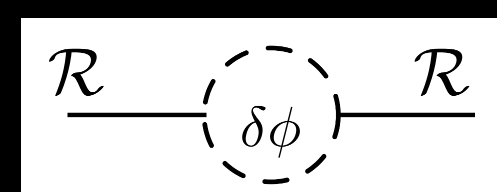
$$h_{ij}(x) = h_{ij}^{(h)}(x) + \int d^4y G_{ij}^{lm}(x-y)\frac{\pi_{lm}(y)}{M_{\rm Pl}^2}$$

- Anisotropic stress appears at higher order in perturbations

$$\pi_{ij} \sim \partial_i \delta\phi \partial_j \delta\phi$$

- GWs ***and*** scalars sourced at one-loop





- Generically:

$$r_{\rm sourced} \sim \epsilon^2 < r_{\rm vac} \sim \epsilon$$

(Mirbabayi, Silverstein, Senatore, Zaldarriaga)

Gravitational Waves from Inflation

$$h_k \sim \frac{2}{M_{\rm Pl}} \times \frac{H}{2\pi} \sim \left(\frac{V}{M_{\rm Pl}}\right)^{1/4}$$

Canonical quantization

Massless free-field in de Sitter

$$\Lambda_{\rm inf} \sim 10^{16}{\rm GeV}\left(\frac{r}{0.01}\right)^{1/4}$$

Tilt inherited from evolution of H, guaranteed to be red!

- Therefore observation of B-modes implies:
  - Inflation happened at the GUT scale
  - Gravity is quantized
  - (The inflaton moved over a Planck sized region in field space — Lyth-Turner bound)

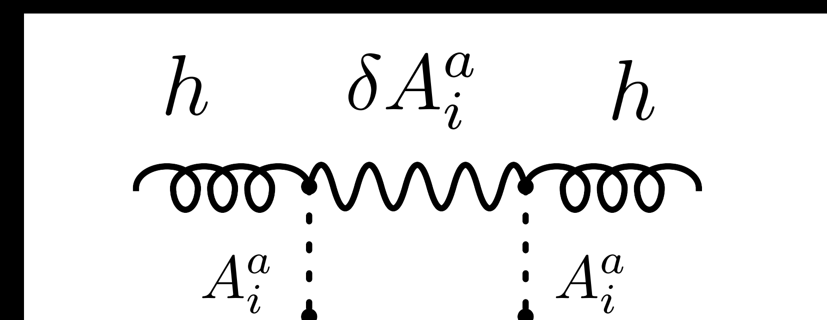
Gauge-field inflation loophole

- Background vector field sidesteps this by allowing

$$\pi_{ij} \sim \frac{A_i^a \delta A_j^a}{M_{\rm Pl}^2} \qquad A_i^a = a\psi\delta_i^a, \quad \psi \sim 10^{-2} M_{\rm Pl}$$

- Linear sourcing of gravitational waves:

$$h_{ij}^{(p)}(x) \sim \int d^4y\, G_{ij}^{lm}(x-y)\frac{A_l^a \delta A_m^a(y)}{M_{\rm Pl}^2}$$



- Analogous linear sourcing of scalars prohibited by decomposition theorem

- Gauge field fluctuations ‘oscillate’ into GWs

- GW spectra (can be) set by gauge-field tensor fluctuations

Chiral GWs — observational impact

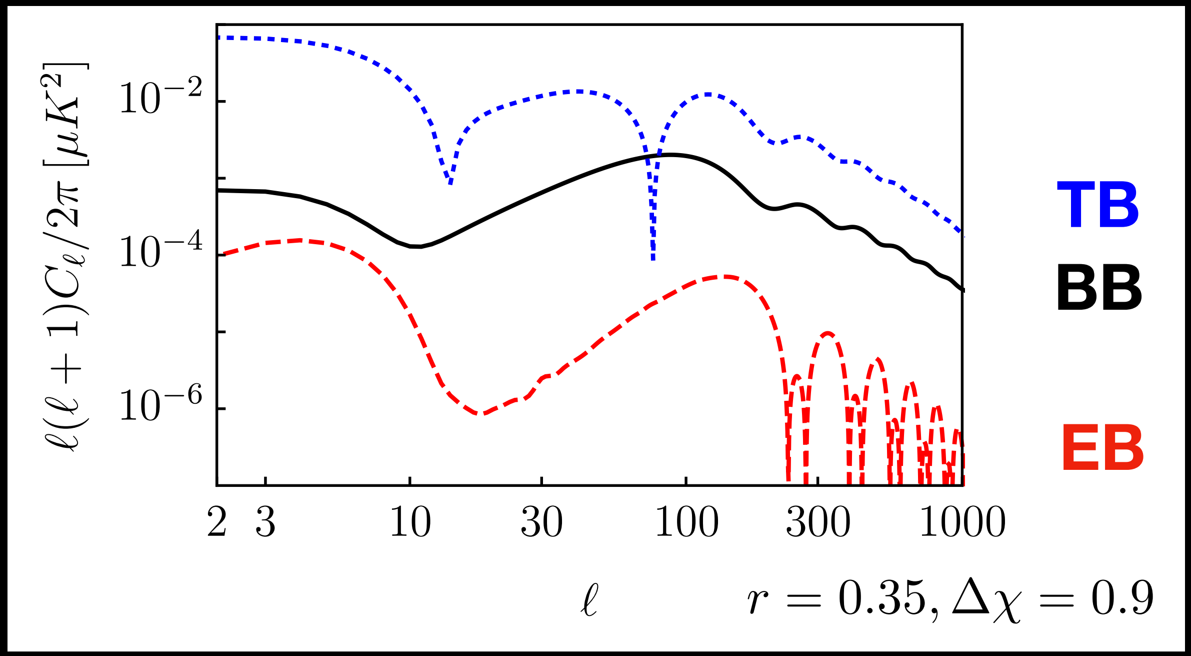
- Parity violating GWs generate TB, EB spectra

