Strong-gravity signatures from relics of the early universe

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General Relativity + Standard Model

$$S = \int d^4x \sqrt{-g} \left[L_{GR} + L_{SM} \right]$$

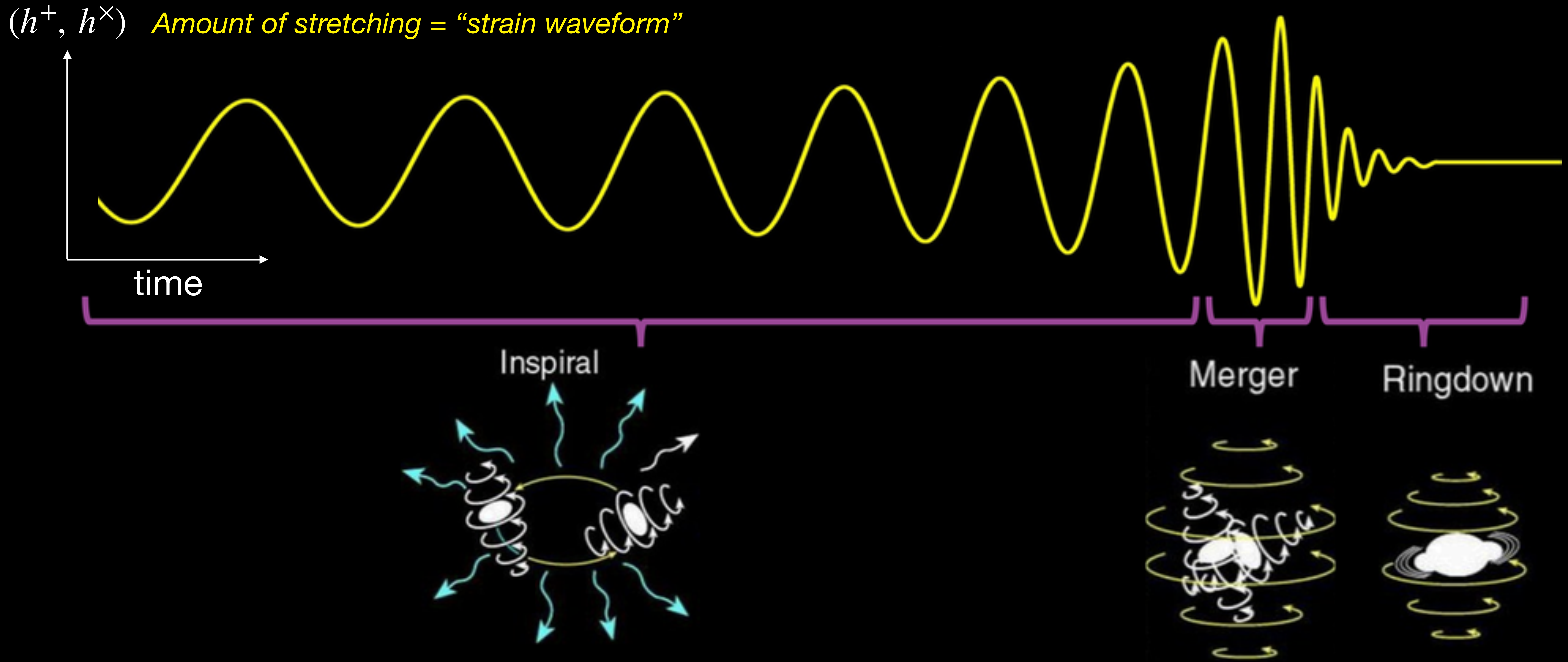
?

Add new forces

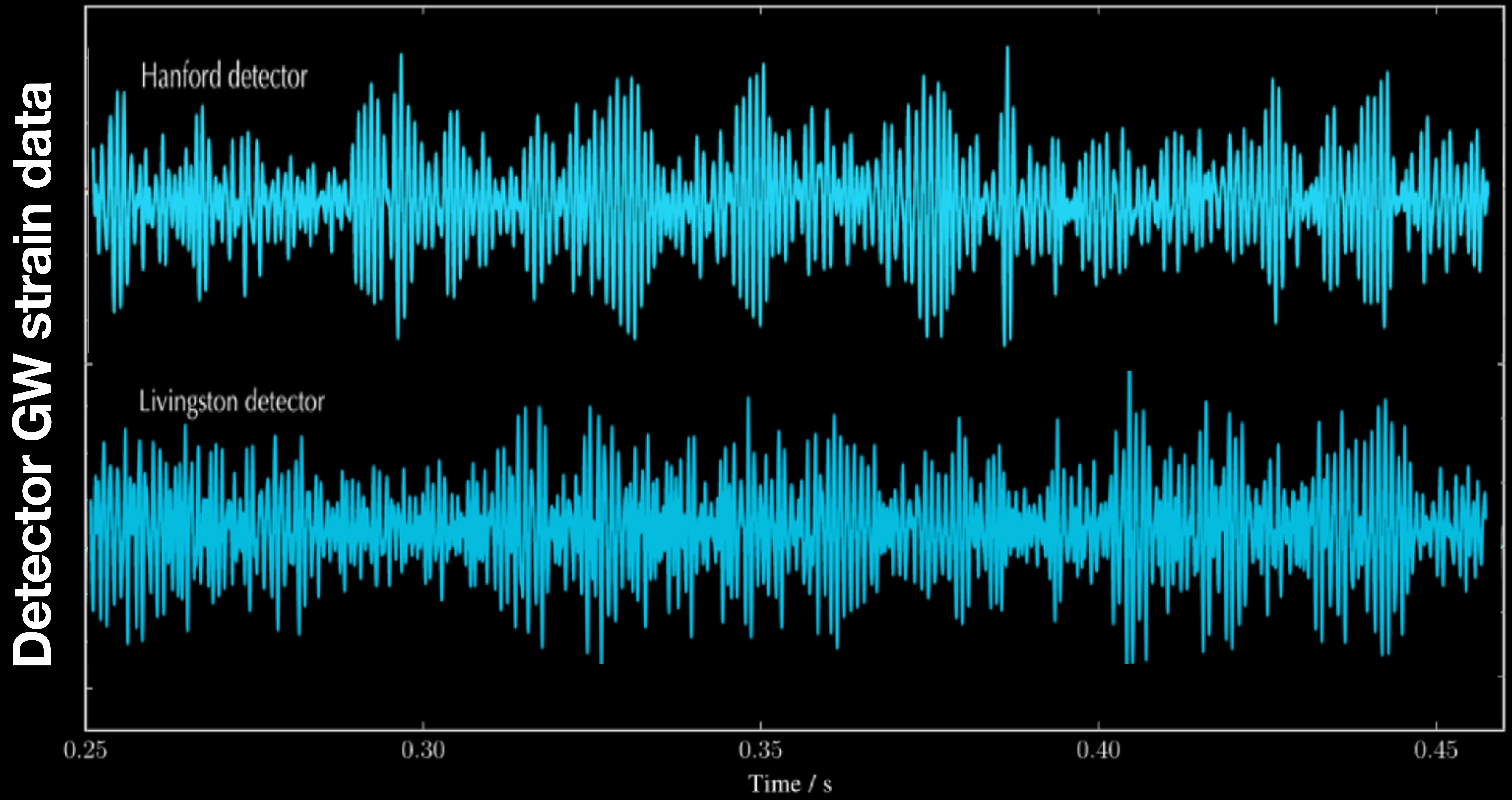
Add new matter

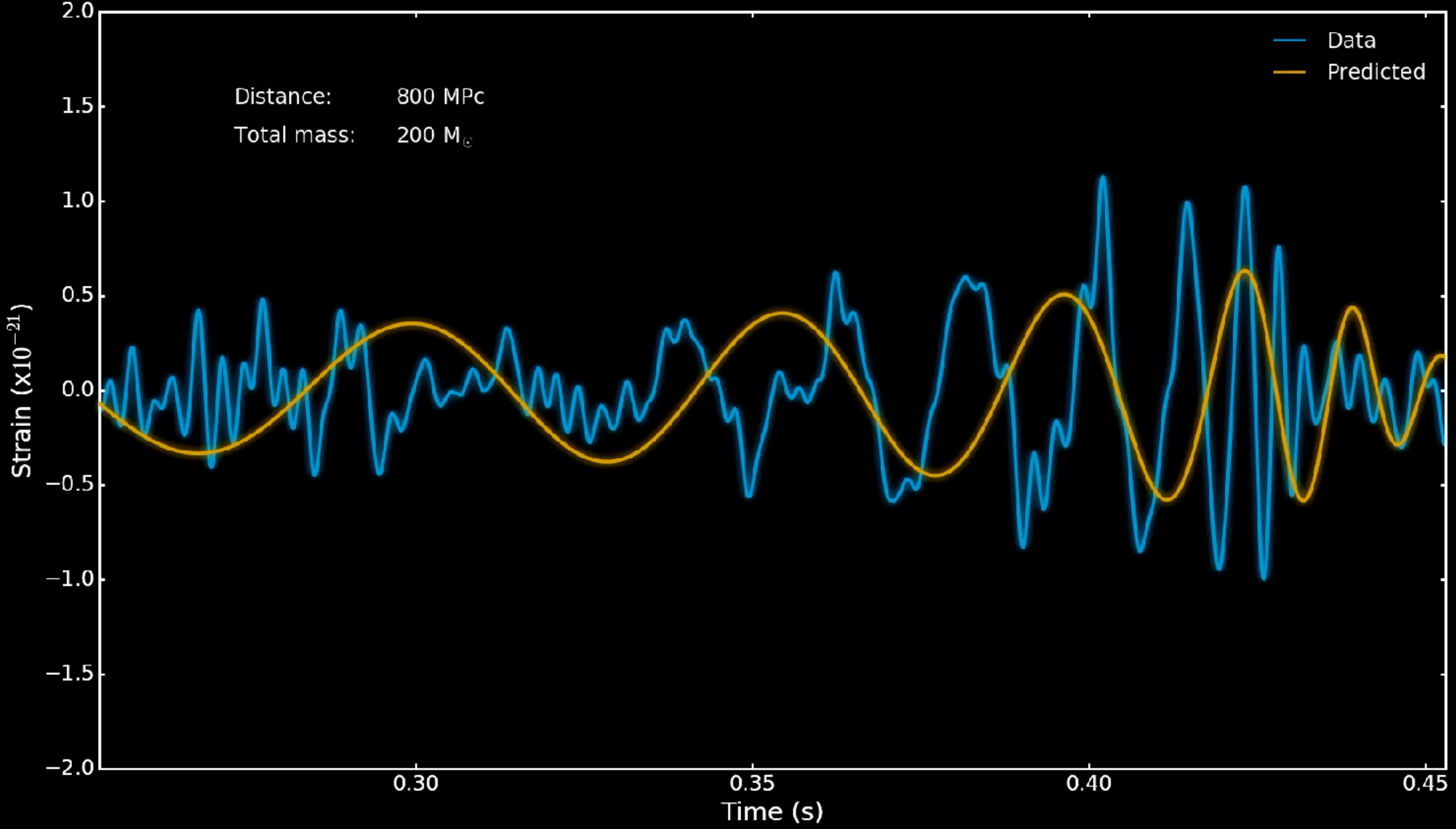
Add new physics

Ingredient 1: Theory

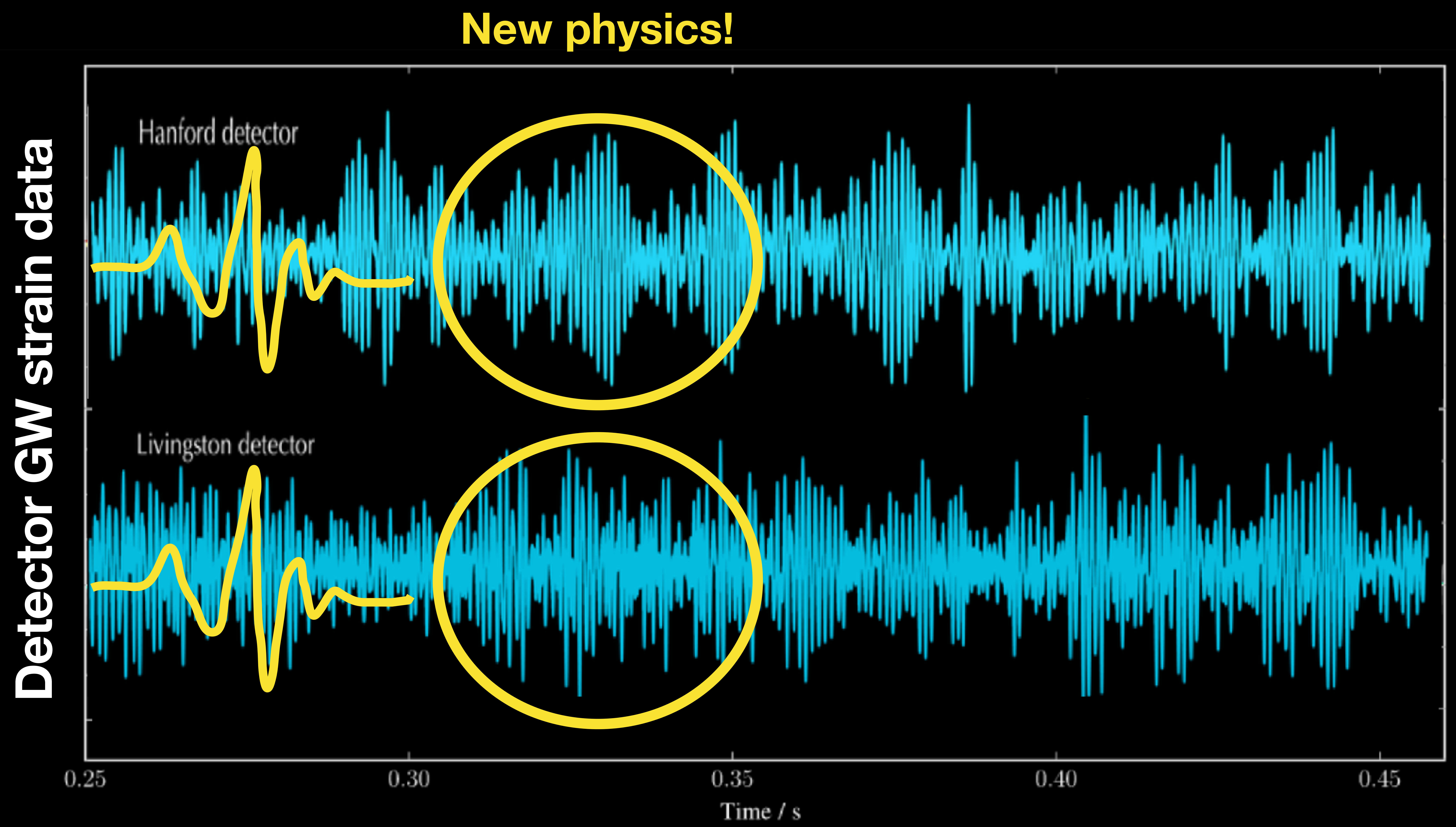


Ingredient 2: Data





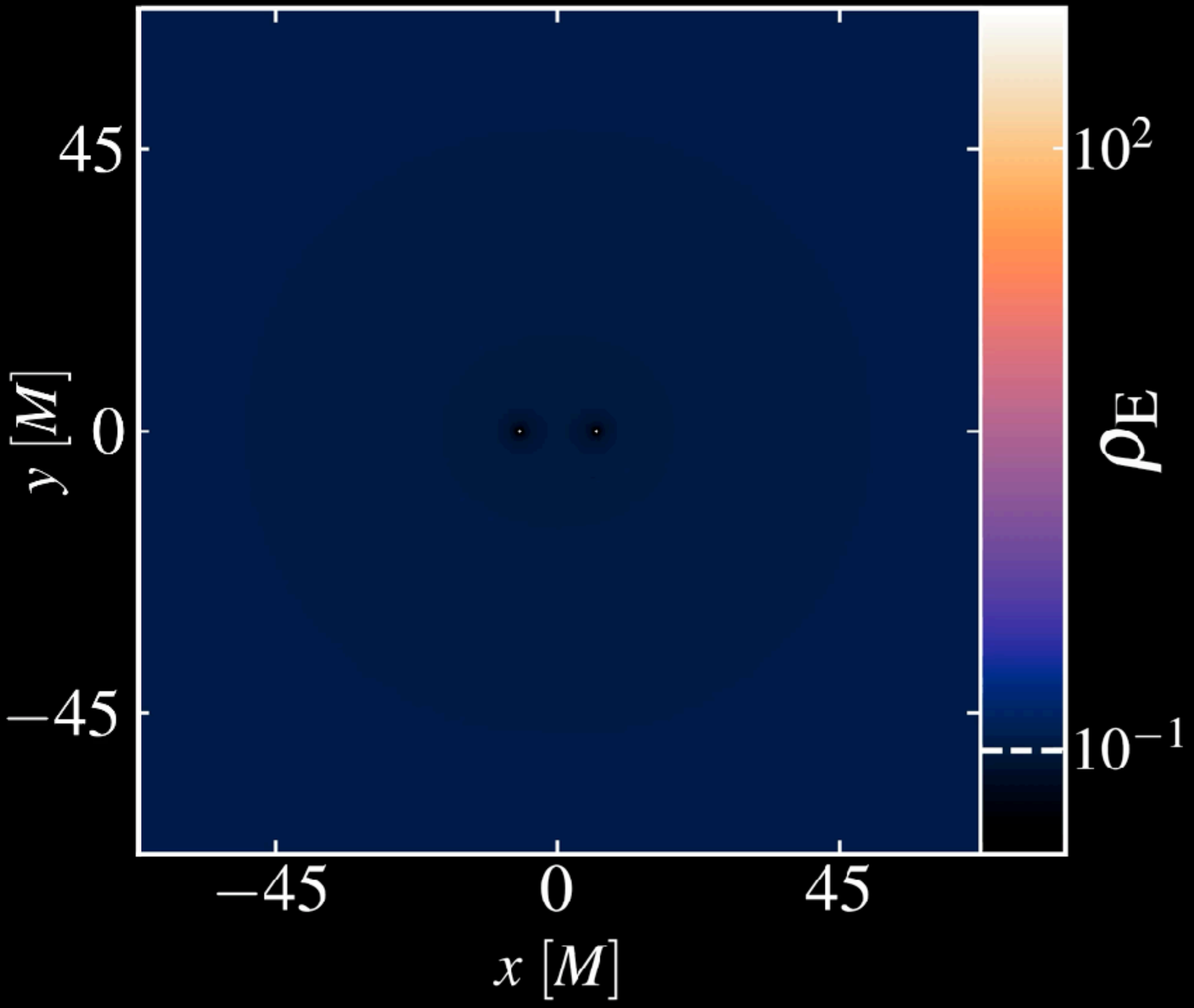
Data & Best-fit Waveform: LIGO Open Science Center (losc.ligo.org); Prediction & Animation: C.North/M.Hannam (Cardiff University)


New physics!
Detector GW strain data
Hanford detector
Livingston detector
0.25
0.30
0.35
0.40
0.45
Time / s

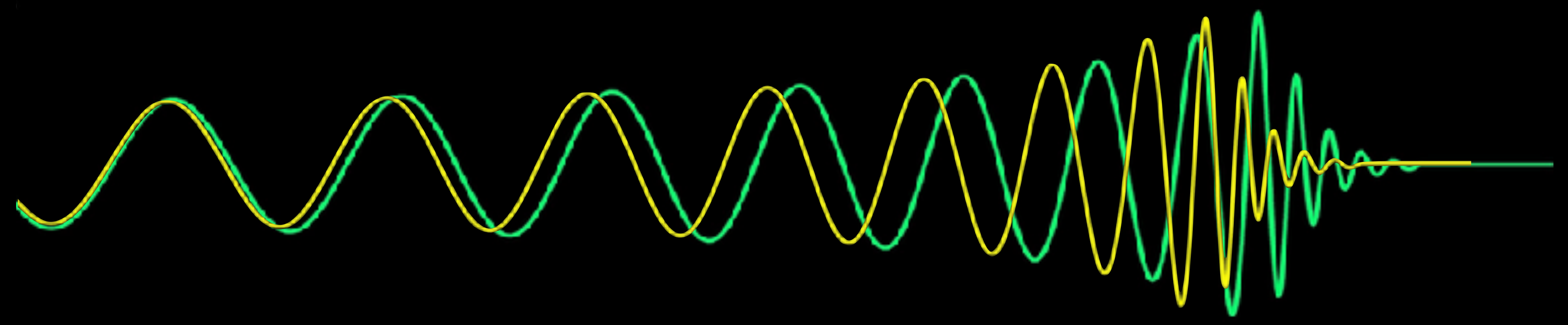
What are the GW signatures of new physics?

Near black holes

Bamber, **Aurrekoetxea**, Clough, Ferreira (2022)
Black hole merger simulations in wave dark matter environments



BeyondSM matter around BBH $L_{SM} \in \phi$



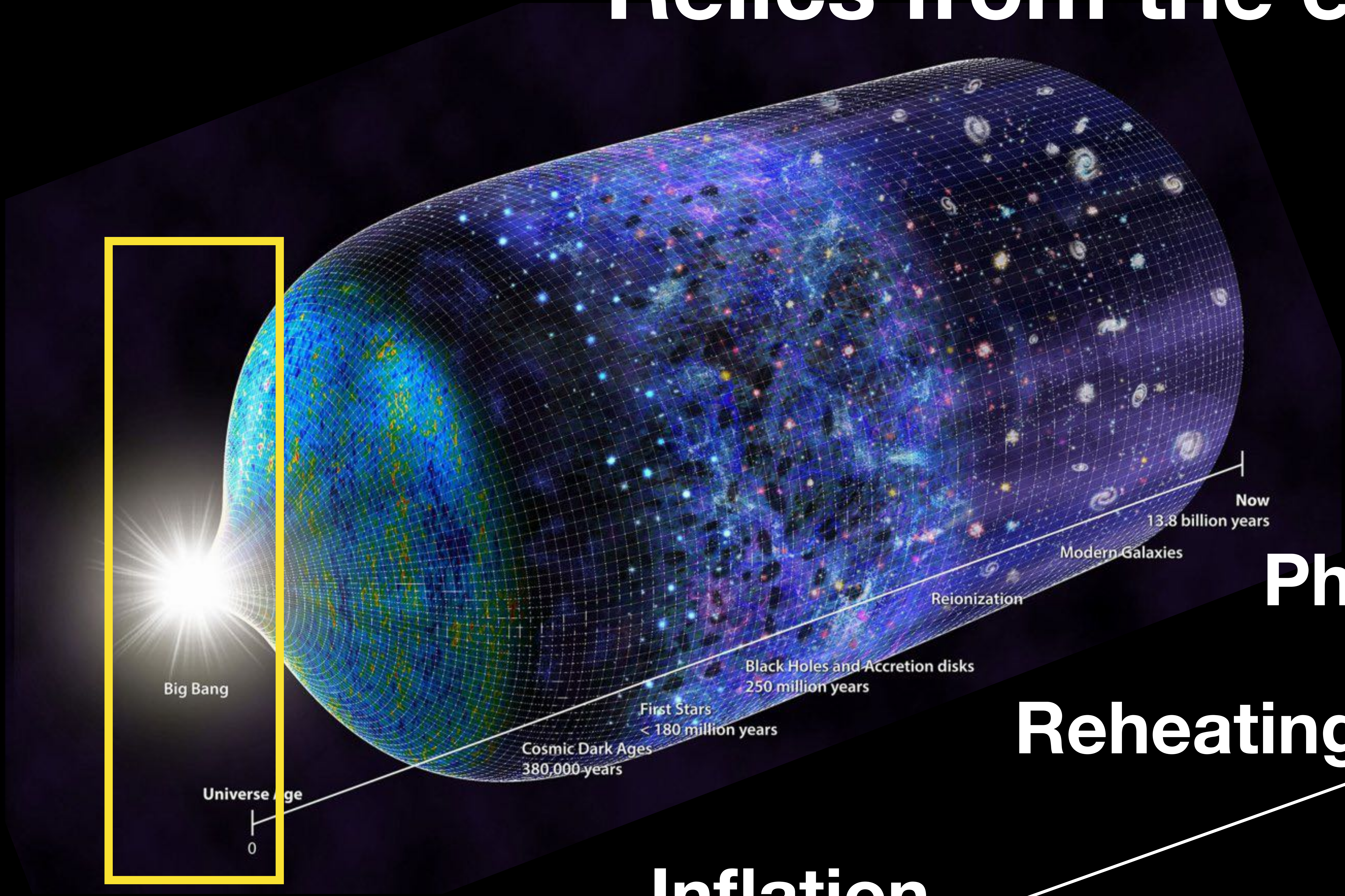
Aurrekoetxea, Bamber, Clough, Ferreira (inprep)
The effect of wave dark matter on binary black hole mergers

Non-minimal couplings $L_{GR} \in \phi R$

Aurrekoetxea, Ferreira, Clough, Lim, Tattersal (2022)
Where is the ringdown? Reconstructing QNMs from dispersive waves

Image credit: NSF

Relics from the early universe



Phase transitions

Reheating

Inflation

Ingredient 1:
Solving GR in a computer:

