multi-messenger astrophysics & fundamental physics

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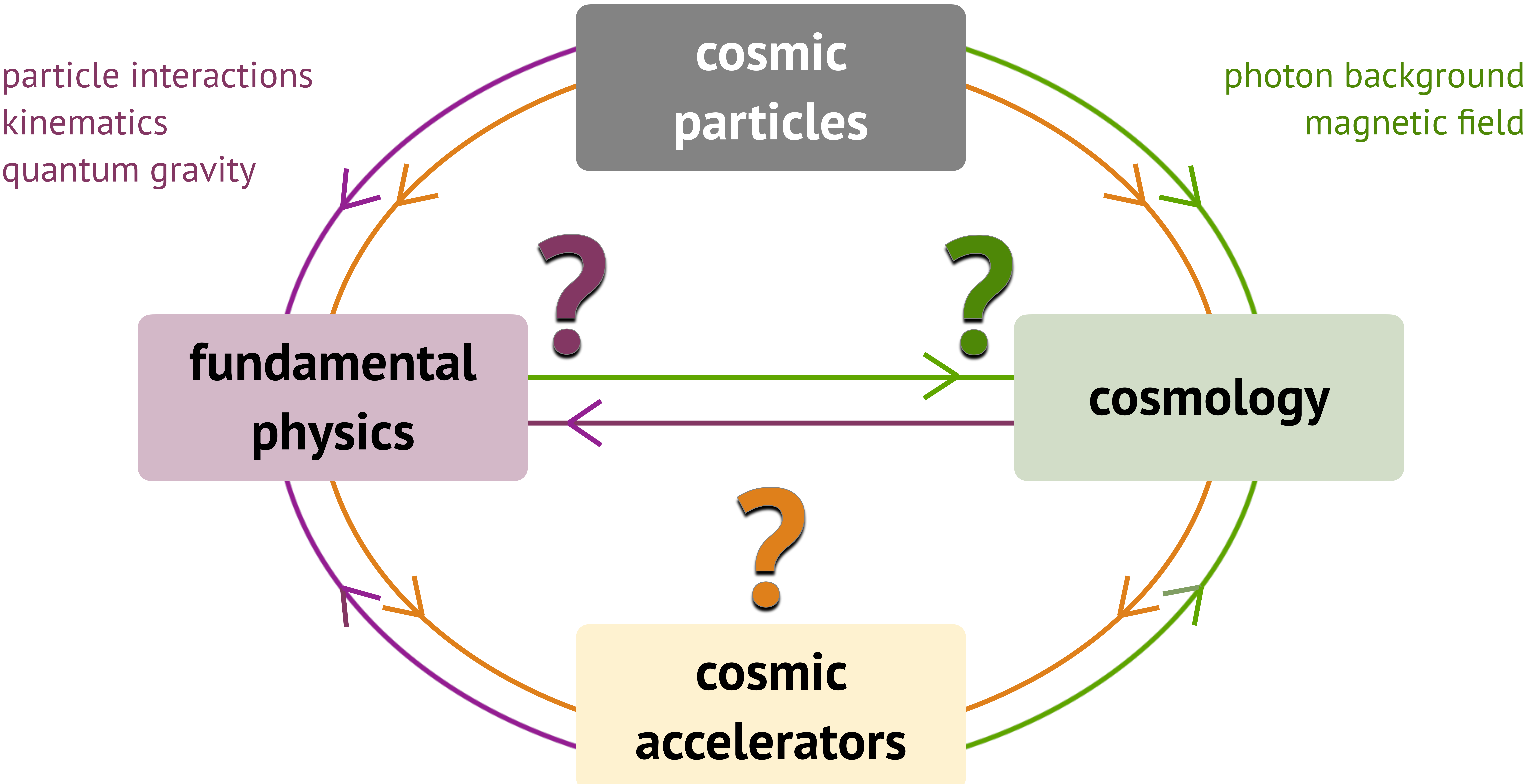
in this lecture...

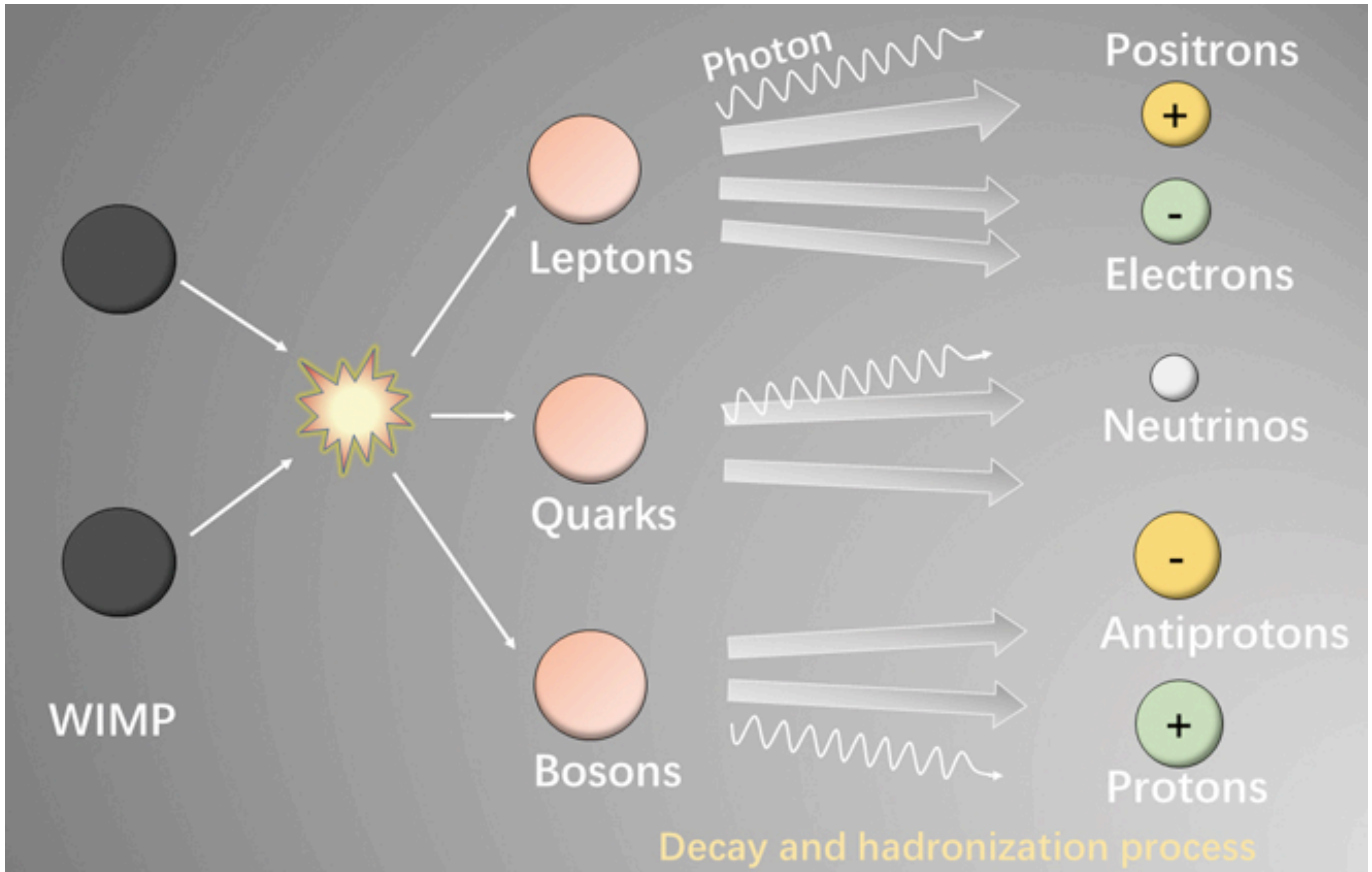
- dark matter
- Hubble "tension"
- cosmic magnetism
- neutrino probes
- quantum gravity and fundamental interactions

"it's all connected"



