Disentangling LIV from intrinsic lag ?

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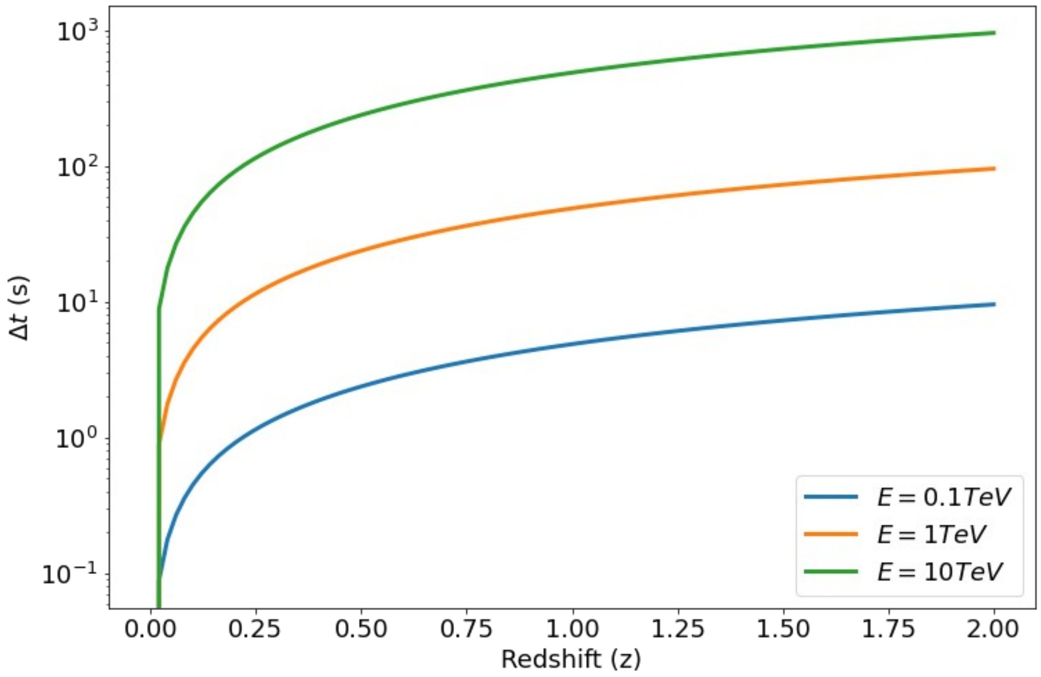
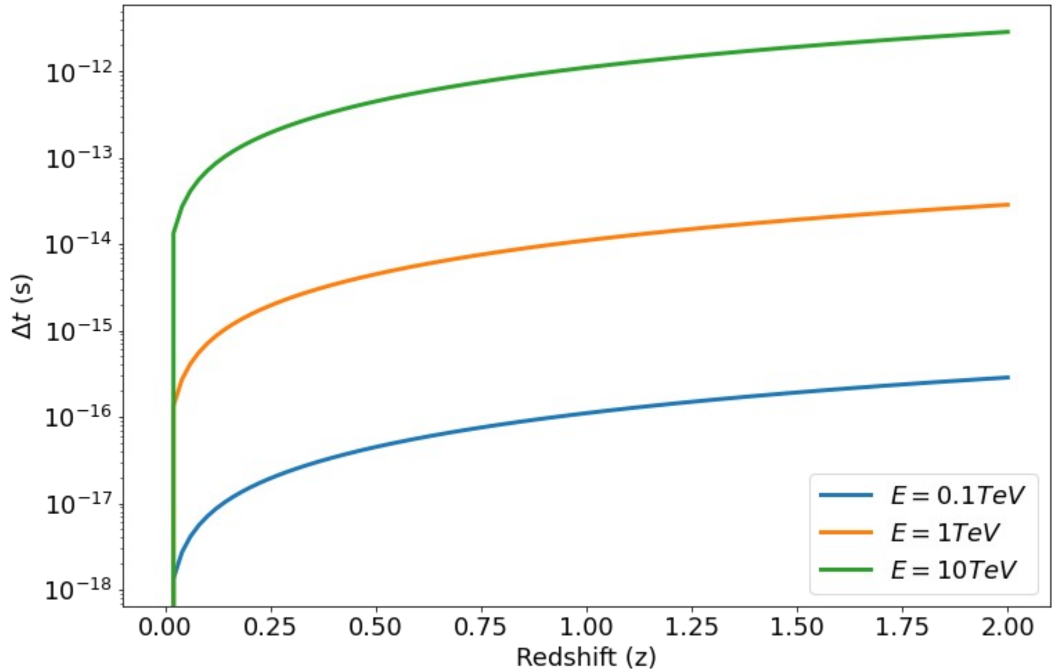
Based on Bolmont et al 2022 ApJ 930 75

