# Probing for Lorentz Invariance Violation in Pantheon Plus Dominated Cosmology

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Based on Class. Quantum Grav. 40 195012, 2023 (arXiv:2305.06504) and Universe 10 (2024) 2, 75 (arXiv:2401.06068)

**5th Annual QGMM conference.**
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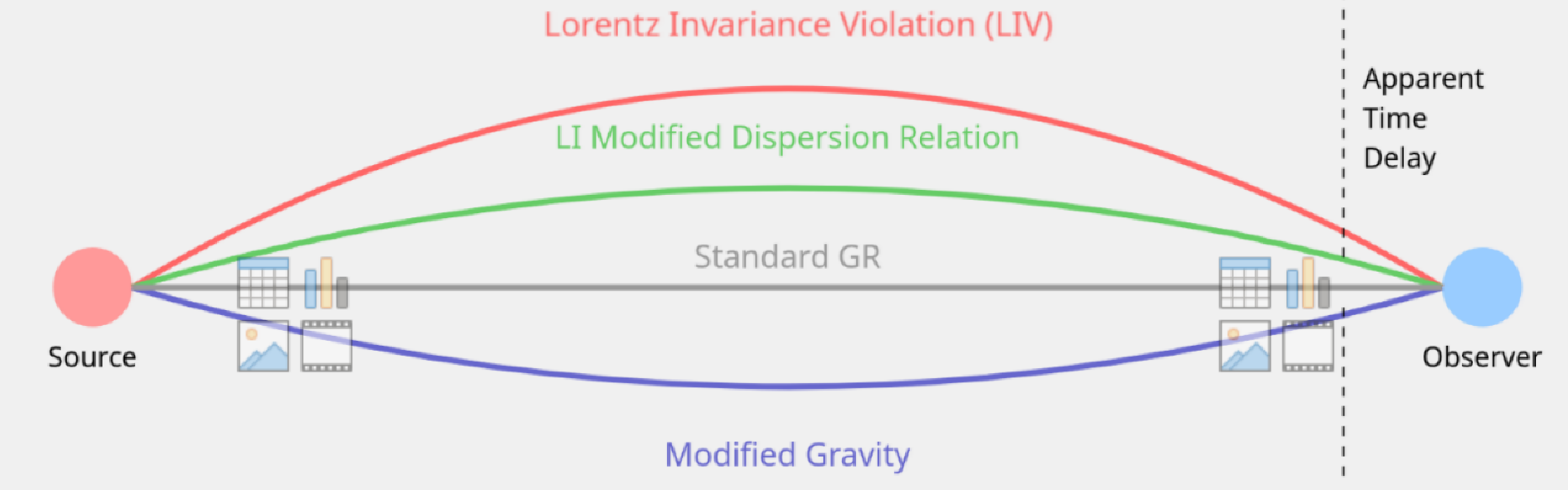
# The possible origins of apparent time delays

Lorentz invariance – the equivalence of physical laws in all inertial reference frames

QG Time Delay – the delay in arrival time due to MDR



So a time delay from LIV or else or not at all?

# „To Time Delay or Not“

**Predicting Time Delays**

- Effective Field Theory (EFT)
- Standard Model Extension (SME)
- Doubly Special Relativity (DSR) (not always)
- Horava-Lifshitz Gravity
- Loop Quantum Gravity (LQG)
- Non-Commutative Geometry

**Not predicting Time Delays**

- **GR**
- DSR (under some conditions) (Carmona et al. PRD 2012)
- Causal Dynamical Triangulations (Amelino-Camelia PRD 87, 123532 (2013))
- Black holes in LQG (PRD70 (2004))
- Conformal Field Theory (CFT) in AdS/CFT (some cases).
- String Theory (cases without spontaneous symmetry breaking)

Both detection and non-detecion of TD is exciting!

# Time delays

- Some quantum gravity theories predict **modified dispersion relation**

$$E^2 = p^2c^2 \longrightarrow E^2 = p^2c^2\left[1 - s_\pm\left(\frac{E}{\xi_n E_{QG}}\right)^n\right],$$

- This leads to **changed group velocity**

$$v(E) = \frac{\partial E}{\partial p} \simeq c\left[1 - s_\pm \frac{n+1}{2}\left(\frac{E}{E_{\mathrm{QG,n}}}\right)^n\right].$$

- The modified velocity leads to a **modified time of flight of the photons:**

$$t = \int_0^z \left[1 + \frac{E}{E_{QG}}(1+z')\right]\frac{dz'}{H(z')}$$

$$\Delta t_{LIV} = \pm s\frac{\Delta E}{E_{QG}}\int_0^z (1+z')\frac{dz'}{H(z')}$$

**Addazi et al ,**
**Prog.Part.Nucl.Phys. 125 (2022)**
**arXiv: 2111.05659**

$$\frac{\Delta t_{obs}}{1+z} = a_{LIV}K + \beta\,,$$

$$K \equiv \frac{1}{1+z}\int_0^z \frac{(1+\tilde{z})\,d\tilde{z}}{h(\tilde{z})}\,.$$

$$a_{LIV} \equiv \Delta E/(H_0 E_{QG})$$

# The promise of GRBs

- Gamma-Ray Bursts

  -- high energies ($E_{iso}$>$10^{52}$erg)

  -- high redshifts (z~9)

  -- very high energy emissions (~TeV)

  -- numerous observations

  -- (good) theoretical models

# Known Unknowns:

- No final GRB model so far
- Short or Long, One or Many
- Propagational time-delay
- What effects can we ignore?
- Methods for finding the time-delay

  -- discrete cross correlation function (CCF)

  -- wavelet method

  -- difference between time of arrival of different channels (for single GRB)

$$\Delta t_{\mathrm{obs}} = \Delta t_{\mathrm{int}} + \Delta t_{\mathrm{QG}} + \Delta t_{\mathrm{spec}} + \Delta t_{\mathrm{DM}} + \Delta t_{\mathrm{gra}}$$