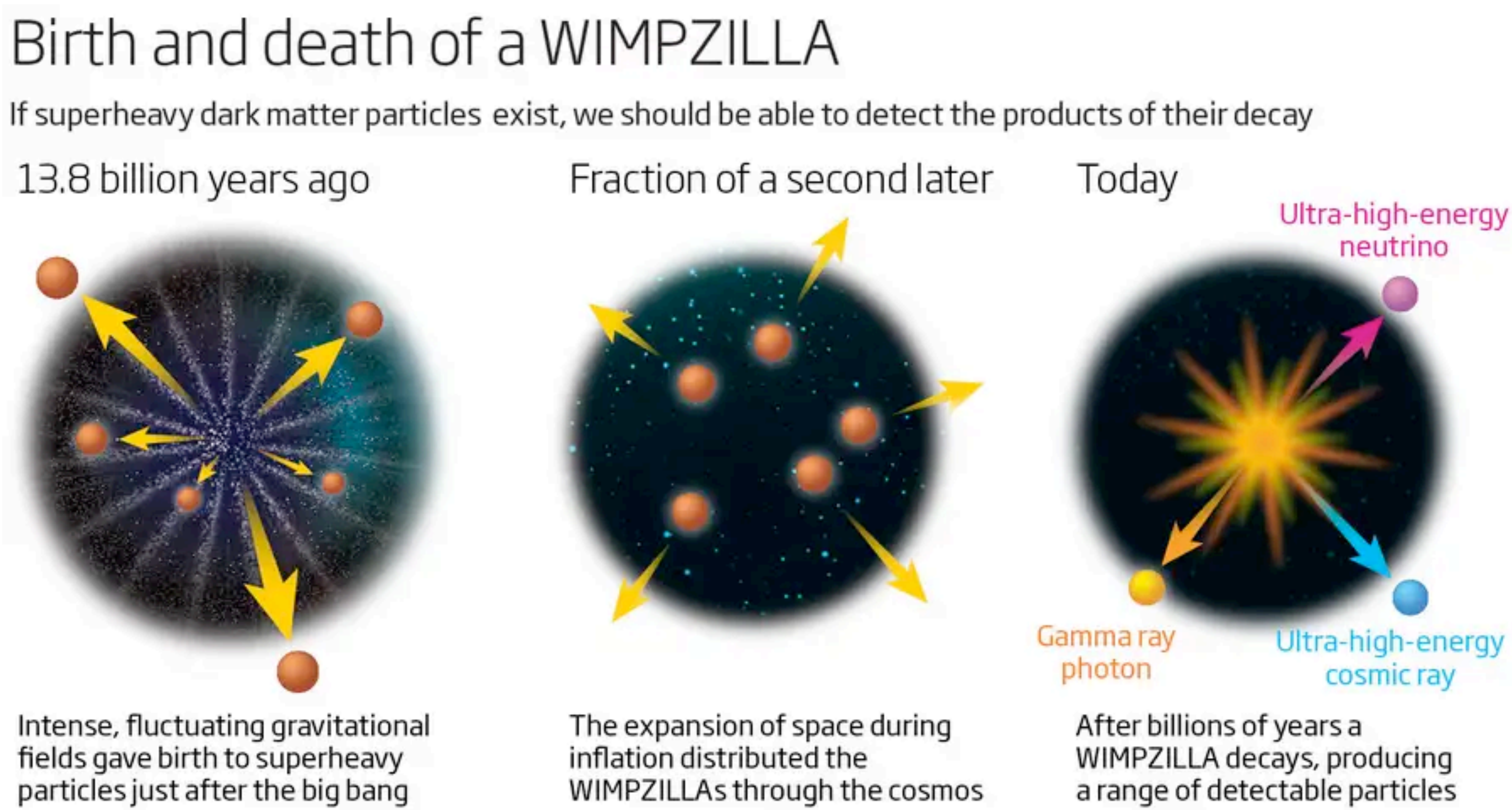
dark matter

WIMPs



Credits: Linqing Gao and Sujie Lin

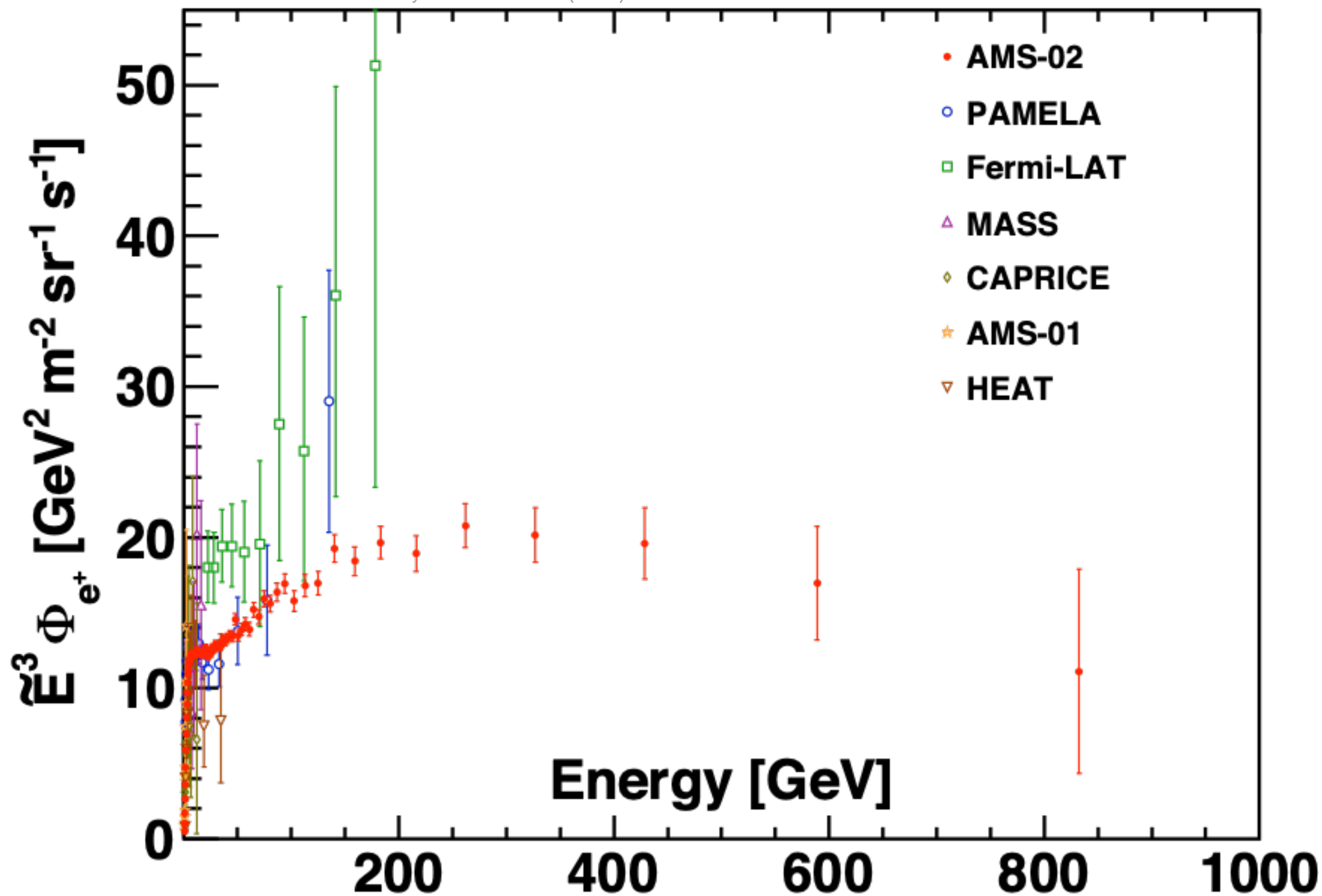
super-heavy dark matter



https://www.newscientist.com/article/mg22630260-400-wimpzillas-monster-particles-from-the-dawn-of-time/

