Physics from Multi-Messenger Time Delays

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Workshop on Testing Gravity

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Overview

- Motivations - the basic idea
- Computing multi-messenger time delays
- A plethora of caveats
- Future work

Based on very recent work:

Multi-Messenger Time Delays from Lensed Gravitational Waves

Tessa Baker and MT

arXiv:1612.02004

Lots of (boring) calculations

Motivations

Until fairly recently, astronomy and cosmology consisted of observing electromagnetic waves from many parts of the spectrum

More recently, a number of new ways of observing the universe have become available, opening up messenger particles from:

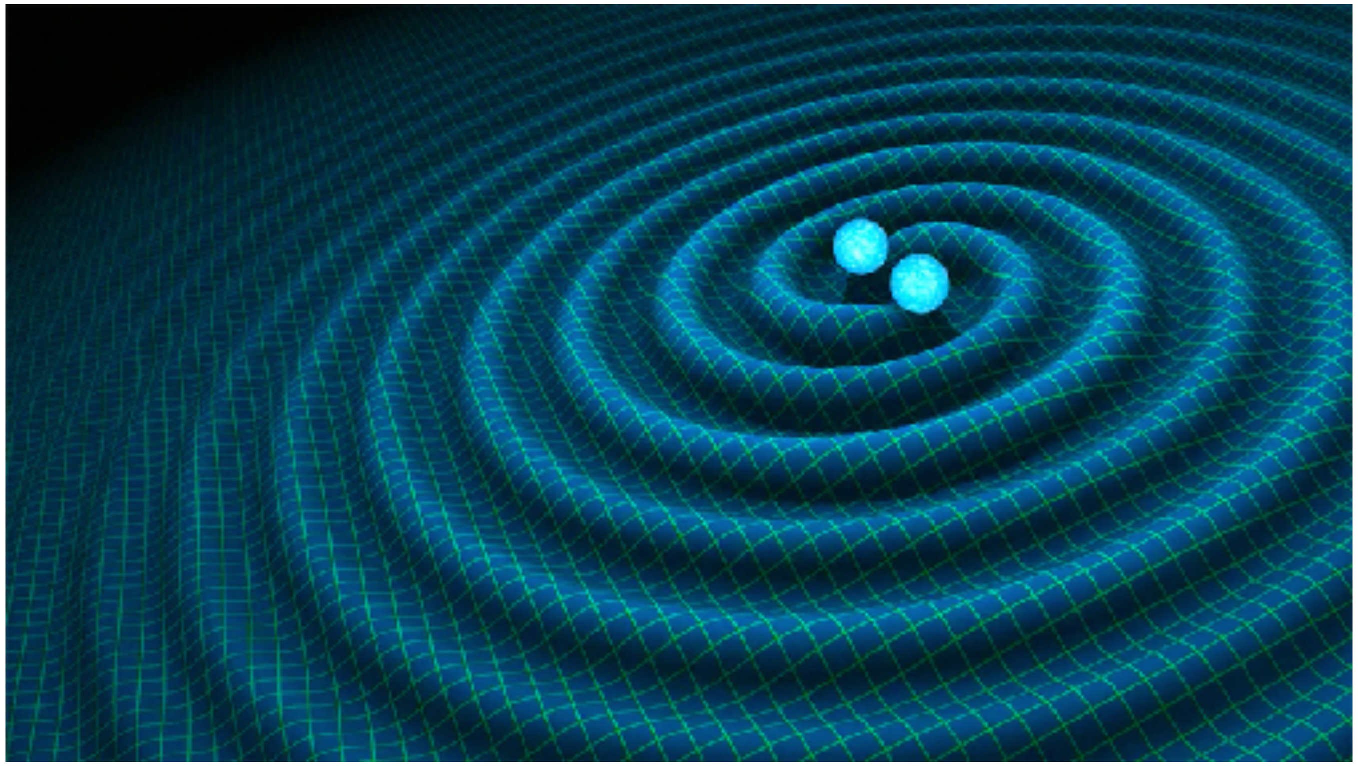
- Other parts of the Standard Model - neutrinos
- The gravitational sector of physics - gravitational waves

And even inspire us to imagine that we might some day directly measure messengers from currently hidden sectors of physics:

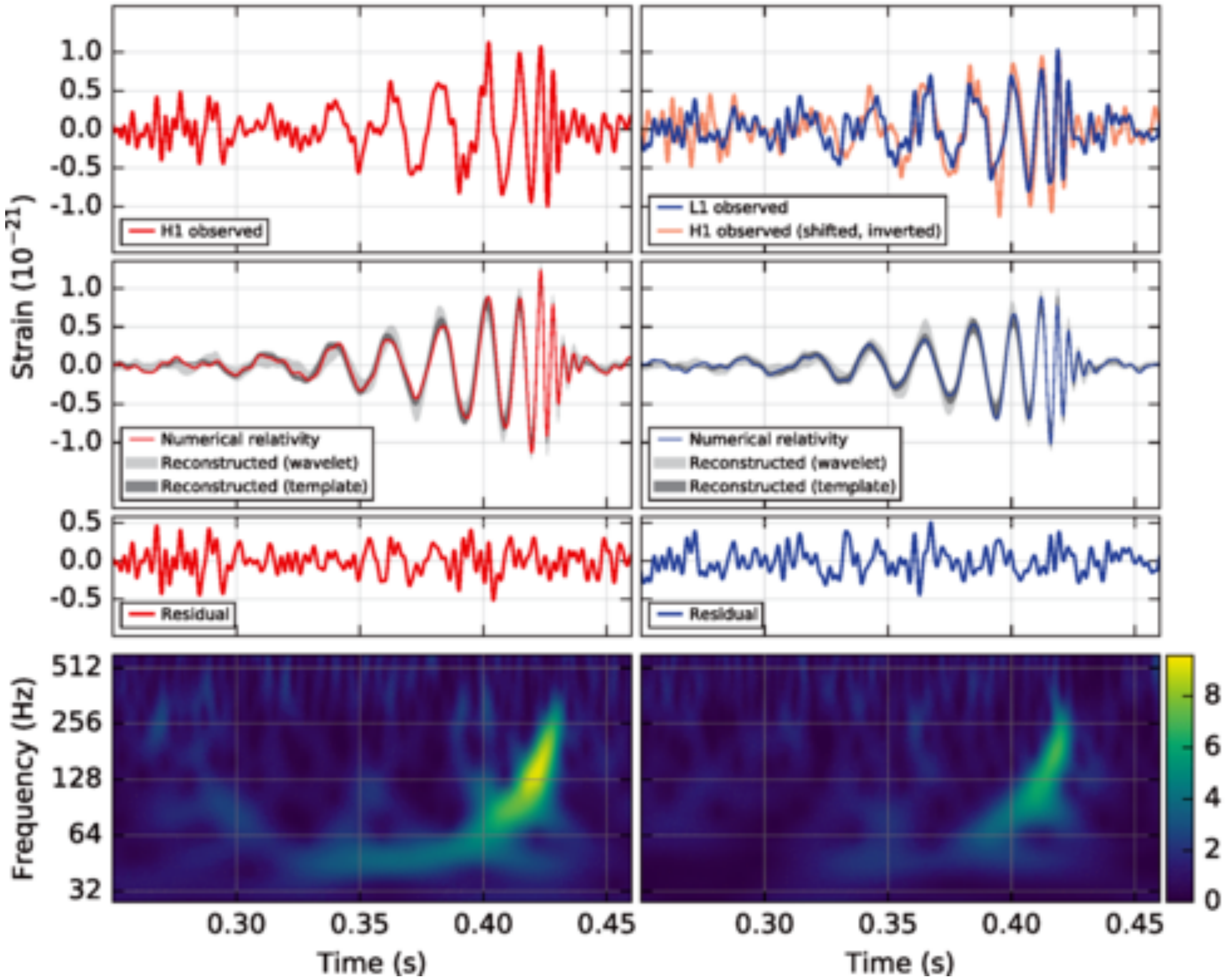
- Axions
- Other massless or light neutral particles

Gravitational Wave Astronomy

Indeed, gravitational wave astronomy is less than one-year old



$$g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu}$$



Black-hole coalescences are not the only expected sources of these waves.

