Axion inflation with non-Abelian gauge fields

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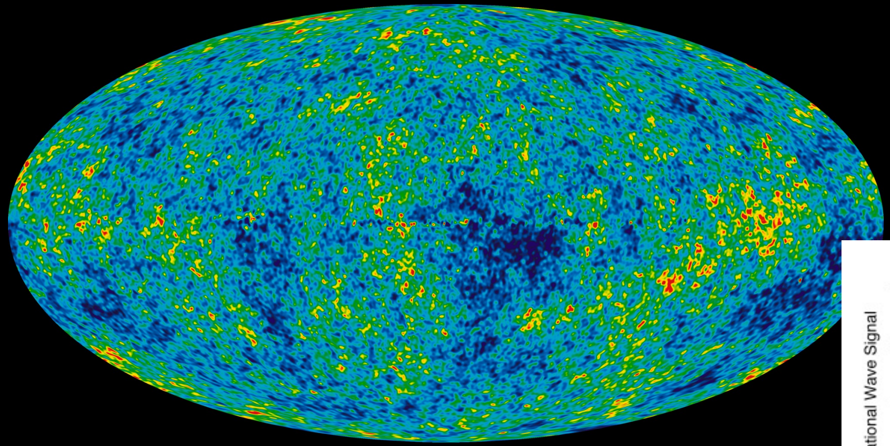
MARIE CURIE ACTIONS

Funded by the European Union

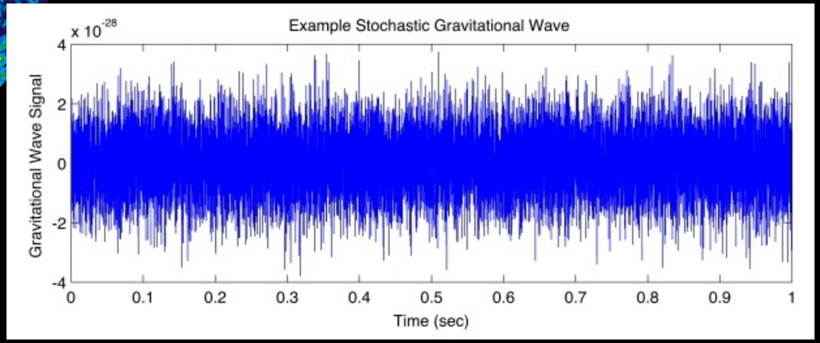
Multi-messenger cosmology from gauge fields

Scalar perturbations



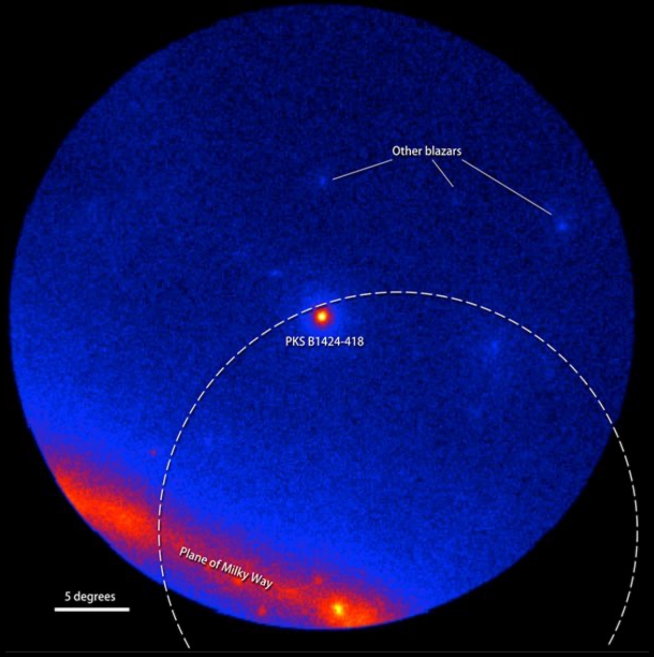
[Planck]

Graviational waves



[LIGO/VIRGO]

Primordial magnetic fields



[NASA/DOE/LAT Collaboration]

Multi-messenger cosmology from gauge fields

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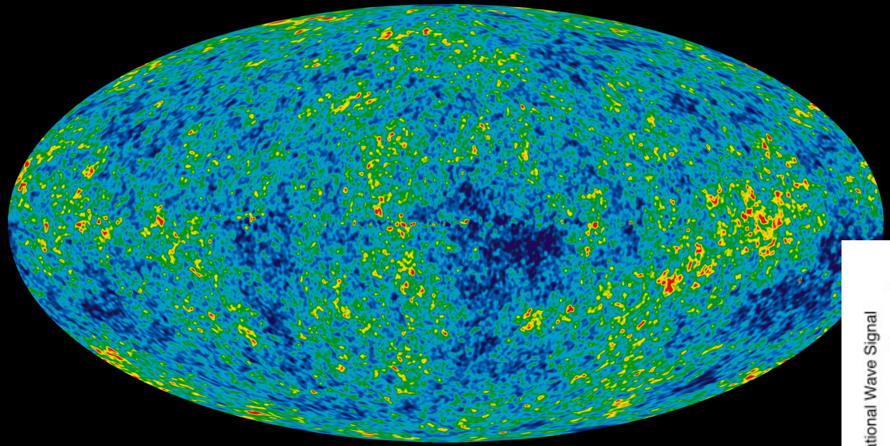

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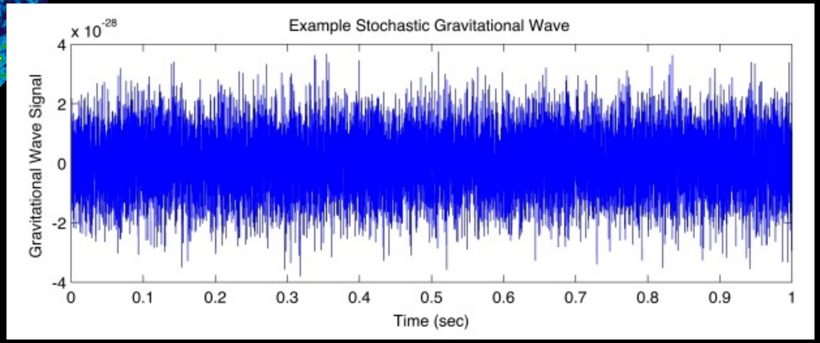

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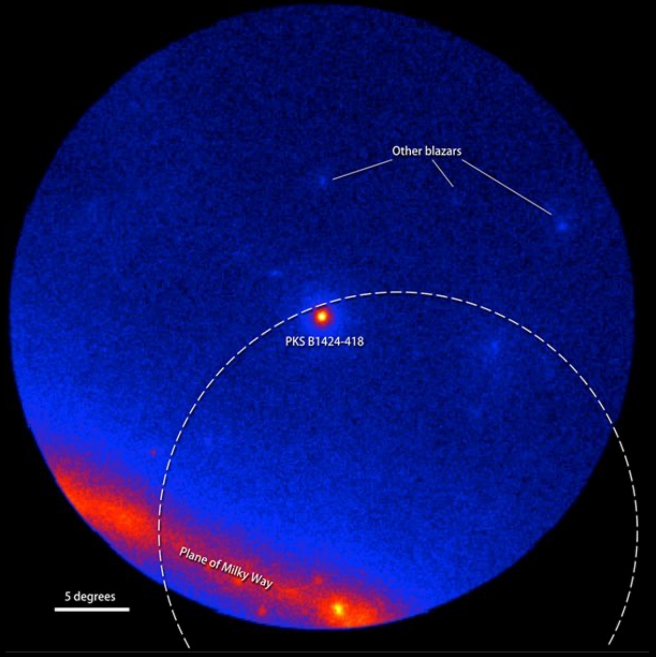
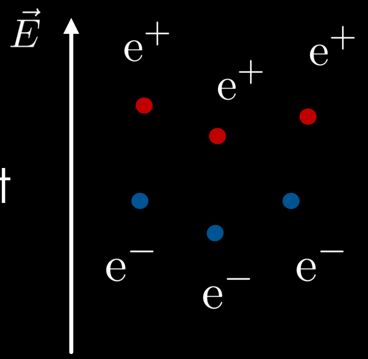


[NASA/DOE/LAT Collaboration]

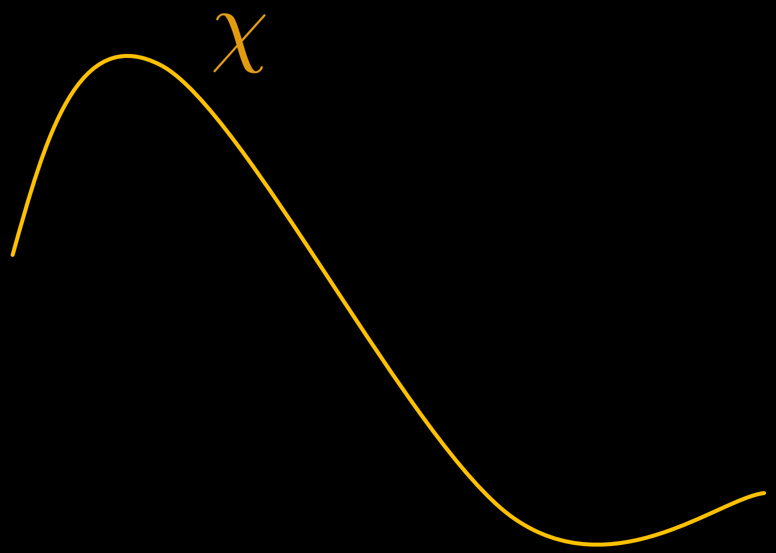
+ bonus
Schwinger effect



axion $\longrightarrow$ $\frac{\chi}{4f}\lambda F^a_{\mu\nu}\tilde{F}^{a\,\mu\nu}$

axion → $$\frac{\chi}{4f}\lambda F^a_{\mu\nu}\tilde{F}^{a\,\mu\nu}$$ ← gauge field

$$\frac{\chi}{4f}\lambda F^{a}_{\mu\nu}\tilde{F}^{a\,\mu\nu}$$



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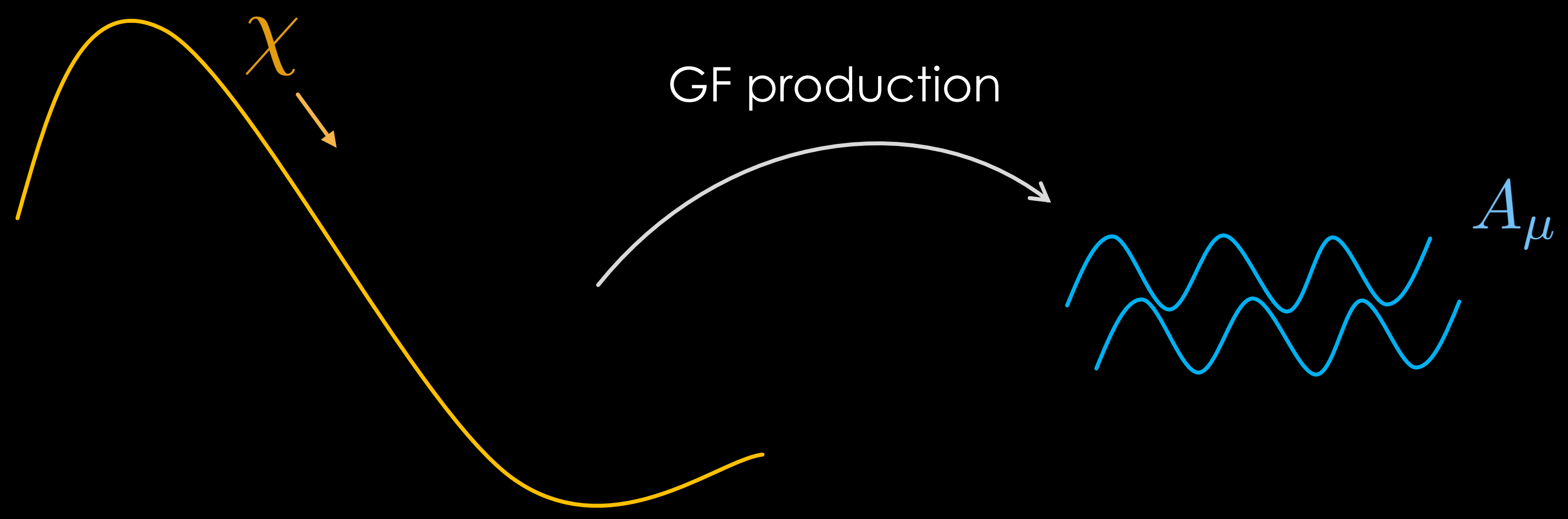

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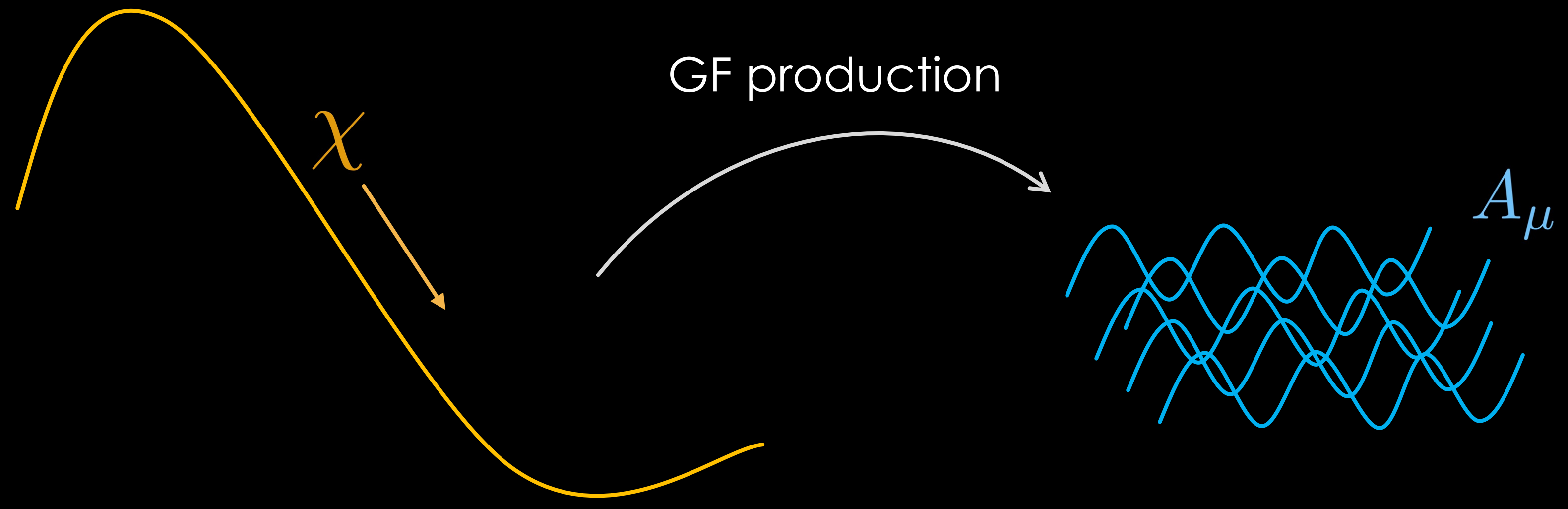

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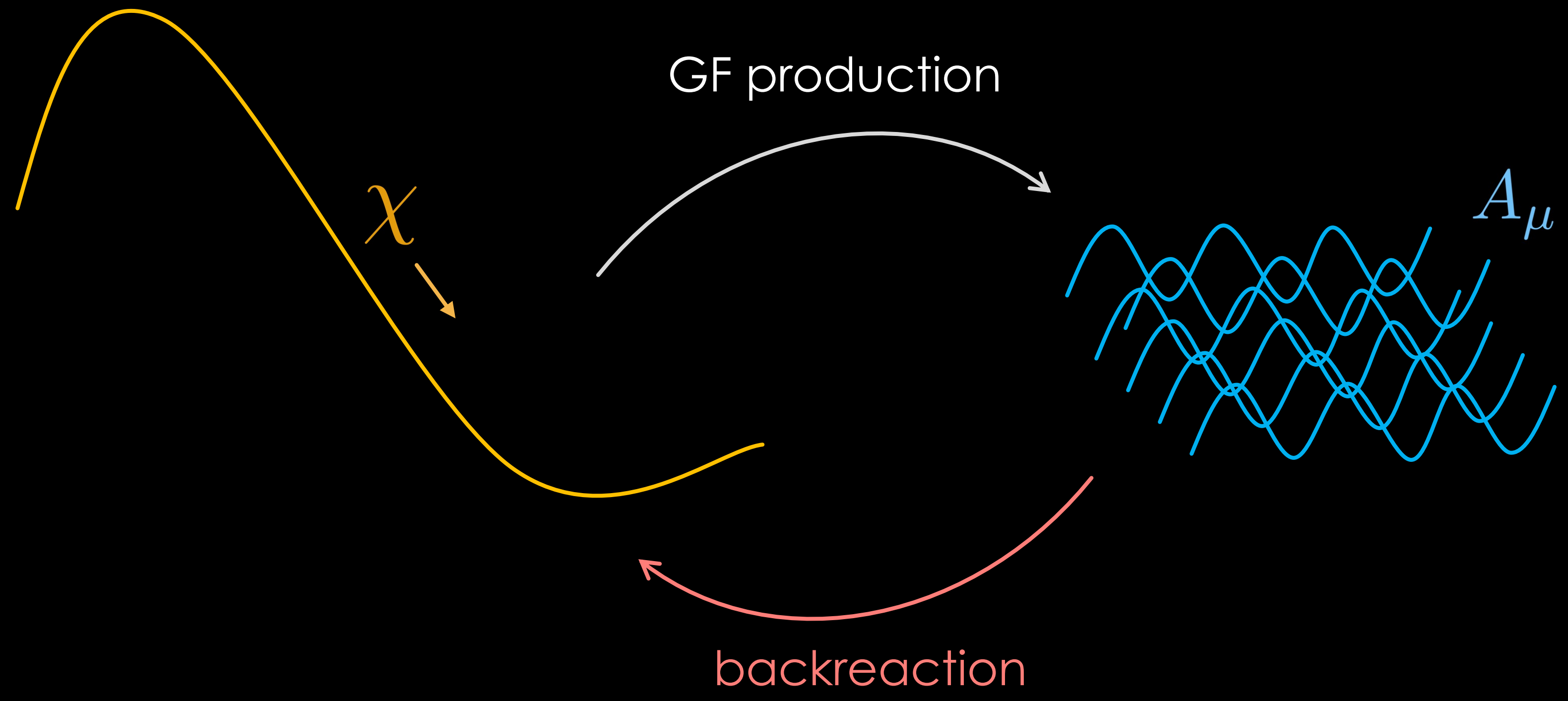
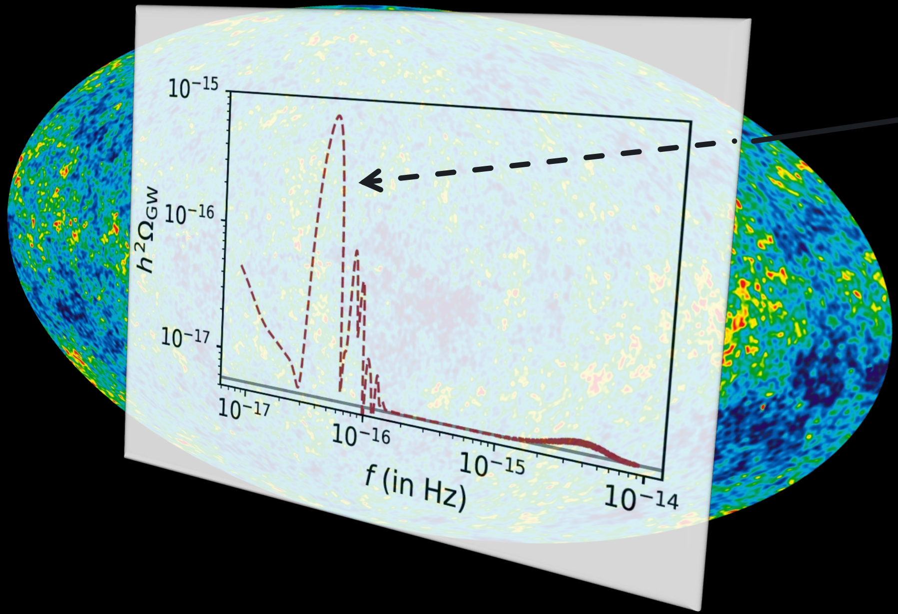
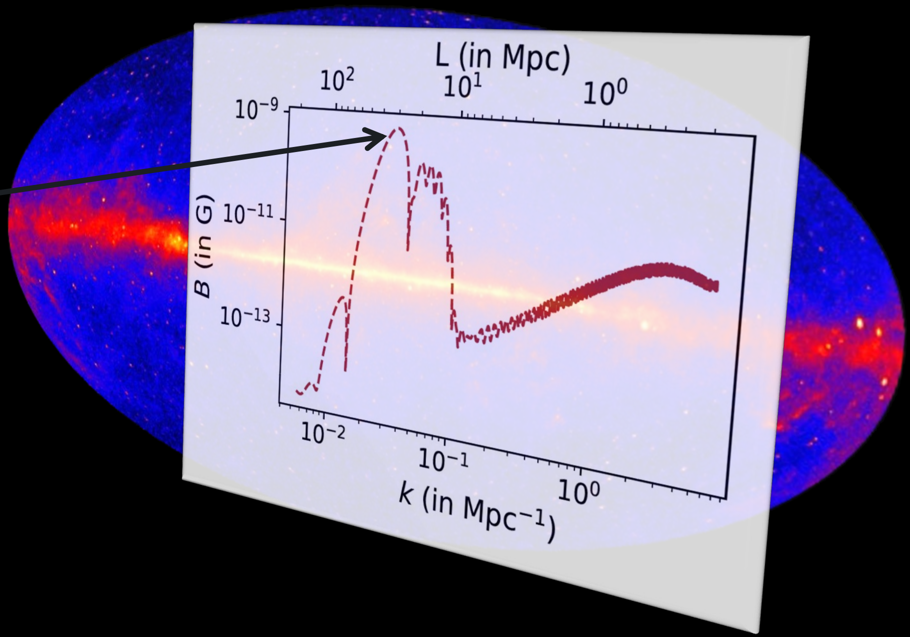


Backreaction effects lead to correlated signal in
gravitational waves & primordial magnetic fields