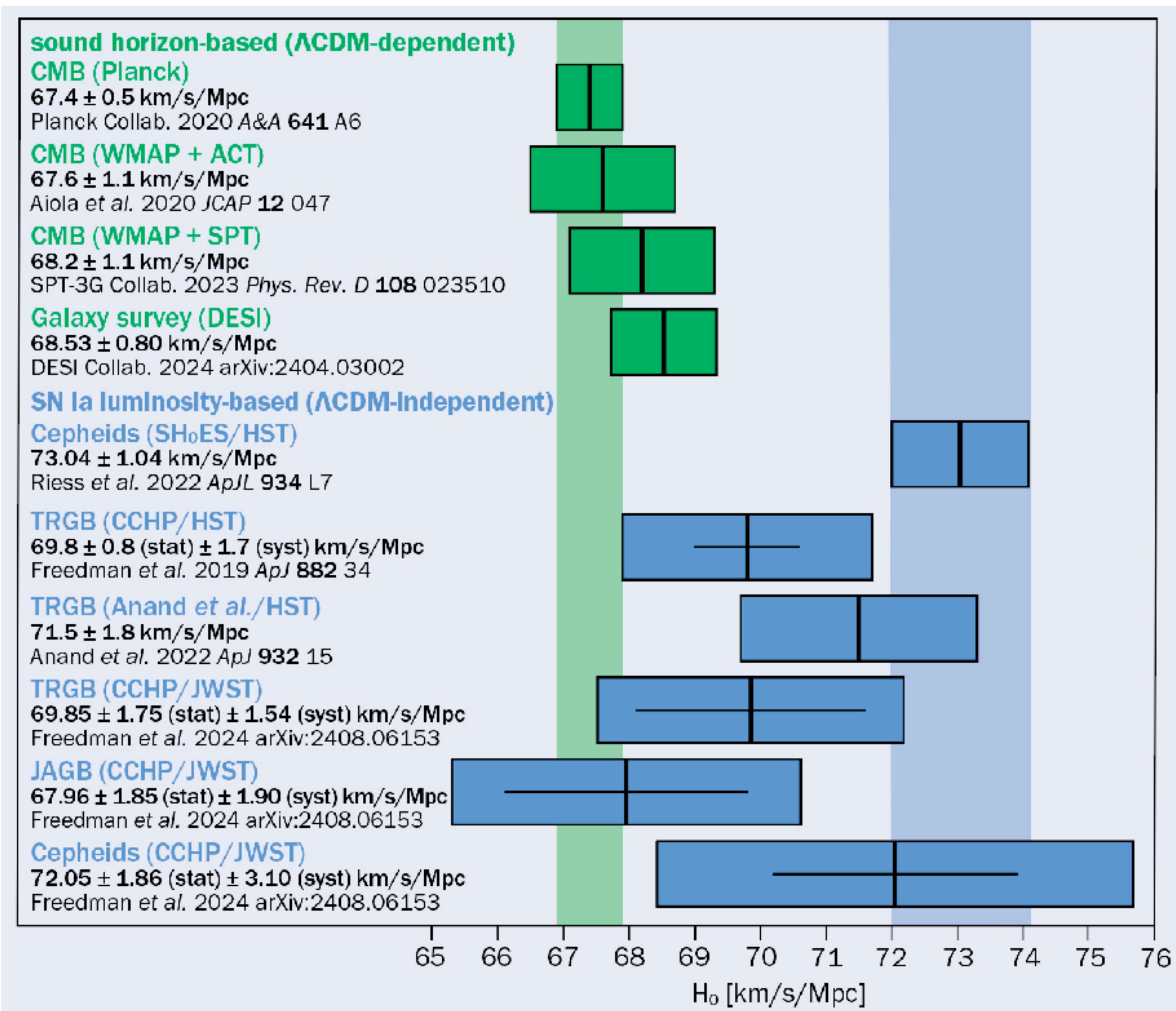
the positron fraction and dark matter

AMS Collaboration. Phys. Rev. Lett. 122 (2019) 041102

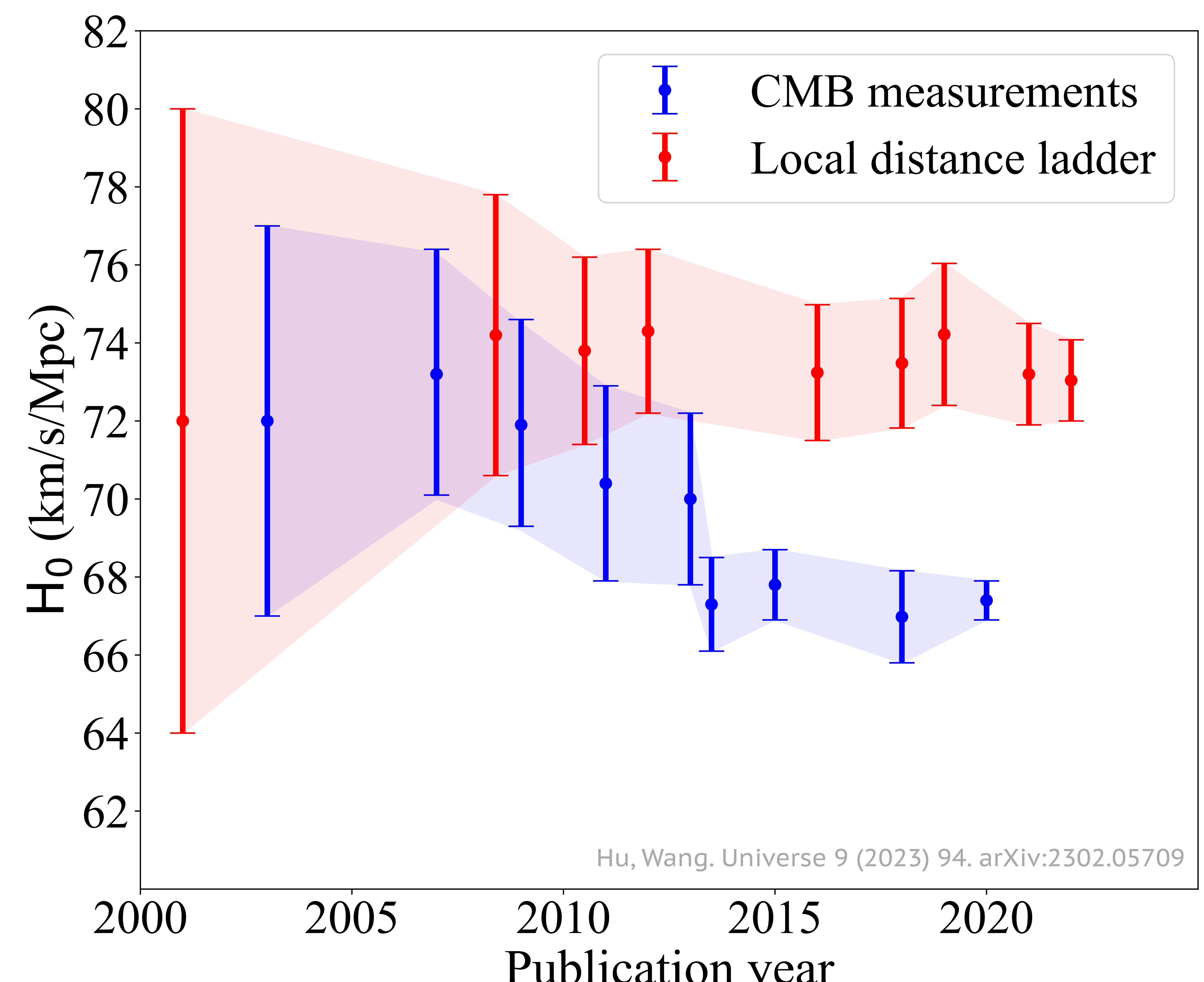


Hubble "tension"

the "tension"