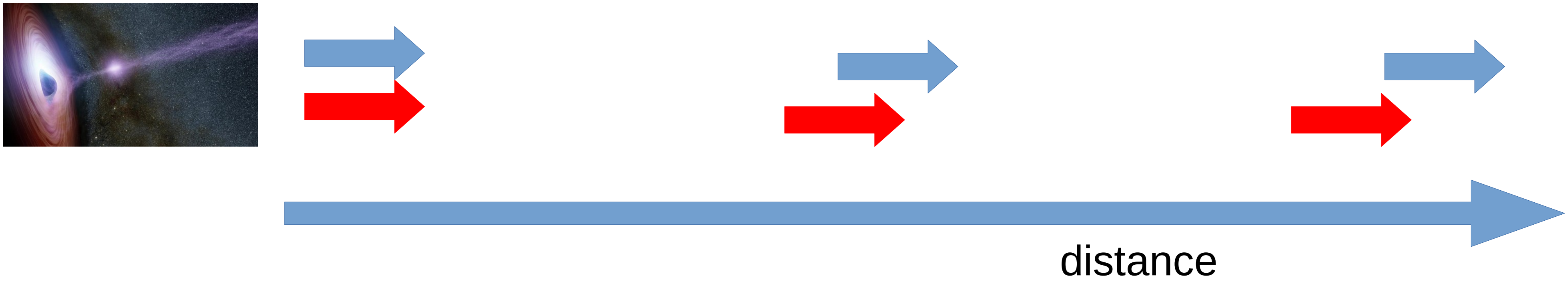
Time lag

n=1



n=2

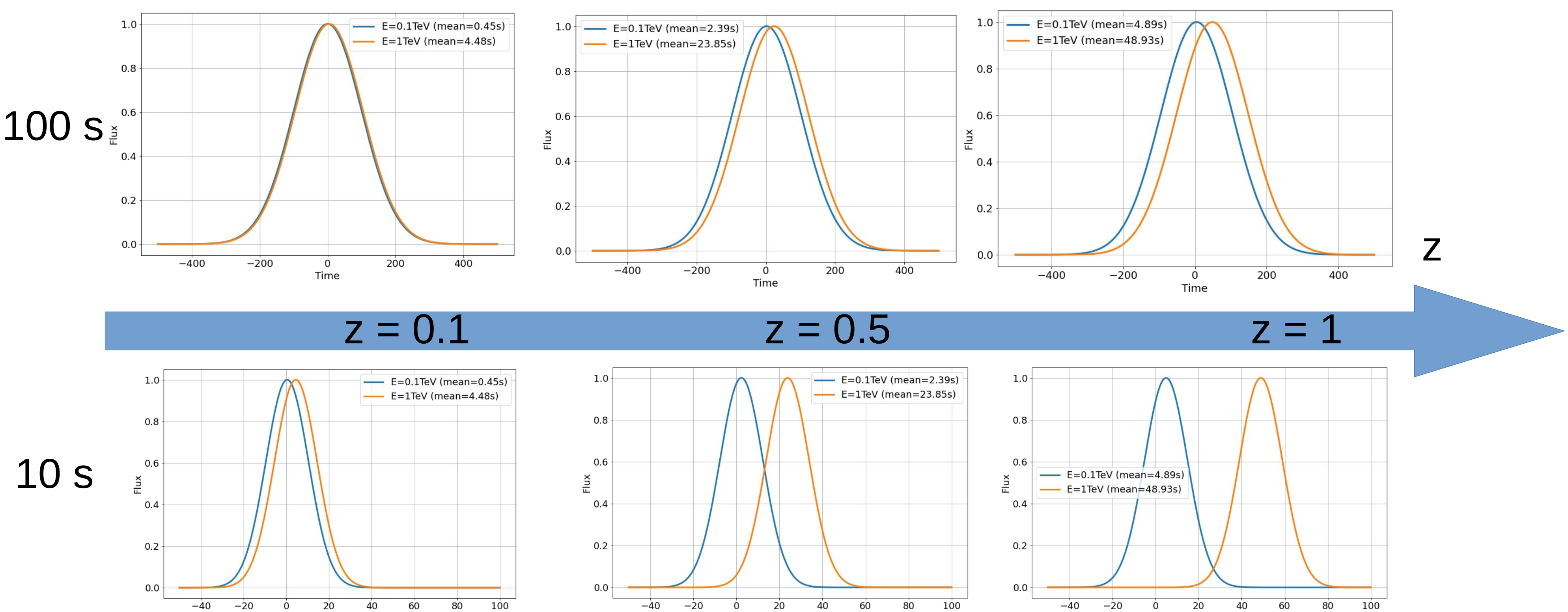




Impact on flaring sources

$$\frac{dP}{dtdE}(t, E) = \phi_E(E)\phi_t(t)$$

$$\frac{dP}{dtdE}(t + \boxed{\lambda_n \kappa_n(z) E^n}, E) = \phi_E(E)\phi_t(t + \boxed{\lambda_n \kappa_n(z) E^n})$$