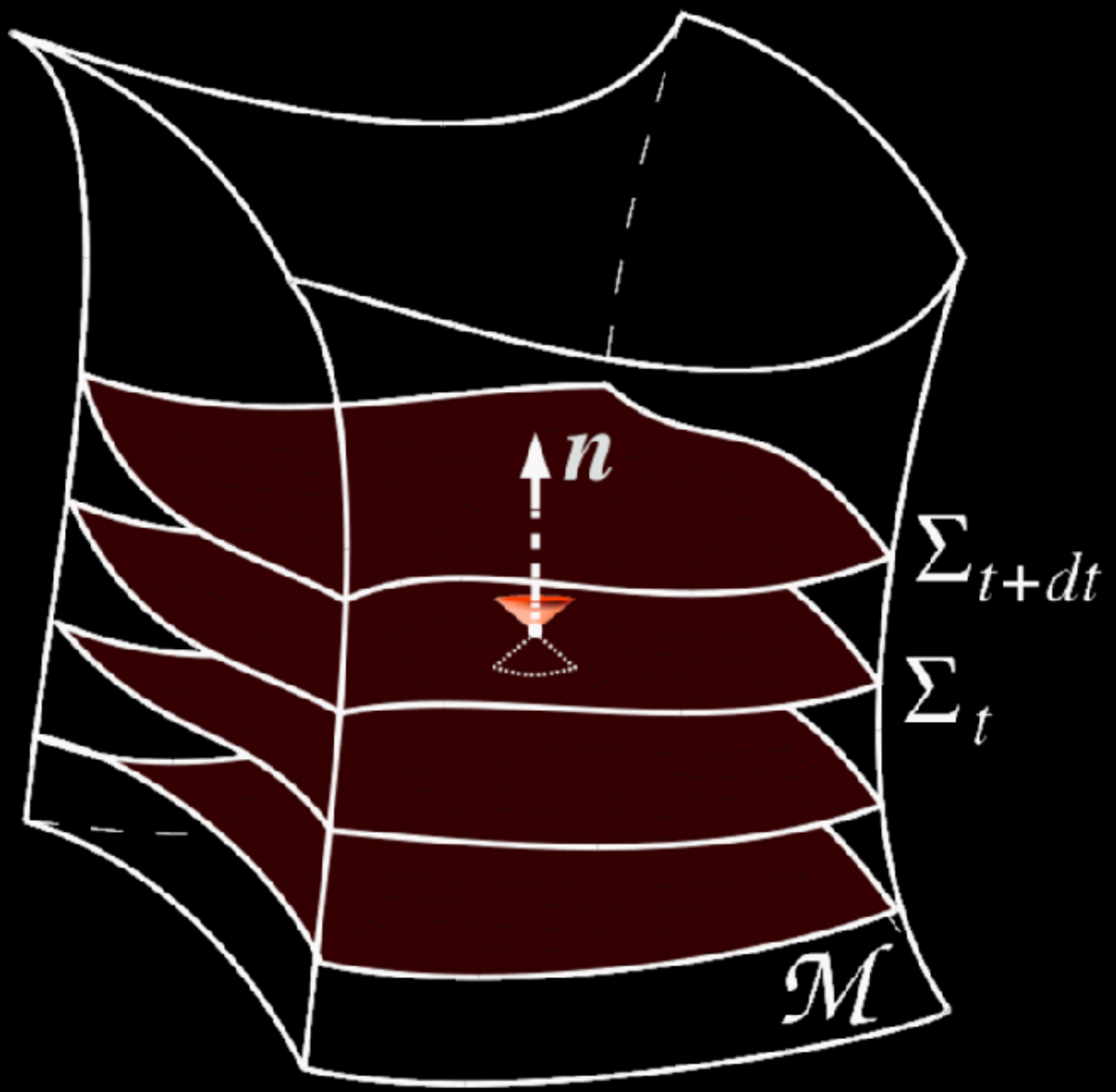
Solving GR in a computer:

Covariant form

$$R_{\mu\nu} - \frac{R}{2} g_{\mu\nu} = 8\pi T_{\mu\nu}$$

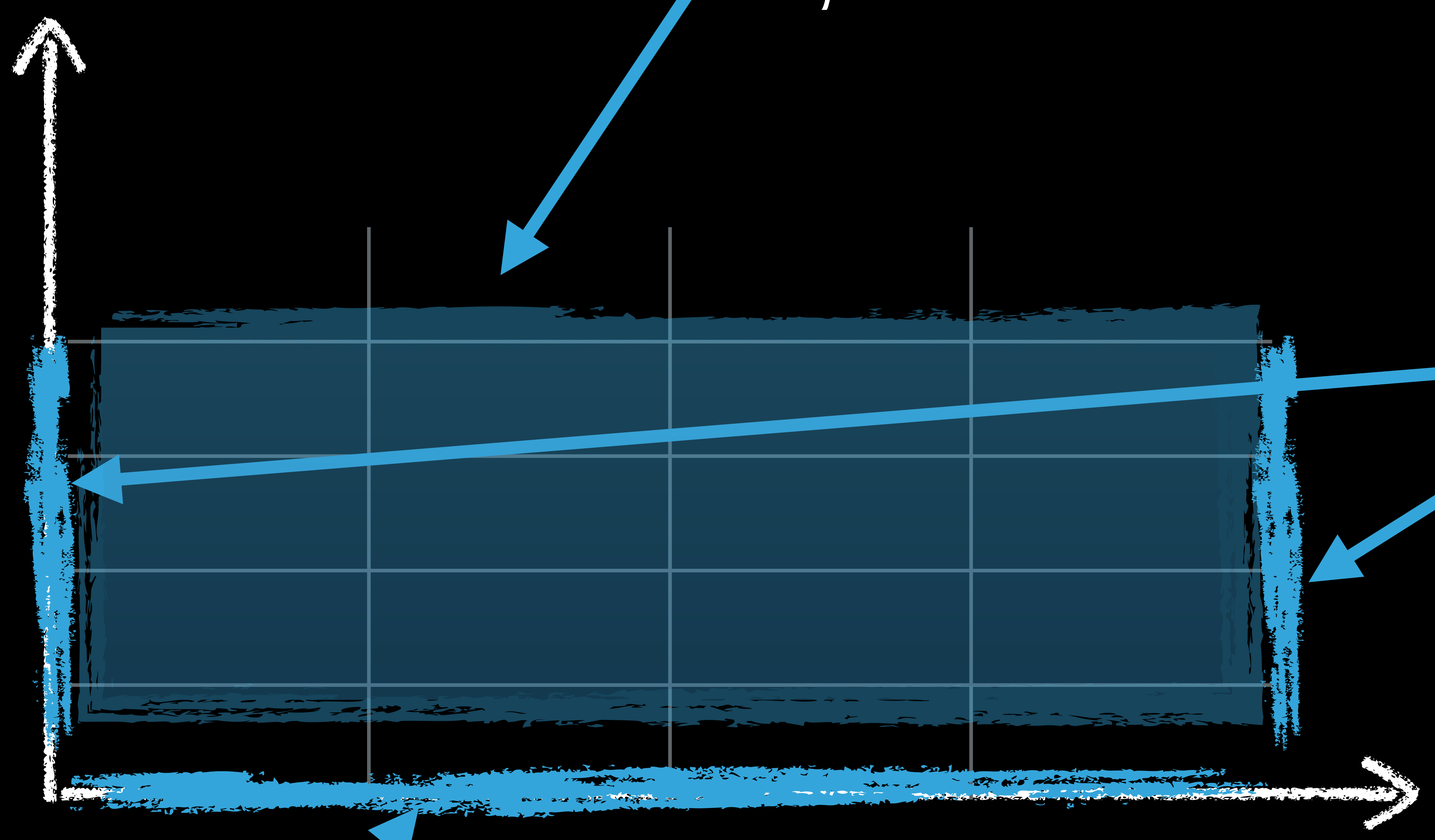
$$\partial_t g_{\mu\nu} = \dots$$

Initial value form



Arnowitt, Deser, Misner
Baumgarte, Shapiro, Shibata, Nakamura

Solving GR in a computer:

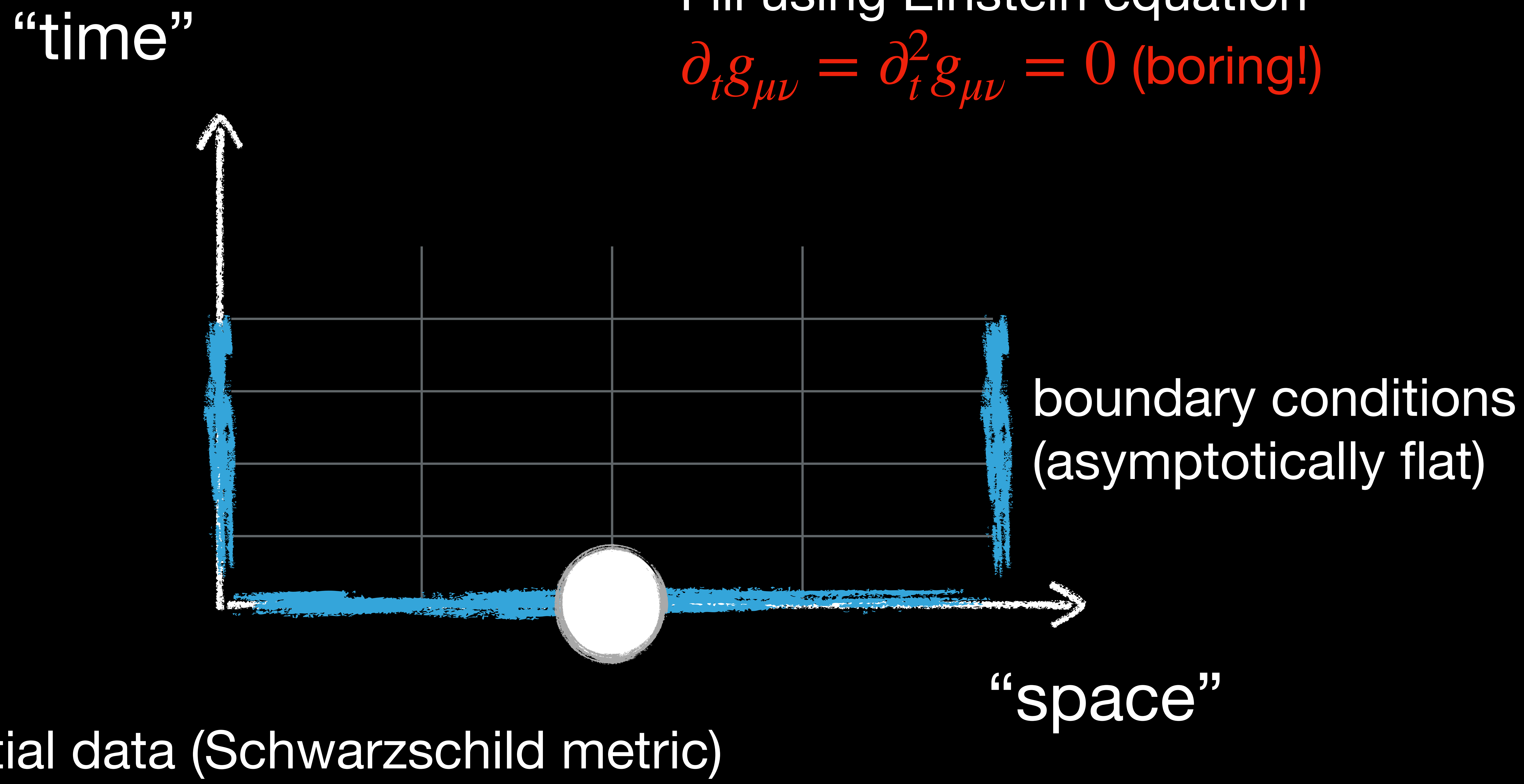


CTTK: A new method to solve the initial data constraints
Aurrekoetxea, Clough, Lim (2022)

Solving GR in a computer:

Fill using Einstein equation

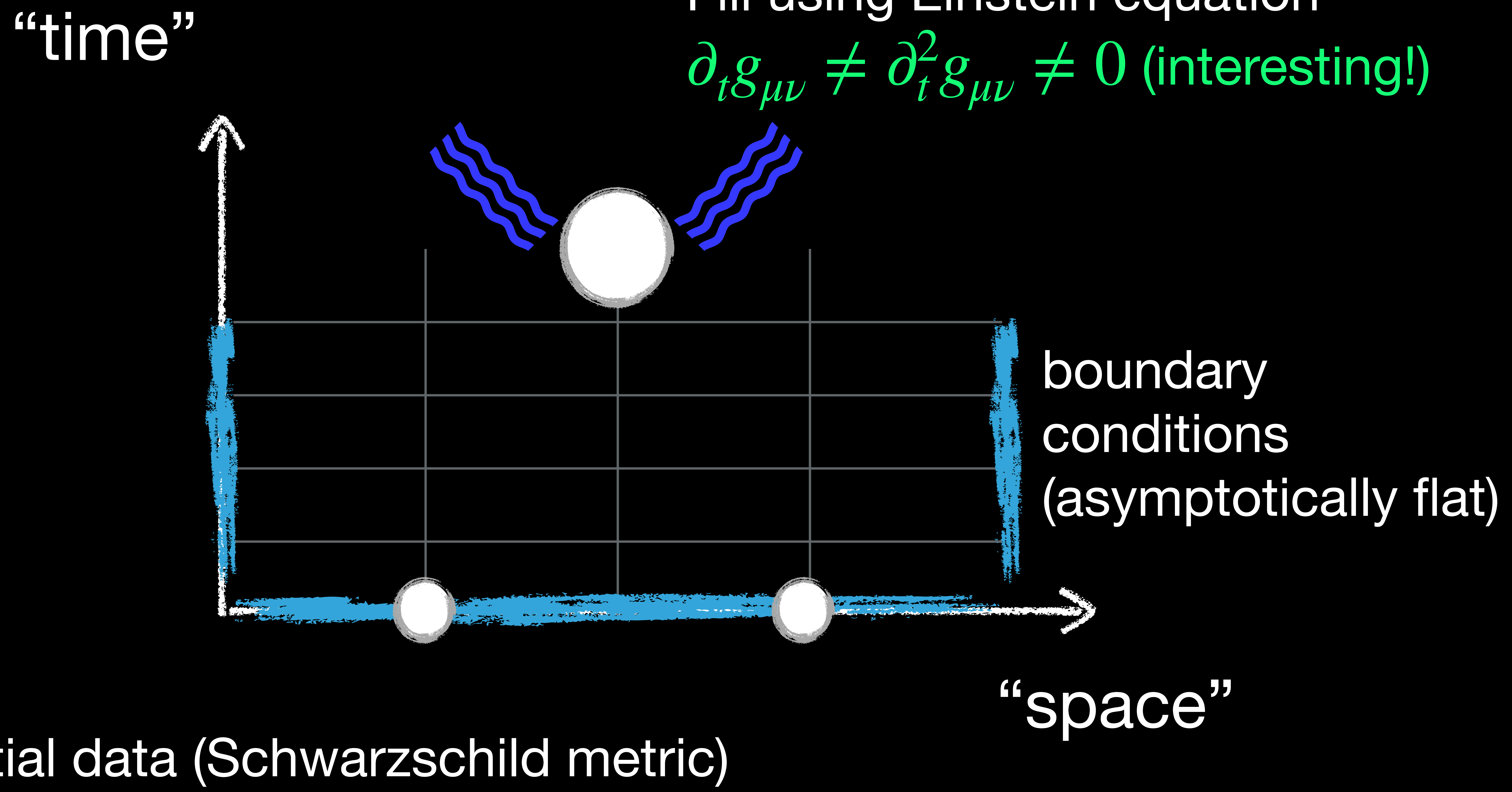
$\partial_t g_{\mu\nu} = \partial_t^2 g_{\mu\nu} = 0$ (boring!)



Solving GR in a computer:

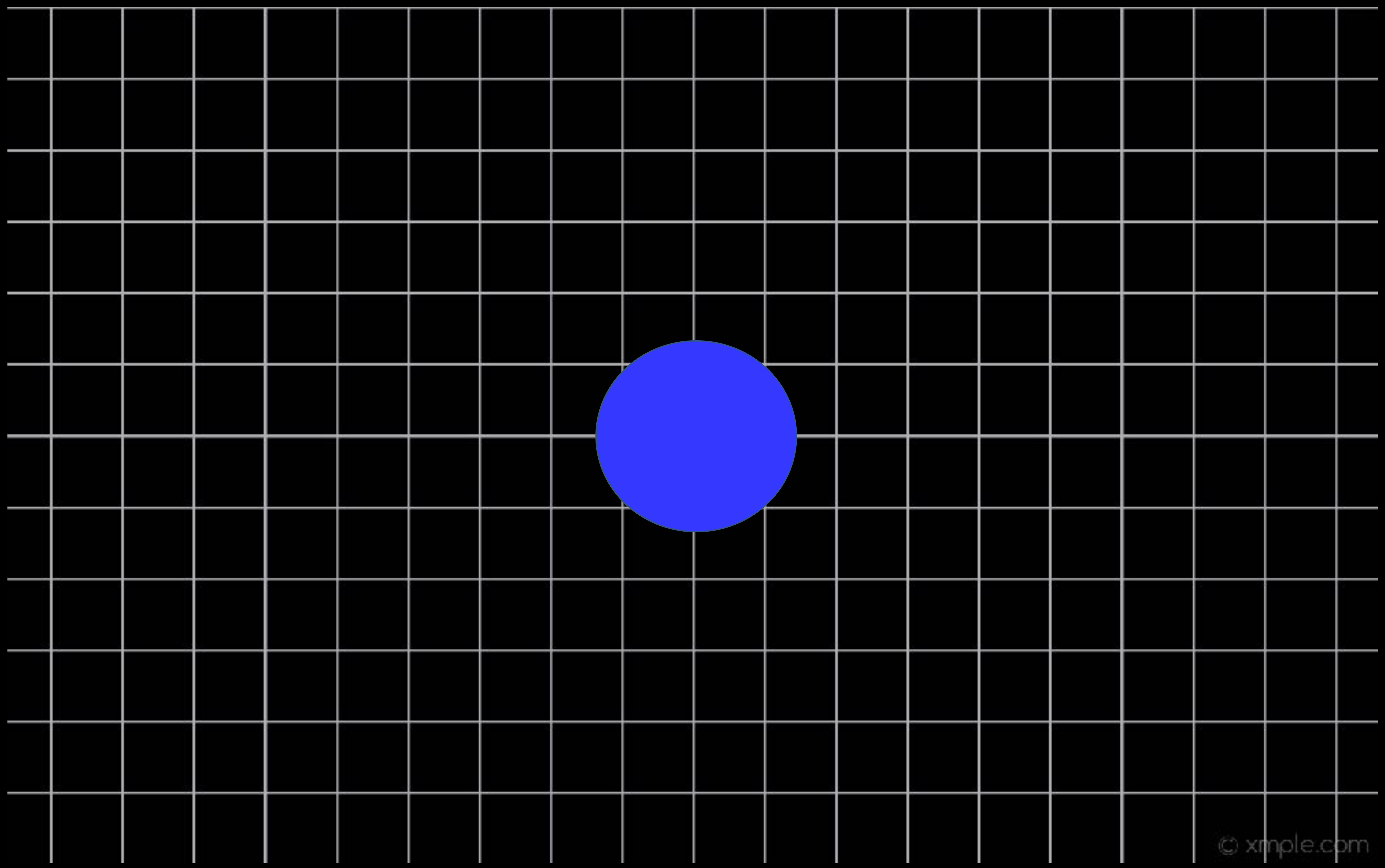
Fill using Einstein equation

$\partial_t g_{\mu\nu} \neq \partial_t^2 g_{\mu\nu} \neq 0$ (interesting!)

