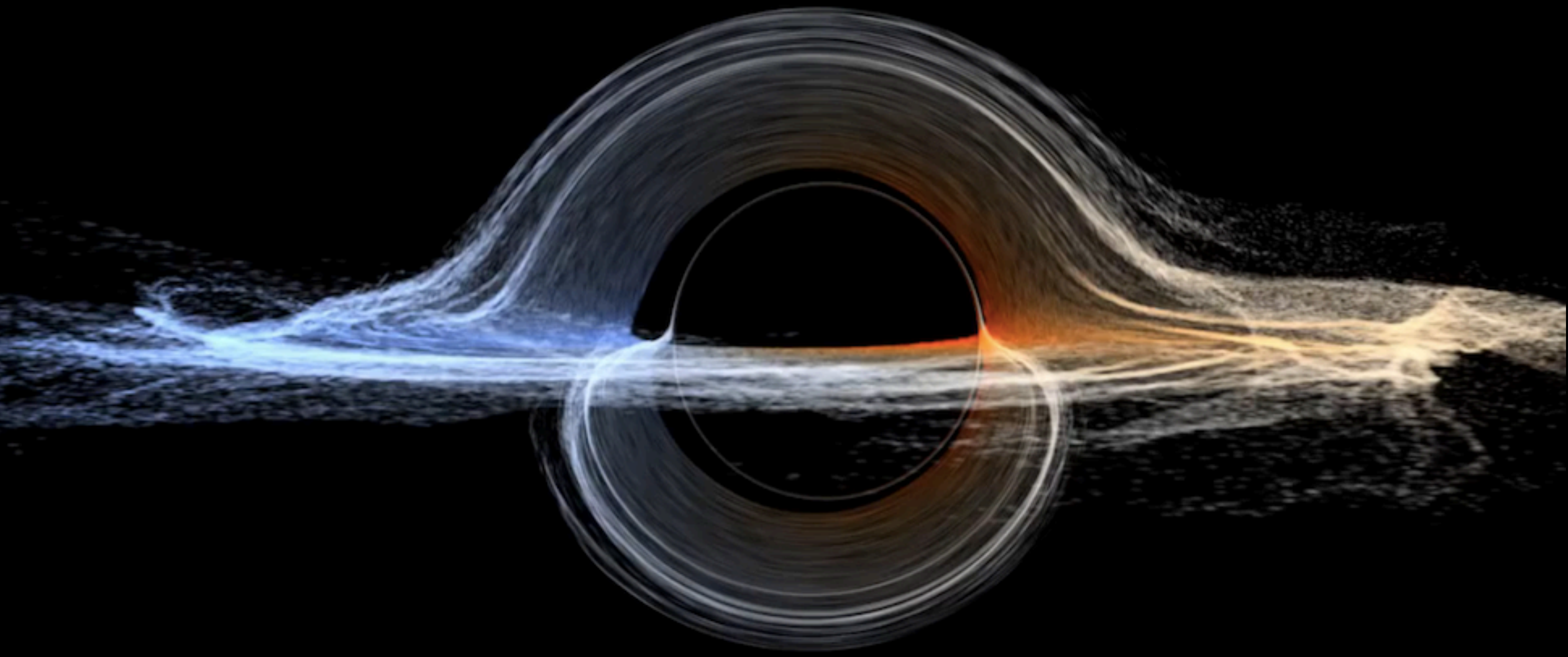


Lentes gravitacionales en astrofísica y cosmología
Semana - 15
Parte IV:
Tópicos avanzados

Martín Makler
ICAS/IFICI/CONICET&UNSAM y CBPF

ICAS
CONICET
Instituto de Ciencias Físicas
ICIFI-ECYT_UNSAM-CONICET
CBPF
Instituto de Tecnología Sabato 30 años

Estructura general de la materia

Parte IV: Tópicos avanzados

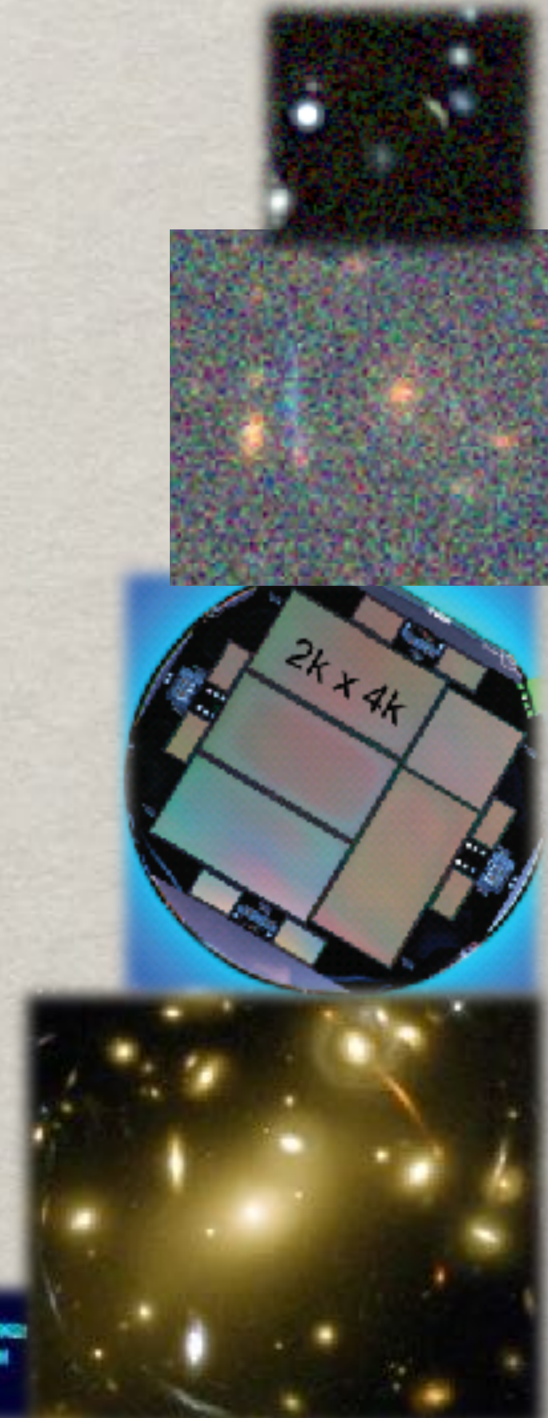
[gravedad fuerte, ondas gravitacionales, Maxwell]

- Lentes en gravedad modificada
- Gravedad fuerte: “sombras de agujeros negros”
- *Lensing* de ondas gravitacionales
- Lentes en óptica ondulatória

Lentes gravitacionales

Hipótesis/condiciones/regímenes

- Lente fina
- Relatividad general
- Campo débil (gravedad linear)
- Óptica geométrica
- Ondas electromagnéticas



¿Para qué sirve el *Strong Lensing*?

- Estúdio de la estructura de las galáxias (lentes)
- Estúdio de galáxias lejanas (fuentes)
- Límites en modelos cosmológicos (por las distancias)
- Medidas de la curvatura del Universo
- Tasa de expansión (parámetro de Hubble)
- **Modificaciones de la gravedad**
  - En teorías (métricas) generales de la gravitación surgen 2 métricas

$$\mathrm{d}s^2 = a^2(\tau)[-(1+2\Phi)\,\mathrm{d}\tau^2 + (1-2\Psi)\gamma_{ij}\,\mathrm{d}x^i\,\mathrm{d}x^j]$$

- Los movimientos de las estrellas en las galaxias "sienten" un potencial
- El efecto de lente "siente" la suma
- Combinando la dinámica de galaxias con lentes podemos medir

slip parameter

$$\boxed{\gamma = \frac{\Phi}{\Psi}}$$

Ecuaciones de Einstein

Tensor de Einstein descompuesto en escalar-tensorial-vectorial:

$$G^0{}_0: \quad \left(\nabla^2 + 3K\right)\Phi - 3\frac{\dot a}{a}\left(\dot\Phi + \frac{\dot a}{a}\Psi\right) = 4\pi G a^2 \delta\rho \ ,$$

$$G^0{}_{i,\parallel}: \quad -(\dot\Phi + \frac{\dot a}{a}\Psi)_{;i} = 4\pi G a^2 \left[(\rho+p)(v_i + W_i)\right]_\parallel \ ,$$

$$G^0{}_{i,\perp}: \quad \left(\nabla^2 + 2K\right) W_i = 16\pi G a^2 \left[(\rho+p)(v_i + W_i)\right]_\perp \ ,$$

$$G^i{}_i: \quad \ddot\Phi - K\Phi + \frac{\dot a}{a}(\dot\Psi + 2\dot\Phi) + \left[2\frac{\dot a}{a} + \left(\frac{\dot a}{a}\right)^2\right]\Psi - \frac{1}{3}\nabla^2(\Phi - \Psi) = 4\pi G a^2 \delta p$$

$$G^i{}_{j\neq i,\parallel}: \quad \boxed{\left(\Phi - \Psi\right)_{,(i;j)} - \frac{1}{3}\gamma_{ij}\nabla^2\left(\Phi - \Psi\right) = 8\pi G a^2 \Sigma_{ij,\parallel}} \ ,$$

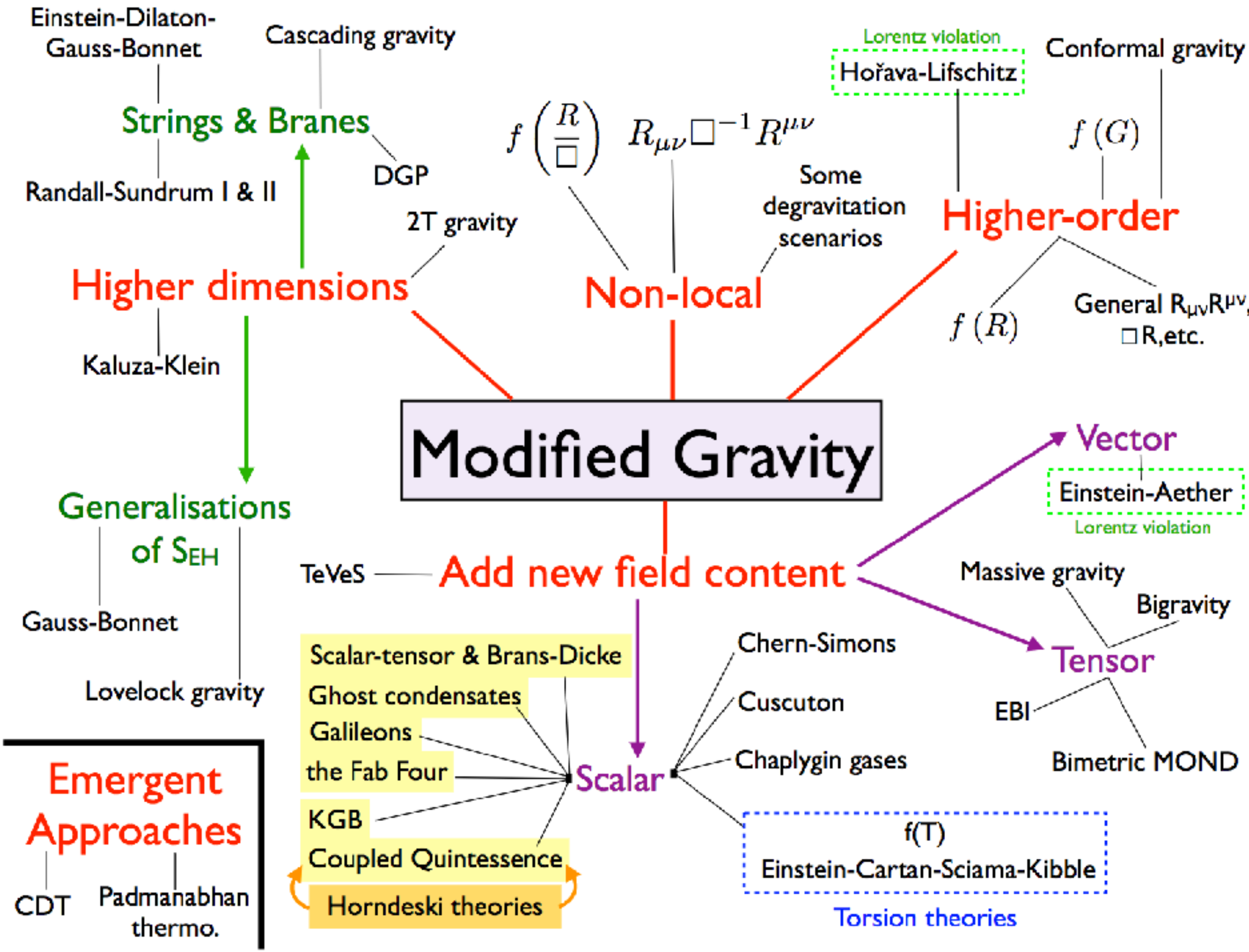
Se pueden generar diferencias entre los potenciales en RG (en ese caso, en general, materia oscura)

$$G^i{}_{j,\perp}: \quad \dot W_{(j;i)} + 2\frac{\dot a}{a}W_{(j;i)} = -8\pi G a^2 \Sigma_{ij,\perp} \ ,$$

$$G^i{}_{j,\mathrm{T}}: \quad \ddot S_{ij} + 2H\dot S_{ij} - \nabla^2 S_{ij} + 2K S_{ij} = 8\pi G a^2 \Sigma_{ij,\mathrm{T}} \ ,$$

obs.: neste módulo $\dot{} = \frac{d}{d\tau}$ e $H = \frac{\dot a}{a}$

$$\left(\nabla^2 A_{ij} := A_{ij;k}{}^{;k}\right)$$



From arXiv:1512.05356

(e.g. 1902.06978)

Exemplo: Horndeski e além

- Expressão mais geral para campo escalar e métrica, com equações de movimento com derivadas de 2a ordem no tempo (para evitar *ghosts*)

$$S = \int d^4x \sqrt{-g} \sum_{i=2}^{5} \mathcal{L}_i + S_m$$

$$X \equiv -\frac{1}{2\Lambda^4} (\partial\phi)^2$$

$$\begin{aligned}
\mathcal{L}_2 =& K(\phi, X)\,, \\
\mathcal{L}_3 =& -G_3(\phi, X)\Box\phi\,, \\
\mathcal{L}_4 =& G_4(\phi, X)R + G_{4,X}\left[(\Box\phi)^2 - (\nabla_\mu\nabla_\nu\phi)^2\right]\,, \\
\mathcal{L}_5 =& G_5(\phi, X)G_{\mu\nu}\nabla^\mu\nabla^\nu\phi - \frac{G_{5,X}}{6}\left[(\Box\phi)^3 - 3\,(\Box\phi)\,(\nabla_\mu\nabla_\nu\phi)^2 + 2\,(\nabla_\mu\nabla_\nu\phi)^3\right]
\end{aligned}$$

4 funções arbitrárias

Problema com Ockham de partida

Gravidade Modificada

- Calibre longitudinal

$$ds^2 = -(1+2\Psi)dt^2 + a^2(t)(1+2\Phi)\delta_{ij}dx^i dx^j$$

- Aproximação quase estática (e.g. 1902.06978)

$$k^2\Phi = \frac{1}{2}Y(k,z)\eta(z,k)\rho_m(z)\delta_m(z,k)$$

$$k^2\Psi = -\frac{1}{2}Y(k,z)\rho_m(z)\delta_m(z,k)$$

$$\eta = -\frac{\Phi}{\Psi}$$

parâmetro de *slip*

$$\eta = h_2\left(\frac{1+k^2h_4}{1+k^2h_5}\right), \; Y = h_1\left(\frac{1+k^2h_5}{1+k^2h_3}\right)$$

apenas funções do tempo
Silvestri A, Pogosian L, Buniy RV., PRD87:104015 (2013)

One gravitational potential or two? Forecasts and tests

BY EDMUND BERTSCHINGER*

Phil. Trans. R. Soc. A (2011) **369**, 4947–4961
doi:10.1098/rsta.2011.0369

métrica no calibre newtoniano conforme (premissas):

$$ds^2 = a^2(\tau)[-(1+2\Phi)\,d\tau^2 + (1-2\Psi)\gamma_{ij}\,dx^i\,dx^j]$$

geodésicas

$$\frac{dx^i}{d\tau} = (1+\Phi+\Psi)v^i$$

$$\frac{1}{\gamma a(1-\Psi)}\frac{d}{d\tau}[\gamma a(1-\Psi)v^i] = -\nabla^i(\Phi+v^2\Psi) - (1+\Phi+\Psi)\gamma^i_{jk}v^j v^k$$

Example Science: Modified Gravity

conformal newtonian metric (choices and assumptions):

$$\mathrm{d}s^2 = a^2(\tau)[-(1+2\Phi)\,\mathrm{d}\tau^2 + (1-2\Psi)\gamma_{ij}\,\mathrm{d}x^i\,\mathrm{d}x^j]$$

geodesics

$$\frac{1}{a}\frac{\mathrm{d}(a\boldsymbol{v})}{\mathrm{d}\tau} = -\boldsymbol{\nabla}\Phi, \quad v^2 \ll 1 \text{ (CDM)} \longrightarrow \text{Jean's equation}$$

$$\frac{\mathrm{d}\boldsymbol{v}}{\mathrm{d}\tau} = -\boldsymbol{\nabla}_{\perp}(\Phi+\Psi), \quad v^2 = 1 \text{ (photons)} \longrightarrow \text{lensing}$$

kinematics: Φ

deflection angle: $\Phi + \Psi$

on ~ 100 kph galaxy scales

from galaxy velocity dispersion

from strong lensing

Modified Gravity

conformal newtonian metric (choices and assumptions):

$$\mathrm{d}s^2 = a^2(\tau)[-(1+2\Phi)\,\mathrm{d}\tau^2 + (1-2\Psi)\gamma_{ij}\,\mathrm{d}x^i\,\mathrm{d}x^j]$$

for General Relativity (for *standard* matter components) in general

$$\Phi = \Psi$$

slip parameter

$$\eta = \frac{\Phi}{\Psi}$$

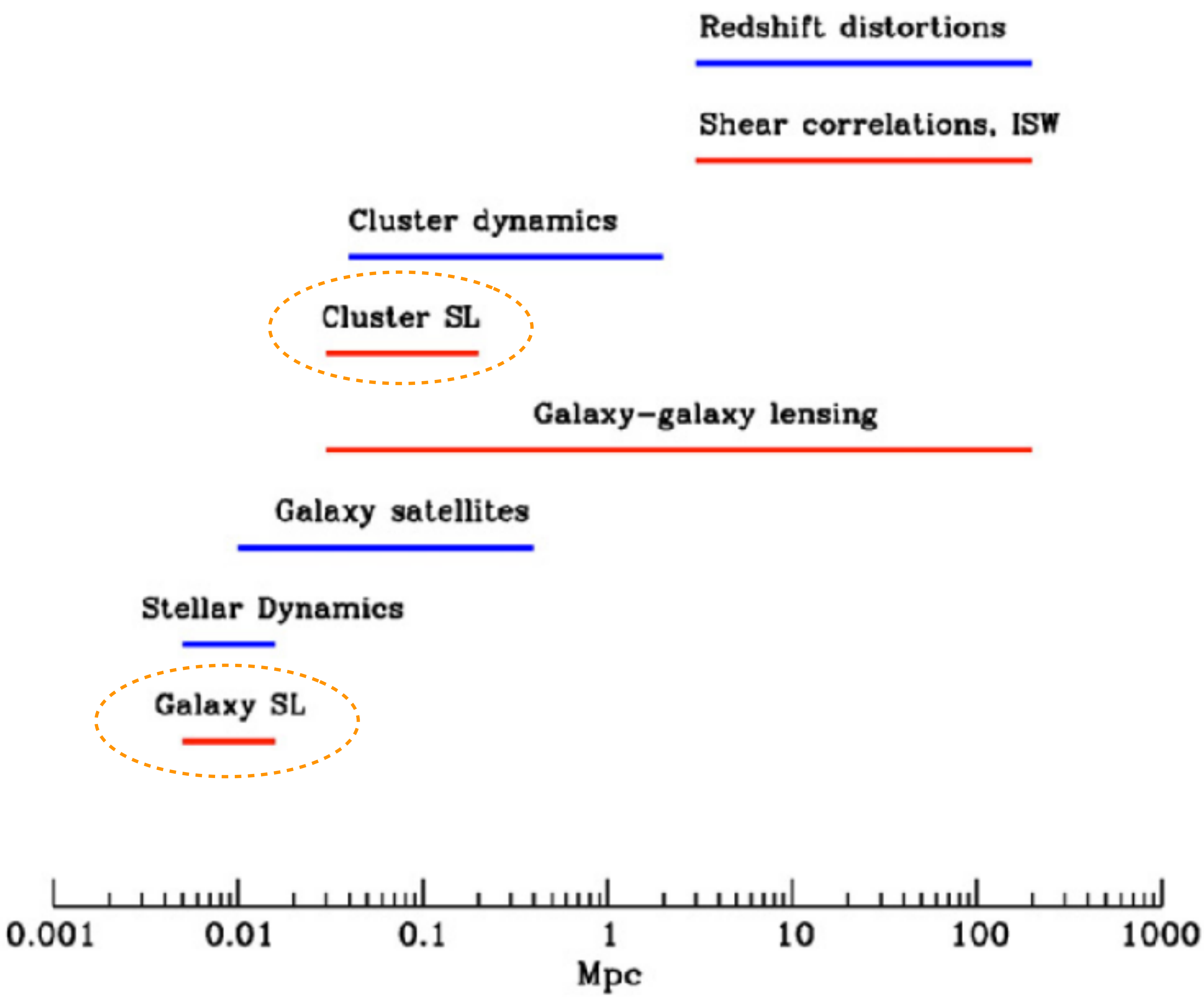
for $\eta = \mathrm{const.}, \quad \eta = \gamma_{\mathrm{PPN}}$

$\gamma = 1$ compatible with GR

$\gamma \neq 1$ GR ruled out

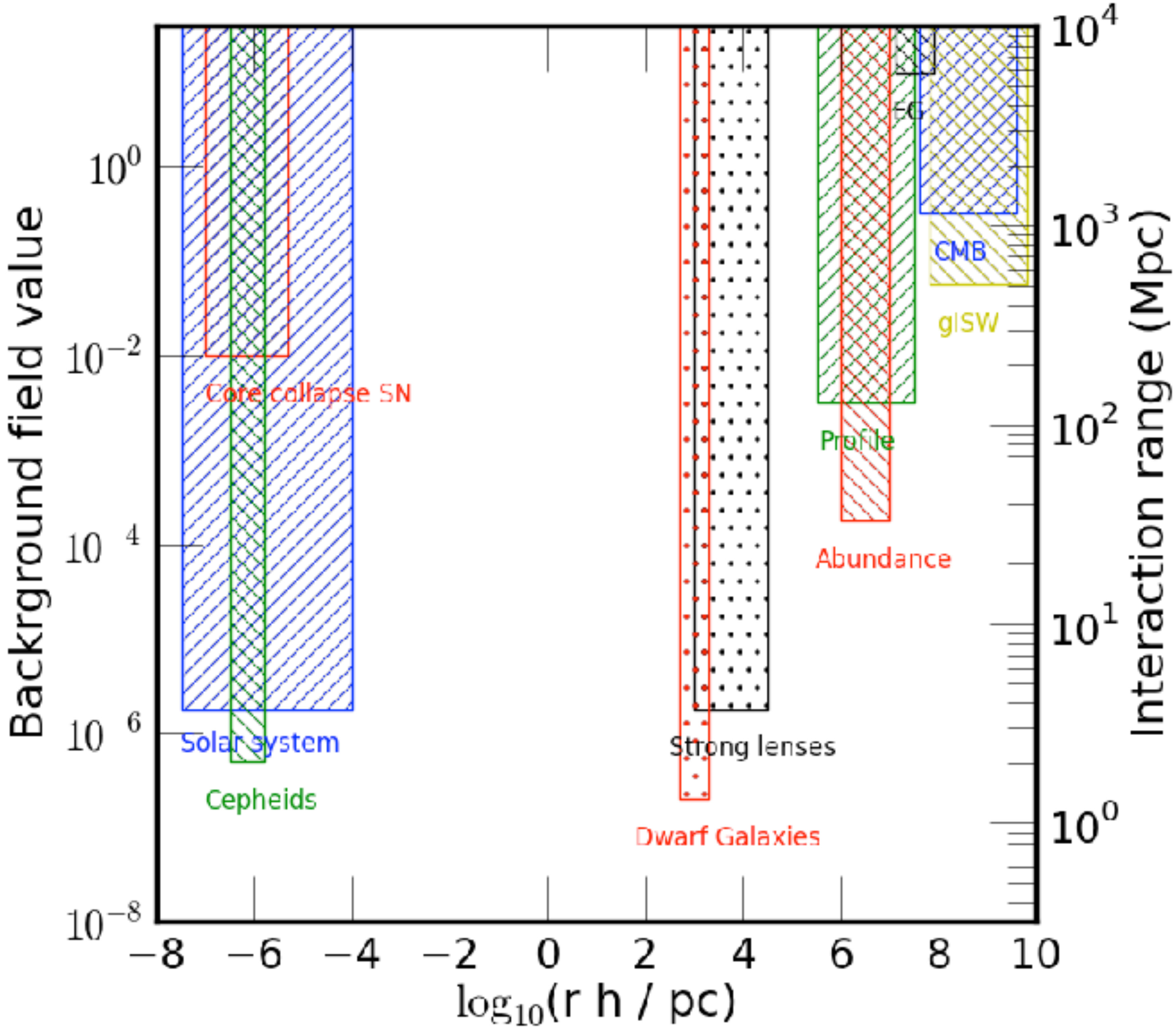
E.g. DHOST, Beyond Horndeski: E. Valadão, F. Araújo++in prep.

Testing Gravity at Different Scales



Jain, Bhuvnesh; Khoury, Justin, 2010, *Cosmological tests of gravity*, Annals of Physics, 325, 1479

Testing Gravity at Different Scales



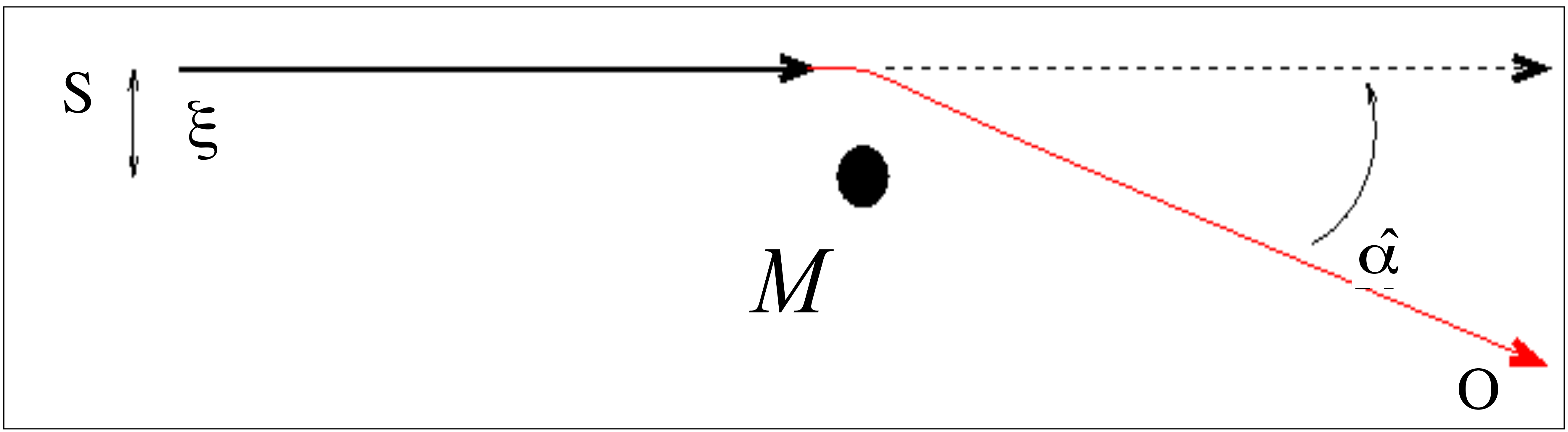
Jain, Bhuvnesh, et al., 2013, *Novel Probes of Gravity and Dark Energy*, arXiv:1309.5389 (adapted from Lombriser et al. 2012, Phys.Rev., D85:102001)

Bending of light by gravity

Null geodesic,
Fermat principle

$$ds^2 = \left(1 + \frac{2\phi}{c^2}\right) c^2 dt^2 - \left(1 - \frac{2\phi}{c^2}\right) d\sigma^2$$

$$\frac{d\sigma}{dt} := c' = \sqrt{\frac{1 + 2\phi/c^2}{1 - 2\phi/c^2}} \simeq c\left(1 + \frac{2\phi}{c^2}\right)$$

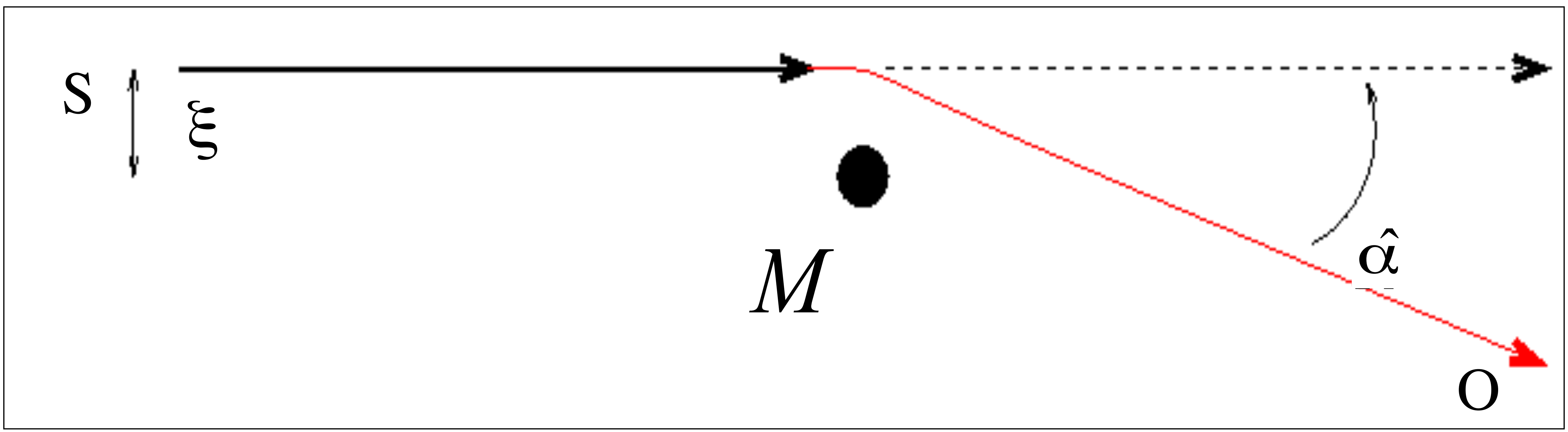


Bending of light by (modified) gravity

Null geodesic,
Fermat principle

$$ds^2 = \left(1 + \frac{2\psi}{c^2}\right) c^2 dt^2 - \left(1 - \frac{2\phi}{c^2}\right) d\sigma^2$$

peculiar gravitational potentials
(in GR $\psi = \phi$)

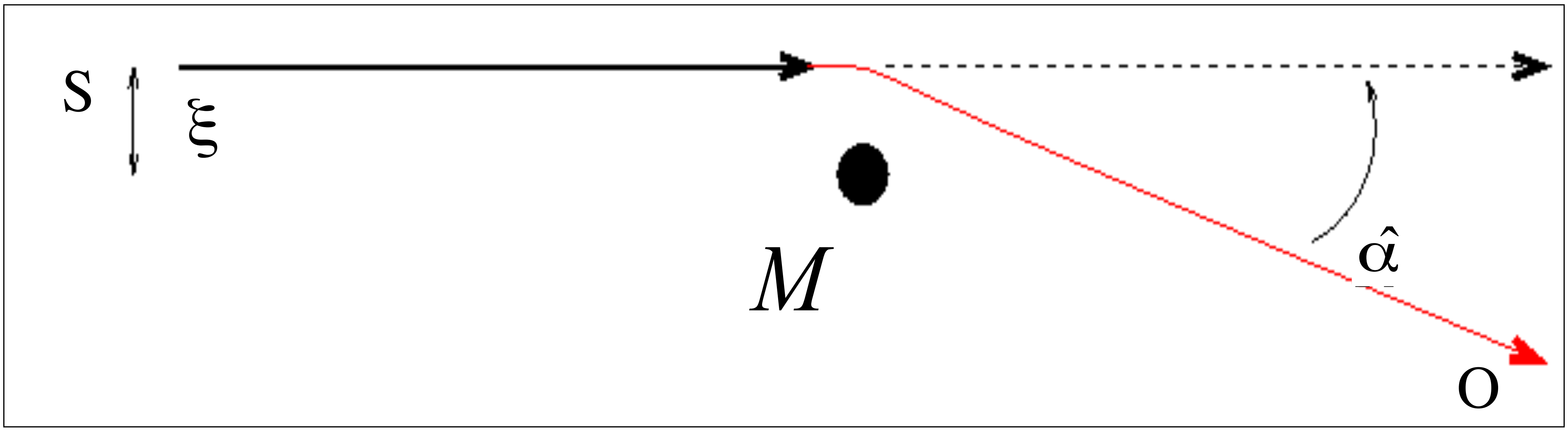


Bending of light by (modified) gravity

Null geodesic,
Fermat principle

$$ds^2 = \left(1 + \frac{2\psi}{c^2}\right) c^2 dt^2 - \left(1 - \frac{2\phi}{c^2}\right) d\sigma^2$$

$$\frac{d\sigma}{dt} = c' = c\sqrt{\frac{1+\frac{2\psi}{c^2}}{1-\frac{2\phi}{c^2}}} \simeq c\left(1 + \frac{\psi+\phi}{c^2}\right) = c\left(1 + \frac{2\phi}{c^2}\left[\frac{1+\gamma}{2}\right]\right)$$