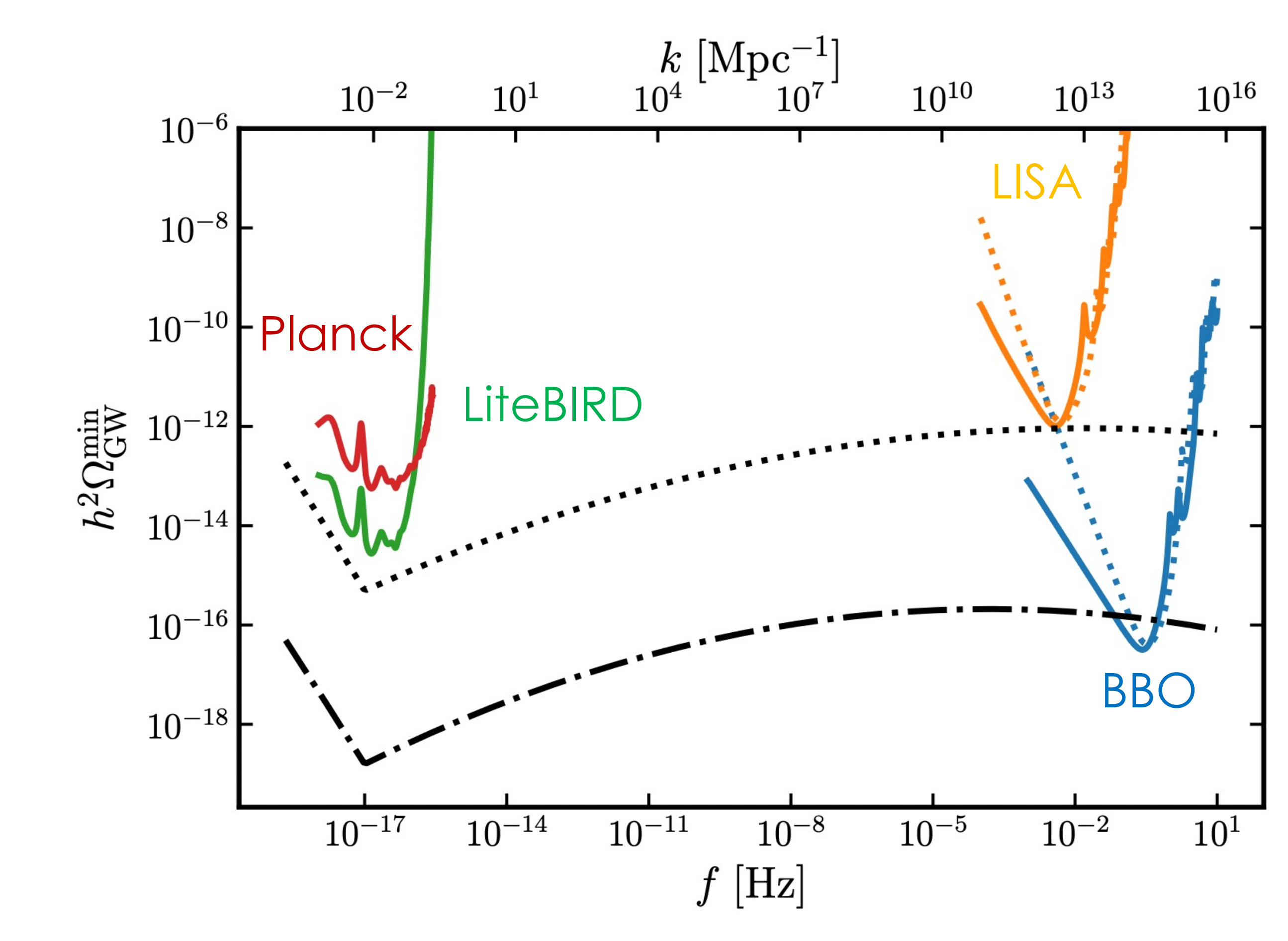
[LISA, LiteBIRD, SO]

[Fermi telescope, CTA, SKA]

Sourced gravitational waves

$$\ddot{h}_{ij} + 3H\dot{h}_{ij} + k^2 h_{ij} = 16\pi G \Pi^{TT}_{ij}$$

the transverse-traceless part of the anisotropic stress tensor



[B. Thorne, T. Fujita, M. Hazumi, N. Katayama, E. Komatsu, M. Shiraishi, 2018]

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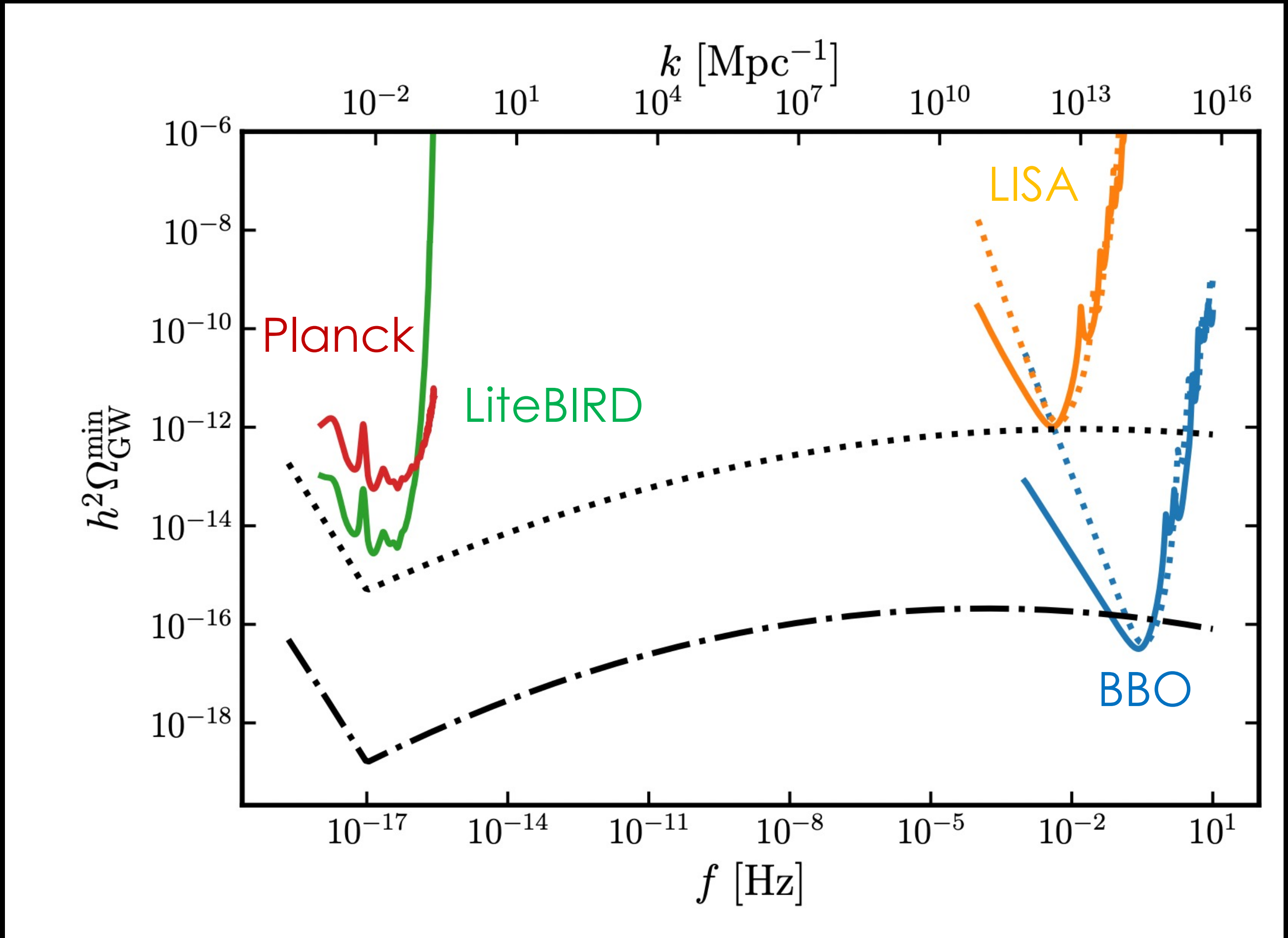

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- gauge fields,
- scalar field gradients,
- gradients of second order scalar perturbations

…

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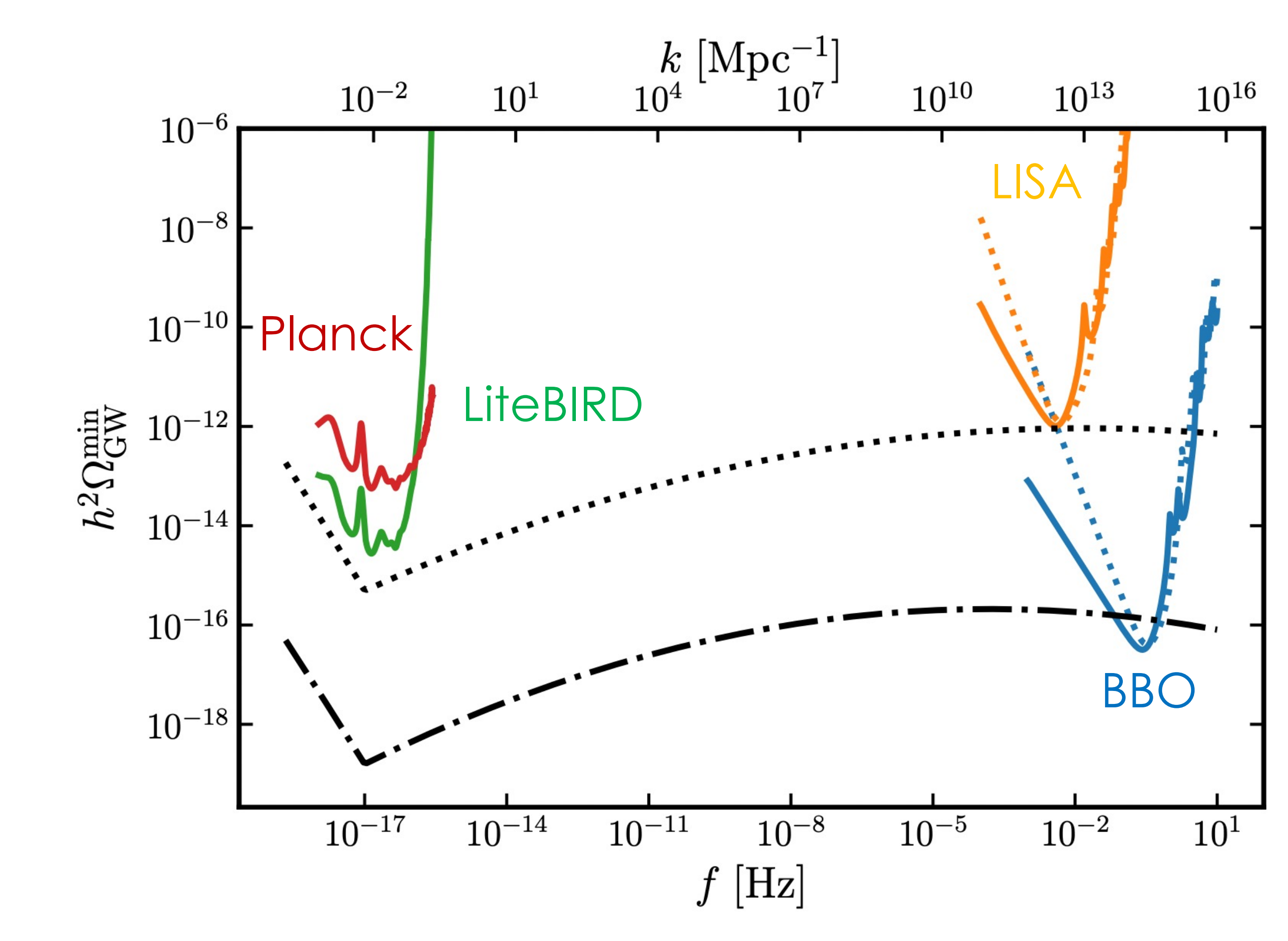

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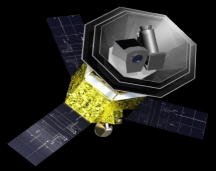
Characteristic signatures from gauge fields

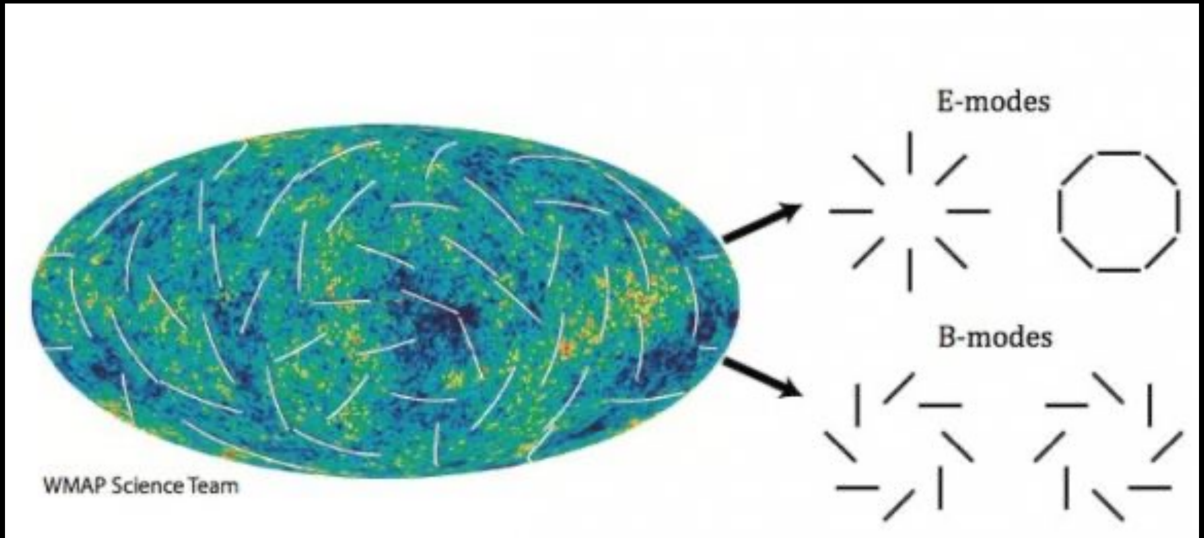


[Litebird]

- Polarization: B-modes

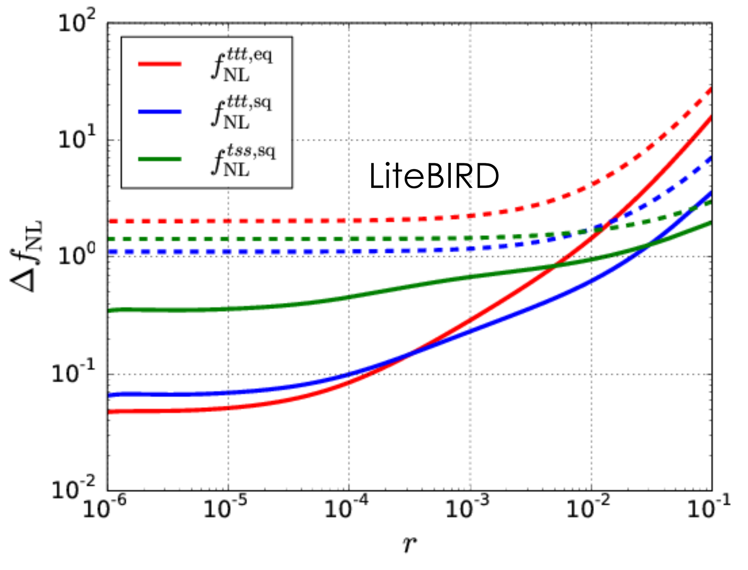
+ parity odd CMB correlations

$$TB \neq 0, EB \neq 0$$



[WMAP]

- Chiral gravitational waves
- Non-zero tensor non-Gaussianity



[M. Shiraishi, 2019]

Dilution during inflation due to conformal invariance

$$A_\mu \sim 1/a(t)$$

$$f^2(\phi) F^a_{\mu\nu} F^{a\,\mu\nu}, \quad \chi F\tilde{F}, \quad \left(F\tilde{F}\right)^2$$

To avoid dilution, new terms in the gauge theory are required or a coupling with inflaton!

Spectator Chromo-natural inflation

$$-\frac{1}{2}(\partial\chi)^2 - \mu^4\left(1+\cos(\frac{\chi}{f})\right)$$

Natural inflation

[K. Freese, J. A. Frieman and A. V. Olinto, 1990]

Spectator Chromo-natural inflation

$$-\frac{1}{2}(\partial\chi)^2 - \mu^4\left(1+\cos(\frac{\chi}{f})\right) - \frac{1}{4}F^a_{\mu\nu}F^{a\,\mu\nu} + \frac{\chi}{4f}\lambda F^a_{\mu\nu}\tilde{F}^{a\,\mu\nu}\Big]$$

Chromo-natural inflation

additional friction

[P. Adshead , M. Wyman, 2012]

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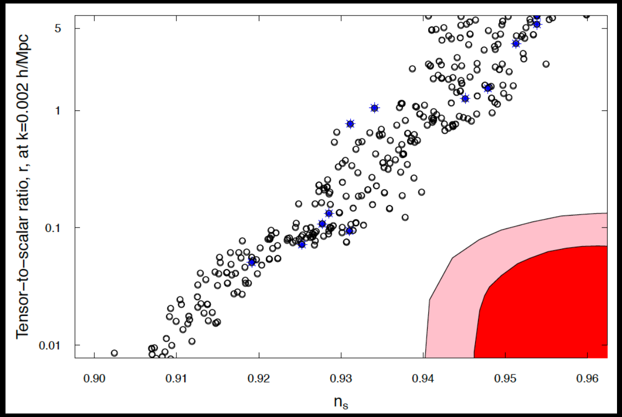

Ruled out by observations!

[P. Adshead, E. Martinec, and M. Wyman, 2013]

Spectator Chromo-natural inflation

$$S = \int d^4x \sqrt{-\det(g_{\mu\nu})} \left[\frac{M_{\rm Pl}^2}{2} R - \frac{1}{2}(\partial\phi)^2 - V(\phi) \right.$$
$$\left. - \frac{1}{2}(\partial\chi)^2 - \mu^4 \left(1 + \cos(\frac{\chi}{f})\right) - \frac{1}{4} F^a_{\mu\nu} F^{a\,\mu\nu} + \frac{\chi}{4f} \lambda F^a_{\mu\nu} \tilde{F}^{a\,\mu\nu} \right]$$

[E. Dimastrogiovanni, M. Fasiello, T. Fujita, 2017]

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[E. Dimastrogiovanni, M. Fasiello, T. Fujita, 2017]

Isotropic (attractor) solution for the background:

[A.Maleknejad and M.M.Sheikh-Jabbari, 2011]

$$A^a_0 = 0,$$

$$A^a_i = \delta^a_i a(t) Q(t)$$

“hedgehog ansatz”

Dictionary of perturbations

Scalar perturbations:

- inflaton $\delta\phi$
- axion $\delta\chi$
- gauge field δQ
- metric φ

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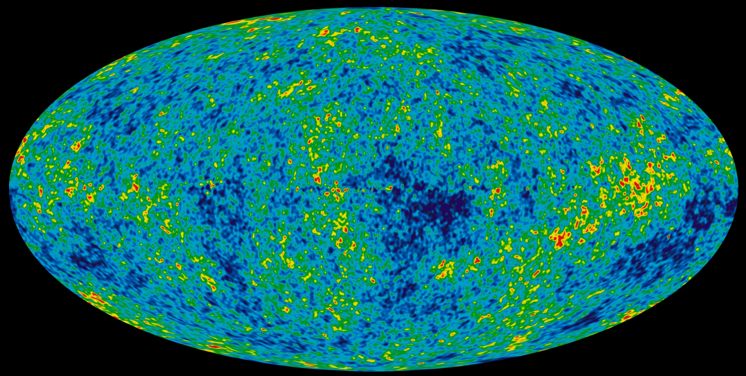
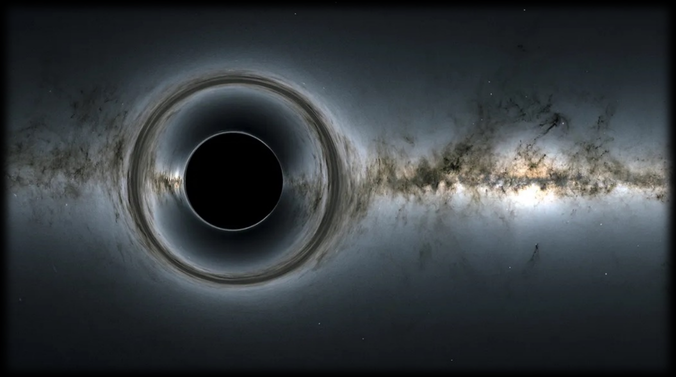
[E. Dimastrogiovanni, M. Fasiello, T. Fujita ,2017]
[A. Papageorgiou, M. Peloso, C. Unal, 2019]
[T. Fujita,T. Murata, I. Obata, M. Shiraishie, 2023]
...
[E. Dimastrogiovanni, M. Fasiello,
A. Papageorgiou, 2024]

CMB



[Planck]

Primordial black holes



[NASA/ESA/Gaia/DPAC]

Dictionary of perturbations

Tensor perturbations:

- metric $\delta g_{ij} \supset h_{ij} \supset \psi_{R,L}$
- gauge field $\delta A_i^a \supset T_{ia} \supset T_{R,L}$

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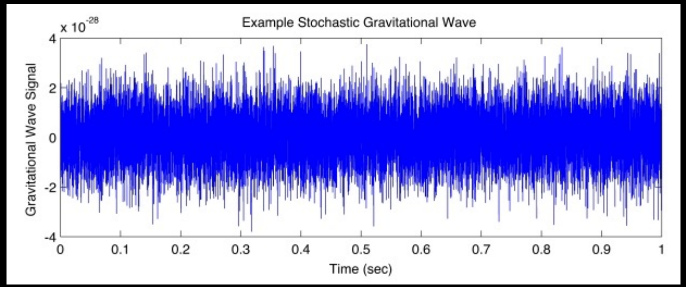
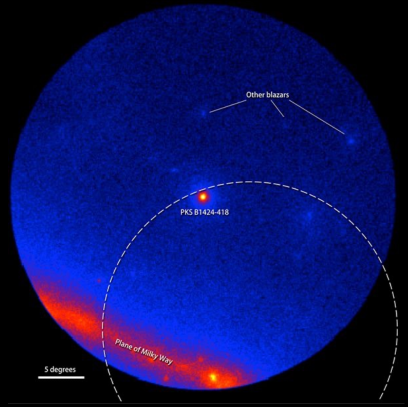
Primordial graviational waves



[LIGO/VIRGO]

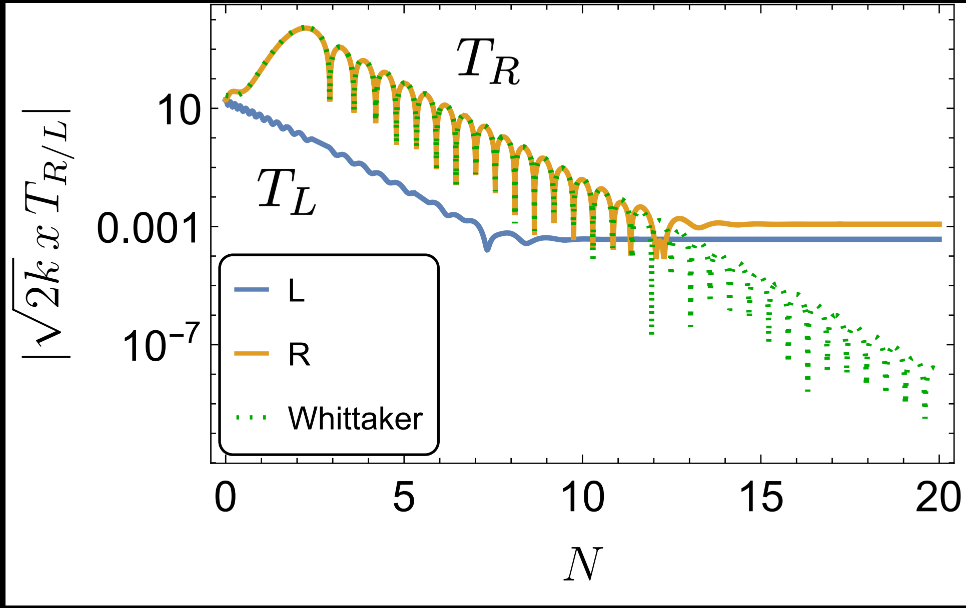
Primordial magnetic fields



[NASA/DOE/LAT Collaboration]

