Title: Choosing equations of state for neutron star inspiral

Date: Jun 23, 2011 03:00 PM

URL: http://pirsa.org/11060035

Abstract:

Exploring equations of state using neutron-star inspiral

Making things as simple as possible, but no simpler

Jocelyn Read
MICRA 2011

University of Mississippi

30 April 2011

Outline

Parameterization of the cold equation of state

Comparison of parameterized EOS used in simulations with current constraints

Effect of cold EOS on inspiral

Effect of cold EOS on numerical simulations

Measurability estimates

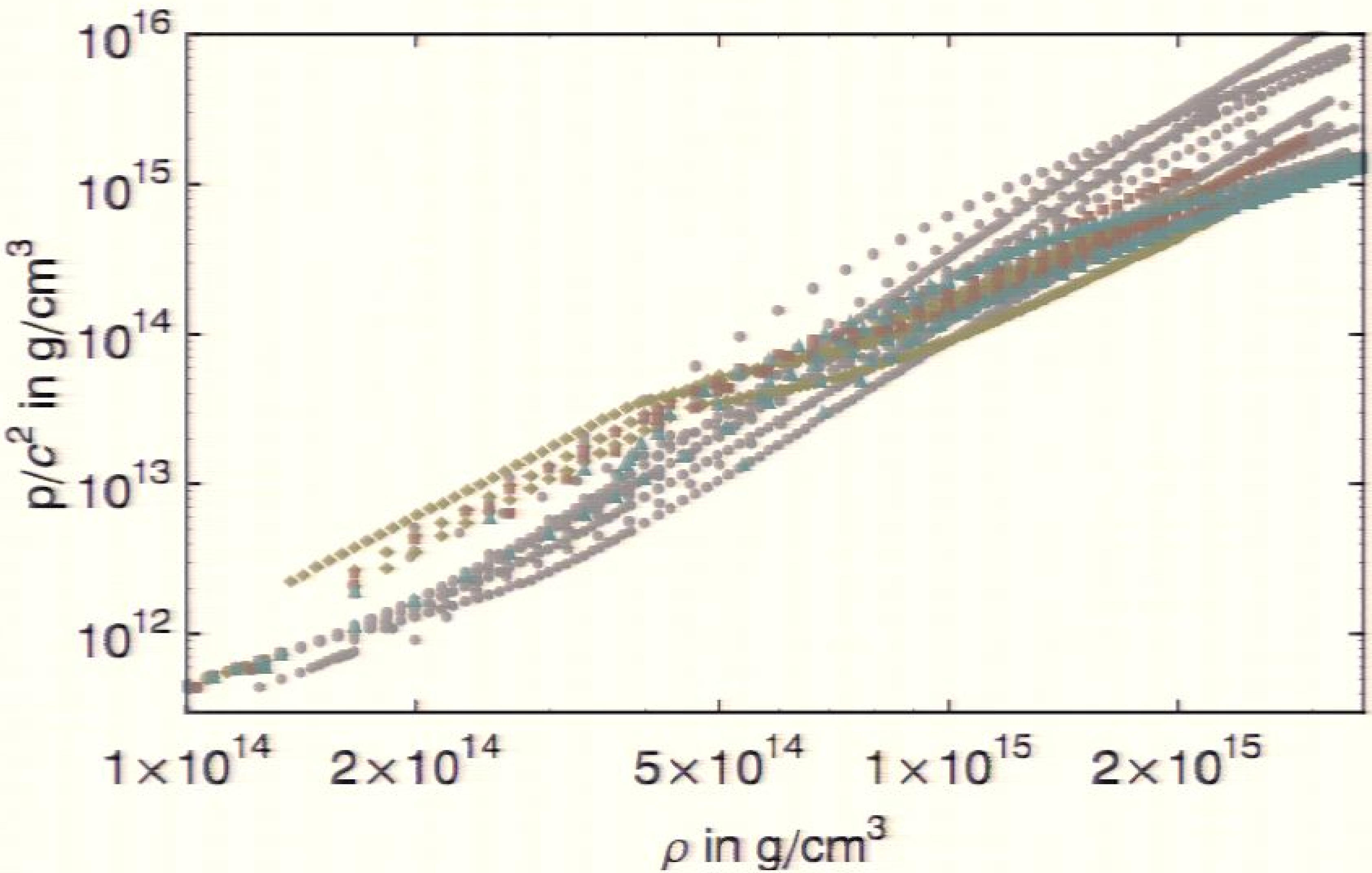
Collaborators

Piecewise polytropic parameterization: Ben Lackey, John Friedman, Ben Owen

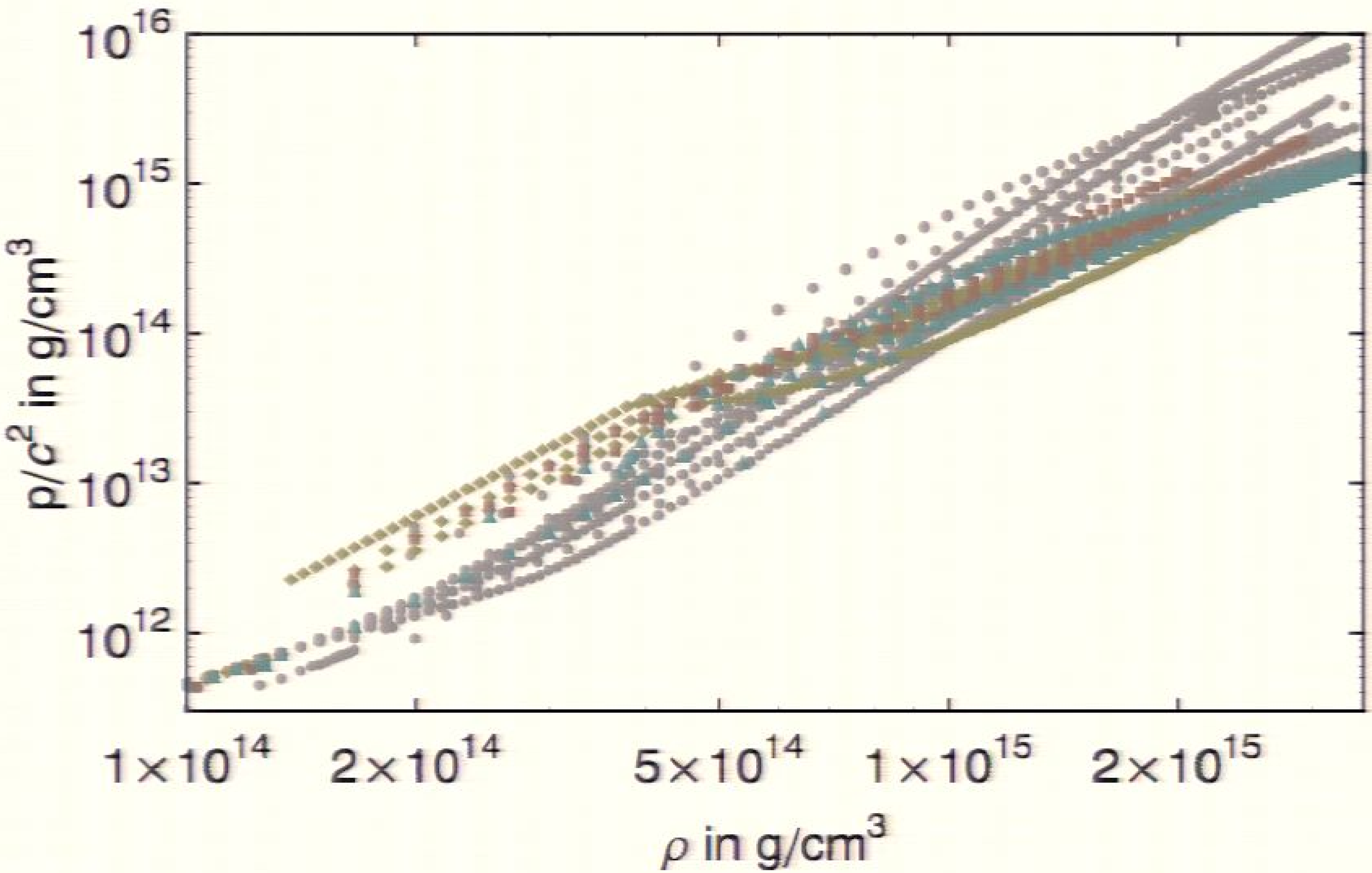
PN/Perturbative tidal with realistic EOS: Tanja Hinderer, Ben Lackey, Ryan Lang

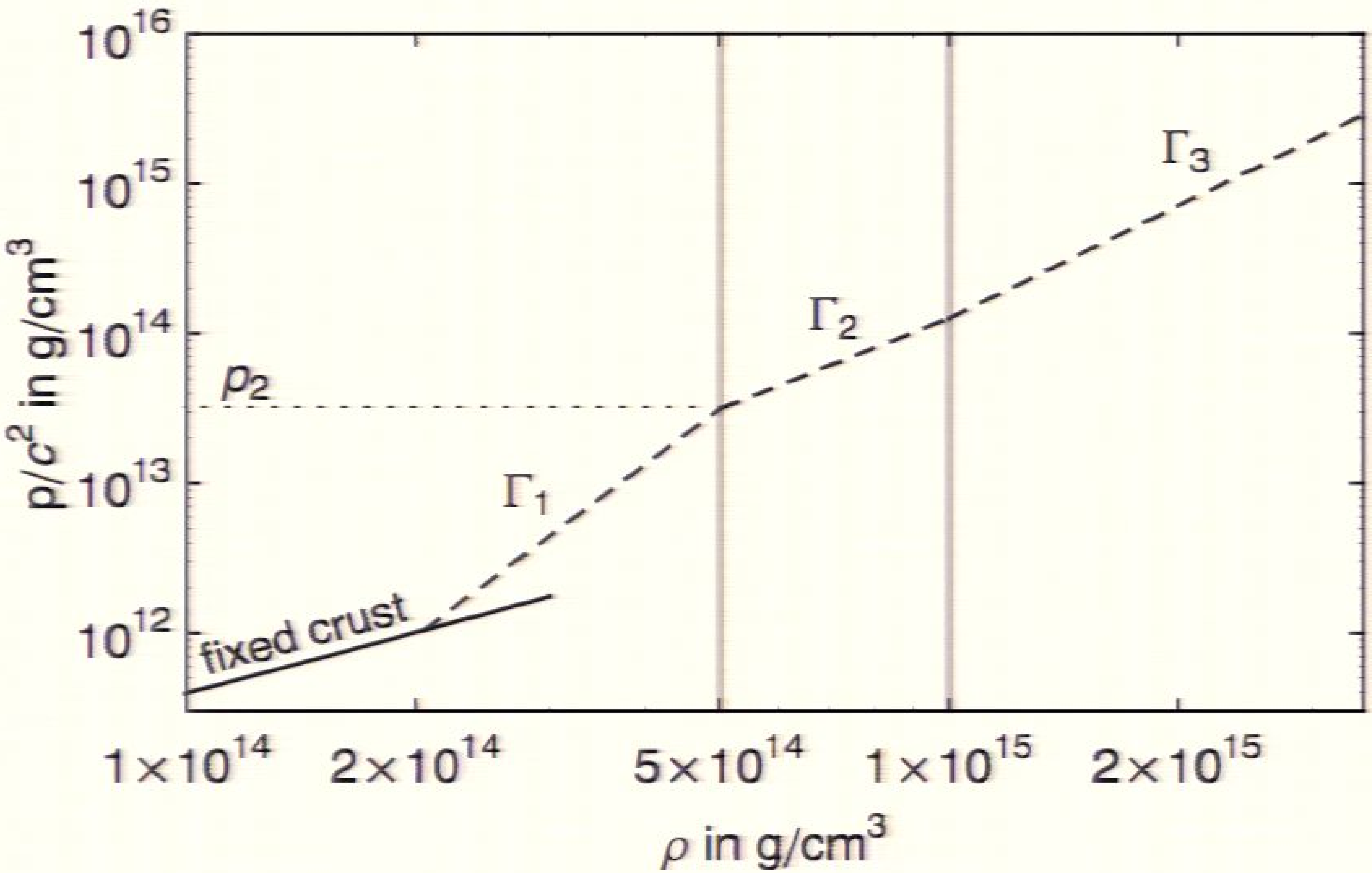
Numerical Simulations:
Initial data - Keisuke Taniguchi
Whisky - Luca Baiotti, Bruno Giacomazzo, Luciano Rezzola
SACRA - Koutarou Kyutoku, Masaru Shibata
Waveform Analysis: Jolien Creighton, John Friedman

Candidate cold EOS in 2007

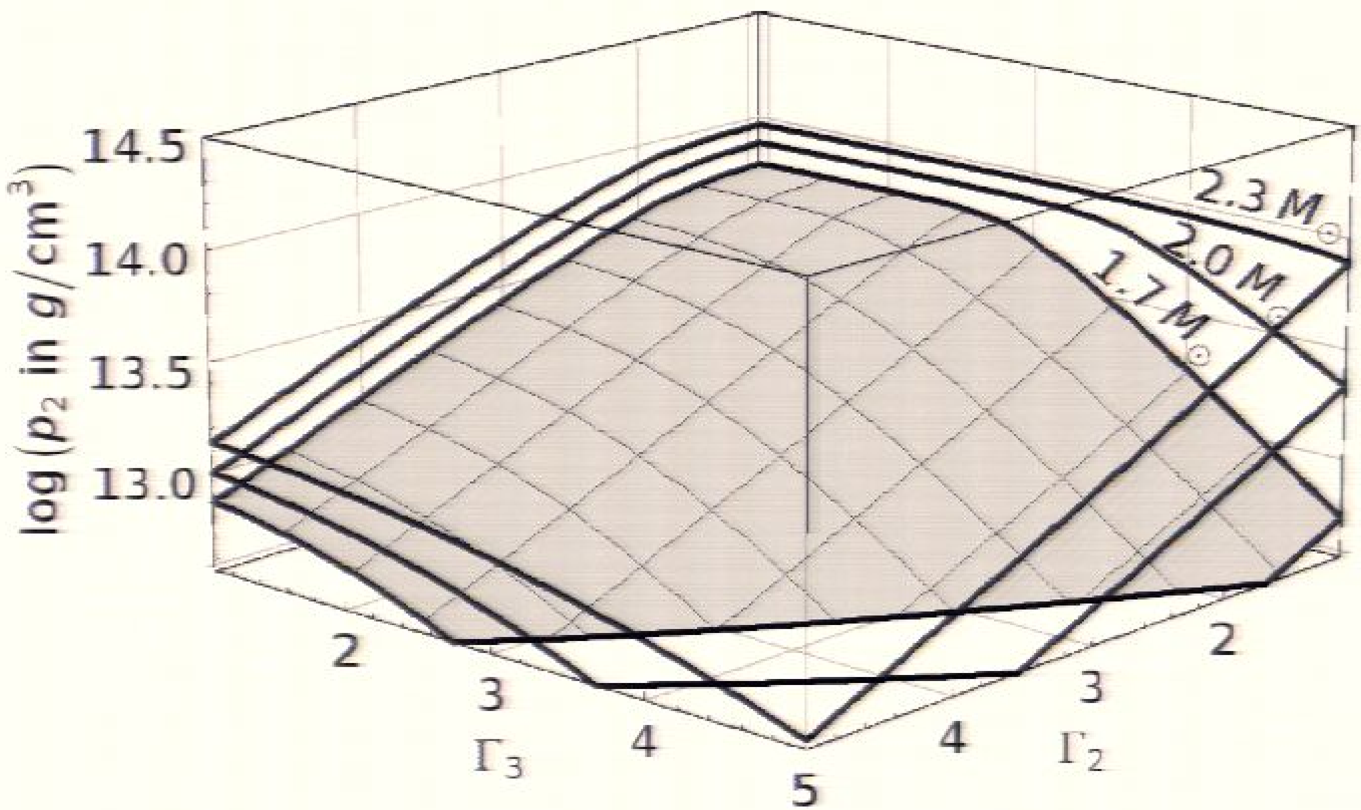


Goal: Find a systematic way to characterize the set of candidate equatio
of state above nuclear density with a small number of parameters that ar
independent of the particular microphysical model and fitting errors
smaller than current uncertainties and expected constraints


10^{16}
10^{15}
10^{14}
10^{13}
10^{12}
p/c^2 in g/cm^3
1×10^{14}
2×10^{14}
5×10^{14}
1×10^{15}
2×10^{15}
ρ in g/cm^3


10^{16}
10^{15}
10^{14}
10^{13}
10^{12}
p/c^2 in g/cm^3
Γ_3
Γ_2
p_2
Γ_1
fixed crust
1×10^{14}
2×10^{14}
5×10^{14}
1×10^{15}
2×10^{15}
ρ in g/cm^3

Constraints on a phenomenologically parametrized neutron-star equation of state
JR, B. Lackey, J. Friedman, B. Owen PRD 79 (2009) 124033

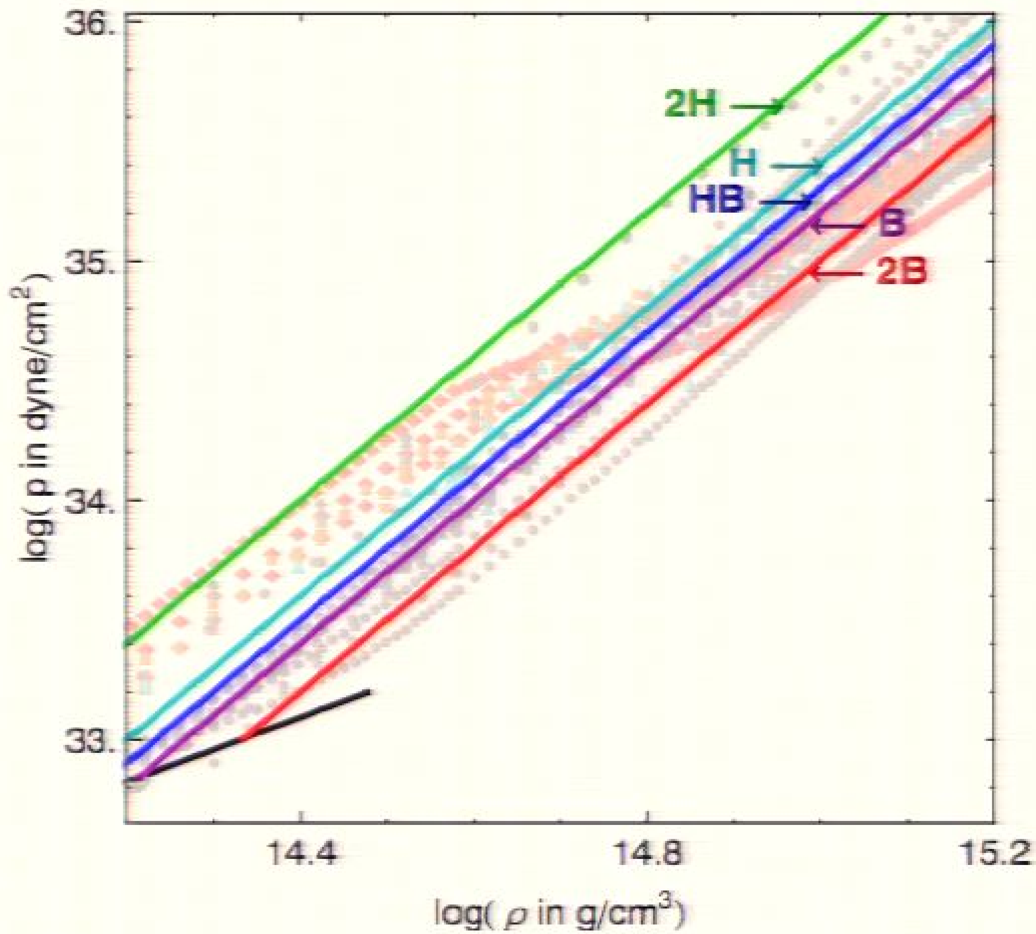


example: constraints from maximum mass

Systematically vary equations of state for simulations

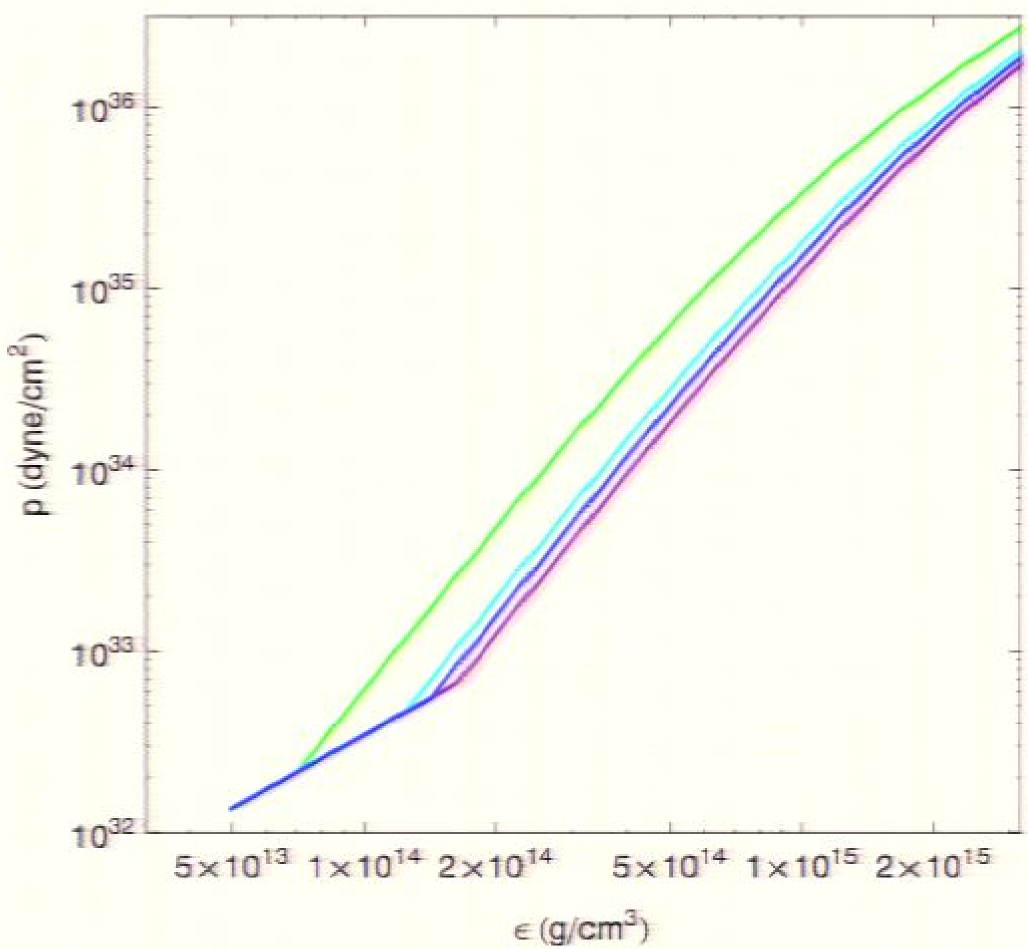
A limited number of simulations are feasible (particularly for long inspiral

Try to cover parameter space:



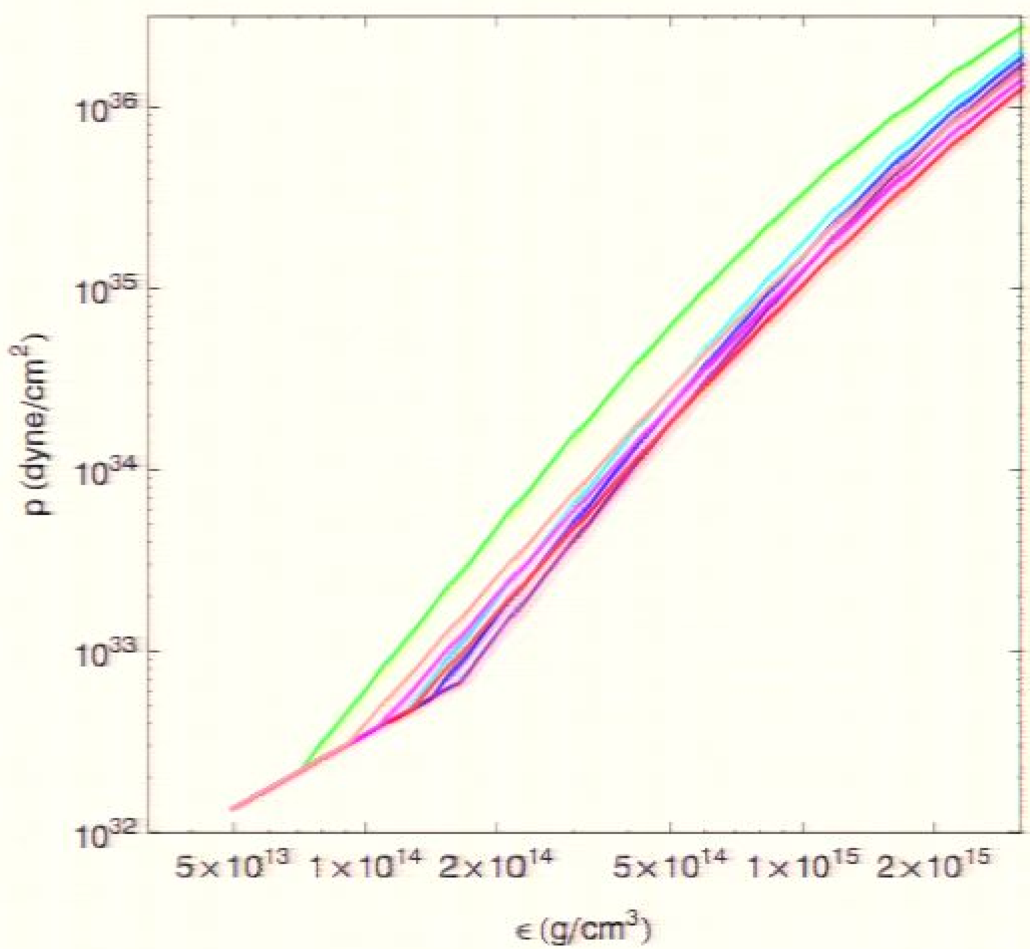
How relevant are these choices with astrophysical constraints?

