Baryon asymmetry of the universe

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Baryogenesis

QUPosium2023
Addressing five mysteries of the Universe with new eyes

- new ideas
- connection to new and future observations, ***"new eyes"***

Sakharov's conditions

- Baryon number nonconservation
- C, CP violation
- **Departure from thermal equilibrium**

Novel possibility: early structure formation, a new era in the history of the universe!

Early structure formation from Yukawa "fifth force"

Yukawa interactions:

$$V(r) = \frac{y^2}{r} e^{-m_\chi r}$$

$$y\chi\bar{\psi}\psi$$

a heavy fermion interacting with a light scalar

A light scalar field $\Rightarrow$ long-range attractive force, stronger than gravity $\Rightarrow$ instability similar to gravitational instability, only stronger

$\Rightarrow$ **halos form** even in **radiation dominated universe**

[Amendola et al., 1711.09915; Savastano et al., 1906.05300; Domenech, Sasaki, 2104.05271]

Same Yukawa coupling provides a source of **radiative cooling** by emission of gravitational radiation $\Rightarrow$ **halos collapse to black holes**

[Flores, AK, 2008.12456, PRL 126 (2021) 041101; 2008.12456]

Strong long-range force: instability and structure formation

$$\delta(x,t) = \delta\rho/\rho$$ energy density perturbations (radiation)

$$\Delta(x,t) = \Delta n_\psi / n_\psi$$ density perturbations of a kinetically decoupled particle

$$\ddot{\delta}_k + \frac{1}{t}\dot{\delta}_k - \frac{3}{8t^2}(\Omega_r \delta_k + \Omega_m \Delta_k) = 0$$

$$\ddot{\Delta}_k + \frac{1}{t}\dot{\Delta}_k - \frac{3}{8t^2}[\Omega_r \delta_k + \Omega_m (1+\beta^2)\Delta_k] = 0$$

$\Rightarrow$

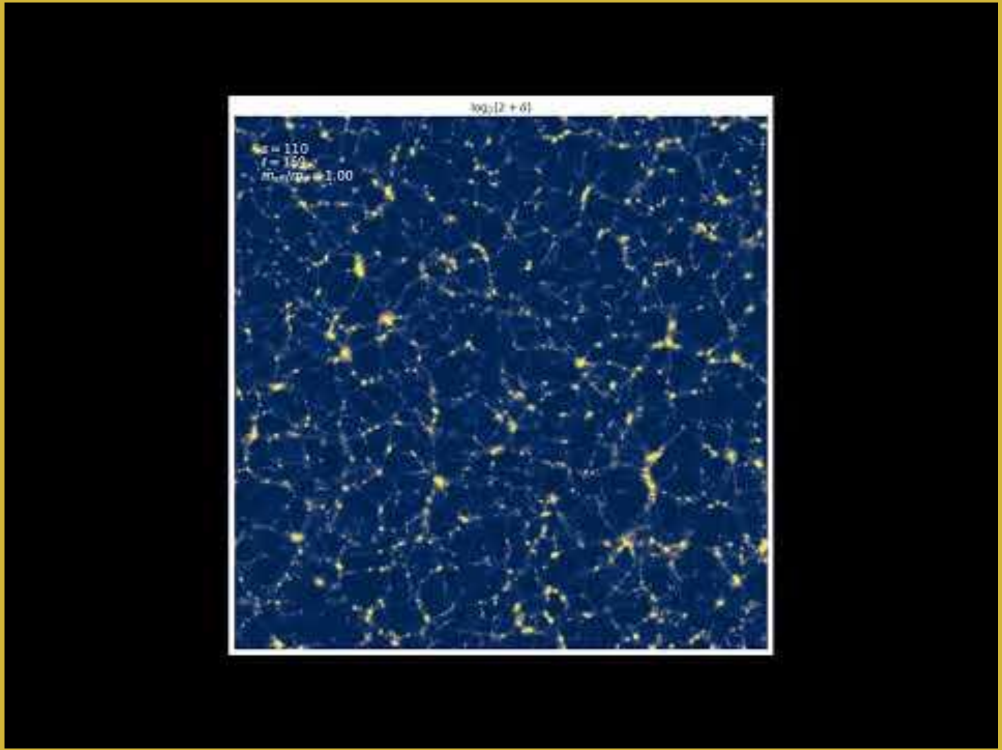
$$\Delta_k(a) \approx \Delta_{k,\mathrm{in}} \left(\frac{t}{t_{\mathrm{in}}}\right)^{p/2}, \quad p = \sqrt{\frac{3}{2}(1+\beta^2)\Omega_\psi}$$

$$\beta \equiv y(M_P/m_\psi) \gg 1$$

p = huge $\Rightarrow$

[Flores, AK, 2008.12456, PRL] **fast growth, even in the radiation-dominated era!**

Growth of structures due to Yukawa force: N-body simulations

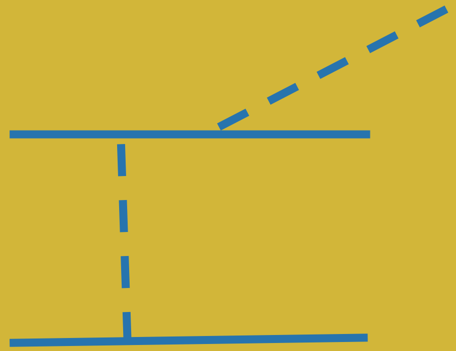


N-body simulation of the structure growth from Yukawa interactions

Domenech, Inman, Sasaki, AK [Phys.Rev. D 108 (2023) 10; 2304.13053]

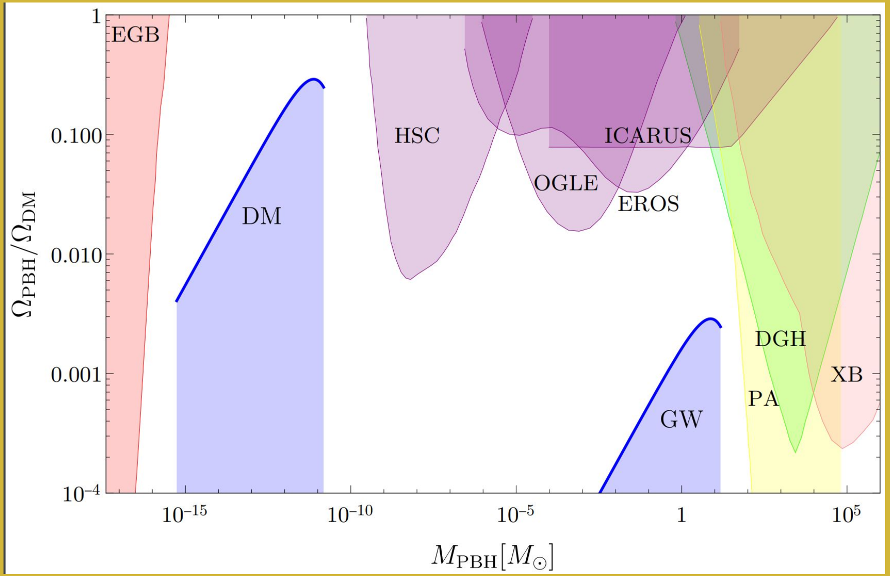
Rapid growth of structures... plus radiative cooling!

Same Yukawa fields allow particles moving with acceleration emit scalar waves



$\Rightarrow$ **radiative cooling and collapse (to black holes)**

Flores, AK, Phys.Rev.Lett. 126 (2021) 4, 041101; 2008.12456



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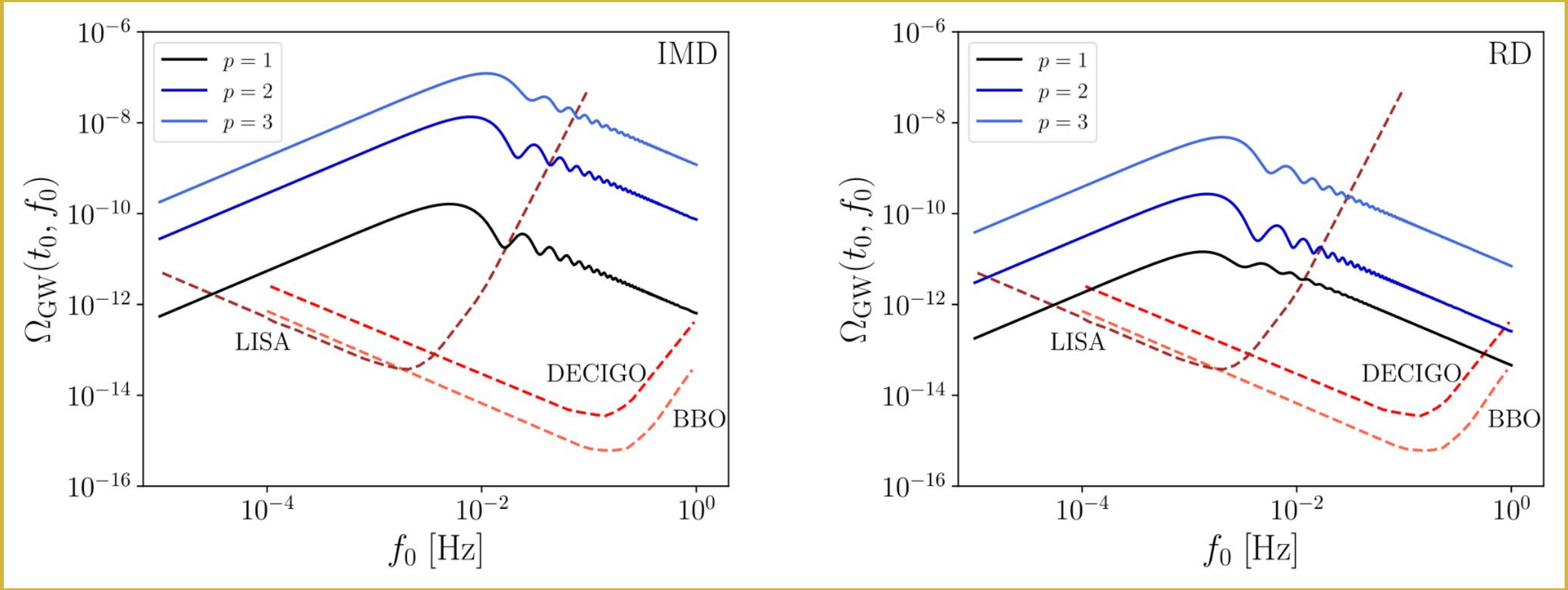
Addressing five mysteries of the Universe with new eyes

Gravitational waves from early halo formation



[Flores, AK, Sasaki, Phys.Rev.Lett. 131 (2023) 1, 1; 2209.04970]

Possible consequences of early halo formation

Structure formation in RD era!