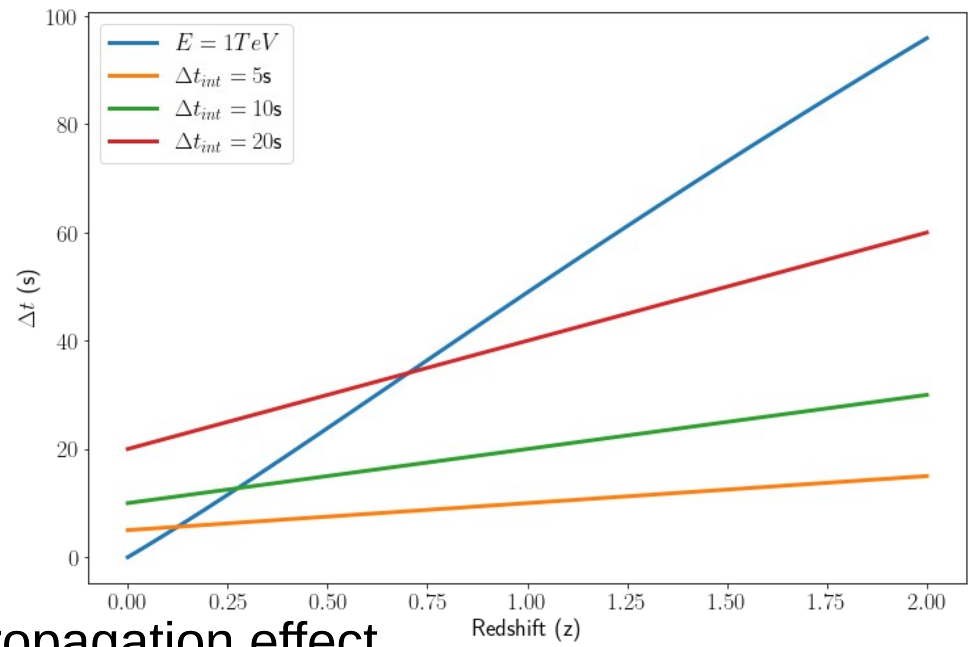


Intrinsic time delays ?

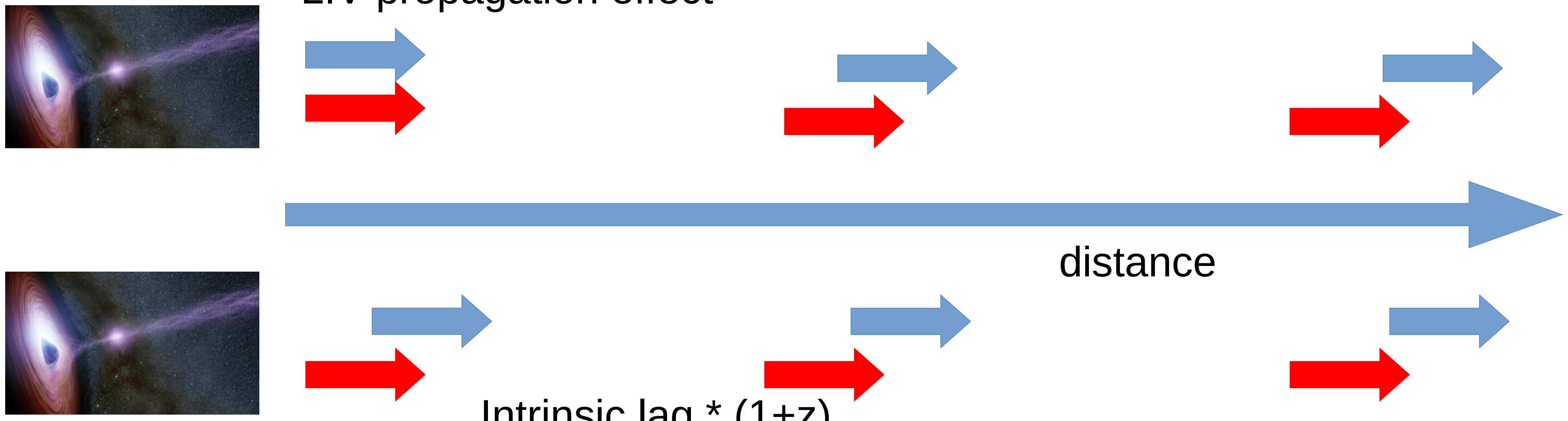
Intrinsic delay

$$\Delta t_{total}(z) = \Delta t_{LIV}(z) + \Delta t_{int}(1+z)$$

$$\Delta \tau_{total}(z) = \Delta \tau_{LIV}\,\kappa(z) + \Delta \tau_{int}(1+z)^2$$



LIV propagation effect



distance

Intrinsic lag * (1+z)