Current set of waveforms: vary pressure p



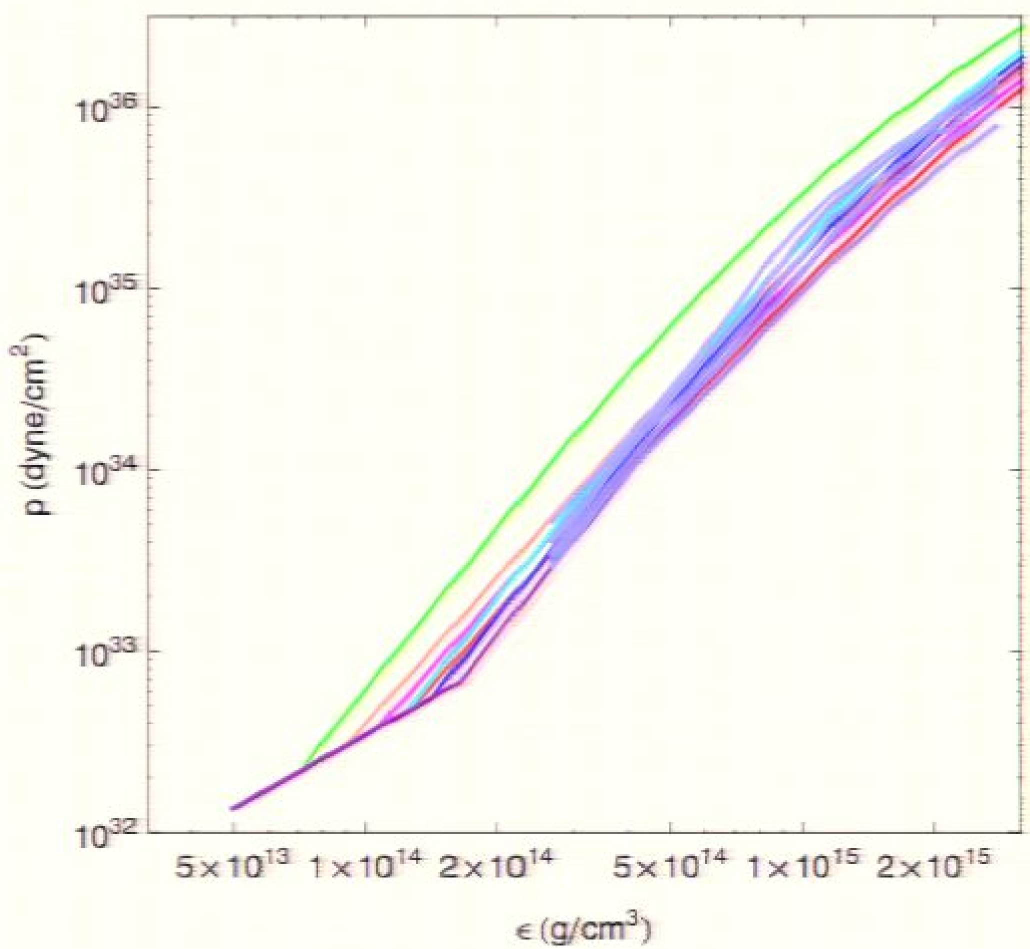
How relevant are these choices with astrophysical constraints?

Current set of waveforms: and vary Γ



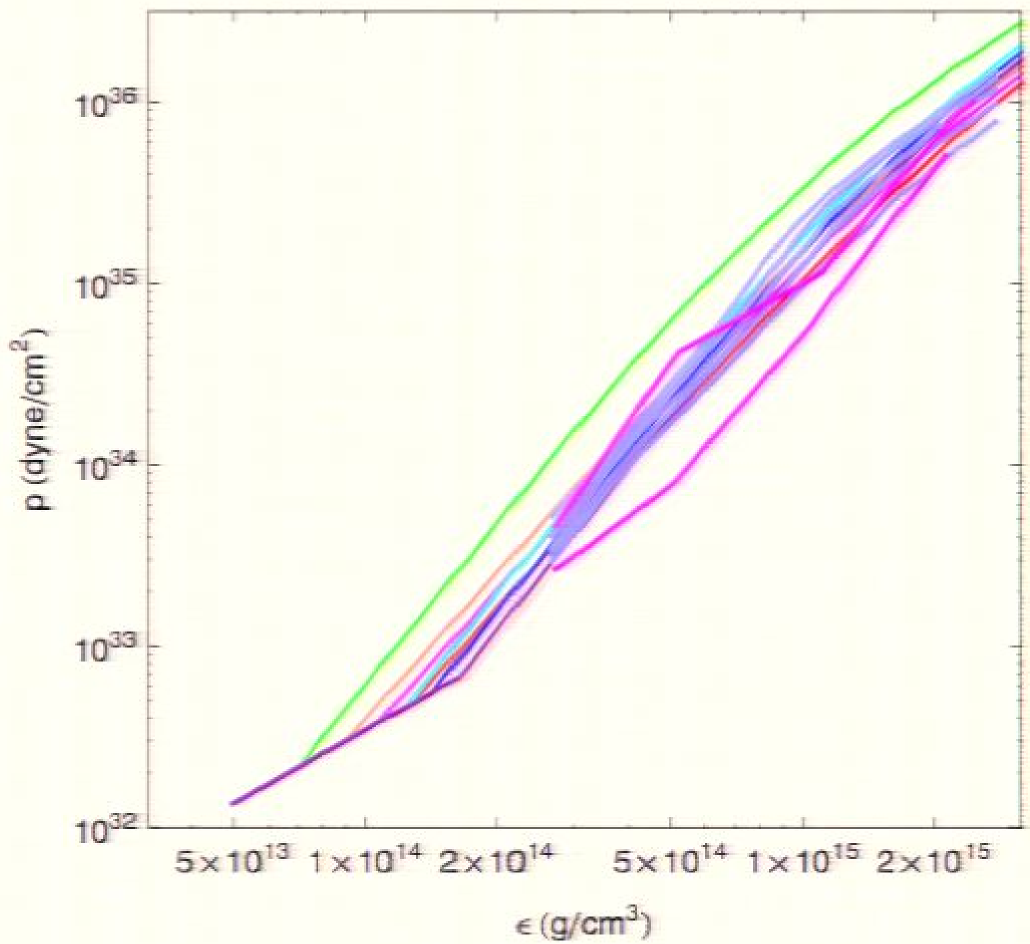
How relevant are these choices with astrophysical constraints?

Comparison with Steiner et al high density EOS constraint:



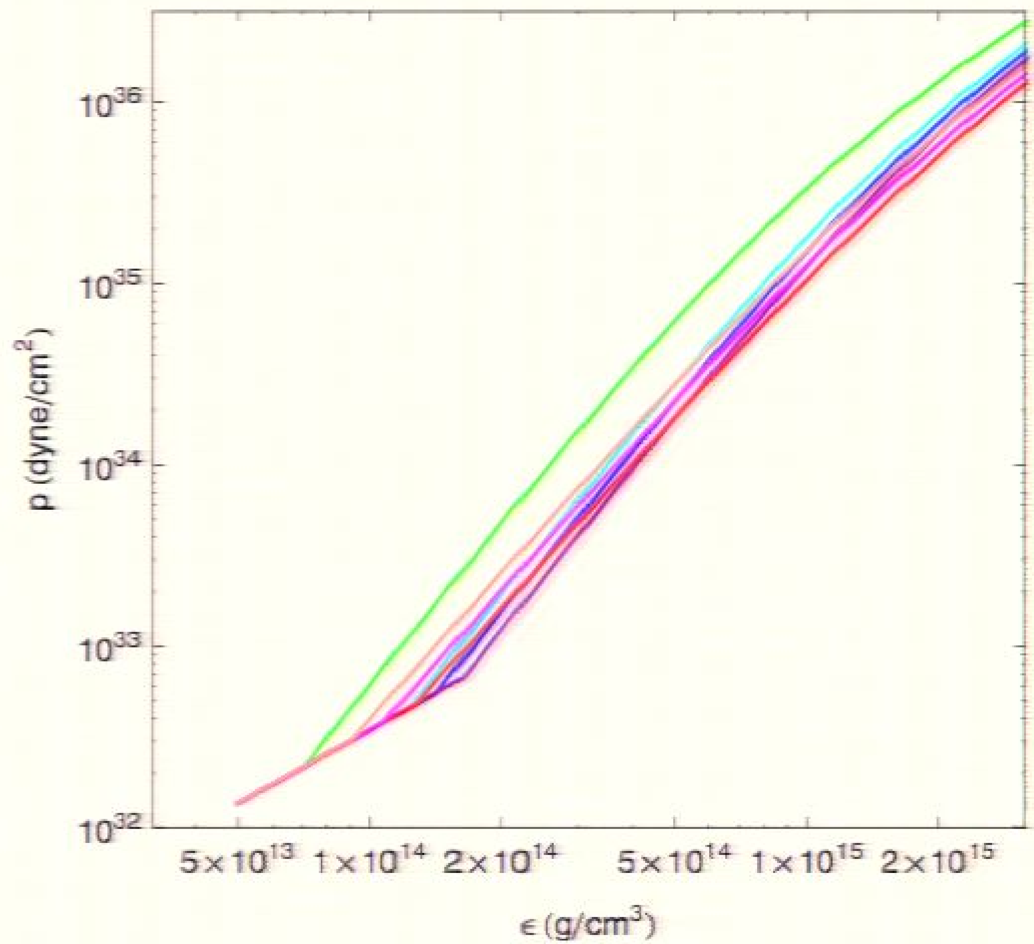
How relevant are these choices with astrophysical constraints?

Comparison with Ozel et al high density EOS constraint:



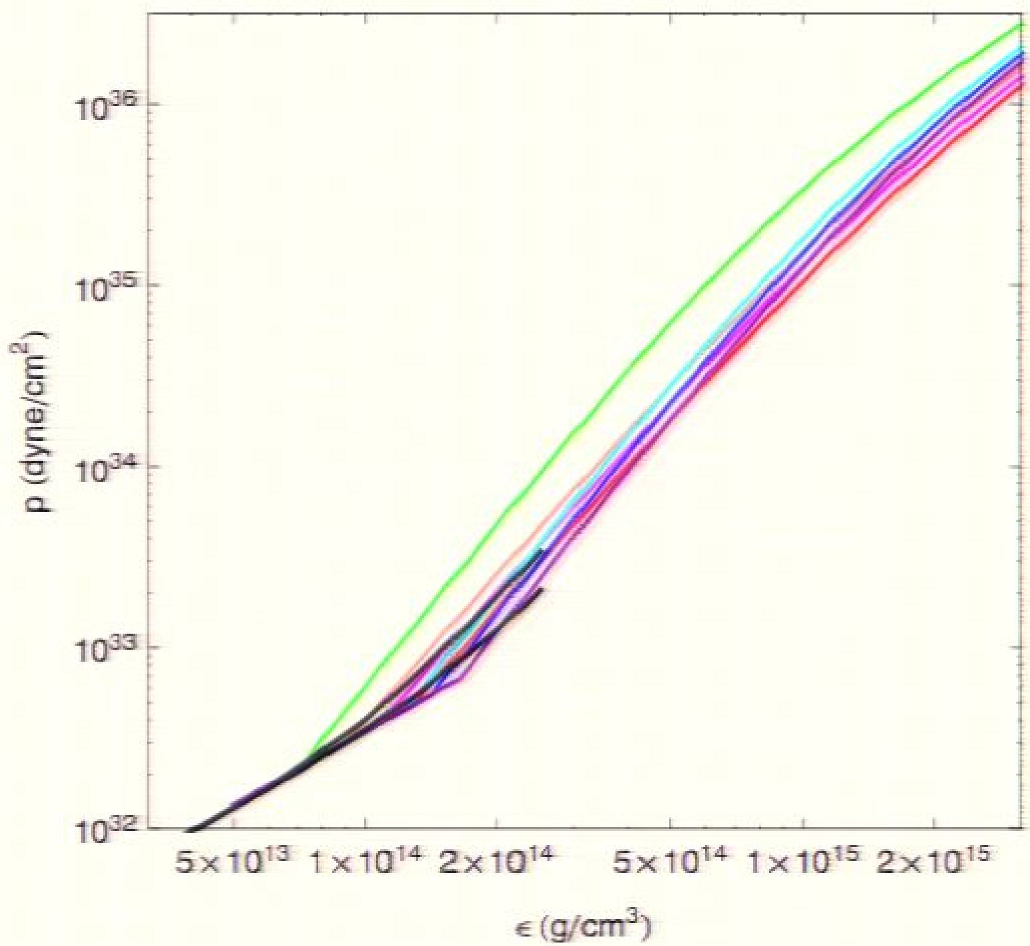
What about nuclear physics constraints?

Current set of waveforms:

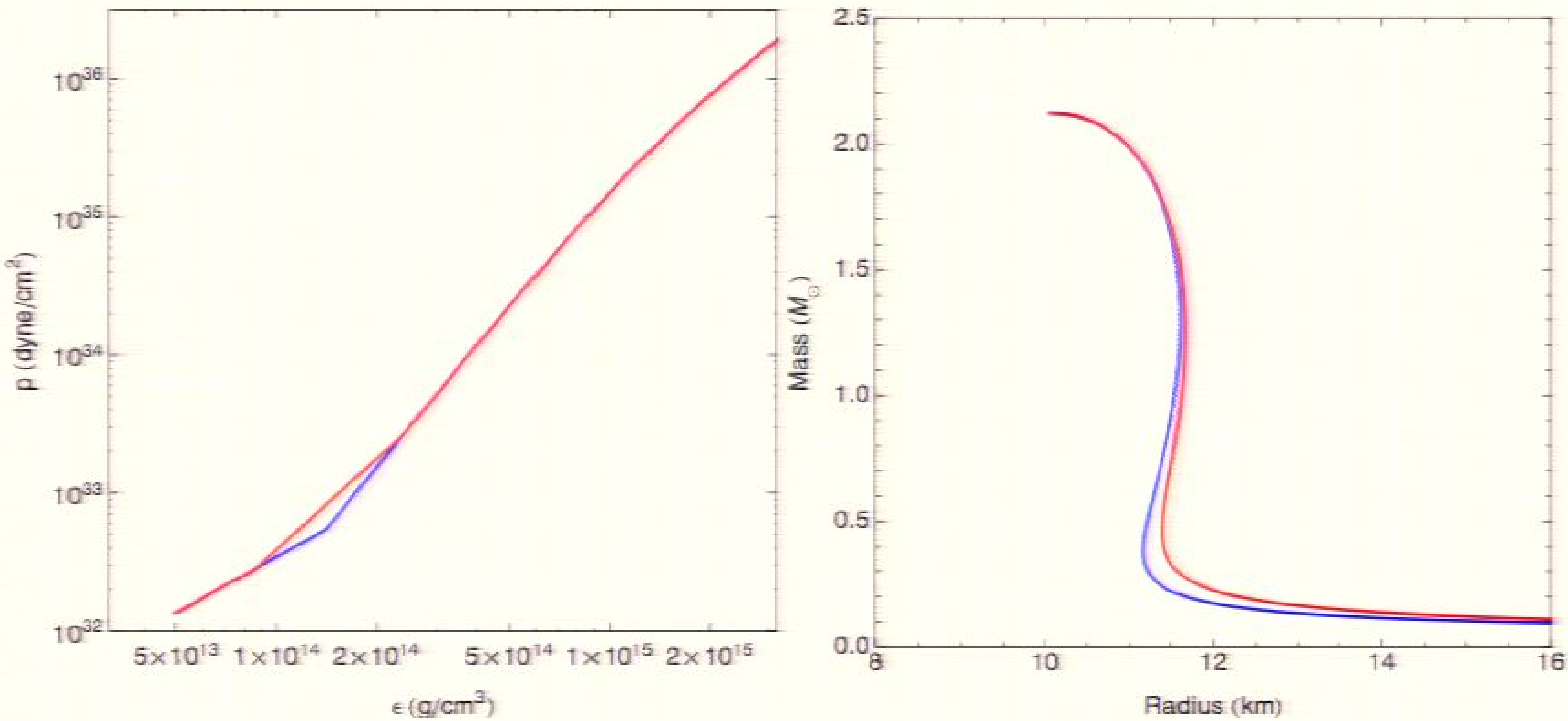


What about nuclear physics constraints?

Comparison with Hebeler et al EOS constraint:

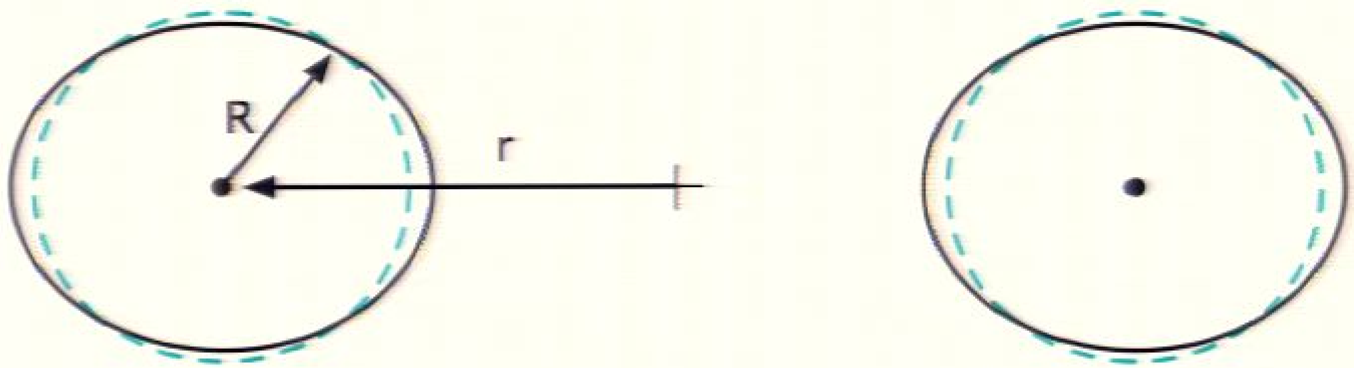


Effect of low density EOS on relevant characteristics



Matter effects in a binary system

Consider two extended bodies in orbit or free-fall:

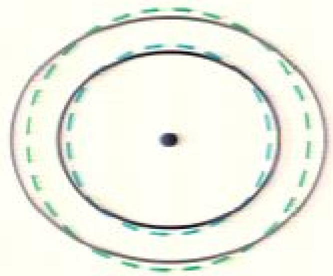


Residual gravitational effect is tidal deformation.

Amount of deformation depends on size and matter properties.

Deformations induce changes in the gravitational potential.

Tidal deformability λ for realistic EOS



$$\lambda = \frac{Q}{\mathcal{E}} = \frac{\text{size of quadrupole deformation}}{\text{strength of external tidal field}}$$

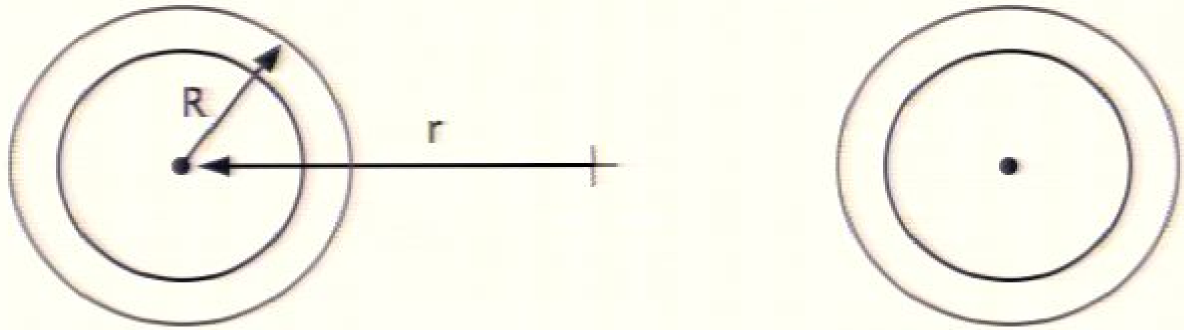
$$\lambda = \frac{2}{3} k R^5$$

R is radius, k is Love number

For given realistic EOS, R and k are functions of M

Effect of matter on inspiral

Incorporate first order tidal correction to post-Newtonian waveform



$$E = -\frac{1}{2}\left(\frac{Gm\mu}{r}\right)(1 + [\mathrm{PN}])$$

$$\dot{E}_{GW} = -\frac{32}{5}\frac{c^5}{G}\left(\frac{\mu}{m}\right)^2\left(\frac{Gm}{c^2 r}\right)^5(1 + [\mathrm{PN}])$$

$m = m_1 + m_2$
$\mu = m_1 m_2 / m$

Evolve orbit using balance of luminosity and orbital energy
Flanagan and Hinderer 2008

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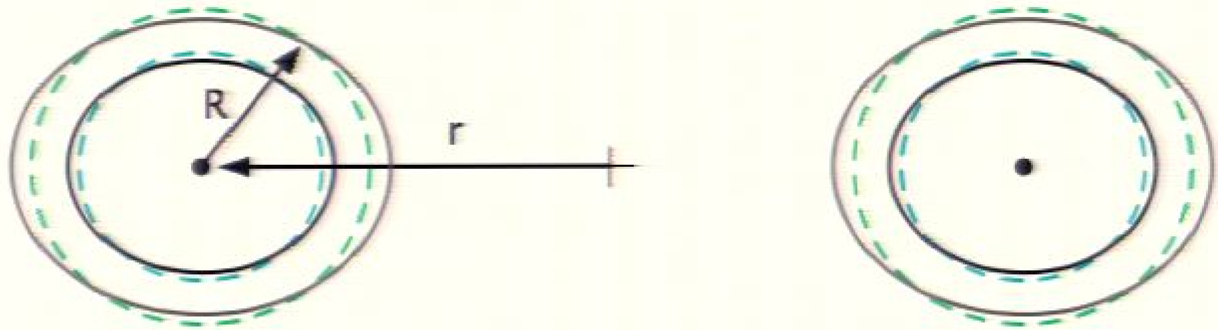

$$E = -\frac{1}{2}\left(\frac{Gm\mu}{r}\right)\left(1 + [\mathrm{PN}] - \frac{1}{2}Q^1_{ij}\mathcal{E}^2_{ij} + 2 \leftrightarrow 1\right)$$

$$\dot{E}_{GW} = -\frac{32}{5}\frac{c^5}{G}\left(\frac{\mu}{m}\right)^2\left(\frac{Gm}{c^2 r}\right)^5\left(1 + [\mathrm{PN}] + \frac{1}{5}\langle \dddot{Q}^1_{ij}\dddot{Q}^1_{ij}\rangle + 2 \leftrightarrow 1\right)$$

$m = m_1 + m_2$
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Evolve orbit using balance of luminosity and orbital energy Flanagan and Hinderer 2008

Measurable effect in inspiral?