Many possible consequences

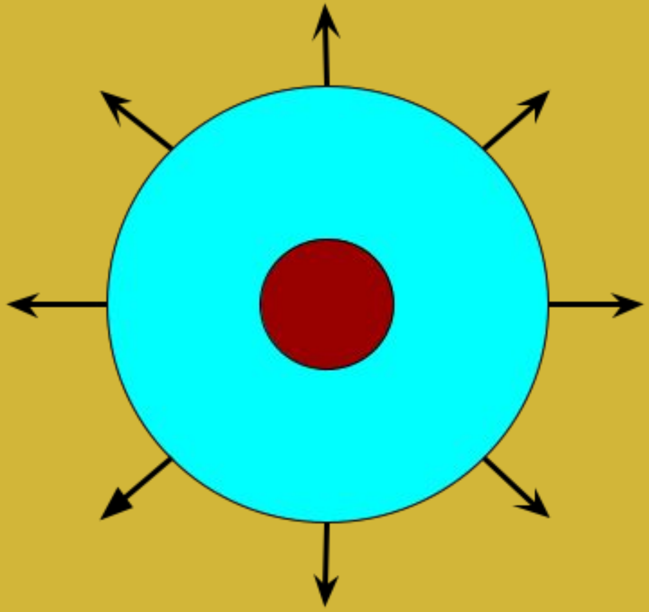
Inhomogeneous heating by collapsing halos

$\Rightarrow$ Electroweak baryogenesis, even if the phase transition is second order!
[Flores et al., Phys.Rev.D 108 (2023) 9, 9]

$\Rightarrow$ Defrosting and Blast Freezing Dark Matter
[Flores et al., Phys.Rev.D 108 (2023) 10, 10]

$\Rightarrow$ Magnetogenesis
[Durrer, AK, JCAP 11 (2023) 002; 2209.13313]

Side note: inhomogeneous cold electroweak baryogenesis



Baryogenesis

- **without a first-order PT**
- **at low temperature**
  (10 MeV < T < 100 GeV)

SM second-order phase transition OK

[Flores et al. 2208.09789]

Second order phase transition: Baryon asymmetry too small

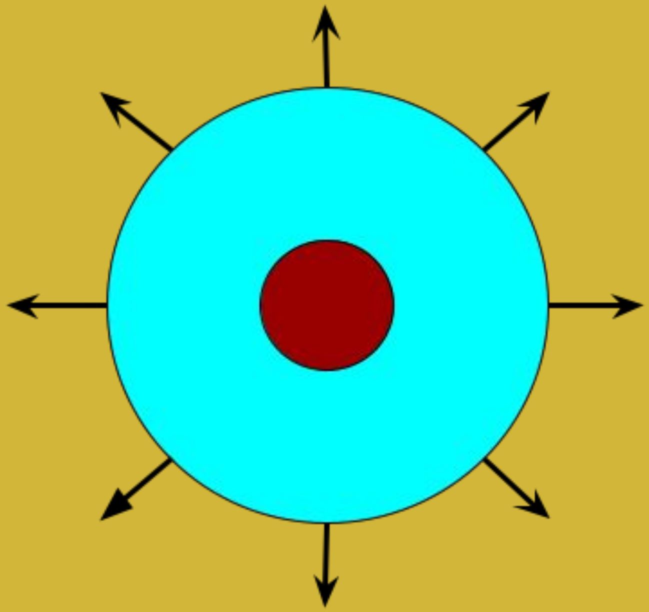
$$\dot{B} = -\Gamma(B + \mathcal{C}\dot{\theta}) \,, \quad \mathcal{C} = g_\theta \frac{3m_t^2}{2\pi^2}\left(1 - \frac{m_t}{3T}\right), \quad \Gamma = 12 N_F \frac{\Gamma_{sph}}{VT^3},$$

$$\dot{\theta} = H\theta \frac{1}{(T_0/T)^2 - 1} = \epsilon H \frac{T}{T_0}\left[T_0^2/T^2 - 1\right]^{-1/2}$$

$$\frac{B}{s} \leq 1.5 \times 10^{-19} |\epsilon|$$

Prokopec et al.,
hep-ph/9601327

Fireball baryogenesis: low-energy baryogenesis T<100 GeV



Halos of fermions form -> annihilate -> heat SM plasma inhomogeneously -> departure from thermal equilibrium

$t \sim t_{\text{fireball exp}} \ll (1/H)$

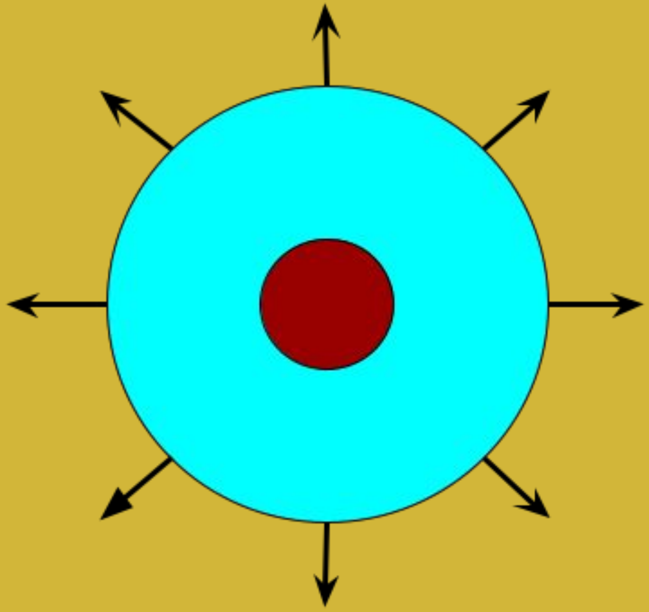
SM transition OK; still need a source of CPV - but two Higgs doublets can provide enough CPV

B/s ~ 10^{-10} for **MeV < T < 100 GeV**

[Flores et al. Phys.Rev.D 108 (2023) 9, 92208.09789]

Side note: WIMP reheating and blast freezing!

Halos of fermions form -> annihilate -> heat SM plasma inhomogeneously -> departure from thermal equilibrium $t \sim t_{\text{fireball exp}}$



- **WIMP rethermalize, then freeze out faster: $t_{\text{fireball exp}} \ll H^{-1}$**
- **WIMP dark matter OK for cross sections believed to be ruled out $\langle \sigma n v \rangle \sim 1/t_{\text{fireball exp}} \gg H$**

[Flores et al. Phys.Rev.D 108 (2023) 10; 2306.04056]

Sakharov's conditions

- Baryon number nonconservation
- C, CP violation
- Departure from thermal equilibrium

Not necessary if CPT is broken!

[cf. Davoudiasl, Kitano, Murayama, Steinhardt]

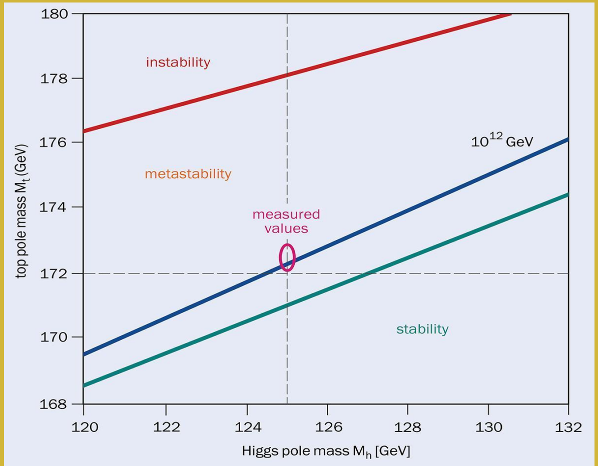
Higgs potential

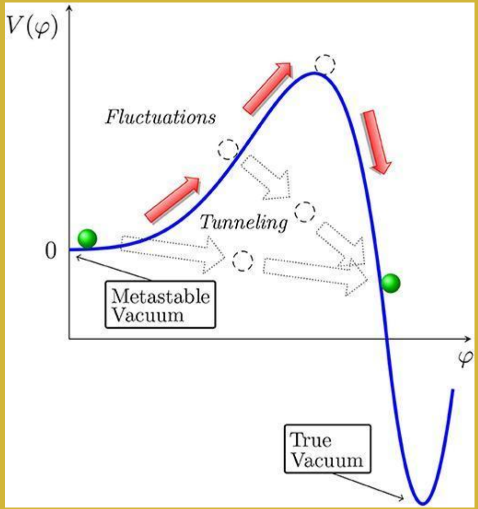
$$V(\Phi) = m^2\Phi^\dagger\Phi + \lambda(\Phi^\dagger\Phi)^2$$

where Φ is an SU(2) doublet. $\Phi = (1/\sqrt{2})\{e^{i\theta}\phi, 0\}$, where $\phi(x)$ is real.

LHC Higgs mass measurement $\Rightarrow$ λ is smaller than was previously expected. The value of the running coupling

$$\lambda_{\text{eff}} \approx \lambda_* + b\ln^2(\phi/\phi_*) \lesssim 10^{-4} \quad \text{for} \quad \phi \gtrsim 10^{12}\,\text{GeV}, \quad \text{and can be negative.}$$

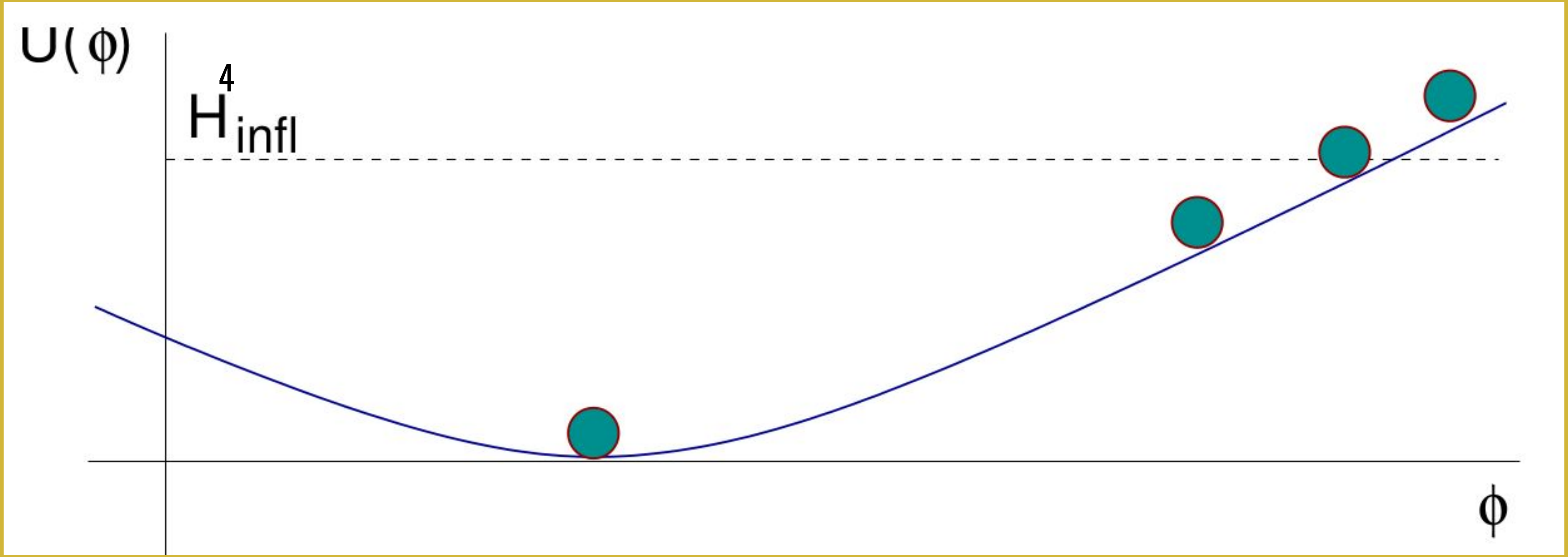




Talk by Daniela Bortoletto

Scalar fields in de Sitter space during inflation

A scalar with a small mass develops a VEV
[Chernikov, Tagirov; Starobinsky, Zeldovich; Bunch, Davies; Linde; Affleck, Dine; Starobinsky, Yokoyama]