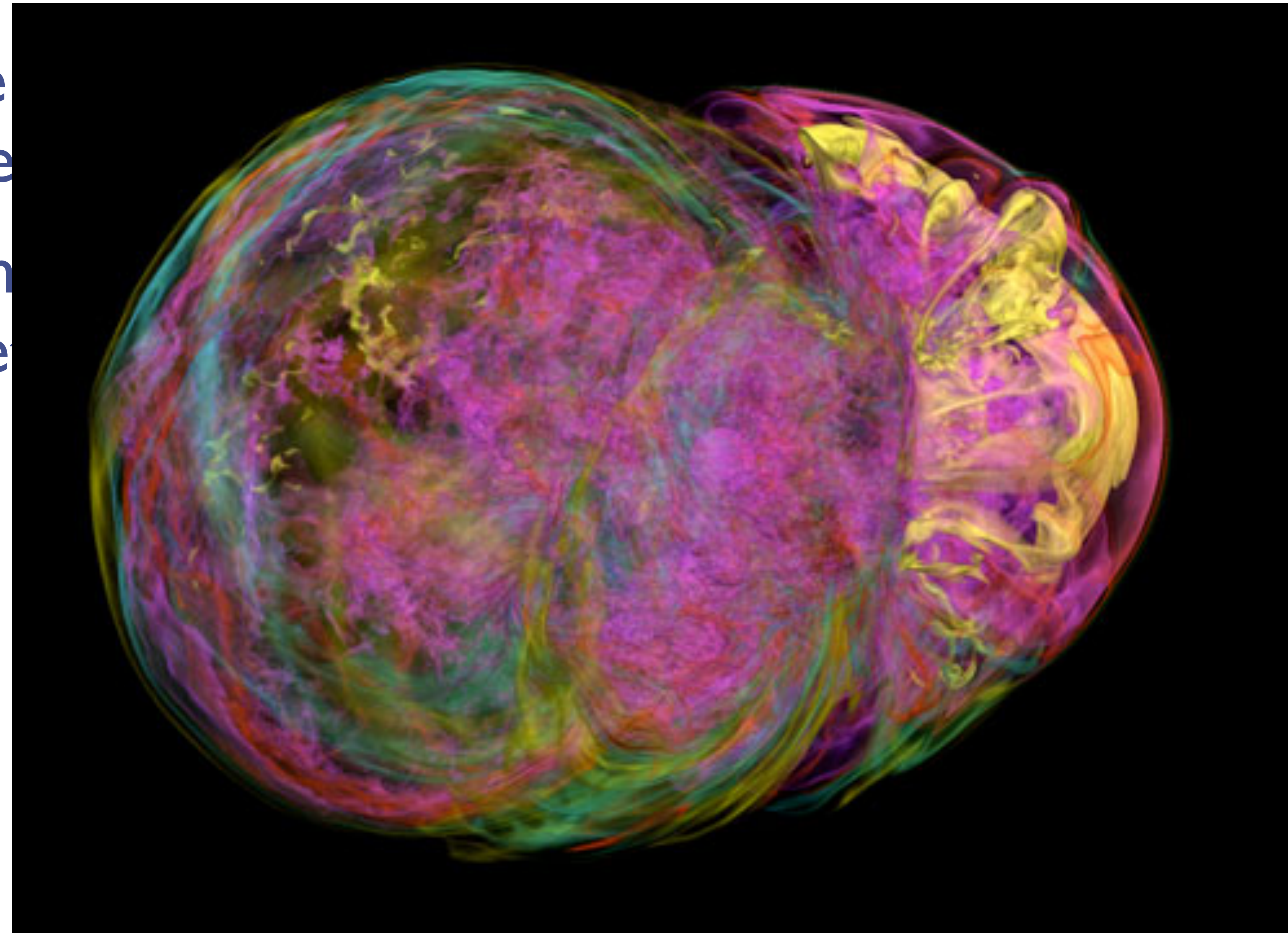
Other events may provide multiple signatures

Have been detecting neutrinos for decades

Motivations

For example:

- Core-collapse supe
- NS-NS coalescence



Depending on the even
(symmetric or asymme
one of more of:

- Photons
- Neutrinos
- Gravitational waves

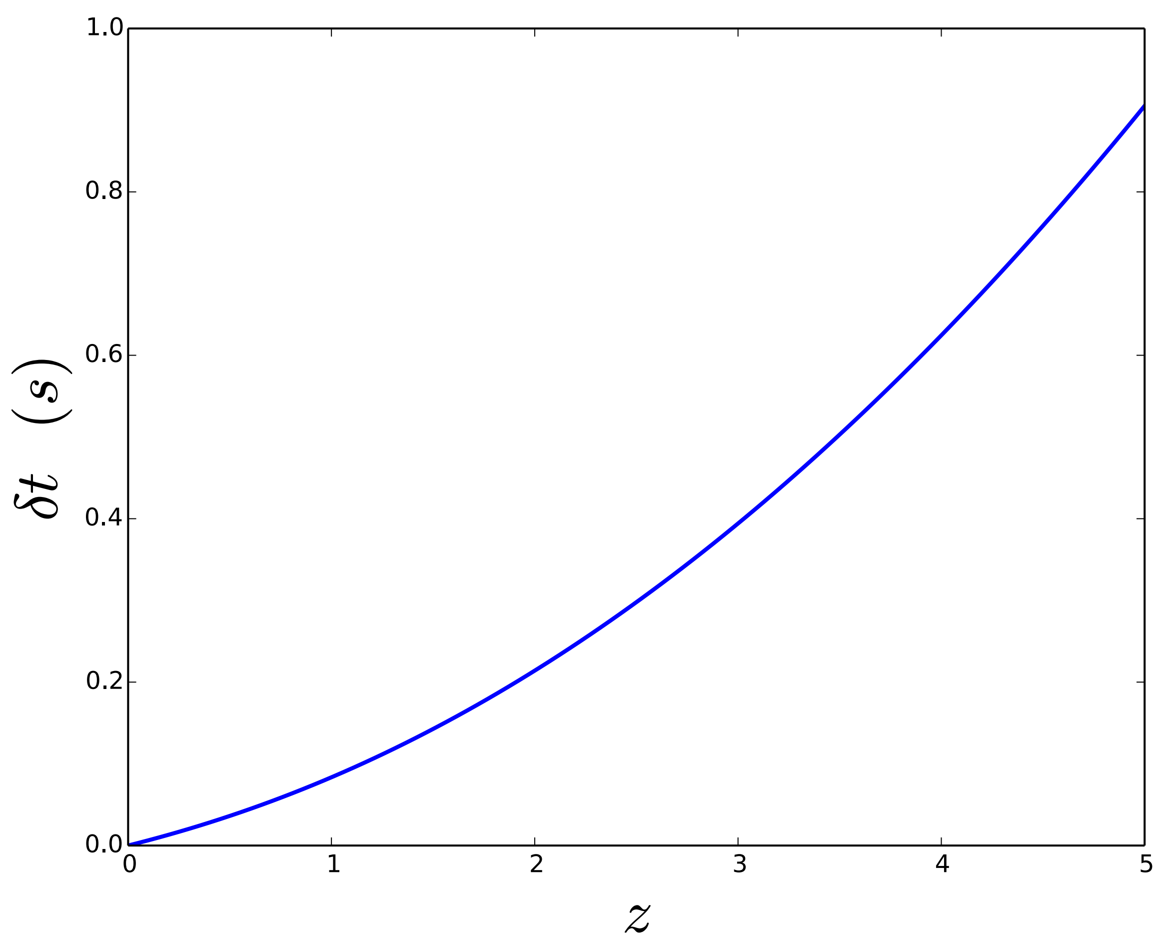
The story of how each of these carriers find their way to our detectors can differ in either how they are produced and get out of the event (hard), and/or how they propagate to us (easier?).

