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Gravitational Wave constraints on Gravitational Effective Field Theories

(in progress)

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in collaboration with Jun Zhang

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Why (D6)EFT

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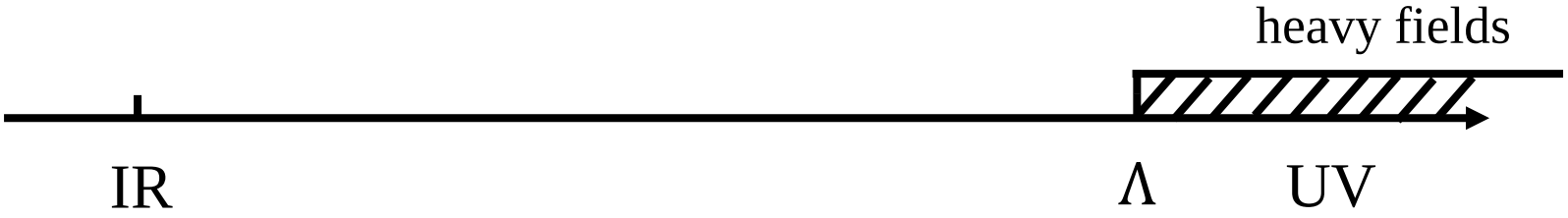
Effective-field-theory of General Relativity



$$\mathcal{L}_{\rm EFT} = \frac{M_{\rm Pl}^2}{2}\left(R + \frac{\mathcal{L}_{\rm D4}}{\Lambda^2} + \frac{\mathcal{L}_{\rm D6}}{\Lambda^4} + \frac{\mathcal{L}_{\rm D8}}{\Lambda^6} + \cdots\right)$$

1. Integrating out the heavy particle
2. The remaining leading correction comes from cubic EFT
3. There are some causality violation problems exist in quartic EFT

Claudia de Rham, Andrew J. Tolley, and Jun Zhang
Phys.Rev.Lett. 128 (2022) 13, 131102

D6 EFT

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$$\mathcal{L}_{\rm D6} = b_1 R_{\mu\nu}{}^{\alpha\beta} R_{\alpha\beta}{}^{\gamma\sigma} R_{\gamma\sigma}{}^{\mu\nu} + b_2 R^{\mu\nu} R_{\mu\alpha\beta\gamma} R_{\nu}{}^{\alpha\beta\gamma} + b_3 R R_{\mu\nu\alpha\beta} R^{\mu\nu\alpha\beta} + b_4 R_{\mu}{}^{\alpha}{}_{\nu}{}^{\beta} R_{\alpha}{}^{\gamma}{}_{\beta}{}^{\sigma} R_{\gamma}{}^{\mu}{}_{\sigma}{}^{\nu}$$
$$+ b_5 R \Box R + b_6 R_{\mu\nu} \Box R^{\mu\nu} + b_7 R^3 + b_8 R R_{\mu\nu}^2 + b_9 R_{\mu\nu}^3 + b_{10} R^{\mu\nu} R^{\alpha\beta} R_{\mu\nu\alpha\beta}.$$

$$I_1 = R_{\mu\nu}{}^{\alpha\beta} R_{\alpha\beta}{}^{\gamma\sigma} R_{\gamma\sigma}{}^{\mu\nu} \quad \text{and} \quad I_2 = R_{\mu}{}^{\alpha}{}_{\nu}{}^{\beta} R_{\alpha}{}^{\gamma}{}_{\beta}{}^{\sigma} R_{\gamma}{}^{\mu}{}_{\sigma}{}^{\nu}$$

$$G_3 = I_1 - 2I_2$$

$$\mathcal{L}_{\rm D6} = \left(b_1 + \frac{b_4}{2}\right) I_1 + \left(\frac{b_2}{3} + \frac{4}{3} b_3 - \frac{b_4}{2}\right) G_3 + \mathcal{O}(R_{ab})^2$$

G_3 term:

In vacuum: can be removed through field redefinition

In present of matter: nonminimal coupling will be introduced

EFT correction on Waveform

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$$S_{\rm EFT} = \int {\rm d}^4x\sqrt{-g}\left[-\frac{2}{\kappa^2}R - \frac{2}{\kappa^2}\left(\frac{\alpha_1}{48}I_1 + \frac{\alpha_2}{24}G_3\right)\right]$$

$$\alpha_1\Lambda^4 = 48b_1 + 24b_2\,, \quad \alpha_2\Lambda^4 = 8b_2 + 32b_3 - 12b_4$$

$$\bar{\alpha}_1 = \alpha_1\Lambda^4/48, \quad \bar{\alpha}_2 = \alpha_2\Lambda^4/12.$$