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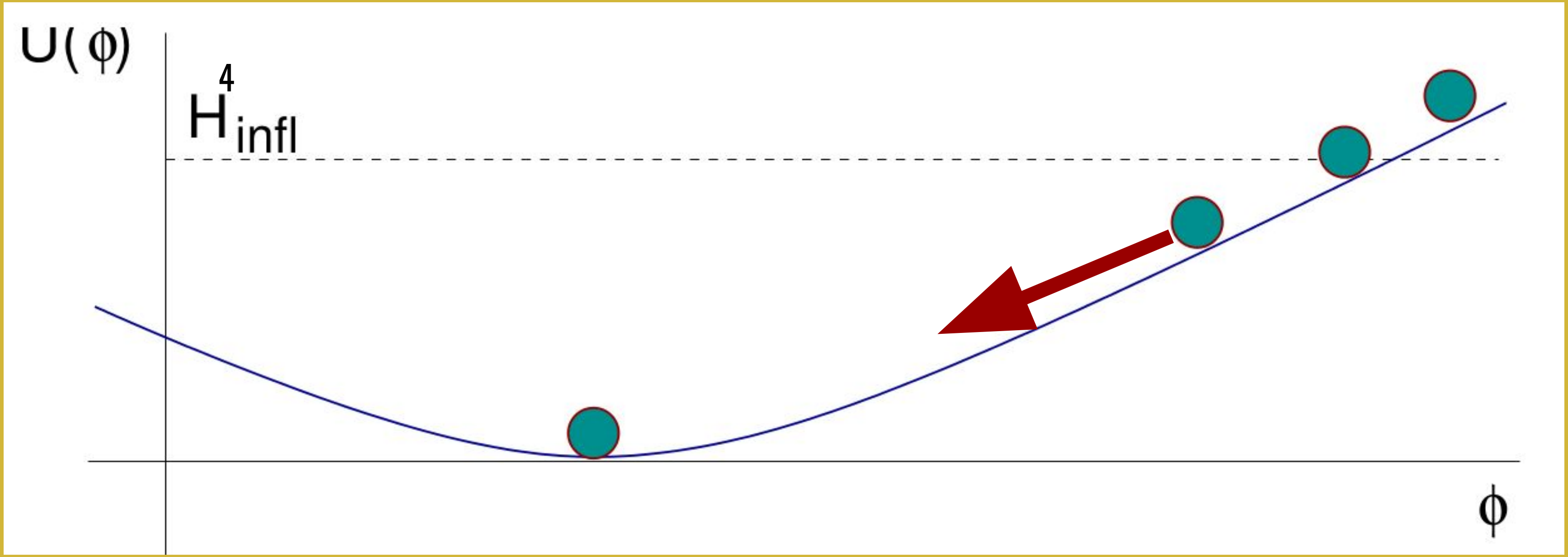


Scalar fields in de Sitter space during inflation

- If m=0, V=0, the field performs random walk:

$$\langle \phi^2 \rangle = \frac{H^3}{4\pi^2} t$$

- Massive, non-interacting field:

$$\langle \phi^2 \rangle = \frac{3H^4}{8\pi^2 m^2}$$

- $V(\phi) = \frac{1}{2} m^2 \phi^2 + \frac{\lambda}{4} \phi^4$

$$H \partial_t \langle \phi^2 \rangle = \frac{H^4}{4\pi^2} - \frac{2m^2}{3} \langle \phi^2 \rangle - 2\lambda \langle \phi^2 \rangle^2$$

$$\langle \phi^2 \rangle \to \frac{H^2}{\pi \sqrt{8\lambda}} \text{ for } m = 0$$

- Standard Model Higgs:

$$\sqrt{\langle \phi^2 \rangle} = \phi_0 \sim 0.36\, H_I / \lambda^{1/4}$$

Higgs relaxation epoch at the end of inflation

The initial value of the Higgs field can be very large for a small quartic coupling:

$$\sqrt{\langle\phi^2\rangle} = \phi_0 \sim 0.36\, H_I/\lambda^{1/4}$$

After inflation, the Higgs field must relux to the minimum of the effective potential.

New physics at a high scale

A number of higher-dimensional operators can play a role. For example, the following operator is unsuppressed for large VEVs:

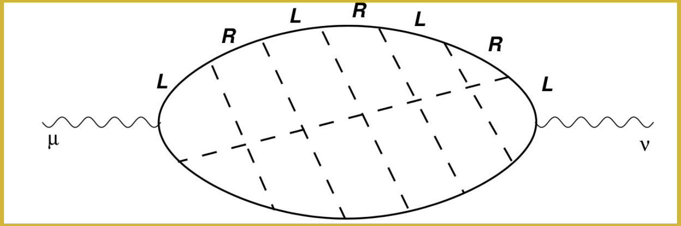
$$\mathcal{O}_6 = \frac{1}{M_n^2}\partial_\mu(\Phi^\dagger\Phi)\, j^\mu, \quad \text{where} \quad j^\mu = \bar{\psi}\gamma^\mu\psi$$

CP violating diagrams with new physics at a scale M_n yields $\frac{1}{M_n^2}(\Phi^\dagger\Phi)F_{\mu\nu}\tilde{F}^{\mu\nu}$, equivalent to the above after replacing $F_{\mu\nu}\tilde{F}^{\mu\nu}$ with j^μ via anomaly (and integrating by parts):

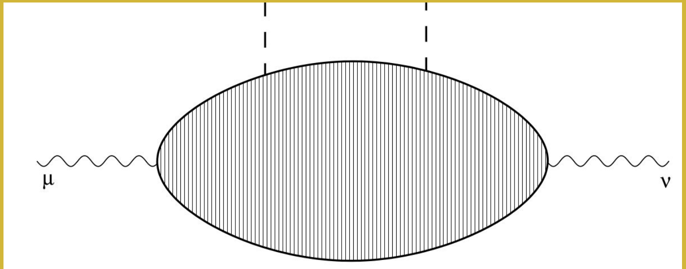
$$\partial_\mu j^\mu = \frac{1}{32\pi^2}\mathrm{Tr}(F_{\mu\nu}\tilde{F}^{\mu\nu})$$

CP violating higher-dimension operators

In the Standard Model, at finite temperature, there are diagrams that have a non-vanishing part antisymmetrized in [μν] :



A large VEV of the Higgs boson makes the system sensitive to high-scale physics:



$$\mathcal{O}_6 = \frac{1}{M_n^2}\partial_\mu(\Phi^\dagger\Phi)\ \bar{\psi}\gamma^\mu\psi$$

Effective chemical potential

Fermion number density and the lepton number density:

$$n_{B+L} = j^0_{B+L} = \bar{\psi}\gamma^0\psi$$

While the Higgs is in motion, the operator $\mathcal{O}_6$ serves as an effective chemical potential for the lepton number

$$\mathcal{O}_6 = \frac{1}{M_n^2}\partial_0(\Phi^\dagger\Phi)\, j^0 = \frac{1}{M_n^2}\partial_0|\phi|^2\, j^0 = \mu_{\text{eff}}(t)\, j^0$$

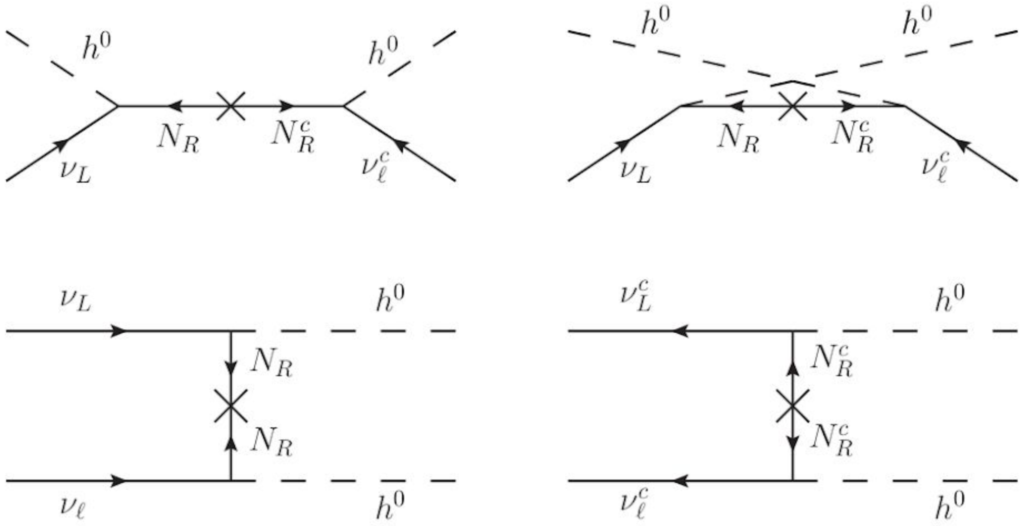
This operator and its effect as a chemical potential have been used extensively in models for electroweak baryogenesis [Dine et al.; Cohen, Kaplan, Nelson].

In the case of electroweak baryogenesis, $\phi(t)$ was the profile of the wall of the bubble in a first-order phase transition.

Our case: the "wall" moves in the timelike direction.

Lepton number violation

The term $\boldsymbol{\mu}_{\text{eff}}(\boldsymbol{t})\ j^0$ violates CPT and splits the energy levels of leptons and antileptons. No additional source of CP violation is required. In particular, the baryon asymmetry does not depend on the phases in the neutrino mass matrix. If B,L were conserved, this would have no consequence. However, L (and, therefore, $(B+L)$ and $(B-L)$ are violated by the processes involving heavy neutrino exchanges ($M_R \gg T$):

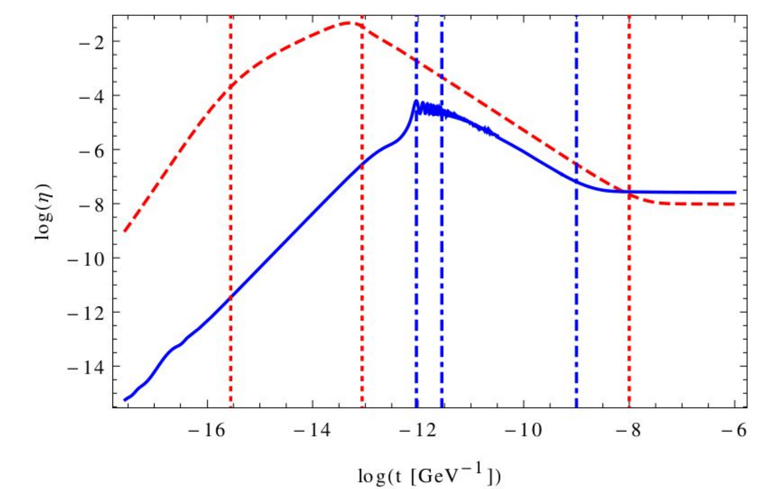


Lepton number generation

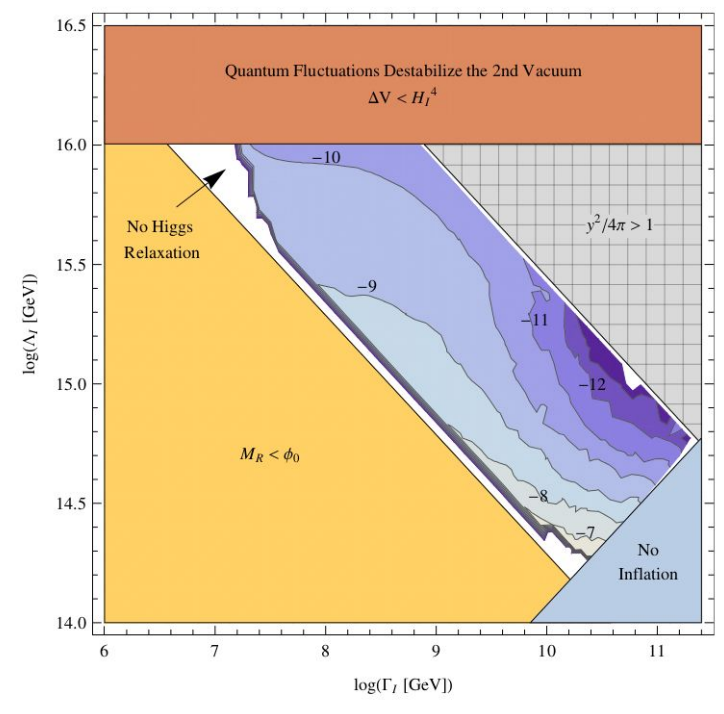
The lepton asymmetry:

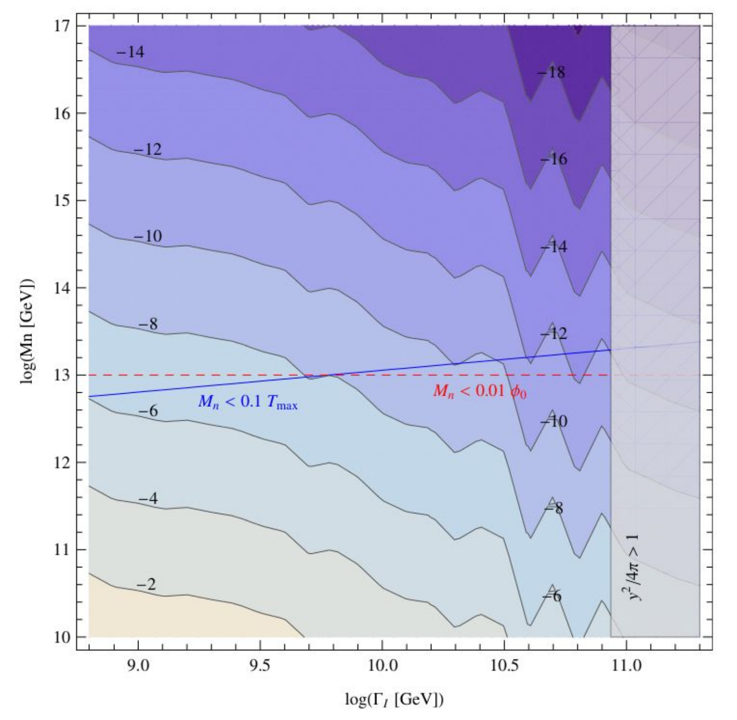
$$\frac{d}{dt}n_L + 3Hn_L \cong -\frac{2}{\pi^2}T^3\sigma_R\left(n_L - \mu_{\text{eff}}T^2\right)$$

$$\mu_{\text{eff}} = \frac{\partial_t|\phi^2|}{M_n^2} \sim \frac{H_\phi\phi_0^2}{M_n^2} \sim \frac{\sqrt{\lambda}\phi_0^3}{M_n^2}$$



Parameter space for generating baryon asymmetry





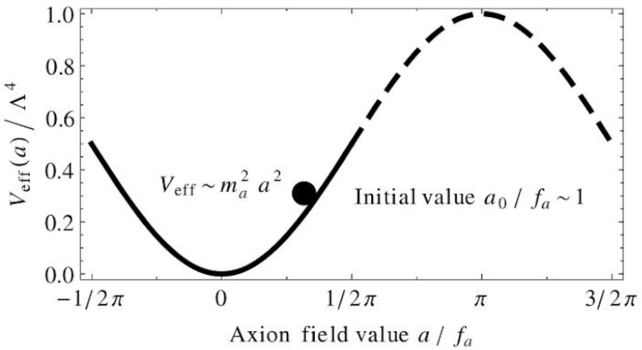
Pearce, AK, Yang

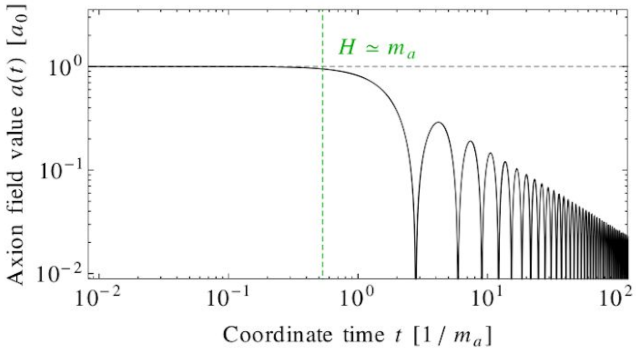
Axion relaxation

Chemical potential induced by axion **[AK, Schmitz, Yanagida]**

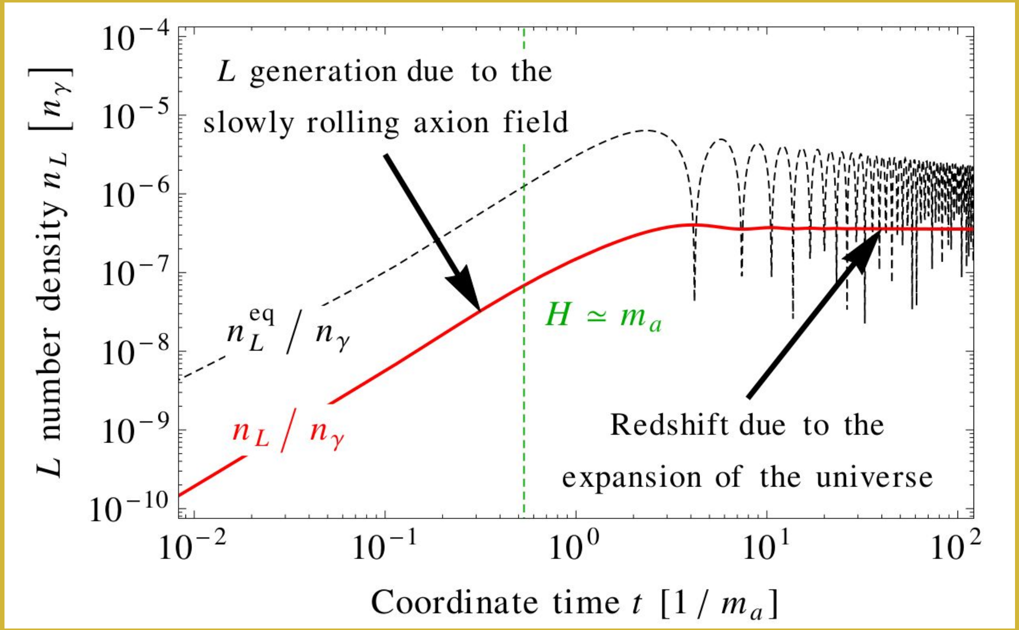
$$\mathcal{L}_{\text{eff}} \supset \frac{g_2^2}{32\pi^2}\frac{a(t)}{fa}F\tilde{F} = -\frac{a(t)}{N_f fa}\partial_\mu\left(\bar{\psi}\gamma^\mu\psi\right)$$

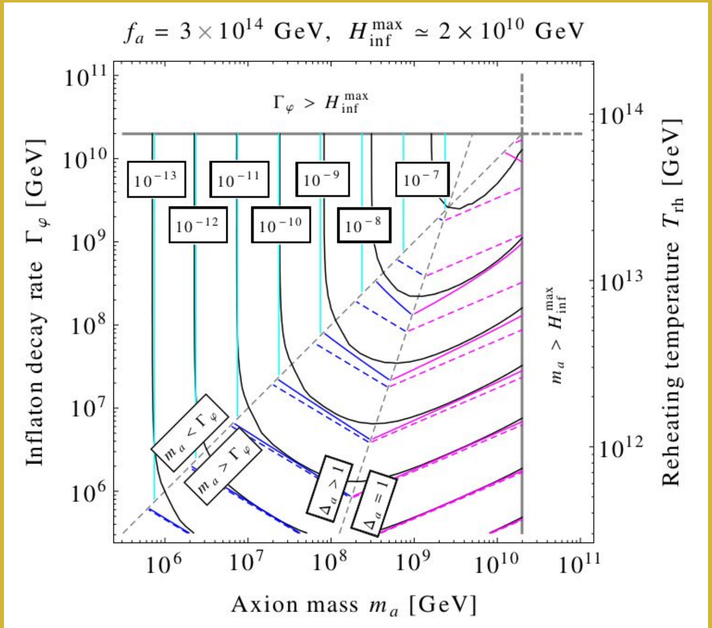
$$= \frac{\partial_t a(t)}{N_f fa}\left(\bar{\psi}\gamma^0\psi\right) + \cdots = \mu_{\text{eff}}\, j^0 + \cdots,$$





Axion relaxation





[AK, Schmitz, Yanagida]

Majoron relaxation

[Ibe, Kaneta]

Majoron is the Nambu-Goldstone field

associated with spontaneous breakdown of BL symmetry.

$\Rightarrow$ Successful leptogenesis

Scalar field relaxation baryogenesis

Possible with various scalar fields:

- Axion
- Majoron
- Higgs

$\Rightarrow$ Novel avenue for *leptogenesis* with *different parameters*

For example, the famous limit from standard leptogenesis [Fukugita,Yanagida]

$m_\nu < 0.2$ eV does *not* apply.

Cosmic infrared background

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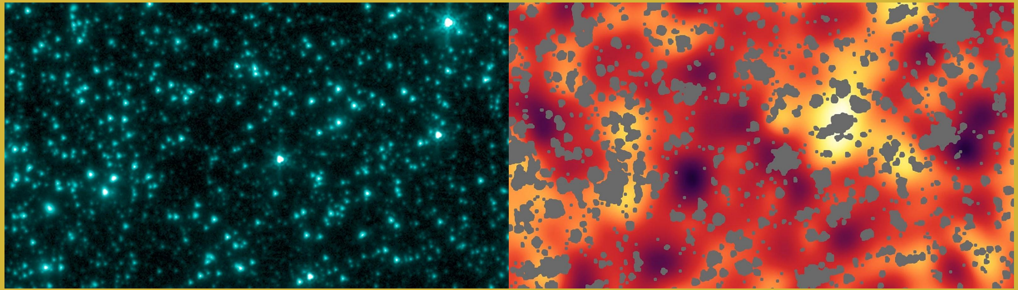
CIB is difficult to measure because of zodiacal light, galactic foregrounds.

However, fluctuations appear less dependent on the zodiacal light and other systematics.

