SDU VILLUM FONDEN CP3

# Probing new physics and gravity across scales

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Warszawa - 30.05.2023


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Zone

# The predictive power of asymptotic safety

## (for ALPs and Horndeski models)

- Prelude: what is asymptotically safe quantum gravity ?
- Intermezzo: interplay between gravity and matter
- Cadenza: asymptotically safe landscape
    - Axion-like particles
    - Horndeski-like model

Based on works with Astrid Eichhorn, Fabian Wagner and Gustavo P. de Brito

# Quantum Gravity

## Prelude

- **Asymptotic safety**
- Causal Dynamics Triangulation
- Causal Sets
- Dualities
- Euclidean Dynamics Triangulation
- Loop Quantum Gravity
- Semi-classical approaches.
- Strings
- Tensor models
- …

# Quantum Gravity

## Prelude

- **Asymptotic safety**
- Causal Dynamics Triangulation
- Causal Sets
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- Loop Quantum Gravity
- Semi-classical approaches.
- Strings
- Tensor models
- …

**Goal: restore the predictive power of GR at high energies, by demanding (quantum) scale symmetry.**

# Asymptotic safety

## Prelude

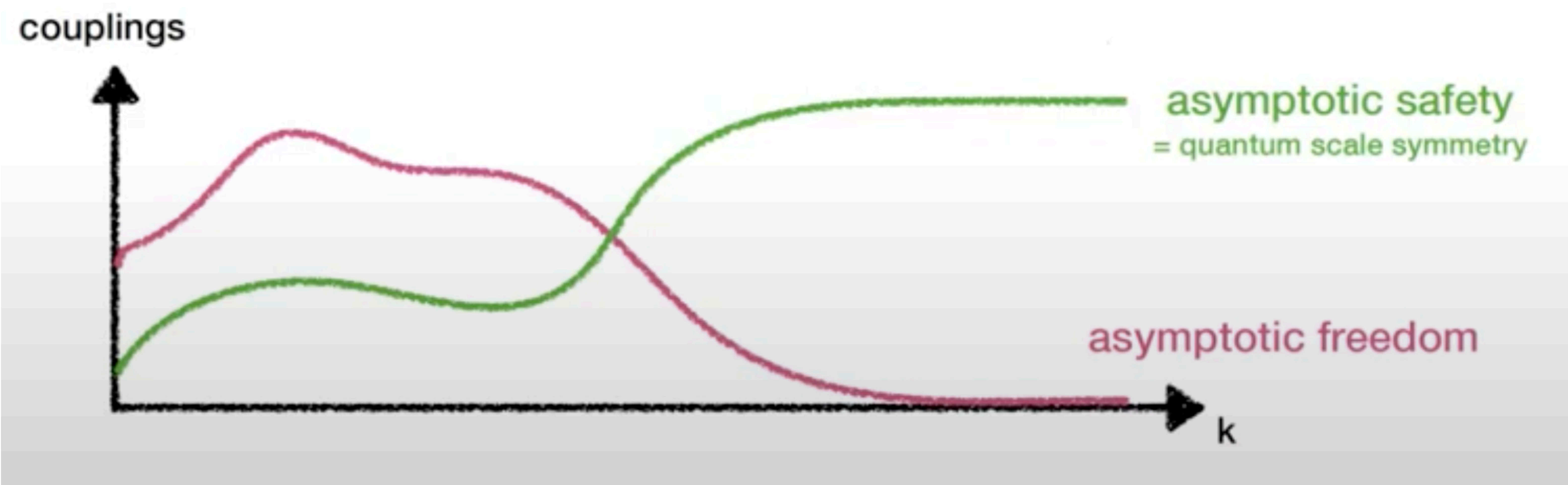


Illustration: Astrid Eichhorn

- At $k \to \infty, \beta_g(g_*) = 0$.
- If $g_* \neq 0$, asymptotic safety (interacting, non-trivial, non-Gaussian fixed point).
- If $g_* = 0$, asymptotic freedom (free, trivial, Gaussian fixed point). Example: QCD

Examples (AS):
Yang-Mills $d = 4 + \epsilon$
Non-linear sigma model $d = 2 + \epsilon$
Gross-Neveu model $d = 3$

# Asymptotic safety

## Prelude

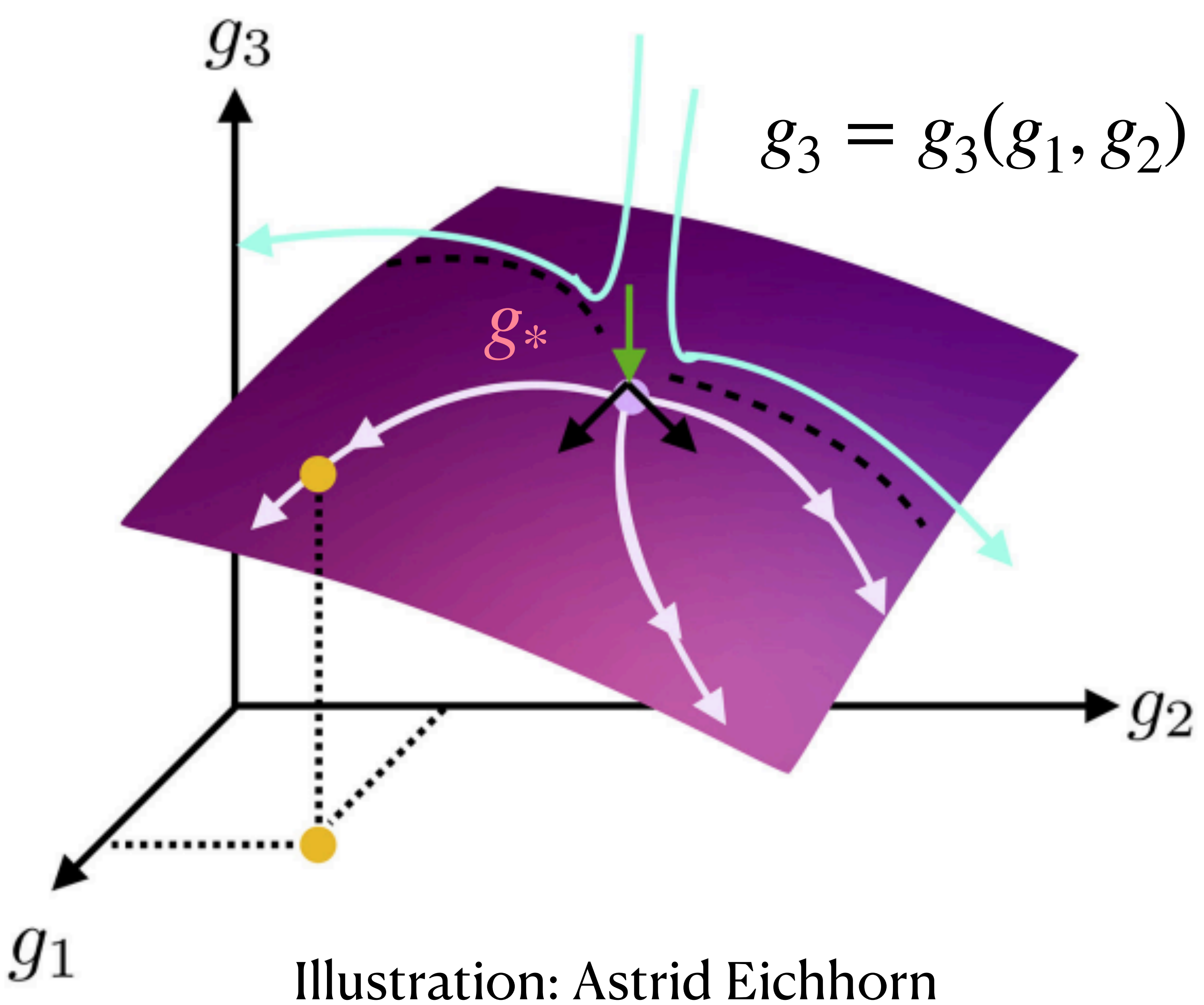


Illustration: Astrid Eichhorn

Dimensionless couplings

$g_* \in \mathbb{R}$ :

- Gaussian fixed points: $g_* = 0$
- Interacting fixed points: $g_* \neq 0$

$$M_{ij} = \frac{\partial \beta_{g_i}}{\partial g_j}\Big|_{g_*}, \qquad \theta_i = -\operatorname{eig}(M)\,.$$

- Relevant directions ~ $\theta_i > 0$ IR-repulsive
- Irrelevant directions ~ $\theta_i < 0$ IR-attractive

Free parameters

Predictions

# Asymptotic safety

## Prelude

- The effective action ($\Gamma_k$, generator of 1PI diagrams) contains all operators which are compatible with the symmetries of a theory;
- Infinite dimensional theory space: $\Gamma_k = \int_x \sum_i \bar{g}_i(k)\mathcal{O}_i$;
- Define dimensionless couplings: $g_i(k) = \bar{g}_i(k)k^{-d_i}$
- Asymptotic safety demands:
  - 1) $\beta_g(g_*) = 0,\ g_* \in \mathbb{R}$; (scale symmetry)
  - 2) Finite number of free parameters (# experiments)

$g = (g_1, g_2, \dots)$

( $g_*$: fixed point)

$\beta_g = k\partial_k g$

Beta function

# Functional renormalization group

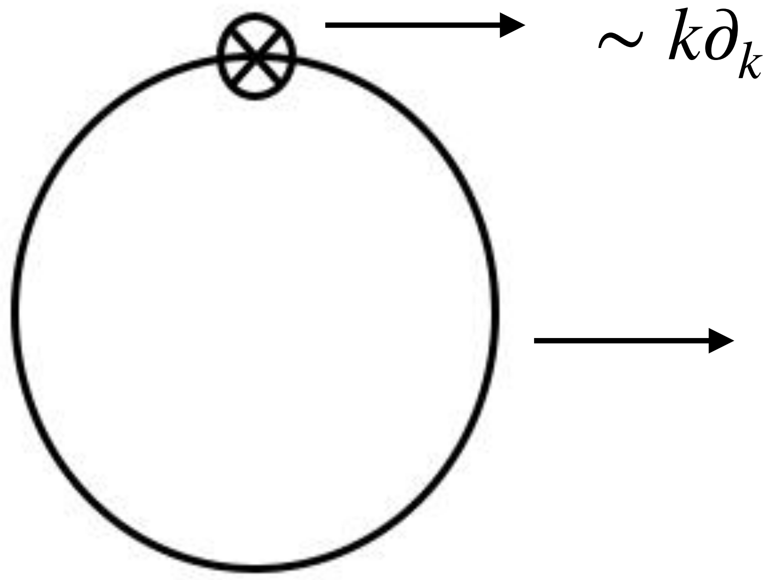
## Machinery

- $\Gamma_k[\phi] = \int J \cdot \phi - \log Z_k[J] - \Delta S_k[\phi]$
- Flow equation:

$$k\partial_k \Gamma_k = \frac{1}{2}\mathrm{STr}\left[(\Gamma_k^{(2)} + R_k)^{-1} k\partial_k R_k\right]$$

Wetterich *Phys.Lett.B 301 (1993),* Reuter *Phys.Rev.D 57 (1998)*

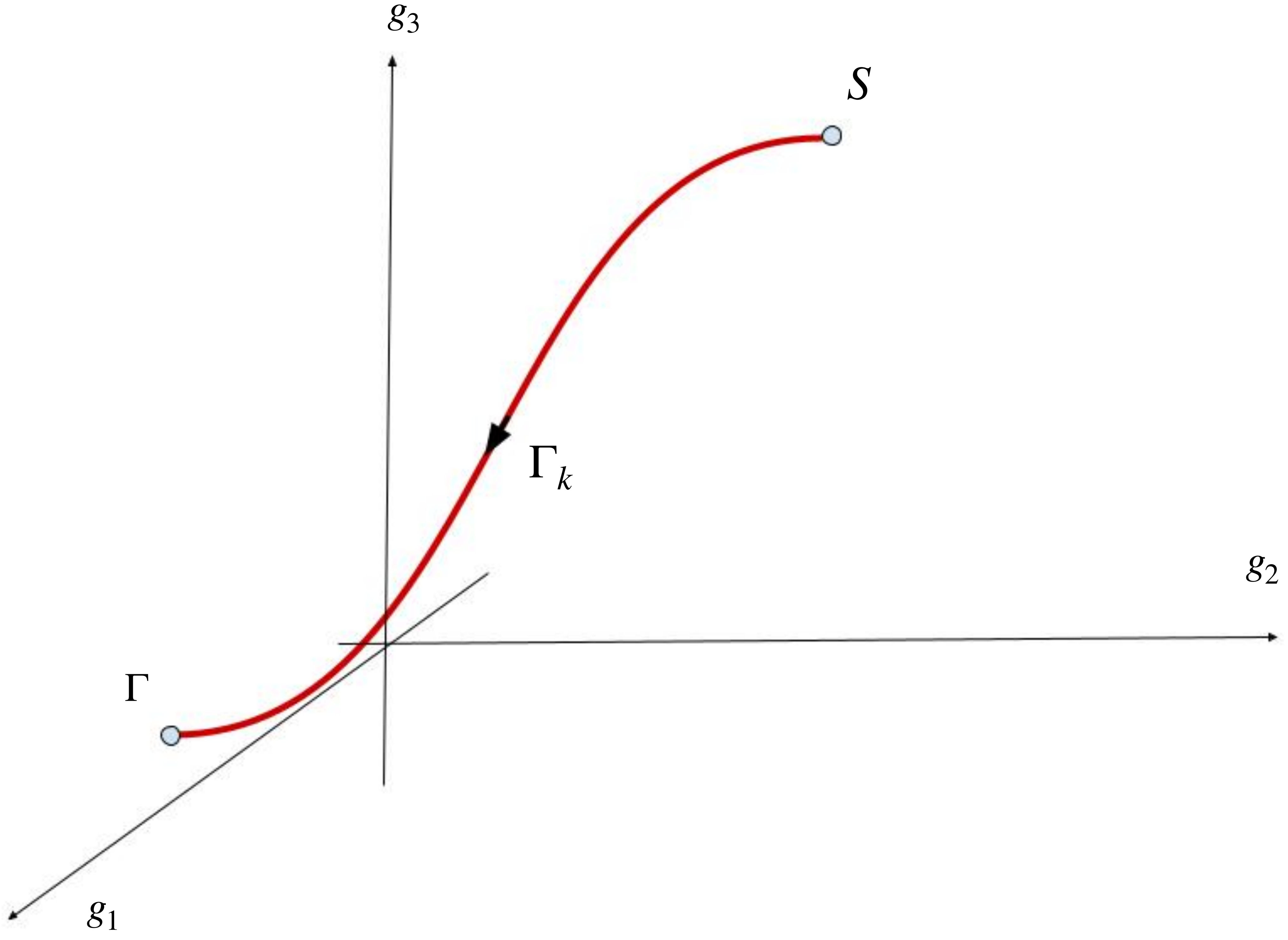
- Exact 1-loop equation



$\sim k\partial_k R_k(p)$

$\sim (\Gamma_k^{(2)} + R_k)^{-1}(p)$

$\sim k\partial_k \Gamma_k$



Interpolation between the bare action $S(k \to \infty)$ and the full effective action $\Gamma(k \to 0)$

FRG applications: Dupuis et al. *Phys.Rept. 910 (2021)*

# Asymptotically safe quantum gravity

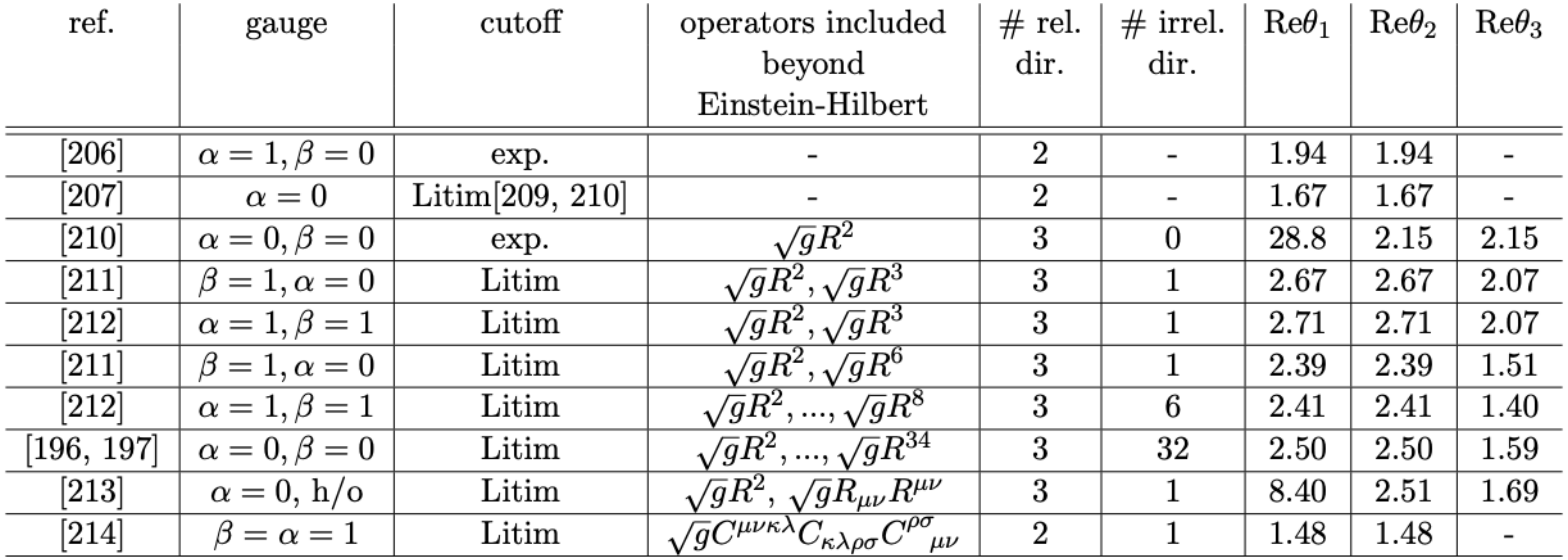
## Panoramic view

- Evidence for a purely-gravitational fixed point.
- Evidence for a finite number of relevant directions: 3

- For Diff-invariant truncations:
  - Einstein-Hilbert:
    - 2 relevant directions associated with $G_N$ and $\Lambda$.
  - Einstein-Hilbert + Operators quadratic in curvature $R^2, R_{\mu\nu}R^{\mu\nu}$
    - 3 relevant directions associated with $G_N, \Lambda$ and one of the quadratic-curvature couplings.

# Asymptotically safe quantum gravity

## Panoramic view



| ref. | gauge | cutoff | operators included beyond Einstein-Hilbert | # rel. dir. | # irrel. dir. | $\mathrm{Re}\theta_1$ | $\mathrm{Re}\theta_2$ | $\mathrm{Re}\theta_3$ |
|---|---|---|---|---|---|---|---|---|
| [206] | $\alpha = 1, \beta = 0$ | exp. | - | 2 | - | 1.94 | 1.94 | - |
| [207] | $\alpha = 0$ | Litim[209, 210] | - | 2 | - | 1.67 | 1.67 | - |
| [210] | $\alpha = 0, \beta = 0$ | exp. | $\sqrt{g}R^2$ | 3 | 0 | 28.8 | 2.15 | 2.15 |
| [211] | $\beta = 1, \alpha = 0$ | Litim | $\sqrt{g}R^2, \sqrt{g}R^3$ | 3 | 1 | 2.67 | 2.67 | 2.07 |
| [212] | $\alpha = 1, \beta = 1$ | Litim | $\sqrt{g}R^2, \sqrt{g}R^3$ | 3 | 1 | 2.71 | 2.71 | 2.07 |
| [211] | $\beta = 1, \alpha = 0$ | Litim | $\sqrt{g}R^2, \sqrt{g}R^6$ | 3 | 1 | 2.39 | 2.39 | 1.51 |
| [212] | $\alpha = 1, \beta = 1$ | Litim | $\sqrt{g}R^2, ..., \sqrt{g}R^8$ | 3 | 6 | 2.41 | 2.41 | 1.40 |
| [196, 197] | $\alpha = 0, \beta = 0$ | Litim | $\sqrt{g}R^2, ..., \sqrt{g}R^{34}$ | 3 | 32 | 2.50 | 2.50 | 1.59 |
| [213] | $\alpha = 0$, h/o | Litim | $\sqrt{g}R^2,\ \sqrt{g}R_{\mu\nu}R^{\mu\nu}$ | 3 | 1 | 8.40 | 2.51 | 1.69 |
| [214] | $\beta = \alpha = 1$ | Litim | $\sqrt{g}C^{\mu\nu\kappa\lambda}C_{\kappa\lambda\rho\sigma}C^{\rho\sigma}{}_{\mu\nu}$ | 2 | 1 | 1.48 | 1.48 | - |

Taken from Eichhorn 1810.07615

**Truncations with higher-order in curvature operators: stable number of relevant directions (3) and near-canonical scaling behaviour.**

# Functional renormalization group

## Limitations

- Infinite dimensional theory space requires truncation.
- Check convergence of expansion schemes.

- Regulator can break gauge invariance.
- Work Ward-Takahashi identities.

- ($k^2 > p^2$) requires Euclidean signature!
- Wick rotation is not well defined for non-perturbative calculations!

- Under truncation, universal quantities may depend on gauge choice and/or scheme.

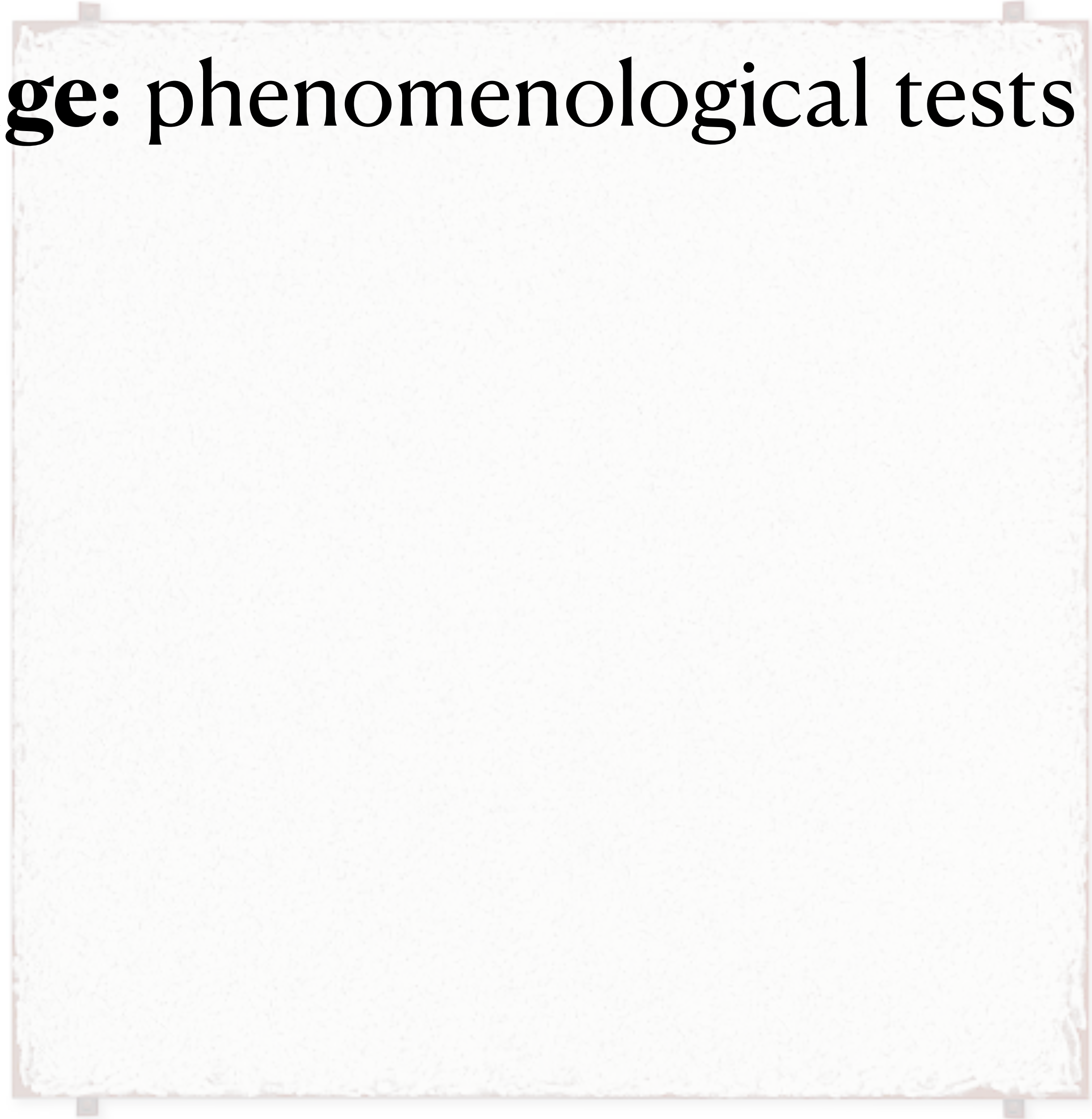
**Warning: Results depend on truncation and systematical uncertainties!**

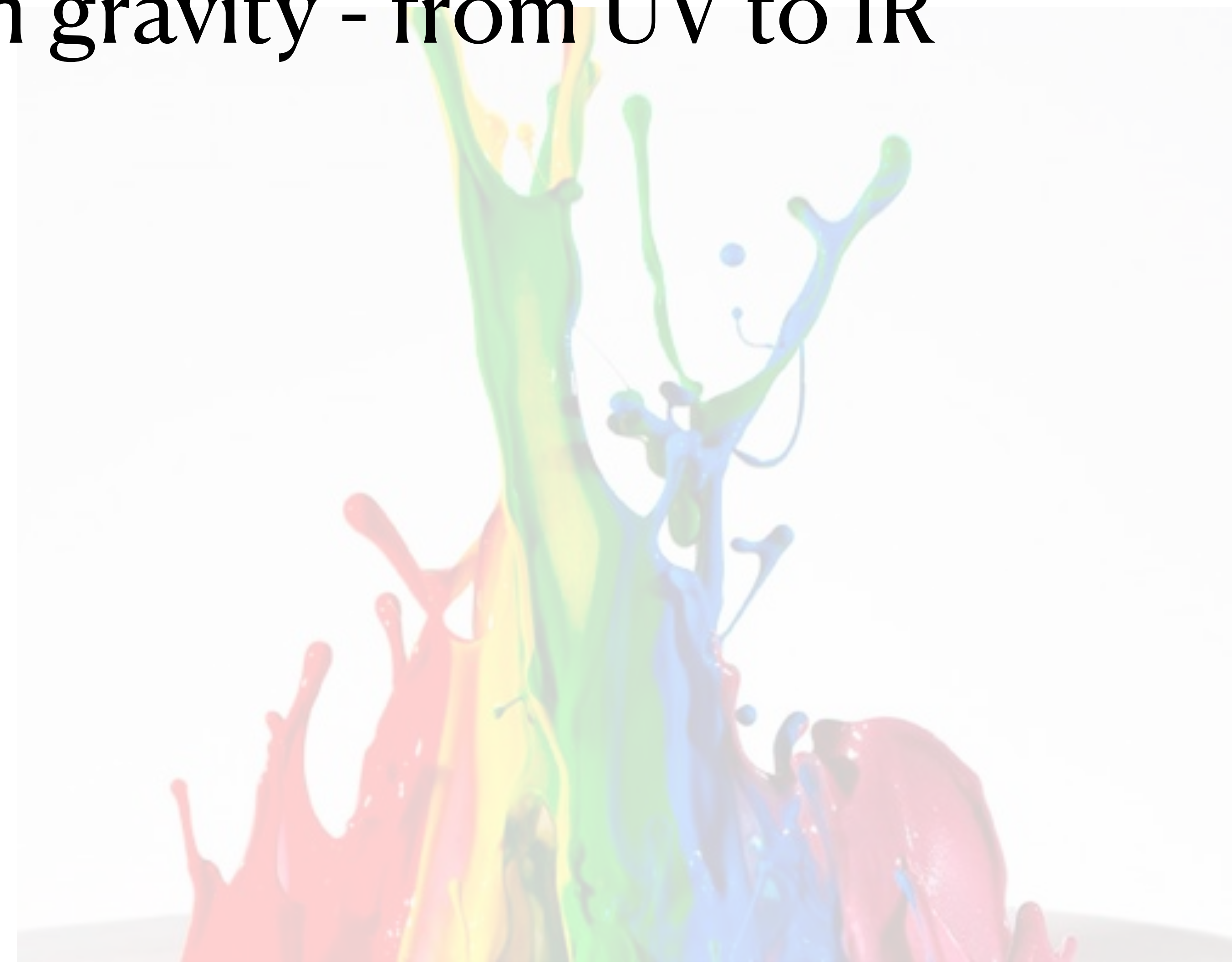
$$k\partial_k \Gamma_k = \frac{1}{2}\mathrm{STr}\left[(\Gamma_k^{(2)} + R_k)^{-1} k\partial_k R_k\right]$$

# The interplay of gravity and matter

## Intermezzo

- Without matter, indications for **interacting fixed point.**
- **Key open challenge:** phenomenological tests of quantum gravity - from UV to IR





# The interplay of gravity and matter

## Matter matters

- Without matter, indications for **interacting fixed point.**

- Does the **matter content** spoil the fixed-point structure of the gravitational sector?
- Does the **gravitational sector** change the fixed-point structure of the matter content?