$d_\Lambda = \Lambda^{-1}$

- Stationary Phase Approximation:

$$\tilde{h}_{\rm SPA}(f) \sim \exp\left[i\left(\psi_f(t_f) - \frac{\pi}{4}\right)\right]$$

$$\psi_{\rm SPA}(t_f) = \psi^{\rm EH}_{\rm SPA}(t_f) + \psi^{I_1+I_2}_{\rm SPA}(t_f) + \psi^{\rm tidal}_{\rm SPA}(t_f)$$

- Contribution from EFT correction:

$$\psi^{I_1+I_2}_{\rm SPA}(t_f) = -\frac{3}{128\,\nu\,v_f^5}\left[156\frac{\alpha_2}{(GM)^4}v_f^{10} - \frac{545\,\alpha_1 + (665 - 850\,\nu)\,\alpha_2}{14(GM)^4}v_f^{12}\right]$$

$$\psi^{\rm Tidal}_{\rm SPA} \sim v^{10} - v^{15}$$

Manuel Accettulli Huber, Andreas Brandhuber, Stefano De Angelis and Gabriele Travaglini
Phys.Rev.D 103 (2021) 4, 045015

Bayes Method

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- likelihood:

$$p(d|\vec{\theta},\mathcal{H},I)=\mathcal{N}\exp(-\frac{1}{2}\langle d-s(\vec{\theta})|d-s(\vec{\theta})\rangle)$$

- posterior:

$$p(\mathcal{H}|d,I)=\frac{p(\mathcal{H}|I)p(d|\mathcal{H},I)}{p(d|I)}$$

- bayes factor:

$$\mathcal{B}^1_0=\frac{Z_1}{Z_0}$$

$$\mathcal{O}^1_0=\frac{p(\mathcal{H}_1|d,I)}{p(\mathcal{H}_0|d,I)}=\mathcal{B}^1_0\,\frac{p(\mathcal{H}_1|I)}{p(\mathcal{H}_0|I)}$$

- Free parameter: $\bar{\alpha}_2$
- fixed parameter: $\bar{\alpha}_1=1$
- different EFTs: d_Λ

$$\langle A|B\rangle=4\Re\int_{f_{\min}}^{f_{\max}}\frac{\tilde{A}^*\tilde{B}}{S(f)}df$$

$$f_{\max}=\min[f_{\mathrm{ISO}},0.25\,f_{\mathrm{cutoff}}]$$

$$f_{\mathrm{cutoff}}=\sqrt{GM\Lambda^3}$$

Noah Sennett, Richard Brito, Alessandra Buonanno, Victor Gorbenko, and Leonardo Senatore
Phys.Rev.D 102 (2020) 4, 044056