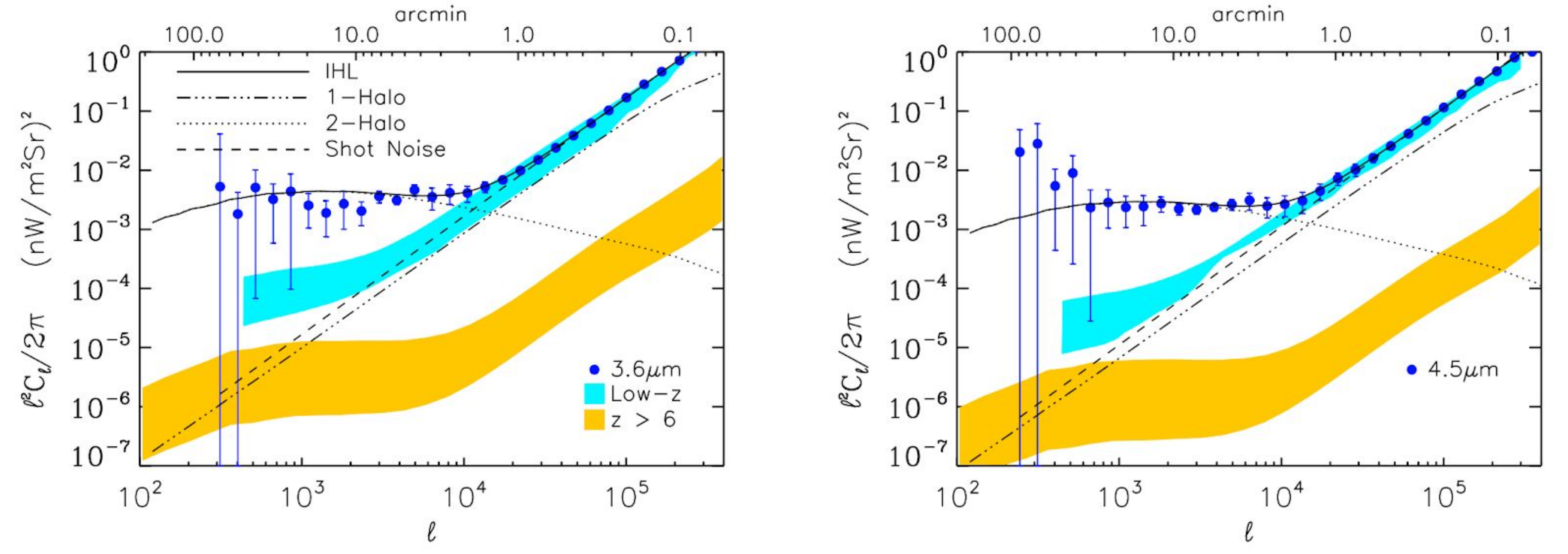
Spitzer, Akari: Excess in fluctuation at few arcmin scale in the near-IR (2-5 µm),



Spitzer image of an area of Ursa Major (left), and CIB after stars have been masked (right)

$$\delta F_{2-5\mu\mathrm{m}}\left(5'\right) \simeq 0.09\,\mathrm{nW m^{-2} sr^{-1}}$$

Cosmic infrared background fluctuations



Cooray et al. Nature 494 (2012) 514-517

Possible explanations

- CIB fluctuations could come from stars at z>10, but not enough clustering from standard structure (standard inflation)
- Unresolved galaxies (in the case of Akari, not Spitzer), orphan stars, some new population or a new physical mechanism for clustering...
- Primordial black holes with masses ~10 $M_\odot$ (need $\Omega_{PBH} = \Omega_{DM}$)
  [Kashlinsky, ApJ 823 (2016) L25]

- Inhomogeneities in baryogenesis?

Baryon number inhomogeneities can explain CIB fluctuations

A coupling between the Higgs boson and the inflaton can make the field heavy and prevent it from oscillating until the very end of inflation.

Large baryon density perturbations on **small** scales $(\delta_B = \delta\rho_B/\rho_B \sim 0.1)$

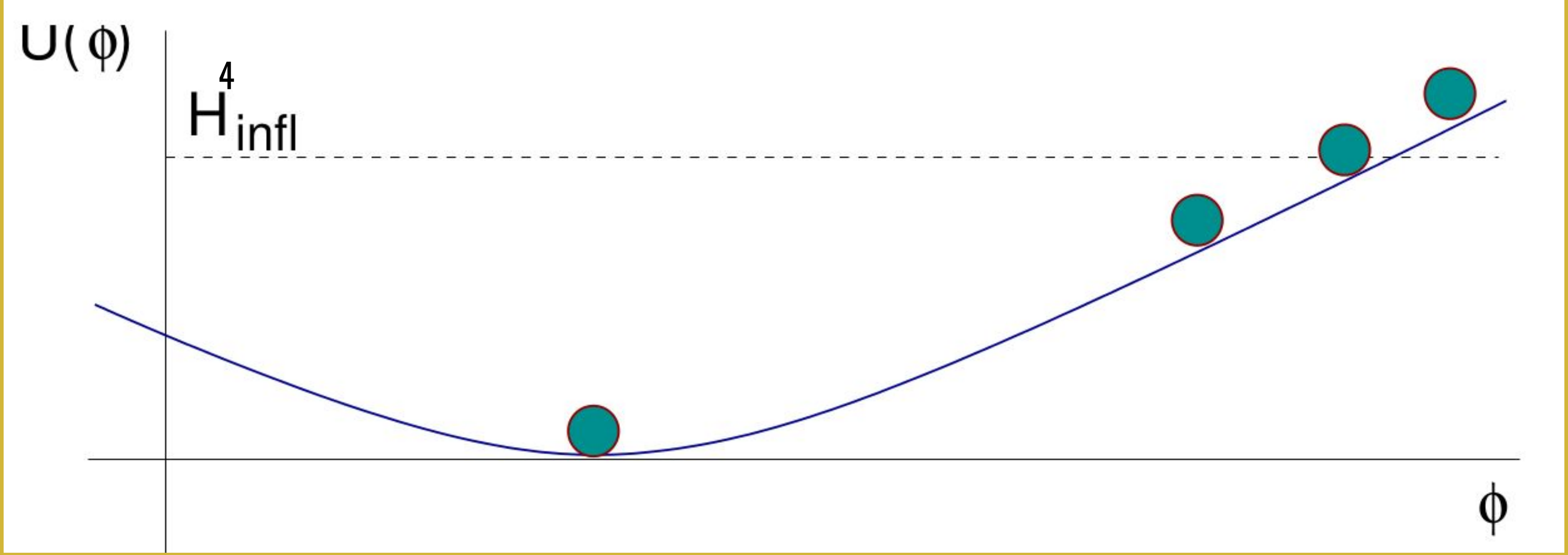
Adiabatic density perturbations in both B and DM develop (only) on the small scales

and the induced dark matter density fluctuations lead to an earlier collapse of small halos $(M_{\rm halo} \sim 10^6 M_\odot)$ which result in CIB perturbations ~few %.

AK, Kawasaki, Pearce, Yang Phys.Rev.D 95 (2017) 10, 103006

Affleck-Dine baryogenesis: a GW signal

A scalar with a small mass develops a VEV
[Chernikov, Tagirov; Starobinsky, Zeldovich; Bunch, Davies; Linde; Affleck, Dine; Starobinsky, Yokoyama]



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$$H\partial_t \langle \phi^2 \rangle = \frac{H^4}{4\pi^2} - \frac{2m^2}{3}\langle \phi^2 \rangle - 2\lambda \langle \phi^2 \rangle^2$$

- Potential $V(\phi) = \frac{1}{2}m^2\phi^2 + \frac{\lambda}{4}\phi^4$

$$\langle \phi^2 \rangle \to \frac{H^2}{\pi\sqrt{8\lambda}} \text{ for } m = 0$$

Starobinsky, Yokoyama, Phys.Rev.D 50 (1994) 6357

Supersymmetry breaking in expanding universe

Flat directions: $\mathbf{V(\varphi) = 0}$ guaranteed by SUSY

Nonzero energy density $\Rightarrow$ SUSY breaking

During inflation, the energy density Λ alters the flat direction potential by terms of the order $\boldsymbol{\delta V \sim c\,(\Lambda^4/M_{Pl}^2) \sim c\,H^2\varphi^2}$

If $\mathbf{c < 0}$, the min of $\mathbf{V(\varphi)}$ is shifted.

Two effects: (1) the min of V is at a large φ, ***not*** $\varphi=0$

(2) φ is ***not*** at the minimum of $V(\varphi)$

Scalar fields in de Sitter space (used by Affleck-Dine)

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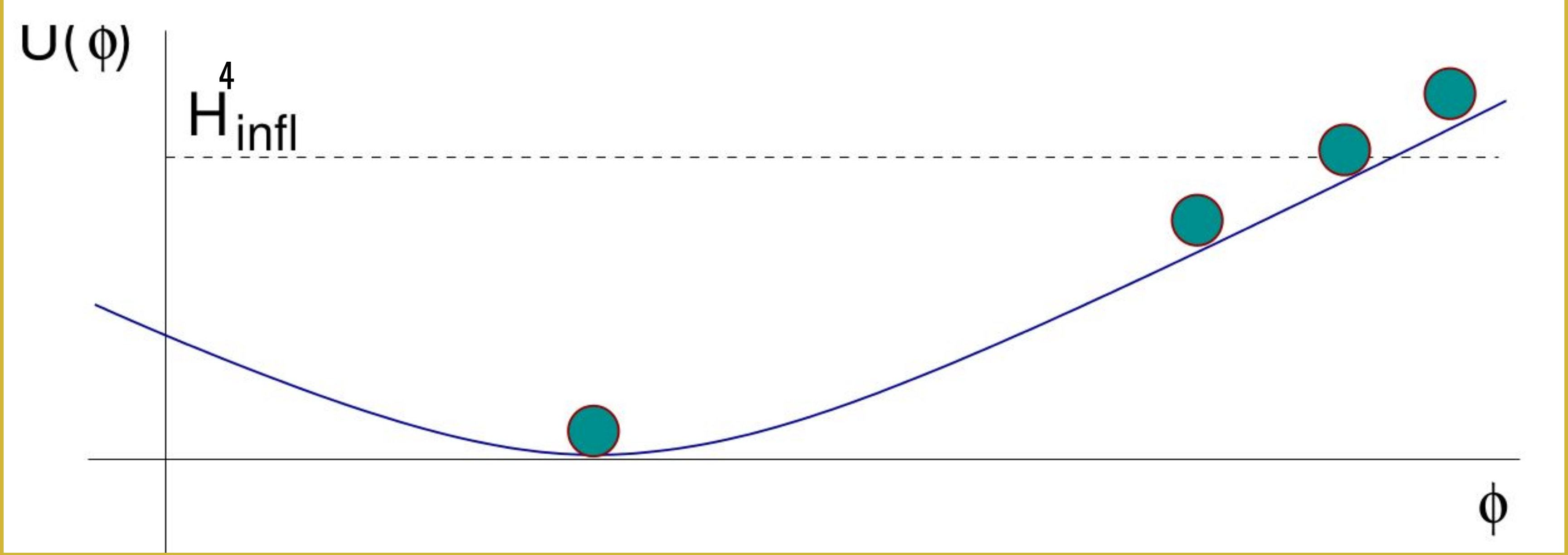