Chiral GW production from tensor perturbations

$$\partial_x^2 T_{R,L} + \left[1 + \frac{2}{x^2}\left(m_Q\xi \mp x(m_Q+\xi)\right)\right] T_{R,L} = \tilde{f}(\psi_{R,L})$$



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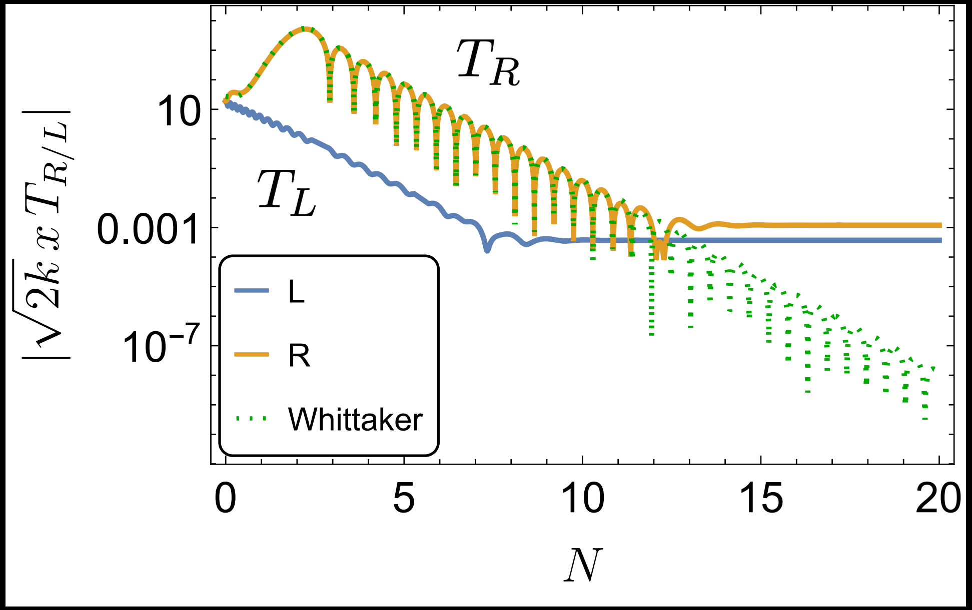

Transient tachyonic instability only in one of polarizations

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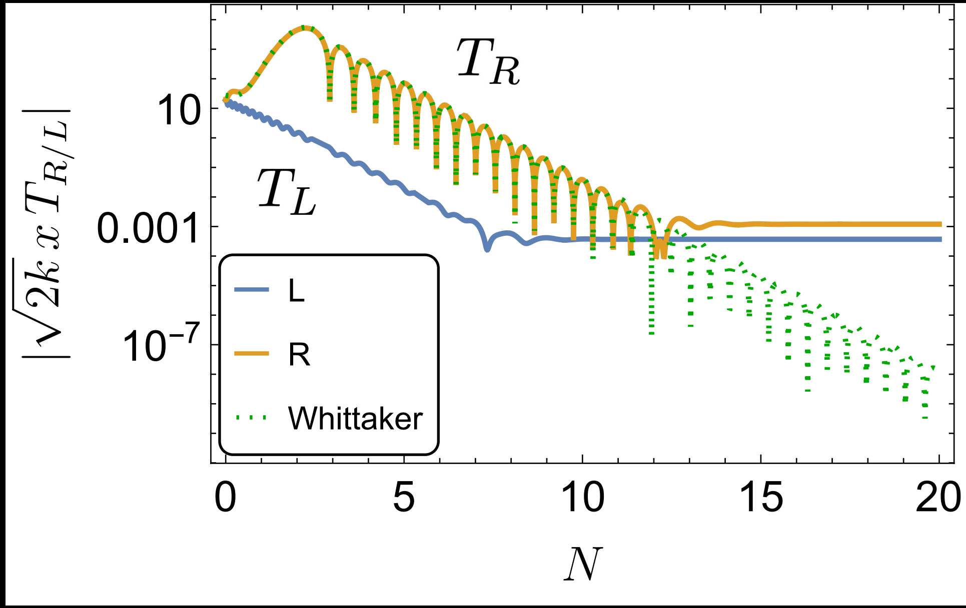

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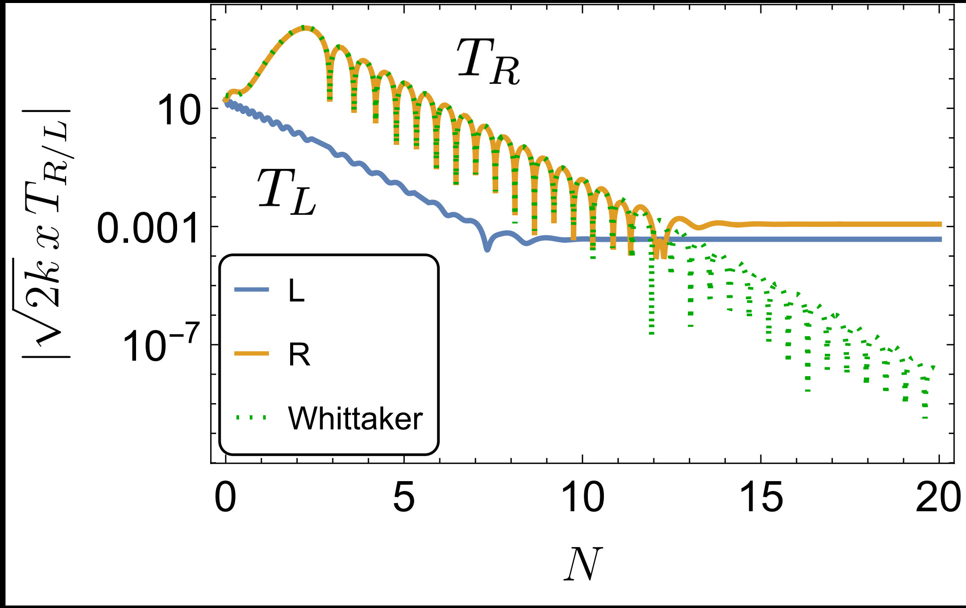

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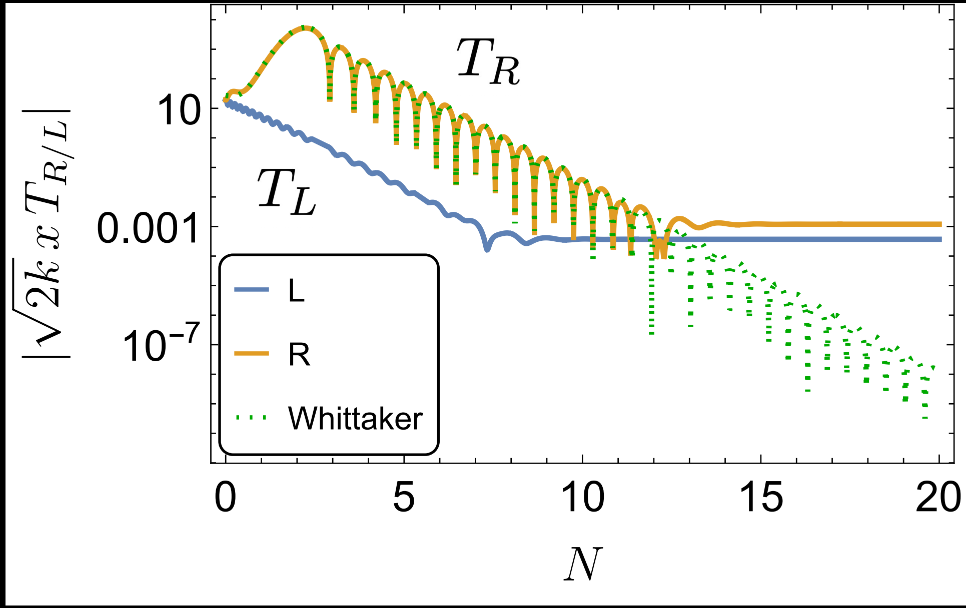

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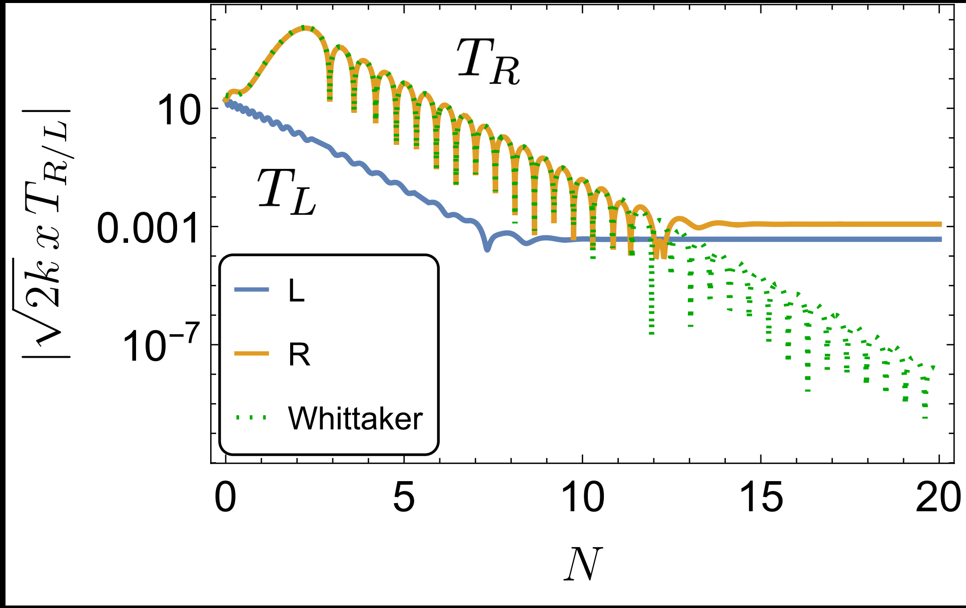

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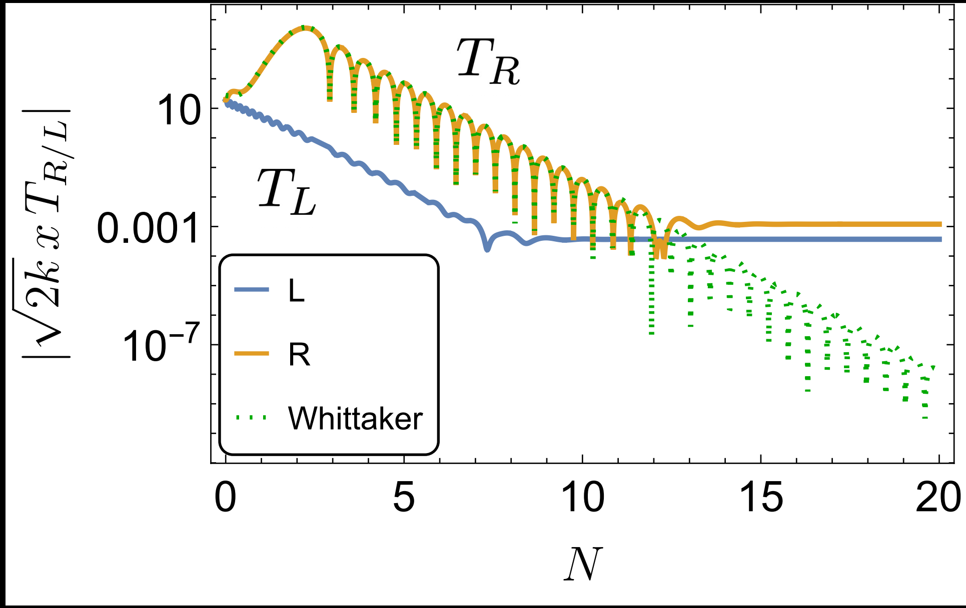
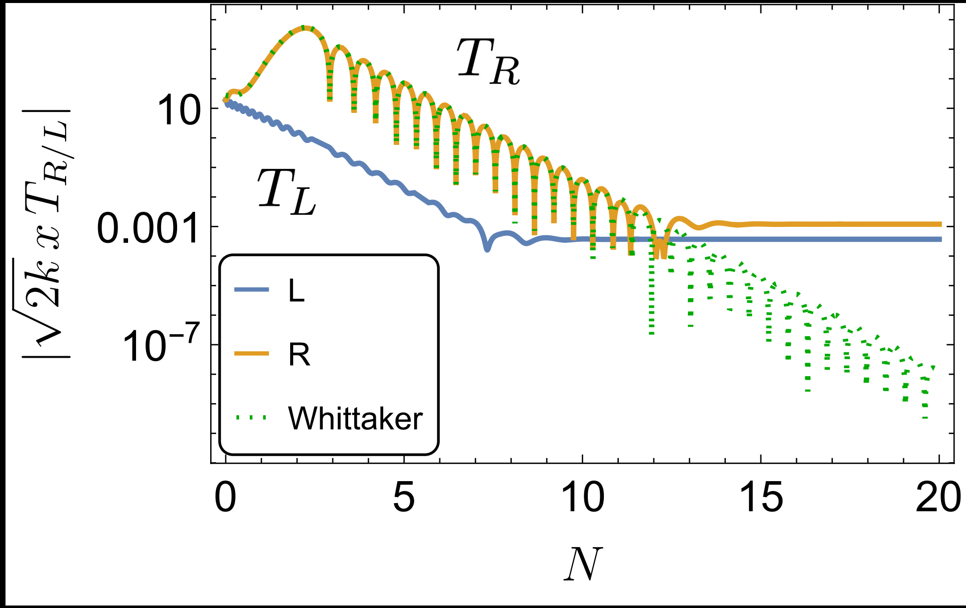


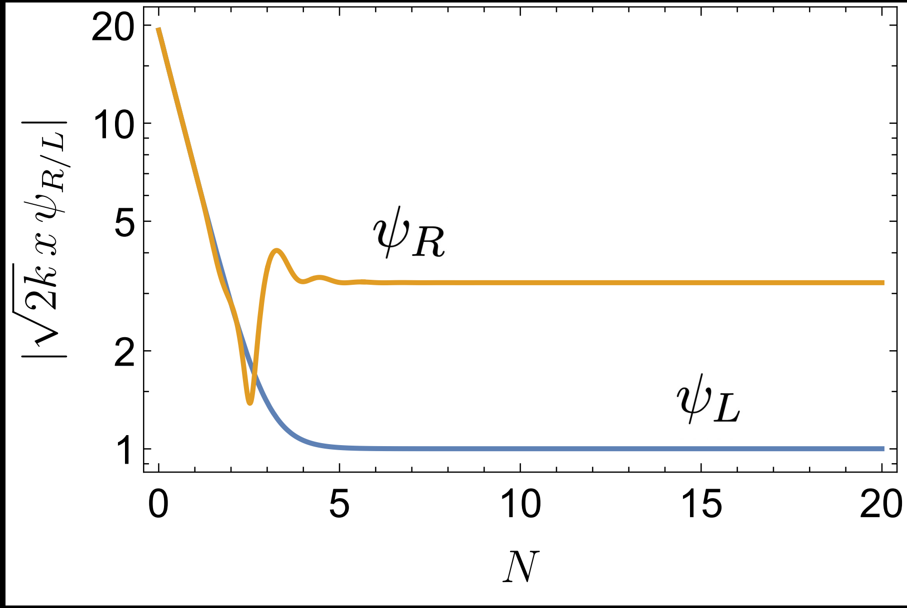
chirality

$$T_R(x) \gg T_L(x)$$

Chiral GW production from tensor perturbations

$$\partial_x^2 \psi_{R,L} + \left(1 - \frac{2}{x^2}\right)\psi_{R,L} = f(T_{R,L})$$

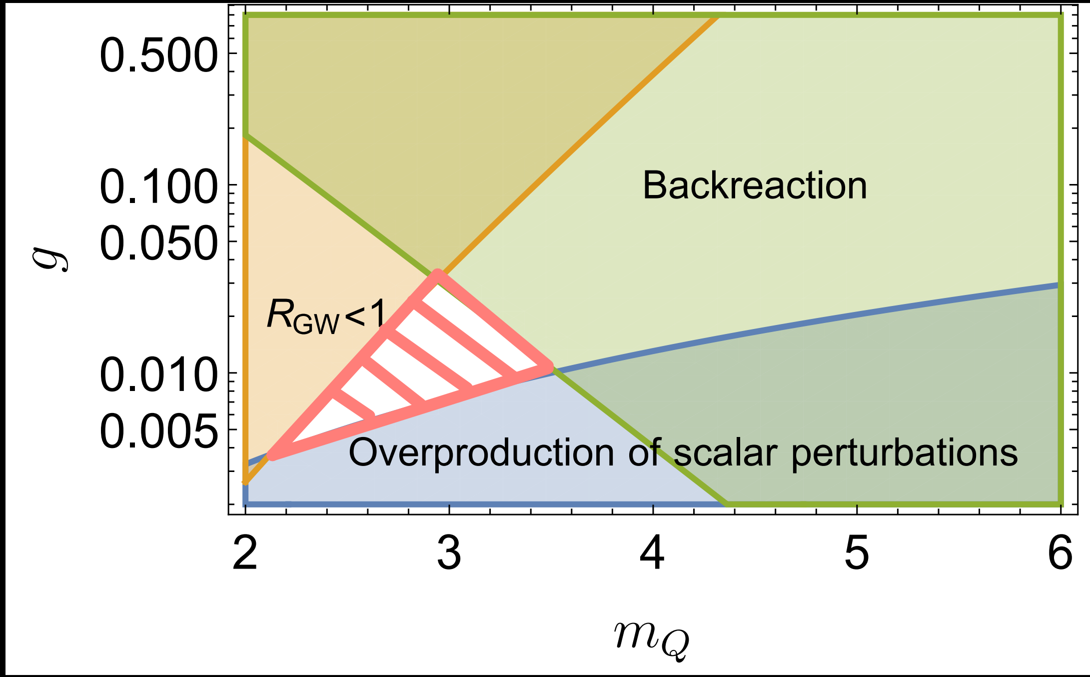


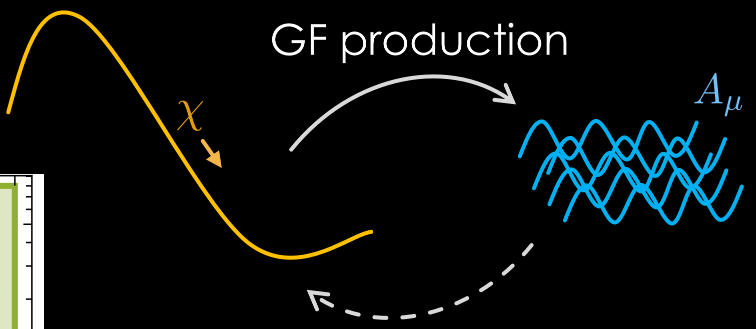


Chiral gravitational waves! $\psi_R(x) \gg \psi_L(x)$

Viable parameter space of spectator axion-SU(2) inflation

$$\mathcal{R}_{\rm GW} = \frac{\mathcal{P}_h^{(s)}}{\mathcal{P}_h^{(v)}} \qquad m_Q = \frac{gQ}{H}$$

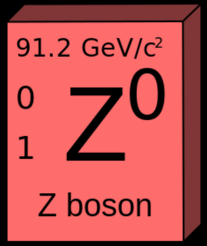


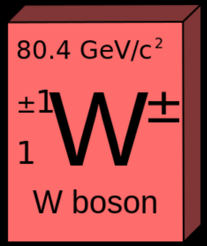


[E. Dimastrogiovanni, M. Fasiello and T. Fujita, 2017]
[A.Papageorgiou, M. Peloso, C. Unal, 2019]

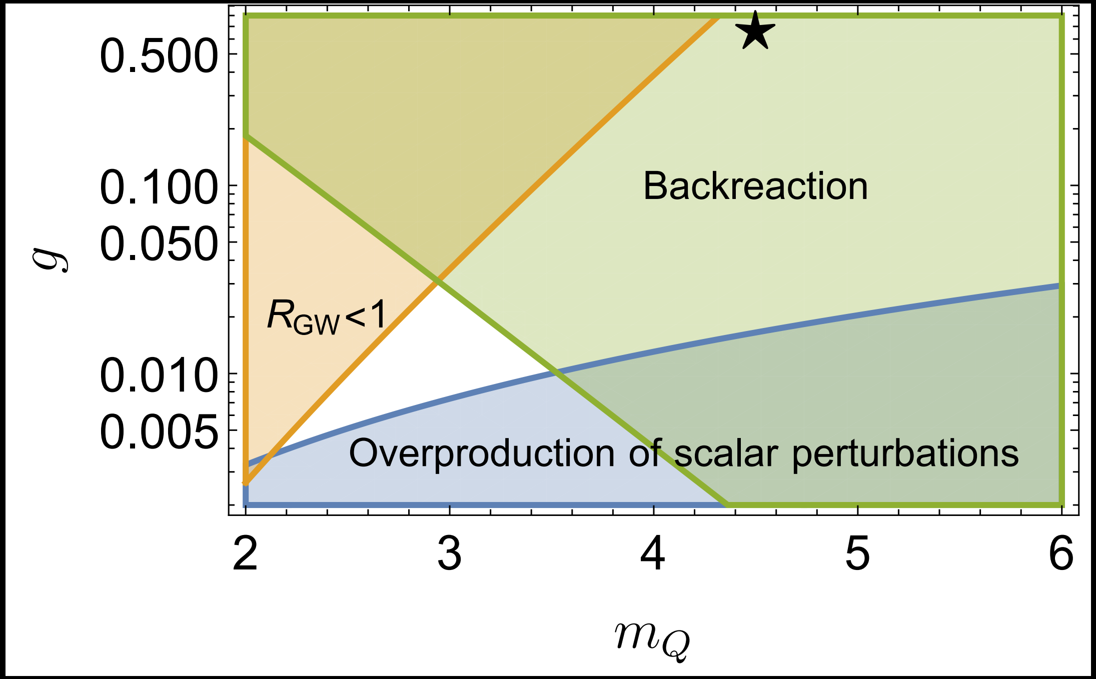
Identifying Standard Model weak bosons as the SU(2) sector

$\mathrm{SU}(2) \longleftrightarrow$





$g \propto \mathcal{O}(0.1)$



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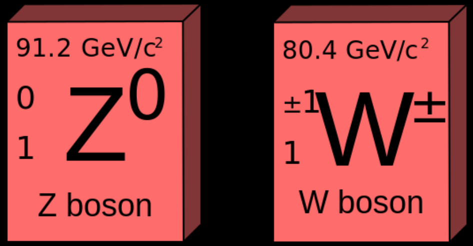