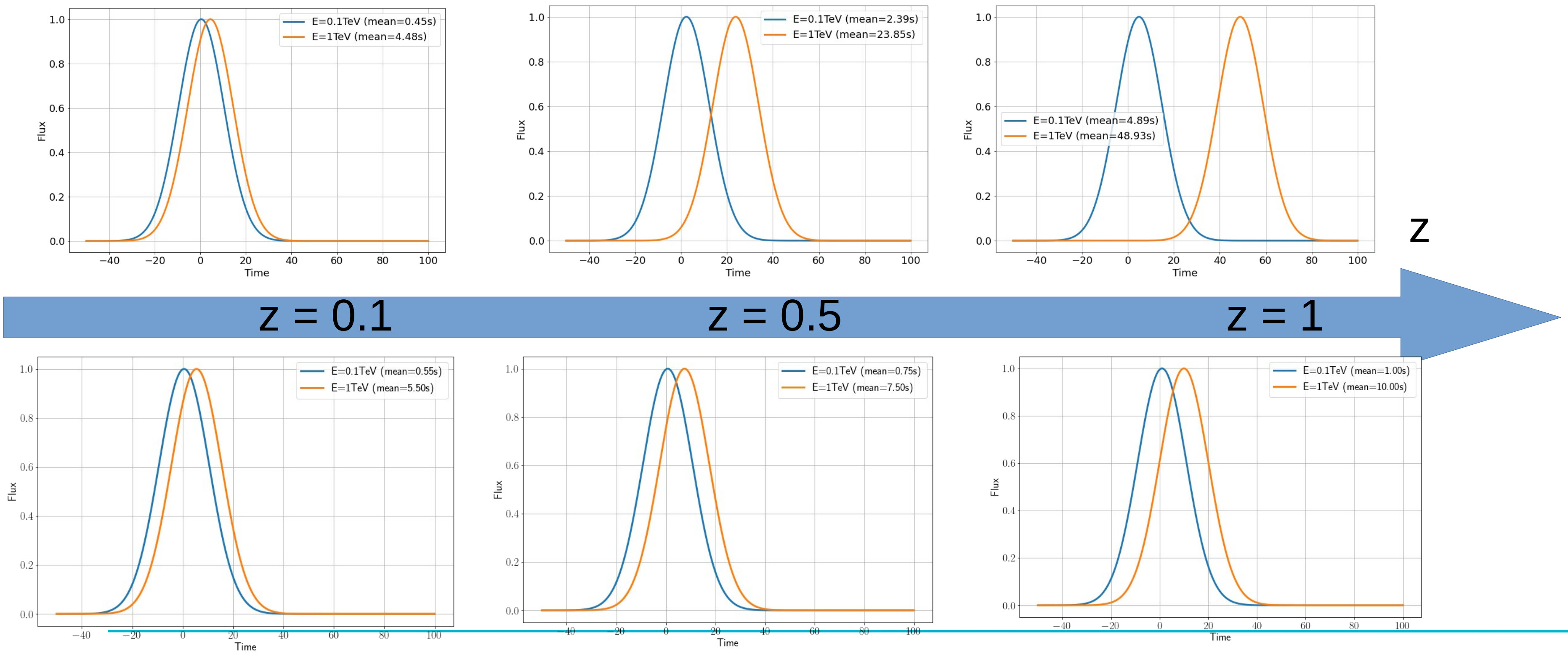
Impact on light curve

LIV

$$\frac{dP}{dtdE}(t+\boxed{\lambda_n\kappa_n(z)E^n}, E) = \phi_E(E)\phi_t(t+\boxed{\lambda_n\kappa_n(z)E^n})$$

Intrinsic (linear)

$$\frac{dP}{dtdE}(t+\boxed{\lambda(1+z)^2E}, E) = \phi_E(E)\phi_t(t+\boxed{\lambda(1+z)^2E})$$



Distinction between LIV and intrinsic delays

- We can use the two dimension of the time lag to distinguish it with intrinsic
  - Redshift
  - Energy
- What is the problem ?
  - We have poor understanding of how both time lag vary versus redshift and energy for both intrinsic and LIV !
  - For Quantum Gravity induced lag, we simply don't know !
  - Better understanding for intrinsic time lag, but probably source dependent and even worst flare dependent

- Will try to show you under some approximations and simple scenarios, we can try to tackle this challenge
- But this possible approximations need to be corroborated with models, and even better with data

LIV redshift dependance (reminder)

QG perturbation term

$$E^2 = \frac{p^2c^2}{a^2(t)}(1 + h_{QG}(E, E_{QG}))$$

Cosmological scale factor

$$E^2 = \frac{p^2c^2}{a^2(t)}\left(1 + \sum_1^n \left(\frac{E}{E_{QG,n}}\right)^n\right)$$

$$v(E,t) = \frac{\partial E}{\partial p} \simeq \frac{c}{a(t)}\left(1 + \frac{n+1}{2}\left(\frac{E(t)}{E_{QG,n}}\right)^n\right)$$

$$\left(\frac{E(t)}{E_{QG,n}}\right)^n \simeq \left(\frac{pc}{a(t)E_{QG,n}}\right)^n$$

$$\Delta t(E_h, E_l, z) = \frac{n+1}{2}\frac{E_h^n - E_l^n}{E_{QG}^n}\int_0^z \frac{(1+z')^n}{H(z')}dz'$$

LIV redshift dependence

QG perturbation term

$$E^2 = \frac{p^2c^2}{a^2(t)}(1 + h_{QG}(p, E_{QG}))$$

$$E^2 = \frac{p^2c^2}{a^2(t)}\left(1 + \sum_1^n \left(\frac{pc}{E_{QG,n}}\right)^n\right)$$

$$\Delta t(E_h, E_l, z) = \frac{n+1}{2}\frac{E_h^n - E_l^n}{E_{QG}^n}\int_0^z \frac{1}{H(z')}dz'$$