- GW helicity potentially observable

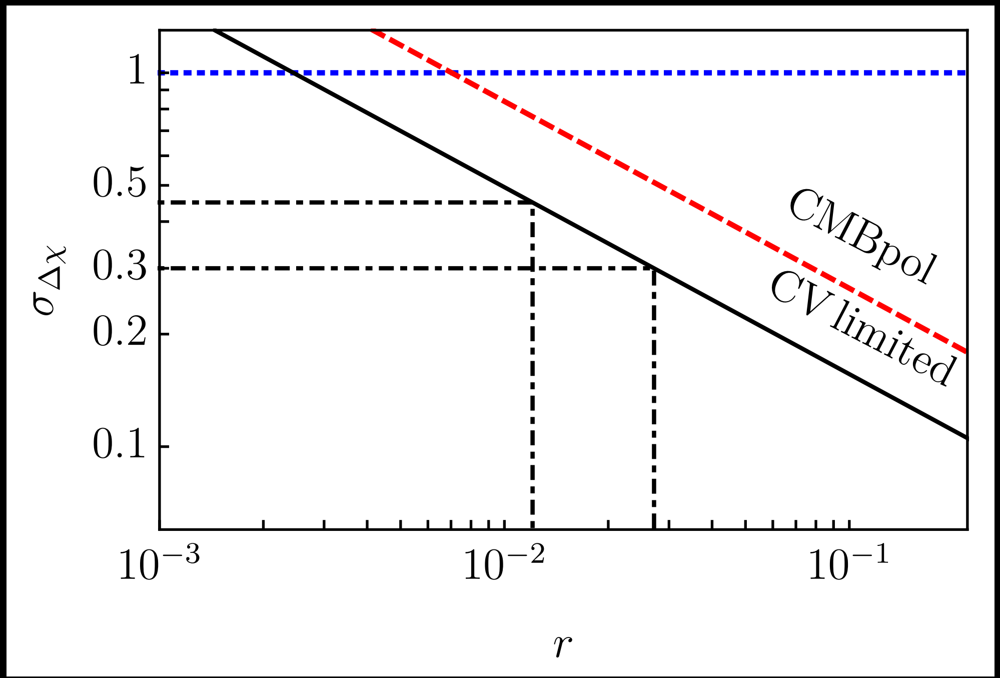
$$\chi = \frac{\Delta_R^2 - \Delta_L^2}{\Delta_R^2 + \Delta_L^2}$$

- Typically

$$|\chi| \gtrsim 0.9$$



(Caldwell 2017)



(Gluscevic and Kamionkowski 2010)

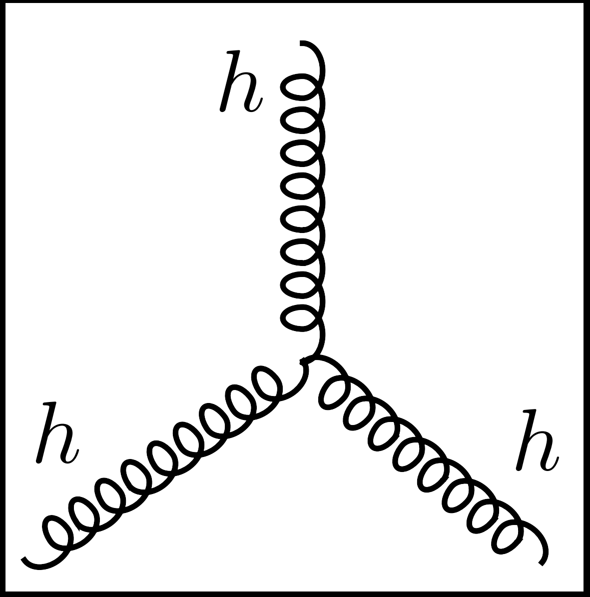
Tensor non-G

$$\langle h(\mathbf{k}_1)h(\mathbf{k}_2)h(\mathbf{k}_3)\rangle = (2\pi)^3\delta^3\left(\sum_{i=1}^{3}\mathbf{k}_i\right)B_{hhh}(k_1,k_2,k_3)$$

- 3-pt function from vacuum modes

$$\frac{B_{hhh}(k,k,k)}{P^2(k)} \sim \mathcal{O}(1)$$

(Maldacena 2003)

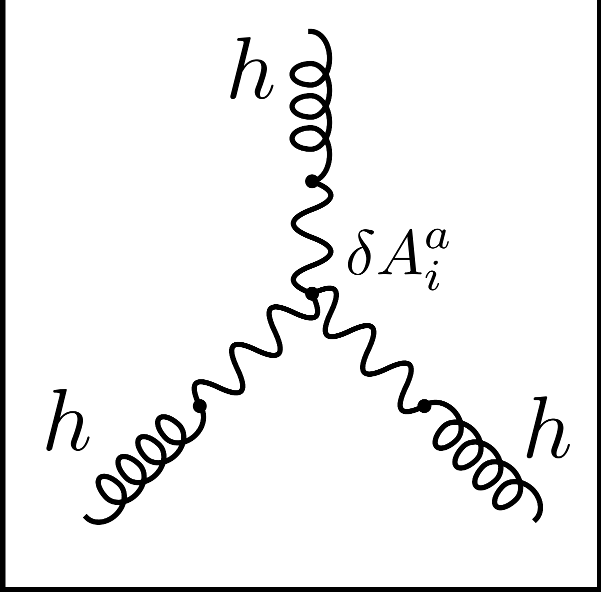


- n-pt statistics inherited from gauge field

$$\frac{B_{hhh}(k,k,k)}{P^2(k)} \sim \mathcal{O}\left(\frac{10}{\Omega_A}\right) \gg 1$$

$$\Omega_A = \frac{1}{2}\left(E_i^a E_i^a + B_i^a B_i^a\right)$$

(Agrawal, Fujita, Komatsu 2017)



Summary I

- Classical non-Abelian gauge fields allow for the construction of novel inflationary scenarios
- Symmetry breaking in models of inflation with non-Abelian gauge fields can bring them into agreement with data
- Requires very weakly coupled gauge fields
- Chiral, possibly blue-tilted GW spectra
- Observable GW spectra at sub-GUT energies

$$\Lambda_{\rm inf} \sim \sqrt{H M_{\rm Pl}} \neq 1.04 \times 10^{16} {\rm GeV} \left(\frac{r}{0.01}\right)^{1/4}$$

Implications for B-mode searches

- Observation of B-modes does not imply
  - Inflation happened at the GUT scale
  - The inflaton moved over a Planck sized region in field space
  - Gravity is quantized

Unless:

- Small Tensor Gaussianity
- Vanishing of parity odd correlators (TB, EB)
- Scale invariance

…and the origin of the matter-antimatter asymmetry

> Why is there stuff?