# The intrinsic lag: different ways to go

- Standard assumption – constant term Ellis et al. 2005, Shao 0911.2276

$$\frac{\Delta t_{obs}}{1+z} = a_{LIV} K + \beta\,,$$

- For a single GRB in multiple channels or multiple GRBs – energy fit

  Du et al. 2010.16029, Wei 1612.09425, Desai et al. 2205.12780, Xiao et al. 2022, Agrawal 2102.11248

$$\Delta t_{\rm int,z}(E) = \tau\left[\left(\frac{\mathcal{E}_0}{1\ {\rm keV}}\right)^{-\alpha} - \left(\frac{E}{1\ {\rm keV}}\right)^{-\alpha}\right],$$

- A new fireball model

  Chang et al. 1201.3413

$$\Delta t = \frac{3r_0(1+z)}{2c}\left[\left(\frac{r_{\gamma\gamma}(E_0)}{r_0}\right)^{1/3} - \left(\frac{r_p}{r_0}\right)^{1/3}\right].$$

- Luminosity dependence Vardanyan et al. 2212.02436

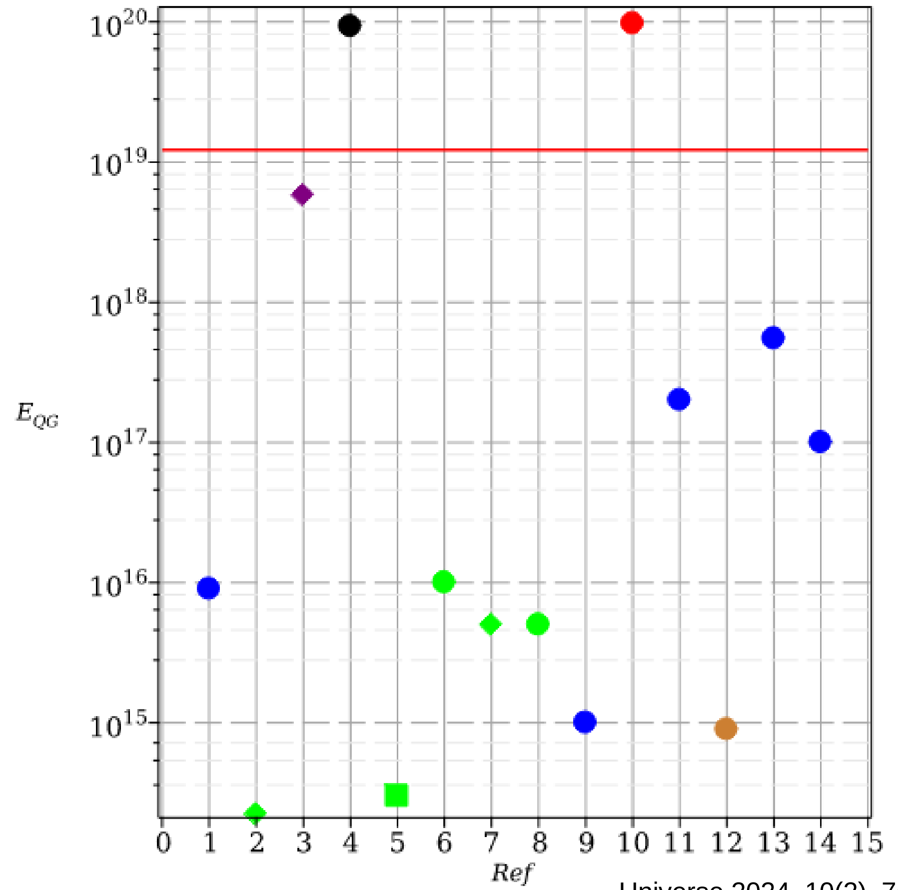
$$\tau_{\rm RF}^{{\rm int},i} = \frac{\tau_{\rm obs}^{{\rm int},i}}{1+z} = \beta_{\rm long}\left(\frac{L^i_{\rm iso}}{L_*}\right)^{\gamma},$$

- SME framework Vasileu et al. 1305.3463

$$\tau_n \simeq \frac{1}{H_0}\left(\sum_{jm} {}_0Y_{jm}(\hat{n})\, c^{(n+4)}_{(I)jm}\right)\times \kappa_n;$$

# The existing bounds:

1. **Ellis et al. Astropart. Phys. 2006 (2015)**
2. Du et al., Astrophys.J. 906 (2021)
3. MAGIC and ICRANet-Armenia, Phys.Rev.Lett. 125 (2020),
4. Vasileiou et al., Phys.Rev.D 87 (2013)
5. Pan et al, Astrophys.J. 890 (2020), +
6. Agrawal et al, JCAP 05 (2021)
7. Wei et al, Astrophys.J.Lett. 834 (2017),
8. Desai et al, Eur.Phys.J.C 83 (2023),
9. Xiao et al,.J.Lett. 924 (2022),
10. Chang et al, Astropart.Phys. 36 (2012),
11 Shao et al. , Astropart.Phys. 33 (2010),
12 Vardanyan et al., 2212.02436,
13. & 14. Staicova CQG9 (2023)



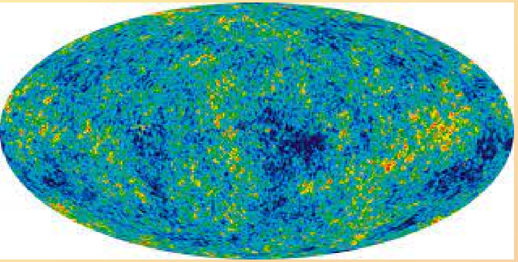
Universe 2024, 10(2), 75;