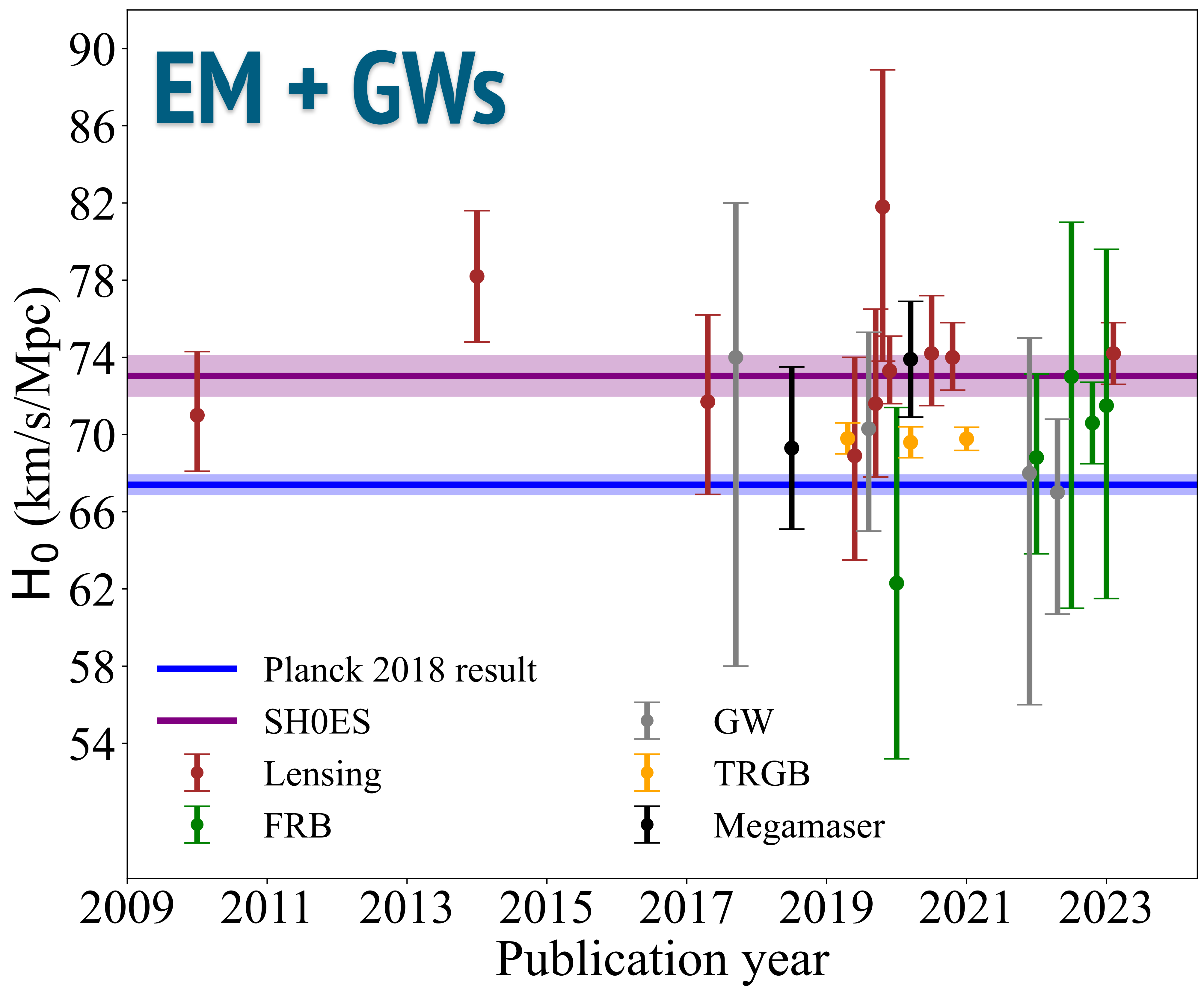


https://cerncourier.com/the-hubble-tension/

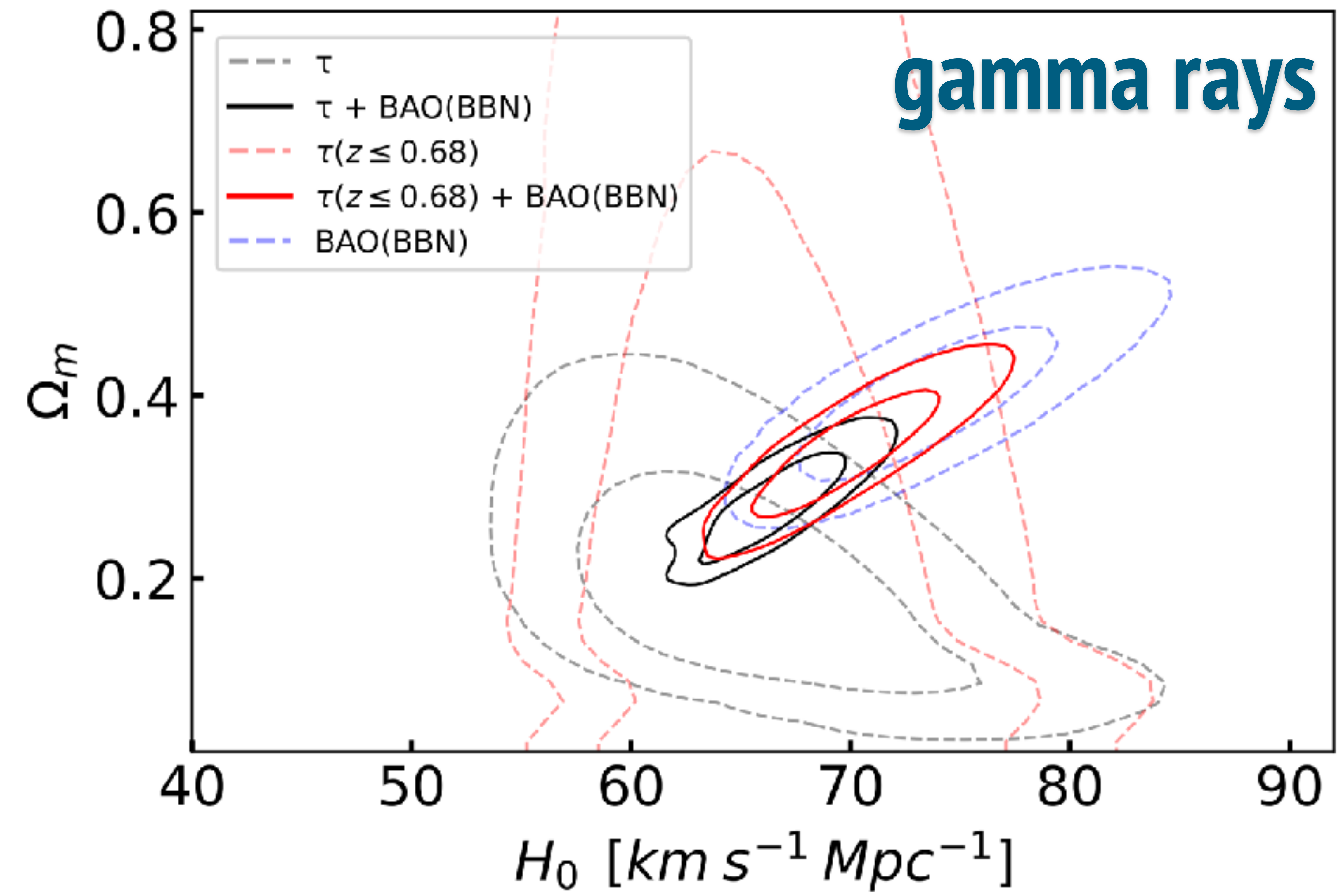


multi-messenger constraints on the Hubble constant

Hu, Wang. Universe 9 (2023) 94. arXiv:2302.05709



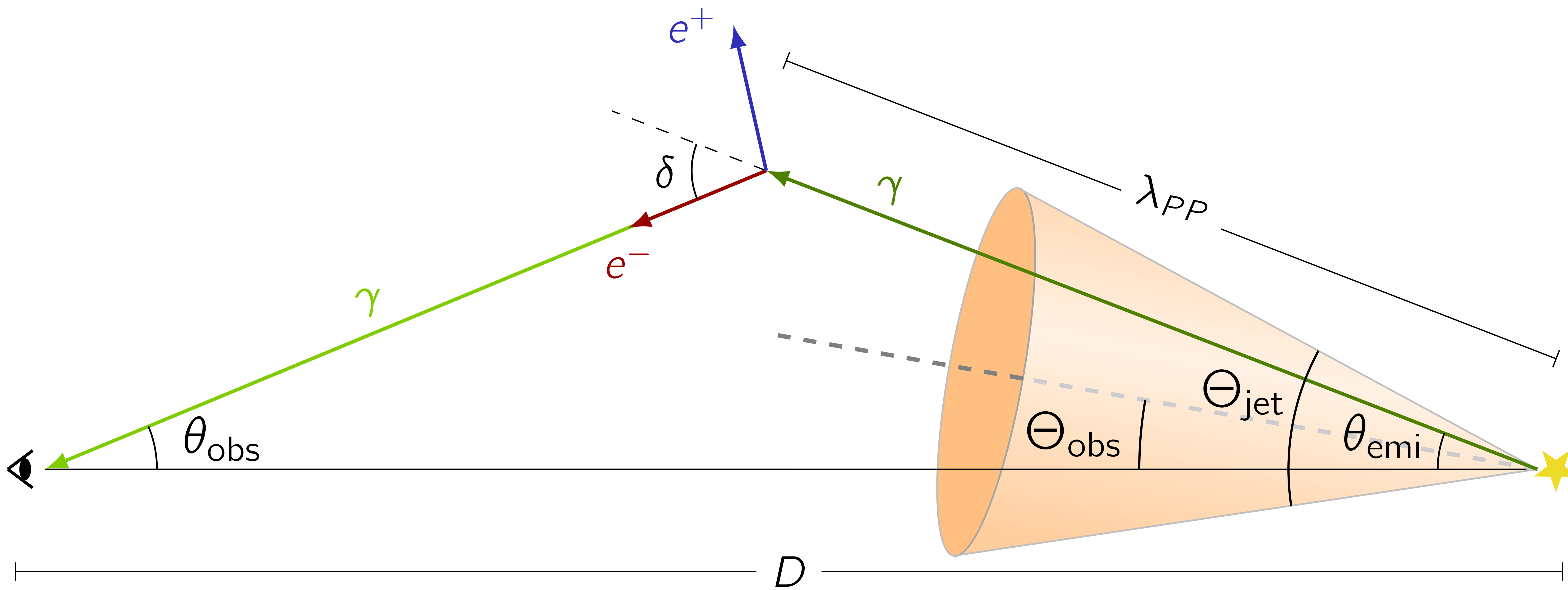
Domínguez et al. MNRAS 527 (2024) 4632. arXiv:2306.09878