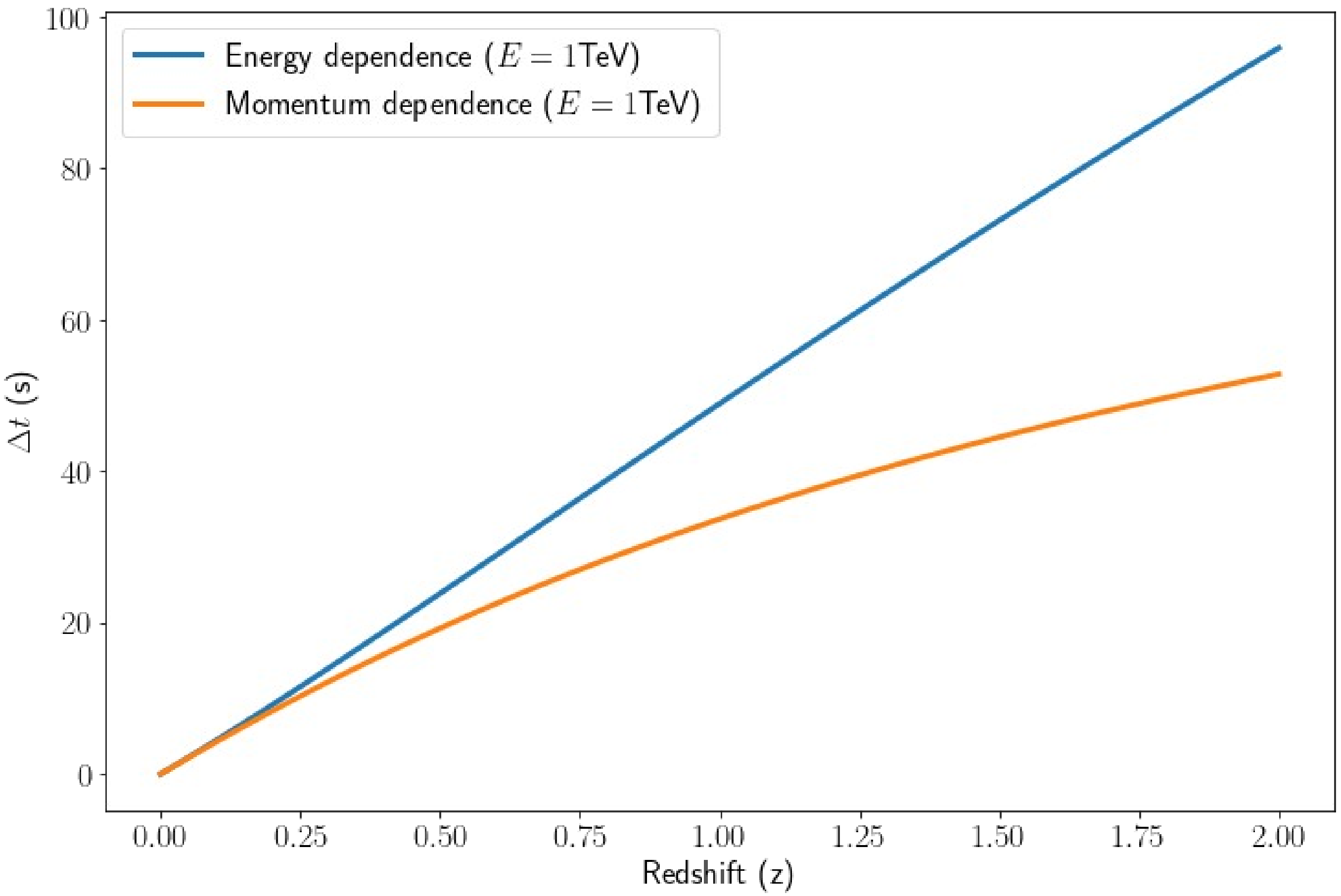
LIV redshift dependence

Pure spatial momentum

$$\Delta t(E_h, E_l, z) = \frac{n+1}{2}\frac{E_h^n - E_l^n}{E_{QG}^n}\int_0^z \frac{1}{H(z')}dz'$$

Pure Energy (so called Jacob and Piran)

$$\Delta t(E_h, E_l, z) = \frac{n+1}{2}\frac{E_h^n - E_l^n}{E_{QG}^n}\int_0^z \frac{(1+z')^n}{H(z')}dz'$$



LIV redshift dependence

QG perturbation term

$$E^2 = \frac{p^2c^2}{a^2(t)}\left(1 + h_{QG}(E, p, E_{QG})\right)$$

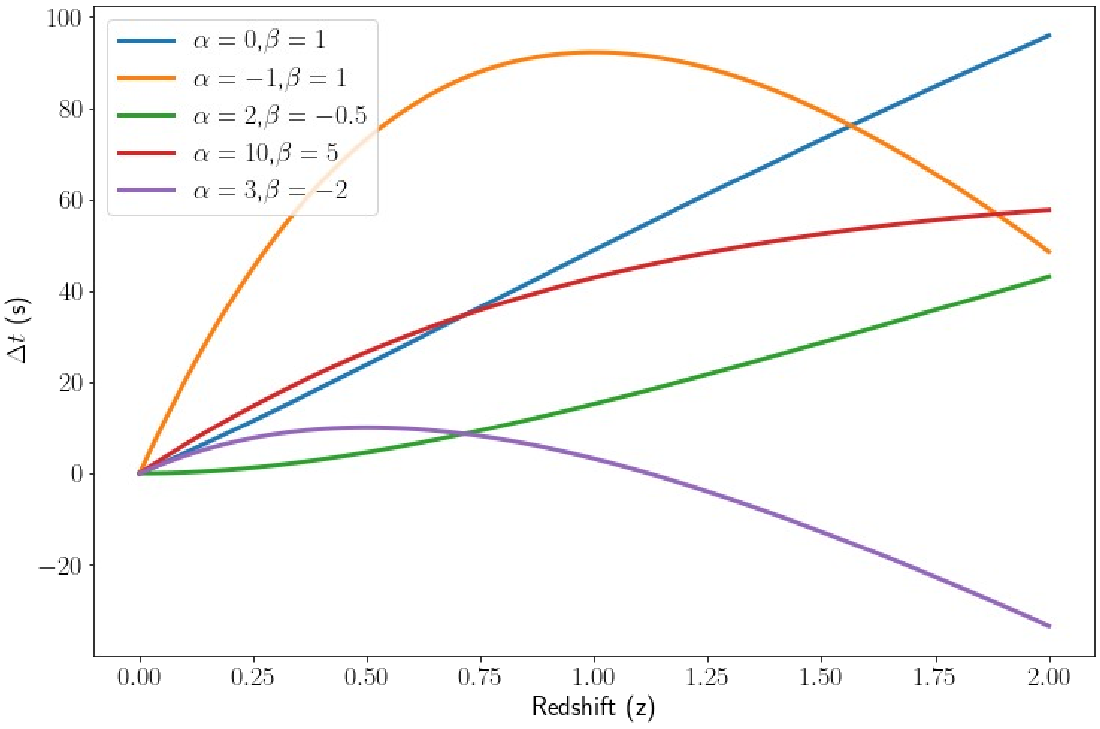
$$E^2 = \frac{p^2c^2}{a^2(t)}\left(1 + \alpha\sum_1^n\left(\frac{E}{E_{QG,n}}\right)^n + \beta\sum_1^n\left(\frac{pc}{E_{QG,n}}\right)^n\right)$$