An Opportunity

Comparing, in particular, the propagation of massless and massive carriers, may provide insights into

- Cosmology - basic cosmological parameter, such as H_0
- Fundamental physics - (absolute) neutrino masses, etc.

Simplest question to ask: Since for massive particles v<c, what is the time delay between otherwise identically emitted particles?



$$\delta t = t_\nu - t_{\rm GW}$$

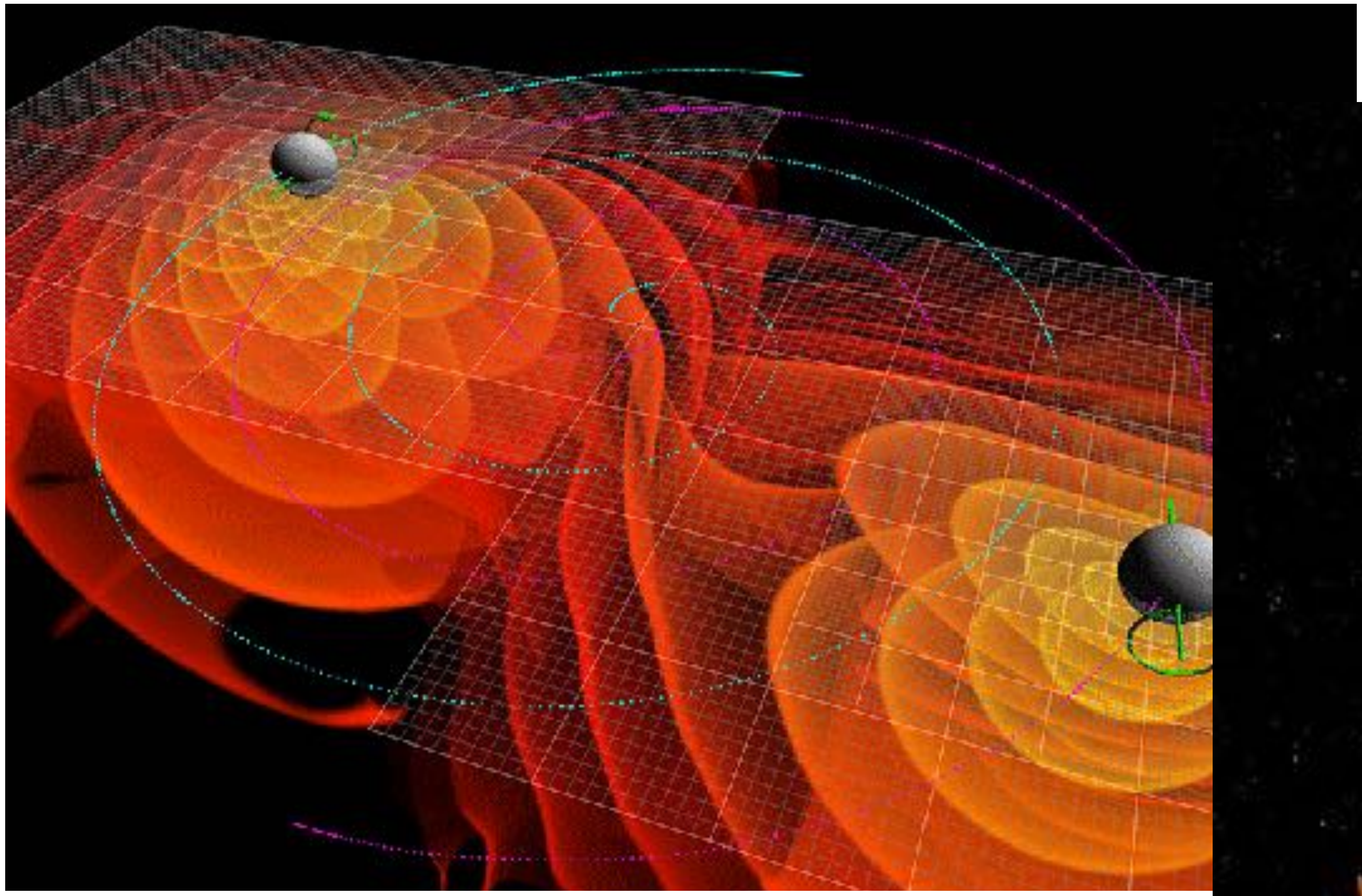
Propagation in flat space gives a delay of order seconds between photon and massive particle with

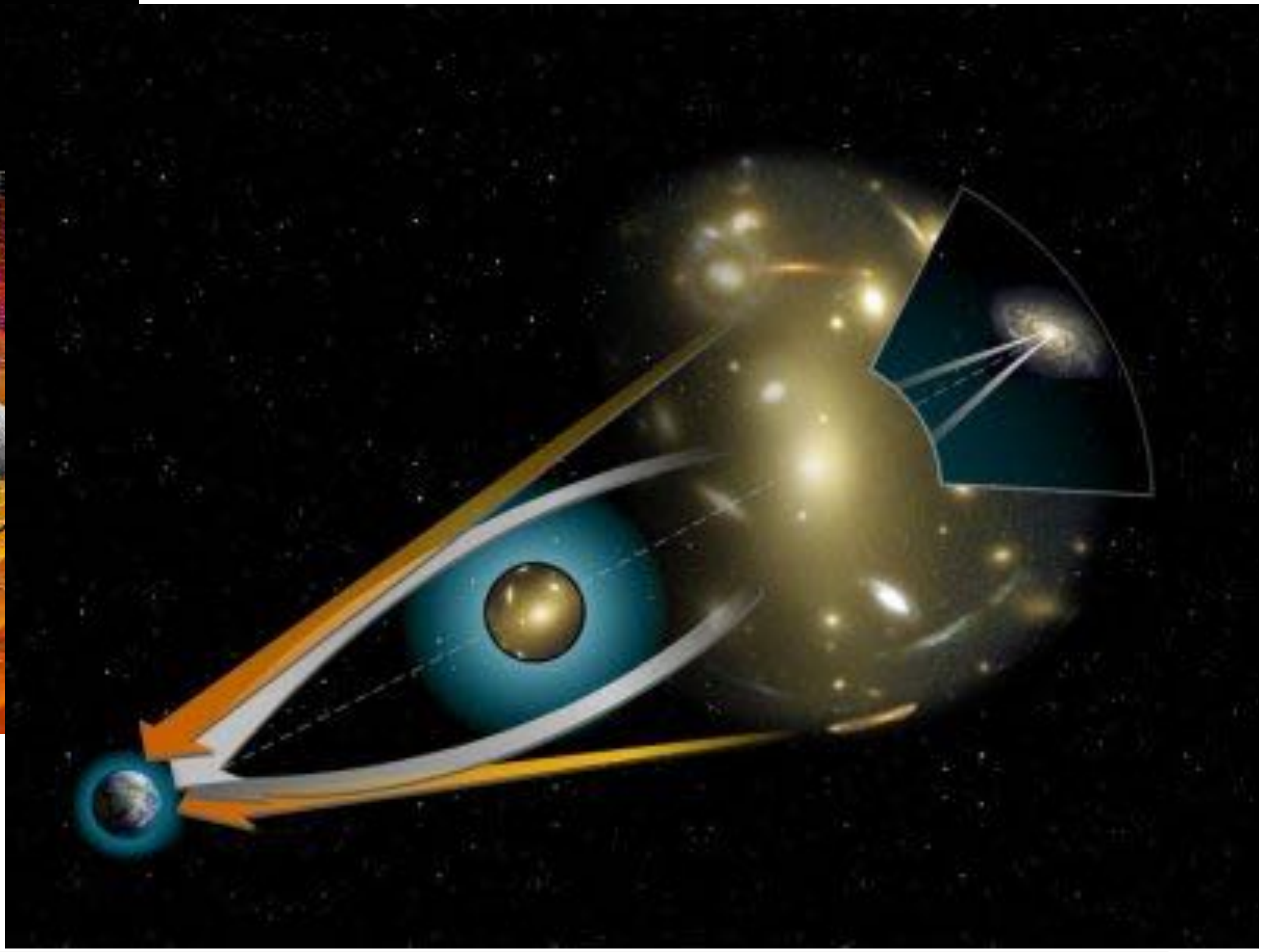
$$m = 0.3 \text{ eV} \qquad E_0 = 10 \text{ MeV}$$