Dynamical mass obtained from

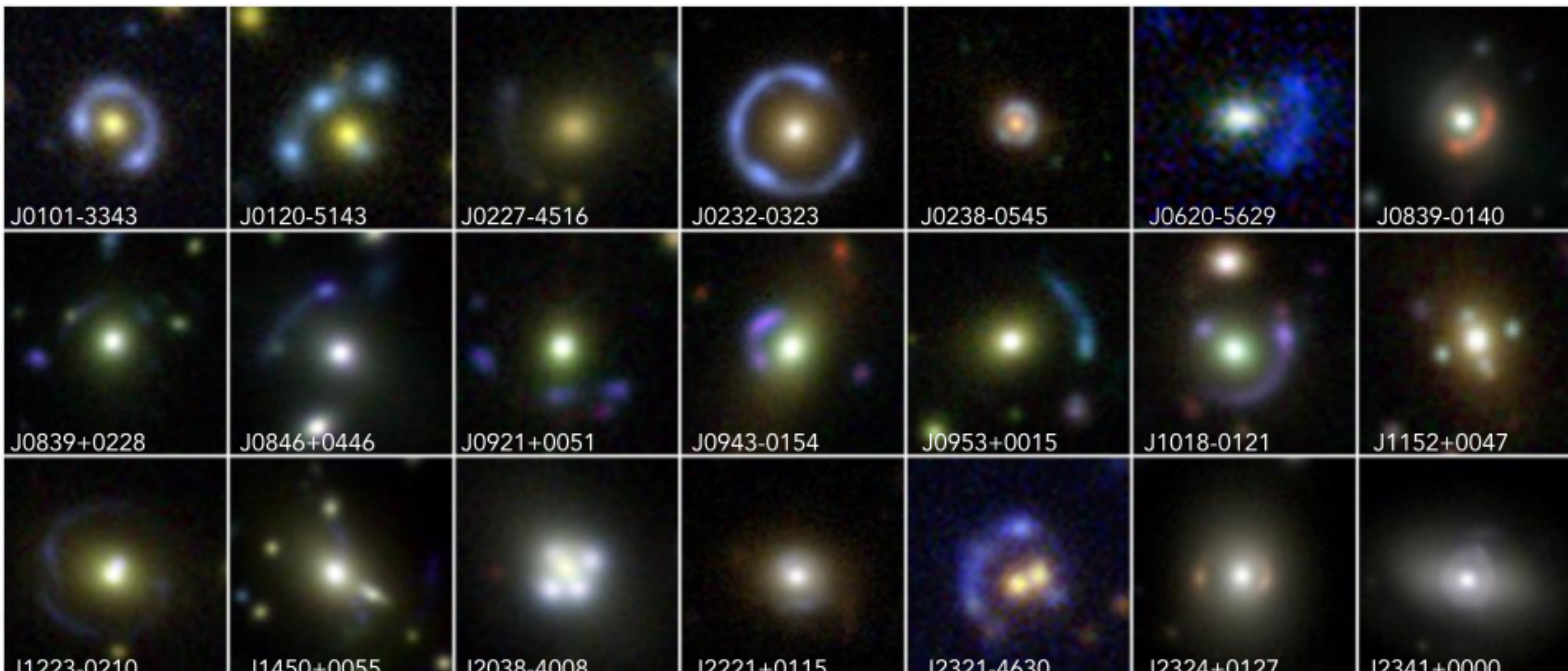
$$\nabla^2\psi = 4\pi G\rho$$

Use combination of lensing + dynamics to test gravity

Joint Arc sample for Investigations into Relativity (JAIR): Follow-up Observations and Implications (FOI)

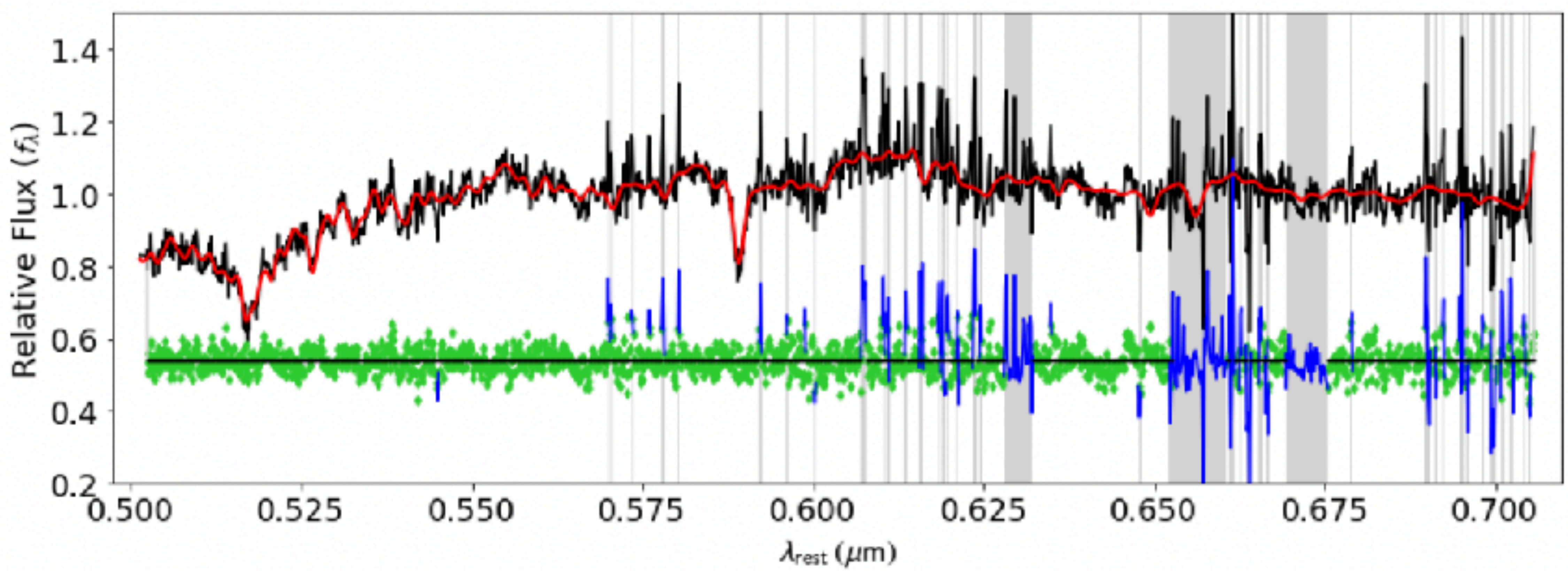
SOAR program focusing on the determination of σ_v

23 systems observed in 2022 (A+B) + 1 Gemini FT (Arg)



Testing general relativity in galaxies with combined velocity dispersion and gravitational lensing

SOAR program focusing on the determination of σ_v

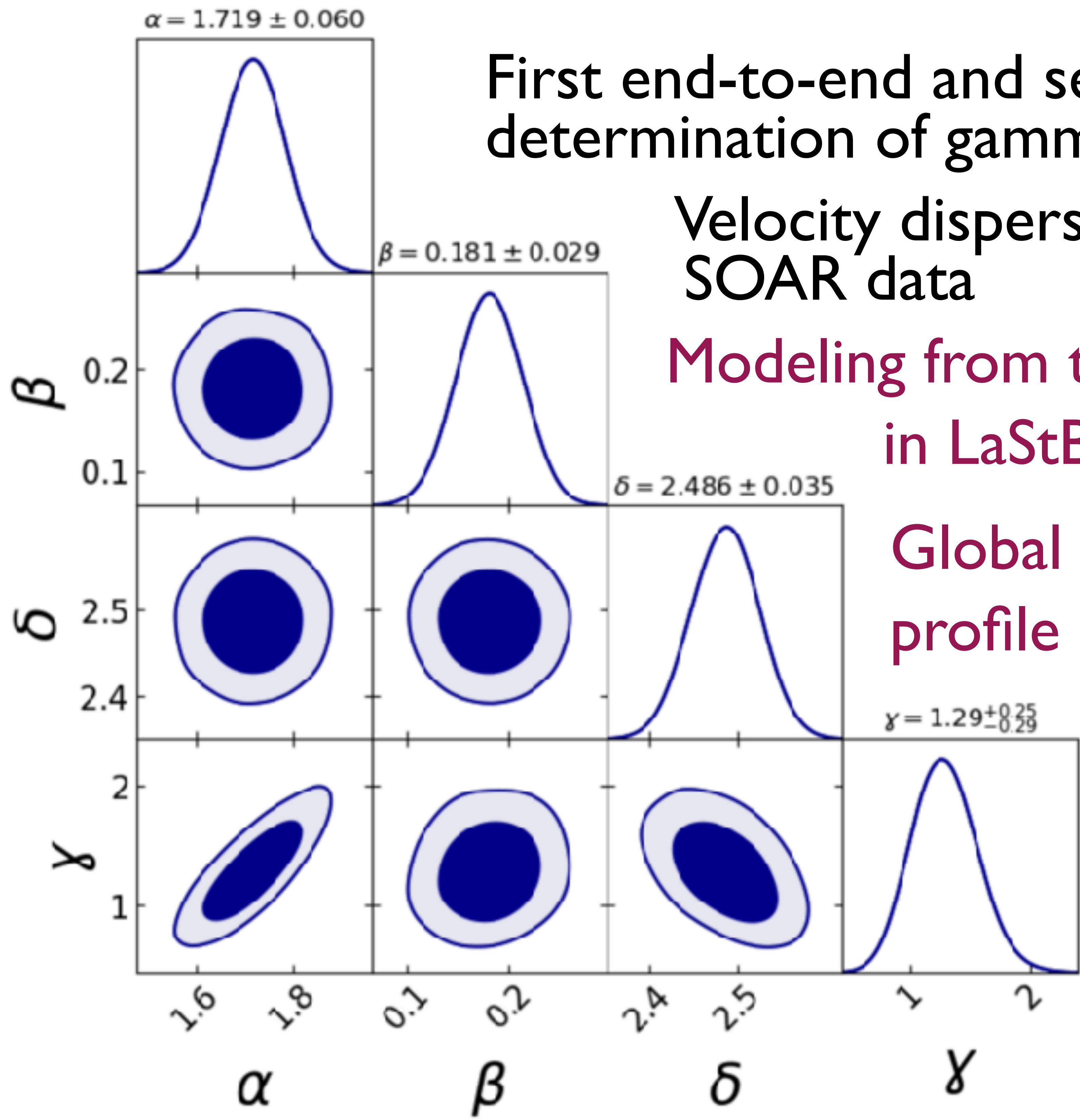


- Highly efficient/successful (know z_L, z_S in advance)
- 2022A: 10 (out of 13) systems with velocity dispersion (and z_L) measurements
- 9 with S/N > 10, 5 with S/N > 15, 3 with S/N > 20 (new strategy for 2022B)
- spectra modeled with (pPXF: Penalized PiXel-*Fitting)*

  7 systems with $\frac{\Delta\sigma_v}{\sigma_v} < 10\%$

(not all systems are suitable for testing MoG)

Joint Arc sample for Investigations into Relativity (JAIR): Follow-up Observations and Implications (FOI)



First end-to-end and self-consistent determination of gamma

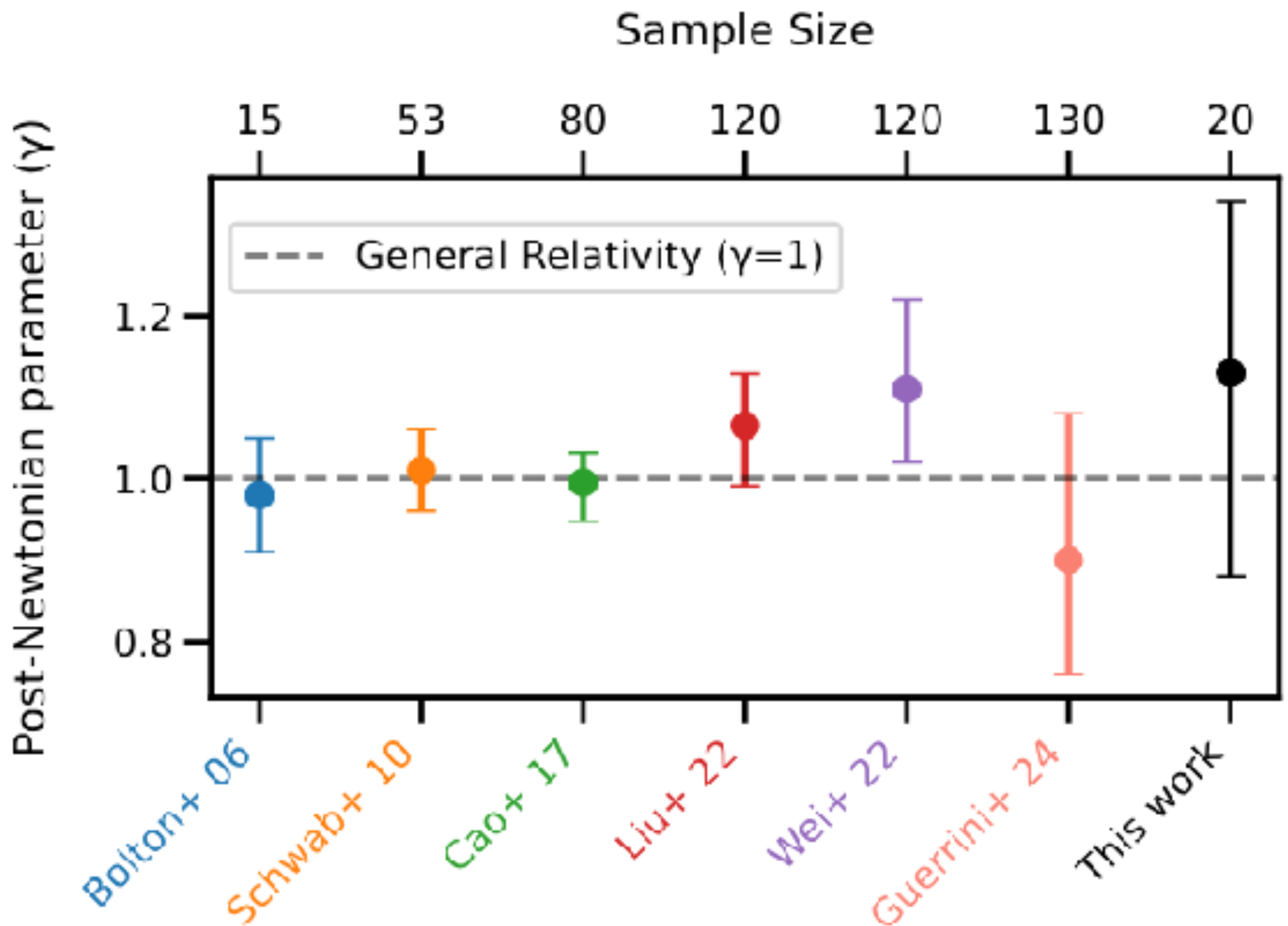
Velocity dispersions for 21 systems from SOAR data

Modeling from the ground based images in LaStBeRu

Global priors in the density profile and the light distribution from the ground based modeling

Modified gravity tests with JAIR-FOI

J. França, M. Makler ++ (In prep)



João Paulo França

First end-to-end and self-consistent determination of γ_{PPN}

Velocity dispersions for 20 systems from SOAR data

Aperture correction accounting for the seeing in each observation

Light profile directly measured on the images

Uniform lens modeling from the ground

Prior on the lens and light profiles from the data

Motivation to test modified gravity from the ground: larger samples!

베르

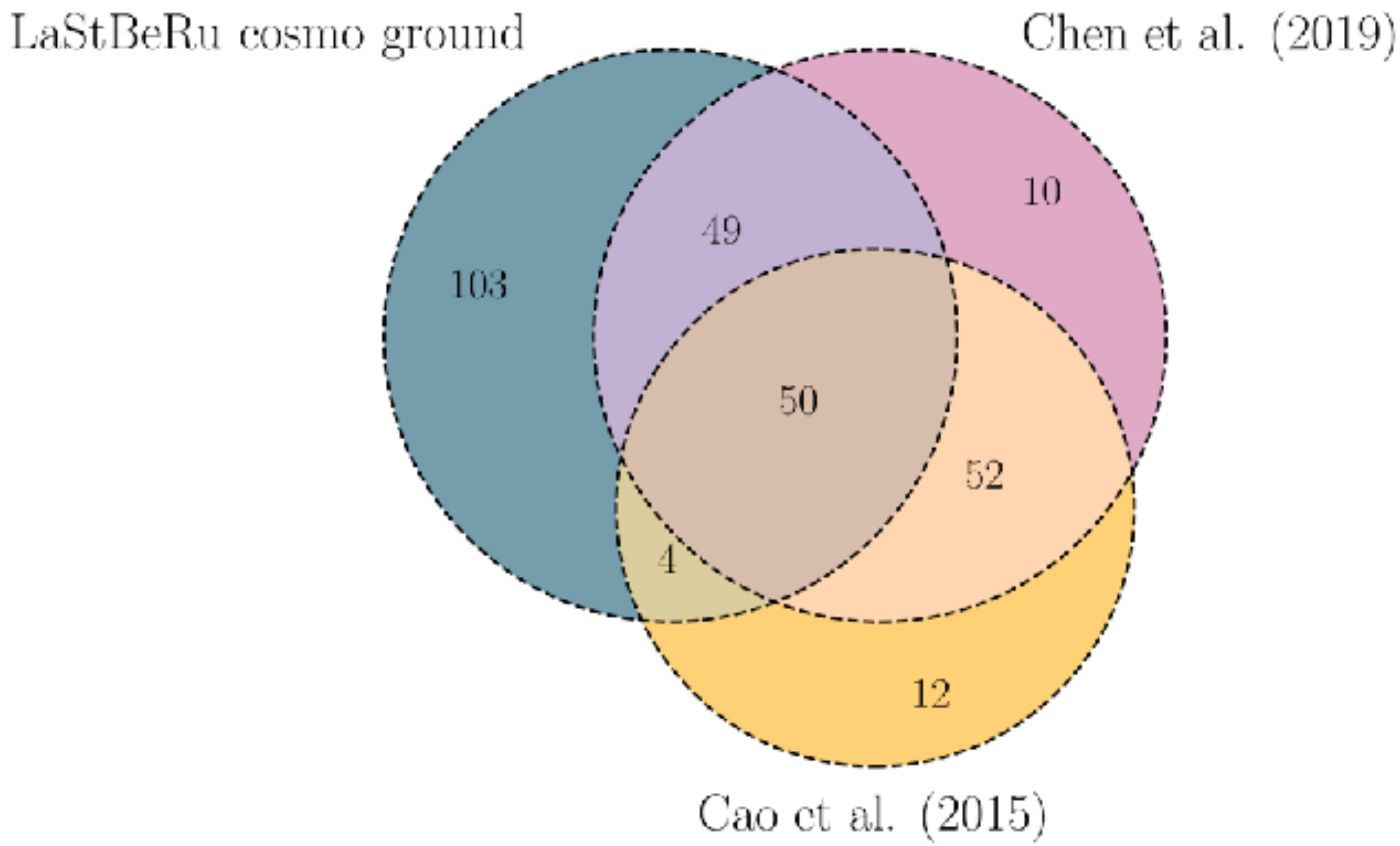
LaStBeRu_cosmo_ground sample

- Visual inspection of all cutouts:
  - clear SL morphology, modelable systems
  - isolated
- SDSS velocity dispersion
- Largest, complementary sample for many applications
- Application to test modified gravity

Application: modified gravity

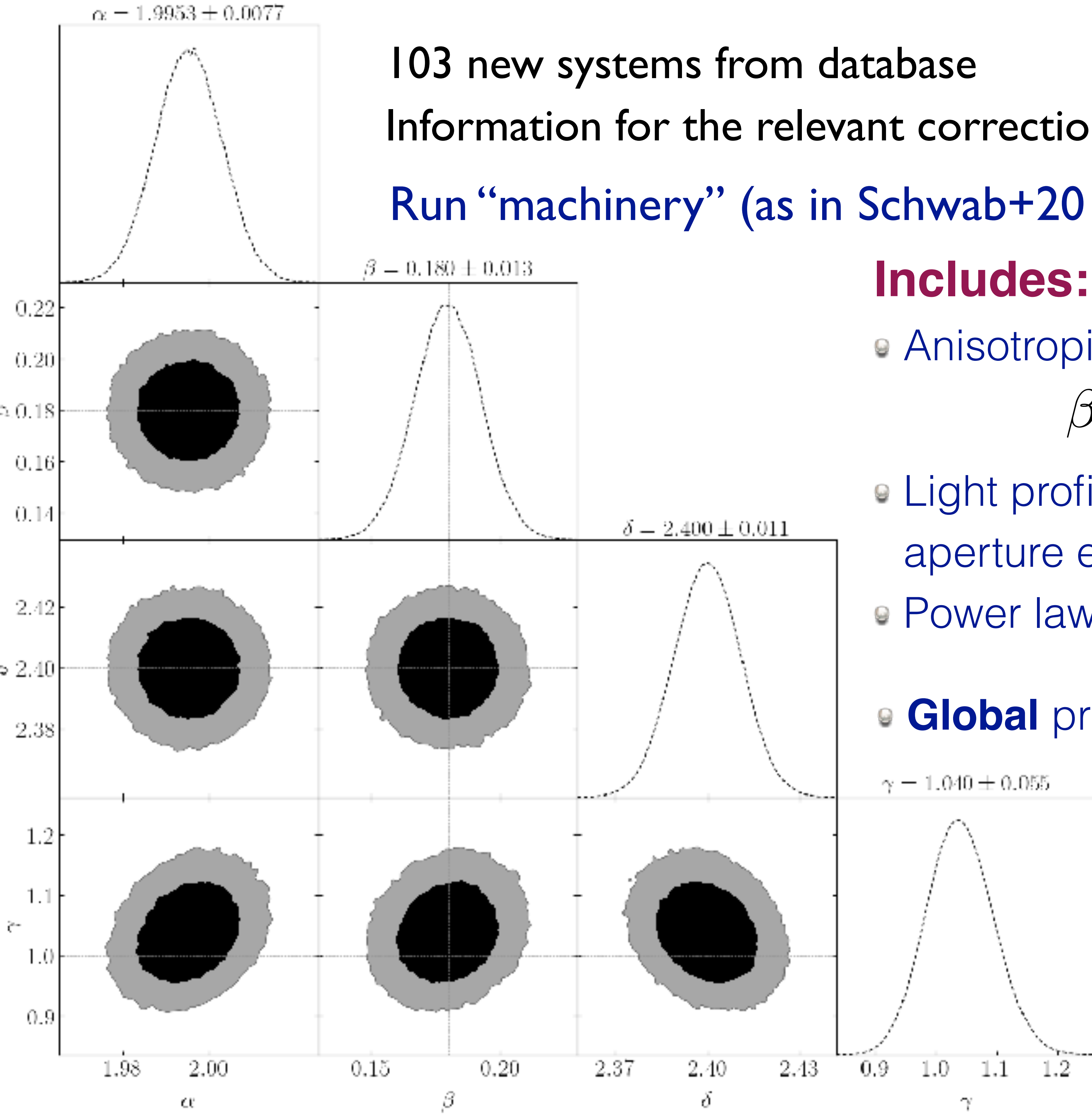
- queried the database for systems containing $z_L, z_S, \sigma_v, \delta\sigma_v,$ and θ_{E}: 409 systems
- 352 with SDSS spectroscopy (+ seeing, light profile fitting)
- 249 good data, galaxy-galaxy
- Visual inspection to select good systems: **206**
  - Final sample of 206, of which 103 not in Chen et al.
- Use for "gammology"

LaStBeRu_cosmo_ground sample



- Largest, complementary sample for many applications
- Uniform velocity dispersion measurements from SDSS
- Example application from purely archival data:
  test of modified gravity

Gamma from LaStBeRu_cosmo_ground



103 new systems from database

Information for the relevant corrections from the database!

Run "machinery" (as in Schwab+2010, Cao+2017, Chen+2022)

Includes:

- Anisotropic velocity dispersion

$$\beta = 1 - \sigma_t^2/\sigma_r^2$$

- Light profiles, seeing and fiber/slit aperture effects
- Power law density profile $\rho(r) \propto r^{-\alpha}$
- **Global** priors on

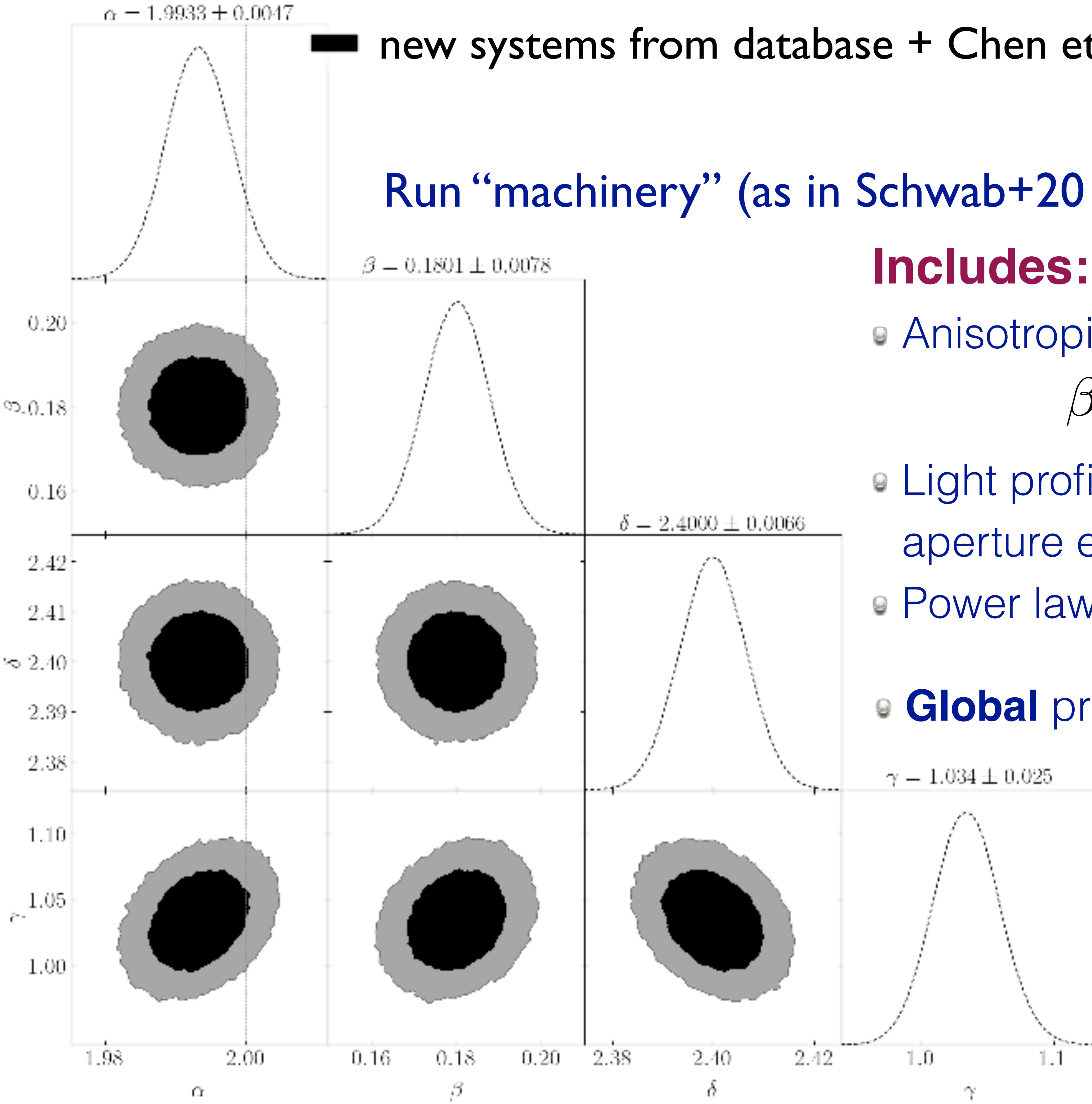
$$\beta = 0.180^{+0.014}_{-0.014}$$

$$\alpha = 1.995^{+0.009}_{-0.009}$$

$$\gamma = 1.04 \pm 0.05$$

First constraint from "ground based" systems

Gamma from LaStBeRu_cosmo_ground



new systems from database + Chen et al. + Cao et al. (280 systems)

Run "machinery" (as in Schwab+2010, Cao+2017, Chen+2022)

Includes:

- Anisotropic velocity dispersion

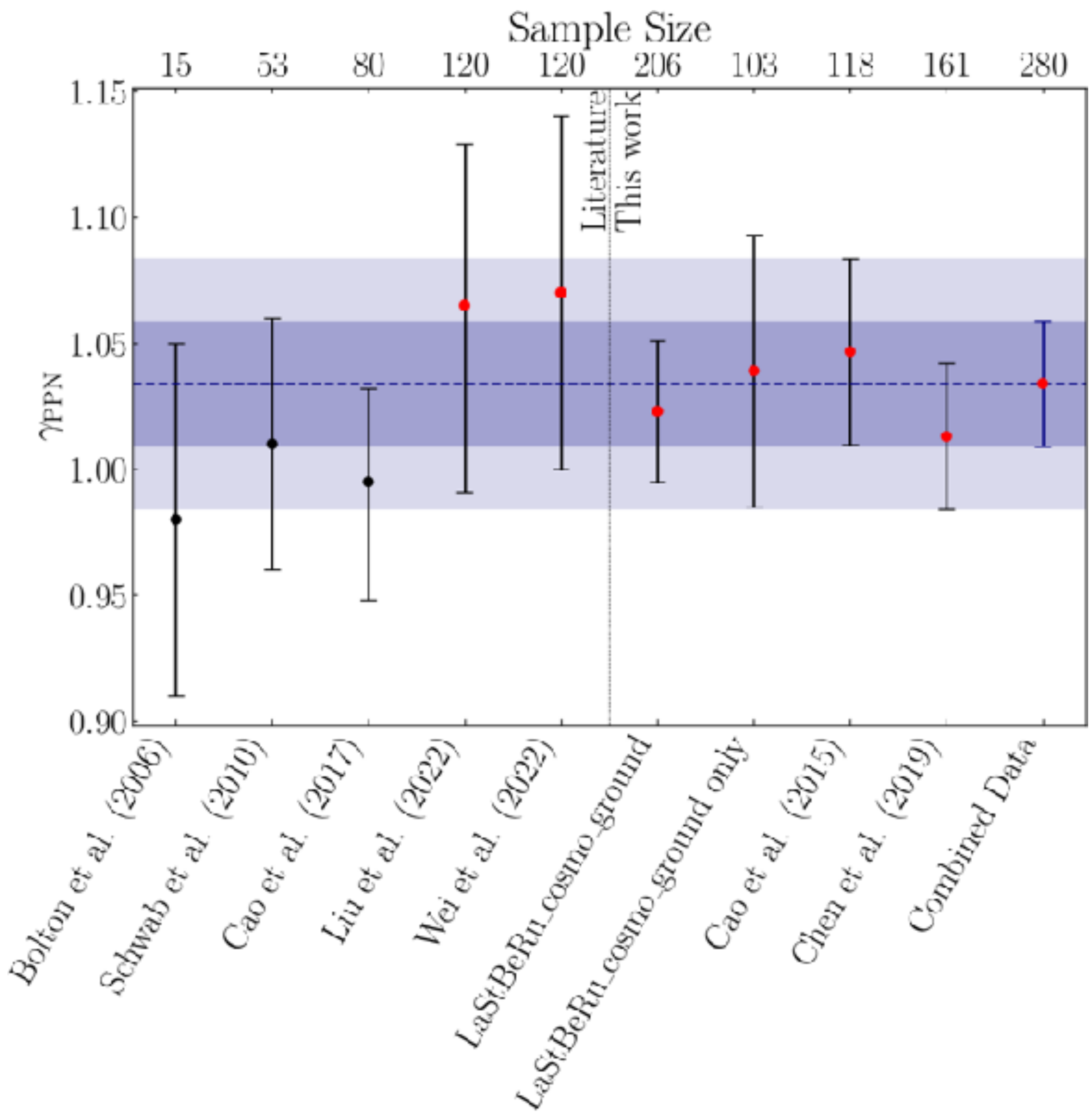
$$\beta = 1 - \sigma_t^2/\sigma_r^2$$

- Light profiles, seeing and fiber/slit aperture effects
- Power law density profile $\rho(r) \propto r^{-\alpha}$
- **Global** priors on $\beta = 0.180^{+0.014}_{-0.014}$ $\alpha = 1.995^{+0.009}_{-0.009}$

$$\gamma = 1.034 \pm 0.025$$

Tightest constraint from this type of analysis

LaStBeRu_cosmo_ground sample



- Constraint on γ_{PPN} from purely ground based systems
- Totally independent sample from previous studies
- Most stringent constraints on γ_{PPN} when combined with other data
- Uniformity: SDSS
- Next: fully end-to-end measurement

LaStBeRu

meets

JAIR

Strong Lensing

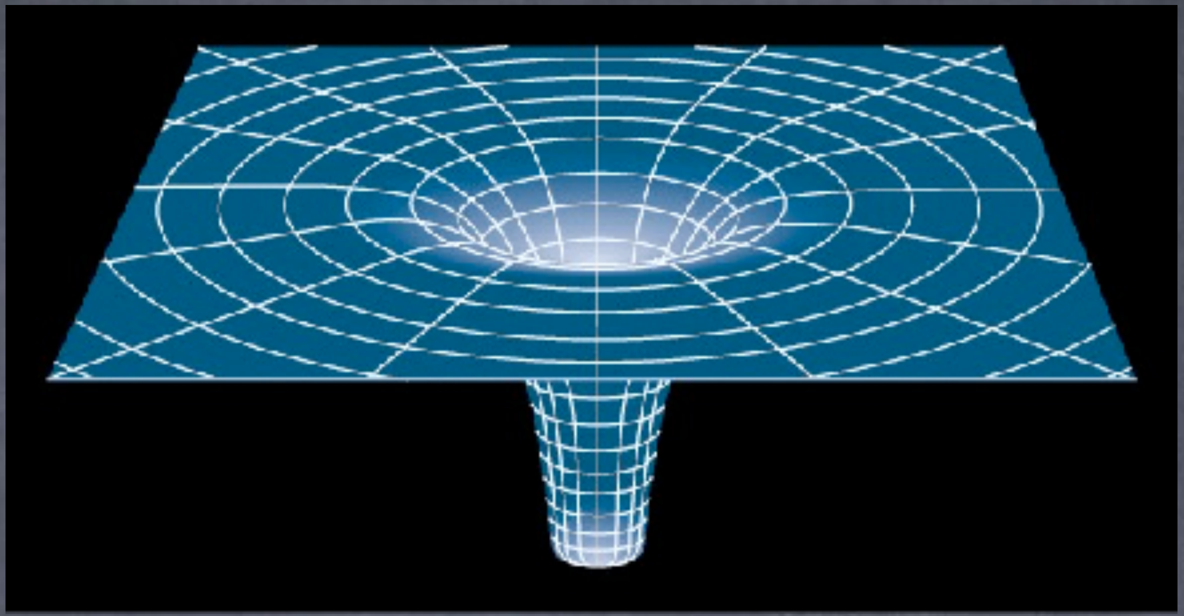
in

Strong Gravity

Buracos negros

O que são?