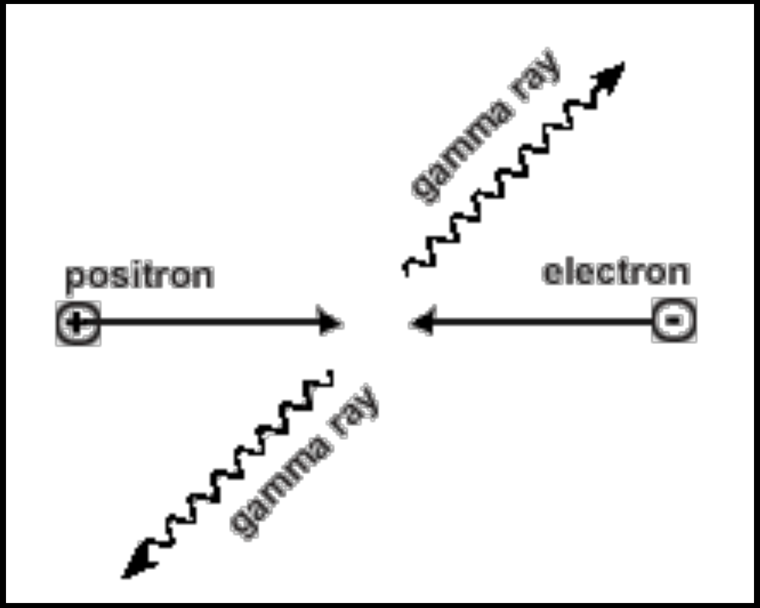
Andrew Long

Evangelos Sfakianakis

PRD: 98, 043525 (2018), with A. Long and E. Sfakianakis

There is a matter-antimatter asymmetry

- How do we know there are not vast anti-matter domains in the Universe?

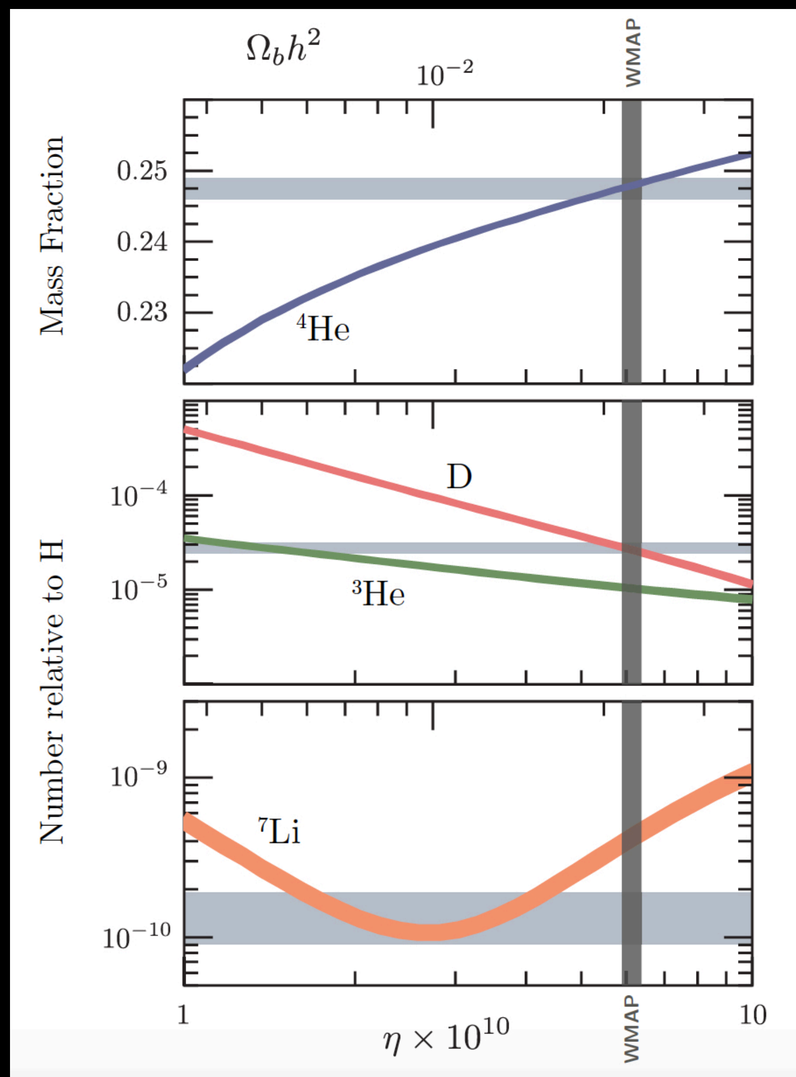


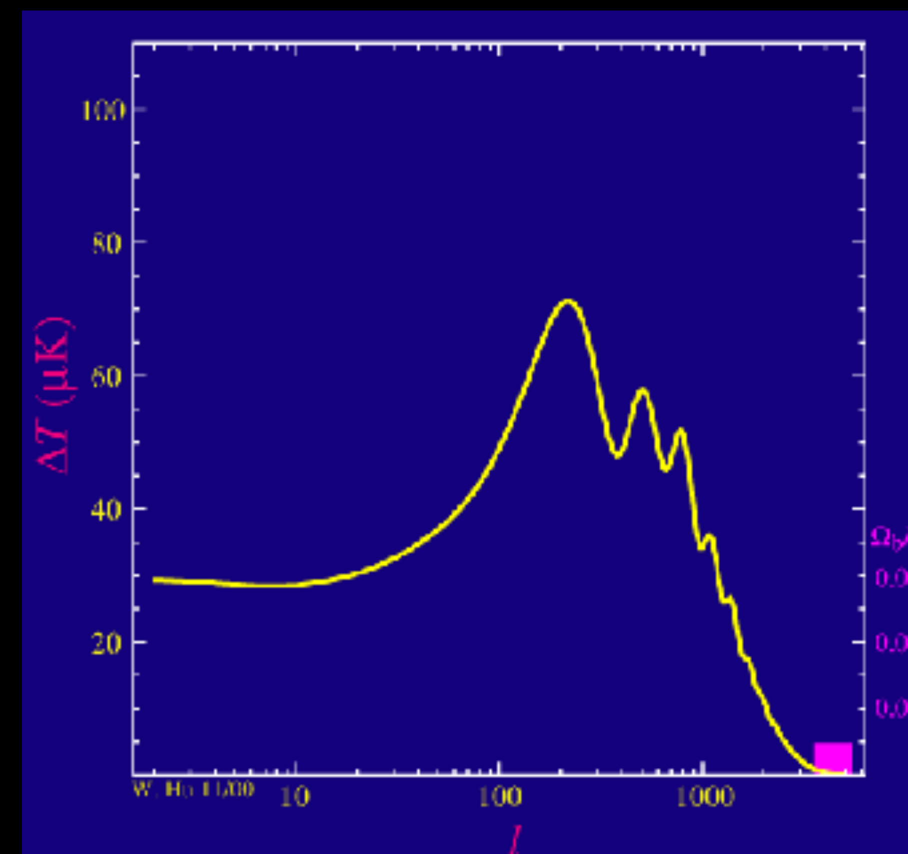
- Non-observation of gamma-ray emission excludes anti-matter domains from within our horizon