A Better Question

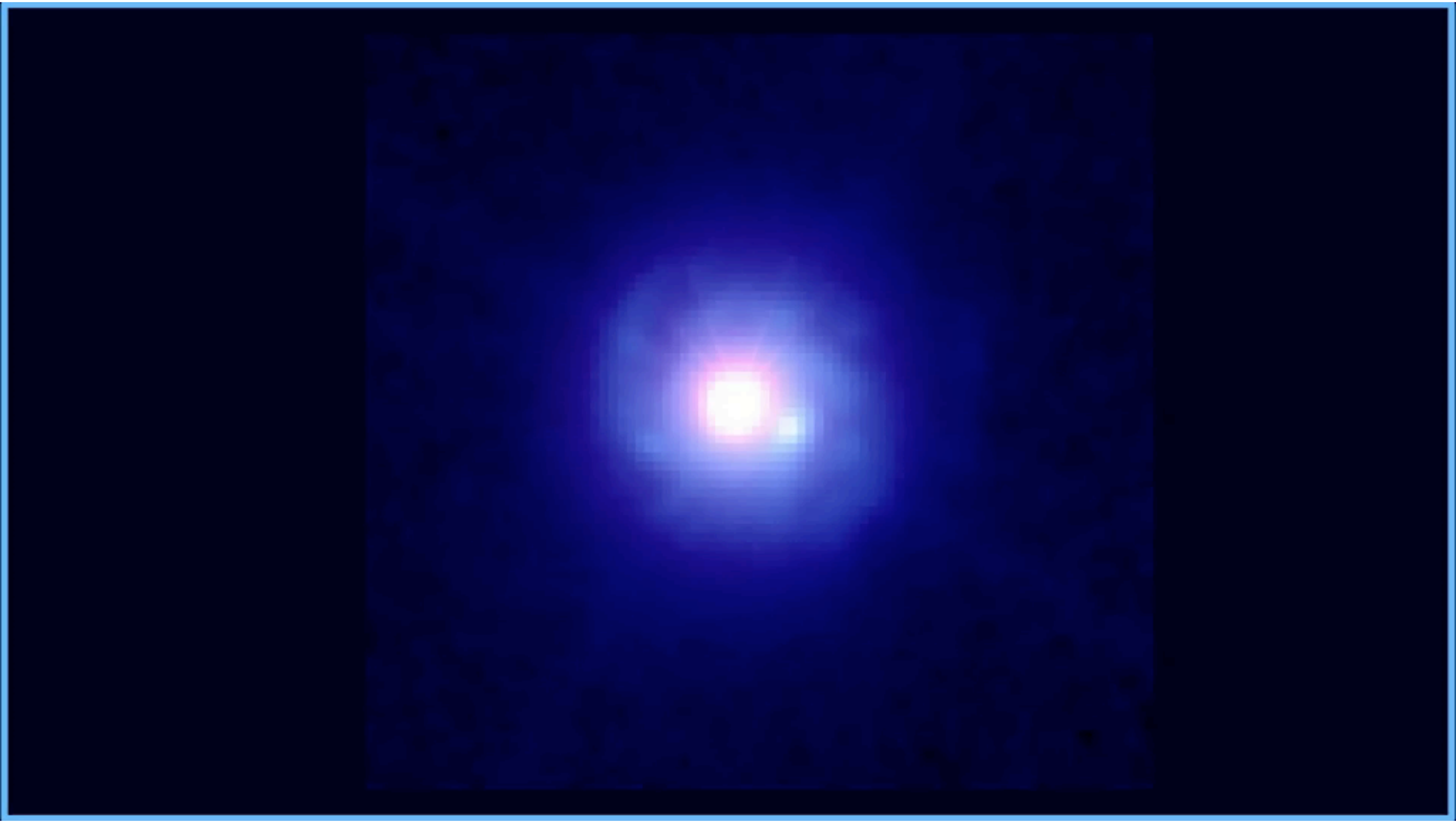
Astrophysical complexities likely to dominate fundamental physics. Neutrinos from1987A arrived four hours earlier than photons.

What about measuring the time delay between different signals if they are lensed by an intervening distribution?





Different Paths give Different Times



Lensing Multiple Messengers

So, idea is to lens both massless (e.g. gravitational waves) and massive (e.g. neutrinos) messengers and look at time differences.

Four times are relevant:

- t_1 - First observed time of GW event
- t_2 - First observed time of neutrino event (peak flux, say)
- t_3 - Observed time of GW echo
- t_3 - Observed time of neutrino echo

As we've seen

$$t_2 - t_1 \sim \ \text{seconds} \quad \text{and} \quad t_4 - t_3 \sim \ \text{seconds}$$

And it is possible for

$$t_3 - t_2 \sim \ \text{months} - \text{years}$$

Advantages

Time between initial signals, and time between the echoes depend sensitively on two broad classes of effects:

- The time delay between the massive and massless signals, following almost, but <u>not precisely</u>, the same path
- The intrinsic delay between the signals due to effects at the source.

However, the following quantity doesn't depend on intrinsic effects

$$\mathcal{T} = (t_4 - t_3) - (t_2 - t_2)$$

$$= \eta_{\rm massive}(\theta_2) - \eta_{\rm massive}(\theta_1)$$

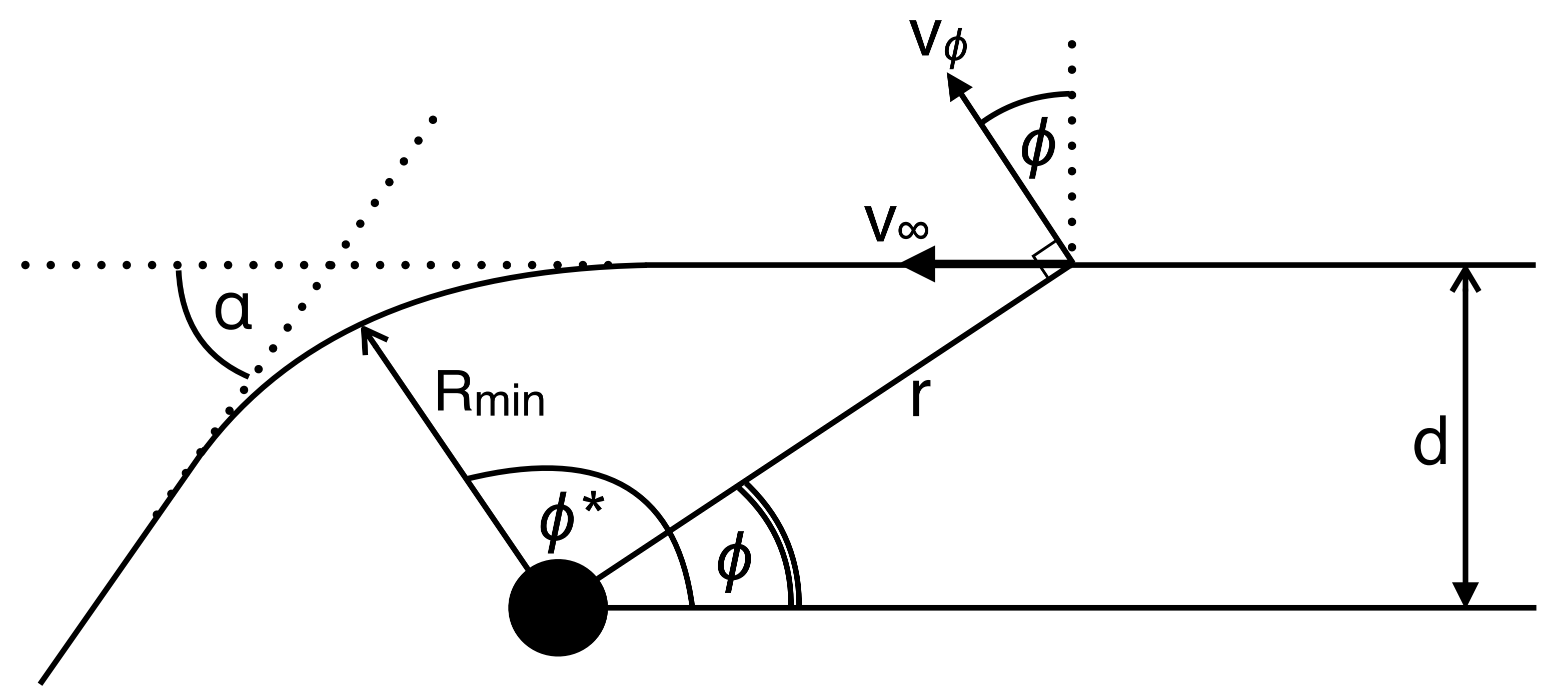
Differential Massive Time Delay

We'll be studying how this is calculated and what quantities it depends on. As we'll see: a tiny effect, but if measured, can be very useful.

Deflection Angle Calculation

We've all performed the classic "bending of light" calculation around an idealized point mass, yielding a deflection angle

$$\alpha = \frac{4GM}{dc^2}$$



For a massive particle this is a little more involved, but in the relativistic limit, one can show:

$$\alpha = \frac{4GM}{dc^2}\left[1 + \frac{1}{2}\left(\frac{c^2}{v^2} - 1\right)\right] + \mathcal{O}\left(\frac{r_S^2}{R_{\rm min}^2}\right)$$

Mass Distributions

Analogous derivation for extended lensing mass (need not be entirely interior to particle trajectory) follows by integration over distribution of point masses. The resulting deflection angle is:

$$\vec{\alpha}(\vec{\theta}) = \frac{1}{\pi}\int d^2\theta' \; \kappa(\vec{\theta}') \left[1 + \frac{1}{2}\left(\frac{c^2}{v^2} - 1\right)\right] \left(\frac{\vec{\theta} - \vec{\theta}'}{|\vec{\theta} - \vec{\theta}'|^2}\right)$$

with $\kappa(\theta) = \dfrac{\Sigma(\theta)}{\Sigma_{\rm cr}}$ dimensionless surface mass density

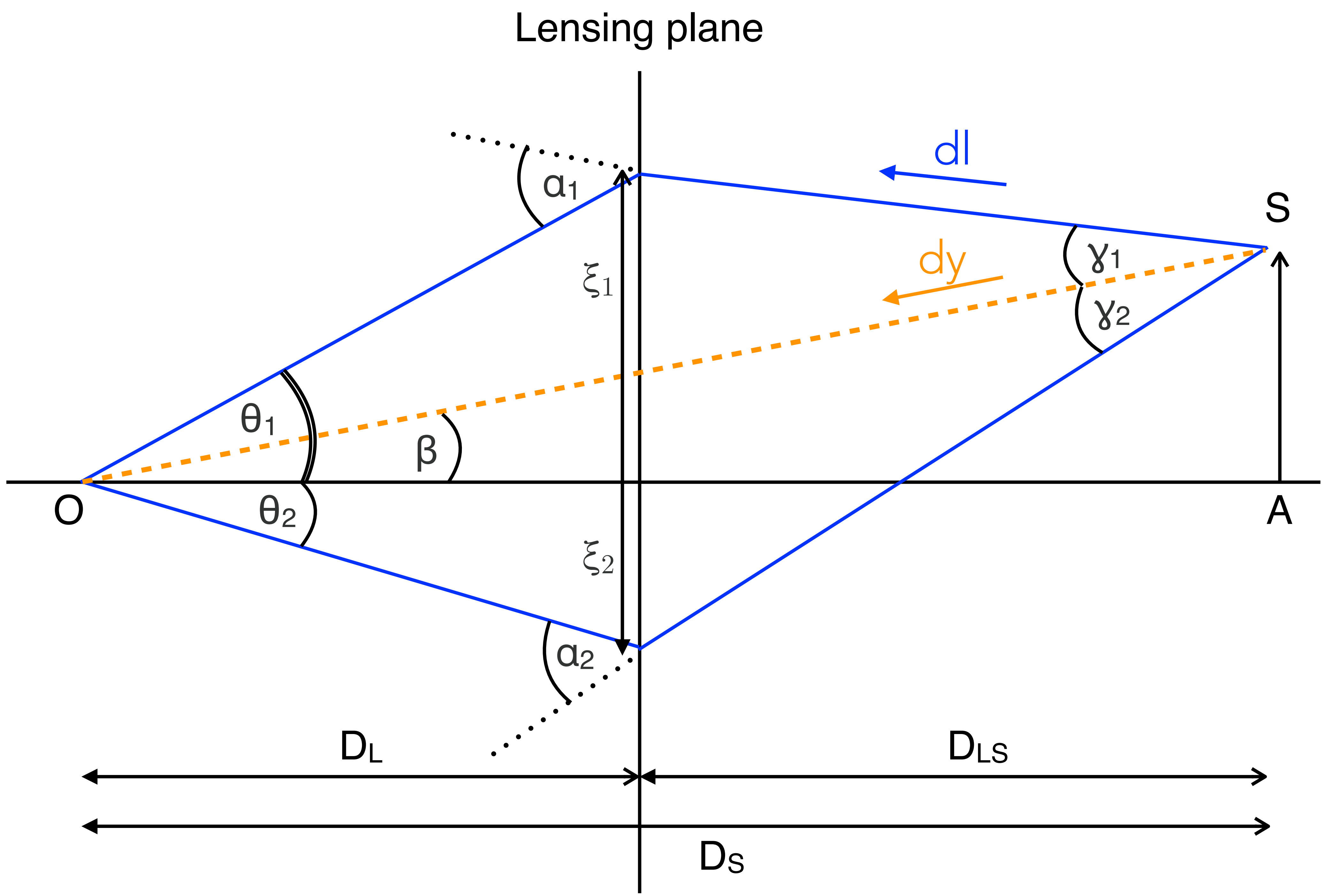
$\Sigma(\vec{\xi}) = \displaystyle\int dr_3 \, \rho(\vec{r})$ projected surface mass density

$\vec{r} = \left\{\vec{\xi}, r_3\right\}$ 3D position vector centered on lens

2D position vector in lensing plane

An Idealized Setup

We'll set c=1 unless explicitly needed, and work in the thin-lens approximation:



(Comment: To first order path is same for massless and massive particles)

Calculation

Total conformal time for a massive relativistic particle has structure

$$\eta_{\text{total}}(\theta) = \eta_{\text{undeflected}} + \eta_{\text{massless}}(\theta) + \underline{\eta(\theta)_{\text{massive}}}$$