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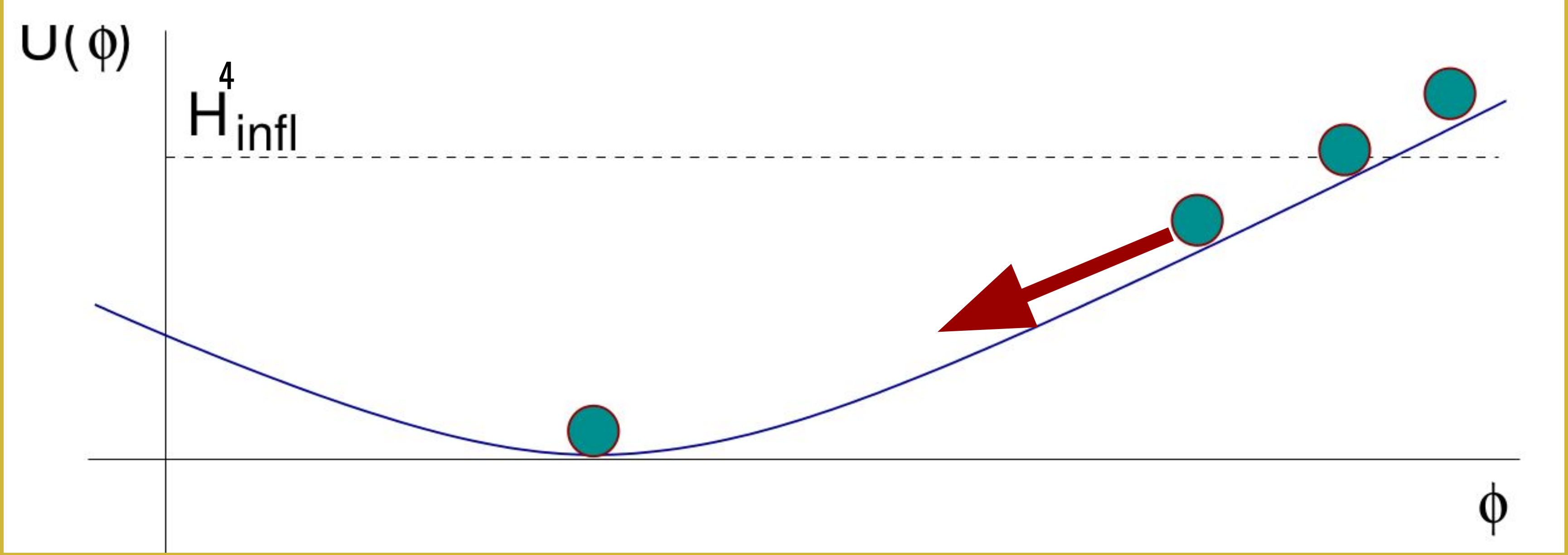
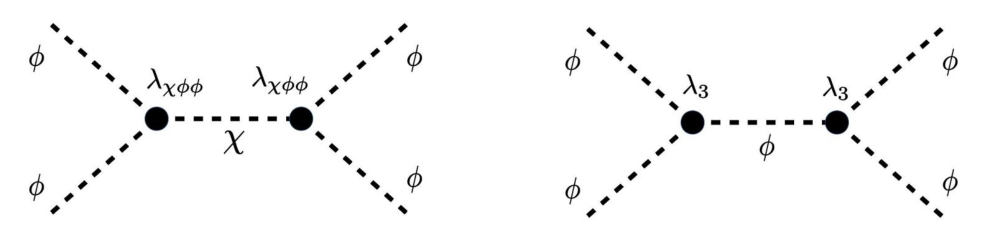


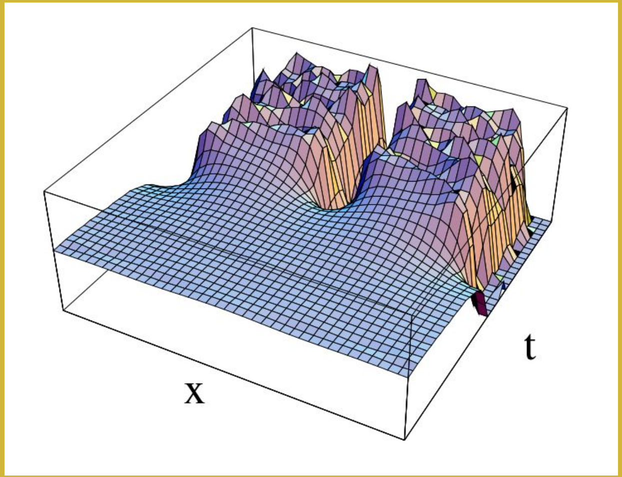
Scalar fields: an instability (Q-balls)

Gravitational instability can occurs due to the attractive force of gravity.

Similar instability can occur due to scalar self-interaction which is **attractive**:

$U(\phi) \supset \lambda_3 \phi^3$ or $\lambda_{\chi\phi\phi}\chi\phi^\dagger\phi$





[AK, Shaposhnikov, hep-ph/9709492]

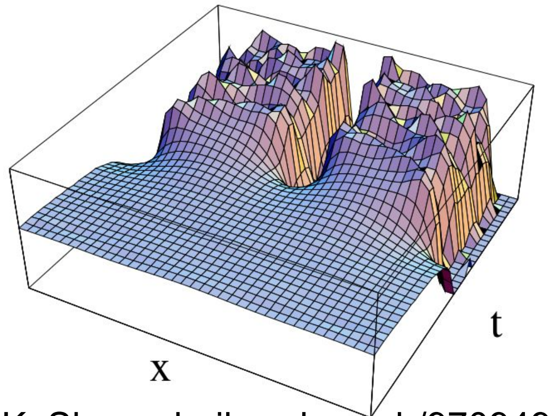
Scalar fields: an instability (Q-balls)

homogeneous solution $\varphi(x,t) = \varphi(t) \equiv R(t)e^{i\Omega(t)}$

$$\delta R, \delta\Omega \propto e^{S(t)-i\vec{k}\vec{x}}$$

$$\delta\ddot{\Omega} + 3H(\delta\dot{\Omega}) - \frac{1}{a^2(t)}\Delta(\delta\Omega) + \frac{2\dot{R}}{R}(\delta\dot{\Omega}) + \frac{2\dot{\Omega}}{R}(\delta\dot{R}) - \frac{2\dot{R}\dot{\Omega}}{R^2}\delta R = 0,$$

$$\delta\ddot{R} + 3H(\delta\dot{R}) - \frac{1}{a^2(t)}\Delta(\delta R) - 2R\dot{\Omega}(\delta\dot{\Omega}) + U''\delta R - \dot{\Omega}^2\delta R = 0.$$



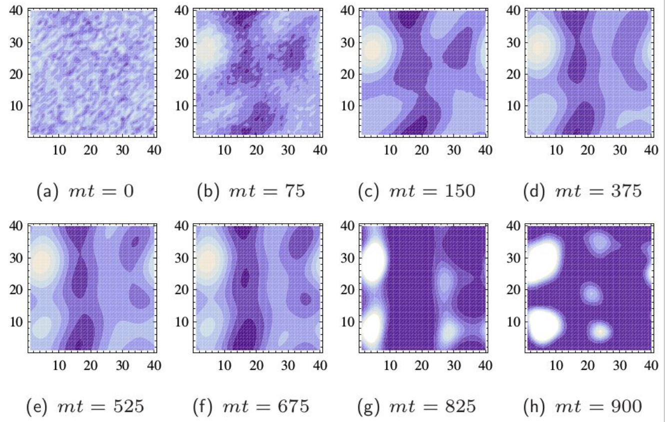
AK, Shaposhnikov, hep-ph/9709492

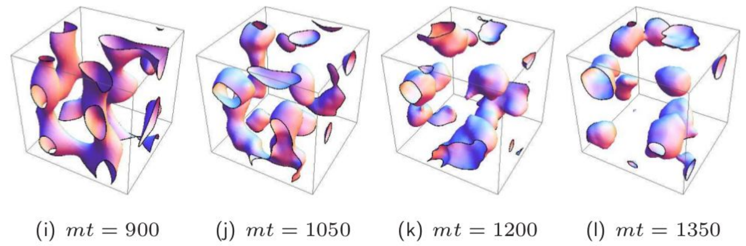
$(\dot{\Omega}^2 - U''(R)) > 0$ $\Rightarrow$ growing modes: $0<k<k_{max}$

$$k_{max}(t) = a(t)\sqrt{\dot{\Omega}^2 - U''(R)}$$

Also of interest: oscillons [Cotner, AK, Takhistov, 1801.03321]

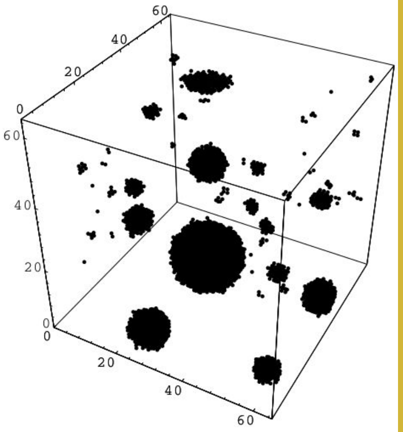
Numerical simulations of scalar field fragmentation





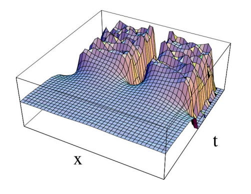
[Multamaki].

SUSY Q-balls



[Kasuya, Kawasaki]

Affleck - Dine baryogenesis (SUSY): scalars are flat directions



Inflation

origin of
primordial
perturbations

radiation dominated

$p=(\frac{1}{3})\,\rho$

$\rho \propto a^{-4}$

structures don't grow

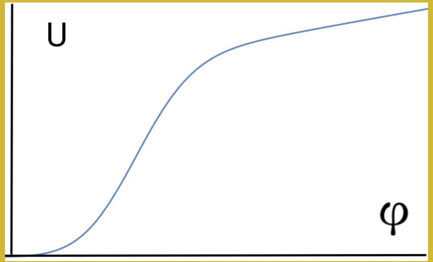
matter dominated

$p=0$

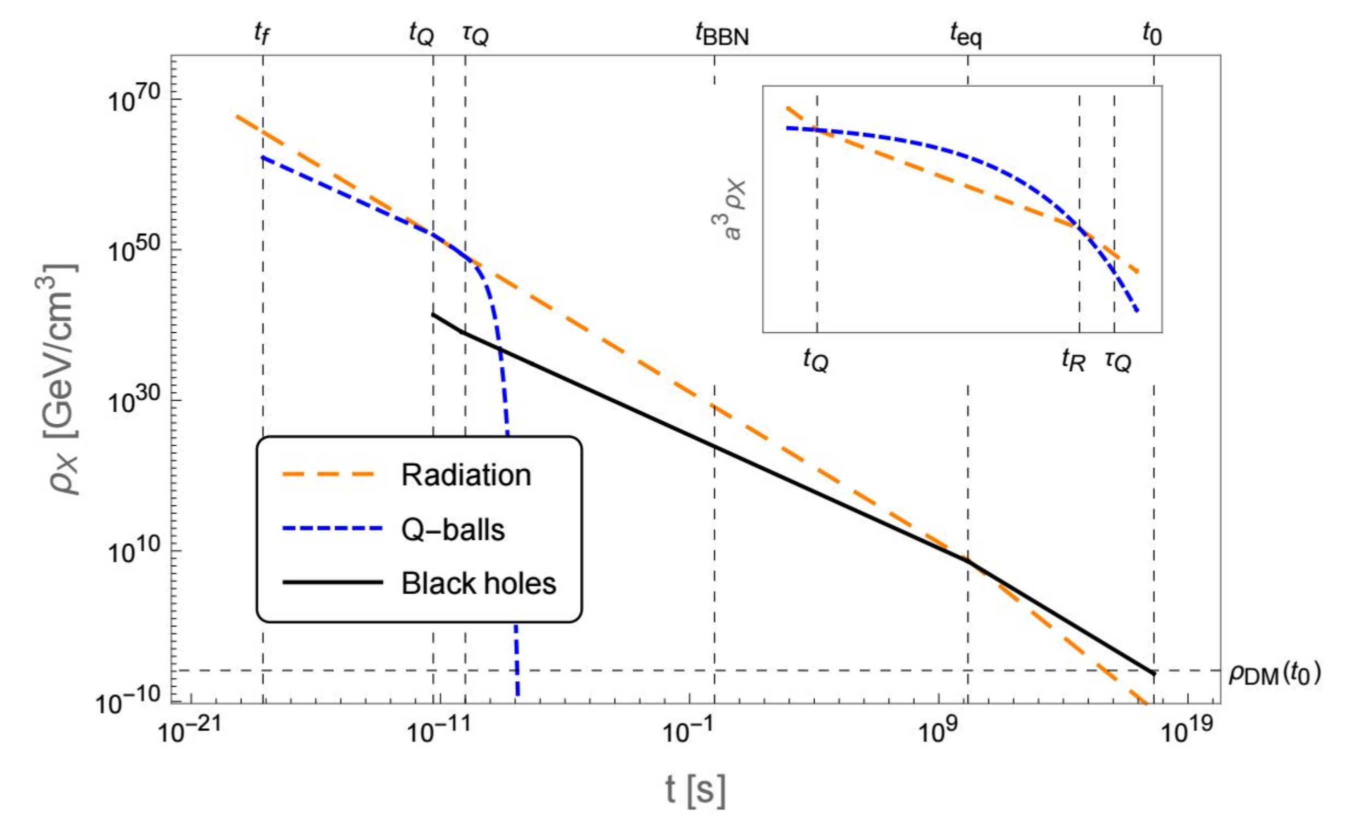
$\rho \propto a^{-3}$

structures grow

modern era
(dark energy
dominated)