- Constraining power of asymptotic safety:
    - **Asymptotically safe (AS) landscape:** Set of EFTs compatible with an AS(QG) UV completion.

- Systematic errors:
    - Pastor-Gutierrez, Pawlowski, Reichert 2207.09817
    - Kotlarski, Kowalska, Rizzo, Sessolo 2304.08959

**Review AS + matter:** Eichhorn Front.Astron.Space Sci. 5 (2019) 47; Eichhorn, Schiffer 2212.07456

# Connecting theory with observations

A) Theoretical constraints on dark matter/energy candidates:

- Gravity-induced UV completion of dark universe models.
- IR predictions.

B) Indirect tests of (asymptotic safety) quantum gravity:

- What are the dark universe models in the landscape?
- Consistency between UV theory and observations.

# Predictive power of AS

## Cadenza: The asymptotically safe landscape

- The AS landscape: set of effective field theories for matter fields which is compatible with an asymptotically safe UV completion at high energies.
- In this talk, two toy-models (phenomenologically motivated):
  - Axion-like particle model:

$$\Gamma_k = \int d^4x \sqrt{\det g} \left( -\frac{M_P^2}{2} R + \frac{Z_\phi}{2} g^{\mu\nu} \partial_\mu \phi \partial_\nu \phi + \frac{\bar{m}^2}{2} \phi^2 + \frac{Z_A}{4} g^{\mu\alpha} g^{\nu\beta} F_{\mu\nu} F_{\alpha\beta} + \frac{i \bar{g}_{\phi AA}}{8} \frac{\epsilon^{\mu\nu\alpha\beta}}{\sqrt{\det g}} \phi F_{\mu\nu} F_{\alpha\beta} \right);$$

  - Horndeski-like model:

$$\chi = -1/2 \partial_\mu \phi \partial^\mu \phi, \qquad \Gamma_k = -\int d^4x \sqrt{\det g} \left( \frac{M_P^2}{2} R + Z_\phi \, \chi + \bar{g} \, \chi^2 - \bar{h}_1 \, \chi \, \Box \, \phi \right).$$

# Predictive power of AS

## Are there ALPs in the AS landscape?

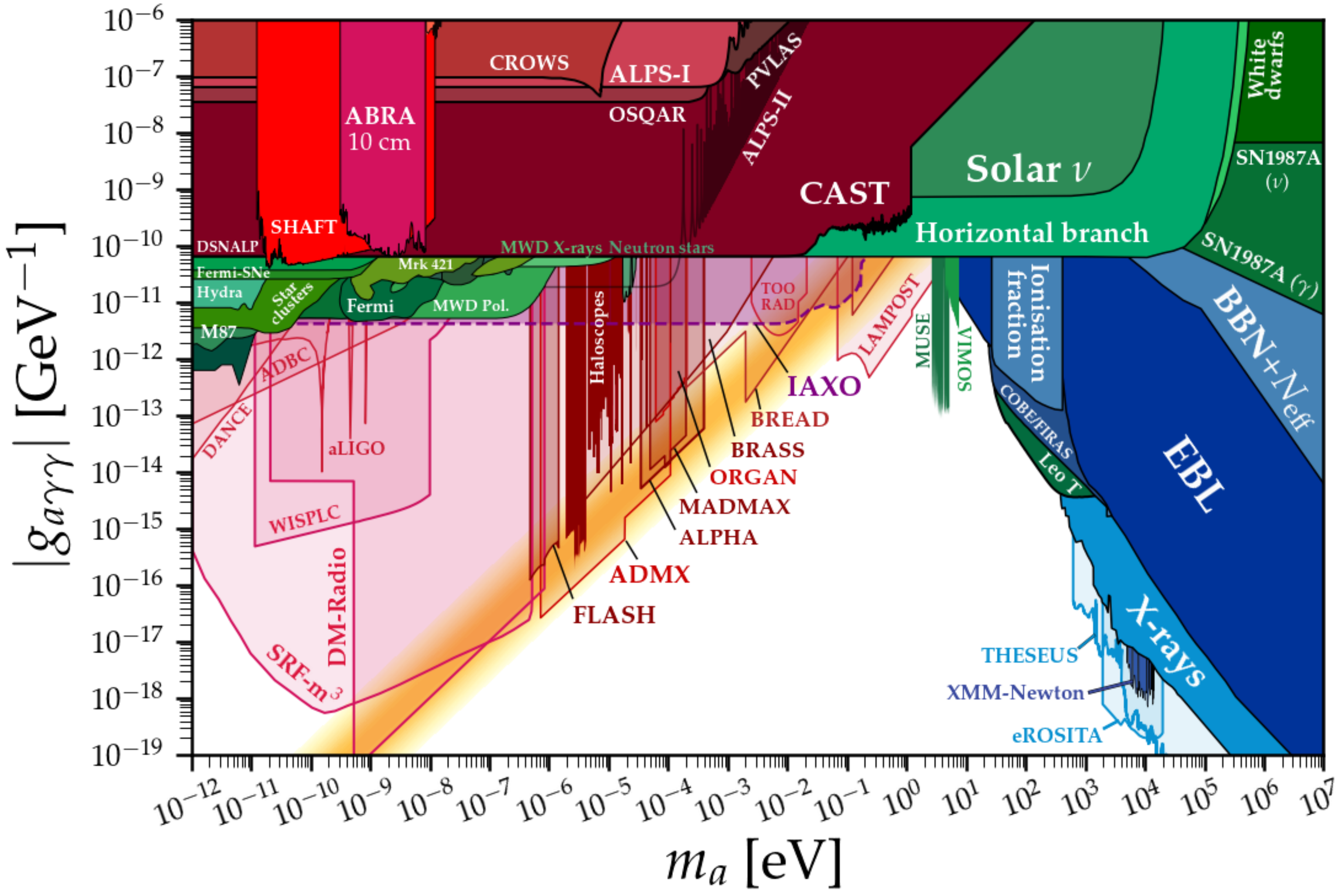
- ALP model: $$\Gamma_k = \int_x \sqrt{\det g}\left(\frac{Z_\phi}{2} g^{\mu\nu}\partial_\mu\phi\partial_\nu\phi + \frac{m^2\, k^2 Z_\phi}{2}\phi^2 + \frac{Z_A}{4} g^{\mu\alpha}g^{\nu\beta}F_{\mu\nu}F_{\alpha\beta} + \frac{i g_{\phi AA} k^{-1} Z_\phi^{1/2} Z_A}{8}\,\frac{\epsilon^{\mu\nu\alpha\beta}}{\sqrt{\det g}}\phi F_{\mu\nu}F_{\alpha\beta}\right)$$

- Phenomenology: ALPs as **light dark matter** candidates:

  Small, non-vanishing, **axion-photon**

  and **mass couplings** at IR.

- Can this ALP-model be accommodated in the AS landscape?



G. de Brito, A. Eichhorn, RRLdS *JHEP* 06 (2022) 013

From Ciaran O'Hare: https://cajohare.github.io/AxionLimits/

# Are there ALPs in the AS landscape?

$$\Gamma_k = \int_x \sqrt{\det g}\left(\frac{Z_a}{2} g^{\mu\nu}\partial_\mu a \partial_\nu a + \frac{m_a^2}{2}a^2 + \frac{Z_A}{4} g^{\mu\alpha}g^{\nu\beta}F_{\mu\nu}F_{\alpha\beta} + \frac{i g_{a\gamma\gamma}}{8}\frac{\epsilon^{\mu\nu\alpha\beta}}{\sqrt{\det g}} a F_{\mu\nu}F_{\alpha\beta}\right) - \frac{1}{16\pi G_N}\int_x \sqrt{\det g}\,(R-2\Lambda)+\Gamma_{\mathrm{gf}}$$

Asymptotic safety: $\beta_{m_a^2} = 0, \beta_{g_{a\gamma\gamma}^2} = 0.$

(dimensionless couplings!)

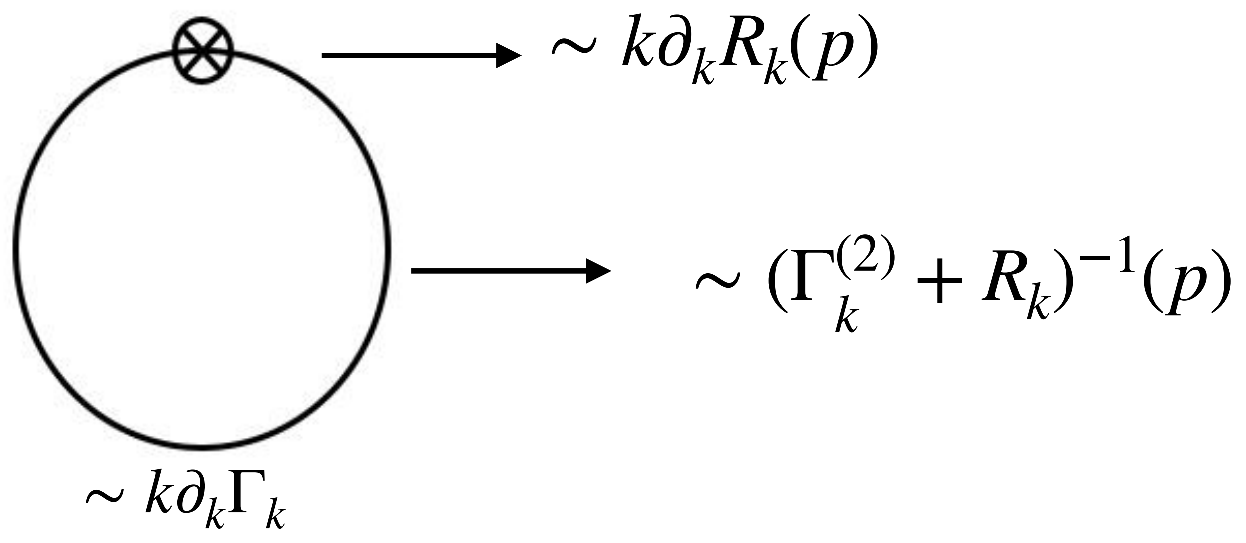
i) Couple gravity with the matter sector

ii) $\Gamma_k = \Gamma_k[a, A, h]$ (momentum space)

iii) $\partial_k \Gamma_k \sim \partial_k m_a^2, \partial_k g_{a\gamma\gamma} \sim \beta_{m_a^2}, \beta_{g_{a\gamma\gamma}^2}$

$$\boxed{k\partial_k \Gamma_k = \frac{1}{2}\mathrm{STr}\left[(\Gamma_k^{(2)} + R_k)^{-1} k\partial_k R_k\right]}$$

**FRG** - flow equation



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# Are there ALPs in the AS landscape?

$$\Gamma_k = \int_x \sqrt{\det g}\left(\frac{Z_a}{2} g^{\mu\nu}\partial_\mu a \partial_\nu a + \frac{m_a^2}{2}a^2 + \frac{Z_A}{4} g^{\mu\alpha}g^{\nu\beta}F_{\mu\nu}F_{\alpha\beta} + \frac{i g_{a\gamma\gamma}}{8}\frac{\epsilon^{\mu\nu\alpha\beta}}{\sqrt{\det g}} a F_{\mu\nu}F_{\alpha\beta}\right) - \frac{1}{16\pi G_N}\int_x \sqrt{\det g}\,(R - 2\Lambda) + \Gamma_{\mathrm{gf}}$$

Asymptotic safety: $\beta_{m_a^2} = 0, \beta_{g^2_{a\gamma\gamma}} = 0.$

(dimensionless couplings!)

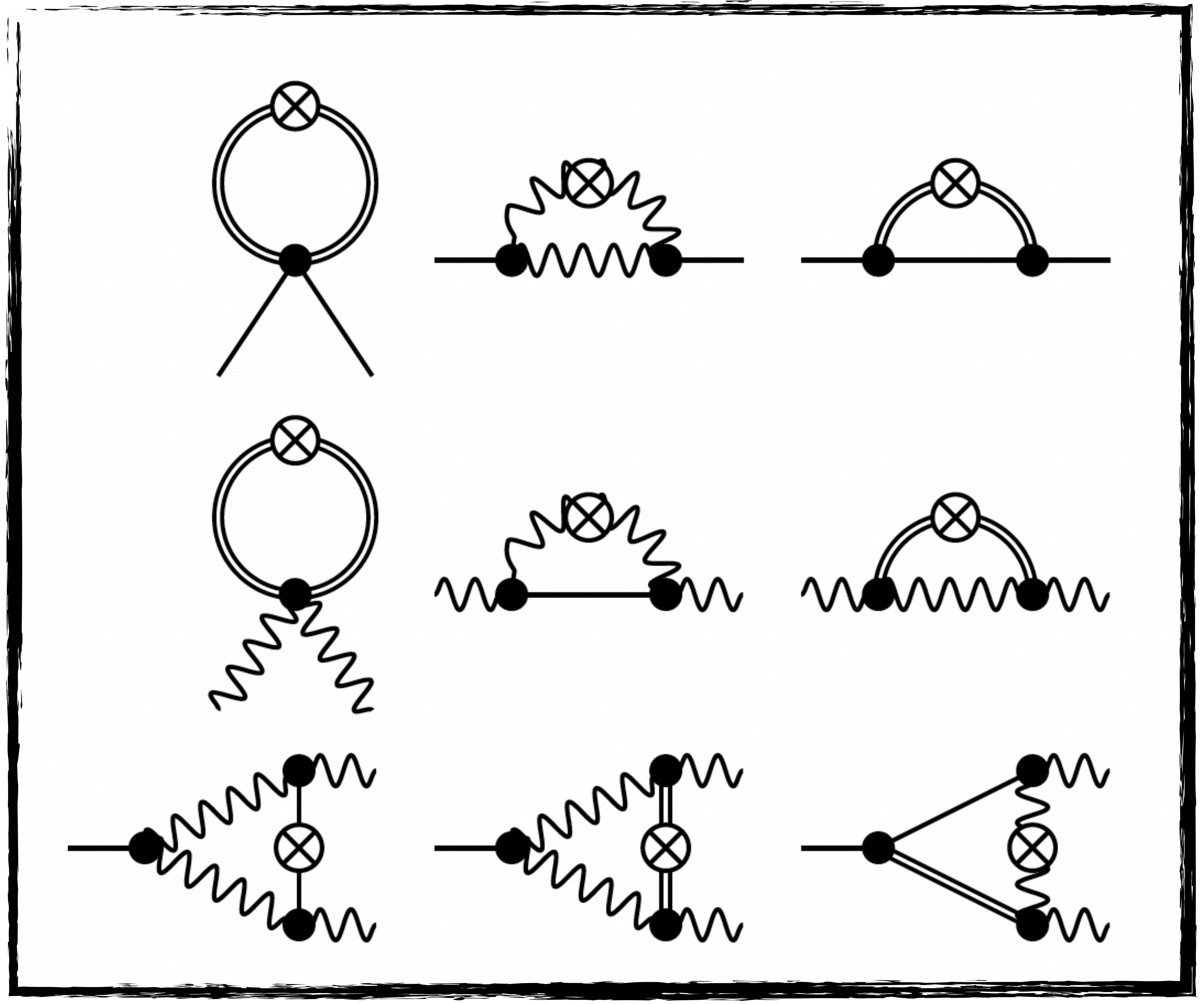
i) Couple gravity with the matter sector

ii) $\Gamma_k = \Gamma_k[a, A, h]$ (momentum space)

iii) $\partial_k \Gamma_k \sim \partial_k m_a^2, \partial_k g_{a\gamma\gamma} \sim \beta_{m_a^2}, \beta_{g^2_{a\gamma\gamma}}$

$$\beta_{m_a^2} = -2m_a^2 + \frac{m_a^2 g_{a\gamma\gamma}^2}{16\pi^2} + f_{m_a^2}(m_a^2, \Lambda) m_a^2 G,$$

$$\beta_{g^2_{a\gamma\gamma}} = 2g_{a\gamma\gamma}^2 + f_{1g^2}(m_a^2) g_{a\gamma\gamma}^4 + f_{2g^2}(m_a^2, \Lambda) g_{a\gamma\gamma}^2 G$$



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# Are there ALPs in the AS landscape?

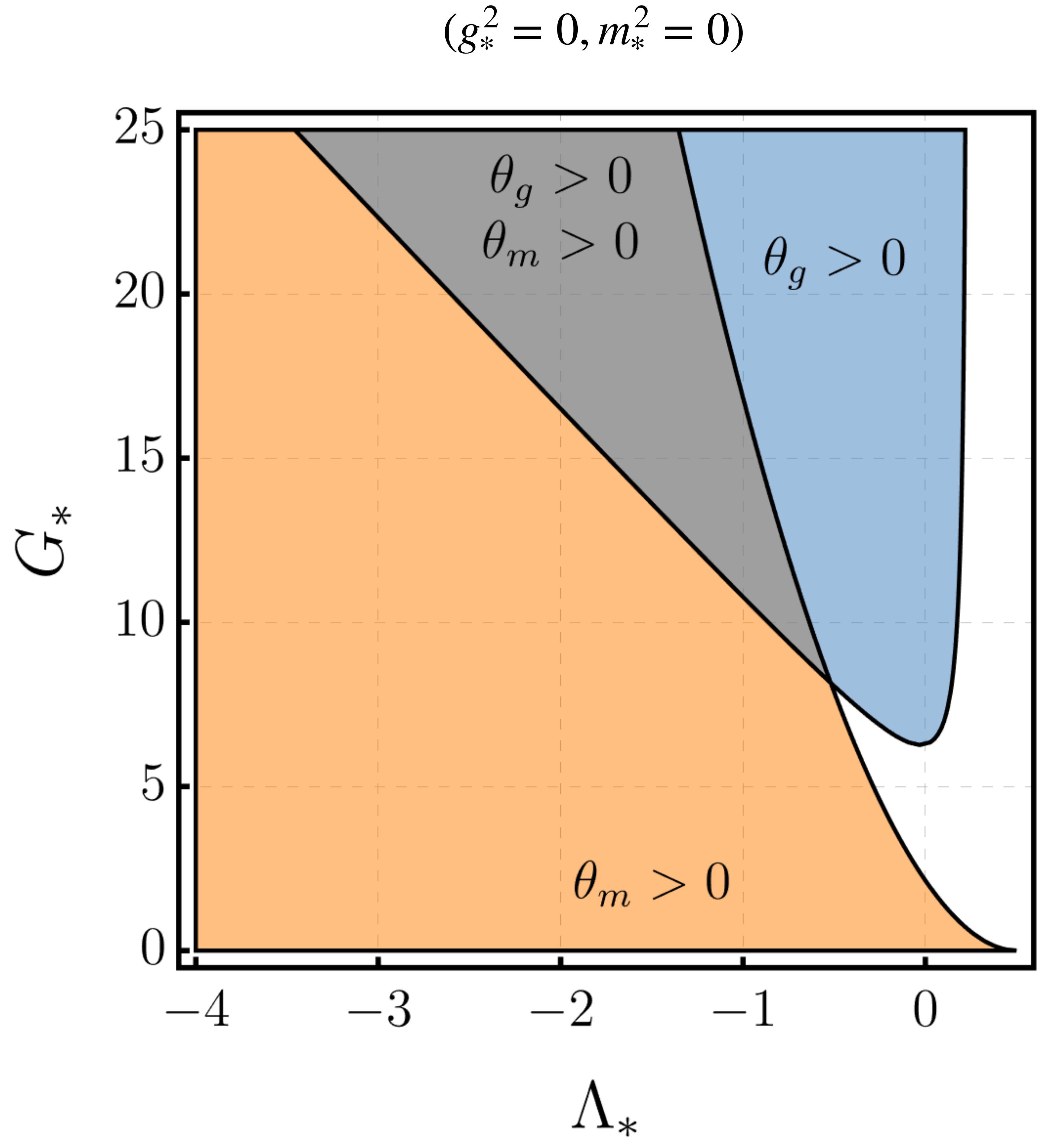
$$\Gamma_k = \int_x \sqrt{\det g}\left(\frac{Z_a}{2} g^{\mu\nu}\partial_\mu a \partial_\nu a + \frac{m_a^2}{2}a^2 + \frac{Z_A}{4} g^{\mu\alpha} g^{\nu\beta} F_{\mu\nu} F_{\alpha\beta} + \frac{i g_{a\gamma\gamma}}{8} \frac{\epsilon^{\mu\nu\alpha\beta}}{\sqrt{\det g}} a F_{\mu\nu} F_{\alpha\beta}\right)$$

- The mass dimension (in d=4) of the axion operator is five.
  - Canonically irrelevant coupling;
  - Irrevelant direction at UV free fixed point:
    - coupling flows from zero to zero!

- Without gravity: Eichhorn, Gies, Roscher PRD 86 (2012) 125014
  - Free fixed point is not viable: $g_{a\gamma\gamma}^2$ is an irrelevant direction;
  - No interacting fixed points.

# Are there ALPs in the AS landscape?

- With gravity:
  - Free fixed point requires relevant directions for both $g^2$ and $m^2$;
  - otherwise, couplings flow to zero;
    - $g^2_{IR} = 0 \Rightarrow$ no ALP.
    - $m^2_{IR} = 0 \Rightarrow$ no DM.



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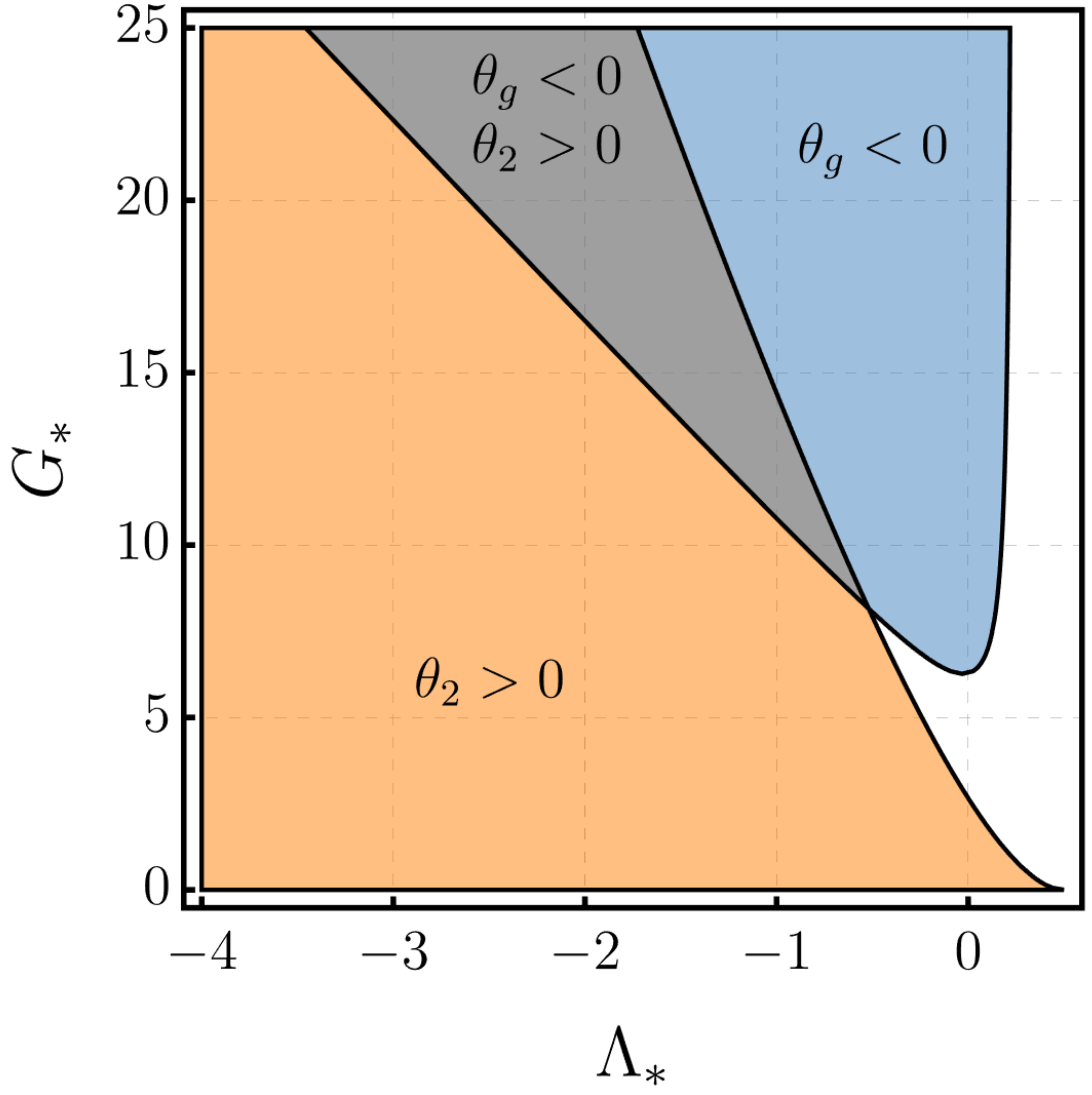
# Are there ALPs in the AS landscape?