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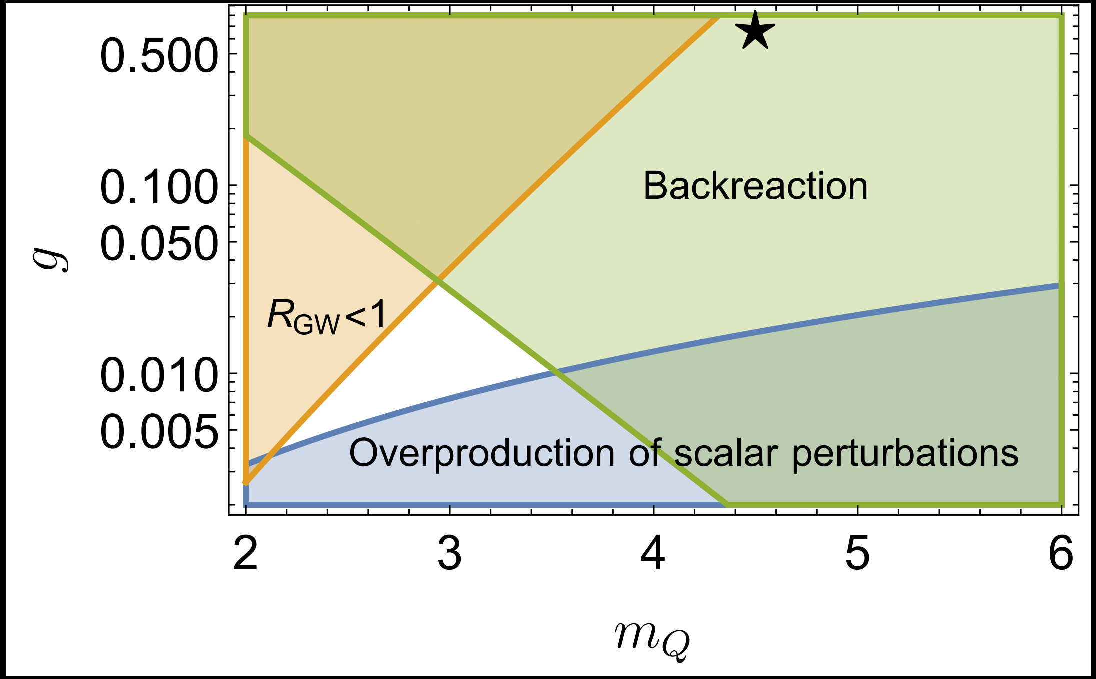


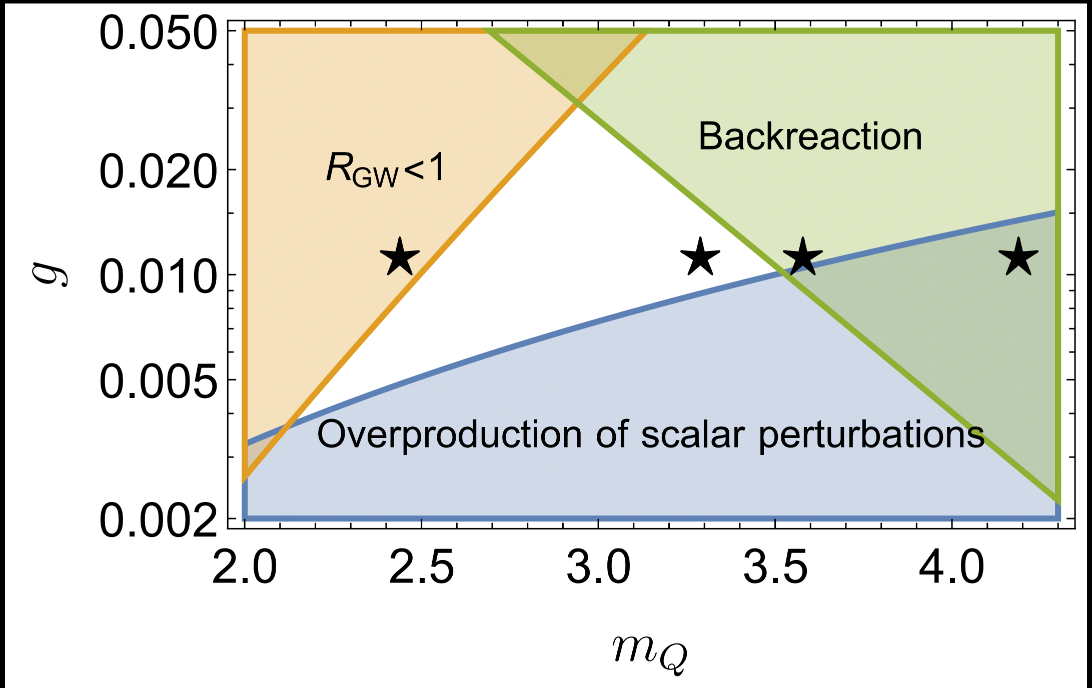
We need to know the dynamics in

the backreaction regime!

Fiducial parameters for numerical simulations

The Pencil Code

[OI, E. I. Sfakianakis, R. Sharma, A. Brandenburg, 2023]

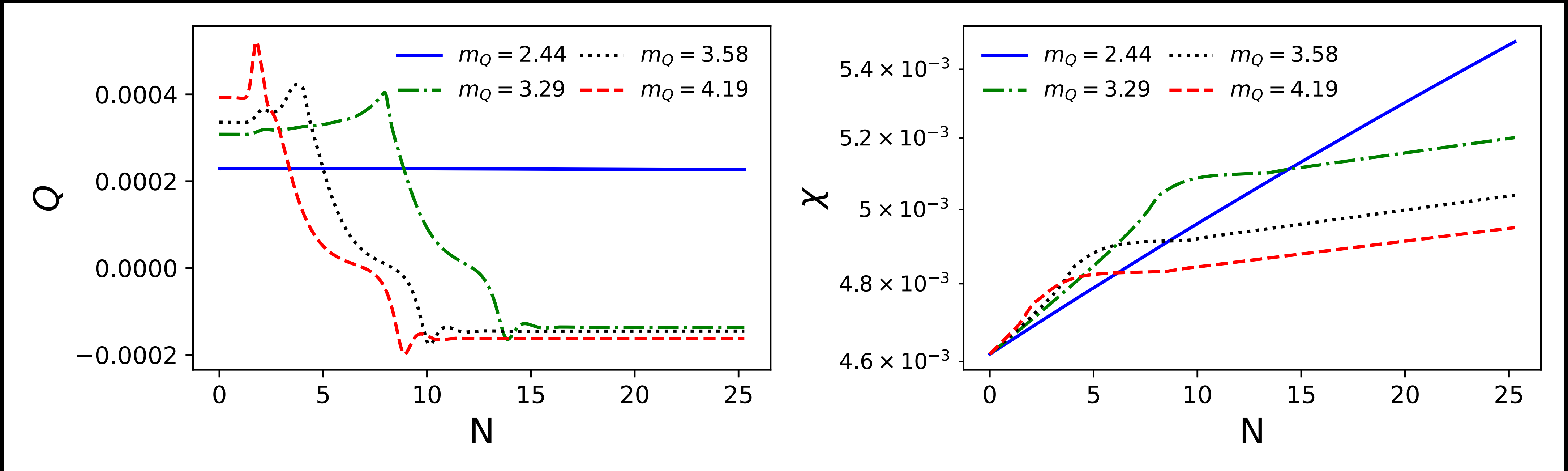


$$F^a_{\mu\nu} = \partial_\mu A^a_\nu - \partial_\nu A^a_\mu - g\epsilon^{abc} A^b_\mu A^c_\nu$$

$$m_Q = \frac{gQ}{H}$$

Novel backreaction-supported attractor

[OI, E. I. Sfakianakis, R. Sharma, A. Brandenburg, 2023]



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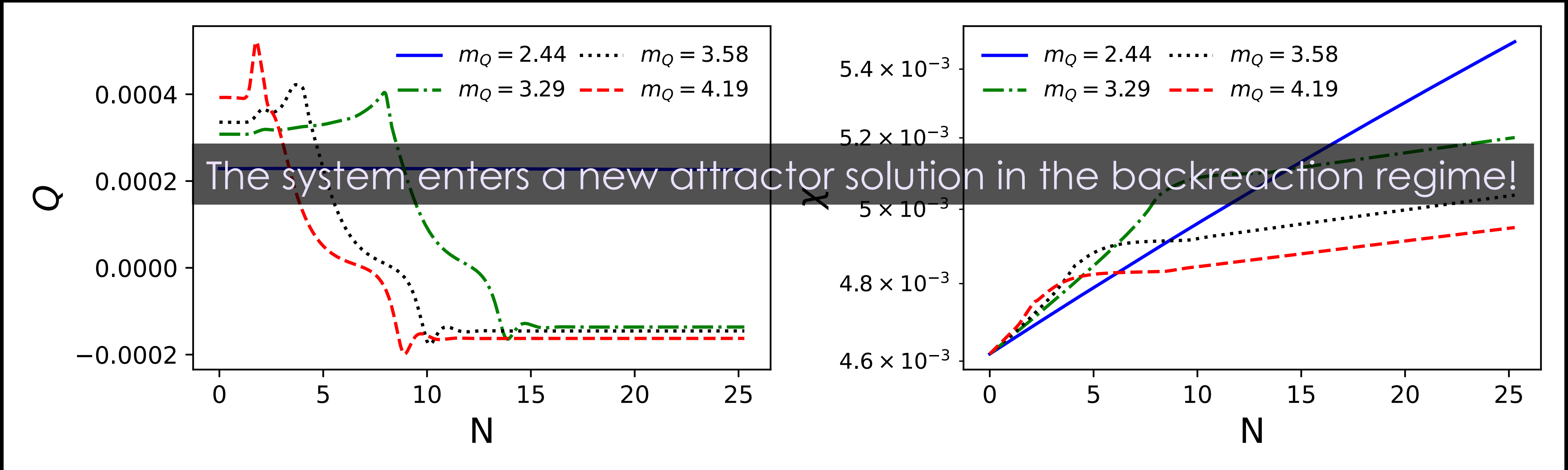
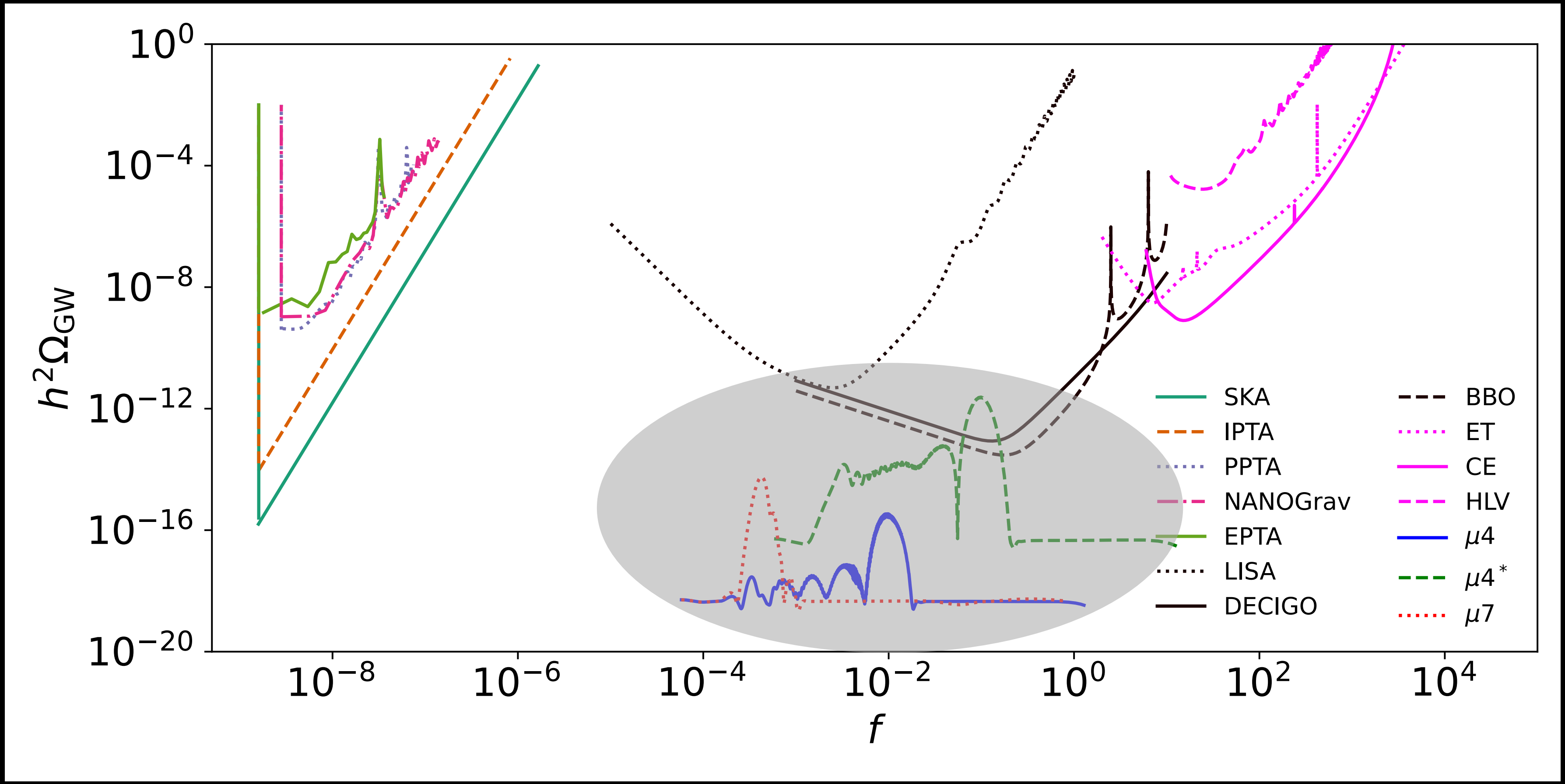


The system enters a new attractor solution in the backreaction regime!

$$\frac{\lambda}{af}\chi' \simeq -\frac{2H^2}{gQ}, \qquad Q \simeq \text{const}$$

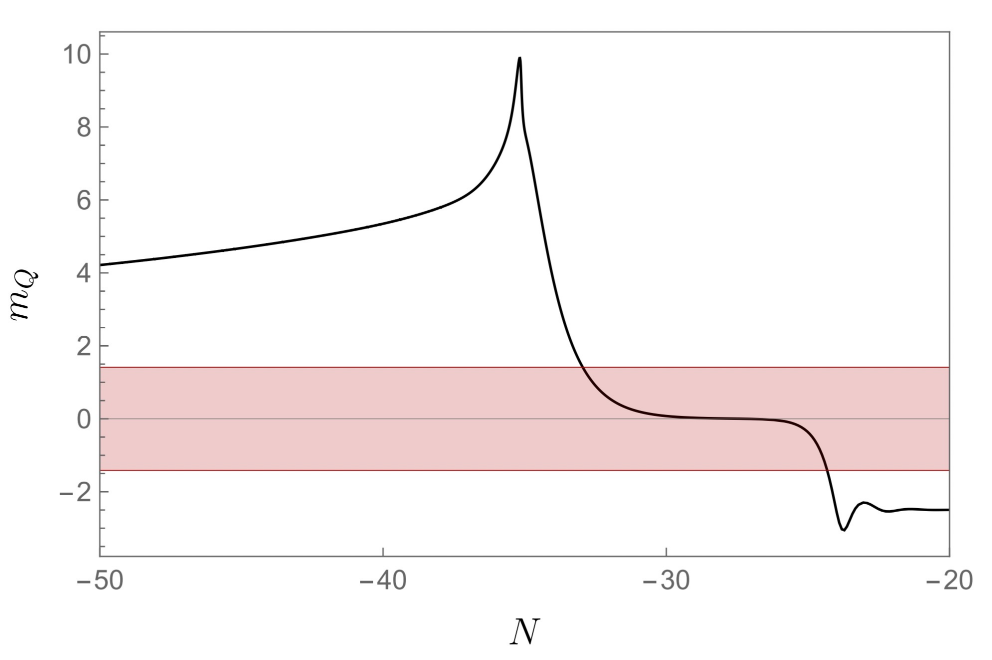
Oscillatory features in gravitational waves

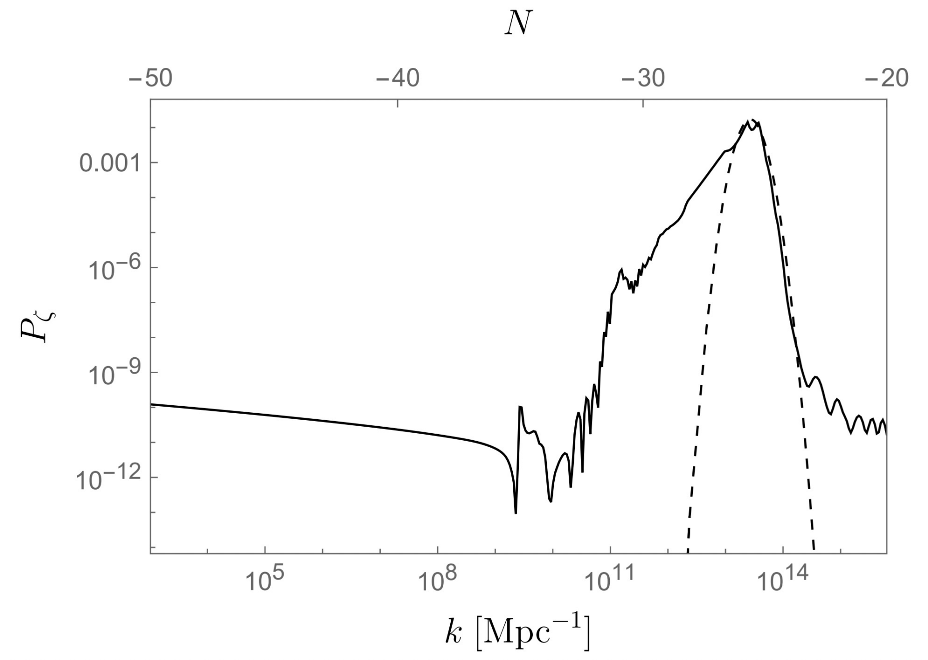


[OI, E. I. Sfakianakis, R. Sharma, A. Brandenburg, 2023]

Primordial black holes in the backreaction regime

$|m_Q| < \sqrt{2}$ instability band leads to primordial black holes production





[E. Dimastrogiovanni, M. Fasiello, A. Papageorgiou, 2024]

Primordial magnetic fields: why care?

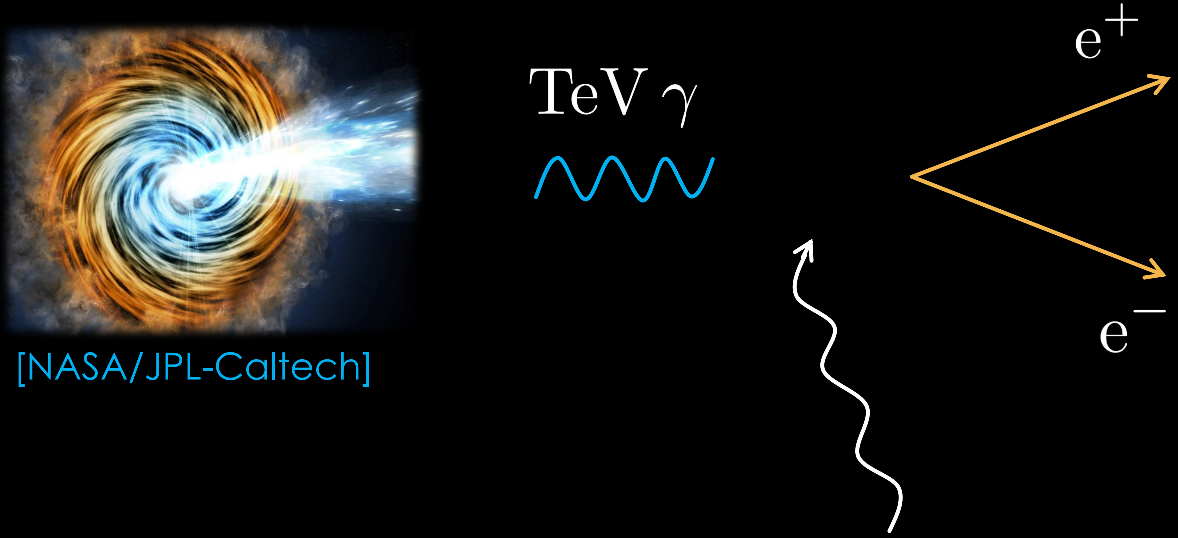
Primordial magnetic fields in intergalactic voids from blazar observations

Blazar

[NASA/JPL-Caltech]