EoS-independent relationship

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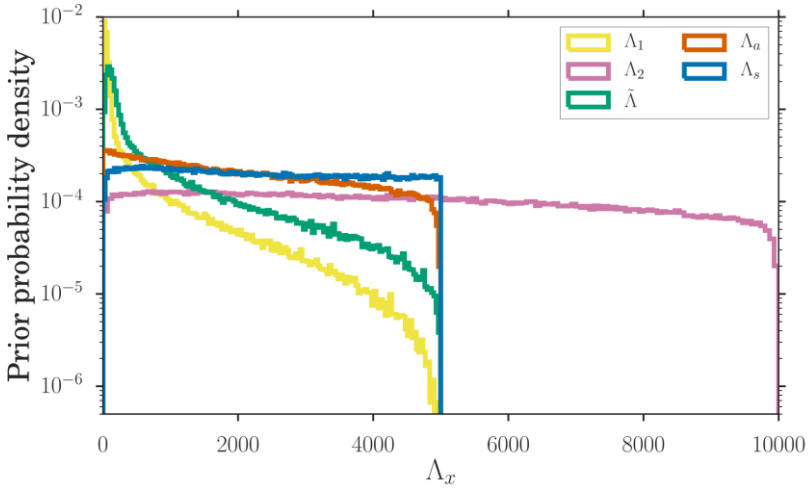
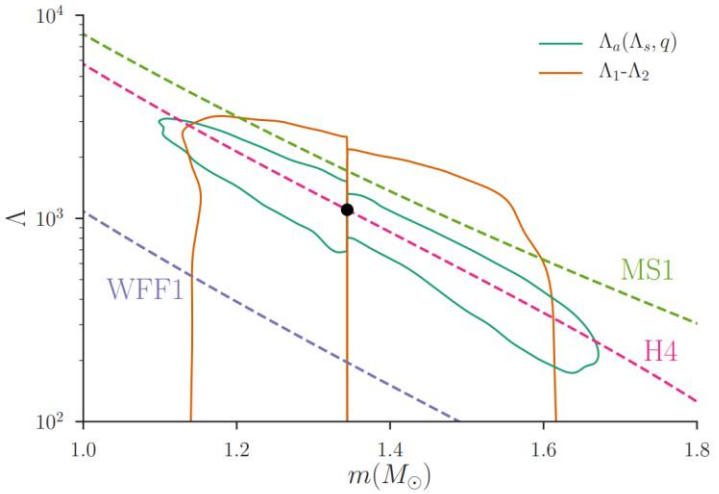
$$\Lambda_a(\Lambda_s, q; \vec{b}) = F_n(q)\Lambda_s \frac{a + \sum_{i=1}^{3}\sum_{j=1}^{2} b_{ij} q^j \Lambda_s^{-i/5}}{a + \sum_{i=1}^{3}\sum_{j=1}^{2} c_{ij} q^j \Lambda_s^{-i/5}}$$

$$\Lambda_s = (\Lambda_2 + \Lambda_1)/2$$
$$\Lambda_a = (\Lambda_2 - \Lambda_1)/2$$

$$\Lambda_a = \Lambda_a(\Lambda_s, q; \vec{b}) + \mathcal{N}(\mu(\Lambda_s, q), \sigma(\Lambda_s, q))$$





Katerina Chatziioannou, Carl-Johan Haster, and Aaron Zimmerman
Phys.Rev.D 97 (2018) 10, 104036

