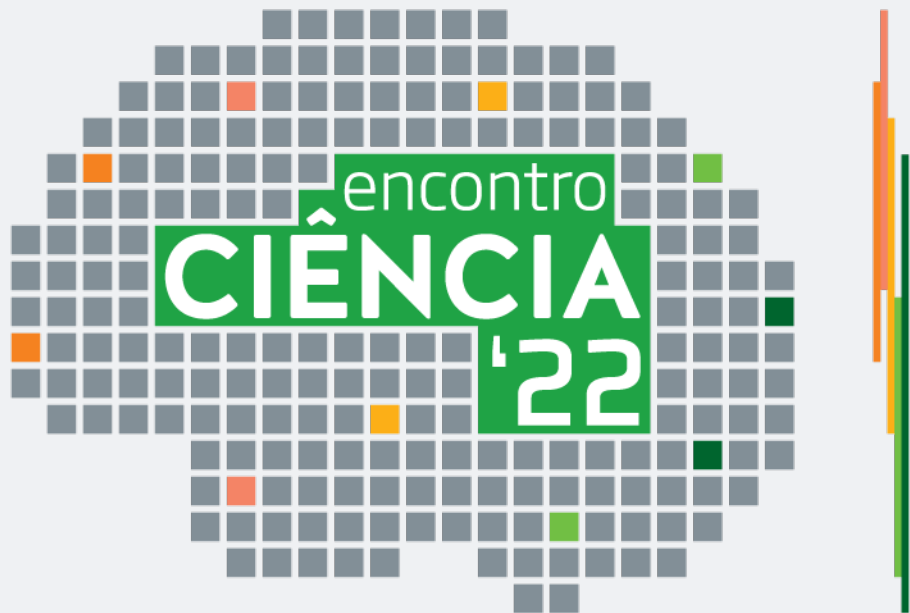


# Exploring Strong Gravity with GRIT



Guilherme Raposo

Encontro Ciência 2022

16/05/2022

# About Us

Who are we?



**centra**

Centre for astrophysics and gravitation

+25 Professors and Researchers

+35 Students

3 Research Groups (GRIT, COSTAR, SIM)

**CENTRA Focus:** Astrophysics, cosmology, gravitation, dark matter



**grit**

gravitation in técnico

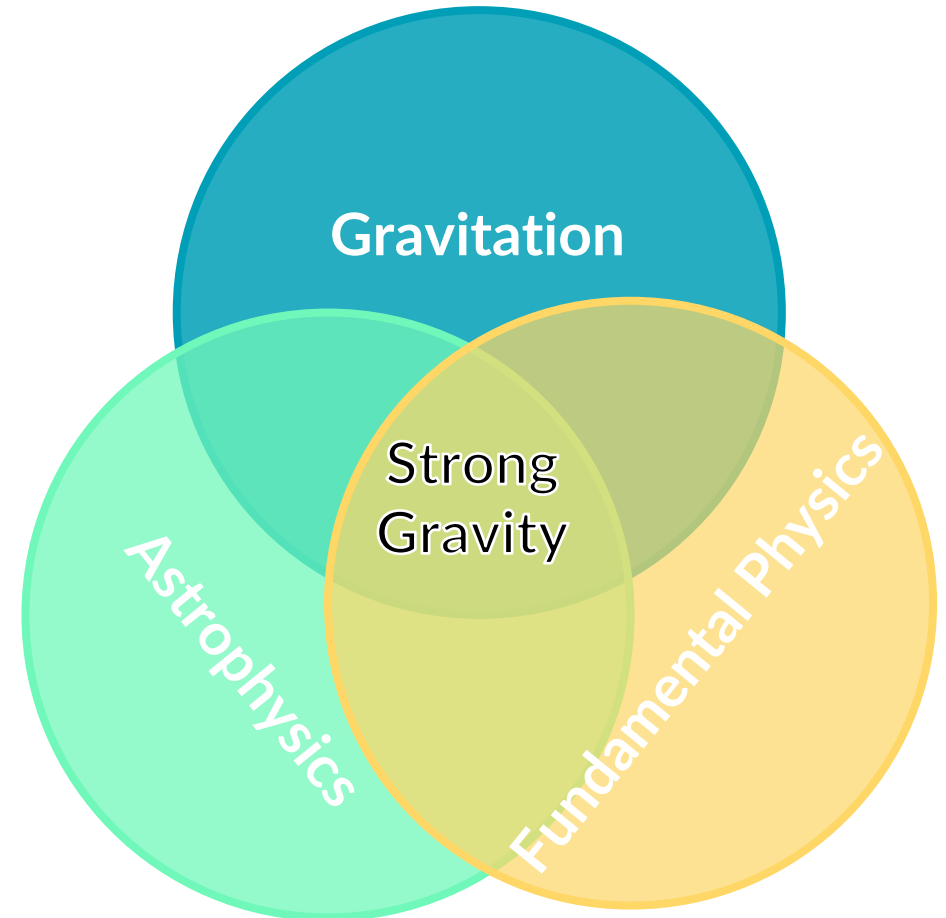
+10 Professors and Researchers

+15 Students

3 ERC Grants (Prof. Vitor Cardoso)



**GRIT Focus:** Strong Gravity: Black holes, Einstein's gravity and beyond



[Credits: P. Pani]