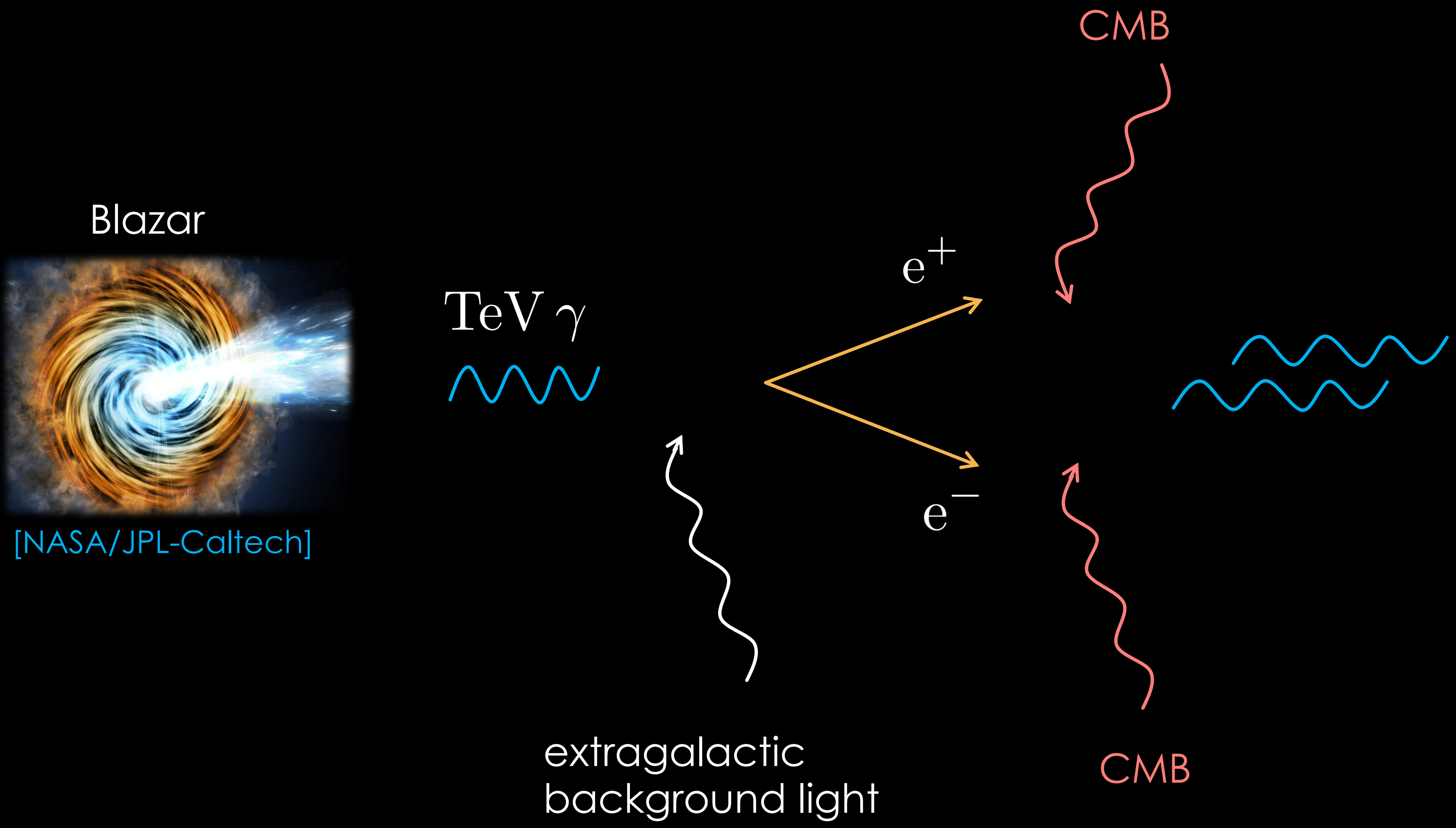
TeV γ

Primordial magnetic fields in intergalactic voids from blazar observations

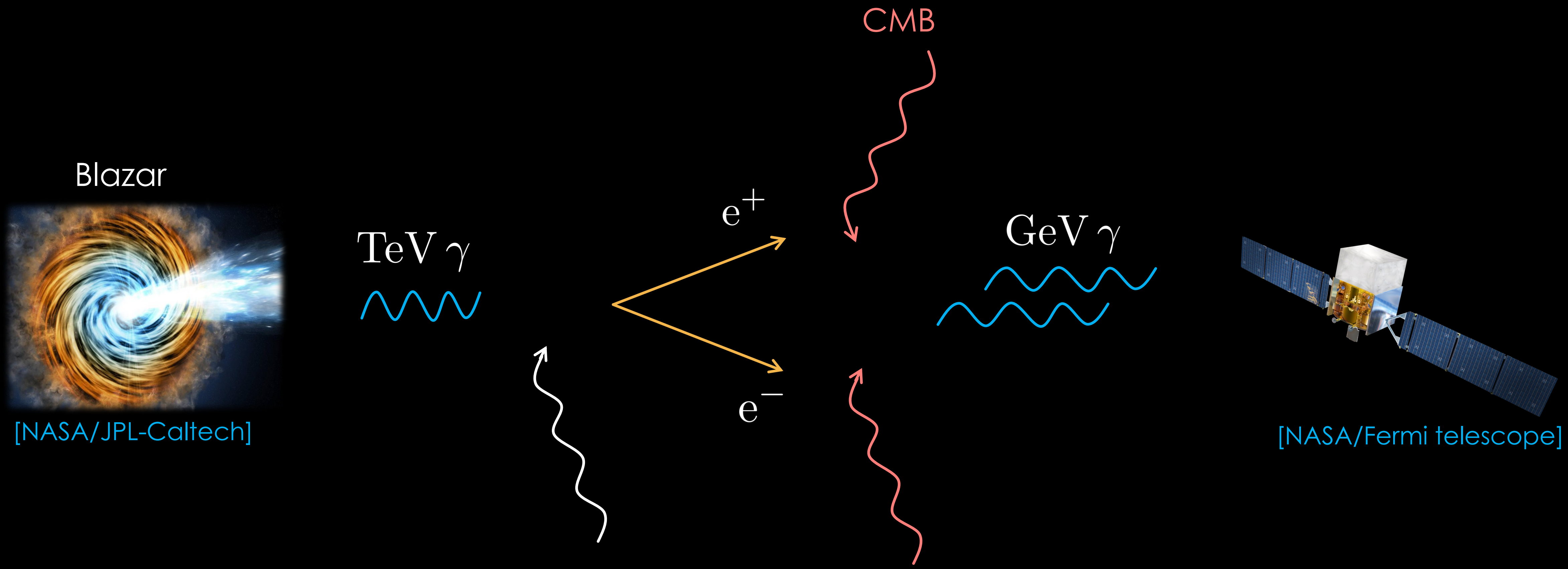


[NASA/JPL-Caltech]

Primordial magnetic fields in intergalactic voids from blazar observations

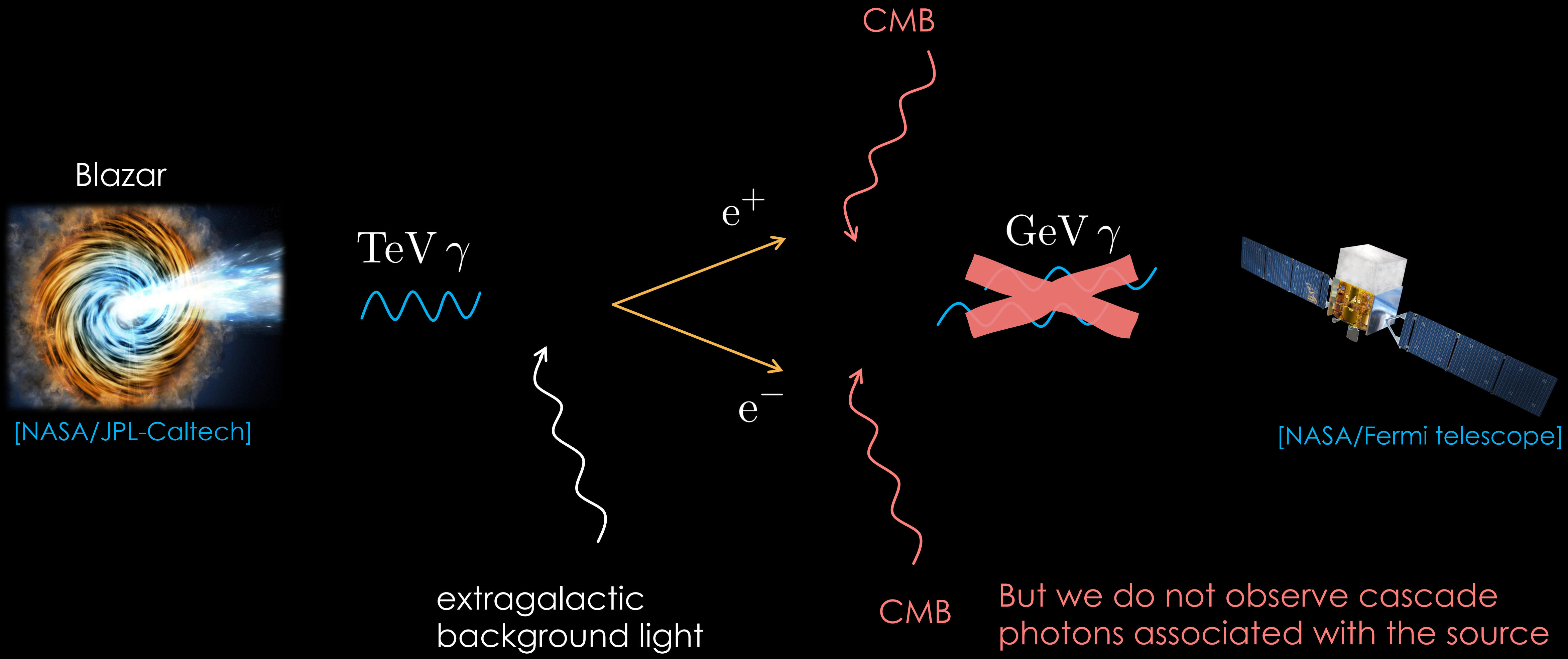


Primordial magnetic fields in intergalactic voids from blazar observations



TeV blazars should be observed to have GeV halos

Primordial magnetic fields in intergalactic voids from blazar observations



But we do not observe cascade photons associated with the source

Primordial magnetic fields in intergalactic voids from blazar observations

Blazar

[NASA/JPL-Caltech]

TeV γ

B

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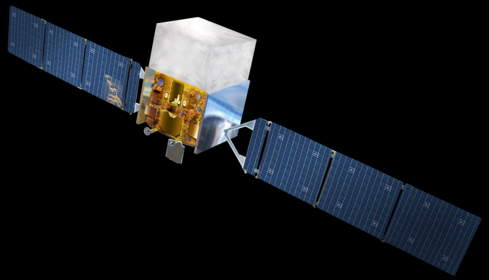
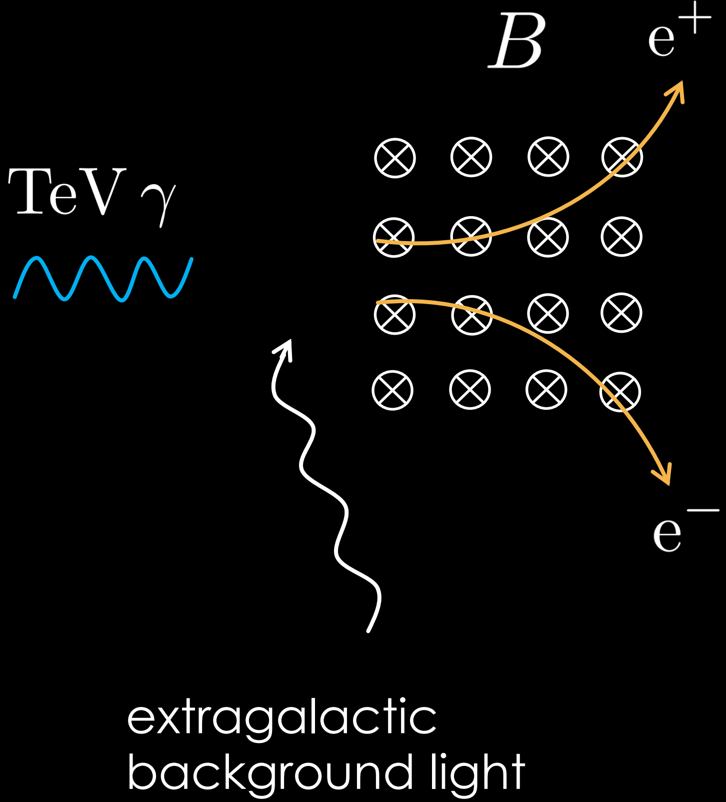


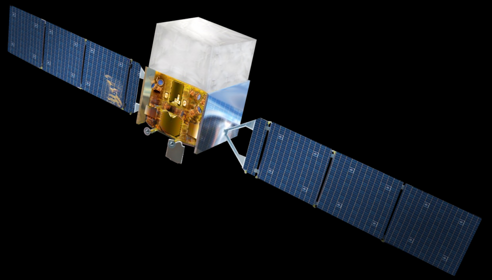
[NASA/Fermi telescope]

Primordial magnetic fields in intergalactic voids from blazar observations

Blazar

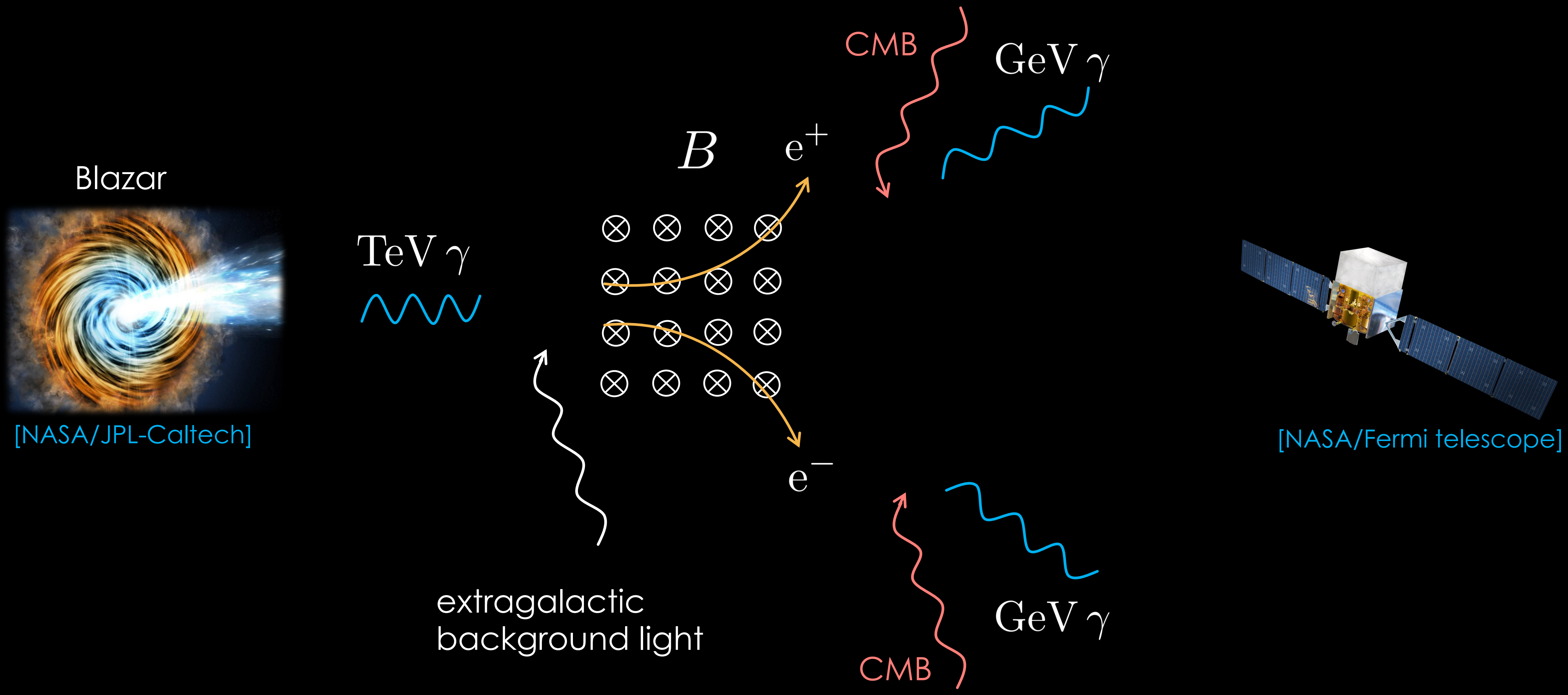
[NASA/JPL-Caltech]





[NASA/Fermi telescope]

Primordial magnetic fields in intergalactic voids from blazar observations



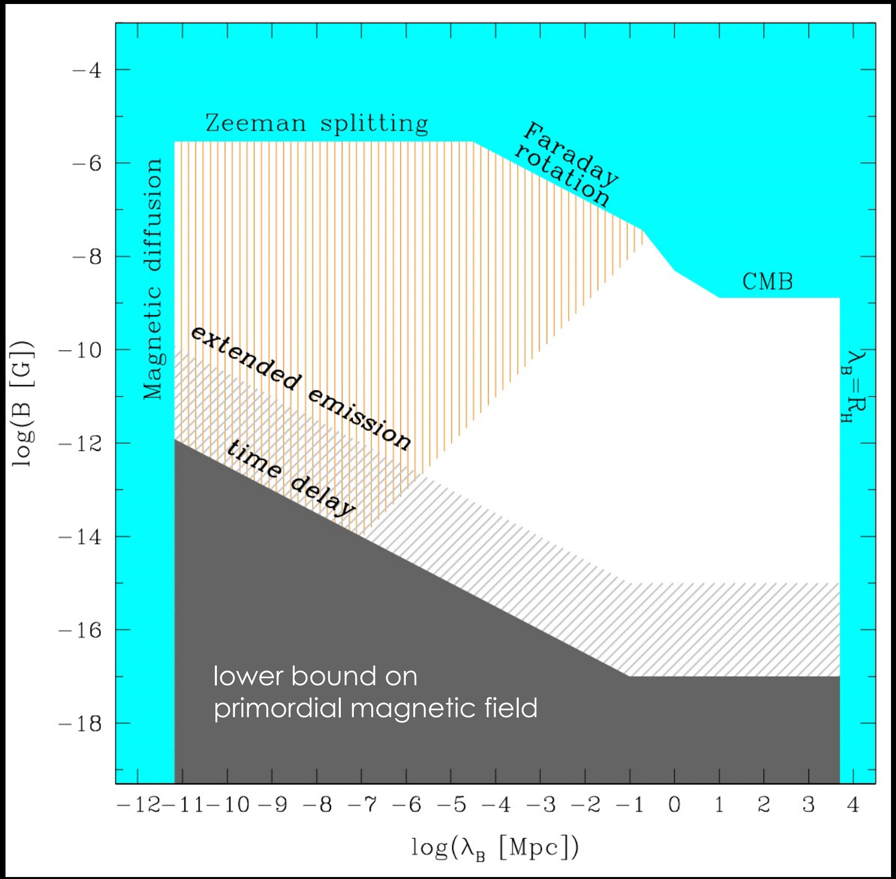
Primordial magnetic fields in intergalactic voids from blazar observations

$B \gtrsim 10^{-15}\text{G}$ with correlation length $\gtrsim$ Mpc

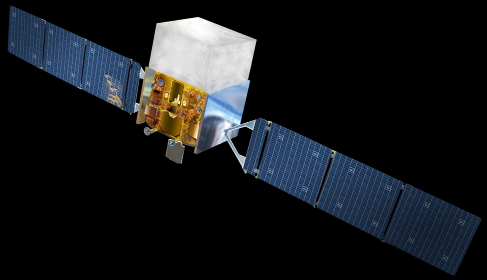
Blazar

[NASA/JPL-Caltech]

TeV γ



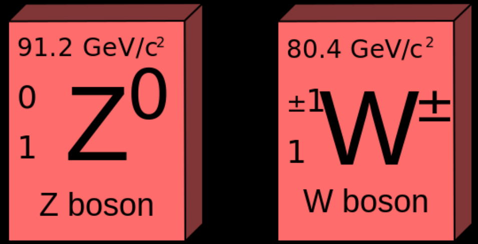
[A. M. Taylor, I. Vovk and A. Neronov, 2013]



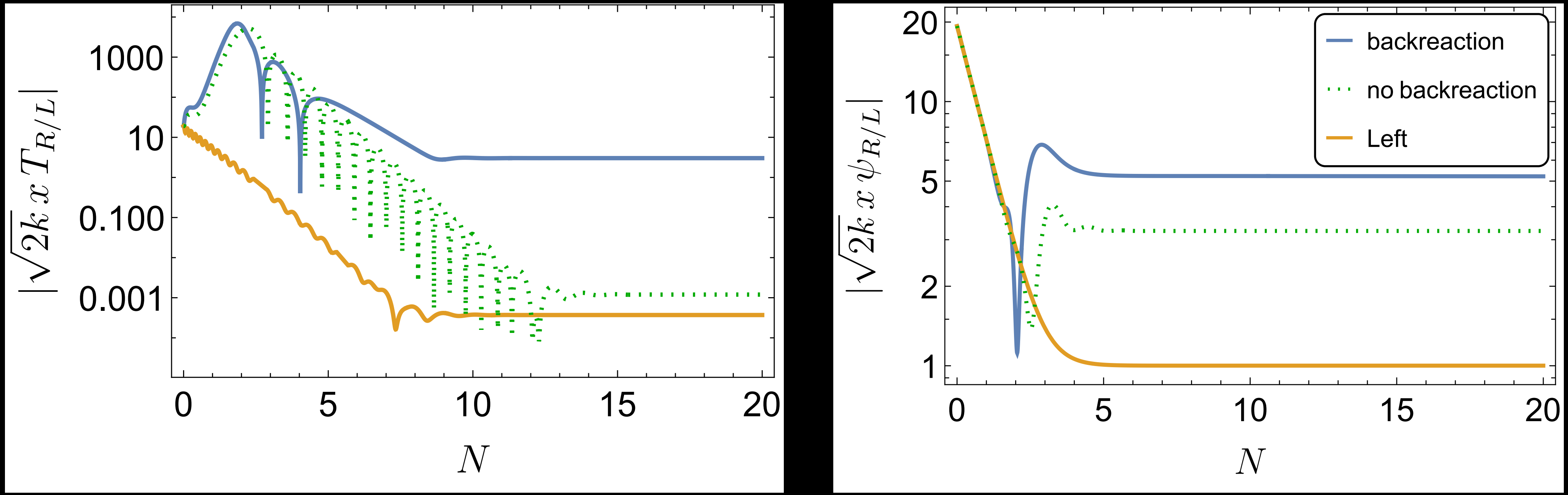
[NASA/Fermi telescope]

[Tavecchio et al, 2010; Neronov, Vovk, 2010;
Ando, Kusenko, 2010; Chen et al. 2014; Fermi-LAT 2018; …]

$\mathrm{SU}(2) \longleftrightarrow$



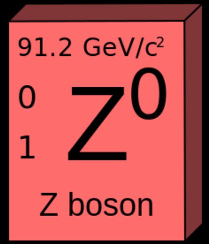
[OI, E. I. Sfakianakis, R. Sharma, A. Brandenburg, 2023]

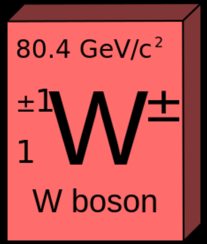


$$W_0^a = a(Y_a + \partial_a Y)\,,$$

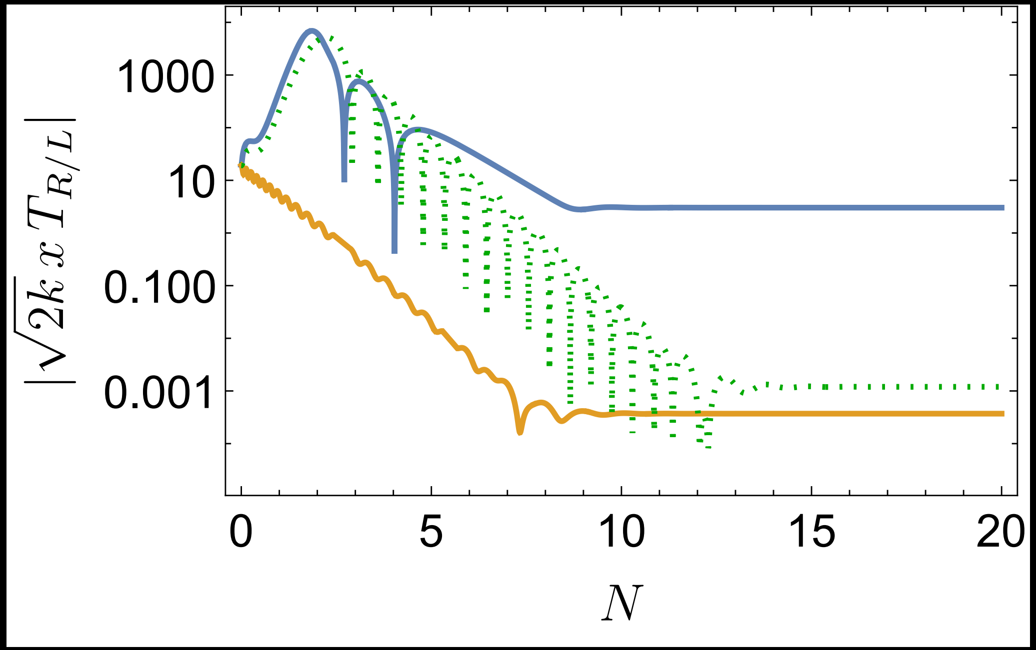
$$W_i^a = a\left[(Q + \delta Q)\,\delta_{ai} + \partial_i\,(M_a + \partial_a M) + \epsilon_{iac}\,(U_c + \partial_c U) + t_{ia}\right]$$