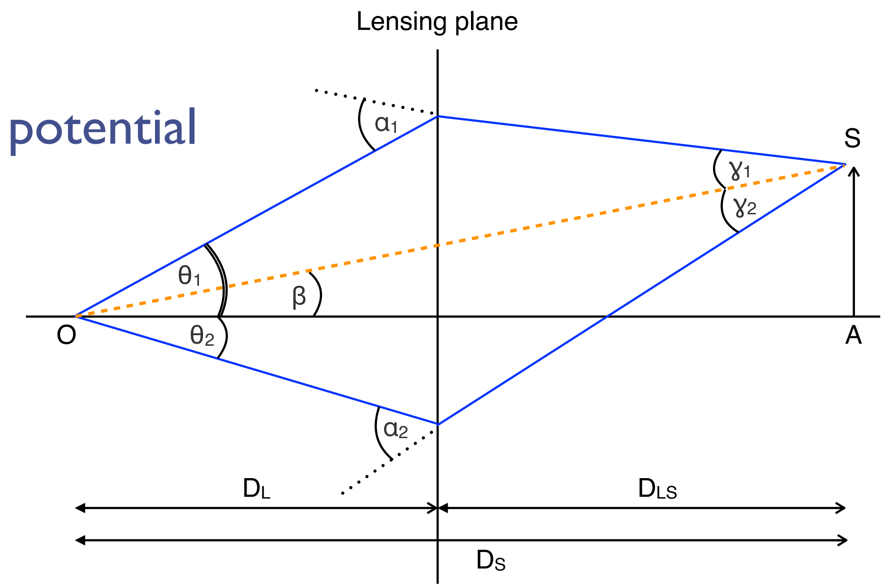
Only for massive particles

with

$$\eta_{\text{undeflected}} = \int_0^{D_s} dy$$

2d projected potential

$$\eta_{\text{massless}}(\theta) = \frac{D_L D_S}{c\, D_{LS}} \left[\underbrace{\frac{1}{2}(\theta \pm \beta)^2}_{\text{Geometric}} - \underbrace{\psi(\theta)}_{\text{Shapiro effect}} \right]$$



$$\boxed{\eta_{\text{massive}}(\theta) = \frac{1}{2}\left(\frac{mc}{p_0}\right)^2 \left\{ \frac{1}{2}(\theta \pm \beta)^2 \left[\int_1^{a_L} \frac{da}{H(a)} + \frac{D_L^2}{D_{LS}^2} \int_{a_L}^{a_S} \frac{da}{H(a)} \right] - a_L^2 \frac{D_L D_S}{c\, D_{LS}} \psi(\theta) \right\}}$$

Geometric

Shapiro effect

Parameters in our Results

We have most certainly not attempted to do a professional job of modeling the lensing halo. Because of time, I'll show only the power-law lens model

$$\rho(r) = \rho_* \left(\frac{r_*}{r}\right)^n$$

We choose parameters ρ_* and r_*
Note, n=2 is singular isothermal sphere

We also need to introduce an alignment parameter. Our images are at angular positions θ_1 and θ_2. We may trade these for the Einstein radius θ_E and the alignment parameter S. Defining

$$\theta_2 = \mathcal{S}\theta_E \qquad\qquad 0 < \mathcal{S} < 1$$

with the position of the other image, θ_1, then automatically fixed.

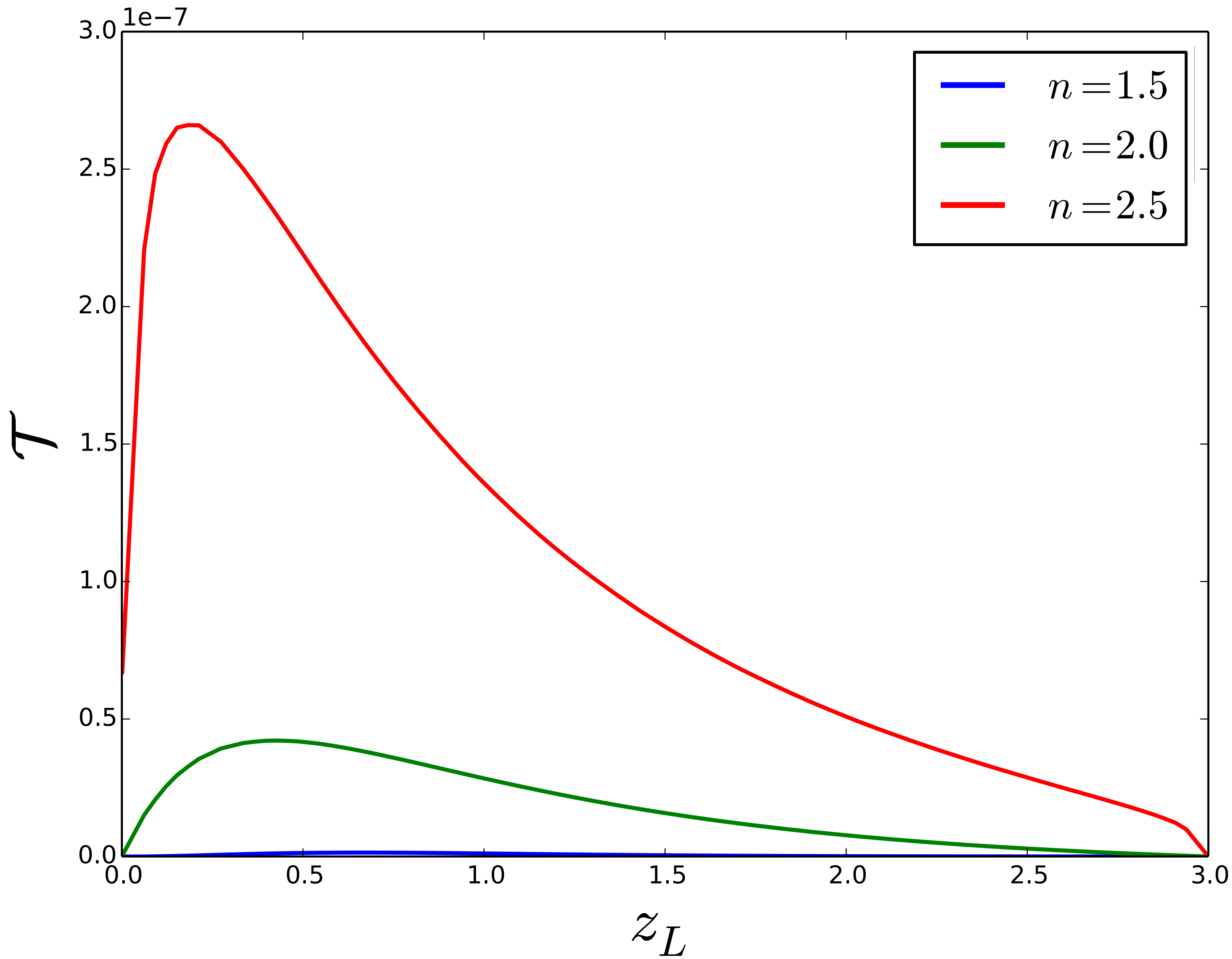
Results then depend on cosmological parameters, plus choices for