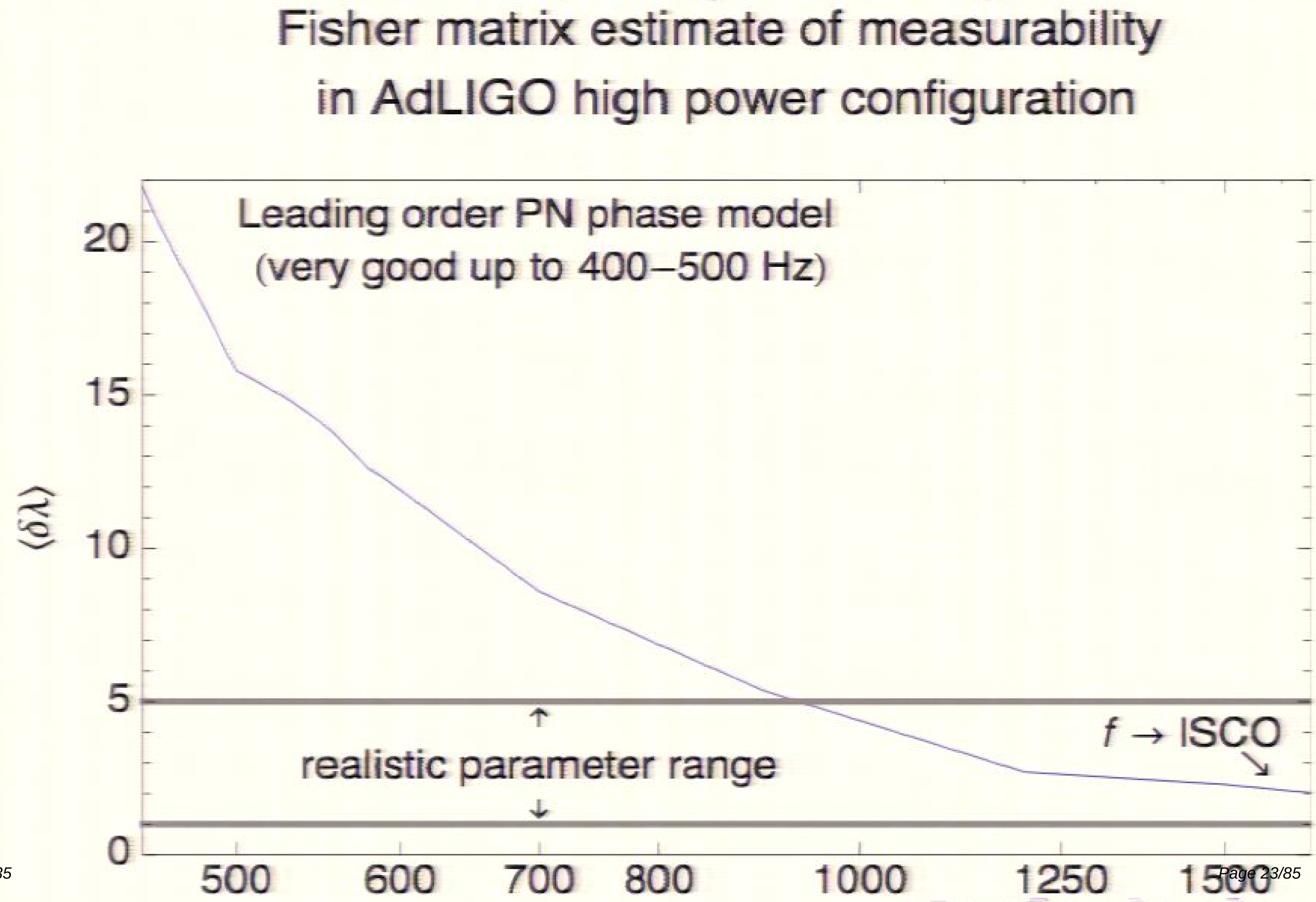
NSNS: arxiv:0911.3535 inspiral below 450Hz

Advanced LIGO

M ($M_\odot$)	m_2/m_1	$\Delta\mathcal{M}/\mathcal{M}$	$\Delta\eta/\eta$	$\Delta\tilde{\lambda}(10^{36}\,\mathrm{g\,cm^2\,s^2})$	ρ
2.0	1.0	0.00028	0.073	8.4	27
2.8	1.0	0.00037	0.055	19.3	35
3.4	1.0	0.00046	0.047	31.3	41
2.0	0.7	0.00026	0.058	8.2	26
2.8	0.7	0.00027	0.058	18.9	35
3.4	0.7	0.00028	0.055	30.5	41
2.8	0.5	0.00037	0.06	17.8	33

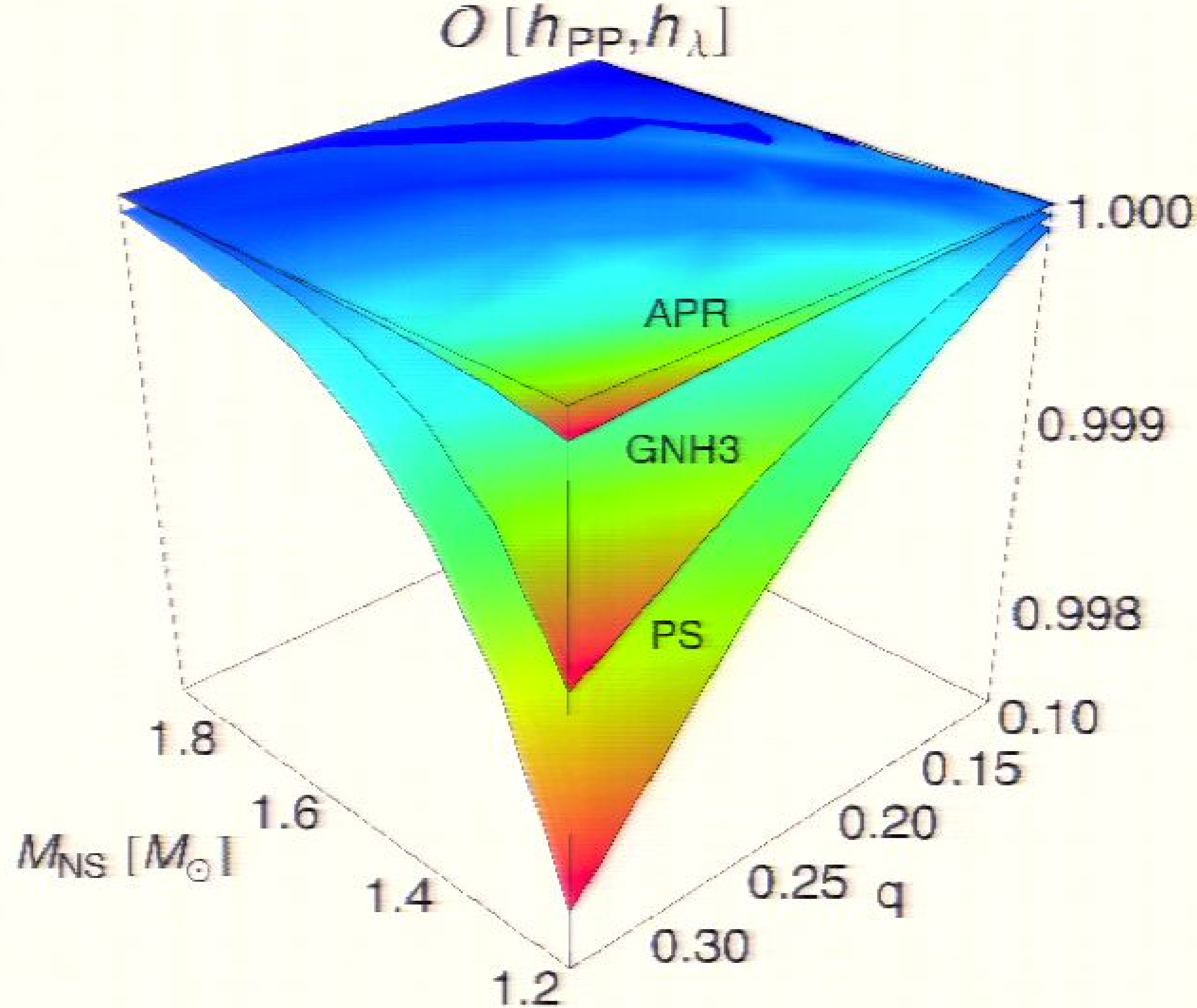
Measurable effect in inspiral?

NSNS: Extrapolating toward merger



Measurable effect in inspiral?

NSBH: Extrapolated inspiral with cutoff in arxiv:1103.3526



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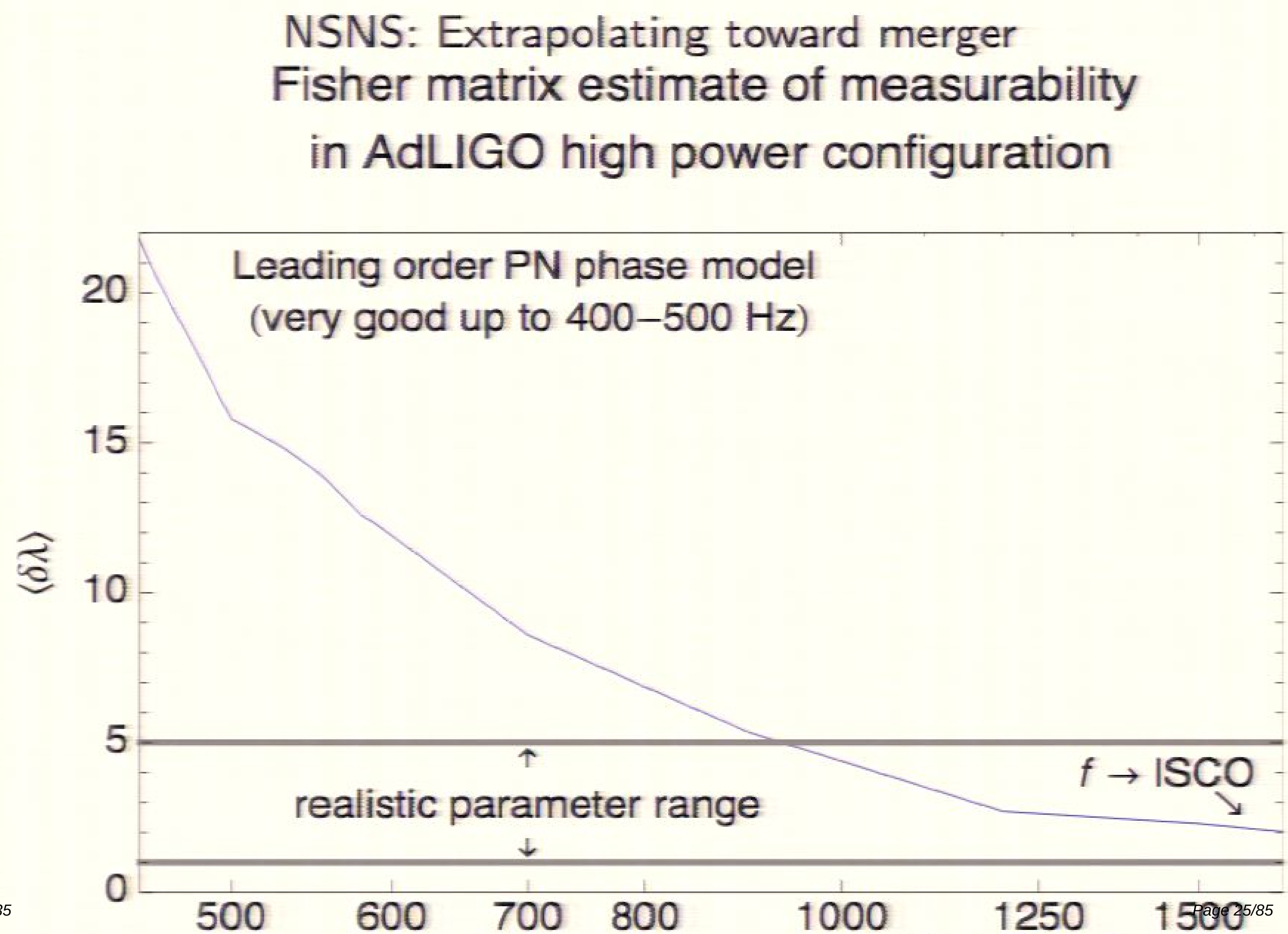

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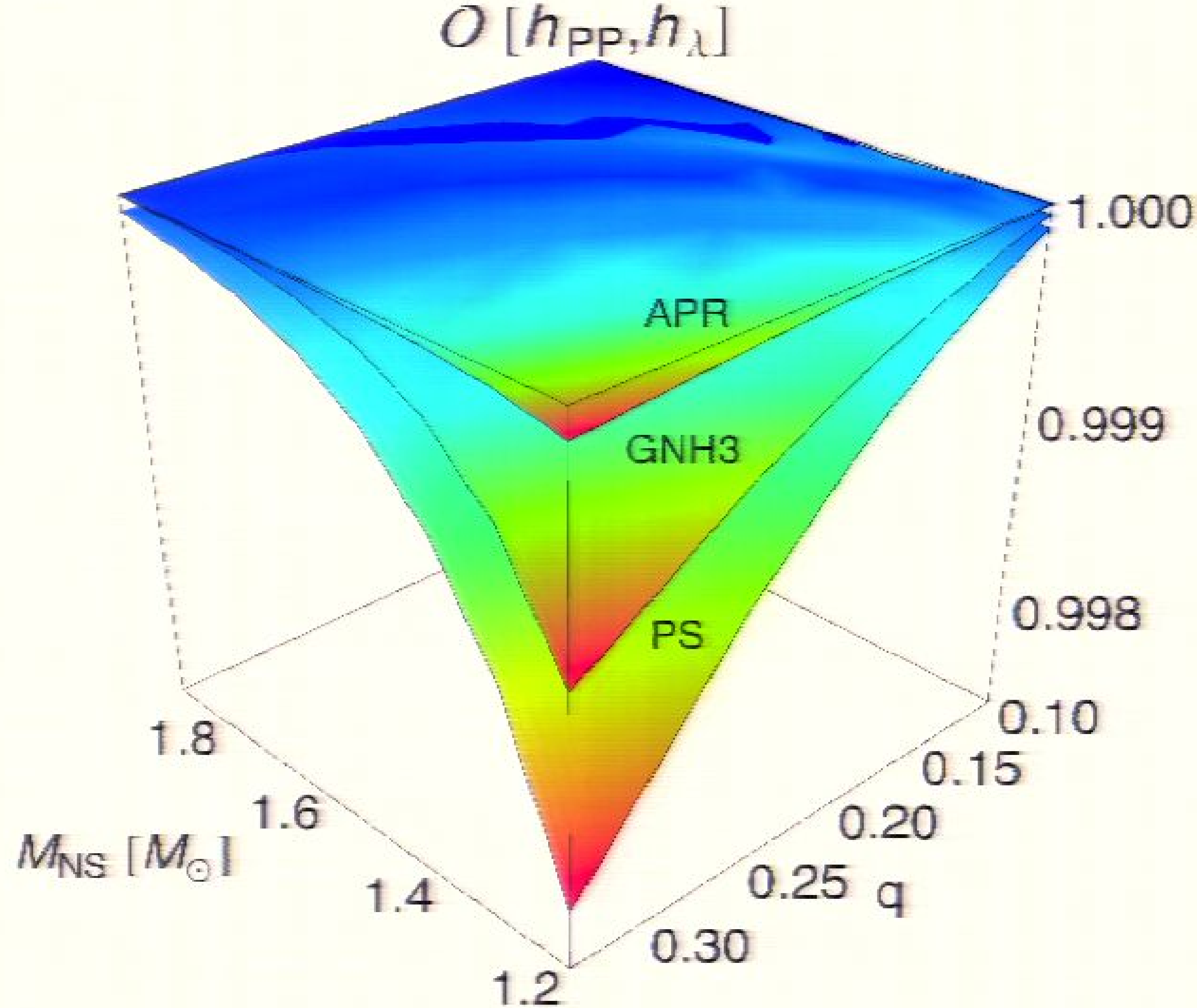
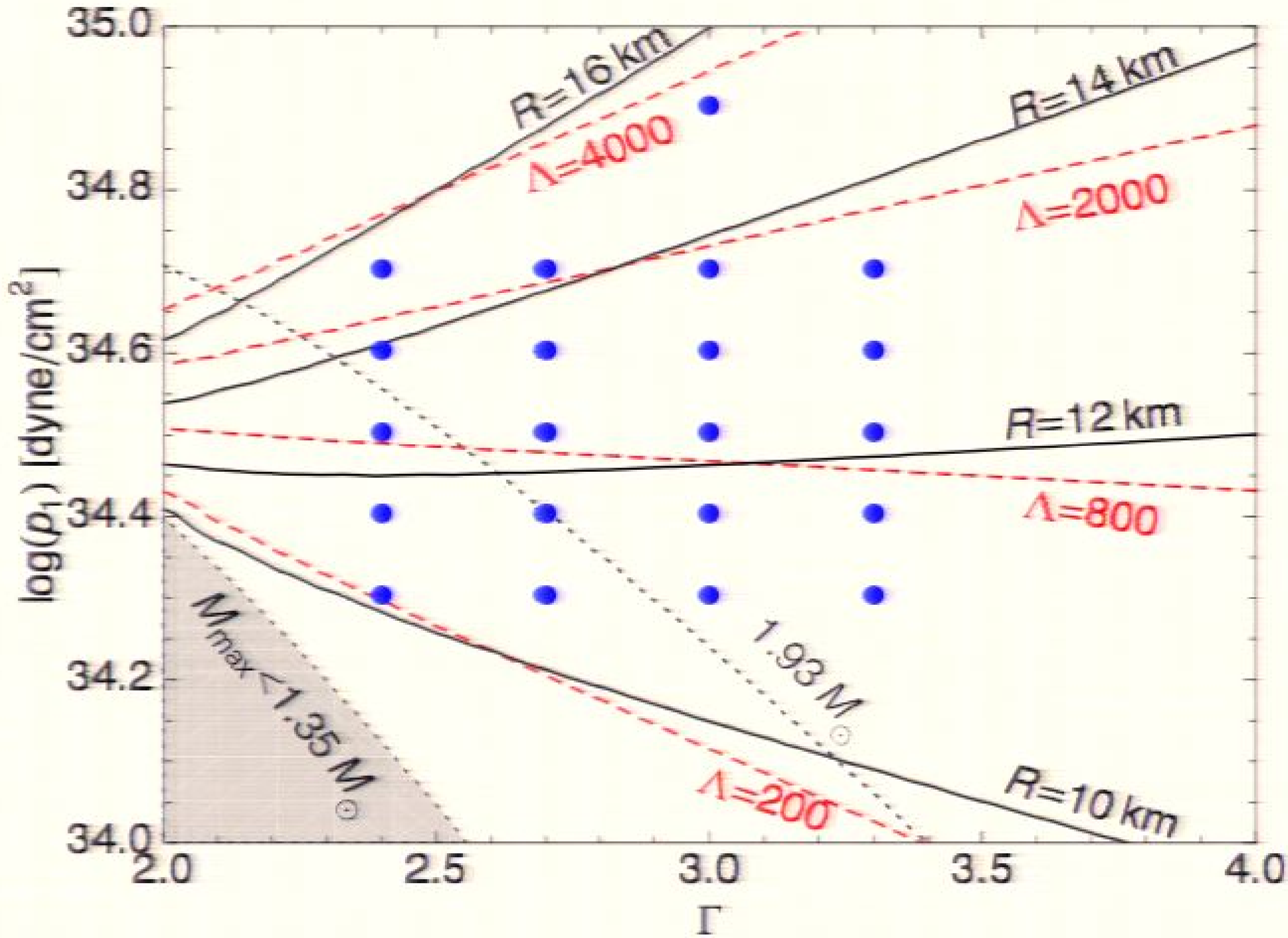


Characteristic parameters in NSBH Merger

Work by B. Lackey, K. Kyutoku, M. Shibata, P. Brady, J. Friedman
EOS with range of characteristic pressure and Γ



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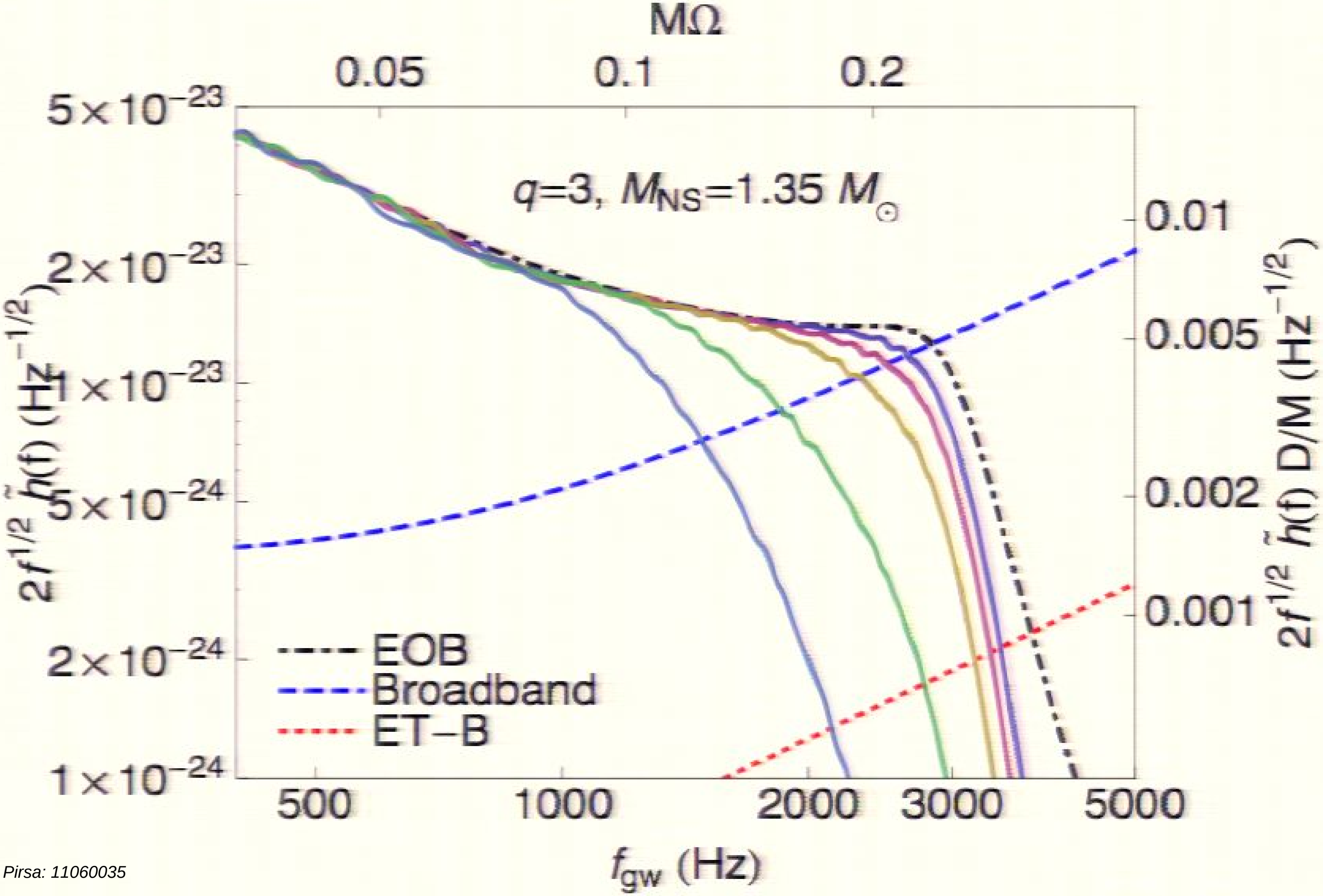
WF approach BHBH WF as R or λ decrease