- Grande distorção do espaço do tempo
- Gravidade tão forte que nem a luz pode sair
- Horizonte de eventos



De onde vêem?

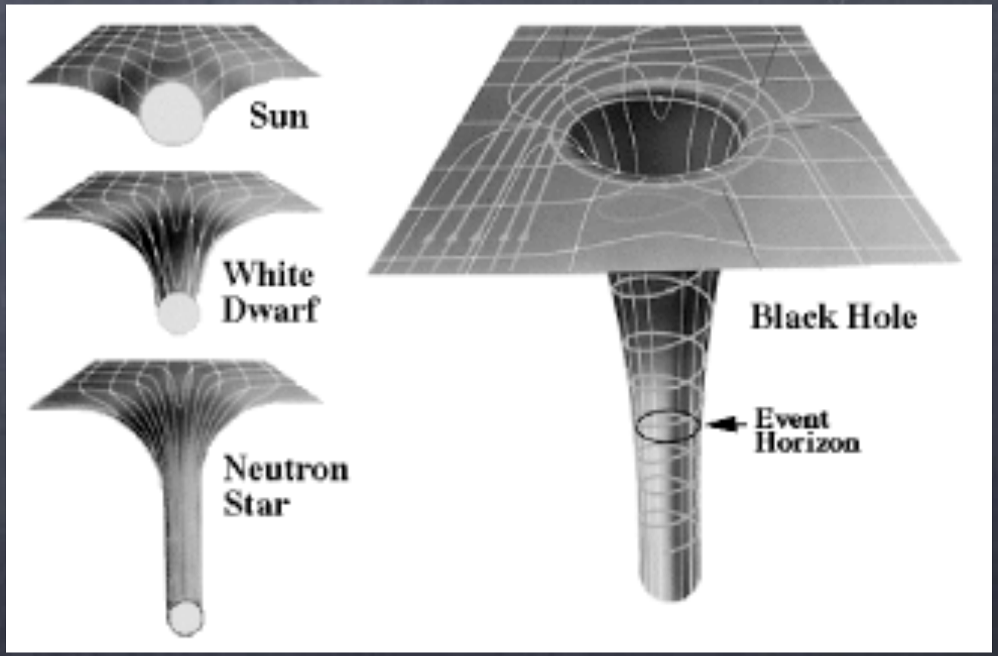
- Fim "inevitável" de estrelas muito massivas (Penrose!)

Devoram tudo ao seu redor?

- Depende da massa e do meio!

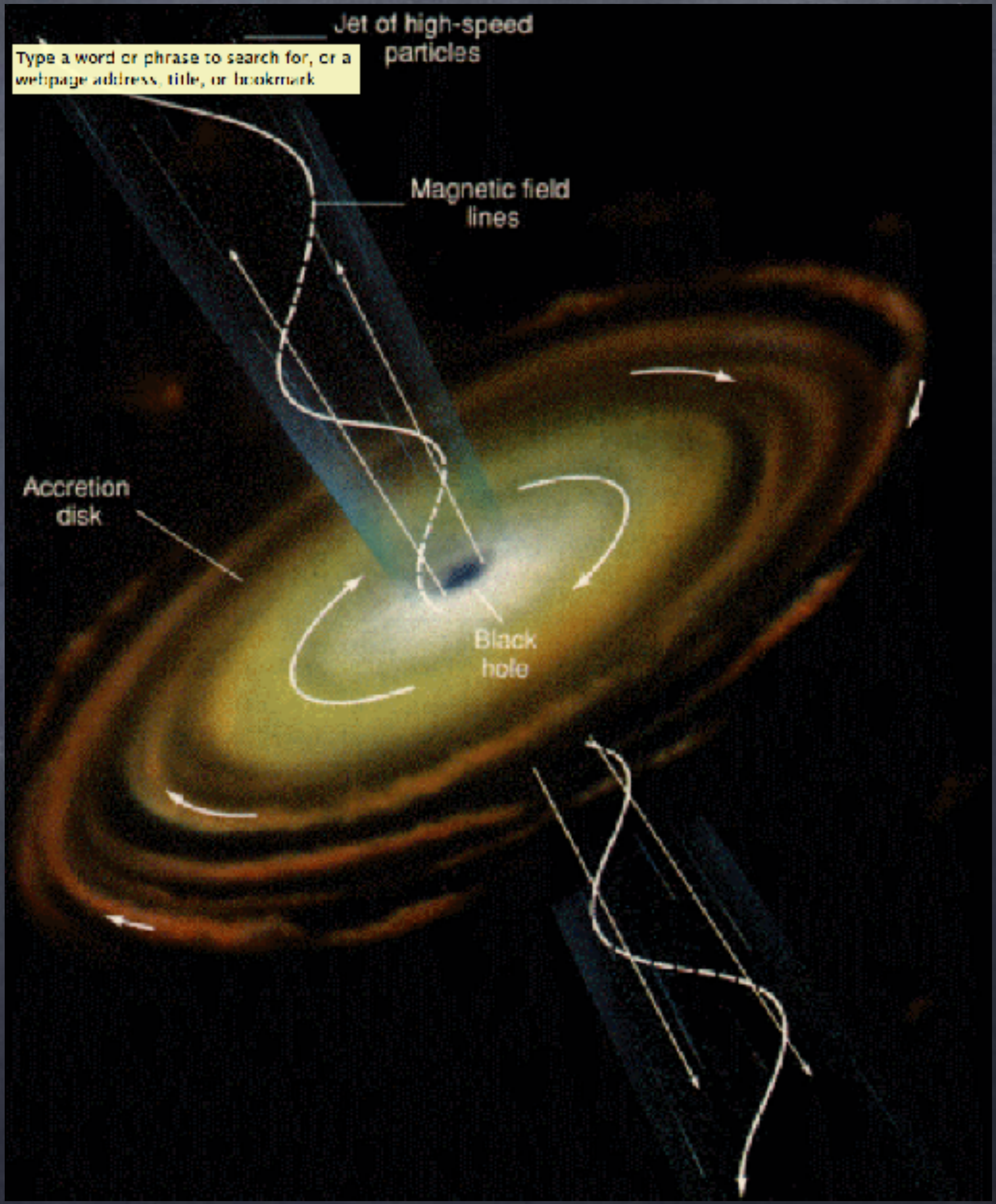
Sem limite na massa

- Estelares, supermassivos (e primordiais?)



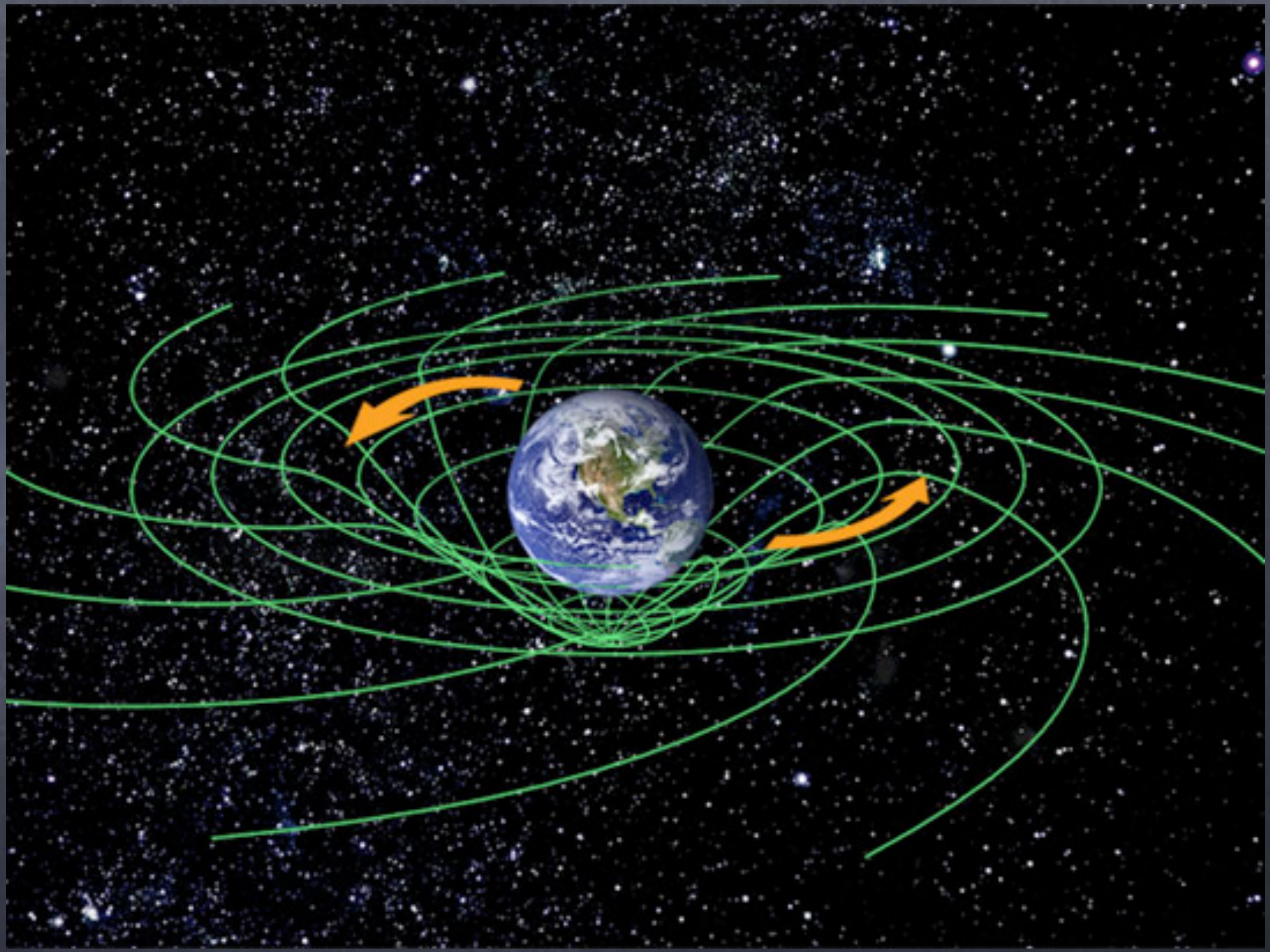
Buracos negros "ativos"

- Núcleos ativos de galáxias (Quasares) [década de 1960]
- Mais brilhantes que toda a galáxia!
- Gás circundante, disco de acresção, jatos
- Época cósmica bem definida



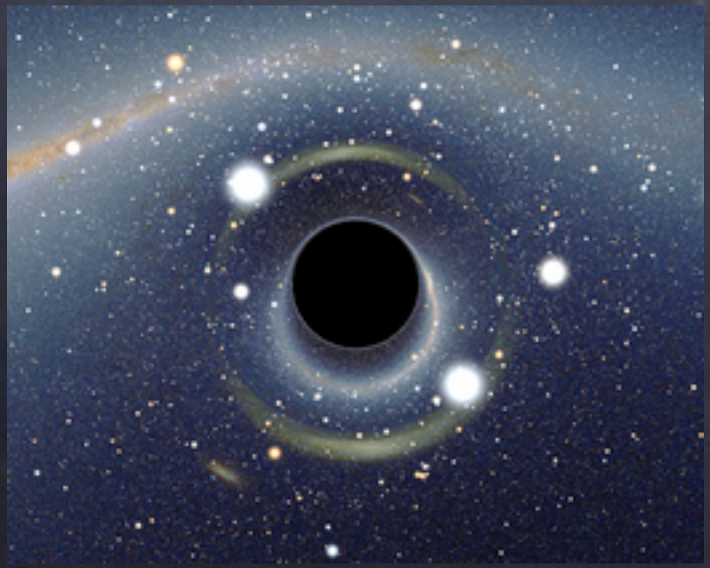
Arrasto dos referenciais

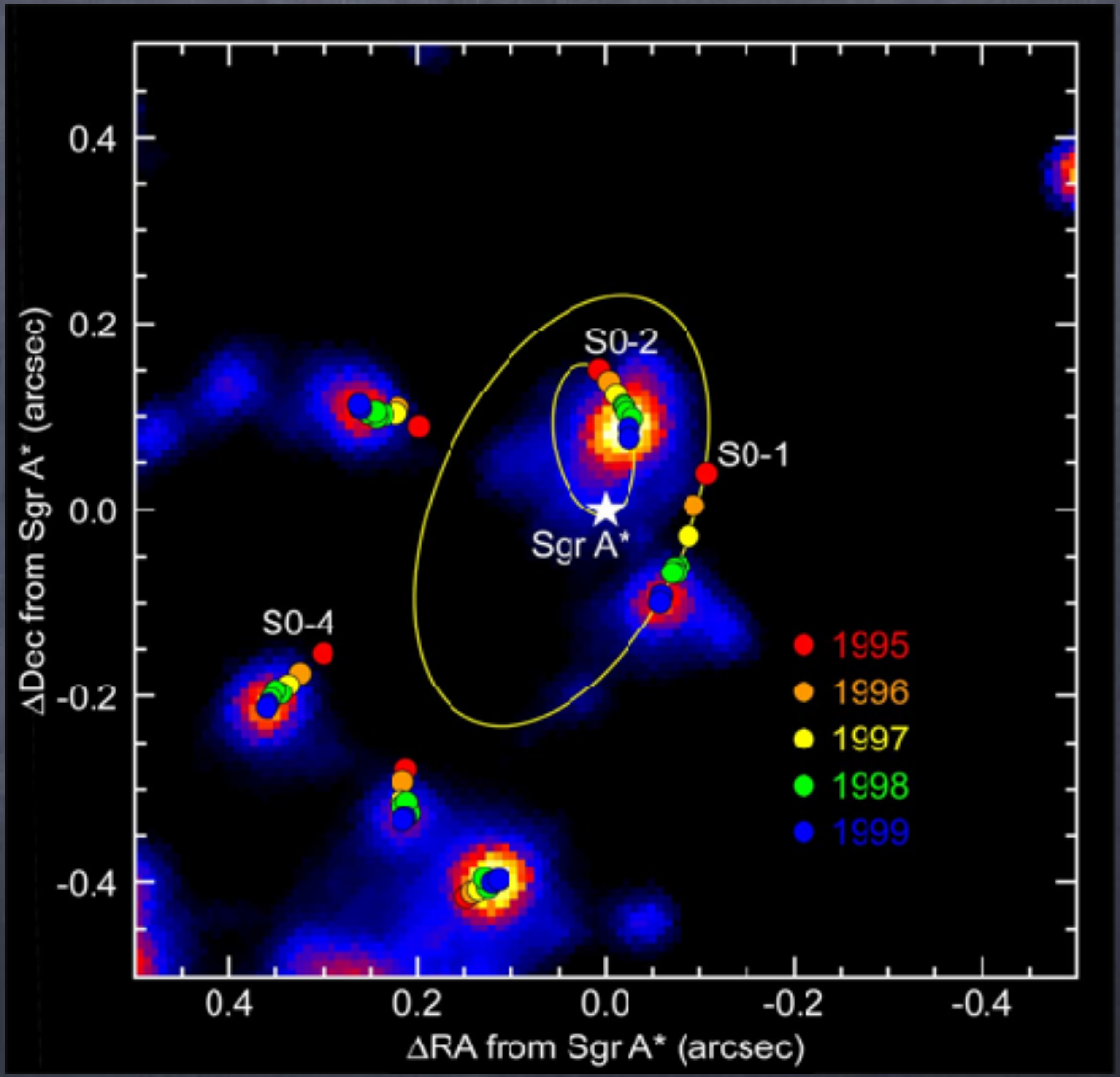
- Objetos em rotação "arrastam" o espaço-tempo no seu entorno
- Buracos negros em rotação (Kerr, Kerr-Newman)
- Efeito no tempo medido na Terra, com relógios atômicos em aviões
- Acoplamento das rotações medido com o satélite Gravity Probe B



Buracos negros "quietos"

- Centro de nossa galáxia
- Efeito no movimento das estrelas vizinhas
- Centro das galáxias
- Lente gravitacional

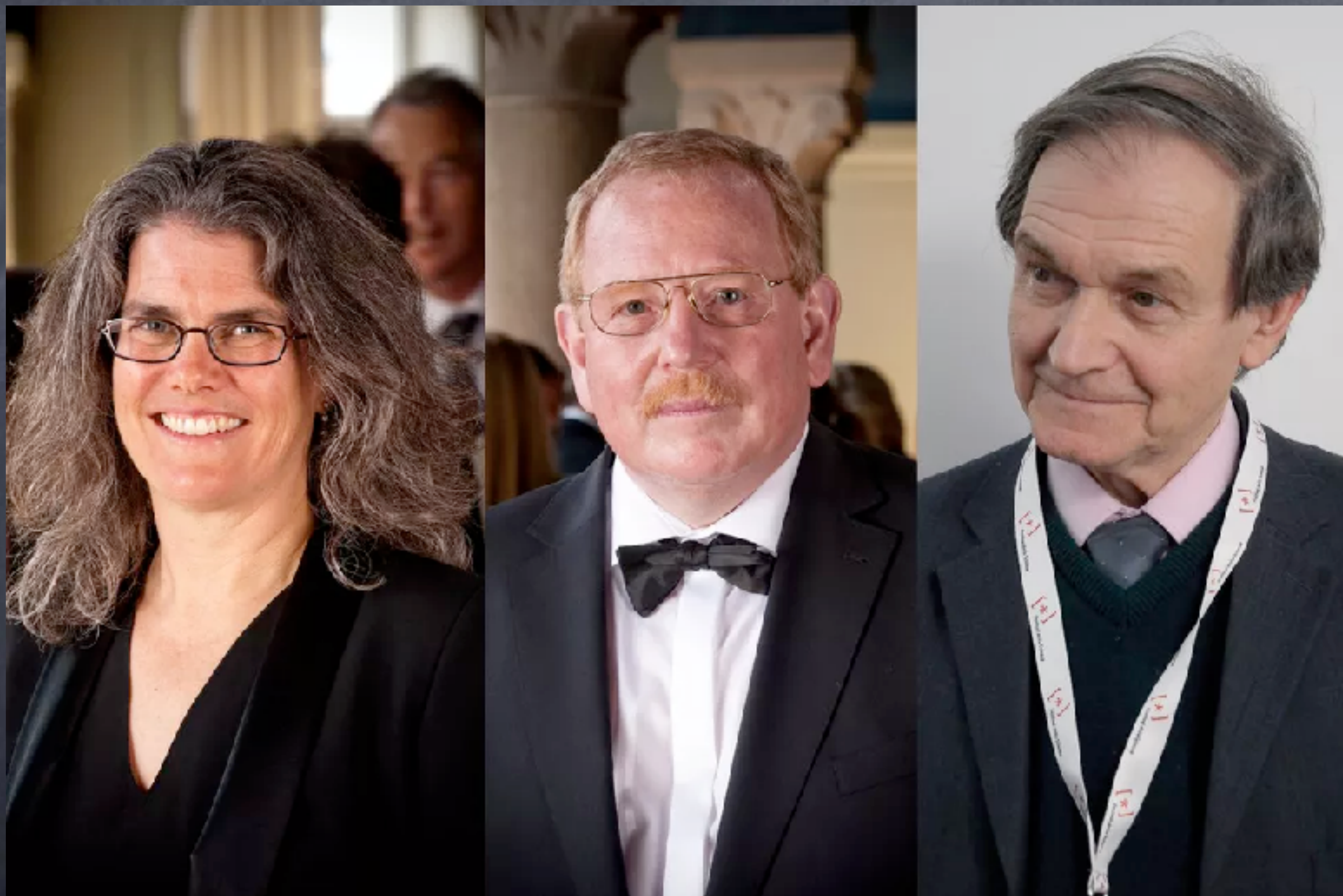




Prêmio Nobel 2020

- O mundo estava preparado para aceitar a natureza física dos buracos negros
- A quem premiar?
  - Teoria: formação
  - Observação: primeira detecção mais direta

Prêmio Nobel de física de 2020



Andrea Ghez
Prize share: 1/4

Reinhard Genzel
Prize share: 1/4

Roger Penrose
Prize share: 1/2

Roger Penrose

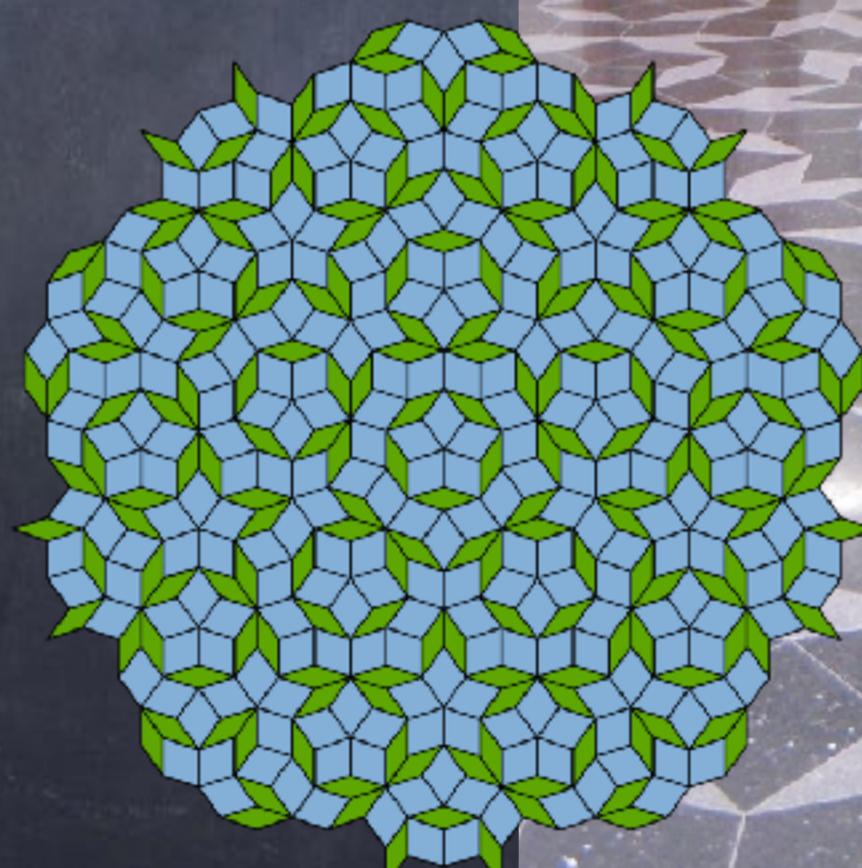
- Solução de buraco negro: Karl Schwarzschild, 1916
- Ninguém entendeu nem acreditou
- Décadas até entender a natureza do horizonte
- Colapso esférico (1939)
- Seria possível formar em situações realistas?
- Roger Penrose: formalismo matemático inovador
- 1965: teoremas de **singularidade** (também com Hawking)
- 1969: hipótese da **censura cósmica** (horizonte)
- Conclusão: sob certas condições (e sendo a hipótese correta) é **inevitável** formar um buraco negro

Roger Penrose

- Mente criativa atuando em várias áreas da física
- Triângulo de Penrose
- Inspirou Escher

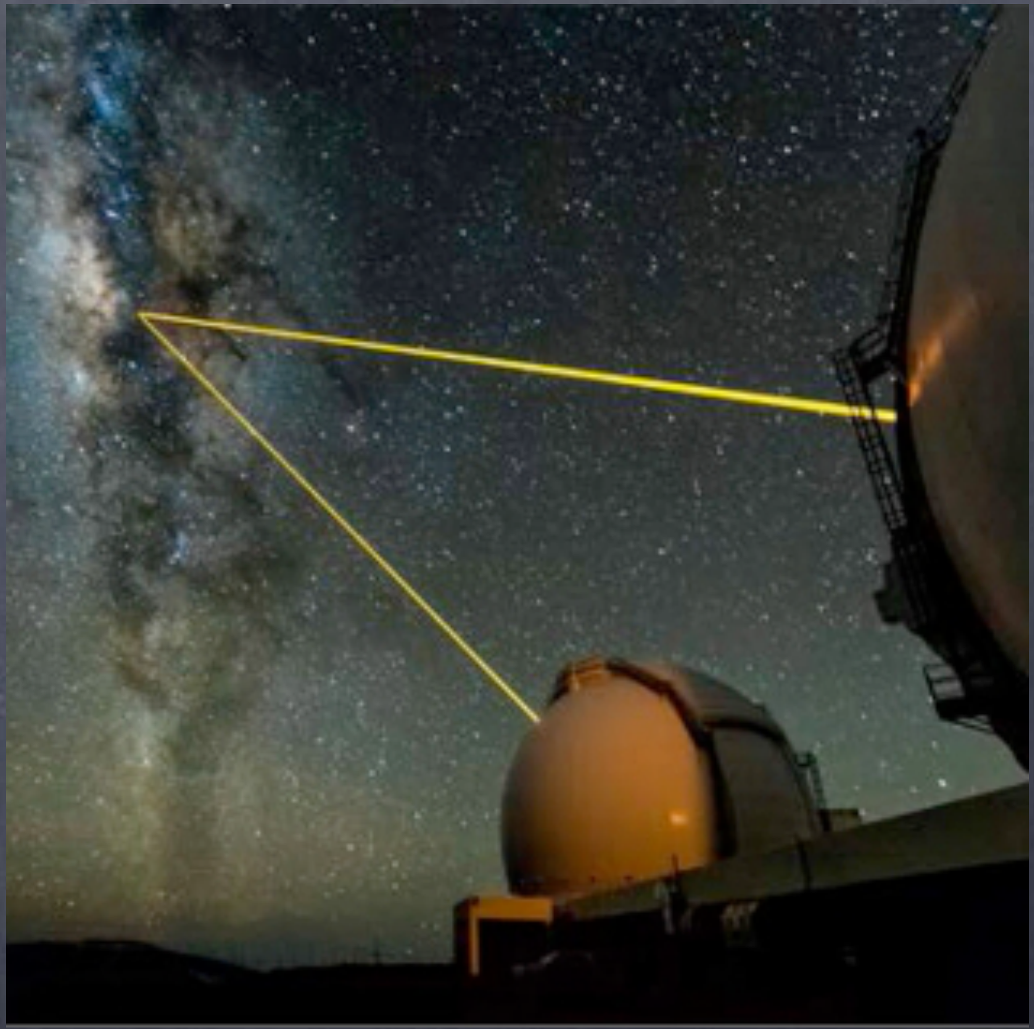
Roger Penrose

- Mente criativa atuando em várias áreas da física
- Recobrimento de Penrose
- Quasi-cristais



Andrea Ghez (e Reinhard Genzel)

- Como testar de forma direta a possível existência de um buraco negro supermassivo no centro de nossa galáxia?
- Movimento de estrelas!
- Região povoada de estrelas e gás, "impossível de ver"
- Desenvolvimento de novos métodos de observação e análise dos dados!

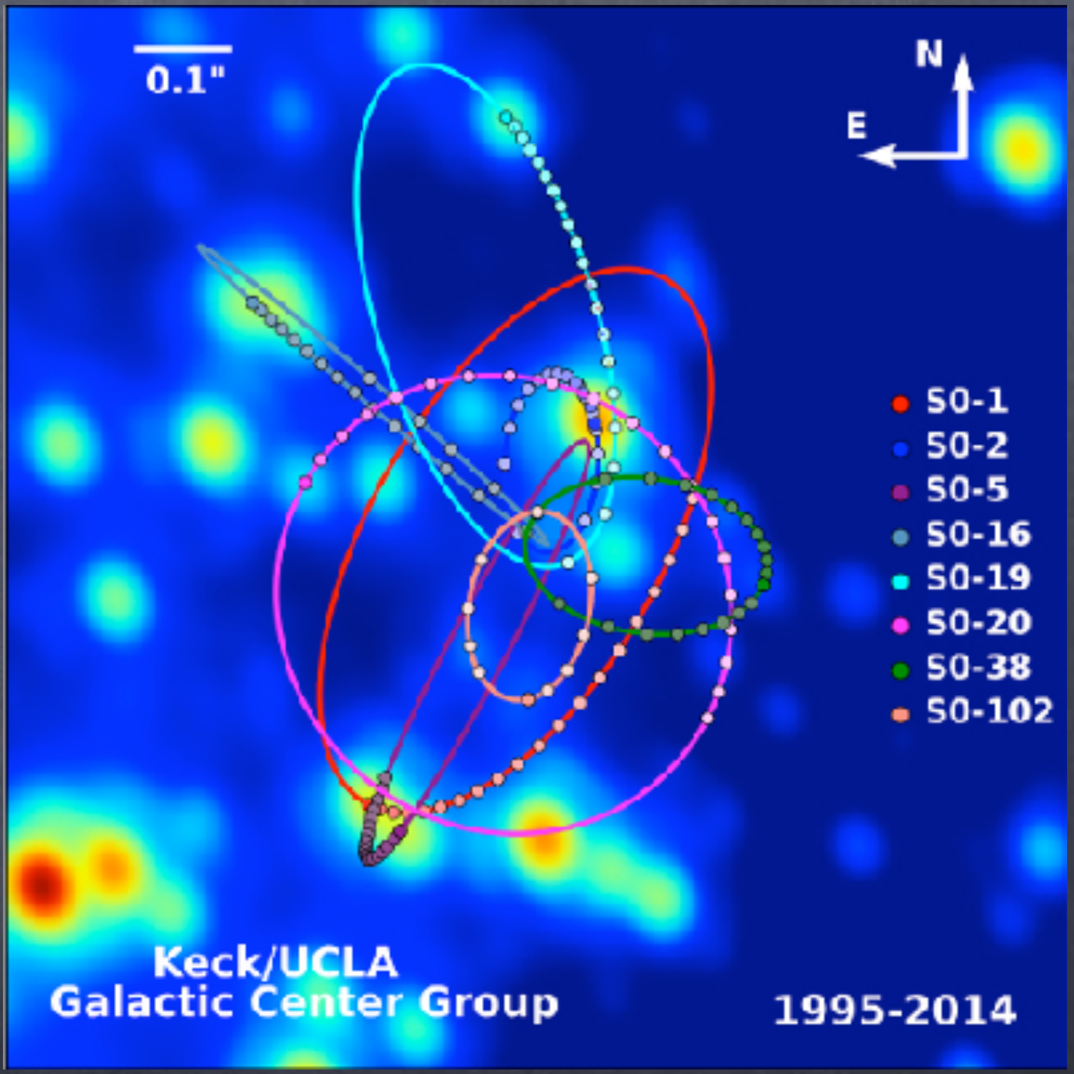


Interferometria speckle

ótica adaptativa para corrigir a atmosfera

Andrea Ghez

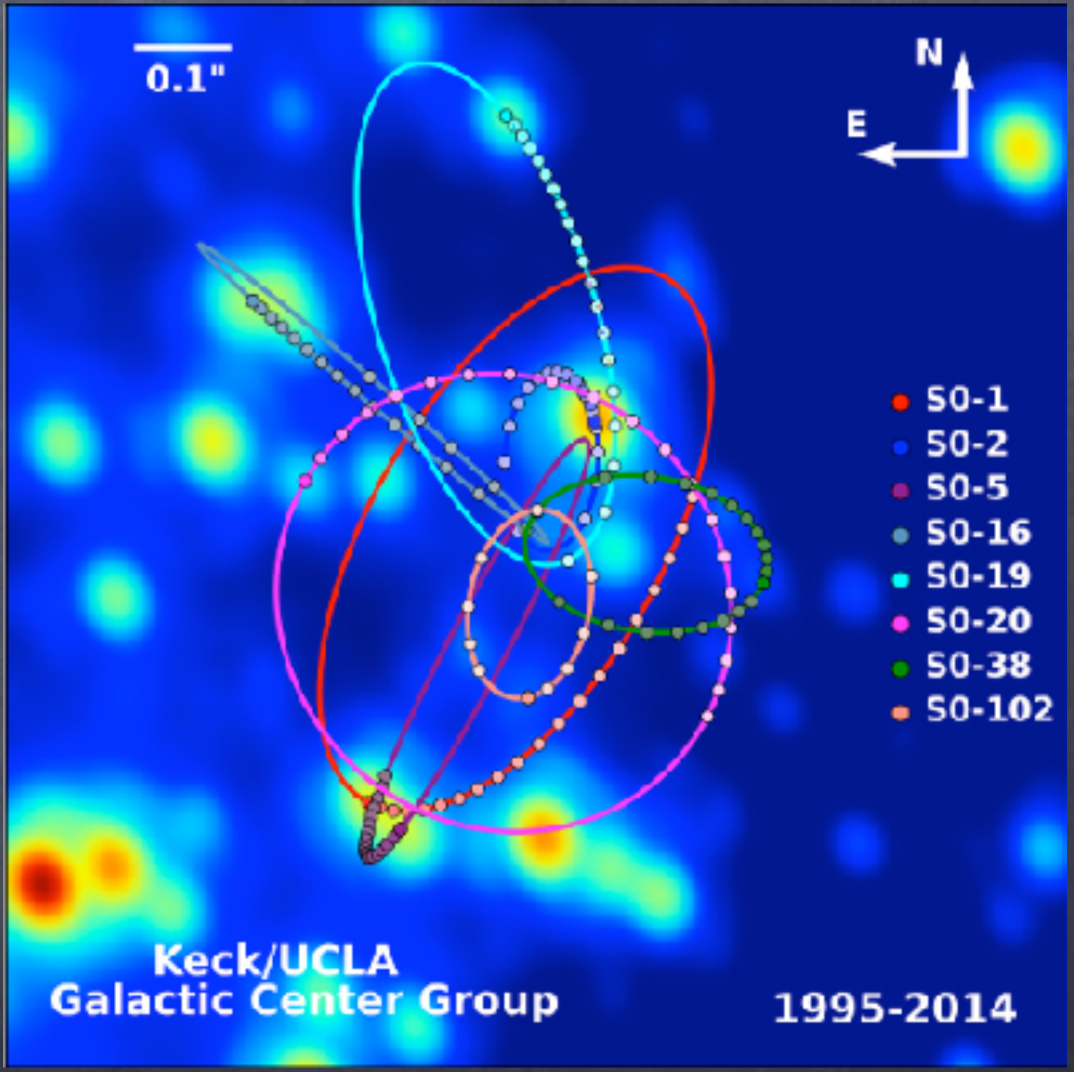
- Como testar de forma direta a possível existência de um buraco negro supermassivo no centro de nossa galáxia?
- Movimento de estrelas!
- Região povoada de estrelas e gás, "impossível de ver"
- Desenvolvimento de novos métodos de observação e análise dos dados!