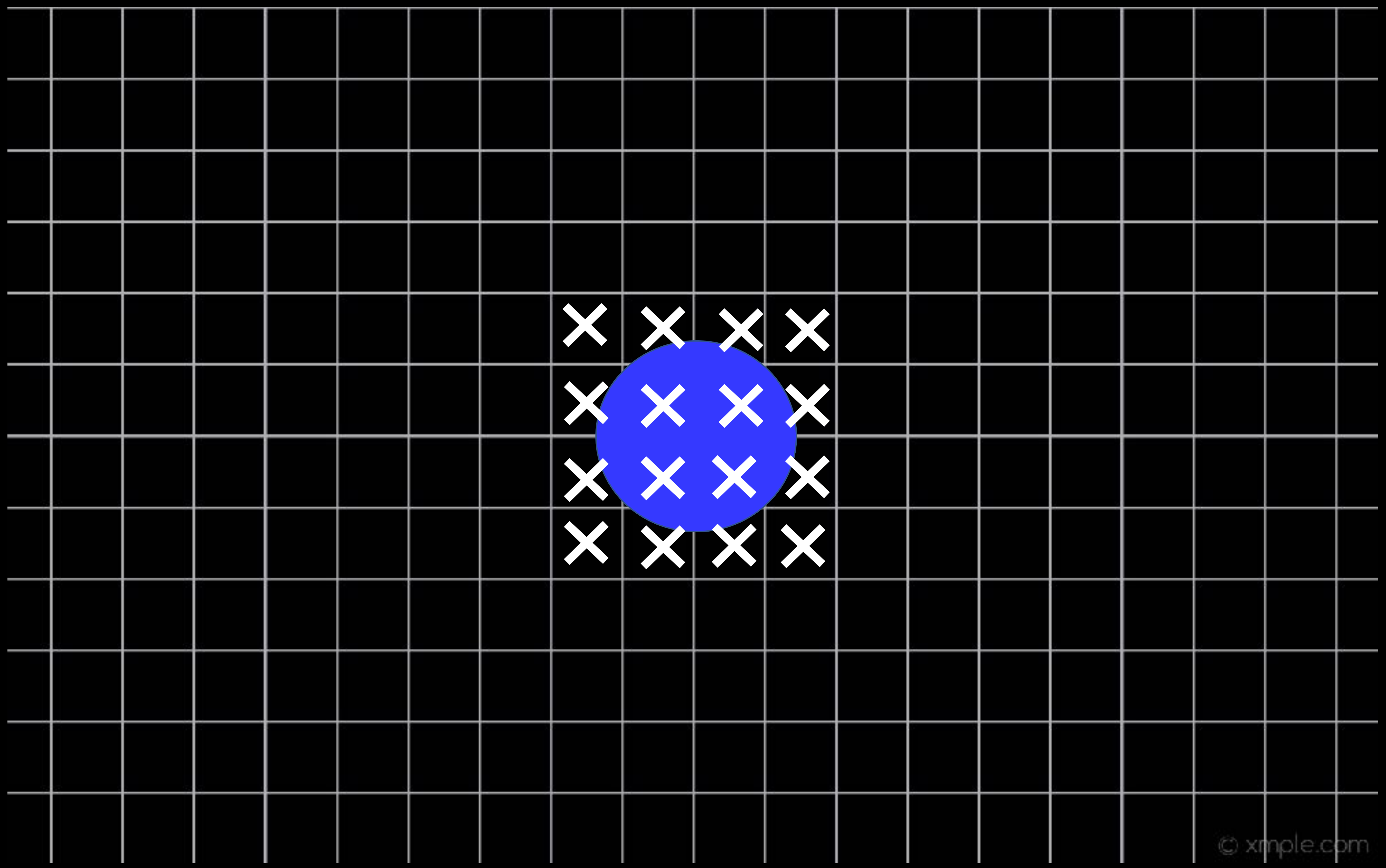


Ingredient 2:
Adaptive Mesh Refinement

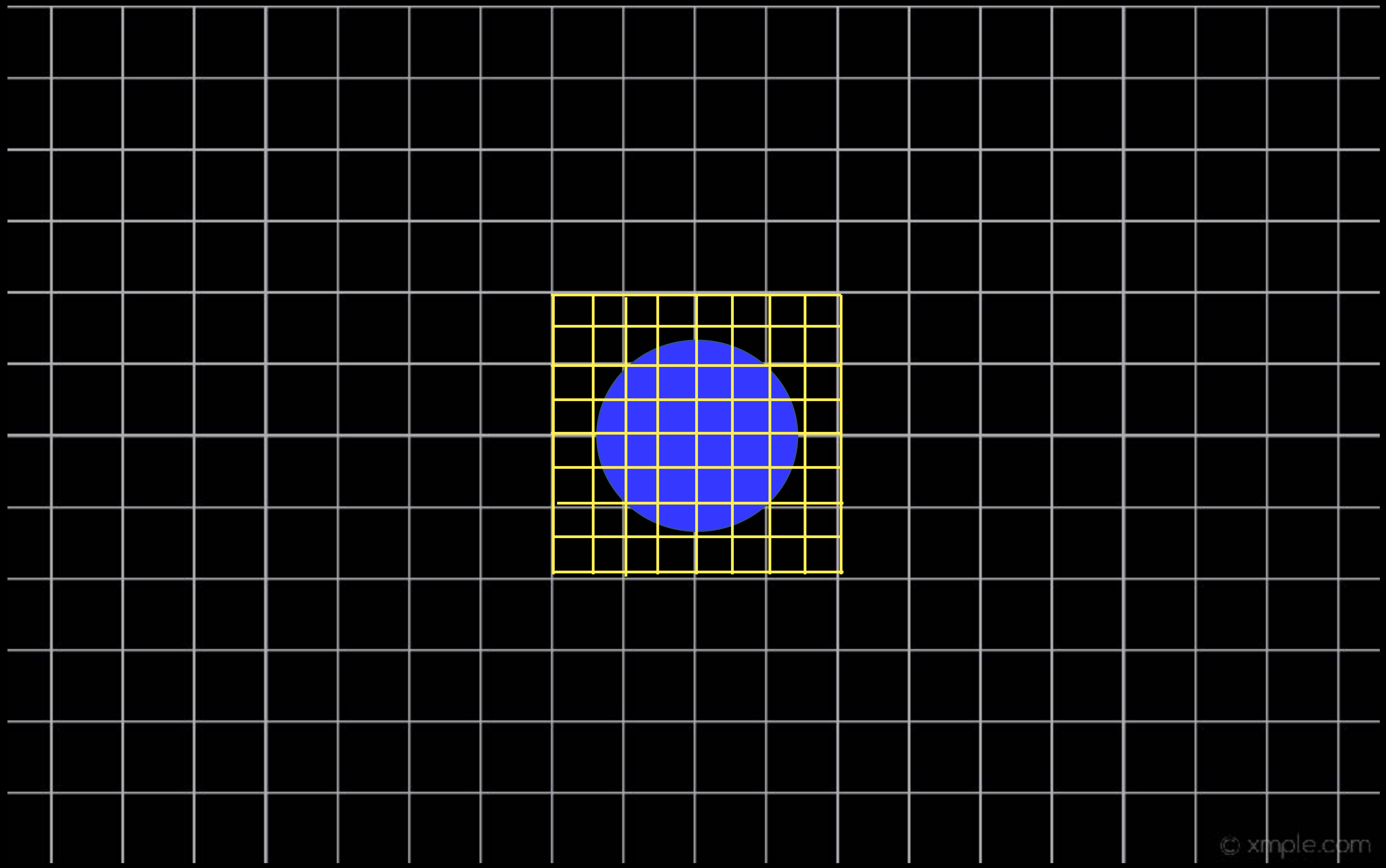
Adaptive Mesh Refinement



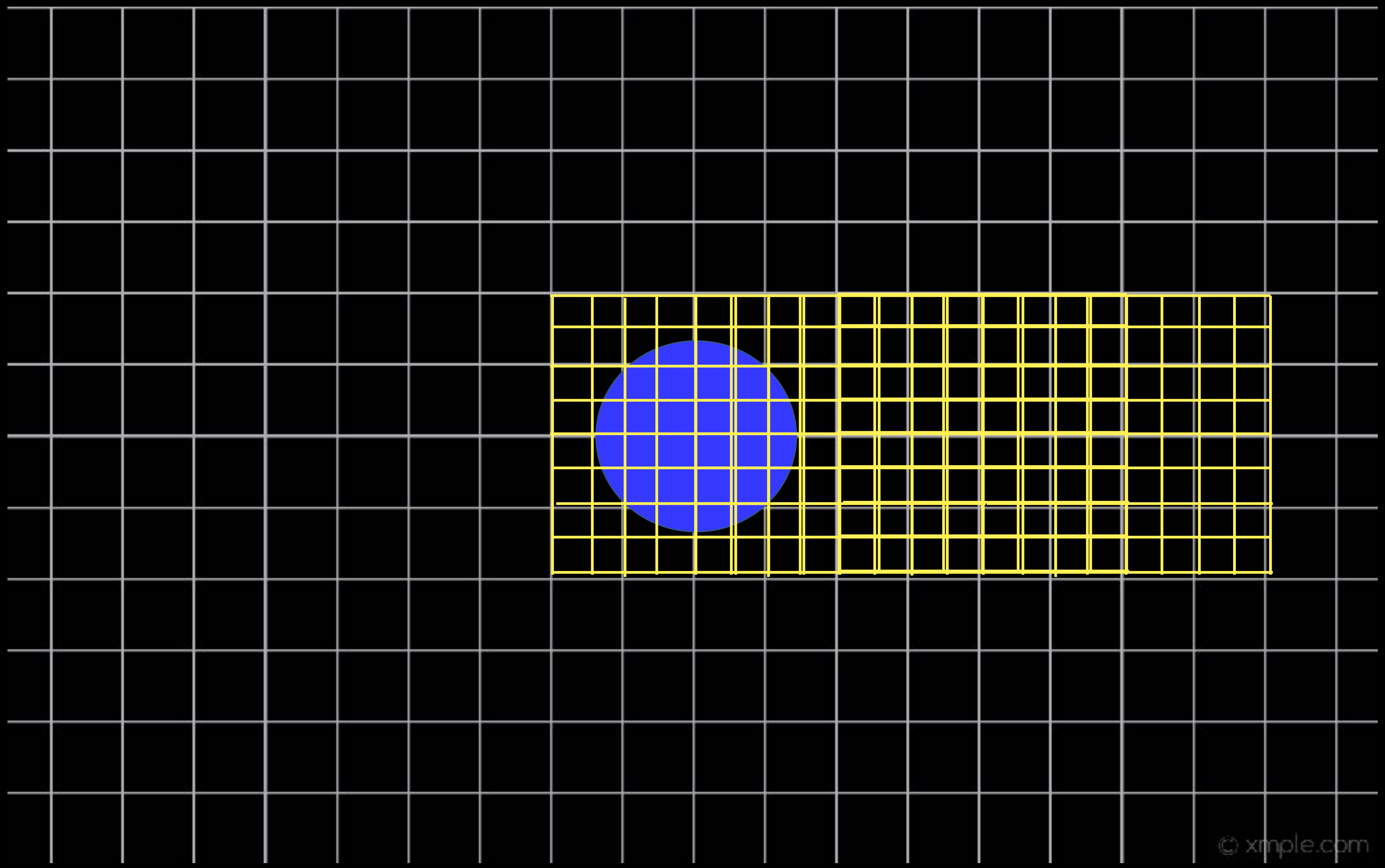
Adaptive Mesh Refinement



Adaptive Mesh Refinement

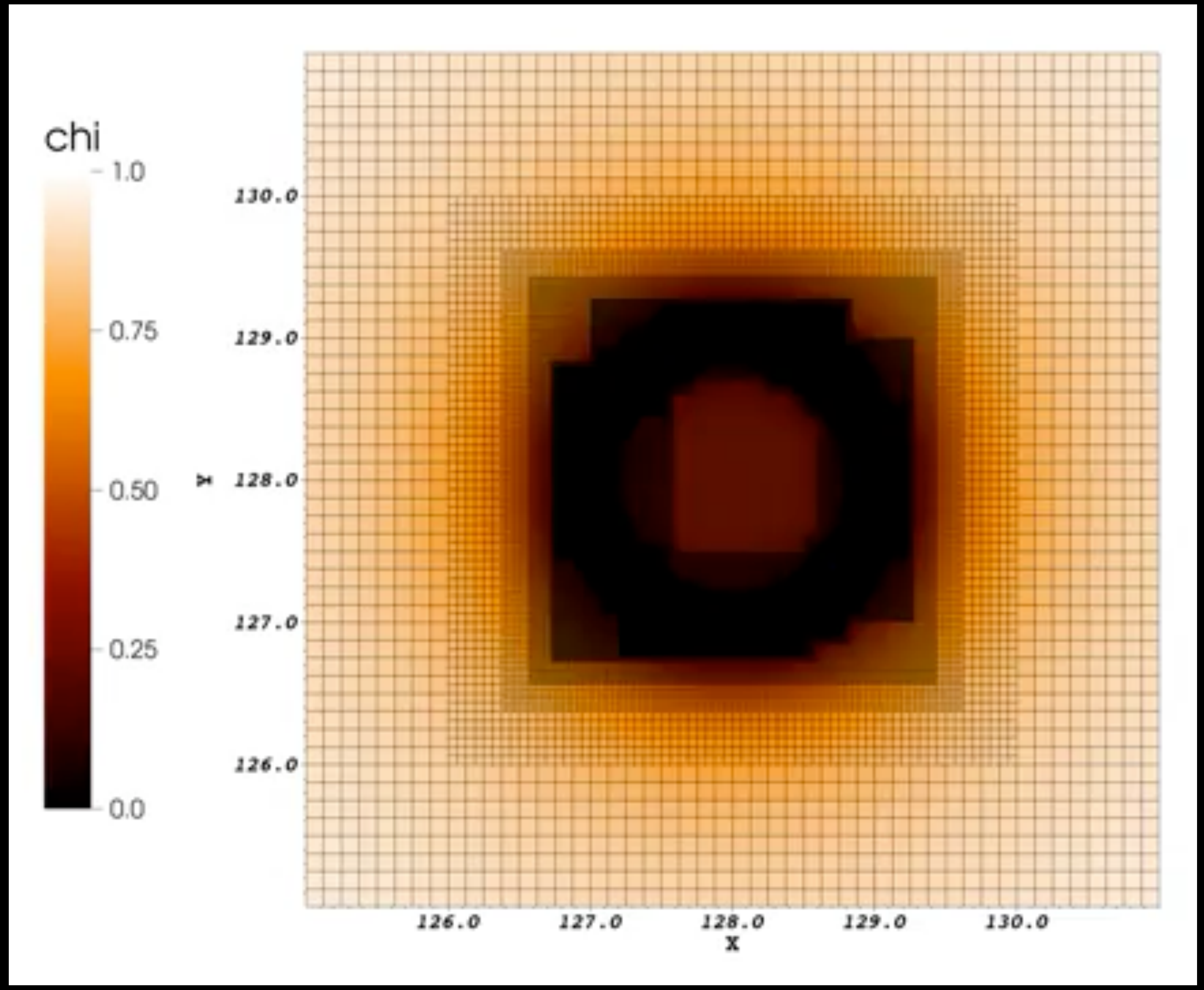


Adaptive Mesh Refinement



Numerical relativity with Adaptive Mesh Refinement

www.grchombo.org

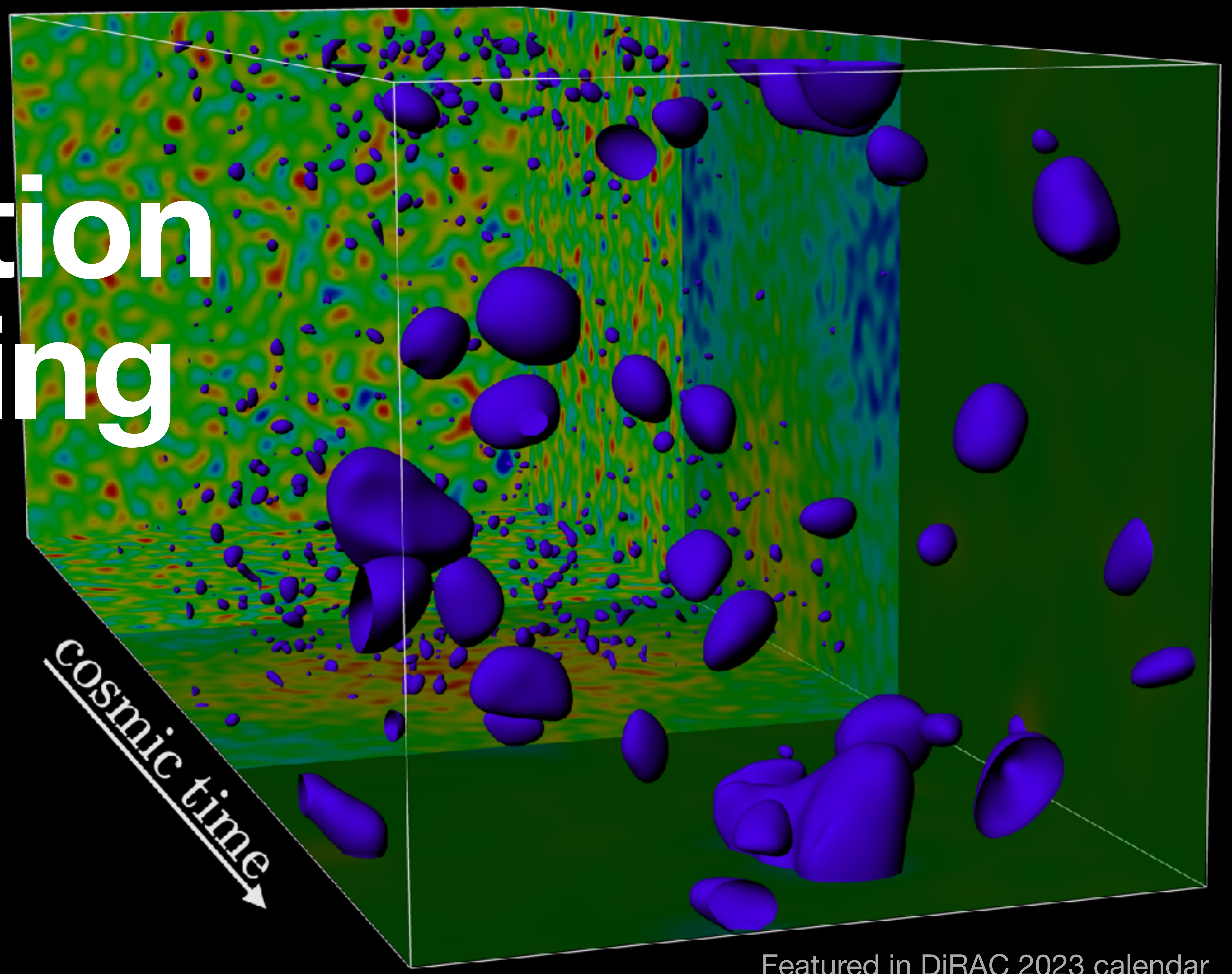


Figueras et al.

Oscillon formation during preheating

Oscillon formation during inflationary preheating with general relativity

Aurrekoetxea, Clough, Muia (2023)



Featured in DiRAC 2023 calendar

Oscillon formation during preheating

Can PBHs form? What is the spectrum of GWs?

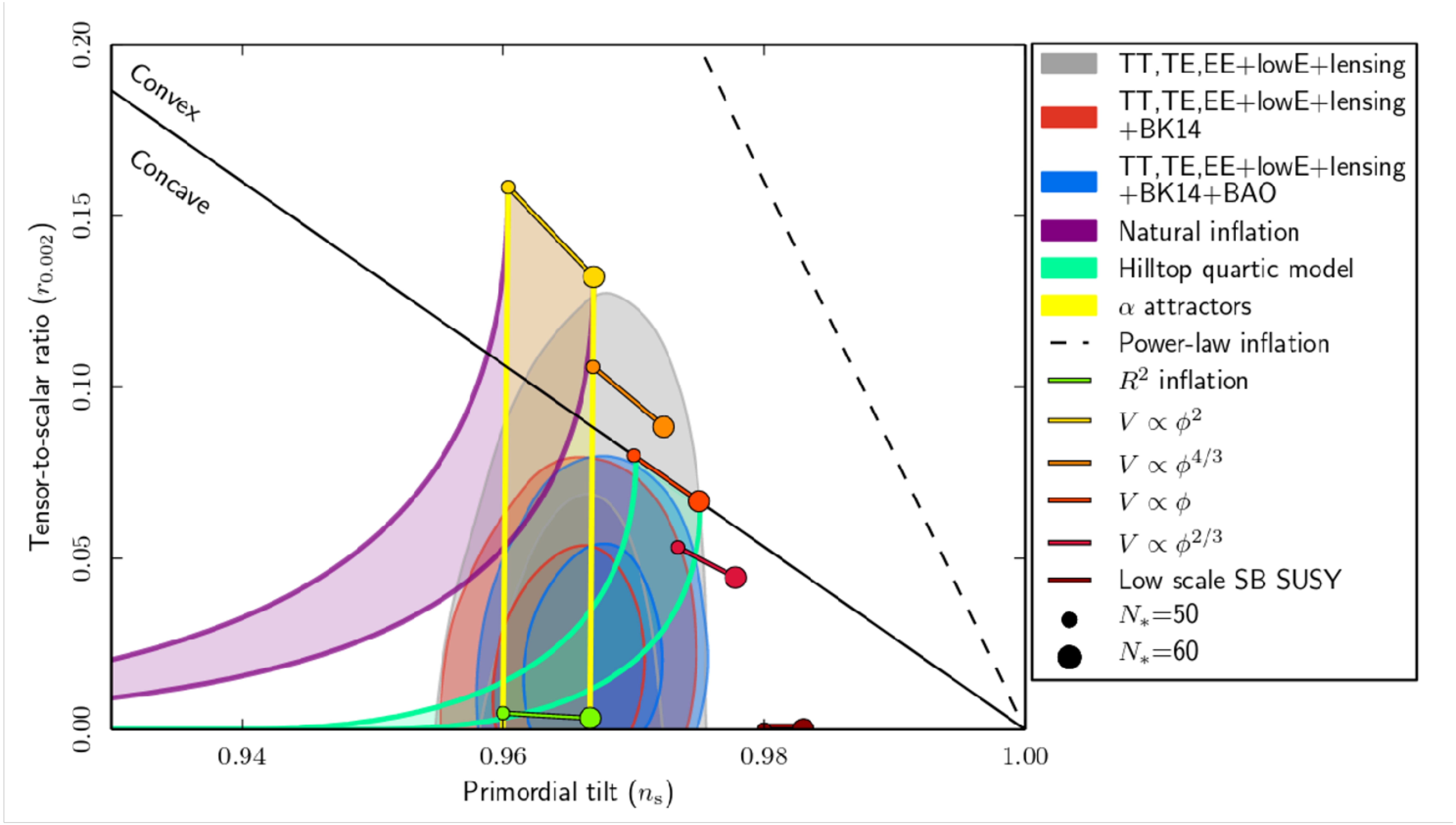
What is the effect of gravity in their formation? $C = \dfrac{GM}{R}$

Compactness

Amin, Copeland, Easther,
Figueroa, Garcia, Giblin, Guth,
Hertzberg, Kaiser, Kou,
Mertens, Sfakianakis, Tian
+ many others

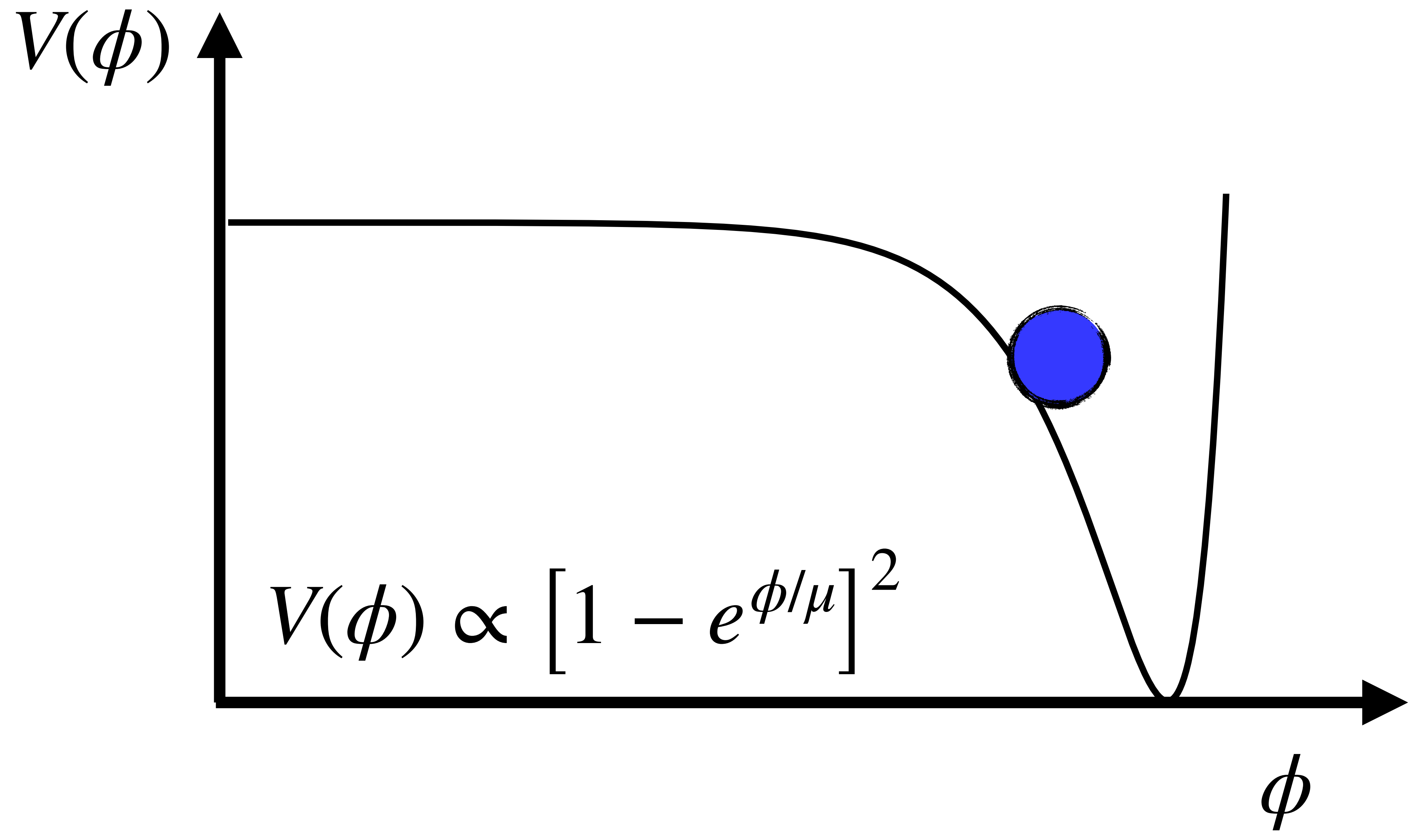
Inflation

- Solves homogeneity and flatness problems
- Mechanism for spectrum of scale invariant fluctuations



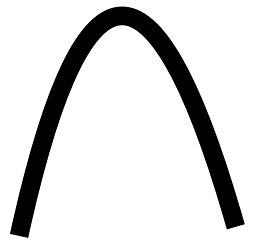
Inflation has to end… Reheating

$$\phi(t,\mathbf{x}) = \bar{\phi}(t) + \delta\phi(t,\mathbf{x})$$



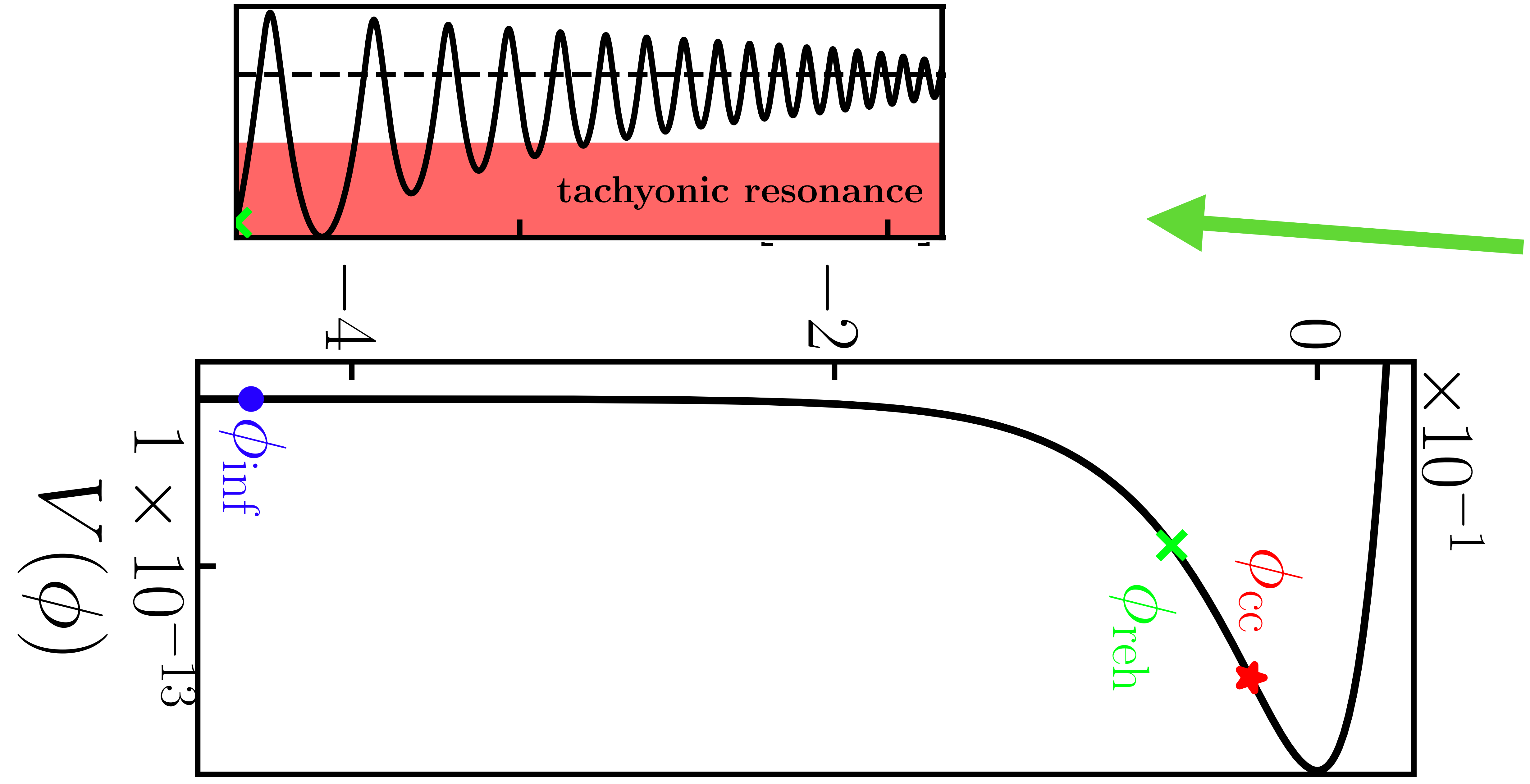
Resonances: $\delta\phi$ ***grows***

- *Parametric*: if $\bar{\phi}(t)$ periodic
- *Tachyonic*: if $\bar{\phi}(t)$ probes $V'' < 0$