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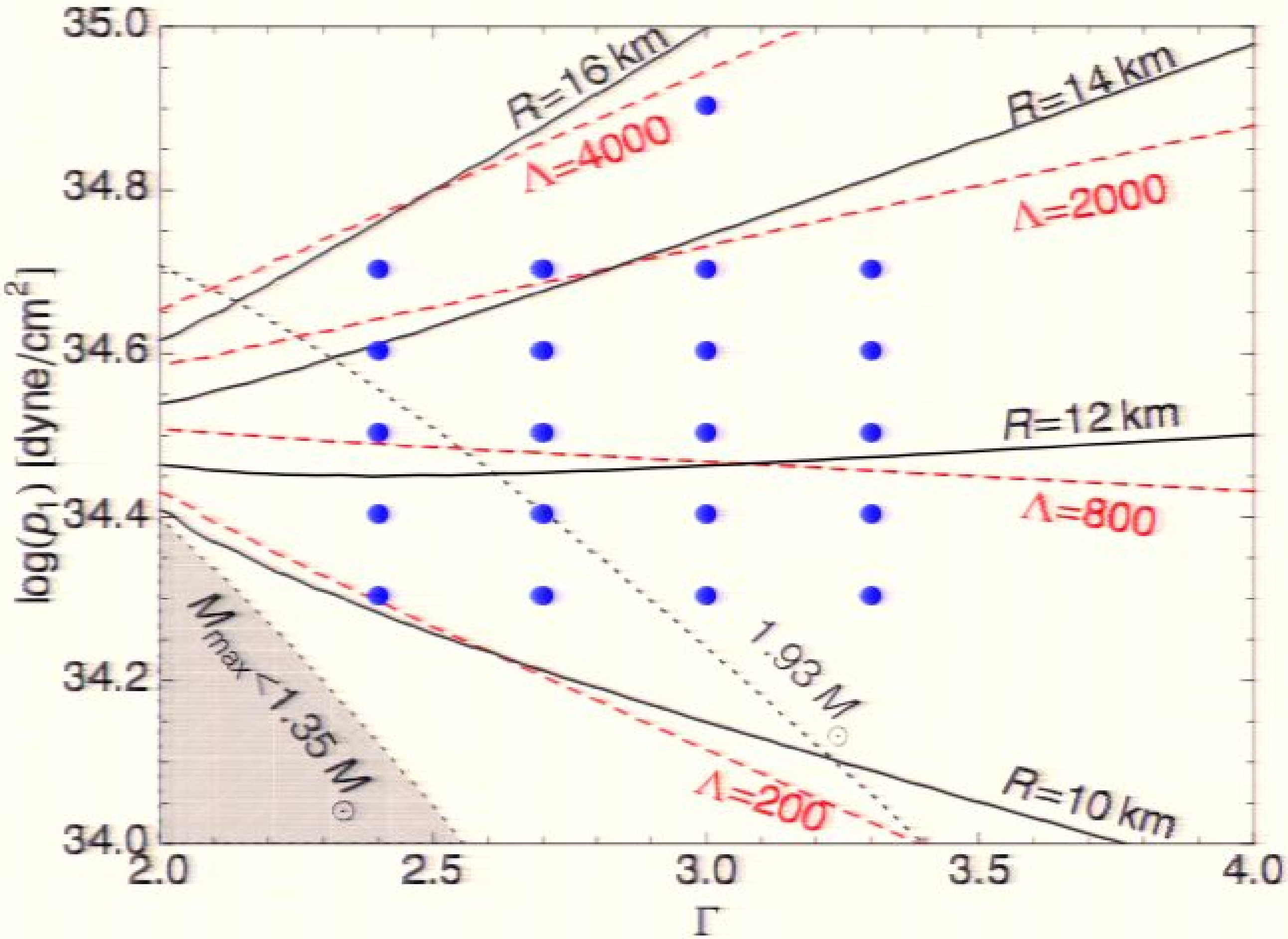

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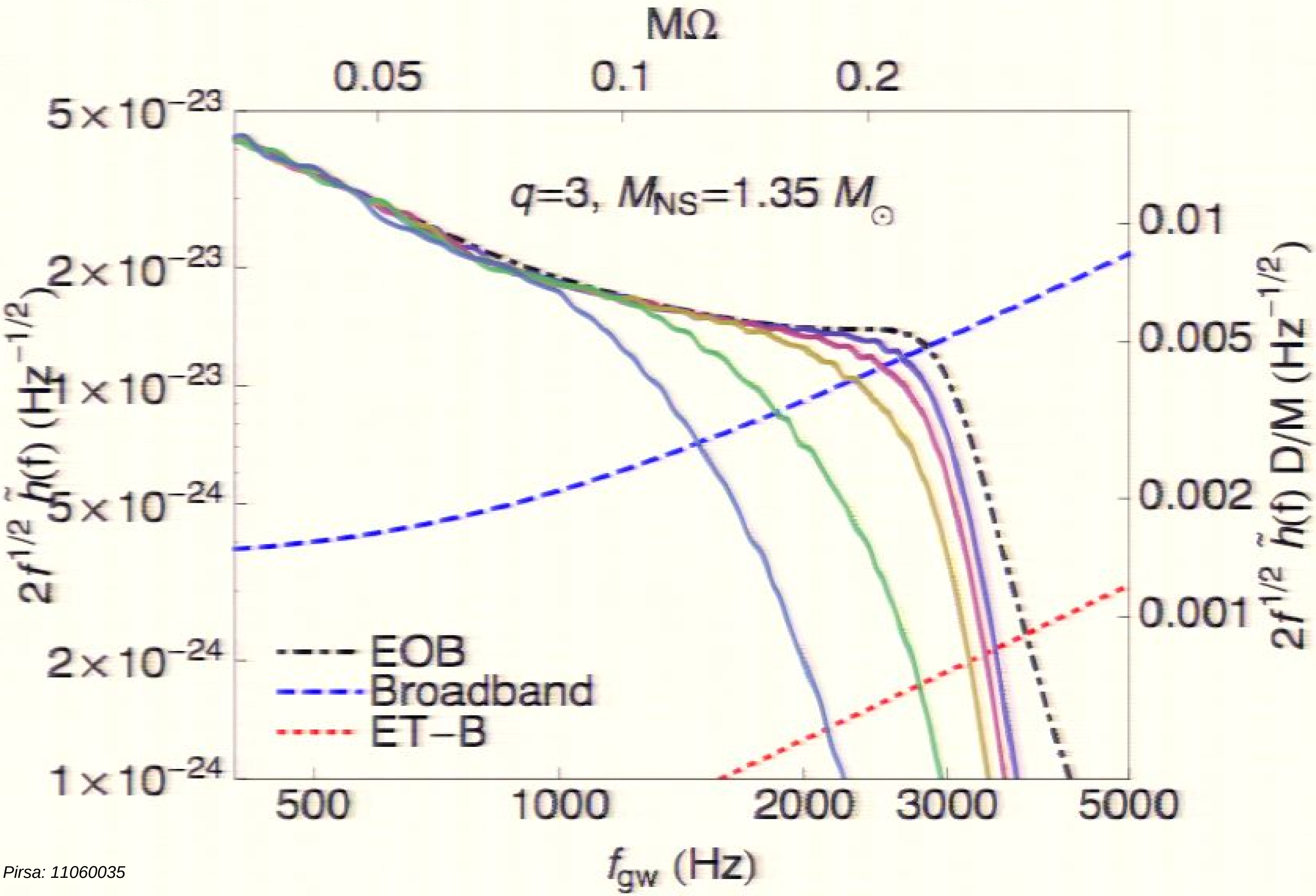

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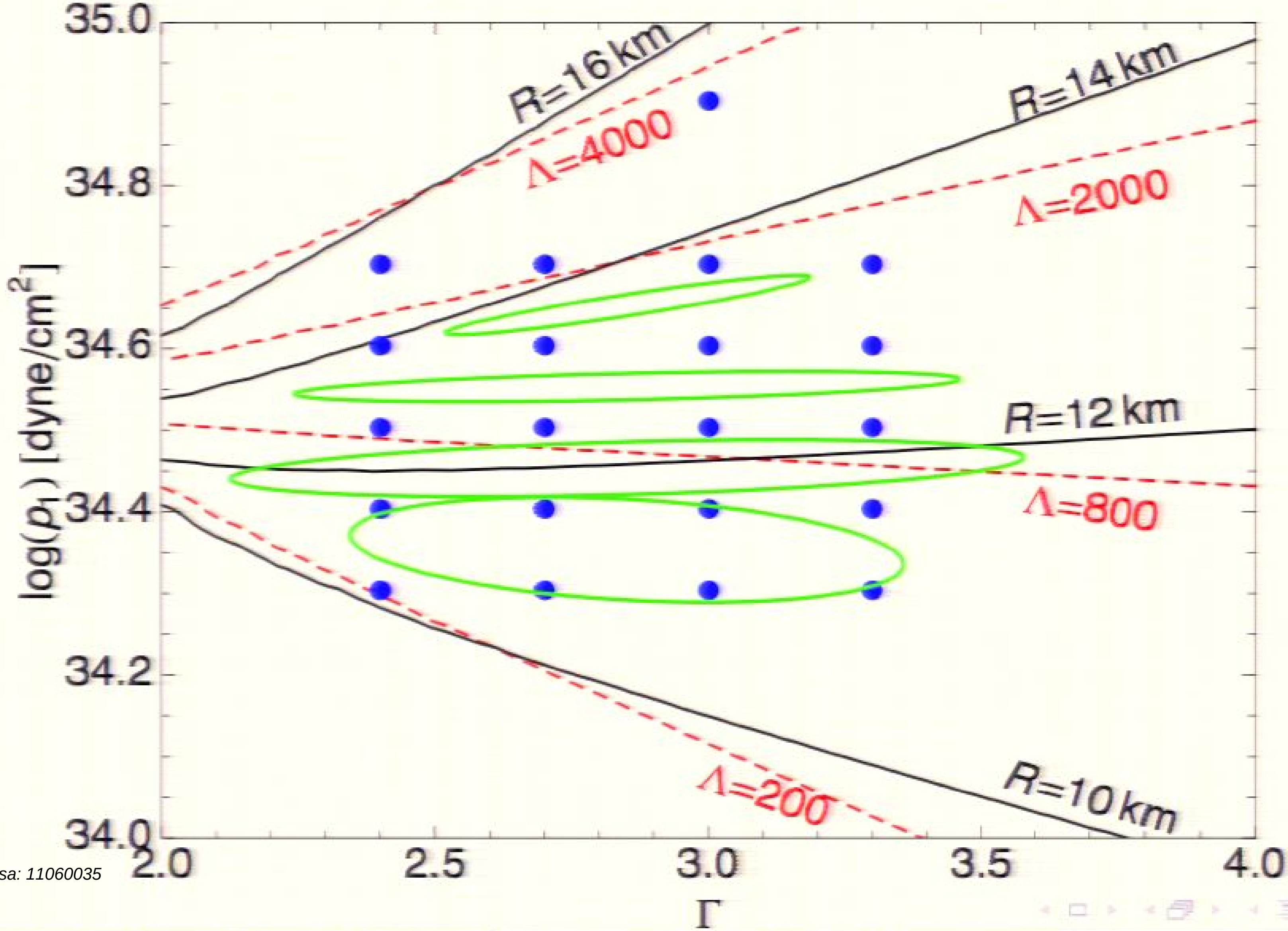
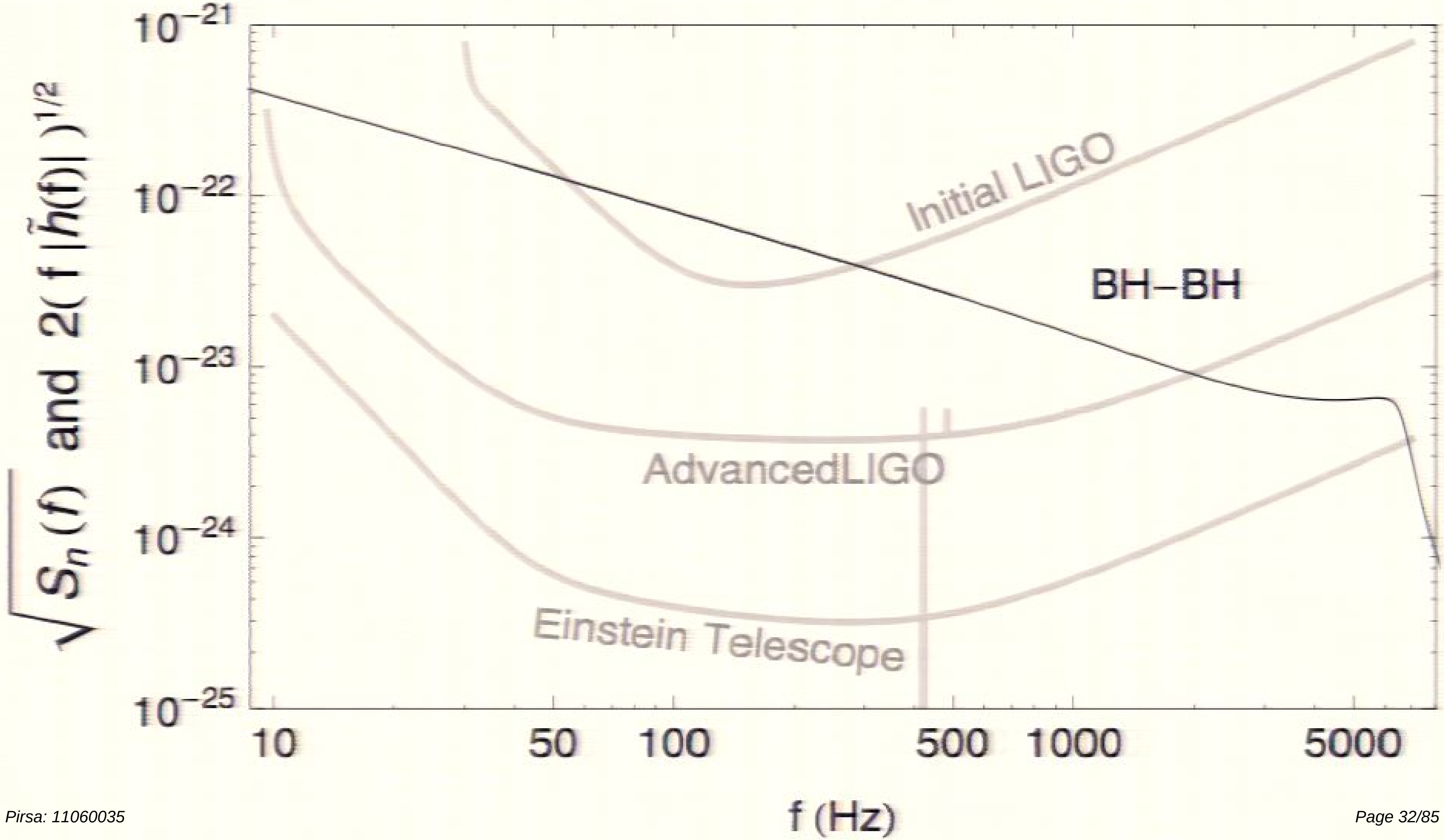
ET measurability: ellipses in p, Γ



Numerical simulation of binary neutron stars

SACRA and Whisky codes, multiple resolutions
(codes compared in arxiv:1007.1754)



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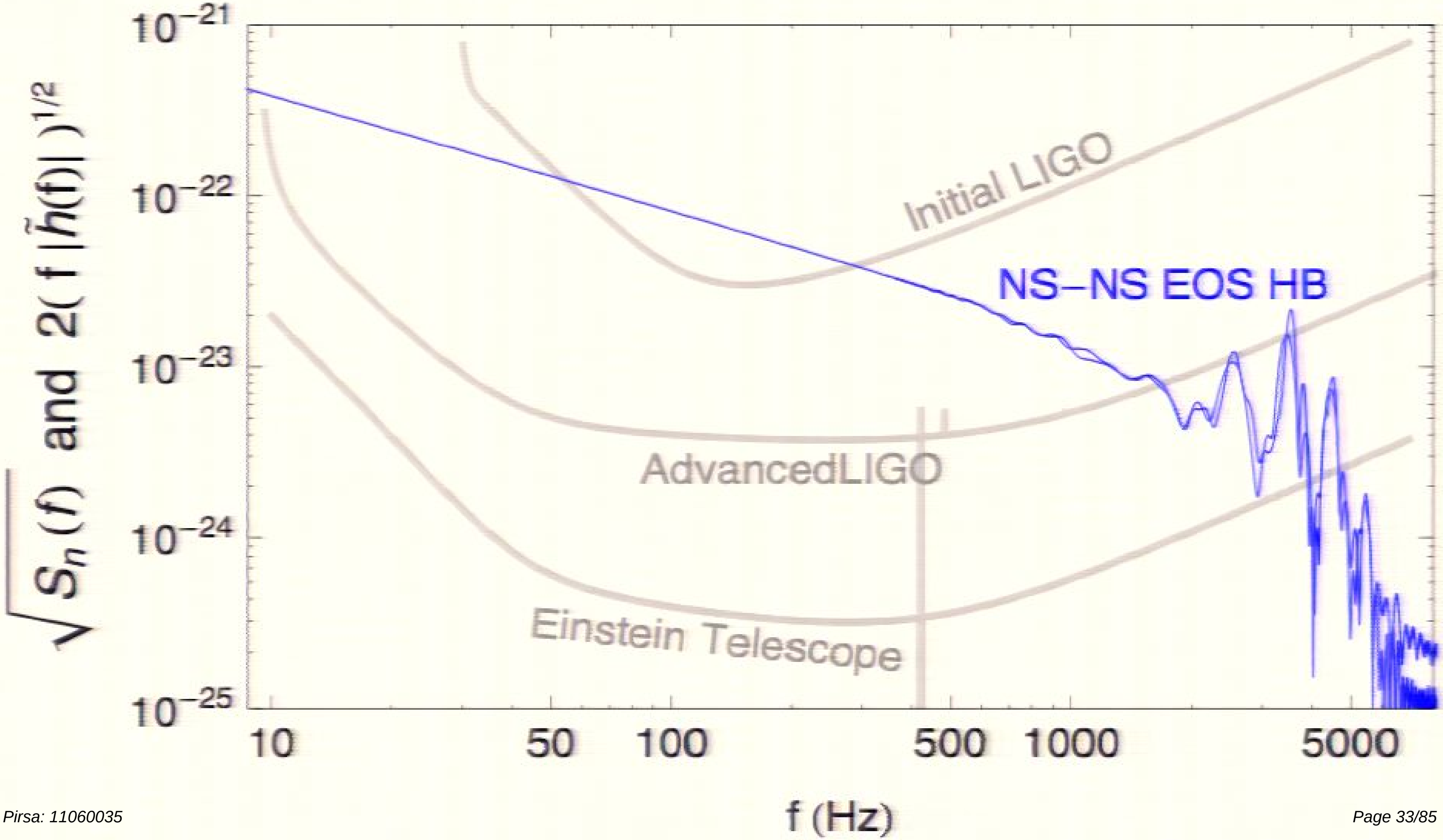

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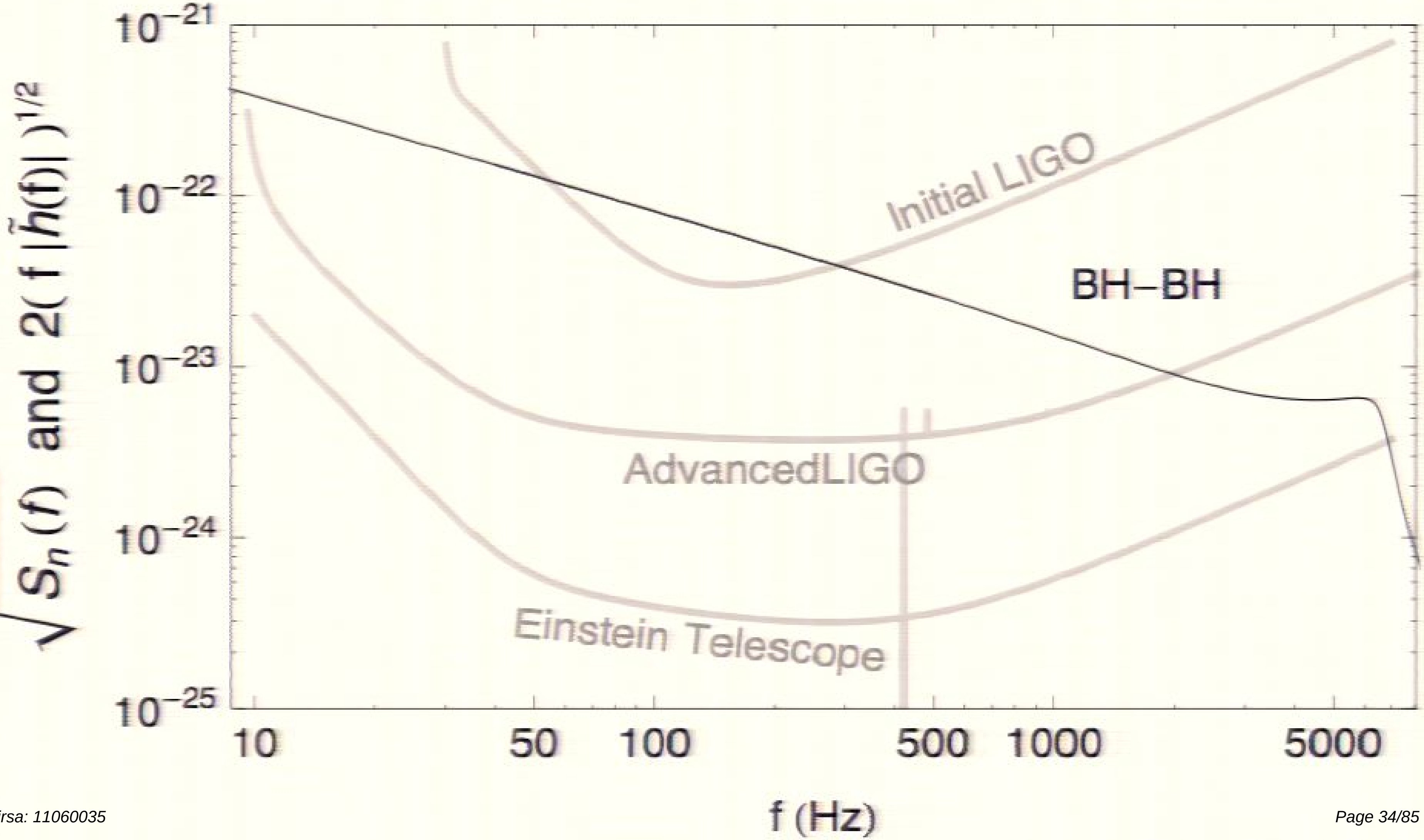