The most stringent bounds comes from the TeV emissions of GRB 221009A (18 TeV) ($E<10\ E_{pl}$) and GRB 190114C (0.2 TeV) $E>0.58\times10^{19}$GeV

# What about the cosmology?

To investigate cosmology, we combine combine GRB TD data with other astrophysical sources

CMB



NASA/WMAP

z~1100

GRB

Cruz deWilde / Swift / NASA

z~6

BAO

BOSS

z~2

SN

NASA/ESA/CSA WEBB

z~2

For all, we solve the Friedmann equations:

$$H(z)/H_0 = E(z)$$

$$E(z)^2 = \Omega_r(1+z)^4 + \Omega_m(1+z)^3 + \Omega_k(1+z)^2 + \Omega_{DE}(z),$$

# The quantities we use

- SN/GRB

$$\mu_B(z) - M_B = 5\log_{10}\left[d_L(z)\right] + 25\,,$$

- CMB distance priors

$$l_{\rm A} = (1+z_*)\frac{\pi D_{\rm A}(z_*)}{r_s(z_*)},$$

$$R \equiv (1+z_*)\frac{D_{\rm A}(z_*)\sqrt{\Omega_m}H_0}{c},$$

- BAO

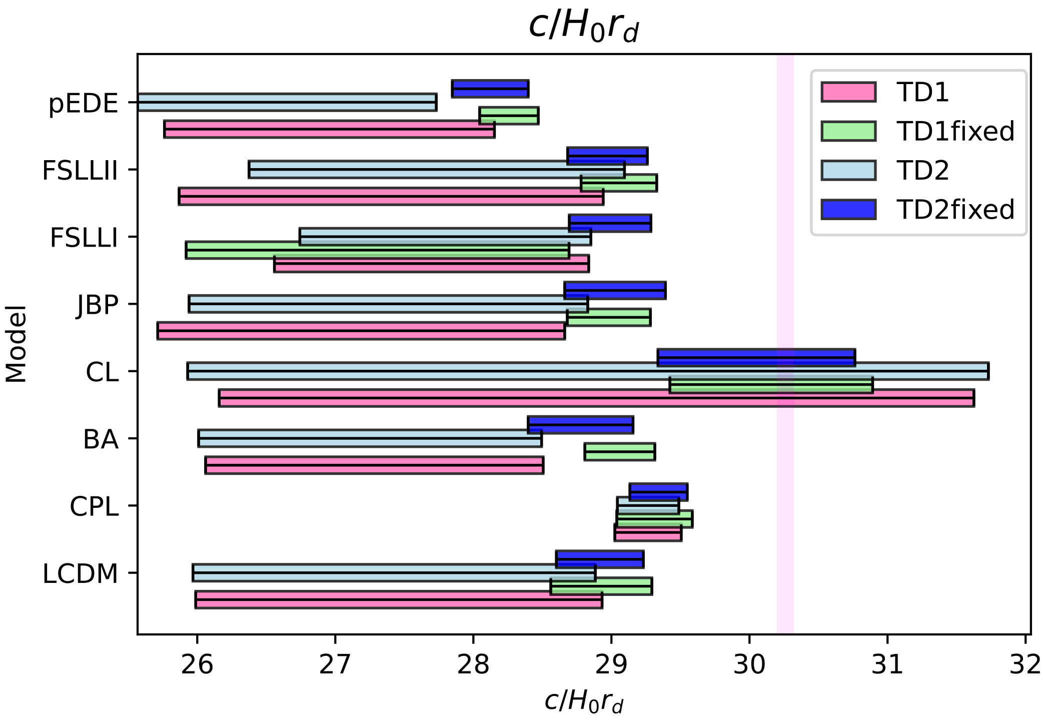
$$D_{\rm A} = \frac{c}{(1+z)H_0\sqrt{|\Omega_k|}}\,{\rm sinn}\left[|\Omega_k|^{1/2}\int_0^z \frac{dz'}{E(z')}\right]$$