Insights: instrumentos + análises + muita paciência!

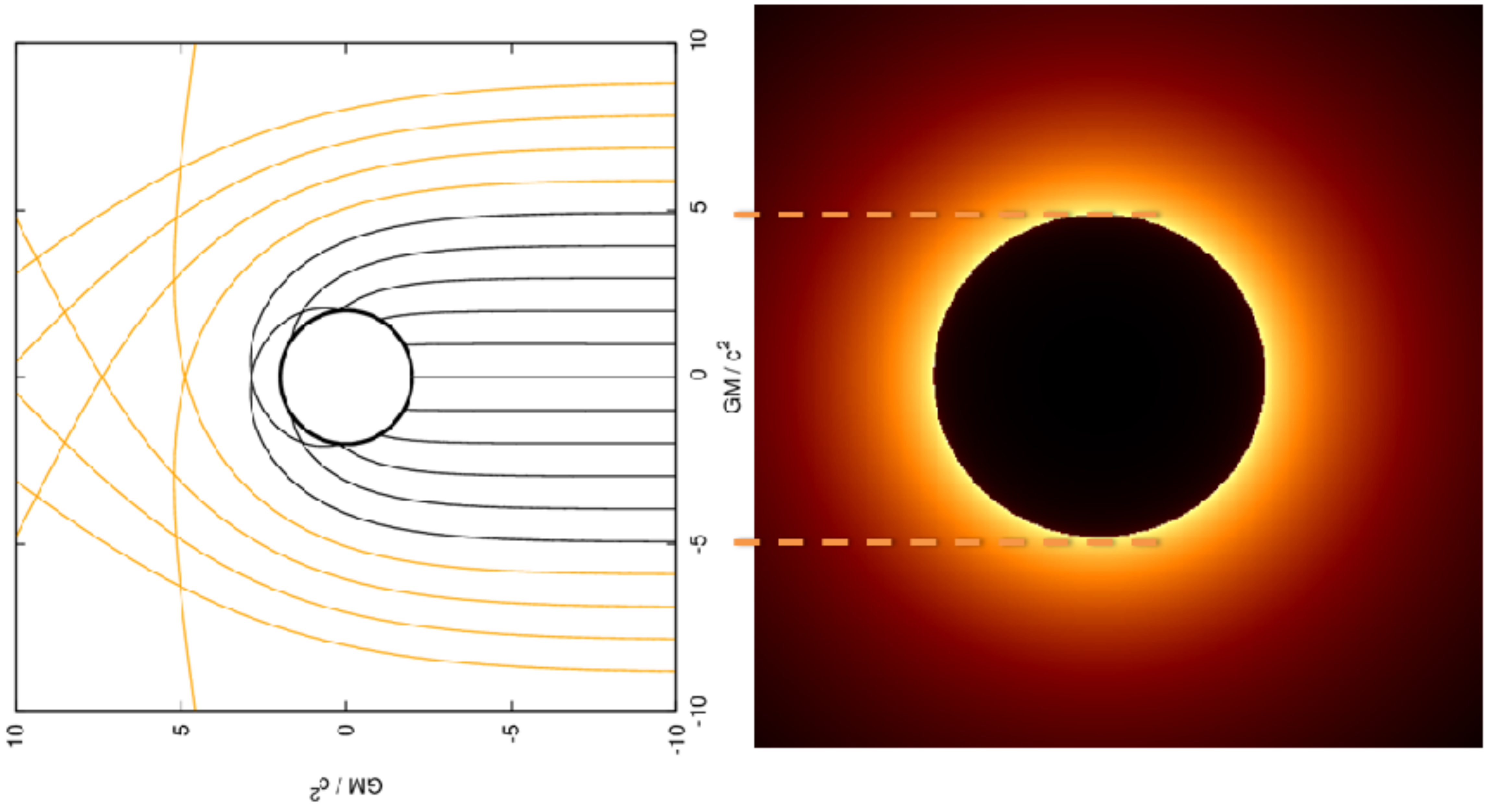
Andrea Ghez

- Resultado: presença de um objeto de massa 4 milhões de vezes maior que a do sol (em uma região menor que nosso sistema solar!)
- Evidência direta para a presença de um buraco negro supermassivo
- Testes da relatividade geral

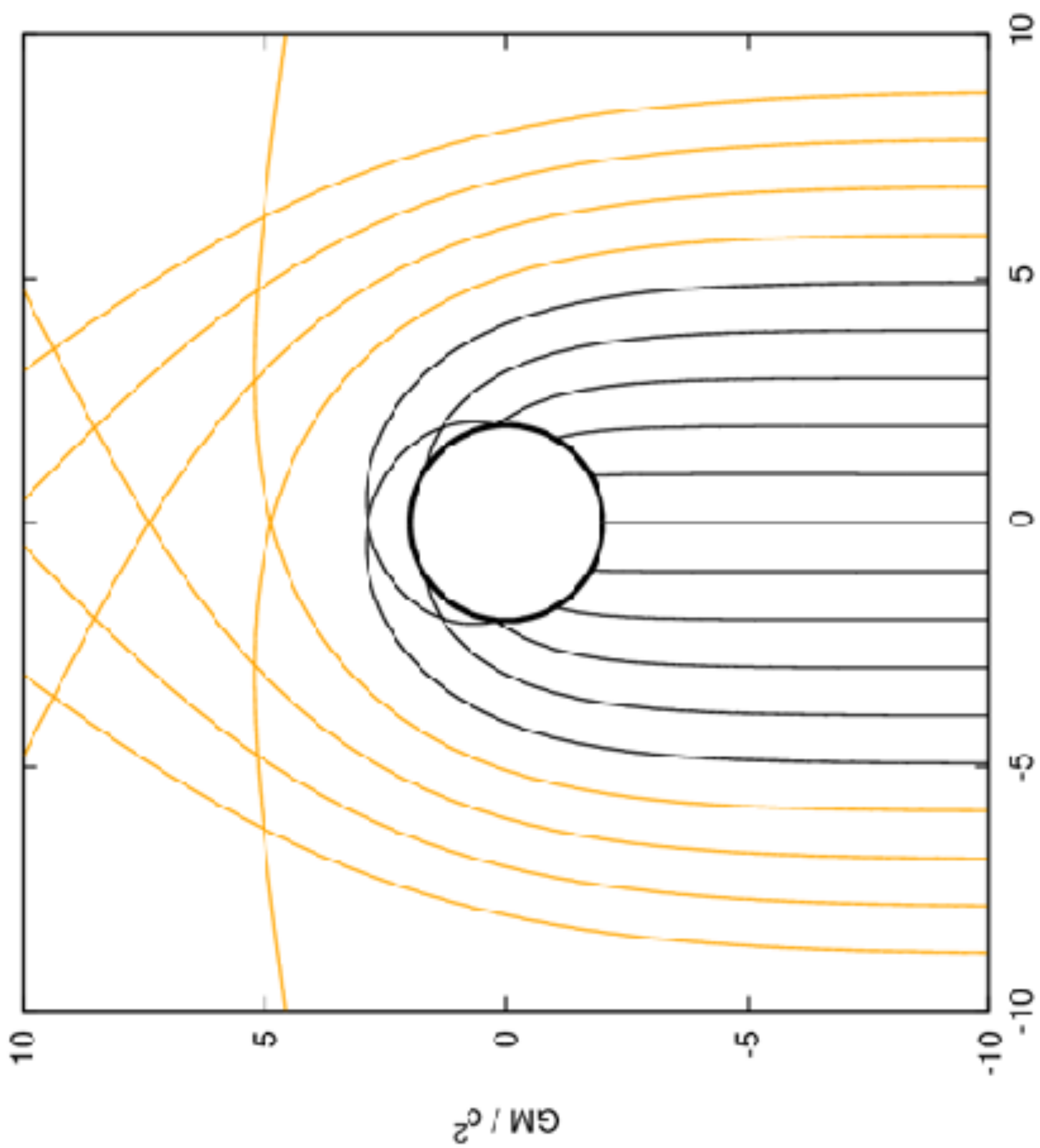


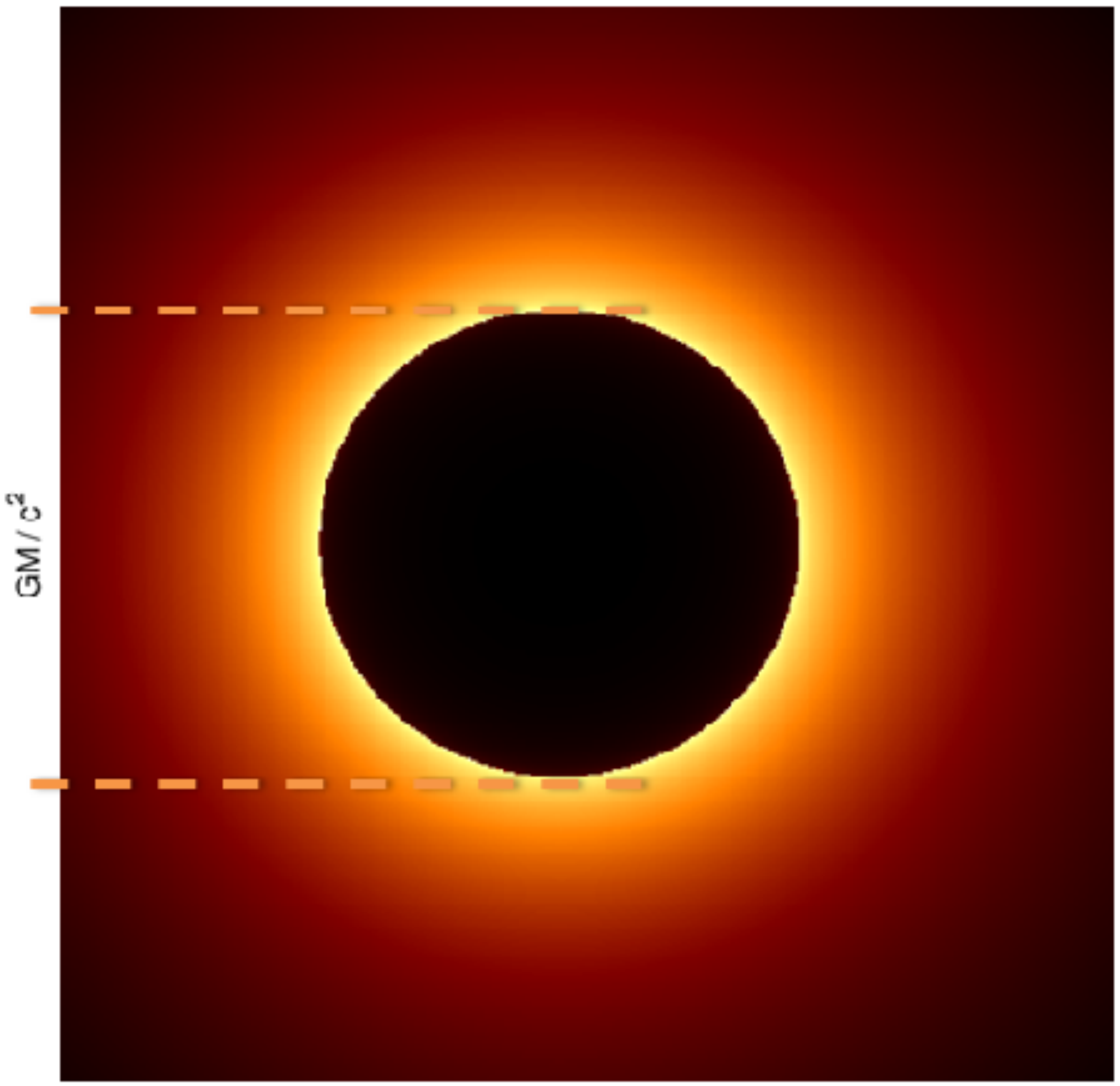
Insights: instrumentos + análises + muita paciência!

A sombra do Buraco Negro

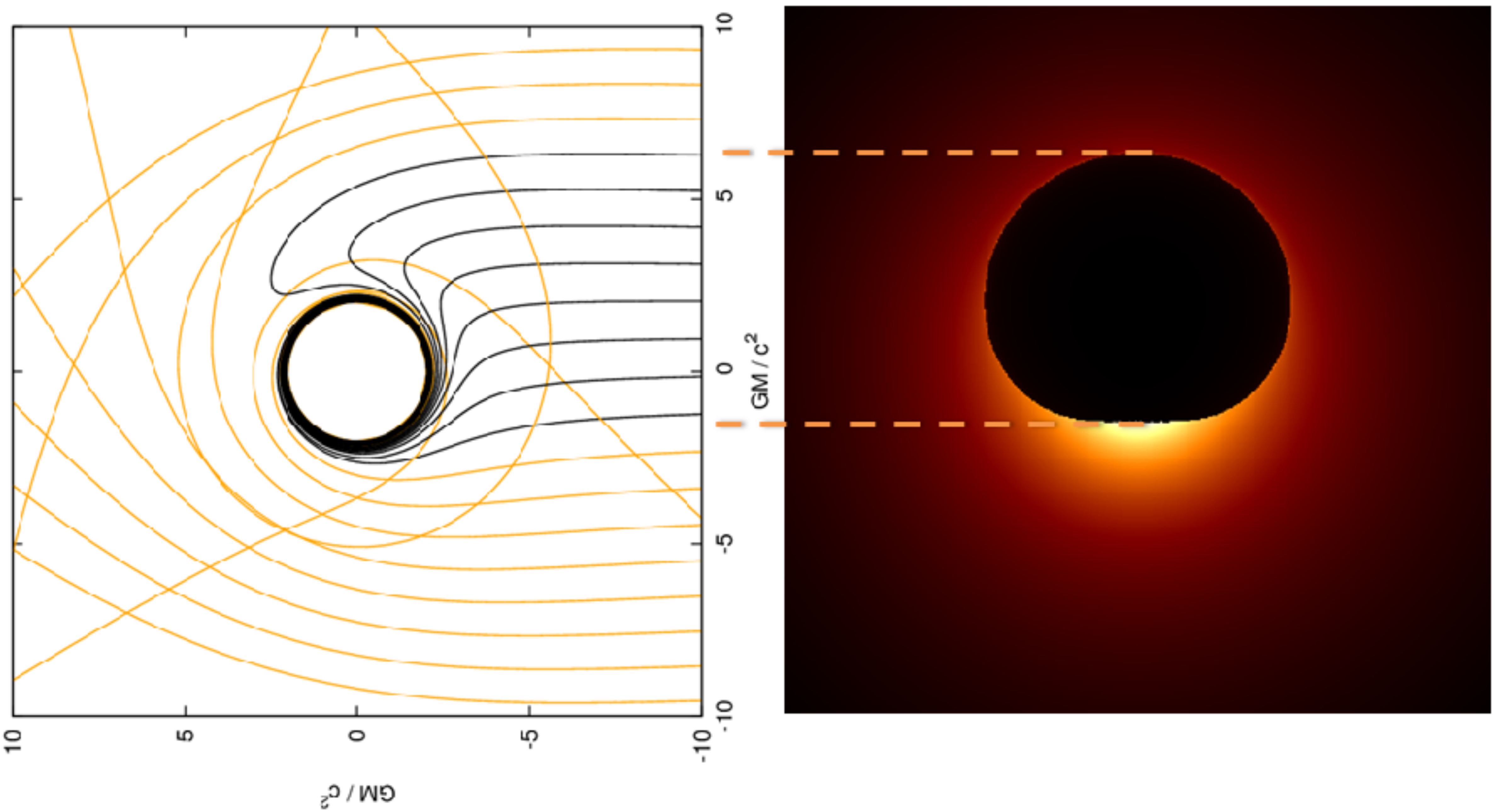


Buraco negro estático (sem rotação)

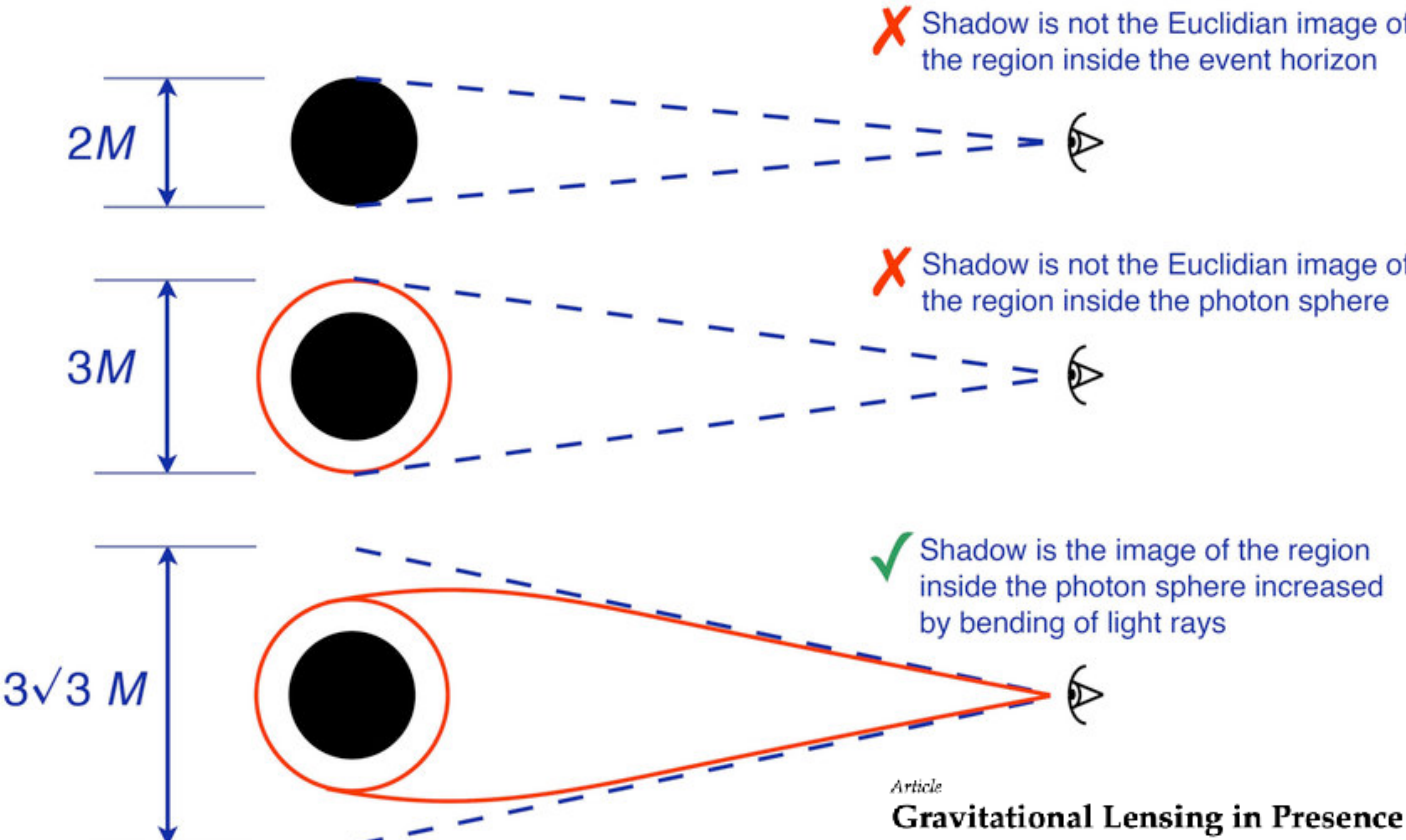




Buraco negro girante



A sombra do Buraco Negro

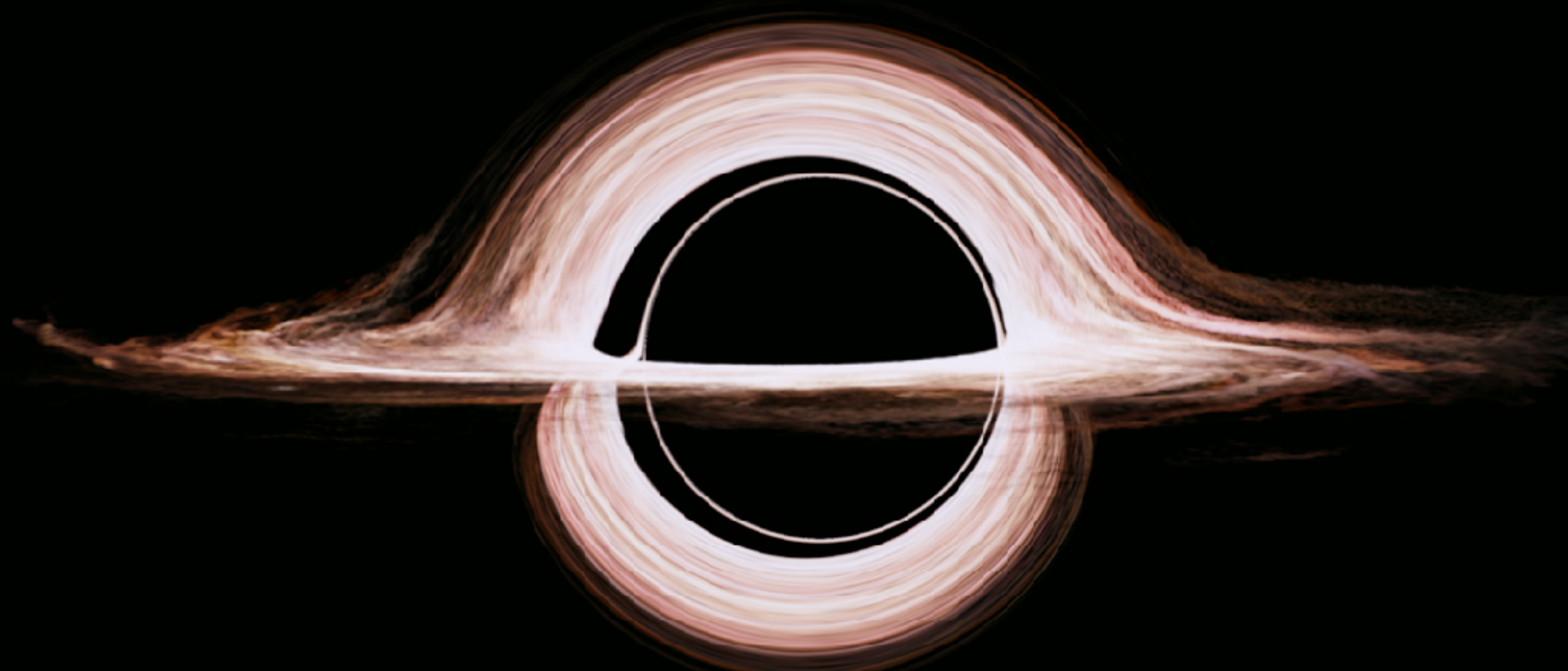


Article

Gravitational Lensing in Presence of Plasma: Strong Lens Systems, Black Hole Lensing and Shadow

Gennady S. Bisnovatyi-Kogan [1,2] and Oleg Yu. Tsupko [1,*]

Gargantua (filme interstellar)



Gravitational lensing by spinning black holes in astrophysics, and in the movie Interstellar, Oliver James et al 2015 Class. Quantum Grav. 32 065001

Class. Quantum Grav. **32** (2015) 065001 (41pp) doi:10.1088/0264-9381/32/6/065001

Gravitational lensing by spinning black holes in astrophysics, and in the movie *Interstellar*

Oliver James[1,*], **Eugénie von Tunzelmann**[1], **Paul Franklin**[1] **and Kip S Thorne**[2]

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CrossMark

Abstract

Interstellar is the first Hollywood movie to attempt depicting a black hole as it would actually be seen by somebody nearby. For this, our team at *Double Negative Visual Effects*, in collaboration with physicist Kip Thorne, developed a code called Double Negative Gravitational Renderer (DNGR) to solve the equations for ray-bundle (light-beam) propagation through the curved spacetime of a spinning (Kerr) black hole, and to render IMAX-quality, rapidly changing images. Our ray-bundle techniques were crucial for achieving IMAX-quality smoothness without flickering; and they differ from physicists' image-generation techniques (which generally rely on individual light rays rather than ray bundles), and also differ from techniques previously used in the film industry's CGI community. This paper has four purposes: (i) to describe

A sombra do Buraco Negro

Esta é uma imagem gravitacionalmente lenteada!

Event Horizon Telescope

Este não é o horizonte de eventos
do Buraco Negro

Diffractive Gravitational Lensing

Ecuaciones de Maxwell en el espacio-tiempo curvo

$$\begin{aligned} F_{\alpha\beta,\gamma} + F_{\beta\gamma,\alpha} + F_{\gamma\alpha,\beta} &= 0 \\ F^{\alpha\beta}_{;\gamma} &= 0 \end{aligned}$$

Perturbación escalar, expansión lineal:

$$\nabla^2 \vec{E} = (1 + 2U) \frac{\partial^2 \vec{E}}{\partial t^2}$$

Onda estacionaria: $\vec{E}(\vec{r}, t) = \phi(\vec{r}) e^{i\omega t}$

Amplitud de la onda en la presencia del campo gravitacional

$$\left(\nabla^2 + \omega^2\right) \phi = 4\omega^2 U \phi$$

Wave optics effects

- Maxwell's equations on a curved background
  Solution for the amplitude ratio of the field:

$$F(\omega, \vec{\eta}) = \frac{D_{\mathrm{S}}}{D_{\mathrm{L}} D_{\mathrm{LS}}} \frac{\omega}{2\pi i} \int d^2\xi \exp\left[i\omega t'(\vec{\xi}, \vec{\eta})\right]$$

Where $F = \phi/\phi_0$ and *t'* is the time delay function

$$t'(\vec{\xi}, \vec{\eta}) = \frac{D_L D_S}{2 D_{LS}} \left(\frac{\vec{\xi}}{D_L} - \frac{\vec{\eta}}{D_S} \right)^2 - \hat{\psi}(\vec{\xi})$$

with $\nabla_\xi^2 \hat{\psi} = 8\pi\Sigma$

Wave optics effects

- Maxwell's equations on a curved background
  Solution for a **point lens**

$$F(w,u) = e^{\frac{i}{2}(u^2 - \ln(w/2))} e^{\frac{\pi}{4}w} \Gamma\left(1 - \frac{i}{2}w\right) {}_1F_1\left(1 - \frac{i}{2}w, 1; -\frac{i}{2}wu^2\right)$$

The magnification is therefore: $\mu = |F|^2$

$$\mu_{\mathrm{ond}}^{\mathrm{inf}}(w,u) = \frac{\pi w}{1 - e^{\pi w}} \left| {}_1F_1\left(\frac{i}{2}w, 1; \frac{i}{2}wu^2\right)\right|^2$$

Dimensionless, characteristic frequency:

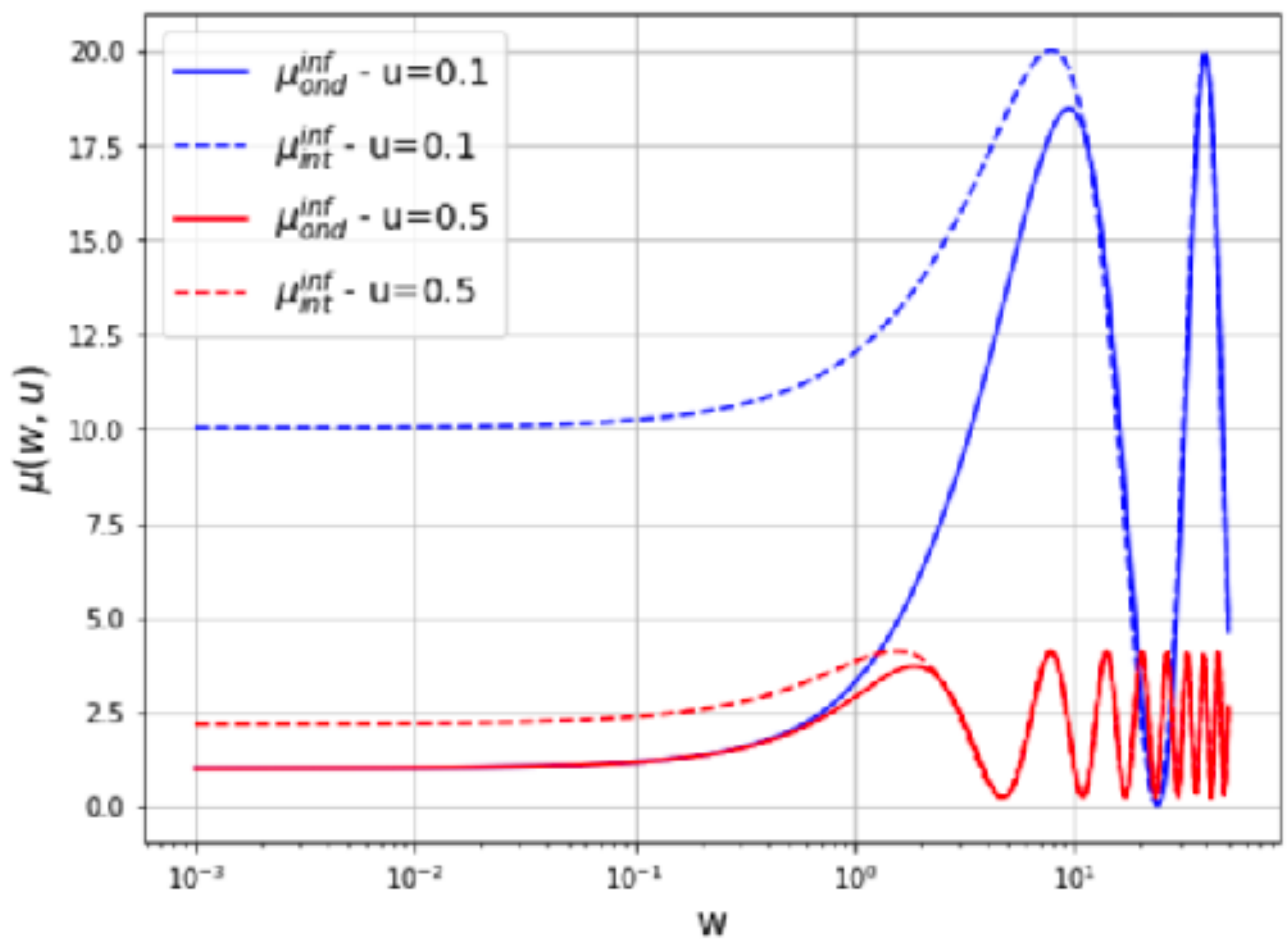
$$w = \frac{4GM}{c^2}\omega(1 + z_L) = 4\pi(1 + z_{\mathrm{L}})\frac{r_{\mathrm{sch}}(M)}{\lambda}$$

- If the wavelength is comparable to the Schwarzschild radius, one has to account for wave optics!