$$\Delta t(E_h, E_l, z) = \frac{n+1}{2}\frac{E_h^n - E_l^n}{E_{QG}^n}\int_0^z \frac{\alpha + \beta(1+z)^n}{H(z')}dz'$$

LIV redshift dependence

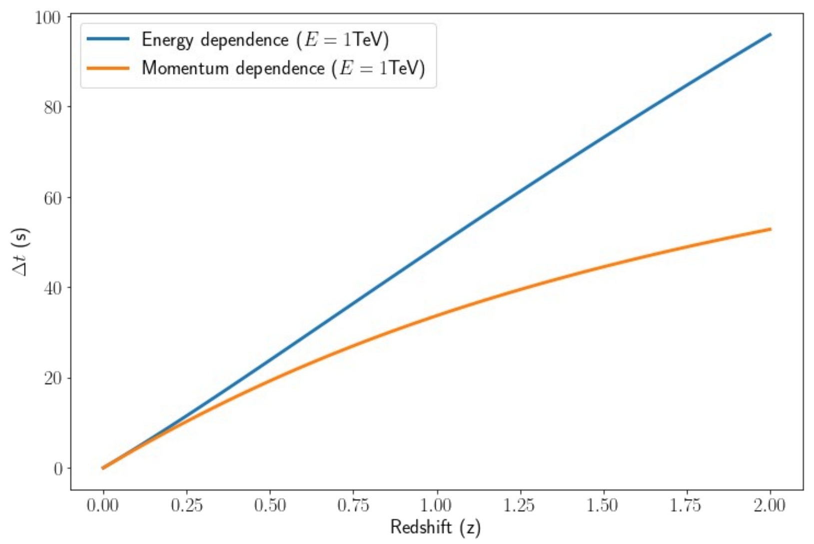
Mix momentum/energy

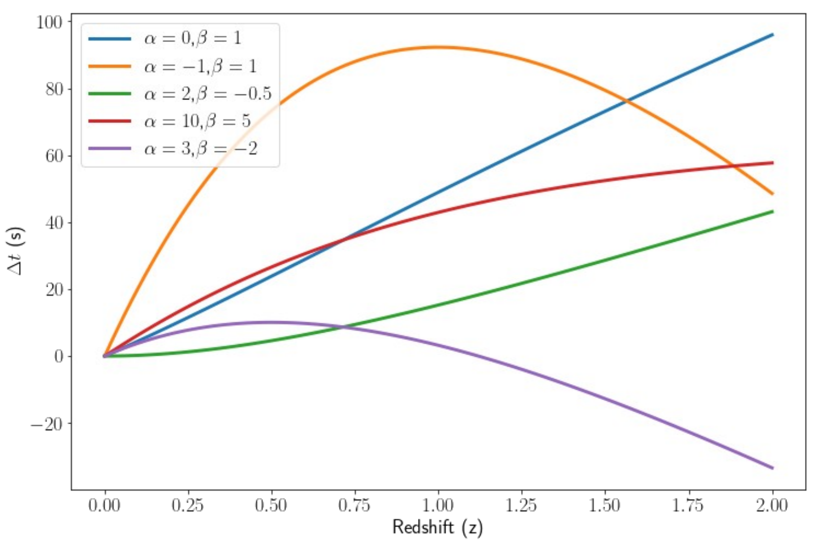
$$\Delta t(E_h, E_l, z) = \frac{n+1}{2}\frac{E_h^n - E_l^n}{E_{QG}^n}\int_0^z \frac{\alpha + \beta(1+z)^n}{H(z')}dz'$$



LIV redshift dependence conclusion ?