# Why Strong Gravity?

A new age in observational astronomy has started

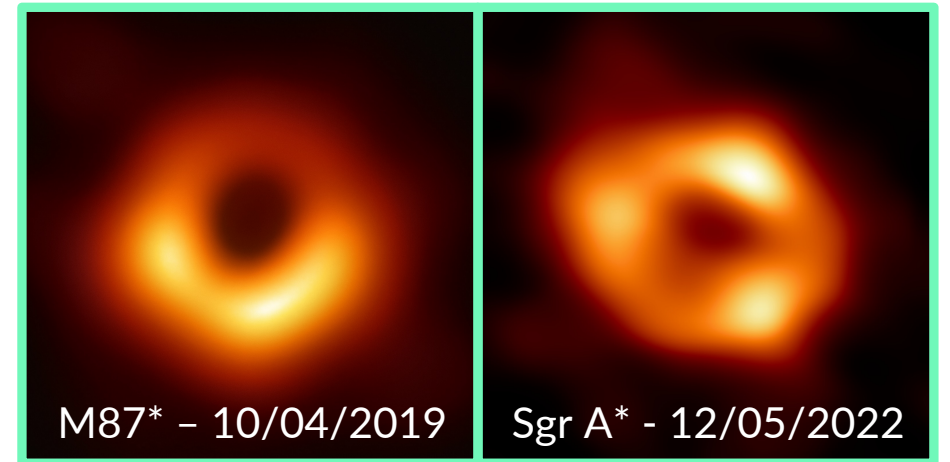
Dawn of gravitational wave astronomy



[Credits: Video: N. Fischer and H. Pfeiffer; Simulation: SXS collaboration]

Hundreds of black holes have been observed since 2015!

Black hole imaging



[Credits: EHT collaboration]

The first images of black holes have been taken!

New ways to put Einstein's theory to test!

# Extreme Gravity

How to solve Einstein's equations in extreme gravity?

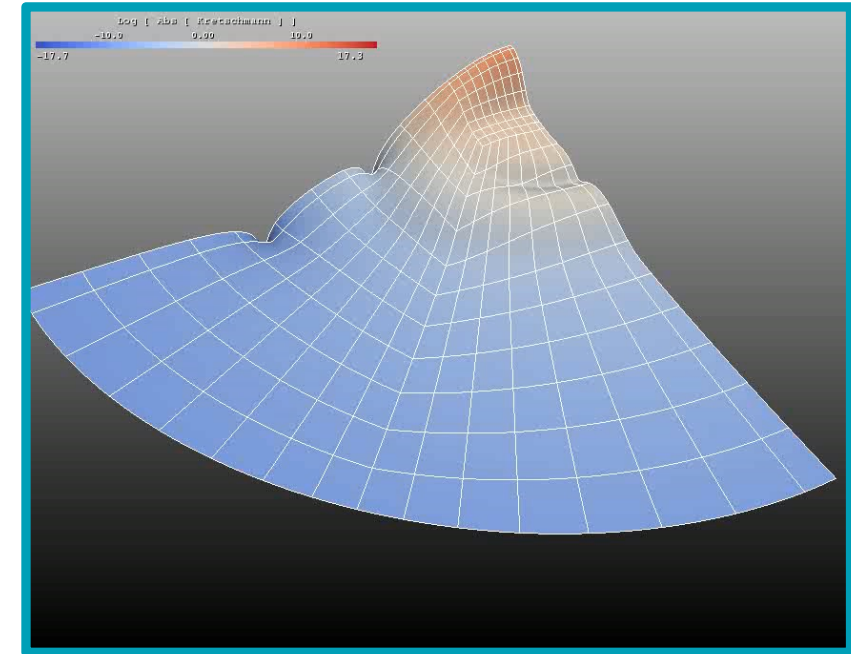
Spacetime tells matter  
how to move...

$$G_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

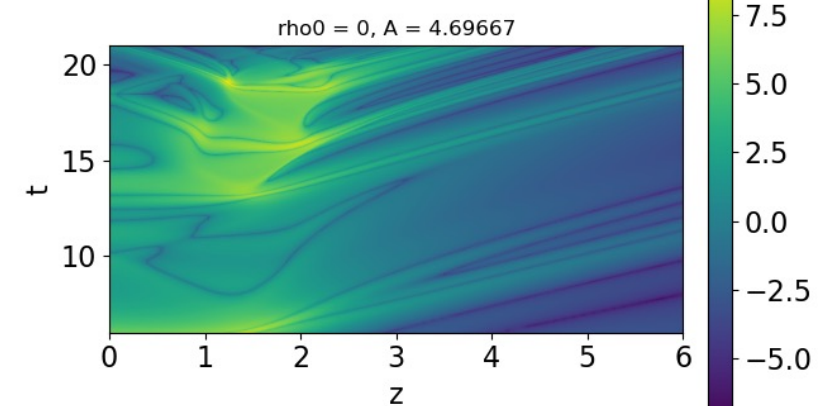
...matter tells spacetime  
how to curve

Simple Theory?