- With gravity:
  - Interacting fixed point does not require relevant direction for $g^2$ (blue);
  - But it requires for $m^2$ (orange).
  - Here, the existence of the fixed point demands irrelevance for $g^2$.

$(g_*^2 > 0, m_*^2 = 0)$



[Viable region of parameter space for both free and interacting fixed point cases is similar. The same mechanism is found for Abelian gauge and Yukawa couplings.]

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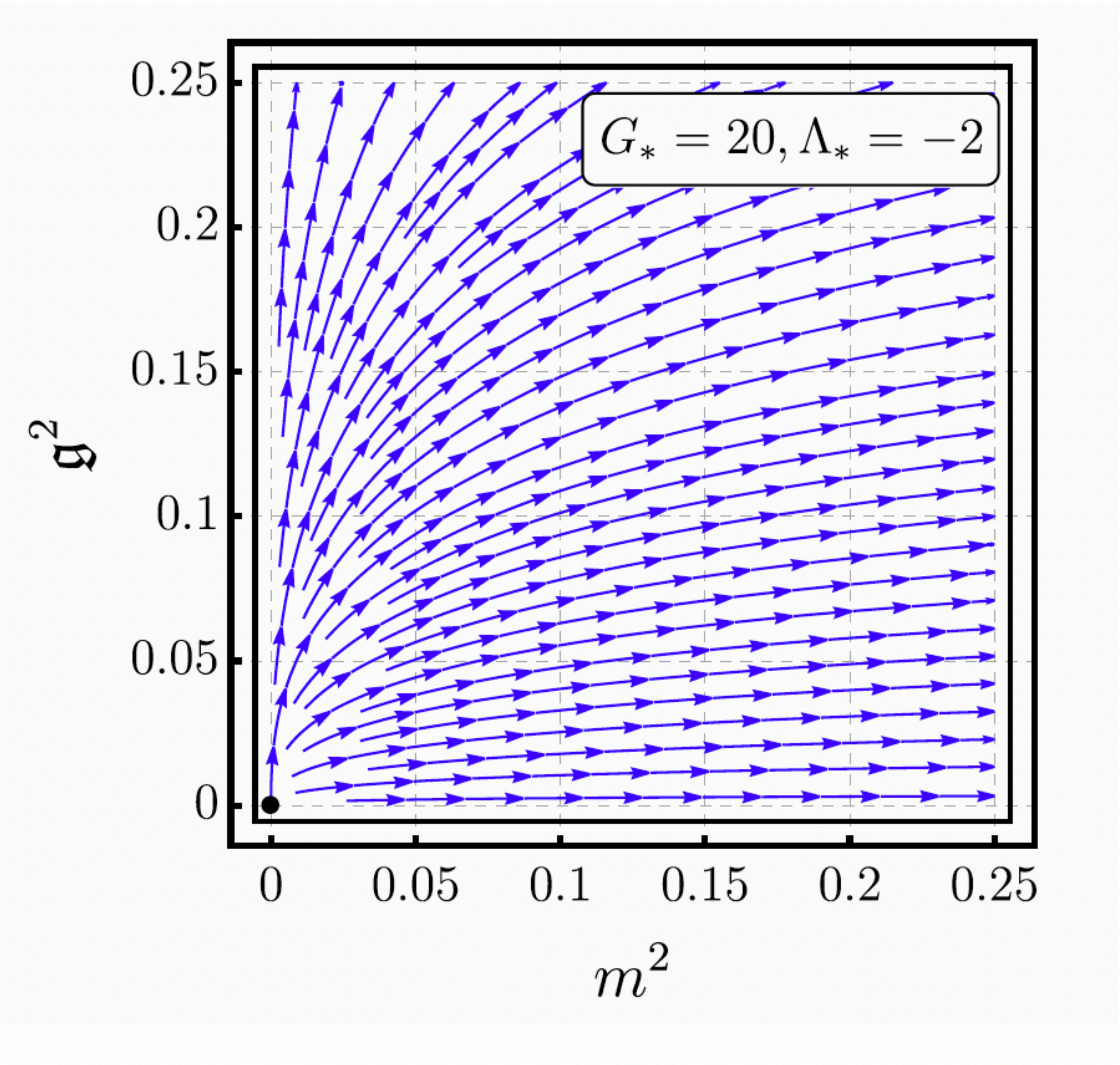
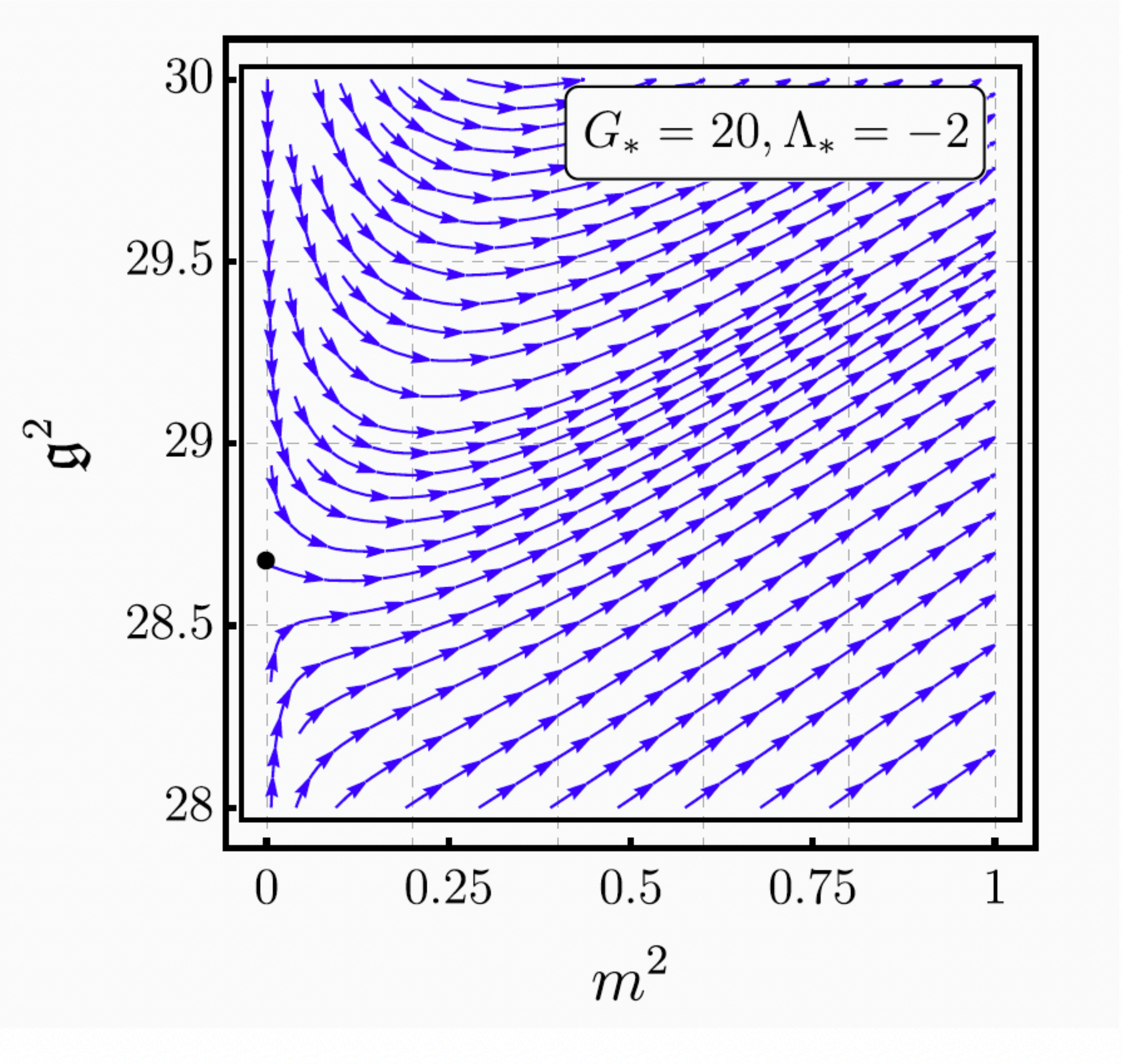
# Are there ALPs in the AS landscape?

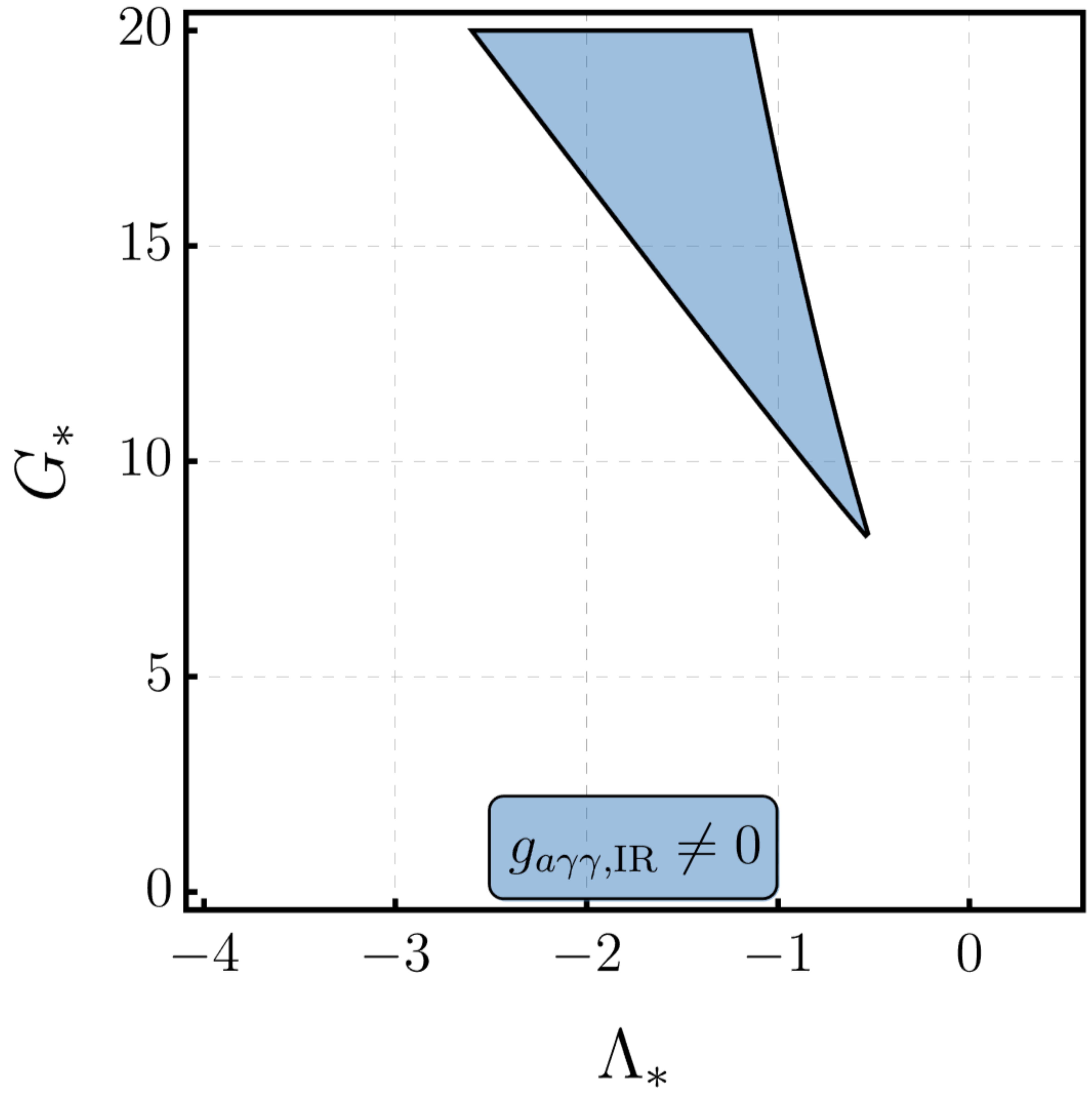
[Small and non-vanishing couplings]

- For both cases, $(g_*^2 = 0, m_*^2 = 0)$ $(g_*^2 > 0, m_*^2 = 0)$

  Large quantum gravity fluctuations!







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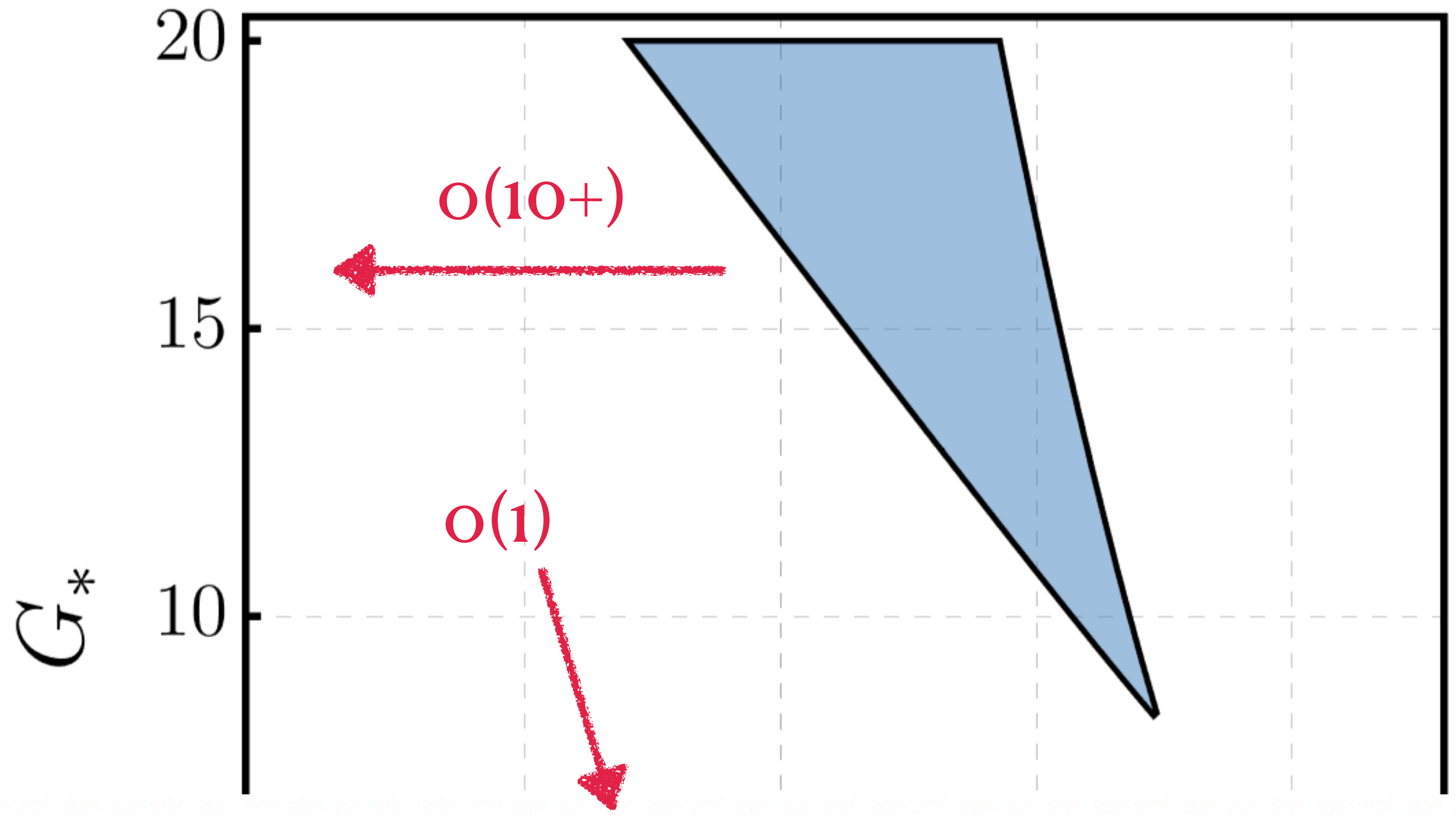
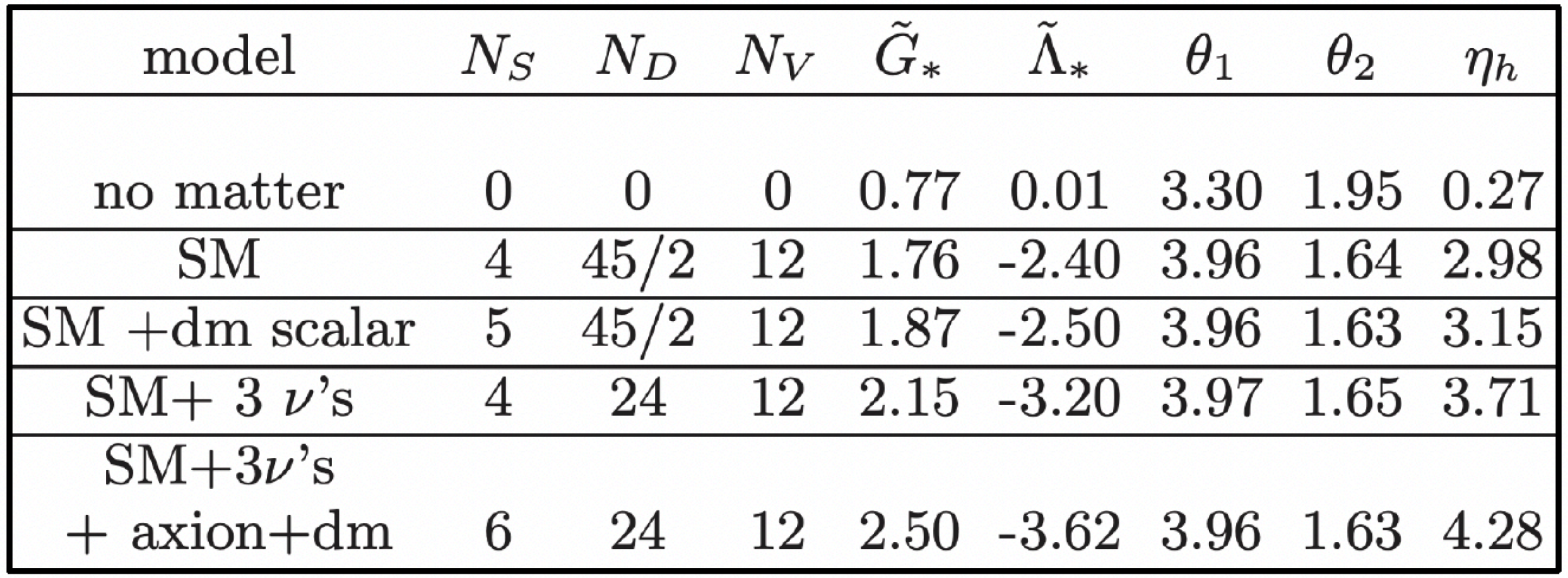
[Small and non-vanishing couplings]

- For both cases, $(g_*^2 = 0, m_*^2 = 0)$ $(g_*^2 > 0, m_*^2 = 0)$

  Large quantum gravity fluctuations!

- ALPs: *likely cannot* be accommodated in the AS landscape.
  - Too large values of $G_*$;





| model | $N_S$ | $N_D$ | $N_V$ | $\tilde{G}_*$ | $\tilde{\Lambda}_*$ | $\theta_1$ | $\theta_2$ | $\eta_h$ |
|---|---|---|---|---|---|---|---|---|
| no matter | 0 | 0 | 0 | 0.77 | 0.01 | 3.30 | 1.95 | 0.27 |
| SM | 4 | 45/2 | 12 | 1.76 | -2.40 | 3.96 | 1.64 | 2.98 |
| SM +dm scalar | 5 | 45/2 | 12 | 1.87 | -2.50 | 3.96 | 1.63 | 3.15 |
| SM+ 3 $\nu$'s | 4 | 24 | 12 | 2.15 | -3.20 | 3.97 | 1.65 | 3.71 |
| SM+3$\nu$'s<br>+ axion+dm | 6 | 24 | 12 | 2.50 | -3.62 | 3.96 | 1.63 | 4.28 |

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Donà, Eichhorn, Percacci *Phys.Rev.D* 89 (2014) 8, 084035

# Are there ALPs in the AS landscape?

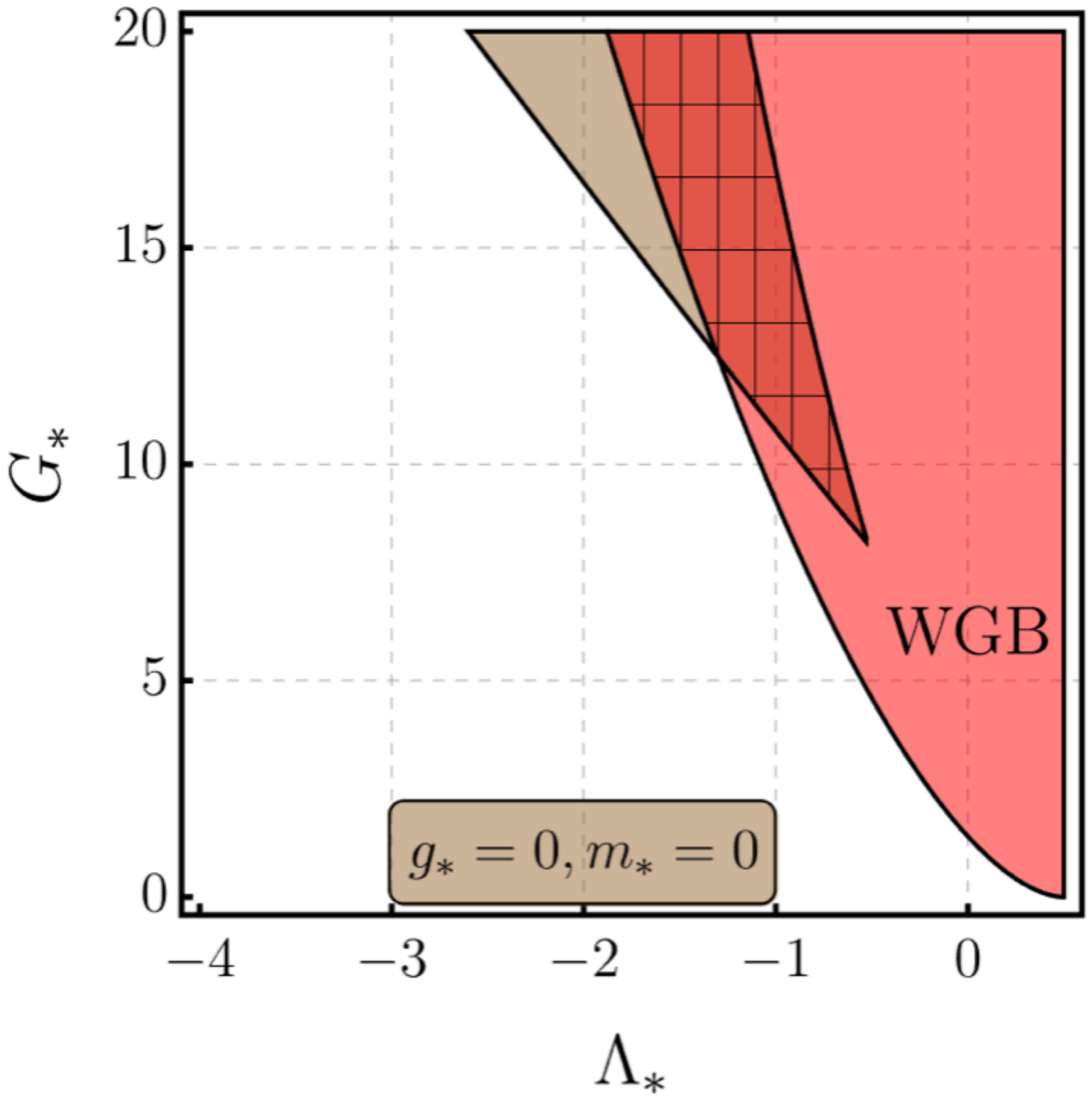
[Small and non-vanishing couplings]

- For both cases, $(g_*^2 = 0, m_*^2 = 0)$ $(g_*^2 > 0, m_*^2 = 0)$

  Large quantum gravity fluctuations!