Wave optics effects in gravitational lensing

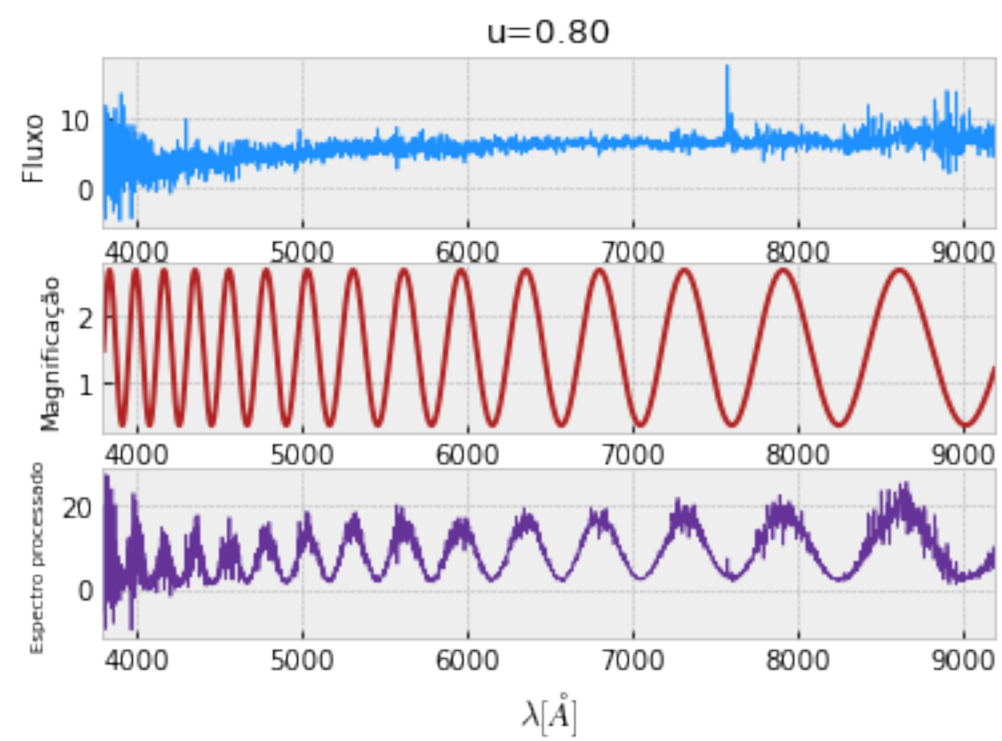
- Maxwell's equations on a curved background
  Solution for a point lens:

$$\mu_{\text{ond}}^{\text{inf}}(w,u) = \frac{\pi w}{1-e^{\pi w}} \left| {}_1F_1\left(\frac{i}{2}w, 1; \frac{i}{2}wu^2\right)\right|^2$$



Arthur Mesquita, CBPF

Effect on a spectrum



Wavelensing!

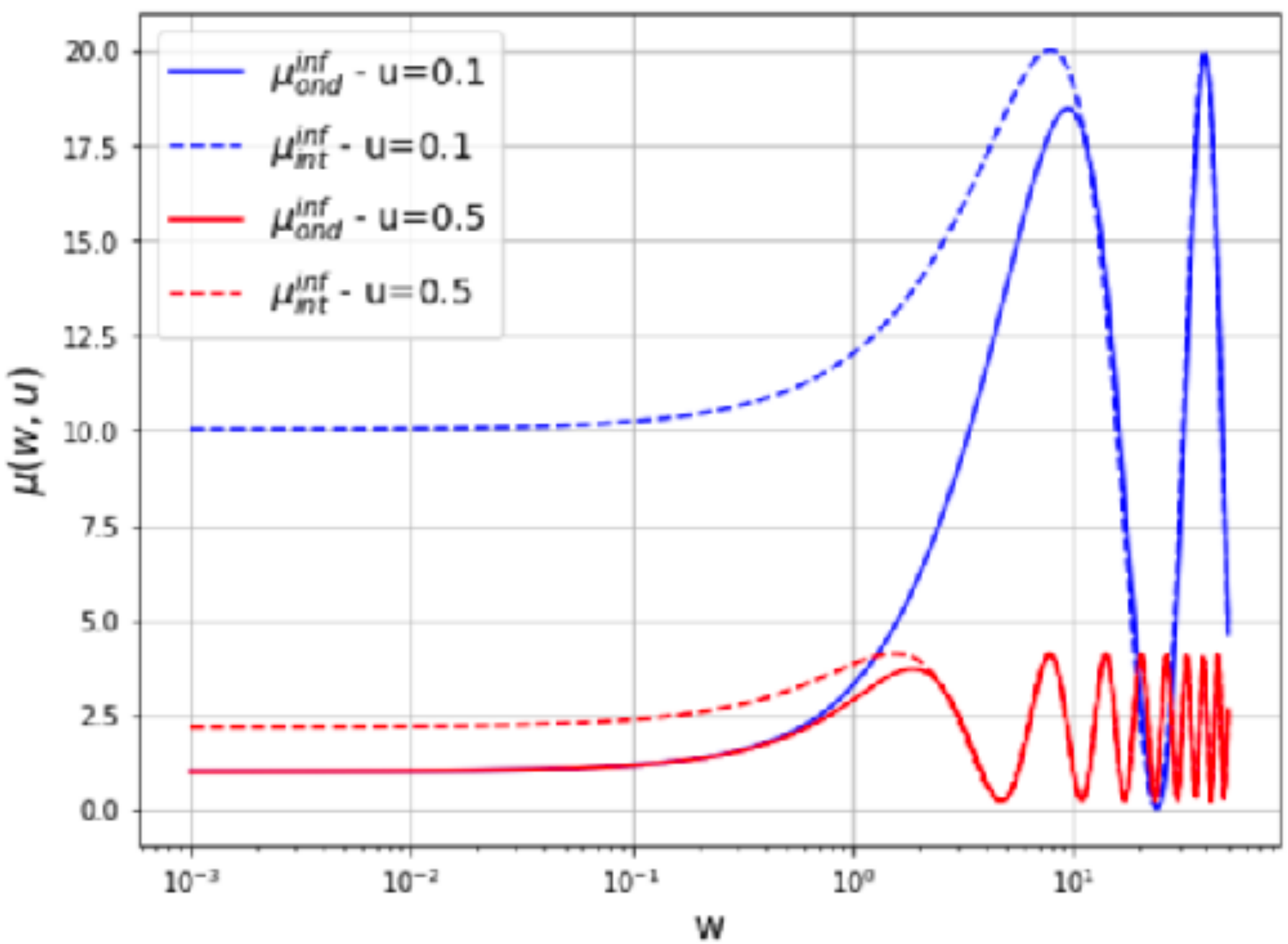
wave optics kills microlensing at the refractive limit

$$w = \frac{4GM}{c^2}\omega(1+z_L) = 4\pi(1+z_\text{L})\frac{r_\text{sch}(M)}{\lambda}$$

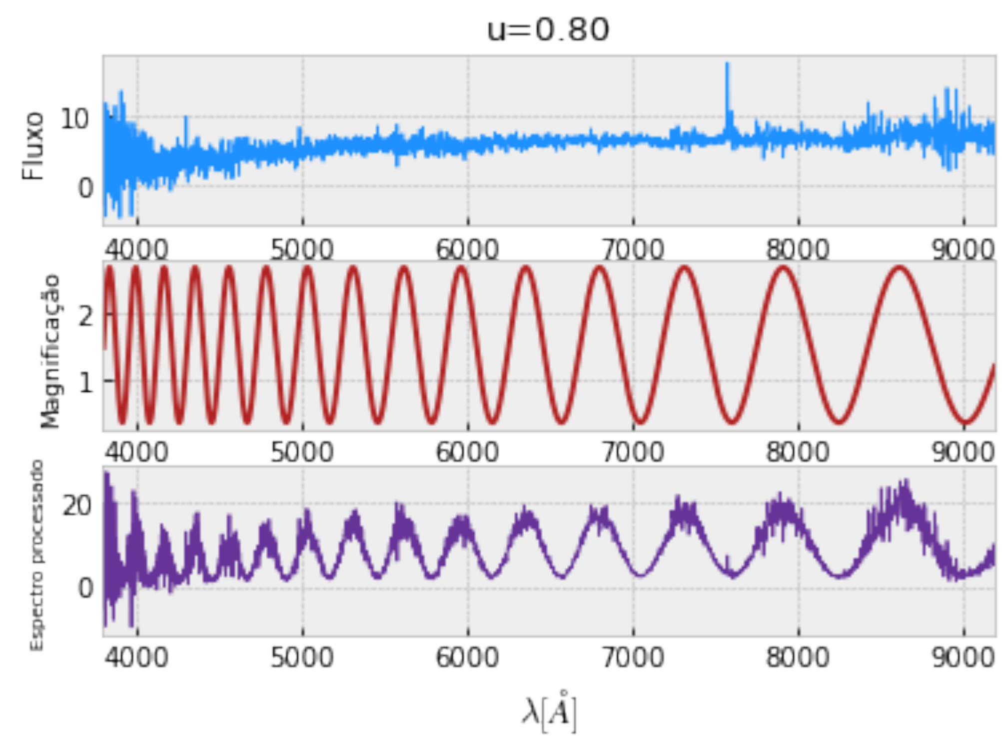
Wave optics effects

- For high frequencies (eikonal limit)

$$\mu_{\rm int}^{\rm inf}(w,u) = \frac{u^2+2}{u\sqrt{u^2+4}} + \frac{2}{u\sqrt{u^2+4}}\sin\left\{w\left[\frac{1}{2}u\sqrt{u^2+4}+\ln\left(\frac{\sqrt{u^2+4}+u}{u-\sqrt{u^2+4}}\right)\right]\right\}$$



Effect on a spectrum

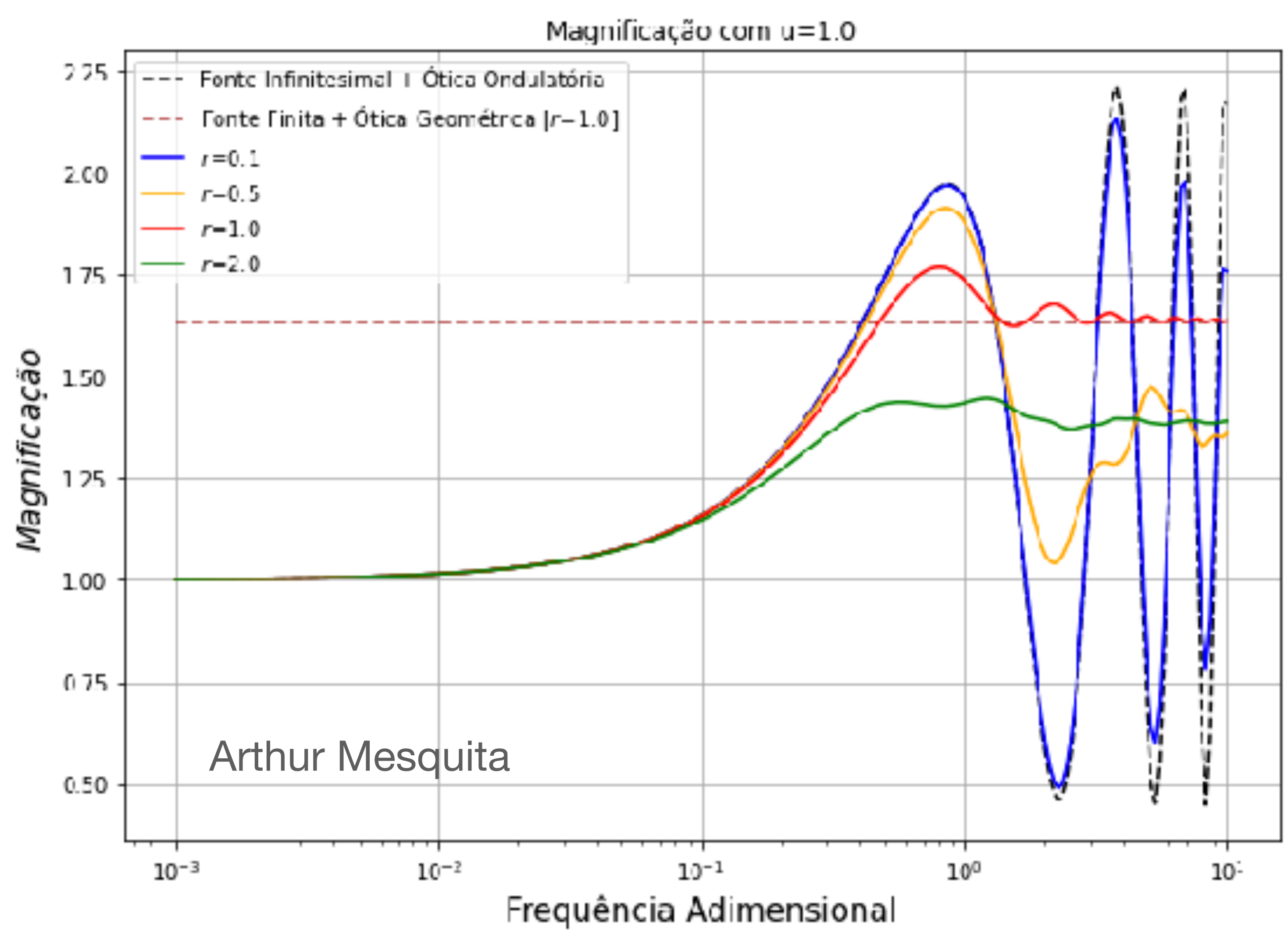


Femtolensing!

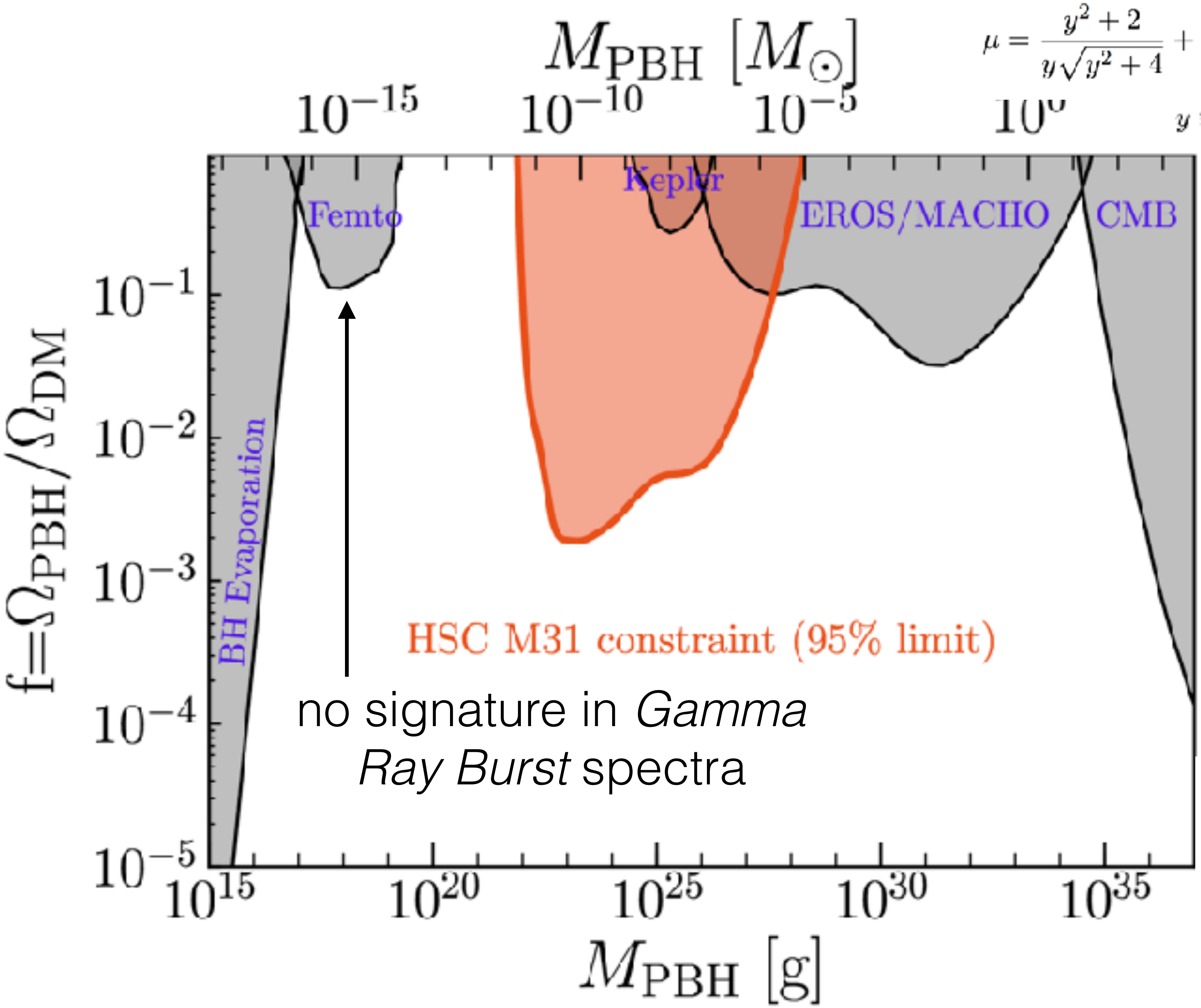
$$w = \frac{4GM}{c^2}\omega(1+z_L) = 4\pi(1+z_{\rm L})\frac{r_{\rm sch}(M)}{\lambda}$$

Finite source size

- Fuente incoerente: $$\mu = \frac{\int_{-\infty}^{+\infty} W(\vec{u})\mu(w,u)d^2u}{\int_{-\infty}^{+\infty} W(\vec{u})d^2u}$$
- Fuente uniforme circular: $$\mu(w,r,u) = \frac{1}{\pi r^2}\int_0^r\int_0^{2\pi} \mu(w,\nu)\,\chi d\alpha d\chi$$

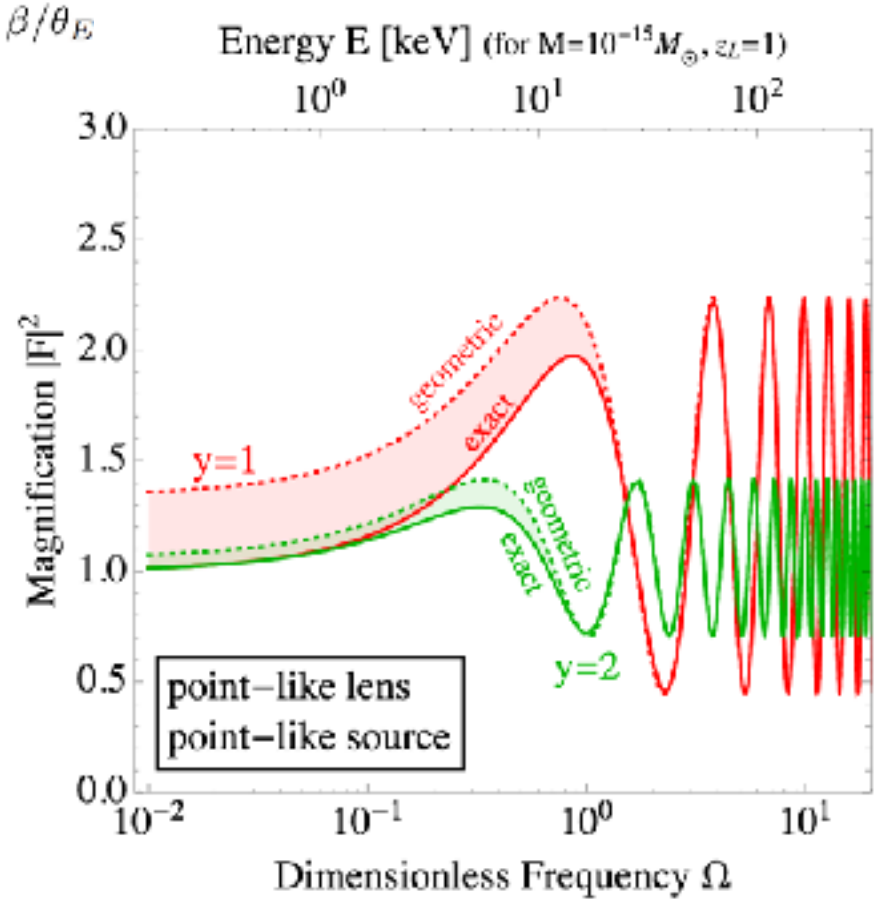


Femtolensing: wave optics



$$\mu = \frac{y^2+2}{y\sqrt{y^2+4}} + \frac{2}{y\sqrt{y^2+4}} \sin\left(\Omega\left[\frac{y\sqrt{y^2+4}}{2} + \log\left|\frac{y+\sqrt{y^2+4}}{y-\sqrt{y^2+4}}\right|\right]\right)$$

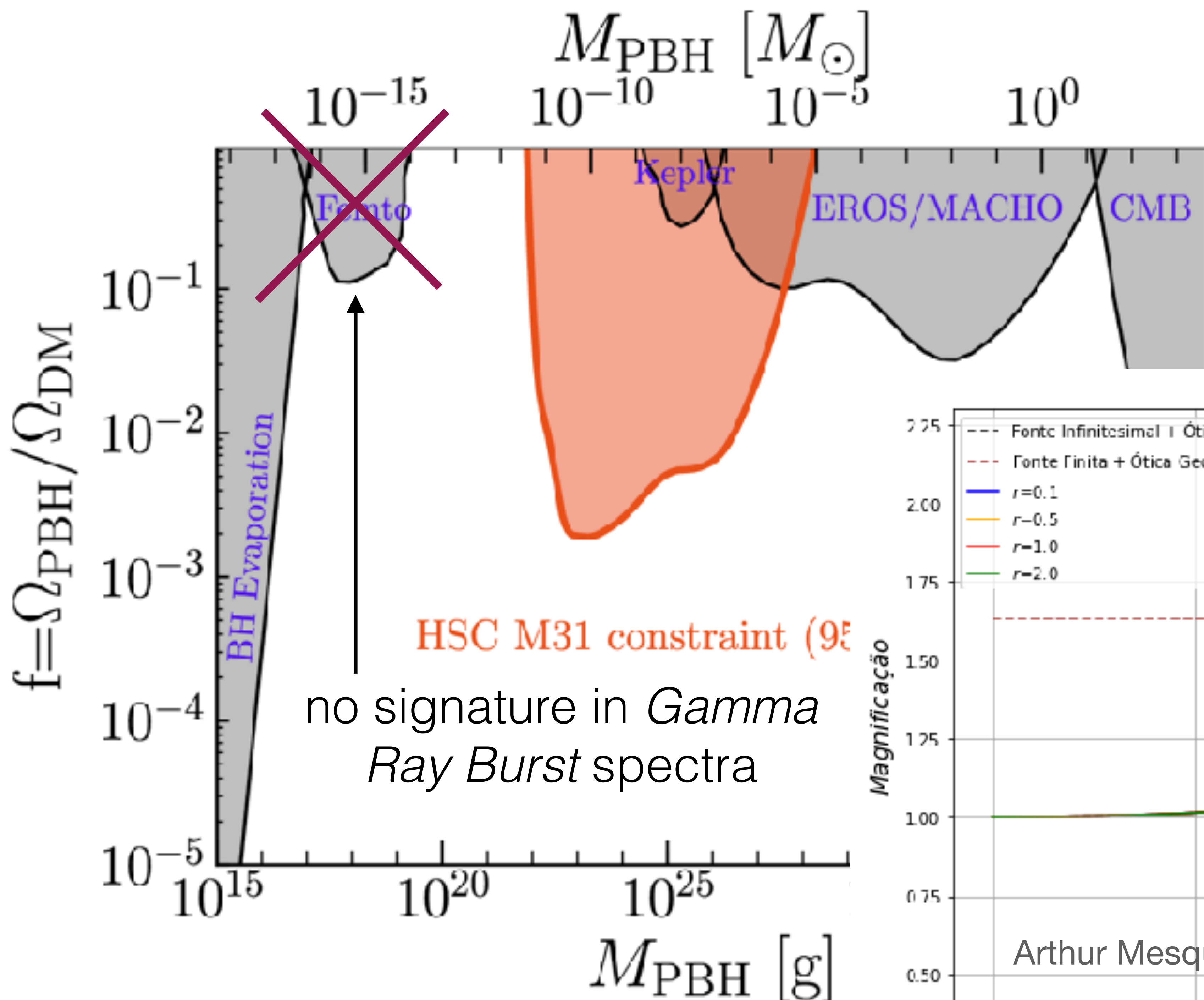
$y = \beta/\theta_E$



$$\Omega \equiv \frac{1}{c}\frac{D_S D_L}{D_{LS}}\theta_0^2(1+z_L)\,\omega \equiv \Delta t_0\,\omega\,.$$

arXiv:1701.02151v3

Femtolensing: wave optics

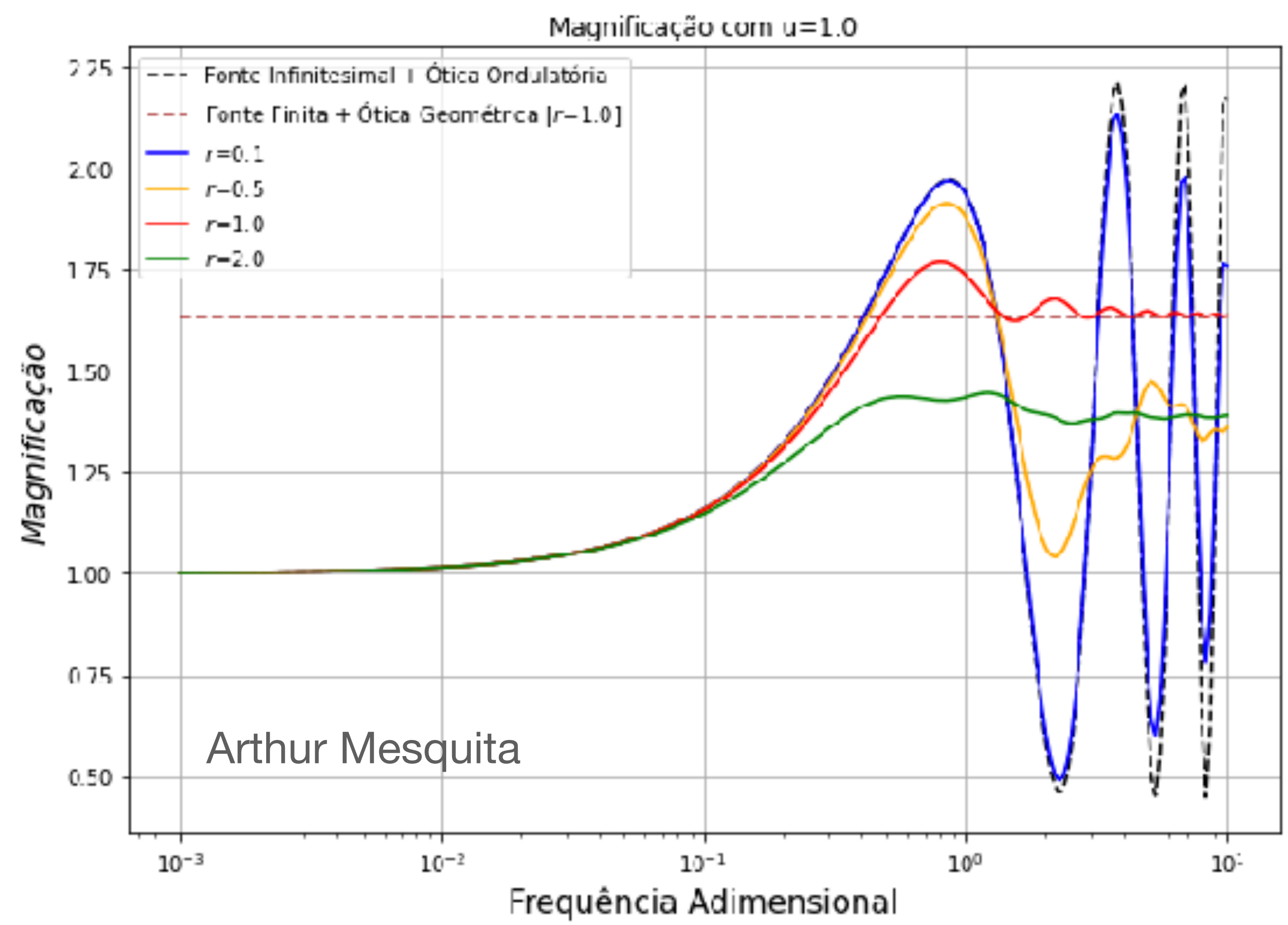


arXiv:1701.02151v3

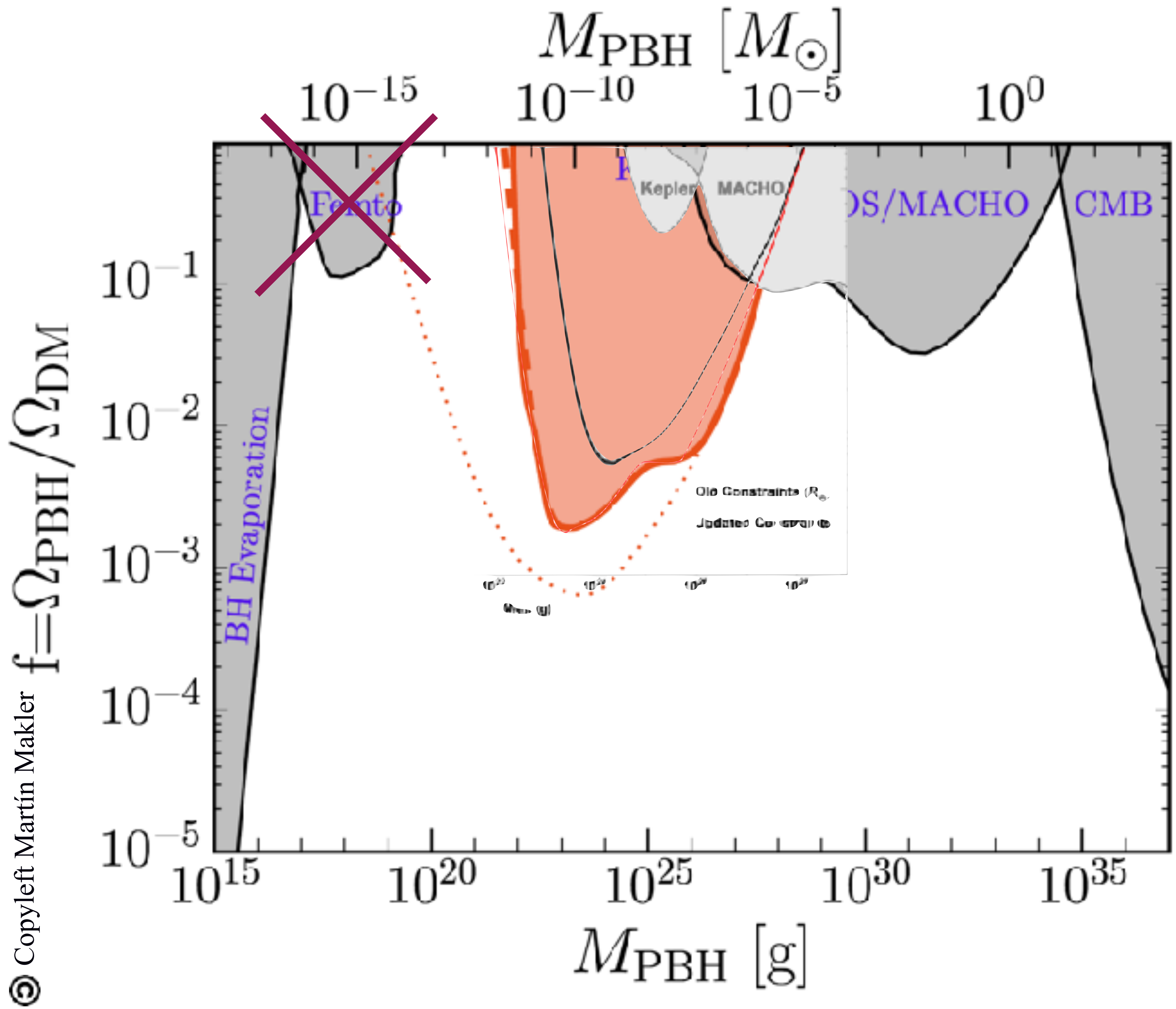
Finite size effects destroy the signal!

arXiv:1807.11495

Projections for femtolensing of GRB: arXiv:1807.11495



Limits on the fraction of Dark Matter in condensed objects



Can we improve over the low mass limits with higher cadence observations of M31?

Rubin micro-survey?