[Steigman (1976); Cohen, De Rujula, & Glashow (1998)]

- If global universe is symmetric, our matter pocket is larger than ~100 Gly

Quantitatively





(Wayne Hu)

$$\Omega_{\rm b} h^2 = 0.02205 \pm 0.00028$$

$$\longrightarrow Y_B = \frac{n_B}{s} = (0.861 \pm 0.008) \times 10^{-10}$$

- For every 10^{10} anti-protons there are ~ 10^{10} +1 protons

Inflation requires Baryogenesis!

- Inflation dilutes relics to unobservable small densities
  - Same is true of baryon density
- Baryon asymmetry must be generated dynamically after inflation
  - Sakharov conditions:
    - Baryon number violation
    - CP violation
    - Out of equilibrium

(Sakharov, 1967)

(history.aip.org)

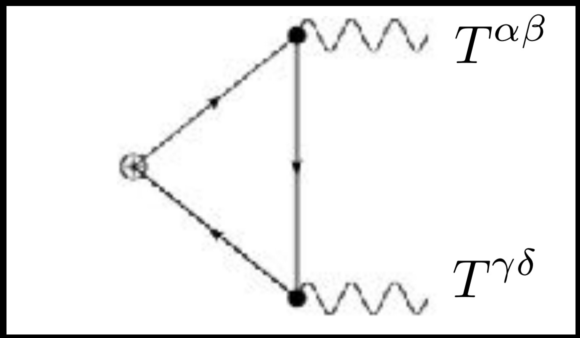
Can we baryogenesis happen *during* inflation?

Cosmological non-conservation of fermions

- Fermion number is **not** conserved cosmologically

- Chiral fermion currents are anomalous

$$\nabla_\mu j^\mu_{L,R} = \pm \frac{1}{24}\frac{R\tilde{R}}{16\pi^2}$$



Eguchi, Gilkey, Hanson (1980)

- Standard model lepton-current is anomalous

$$\nabla_\mu j^\mu_\ell = \sum_{i=1}^{3} \nabla_\mu \left(j^\mu_{e^i_L} + j^\mu_{\nu^i_L} + j^\mu_{e^i_R} \right) = \frac{3}{24}\frac{R\tilde{R}}{16\pi^2}$$

- Whenever $R\tilde{R}$ is non-zero, the lepton current changes

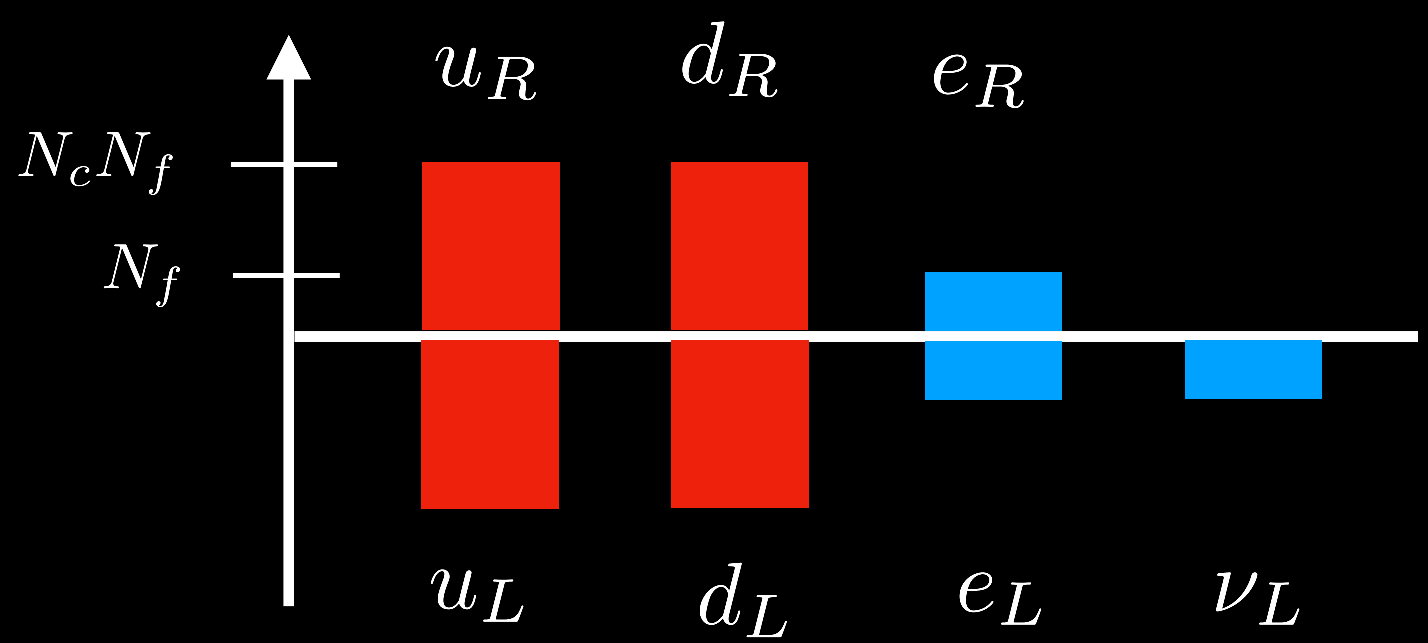
Alexander, Peskin, Sheikh-Jabbari (2004)