- ALPs: *likely cannot* be accommodated in the AS landscape.
  - Too large values of $G_*$;
  - ~~Weak Gravity Bound (WGB).~~
  - Indications of flawed truncation

[de Brito, Knorr, Schiffer, 2302.10989]



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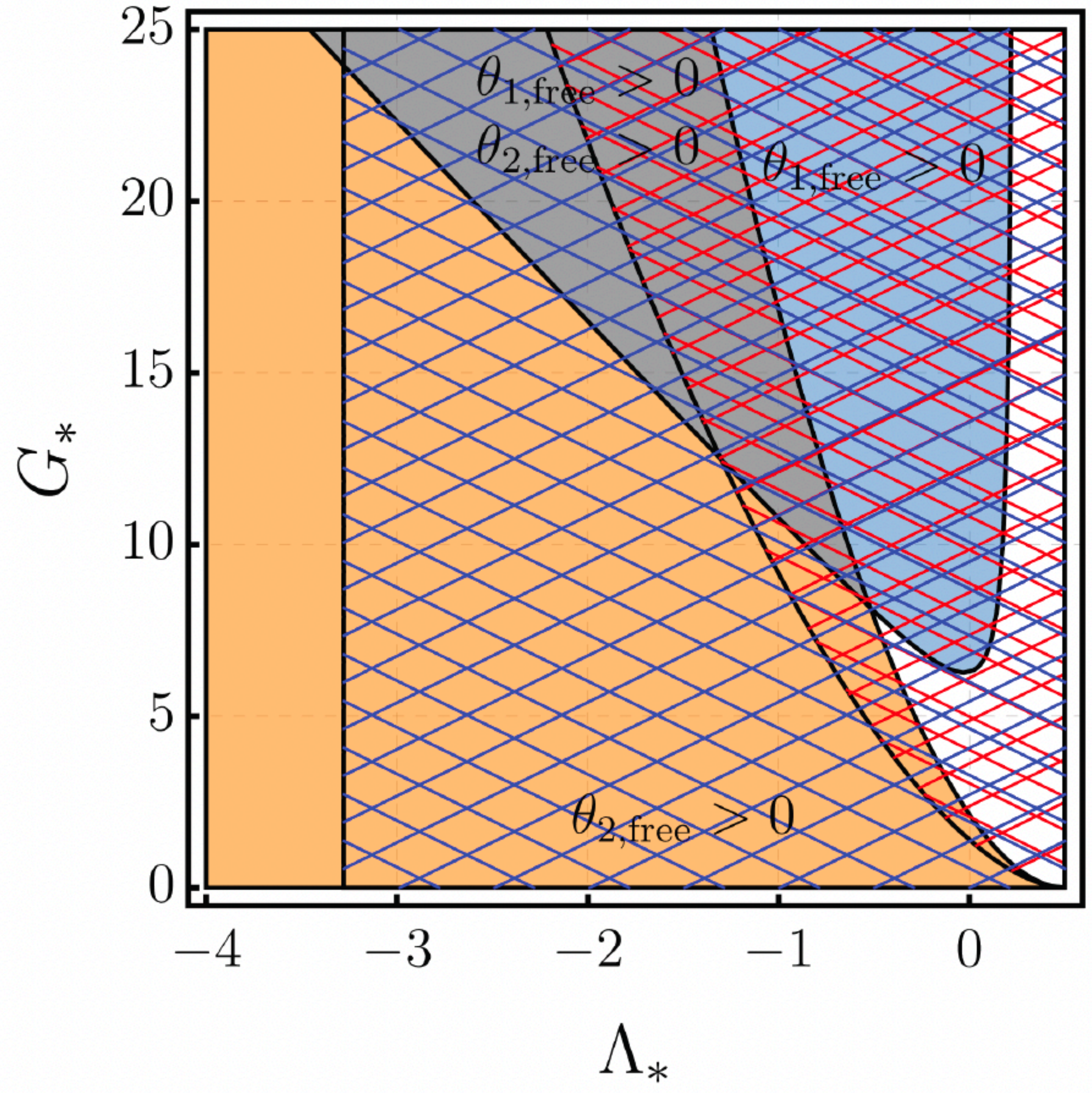
# Are there ALPs in the AS landscape?

[Small and non-vanishing couplings]

- For both cases, $(g_*^2 = 0, m_*^2 = 0)$ $(g_*^2 > 0, m_*^2 = 0)$

  Large quantum gravity fluctuations!

- ALPs: *likely cannot* be accommodated in the AS landscape.
  - Too large values of $G_*$;
  - Gravity-induced UV completion of the Yukawa sector ($\Lambda_*$).



from Gustavo de Brito

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# Beyond our truncation

- SM + ALP + gravity (no axion-SM fermion couplings):
  - Gaussian fixed point persist.
    - $\beta_{g^2_{aAA}} \sim 2\eta_A\, g^2_{aAA}$
  - Can the SM degrees of freedom make the direction relevant?
    - Hypercharge field strength: $\frac{g_{aBB}}{4} a B_{\mu\nu}\tilde{B}^{\mu\nu} \Rightarrow \Delta\beta_{g^2_{aBB}} = (N > 0)\, g_Y^2\, g^2_{aBB}$
    - If $g_{Y,*} = 0$ (asymptotically free), $\Delta\theta_{1,\mathrm{free}} = 0$.
    - If $g_{Y,*} \neq 0$ (asymptotically safe), $\Delta\theta_{1,\mathrm{free}} = -Ng^2_{Y,*} < 0$ (even more irrelevant)

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# Beyond our truncation

- SM + ALP + gravity :
  - Hypercharge field strength: $\frac{g_{aBB}}{4} a B_{\mu\nu}\tilde{B}^{\mu\nu} \Rightarrow \Delta\beta_{g^2_{aBB}} = (N > 0)\, g_Y^2 g_{aBB}^2$
  - If $g_{Y,*} = 0$ (asymptotically free), $\Delta\theta_{1,\text{free}} = 0$.
  - If $g_{Y,*} \neq 0$ (asymptotically safe), $\Delta\theta_{1,\text{free}} = -Ng^2_{Y,*} < 0$ (even more irrelevant)

- We did neglect any BSM field other than the ALP;
- We did not work with the QCD axion ($m^2$ and $g_a^2$ are not independent);
- We did assume no new physics between TeV and the Planck scale.

Ishida, Matsuzaki, Peng,
EPJC 82 (2022) 2

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# Are there ALPs in the AS landscape?

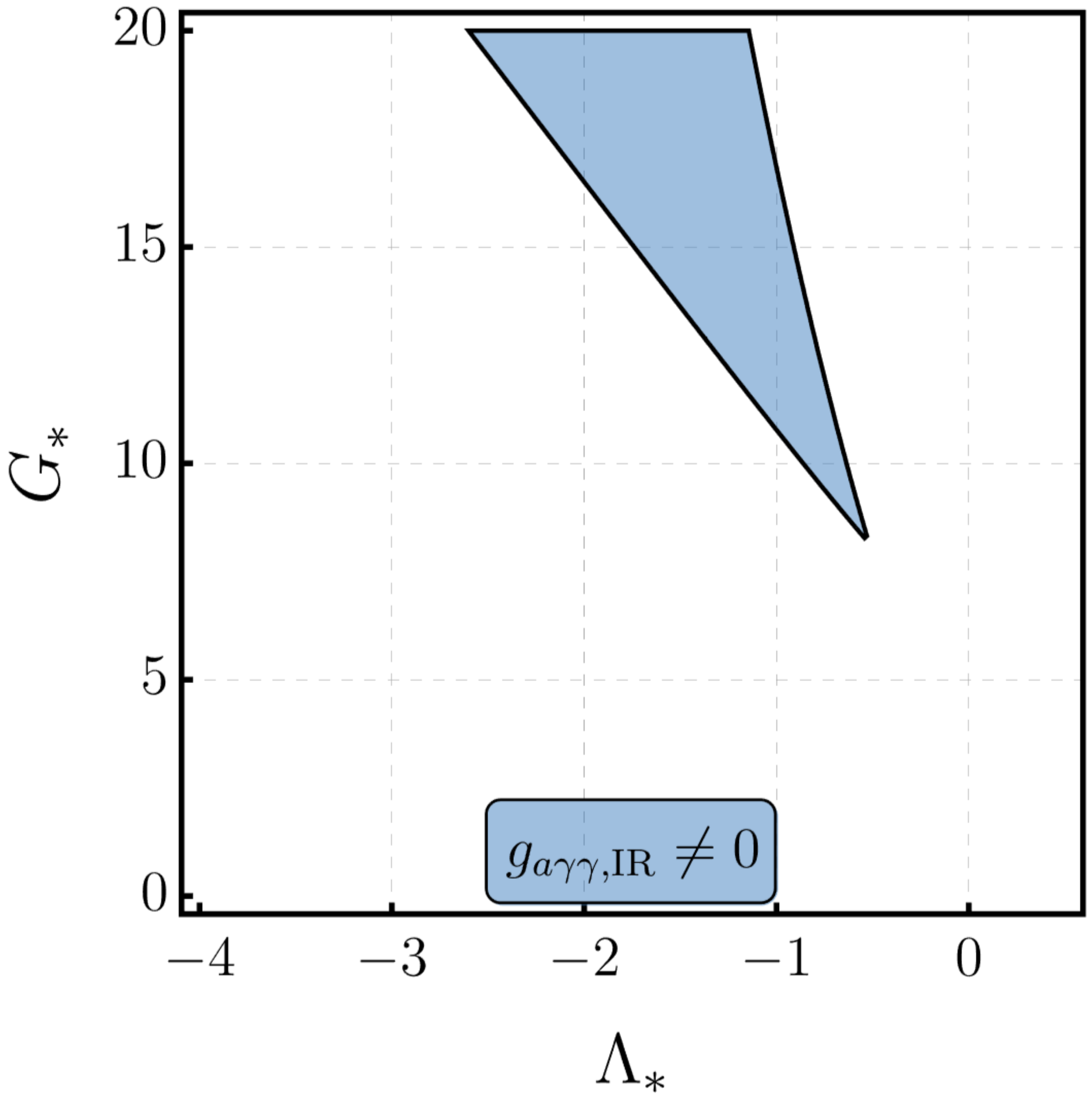
- Final remarks
- ALP DM phenomenology:

  Small and non-vanishing couplings
- AS + phenomenology:

  Large quantum gravity fluctuations.
- ALPs: *likely cannot* be accommodated in the AS landscape.

  Different from string predictions?
  QCD axions?
  Another fundamental theory?

$(g_*^2 = 0, m_*^2 = 0)$ $(g_*^2 > 0, m_*^2 = 0)$



G. de Brito, A. Eichhorn, RRLdS *JHEP* 06 (2022) 013

# Predictive power of AS

## Shift-symmetric Horndeski gravity in asymptotic safety

- Horndeski family (Lorentzian): $\int \quad \Big[ \sum^{5} \mathscr{L}_i + \mathscr{L}_m(\psi_m, g_{\mu\nu}) \Big]$

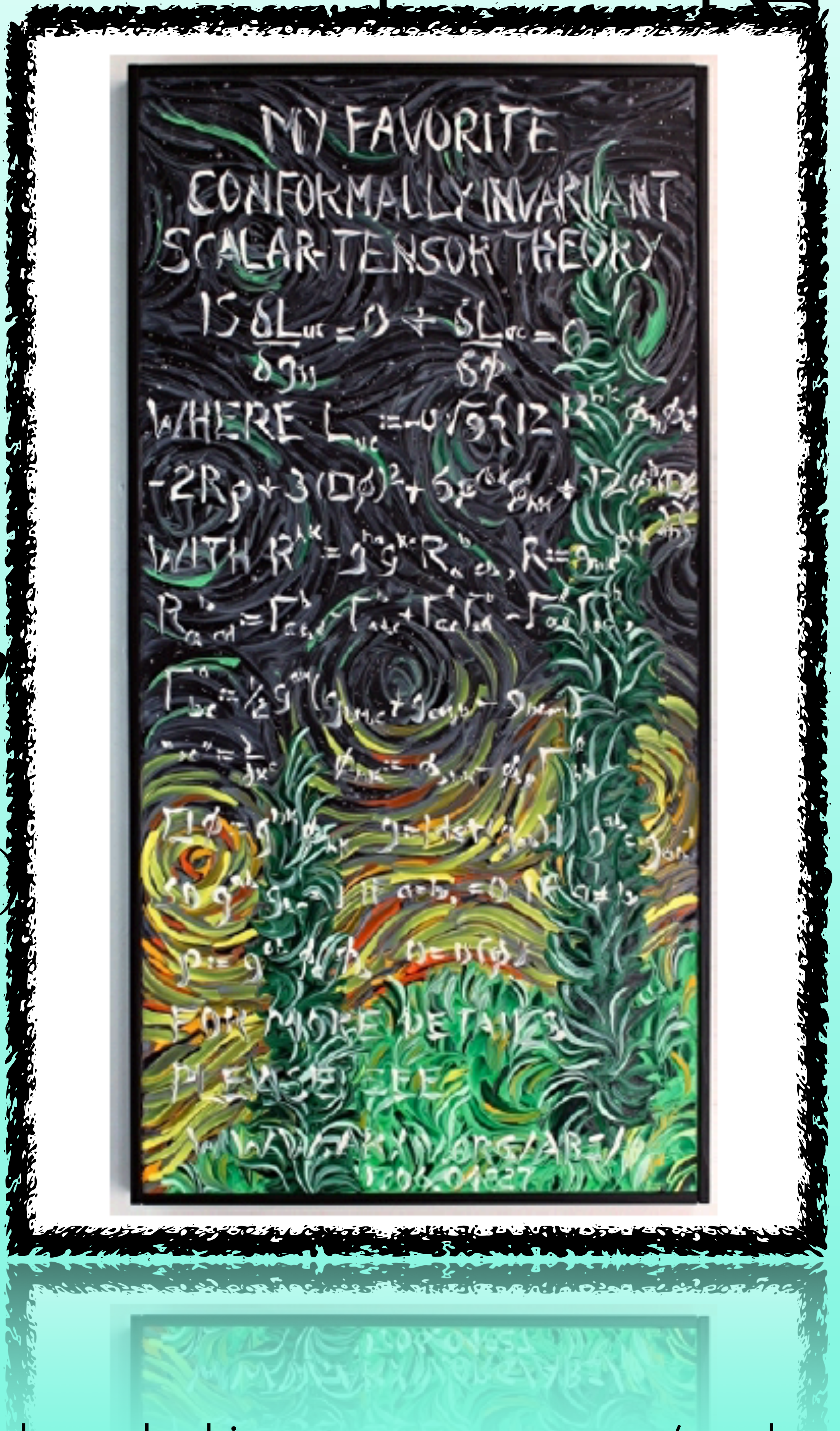
$$\chi = -1/2\partial_\mu\phi\partial^\mu\phi$$

$$\mathscr{L}_2 = K(\phi,\chi)$$

$$\mathscr{L}_3 = -G_3(\phi,\chi)\Box\phi$$

$$\mathscr{L}_4 = G_4(\phi,\chi)R + G_{4,\chi}\Big[(\Box\phi)^2 - \nabla_\mu\nabla_\nu\phi$$

$$\mathscr{L}_5 = G_5(\phi,\chi)G_{\mu\nu}\nabla^\mu\nabla^\nu\phi - \frac{1}{6}G_{5,\chi}\Big[(\Box\phi) \quad + 2\nabla_\mu\nabla_\alpha\phi\nabla^\alpha\nabla^\beta\phi\nabla_\beta\nabla^\mu\phi\Big]$$



https://www.horndeskicontemporary.com/workszoom/2534281/

# Horndeski gravity

- Horndeski family (Lorentzian):

$$S = \int d^4x\sqrt{-g}\left[\sum_{i=2}^{5}\mathscr{L}_i + \mathscr{L}_m(\psi_m, g_{\mu\nu})\right]$$

$$\mathscr{L}_2 = K(\phi, \chi)$$

$$\chi = -1/2\partial_\mu\phi\partial^\mu\phi$$

$$\mathscr{L}_3 = -G_3(\phi, \chi)\Box\phi$$

$$\mathscr{L}_4 = G_4(\phi, \chi)R + G_{4,\chi}\left[(\Box\phi)^2 - \nabla_\mu\nabla_\nu\phi\,\nabla^\mu\nabla^\nu\phi\right]$$

$$\mathscr{L}_5 = G_5(\phi, \chi)G_{\mu\nu}\nabla^\mu\nabla^\nu\phi - \frac{1}{6}G_{5,\chi}\left[(\Box\phi)^3 - 3\Box\phi\,\nabla_\mu\nabla_\nu\phi\,\nabla^\mu\nabla^\nu\phi + 2\nabla_\mu\nabla_\alpha\phi\,\nabla^\alpha\nabla^\beta\phi\,\nabla_\beta\nabla^\mu\phi\right]$$

Flat background: Galileon symmetry

Challenges for UV-completion in curved backgrounds: no protecting symmetry

# Horndeski gravity

- Phenomenology:
  - Electromagnetic sources: CMB, …
  - Gravitational waves: GW170817

$$\mathscr{L}_2 = K(\phi,\chi)$$

$$\mathscr{L}_3 = -\,G_3(\phi,\chi)\,\Box\,\phi$$

$$\mathscr{L}_4 = G_4(\phi,\chi)R + G_{4,\chi}\left[(\Box\phi)^2 - \nabla_\mu\nabla_\nu\phi\,\nabla^\mu\nabla^\nu\phi\right]$$

$$\mathscr{L}_5 = G_5(\phi,\chi)G_{\mu\nu}\,\nabla^\mu\nabla^\nu\phi - \frac{1}{6}G_{5,\chi}\left[(\Box\phi)^3 - 3\,\Box\,\phi\,\nabla_\mu\nabla_\nu\phi\,\nabla^\mu\nabla^\nu\phi + 2\,\nabla_\mu\nabla_\alpha\phi\,\nabla^\alpha\nabla^\beta\phi\,\nabla_\beta\nabla^\mu\phi\right]$$

- Propagation is luminal: $G_{4,\chi}, G_5, G_{5,\chi} \approx 0$

(tensor speed parameter) $\alpha_T < 10^{-15} \Rightarrow c_T \approx c,$

Baker et al. Phys.Rev.Lett. 119 (2017) 25; 1710.06394

Ishak *Liv.Rev.Rel*. 22 (2019) 1, 1; 1806.10122

- Kinetic braiding model:

$$S = \int d^4x\sqrt{-g}\left[\frac{1}{2}M^2_{eff}(\phi)R + K(\phi,\chi) - G_3(\phi,\chi)\,\Box\,\phi\right]$$

Deffayet, Pujolas, Sawicki, Vikman *JCAP 10* (2010) 026; 1008.0048

# Shift-symmetric Horndeski gravity in asymptotic safety

- Practical implementation (Euclidean):
  - Shift symmetry:

$$M^2_{eff}(\phi) = M_P$$

(Minimal coupling)

$$K(\phi,\chi) = K(\chi)$$

$$G_3(\phi,\chi) = G_3(\chi)$$

  - Polynomial expansion:

$$K(\chi) = Z_\phi\,\chi + \bar{g}\,\chi^2$$

$$G_3(\chi) = \bar{h}_1\,\chi$$

$$\chi = -1/2\partial_\mu\phi\partial_\mu\phi,$$

$$\Gamma_k = -\int d^4x\sqrt{\det g}\left(\frac{M_P^2}{2}(R-2\bar{\Lambda}) + Z_\phi\,\chi + \bar{g}\,\chi^2 - \bar{h}_1\,\chi\,\Box\,\phi\right).$$

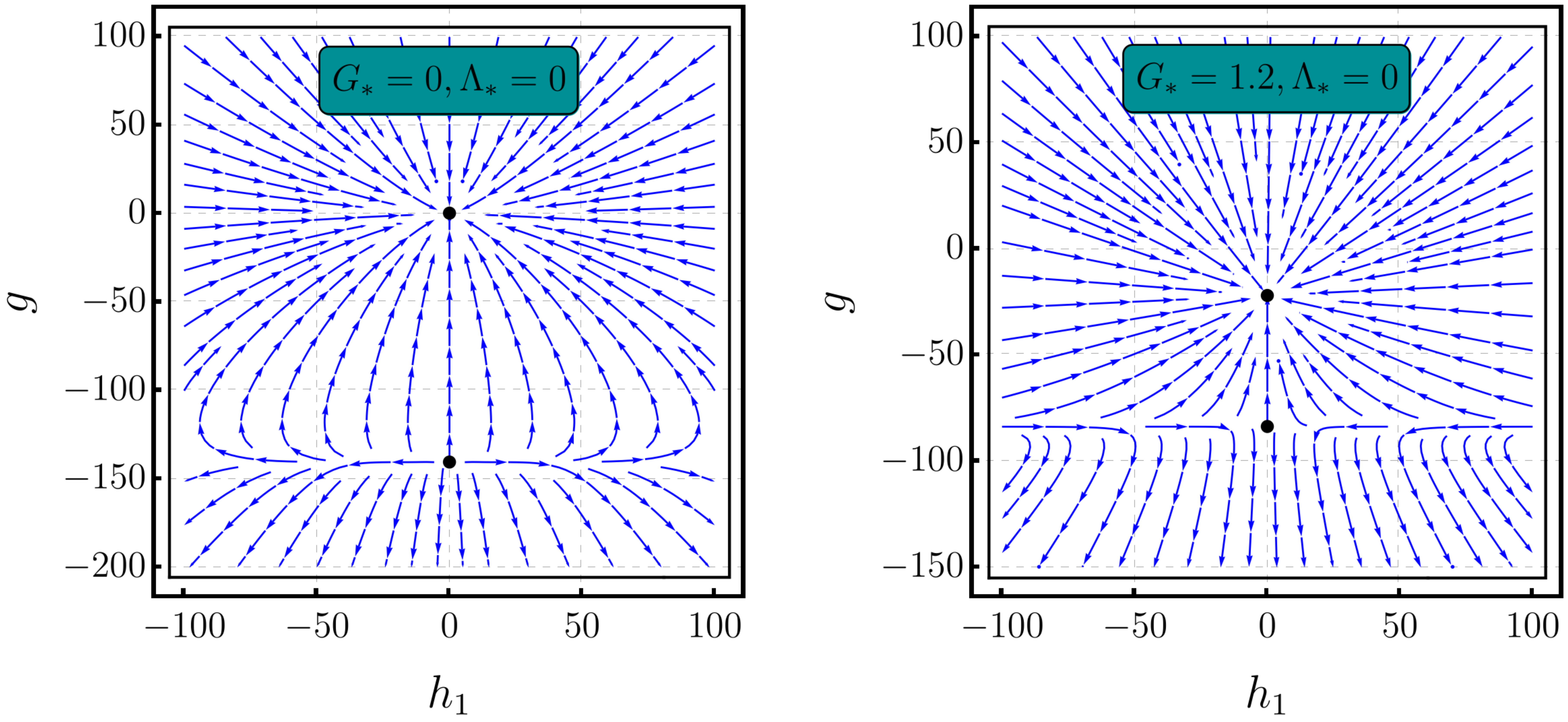
- Can this Horndeski-like model be accommodated in the AS landscape?

Again: $h_{1*} = 0 \Rightarrow$ non-vanishing IR value demands relevant direction

Eichhorn, RRLdS, Wagner JCAP 02 (2023) 052

# Shift-symmetric Horndeski gravity in asymptotic safety

Fixed point structure:

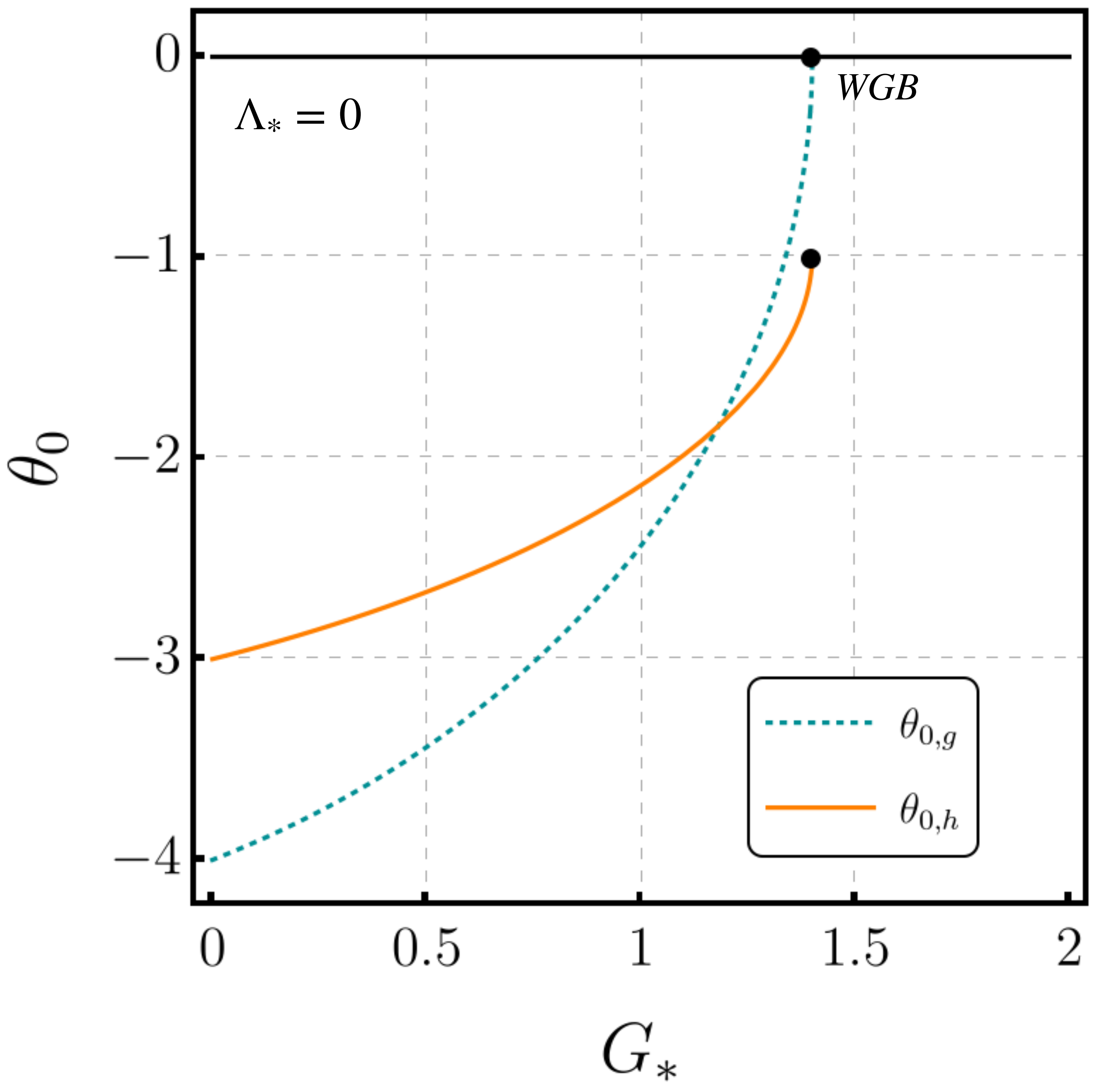


Both cases: $h_{1*} = 0 \Rightarrow$ Flow towards vanishing values at IR.

Eichhorn, RRLdS, Wagner JCAP 02 (2023) 052

# Shift-symmetric Horndeski gravity in asymptotic safety

Critical exponent (at shifted Gaussian fixed point):



- Gravity is not strong enough to render the coupling $h_1$relevant.

⇒ Bound to observational constraints (braiding parameter): $|\alpha_B| < 10^{-2}$.