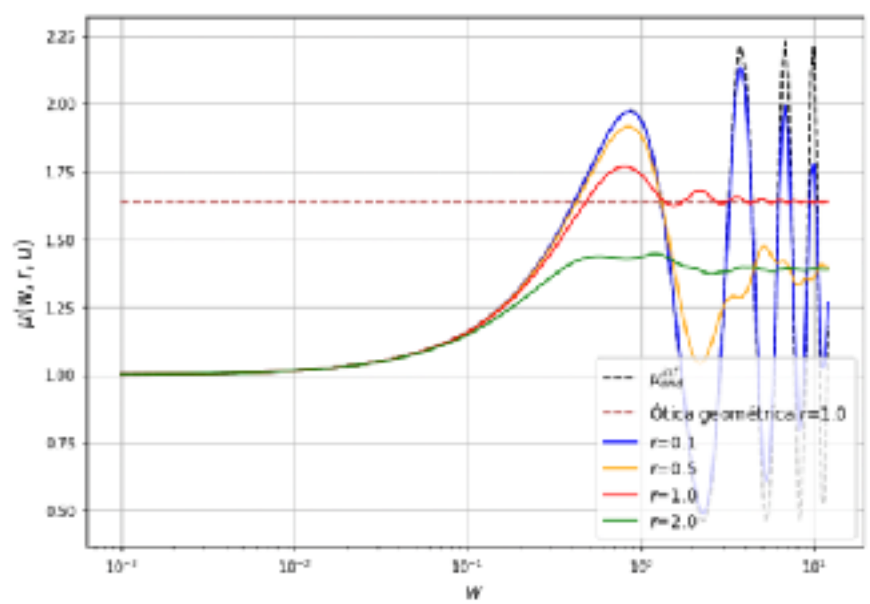
(Anibal Varela, Arthur Mesquita)

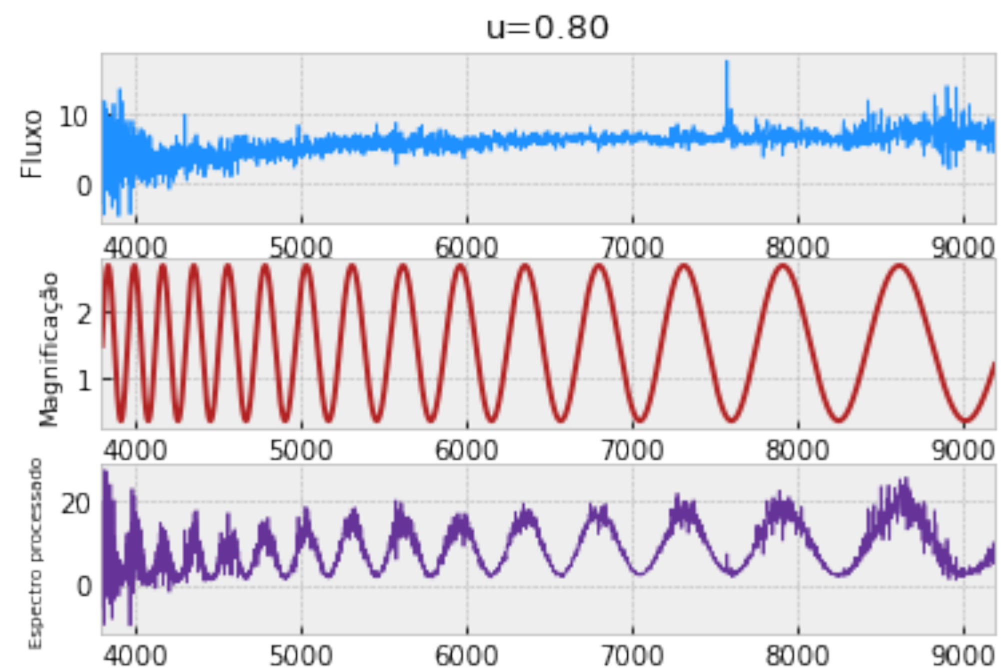
Original femtolensing limits destroyed by finite source effects

Femtolensing

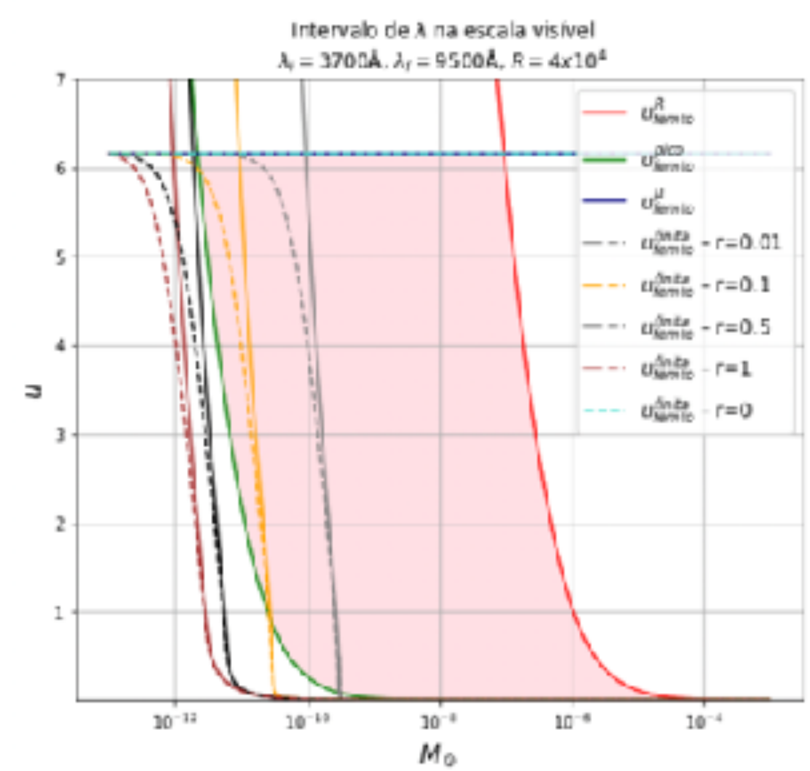
Wave-optics effects in gravitational lensing

- Oscillations on the magnification induce oscillations in the spectrum





- Schwarzschild radius comparable to wavelength
- Finite source size breaks effect
- **Exploring observability for DM and lensing by exoplanets and extragalactic sources!**



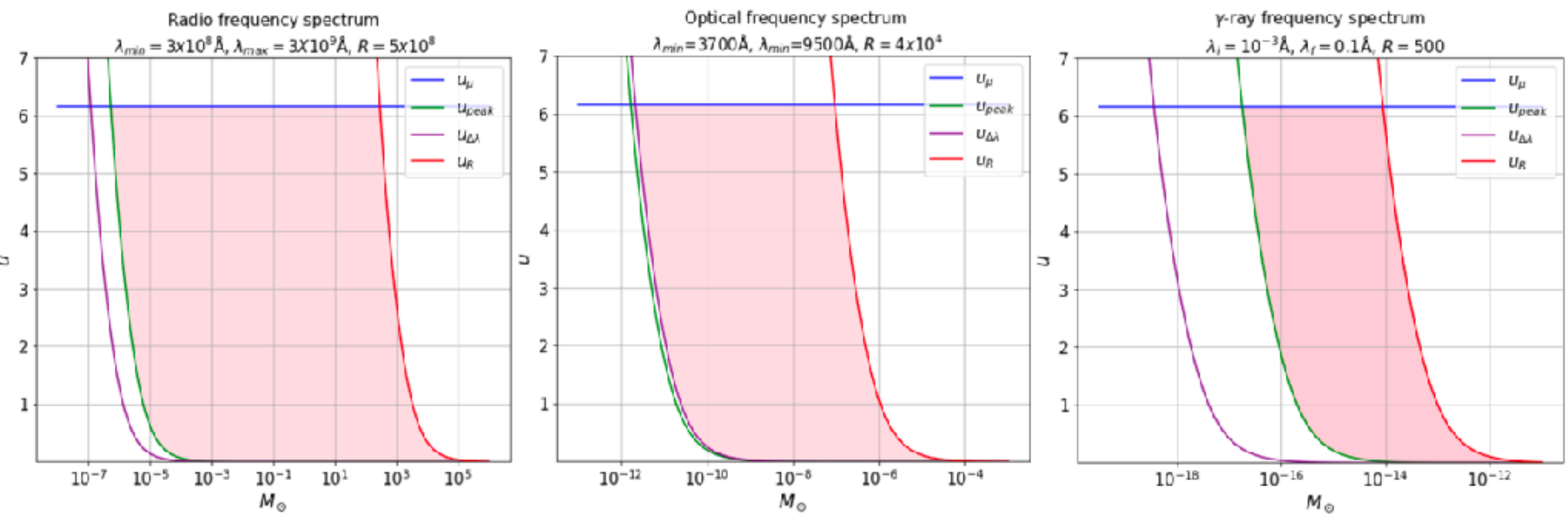
Detectability conditions

Presence of clear oscillatory patters sets constraints on the *u* x lens mass parameter space

- Depends on the wavelength and resolution of the instrument

SETI	Radio	$[3 - 30]\times10^8$	5×10^8
ALMA	Submm	$[3 - 35]\times10^6$	3×10^7
VLT (CRIRES)	IR	$[1 - 5]\times10^4$	1×10^5
VLT (FLAMES)	Optical	3700 - 9500	4×10^4
HST (GHRS)	UV	1150 - 3200	1×10^5
Chandra X-Ray (LETG)	X-ray	50 - 160	1×10^3
INTEGRAL (SPI)	γ-ray	10^{-3} - 0.1	5×10^2

Arthur Mesquita, CBPF

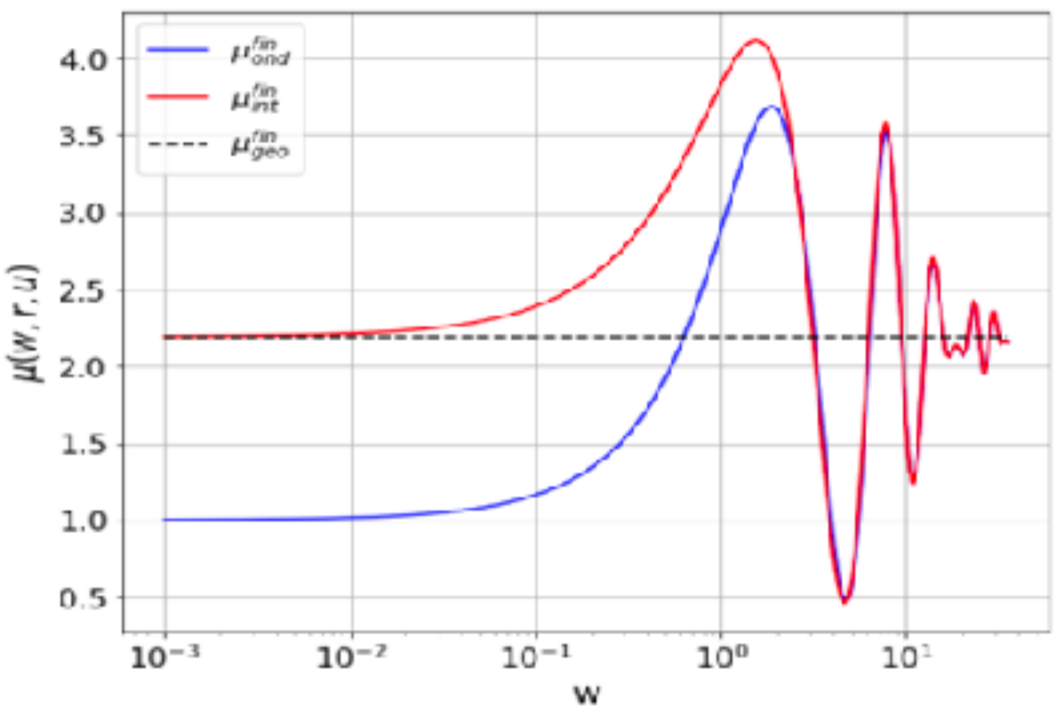


Arthur Mesquita, CBPF

Finite sources

Finite size effects destroy the signal for incoherent sources

$u = 0.5 \ - \ r = 0.01$

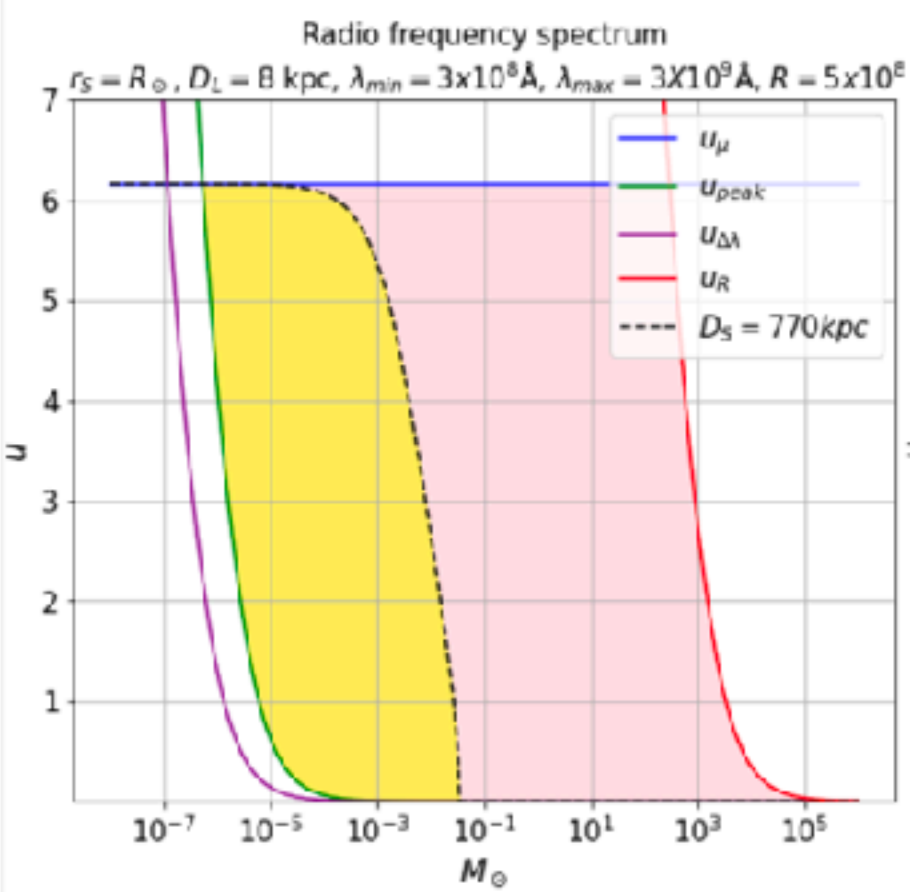


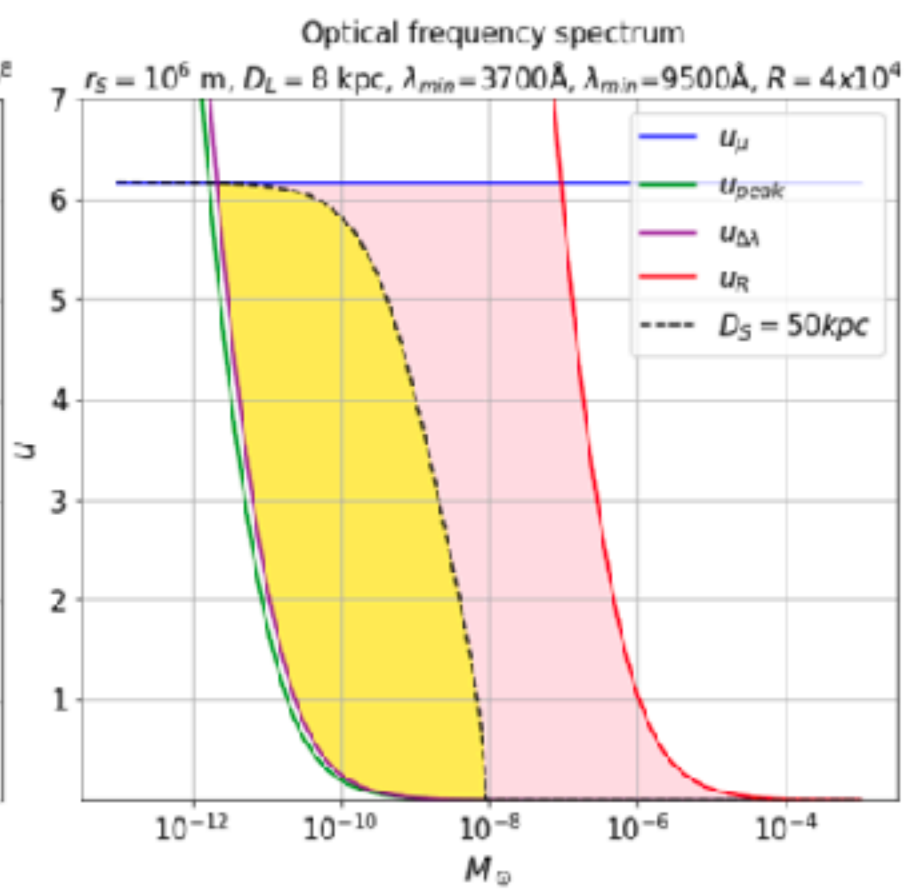
Source	r_S
Neutron Star	$\sim 10^4$m
White Dwarf	$\sim 10^6$m
Main Sequence Star	$\sim R_\odot$
Kilonova	$\sim 10^5$m
sGRB e GRB (short/large γ-ray burst)	$\sim [10^8, 10^9]$m
Supernova	$\sim 10^{12}$m

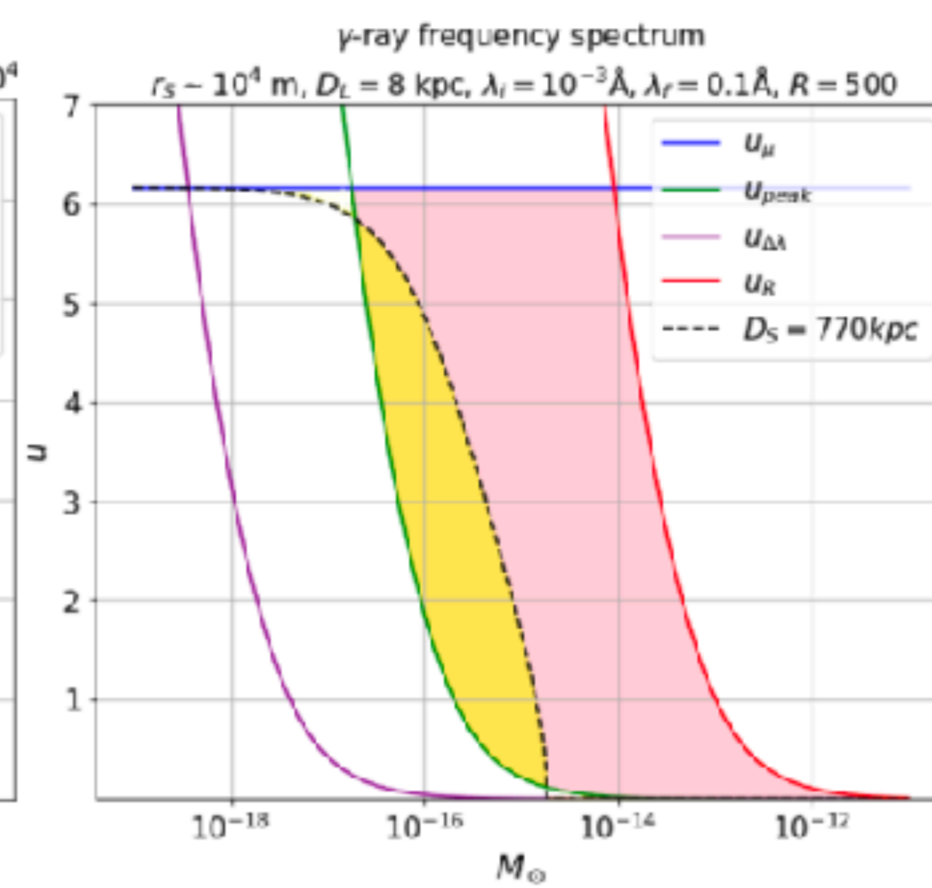
Local Universe

Cosmological Universe

Sources in the local Universe







Gravitational Waves

Ondas gravitacionais

Relatividade geral: métrica $$ds^2 = g_{\mu\nu} dx^\mu dx^\nu$$

Perturbação do espaço plano: $$g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu}$$

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

No regime linear: $$\Box h_{\mu\nu} = -16\pi T_{\mu\nu}$$

Ondas gravitacionais

Solução de onda esférica:

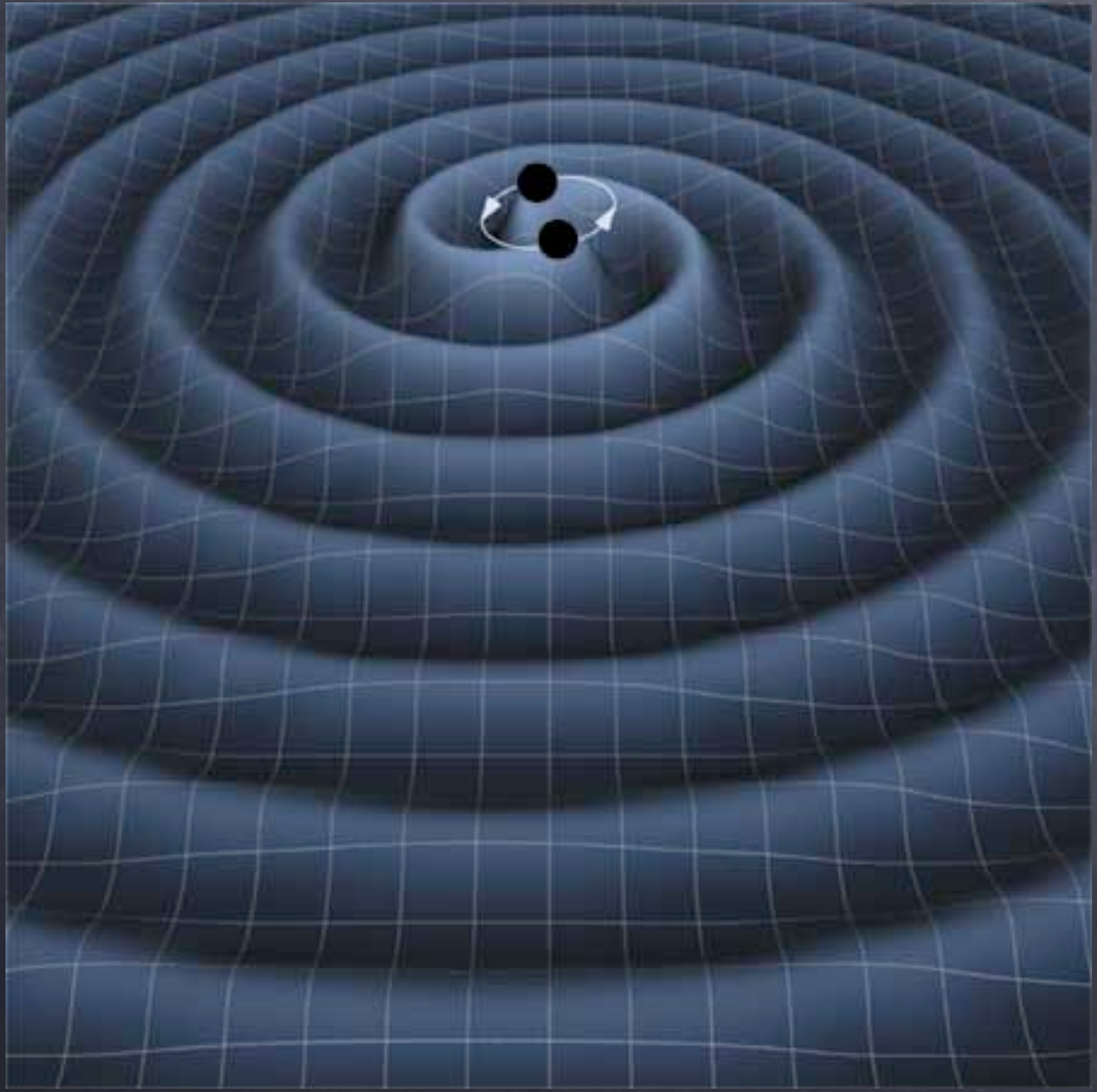
$$\bar{h}^{\alpha\beta} = \frac{1}{r}\begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & A_+(t-r,\theta,\phi) & A_\times(t-r,\theta,\phi) \\ 0 & 0 & A_\times(t-r,\theta,\phi) & -A_+(t-r,\theta,\phi) \end{bmatrix}$$

$$\equiv \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & h_+(t-r,r,\theta,\phi) & h_\times(t-r,r,\theta,\phi) \\ 0 & 0 & h_\times(t-r,r,\theta,\phi) & -h_+(t-r,r,\theta,\phi) \end{bmatrix},$$

onde: $$\bar{h}^{\alpha\beta}(t,\vec{x}) = -16\pi \int G^{\alpha\beta}_{\gamma\delta}(t,\vec{x};t',\vec{x}')\,\tau^{\gamma\delta}(t',\vec{x}')\,\mathrm{d}t'\,\mathrm{d}^3x'$$

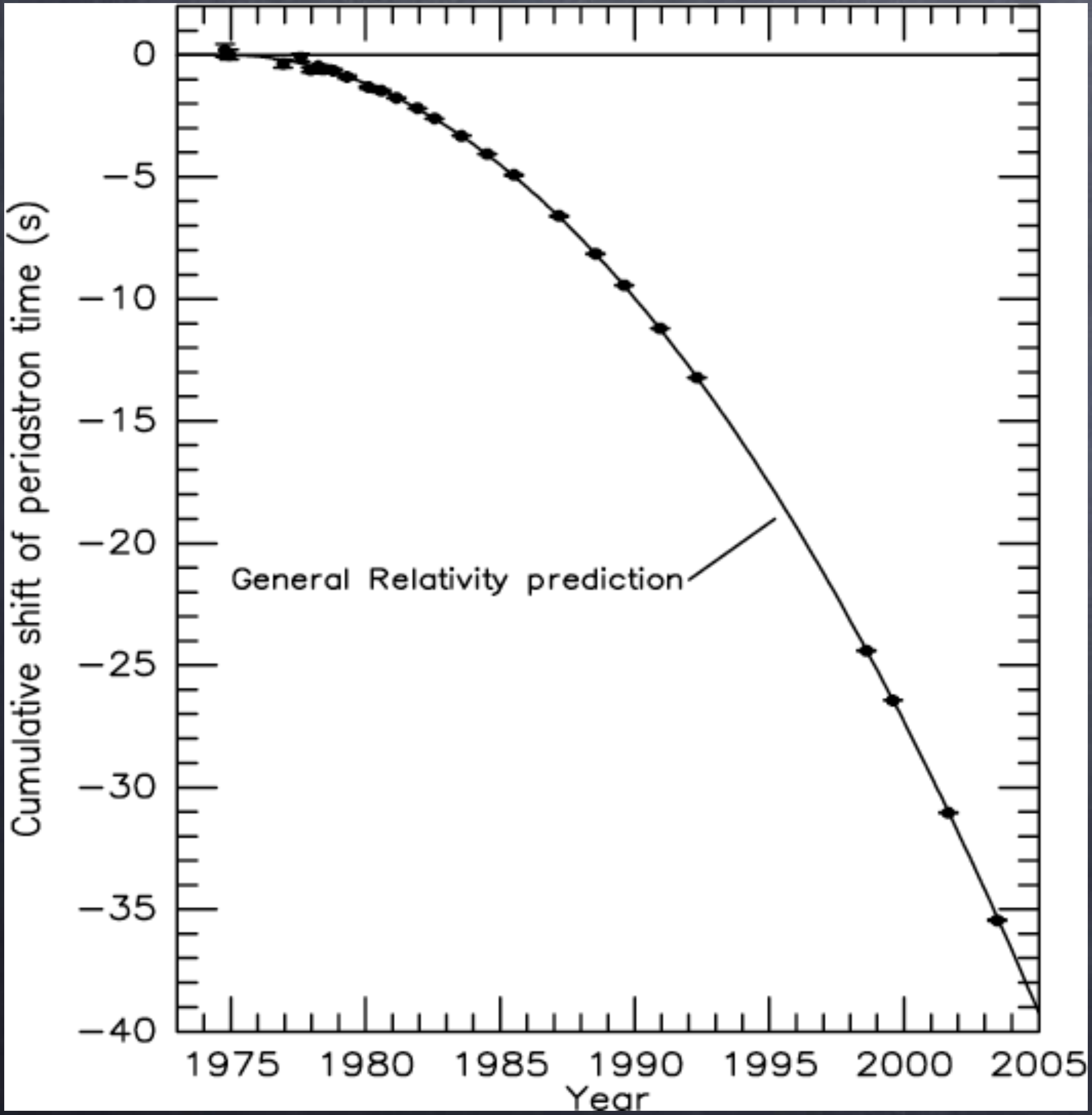
Objetos compactos $$\boxed{\bar{h}_{ij}(t,r) = \frac{2G}{c^4 r}\ddot{I}_{ij}(t-r),}$$ momento de quadrupolo da massa

Ondas Gravitacionais



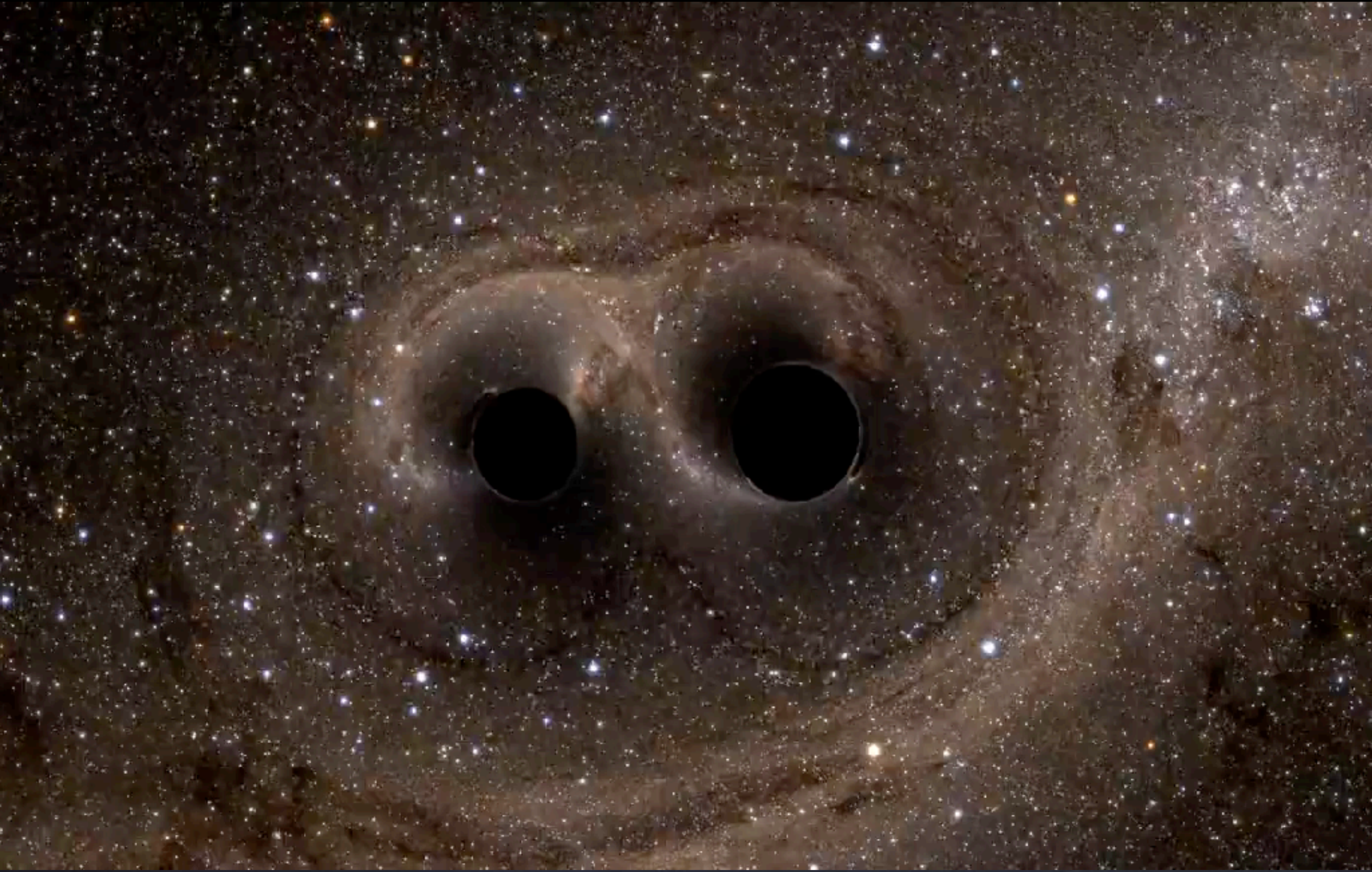
- Variações no próprio espaço-tempo
- Propagação na velocidade da luz
- Propriedades diferentes das ondas de matéria e eletromagnéticas
- Previstas em 1916 por Einstein (mas chegou a desistir)

Ondas Gravitacionais

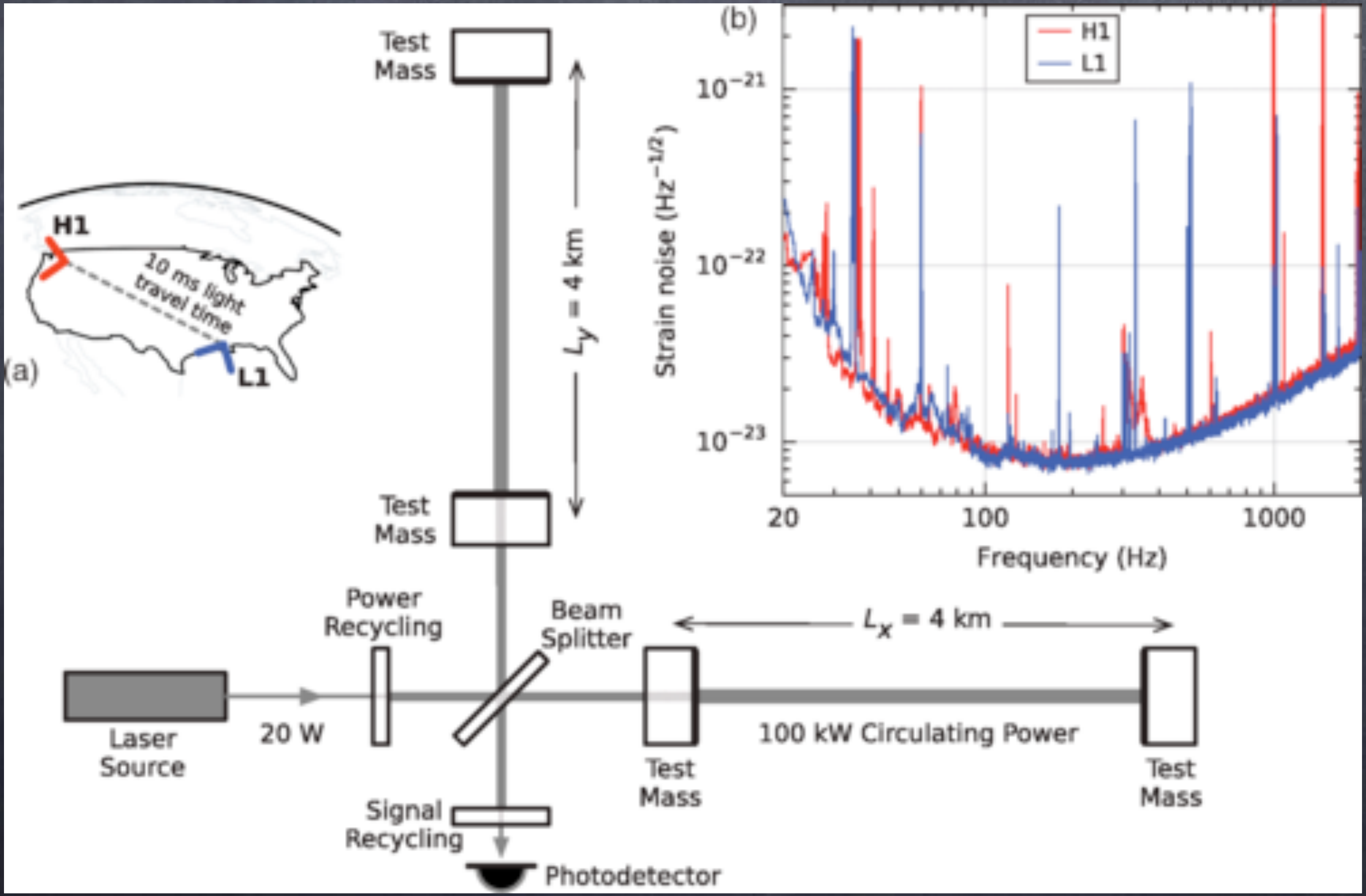


- Pulsar binário: perda de energia por emissão de ondas gravitacionais!
- Resultado em acordo com a relatividade geral (1970)
- Prêmio Nobel de 1993