Extreme Gravity interacting with itself

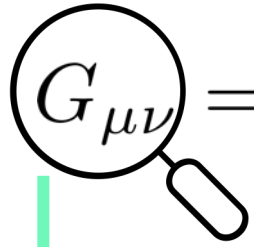


[Credits: Video: D. Hilditch, *Phys.Rev.D.* 96, 104041, 2017  
Picture: I. Fernandez, *arXiv*: 2205.04379]



# Extreme Gravity

How to solve Einstein's equations in extreme gravity?



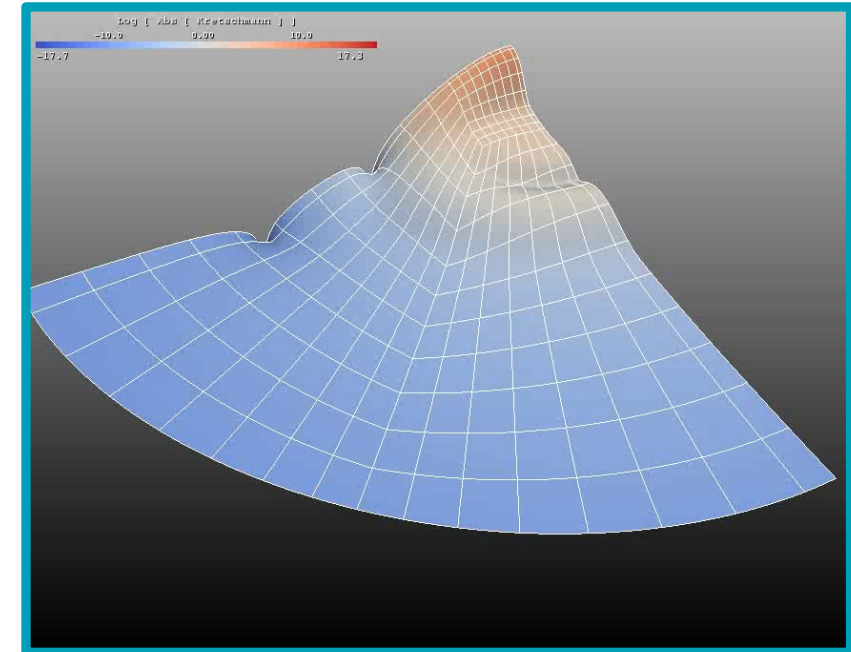
$$G_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$



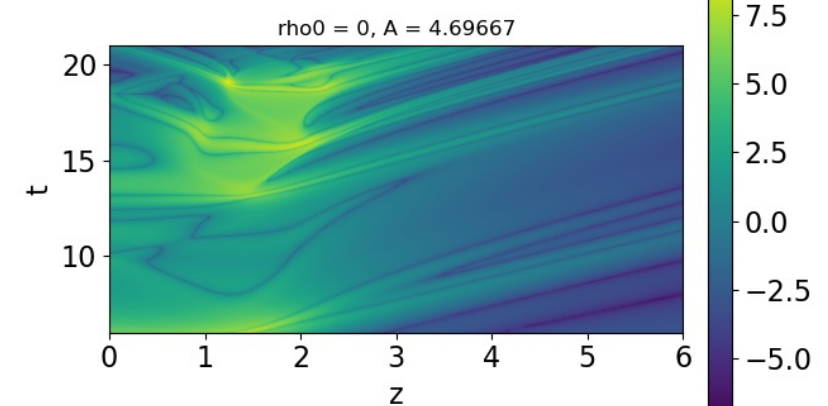
$$\begin{aligned} & \frac{1}{2} \sum_{\alpha=0}^3 \sum_{\beta=0}^3 g^{\alpha\beta} \partial_\alpha \partial_\mu g_{\beta\nu} + \frac{1}{2} \sum_{\alpha=0}^3 \sum_{\beta=0}^3 g^{\alpha\beta} \partial_\alpha \partial_\nu g_{\mu\beta} - \frac{1}{2} \sum_{\alpha=0}^3 \sum_{\beta=0}^3 g^{\alpha\beta} \partial_\alpha \partial_\beta g_{\mu\nu} - \frac{3}{2} \sum_{\alpha=0}^3 \sum_{\beta=0}^3 g^{\alpha\beta} \partial_\mu \partial_\nu g_{\alpha\beta} - \frac{1}{2} \\ & \sum_{\alpha=0}^3 \sum_{\beta=0}^3 \sum_{\rho=0}^3 \sum_{\lambda=0}^3 g^{\beta\lambda} g^{\alpha\rho} \partial_\alpha g_{\rho\lambda} \partial_\mu g_{\beta\nu} - \frac{1}{2} \sum_{\alpha=0}^3 \sum_{\beta=0}^3 \sum_{\rho=0}^3 \sum_{\lambda=0}^3 g^{\beta\lambda} g^{\alpha\rho} \partial_\alpha g_{\rho\lambda} \partial_\nu g_{\mu\beta} + \frac{1}{4} \sum_{\alpha=0}^3 \sum_{\beta=0}^3 \sum_{\rho=0}^3 \\ & \sum_{\lambda=0}^3 g^{\beta\lambda} g^{\alpha\rho} \partial_\nu g_{\alpha\lambda} \partial_\mu g_{\rho\beta} + \frac{1}{4|g|} \sum_{\alpha=0}^3 \sum_{\beta=0}^3 g^{\alpha\beta} \partial_\beta |g| \partial_\nu g_{\mu\alpha} - \frac{1}{4|g|} \sum_{\alpha=0}^3 \sum_{\beta=0}^3 g^{\alpha\beta} \partial_\beta |g| \partial_\alpha g_{\mu\nu} - \frac{1}{4|g|} \sum_{\alpha=0}^3 \\ & \sum_{\beta=0}^3 g^{\alpha\beta} \partial_\beta |g| \partial_\mu g_{\alpha\nu} + \Lambda g_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu} \end{aligned}$$