Creminelli et al. *JCAP* 05 (2020) 002

AS only compatible with Horndeski models without braiding!

(**systematic uncertainties**)

Eichhorn, RRLdS, Wagner JCAP 02 (2023) 052

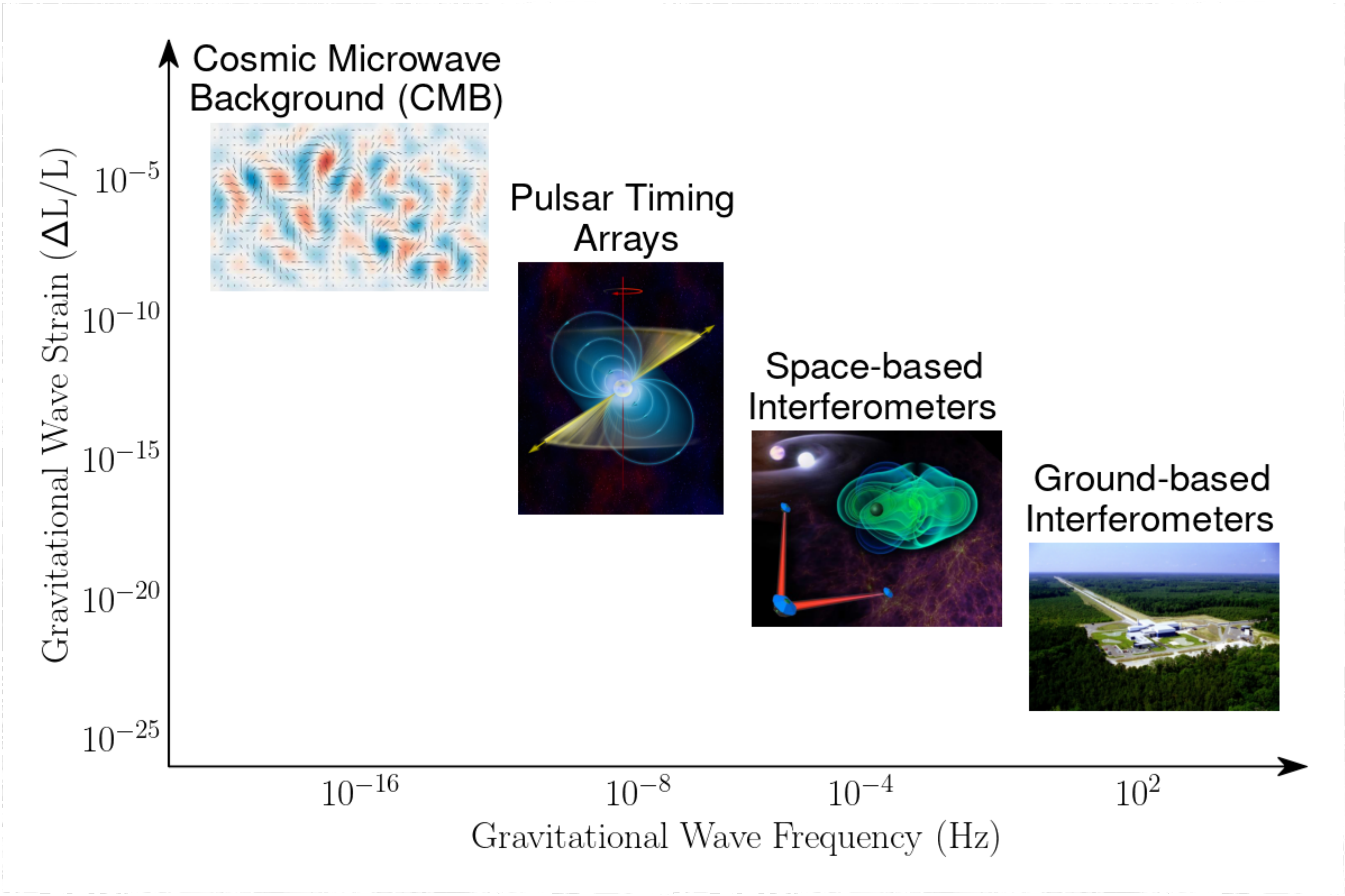
# Pulsar timing

## Beyond SM cosmology with stochastic gravitational waves

Rafael R. Lino dos Santos
CP3-Origins, University of Southern Denmark
Particle Cosmology Münster, WWU Münster

Based on works with Kai Schmitz, Linda van Manen, and the New Physics working group of the NANOGrav collaboration

# General Relativity



RRLdS, van Manen 2212.05594

**Using gravity as a probe for Beyond Cosmology and Particle Physics Standard Models!**

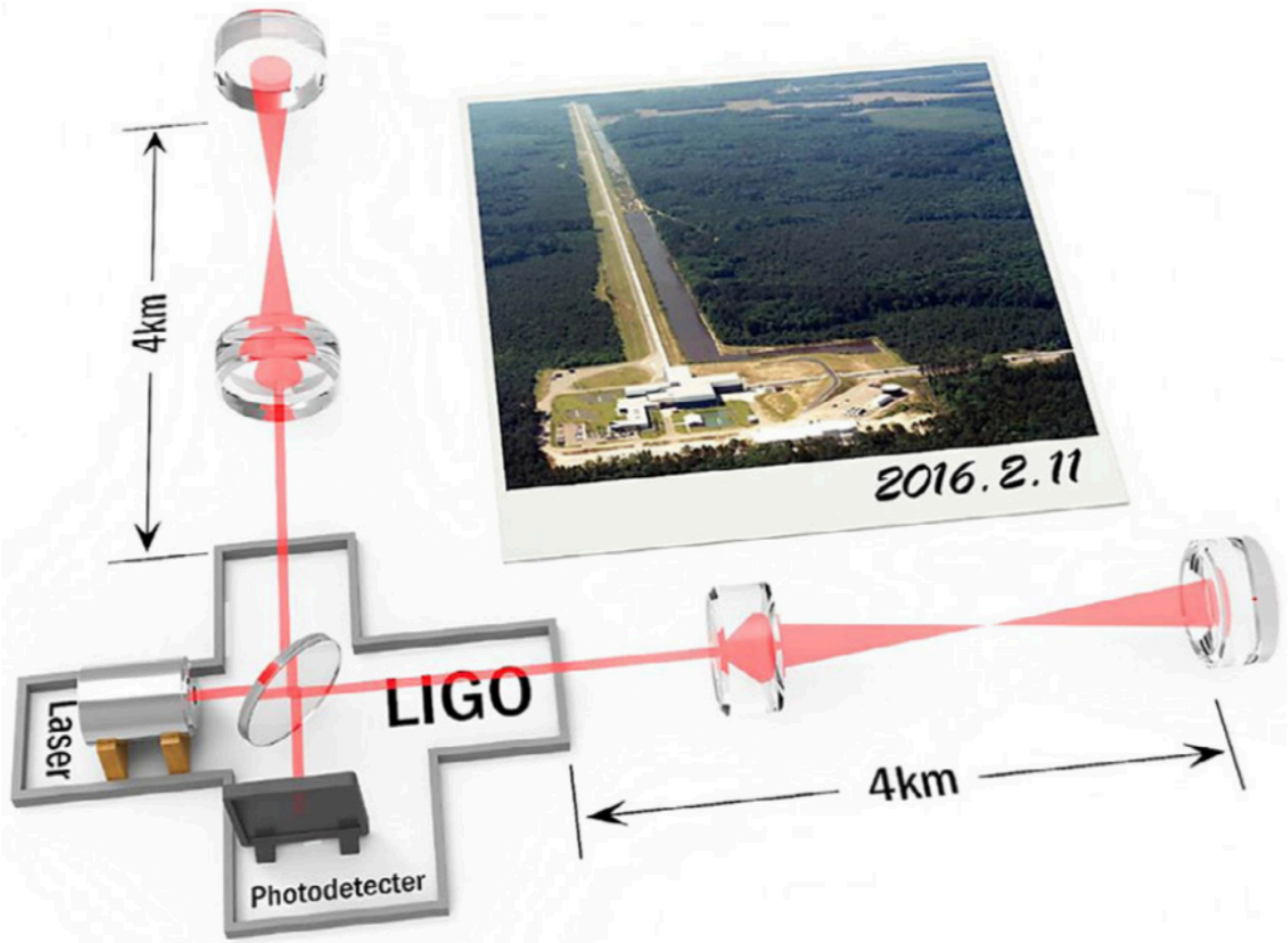
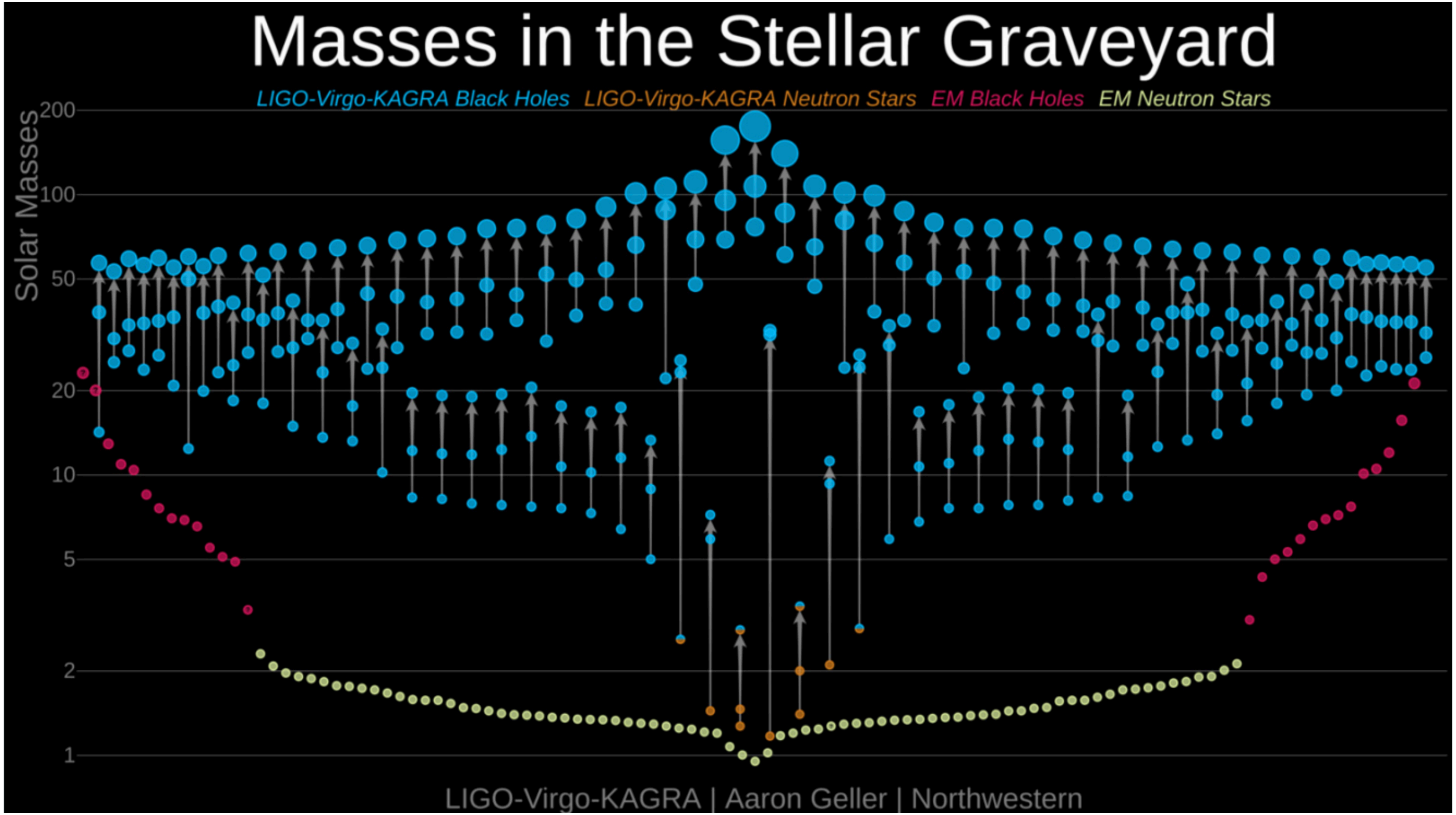


**Figure 5.1:** Sketch of the Advanced LIGO detector in Livingston, Louisiana.



LIGO-Virgo-KAGRA | Aaron Geller | Northwestern

RRLdS, van Manen 2212.05594

# Stochastic gravitational waves

## Summary

- Superposition of different wavenumbers

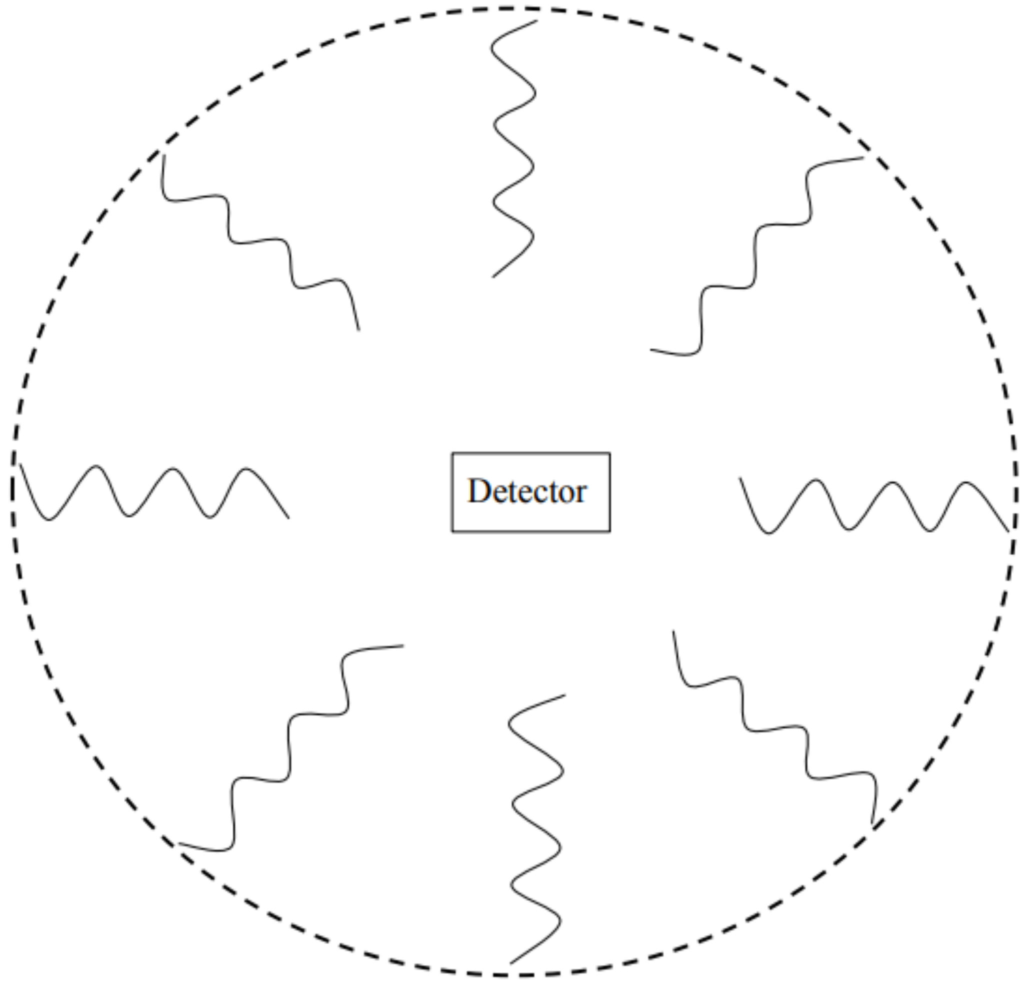
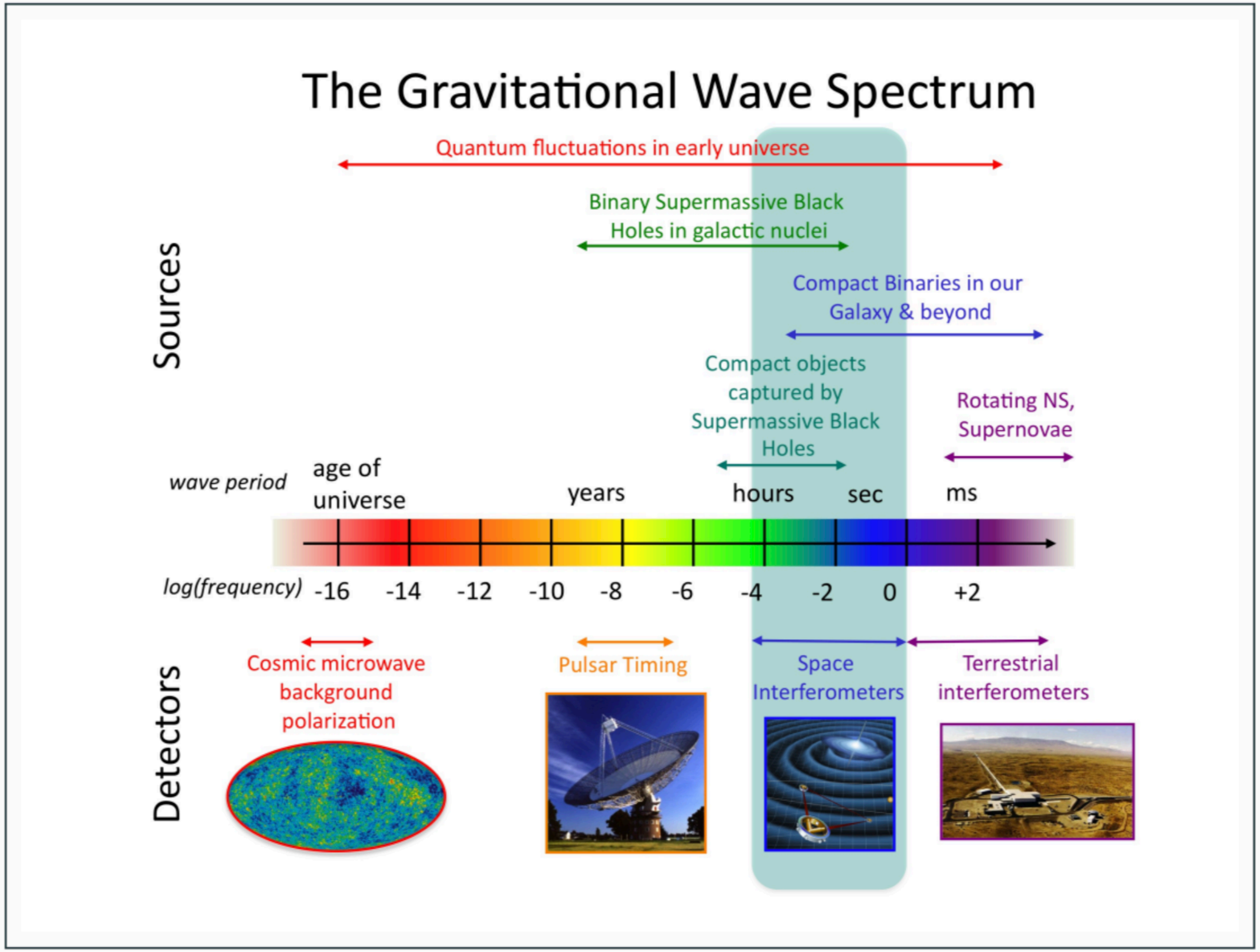


Figure 5: *Here we show a schematic representation of the propagation and detection of SGWBs. The circle represents some cosmic event (gravitational wave source). The waves then propagate through the universe. Occasionally they find a detector. The signal from SGWBs act as additional "noise" in a gravitational wave detector.*

# Towards supermassive black hole binaries and cosmology/BSM physics



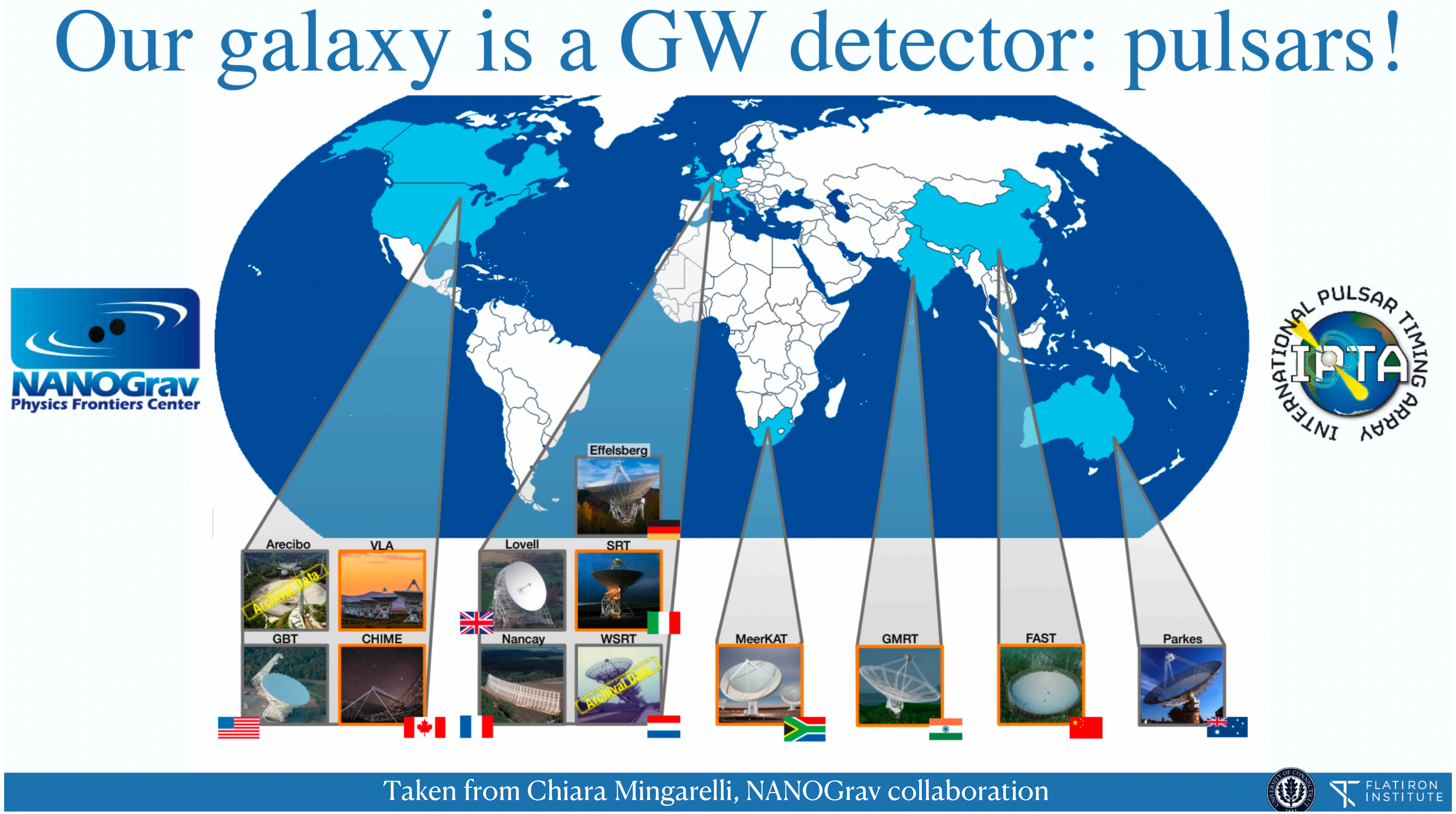
© NASA Goddard Space Flight Center

The larger is M, the lower is f !

The larger is the arm, the lower is f !

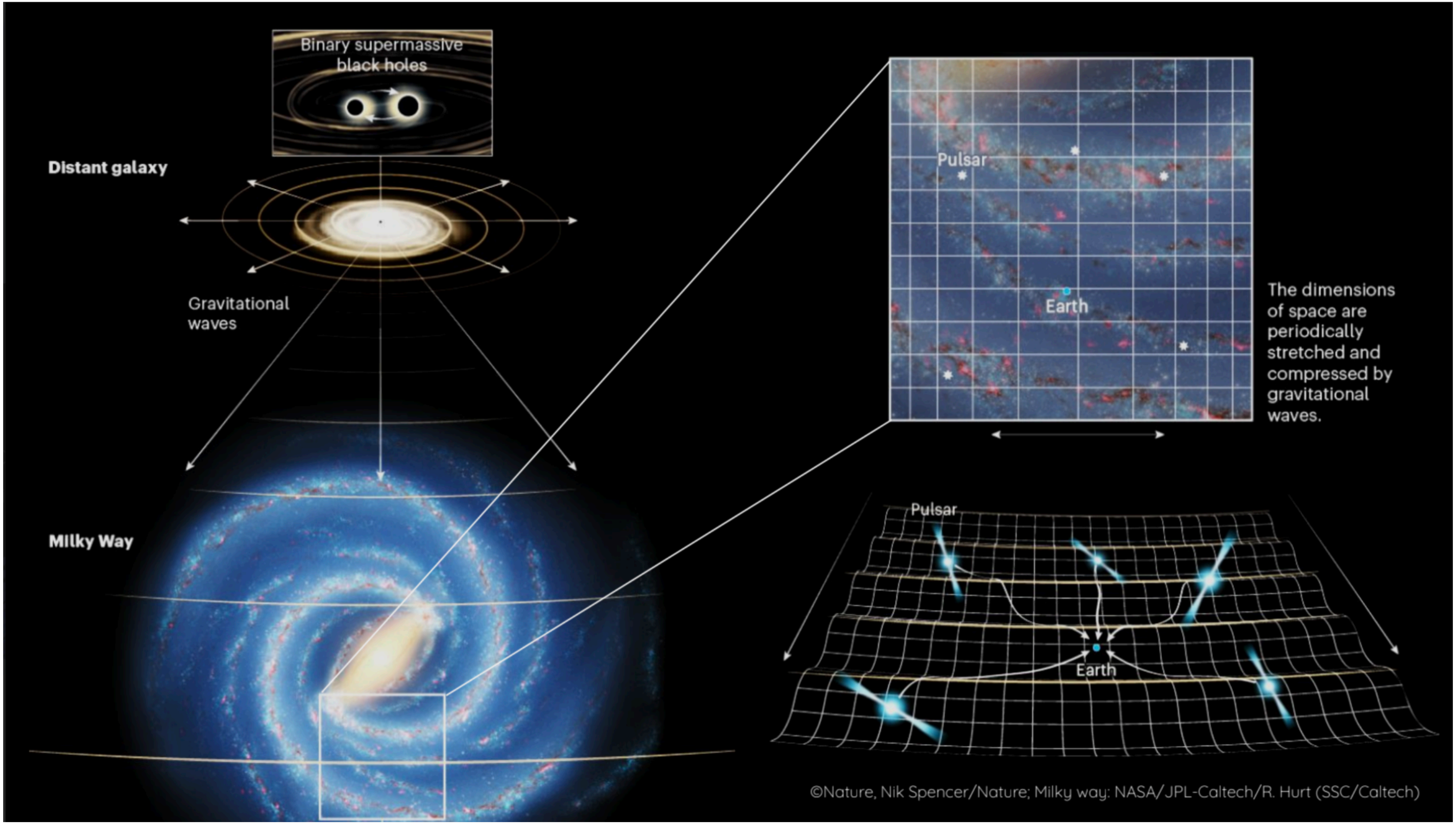
# Pulsar timing

## Beyond LIGO and LISA: go for arms with galactic sizes!



Our galaxy is a GW detector: pulsars!