$$m_\nu,\ p_0,\ z_S,\ S,\ n$$

Results I

We choose: Planck Cosmology,

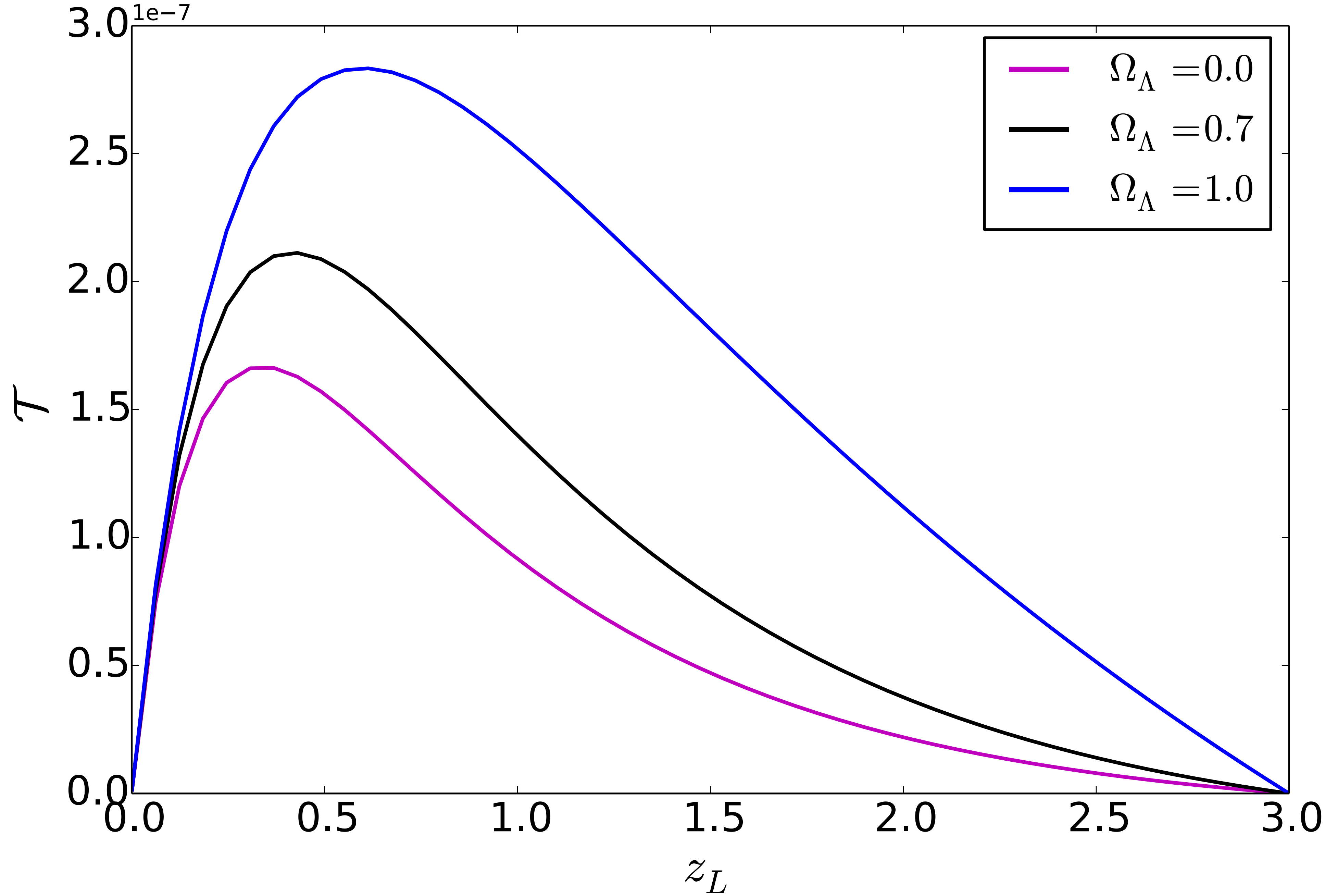
$$m_\nu = 0.3 \text{ eV}, \; p_0 = 10 \text{ MeV}, \; z_S = 3, \; S = 0.75$$



Results II

We choose: Planck Cosmology,

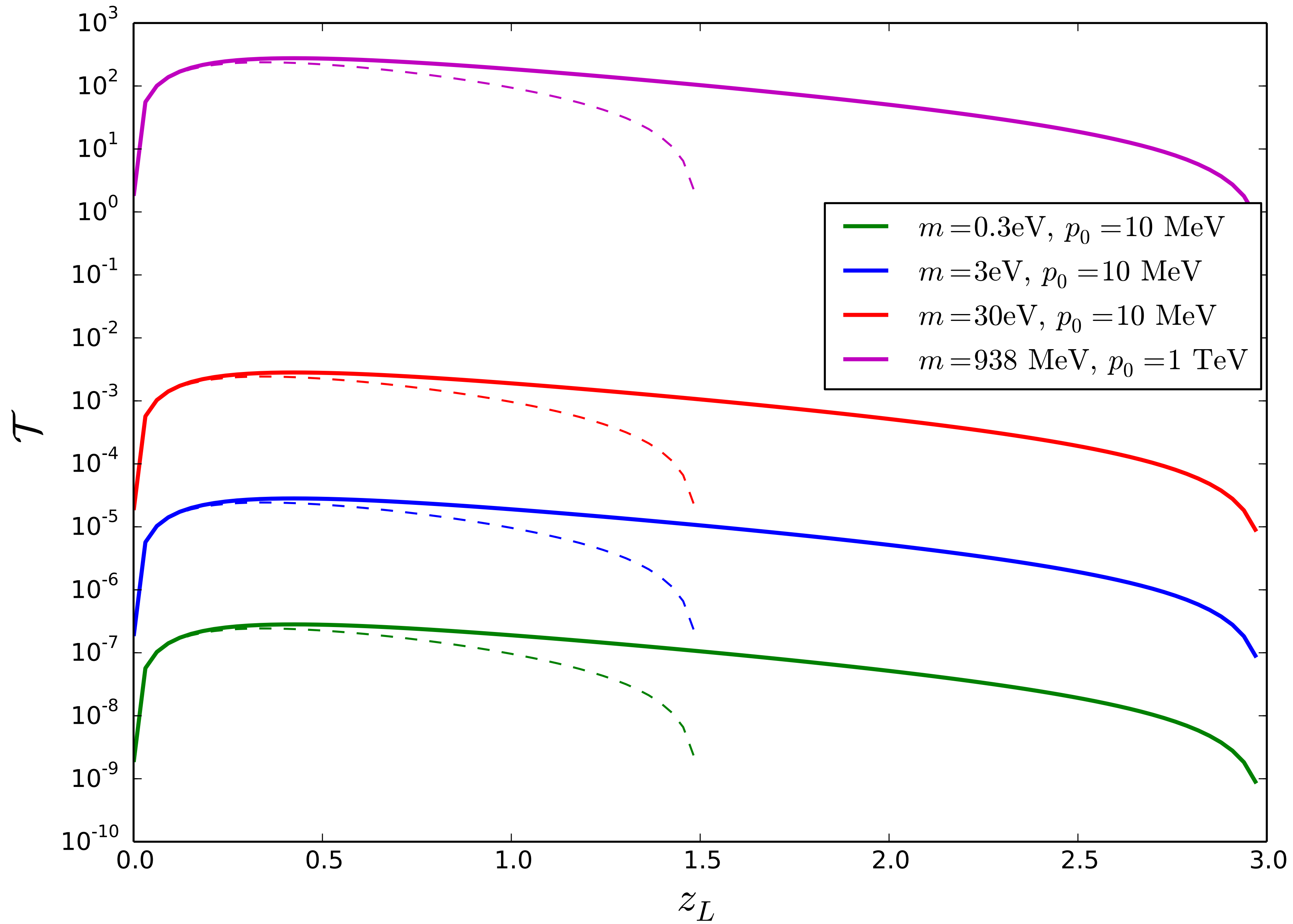
$$m_\nu = 0.3 \text{ eV}, \; p_0 = 10 \text{ MeV}, \; z_S = 3, \; n = 2(\text{SIS model})$$



Results III

We choose: Planck Cosmology,

$$n = 2 \text{ (SIS lens model)}, \; z_S = 3$$



A Subset of Caveats

Idealized analysis faces many practical obstacles. Getting requisite precision seems very hard! Some other considerations are:

- Establishing source redshifts
  - Might be lucky enough to have a source e-m counterpart
  - Often not - need to break merger mass-redshift degeneracy
  - Some suggestions how to do this from NS-NS waveforms

- Lens identification
  - Need optical ID, also infer lens mass distribution from shear
  - Use future surveys like LSST
  - Need to understand multiple lensing events

- Detectors and count rates
  - For neutrinos need array of detectors
  - IceCube, ANTARES, SuperKamiokande, KamLAND, SNO, …