EoS-independent relationship

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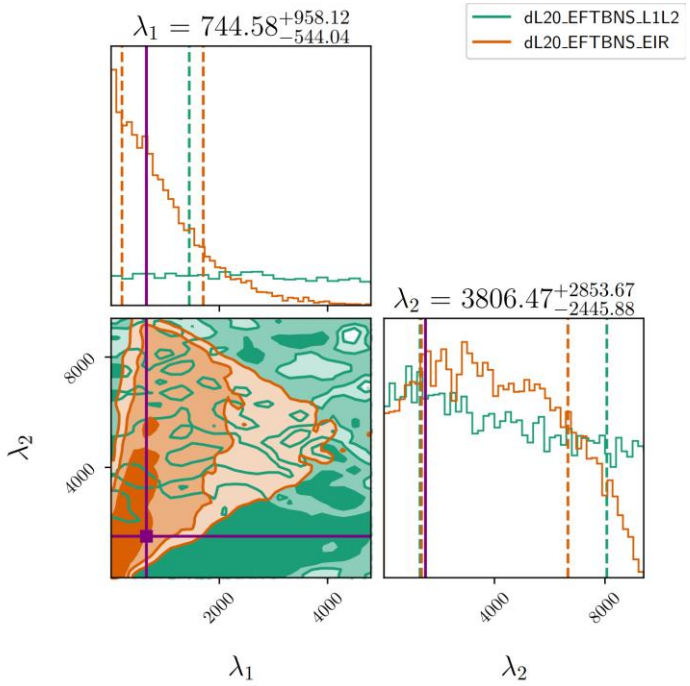
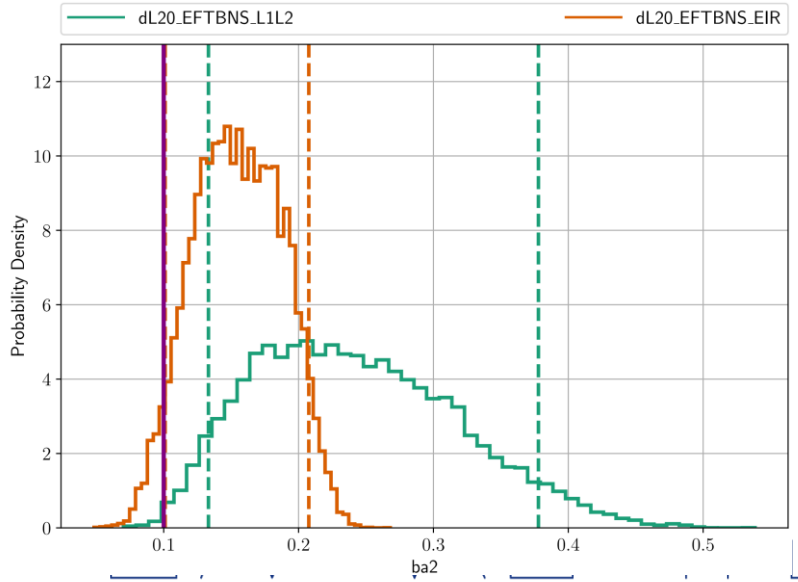
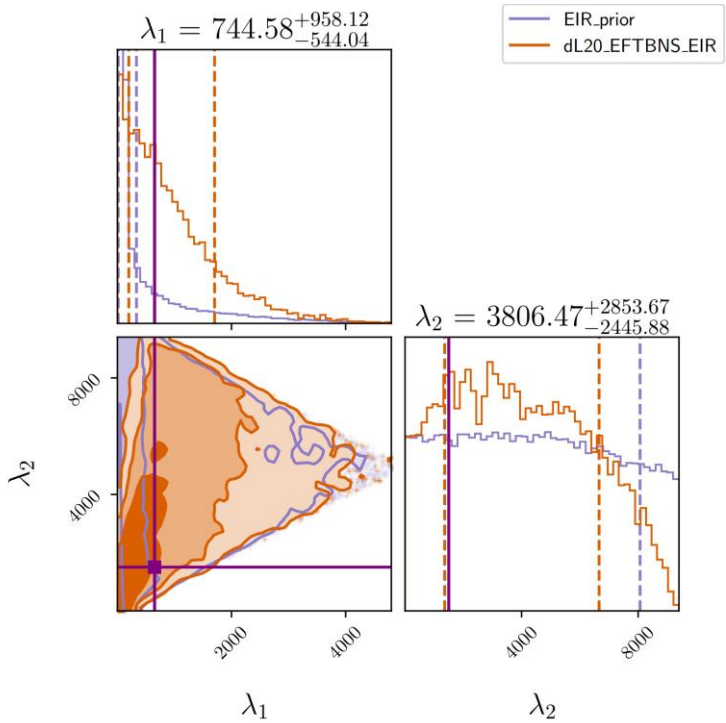




- Injection EFT signal:



Bayes factor & EFT parameter

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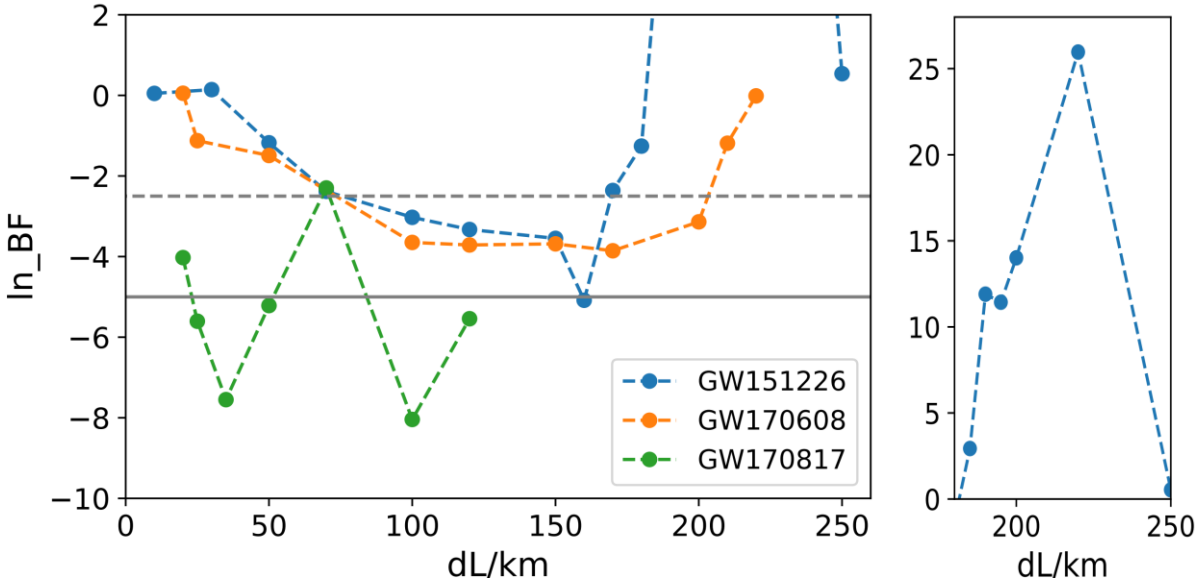
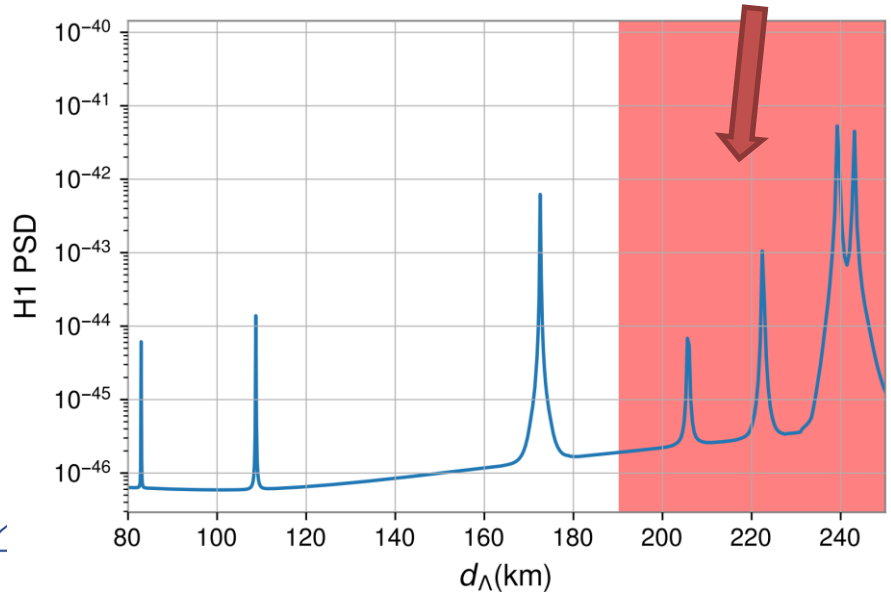
- log Bayes factor ln B_{GR}^{EFT}:





GW170817

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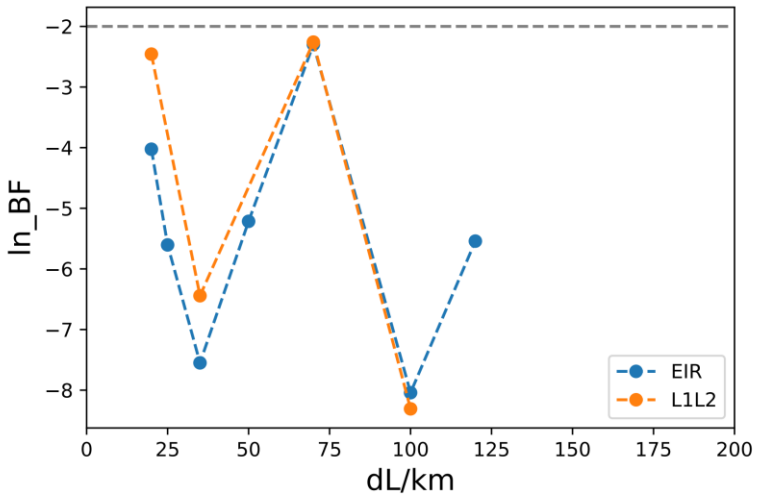
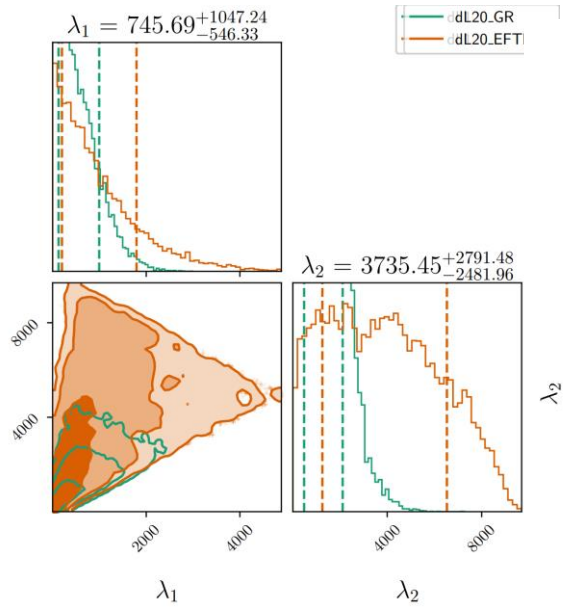
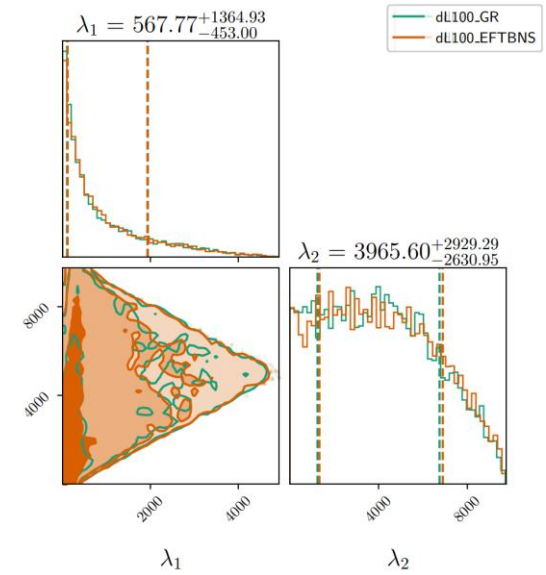
- log Bayes factor ln B_{GR}^{EFT}:



- $d_\Lambda = 20$km:



- $d_\Lambda = 100$km:



- For EFT, deformation is stronger than GR when d_Λ is small
- As d_Λ becomes larger, deformation will be stronger both for GR and EFT

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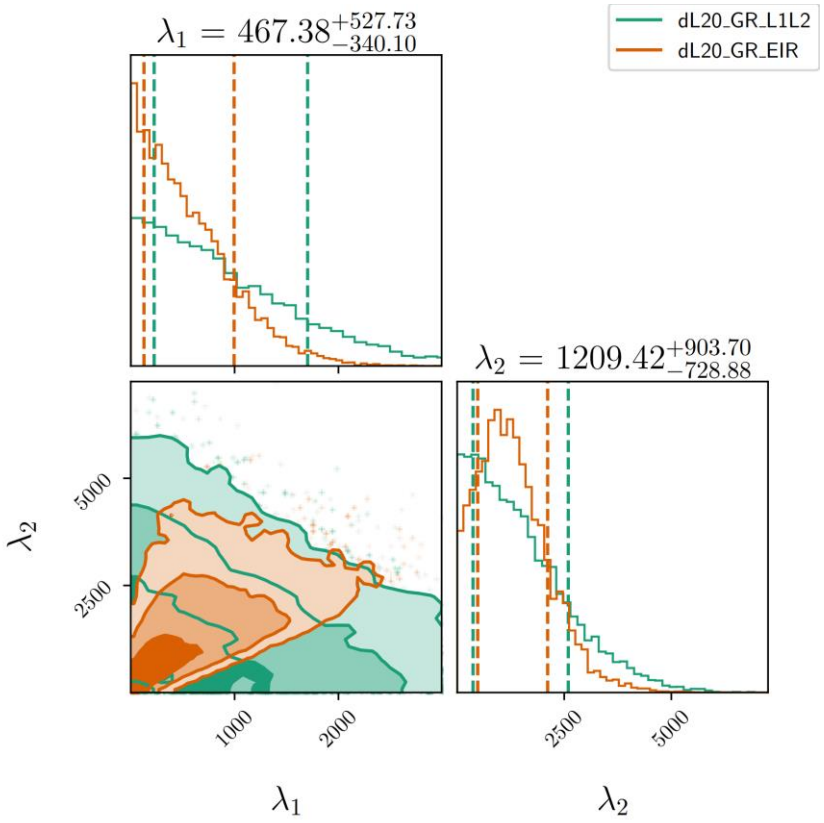
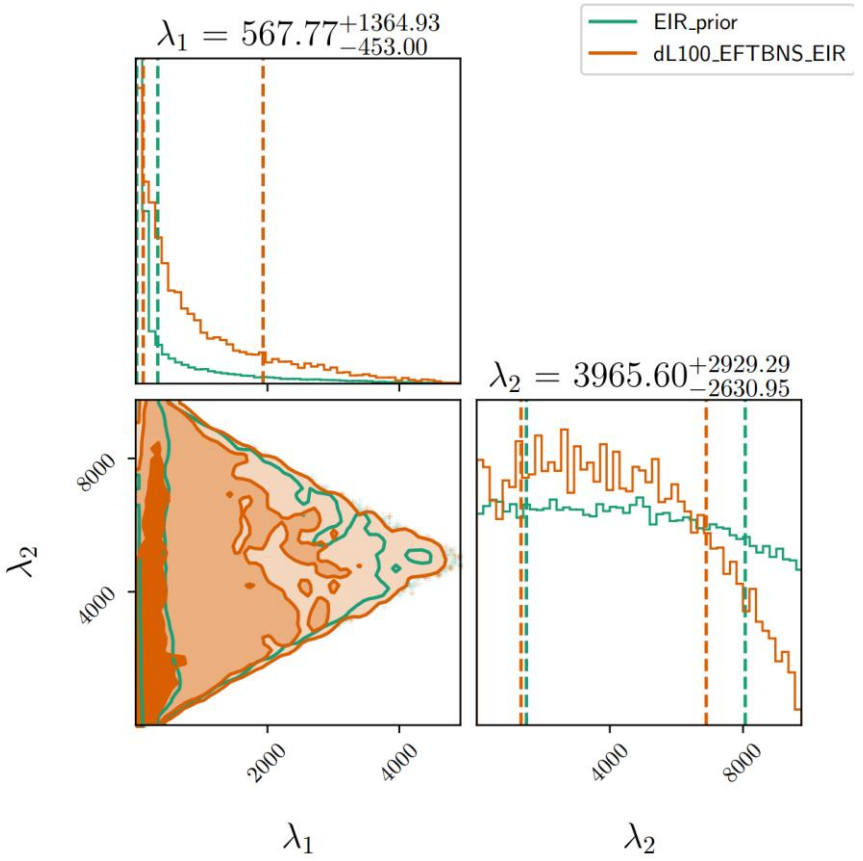
- $d_\Lambda = 20$km:



- $d_\Lambda = 100$km:



- The posterior with EIR is still informative when cutoff is very low

Summary

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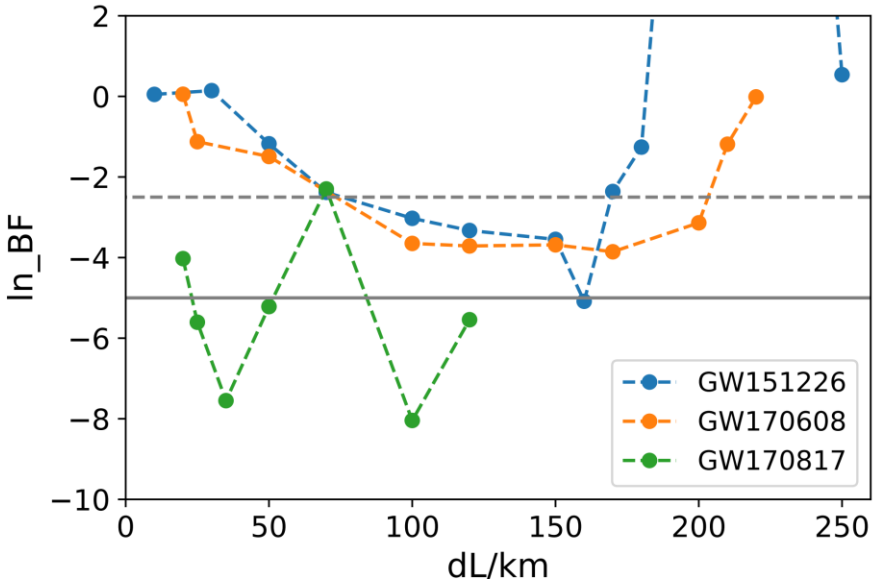

Event	d_Λ [km]		
	$f_{\text{high}} = 0.2 f_\Lambda$	$f_{\text{high}} = 0.25 f_\Lambda$	$f_{\text{high}} = 0.35 f_\Lambda$
GW151226	–	~ [125, 175]	~ [85, 225]
GW170608	~ [135, 160]	~ [65, 190]	~ [65, 230]
Combined	~ [120, 165]	~ [65, 190]	~ [65, 235]