Taken from Chiara Mingarelli, NANOGrav collaboration



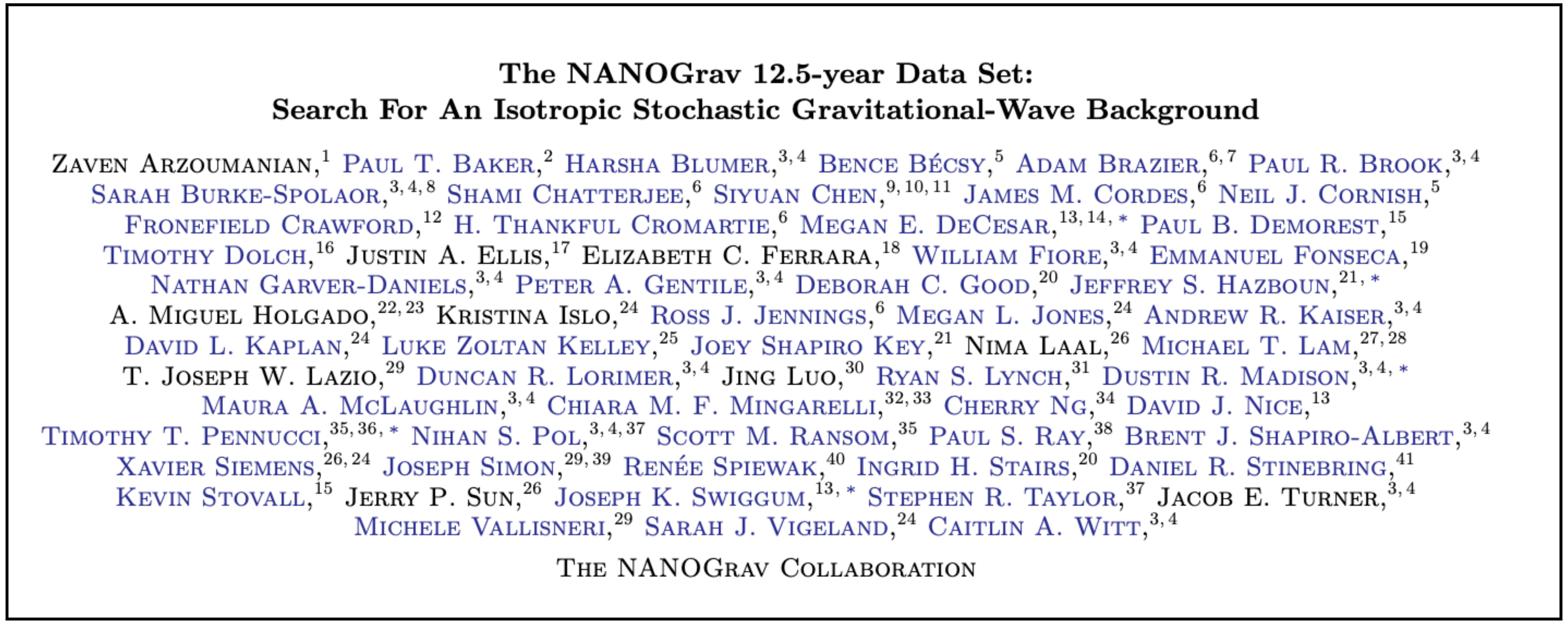
The dimensions of space are periodically stretched and compressed by gravitational waves.

©Nature, Nik Spencer/Nature; Milky way: NASA/JPL-Caltech/R. Hurt (SSC/Caltech)

Taken from Thankful Cromartie, NANOGrav collaboration

# NG12.5 year dataset

## Did they detect stochastic gravitational waves?



**The NANOGrav 12.5-year Data Set:**
**Search For An Isotropic Stochastic Gravitational-Wave Background**

Zaven Arzoumanian,[1] Paul T. Baker,[2] Harsha Blumer,[3,4] Bence Bécsy,[5] Adam Brazier,[6,7] Paul R. Brook,[3,4] Sarah Burke-Spolaor,[3,4,8] Shami Chatterjee,[6] Siyuan Chen,[9,10,11] James M. Cordes,[6] Neil J. Cornish,[5] Fronefield Crawford,[12] H. Thankful Cromartie,[6] Megan E. DeCesar,[13,14,*] Paul B. Demorest,[15] Timothy Dolch,[16] Justin A. Ellis,[17] Elizabeth C. Ferrara,[18] William Fiore,[3,4] Emmanuel Fonseca,[19] Nathan Garver-Daniels,[3,4] Peter A. Gentile,[3,4] Deborah C. Good,[20] Jeffrey S. Hazboun,[21,*] A. Miguel Holgado,[22,23] Kristina Islo,[24] Ross J. Jennings,[6] Megan L. Jones,[24] Andrew R. Kaiser,[3,4] David L. Kaplan,[24] Luke Zoltan Kelley,[25] Joey Shapiro Key,[21] Nima Laal,[26] Michael T. Lam,[27,28] T. Joseph W. Lazio,[29] Duncan R. Lorimer,[3,4] Jing Luo,[30] Ryan S. Lynch,[31] Dustin R. Madison,[3,4,*] Maura A. McLaughlin,[3,4] Chiara M. F. Mingarelli,[32,33] Cherry Ng,[34] David J. Nice,[13] Timothy T. Pennucci,[35,36,*] Nihan S. Pol,[3,4,37] Scott M. Ransom,[35] Paul S. Ray,[38] Brent J. Shapiro-Albert,[3,4] Xavier Siemens,[26,24] Joseph Simon,[29,39] Renée Spiewak,[40] Ingrid H. Stairs,[20] Daniel R. Stinebring,[41] Kevin Stovall,[15] Jerry P. Sun,[26] Joseph K. Swiggum,[13,*] Stephen R. Taylor,[37] Jacob E. Turner,[3,4] Michele Vallisneri,[29] Sarah J. Vigeland,[24] Caitlin A. Witt,[3,4]

The NANOGrav Collaboration

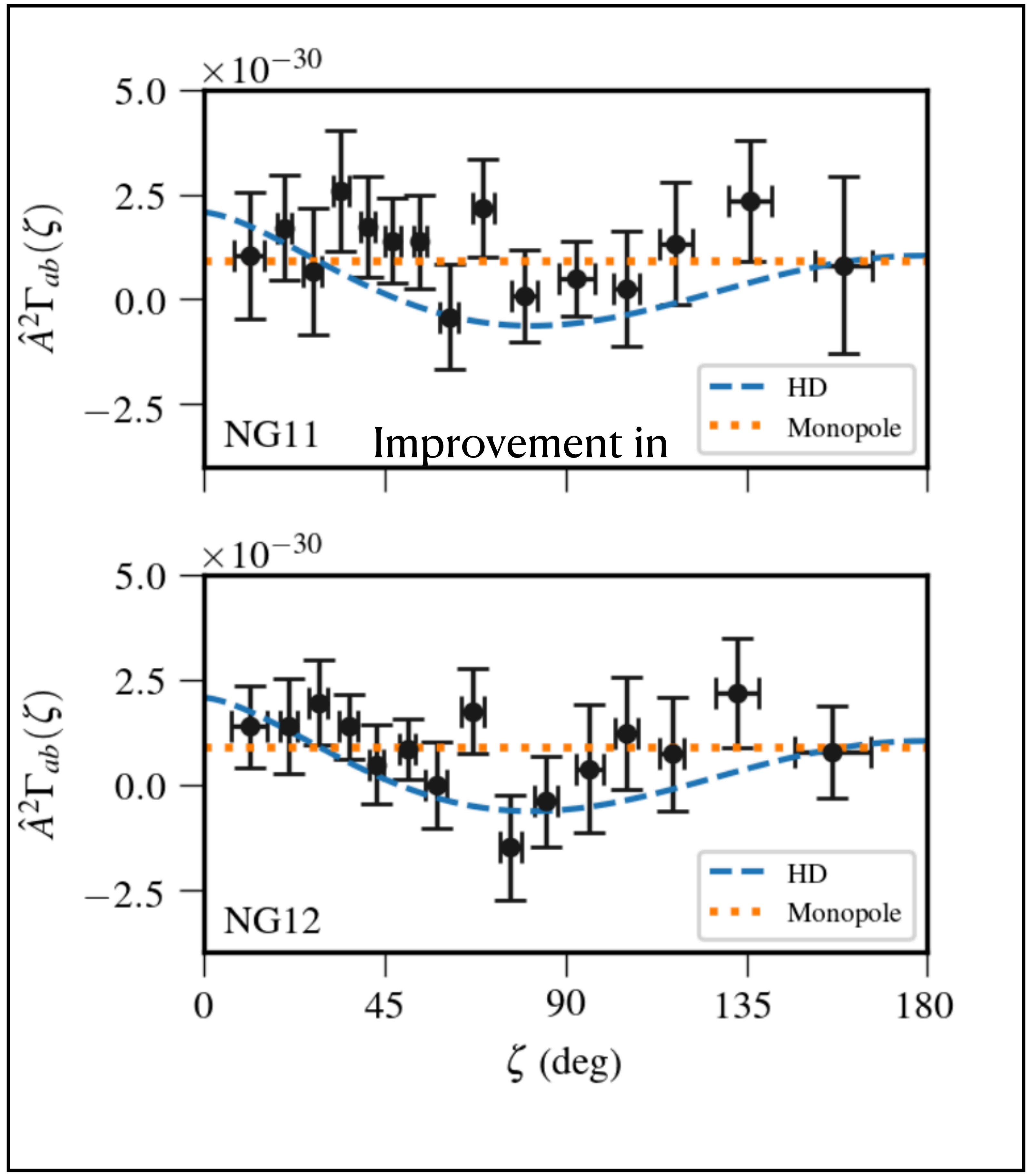
Hints for detection of SGWB!

Statistical evidence for a common-spectrum low-frequency red-noise power-law process (consistent with the expected black hole binary) but without significant evidence for, or against, Helling-Downs correlations. A detection of SGWB can be either confirmed or refuted by coming data releases.

arXiv:2009.04496; The Astrophysical Journal Letters, Volume 905, Number 2 (2020)

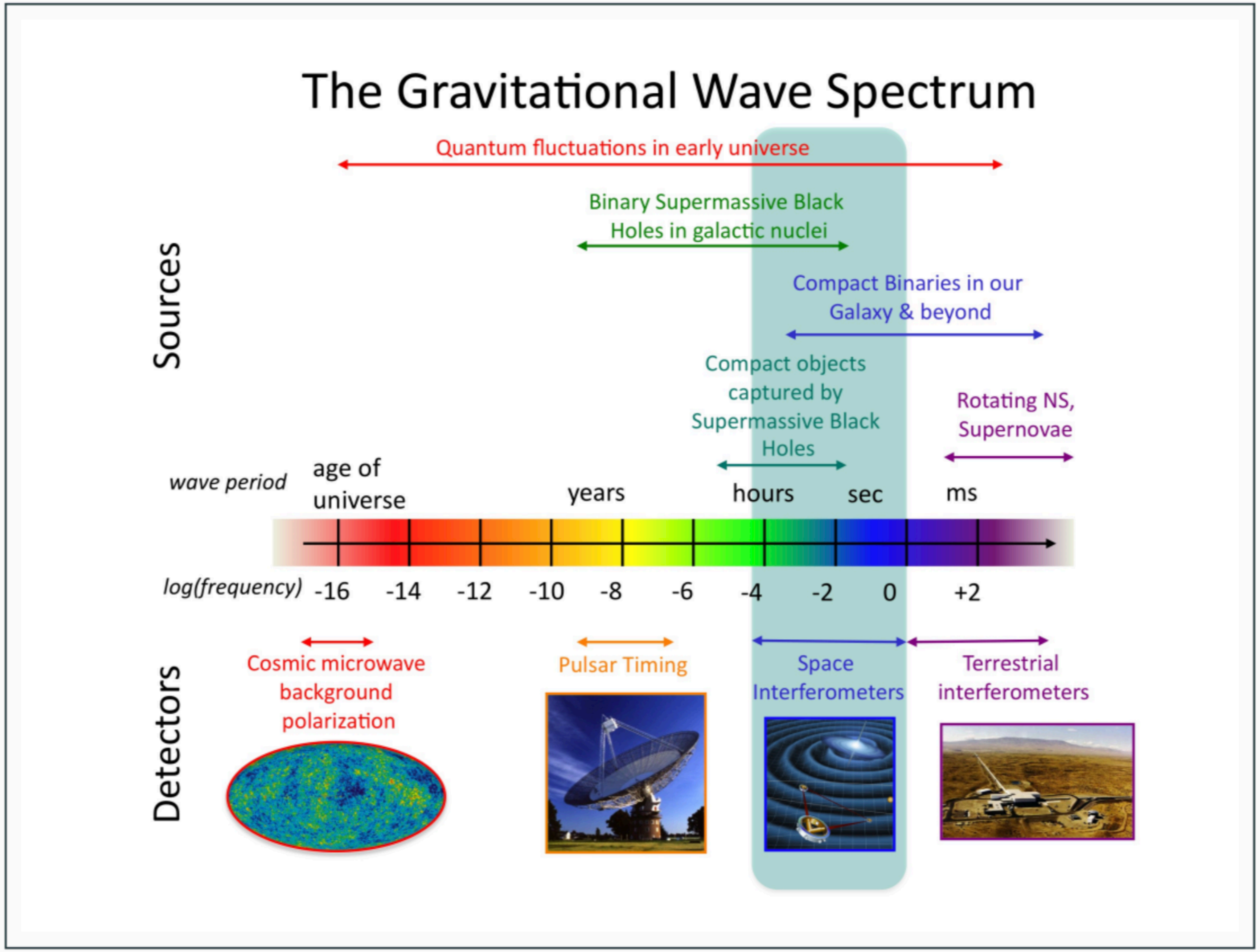
# NG12.5 year dataset

## Did they detect stochastic gravitational waves?



arXiv:2009.04496; The Astrophysical Journal Letters, Volume 905, Number 2 (2020)

# Towards supermassive black hole binaries and cosmology/BSM physics



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# Primordial sources

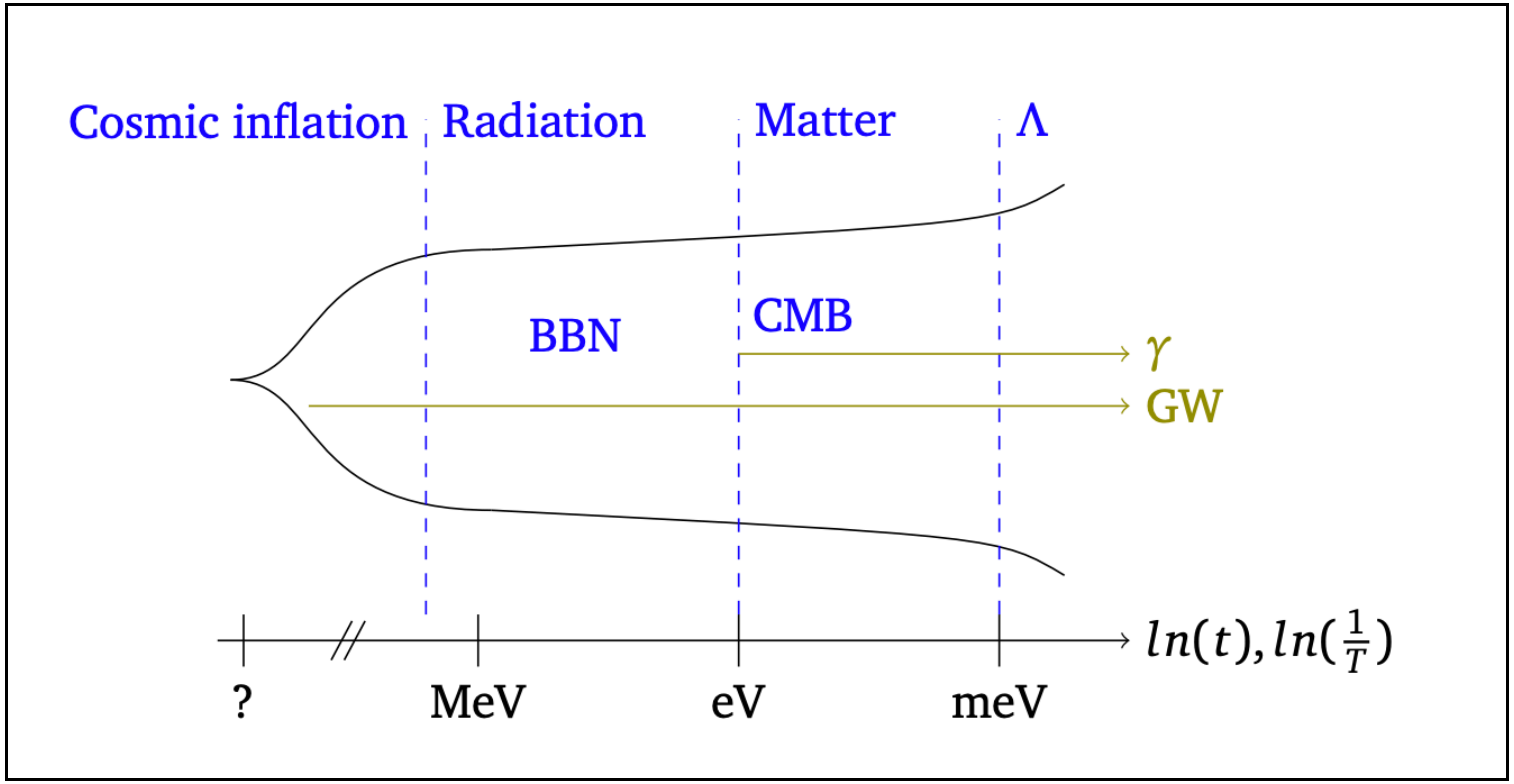
### The search for new physics

- On top of the astrophysical signal, there is a cosmological background
- Produced by different sources in the early universe

RRLdS, van Manen 2212.05594

# Early-universe cosmology

## Beyond CMB



Access to very early stages of the universe (earlier than CMB!)

# Primordial sources

## The search for new physics

- On top of the astrophysical signal, there is a cosmological background
- Produced by different sources in the early universe

- Bayesian search [Work in progress]
- Can these sources fit PTA data?
  - If yes, how likely? Bayes factors
  - If no, bounds from PTA data

# Primordial sources

## The search for new physics

- What can be probed?
  - Everything with a computable GW spectrum (analytical or numerical).
    - Inflation
    - Primordial black holes
    - Cosmic strings
    - Phase transitions
    - Domain walls
    - And so on…

$$\Omega_{GW} = \frac{1}{\rho_c}\frac{d\rho_{GW}}{d\ln k}.$$

$$\Omega_{\mathrm{gw}}^{\mathrm{observed}}(k) = \frac{\Omega_{rad}^{0}}{24}\left(\frac{g_*(k)}{g_*^0}\right)\left(\frac{g_{*,s}^0}{g_{*,s}(k)}\right)^{4/3}\Omega_{\mathrm{gw}}^{\mathrm{emitted}}(k).$$

# Primordial sources

## The search for new physics

- The search for new physics with PTA data has already started
    - NANOGrav 12.5 yr and IPTA DR2 datasets.

- Implications for:
    - Inflation
    - Primordial black holes
    - Cosmic strings

Let us see some examples in the literature!

# Inflation

## Beyond simple power-law inflation

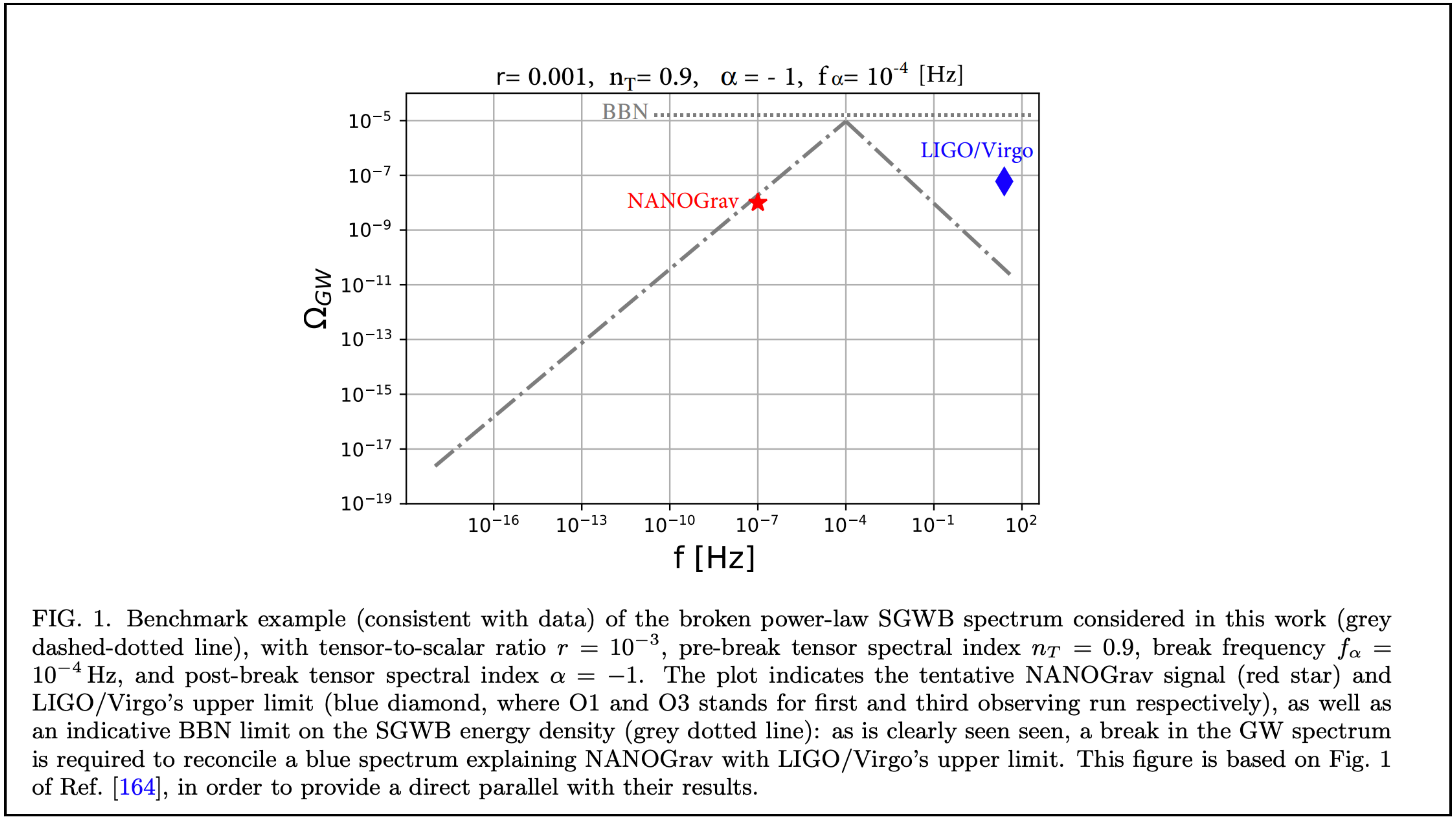
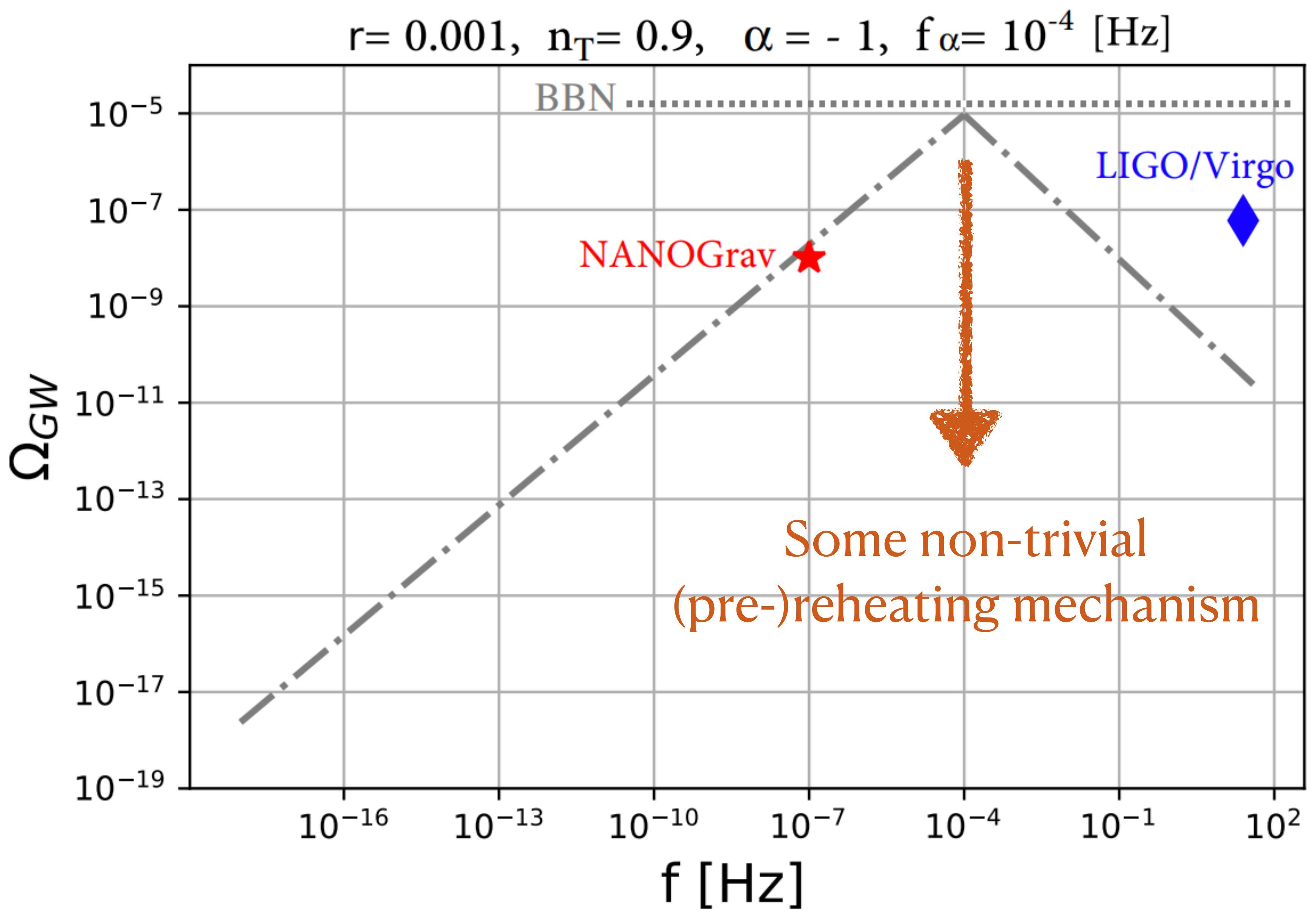


FIG. 1. Benchmark example (consistent with data) of the broken power-law SGWB spectrum considered in this work (grey dashed-dotted line), with tensor-to-scalar ratio $r = 10^{-3}$, pre-break tensor spectral index $n_T = 0.9$, break frequency $f_\alpha = 10^{-4}$ Hz, and post-break tensor spectral index $\alpha = -1$. The plot indicates the tentative NANOGrav signal (red star) and LIGO/Virgo's upper limit (blue diamond, where O1 and O3 stands for first and third observing run respectively), as well as an indicative BBN limit on the SGWB energy density (grey dotted line): as is clearly seen seen, a break in the GW spectrum is required to reconcile a blue spectrum explaining NANOGrav with LIGO/Virgo's upper limit. This figure is based on Fig. 1 of Ref. [164], in order to provide a direct parallel with their results.