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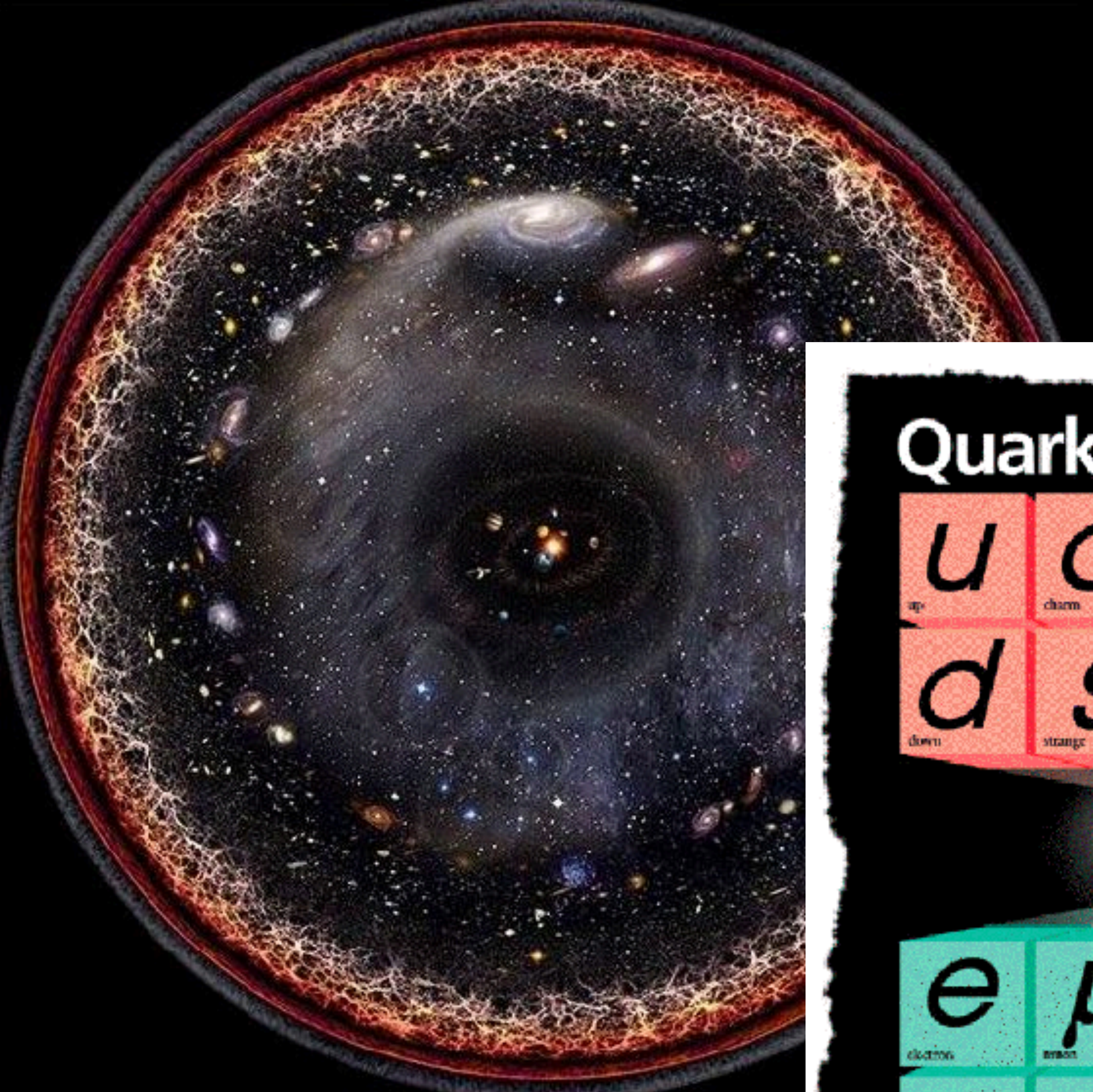

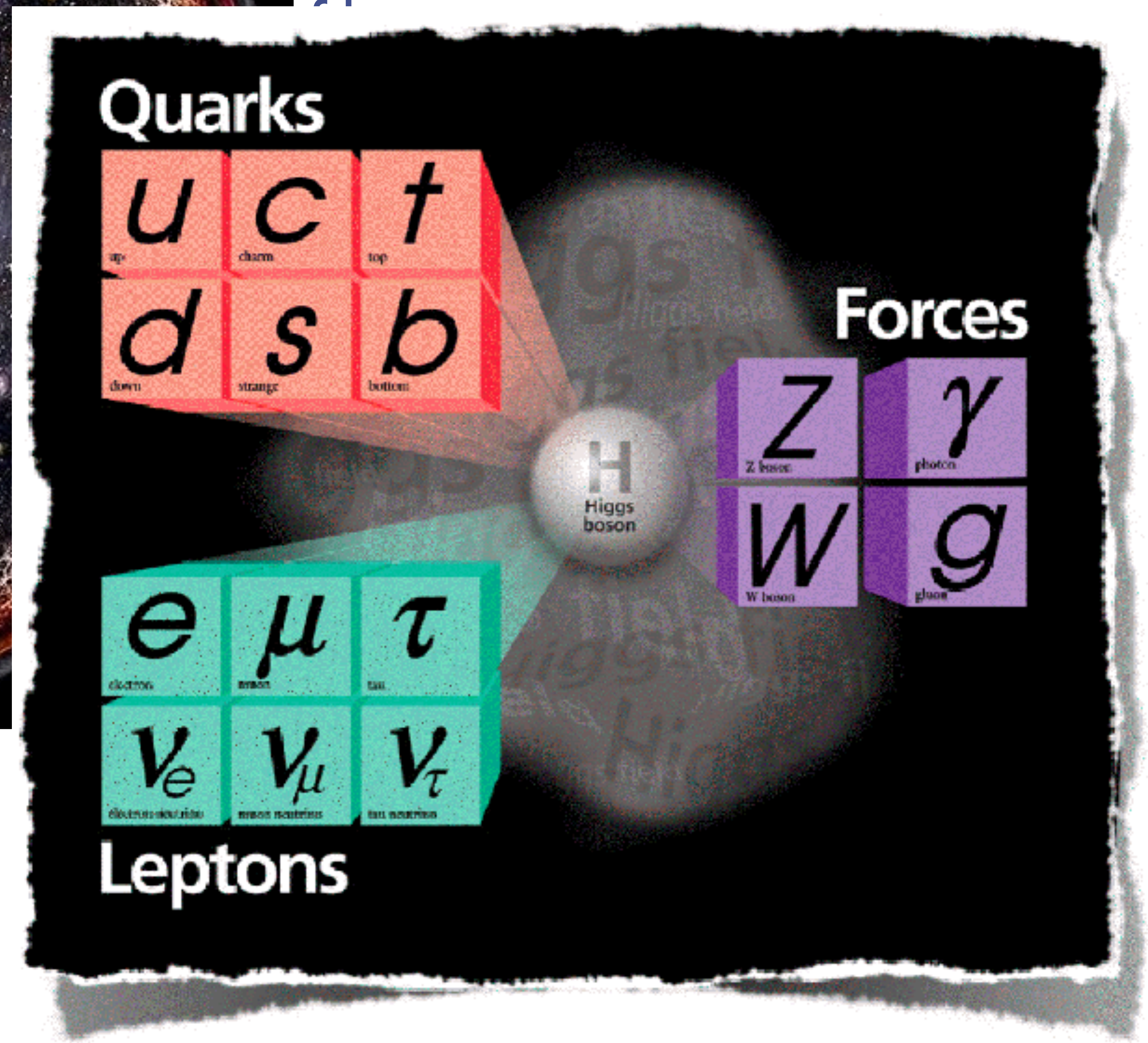

Thank You!