Gravitational Leptogenesis

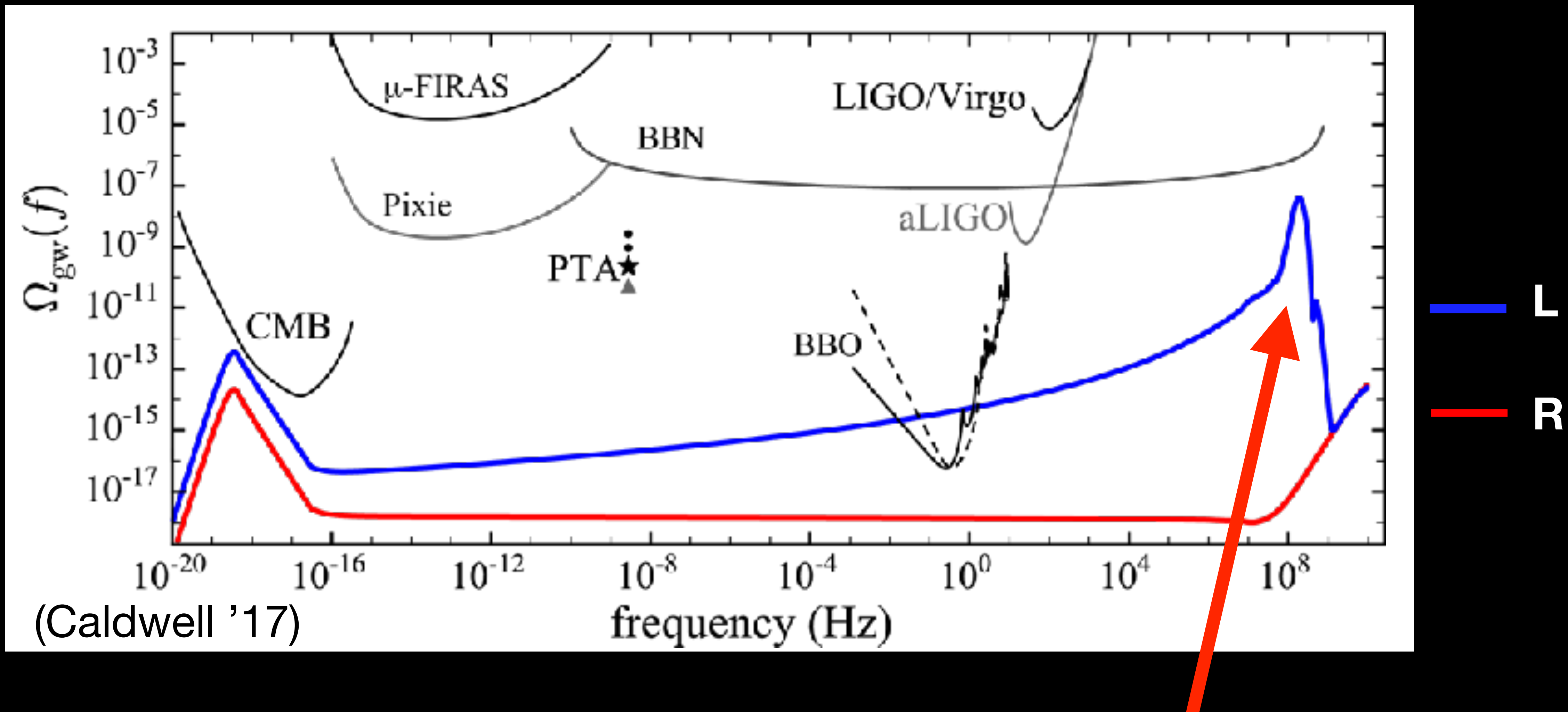
- Chiral gravitational waves generates asymmetries in chiral leptons

$$N_{L,R} - N_{\bar{L},\bar{R}} = \pm \frac{1}{24(16\pi^2)} \int d^4x \sqrt{-g} R\tilde{R}$$

- At the end of inflation, we have in SM (for left-chiral GWs)