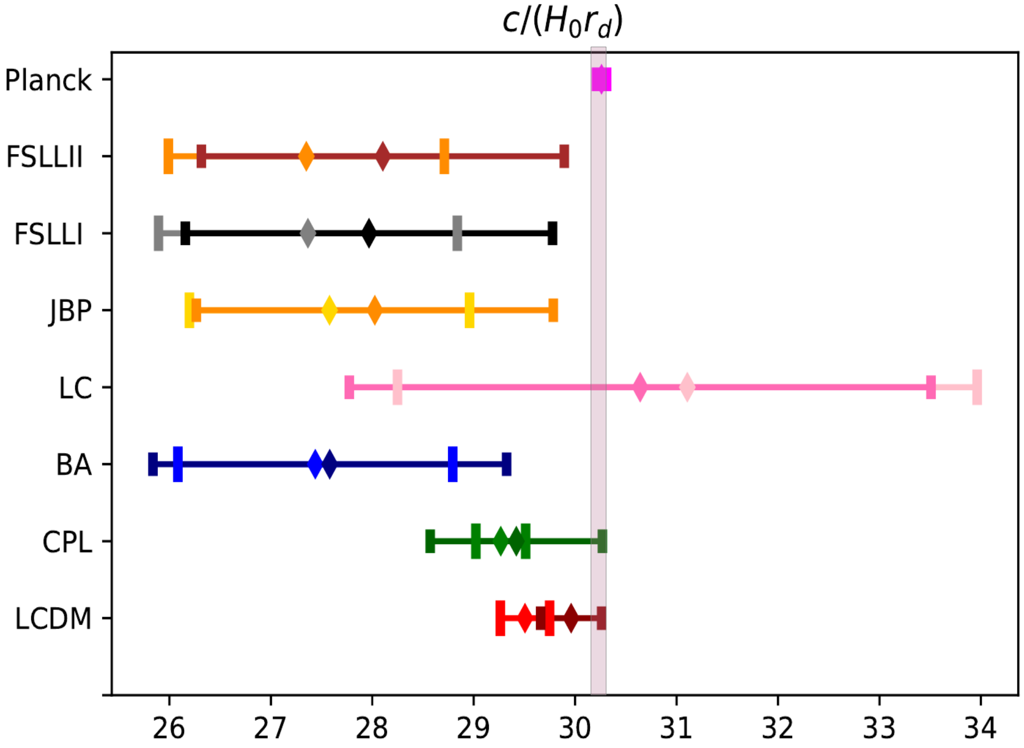
where

$$S_k(x) = \begin{cases} \frac{1}{\sqrt{\Omega_k}}\sinh\left(\sqrt{\Omega_k}x\right) & \text{if} \quad \Omega_k > 0 \\ x & \text{if} \quad \Omega_k = 0 \\ \frac{1}{\sqrt{-\Omega_k}}\sin\left(\sqrt{-\Omega_k}x\right) & \text{if} \quad \Omega_k < 0 \end{cases}$$

**All depend on $c/H_0r_d$ so we take it as 1 factor!**

# The results: $c/H_0r_d$





With TD

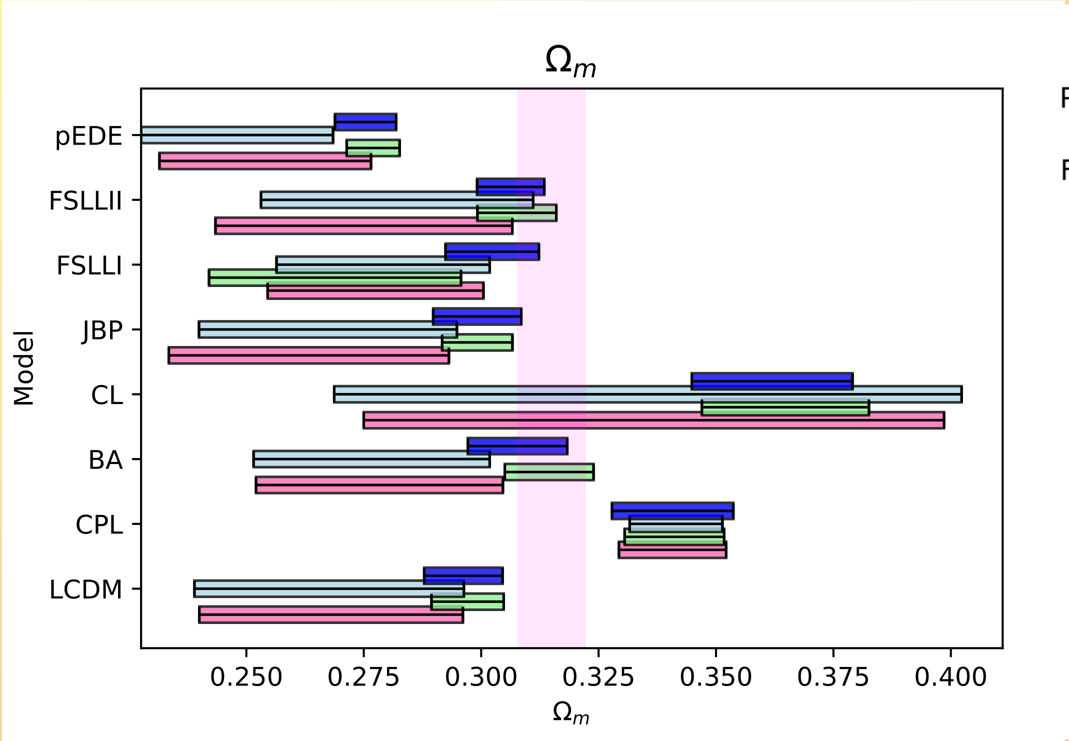
Class. Quantum Grav. 40 195012, 2023

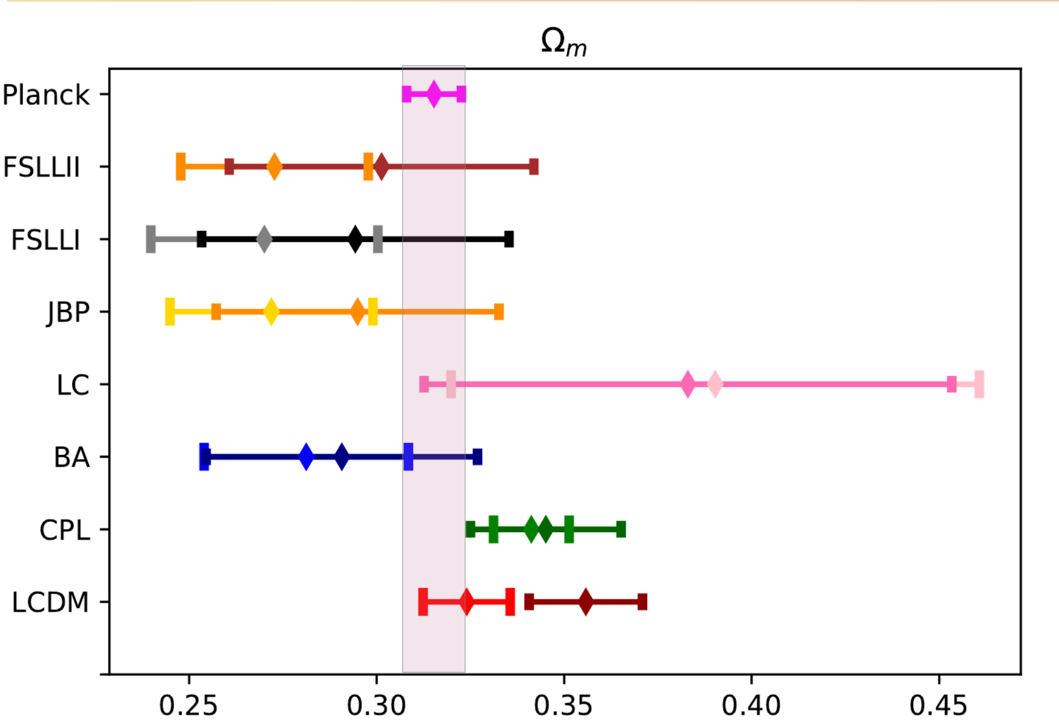
Without

# And $\Omega_m$

BAO+CMB (darker) and BAO+CMB+SN+GRB(lighter)