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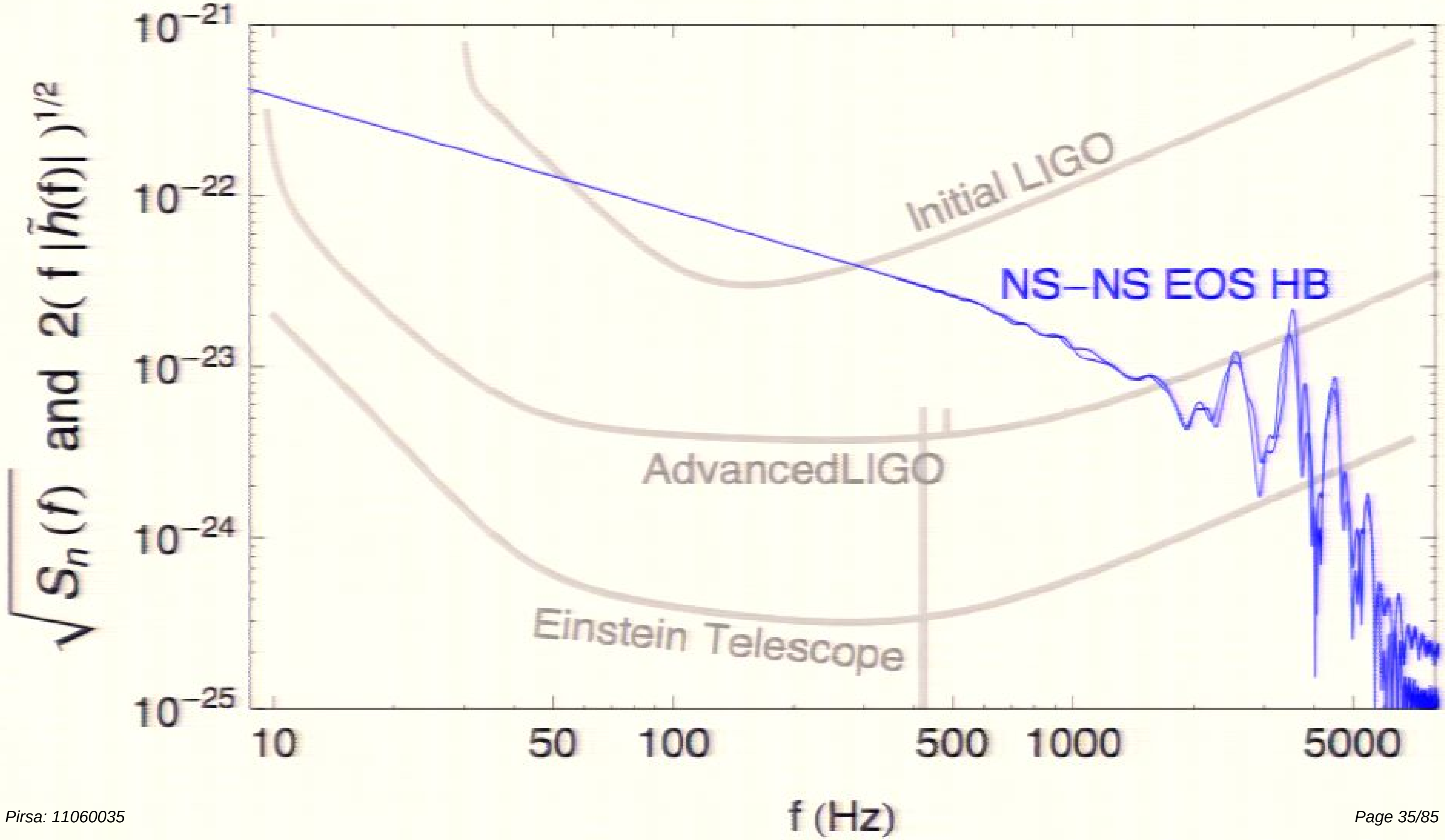

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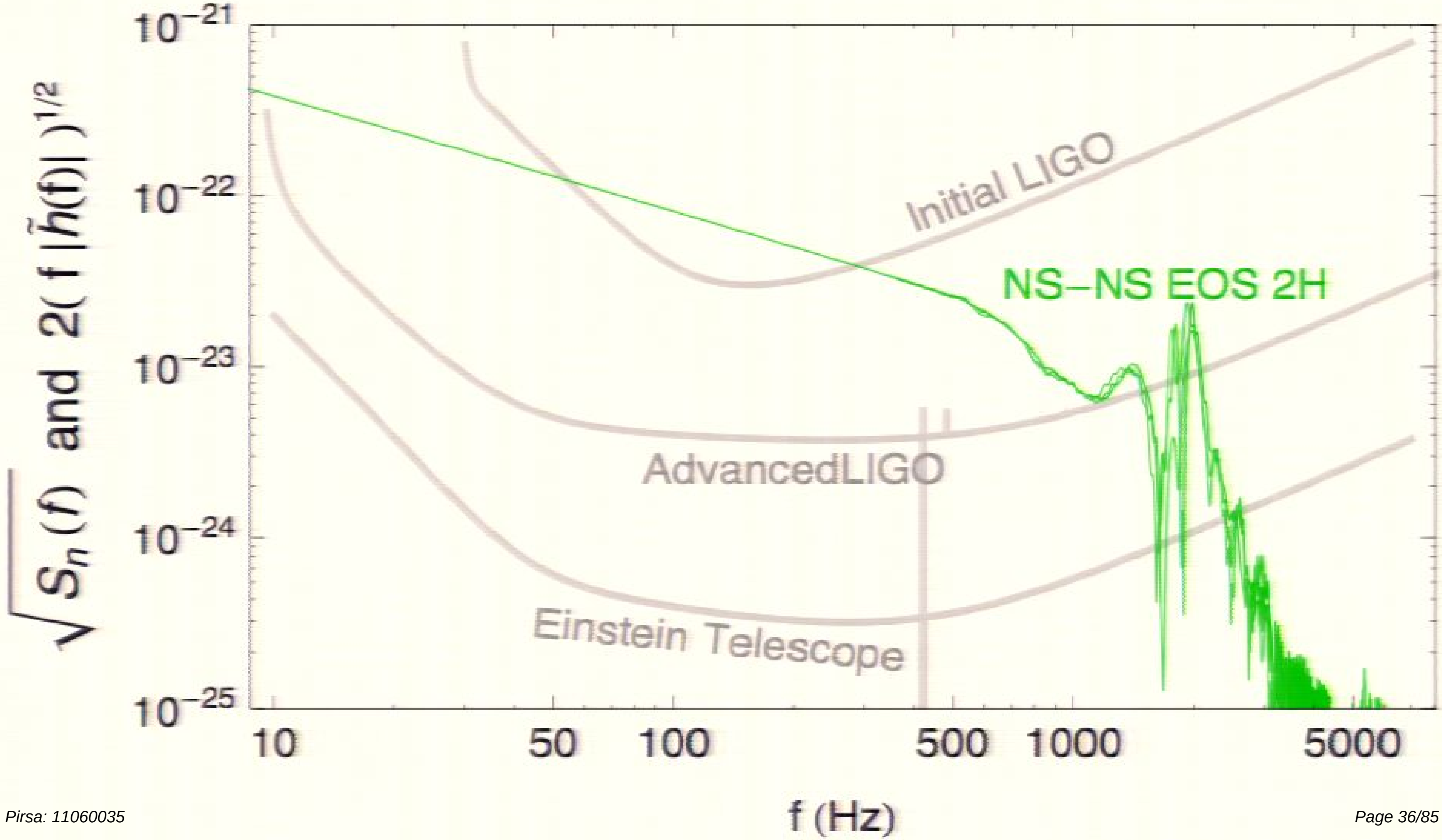

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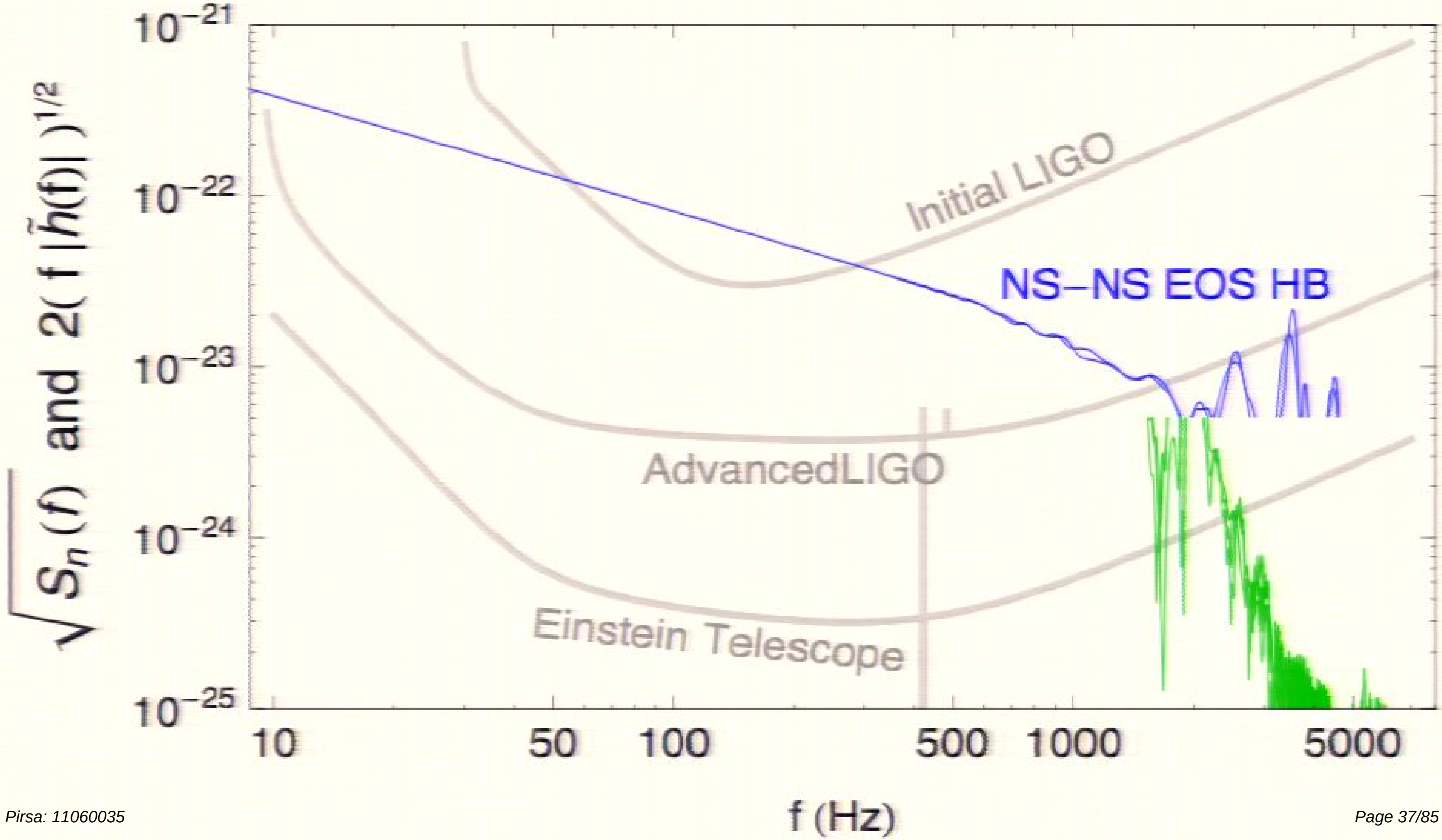
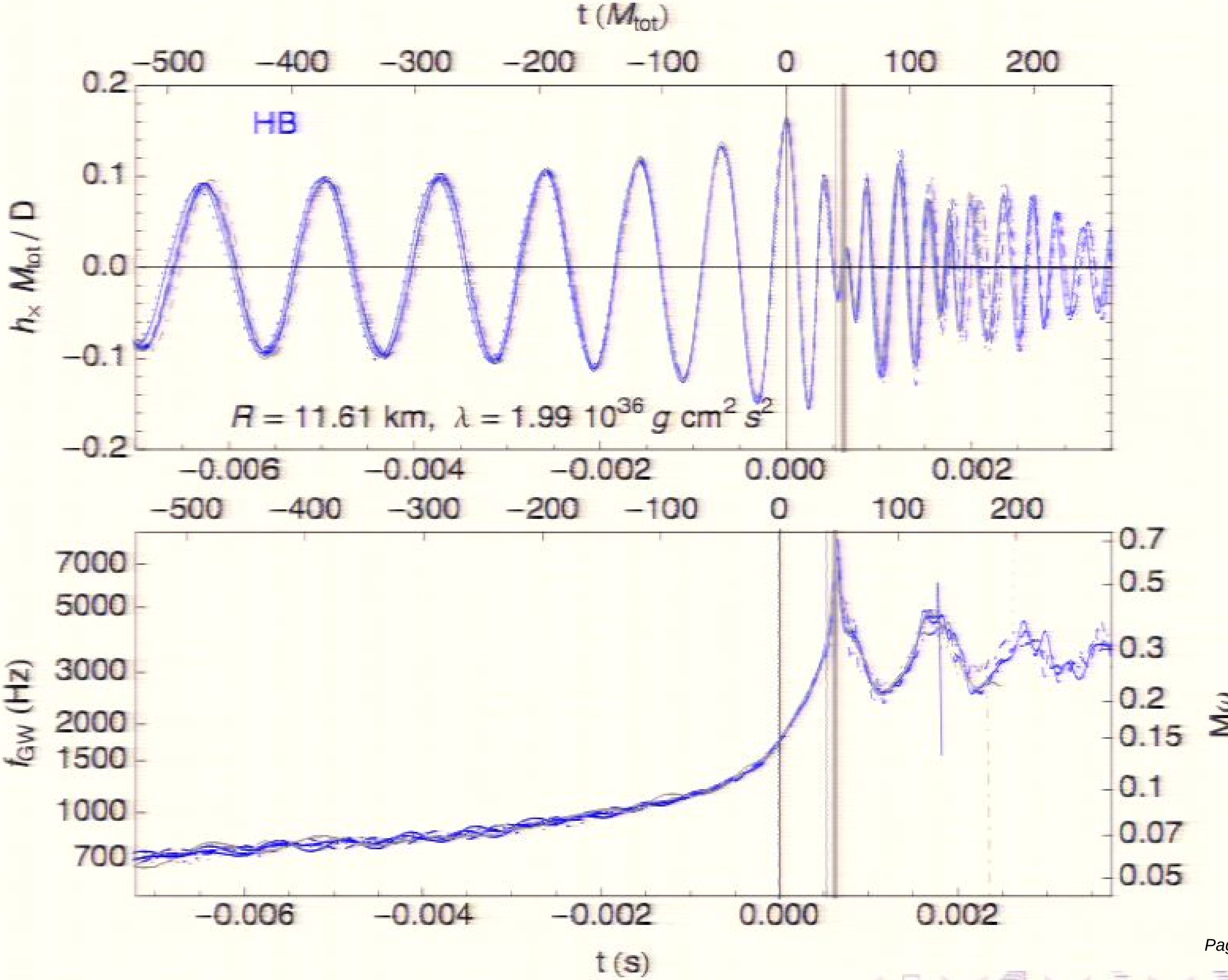


Merger waveform agreement



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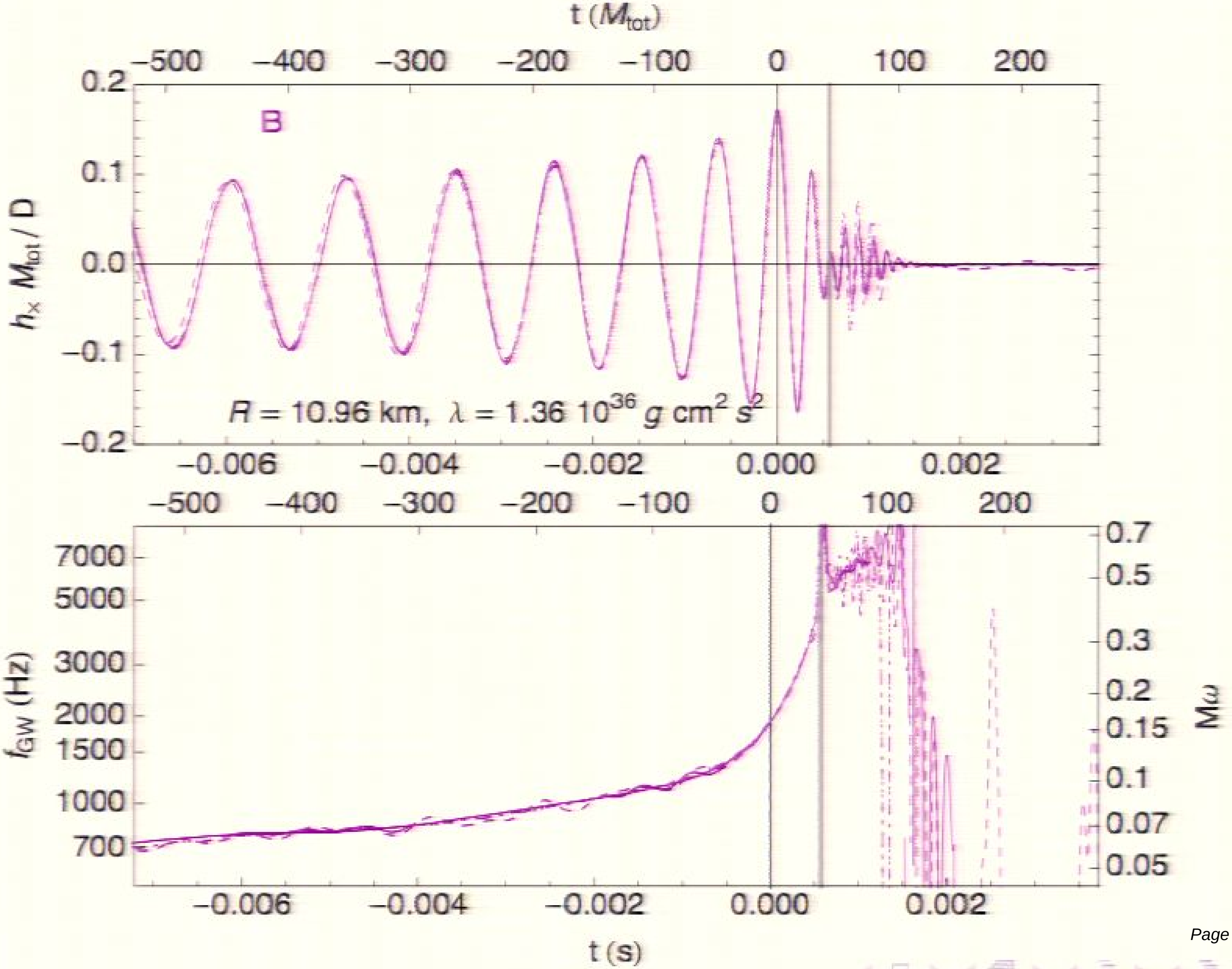

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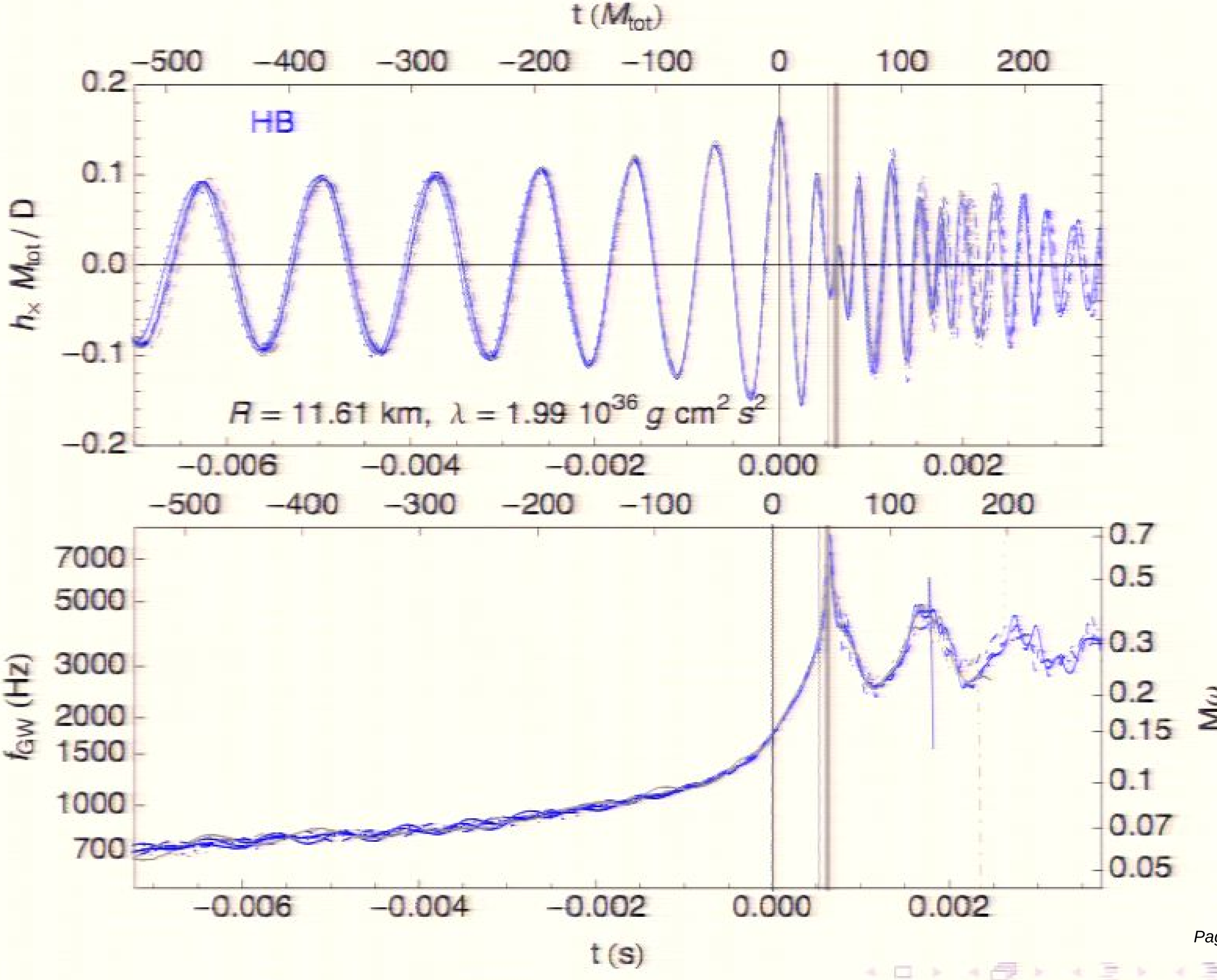