Inflation has to end… Reheating

ϕ



Start simulations here

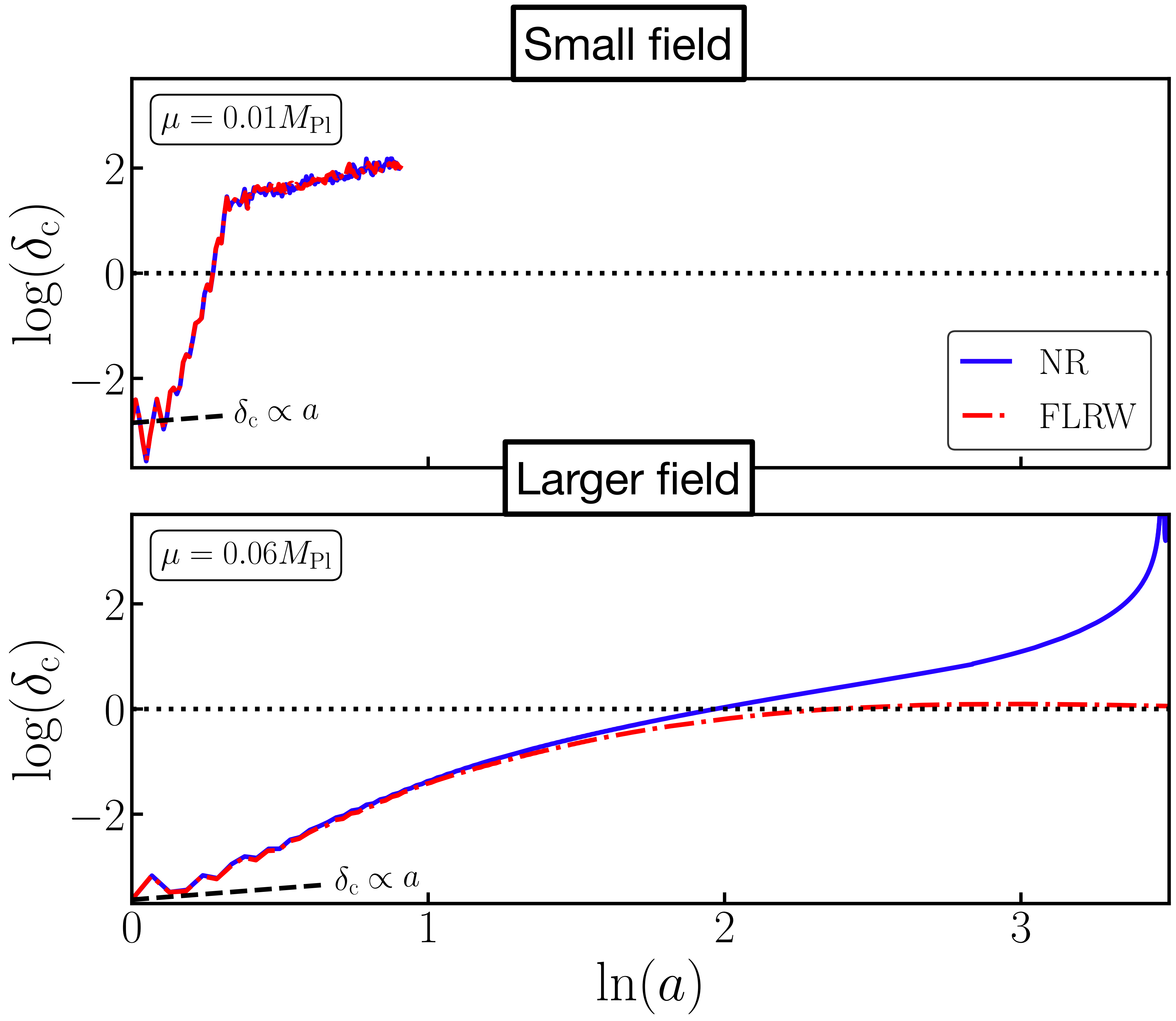
$\ln(a)$

time

$\dot{\phi}_0 \neq 0$ **very important!**

-0.06036
$\phi/M_{\rm Pl}$
-0.0603
-0.0009
δ
0.0013
$\delta \equiv \frac{\rho}{\bar{\rho}} - 1$
20
0
−20
y [1/m]
−20
0
20
x [1/m]
−20
0
20
x [1/m]
$\ln(a) = 0.00$

Why gravity?



$$\nabla^\mu \nabla_\mu \phi = V'(\phi)$$

FLRW:

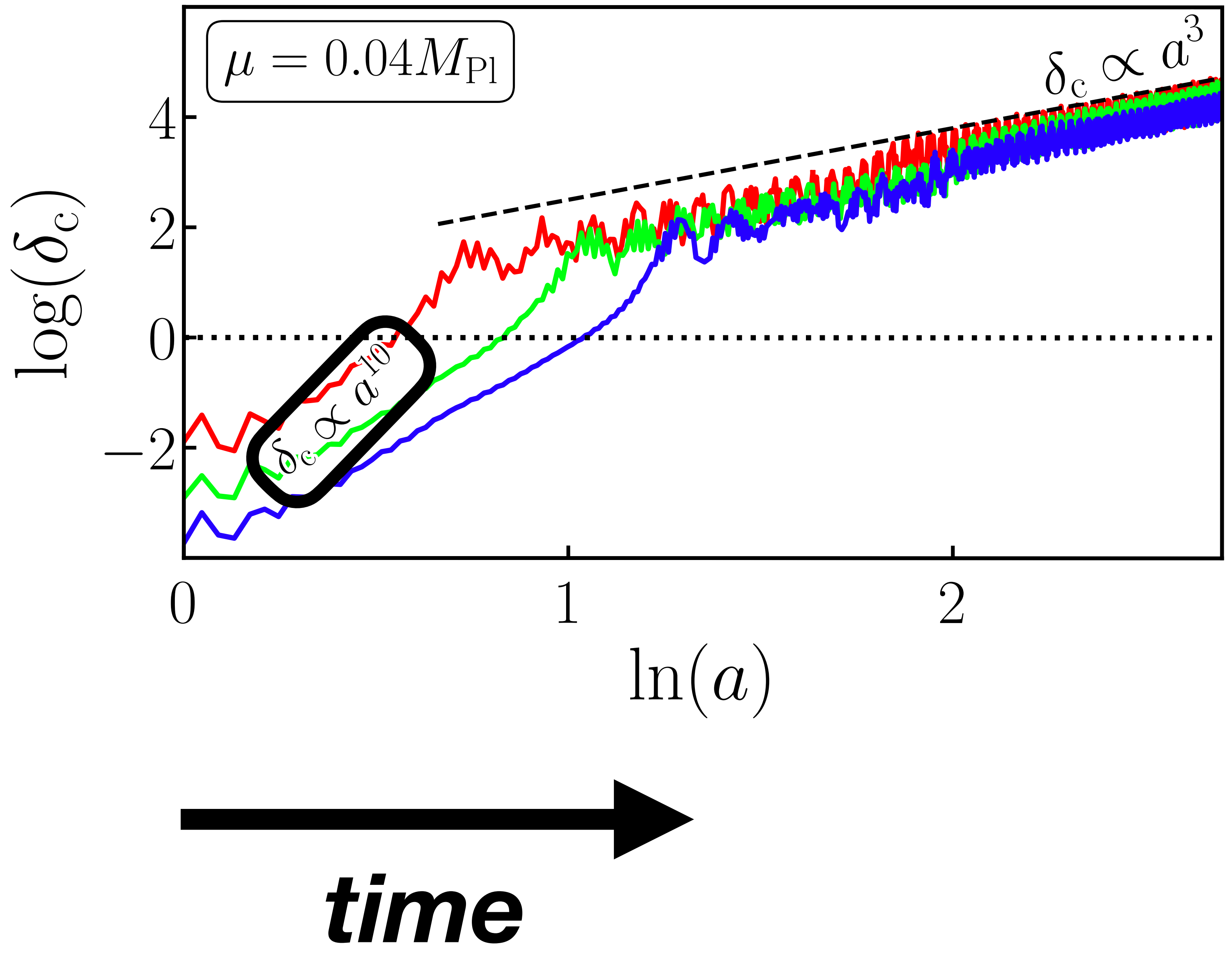
$$\frac{\ddot{a}}{a} = -\frac{\bar{\rho} + 3\bar{p}}{6M_{\rm Pl}^2}$$

NumRel:

$$R_{\mu\nu} - \frac{R}{2} g_{\mu\nu} = \frac{T_{\mu\nu}}{M_{\rm Pl}^2}$$

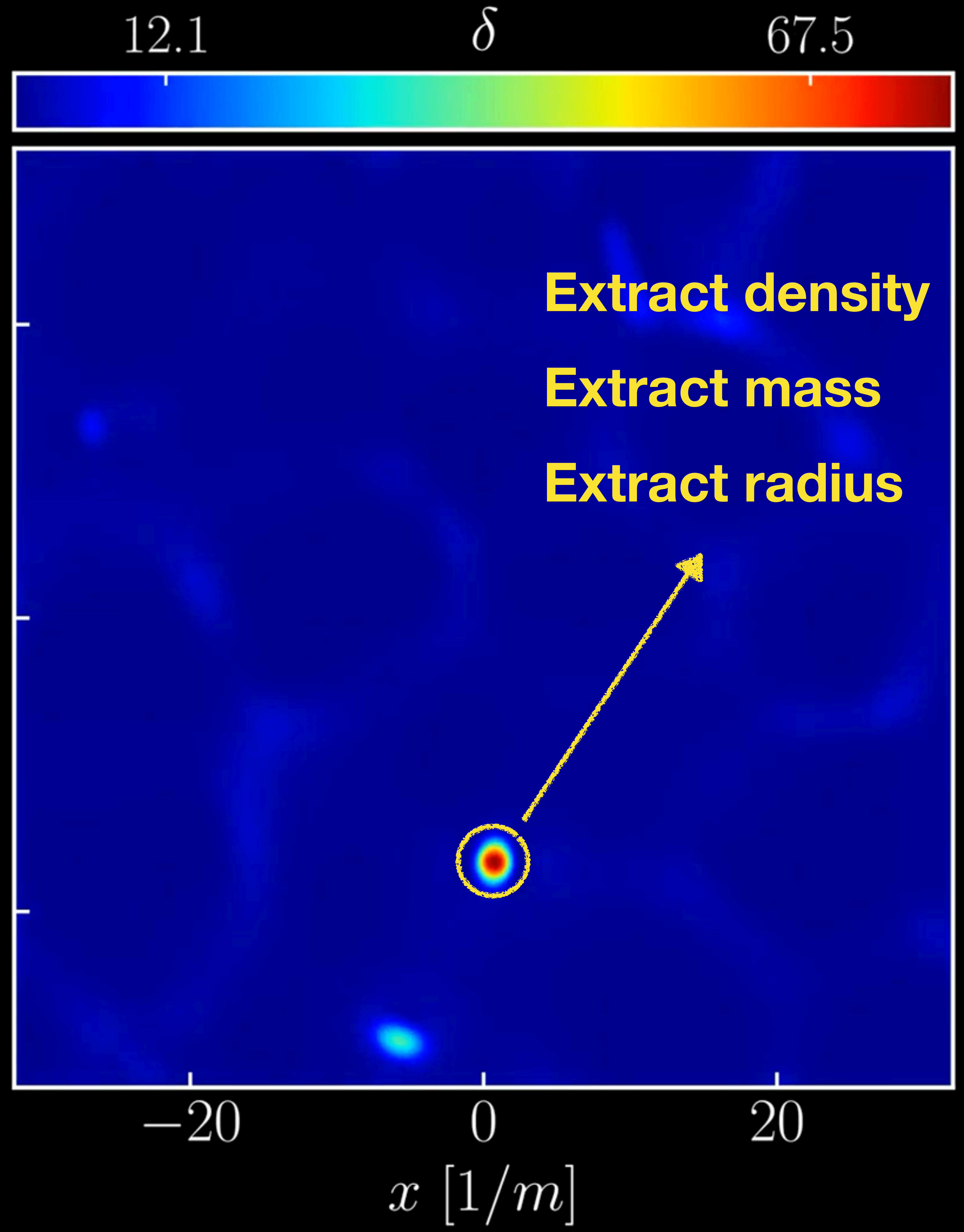
Growth of overdensities

$$\delta_c \equiv \frac{\rho_c}{\bar{\rho}} - 1$$



Different initial fluctuations

$\langle \delta\phi^2 \rangle$ $\langle \delta\phi^2 \rangle$ $\langle \delta\phi^2 \rangle$

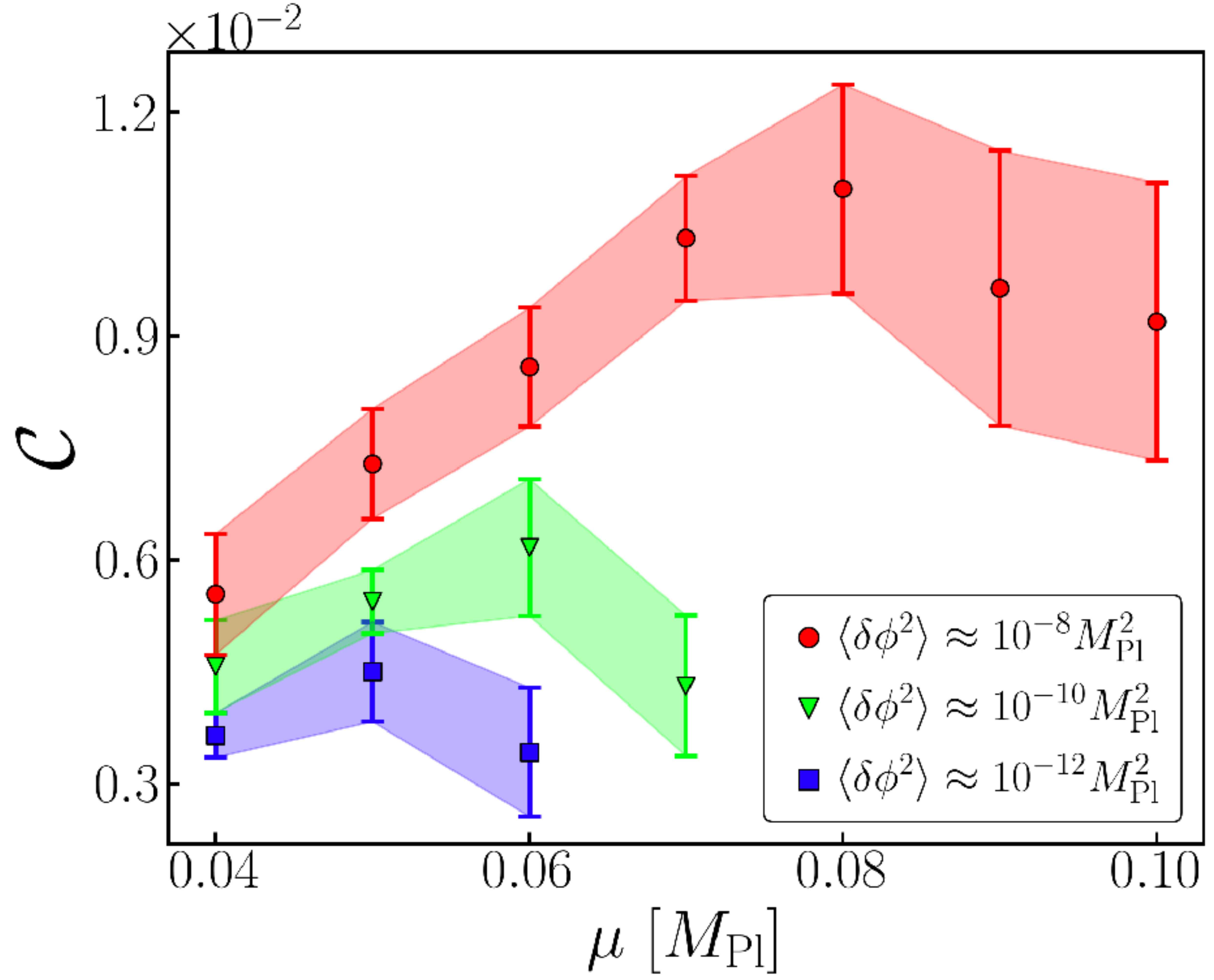


12.1
δ
67.5
Extract density
Extract mass
Extract radius
−20
0
20
$x\ [1/m]$

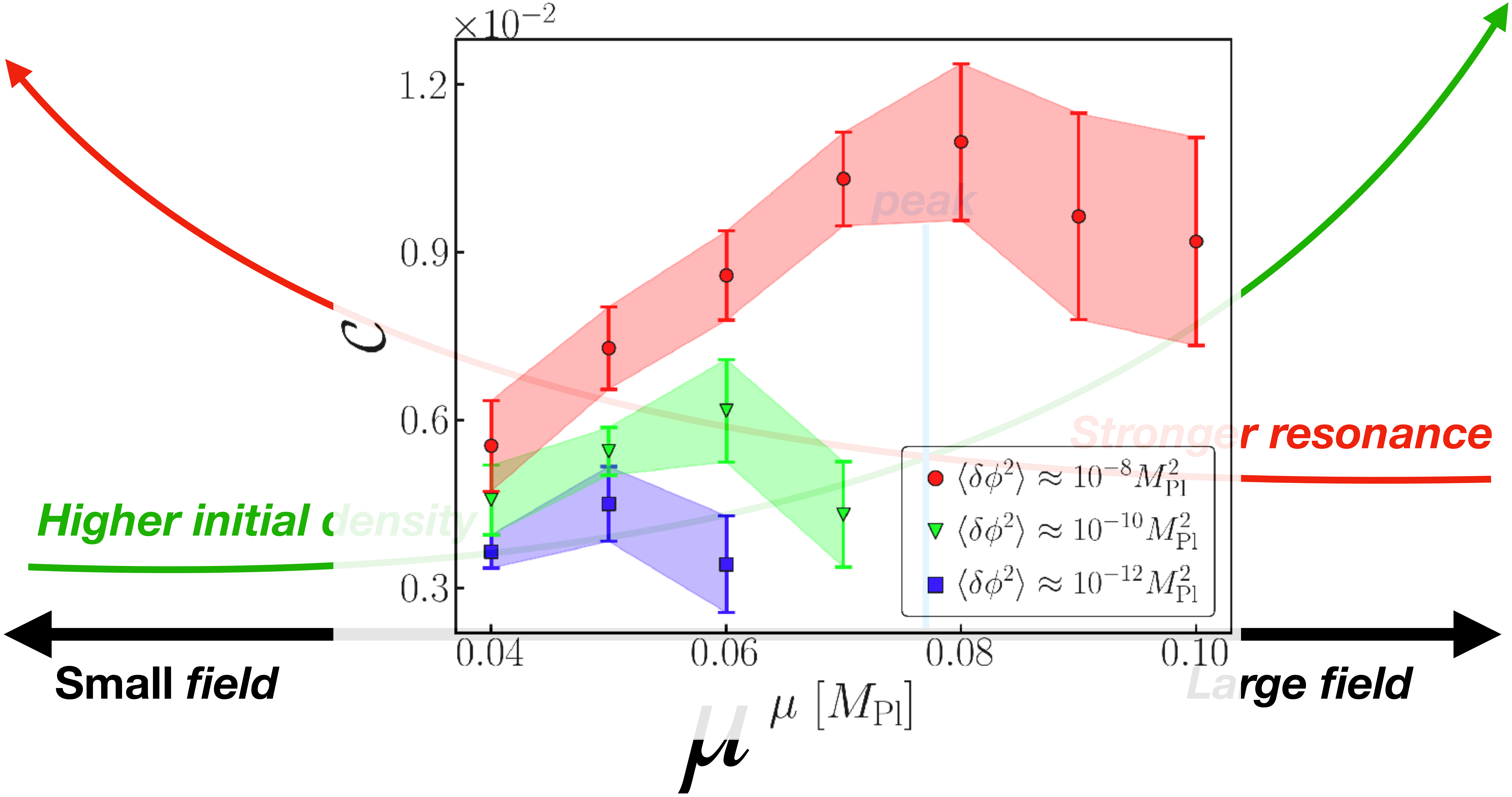
Oscillon properties

$$\mathcal{C} = GM/R$$

Black holes: $\mathcal{C} = 0.5$



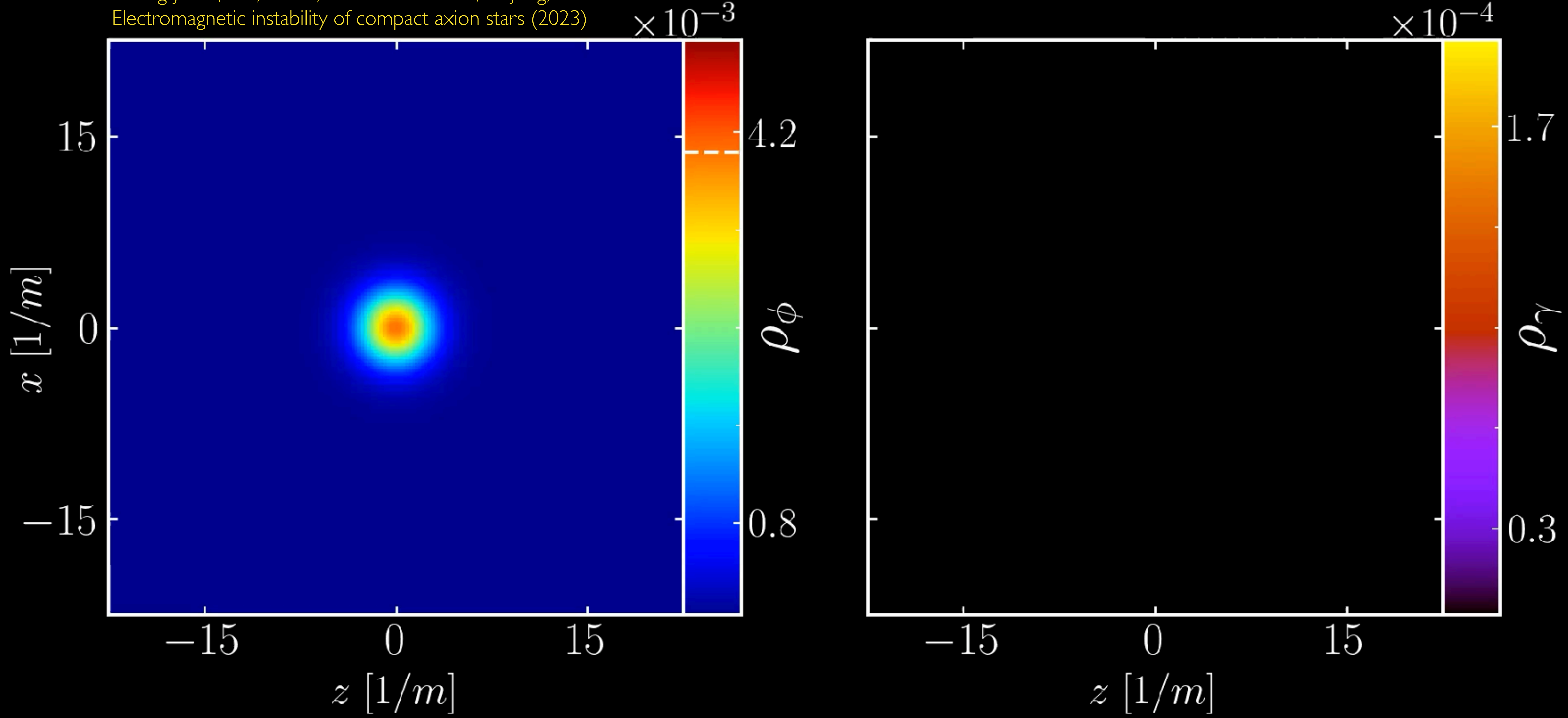
Oscillon properties



$$L \in \frac{g_{a\gamma}}{4}\phi F_{\mu\nu}\tilde{F}^{\mu\nu}$$

$t = 000\ m^{-1}$

Chung-Jukko, Lim, Marsh, **Aurrekoetxea**, de Jong, Ge
Electromagnetic instability of compact axion stars (2023)



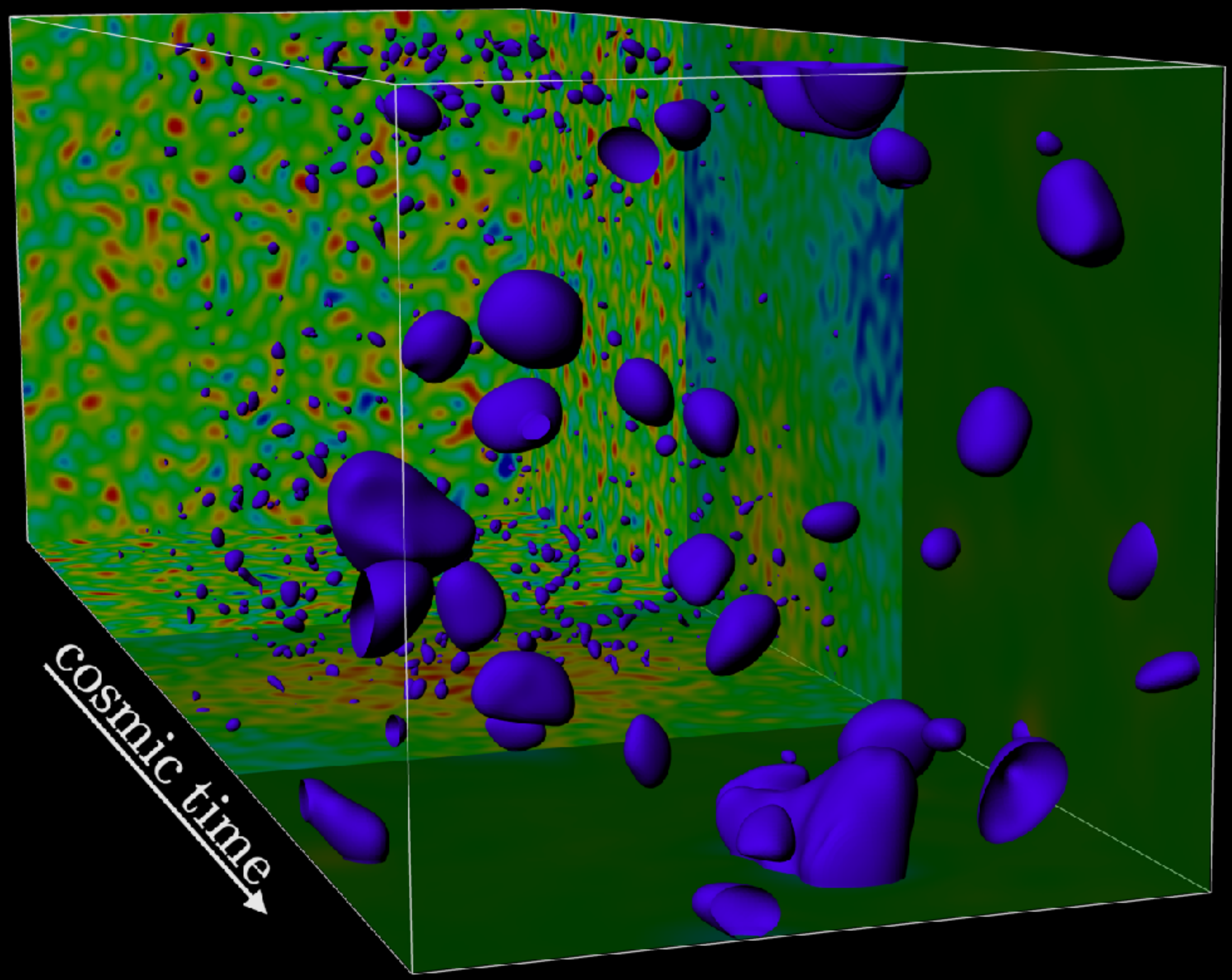
Summary:

- Compactness of order

$$C = 10^{-3} - 10^{-2}$$

- No black hole formation

- $\dot{\phi}_0$ important



Gravitational waves from cosmic strings

Coherent GW waveforms and memory from cosmic string loops

Aurrekoetxea, Helfer, Lim (2020)

Revisiting the cosmic string origin of GW190521

Aurrekoetxea, Hoy, Hannam, Helfer, Lim (inprep)

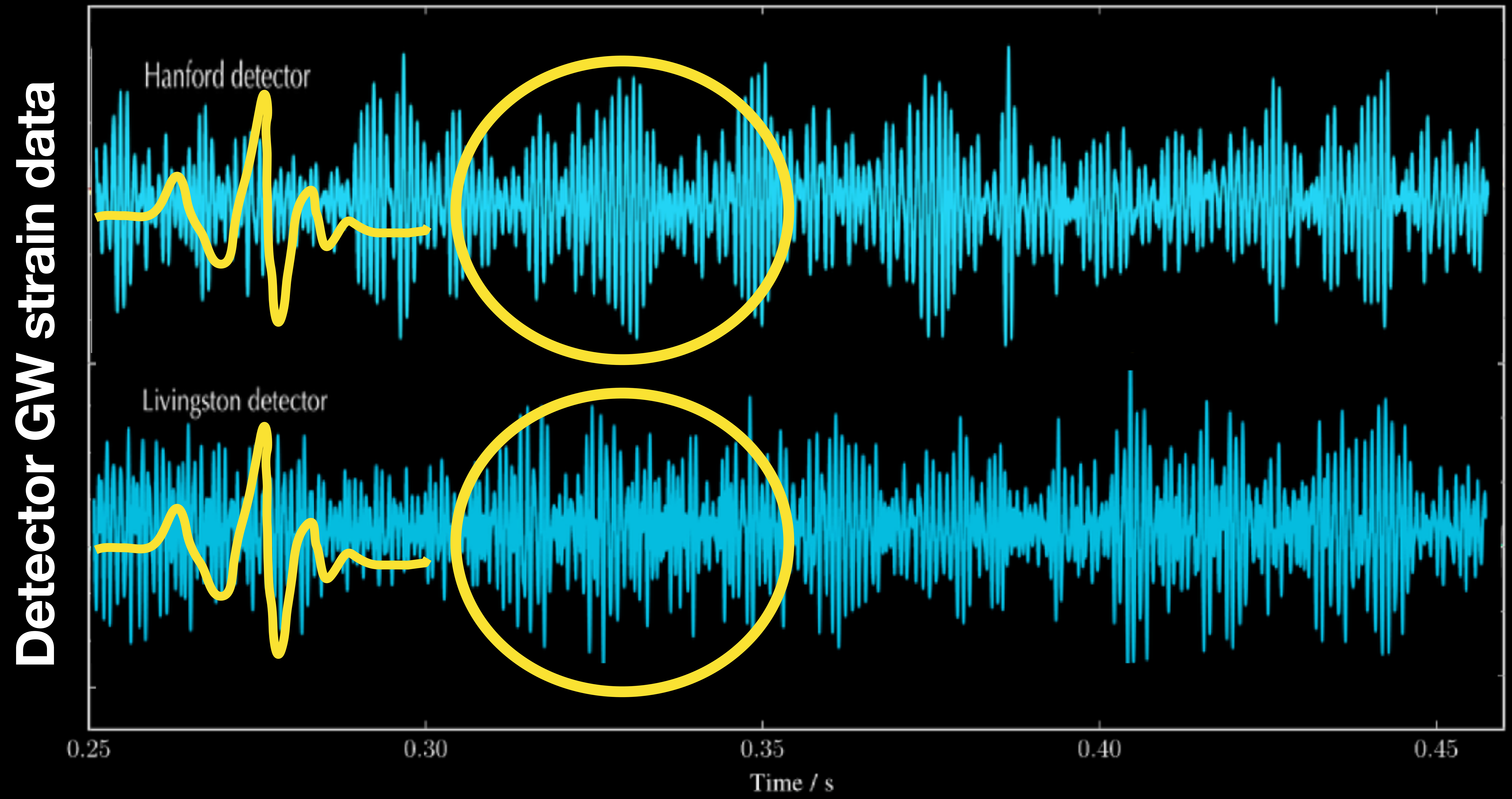
Gravitational waves from cosmic strings

What are the GR waveforms of cosmic strings?

Can we search (and find) them in data?

Damour, Vilenkin
Garfinkle, Vachaspati
Laguna, Matzner
Blanco-Pillado, Olum, Wachter
Chernoff, Flanagan, Wardell

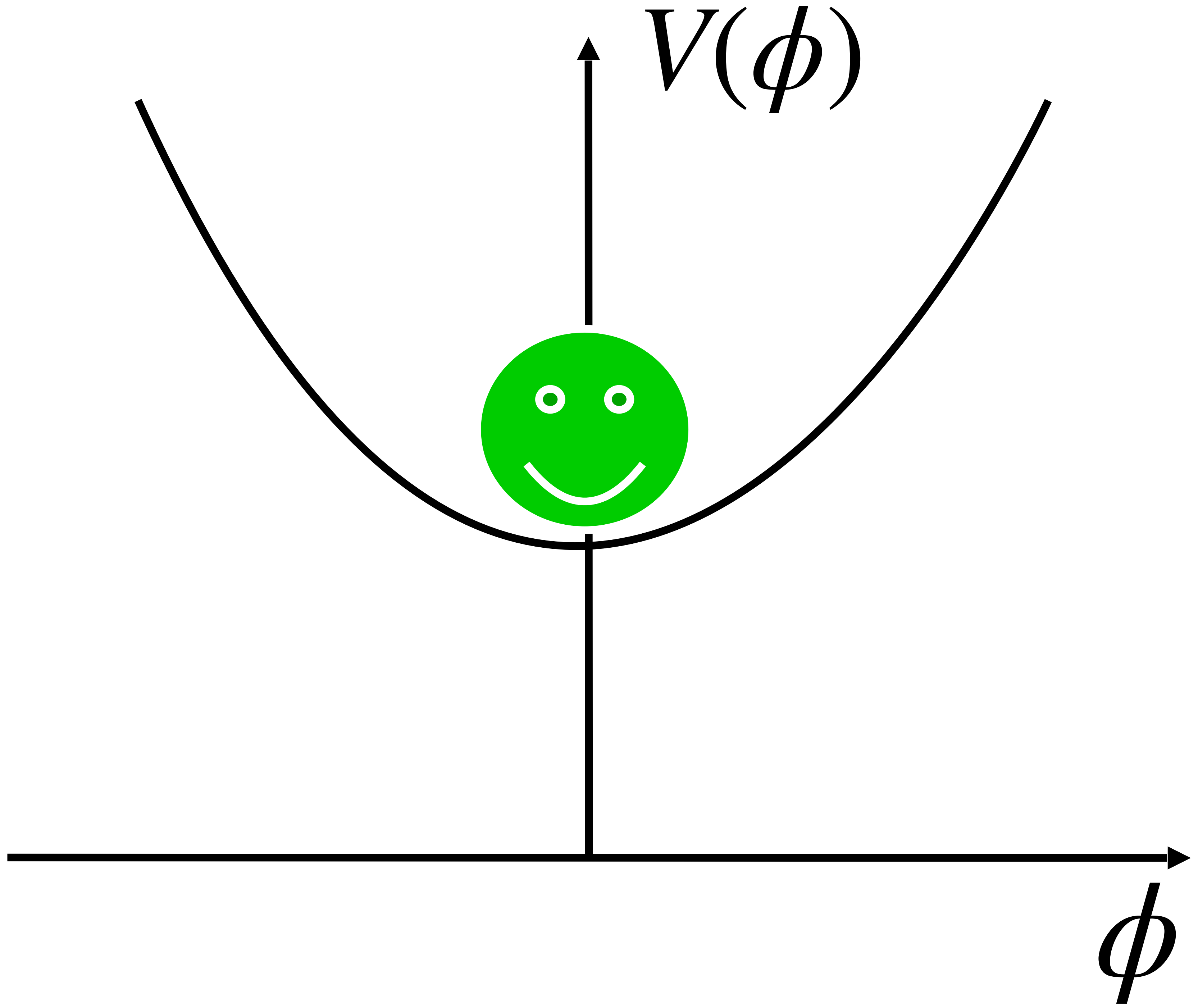
Cosmic string!



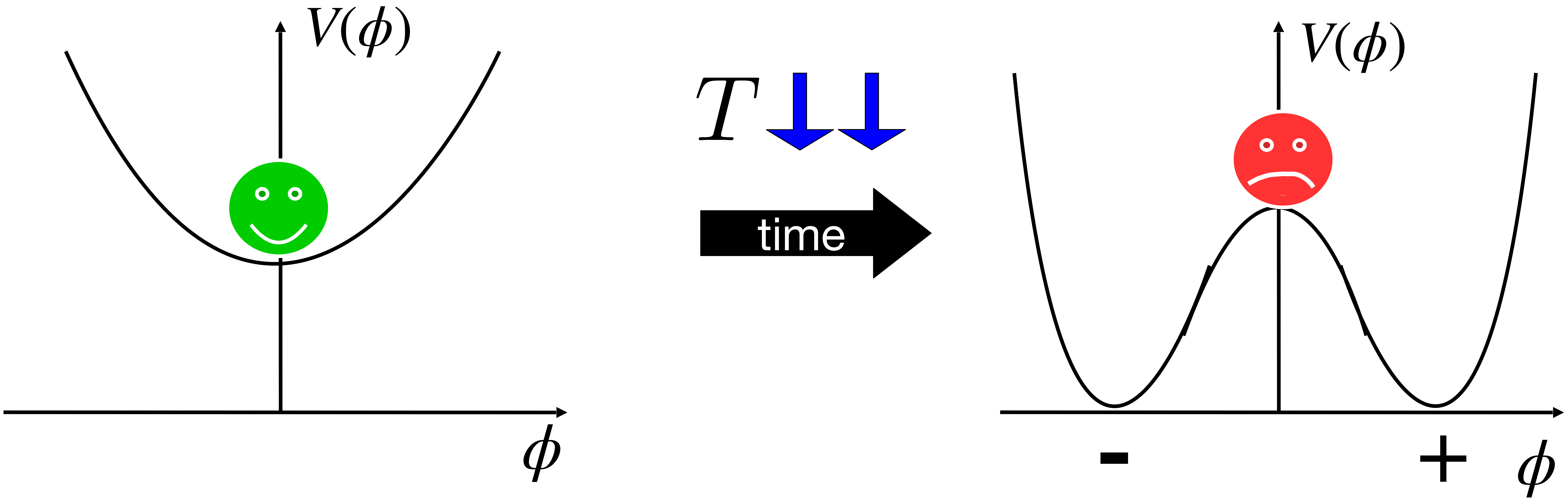
What are cosmic strings?

Image credit: David Daverio

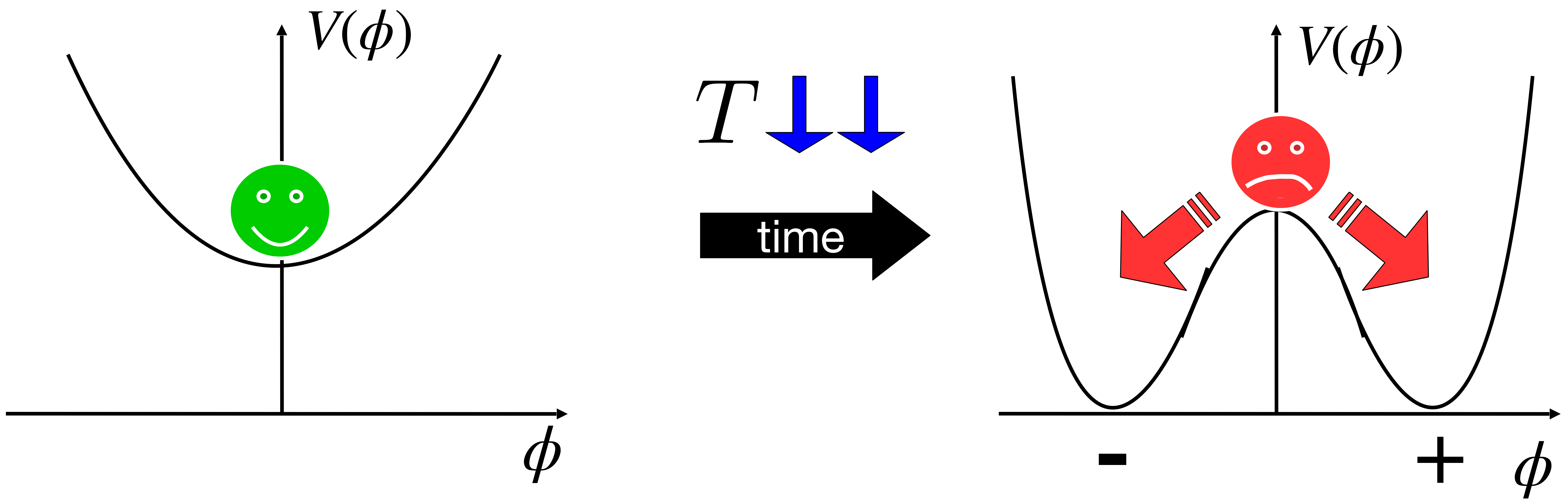
Domain walls (2D)



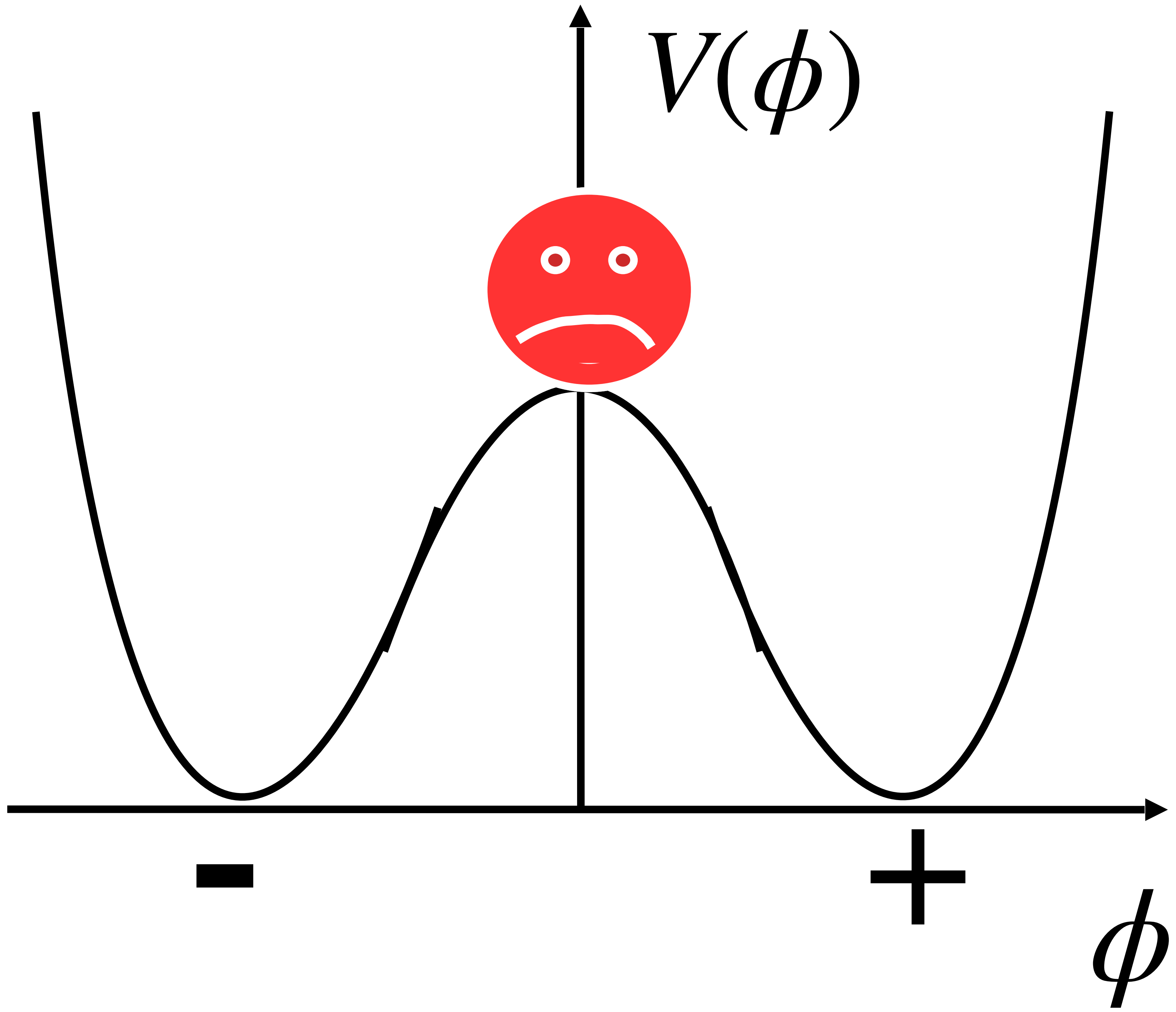
Domain walls (2D)

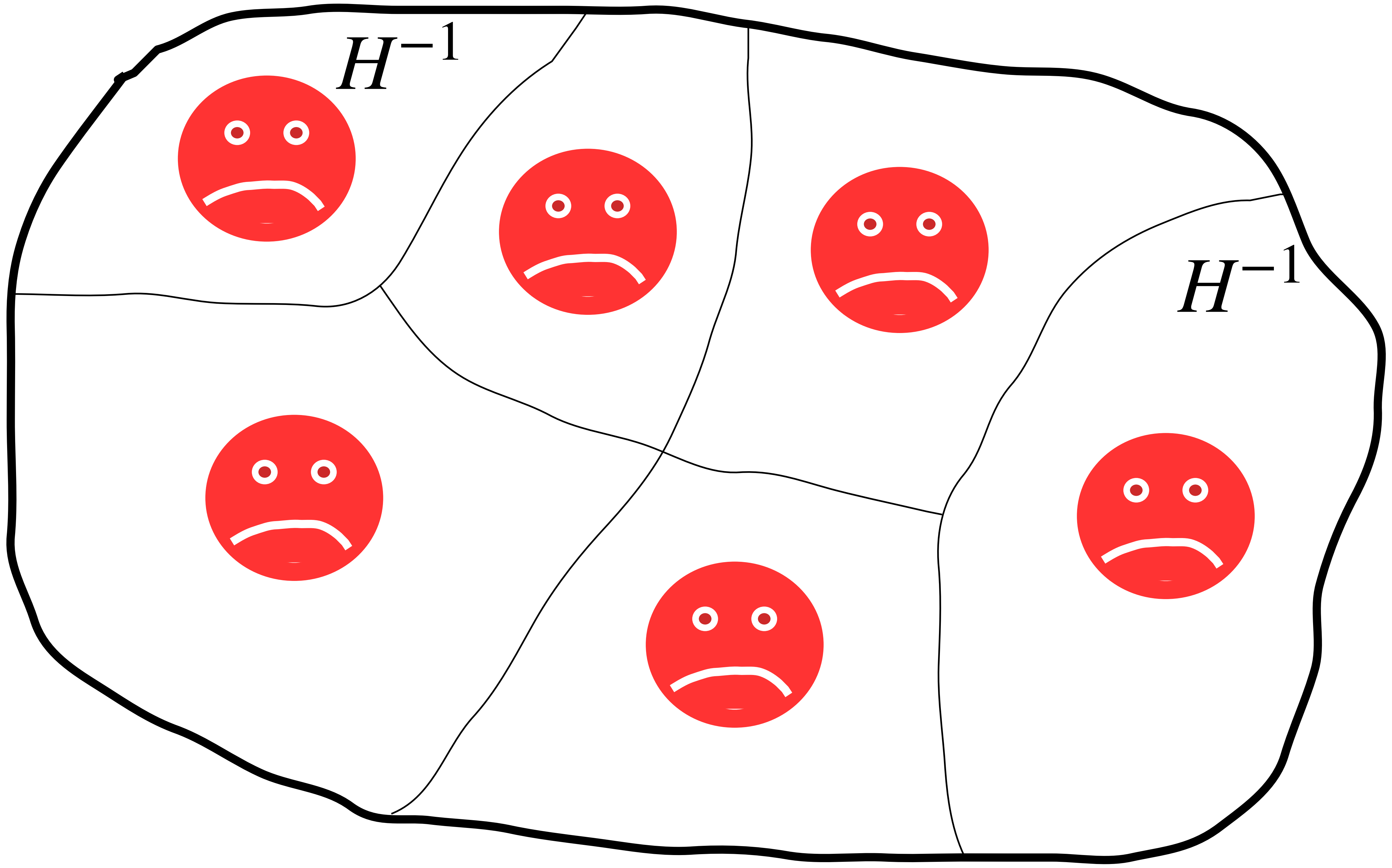


Domain walls (2D)



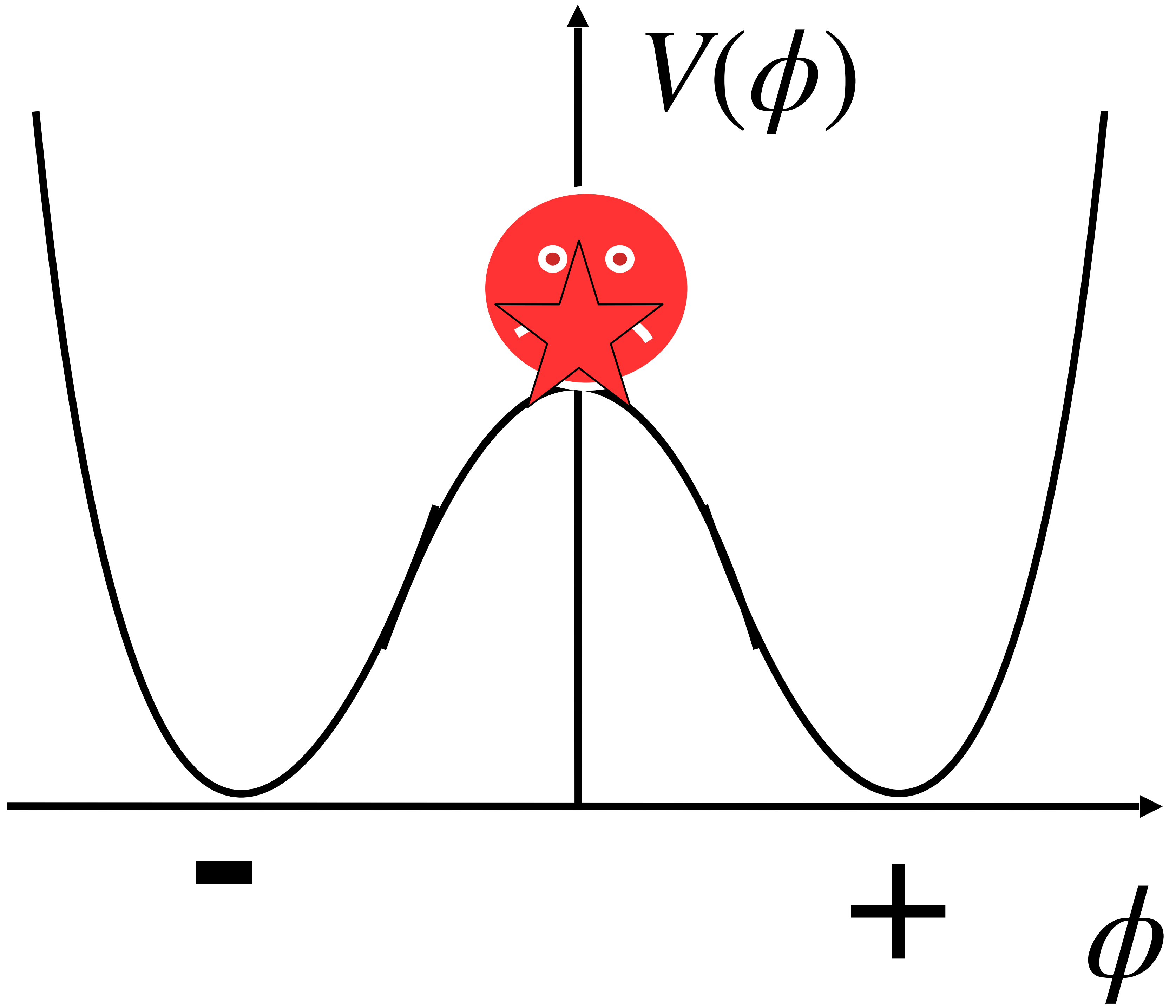
Domain walls (2D)

