Aspects of field theories from astrophysics to cosmology: From early to large scales

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University of Camerino

The University of Camerino: *Location*

University of Camerino

The University of Camerino: *Physics*

The University of Camerino: *Master*

MSc-PHYSICS						
Majors		Astroparticle & nuclear physics	Condensed matter & nanoscience	Physics of materials	Quantum technologies	Theoretical & complex systems
Common activities	30 CFU	Advanced electromagnetism FIS/01				
		Advanced physics laboratory FIS/03				
		Machine learning INF/01				
		Solid state physics FIS/03				
		Theoretical Physics FIS/02				
Characterizing activities	30 CFU	Advanced nuclear physics FIS/04	Advanced spectroscopy FIS/01	Experimental material science FIS/01	Atomic physics FIS/03	Advanced probability and stochastic processes MAT/06
		Astro & particle physics FIS/04	Condensed matter theory FIS/03	Fundamental opf material sciences ING-IND/22	Physics of nanotechnologies FIS/03	Quantum field theory FIS/02
		Cosmology FIS/05	Experimental nanoscience FIS/01	Physics of nanotechnologies FIS/03	Quantum computation FIS/02	Quantum information FIS/02
		Laboratory of astroparticle FIS/01	Physics of nanotechnologies FIS/03	Surface and chemical physics CHIM/02	Quantum optics FIS/03	Statistical mechanics FIS/02
		Quantum field theory FIS/02	Statistical mechanics FIS/02	Synthesis of functional materials ING-IND/22	Statistical mechanics FIS/02	Stochastic dynamics FIS/03
Free choice activities	To choose 12 CFU out of the 24 proposed	Advanced spectroscopy FIS/01	Quantum field theory FIS/02	Advanced spectroscopy FIS/01	Experimental nanoscience FIS/01	Condensed matter theory FIS/03
		General relativity MAT/05	Quantum optics FIS/03	Energy production & storage CHIM/12	Fundamentals of robotics ING-INF/04	Dynamic & stochastic optimization SECS-S/06
		Quantum information FIS/02	Surface and chemical physics CHIM/02	Environmental remediation CHIM/12	Quantum information FIS/02	General relativity MAT/05
		Statistical mechanics FIS/02	Synthesis of functional materials ING-IND/22	Statistical mechanics FIS/02	Stochastic methods and modelling FIS/03	Quantum computation FIS/02
Stage	6 CFU					
Thesis	42 CFU					

University of Camerino

The University of Camerino: *Physics*

Every year

~350 bachelor students

~20 admitted to the Advanced Studies

Italian double degree

~95% of the students: employed

UNICAM
Università di Camerino
1336

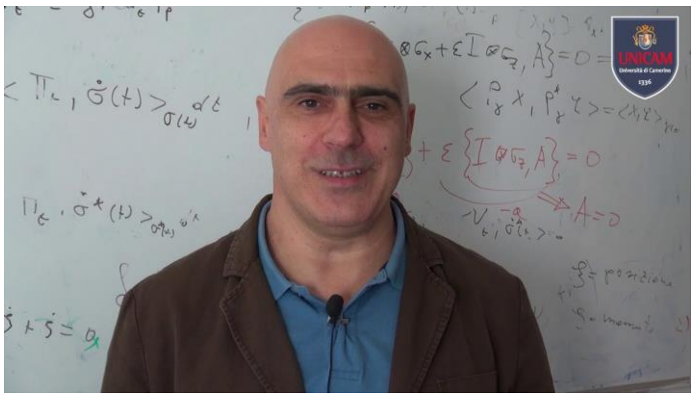
iSAS
international
interdisciplinary
intersectoral

School of Advanced Studies

University of Camerino

The University of Camerino: *My group*

Prof. ***Stefano Mancini:*** *Quantum Information and Quantum Communication*



PhD students, A. Belfiglio, A. Lapponi

*Prof. R****oberto Giambo****, Astrophysics and gravitation*

My role at Unicam

Prof. Of Theoretical Physics and Cosmology.

University of Camerino

The University of Camerino: *Scientific collaborations*

Foreign institutes

- *Al-Farabi University, Almaty: Prof. K. Boshkayev, Ye. Kurmanov, T. Konysbayev,*
- *Nazarbayev University, Astana: Profs. Michael Good, Daniele Malafarina*
- *SUNY University, NY: Prof. Carlo Cafaro*
- *UNAM University, Mexico: Prof. Hernando Quevedo, Dr. Celia Rivera, etc.*
- *Uzbek: Prof. Bobo Ahmedov*
- *University of Cape Town: Prof. Peter Dunsby, Dr. Alvaro De la Cruz, etc.*

National institutes

- *University of Pisa: Prof. Giacomo Tommei*
- *University of Naples: Prof. Salvatore Capozziello, Dr. Rocco D'Agostino, etc.*
- *University of Rome: Prof. Remo Ruffini*
- *National Institute for Nuclear Physics: Dr. Marco Muccino*

University of Camerino

The University of Camerino: *Funds*

Quantum observers in a relativistic world Foundational Questions Institute grant

Cosmology and astrophysics network for theoretical advances and training actions

Quantum readout techniques EU grant

Finite/Infinite Quantum Systems Physics of Informative Systems INFN specific initiatives

Some international collaborations: N. Ay (Max Planck Inst.); Braunstein (Univ. York); A. Ekert (QCT Singapore); S. Lloyd (MIT); M. Pettini (Aix- Marseille Univ.); R. Renner (ETH Zurich); M. Wilde (Louisiana Univ.); A. Winter (Univ. Autonoma Barcelona); H. Wiseman (Univ. Brisbane)

Research activities: *Theoretical Physics*

My Group expertise

- **Cosmology**

i. Dark energy
ii. Dark matter

- **Gravitational physics and astrophysics**

i. Black and worm holes
ii. Extended theories of gravity

- **Field Theories**

i. Particle production in curved spacetime
ii. Baryogenesis

- **Quantum information**

i. Entanglement
ii. Statistical lengths

…Other groups: *Solid state physics, Nuclear Physics, etc.*

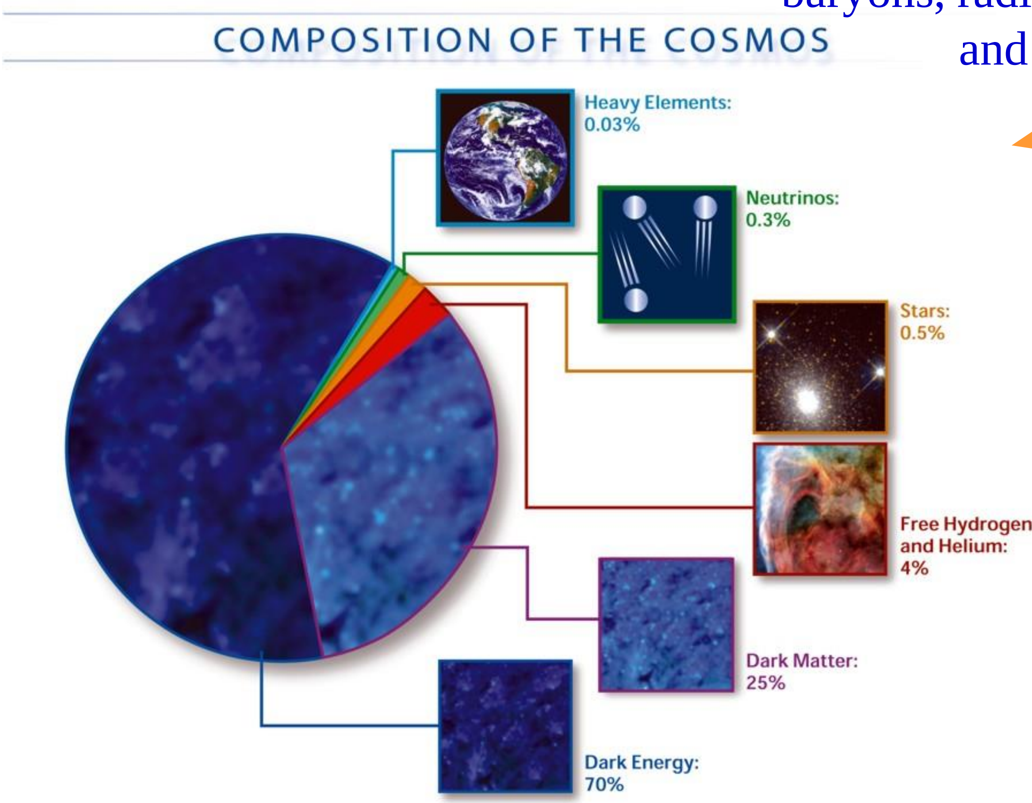
Classical cosmology: data without theory!

Quantum cosmology: theory without data!

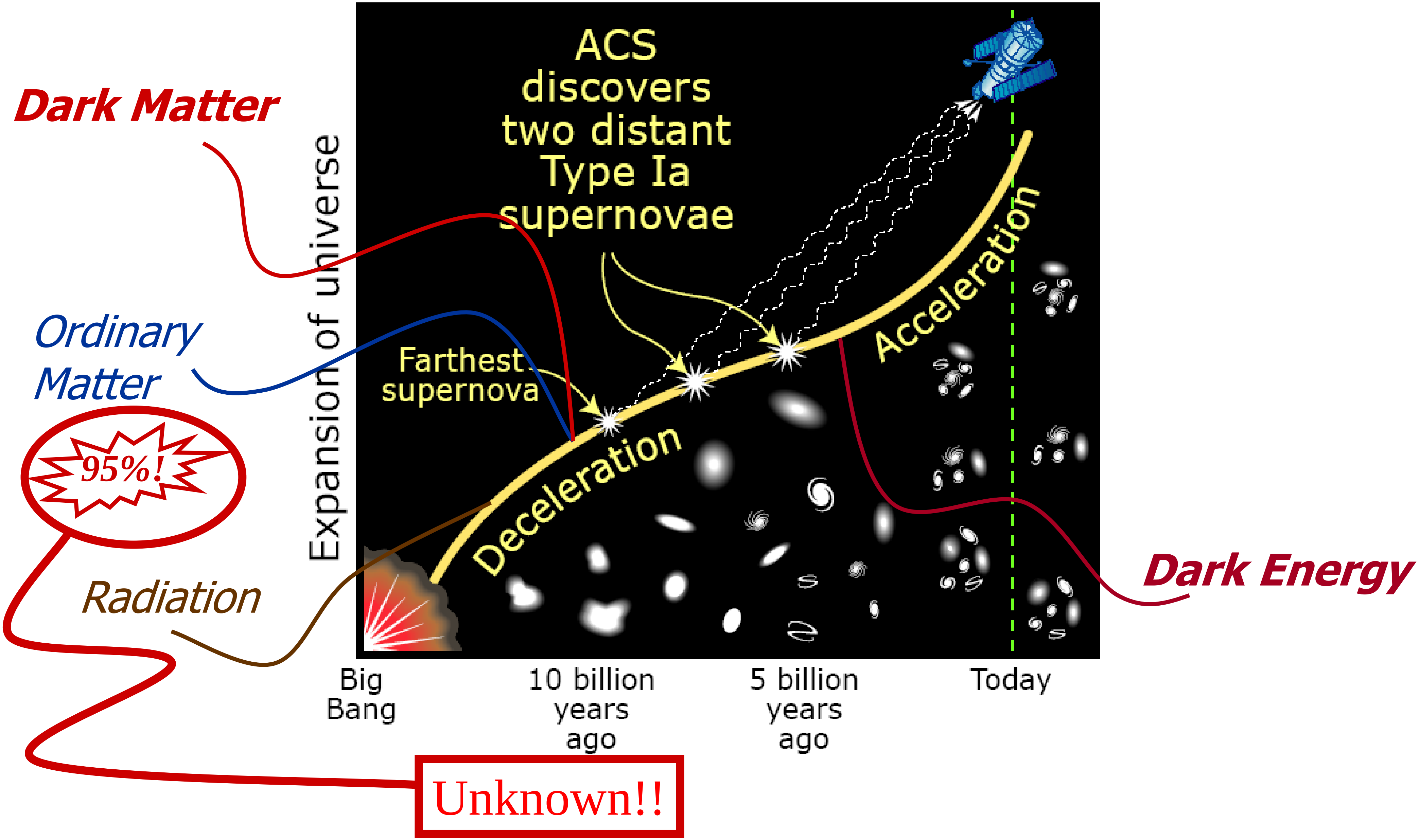
We are able to observe only baryons, radiation, neutrinos and gravity

Dark energy and dark matter as "shortcomings" of GR. *Results of flawed physics?*

The "correct" theory of gravity could be derived by matching the largest number of observations at all scales!



The Observed Universe Evolution

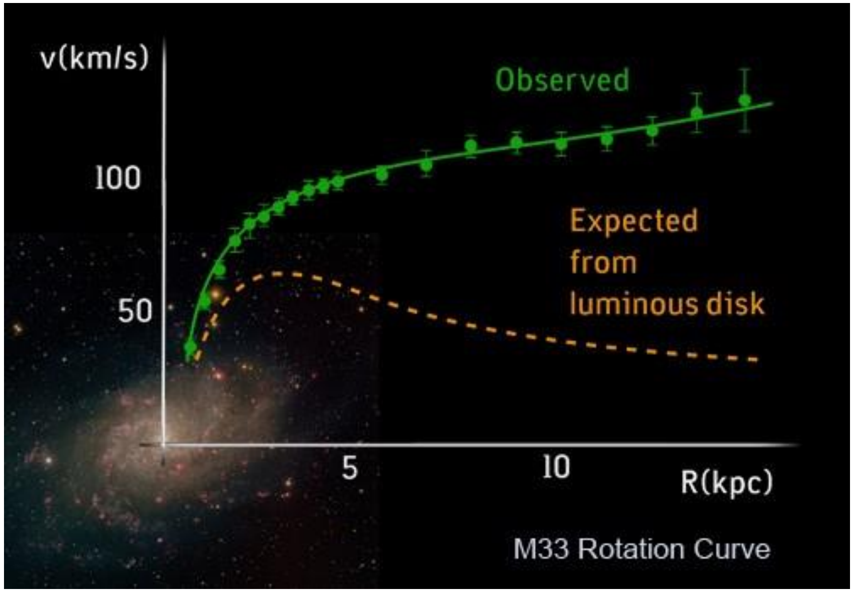


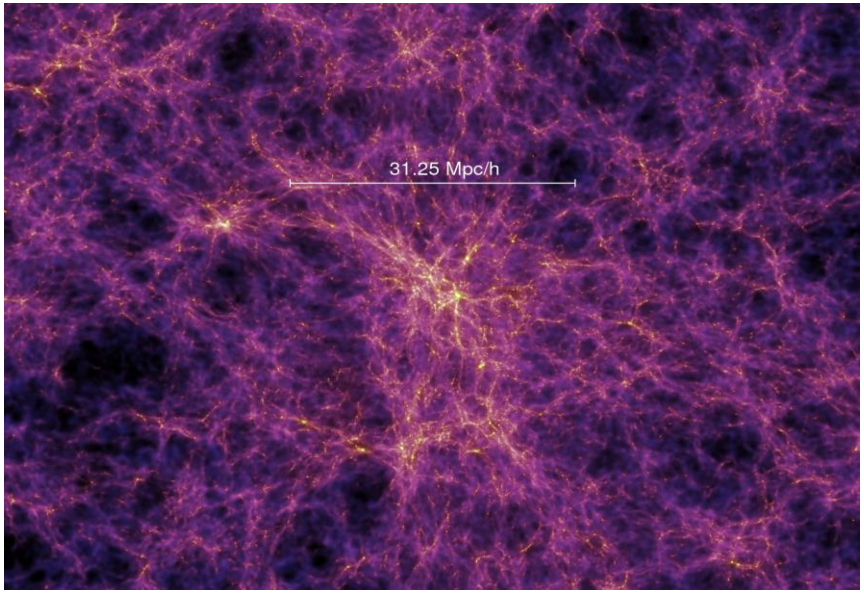
Gravitational effects of Dark matter

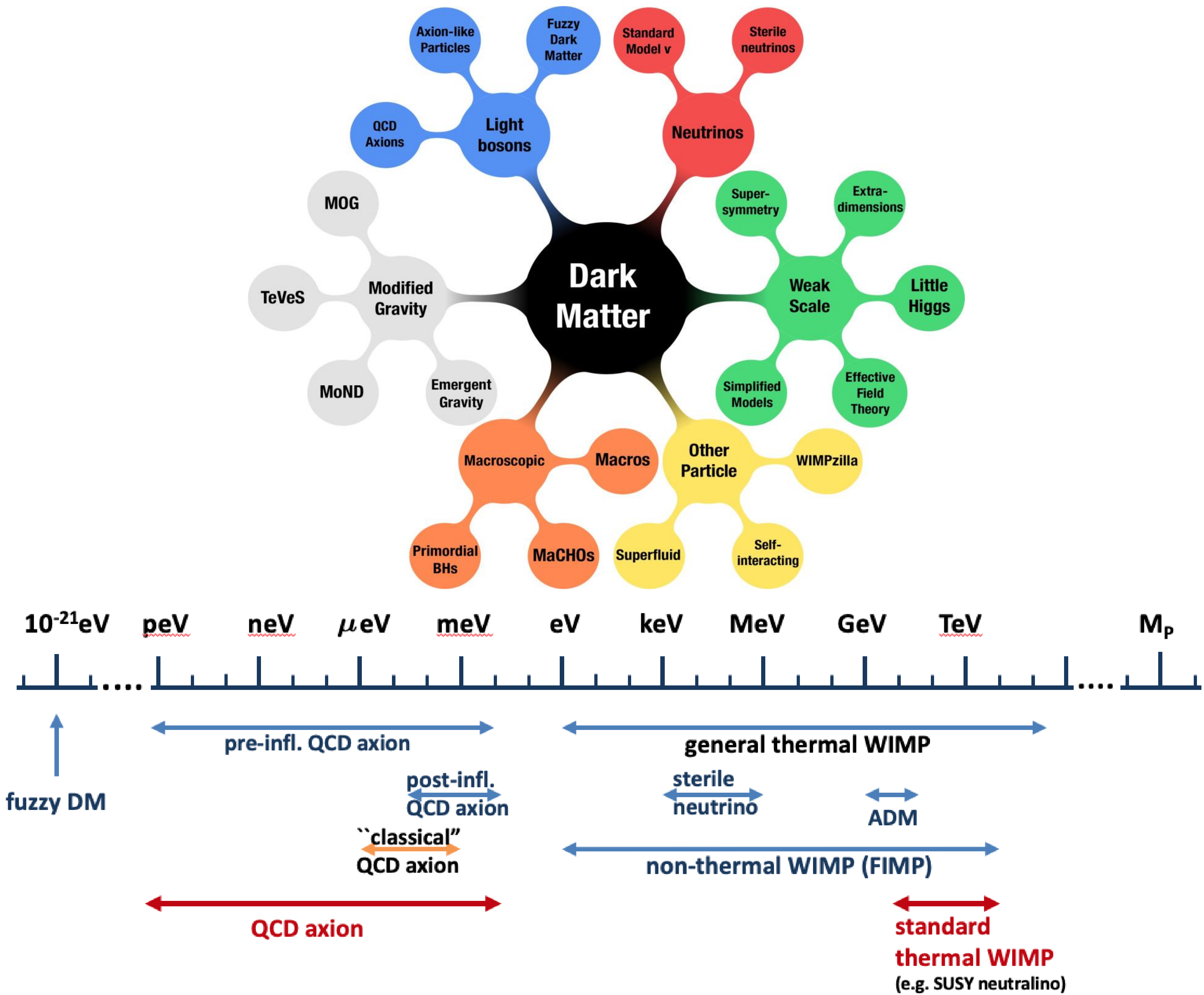
Problem at all scales!

1. Star velocity in galaxies V. Rubin and W. Ford (1970)
2. Star velocity in clusters F. Zwicky (1937)
3. Gravitational lensing J. K. Adelman-McCarthy et al. (2005)

$$\Omega_{dm}h^2 = 0.1200 \pm 0.0012$$







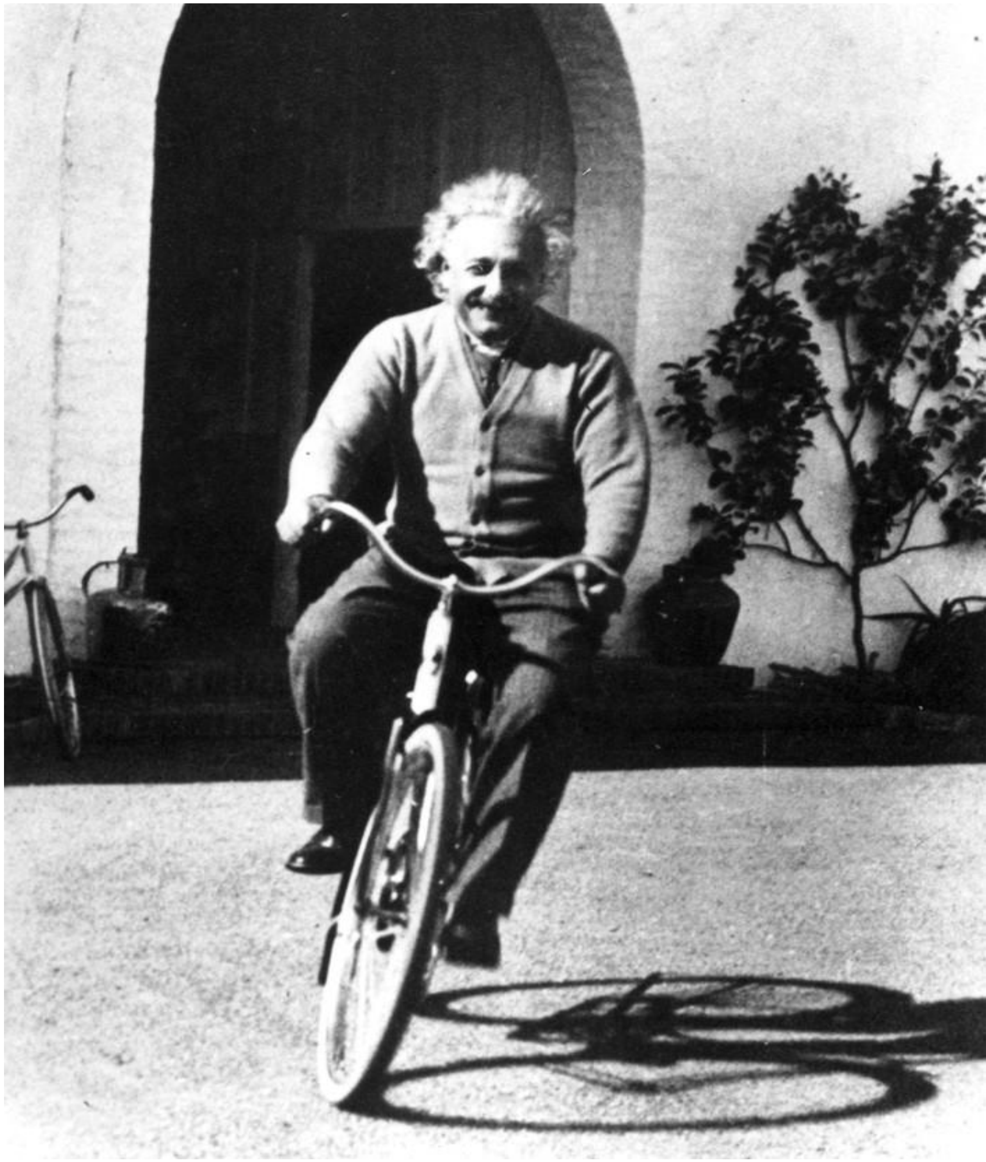
Dark Matter
Light bosons
Axion-like Particles
Fuzzy Dark Matter
QCD Axions
Neutrinos
Standard Model ν
Sterile neutrinos
Weak Scale
Super-symmetry
Extra-dimensions
Little Higgs
Simplified Models
Effective Field Theory
Other Particle
WIMPzilla
Superfluid
Self-interacting
Macroscopic
Macros
Primordial BHs
MaCHOs
Modified Gravity
MOG
TeVeS
MoND
Emergent Gravity
10^-21 eV
peV
neV
μeV
meV
eV
keV
MeV
GeV
TeV
M_P
fuzzy DM
pre-infl. QCD axion
general thermal WIMP
post-infl. QCD axion
sterile neutrino
ADM
``classical" QCD axion
non-thermal WIMP (FIMP)
QCD axion
standard thermal WIMP
(e.g. SUSY neutralino)

Extending gravity

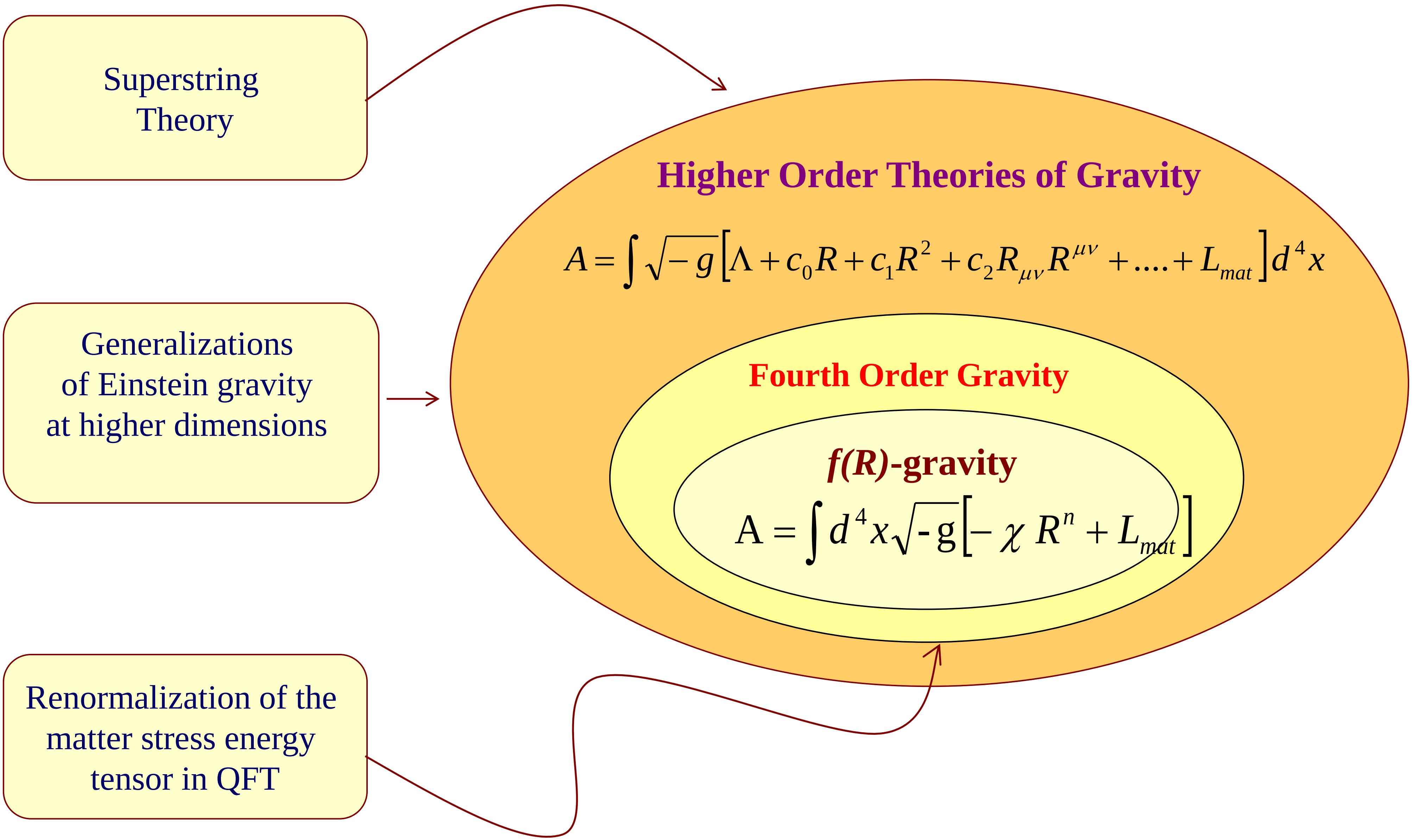
- ✓ Generalization of the Hilbert-Einstein action to a generic (unknown) *f(R)* theory of gravity

$$\mathcal{A} = \int d^4x\sqrt{-g}\left[f(R) + \mathcal{L}_{(matter)}\right]$$

$$f'(R)R_{\alpha\beta} - \frac{1}{2}f(R)g_{\alpha\beta} = f'(R)^{;\mu\nu}(g_{\alpha\mu}g_{\beta\nu} - g_{\alpha\beta}g_{\mu\nu}) + \tilde{T}^{(matter)}_{\alpha\beta}$$



Why Extending Gravity?



Theoretical motivations and features:

- Quantization on curved space-time needs higher-order invariants corrections to the Hilbert-Einstein Action.
- Predicted by several unification schemes as String/M-theory, Kaluza-Klein, etc.
- Compatible with the Equivalence Principle if one takes a generic action:

$$\mathcal{A} = \int d^4x \sqrt{-g}\left[F\left(R, \Box R, \Box^2 R, \ldots \Box^k R\right) + \mathcal{L}_m\right]$$

- Contributing significantly to large scale dynamics if one considers only fourth order terms *f(R)*.
- Dark energy and dark matter emerging at different scales and late times.
- This scheme allows to obtain an "Einstein" two fluid model in which one component has a geometric origin

$$G_{\alpha\beta} = R_{\alpha\beta} - \frac{1}{2} g_{\alpha\beta} R = T^{(curv)}_{\alpha\beta} + T^{(matter)}_{\alpha\beta}$$

$$T^{(curv)}_{\alpha\beta} = \frac{1}{f'(R)}\left\{\frac{1}{2} g_{\alpha\beta}\left[f(R) - Rf'(R)\right] + f'(R)^{;\mu\nu}\left(g_{\alpha\mu} g_{\beta\nu} - g_{\alpha\beta} g_{\mu\nu}\right)\right\}$$

Dark Energy as curvature effect

Starting from the above considerations, it is possible to write a **curvature pressure** and a **curvature energy density** in the FRW metric (**curvature EoS**)

$$p_{(curv)} = \frac{1}{f'(R)} \left\{ 2\left(\frac{\dot{a}}{a}\right) \dot{R} f''(R) + \ddot{R} f''(R) + \dot{R}^2 f'''(R) - \frac{1}{2}\left[f(R) - R f'(R)\right] \right\}$$

$$\rho_{(curv)} = \frac{1}{f'(R)} \left\{ \frac{1}{2}\left[f(R) - R f'(R)\right] - 3\left(\frac{\dot{a}}{a}\right) \dot{R} f''(R) \right\}$$

$$w_{curv} = -1 + \frac{\ddot{R} f''(R) + \dot{R}\left[\dot{R} f'''(R) - H f''(R)\right]}{\frac{1}{2}\left[f(R) - R f'(R)\right] - 3H\dot{R} f''(R)}$$

As a simple toy model, we can assume a power law function for *f(R)* and for the scale factor *a(t)*

$$f(R) = f_0 R^n \,, \qquad a(t) = a_0 \left(\frac{t}{t_0}\right)^{\alpha}$$

Can f(R)-theories reproduce also Dark Matter dynamics?

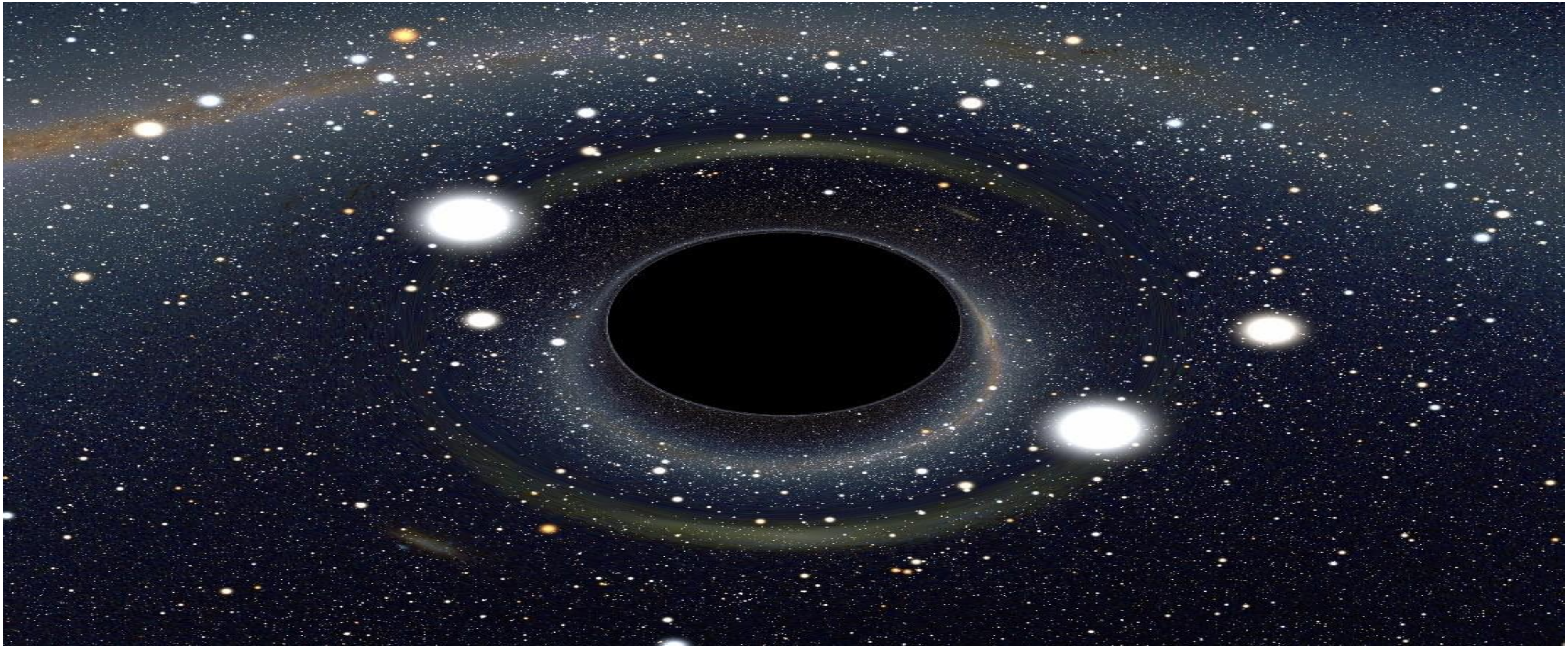
Research interests:

1) Galactic dynamics (rotation curves of spiral galaxies)
2) Dark matter in the Ellipticals
3) Galaxy cluster dynamics

The problem: we search for $f(R)$-solutions capable of fitting consistently the data. A nice feature could be that the same $f(R)$ – model works for Dark Energy (very large, unclustered scales) and Dark Matter (small and clustered scales).

BLACK and WORM HOLES

The **black hole** is a region of space-time where the gravitational field is so strong that it does not allow light to come out

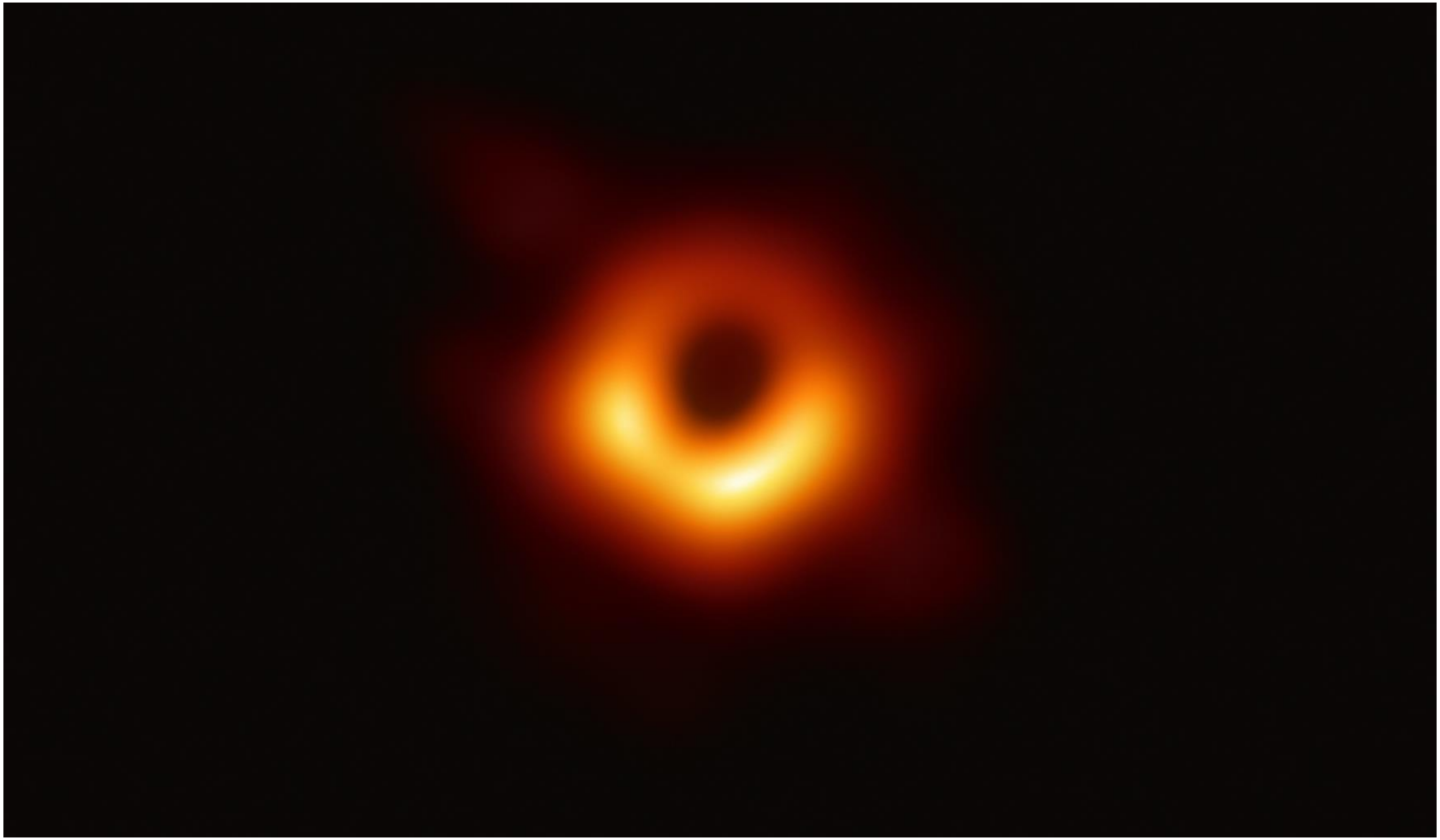


The surface surrounding a black hole is called
event horizon

Thanks to the deformation generated by gravity, it is sufficient to travel around a black hole to perceive time slower as we perceive it on Earth

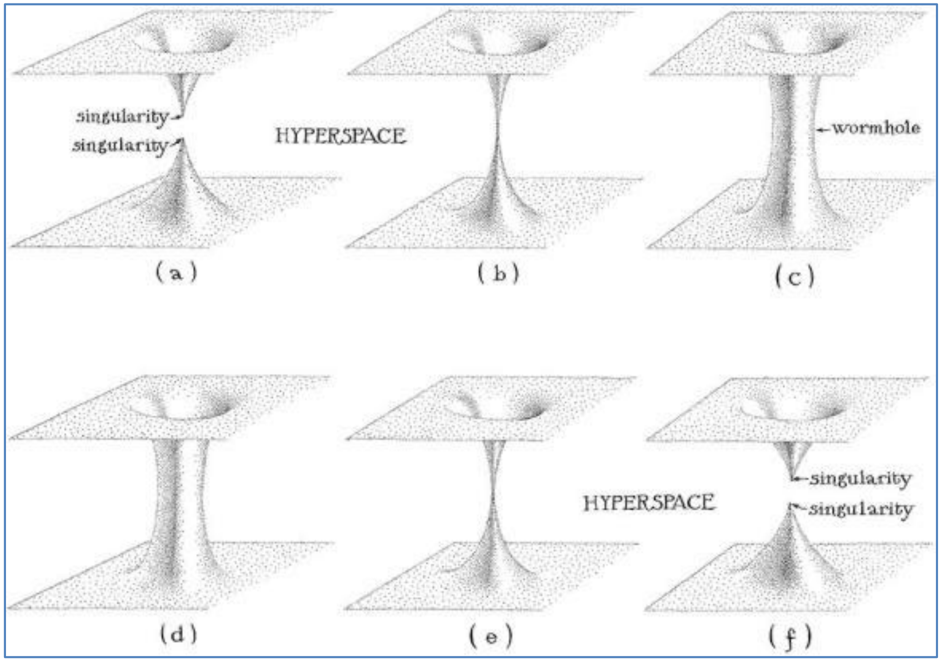
What happens if we cross the event horizon?

Beyond this orbit nothing can go back.

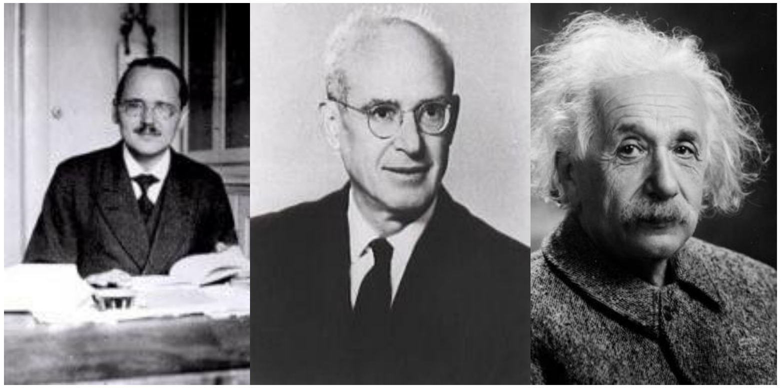


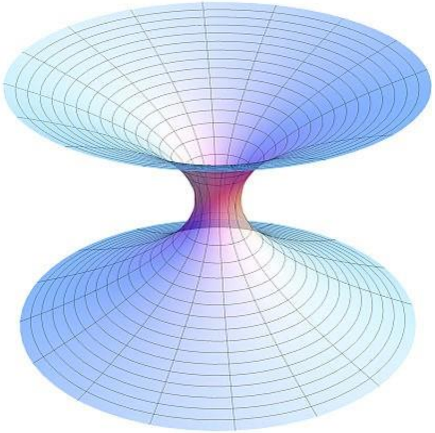
The black hole at the center of M87 galaxy
Event Horizon Telescope, April 10, 2019