Scalar lump (Q-ball) formation, domination, decay

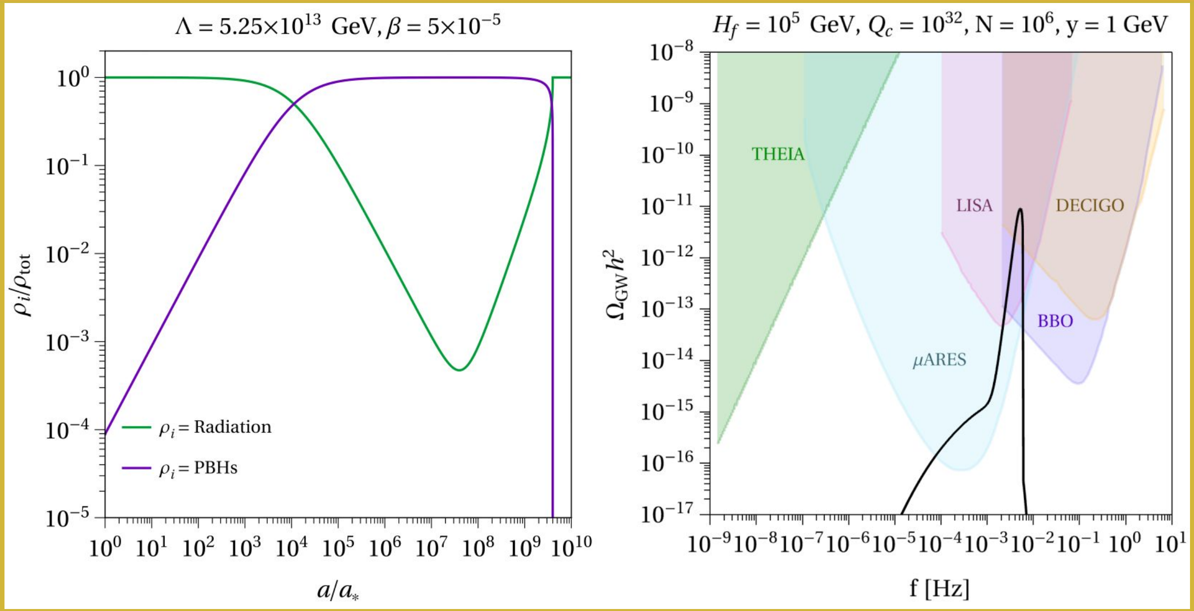


Early matter dominated epoch in the middle of radiation dominated era

Cotner, AK, Phys.Rev.Lett. 119 (2017) 031103

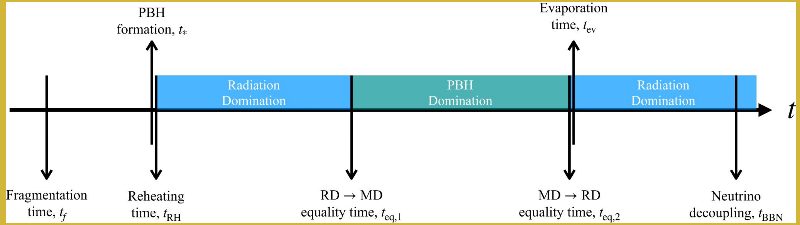
Cotner, AK, Sasaki, Takhistov, JCAP 1910 (2019) 077

Gravitational waves from Q-ball decay



1904.12879, 2003.10455

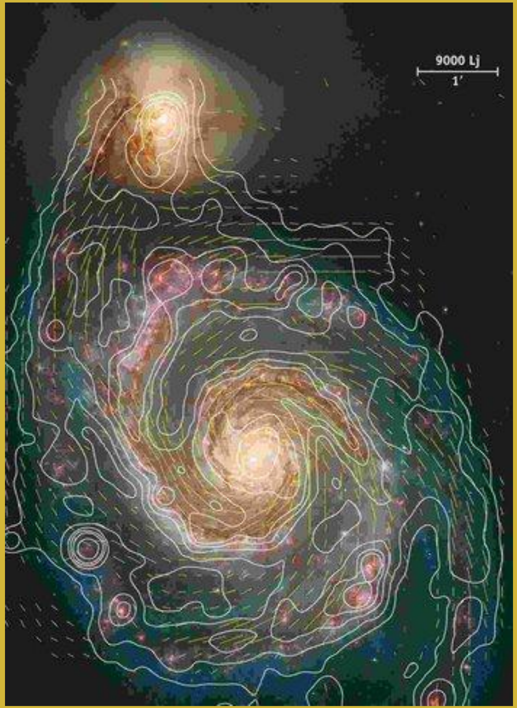
Flores, AK, Pearce, Perez-Gonzalez, White, 2308.15522



Baryogenesis and intergalactic magnetic fields

Magnetic fields in galaxies can arise from dynamo action if there are primordial seeds. Alternatively, they can be generated by Biermann battery or another mechanism.

Intergalactic magnetic fields away from galaxies may be representative of primordial seed fields.



QUPosium2023

Addressing five mysteries of the Universe with new eyes

(B+L) asymmetry and the primordial magnetic helicity

Magnetic helicity or Chern-Simons term for the U(1) of hypercharge:

$$h_Y(t) \equiv \lim_{V \to \infty} \frac{1}{V} \int_V d^3x \, \mathbf{Y} \cdot \mathbf{B}_Y$$

$$\partial_\mu j^\mu_{e_R} = -\frac{g'^2}{16\pi^2} Y_{\mu\nu} \tilde{Y}^{\mu\nu}$$

$$n_{e_R} - n_{e^c_R} = \lim_{V \to \infty} \frac{1}{V} \int_V d^3x \, j^0_{e_R}$$

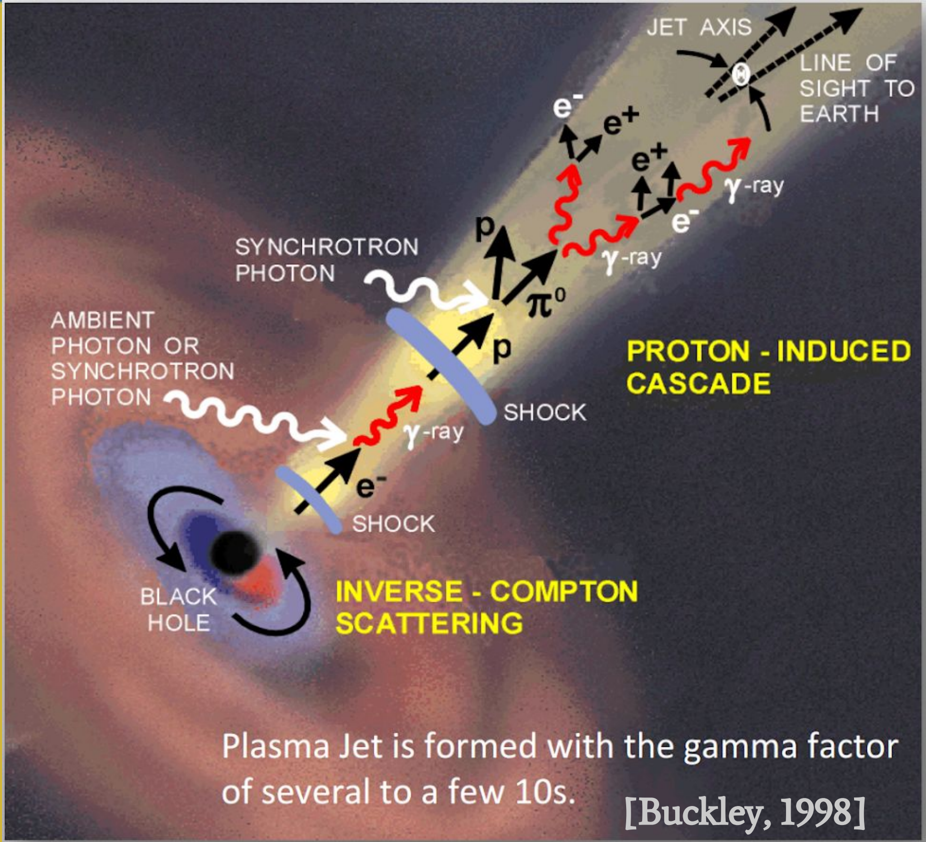
$$h_Y = -\frac{2\pi}{\alpha_Y} \left(n_{e_R} - n_{e^c_R} \right)$$

$$h_Y = -\frac{2\pi}{\alpha_Y} \left(n_{e_R} - n_{e^c_R} \right)$$

[Cornwall; Vachaspati et al.]

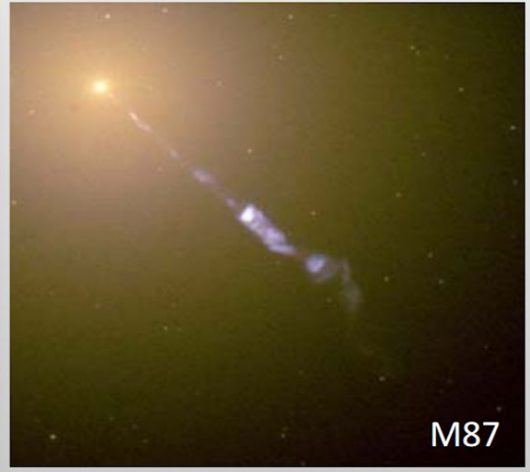
Can the helicity be observed?

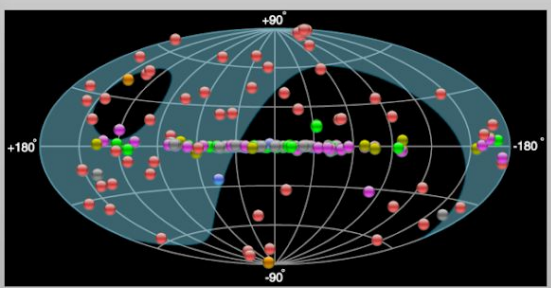
Blazars



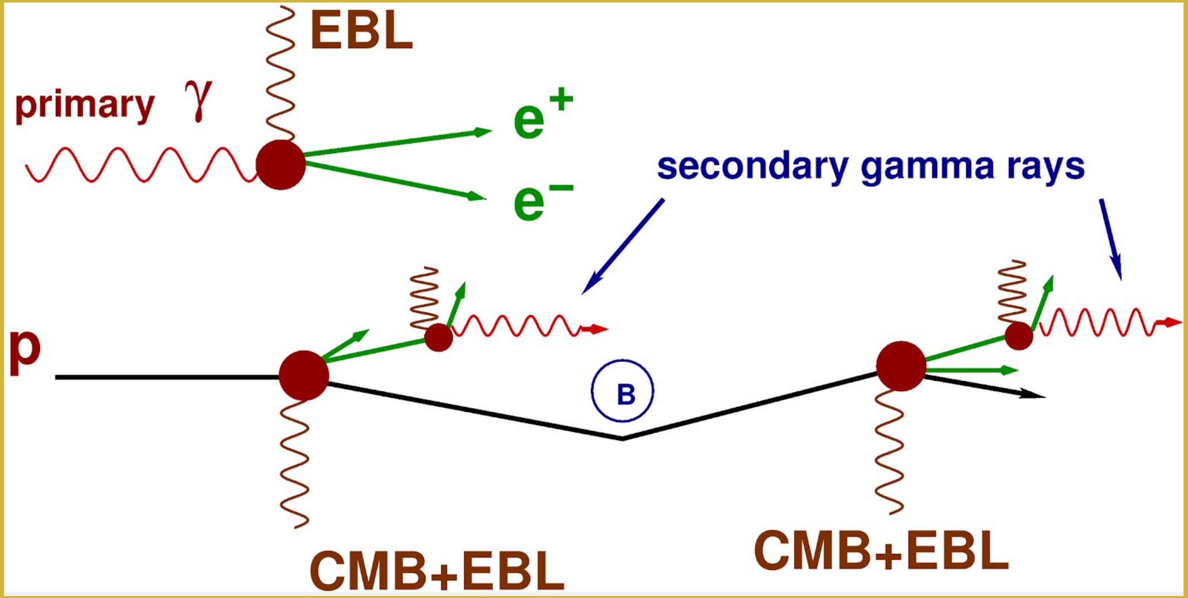
Plasma Jet is formed with the gamma factor of several to a few 10s.