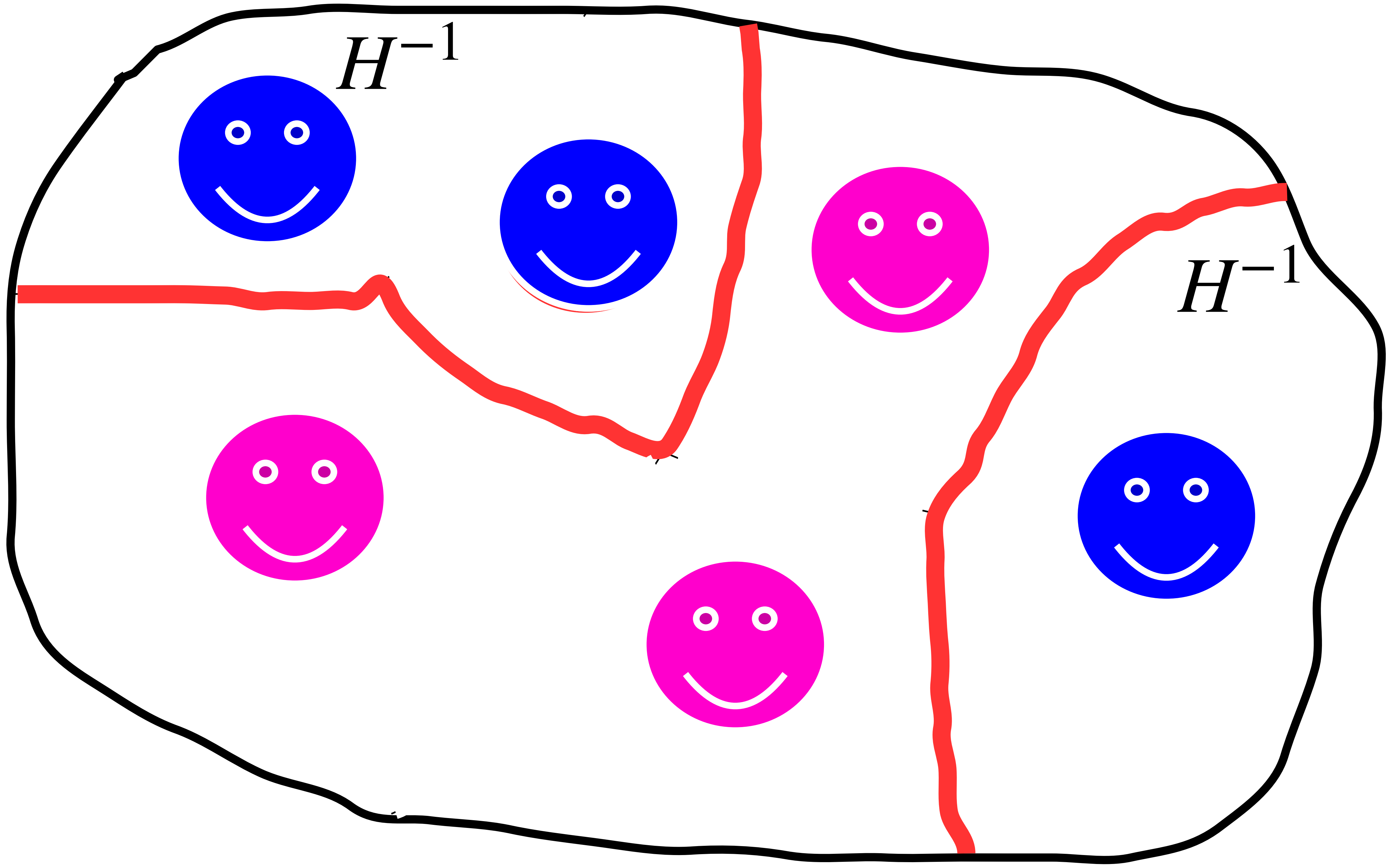




universe

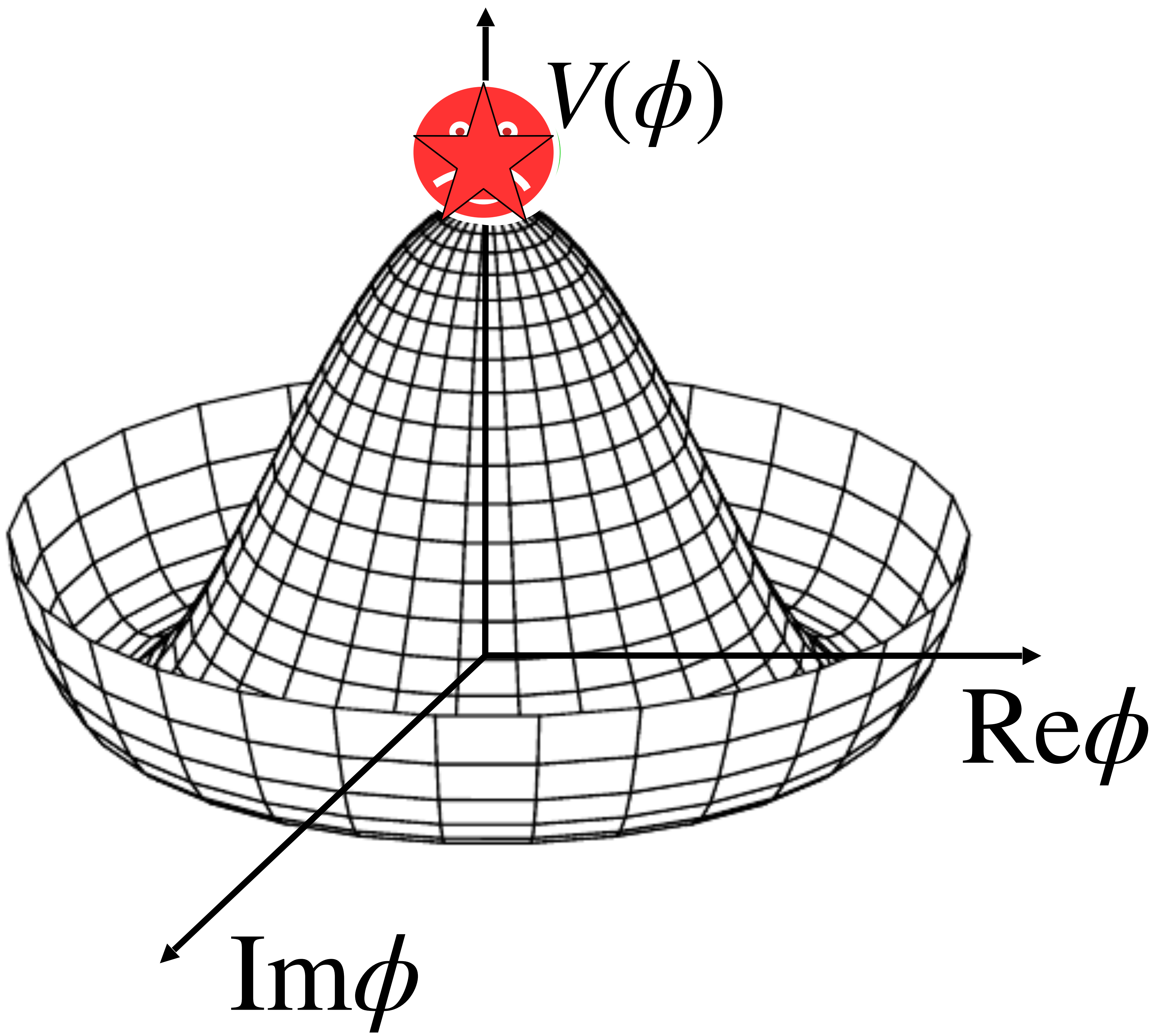
Domain walls (2D)

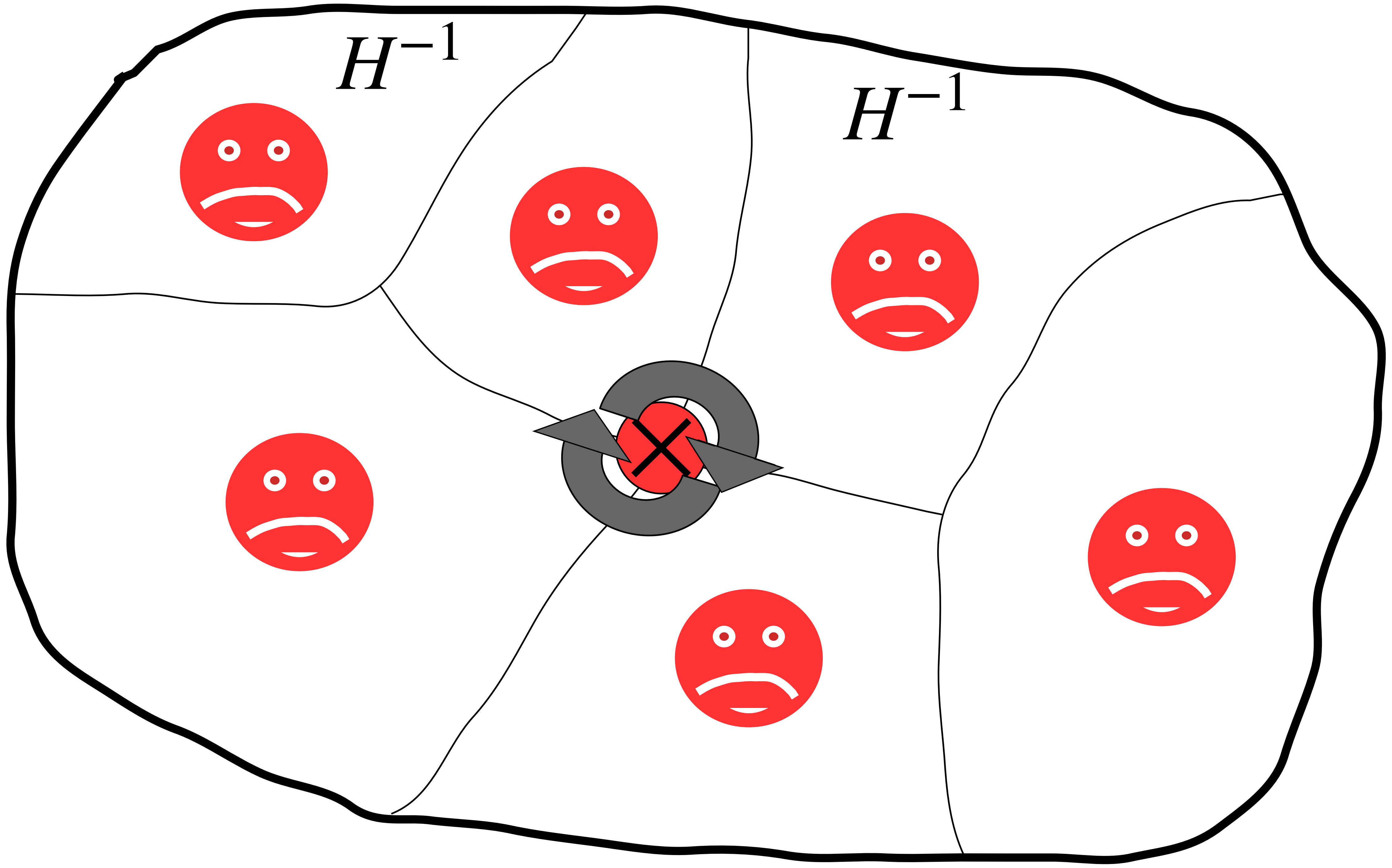




universe

Cosmic strings (1D)

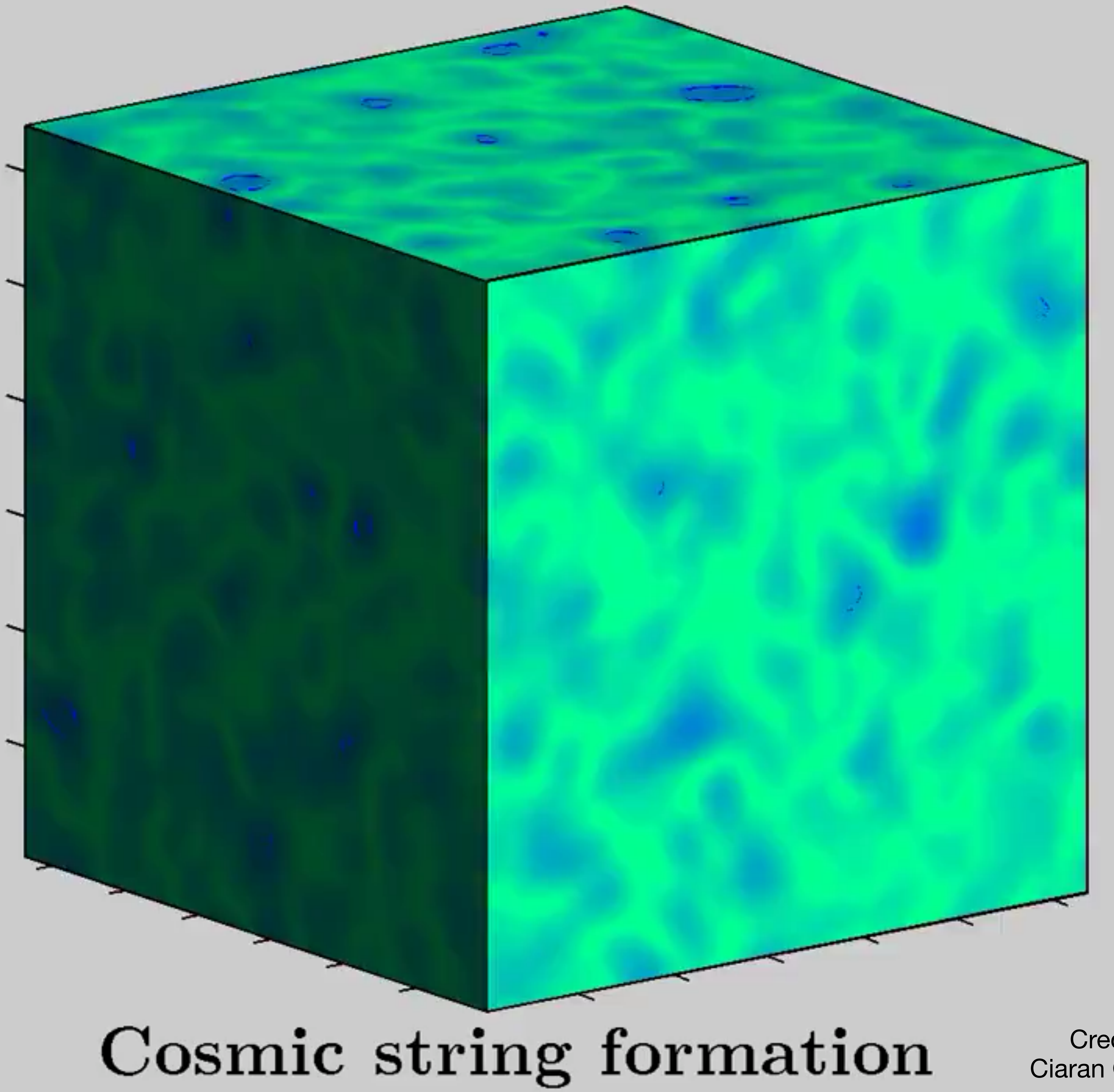




universe

Formation

Key parameter:
string tension $G\mu$



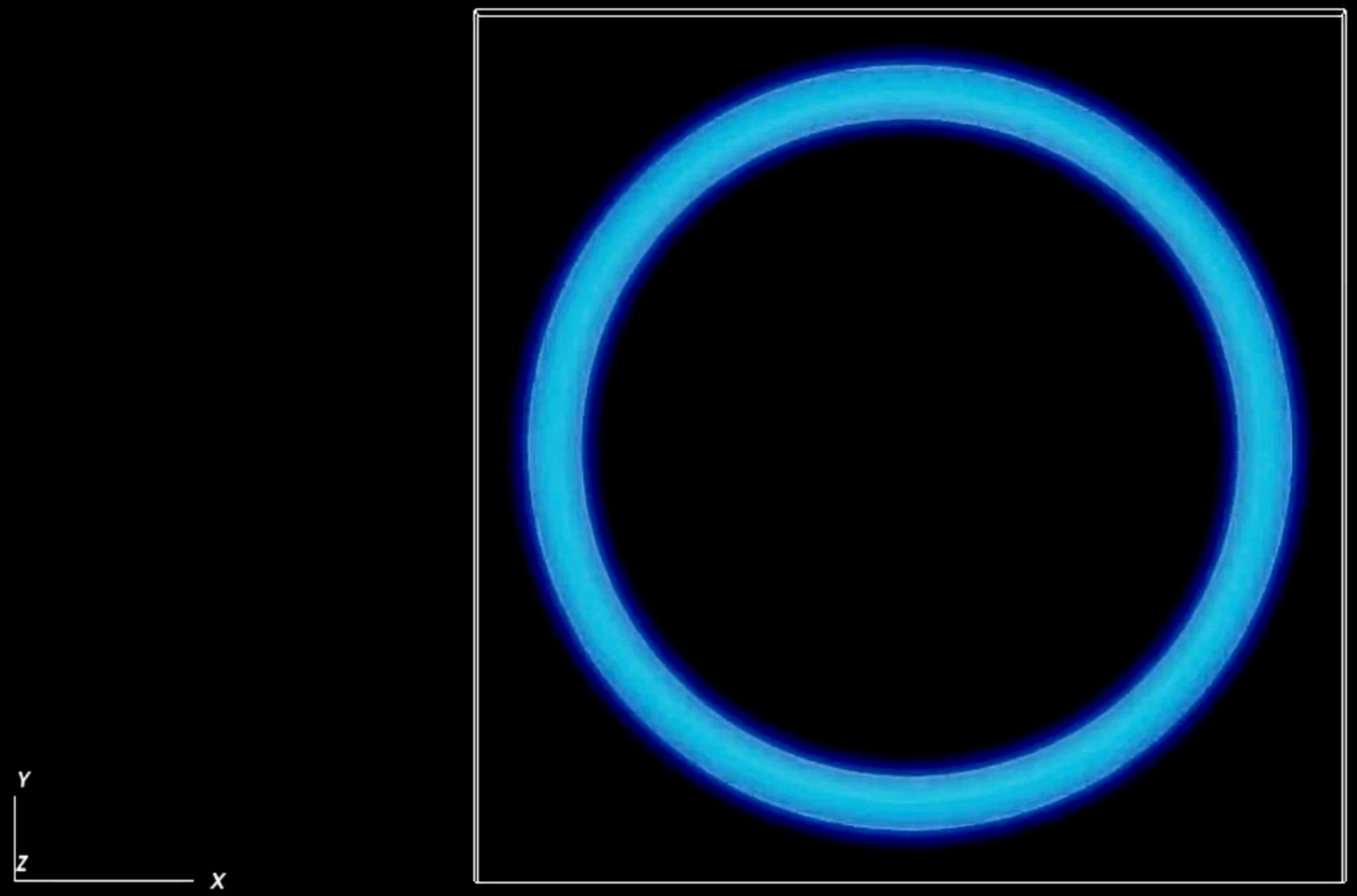
Credit:
Ciaran O'Hare

Abelian Higgs + GR

$$M_0 = 2\pi\mu R_0$$

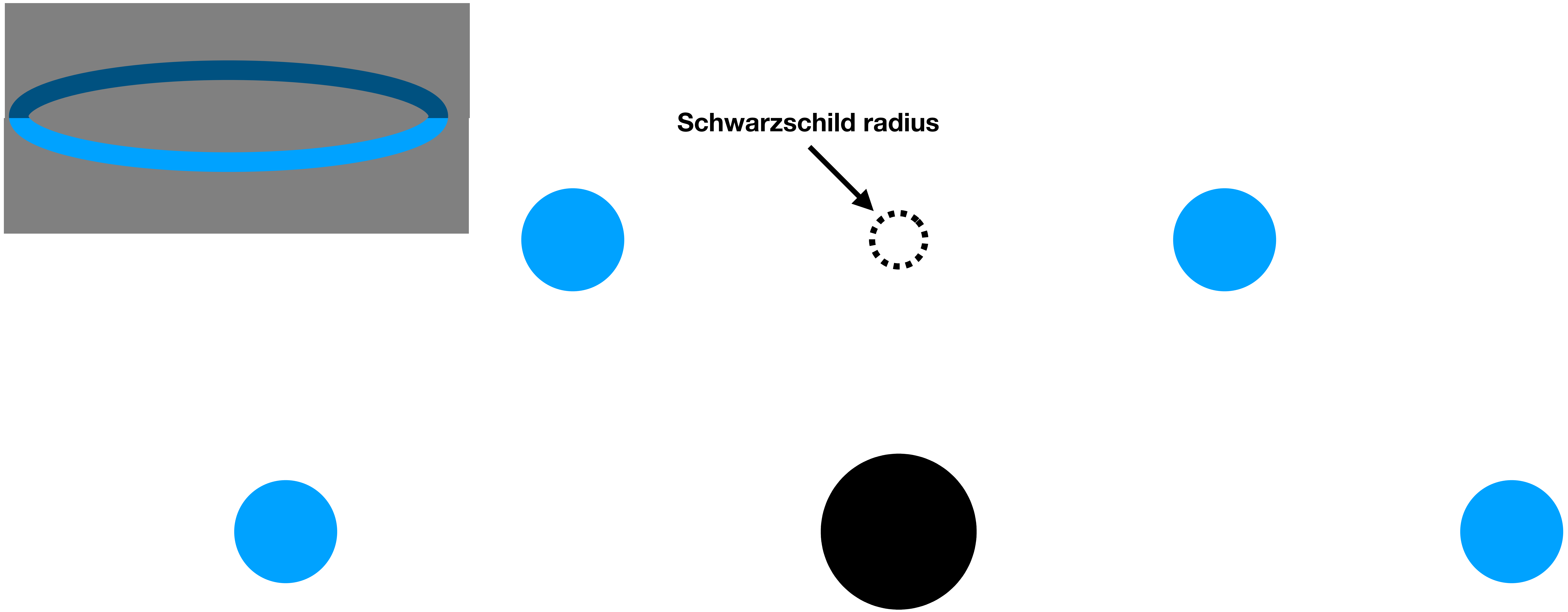
$$G\mu \approx 10^{-8}$$
$$R \approx 100 \text{ a.u.}$$

$$M \approx 100\, M_\odot$$

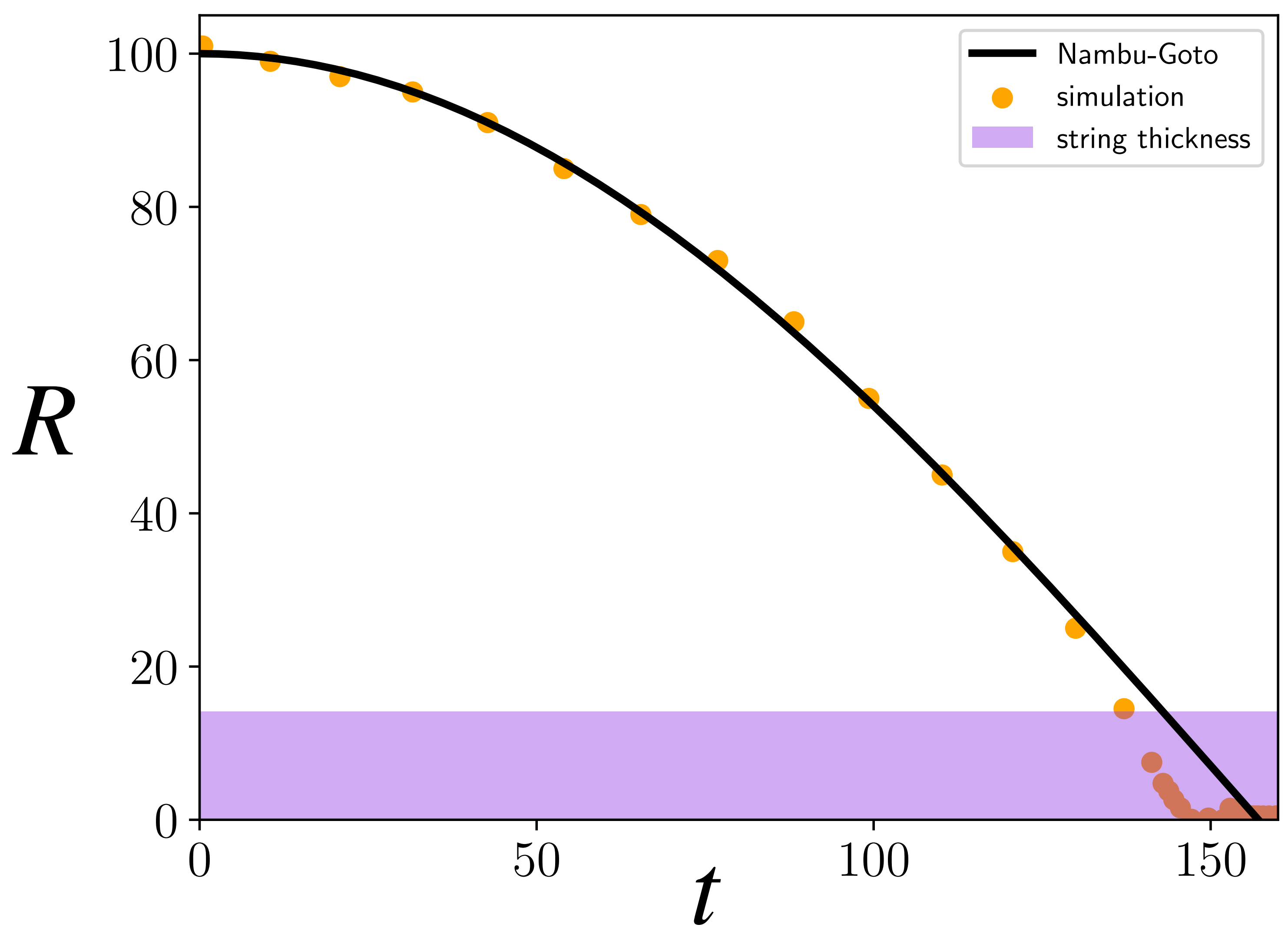


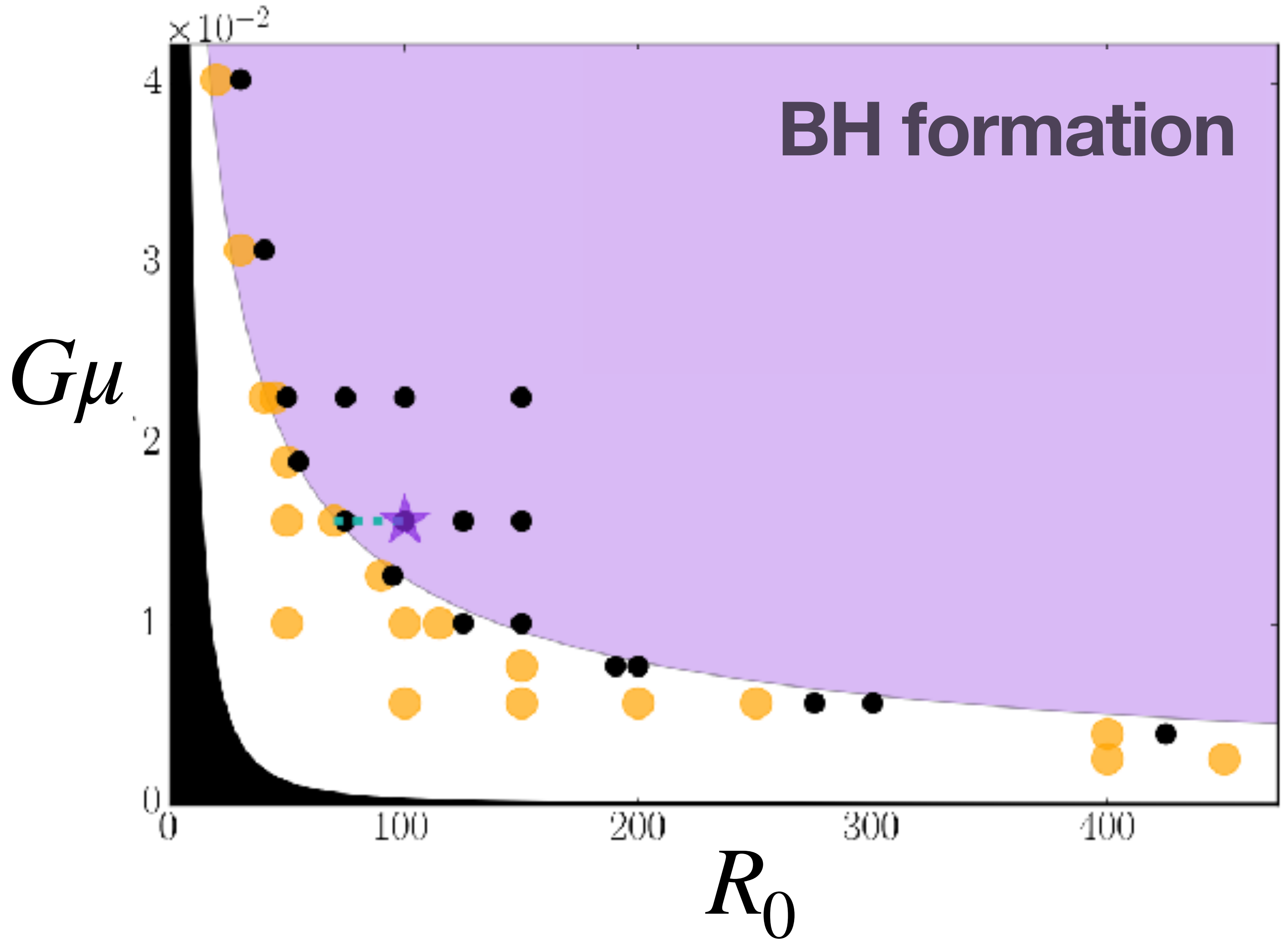
Aurrekoetxea, Helfer, Lim (2020)
Coherent GW waveforms and memory from cosmic string loops