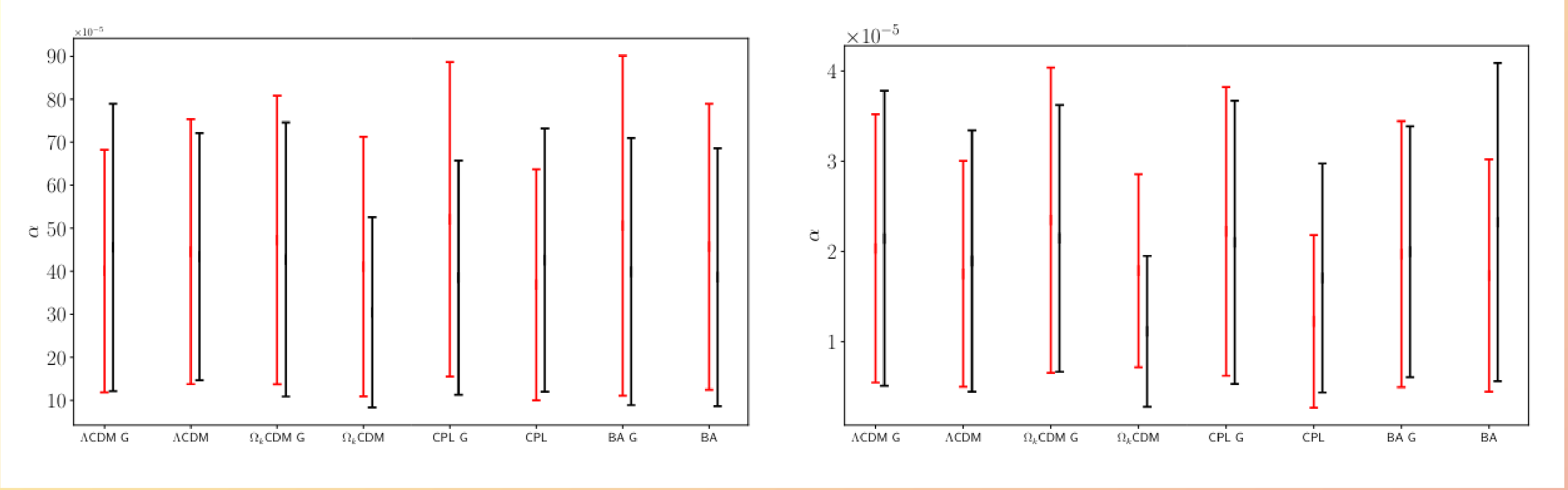
**D.S., Universe 2022, 8(12), 631**





With TD

Without


×10⁻⁵
90
80
70
60
50
40
30
20
10
α
ΛCDM G
ΛCDM
Ω_kCDM G
Ω_kCDM
CPL G
CPL
BA G
BA
×10⁻⁵
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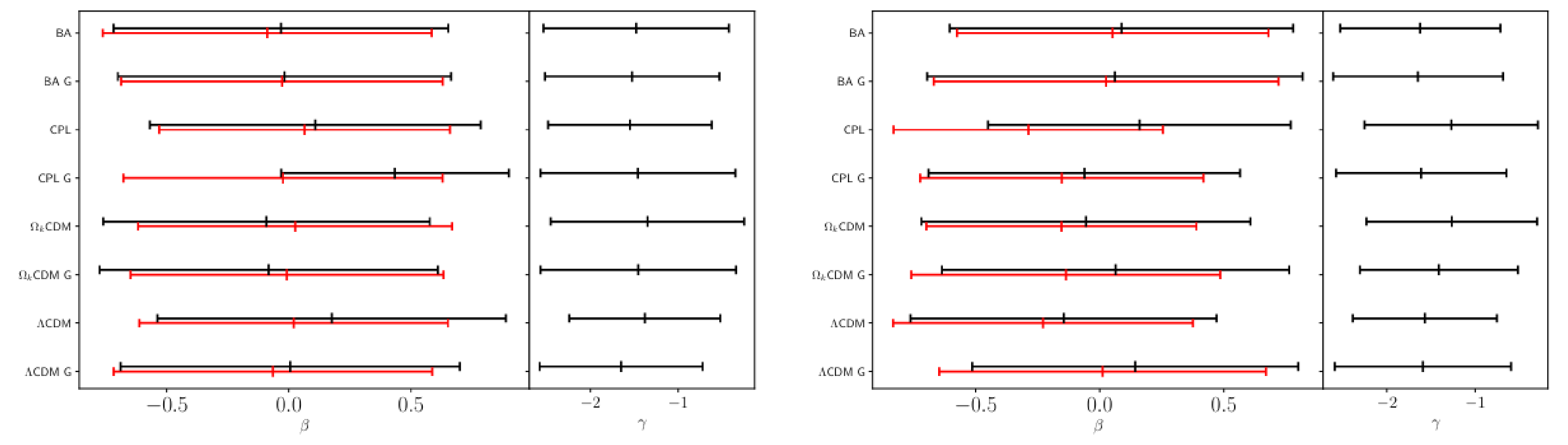
BA G
BA