Benetti, Graef, Vagnozzi *Phys.Rev.D* 105 (2022) 4, 043520; 2111.04758

# Inflation

## Beyond simple power-law inflation



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Benetti, Graef, Vagnozzi *Phys.Rev.D* 105 (2022) 4, 043520; 2111.04758

# Scalar-induced gravitational waves

## Seeding primordial black holes

- Scalar-induced gravitational waves are induced by enhanced scalar density perturbations;
- They are second-order solutions in perturbation theory;
- At second order, tensor and scalar modes are not decoupled;
- These density perturbations also seed primordial black holes;
- Gravitational wave spectrum:

$$\Omega_{\mathrm{GW}}(k,\eta) = \int_0^\infty dv \int_{|1-v|}^{1+v} du\, J(u,v)\, \mathcal{P}_{\mathcal{R}}(vk)\mathcal{P}_{\mathcal{R}}(uk)$$

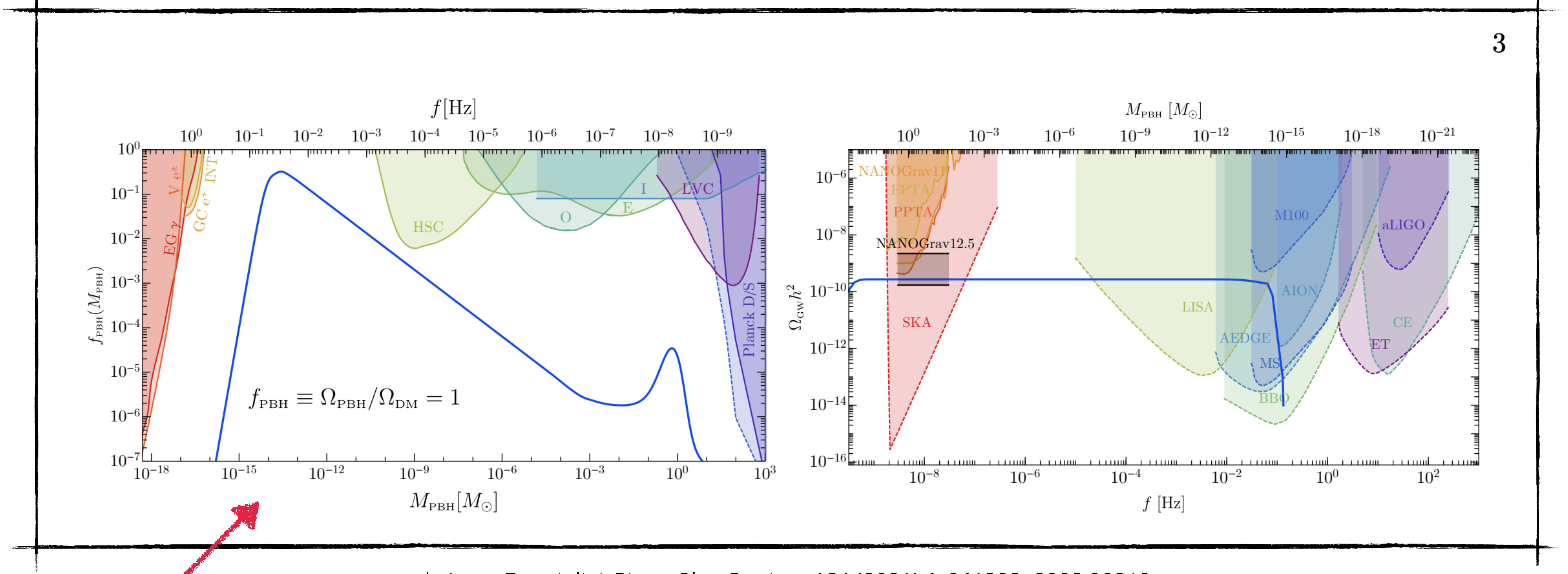
Power spectrum of gauge-invariant comoving curvature perturbation: $\mathcal{P}_{\mathcal{R}}(k)$

Given a scalar power spectrum, we can compute the corresponding GW density.

# Scalar-induced gravitational waves

## Primordial black hole interpretation of NG12.5 yr data set

Flat power spectrum



de Luca, Franciolini, Riotto *Phys.Rev.Lett.* 126 (2021) 4, 041303; 2009.08268

To comprise dark matter in totality
we need asteroid-mass PBH

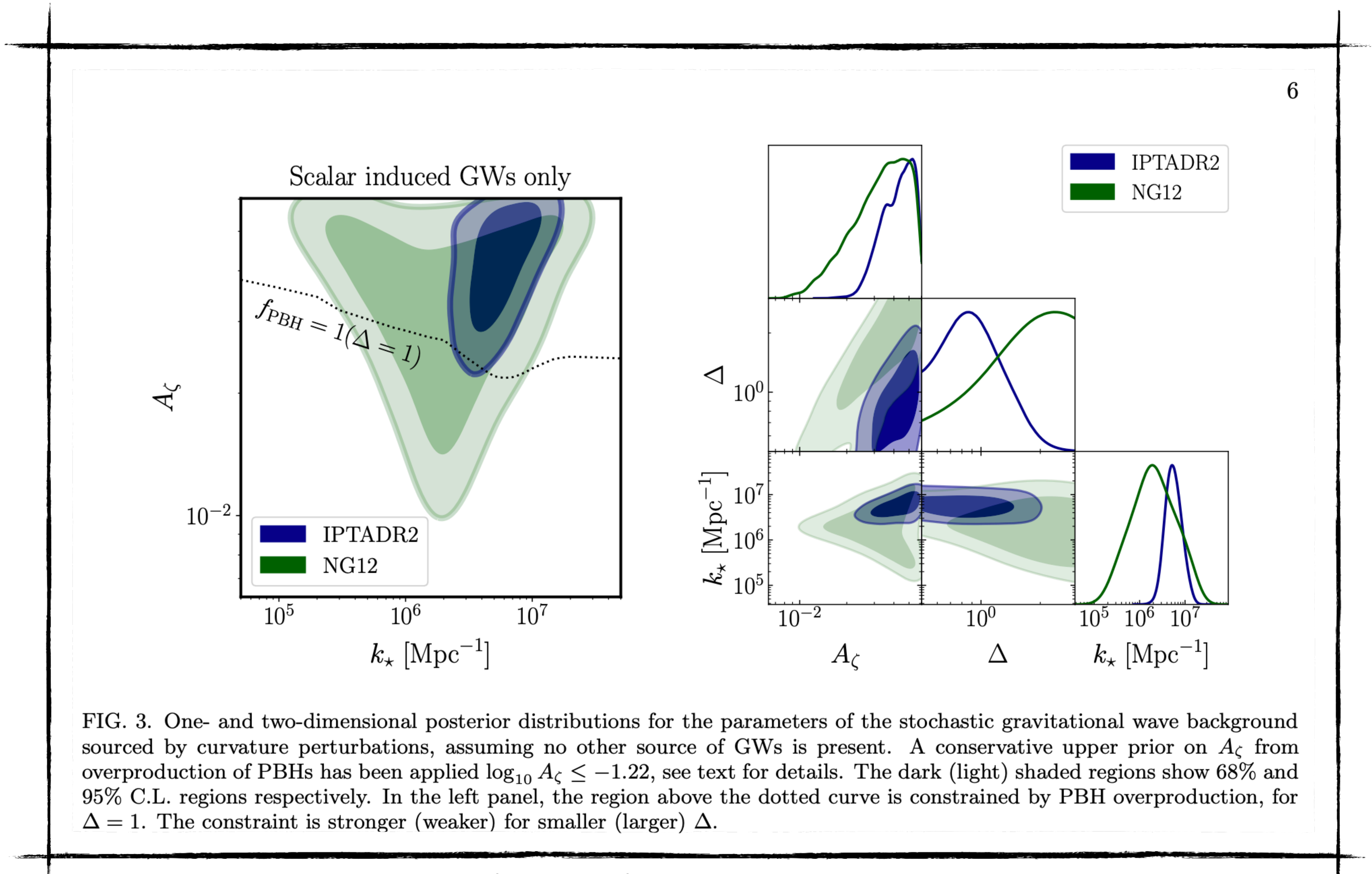
See also Vaskonen, Veermäe *Phys.Rev.Lett.* 126 (2021) 5, 051303; 2009.07832

# Scalar-induced gravitational waves

## Bayesian search

- Gaussian power spectrum in log space
- $\Omega_{\mathrm{GW}}(k,\eta) = \int_0^\infty dv \int_{|1-v|}^{1+v} du\, J(u,v)\, \mathcal{P}_{\mathcal{R}}(vk)\mathcal{P}_{\mathcal{R}}(uk)$
- $\mathcal{P}_{\mathcal{R}}(k) = \frac{A}{\sqrt{2\pi}\Delta} \exp\left(-\frac{\ln^2(k/k_*)}{2\Delta^2}\right)$

- Bayesian search: posterior distributions
- Constraints from PBH dark matter



6

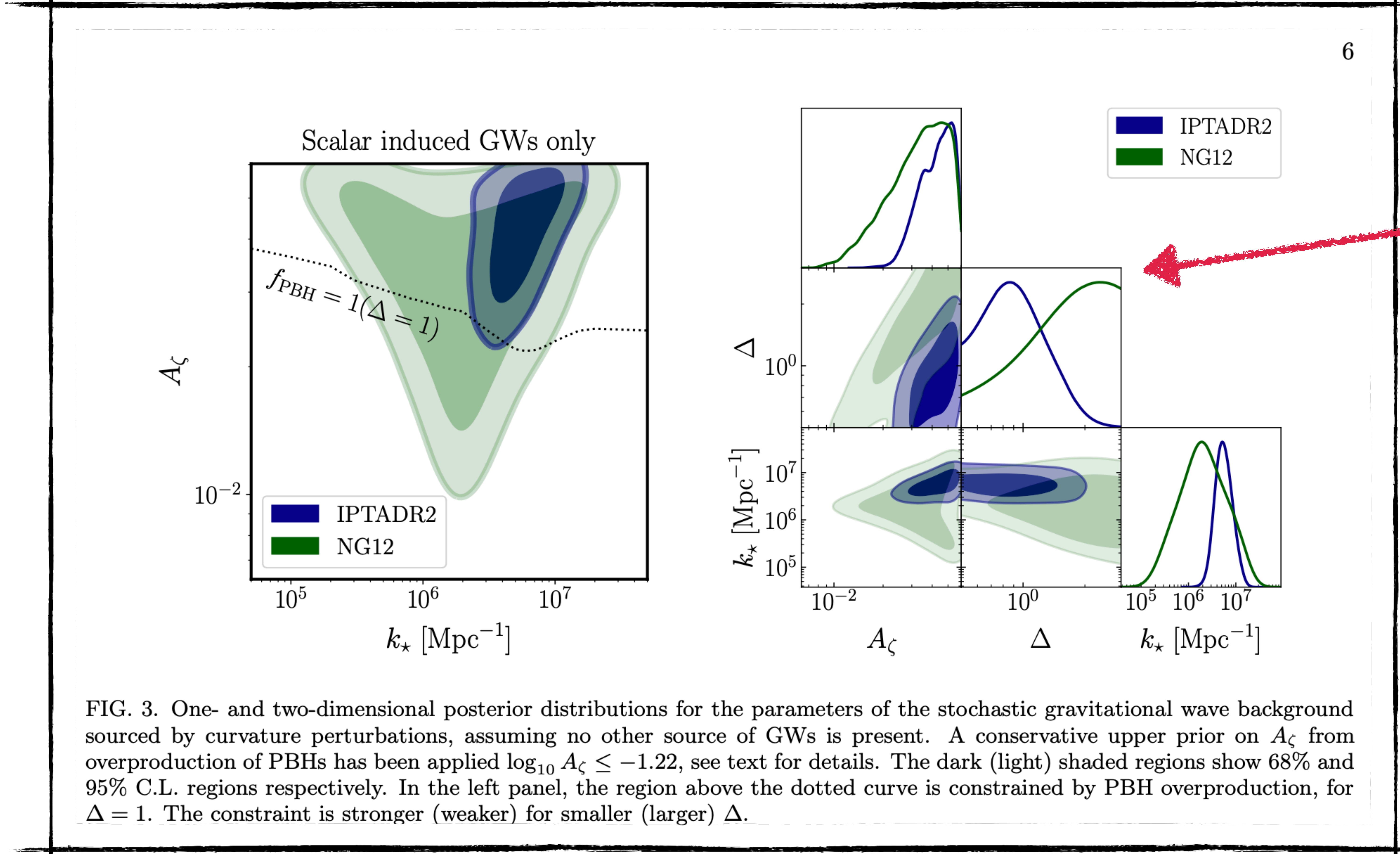
FIG. 3. One- and two-dimensional posterior distributions for the parameters of the stochastic gravitational wave background sourced by curvature perturbations, assuming no other source of GWs is present. A conservative upper prior on $A_\zeta$ from overproduction of PBHs has been applied $\log_{10} A_\zeta \leq -1.22$, see text for details. The dark (light) shaded regions show 68% and 95% C.L. regions respectively. In the left panel, the region above the dotted curve is constrained by PBH overproduction, for $\Delta = 1$. The constraint is stronger (weaker) for smaller (larger) $\Delta$.

See also Zhao, Wang, *Universe* 9 (2023) 157, 2211.09450

Dandoy, Domcke, Rompineve, 2302. 07901

# Scalar-induced gravitational waves

## Bayesian search



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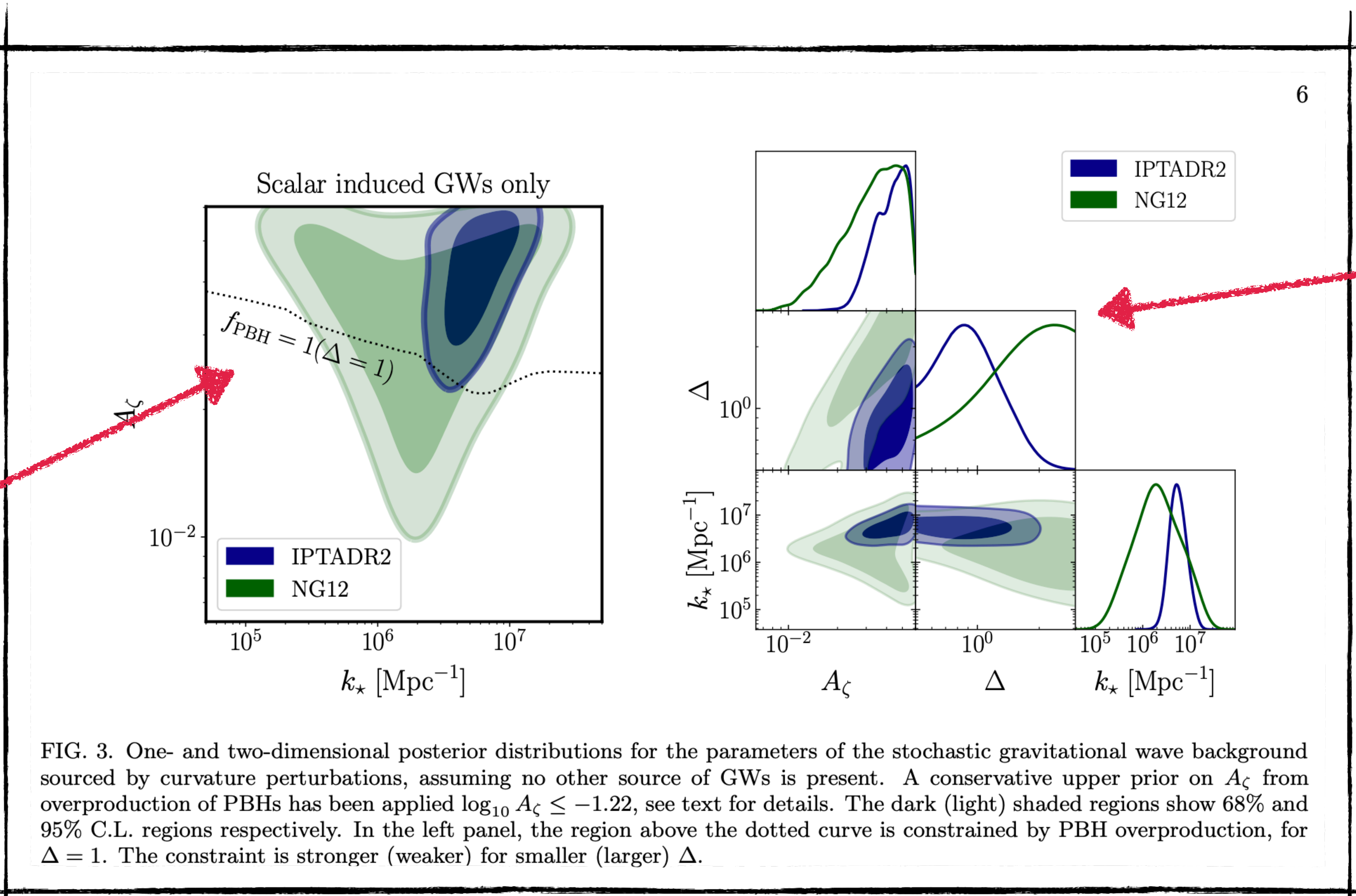
IPTA DR2 prefers
steeper spectra!

Dandoy, Domcke, Rompineve, 2302. 07901

# Scalar-induced gravitational waves

## Bayesian search



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Tendency to overproduce
dark matter!

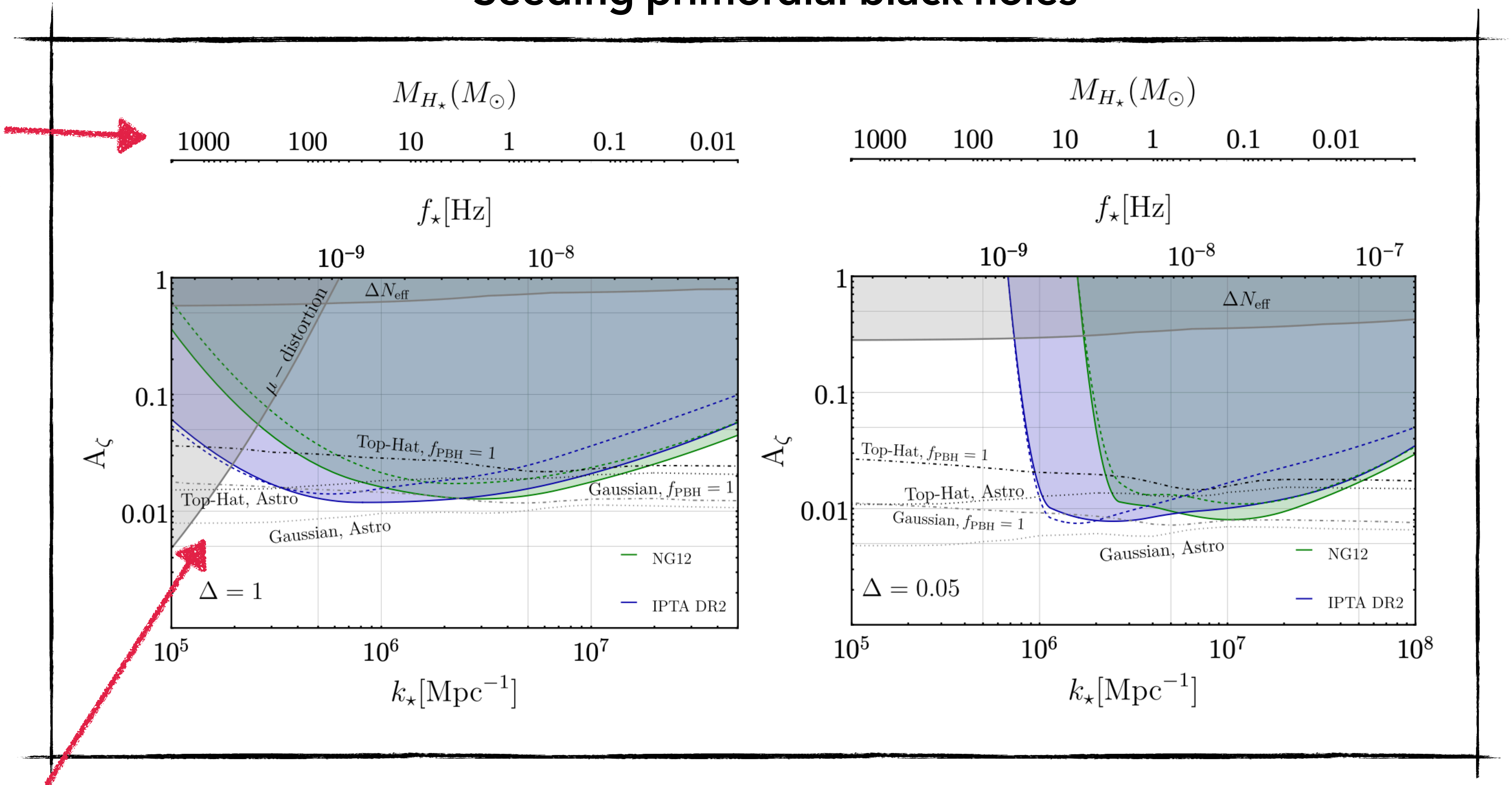
IPTA DR2 prefers
steeper spectra!