Data	$H_0(\mathrm{km\ s^{-1}\ Mpc^{-1}})$	Ω_m
τ	$65.1^{+6.0}_{-4.9}$	0.19 ± 0.08 or (< 0.35 (95 %))
$\tau(z < 0.68)$	$66.0^{+5.7}_{-5.1}$	< 0.8 (95 %) or ($0.3^{+0.3}_{-0.2}$)
τ + BAO(BBN)	$66.5^{+2.2}_{-2.1}$	0.28 ± 0.04
$\tau(z < 0.68)$ + BAO(BBN)	$69.8^{+3.0}_{-2.6}$	0.34 ± 0.04
BAO(BBN)	73.7 ± 3.7	0.396 ± 0.054

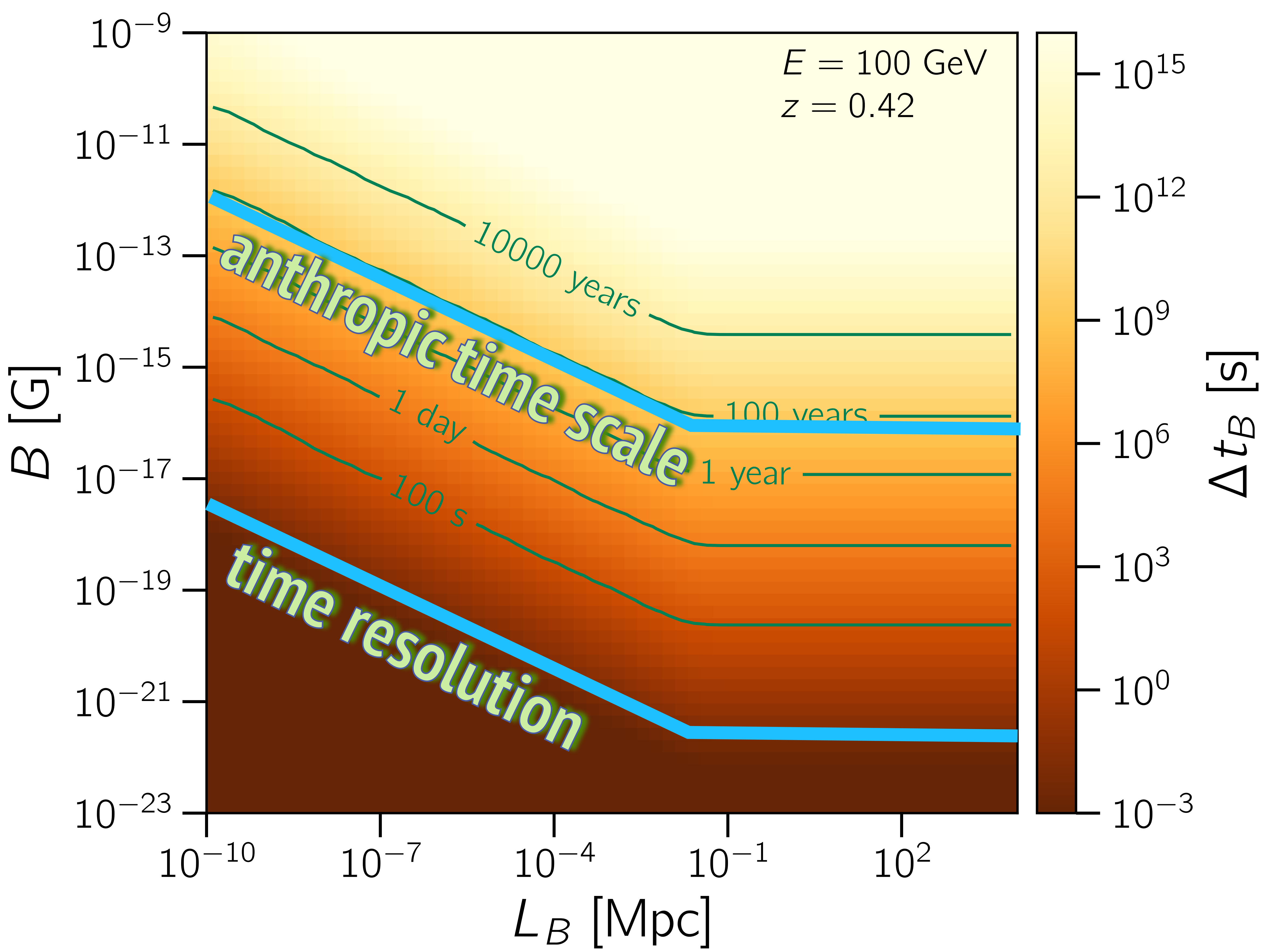
cosmic magnetism

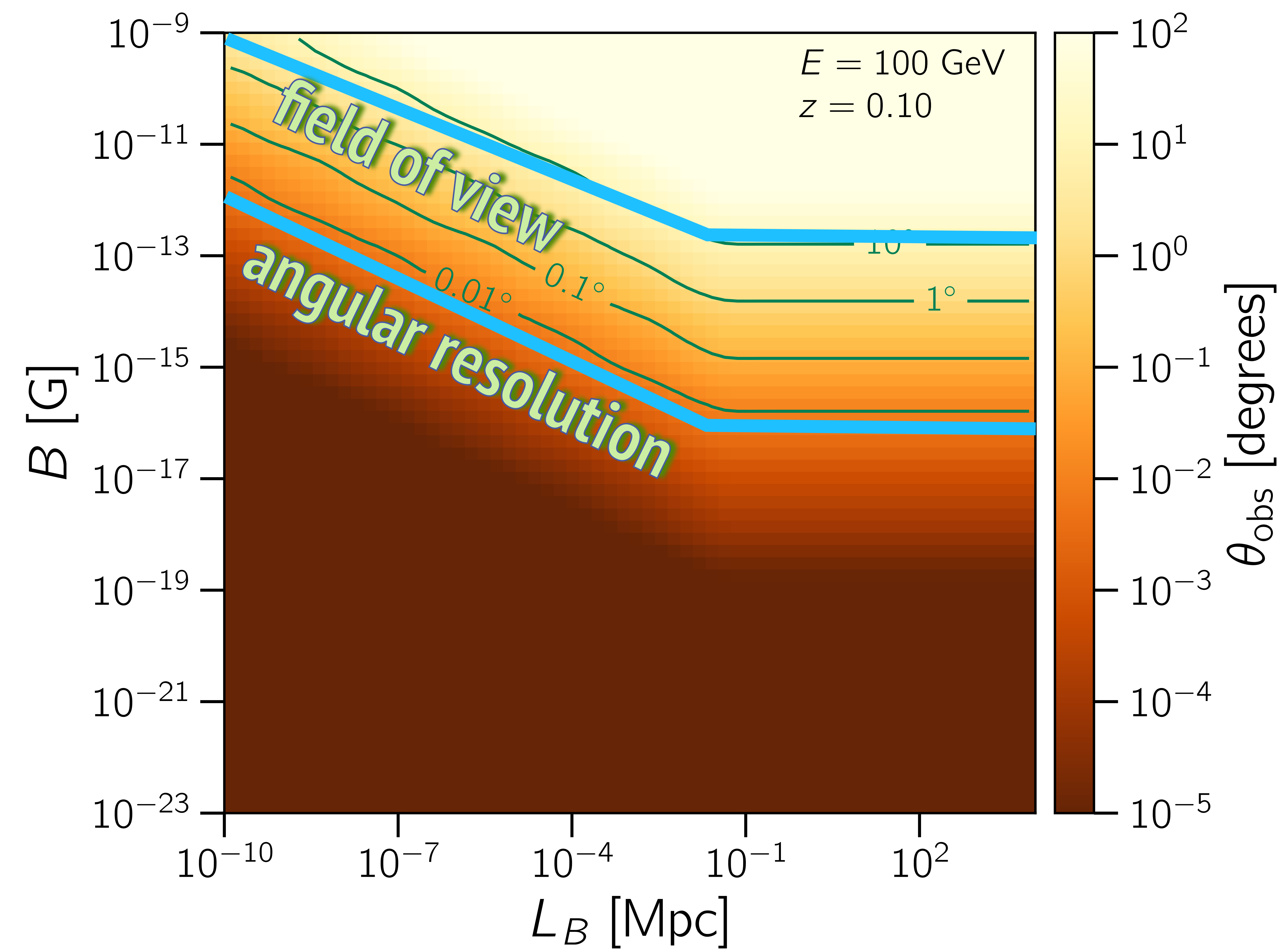
constraining intergalactic magnetic fields: gamma rays