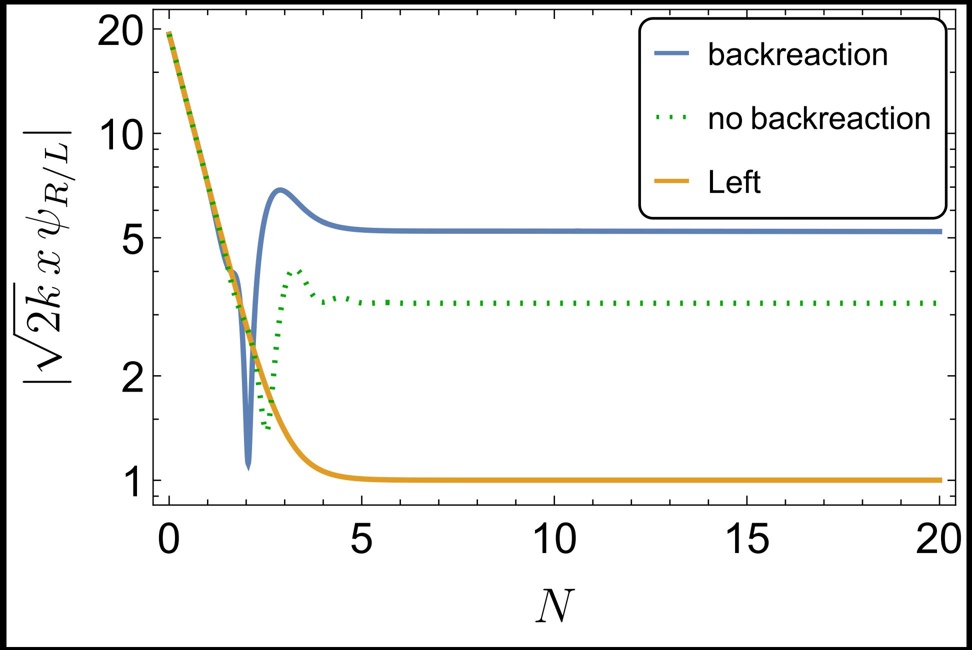
$\mathrm{SU}(2) \quad \longleftrightarrow$





[OI, E. I. Sfakianakis, R. Sharma, A. Brandenburg, 2023]





$$A_\mu = W^3_\mu \sin\theta_W + B_\mu \cos\theta_W$$

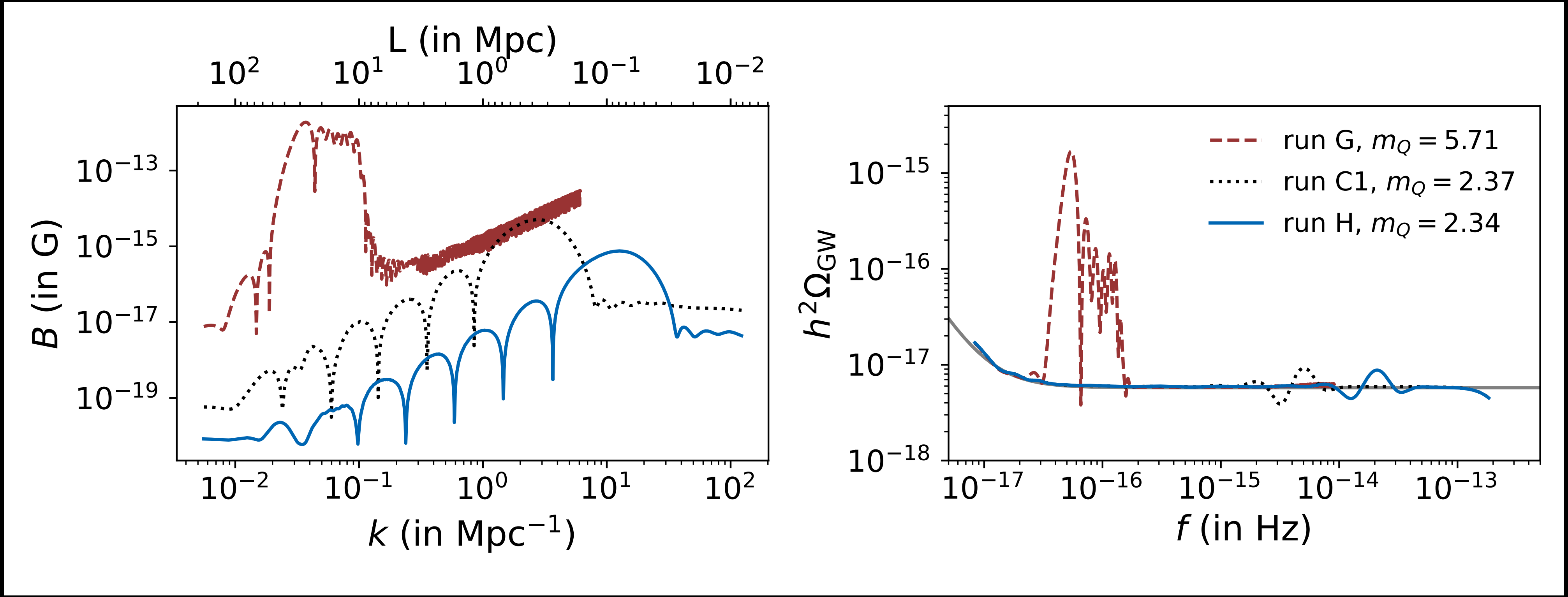
$$Z_\mu = W^3_\mu \cos\theta_W - B_\mu \sin\theta_W$$

$$|A_i|^2 = \frac{1}{4}\left(|T_L|^2 + |T_R|^2\right)$$

Magnetic field energy spectrum

[A. Brandenburg, OI, E. I. Sfakianakis, R. Sharma, 2024]

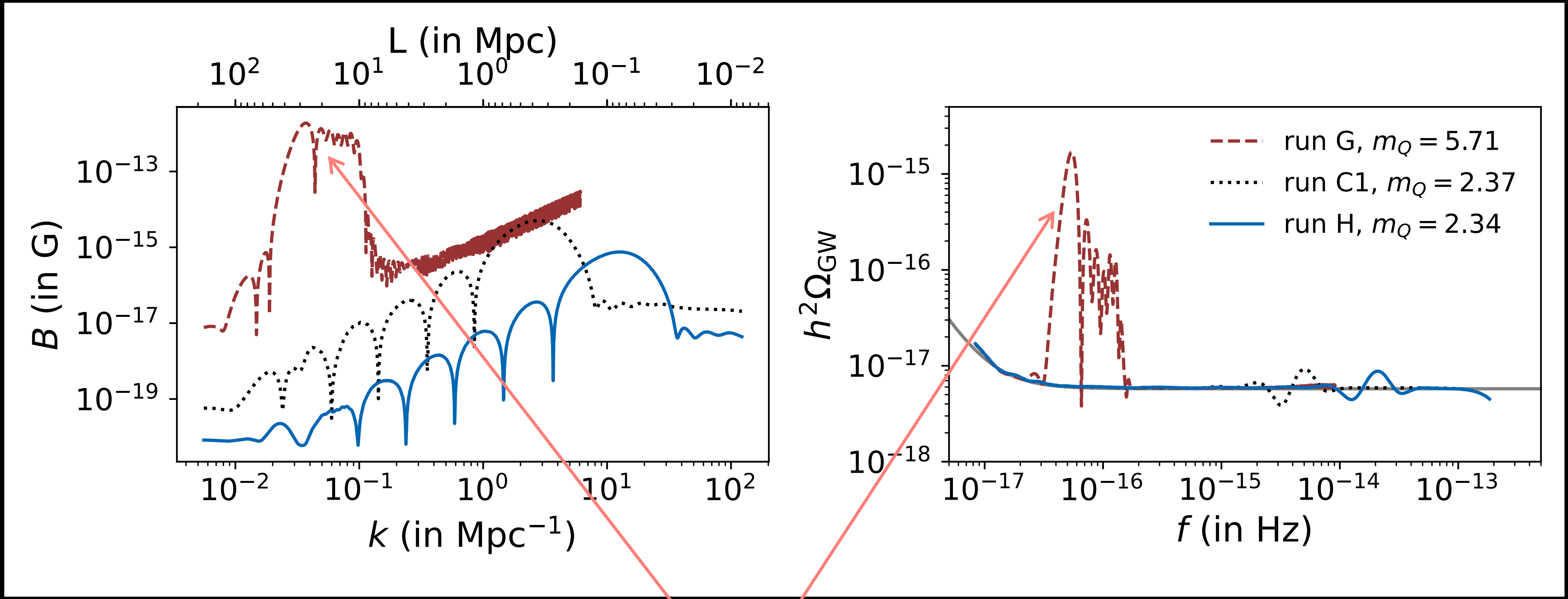
$$\Delta_{\rm B}(k) = \frac{1}{(2\pi)^2}\frac{k^5}{a^4}|A_i|^2 \qquad B \approx \sqrt{2\Delta_{\rm B}(k)\big|_0}$$



Magnetic field energy spectrum

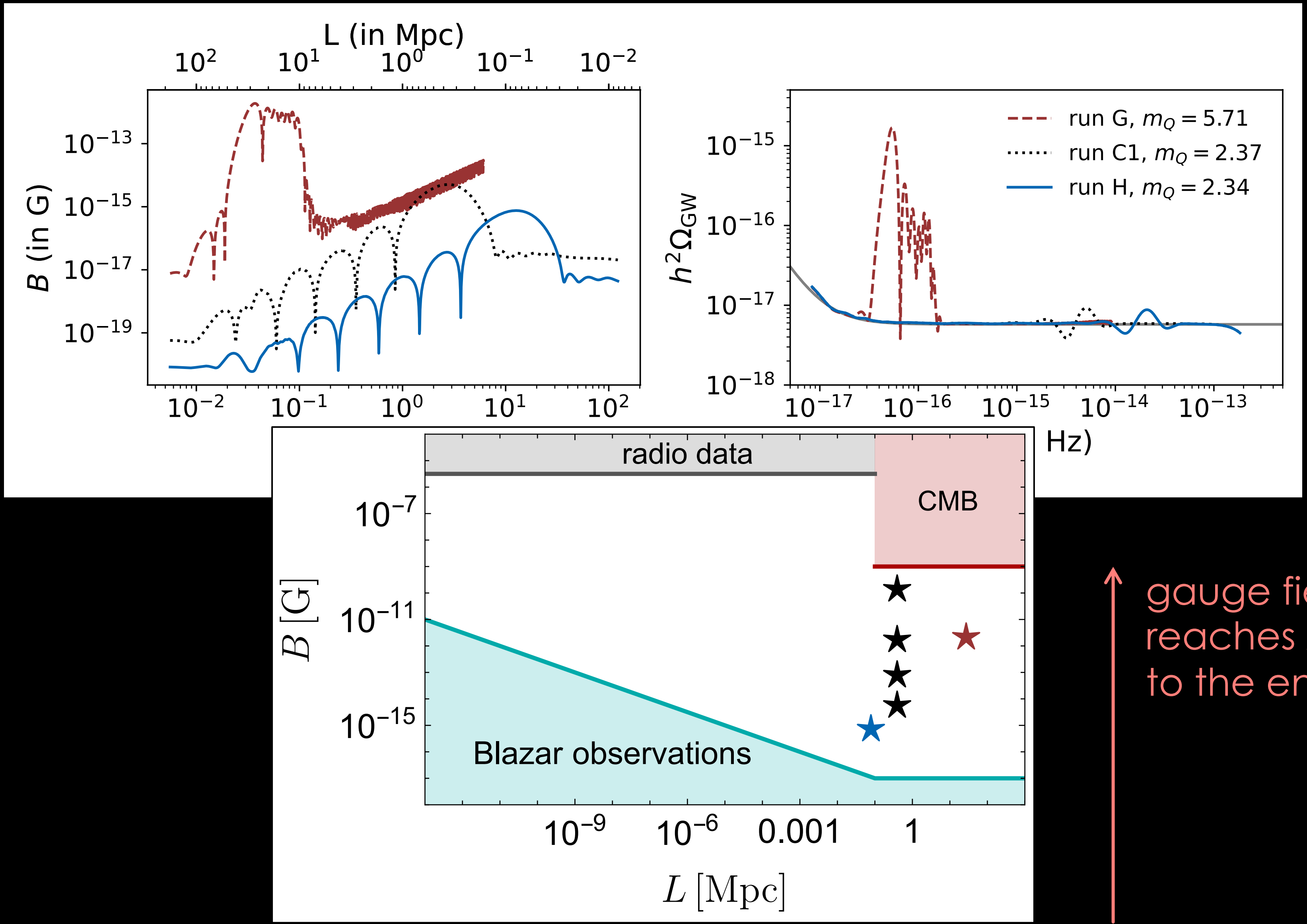
[A. Brandenburg, OI, E. I. Sfakianakis, R. Sharma, 2024]

$$\Delta_B(k) = \frac{1}{(2\pi)^2}\frac{k^5}{a^4}|A_i|^2 \qquad B \approx \sqrt{2\Delta_B(k)|_0}$$



Correlated signal from primordial magnetic fields and gravitational waves

Magnetic field energy spectrum

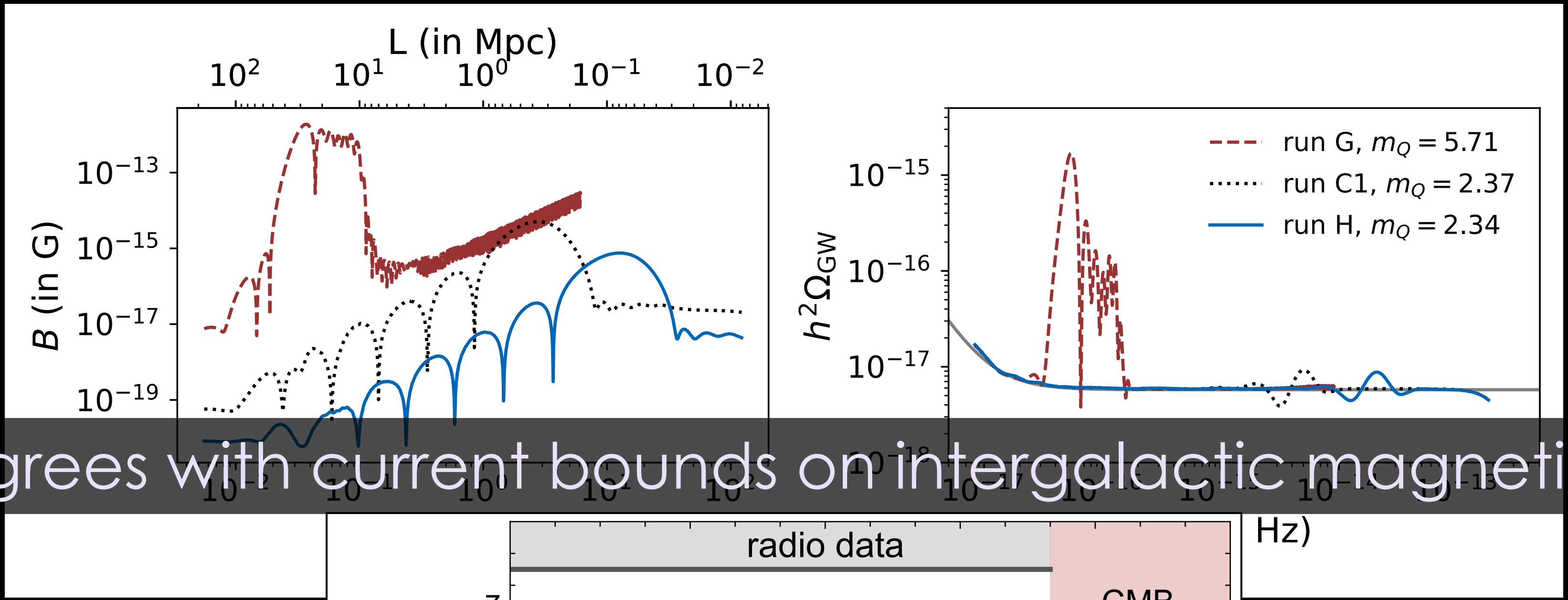


gauge field vev reaches zero close to the end of inflation

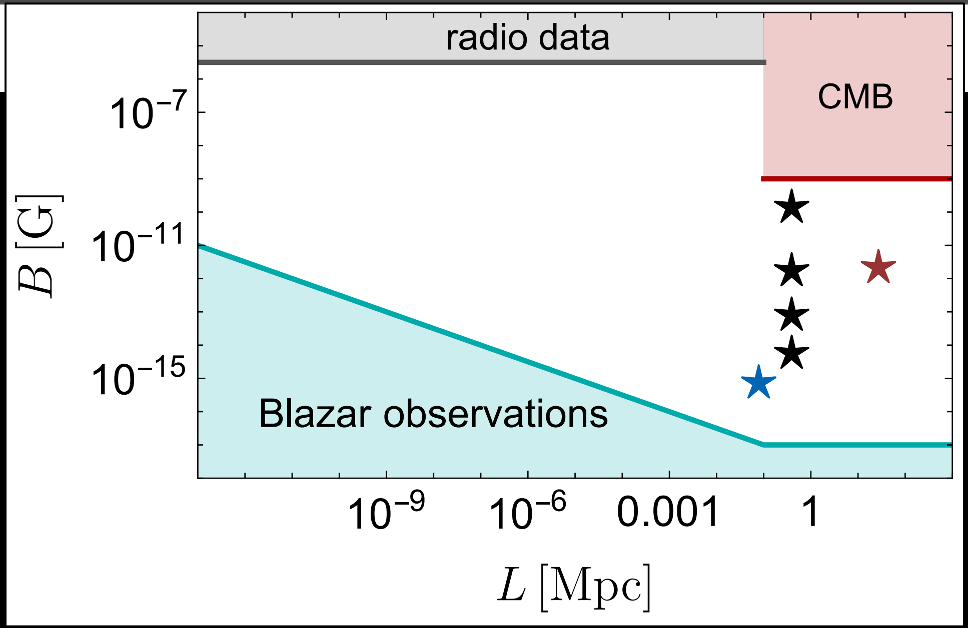
larger instability

[A. Brandenburg, OI, E. I. Sfakianakis, R. Sharma, 2024]

Magnetic field energy spectrum



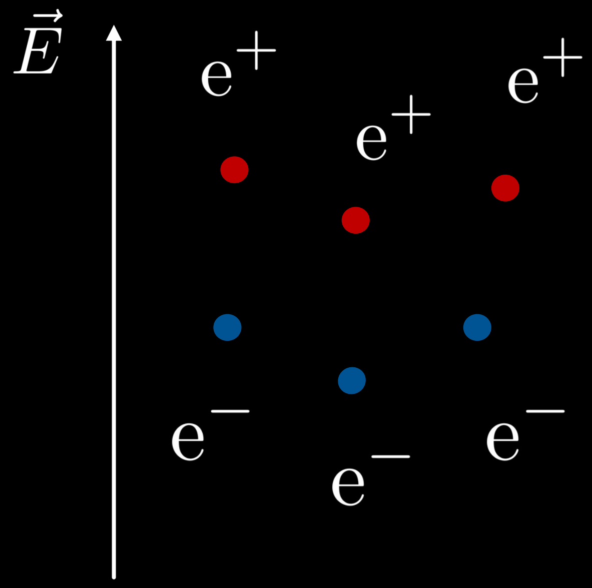
Agrees with current bounds on intergalactic magnetic fields!

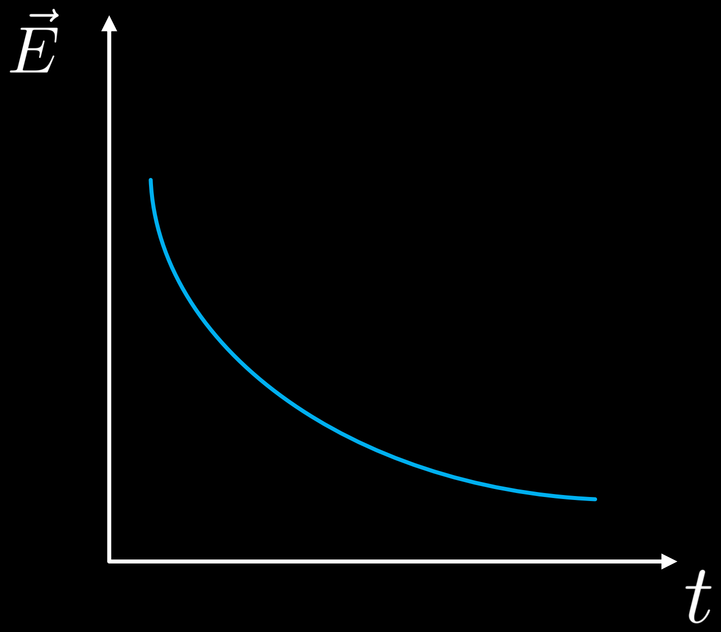


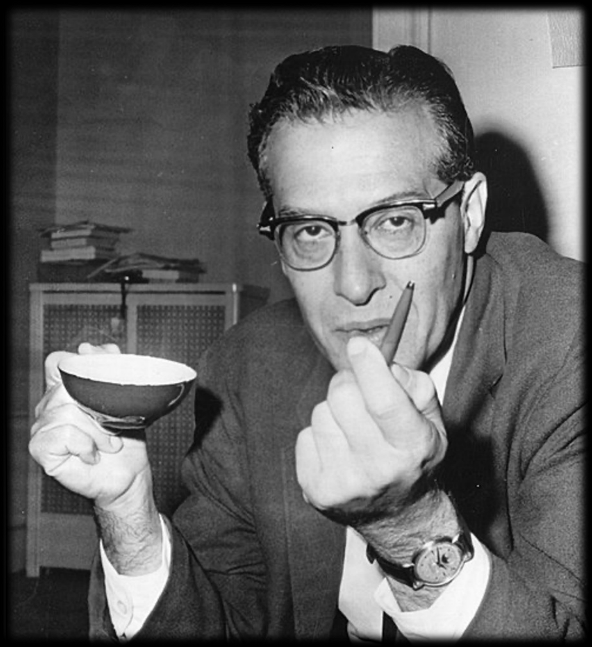
[A. Brandenburg, OI, E. I. Sfakianakis, R. Sharma, 2024]

What about the backreaction from electric currents?