Dandoy, Domcke, Rompineve, 2302. 07901

# Scalar-induced gravitational waves

## Seeding primordial black holes

PBH mass
peaked at
nHz scales:
stellar mass



Dandoy, Domcke, Rompineve, 2302. 07901

Many uncertainties in the PBH abundance mechanism

RRLdS, van Manen 2212.05594

# Cosmic strings

## The search for new physics

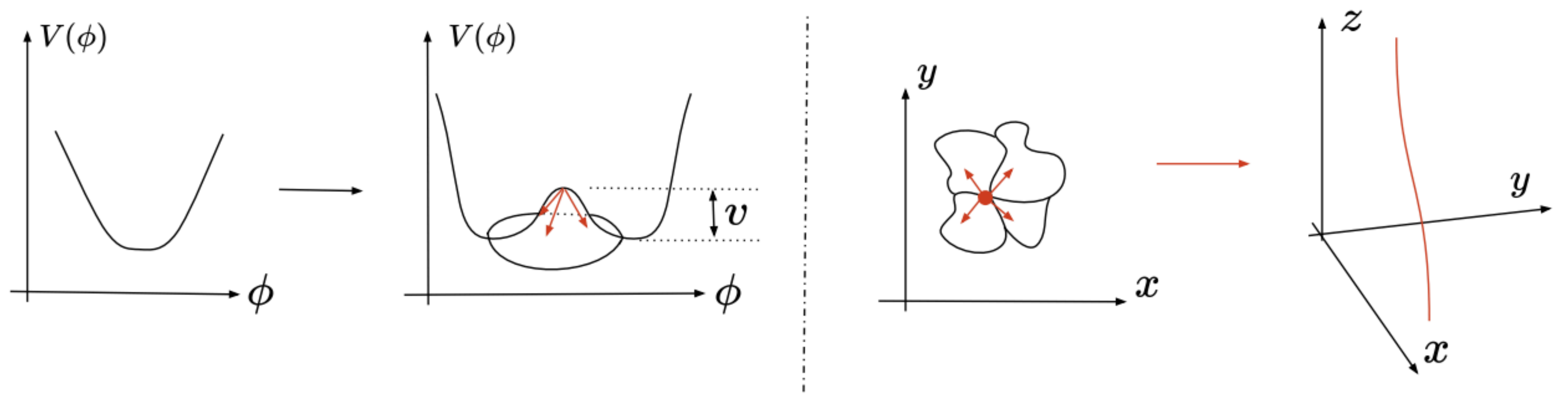


Figure 13: *Representation of cosmic strings - one-dimensional topological defects. In the two first plots, we show a complex scalar field potential versus scalar field configuration, where some mechanism allows for a phase transition with a non-vanishing expectation value $v$. We obtain the two last plots by mapping the solution to real space. In the 2D plot, we show the location of the local extremal point (false vacuum, orange dot) and regions where the scalar field configuration assumes different values; by continuity, these regions intersect each other where the vacuum expectation value $<\phi>$ corresponds to the false vacuum. In the 3D plot, we extrapolate the false vacuum region to three spatial dimensions; the reason for the name strings becomes clear.*

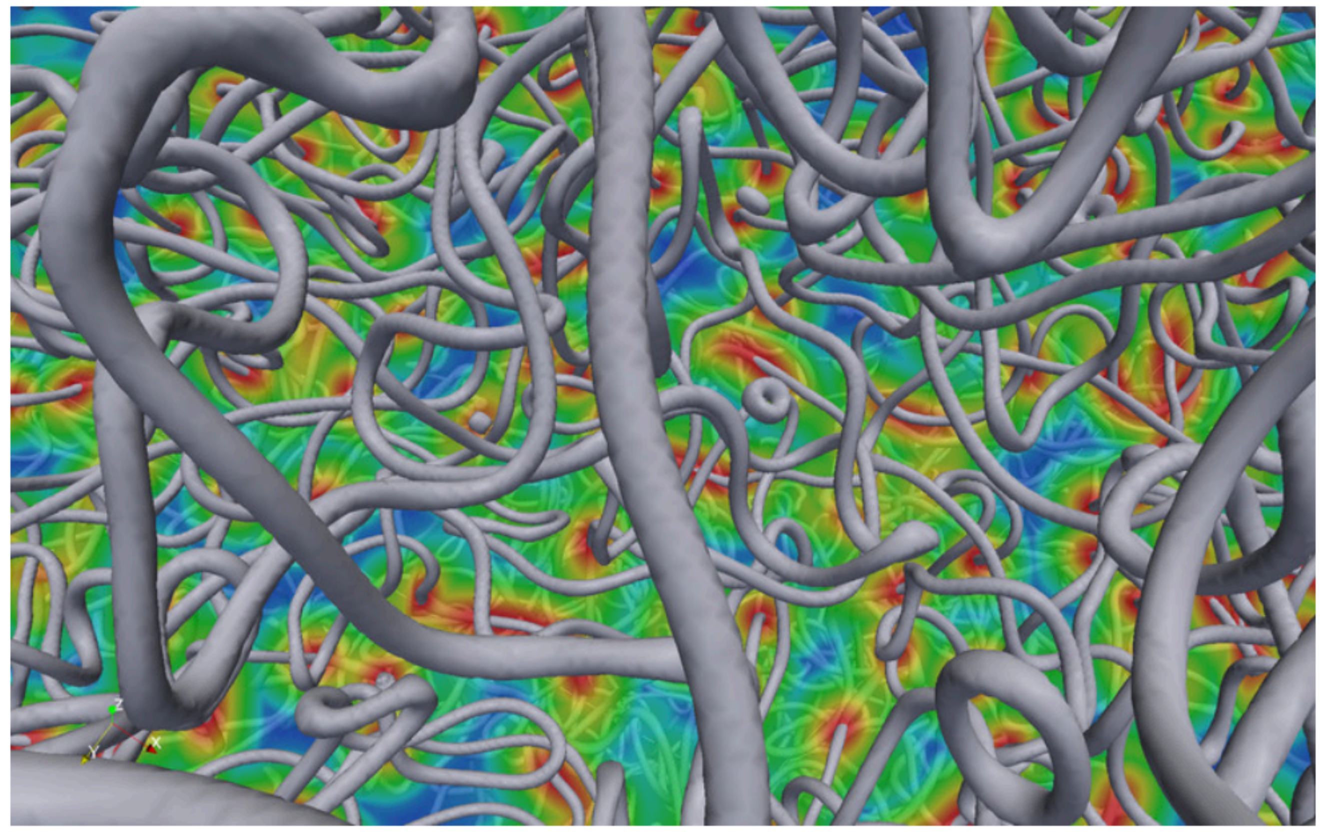


Figure 14: *3D representation of cosmic strings (gray) from a simulation credited to David Daverio, from the group of Professor Martin Kunz, Université de Genève, using simulation data obtained at the Swiss National Supercomputer Centre.*

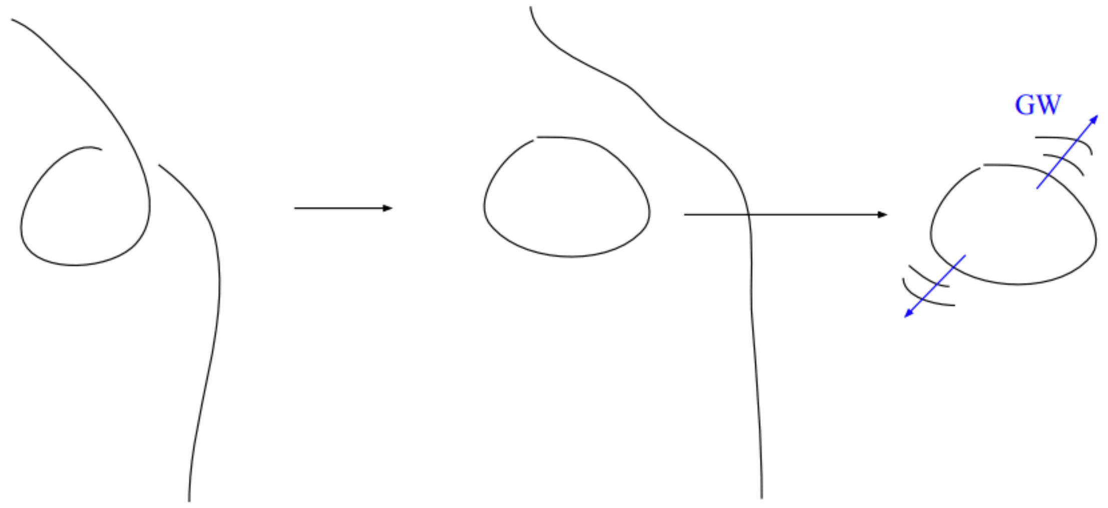


Figure 15: *Representation of gravitational waves emitted by loops from cosmic string networks.*

RRLdS, van Manen 2212.05594

# Cosmic strings

## The search for new physics

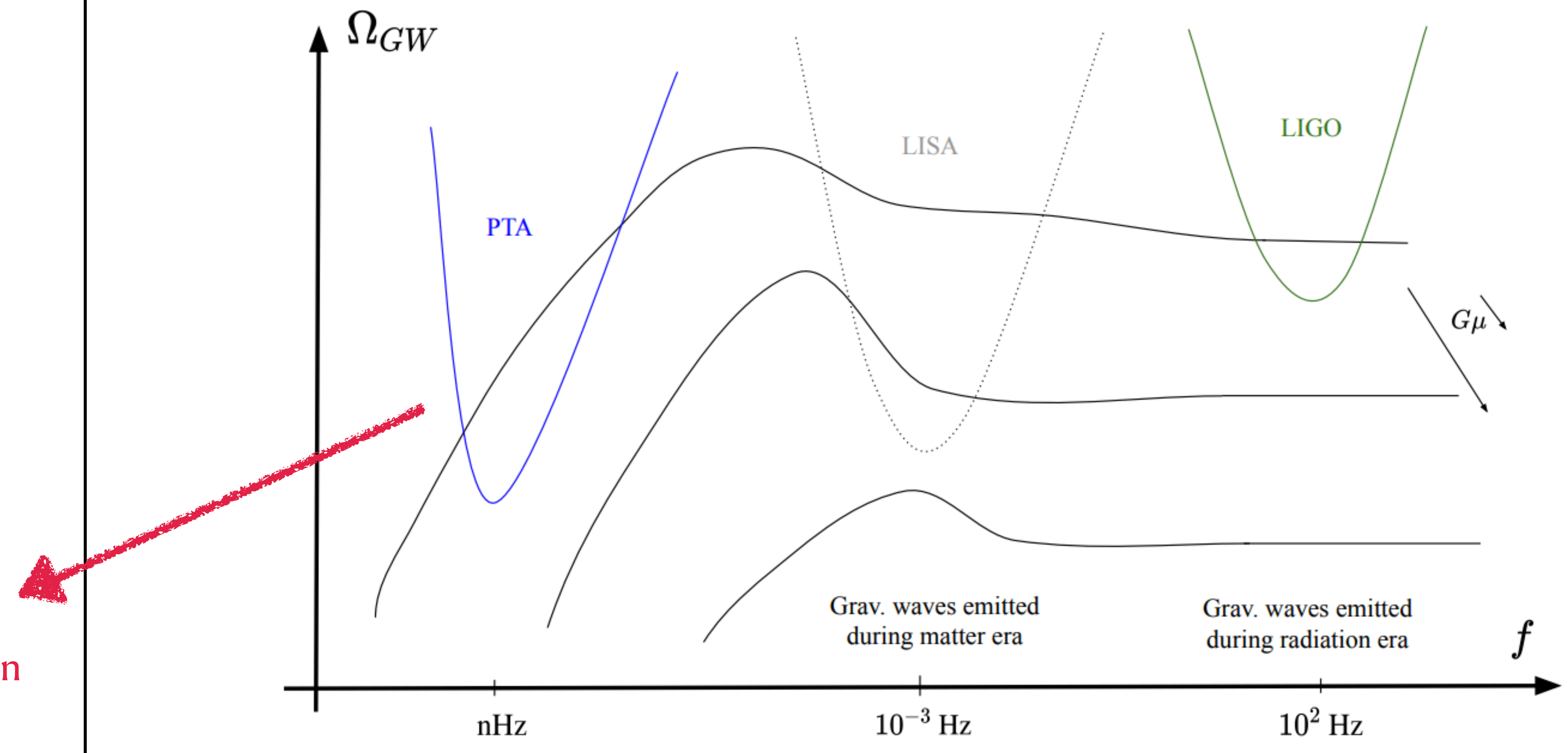


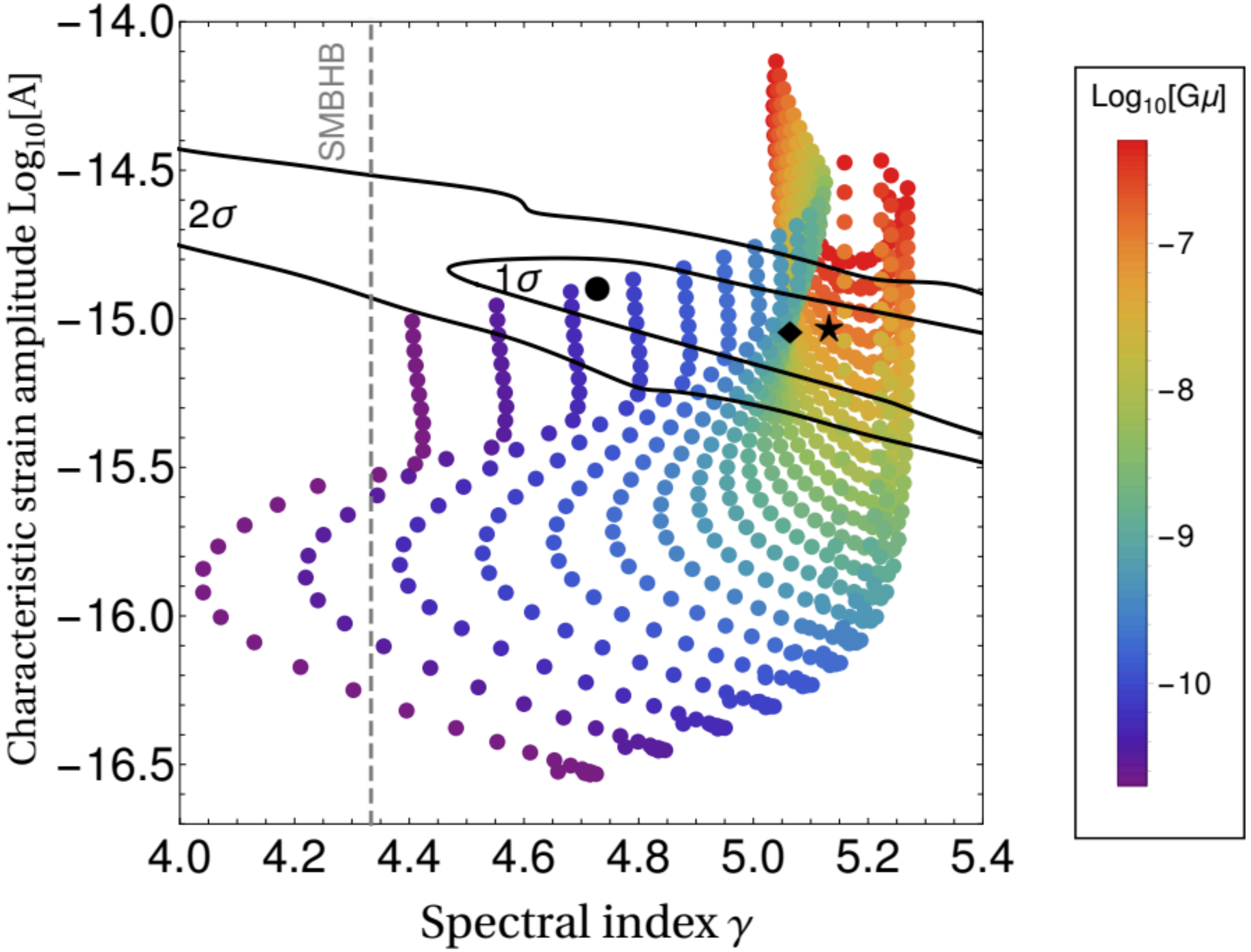
Figure 16: *Amplitude of gravitational waves generated by cosmic strings, with different string tensions $\mu$, as a function of frequency. The larger $G\mu$, the larger the amplitude $\Omega_{GW}$. We also plot the frequency range probed, or expected to be probed, by LIGO, LISA, and PTA collaborations. PTA signals already constrain cosmic string models with large $G\mu$, whose frequency peak is at the nHz scale.*

Very large string tension can
overproduce GWs:
Way to constrain models!

See also Ellis, Lewicki, *Phys.Rev.Lett.* 126 (2021) 4, 041304

# Cosmic strings

**Has NANOGrav found first evidence for cosmic strings?**



Blasi, Brdar, Schmitz, *Phys.Rev.Lett.* 126 (2021) 4, 041305

RRLdS, van Manen 2212.05594

# Cosmic strings

## The search for stable strings

$$v \sim 10^{16}\text{GeV} \left(\frac{G\mu}{10^{-7}}\right)^{1/2}$$

Very large string tension can overproduce GWs:
Way to constrain models!

$$v \sim 10^{14} \ldots 10^{16}\,\text{GeV}$$

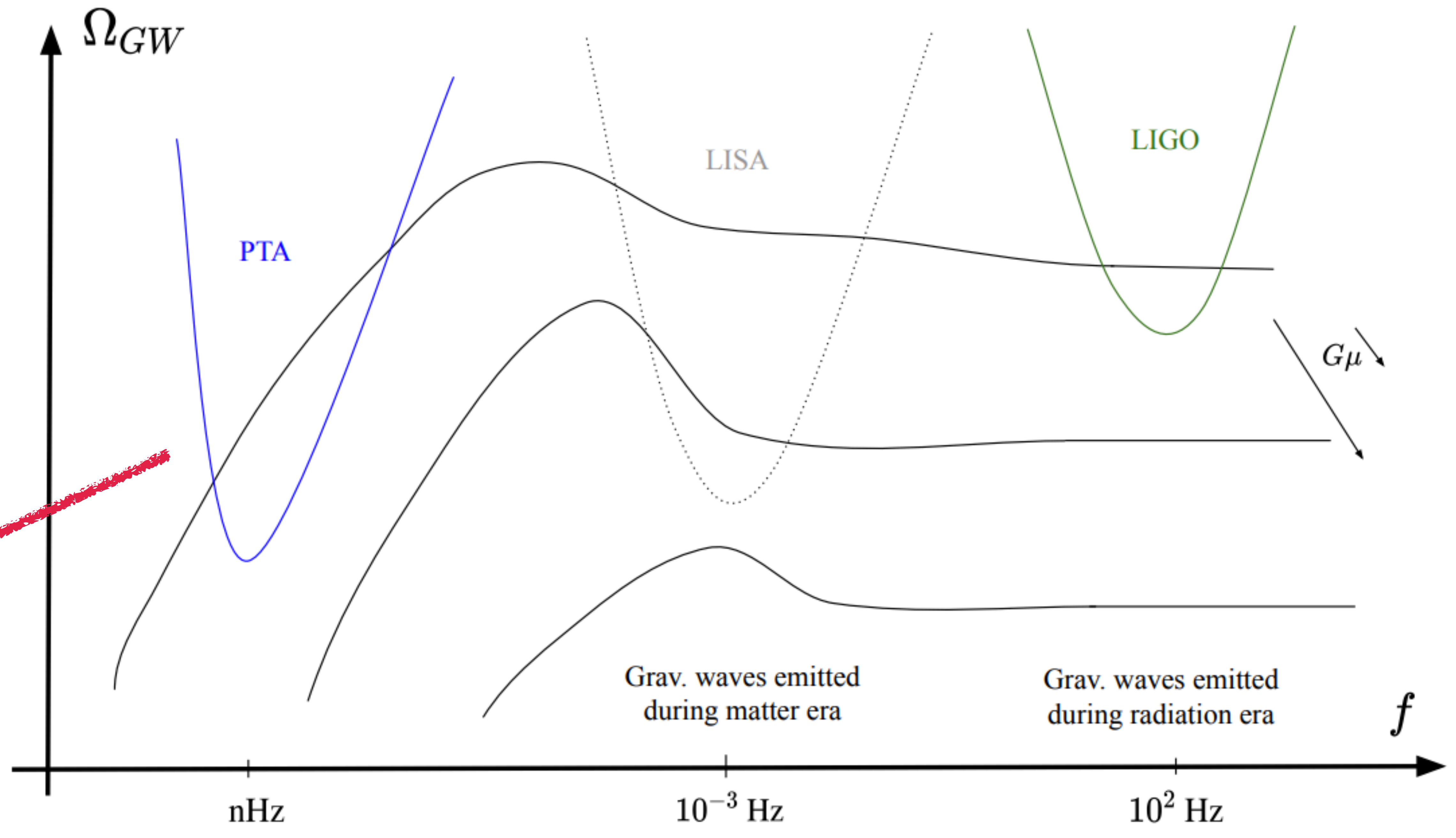
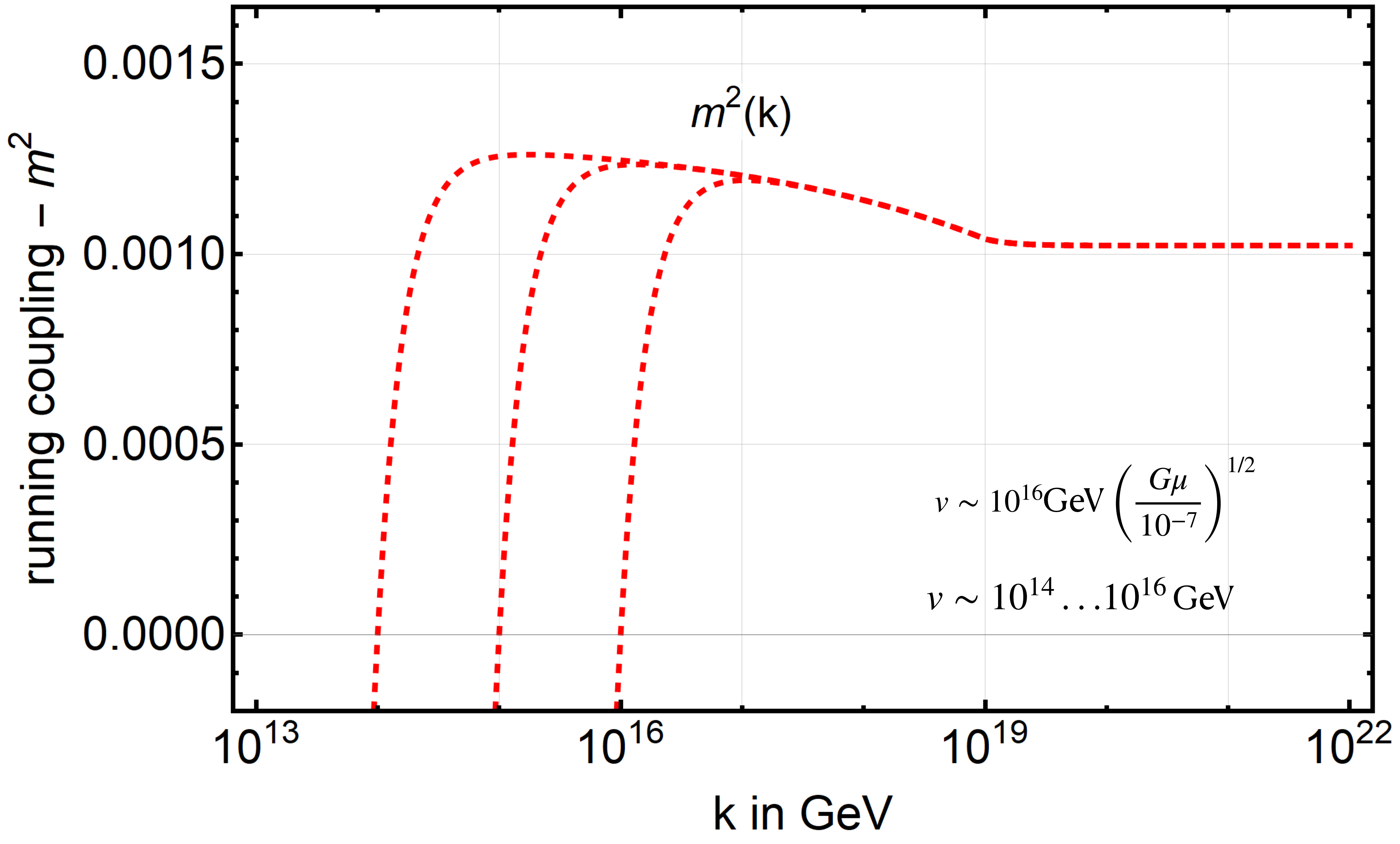


Figure 16: *Amplitude of gravitational waves generated by cosmic strings, with different string tensions $\mu$, as a function of frequency. The larger $G\mu$, the larger the amplitude $\Omega_{GW}$. We also plot the frequency range probed, or expected to be probed, by LIGO, LISA, and PTA collaborations. PTA signals already constrain cosmic string models with large $G\mu$, whose frequency peak is at the nHz scale.*

# Sneak preview

## Cosmic strings in the landscape

How many degrees of freedom, extra to SM, are necessary to induce a U(1) SSB in asymptotic safety?



$$v \sim 10^{16}\mathrm{GeV}\left(\frac{G\mu}{10^{-7}}\right)^{1/2}$$

$$v \sim 10^{14}\dots 10^{16}\,\mathrm{GeV}$$

Eichhorn, RRLdS, Miqueleto 2306.xxxx

# Connecting theory with observations

A) Theoretical constraints on dark matter/energy candidates:

  Gravity-induced UV completion of dark universe models.

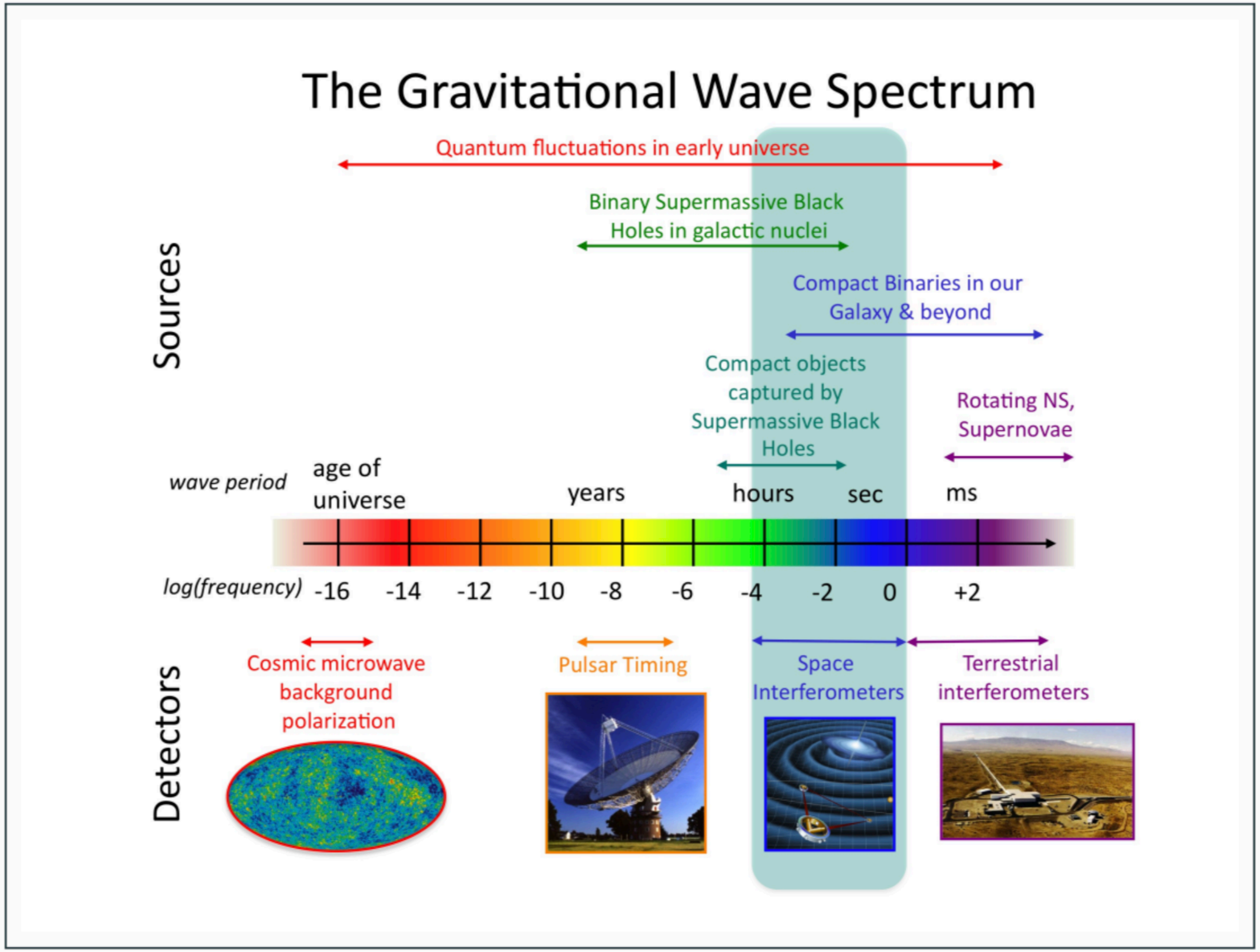
  IR predictions.

B) Indirect tests of (asymptotic safety) quantum gravity:

  What are the dark universe models in the landscape?

  Consistency between UV theory and observations.

# Towards supermassive black hole binaries and cosmology/BSM physics



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# Dziękuję!

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