Develop new **tools** to understand the theory

Extreme Gravity interacting with itself



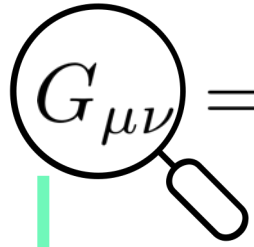
[Credits: Video: D. Hilditch, *Phys.Rev.D.* 96, 104041, 2017  
Picture: I. Fernandez, *arXiv*: 2205.04379]





# Extreme Gravity

How to solve Einstein's equations in extreme gravity?



$$G_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$



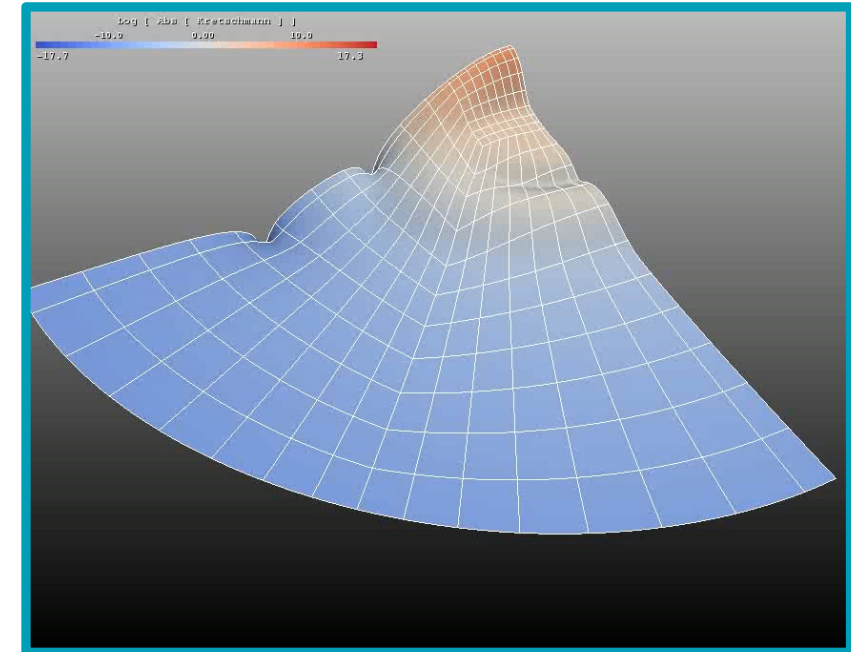
$$\begin{aligned} & \frac{1}{2} \sum_{\alpha=0}^3 \sum_{\beta=0}^3 g^{\alpha\beta} \partial_\alpha \partial_\mu g_{\beta\nu} + \frac{1}{2} \sum_{\alpha=0}^3 \sum_{\beta=0}^3 g^{\alpha\beta} \partial_\alpha \partial_\nu g_{\mu\beta} - \frac{1}{2} \sum_{\alpha=0}^3 \sum_{\beta=0}^3 g^{\alpha\beta} \partial_\alpha \partial_\beta g_{\mu\nu} - \frac{3}{2} \sum_{\alpha=0}^3 \sum_{\beta=0}^3 g^{\alpha\beta} \partial_\mu \partial_\nu g_{\alpha\beta} - \frac{1}{2} \\ & \sum_{\alpha=0}^3 \sum_{\beta=0}^3 \sum_{\rho=0}^3 \sum_{\lambda=0}^3 g^{\beta\lambda} g^{\alpha\rho} \partial_\alpha g_{\rho\lambda} \partial_\mu g_{\beta\nu} - \frac{1}{2} \sum_{\alpha=0}^3 \sum_{\beta=0}^3 \sum_{\rho=0}^3 \sum_{\lambda=0}^3 g^{\beta\lambda} g^{\alpha\rho} \partial_\alpha g_{\rho\lambda} \partial_\nu g_{\mu\beta} + \frac{1}{4} \sum_{\alpha=0}^3 \sum_{\beta=0}^3 \sum_{\rho=0}^3 \\ & \sum_{\lambda=0}^3 g^{\beta\lambda} g^{\alpha\rho} \partial_\nu g_{\alpha\lambda} \partial_\mu g_{\rho\beta} + \frac{1}{4|g|} \sum_{\alpha=0}^3 \sum_{\beta=0}^3 g^{\alpha\beta} \partial_\beta |g| \partial_\nu g_{\mu\alpha} - \frac{1}{4|g|} \sum_{\alpha=0}^3 \sum_{\beta=0}^3 g^{\alpha\beta} \partial_\beta |g| \partial_\alpha g_{\mu\nu} - \frac{1}{4|g|} \sum_{\alpha=0}^3 \\ & \sum_{\beta=0}^3 g^{\alpha\beta} \partial_\beta |g| \partial_\mu g_{\alpha\nu} + \Lambda g_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu} \end{aligned}$$