Coalescência de buracos negros



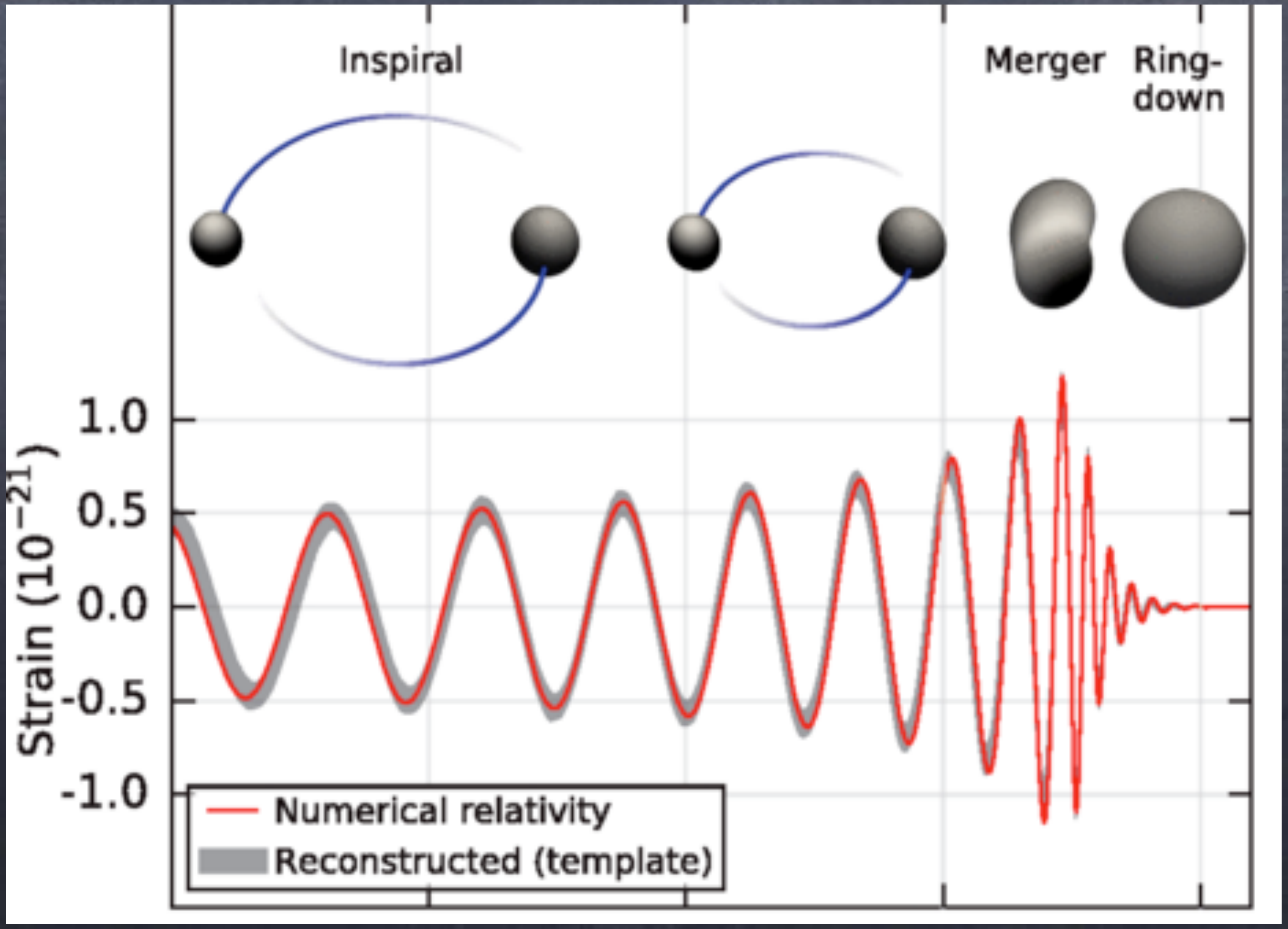
O Laser Interferometer Gravitational-Wave Observatory



Coalescência de buracos negros

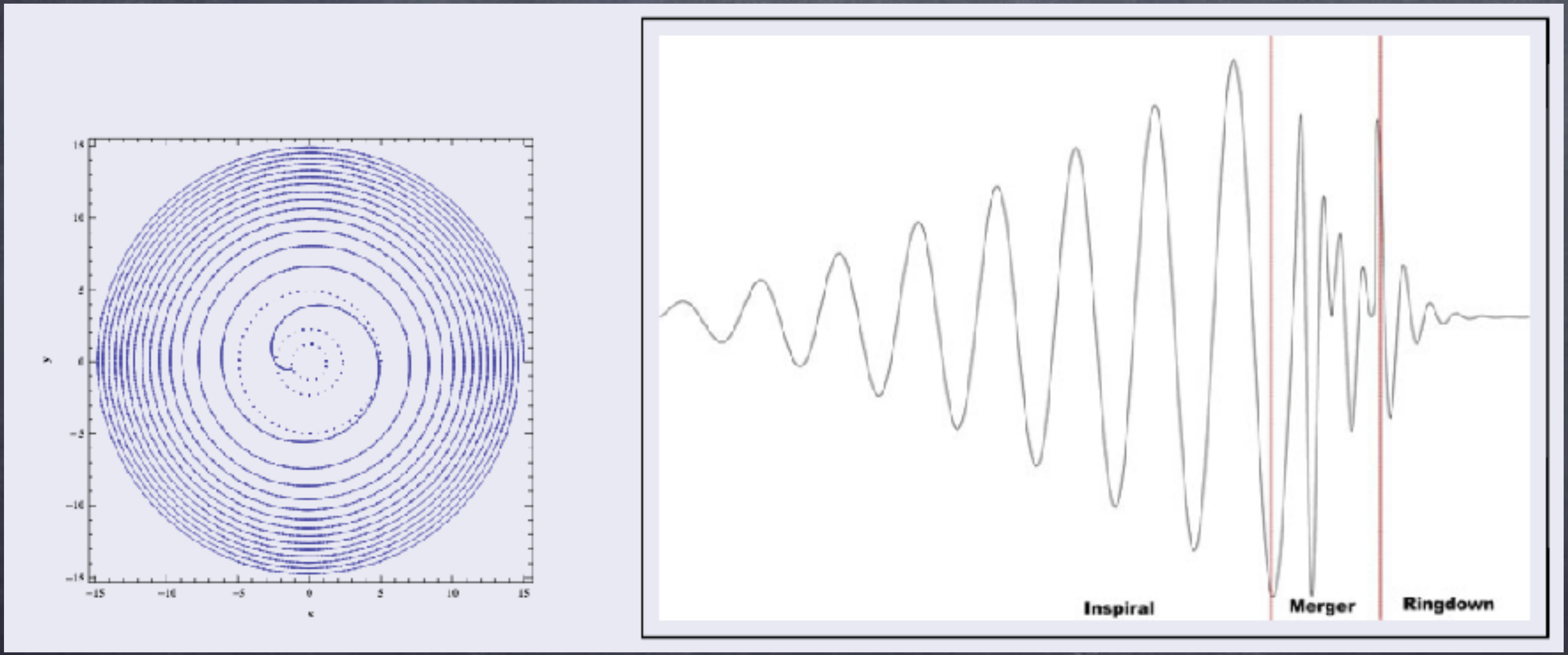
"solo tengo adentro, soy un pobre agujero"
León Gieco

- Intenso (objetos massivos, altas velocidades)
- Sinal muito característico em frequência e amplitude (simulações computacionais + teoria)
- Independente de qualquer outra física



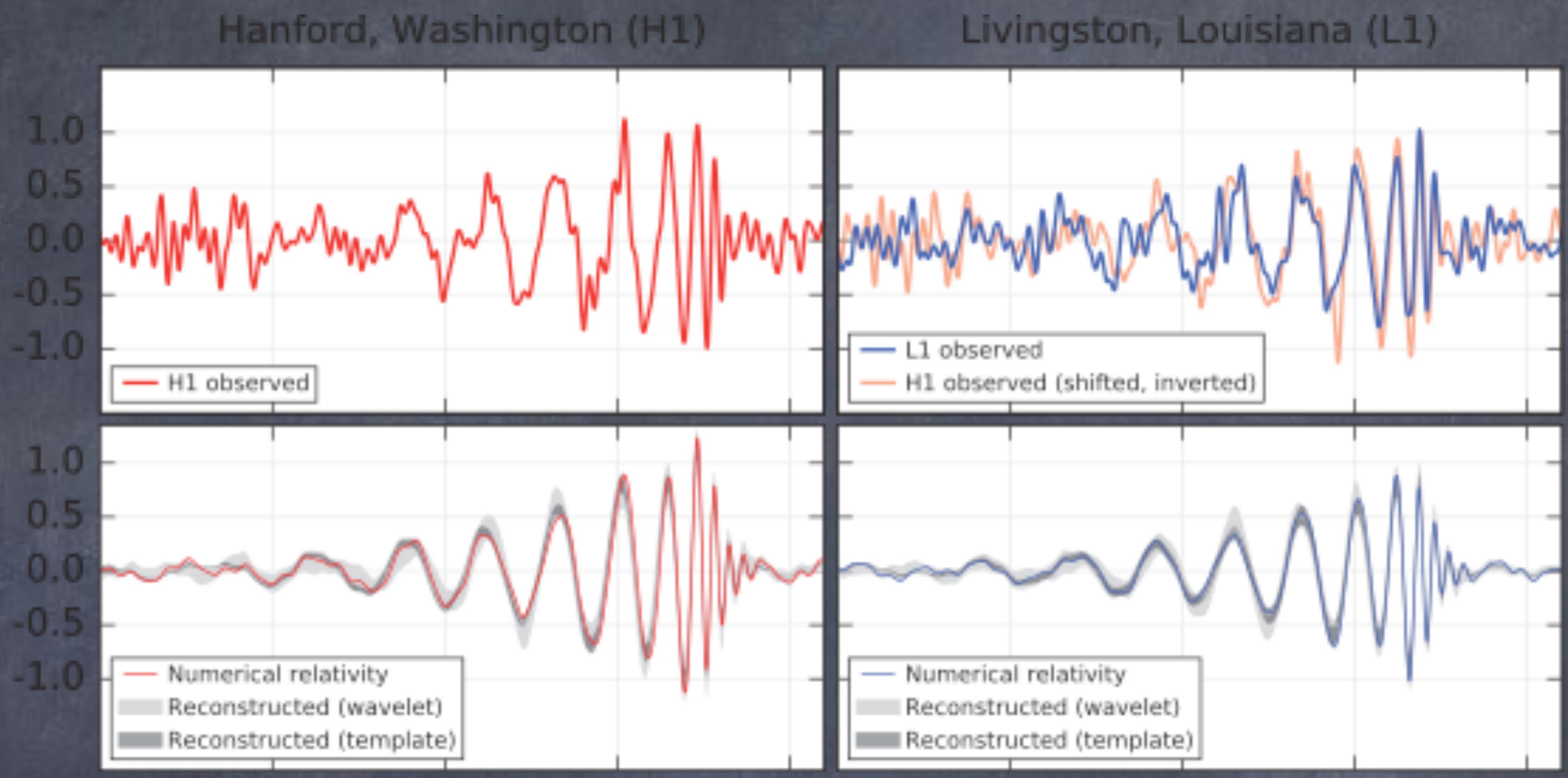
Coalescência de buracos negros

"solo tengo adentro, soy un pobre agujero"
León Gieco



- Assinatura clara e característica
- Templates de relatividade numérica
- Numérico + métodos perturbativos

O evento de 14/09/2015



- Mesmo sinal nos dois detectores! (a menos de ruído)
- Diferença temporal compatível com velocidade da luz
- Forma compatível com coalescência de buracos negros!
- $M_1 = 36\ M_{sol}$, $M_2 = 29\ M_{sol}$, $M_1+M_2 = 62$!

Eventos de 2015-2016

- Existência de ondas gravitacionais
- Existência de Buracos Negros (de massa não esperada)
- Teste da relatividade geral a campo gravitacional intenso
- Limites em teorias alternativas (complementar à cosmologia)
- Limite na massa do gráviton
- População de objetos compactos
- Primeira informação do Cosmos que não é de partículas!
- Nova janela para o Universo!

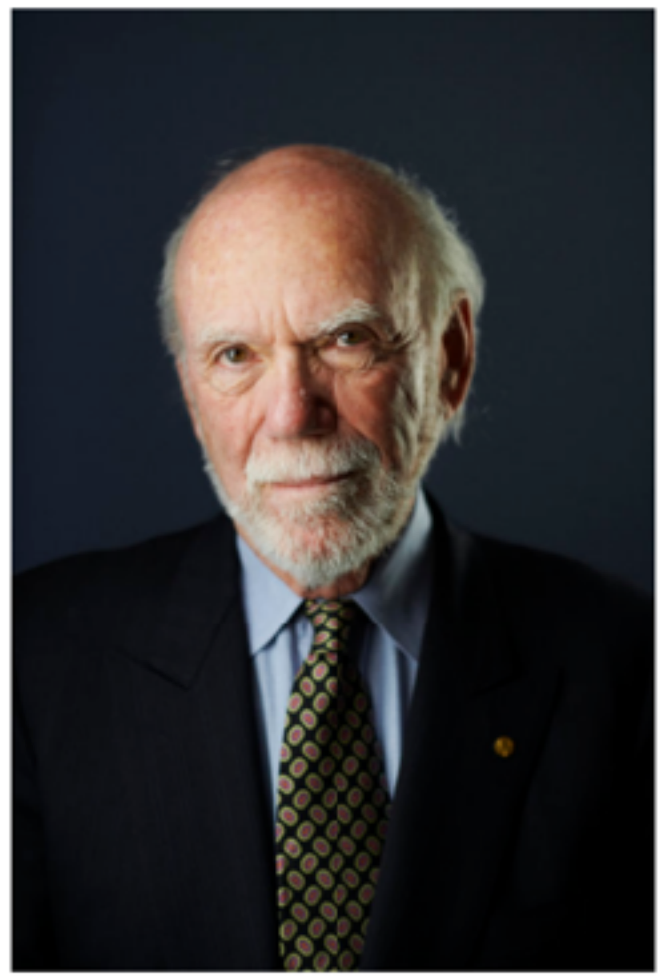
Prêmio Nobel de 2017!

"for decisive contributions to the LIGO detector and the observation of gravitational waves"

© Nobel Media AB. Photo: A.Mahmoud

Rainer Weiss

Prize share: 1/2



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Barry C. Barish

Prize share: 1/4

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Kip S. Thorne

Prize share: 1/4

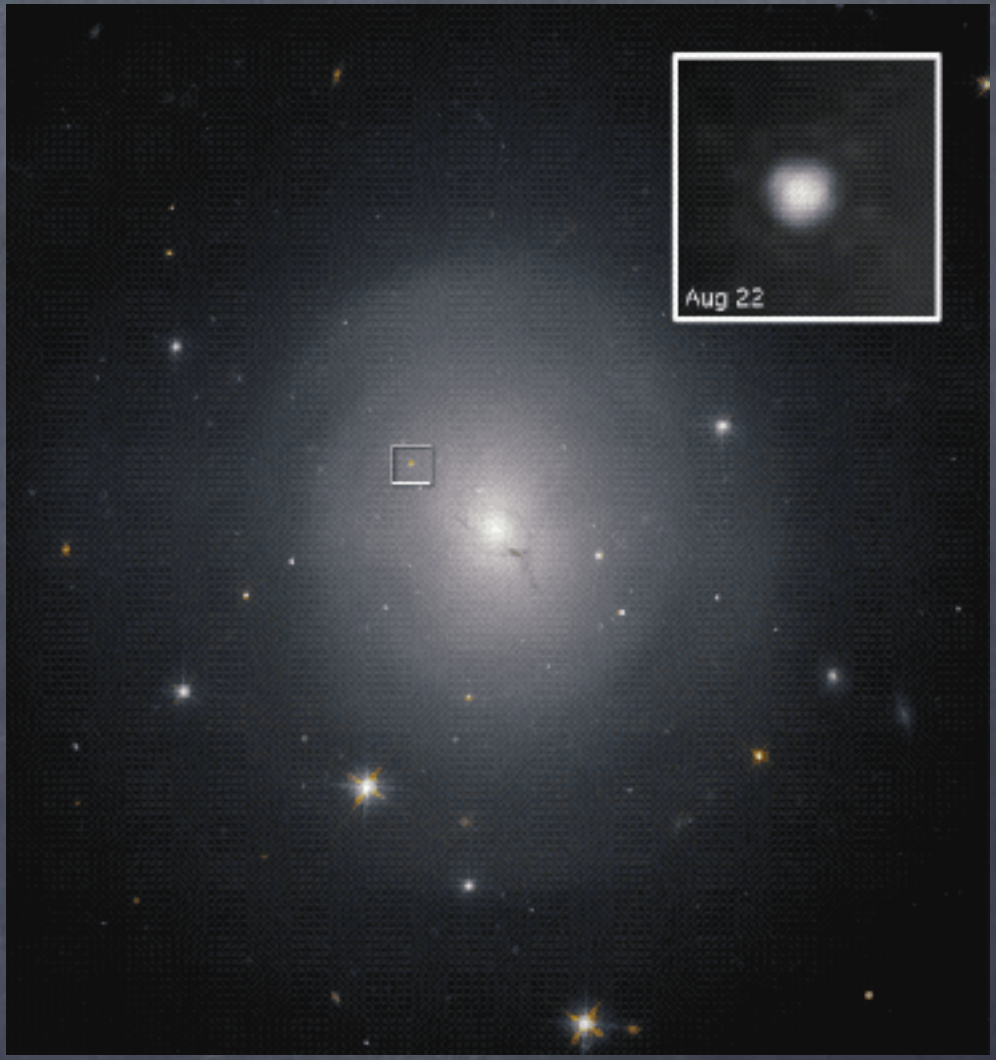
O evento de 17/08/2017

- Busca de contrapartidas óticas, com telescópios
- Virgo em ação: localização da fonte e imagens, inclusive DECam
- Confirmação das ondas gravitacionais
- Fusão de duas estrelas de nêutrons **formando** um buraco negro

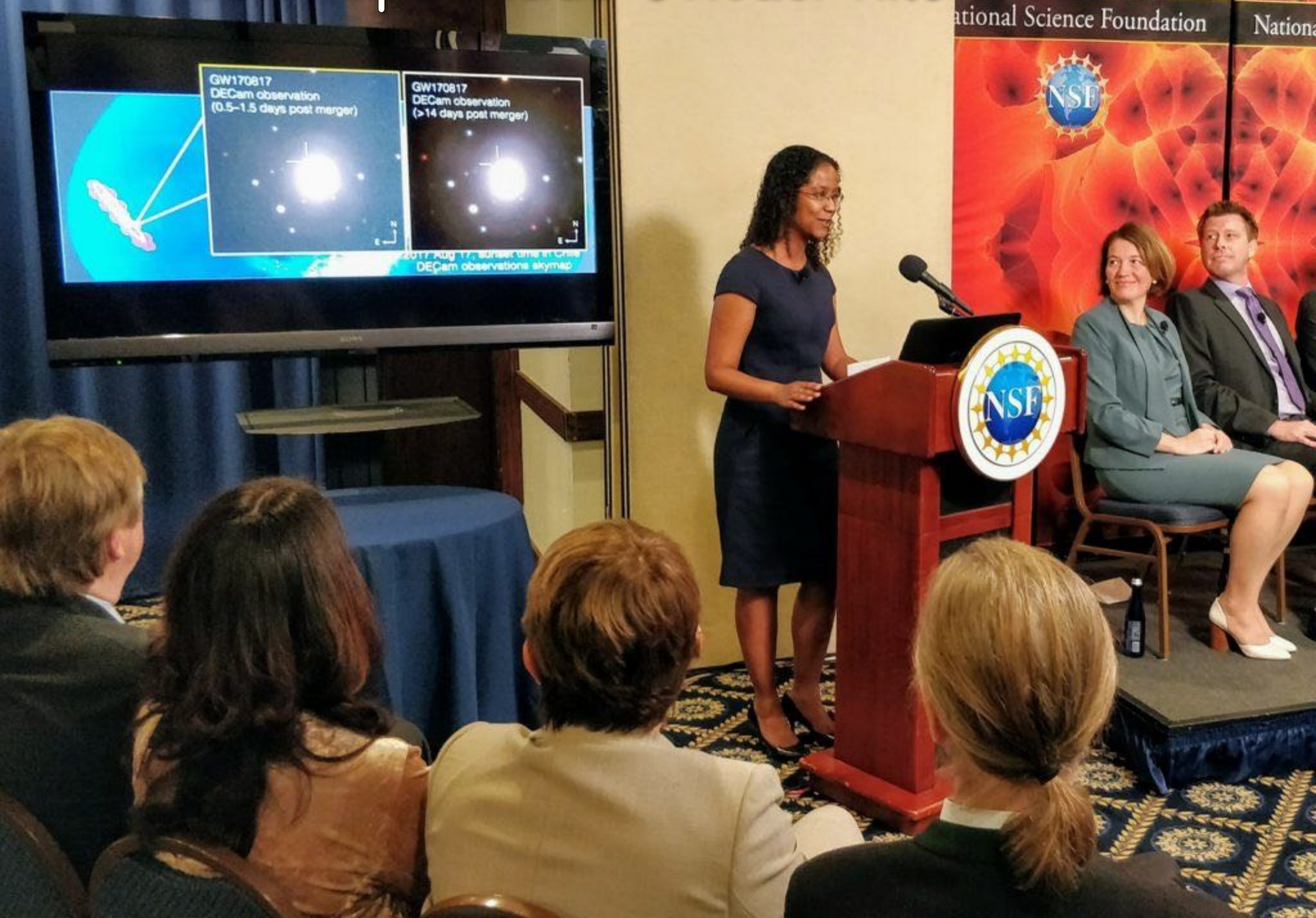
  M_1 = 1.4-2.3 M_{sol}, M_2 = 0.9-1.4 M_{sol}
- Formação de elementos pesados

  16.000 a massa da Terra!

  10x em ouro e platina



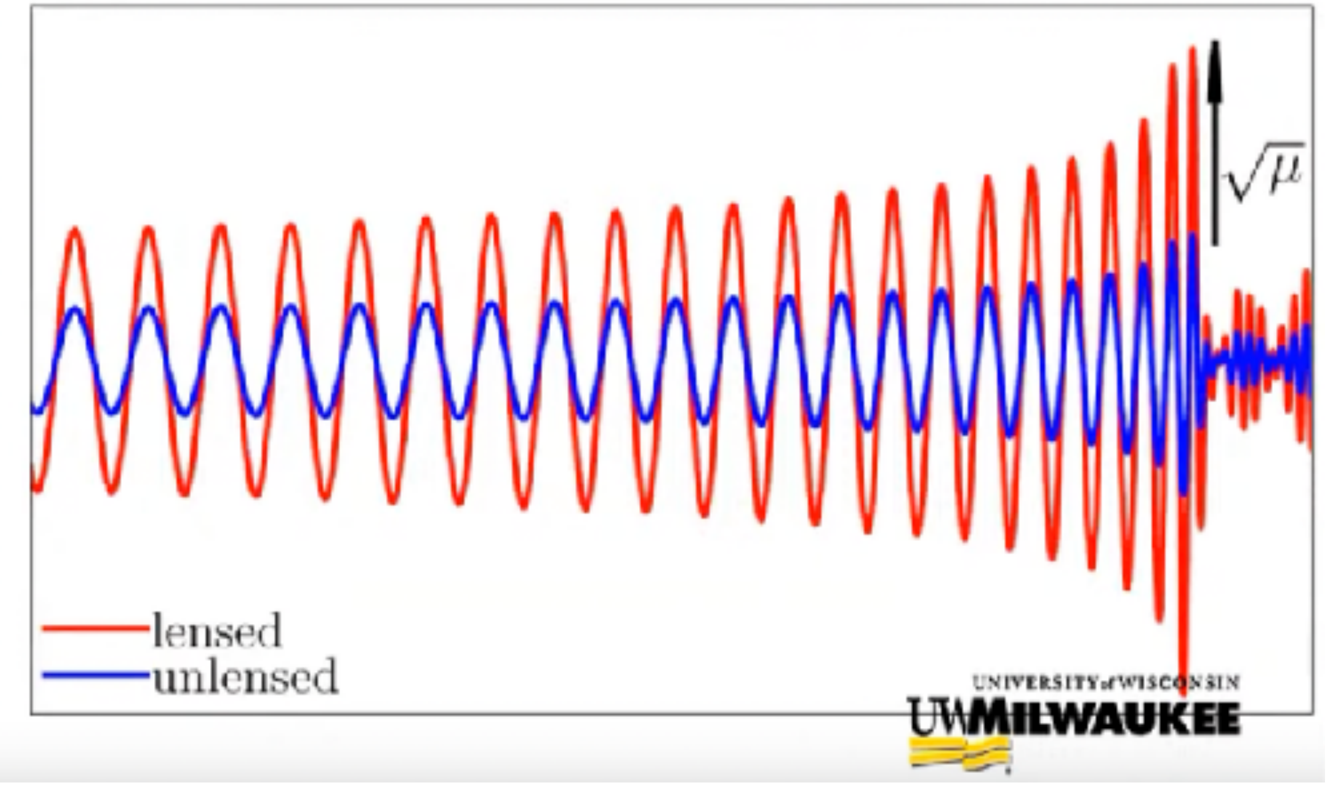
Contrapartidas óticas: kilonovae!



Lensing of Gravitational Waves

Lensing of Gravitational Waves

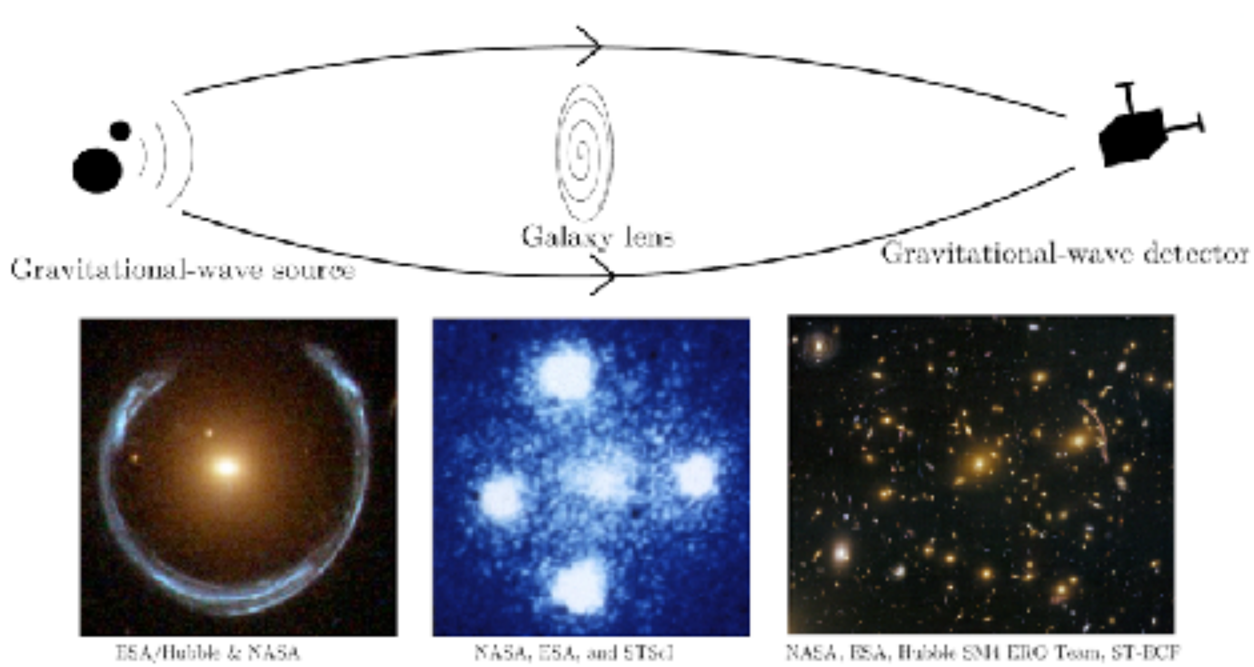
- GW are tensor waves but strain (amplitude) follows same lensing equations
- Detected in interferometers
- Regimes of GW lensing
  - **Magnification:** statistical or individual



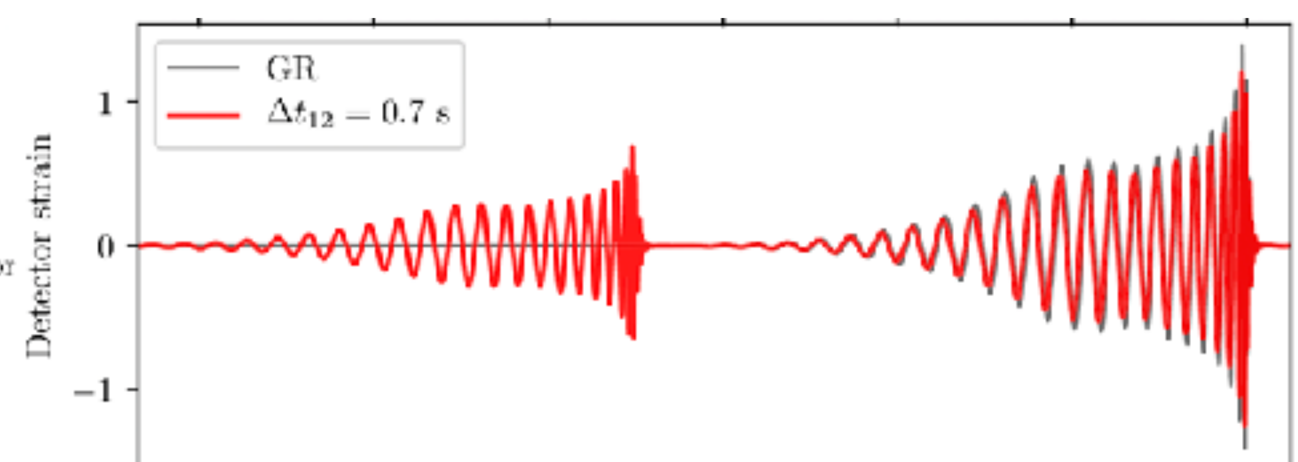
  - could explain mass gap events?