BA
BA G
CPL
CPL G
Ω_kCDM
Ω_kCDM G
ΛCDM
ΛCDM G
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0.0
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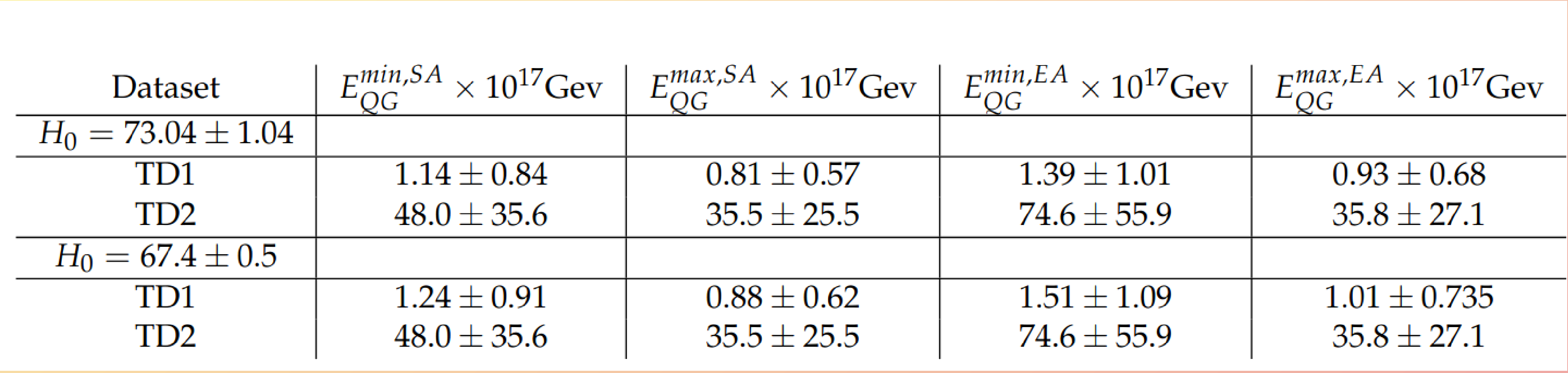
β
−2
−1
γ
BA
BA G
CPL
CPL G
Ω_kCDM
Ω_kCDM G
ΛCDM
ΛCDM G
−0.5
0.0
0.5
β
−2
−1
γ

# In GeV

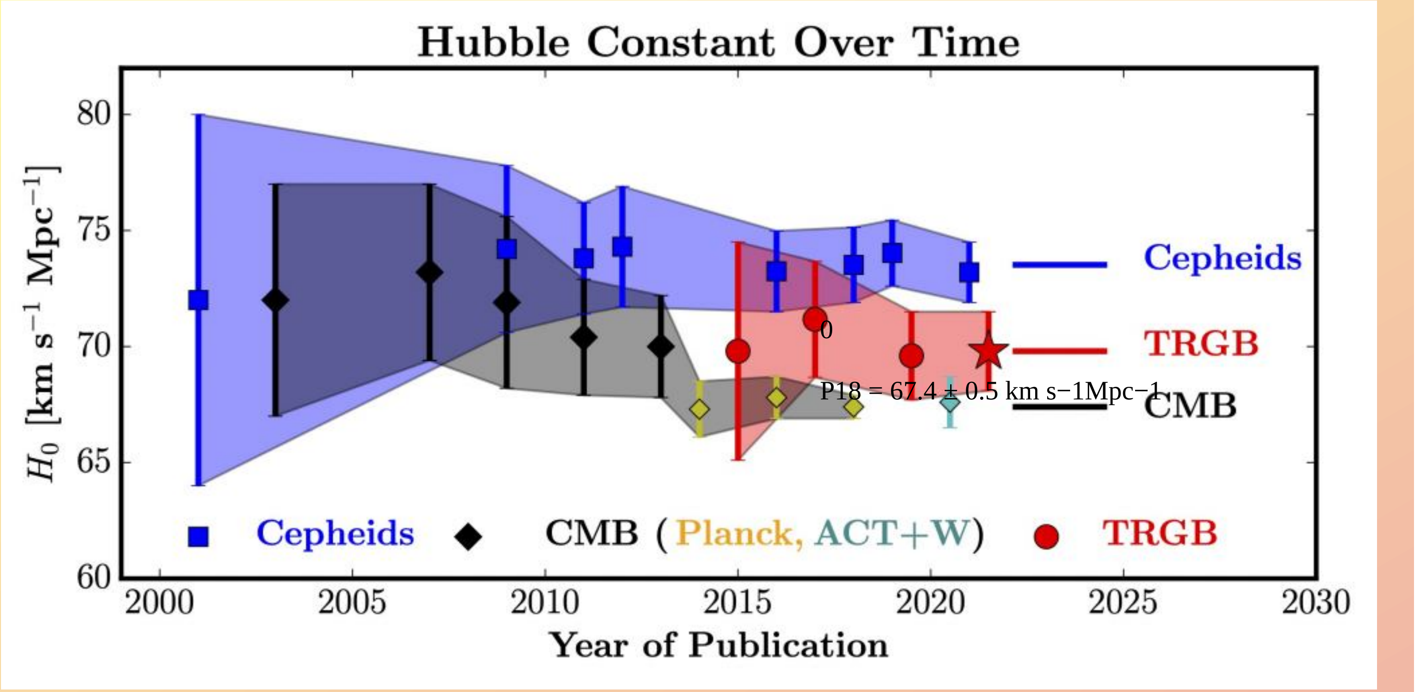


| Dataset | $E_{QG}^{min,SA} \times 10^{17}$Gev | $E_{QG}^{max,SA} \times 10^{17}$Gev | $E_{QG}^{min,EA} \times 10^{17}$Gev | $E_{QG}^{max,EA} \times 10^{17}$Gev |
|---|---|---|---|---|
| $H_0 = 73.04 \pm 1.04$ | | | | |
| TD1 | $1.14 \pm 0.84$ | $0.81 \pm 0.57$ | $1.39 \pm 1.01$ | $0.93 \pm 0.68$ |
| TD2 | $48.0 \pm 35.6$ | $35.5 \pm 25.5$ | $74.6 \pm 55.9$ | $35.8 \pm 27.1$ |
| $H_0 = 67.4 \pm 0.5$ | | | | |
| TD1 | $1.24 \pm 0.91$ | $0.88 \pm 0.62$ | $1.51 \pm 1.09$ | $1.01 \pm 0.735$ |
| TD2 | $48.0 \pm 35.6$ | $35.5 \pm 25.5$ | $74.6 \pm 55.9$ | $35.8 \pm 27.1$ |