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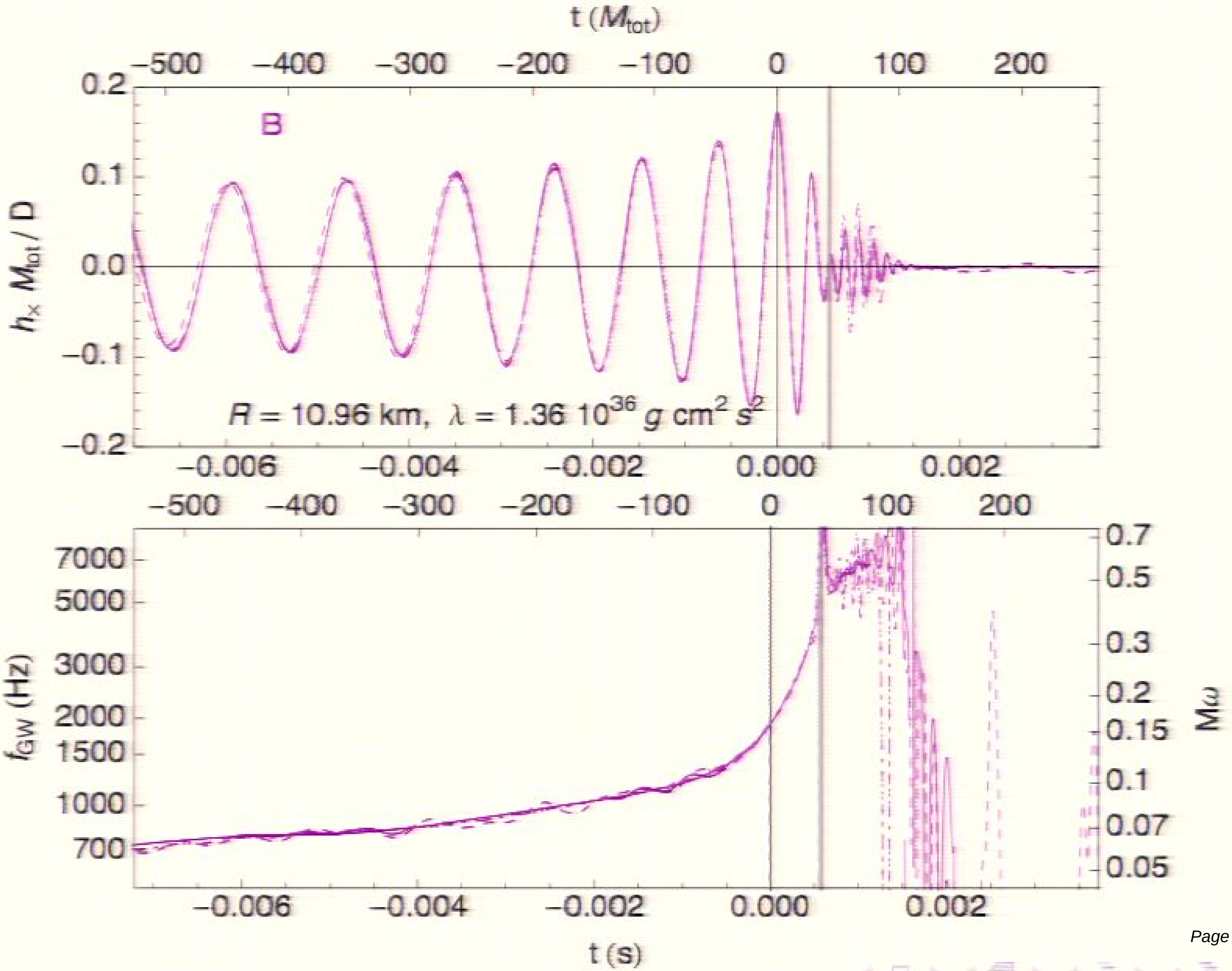

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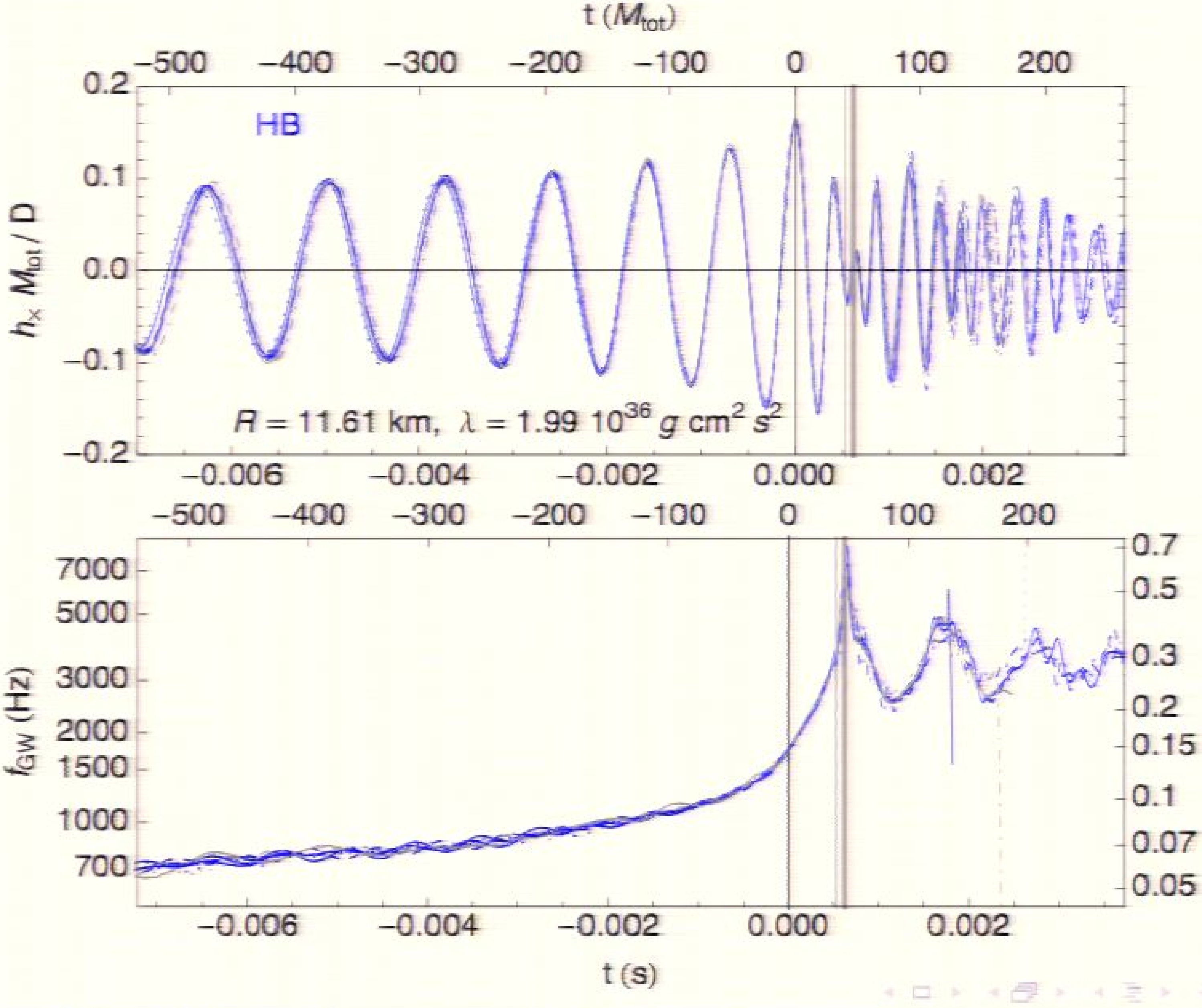

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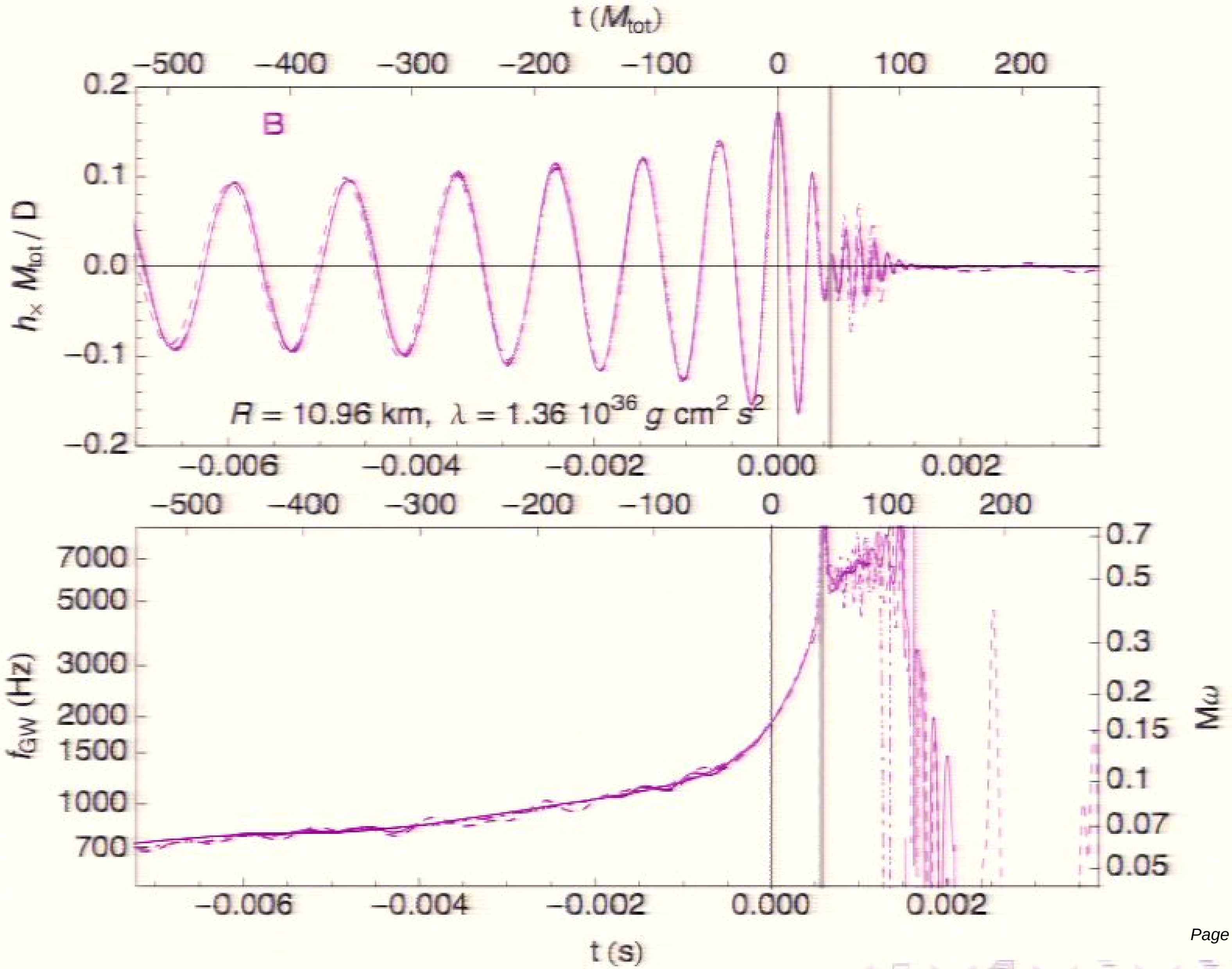

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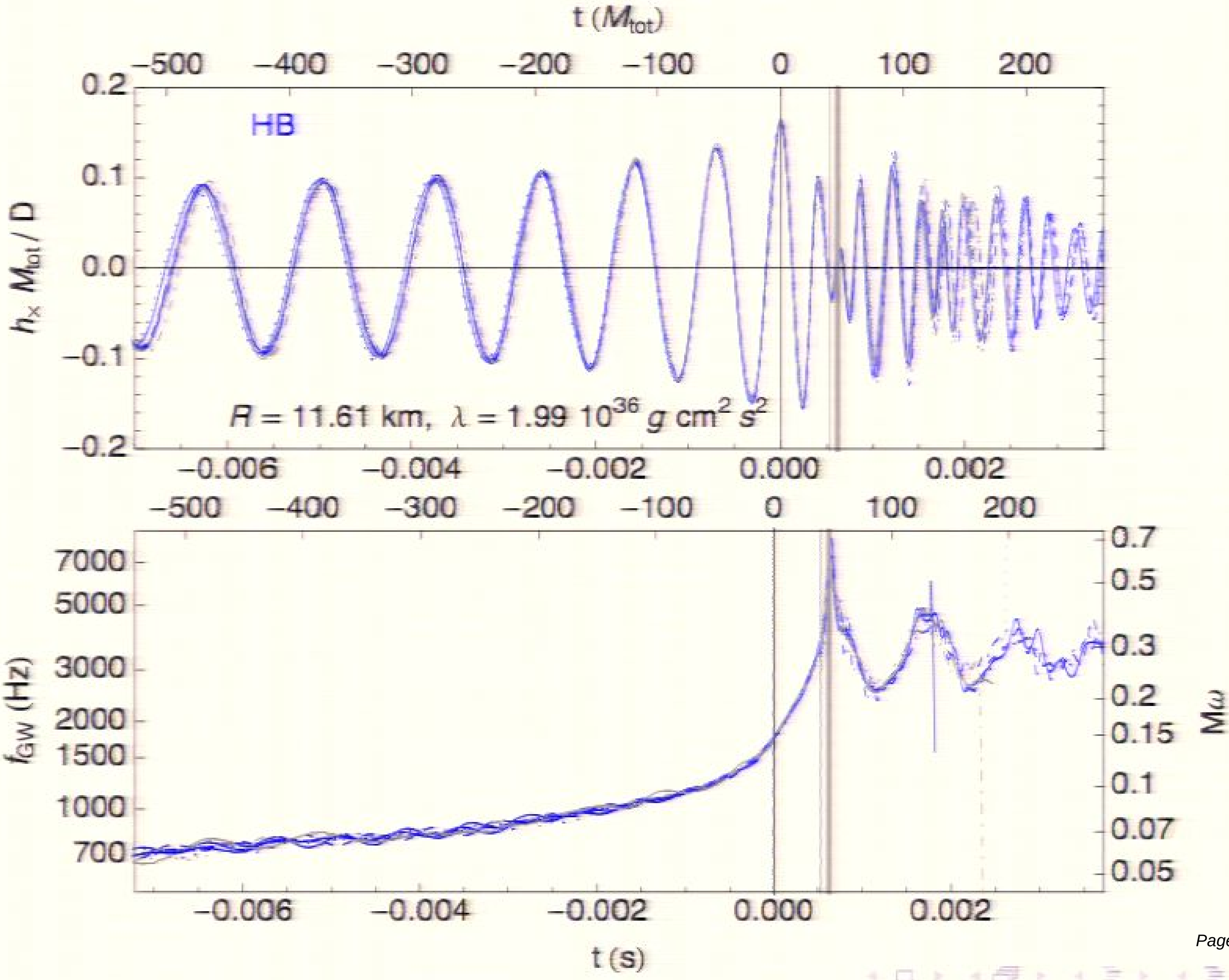

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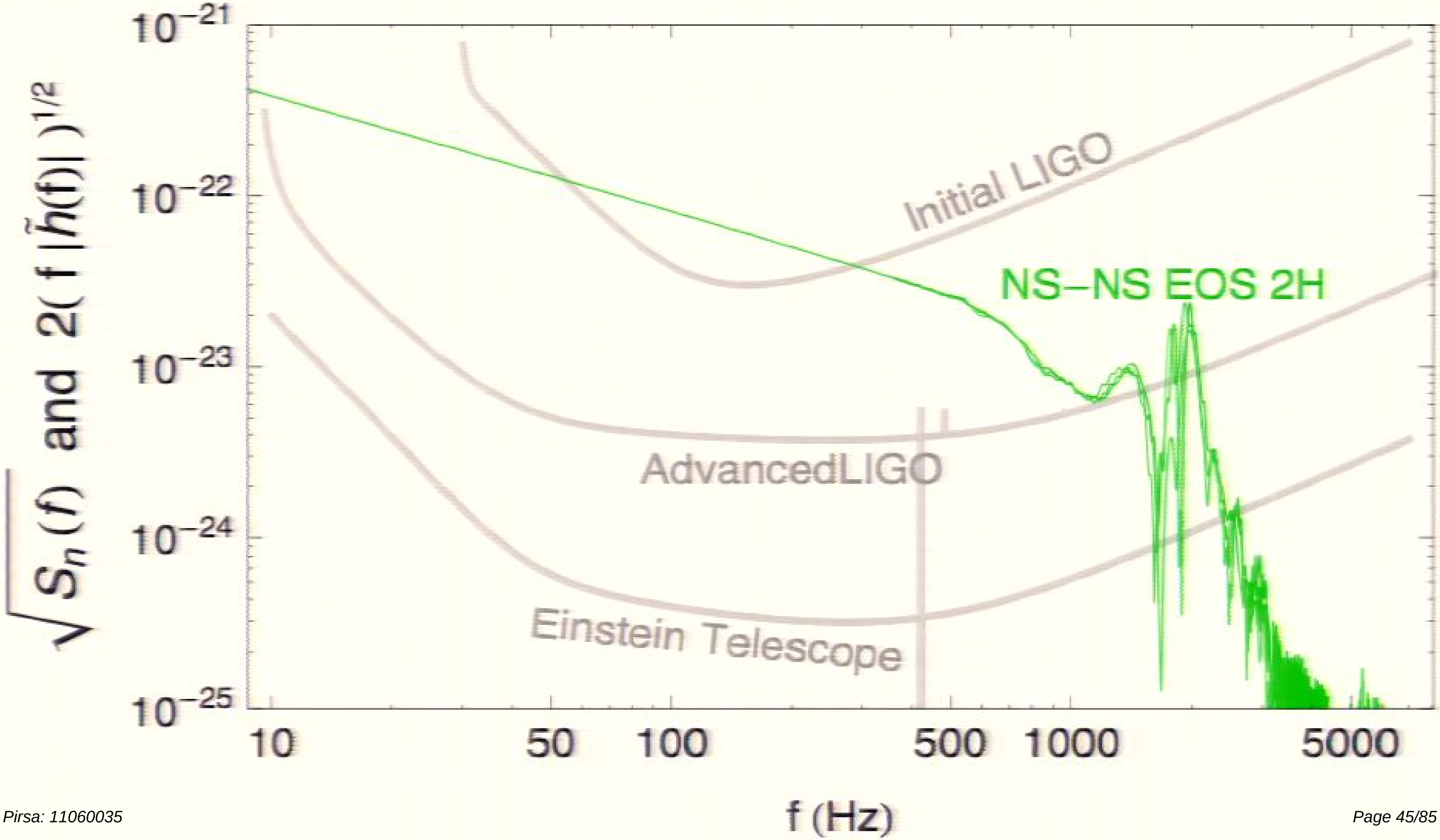

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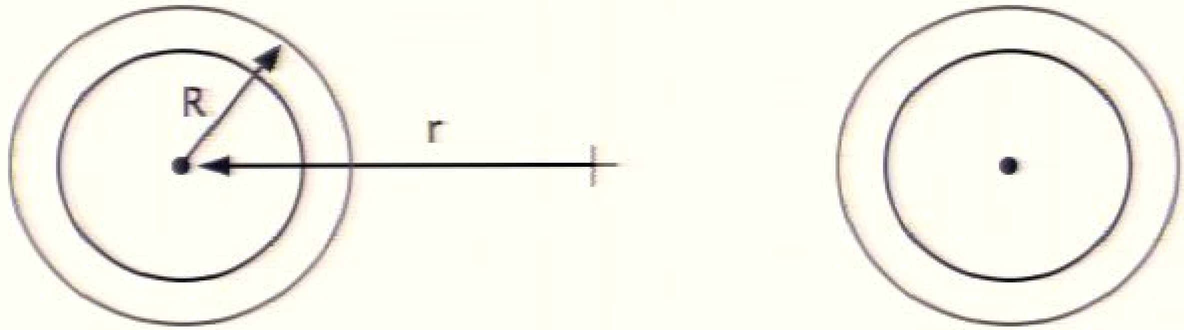
Incorporate first order tidal correction to post-Newtonian waveform



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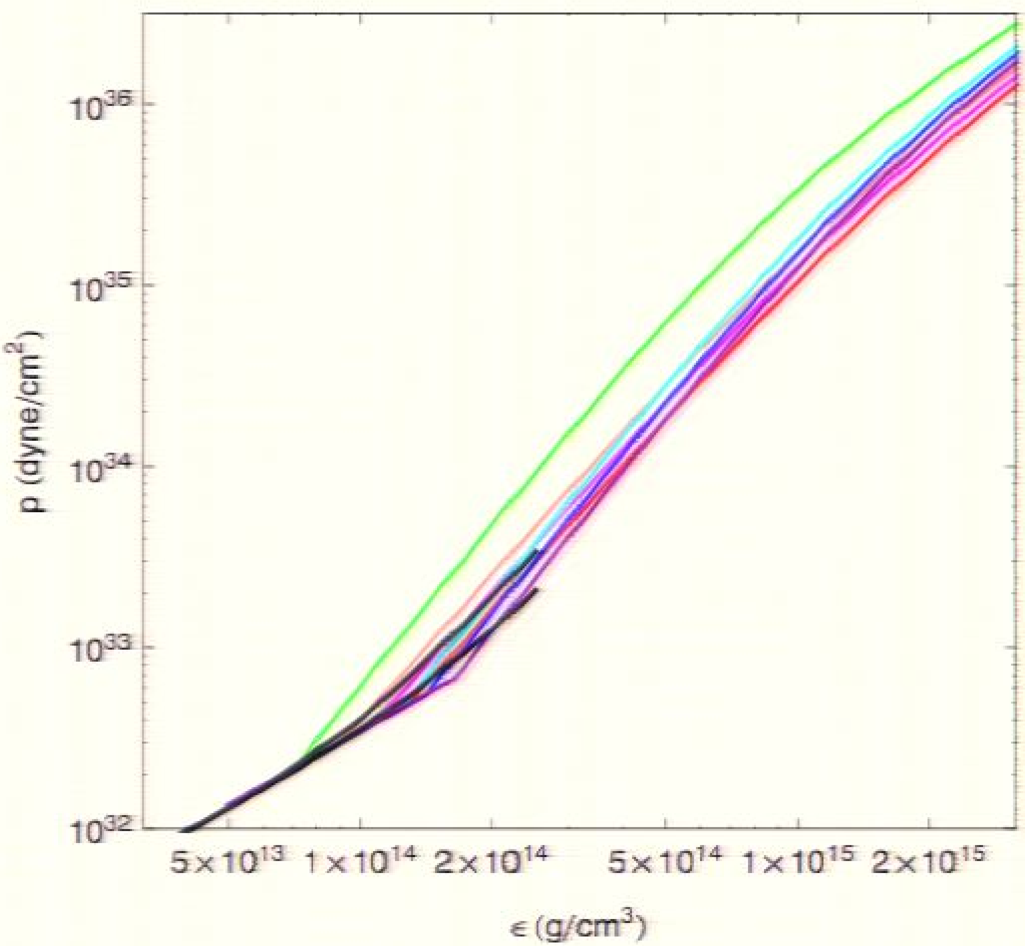
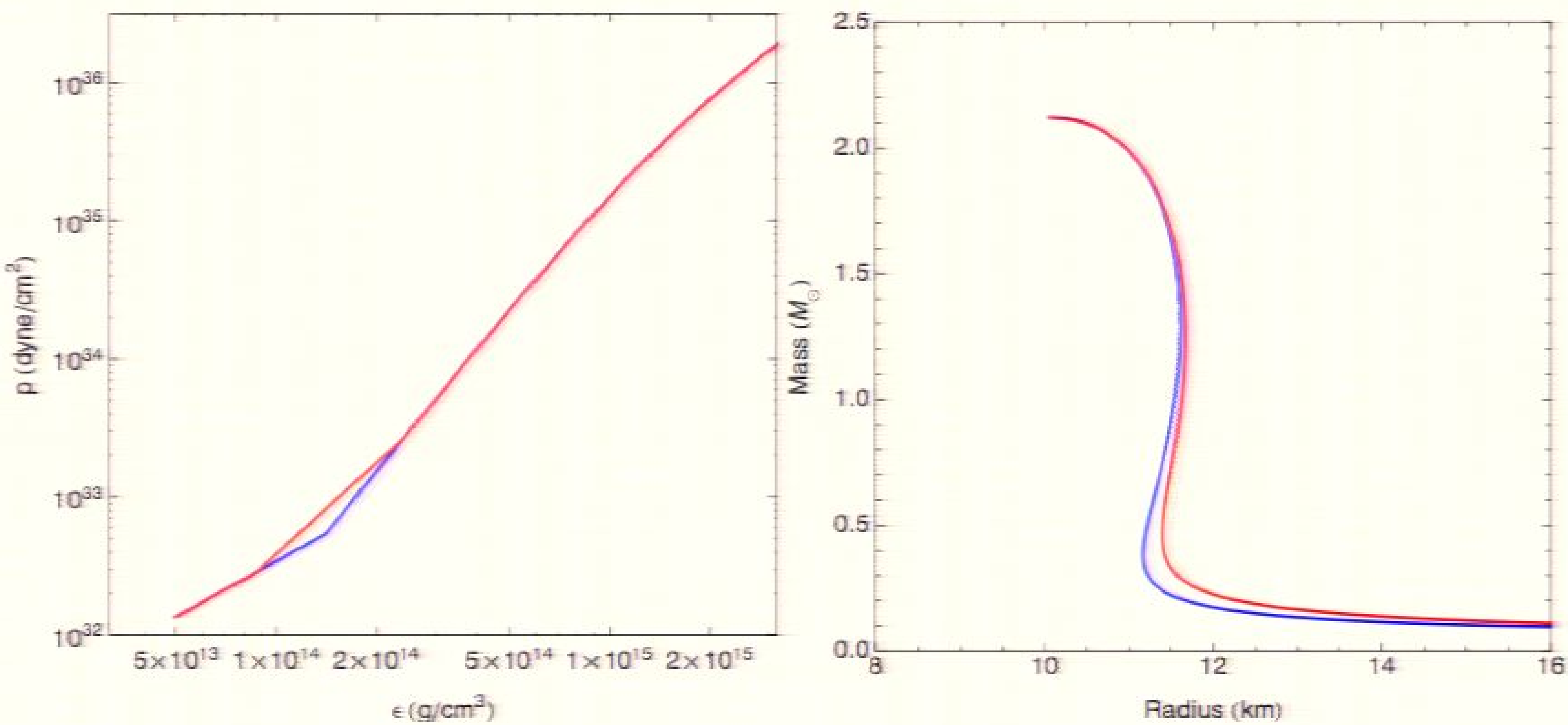
Evolve orbit using balance of luminosity and orbital energy Flanagan and Hinderer 2008

What about nuclear physics constraints?