- **strategies**
  - **haloes:** point-like sources will appear extended
  - **echoes:** time delays from transient sources
  - **spectral suppression:** "deflection" and/or delay

constraining intergalactic magnetic fields: gamma rays

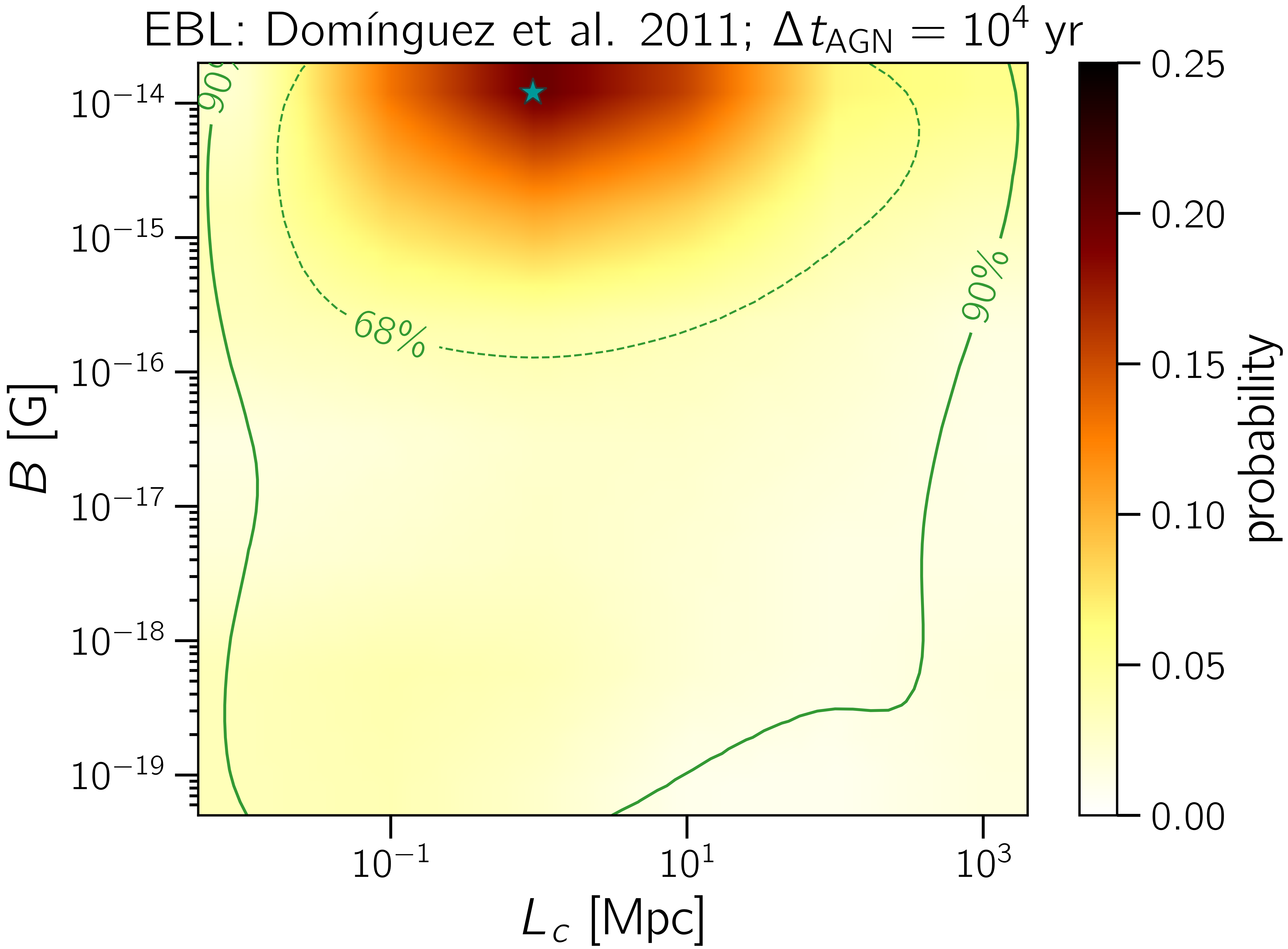


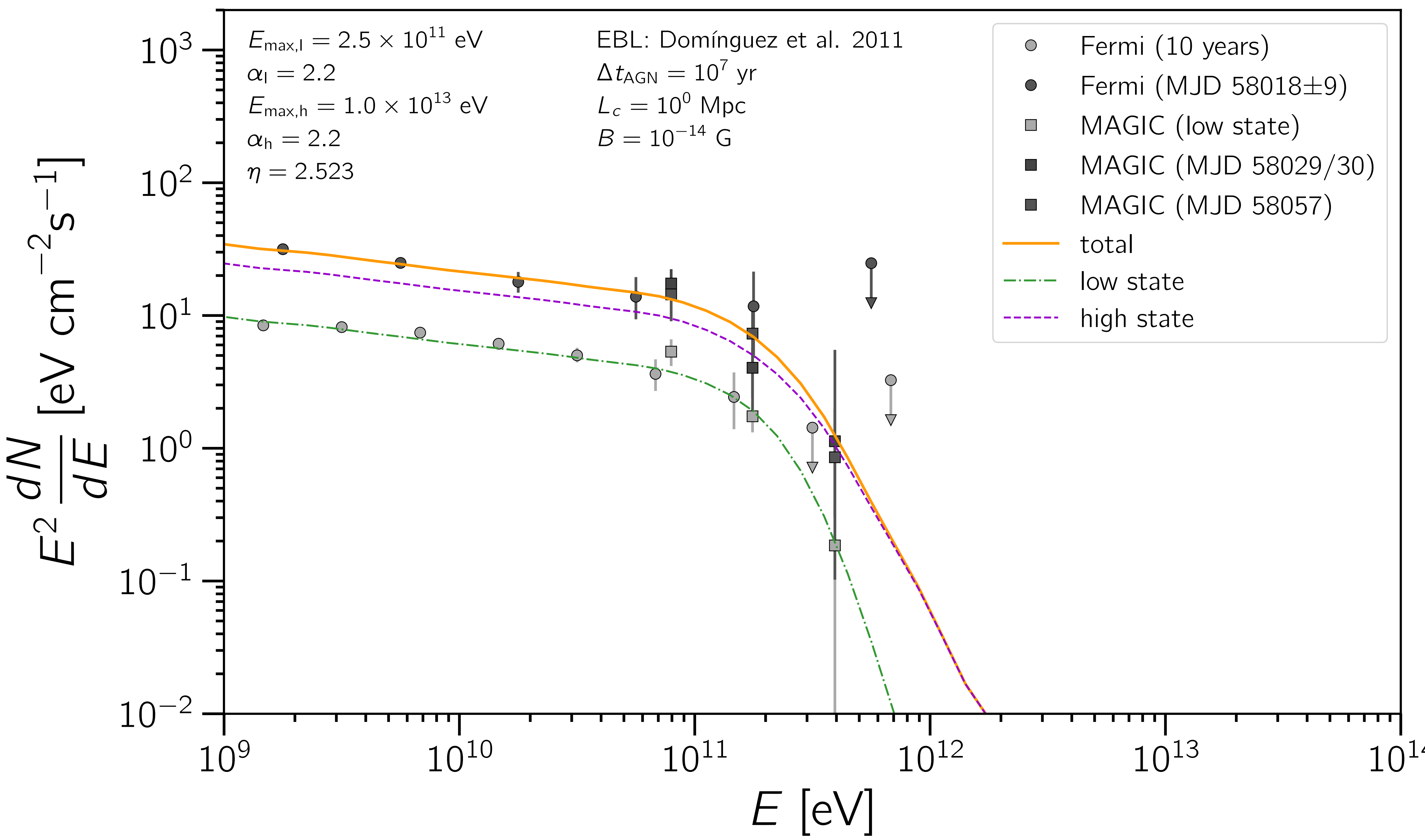


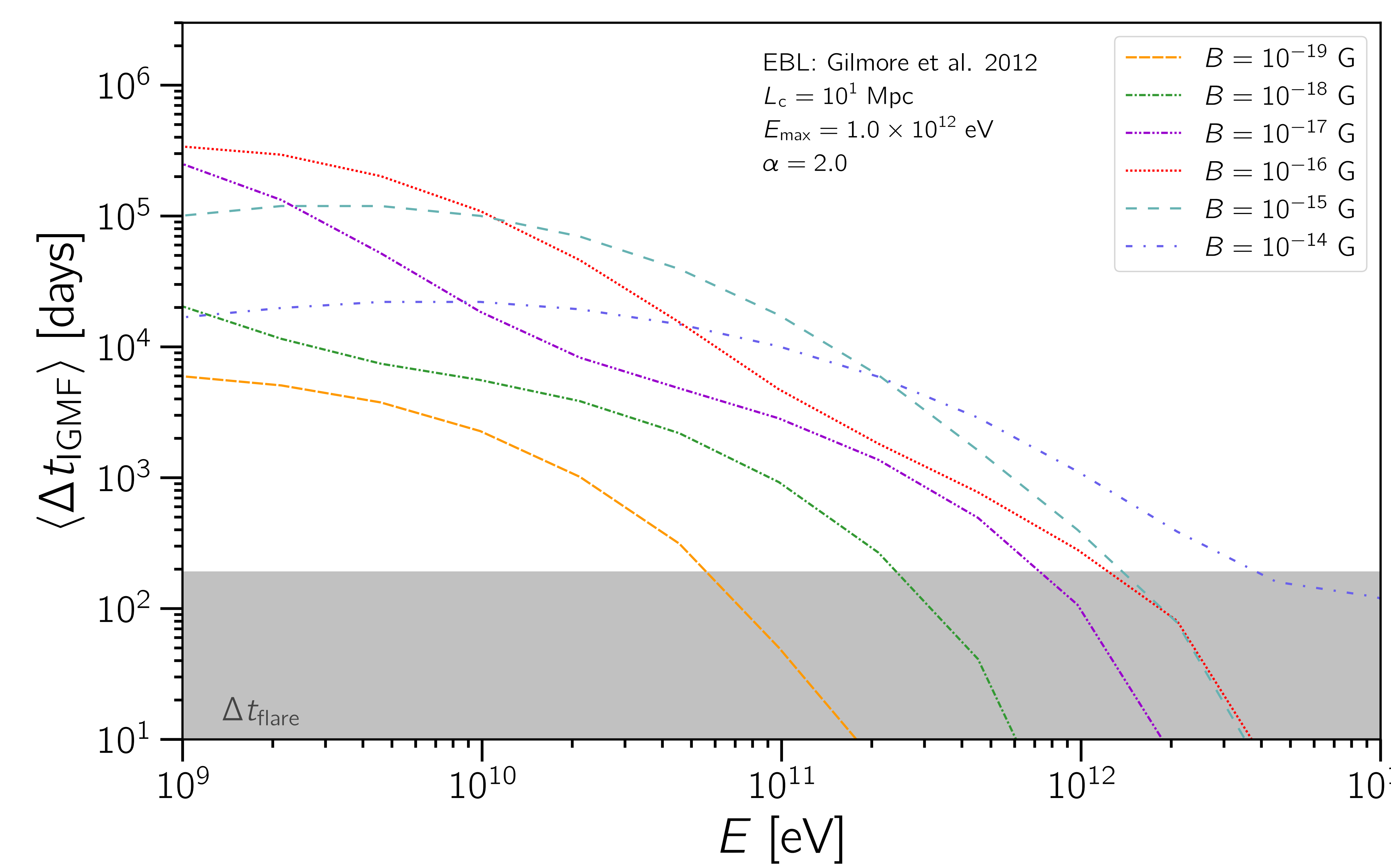