Schwinger effect







[Sauter, 1931,
Heisenberg and Euler, 1936,
Schwinger, 1951]

$$E_c \sim 10^{18}\ \text{V/m}$$

Axion-U(1) inflation

[K. Freese, J. A. Frieman, and A. V. Olinto, 1990]

[M. M. Anber and L. Sorbo, 2009]

$$S = \int d^4x \sqrt{-g} \left[-\frac{1}{2}\partial_\mu\phi\partial^\mu\phi - V(\phi) - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{\alpha}{4f}\phi F_{\mu\nu}\tilde{F}^{\mu\nu} \right]$$

$$F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu$$

Abelian gauge field

Axion-U(1) inflation with the Schwinger effect

[K. Freese, J. A. Frieman, and A. V. Olinto, 1990]

[M. M. Anber and L. Sorbo, 2009]

$$S = \int d^4x \sqrt{-g} \left[-\frac{1}{2}\partial_\mu \phi \partial^\mu \phi - V(\phi) - \frac{1}{4} F_{\mu\nu} F^{\mu\nu} - \frac{\alpha}{4f} \phi F_{\mu\nu} \tilde{F}^{\mu\nu} + \mathcal{L}_{\rm ch} \right]$$

Effective current description of the Schwinger effect

$$J = \frac{(e|Q|)^3}{6\pi^2 \mathcal{H}} E|B| \coth\left(\frac{\pi |B|}{E}\right) e^{-\frac{\pi m^2 a^2}{e|Q|E}}$$

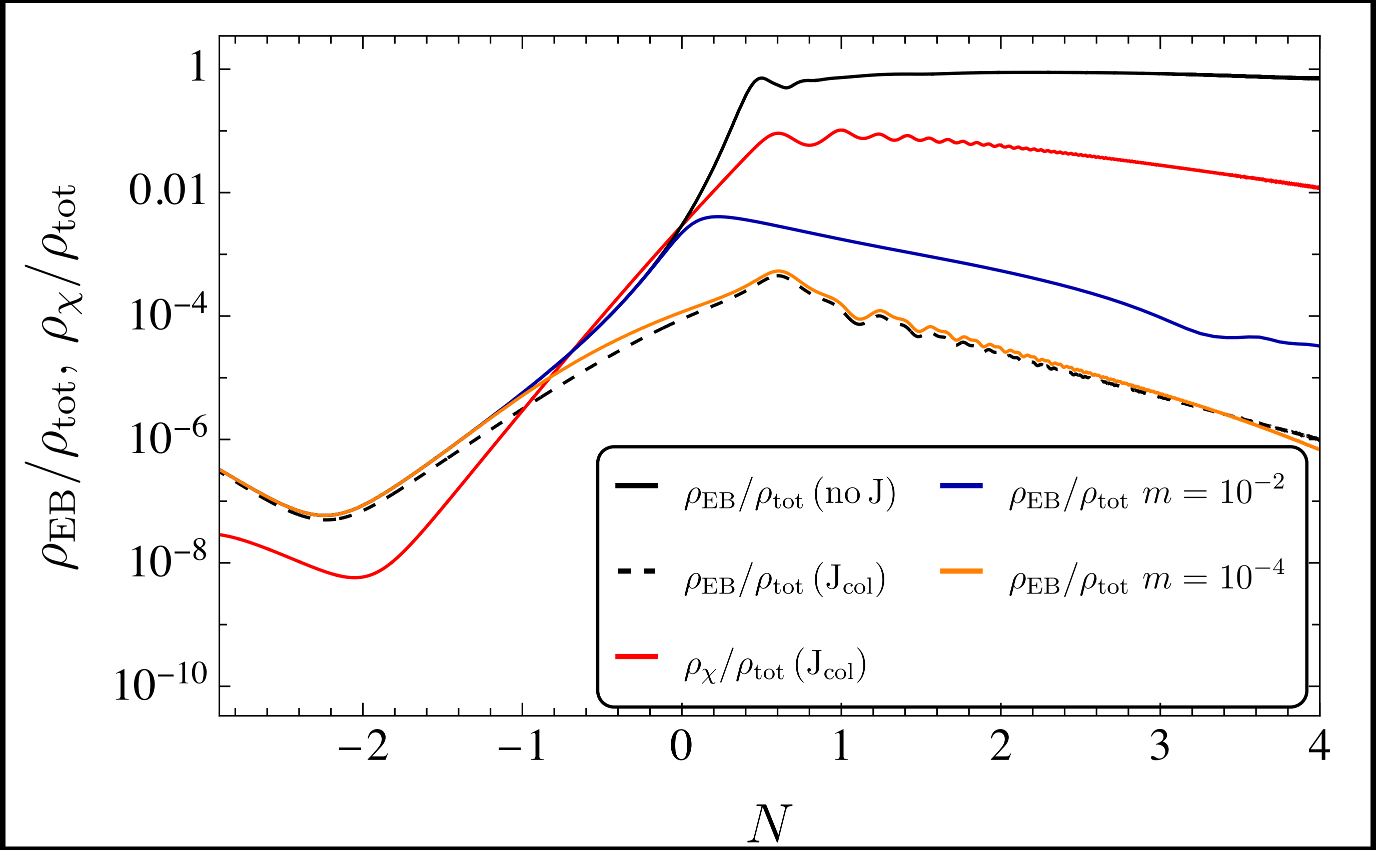
[Kobayashi et al, 2014]
[Bavarsad et al.'18]
[Gorbar et al, 2021]
[Domcke et al, 2018; 2020]
[Fujita et al, 2022]
[von Eckardstein et al, 2025]

Inhomogeneous 3D lattcie simulations using

The Pencil Code

a high-order finite-difference code for compressible MHD

$$\partial_\tau \rho_\chi + 4\mathcal{H}\rho_\chi = \frac{1}{a^3}\left(\langle\sigma_E\rangle\,\langle \boldsymbol{E}^2\rangle + \langle\sigma_B\rangle\langle \boldsymbol{E}\cdot\boldsymbol{B}\rangle\right)$$

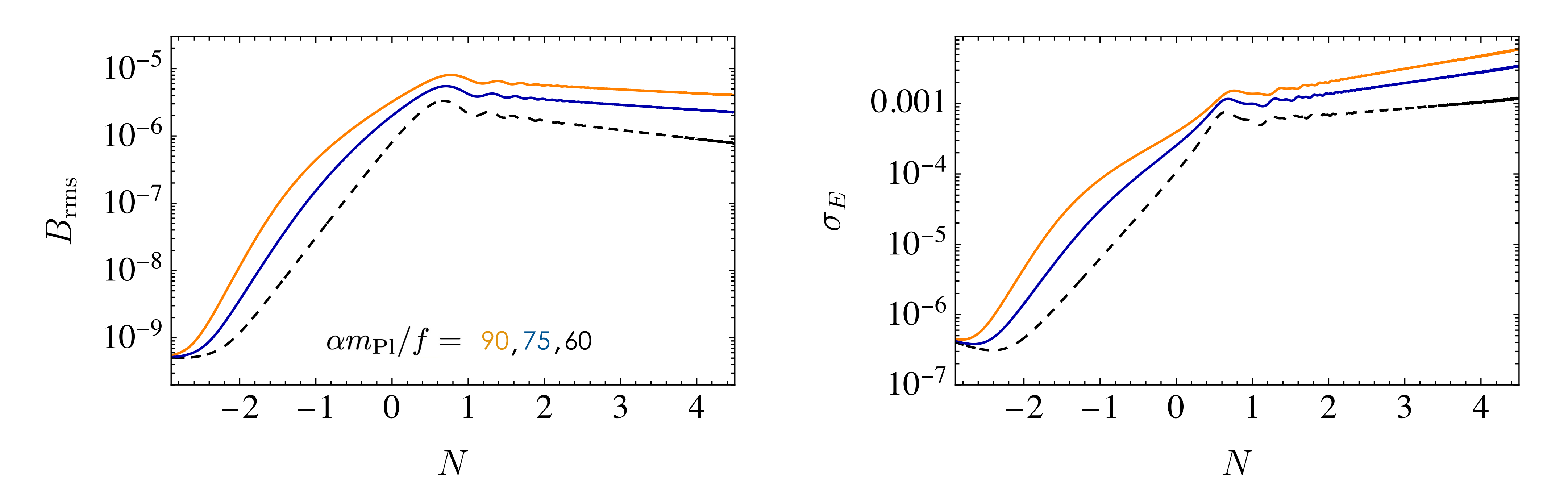


Schwinger suppression challenges gauge preheating!

[OI, A. Brandenburg, E. Sfakianakis, 2025]

Universality of the Schwinger backreaction

[OI, A. Brandenburg, E. Sfakianakis, 2025]



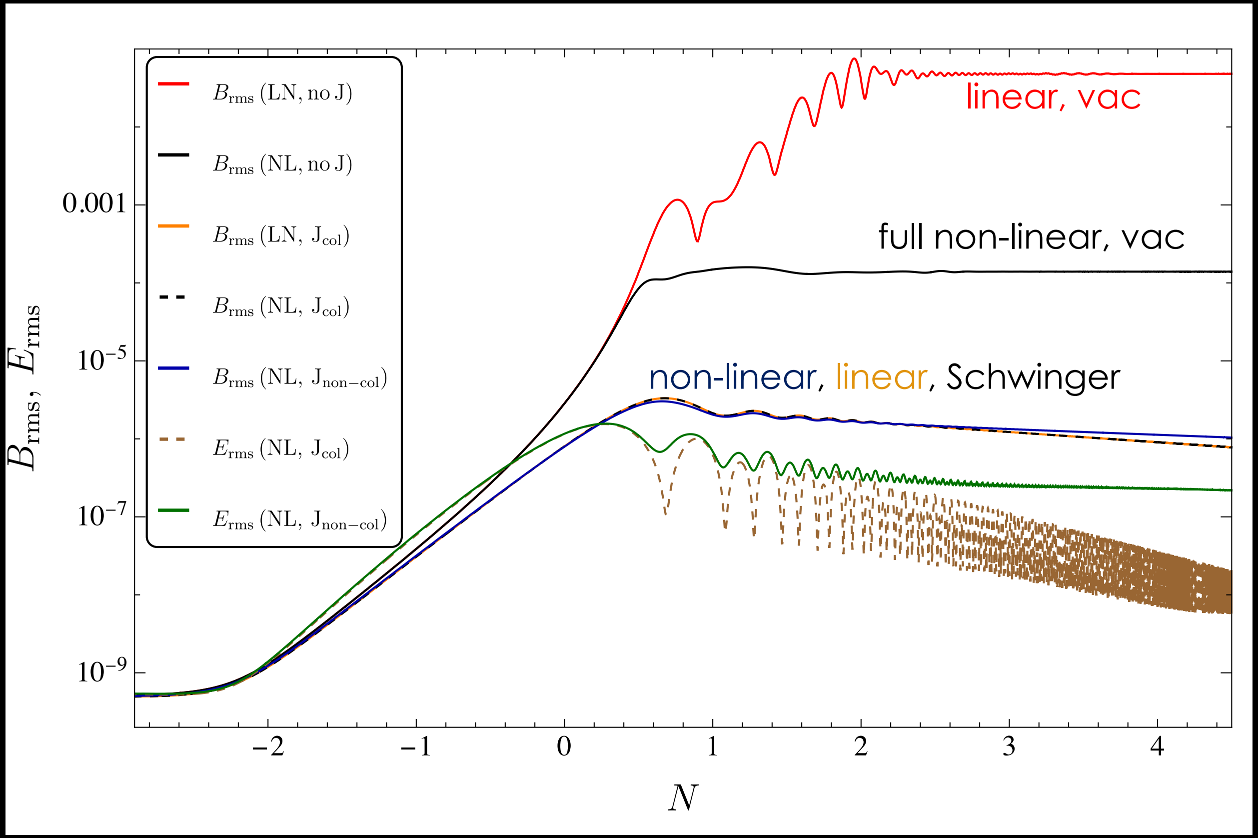
universal suppression for large couplings!

Universality of the Schwinger backreaction

Similar suppression for

- linear
- non-linear
- homoheneous
- inhomogeneous regimes

–> semi-analytical techniques are possible!

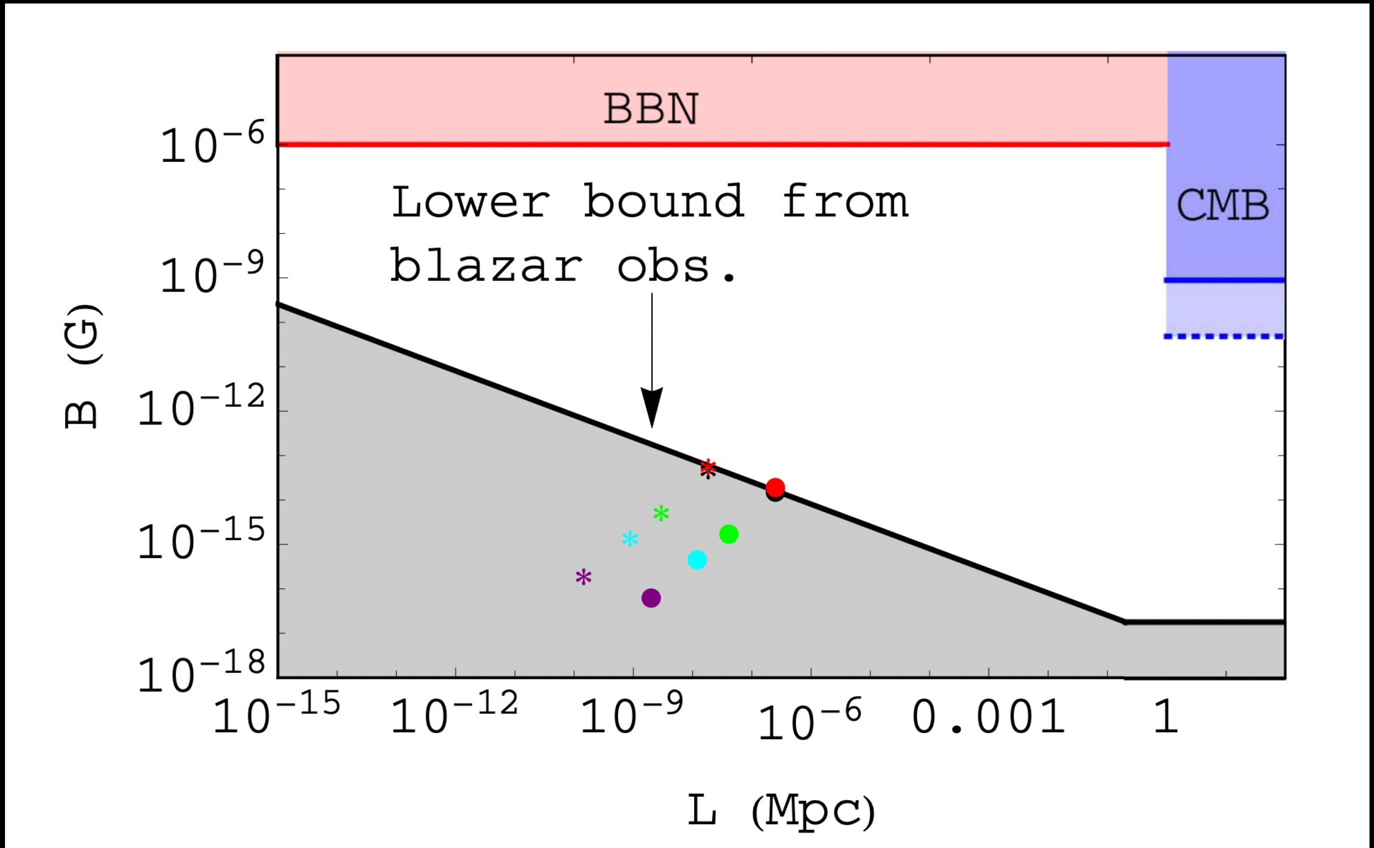


[OI, A. Brandenburg, E. Sfakianakis, 2025]

Schwinger effect becomes important before the onset of the strong backreaction regime!

Consequences for magnetogenesis

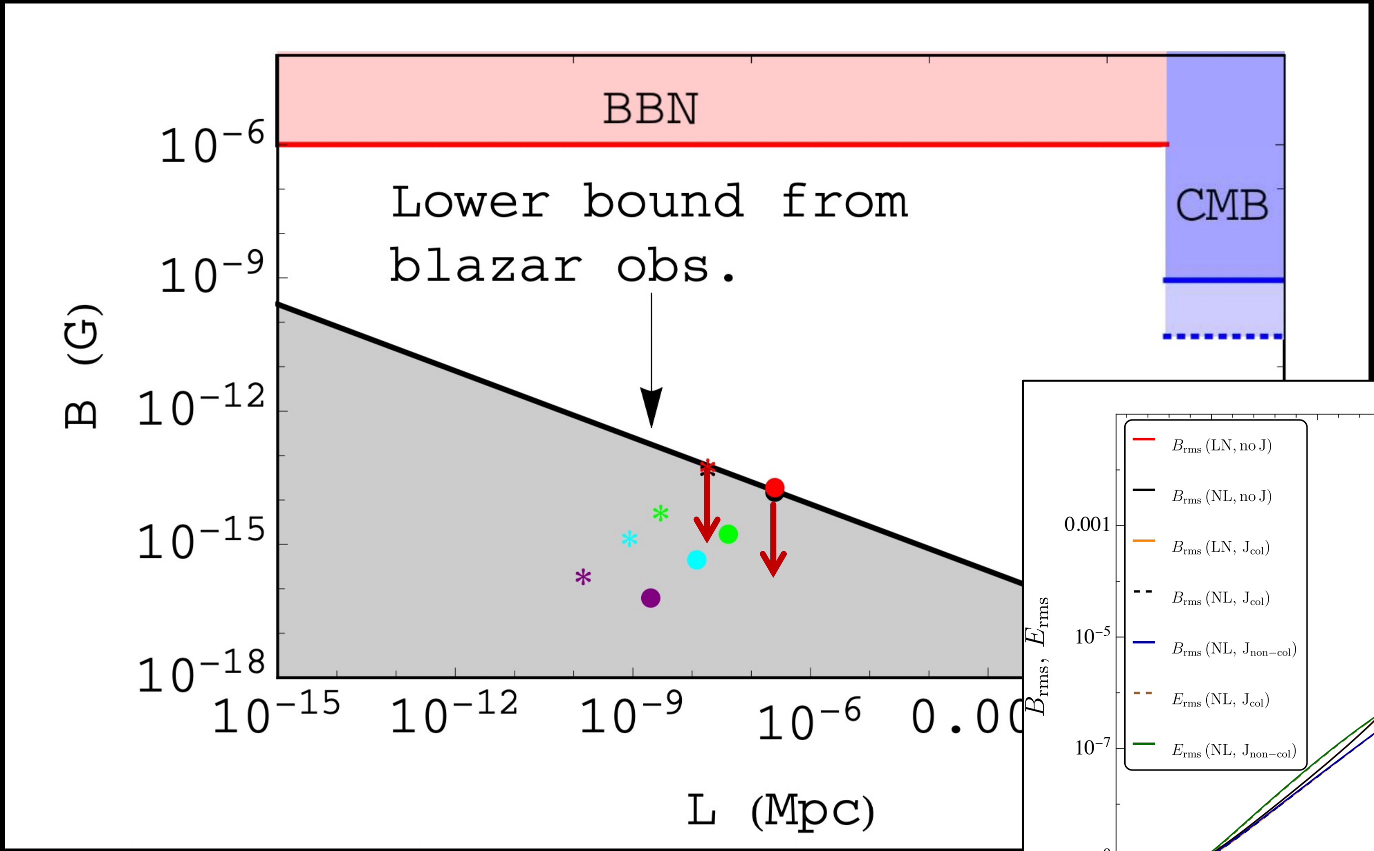
[R. Sharma, A. Brandenburg, K. Subramanian, A. Vikman, 2024]



$$\alpha m_{\rm Pl}/f = 35,\ 50,\ 60, 75,\ 90$$

Consequences for magnetogenesis

[R. Sharma, A. Brandenburg, K. Subramanian, A. Vikman, 2024]



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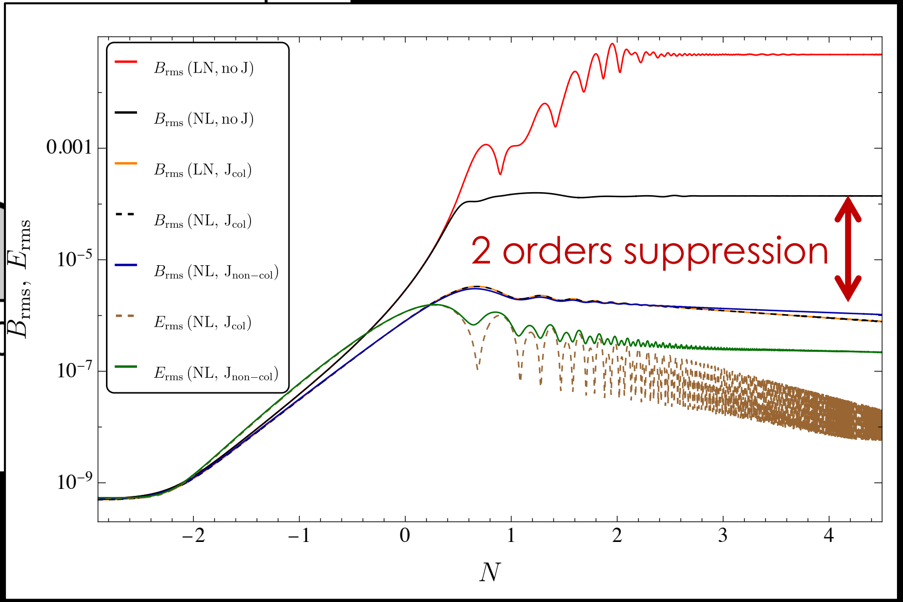

[OI, A. Brandenburg, E. Sfakianakis, 2025]