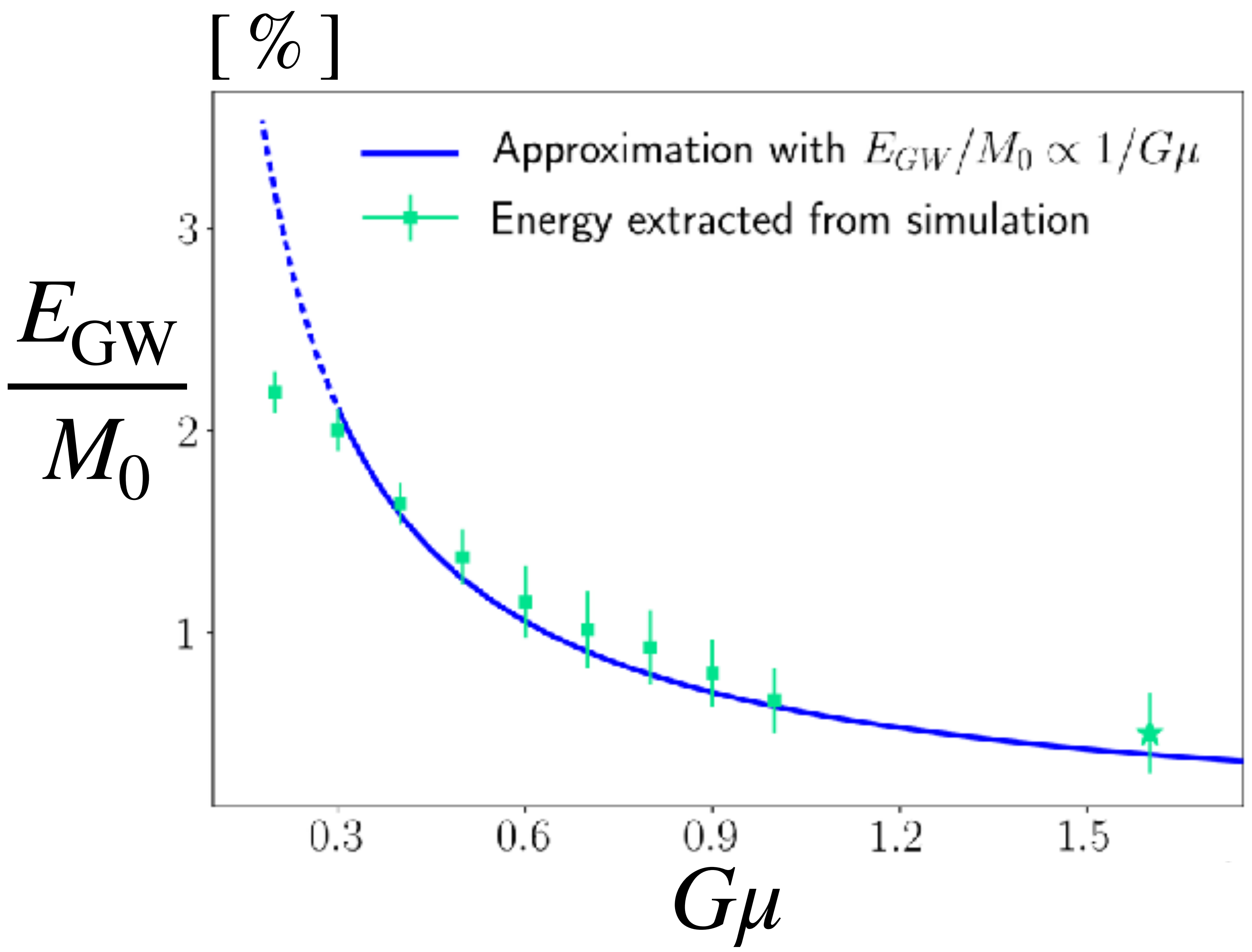
“Hoop conjecture”



String loop dynamics







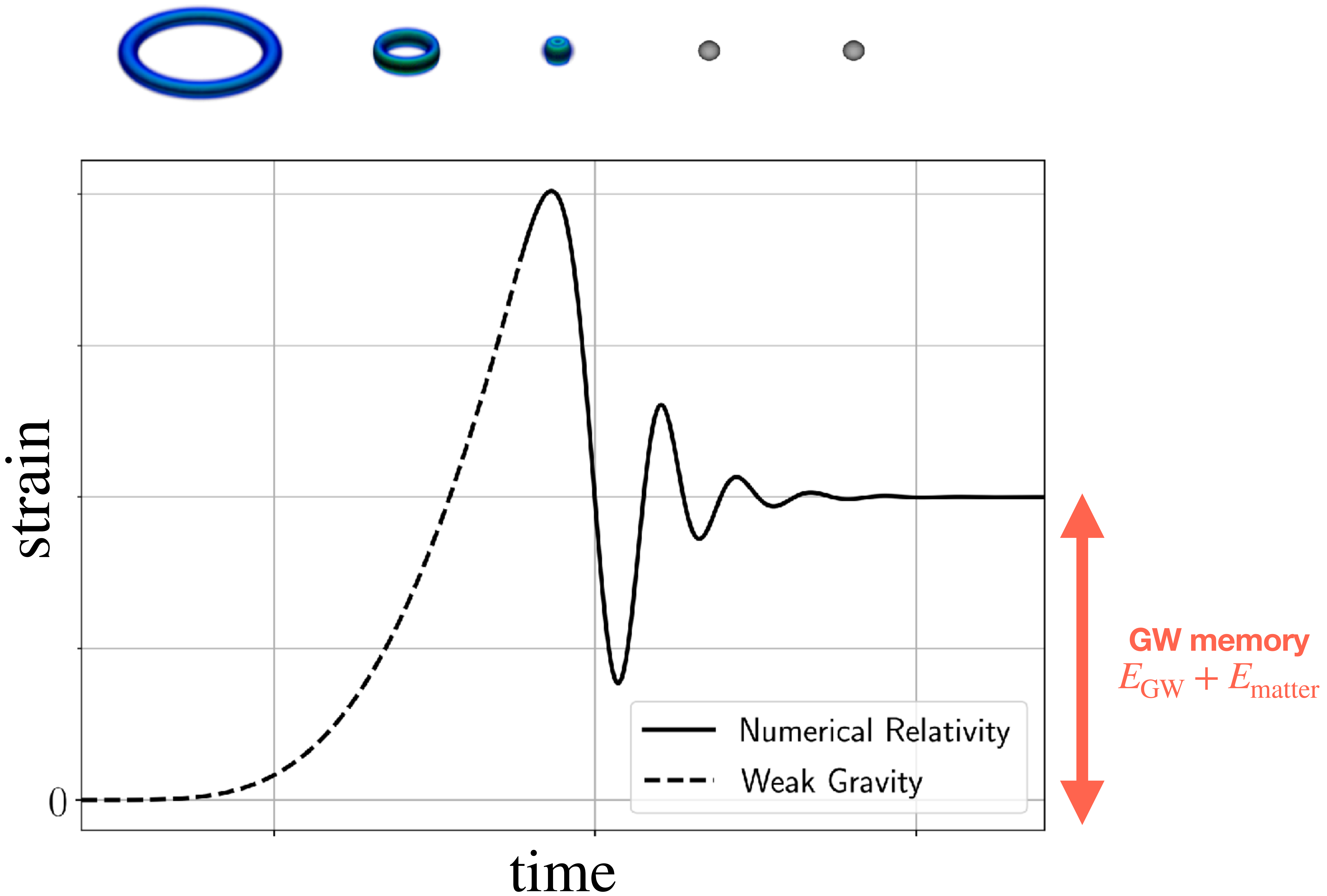
$$R = R_0 \cos\left(t/R_0\right)$$

$$\frac{R_0}{l_{\rm Pl}} \gtrsim (G\mu)^{-3/2}$$

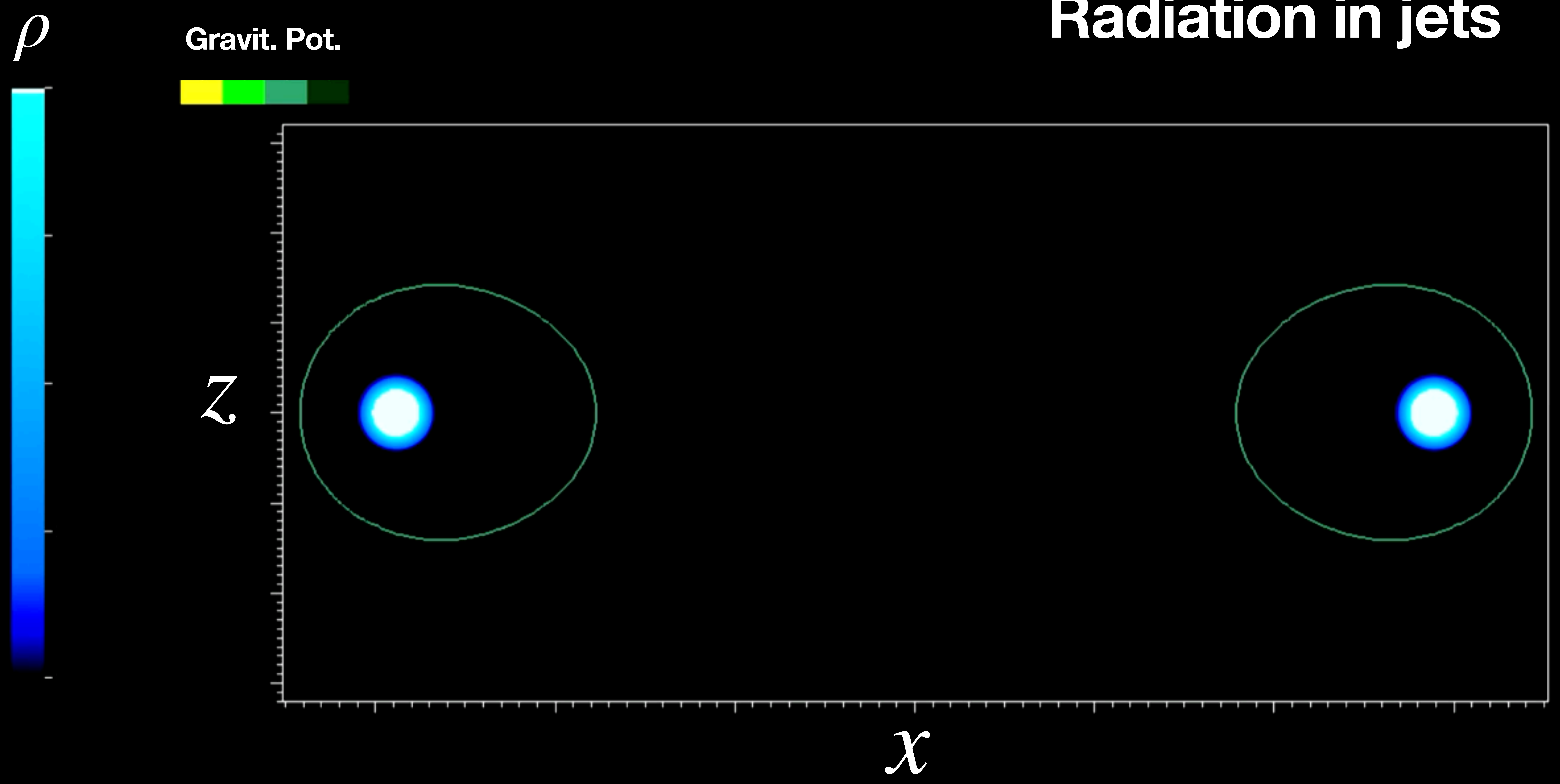
Ask me more later!

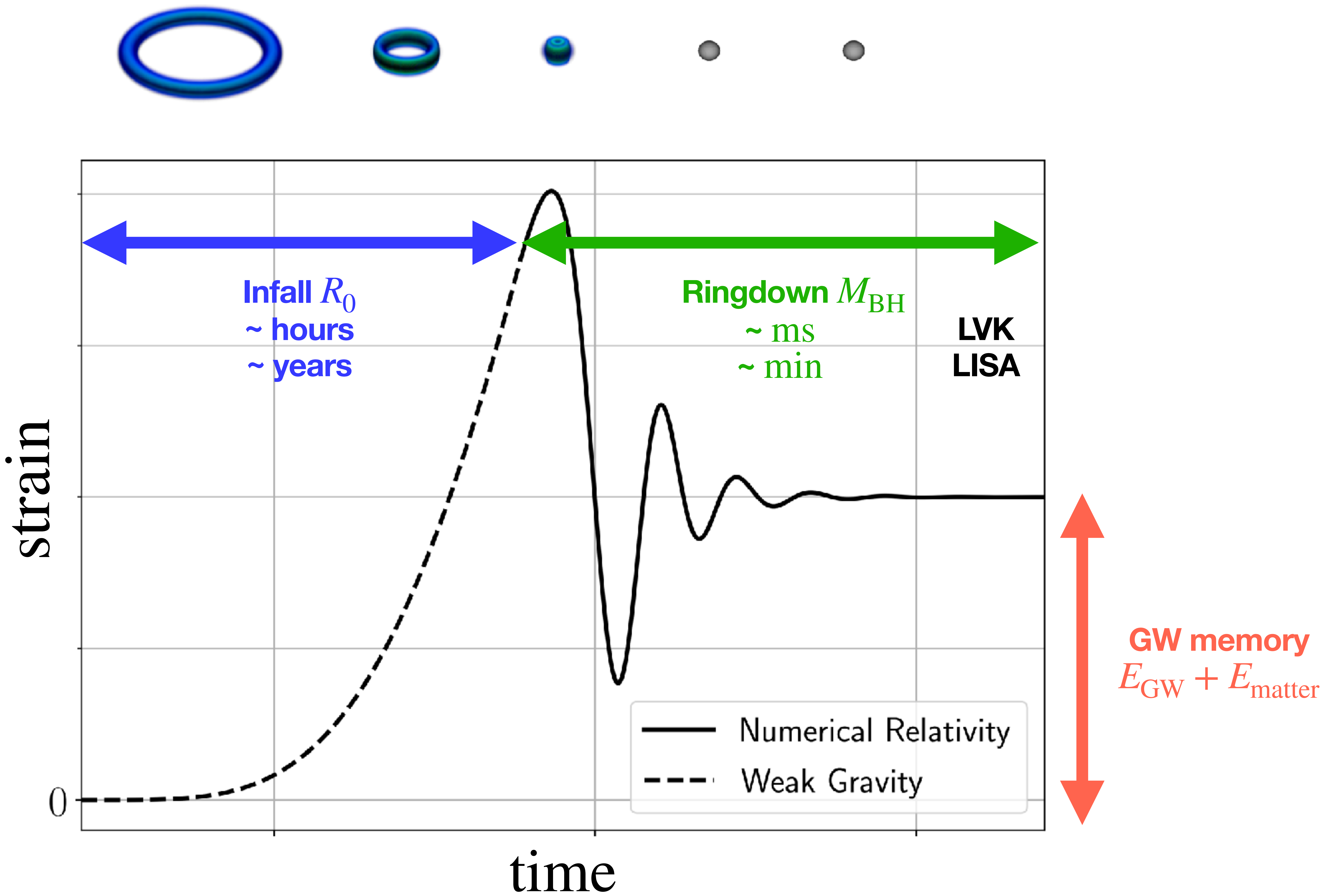
$$E_{\rm GW} \uparrow \ \text{ as } G\mu \downarrow$$

Ask me more later!

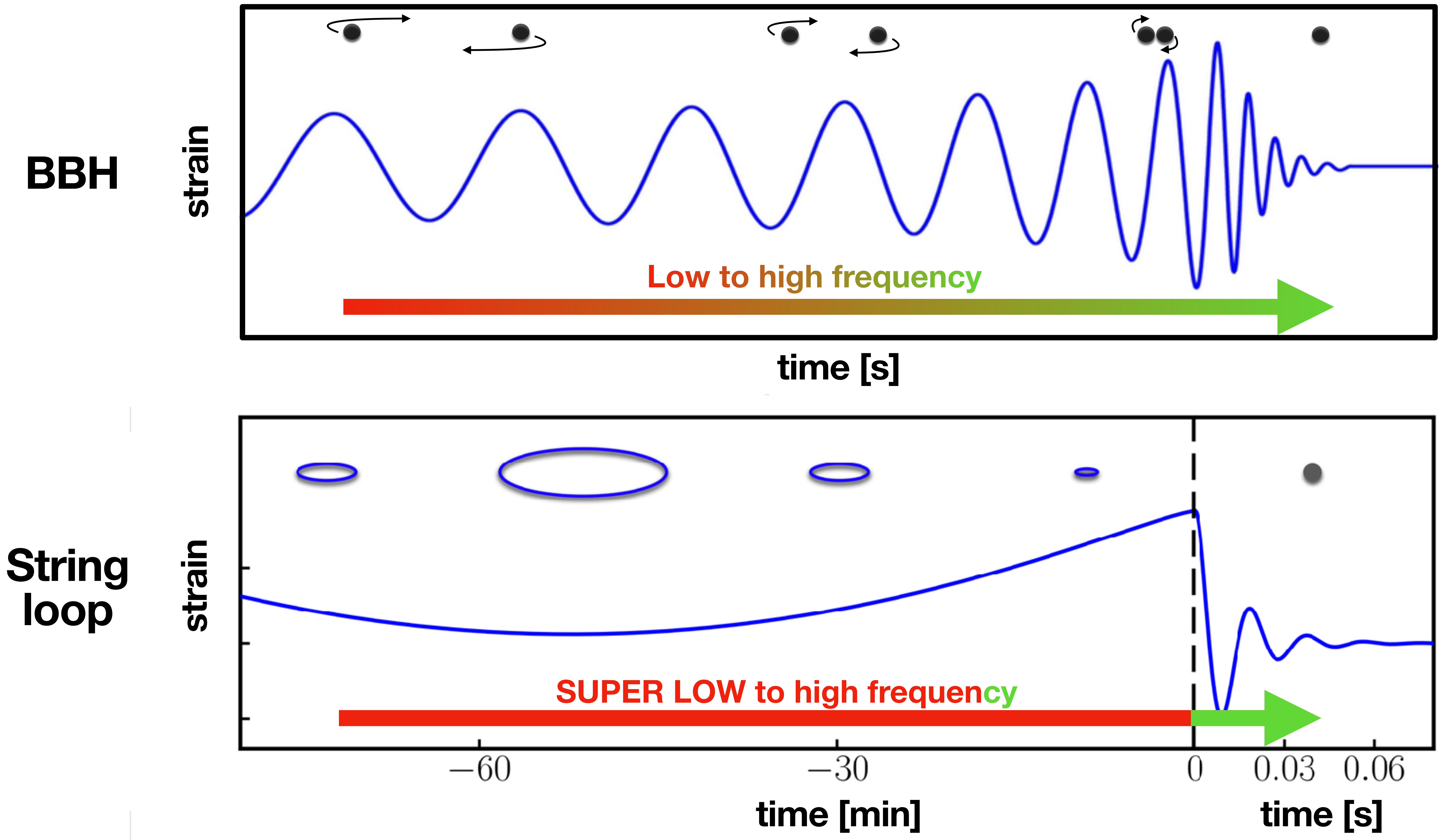

strain
0
time
Numerical Relativity
Weak Gravity
GW memory
$E_{\mathrm{GW}} + E_{\mathrm{matter}}$

Radiation in jets



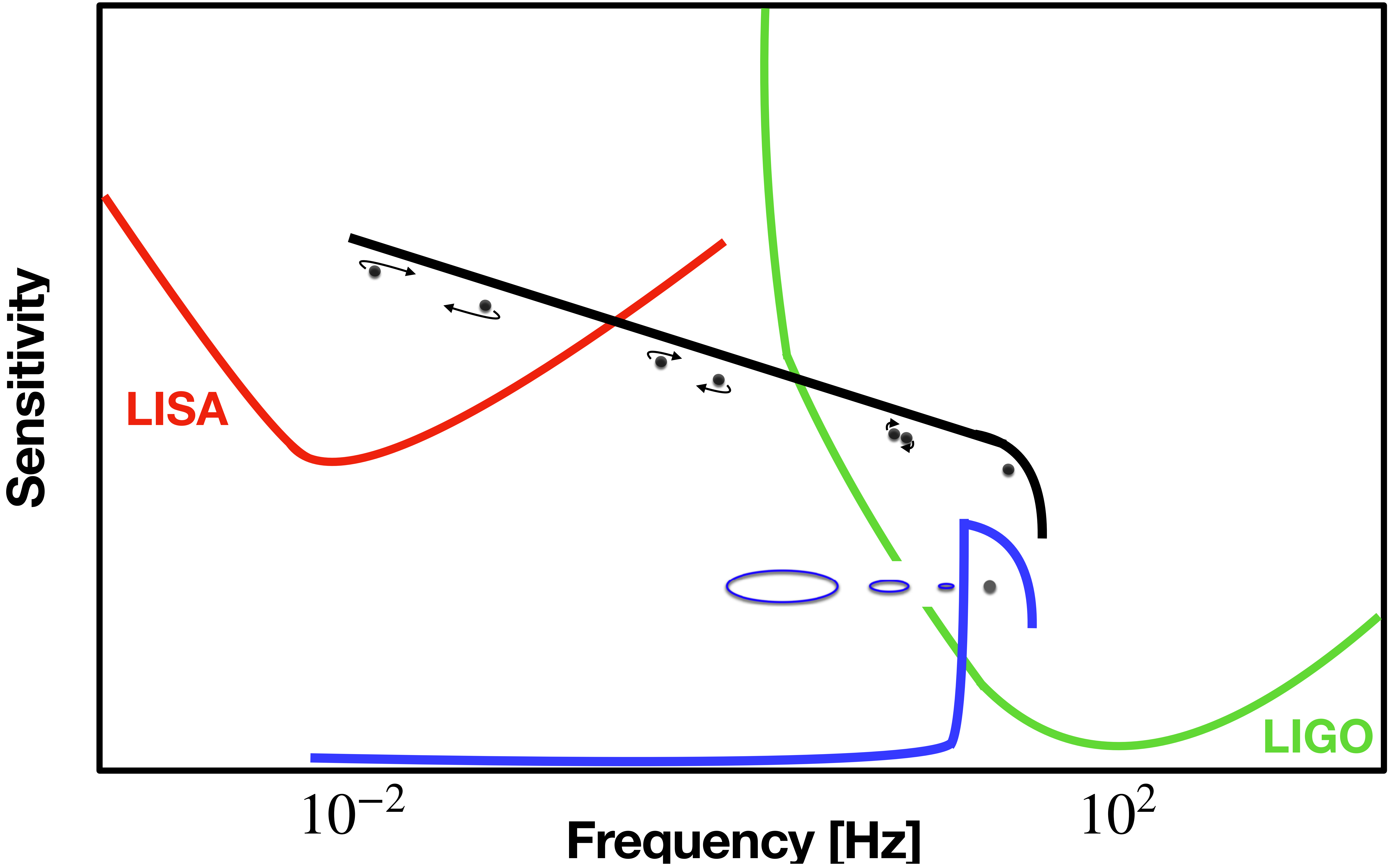


Infall R_0
~ hours
~ years
Ringdown $M_{\rm BH}$
~ ms
~ min
LVK
LISA
strain
0
time
Numerical Relativity
Weak Gravity
GW memory
$E_{\rm GW} + E_{\rm matter}$