- In simple scenarios (pure energy or momentum), redshift dependence is growing monotonously
- Not true anymore if you mix energy and momentum in dispersion
- But two important (and usefull) features appears whatever scenario we are using :
  - This is a propagation effect, lag is 0 at z=0
  - Whatever the model, the function is continuous



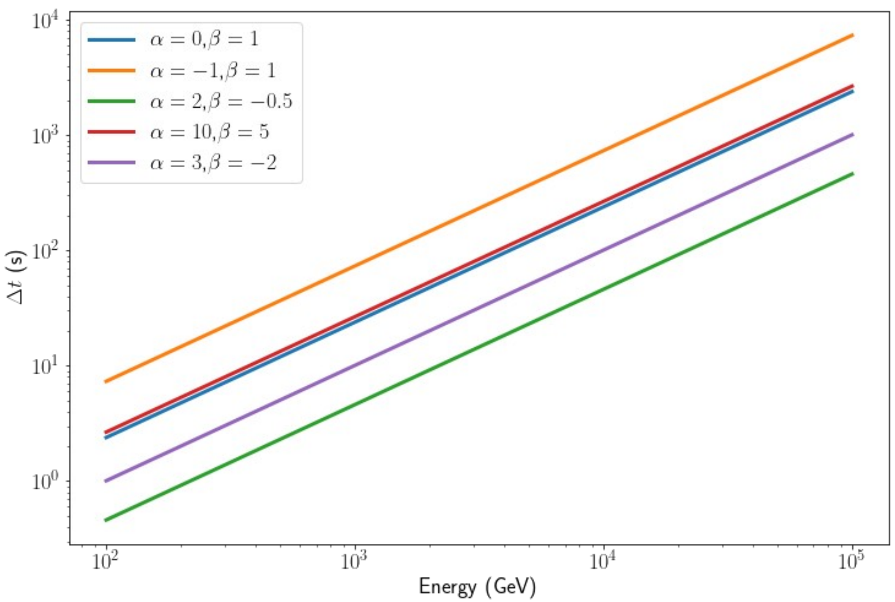


LIV energy dependence

$$E^2 = \frac{p^2c^2}{a^2(t)}\left(1 + h_{QG}(E, p, E_{QG})\right)$$

$$E^2 = \frac{p^2c^2}{a^2(t)}\left(1 + \alpha \sum_1^n \left(\frac{E}{E_{QG,n}}\right)^n + \beta \sum_1^n \left(\frac{pc}{E_{QG,n}}\right)^n\right)$$

- Choosing an order n is only a simplification, the true shape is unknown
- Growing (in absolute) with Energy if we suppose on term n dominates
- If not, it can be whatever… but still for E < E_qg we expect nothing



Simplification ?

- Can we make some simplifications on what can be intrinsic delays ?
- Let’s explore various scenarios (those scenarios would need to be more physically motivated than what I am doing here) :

Same for all sources

$$\Delta t_{int}(E,z) = (1+z)(\boxed{\Delta t_{mean}} + \boxed{\Delta t_{stoch}})$$

Stochastic for each source (each flare?)

3 scenarios :

$$\Delta t_{mean}(E) >> \Delta t_{stoch}(E)$$

$$\Delta t_{mean}(E) << \Delta t_{stoch}(E)$$

$$\Delta t_{mean}(E) \sim \Delta t_{stoch}(E)$$

Scenario 1

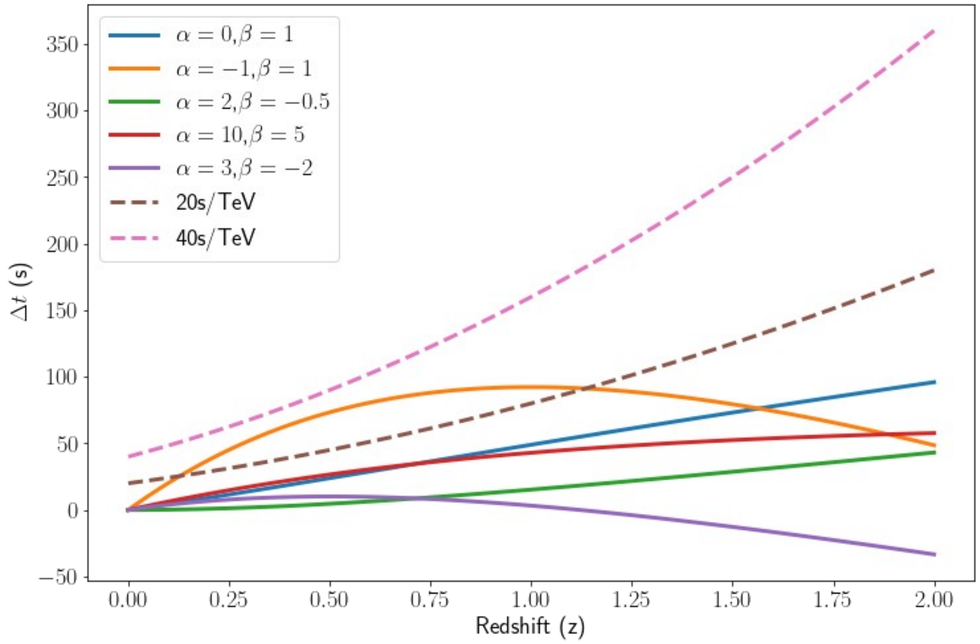
$$\Delta t_{mean}(E) >> \Delta t_{stoch}(E)$$

- Most simple scenario (but likely wrong right ?)