Regimes of GW lensing

- Magnification: statistical or individual
  - could explain mass gap events?
- Strong Lensing (lens is galaxy or cluster): multiple images
  - different arrival times and different magnifications



https://www.ligo.org/science/Publication-O3aLensing/images/O3aLensing-Fig1.png



Ezquiaga & Zumalacárregui, PRD 102, 124048 (2020)

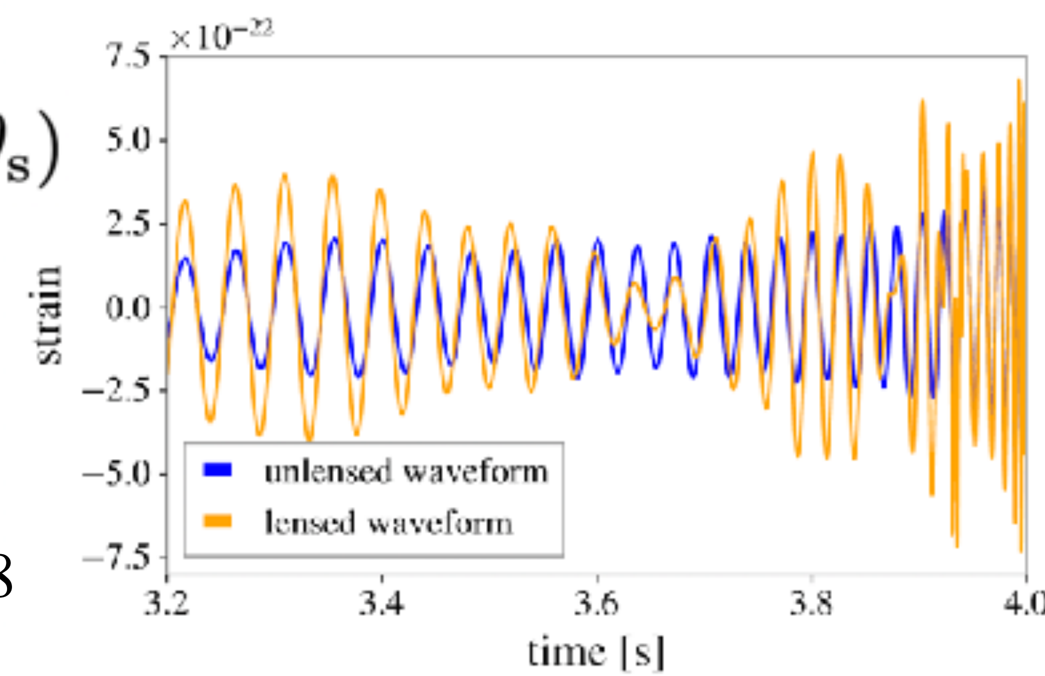
typical time delays from minutes to months

Regimes of GW lensing

- Magnification: statistical or individual
  - could explain mass gap events?
- Strong Lensing (lens is galaxy or cluster): multiple images
  - different arrival times and different magnifications
- Microlensing (lens is a massive BH):
  - frequency dependent magnification: beating pattern

$$h_{\mathrm{ML}}(f, \theta_{\mathrm{s}}, \theta_{\mathrm{ML}}) = F(f, M_{\mathrm{ML}}^{z}, y) \times h_{\mathrm{U}} \quad (f, \theta_{\mathrm{s}})$$

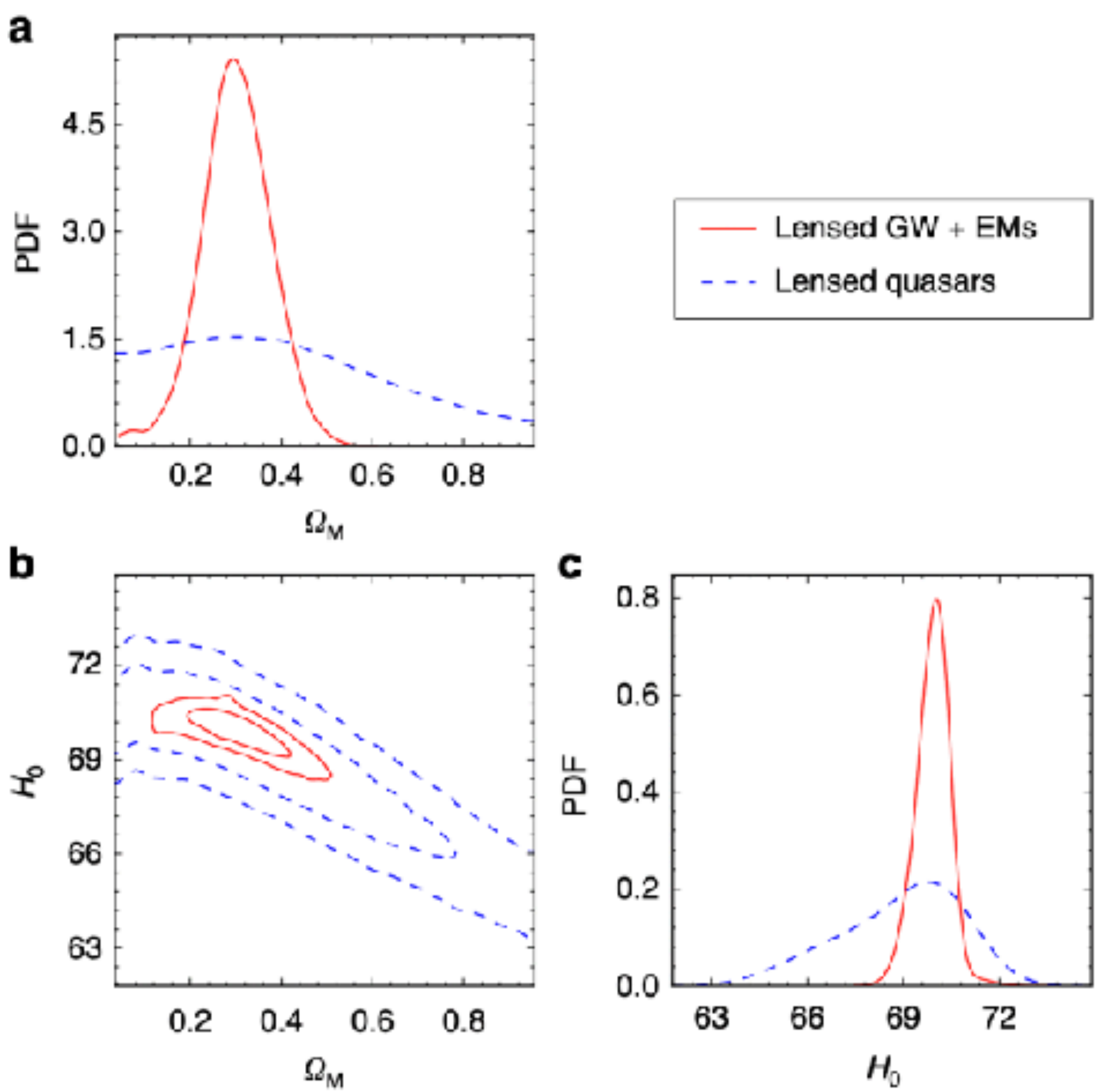
arXiv:2110.03308



Strong Lensing of Gravitational Waves

- Expected numbers
  - LIGO design sensitivity: 1/year
  - Einstein Telescope: ~ 100/year (out of 10^4-10^5 GWs)
- Excellent time delay determination
- Absolute (waveform reconstruction) + Relative strains
- No spatial resolution

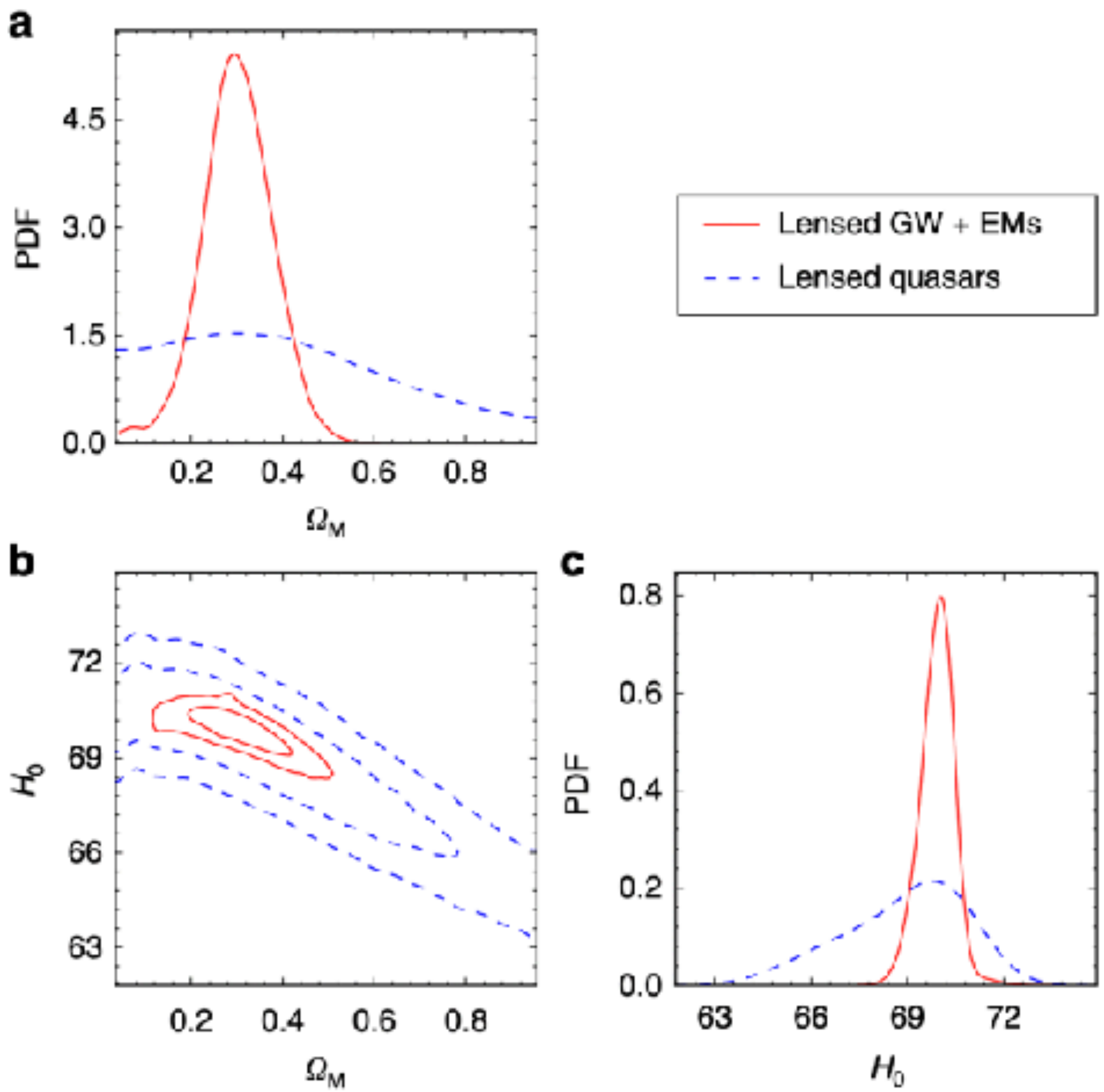
Lensed GW with EM counterpart: prospects for cosmology



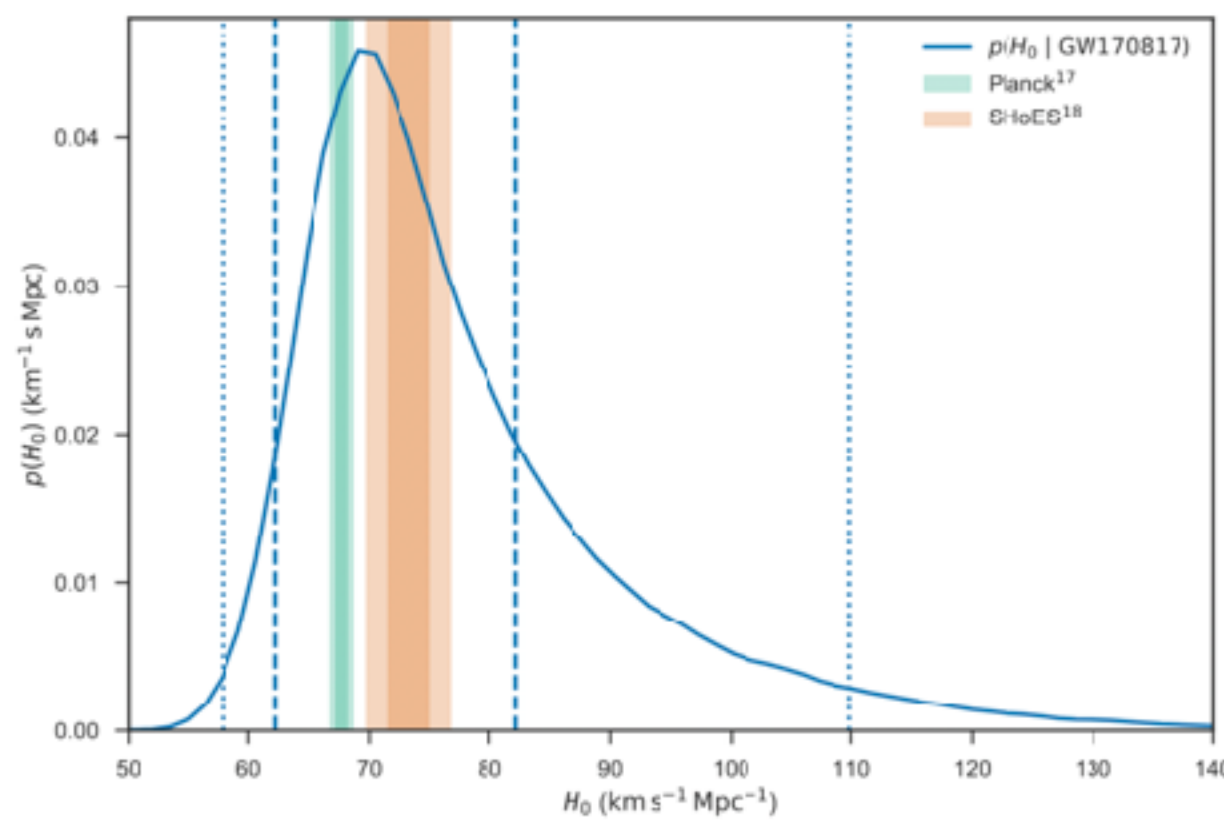
- Typically optical counterparts (MMA)
- Extremely valuable
- Extensive follow-up program
- Only GW170817 for now
- Example not using standard siren:
  - Waveform independent
  - Better reconstruction (transient goes away)
  - < 0.7% determination of H_0 from 10 Strongly Lensed BBH!

Liao et al., Nature Communications, 8, 1148 (2017)

Lensed GW with EM counterpart: prospects for cosmology



- Compare to GW170817 standard siren (complementary to)

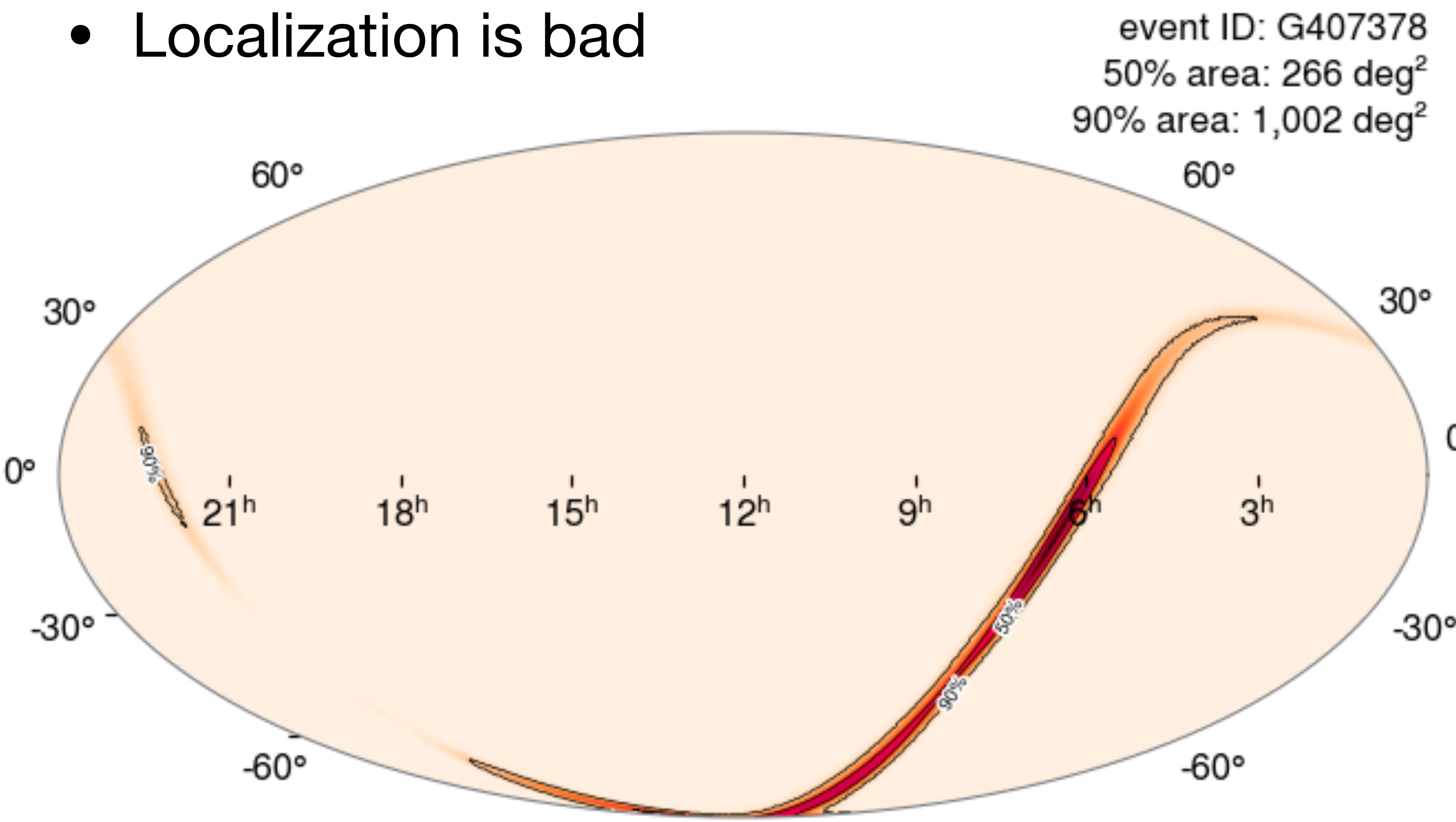


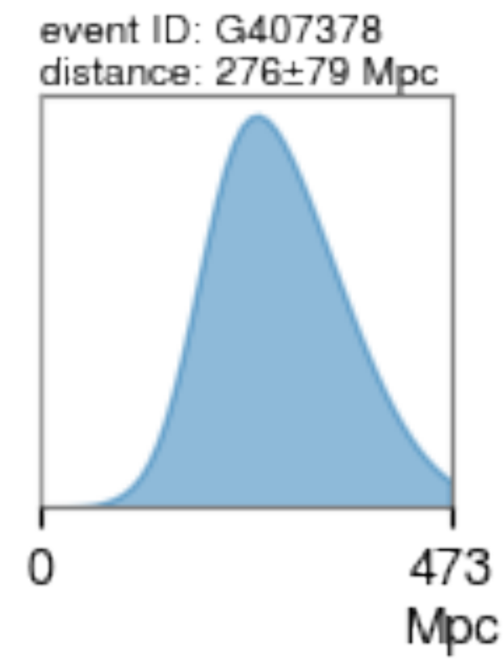
LIGO, Nature 551, 85 (2017); arXiv:1710.05835

Liao et al., Nature Communications, 8, 1148 (2017)

Lensed GW with no EM counterpart

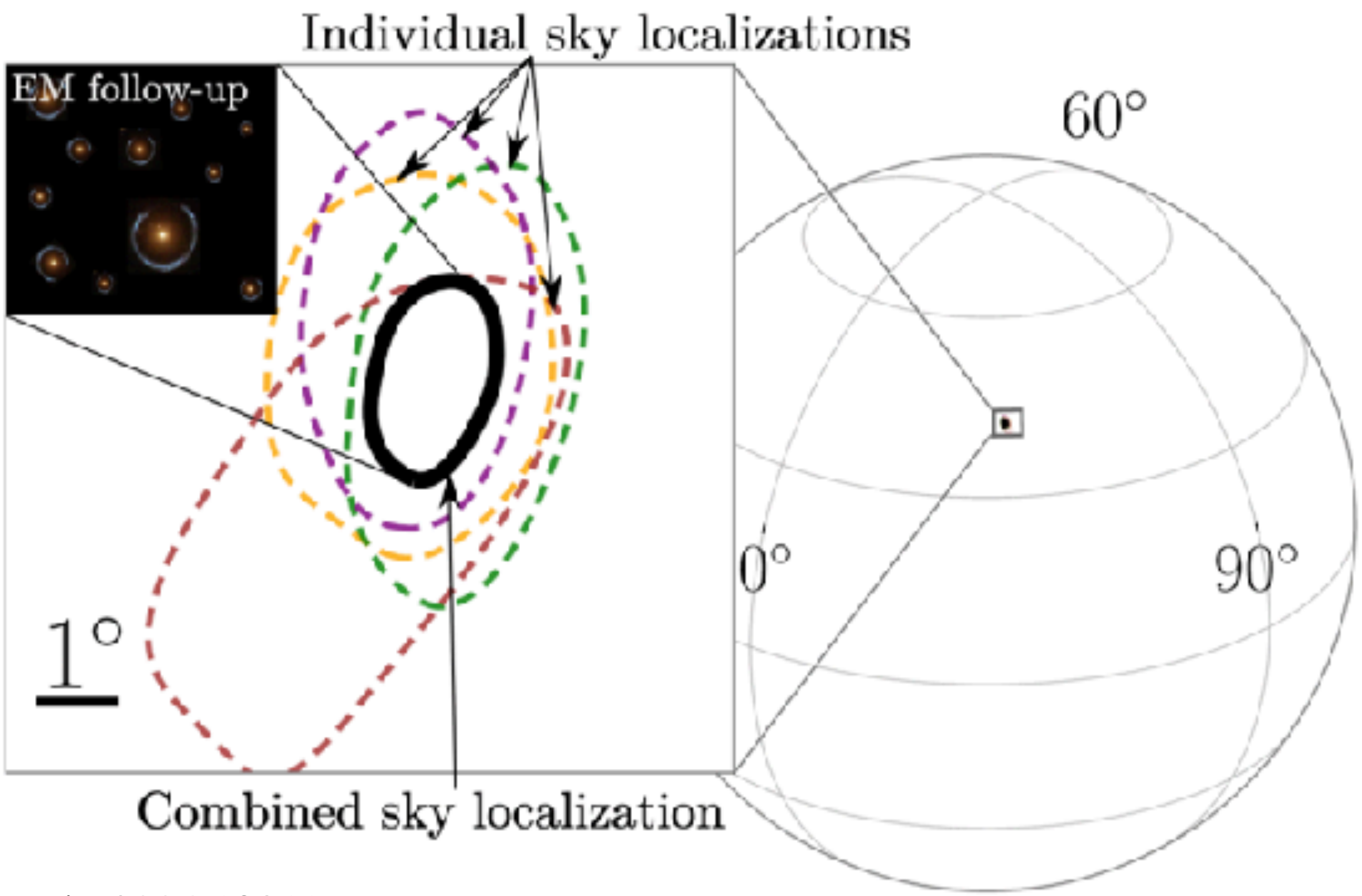
- BBH much more frequent than Kilonovae
- Localization is bad





https://gracedb.ligo.org/superevents/S230518h/

Localization

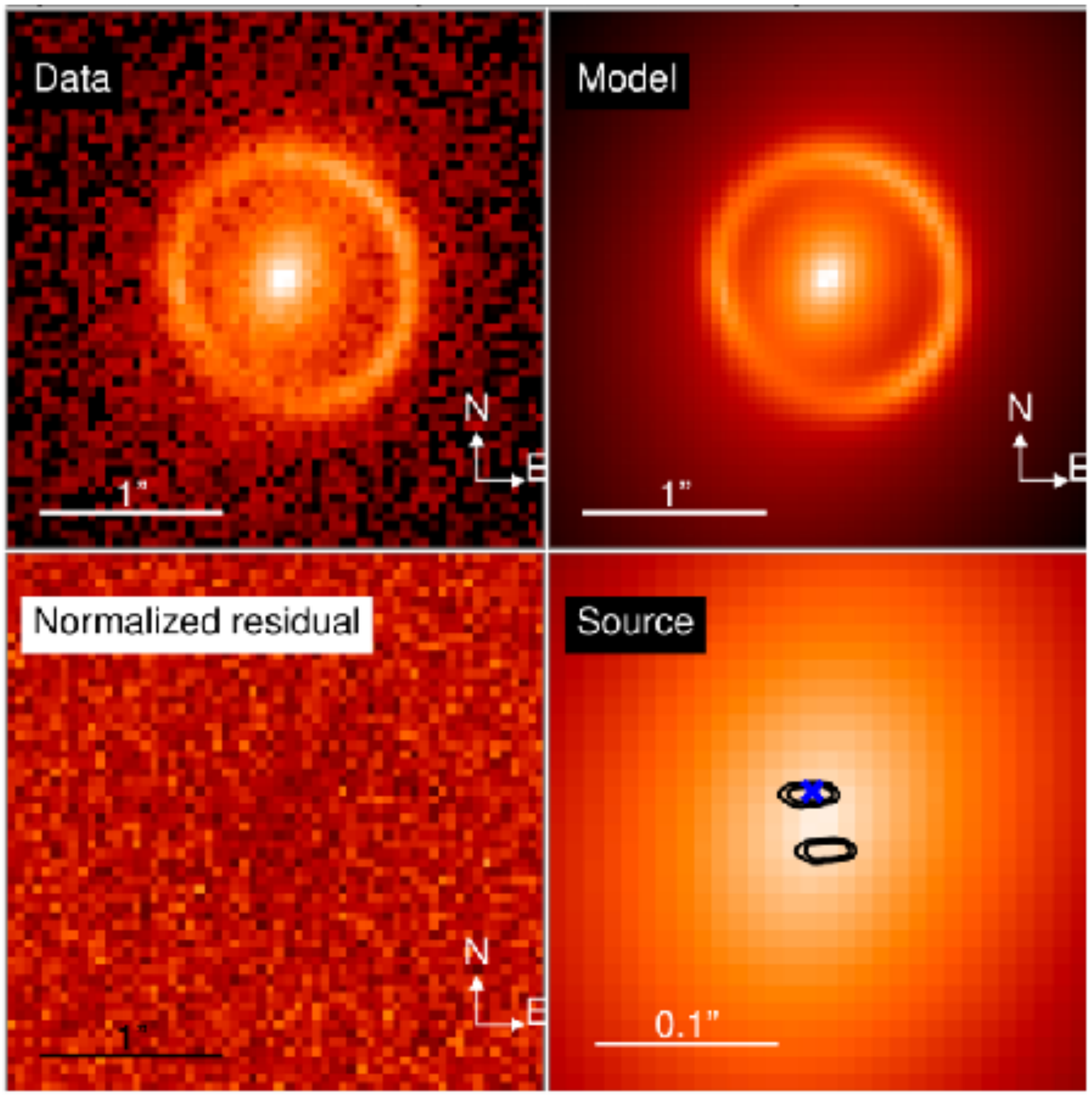


arXiv:2004.13811

- Needs spectroscopic data of both lens and source galaxies
- High resolution imaging of candidate(s)
- Important optical follow-up program (MMA)

- If GW is strongly lensed, its host galaxy should be too!
- Strong Lenses are rare, yet, still ~ 100/sq-deg
- Use relative time-delays and strains to pin-point the right system!
- Use quadruply imaged systems
- Relies on detection of all strongly lensed galaxies to required depth

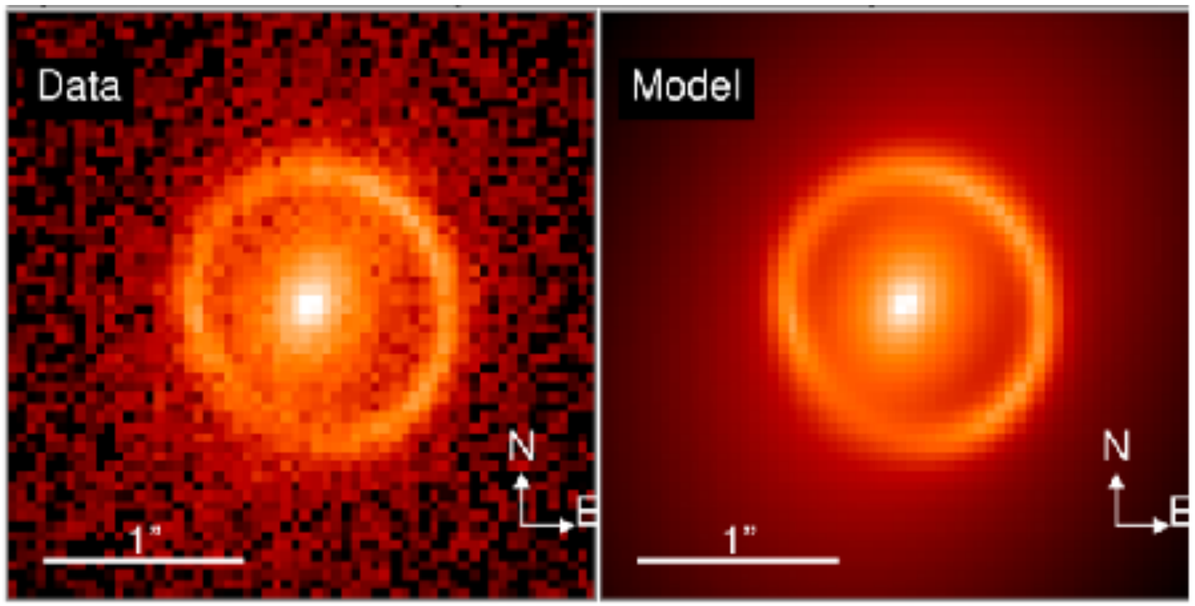
Lensed Binary Black-Holes

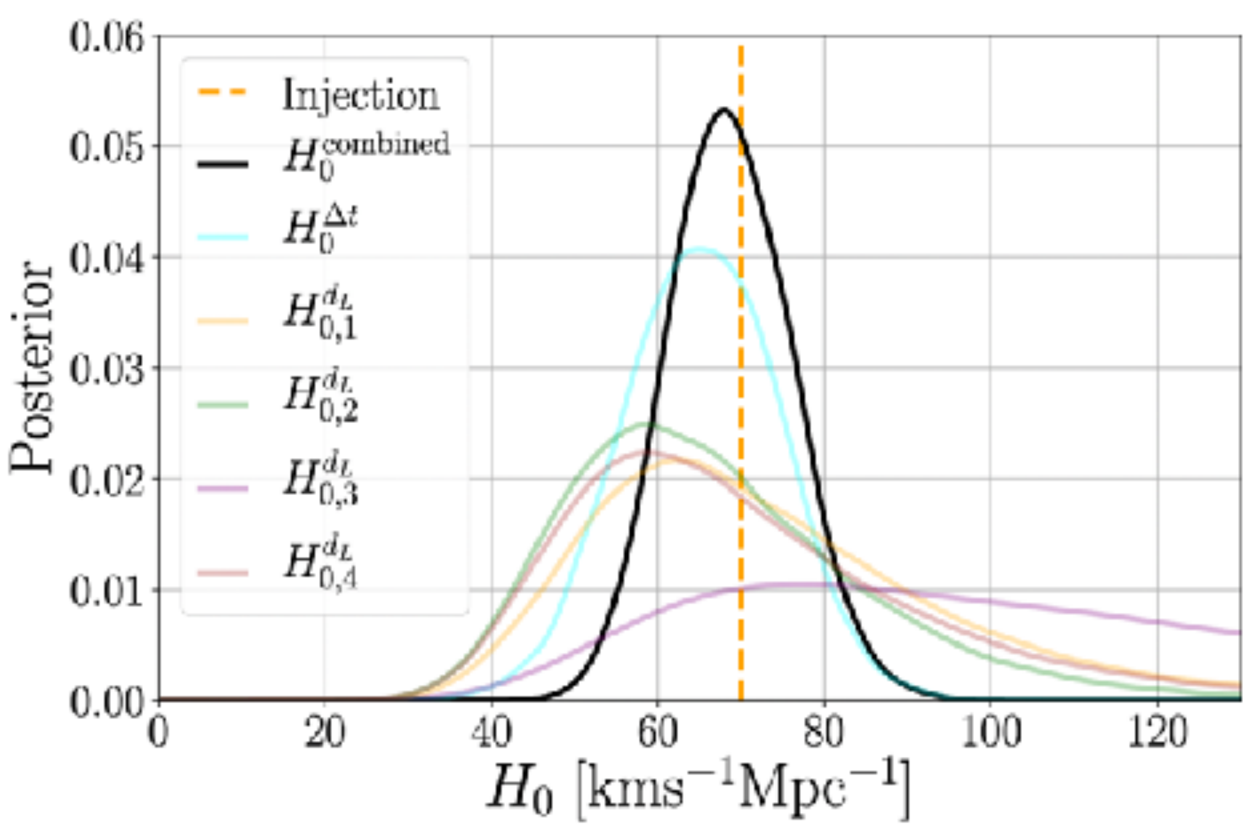


arXiv:2004.13811

- Source and lens potential reconstruction from high resolution imaging
- Extra constraints from relative magnifications and time-delays
- BBH localization within the host galaxy!
- 10% determination of H_0 from a single Strongly Lensed BBH!

Lensed Binary Black-Holes





arXiv:2004.13811

- Source and lens potential reconstruction from high resolution imaging
- Extra constraints from relative magnifications and time-delays
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Multi-messenger

- Kilonovae and dark sirens
  - look for repeating pattern in the strain data
  - Localization of Strongly Lensed transients (even without light!)
  - SL Gravitational Waves: ~ 1 in A+, ~ 100 in ET

Multi-wavelength

- Towards *wavelensing* detection!
- From microlensing LC, estimate physical parameters capable of producing wavelensing and choose follow-up accordingly
- Trigger from galactic and extragalactic microlensing events at the suitable wavelengths

Comentarios Finales

- Durante el siglo XXI las lentes gravitacionales se han transformado de una curiosidad a promesa interesante y después a una herramienta fundamental en astrofísica
  - Los observables son deformaciones, imágenes múltiples, arcos gravitacionales, magnificación y desvíos temporales
  - Permiten estudiar las lentes, las fuentes y la geometría del Universo a grandes escalas
  - En particular, es un observable único para testear la gravedad modificada y la distribución de la matéria oscura en todas las escalas
- Es un área interdisciplinar, involucrando desde física fundamental hasta análisis de datos, incluyendo procesamiento de imágenes, estadística, simulaciones, *deep learning*, etc.
- Una miríada de fenómenos medidos y aún muchos por descubrir
- Muchísimos datos de alta calidad en la actualidad (e.g. LaStBeRu) y en un futuro próximo (Rubin/LSST, Euclid, Roman, DESI, 4MOST, MSE…)


Gracias!