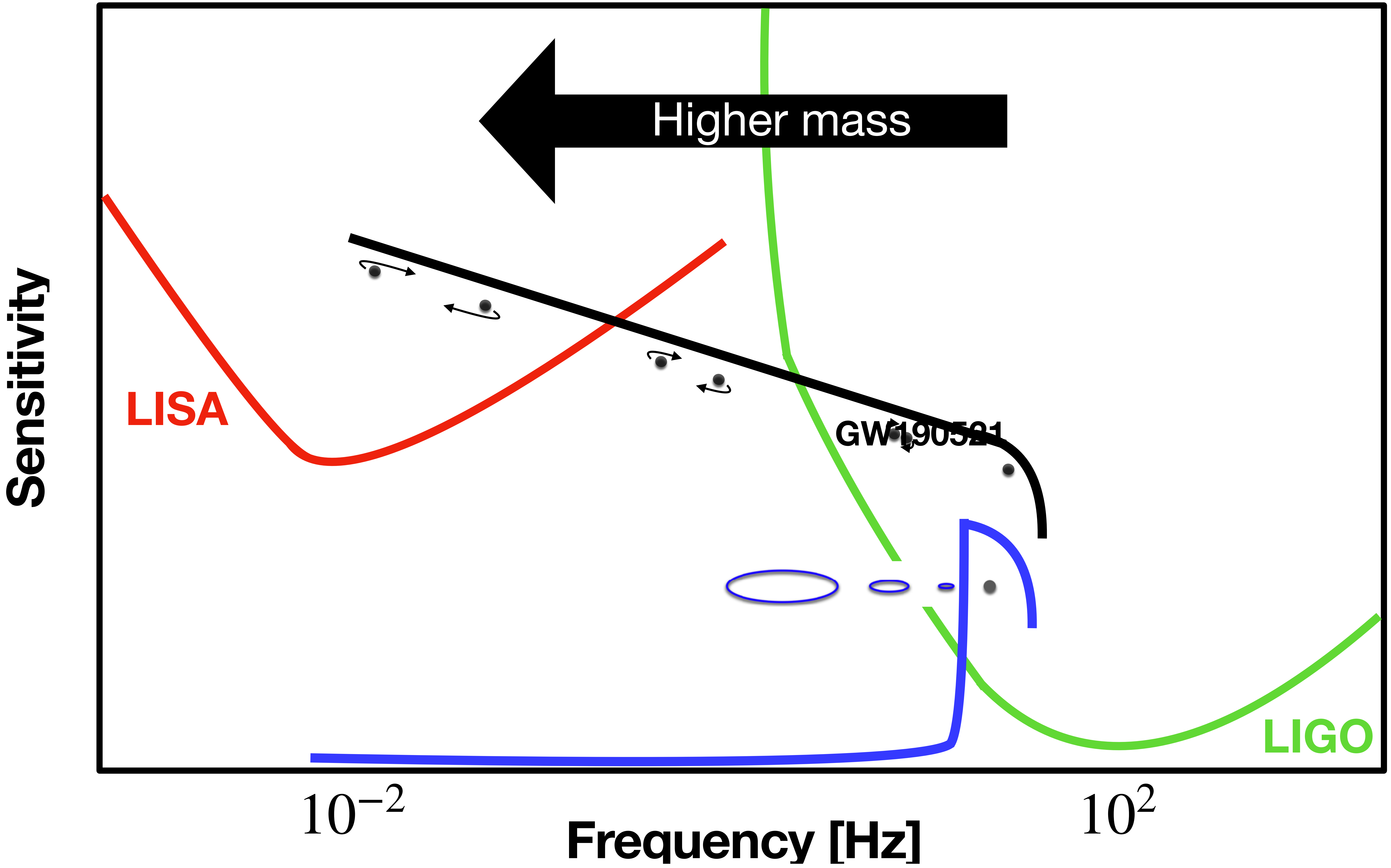


BBH
strain
Low to high frequency
time [s]
String loop
strain
SUPER LOW to high frequency
−60
−30
0
0.03
0.06
time [min]
time [s]

LISA and LIGO sensitivity



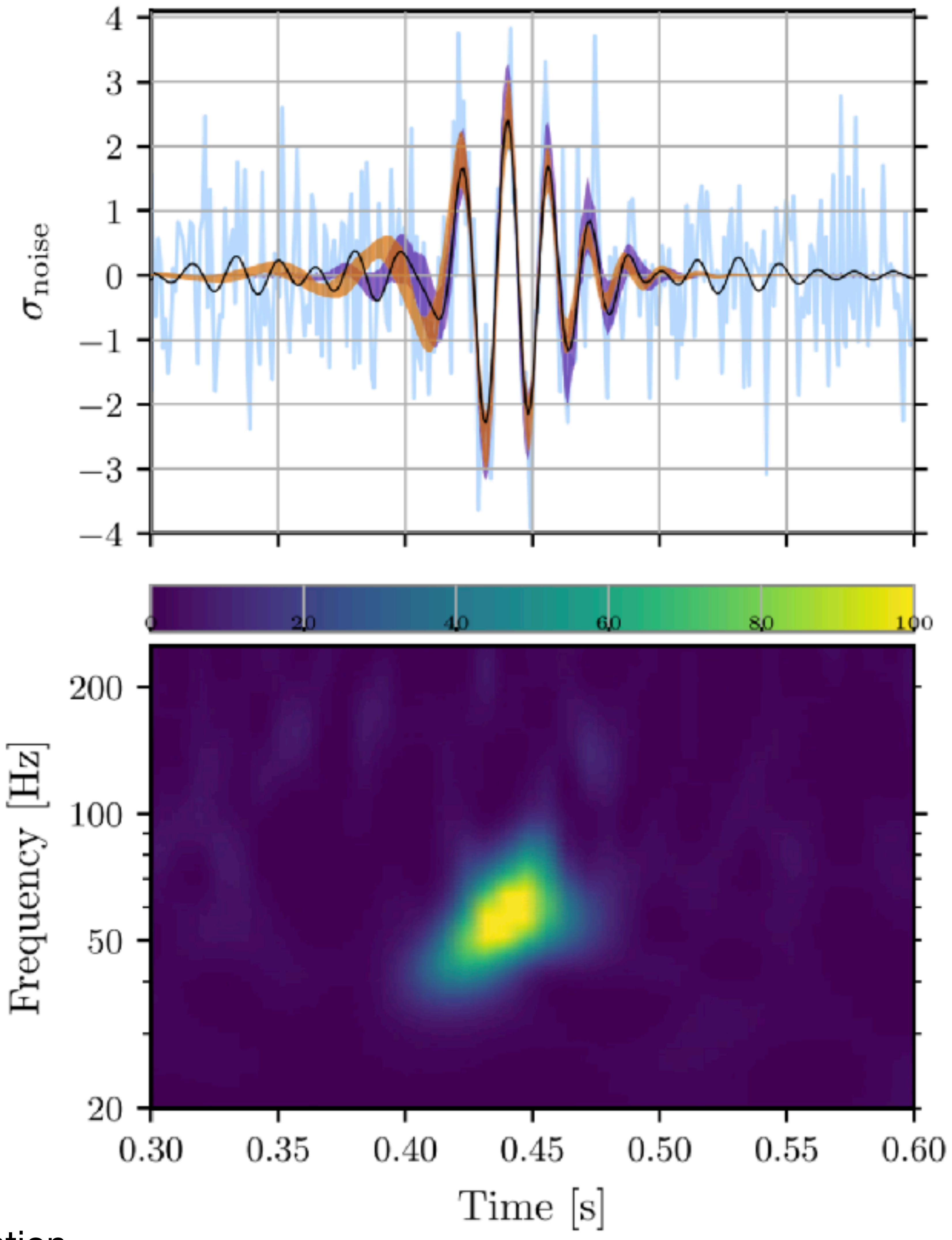
LISA and LIGO sensitivity



Example: GW190521

(in preparation)

with **Charlie Hoy, Hannam, Helfer, Lim**

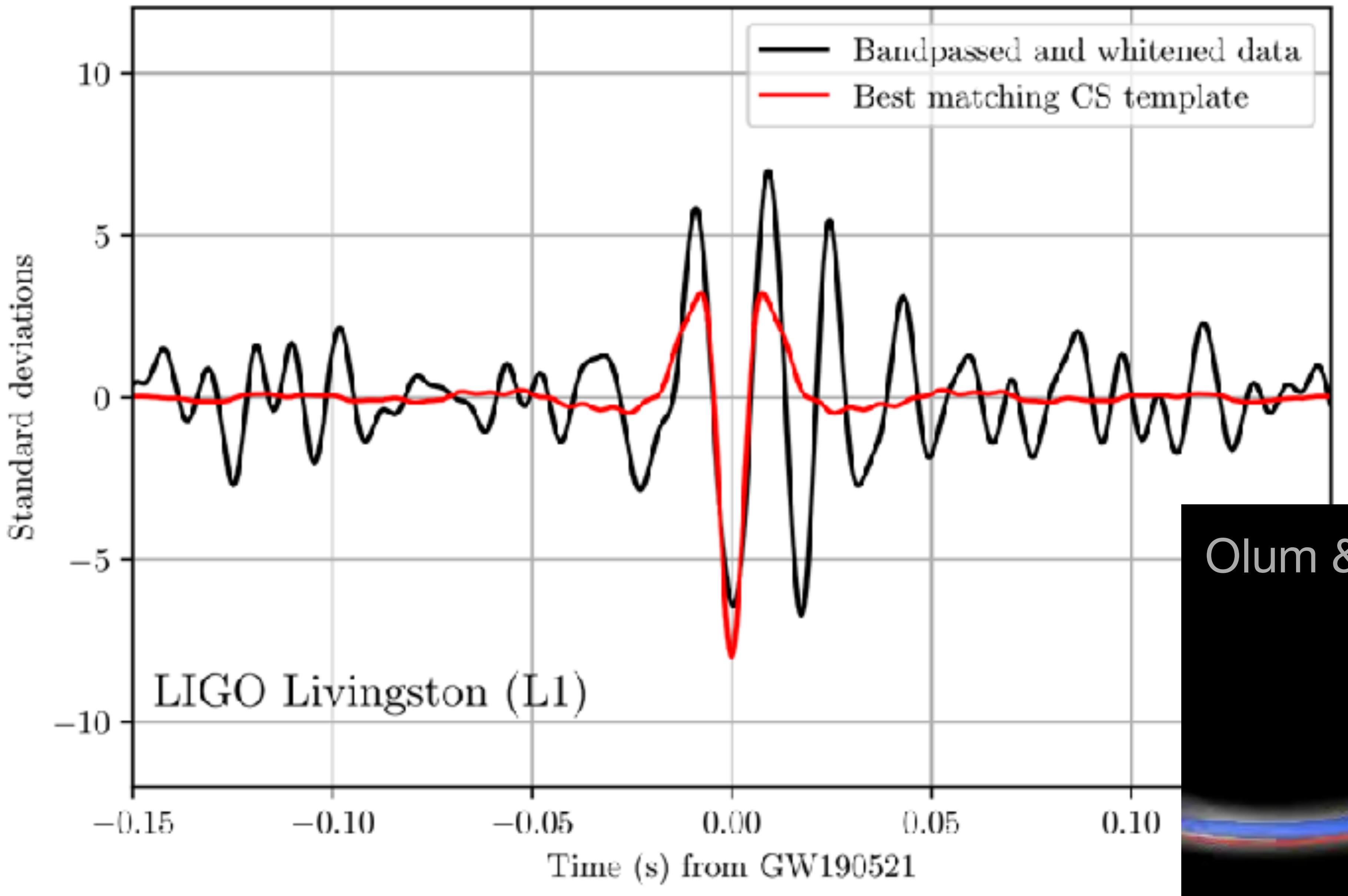


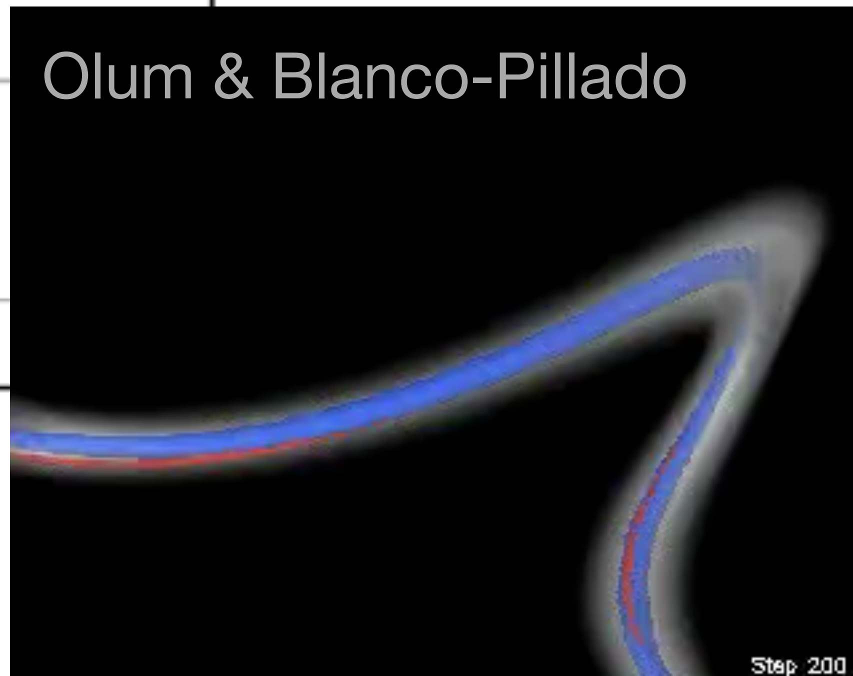
Credit:
LVK collaboration

[2009.01190]

Properties and Astrophysical Implications of the $150 M_\odot$ Binary Black Hole Merger GW190521

GW190521 is identified by the cosmic string matched filter search pipeline (Aasi et al. 2014b; Abbott et al. 2018b); however, the maximum S/Ns in this search (∼6 and ∼8 in LIGO Hanford and Livingston, respectively) are much lower than for modeled BBH search templates, best-fit binary merger waveform models, or unmodeled reconstructions, suggesting that the data strongly prefer a binary merger model to a cosmic string or cusp.



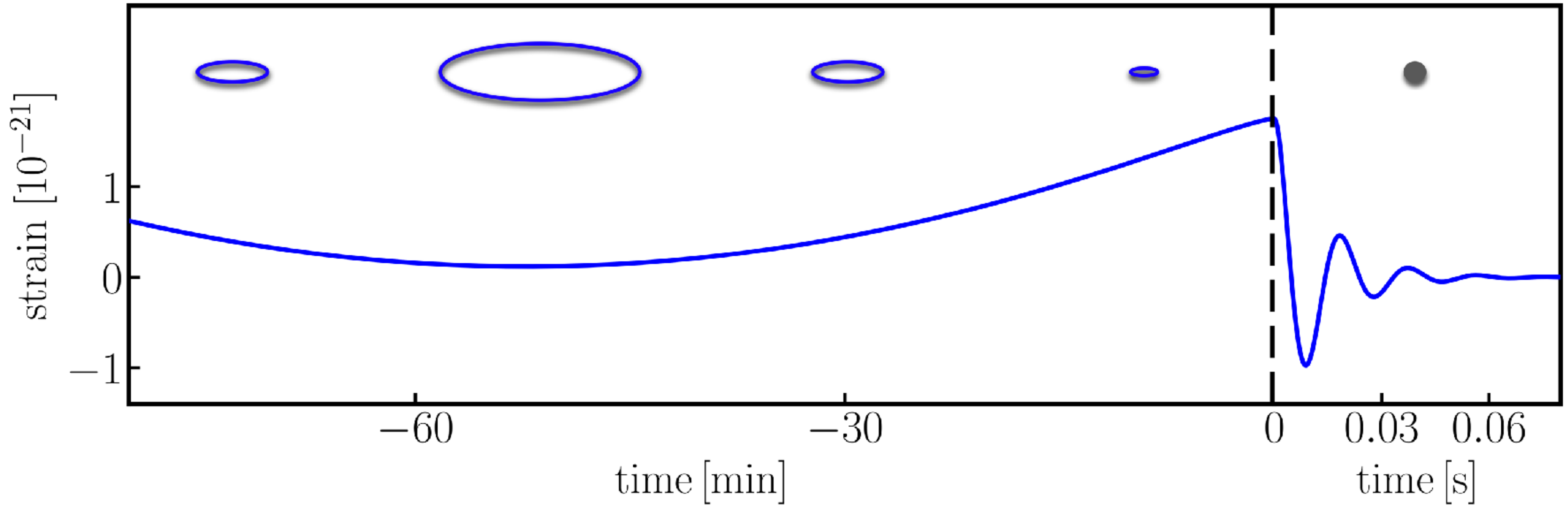


Example: GW190521

(in preparation)

with **Charlie Hoy, Hannam, Helfer, Lim**

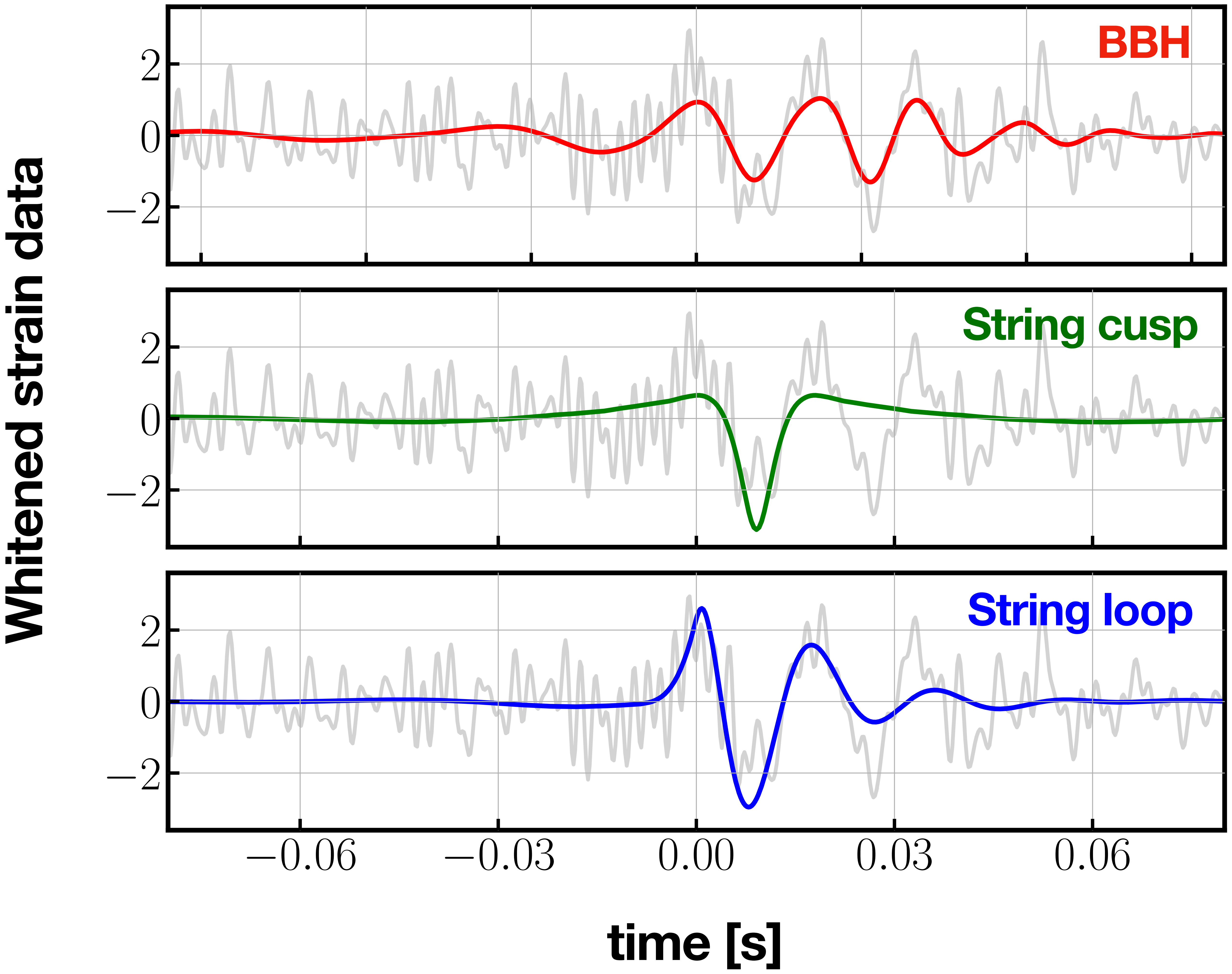
$G\mu \approx 10^{-7}$
$R_0 \approx 4$ AU
$d_L \approx 3$ Gpc

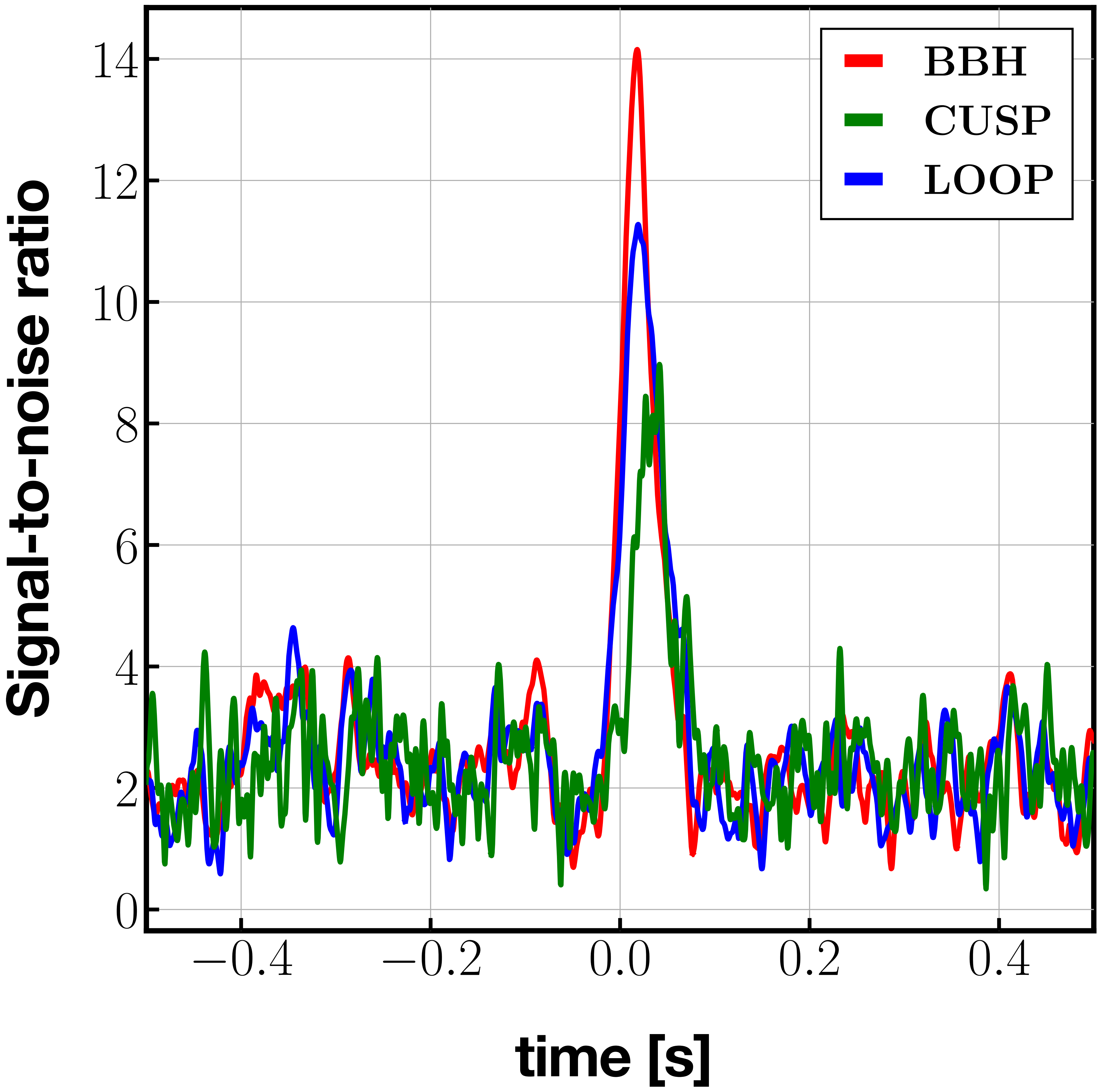


Example: GW190521

(in preparation)

with **Charlie Hoy, Hannam, Helfer, Lim**





Summary:

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Oscillons during preheating:

- Gravity can play an important role
- Compactness $C \approx 10^{-2} - 10^{-3}$
- Not enough for PBH

GWs from cosmic strings:

- First GR waveforms of strings
- Louder events for lighter strings
- Searches: GW190521?

Strong-field gravity interesting for early Universe