LIV
$$\frac{dP}{dtdE}(t+\boxed{\lambda_n \kappa_n(z) E^n}, E) = \phi_E(E)\phi_t(t+\boxed{\lambda_n \kappa_n(z) E^n})$$

Intrinsic (linear)
$$\frac{dP}{dtdE}(t+\boxed{\lambda(1+z)^2 E}, E) = \phi_E(E)\phi_t(t+\boxed{\lambda(1+z)^2 E})$$

- Low redshift are particularly usefull for distinction between intrinsic and LIV
- Absence of delay → we can already derive a limit on Lambda_s
- Detection of delays for source population :
  - LIV versus intrinsic can be tested and compared (Likelihood ratio)
  - In those two models, Lambda can be computed
  - The most constraining sources will probably be low redshift



Scenario 2

$$\Delta t_{mean}(E) << \Delta t_{stoch}(E)$$

- In this scenario, we expect lag to be fully stochastic (between sources, and even more between flares)
- Two major way to distinguish this scenario from LIV :
  - Continuity : delay at redshift z is fully uncorrelated of delay at z+dz, we simply expect a random distribution
  - Still possible to have very similar shape for complex LIV scenario (with momentum + energy mixed in complicated way), but simple simple scenario would be excluded
  - Significant variability between flares or events at a similar redshift are a smocking gun (between scenario 1 and 2, and with LIV as well)
- Can be constrained per source and combined as a mean stochasticity (or limits on mean stochasticity)
- Can as well derive standard deviation of this stochasticity (or limits on it)

$$\frac{dP}{dtdE}(t+\lambda_i(1+z)^2E,E) = \phi_E(E)\phi_t(t+\lambda_i(1+z)^2E)$$

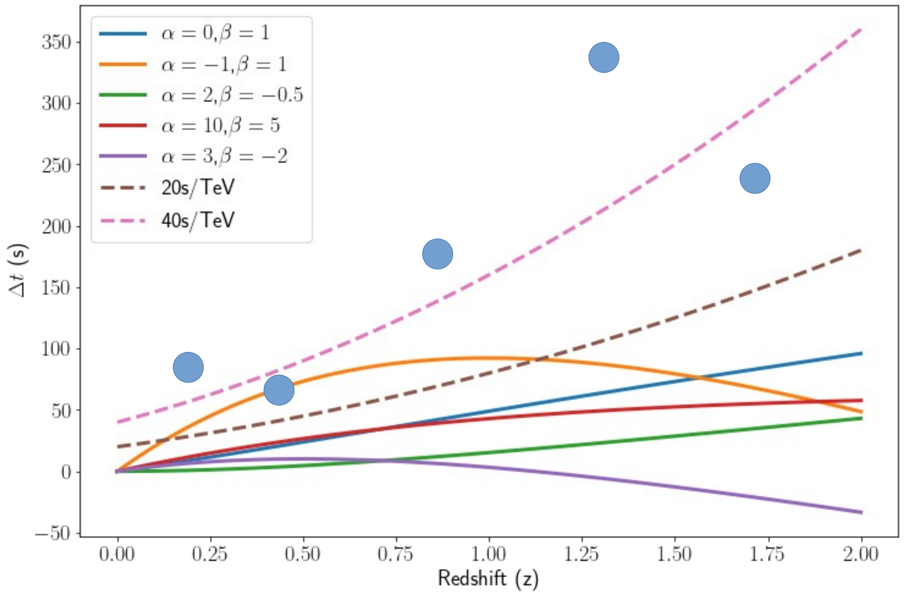
Per source Lambda_i

Scenario 3

$$\Delta t_{mean}(E) \sim \Delta t_{stoch}(E)$$

- General trend + fluctuation around this trend
- Same than before but mixed
- We should still be able to distinguish between the two type of delay (particularly if stochastic lag is strong)
- It would probably need an iterative process to avoid degeneracy (first only mean lag, than adding lag per source for outliers only)

$$\frac{dP}{dtdE}(t + (\lambda_i + \lambda_{mean})(1+z)^2 E, E) = \phi_E(E)\phi_t(t + (\lambda_i + \lambda_{mean})(1+z)^2 E)$$



The full model (to be handled with care)

LIV

Mean delay

$$\frac{dP}{dtdE}(t+\boxed{\lambda_n\kappa_n(z)E^n}+(\boxed{\lambda_i}+\boxed{\lambda_{mean}})(1+z)^2E, E) = \phi_E(E)\phi_t(t+\lambda_n\kappa_n(z)E^n+(\lambda_i+\lambda_{mean})(1+z)^2E)$$

Stochastic
delay

- This model can be implemented in LIVelihood without lot of efforts
- Already many data to constrain the different terms
- Model is probably degenerated but not completely
  - LIV effect for close sources is 0 (kappa(0) = 0 while (1+z=0)^2 = 1)
  - Stochastic delay very degenerated with mean delay :
    - Can be handled with an iterative procedure...
    - … or by input from theory (energy dependence different ? Expected value?)

- Some inputs from theory would be needed
  - Does this model make sense ?
  - Can we simplify it (scenario 1 or 2 ?)
  - Can we have an estimation of lambda_i and lambda_mean ?
  - Variability versus energy of lambda_i and lambda_mean ?

- But it can as well feed the theory :
  - We can already put a limit on lambda_mean based on absence of time dependent delay
  - Can it be used to constrain the models ? (Pulsar, AGN, GRBs ?)

Conclusions

- I believe that a simple model, handling multiple sources can be implemented and tested on data (currently available and future data)
- This model can be more robust by having theoretical input…
- … and can give back to theory constraints
- Current status is that no lag is observed at TeV

Redshift variability of the limit

- Redshift variability of the limit is ruled by three processes :
  - **Distance** (reduce events by D_L^2)
  - **EBL absorption** (high energy events absorbed)
  - **Delay increase with redshift**

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