[Buckley, 1998]





γ rays and cosmic rays



Secondary gamma rays from line-of-sight interactions of CRs

[Essey & AK (2010)]

Different scaling

$$F_{\text{primary},\gamma}(d) \propto \frac{1}{d^2}\exp\{-d/\lambda_\gamma\}$$

$$F_{\text{secondary},\gamma}(d) = \frac{p\lambda_\gamma}{4\pi d^2}\left[1 - e^{-d/\lambda_\gamma}\right] \propto \begin{cases} 1/d, & \text{for } d \ll \lambda_\gamma, \\ 1/d^2, & \text{for } d \gg \lambda_\gamma. \end{cases}$$

$$F_{\text{secondary},\nu}(d) \propto (F_{\text{protons}} \times d) \propto \frac{1}{d}.$$

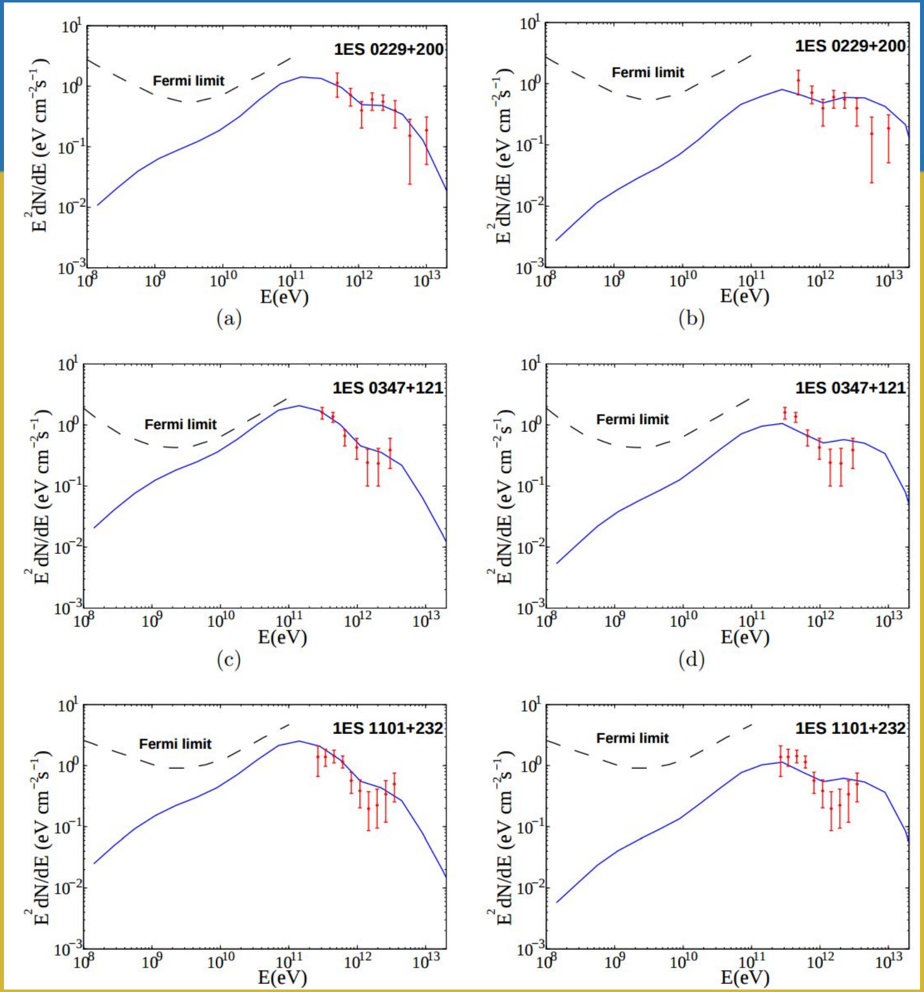
For distant sources, the secondary signal wins!

One-parameter fit (power in CR) for each source [Essey & AK (2010); Essey, Kalashev, AK, Beacom (2011)]

Good agreement with data for high-redshift blazars (both "high" and "low" EBL models).

Reasonable CR power for a source up to z~1 [Aharonian, Essey, AK, Prosekin (2013); Razzaque, Dermer, Finke (2012); Murase, Dermer, Takami, Migliore (2012)]

Consistent with data on time variability [Prosekin, Essey, AK, Aharonian (2012)]



Essey, Kalashev, AK, Beacom, ApJ (2011)

Implications for intergalactic magnetic fields

Magnetic fields along the line of sight:

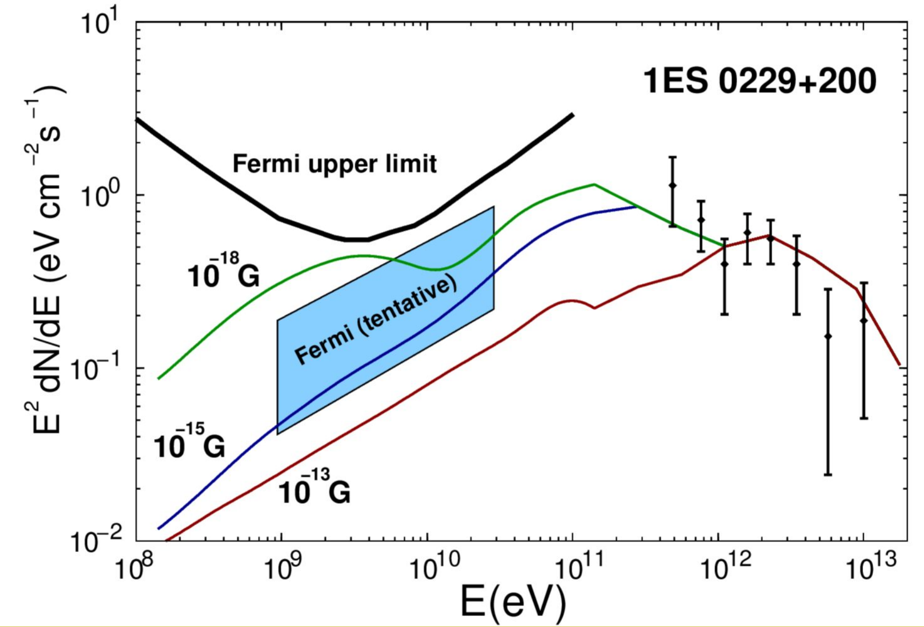
$$1 \times 10^{-17}\ \mathrm{G} < B < 3 \times 10^{-14}\ \mathrm{G}$$

Essey, Ando, AK, arXiv:1012.5313

Lower limits: see also Neronov and Vovk (2010); Finke et al. (2015)

If an intervening filament deflects protons, then no secondary component is expected.

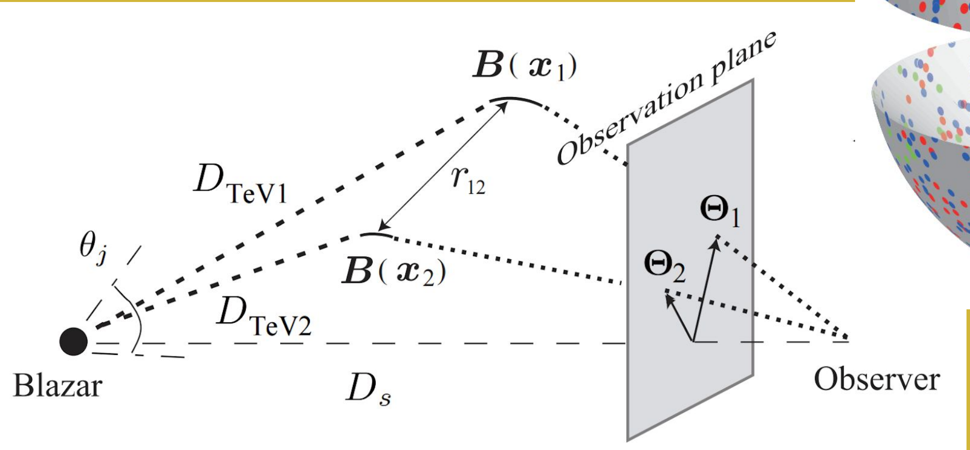
However, even a source at z~1 has an order-one probability to be unobscured by magnetic fields, and can be seen in secondary gamma rays [Aharonian, Essey, AK, Prosekin, arXiv:1206.6715]

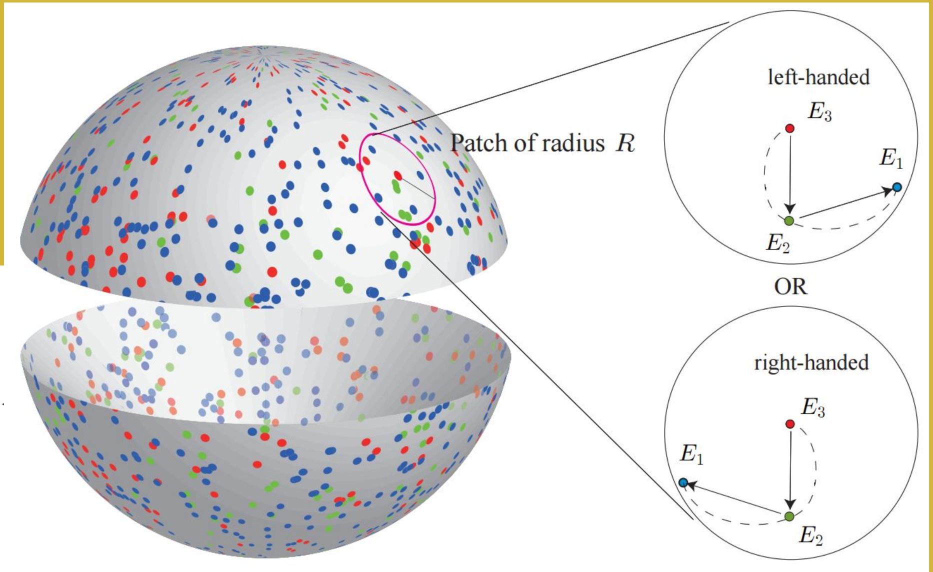


Essey, Ando, AK (2011)

Magnetic helicity may be observable

[Vachaspati et al.] report 3σ evidence of non-zero helicity, with the *correct sign*





Tashiro, Chen, Ferrer, Vachaspati (2014)

Conclusion

Baryogenesis: still many models, but a connection to gravitational waves, magnetic fields, and photon backgrounds may help identify the origin of matter-antimatter asymmetry: