Astroparticle theory

Pierre Binétruy, APC

WIN 2015, Heidelberg
8 June 2015

What is astroparticle theory?

Astroparticle physics is mostly defined as an experimental/observational field.

(Is it just astrophysics?)

Questions that we wish to address (2004, French astroparticle roadmap)

Was there a big bang?
If there was an inflation era , what was the dynamics of it?
What is the origin of the matter-antimatter asymmetry?
Which were the first luminous objects, and when did they appear?
How to detect and identify dark matter? Or to disprove its existence?
What is the geometry and content of the Universe at large scale?
How to confirm or disprove the acceleration of the expansion?
Is there a dark energy? Why is the energy of the vacuum so small?
What are the limits of validity of general relativity ?
How do cosmic accelerators work?
What can we learn from the study of energetic sources on the fundamental laws of physics
How are black holes formed?
Is there new states of matter at extreme energies or densities?
How do supernovae explode? How are formed heavy elements?

Questions that we wish to address (2004, French astroparticle roadmap)

Was there a big bang?
If there was an inflation era , what was the dynamics of it? ✓
What is the origin of the matter-antimatter asymmetry?
Which were the first luminous objects, and when did they appear?
How to detect and identify dark matter? Or to disprove its existence?
What is the geometry and content of the Universe at large scale? ✓✓
How to confirm or disprove the acceleration of the expansion? ✓✓
Is there a dark energy? Why is the energy of the vacuum so small?
What are the limits of validity of general relativity ?
How do cosmic accelerators work? ✓
What can we learn from the study of energetic sources on the fundamental laws of physics
How are black holes formed?
Is there new states of matter at extreme energies or densities?
How do supernovae explode? How are formed heavy elements?

First definition of astroparticle physics

Astroparticle: domain at the interface between astrophysics and particle physics

GRAVITY IS THE ENGINE OF THE UNIVERSE

Fundamental forces of nature

Weak force : range 10^{-18} m

Strong force : range 10^{-15} m

Electromagnetic force: infinite range but screening → finite in practice

Gravitational force: infinite range

constrained by the equivalence principle

↑

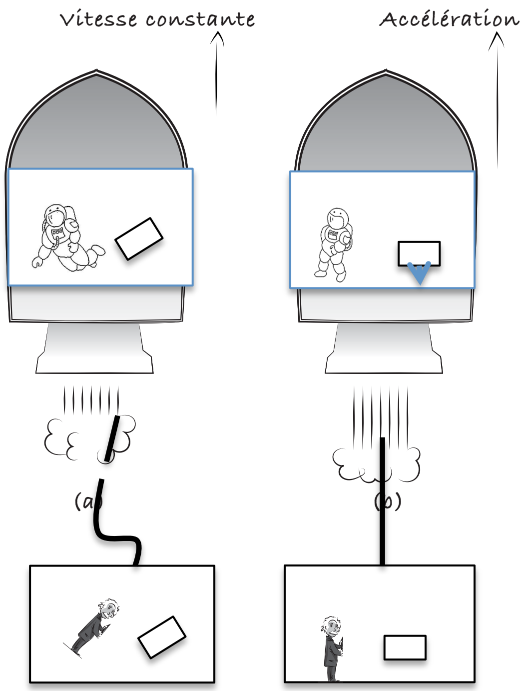
In the absence of violations, applies to any « infinite range » force

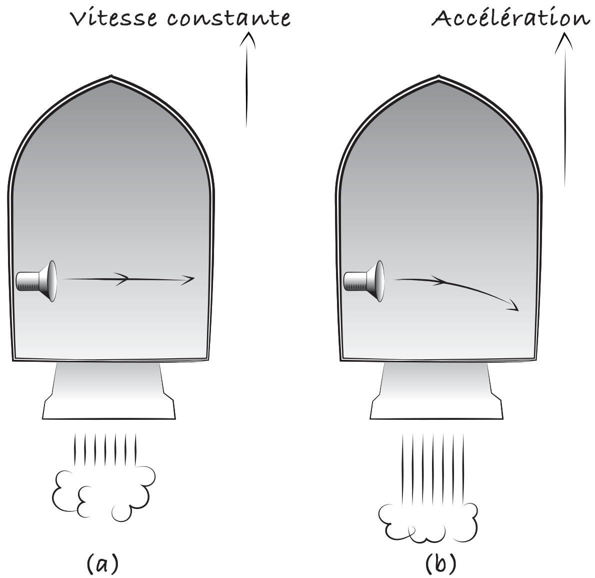
Note: the equivalence principle is not just the equality of inertial mass and gravitational mass

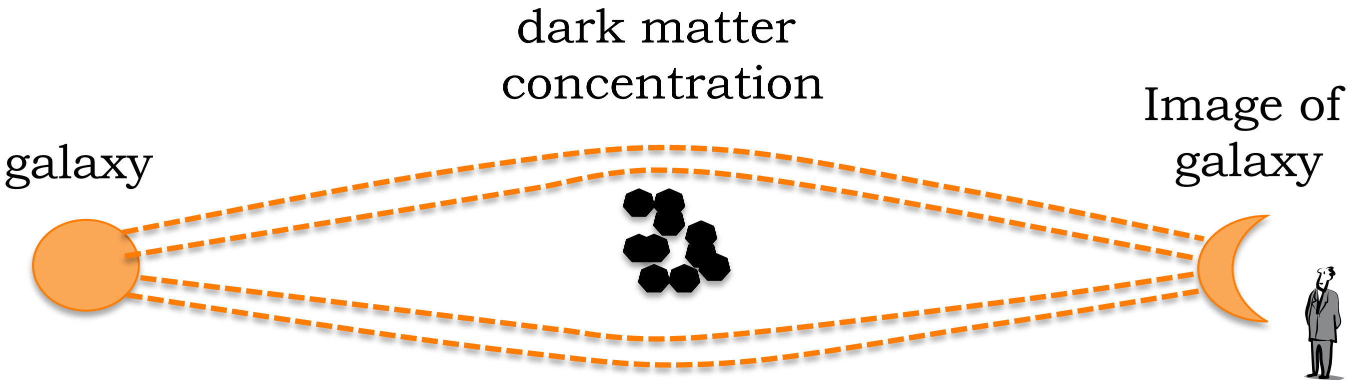
$$m_{inertial} = m_{gravitational}$$

It is the equivalence

$$\text{acceleration} \approx \text{gravitational field}$$







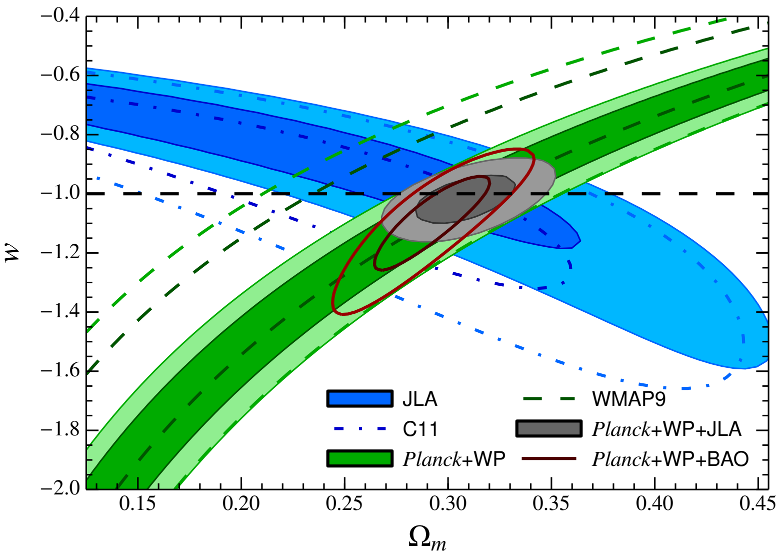
dark matter concentration
galaxy
Image of galaxy

All evidence for the dark components of the Universe is of gravitational nature

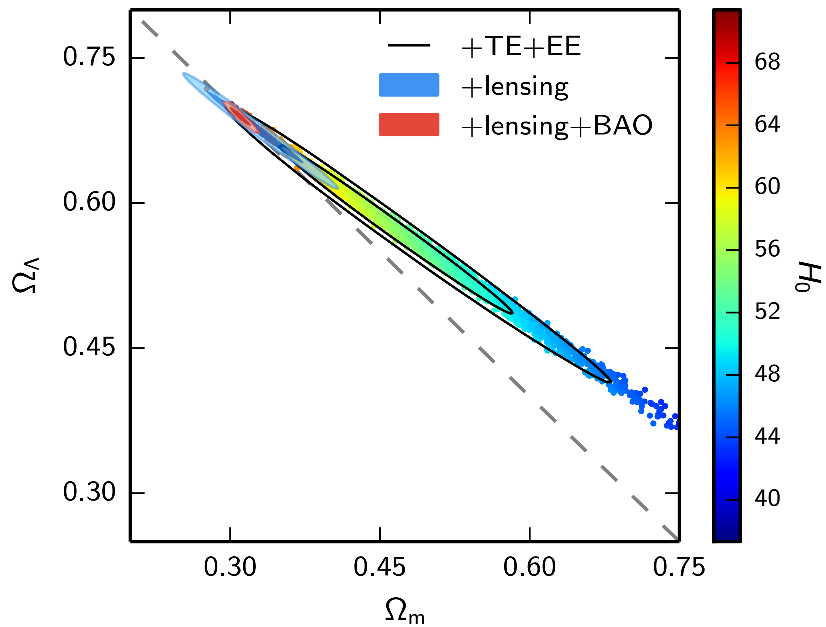
Dark energy

All methods rely on the rate of expansion of the Universe, or on the spatial flatness of the Universe, which are gravitational characteristics of our Universe (i.e. properties of the space-time metric).

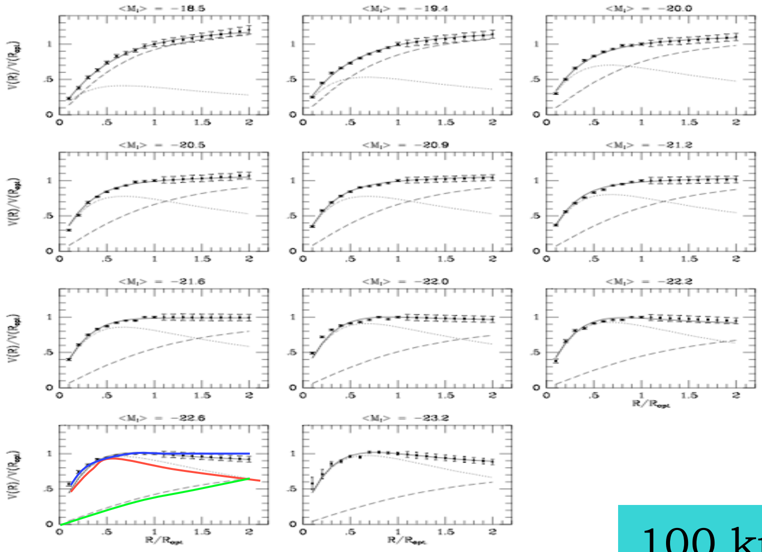
Betoule et al. 1401.4064



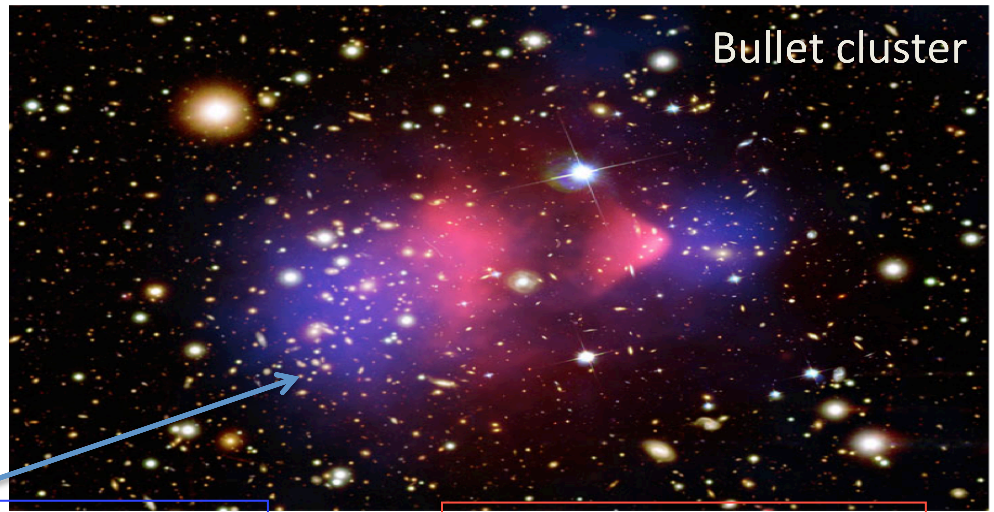
Planck 1502.0589



Dark matter

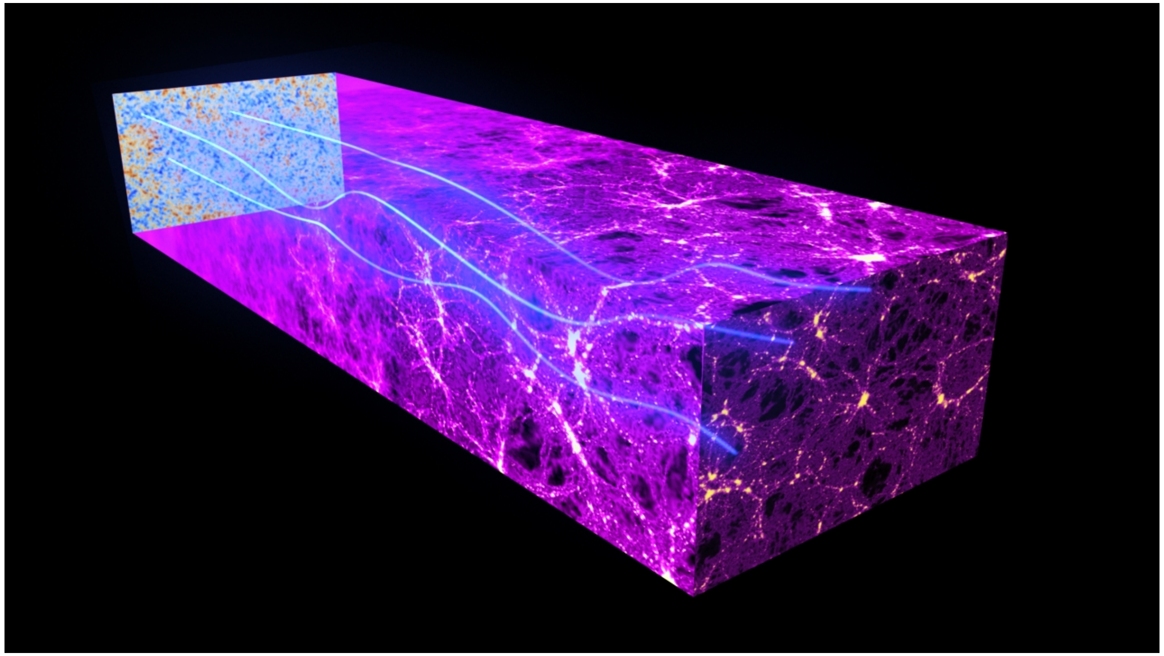


100 kpc

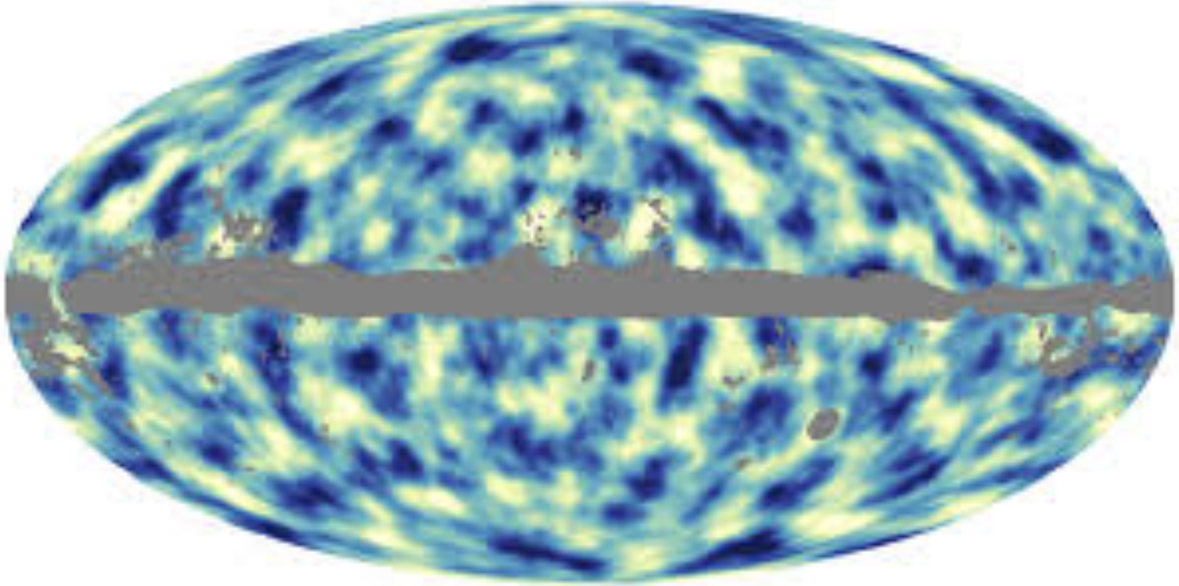


dark matter
gravitational lens

Ordinary matter
X rays

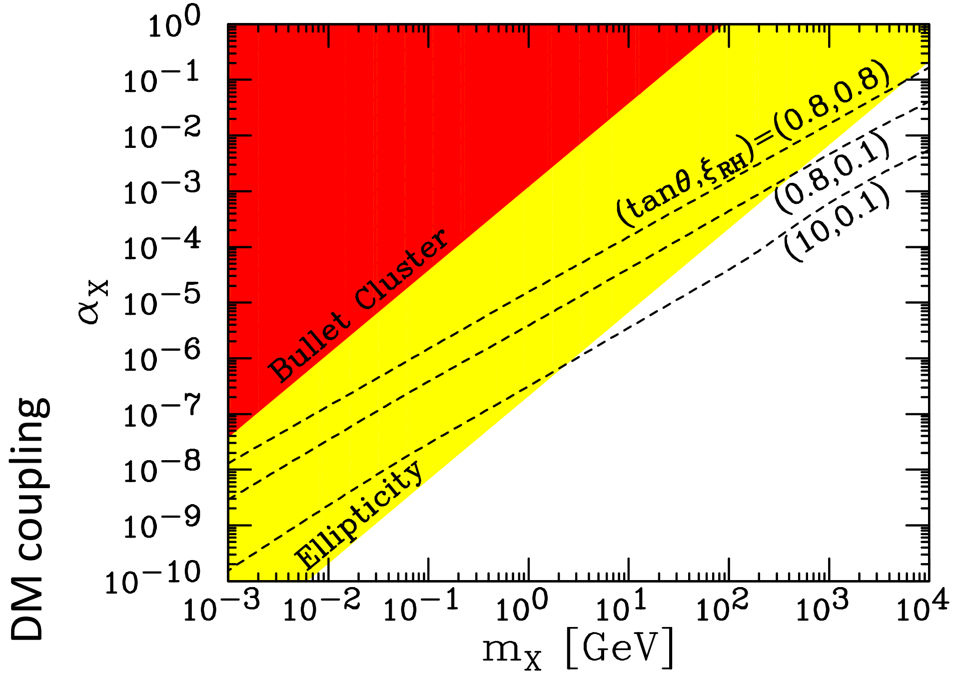


Planck results



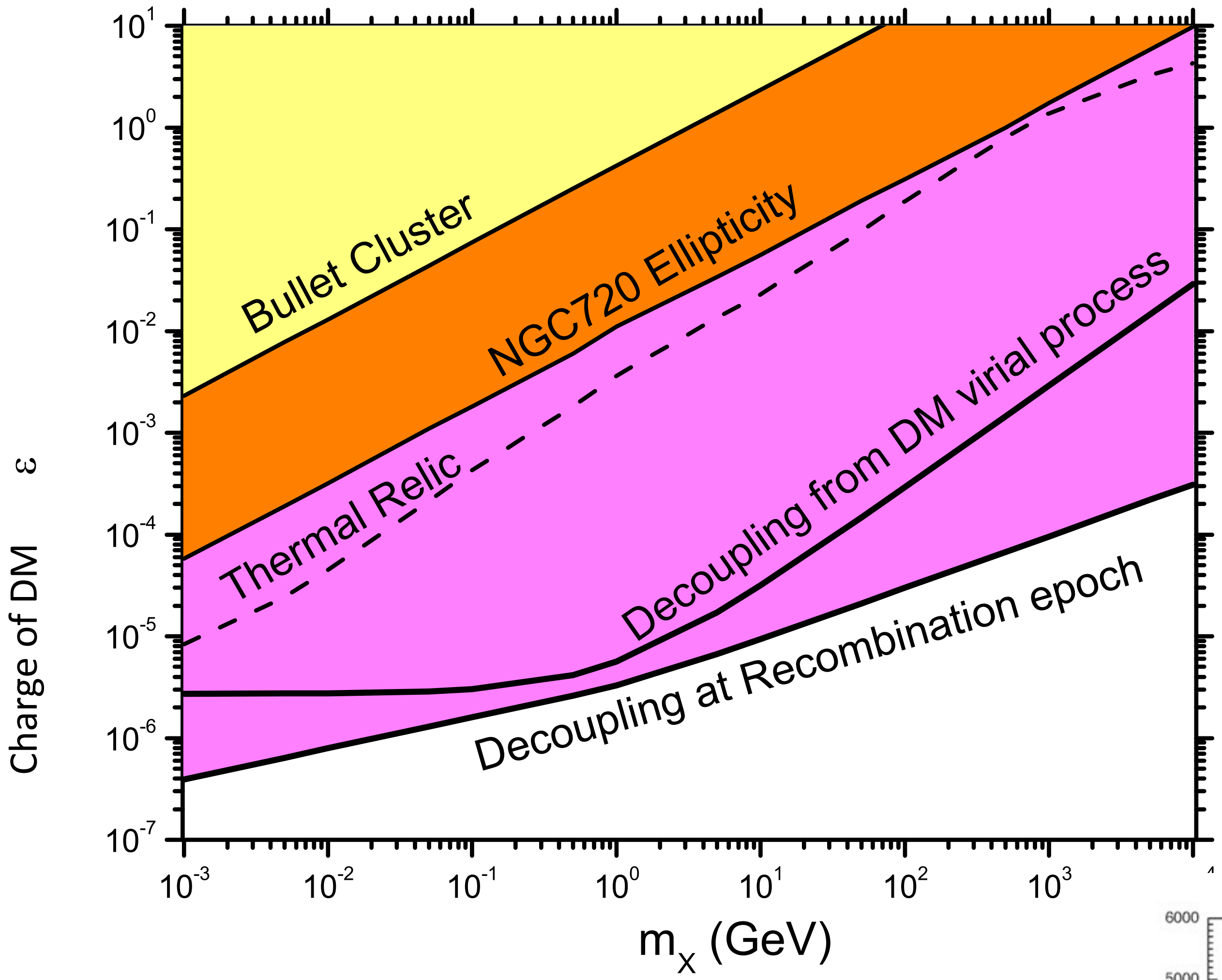
map of dark matter obtained through gravitational lensing

But one can infer some properties of dark matter



Feng, Tu, Yu 0905.3039

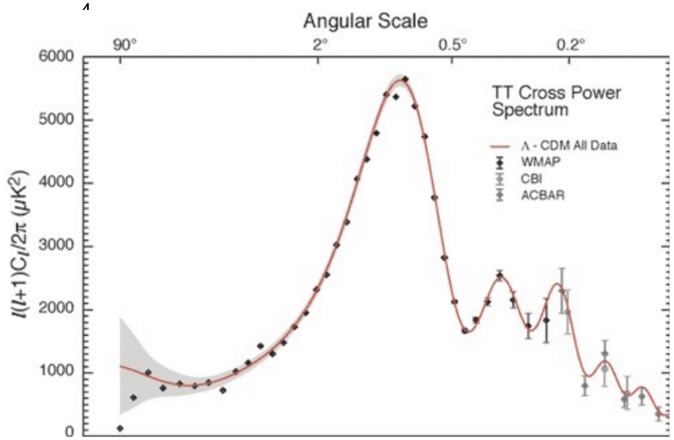
Dark matter interacts weakly: confirmed by flattened shape of cluster or galaxy halos



$d\sigma/d\Omega \propto 1/v^4$

McDermoot, Yu, Zurek

1011.2907

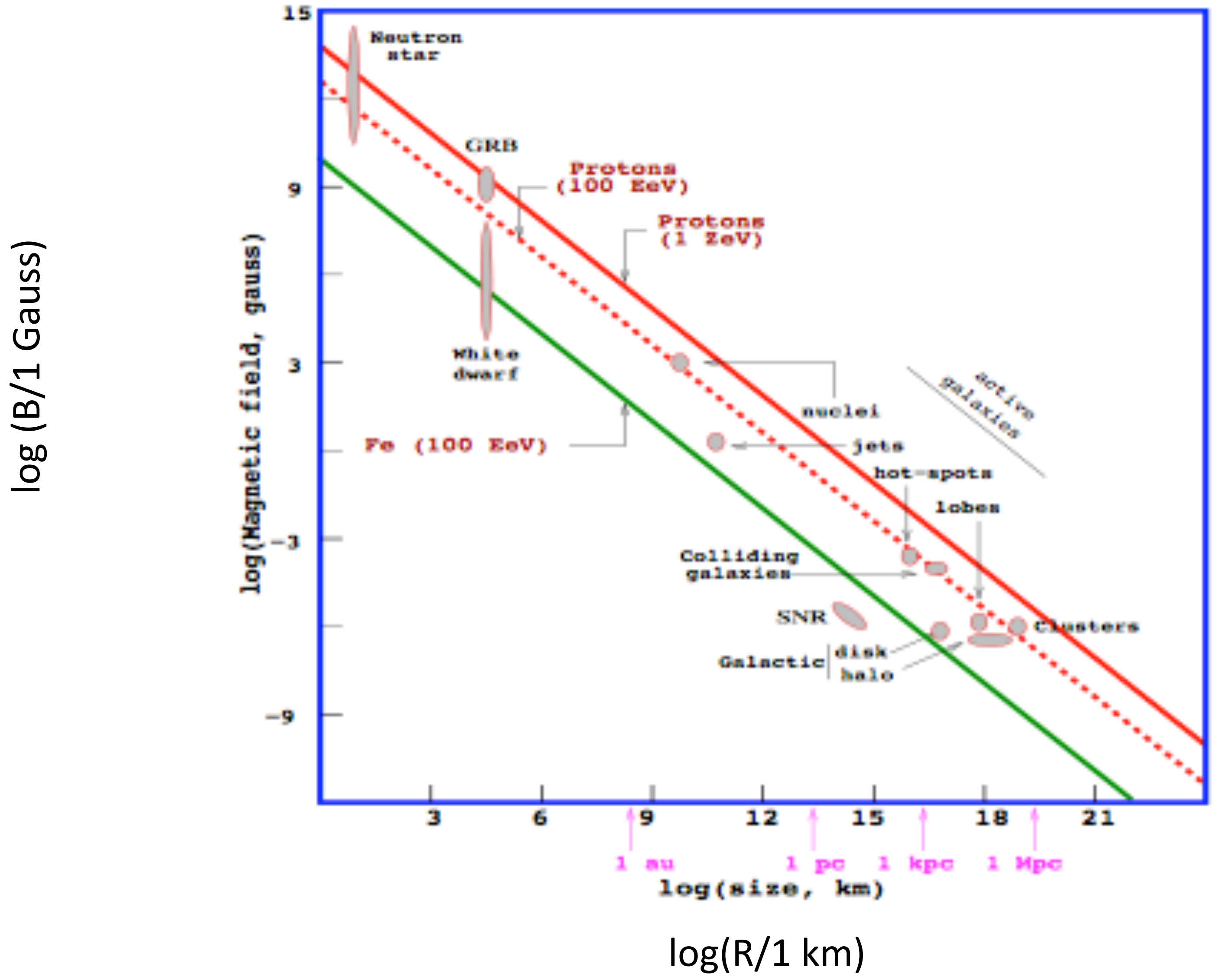


Second definition of astroparticle physics

Astroparticle = Cosmic particle

We are mostly interested in energetic cosmic particles (easier to disentangle , reach energies that are not necessarily available in accelerators, in the case of cosmic rays, more likely to point towards the source).

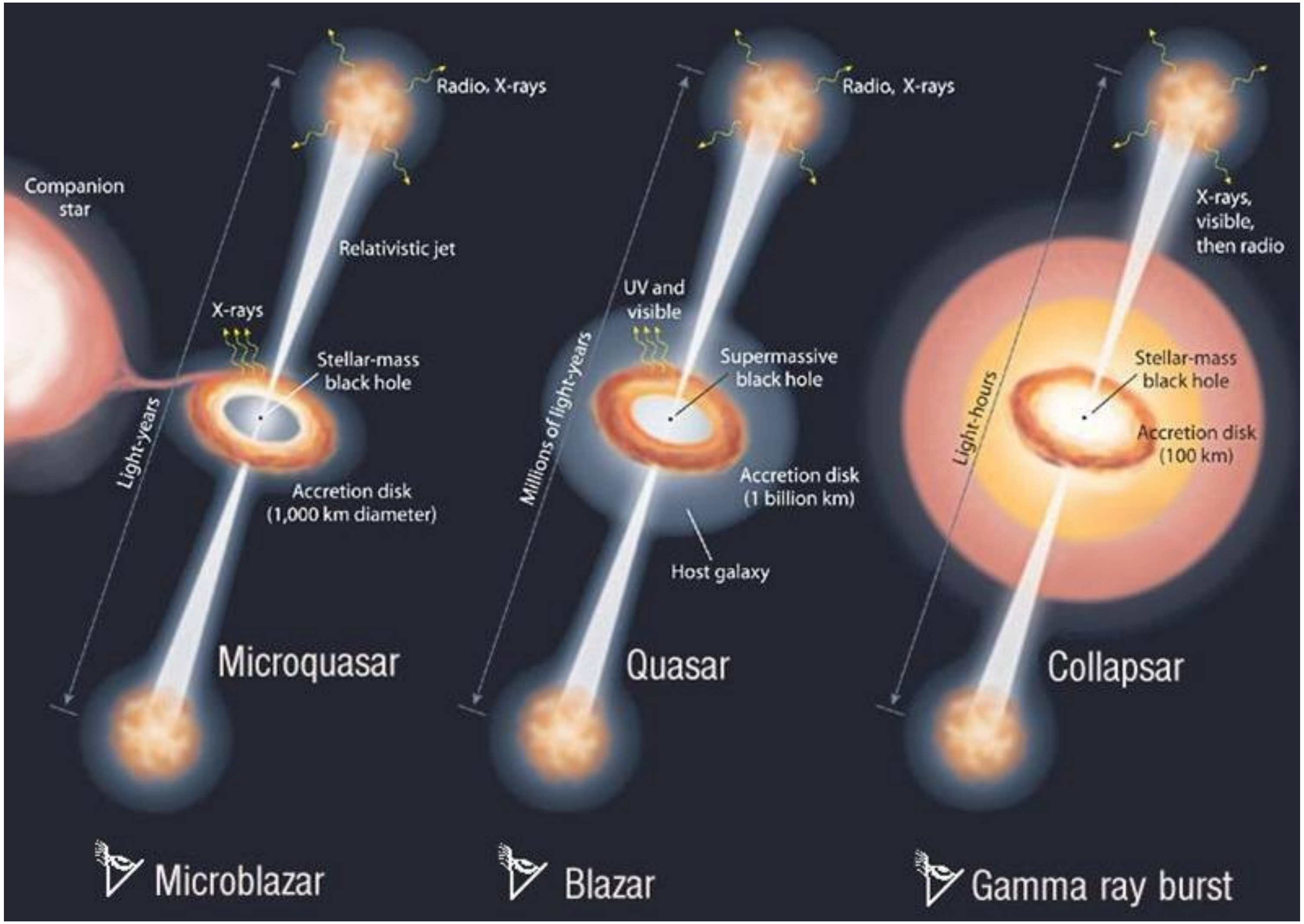
Energetic particles are associated with short time constants and thus with compact astrophysical objects.



Hillas diagram

Towards a reductionist approach?

Despite the diversity of manifestations, striking simplicity of building blocks :



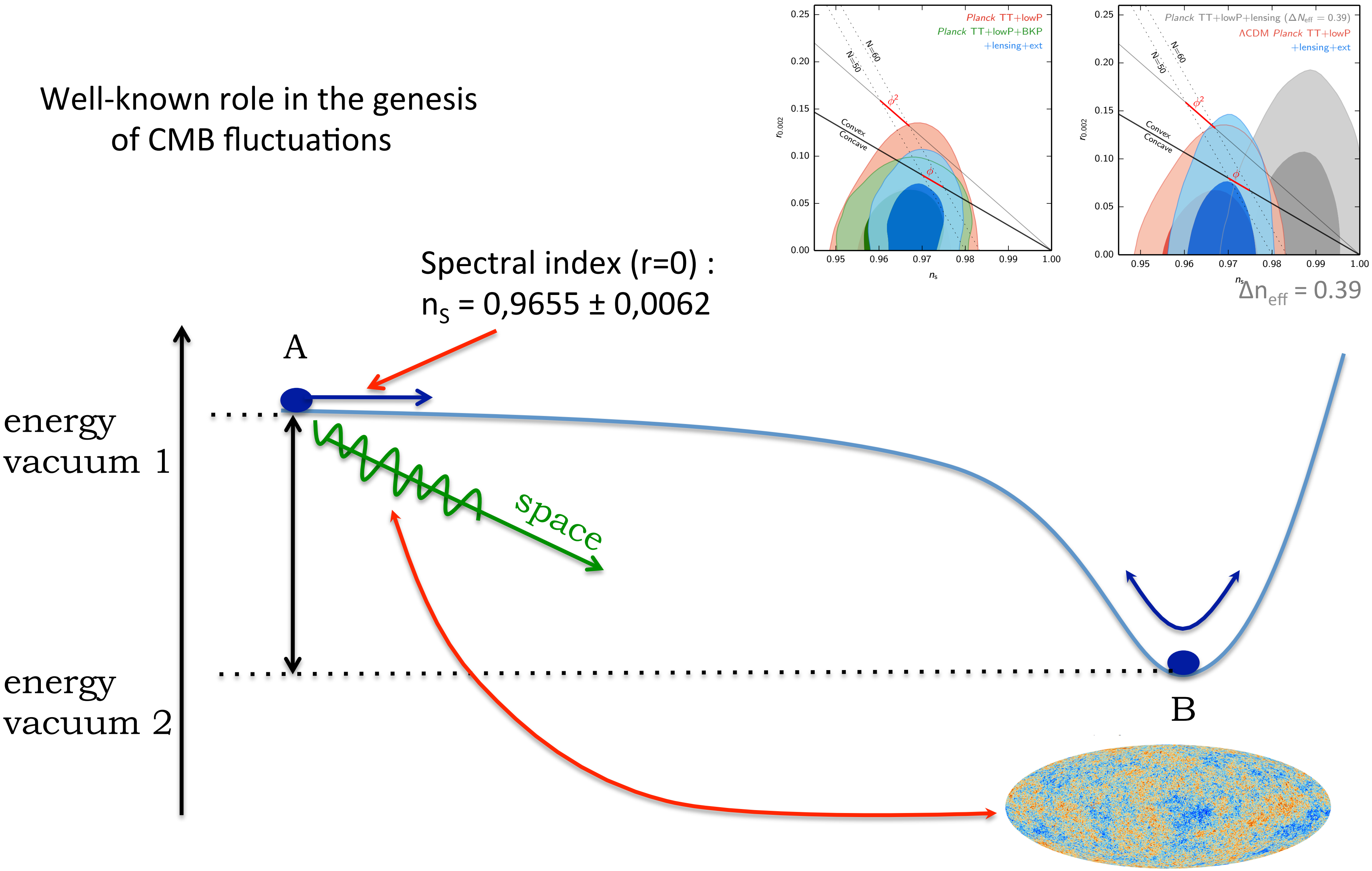
A multi-messenger strategy

Ideally, one would like to study a given source by detecting the photons, neutrinos, hadrons and gravitational waves that they produce:

- gravitational waves give information on the bulk *motion* of matter (explosions, binary systems in rotation)
- energetic photons trace the populations of accelerated particles
- protons give information on the cosmic accelerators
- neutrinos give information on the deepest regions, opaque to photons

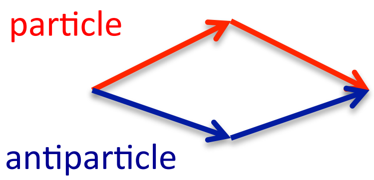
The role of quantum fluctuations

Well-known role in the genesis
of CMB fluctuations



Role in dark energy : vacuum energy

The vacuum is the site of quantum field fluctuations which contribute to its energy



$$\Delta t \leq \Delta E/\hbar = 2mc^2/\hbar$$

Back of an envelope calculation :

$$\rho = m_P^4 \sim 10^{120}\ \rho_{dark\ energy}$$

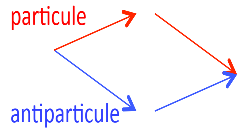
$$\sim \rho_c \sim 10^{-26}\ kg/m^3$$

Vacuum energy problem

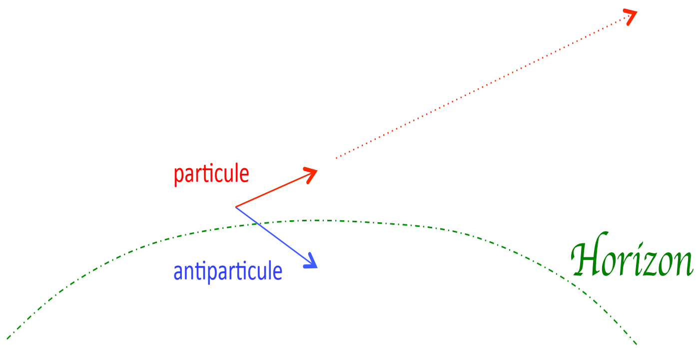
(more later)

Fluctuations play also an important role close to the horizon of a black hole:

Hawking radiation



Thermal radiation
$T \propto M^{-1}$



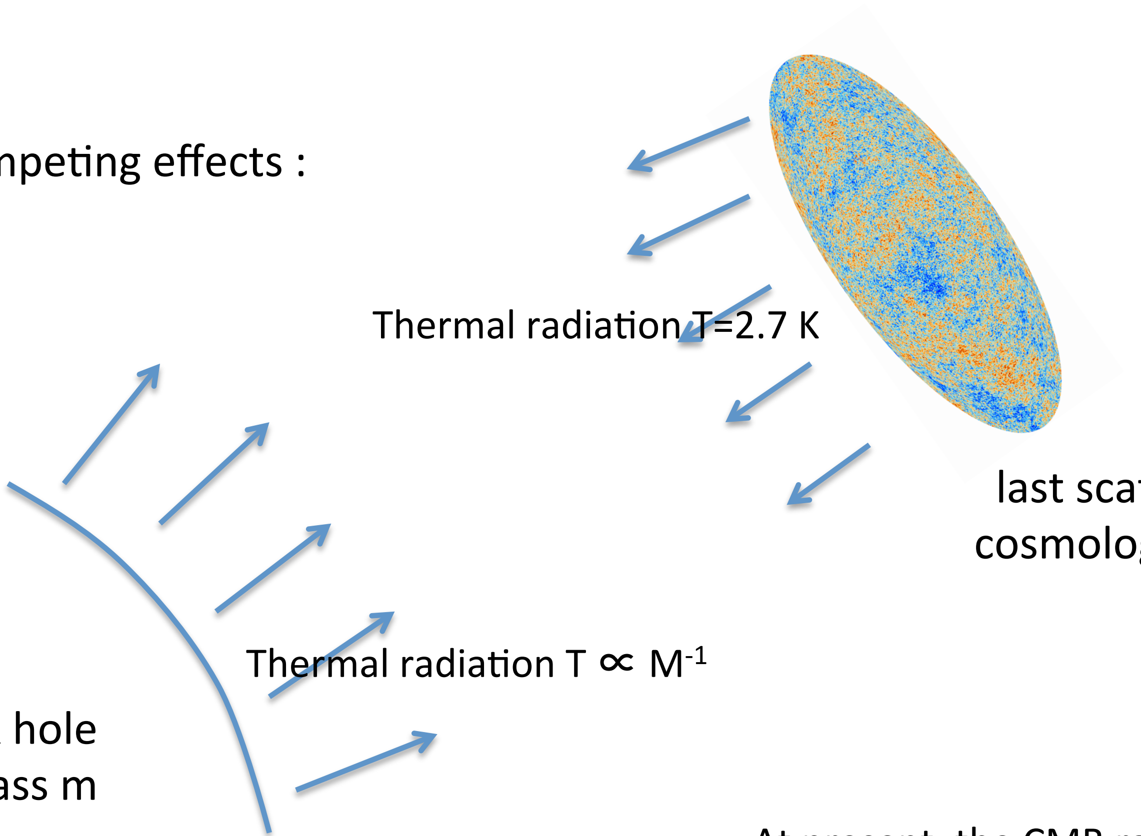
leads in principle to
black hole evaporation

x
singularity
of black hole of mass M

Black hole evaporation vs cosmic microwave background

Hawking 1975
G. Ellis 2014

Two competing effects :



At present, the CMB radiation wins and
stops the Hawking process for all massive BH,
but it also changes the nature of the horizon

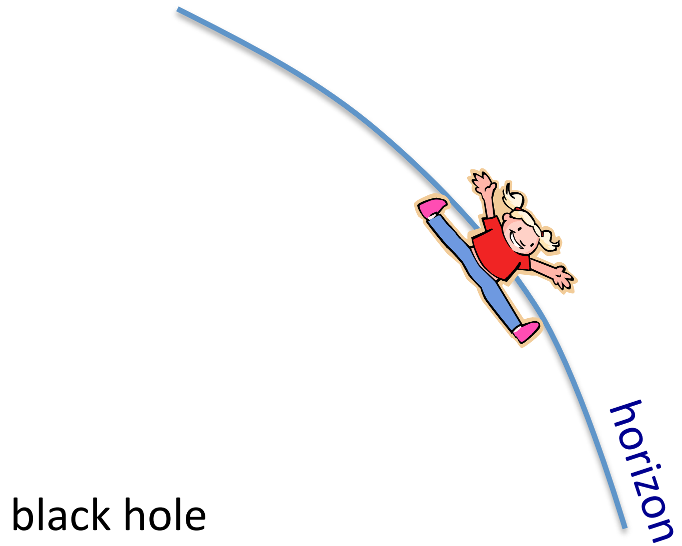
The firewall problem

Almheiri, Marolf, Polchinski, Sully

1207.3123

At the black hole horizon, there appears to be a incompatibility between the laws of quantum mechanics , the laws of quantum field theory (existence of a unitary S matrix) and the laws of general relativity.

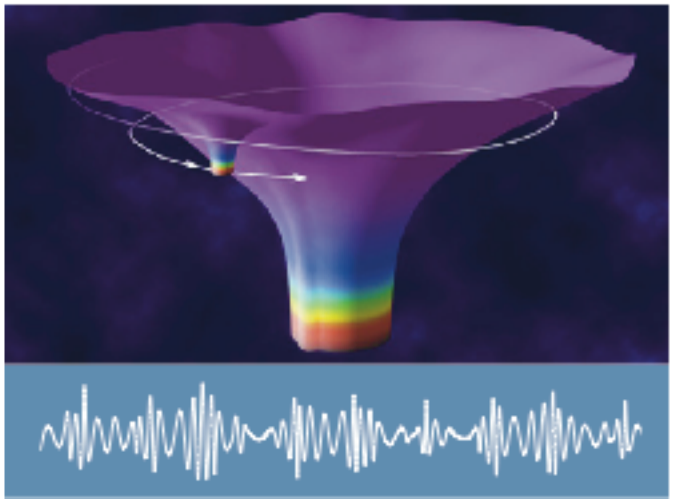
AMBS claim that an observer falling into a black hole horizon will encounter a « firewall »



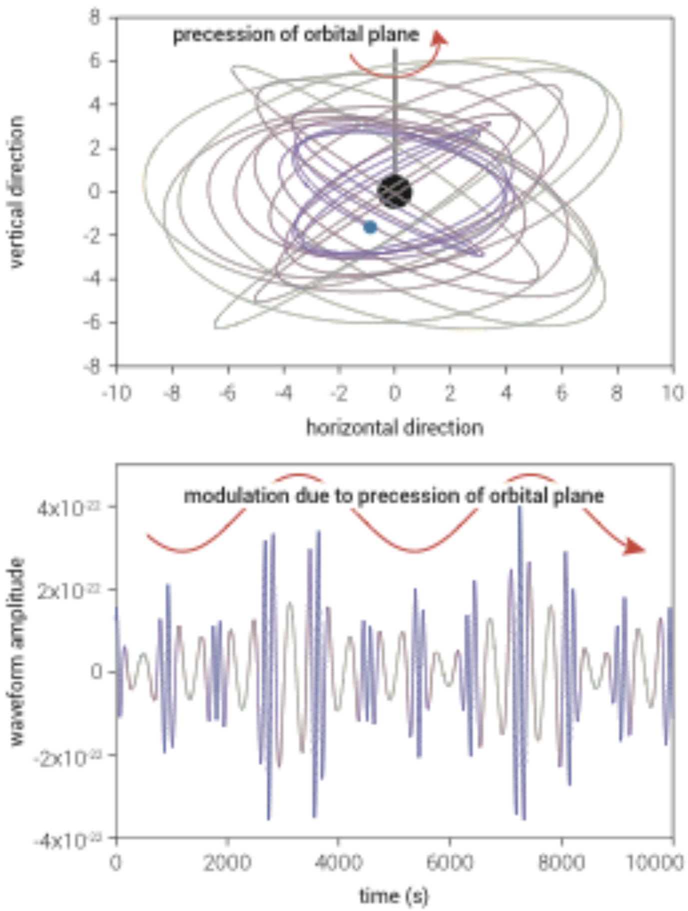
Incompatible with the equivalence principle: free fall ≡ flat space

This led Hawking and others to reconsider the nature or even the existence of the horizon around black holes…

Who will tell? Probably gravitational waves.



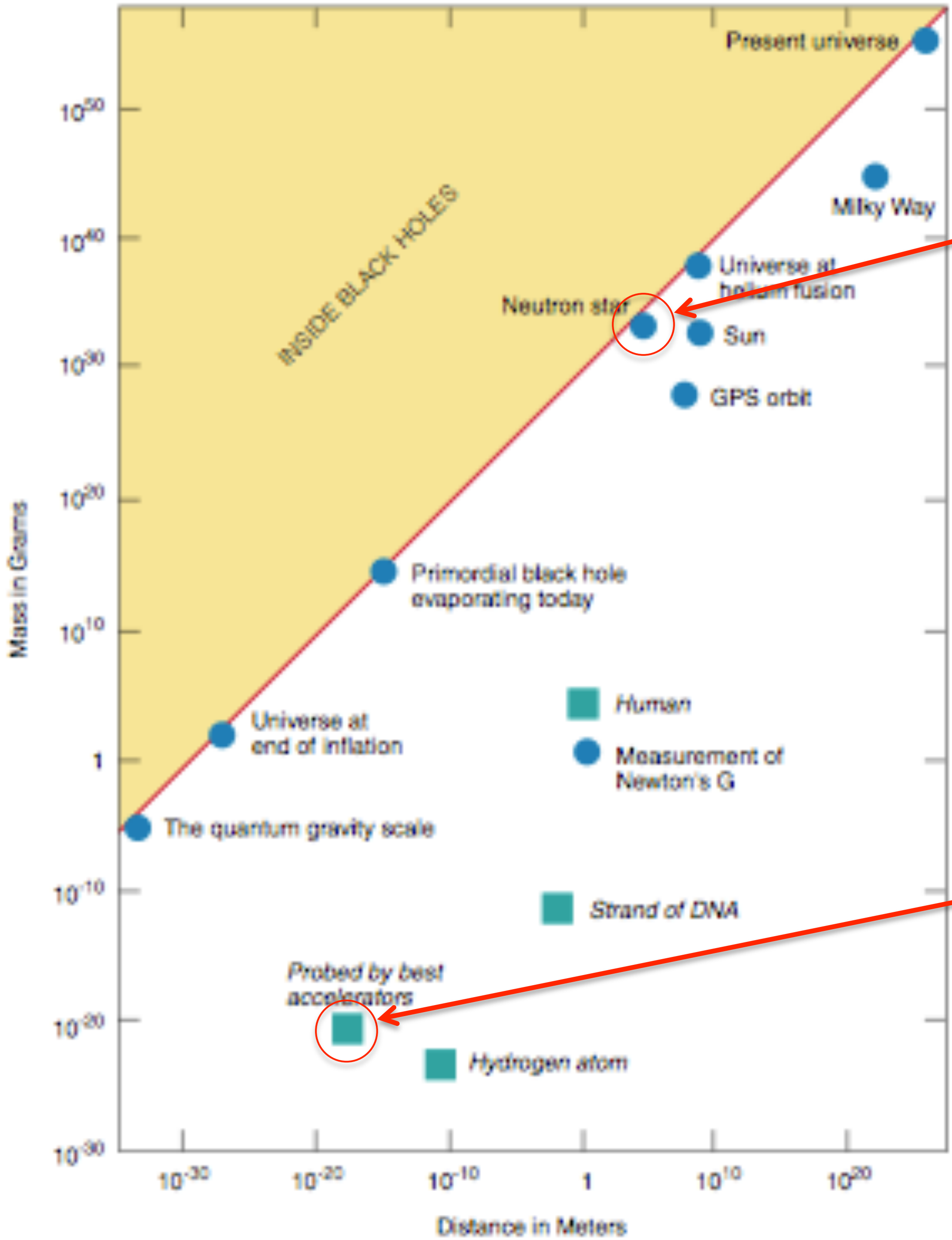
LISA



The stellar black hole cycles some 10^5 times around the supermassive black hole before plunging into its horizon.
Allows to map the geometry of space-time close to the black hole horizon

Electromagnetic signals?

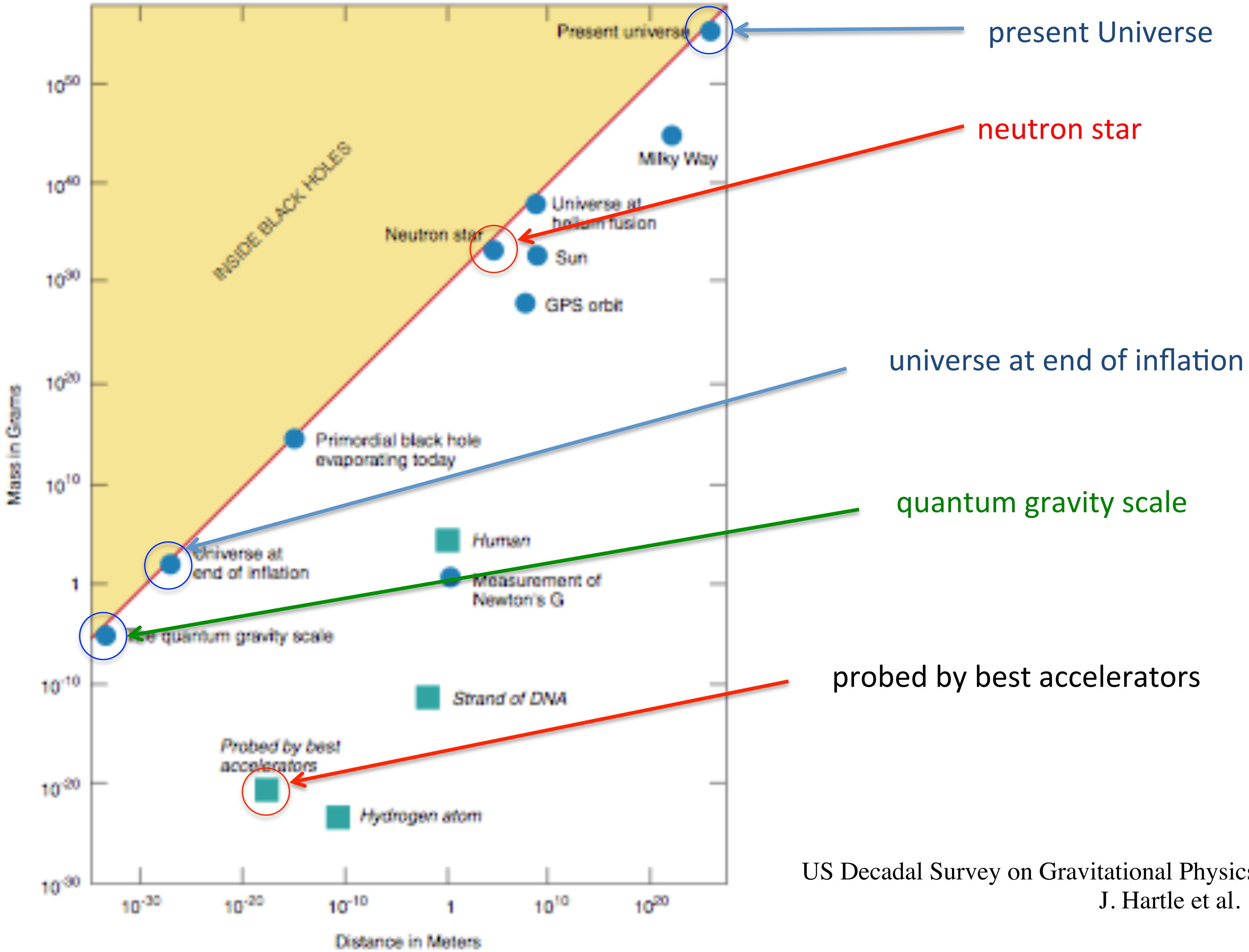
Back to the gravitational force



neutron star

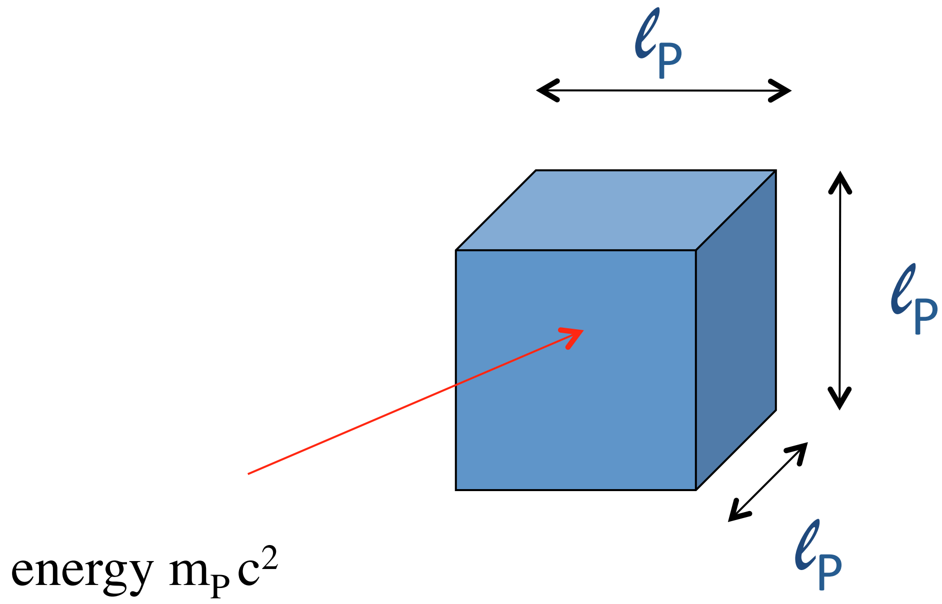
probed by best accelerators

US Decadal Survey on Gravitational Physics
J. Hartle et al.



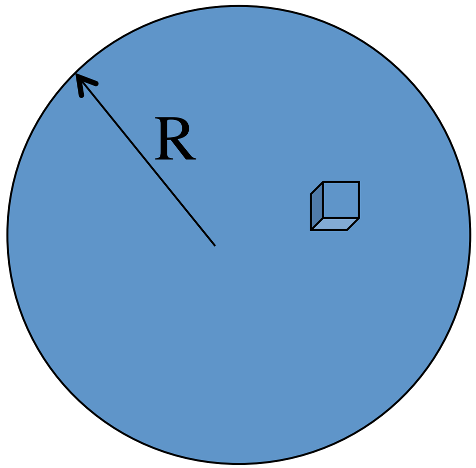
US Decadal Survey on Gravitational Physics
J. Hartle et al.

Put the maximum amount of energy in an elementary Planck cell



$$\varrho = \frac{m_P c^2}{\ell_P^3} = m_P^4 \text{ in units } \hbar = c = 1$$

Next consider a macroscopic region of size R



$$E = (4\pi R^3/3)\,\varrho$$
$$= (4\pi/3)\, m_P\, (R m_P)^3$$

But this object will undergo gravitational collapse when

$$R < R_{schwarschild} = 2\, G_N\, E = E/(4\pi\, m_P^2) = (R m_P)^3 / 3 m_P$$

i.e. $R > 1/m_P = \ell_P$

In other words, gravitational collapse prevents us from storing, in a region of macroscopic size R, an energy larger than $R/2G_N$, i.e. an energy density larger than

$$\varrho_{max} = E/(4\pi R^3/3) = \frac{3}{8\pi G_N R^2}$$

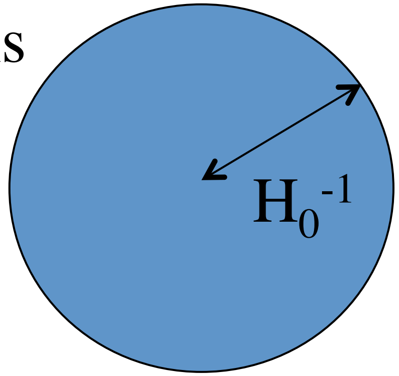
Apply this to the whole observable Universe ($R = H_0^{-1}$)

$$\varrho < \frac{3\,H_0^2}{8\pi G_N} = \varrho_c$$

But why $\varrho \sim \varrho_c$?

Visible Universe as a condensate of gravitons

c=1



Individual quantum state of a graviton:

$$\varepsilon \sim \hbar k \sim \hbar H_0$$

Total energy: $E = N\varepsilon$

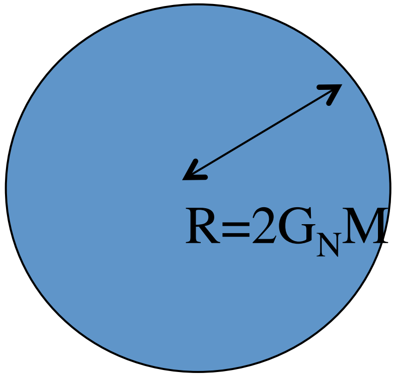
occupation number

$$E < H_0^{-1}/(2G_N) \Rightarrow N = E/\varepsilon < \frac{1}{G_N \hbar H_0^2} = \frac{1}{(\ell_P H_0)^2}$$

Maximal classicity corresponds to maximal value of N:

$$N = N_{max} = \frac{1}{(\ell_P H_0)^2} \sim 10^{84}$$

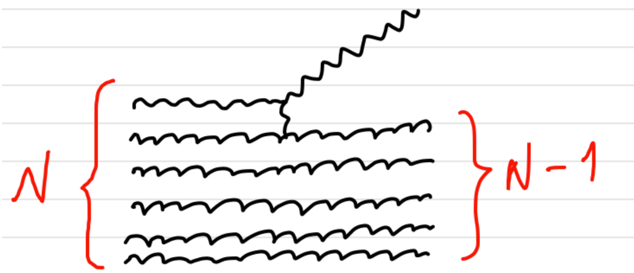
cf. Dvali and Gomez, quantum portrait of a black hole of radius R



1112.3359 [hep-th]

leaking Bose-Einstein condensate :

$N = (R/\ell_P)^2$ soft gravitons of wavelength $\lambda \sim R$, weakly interacting

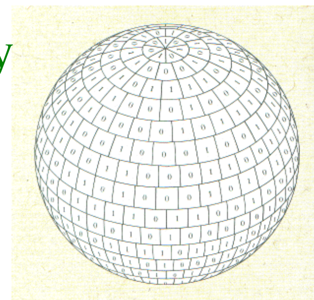


Hawking radiation

$t_{decay} \sim N^{3/2} \ell_P = R^{3/2} / \ell_P^2 \sim NR$

Entropy $S \sim N \propto R^2$

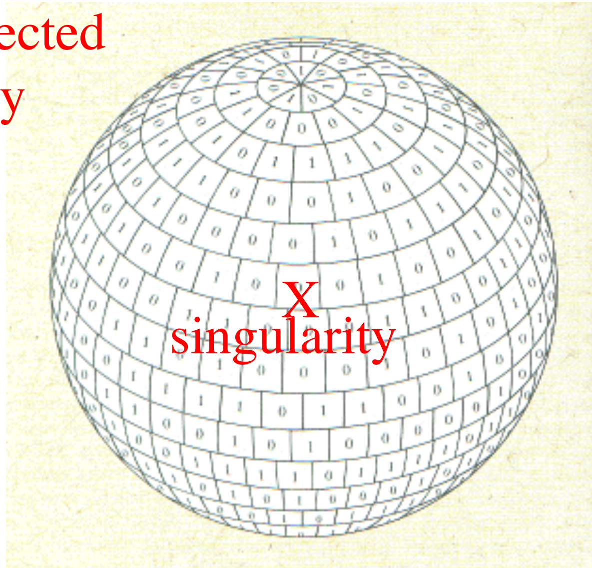
area theorem for the entropy
of black holes (Bekenstein)



Hence maximal entropy corresponds to maximal N i.e. $\rho \sim \rho_c$

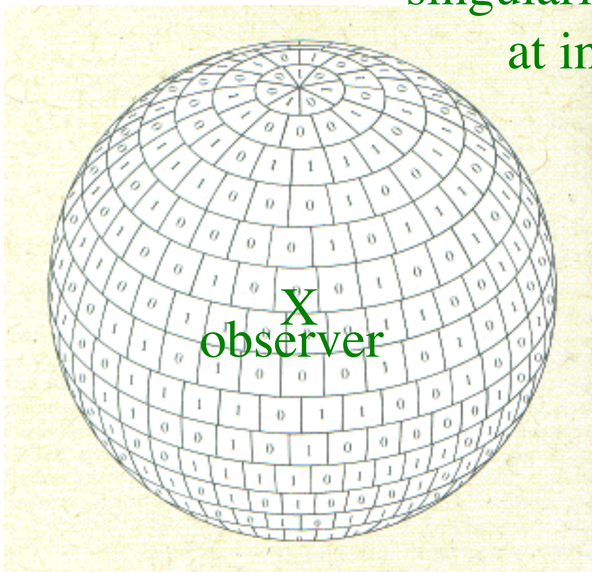
Note however that this does not amount to consider that we are inside a BH

observer rejected
at infinity



Black hole

singularity rejected
at infinity



Visible Universe

It is more like being surrounded by a black hole:
the condensate is then the ouside of the black hole!

Conclusion

Particle astrophysics is not just astrophysics.

It addresses some of the most fundamental issues in our field, in particular the central question of how we reconcile quantum theory with general relativity, the theory of gravitation.

This might lead us to clues on theories beyond the Standard Model, especially if the corresponding physics is beyond the reach of LHC.

Horizons (both black hole and cosmological) may be the place to look for signals of breakdown of our existing theories (general relativity, Standard Model).

Thank you