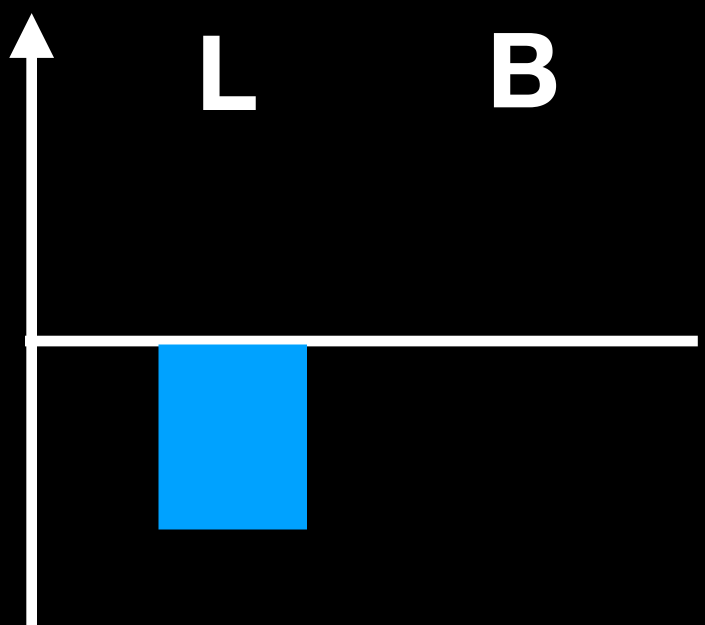
Small scale chiral GWs

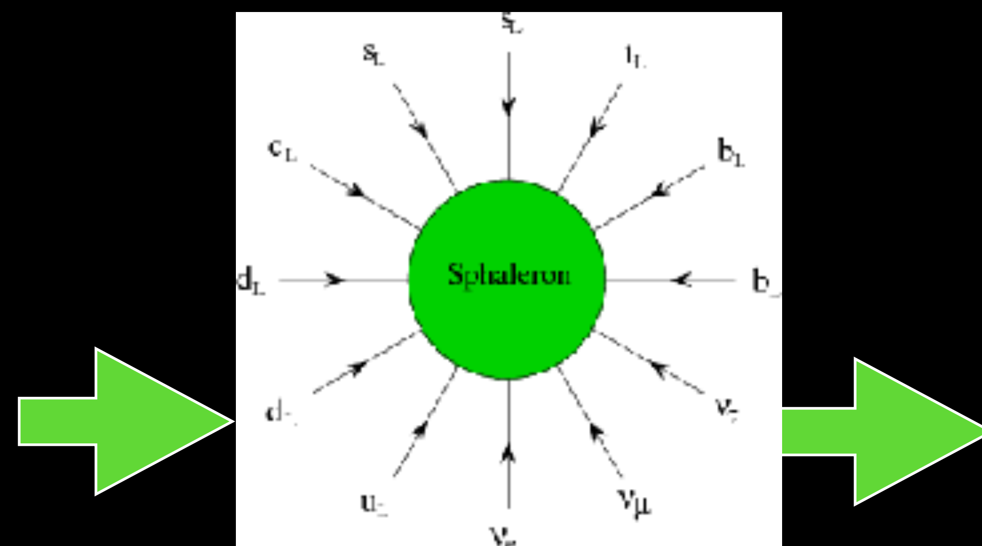


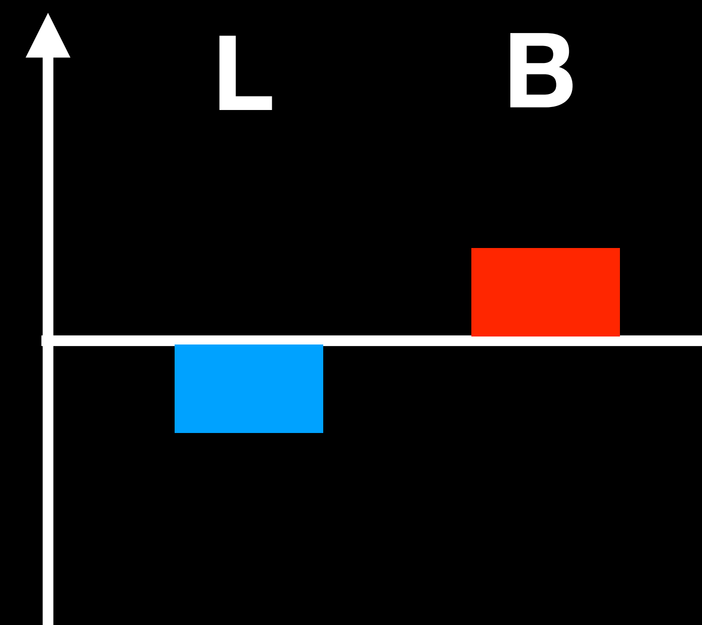
- Blue-tilted spectra generates large gravitational wave density on small scales
- Fairly easy to generate sufficient net lepton number

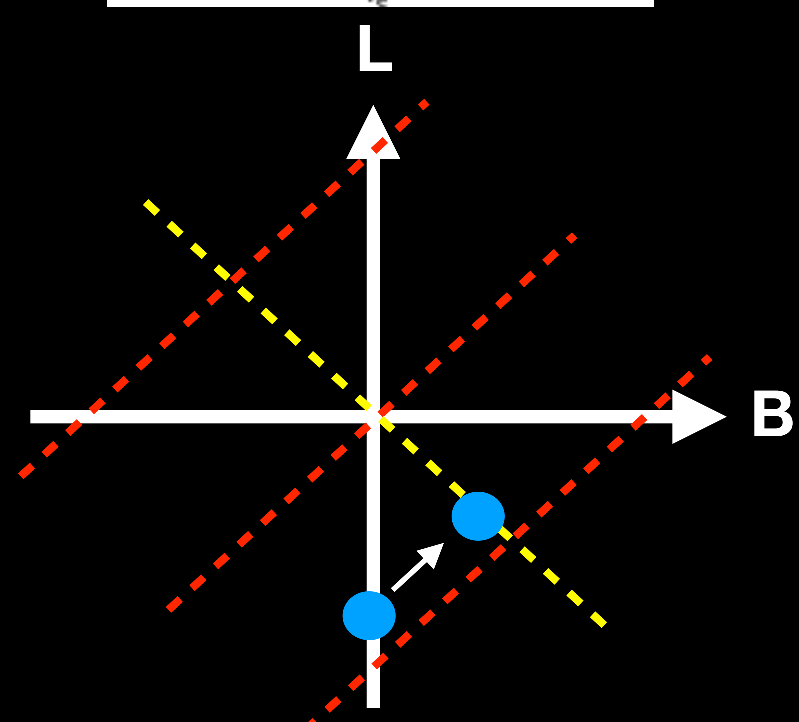
How do (net) leptons get turned into (net) baryons?