**TD1: Ellis et al. 2006**
**35 GRBs,**
**wavelet method**

**Vardanyan et al. 2022,**
**49 GRBs,**
**descrete CCF**

# Why we care?



$H_0^{P18}$ = 67.4 ± 0.5 km\s\Mpc

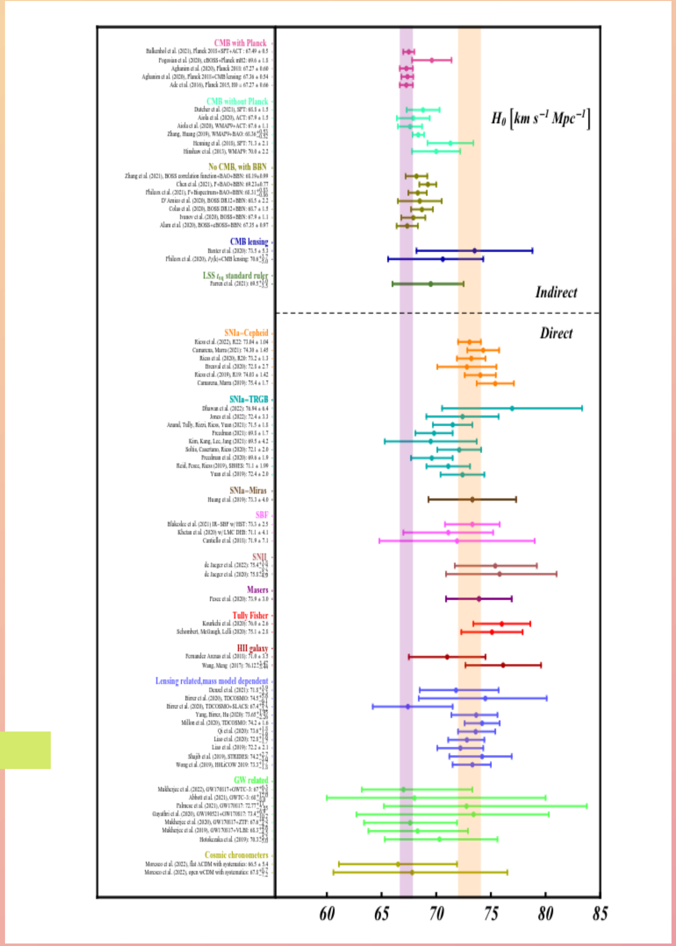
Aghanim et al. , Astron. Astrophys. 641, 2020

$H_0^{SH0ES}$ =73.04 ± 1.04 km\s\Mpc

Riess, A. G. et al. ApJL 934 (2022) L7

Wendy Freedman, Nature Astronomy, 1, 0169 (2017), arXiv:2106.15656 (2021)

The Hubble tensions is at 5.3σ as of 2023!
But it does not affect only $H_0$!



Abdalla et all. JHEAp. 2204 (2022) , Di Valentino et al. CQG, 38 (2021)

# Conclusions:

Questions:
How good is the time-delay data?
How to improve the GRB model?
How strong is the effect of cosmology?
What about QG without TD?!

- $c/H_0r_d$~27 – lower than the expected $c/H_0r_d$~30
- Lower than Planck's matter density
- Similar DDE parameters
- Some limited preference for CPL, BA, FSLLII
- TD1
- TD2

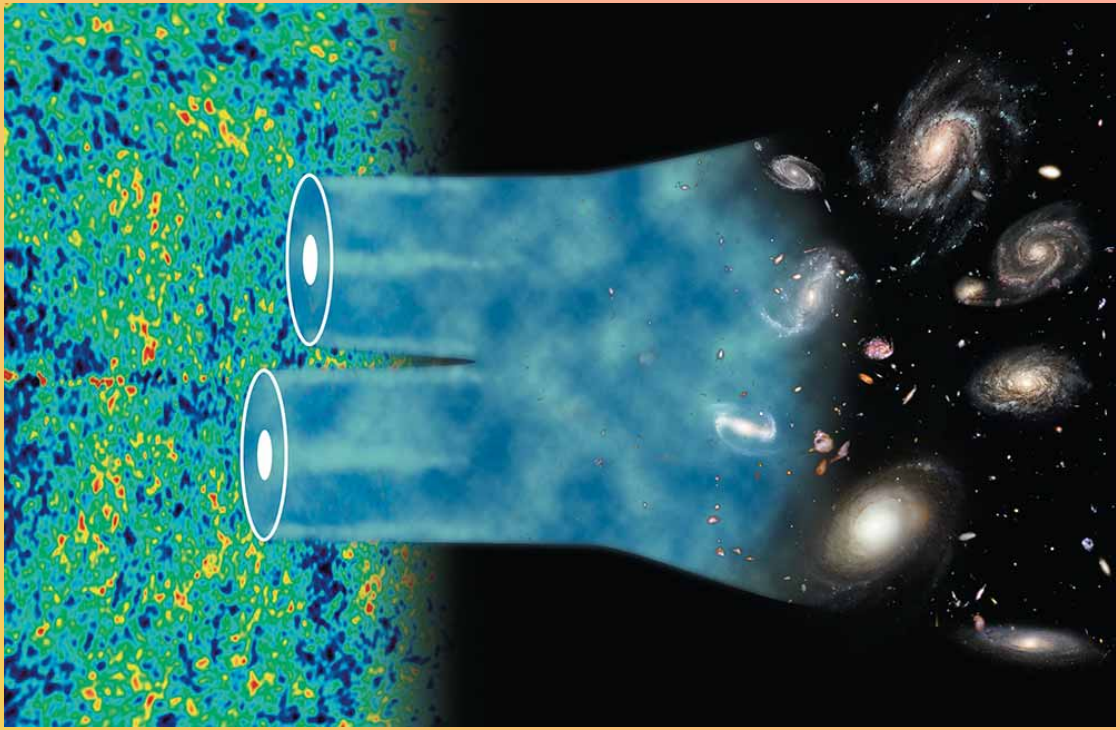
$$E_{QG} > 5 \times 10^{17} \text{ GeV}$$
$$E_{QG} > 1.1 \times 10^{17} \text{ GeV}$$

