Probing Dark Energy and Geometry by GRBs

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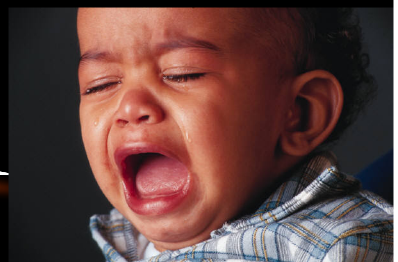
THESEUS Workshop, October 5-6, Napoli 2017

Strange Situation in today Physics

- **Astronomy:** Data without Theory!
- **Quantum Gravity**: Theory without Data!

What is in the middle?

Dark Matter & Dark Energy?



A plethora of theoretical answers!

(A tale of unconstrained fantasy)

DARK MATTER

- Neutrinos
- WIMPs
- Wimpzillas,
- Axions,
- The "particle forest".....
- MOND
- MACHOS
- Black Holes
- ......

DARK ENERGY

- Cosmological Constant
- Scalar field Quintessence
- Phantom fields
- String-Dilaton scalar field
- Braneworlds
- Unified theories
- ....

???

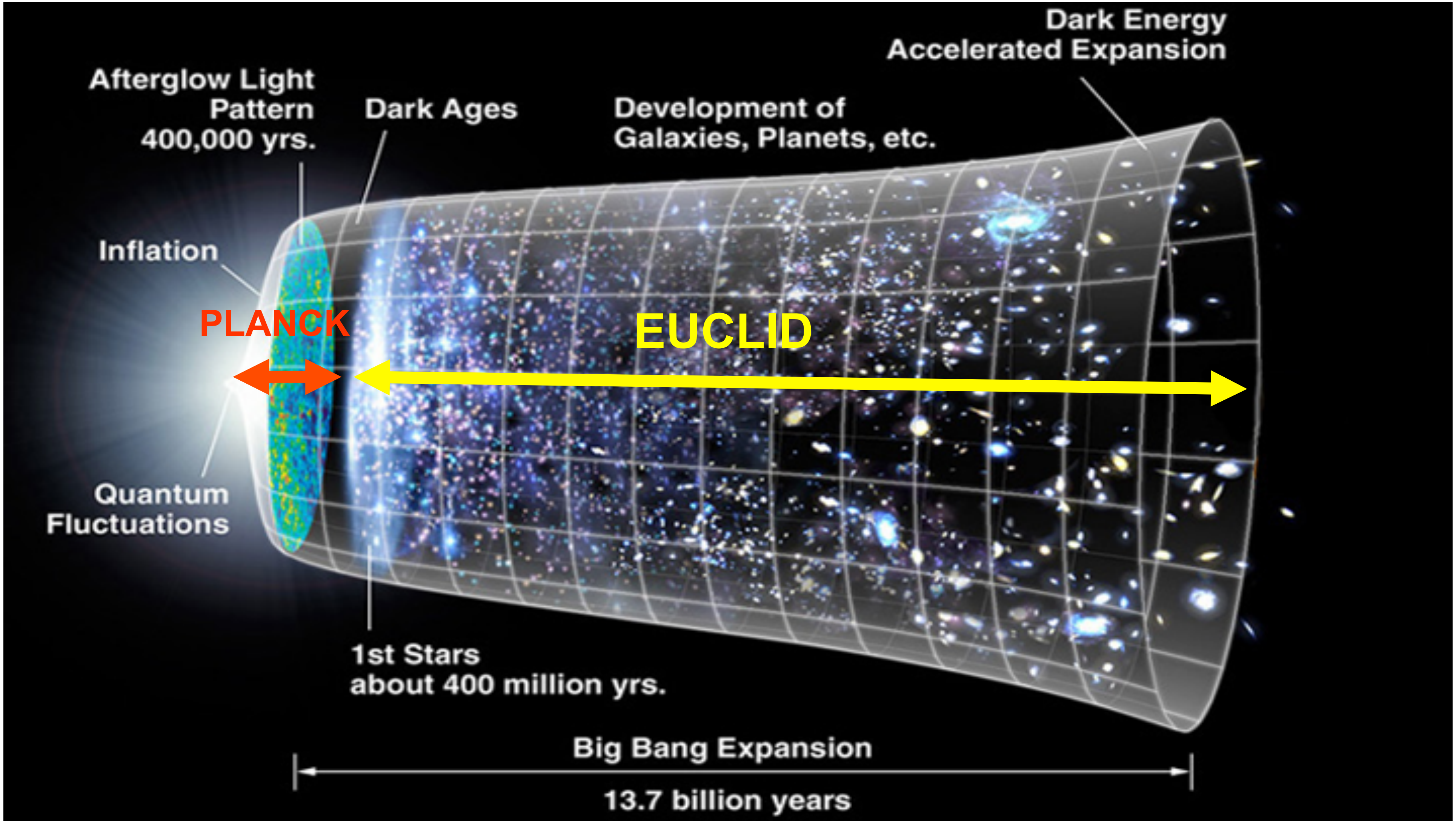
Buridan's Donkey

Several important questions in cosmology

- **How measuring the Universe?**
- **What is the geometry of the Universe?**
- **What is the topology of the Universe?**

Are there standard rulers, rods and clocks to probe these issues at early and late epochs ?

The traditional way to search for solutions is the *cosmic distance ladder*



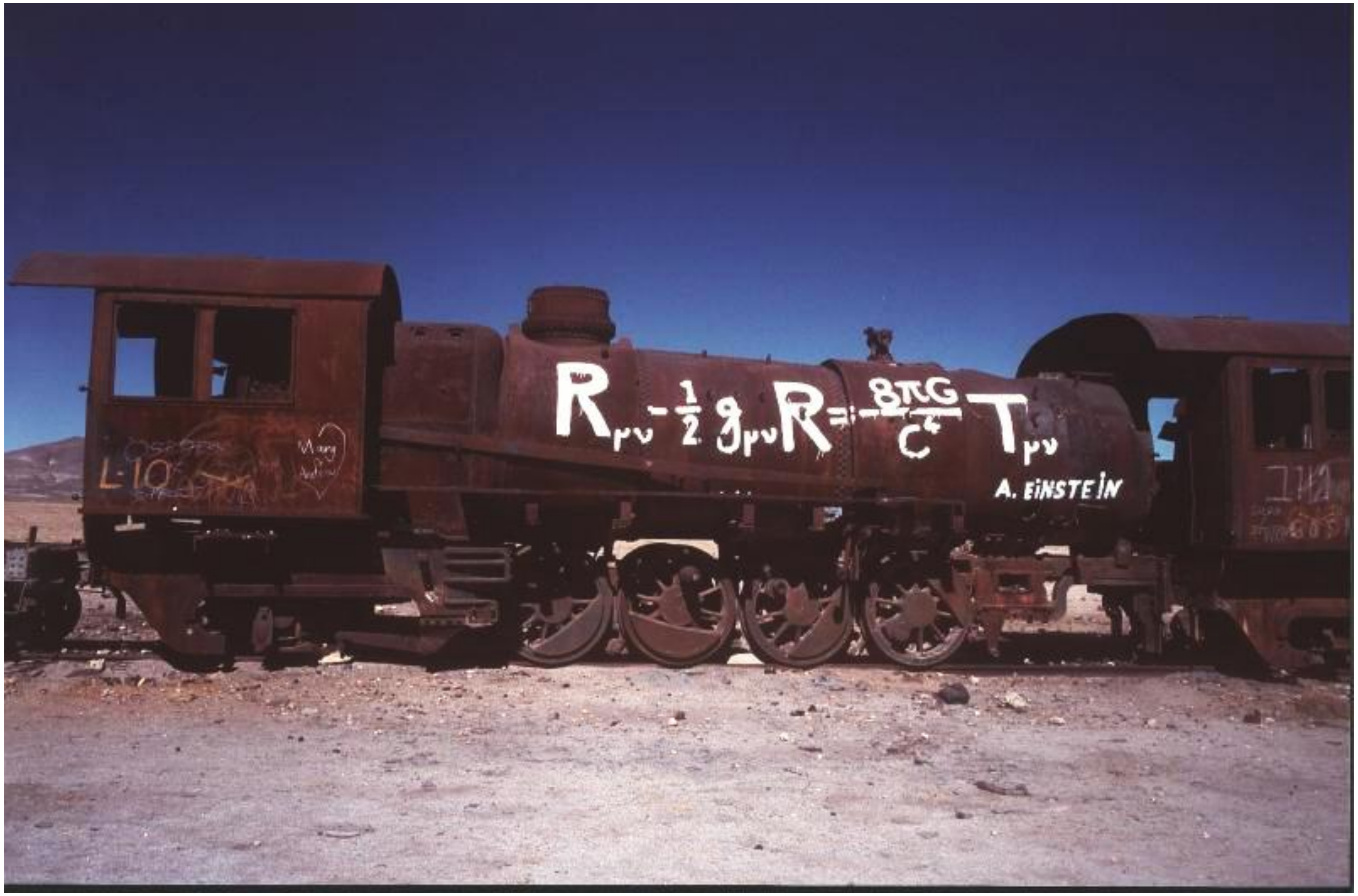
- “The” high precision Dark Energy & Cosmology mission
- Essential and unbeatable synergy of imaging + spectroscopy
- Euclid will impact the whole astrophysics and cosmology for decades to come

Why GRBs in Cosmology

- Most powerful explosions in the Universe
- Hints for structure formation
- Observed at considerable distances
- Their “engine” could probe Quantum Gravity
- Their “engine” could probe Geometry
- GRBs for “fundamental physics”

- **THESEUS could have a main role in these issues**

Besides probing DE, GRBs could be used to probe Geometry of the Universe and then metric theories



Specifically:

- GRBs as distance indicators probe the cosmic background
- GRBs as high energy sources could be used to test GR
- One can improve the "multi-messenger" approach: besides correlating GWs, EM,ν, GRBs emission could be useful to test the geometry of the source
- GRBs emission is comparable with Quantum Gravity energies
- GRBs as "distance rulers" and geometry probes.
- Several alternative theories of gravity work very well at early (Starobinsky 1980) and late epochs (Capozziello 2002) accounting for accelerated expansions.

- One can explore the possibility that the huge radiation of GRBs could be emitted by charged particles if the background is described by any theory of gravity (e.g. Extended Gravity)

- Let us consider a very general class of models like

$$\boxed{\mathcal{L} = \mathcal{L}_{grav} + F\mathcal{L}_{mat}\,,}$$

$$\boxed{\mathcal{L}_{grav} = \mathcal{L}_{grav}(g_{\mu\nu}, R^{\mu}{}_{\nu\alpha\beta})} \qquad \boxed{F = F(g_{\mu\nu}, R^{\mu}{}_{\nu\alpha\beta})}$$

These functions can arbitrarily depend on spacetime metric, Ricci scalar, Ricci tensor, and Riemann tensor

S. Capozziello and G. Lambiase, Phys. Lett. B 750 (2015) 344

- The last term in the Lagrangian describes theories with nonminimal coupling between matter and functions depending on curvature invariants

(S. Capozziello and M. De Laurentis, Phys Rept 509 (2011) 167 .

- In general, one may consider tha possibility that the coupling *F* is a function involving nine parity-even invariants as follows

(D. Puetzfeld and Y.N. Obukhov, PRD 87, (2013) 044045)

$$\boxed{F = F(i_1, \ldots, i_9)}$$

$$i_1 \equiv R^2, \quad i_2 \equiv R_{\mu\nu}R^{\mu\nu}, \quad i_3 \equiv R_{\mu\nu\alpha\beta}R^{\mu\nu\alpha\beta} \quad i_4 \equiv R_{\mu\nu}{}^{\alpha\beta}R_{\alpha\beta}{}^{\sigma\rho}R_{\sigma\rho}{}^{\mu\nu}$$

$$i_5 \equiv R^{\mu}{}_{\nu}R^{\nu}{}_{\rho}R^{\rho}{}_{\sigma}, \quad i_6 \equiv R^{\mu}{}_{\nu}R^{\nu}{}_{\rho}R^{\rho}{}_{\sigma}R^{\sigma}{}_{\delta}, \quad i_7 \equiv R^{\mu\nu}D_{\mu\nu}, \quad i_8 \equiv D_{\mu\nu}D^{\mu\nu}, \quad i_9 \equiv D_{\mu\nu}D^{\nu\rho}R^{\mu}{}_{\rho}$$

$$D_{\mu\nu} \equiv R_{\mu\nu\rho\sigma}R^{\nu\sigma}.$$

In curved spacetimes, the power radiate by a charged particle is

$$\boxed{W = -\frac{2e^2}{3}|\mathcal{D}^2 x^\alpha|^2,}$$

$\mathcal{D}^2 x^\alpha$ covariant four acceleration of particle

In GR, for particle moving along geodesics, the four acceleration vanishes and no radiation can be emitted. Detecting such a radiation can discriminate among competing theories.

- The equation of motion for a particle can be directly derived from the energy-momentum tensor and conservation laws

- Considering the above cases, the four-acceleration is

$$\boxed{\mathcal{D}^2 x^\alpha \equiv \dot{v}^\alpha = \frac{\xi}{m}\left(\delta^\alpha_\beta - v^\alpha v_\beta\right)\nabla^\beta A}$$

- $A = \ln F$, the given model is assigned by F
- v^α = particle velocity
- m = particle mass
- ξ depends on matter distribution

$$\boxed{\xi = \int_{\Sigma(s)} \mathcal{L}_{mat} w^{x_2} d\Sigma_{x_2}}$$

$$\boxed{\mathcal{D}^2 x^\alpha \equiv \dot{v}^\alpha = \frac{\xi}{m}\left(\delta^\alpha_\beta - v^\alpha v_\beta\right)\nabla^\beta A}$$

- This equation implies that massive particles move non-geodesically along their world-lines

- It could be an experimental test for the violation of the Equivalence Principle

- Stringent constraints on $\xi \nabla^\alpha A$ are provided by Gravity-Probe B satellites that test the gravitational coupling with matter

$$|\xi \nabla_0 A| \simeq 2 \times 10^{-4}\mathrm{kg/sec} = 7.4 \times 10^{-2}\mathrm{GeV}^2$$

$$|\xi \nabla_i A| \simeq 2 \times 10^{-10}\mathrm{g/sec} = 7.4 \times 10^{-8}\mathrm{GeV}^2$$

- Squaring the four-acceleration

$$\boxed{\mathcal{D}^2 x^\alpha}$$

and using the normalization of the velocity

$$\boxed{v^\alpha v_\alpha = -1}$$

one obtains the emitted radiation power

$$\boxed{W = -\frac{2}{3}\frac{q^2}{m^2} K^2,}$$

$$\boxed{K^2 = |\nabla_\alpha A|^2 - (v^\alpha \nabla_\alpha A)^2.}$$

The case of Schwarzschild geometry

Outside the source the Ricci tensor vanishes, while the Riemann tensor does not.
In such a case one can assume that the coupling F is only a function of the invariant i_3

$$F = F(i_3) \qquad i_3 = 48\frac{r_s^2}{r^6}$$

$r_s = GM$ is the Schwarzschild radius of the gravitational mass.

The more general form is

$$F(i_3) = (\lambda^4 i_3)^\delta \qquad \lambda, \delta = \text{constants}$$

The functions F and A do only depend on the radial variable r: $F = F(r)$, $A = A(r)$.
For simplicity we also assume that the motion of the particle is radial: $v^\alpha = (v^0, v^r, 0, 0)$
One gets

$$K^2 = \frac{36\delta^2}{\Gamma^2 r^2} \qquad \Gamma = [1 - (v^r)^2]^{-1/2}$$

Referring to

- electron particle, with $m = 0.5\text{MeV}$ and $q = e = 2.8 \times 10^{-1}$
- astrophysical objects with characteristic Schwarzschild radius $r_s = 10\text{km}$ (the mass of black hole are typically of the order $(3-10)M_\odot$, where $M_\odot$ is the solar mass)

the emitted power is

$$W = 24\frac{e^2}{m^2\Gamma^2 r^2}(\xi\delta)^2 \simeq 4\times 10^{-33}\frac{(\xi\delta)^2}{\Gamma^2}\left(\frac{0.5\text{MeV}}{m}\frac{10\text{km}}{r}\right)^2$$

For $\Gamma = 10$ one gets $W \sim 10^{51}\text{erg/sec} \sim 4\times 10^{30}\text{GeV}$ provided $\xi\delta \lesssim 10^{33}\text{GeV}$.

Consider another form of F:

$$F(i_3) = e^{(\lambda^4 i_3)^\delta}$$

For a Schwarzschild background one gets that the emitted power is given by

$$W = 24 \times 48^{2\delta} 10^{-32} \left(\frac{0.5\text{MeV}}{m}\frac{10\text{km}}{r_s}\right)^2 \frac{e^2}{\Gamma^2} \times \left(\frac{\delta\xi}{\text{GeV}}\right)^2 \left(\frac{\lambda}{r_s}\right)^{8\delta} \left(\frac{r_s}{r}\right)^{12\delta} \text{GeV}^2$$

- Taking the characteristic length λ of the order of the Schwarzschild radius, $\lambda \sim r_s$
- Considering the distance $r \sim 10^{15}\text{cm} = 10^9 \text{r}_\text{s}$, corresponding to the distance in which the shock producing GRBs)
- One gets GRBs emitted power $W \sim 10^{52}\text{erg/sec}$ for $\xi \sim \mathcal{O}(1)\text{GeV}$ and $\delta \simeq -0.62$

Kerr geometry

In the case in which the background is described by Kerr's spacetime, the invariant i_3 reads

$$i_3 = 48 \frac{r_s^2}{r^6} I(x) \qquad I(x) \equiv \frac{(1-x^2)[(1-x^2)^2 - 16x^2]}{(1+x^2)^6}$$

$$x = \frac{ay}{r}, \quad y = \cos\theta, \quad a = J/M$$

For $x \ll 1$, i.e. $r \gg ay$, the function I approaches to one, and one recovers the Schwarzschild results.

For $x \approx 1$ one gets that the emitted energy

$$W_{\text{Kerr}} = W \eta_\delta .$$

η_δ is an extra factor that can be larger than 1.

Specifically $\eta_\delta = \eta^{2\delta-1}$ and $\eta = x^2 - 1 << 1$

MAIN RESULT

THE GRB EMISSION CAN PROBE:

- The Geometry of spacetime
- The validity of Equivalence Principle
- The validity of Lorentz Invariance

See

Capozziello and Lambiase PLB 750 (2015) 344

Capozziello and Lambiase MPLA 30 (2015) 1540032

Discussion and conclusions

- A geometrical mechanism for the emission of GRBs can be achieved by Extended Gravity.
- It is based on the nonminimal coupling of matter with the gravitational background.
- This coupling produces an additional force that gives rise to a non-geodesic motion of test particles.
- This aspect is very important in processes where radiation is emitted by accelerated particles.
- In pure GR, one finds $D^2 x^\alpha = (d^2 x^\alpha/dt^2) + \Gamma^\beta{}_{\gamma\alpha}(dx^\beta/dt)\,(dx^\gamma/dt) = 0$ and particles cannot emit radiation
- In the models we are considering, the non-minimal coupling implies $D^2 x^\alpha \neq 0$ so that radiation can be emitted.

Discussion and conclusions

- The models predict a violation of the equivalence principle, so GRBs could test Equivalence Principle and Lotentz invariance.

- We invetigated cases where only the invariant $\mathbf{i_3}$ is considered, but results can be easily extended to more general models involving the Gauss-Bonnet invariant, the Weyl tensor, and non-local terms as $\Box^{-1}R$.
  Capozziello, De Laurentis, Lambiase, in preparation.

- **THESEUS** could have a main role in these researches because it is capable of matching high-energy transients in early universe.

- Transients could probe Equivalence Principle and Lorentz invariance by a systematic study of geodesic deviations.

- Emission at early epochs could probe the geometry .

WORK IN PROGRESS!!!