- Hot electroweak sphaleron violates B+L, conserves B-L





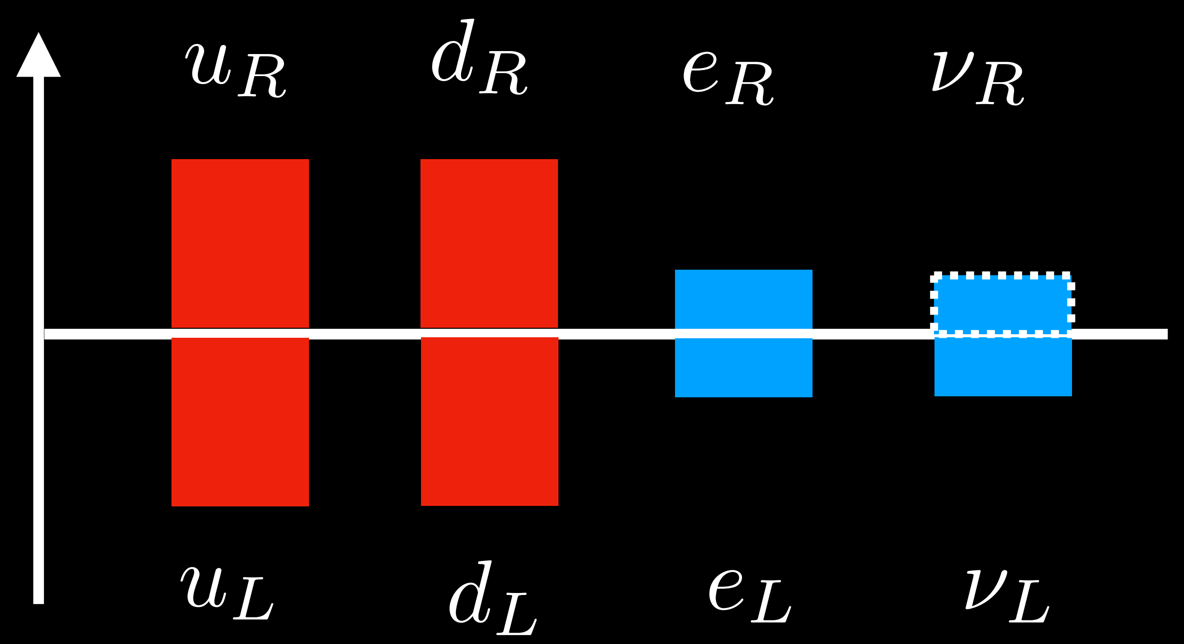




$$Y_{\mathrm{B}} = \frac{28}{79} Y_{\mathrm{B-L}}$$

but neutrino mass…

- But neutrinos are massive…
- Requires adding new degrees of freedom to SM

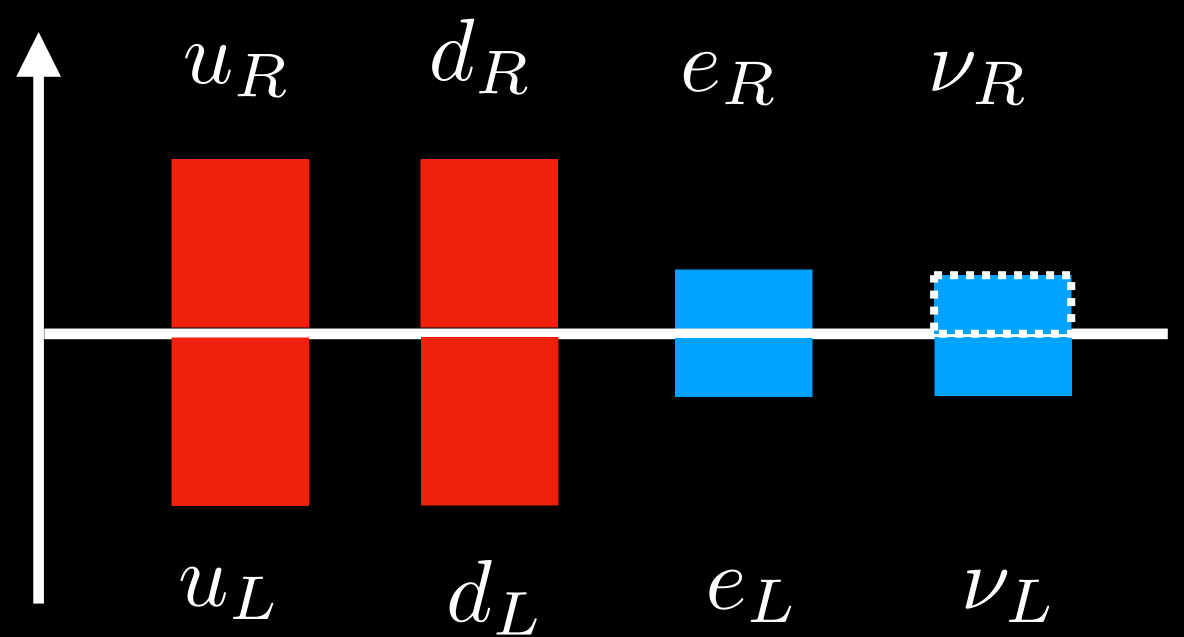


- Neutrinos are Dirac:
    - RH neutrinos are sterile, sequester lepton number

→ **Result unchanged!**

but neutrino mass…

- But neutrinos are massive…
- Requires adding new degrees of freedom to SM



- Neutrinos are Majorana:
    - Theory contains explicit lepton number violation

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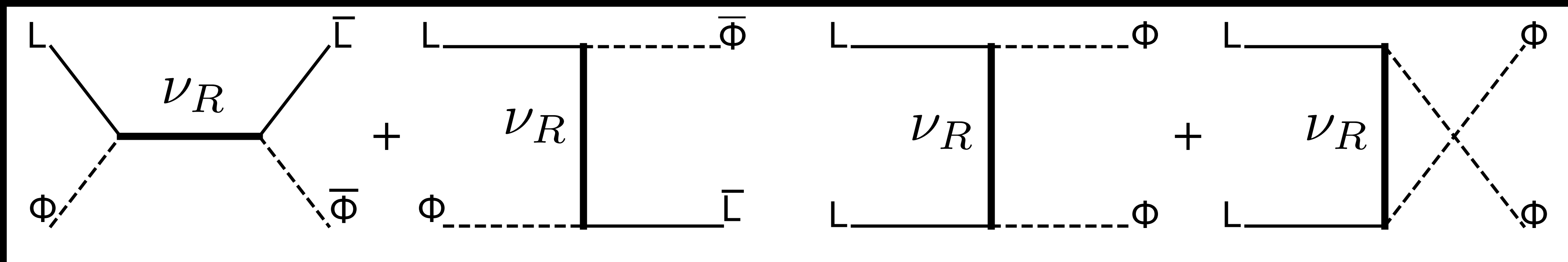
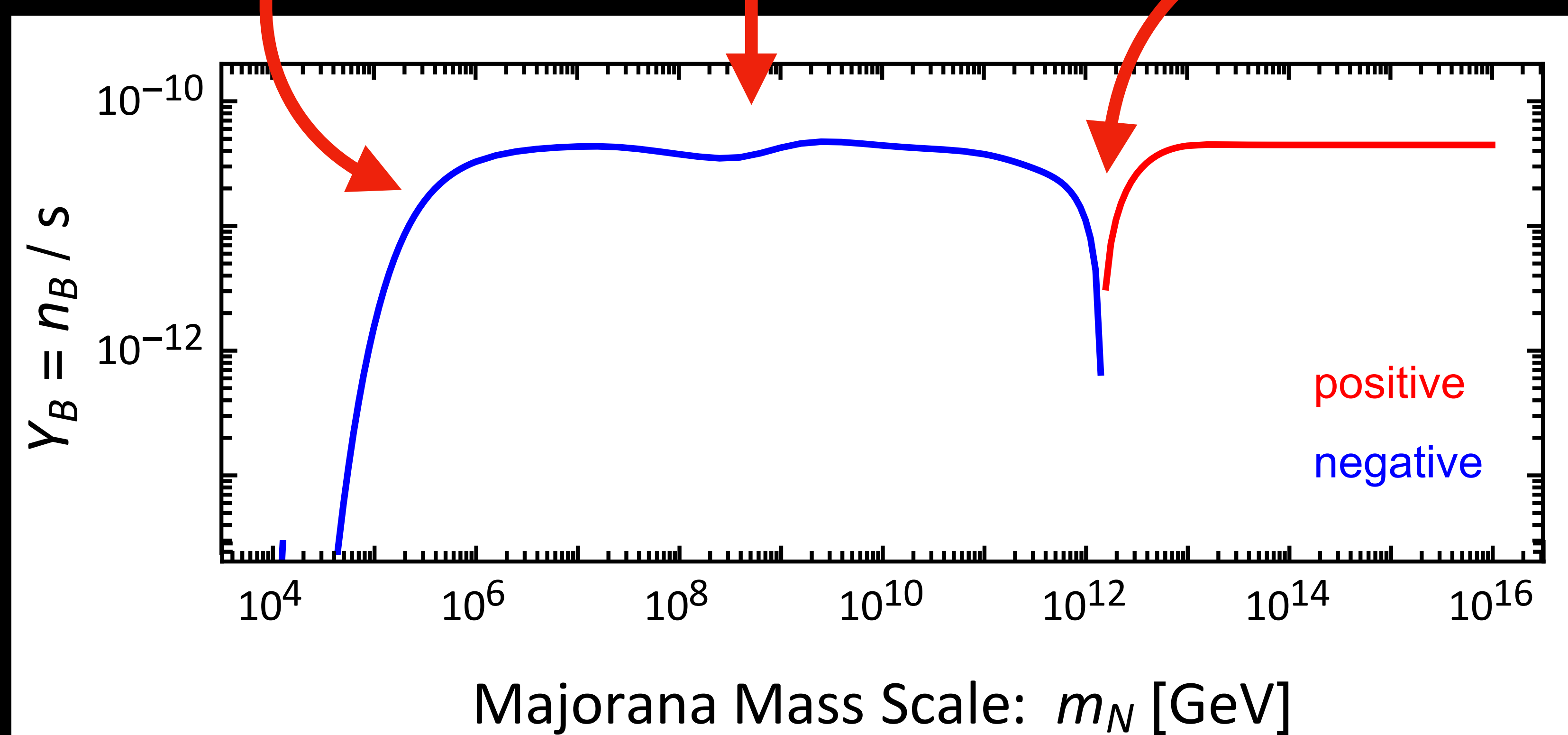
    - Theory contains explicit lepton number violation…



- BUT! Small Yukawas sequester lepton number in right chiral leptons

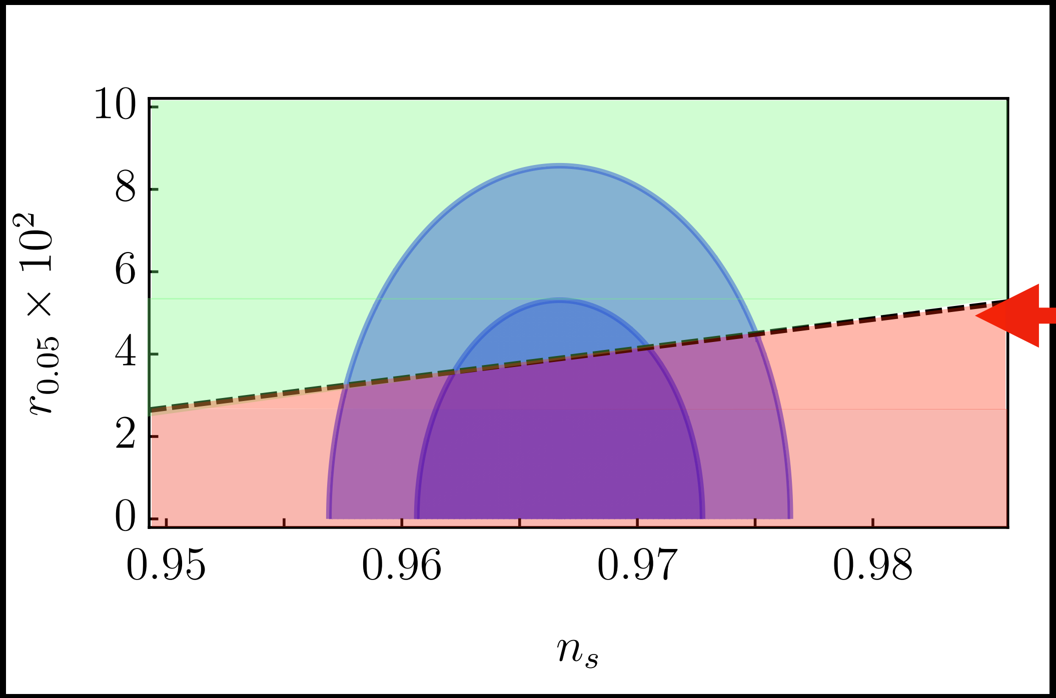
$$e_L \longleftrightarrow e_R \qquad \mu_L \longleftrightarrow \mu_R \qquad \tau_L \longleftrightarrow \tau_R$$



A definite connection between GW helicity and neutrino mass scale!

A lower bound on r?

- Generating a sufficient lepton number puts (so far, model dependent) lower bounds on r:



Chromo-Caldwell inflation

(Caldwell and Devulder 2017)

- Can a more general lower bound be imposed?

Summary II

- Observation of chiral GWs could imply
  - Inflationary origin of baryon asymmetry
  - Left Chiral GW implies Dirac ν, or high-scale see-saw
  - Right Chiral GW implies Majorana mass scale

$$10^6\mathrm{GeV} < m_N < 10^{12}\mathrm{GeV}$$

- Non-observation of B-modes likely rules out inflation as origin of baryon asymmetry

Summary

- Slow roll inflation is in excellent agreement for scalars:
  - Super-Horizon, isotropic, adiabatic, and red-tilted
- But, “extraordinary claims require extraordinary evidence”

We seek gravitational waves with wavelengths of billions of light years

Summary I

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Thanks!