From Schwarzschild to wormhole: Flamm and Einstein-Rosen solutions



In 1916 L.Flamm noticed that the Schwarzschild solution describes also another structure: the white hole. In 1935 Einstein and Rosen found out another solution





Einstein-Rosen bridge (1935)

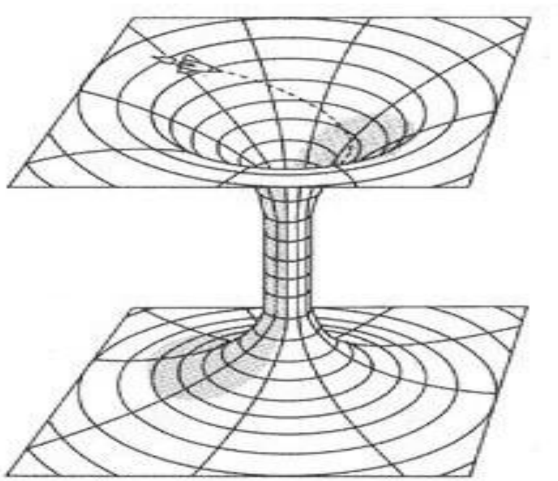
Two Schwarzschild solutions joined by a throat

Einstein-Rosen bridge is not a «suitable» wormhole

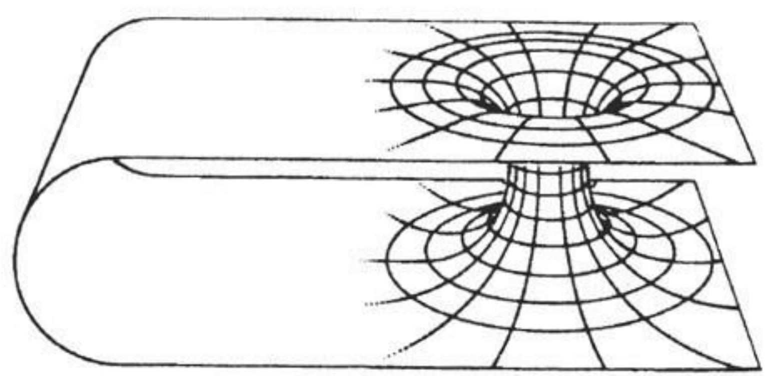
- Huge tidal gravitational forces
- Schwarzschild wormholes are not static
- Horizon instability
- White hole instability

Types of WORMHOLES

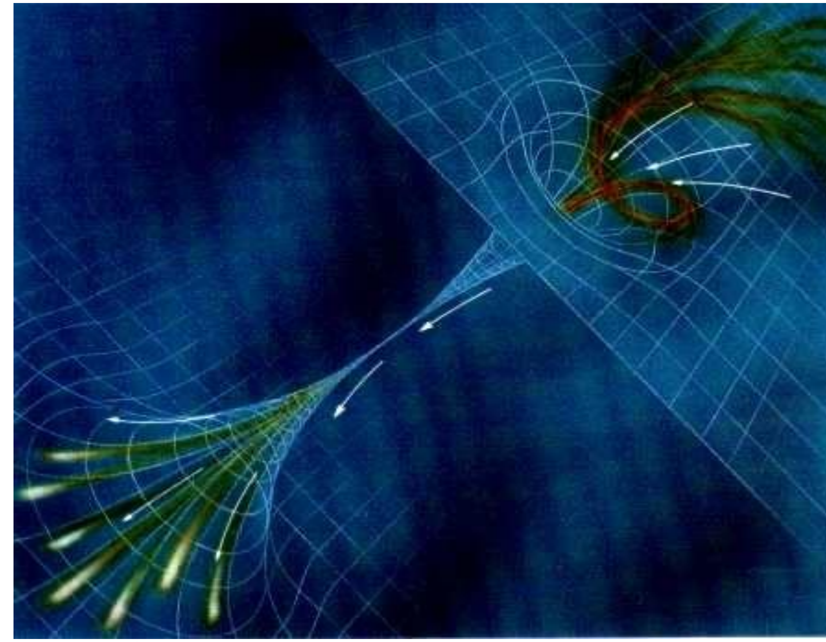
inter-universe



intra-universe



They could also connect **parallel universes**. This last possibility would solve the diatribe that a journey through time could change the past or the future in the same universe by violating the principle of causality (**grandma's paradox**)



The Morris and Thorne solution

$$ds^2 = -e^{2\Phi(r)}c^2dt^2 + \frac{1}{1-\frac{b(r)}{r}}dr^2 + r^2(d\theta^2 + \sin^2\theta d\phi^2)$$

REDSHIFT FUNCTION

SHAPE FUNCTION

$d\Omega^2$

N.B. Spherical symmetry, static metric BUT the stress-energy tensor is non-null. This is not a Schwarzschild solution!

These "**time machines**" have problems: what are the physical laws that we find AFTER having crossed the horizon? Is the return journey possible?

Exotic Matter!!!

Some Big Issues in Theoretical Physics are related to the problem of "origins"

QUANTUM FIELDS

People search for quantum origins trying to connect General Relativity to Quantum Mechanics!

Answering………

- *The origin of the Universe*
- *The origin of Time*
- *The origin of Large Scale Structure*

Some Big Issues in Theoretical Physics are related to the problem of "origins"

Dirac equation (under minimal coupling assumption)

$$[i\gamma^{\mu}(\partial_{\mu}+\Gamma_{\mu})+m]\,\Psi=0$$

Consider a spacetime that has asymptotically stationary regions in the remote past (*input*) and in the far future (*output*). Assume it has also a conformally flat metric.

The expression for the mass entering the Dirac Equation is modified by the presence of curvature, torsion and/or in the context of extended theories of gravity…

Getting solutions, with given «m(a)», provides hints on particle productions at early stages of universe's expansion history.

A more realistic approximation of the scale factor should be based on asymptotically flat behaviors at both late and early times, providing:

- $a_\infty \to 0$,
- $a_0 < \infty$,

motivating these limits by physical properties defined from the space-time properties.

To do so, let us recall a generic function $f(x)$, where x is a set of parameters which do not diverse, as in the FRW picture. The Padé approximant, or better the Padé approximation, with fixed orders (m, n) is defined as:

$$P_{mn}(x) = \frac{a_0 + a_1 x + a_2 x^2 + ... + a_m x^m}{1 + b_1 x + b_2 x^2 + ... + b_n x^n} .$$

Since all observable quantities can be reframed by means of Padé polynomials, because all expansions are matchable between them, we may think to expand the scale factor itself.