Develop new **tools** to understand the theory

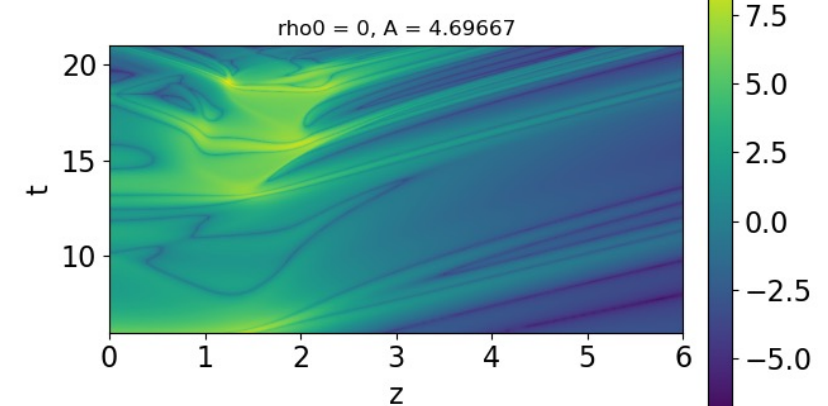
Mathematical Analysis

Perturbation Theory

Extreme Gravity interacting with itself

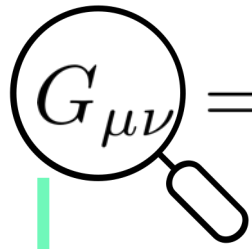


[Credits: Video: D. Hilditch, *Phys.Rev.D.* 96, 104041, 2017  
Picture: I. Fernandez, *arXiv*: 2205.04379]



# Extreme Gravity

How to solve Einstein's equations in extreme gravity?



$$G_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$



$$\begin{aligned} & \frac{1}{2} \sum_{\alpha=0}^3 \sum_{\beta=0}^3 g^{\alpha\beta} \partial_\alpha \partial_\mu g_{\beta\nu} + \frac{1}{2} \sum_{\alpha=0}^3 \sum_{\beta=0}^3 g^{\alpha\beta} \partial_\alpha \partial_\nu g_{\mu\beta} - \frac{1}{2} \sum_{\alpha=0}^3 \sum_{\beta=0}^3 g^{\alpha\beta} \partial_\alpha \partial_\beta g_{\mu\nu} - \frac{3}{2} \sum_{\alpha=0}^3 \sum_{\beta=0}^3 g^{\alpha\beta} \partial_\mu \partial_\nu g_{\alpha\beta} - \frac{1}{2} \\ & \sum_{\alpha=0}^3 \sum_{\beta=0}^3 \sum_{\rho=0}^3 \sum_{\lambda=0}^3 g^{\beta\lambda} g^{\alpha\rho} \partial_\alpha g_{\rho\lambda} \partial_\mu g_{\beta\nu} - \frac{1}{2} \sum_{\alpha=0}^3 \sum_{\beta=0}^3 \sum_{\rho=0}^3 \sum_{\lambda=0}^3 g^{\beta\lambda} g^{\alpha\rho} \partial_\alpha g_{\rho\lambda} \partial_\nu g_{\mu\beta} + \frac{1}{4} \sum_{\alpha=0}^3 \sum_{\beta=0}^3 \sum_{\rho=0}^3 \\ & \sum_{\lambda=0}^3 g^{\beta\lambda} g^{\alpha\rho} \partial_\nu g_{\alpha\lambda} \partial_\mu g_{\rho\beta} + \frac{1}{4|g|} \sum_{\alpha=0}^3 \sum_{\beta=0}^3 g^{\alpha\beta} \partial_\beta |g| \partial_\nu g_{\mu\alpha} - \frac{1}{4|g|} \sum_{\alpha=0}^3 \sum_{\beta=0}^3 g^{\alpha\beta} \partial_\beta |g| \partial_\alpha g_{\mu\nu} - \frac{1}{4|g|} \sum_{\alpha=0}^3 \\ & \sum_{\beta=0}^3 g^{\alpha\beta} \partial_\beta |g| \partial_\mu g_{\alpha\nu} + \Lambda g_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu} \end{aligned}$$

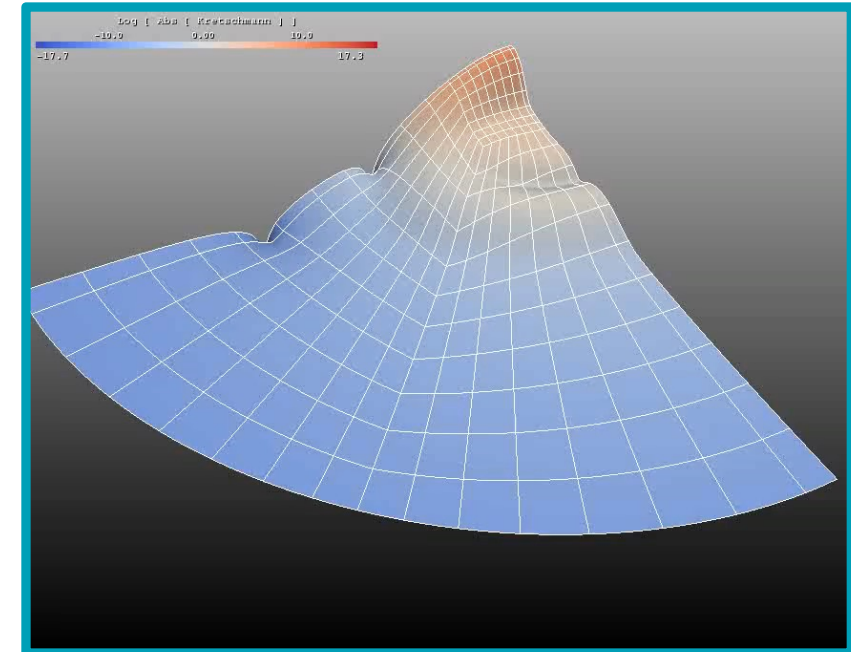
Develop new tools to understand the theory

Mathematical Analysis

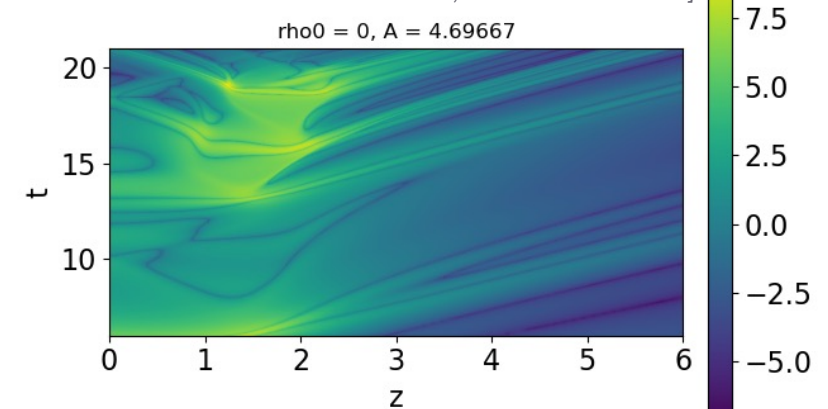
**Numerical Relativity**

Perturbation Theory

Extreme Gravity interacting with itself



[Credits: Video: D. Hilditch, *Phys.Rev.D.* 96, 104041, 2017  
Picture: I. Fernandez, *arXiv:* 2205.04379]



# Gravitational-Wave Phenomenology

How to explore new physics  
with  
gravitational-waves?

**I**

Are we observing black holes or something **exotic**?

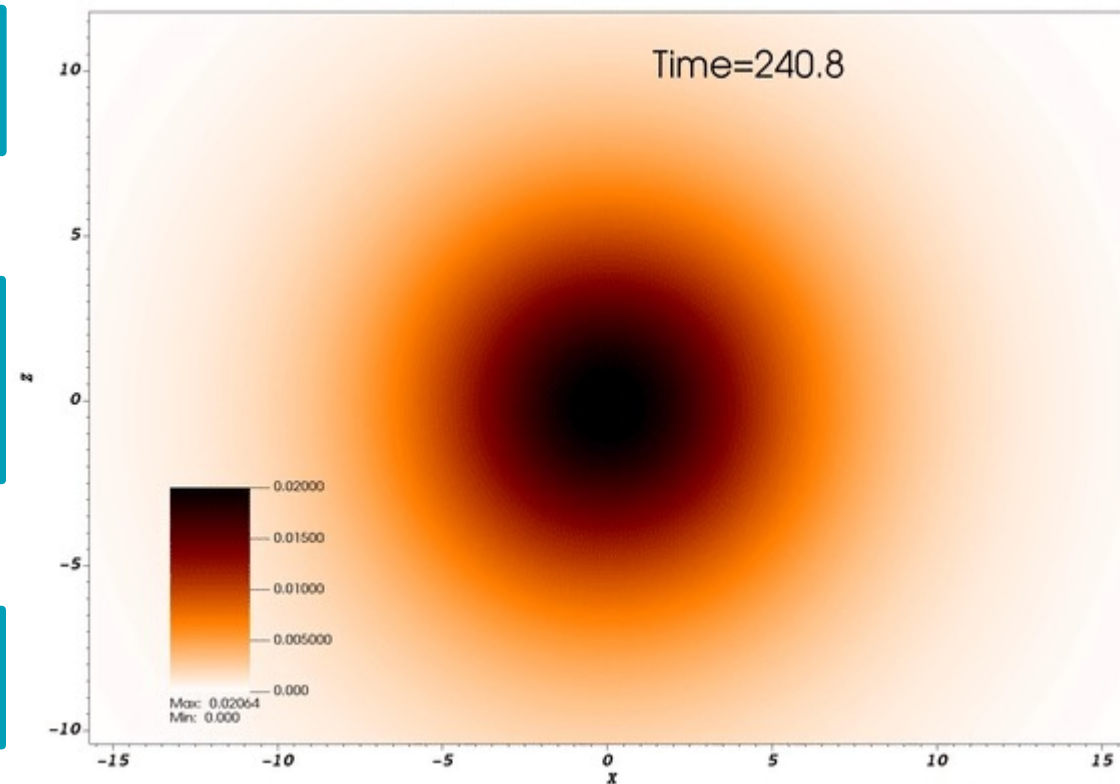
**II**

What is dark matter? How to see it with gravitational waves?

**III**

Will Einstein's theory break down?

Simulation of a **black hole** crossing  
a cloud of **dark matter**

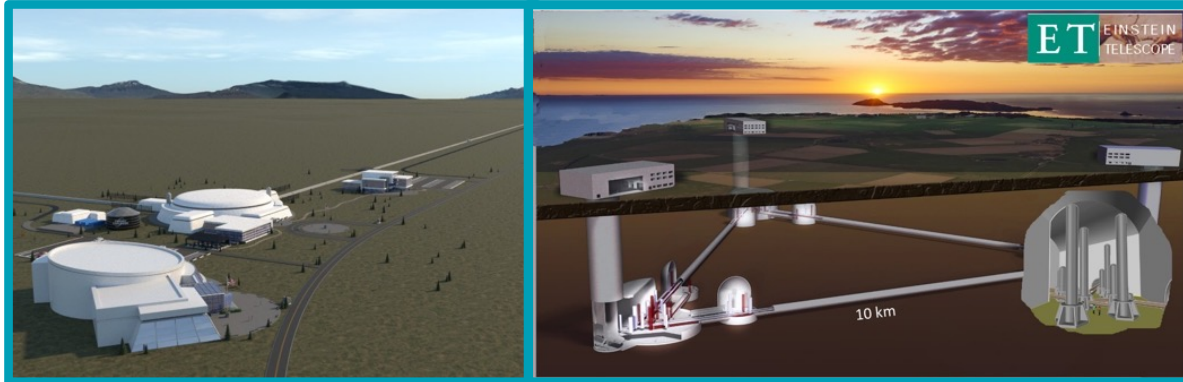


[Credits: Z. Zhong, M. Zilhão, V. Cardoso]

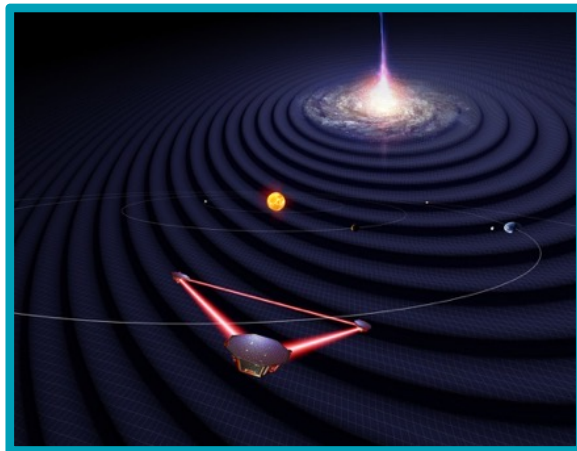


# Future of Strong Gravity

## New Generation Detectors



LISA – Laser Interferometer Space Antenna



## Contact us!



centra

centra.tecnico.ulisboa.pt

/



grit  
gravitation in técnico

centra.tecnico.ulisboa.pt/network/grit/

CENTRA

Instituto Superior Técnico - Location

CENTRA - Location/Directions

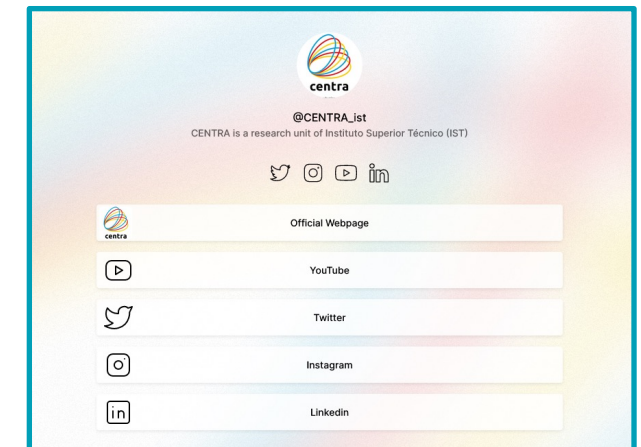
Pavilhão de Física, 4º Piso  
Av. Rovisco Pais 1  
1049-001 Lisboa, PORTUGAL

Phone: +351 21 8417938

Fax: +351 21 8419118

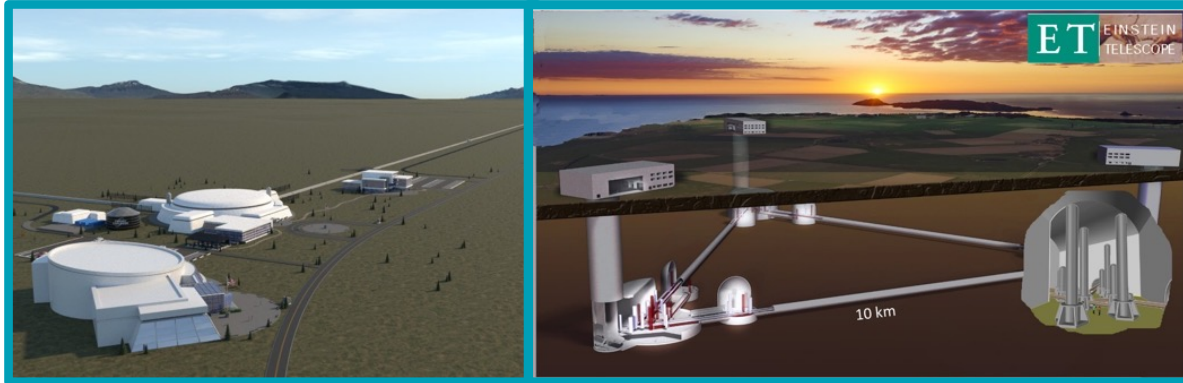
## Find us on Social Media

[linktr.ee/CENTRA\\_ist](https://linktr.ee/CENTRA_ist)

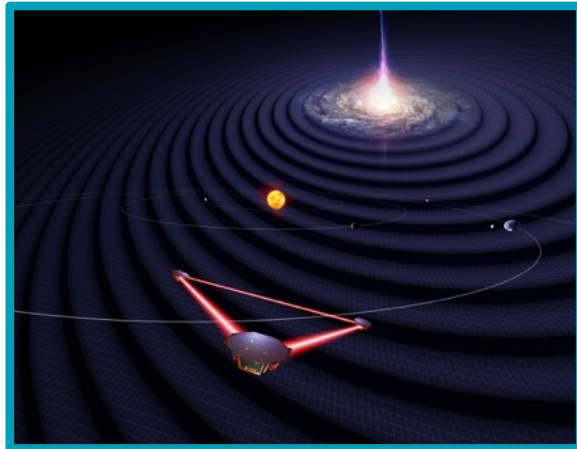


# Future of Strong Gravity

## New Generation Detectors



LISA – Laser Interferometer Space Antenna



Thank you for listening!

## Contact us!



centra

centra.tecnico.ulisboa.pt

/



grit  
gravitation in técnico

centra.tecnico.ulisboa.pt/network/grit/

CENTRA

Instituto Superior Técnico - Location

CENTRA - Location/Directions

Pavilhão de Física, 4º Piso  
Av. Rovisco Pais 1  
1049-001 Lisboa, PORTUGAL

Phone: +351 21 8417938

Fax: +351 21 8419118

## Find us on Social Media

[linktr.ee/CENTRA\\_ist](https://linktr.ee/CENTRA_ist)