Comparison with Hebeler et al EOS constraint:



Effect of low density EOS on relevant characteristics



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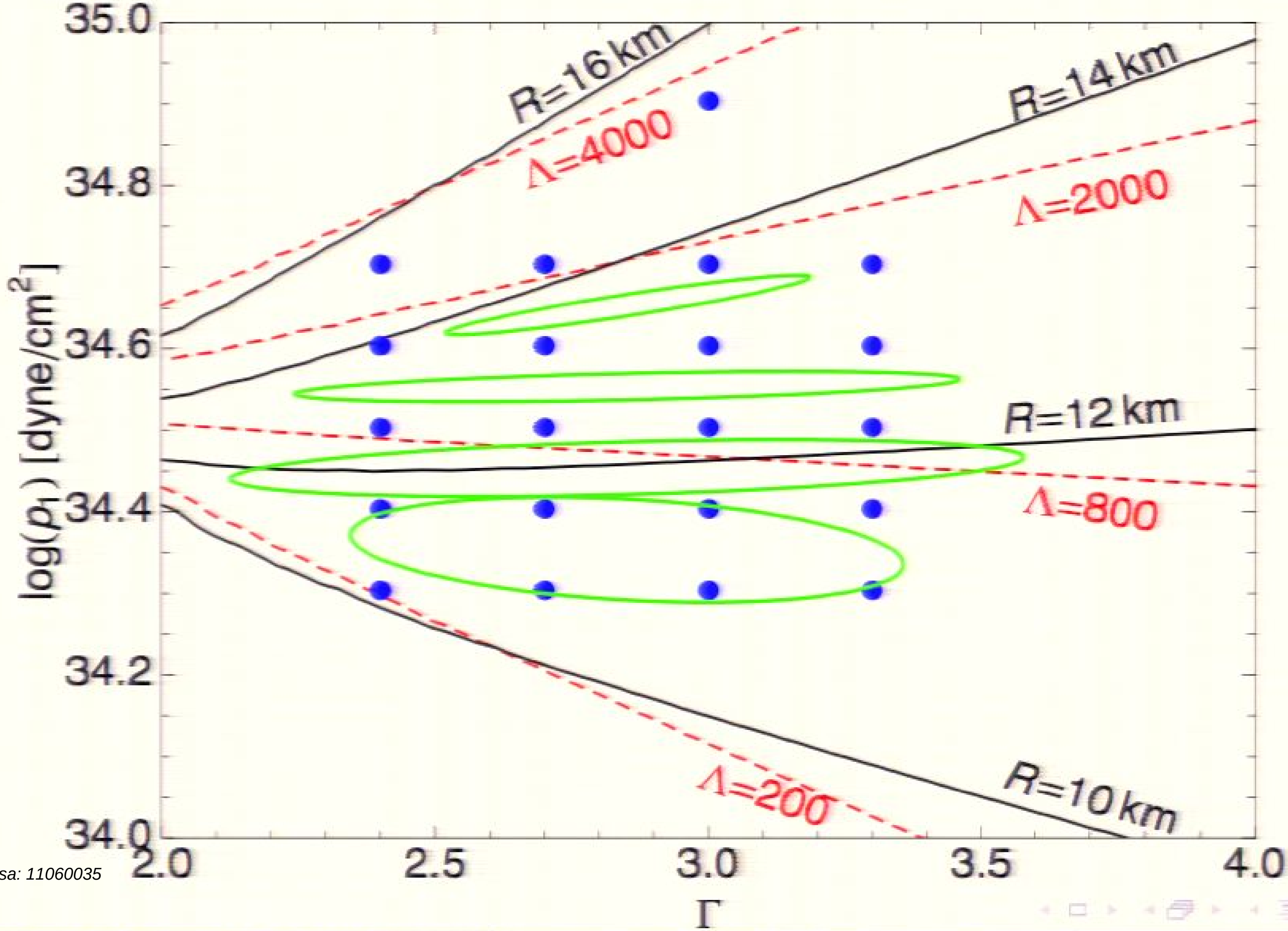

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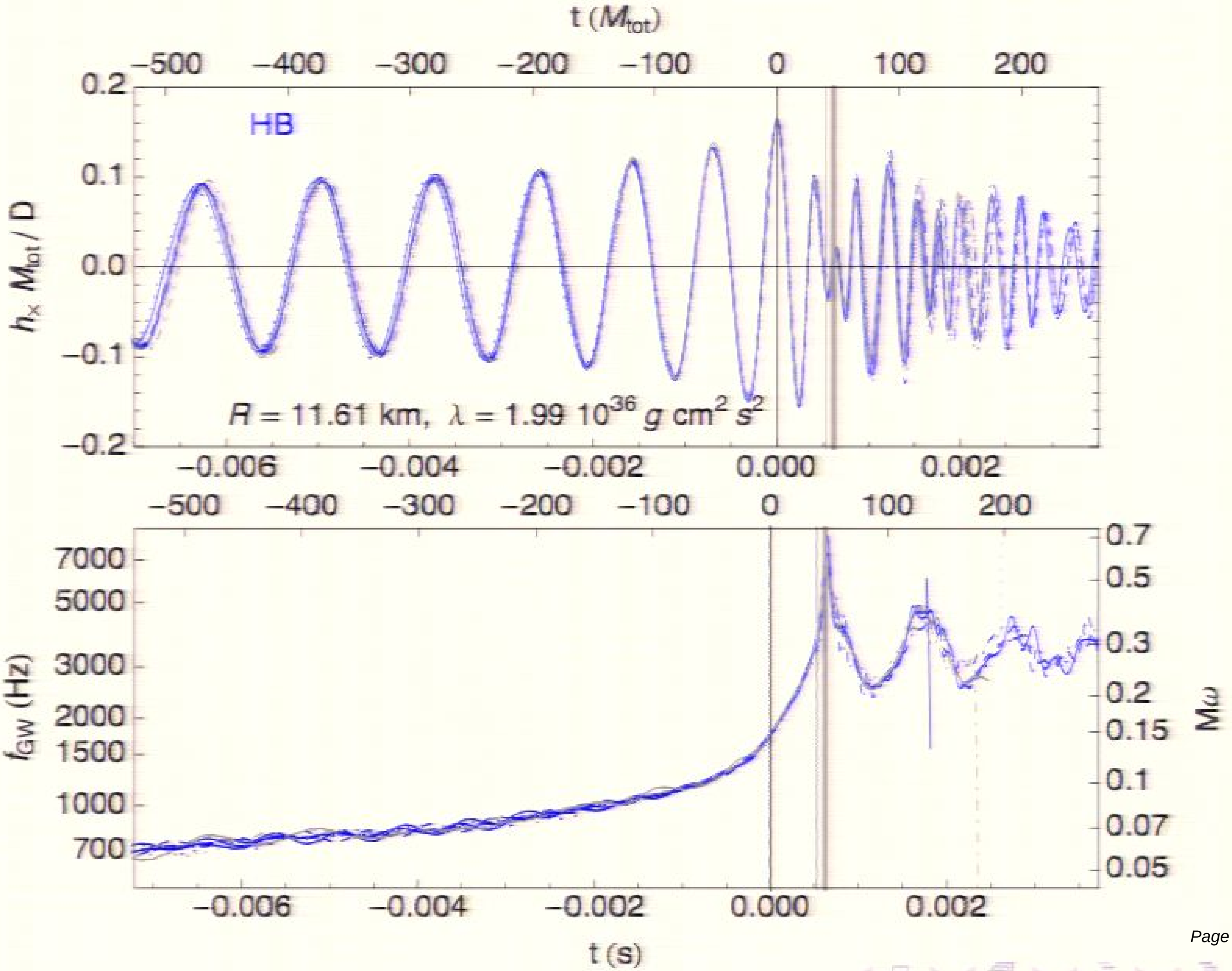
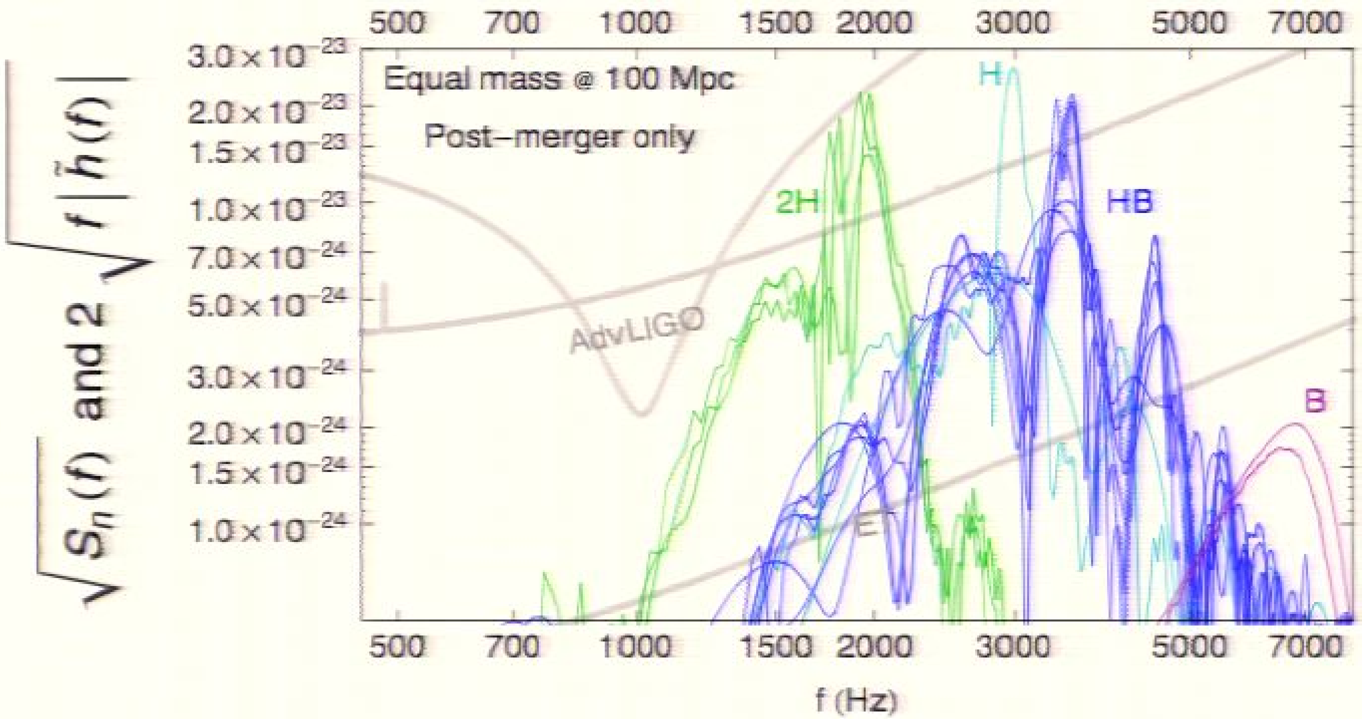


Independent measurability of post-merger signal?



Hypermassive Remnant	ET SNR	Prompt collapse	ET SNR
EOS 2H	$\sim$7	EOS B	$<$1
EOS H	$\sim$4.5		
EOS HB	$\sim$4		

These estimates are very dependent on the uncertain stability of the PM

Numerical WF measurability estimates: EOS effects

From 1.35-1.35$M_\odot$ DNS, optimally oriented, 100 Mpc away:

Numerical waveforms alone:

$\langle \delta R \rangle$, R is radius of isolated neutron star

	Broadband AdLIGO	ET-D
$R = 10.8$	± 0.9 km	± 0.09 km
$R = 11.9$	± 0.8 km	± 0.10 km

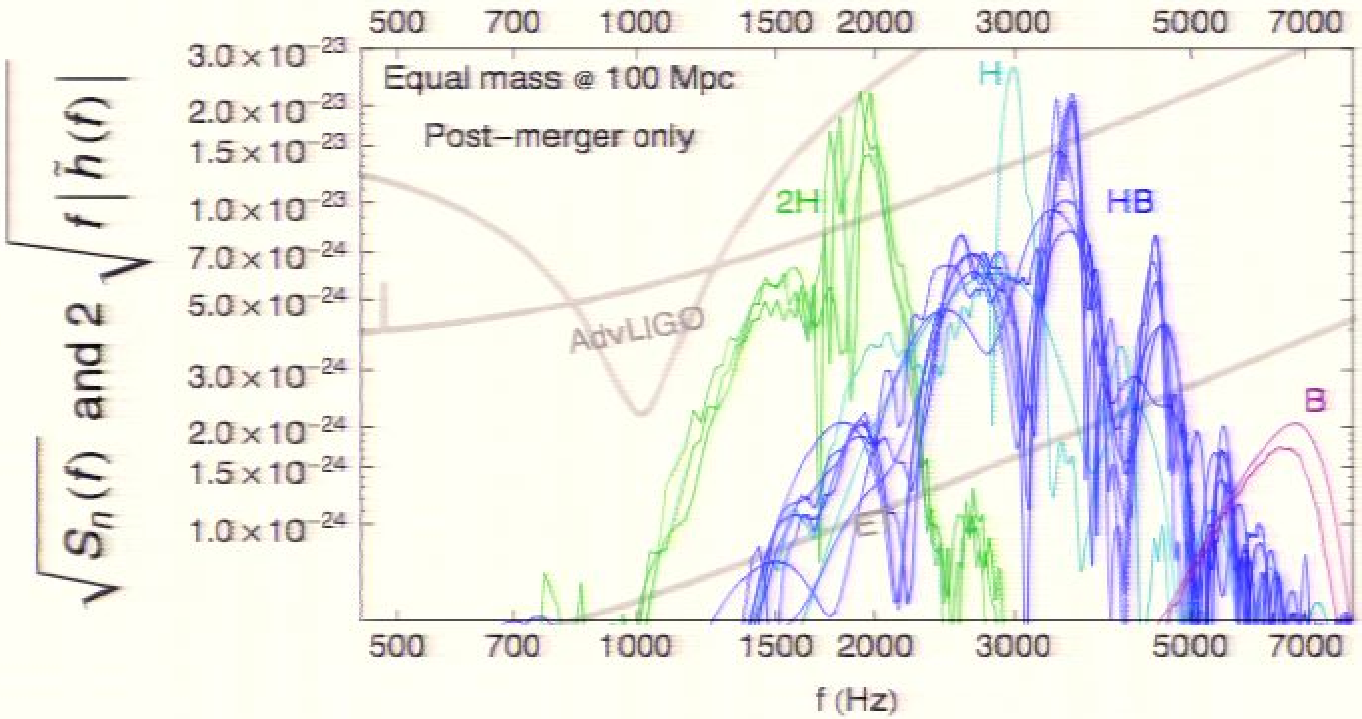
Hybrid construction including PN effects:

$\langle \delta R \rangle$, R is radius of isolated neutron star

	Broadband AdLIGO	ET-D
$R = 13.42$	± 0.50 km	± 0.05 km

Caveats and systematics particularly important in hybrid construction

Independent measurability of post-merger signal?



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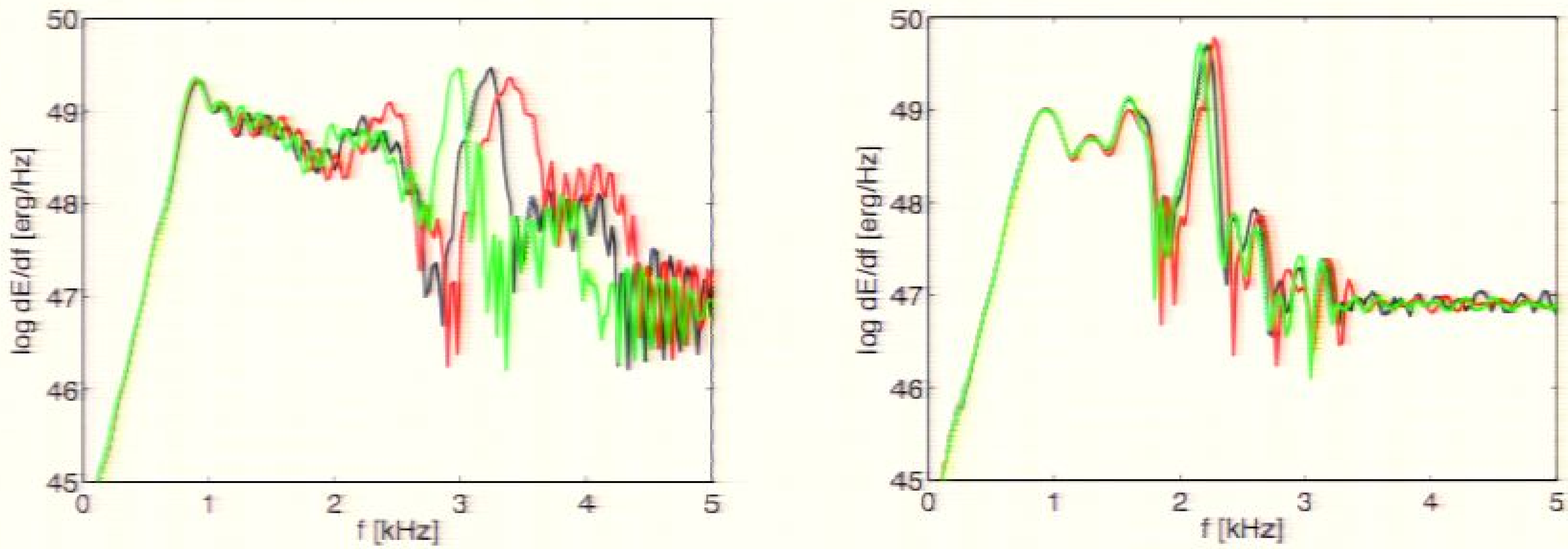
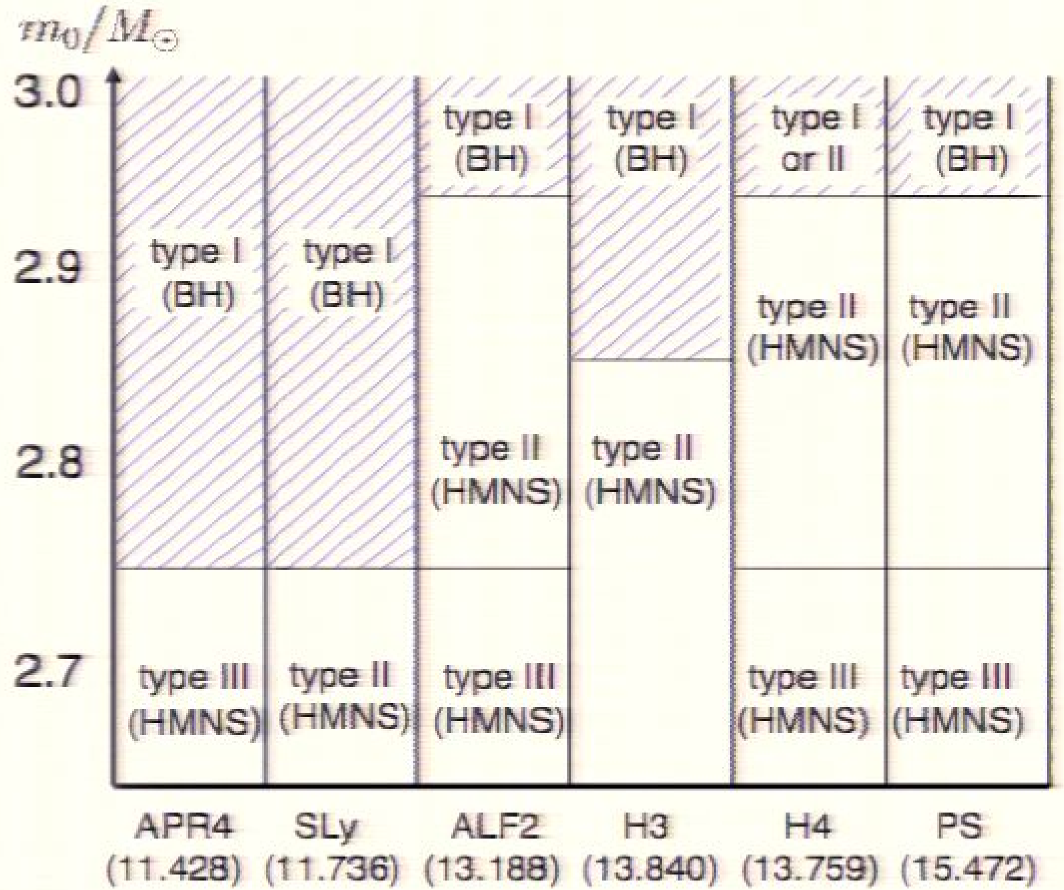
Heating and microphysics shifts the post-merger: Bauswein and Janka



Red/Green: cold EOS and effective thermal pressure with fixed Γ with equilibrium composition.
Black: hot eos with composition fixed to initial values.