Alves Batista & Saveliev. Universe 7 (2021) 223. arXiv:2105.12020

multi-messenger (gamma + neutrinos) constraints on IGMFs

Alves Batista, Saveliev. ApJL 902 (2020) L11. arXiv:2009.12161
Saveliev, Alves Batista. MNRAS 500 (2021) 2188. arXiv:2009.09772

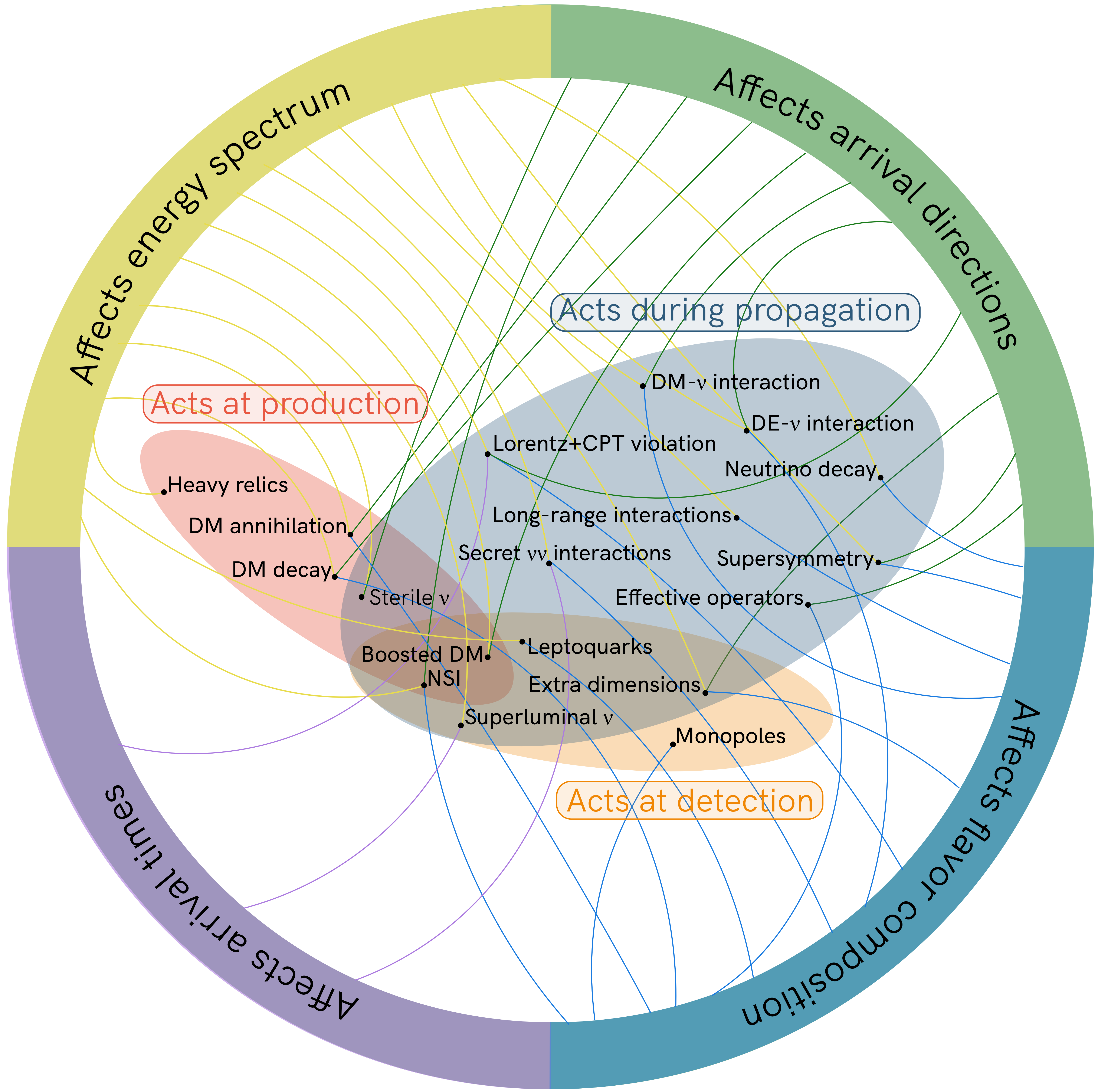






neutrinos

neutrinos are excellent probes of "stuff"