Some Big Issues in Theoretical Physics are related to the problem of "origins"

For our purposes, we thus define a (N, M) Padé approximant as:

$$P_{NM}(z) = \frac{\sum_{n=0}^{N} a_n z^n}{1 + \sum_{m=1}^{M} b_m z^m}$$

Hence, motivated by the above constructions, we can therefore adopt the following expansions:

$$a_1(t) = \frac{\beta_0 + \beta_1 t}{1 + \beta_2 t} \qquad a_2(t) = \frac{\beta_0}{1 + \beta_2 t},$$

which are in agreement with modern observations.
Looking for solutions:

$$\psi = a^{-1/2}(\gamma^\nu \partial_\nu - M)\varphi \qquad M = ma(\tau),$$

we can recast the Dirac equation by $g^{\mu\nu}\partial_\mu\partial_\nu\varphi - \gamma^0 \dot{M}\varphi - M^2\varphi = 0$, with corresponding solutions under the more suitable form:

$$\varphi^{(-)} \equiv N^{(-)} f^{(-)}(\tau) u e^{ikx}, \qquad \varphi^{(+)} \equiv N^{(+)} f^{(+)}(\tau) v e^{ikx},$$

with k the momentum.

$$\ddot{f}^{(\pm)} + \left[k^2 + m^2(1 + a_{1;2})^2 \pm \frac{\beta_1 - \beta_0\beta_2}{(1 + \beta_2 t)^2}\right] f^{(\pm)} = 0\,.$$

Rational approximations compatible with observations

Entanglement in model independent cosmological scenarios

Some Big Issues in Theoretical Physics are related to the problem of "origins"

From Bogolubov transformations to Entropy

$$a_{out}(k) = \alpha(k) a_{in}(k) - \beta(k) b^{\dagger}_{in}(-k),$$
$$b^{\dagger}_{out}(-k) = \beta^{*}(k) a_{in}(k) + \alpha^{*}(k) b^{\dagger}_{in}(-k),$$

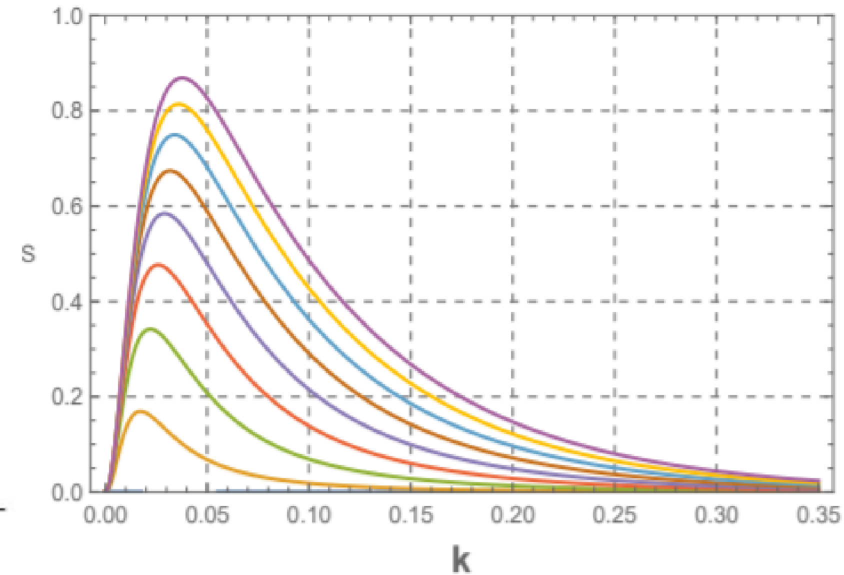
Analogously, Bogolubov transformations interconnect the solutions $f^{(\pm)}_{in/out}$ giving

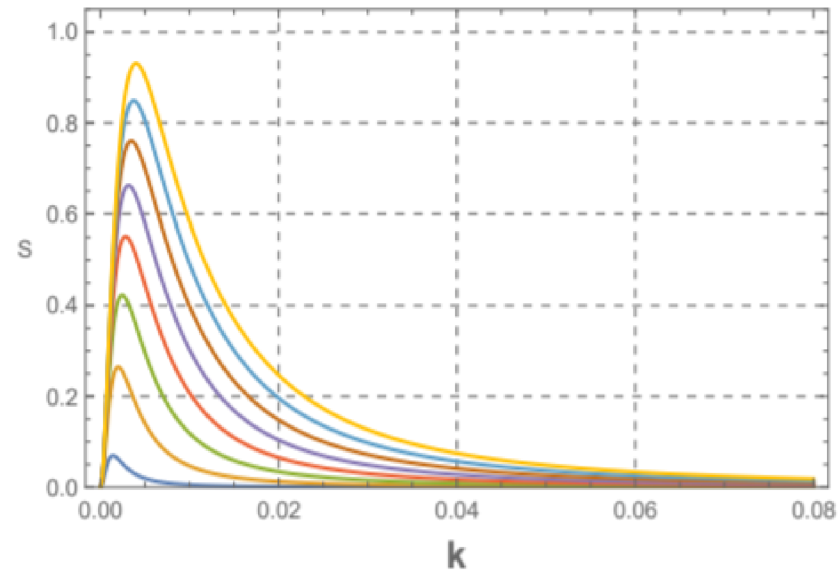
$$f^{(\pm)}_{in}(t) = A^{(\pm)}(k) f^{(\pm)}_{out}(t) + B^{(\pm)}(k) f^{(\mp)*}_{out}(t)\,.$$

Clearly the coefficients $A^{(\pm)}, B^{(\pm)}$ are related to α, β, in particular it results

$$|\alpha(k)|^2 = \frac{E_{out}}{E_{in}} \left(\frac{E_{in} - M_{in}}{E_{out} - M_{out}} \right) \left| A^{(-)}(k) \right|^2 .$$

$$S_{out} = -\frac{n}{2} \log_2 \frac{n}{2} - \left(1 - \frac{n}{2}\right) \log_2 \left(1 - \frac{n}{2}\right)$$





Some Big Issues in Theoretical Physics are related to the problem of "origins"

Geometric cosmological entanglement

Perturbations also *create entanglement* in the final state of the system of particles

$$|\Psi\rangle_{\rm in} = |0_k; 0_p\rangle_{\rm in} \longrightarrow |\Psi\rangle_{\rm out} = \mathcal{N}\left(|0_k; 0_p\rangle_{\rm in} + \frac{1}{2}\hat{S}^{(1)}_{kp}|1_k; 1_p\rangle_{\rm in}\right)$$

Entanglement can be quantified using *von Neumann entropy* $\mathcal{S}$ of the reduced density operator

$$\rho_k = \mathrm{Tr}_p\left(|\Psi\rangle_{\rm out}\langle\Psi|\right) \implies \mathcal{S}(\rho_k) = -\mathrm{Tr}_k\left(\rho_k \log_2 \rho_k\right) \neq 0$$

Geometric (quasi)-particles of dark matter do not interact with other particles. So the generated entanglement may be preserved to our time!

This may lead to:

- Entanglement extraction.
- Deduction of cosmological parameters.
- Characterize dark matter nature.
- Unify the dark sector.

Geometric Particle Production

A first example!

Conclusion

In the University of Camerino (Unicam)

- **There are strong interdisciplinary tasks developed in the contexts of:**

i. Theoretical Physics
ii. Gravitation, astrophysics and particle physics
iii. Quantum information and quantum optics
iv. Solid state physics and material science
v. Complex systems and statistical physics
vi. Experimental physics of all the above (…far from this talk!)

- **We encourage agreements with different universities based on:**

i. Funds and international grants and/or joint master's and Phd programs
ii. Professor and researcher mobility
iii. European fellowships for partnerships and foreign students

- **I summarized, albeit partially, the research activity of my group where:**

i. I am active in cosmology, field theories (classical and quantum) and relativistic quantum information
ii. I collaborate with several Italian and foreign colleagues

- **For admission to Unicam, requests, thesis, scientific collaborations and any queries, please write me at: orlando.luongo@unicam.it**