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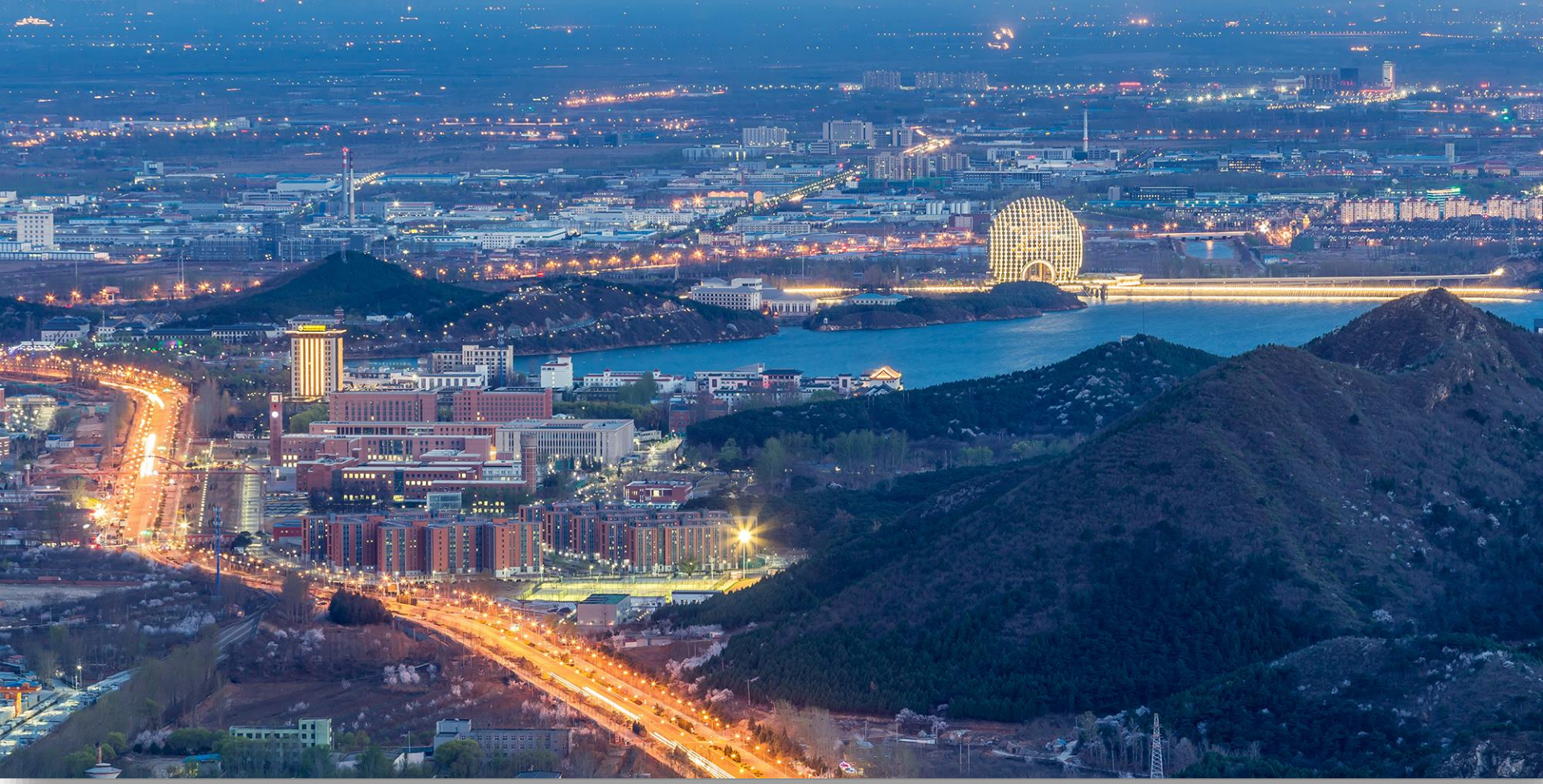
Phys.Rev.D 102 (2020) 4, 044056

- moderate evidence level:
  $d_\Lambda \sim 60km - 200km$
- strong evidence level:
  $d_\Lambda \sim 25km - 50km \,/\, 80km - 120km$
- EoS-independent-relationship improves the result



THANKS

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