- 10%-30% deviation due to cosmology
- To use it for cosmology: $\alpha \sim 10^{-2}$

„Effect of the cosmological model on LIV constraints from GRB Time-Delays datasets“ Class.Quant.Grav. 40 (2023)

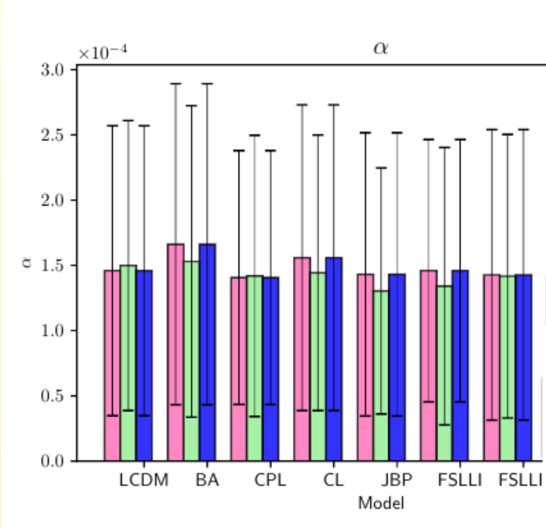
“Probing for Lorentz Invariance Violation in Pantheon Plus Dominated Cosmology” Universe 10 (2024)

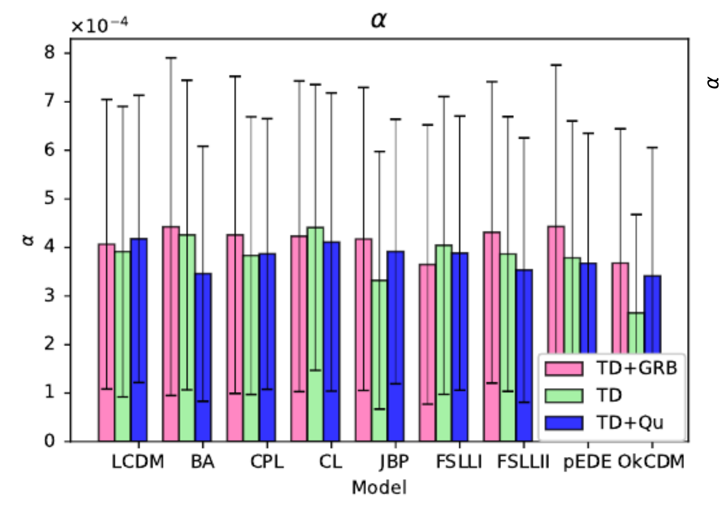
# Thank you for your attention!

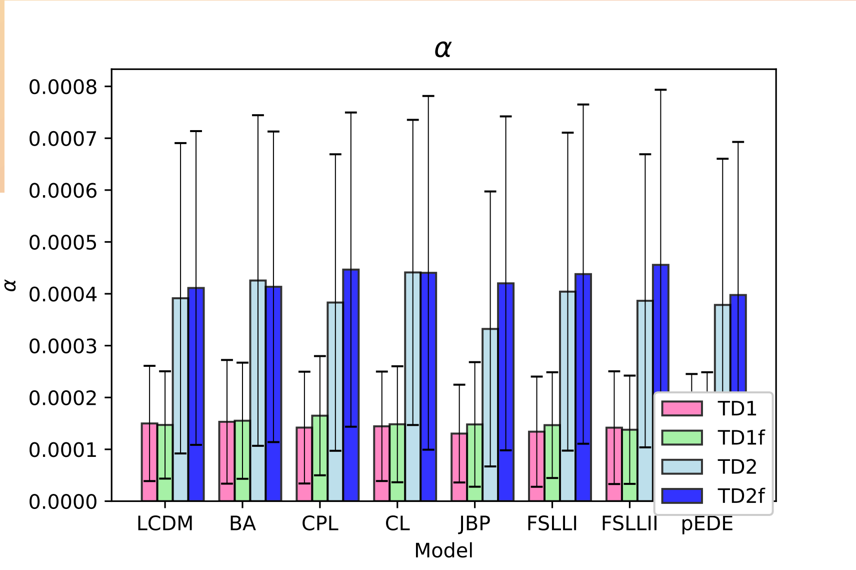


Funded by Bulgarian National Science Fund grant KP-06-N58/5.

# Pantheon dataset: (DS, arXiv:2305.06504)







**Ellis et al. 2006,**
**35 GRBs,**
**wavelet method**

In both cases - we see deviations between DE models

**Vardanyan et al. 2022,**
**49 GRBs,**
**descrete CCF**

# Comparing the 2 two TD models