Consequences for magnetogenesis

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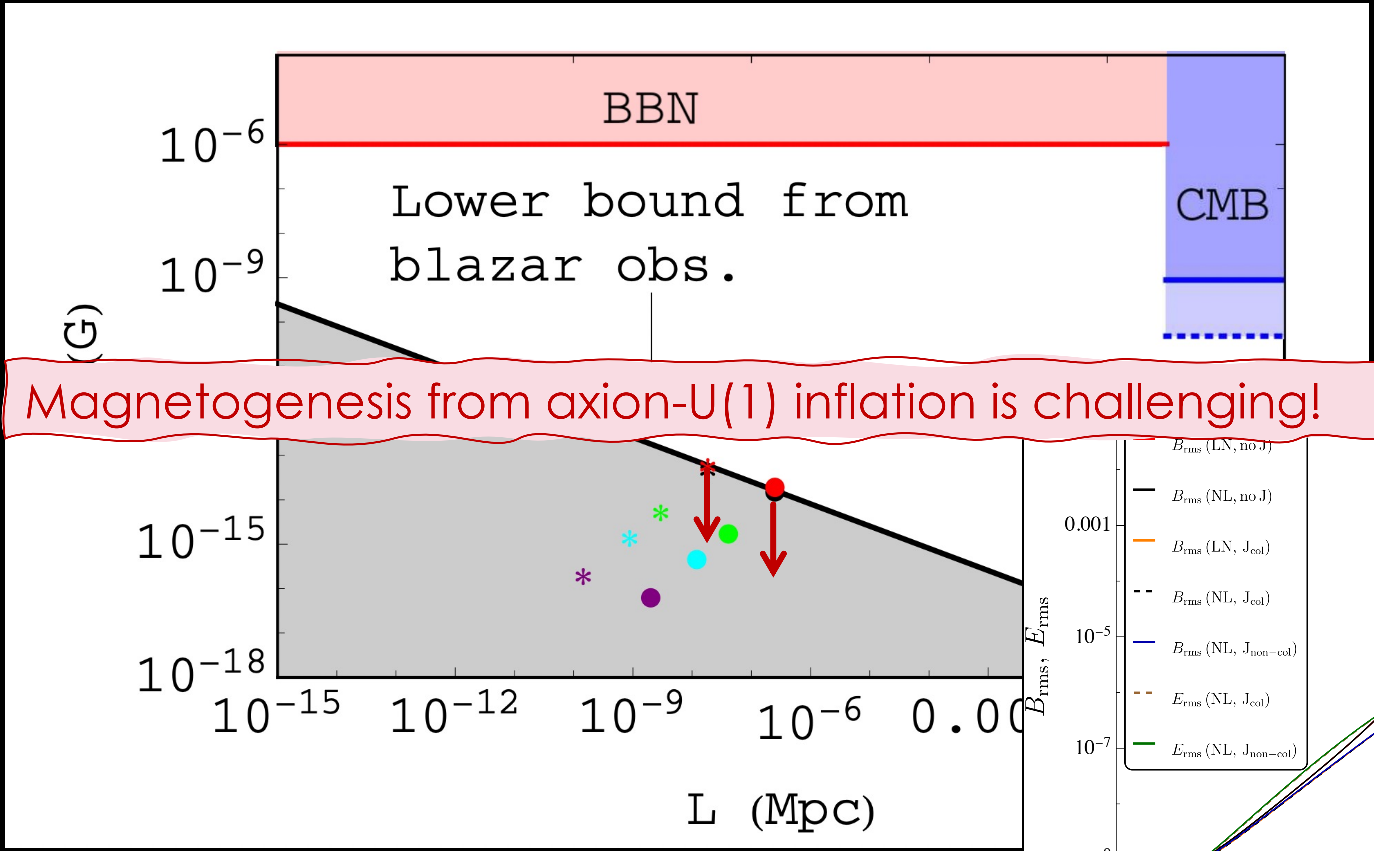
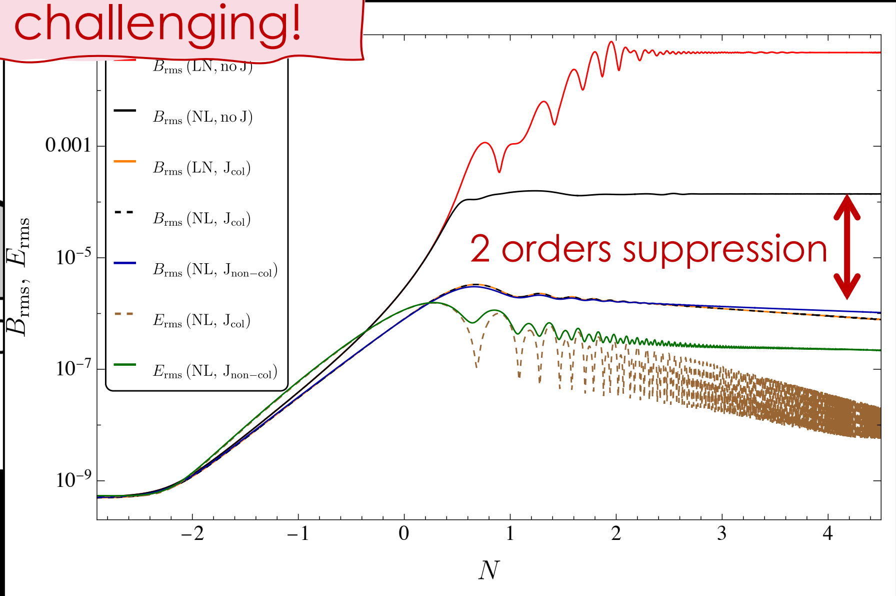


Magnetogenesis from axion-U(1) inflation is challenging!

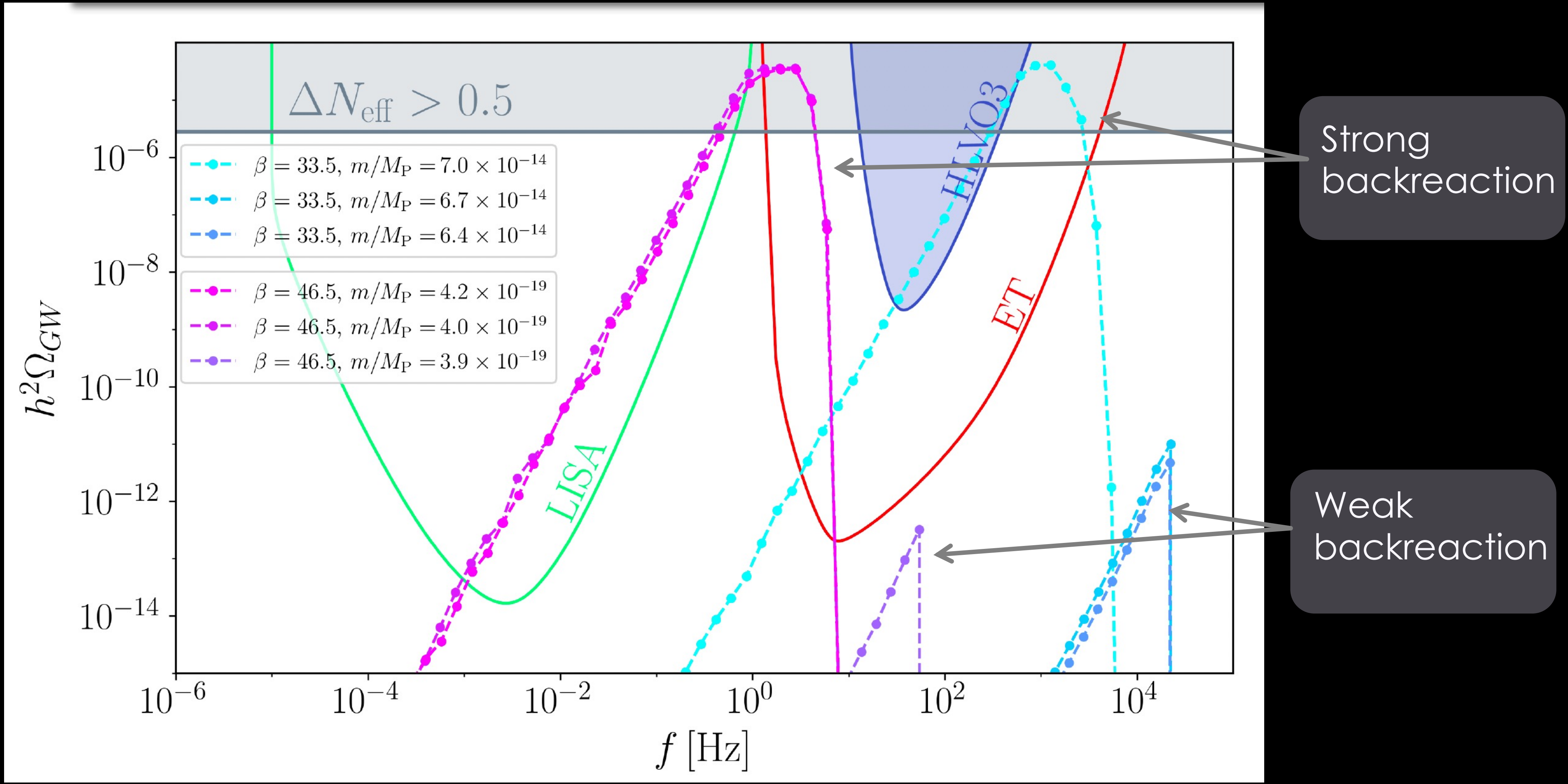
$$\alpha m_{\rm Pl}/f = 35,\ 50,\ 60,\ 75,\ 90$$



[OI, A. Brandenburg, E. Sfakianakis, 2025]

How does the Schwinger effect influence gravitational wave production?

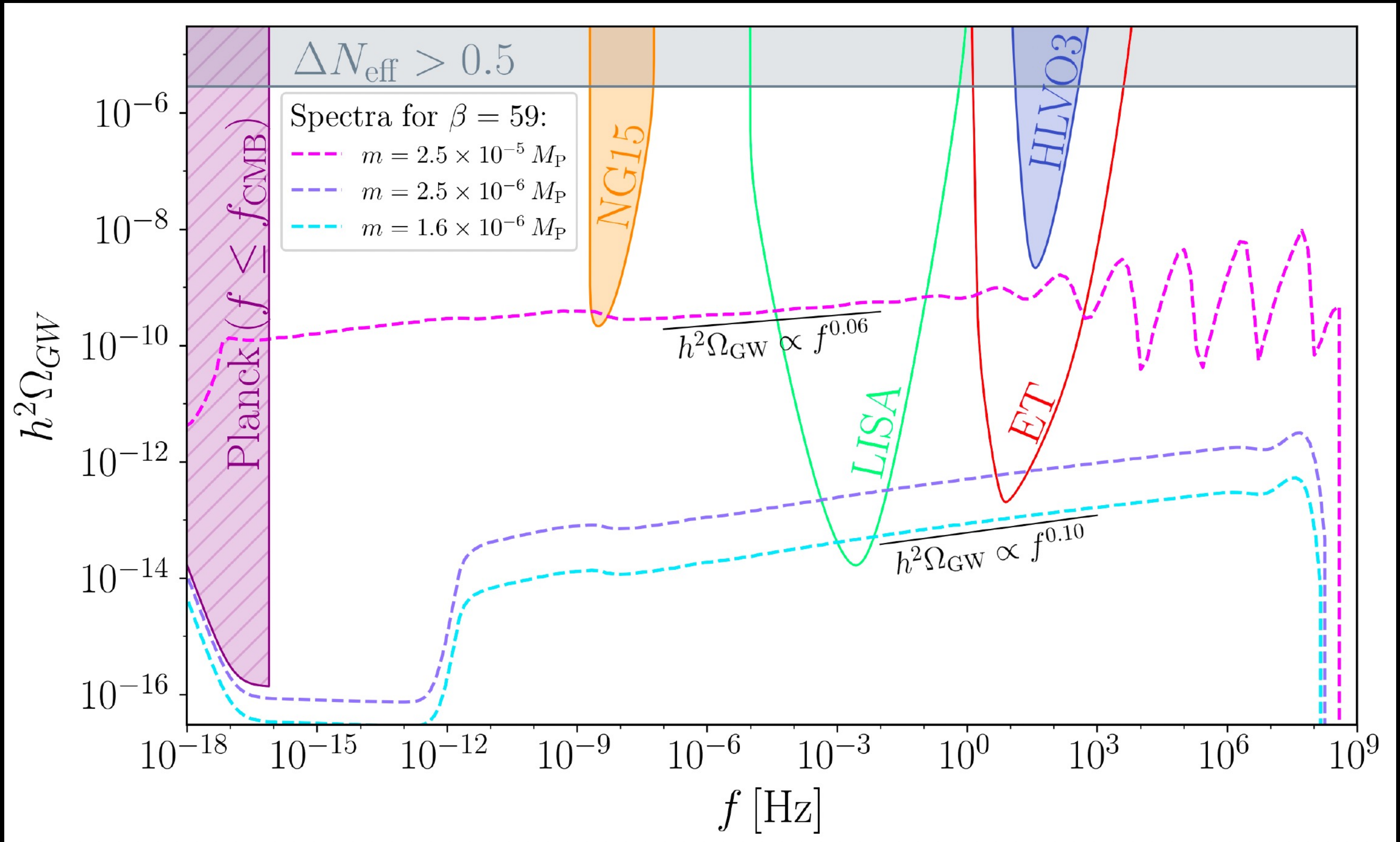
Pure axion-U(1) inflation without the Schwinger effect



[R. von Eckardstein, K. Schmitz, O. Sobol, 2025]

using the Gradient Expansion Formalism (no inhomogeneities)

"Fermionic" axion-U(1) inflation with the Schwinger effect



[R. von Eckardstein, K. Schmitz, O. Sobol, 2025]

using the Gradient Expansion Formalism (no inhomogeneities)

Gravitational waves with the Schwinger effect

Inhomogeneous 3D lattcie simulations with

The Pencil Code
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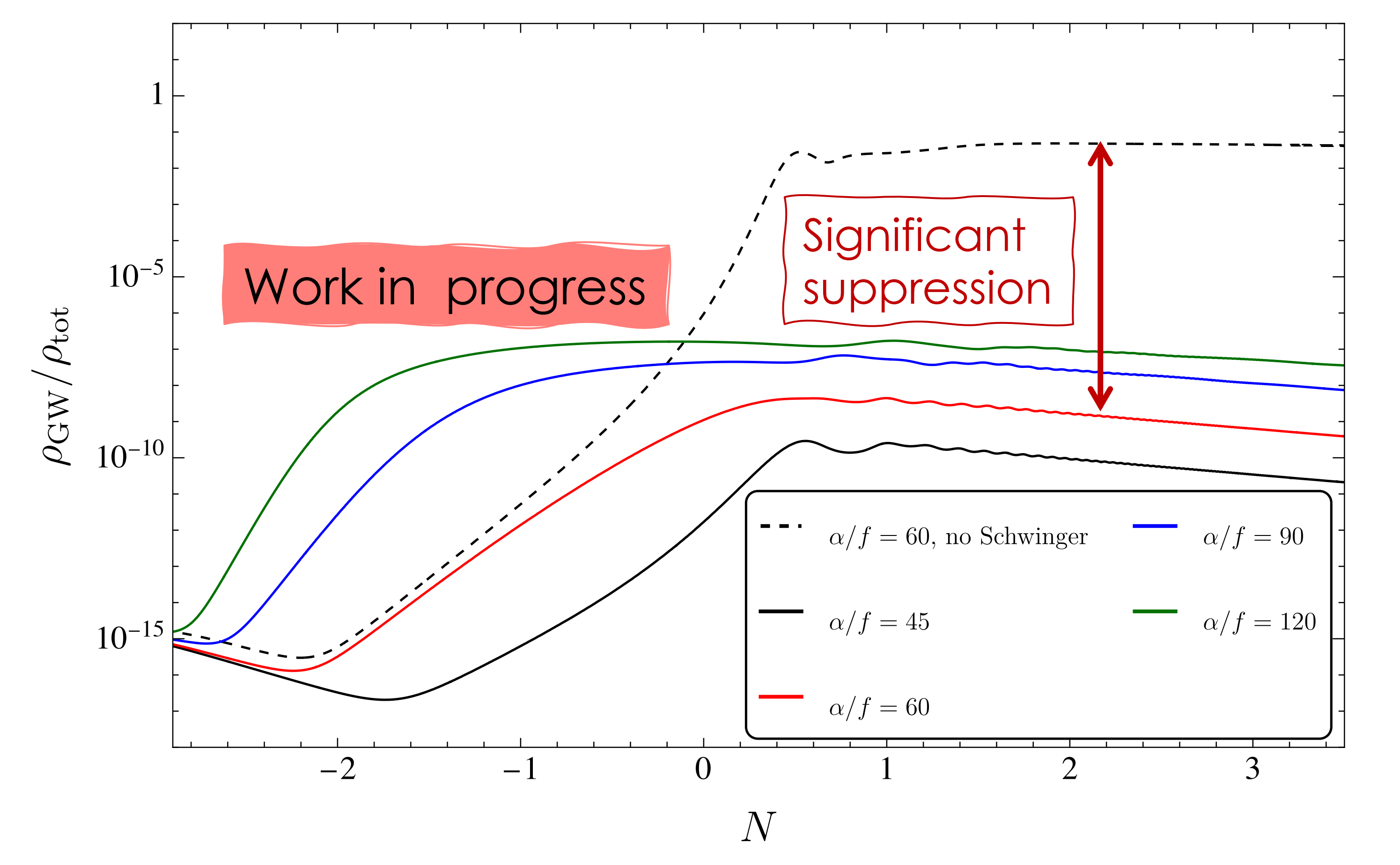
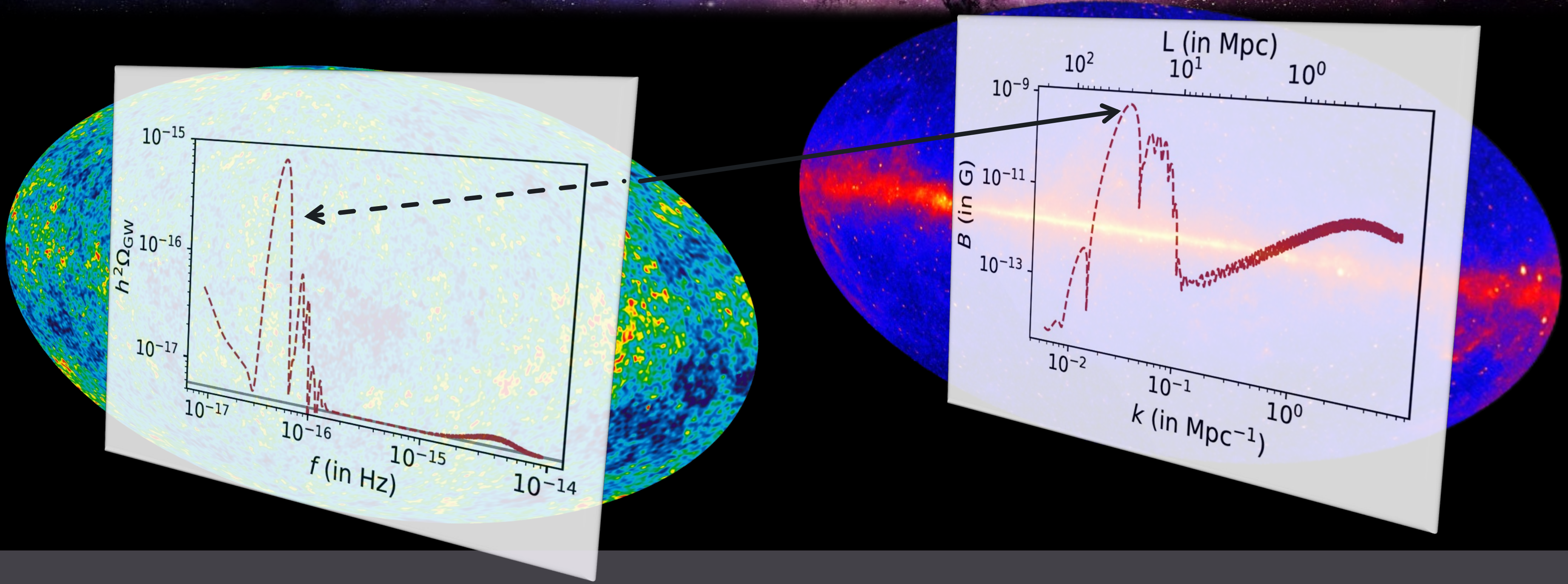


[2025.xxxxx]

Take-home message



- Backreaction effects during axion-SU(2) inflation lead to a novel attractor solution and produce correlated gravitational wave and primordial magnetic field signals.
- Schwinger effect can strongly quench gauge-field growth, challenging axion-U(1) magnetogenesis and preheating.

Open Positions at Nordita

COMING SOON!

NORDITA
The Nordic Institute for Theoretical Physics

Nordita News
2025-11-06

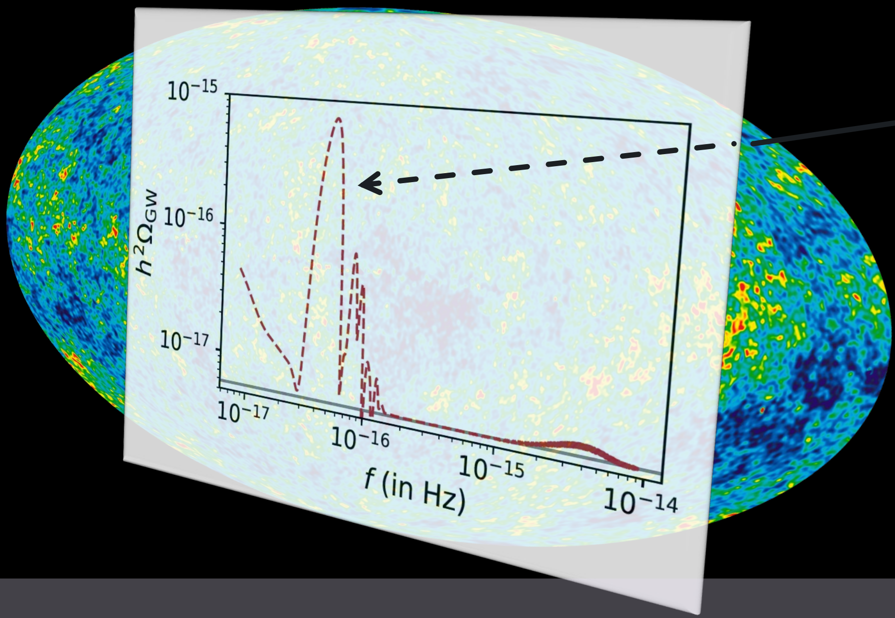
Axel Brandenburg awarded ERC Synergy and VR grants to study the universe’s first microseconds ›

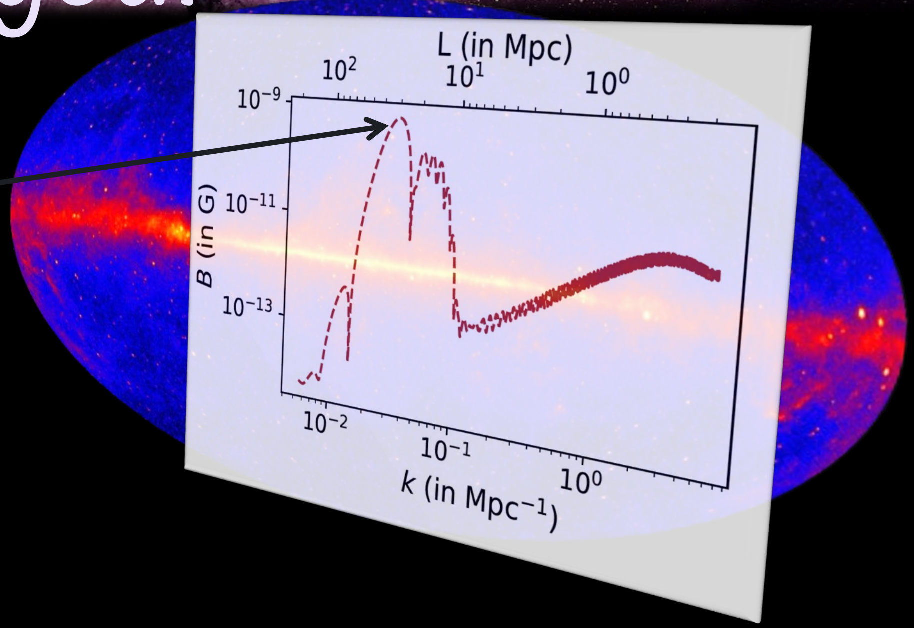
Nordita professor Axel Brandenburg has received an ERC Synergy Grant and a Swedish Research Council grant to explore how...

Nordita News
2025-11-12

Exploring the Universe’s Earliest Moments with a VR Starting Grant ›

Thank you!





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