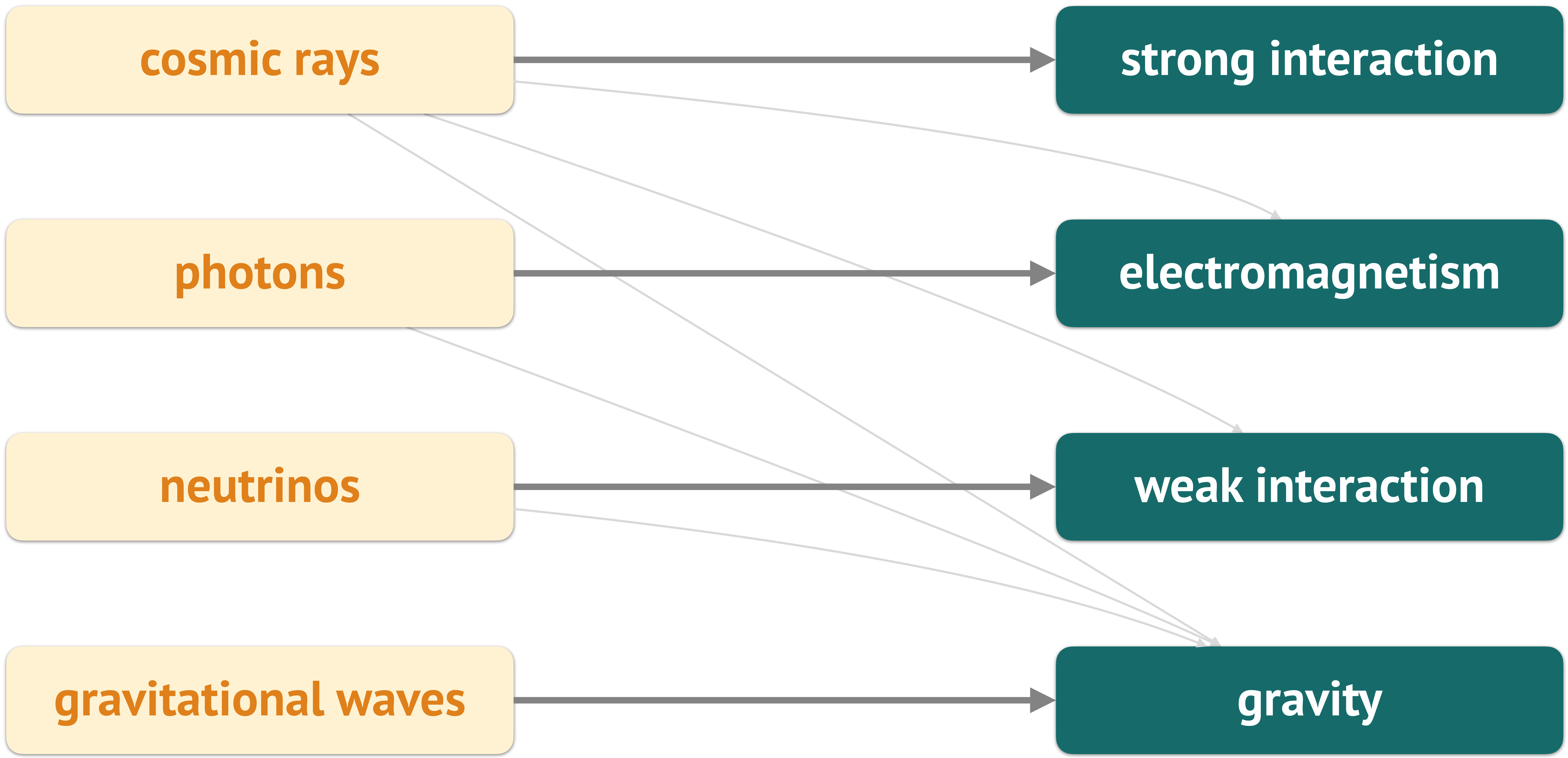


high energies + long baselines

Ackermann et al. arXiv:1903.04333

quantum gravity and fundamental interactions

fundamental interactions



quantum gravity: phenomenological frameworks

- use phenomenological forms for the **modified dispersion relation** (MDR)

$$E^2 = m_o^2 c^4 + p^2 c^2 + f_o(E, \vec{p})$$

- anomalous thresholds and time delays come from the additional term
- group velocity: $v = \dfrac{\partial E}{\partial p}$
- **Lorentz invariance violation (LIV)** $f_o(E, \vec{p}) = f_o(\vec{p}) = p^2 c^2 \sum_{k=0}^{N} \chi_k^o \left(\dfrac{pc}{E_{\rm LIV}} \right)^k$
- **deformed special relativity (DSR)** $f_o(E, \vec{p}) \simeq \chi_k^o p^2 c^2 \left(\dfrac{E}{E_{\rm DSR}} \right)^k + \mathcal{O}\left(\dfrac{E^{k+3}}{E_{\rm DSR}^{k+1}} \right)$

example: pair production with broken Lorentz symmetry

special relativity

$$f_o(E,\vec{p}) = 0$$

$$s_{\rm thr} = 4m_e^2c^4$$

$$\varepsilon_{\rm thr} = \frac{m_e^2c^4}{E}$$

Lorentz invariance violation (LIV)

$$f_o(E,\vec{p}) = f_o(\vec{p}) = p^2c^2\chi_k^o\left(\frac{pc}{E_{\rm LIV}}\right)^k$$

$$s_{\rm thr} \simeq 4m_e^2c^4 + \left(\frac{p_\gamma c}{E_{\rm LIV}}\right)^n \frac{p_\gamma^2c^2}{2^n}\chi_n^e$$

$$\varepsilon_{\rm thr} \simeq \frac{m_e^2c^4}{p_\gamma c} + \frac{1}{4}\left(\frac{\chi_n^e}{2^n} - \chi_n^\gamma\right)\left(\frac{p_\gamma c}{E_{\rm LIV}}\right)^n p_\gamma c$$

deformed special relativity (DSR)

$$f_o(E,\vec{p}) \simeq \chi_k^o p^2c^2\left(\frac{E}{E_{\rm DSR}}\right)^k$$

$$\tilde{s}_{\rm thr,12} = 4E\varepsilon \qquad \tilde{s}_{\rm thr,21} = 4\tilde{E}\varepsilon$$

$$\varepsilon_{\rm thr,12} = \frac{m_e^2c^4}{E} \qquad \varepsilon_{\rm thr,21} = \frac{m_e^2c^4}{\tilde{E}}$$

$$P_1 \oplus P_2 = P_1 + \left(1 + \frac{E_1}{E_{\rm DSR}}\right)P_2 \qquad \tilde{E}_i \equiv E_i\left(1 + \frac{E_i}{E_{\rm DSR}}\right)^{-1}$$

$$\lambda^{-1}(E,z) = \frac{1}{8\beta E^2}\int_{\varepsilon_{\rm min}(E)}^{+\infty}\frac{1}{\varepsilon^2}\frac{dn(\varepsilon,z)}{d\varepsilon}\int_{s_{\rm min}}^{s_{\rm max}(E,\varepsilon)}(s - m^2c^4)\sigma(s)\,ds\,d\varepsilon$$