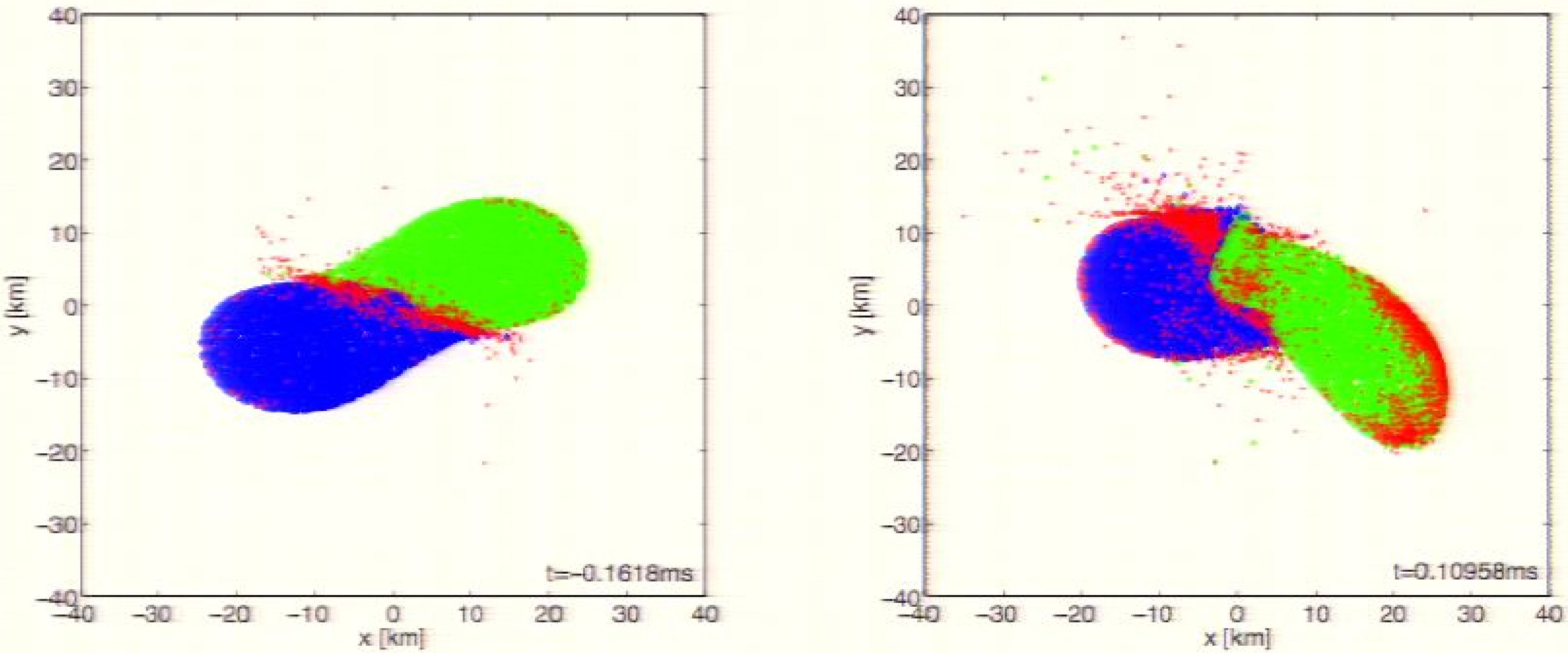
Impact of cold EOS on HMNS and torus formation: Hotokezaka et al 201



arxiv:1105.4370

Torus mass sensitive to: prompt collapse (Type I), short-lived HMNS (Typ II), or long-lived HMNS (Type II). Prompt collapse for $M_{\mathrm{tot}} \gtrsim 1.5 M_{\mathrm{max}}$

Ejecta?



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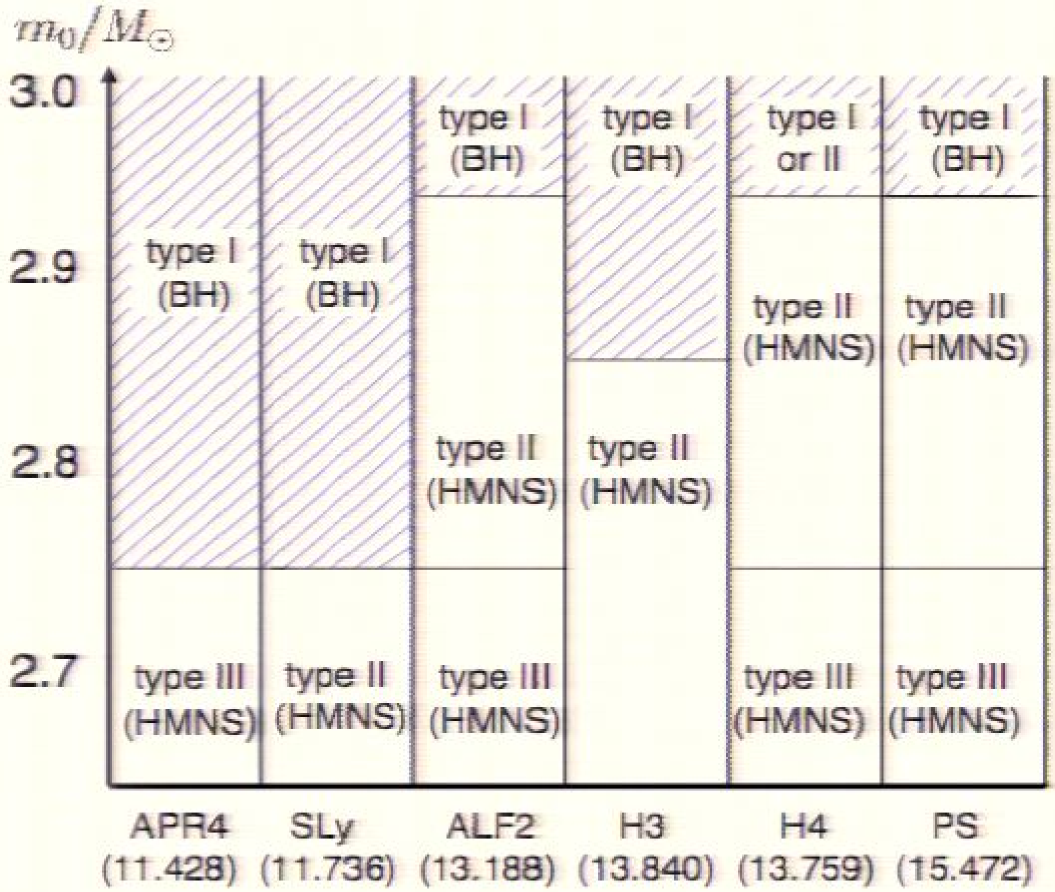
Oechslin, Janka, Marek 2006; hot EOS

Impact of cold EOS on HMNS and torus formation: Hotokezaka et al 201



arxiv:1105.4370

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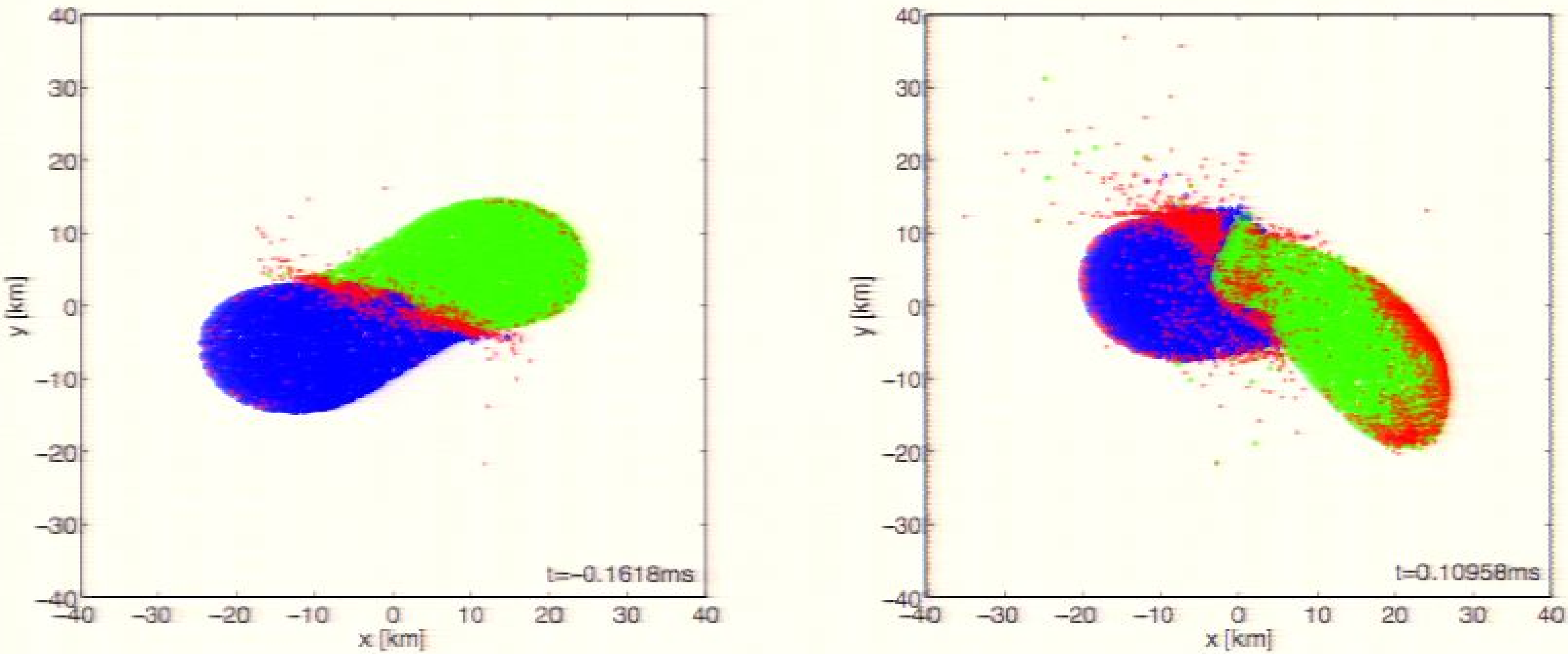

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Exploring equations of state using neutron-star inspiral

Making things as simple as possible, but no simpler

Jocelyn Read
MICRA 2011

University of Mississippi

30 April 2011

Outline

Parameterization of the cold equation of state

Comparison of parameterized EOS used in simulations with current constraints

Effect of cold EOS on inspiral

Effect of cold EOS on numerical simulations

Measurability estimates

Goal: Find a systematic way to characterize the set of candidate equatio
of state above nuclear density with a small number of parameters that ar
independent of the particular microphysical model and fitting errors
smaller than current uncertainties and expected constraints

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Numerical WF measurability estimates: EOS effects

From 1.35-1.35$M_\odot$ DNS, optimally oriented, 100 Mpc away:

Numerical waveforms alone:

$\langle \delta R \rangle$, R is radius of isolated neutron star

	Broadband AdLIGO	ET-D
$R = 10.8$	± 0.9 km	± 0.09 km
$R = 11.9$	± 0.8 km	± 0.10 km

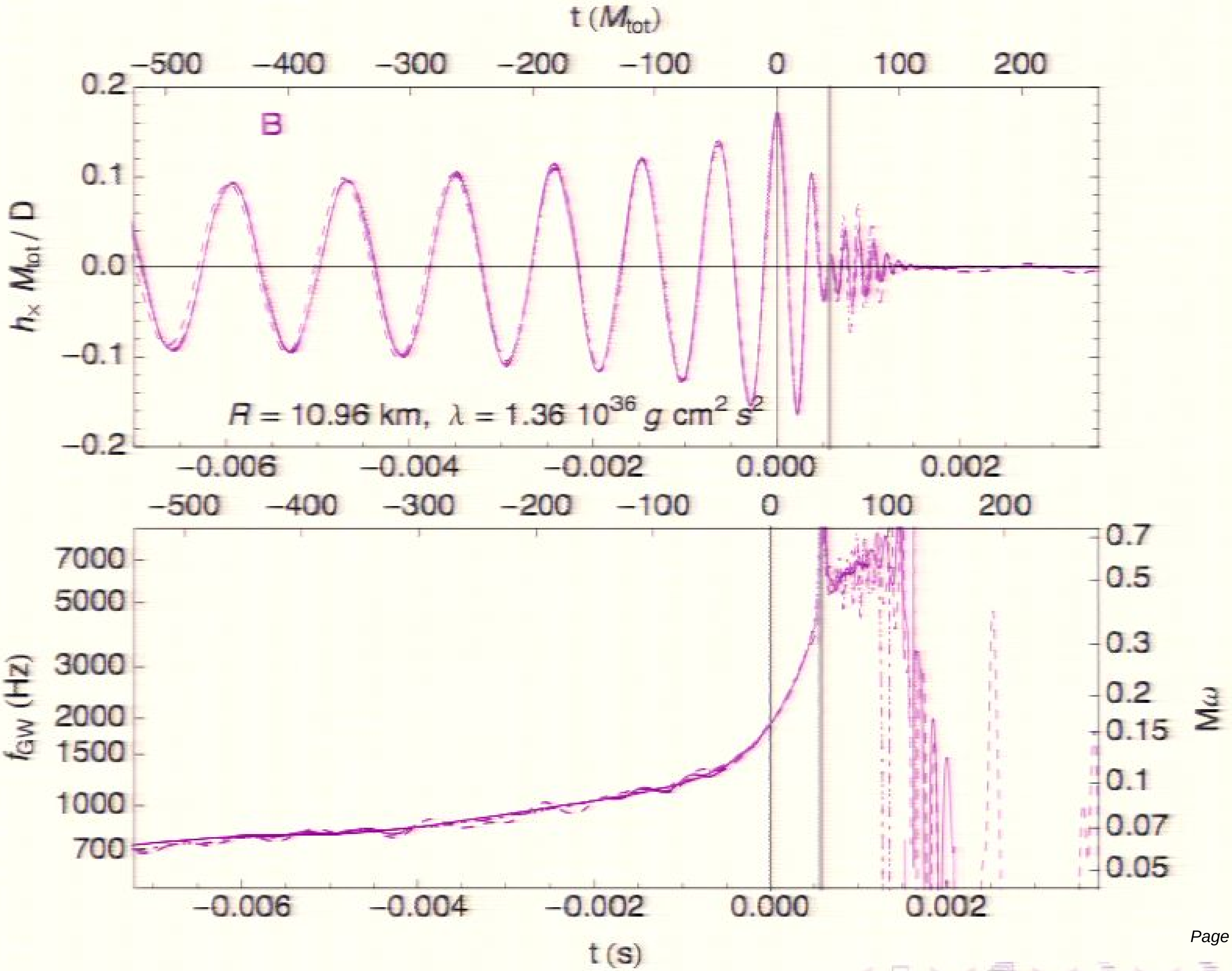
Hybrid construction including PN effects:

$\langle \delta R \rangle$, R is radius of isolated neutron star

	Broadband AdLIGO	ET-D
$R = 13.42$	± 0.50 km	± 0.05 km

Caveats and systematics particularly important in hybrid construction

Merger waveform agreement



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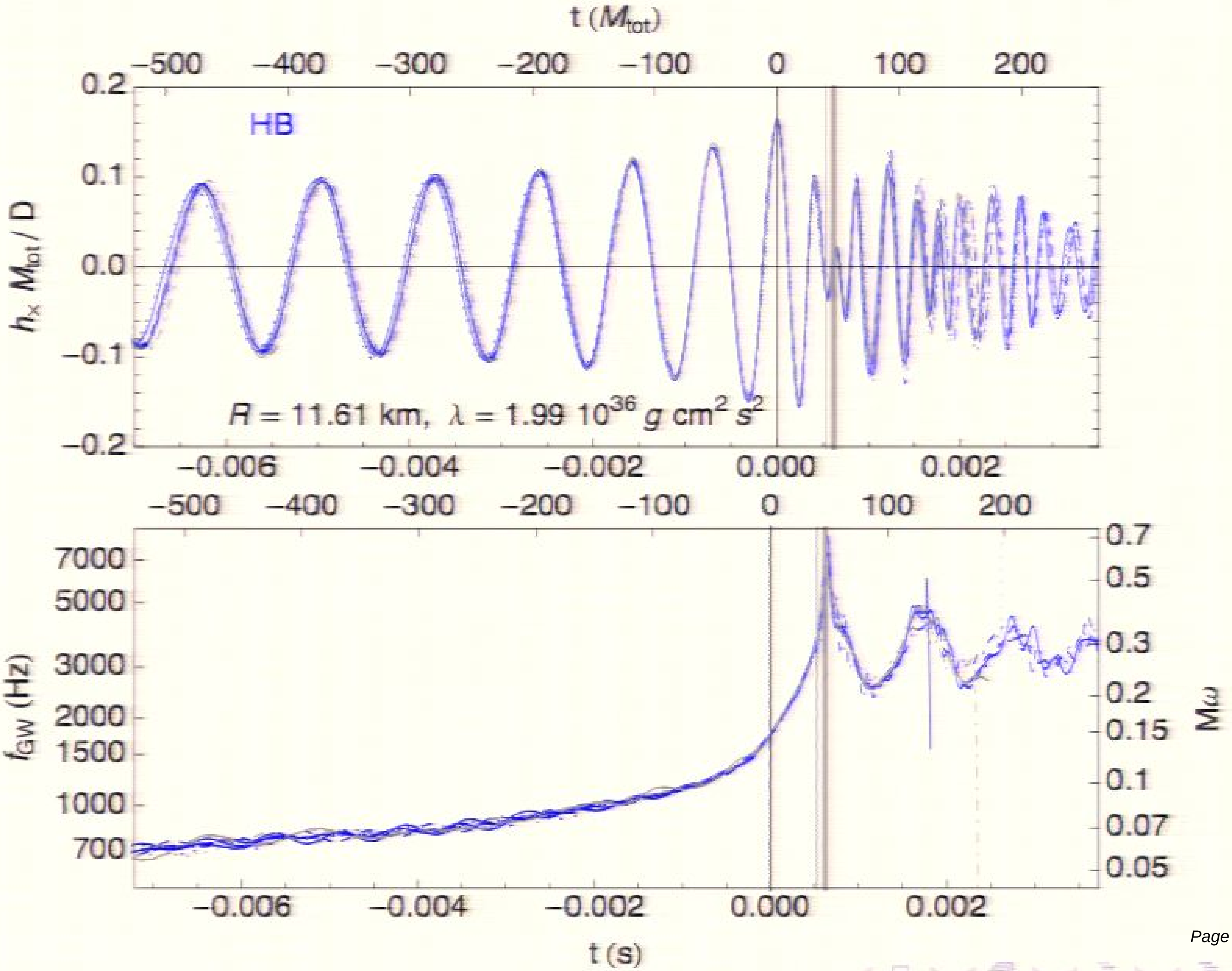

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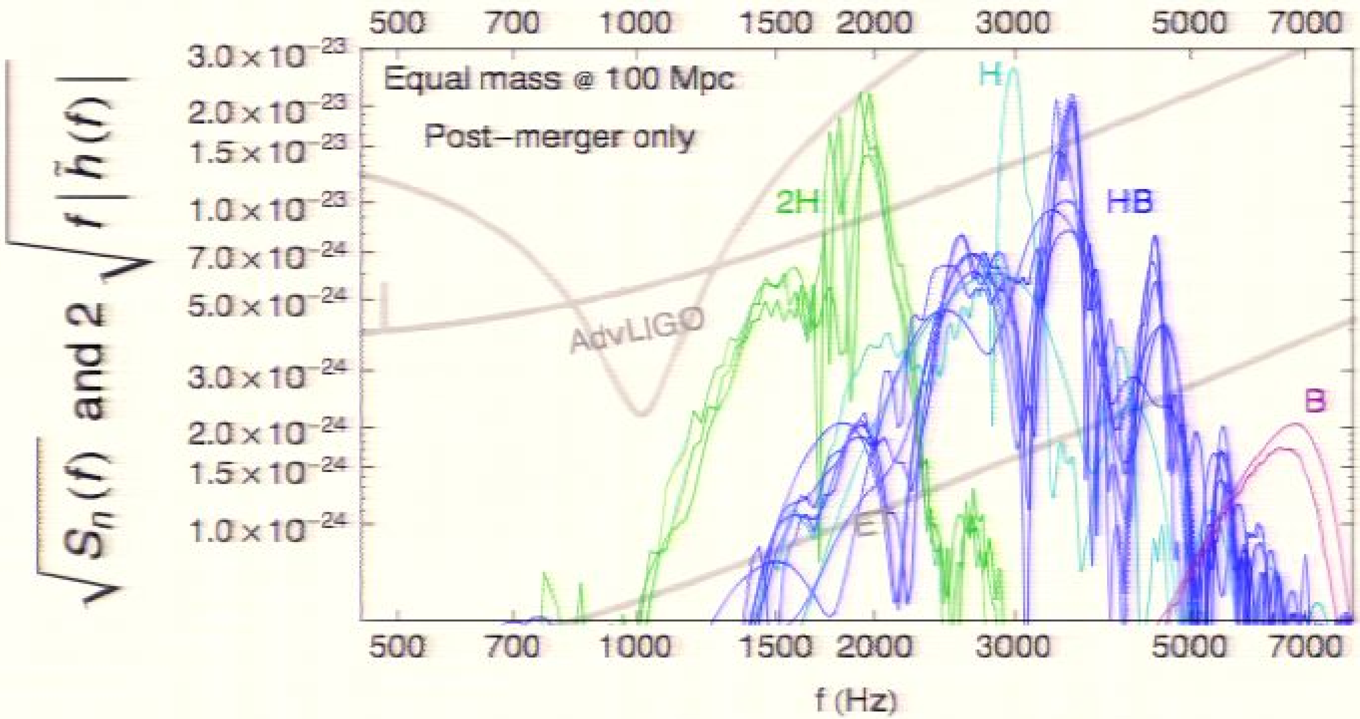
Caveats and systematics particularly important in hybrid construction

Independent measurability of post-merger signal?

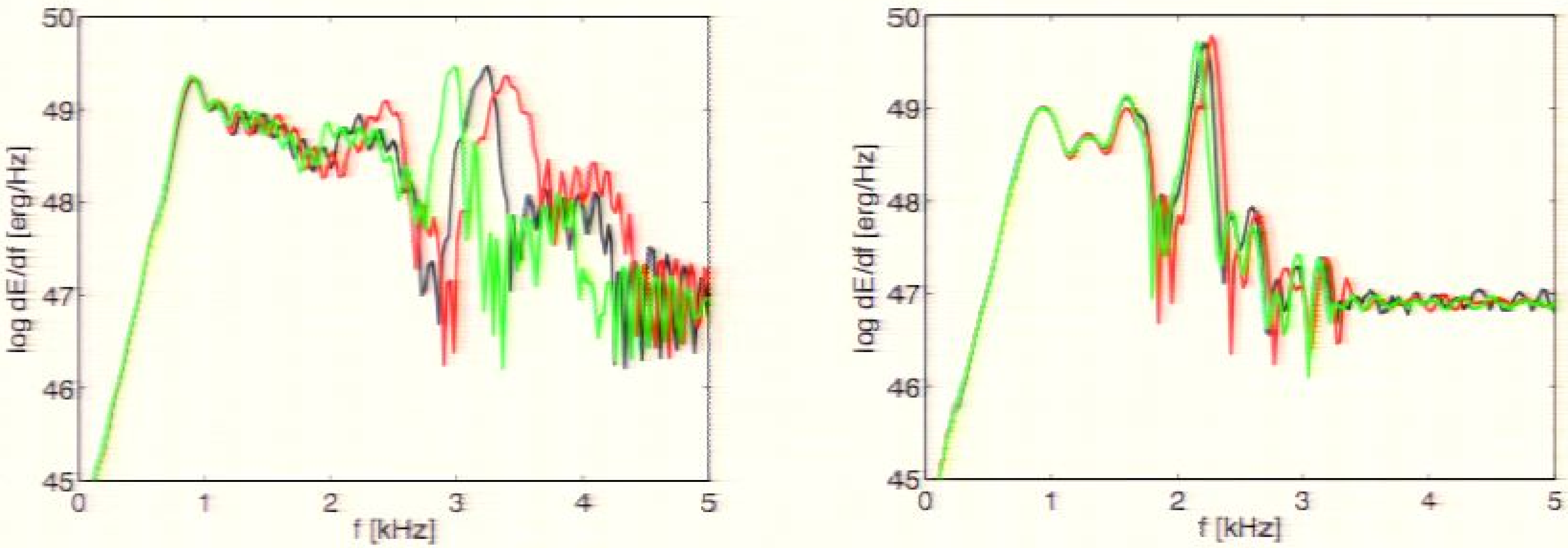


Hypermassive Remnant	ET SNR
EOS 2H	~7
EOS H	~4.5
EOS HB	~4

Prompt collapse	ET SNR
EOS B	<1

These estimates are very dependent on the uncertain stability of the PM

Heating and microphysics shifts the post-merger: Bauswein and Janka



Red/Green: cold EOS and effective thermal pressure with fixed Γ with equilibrium composition.
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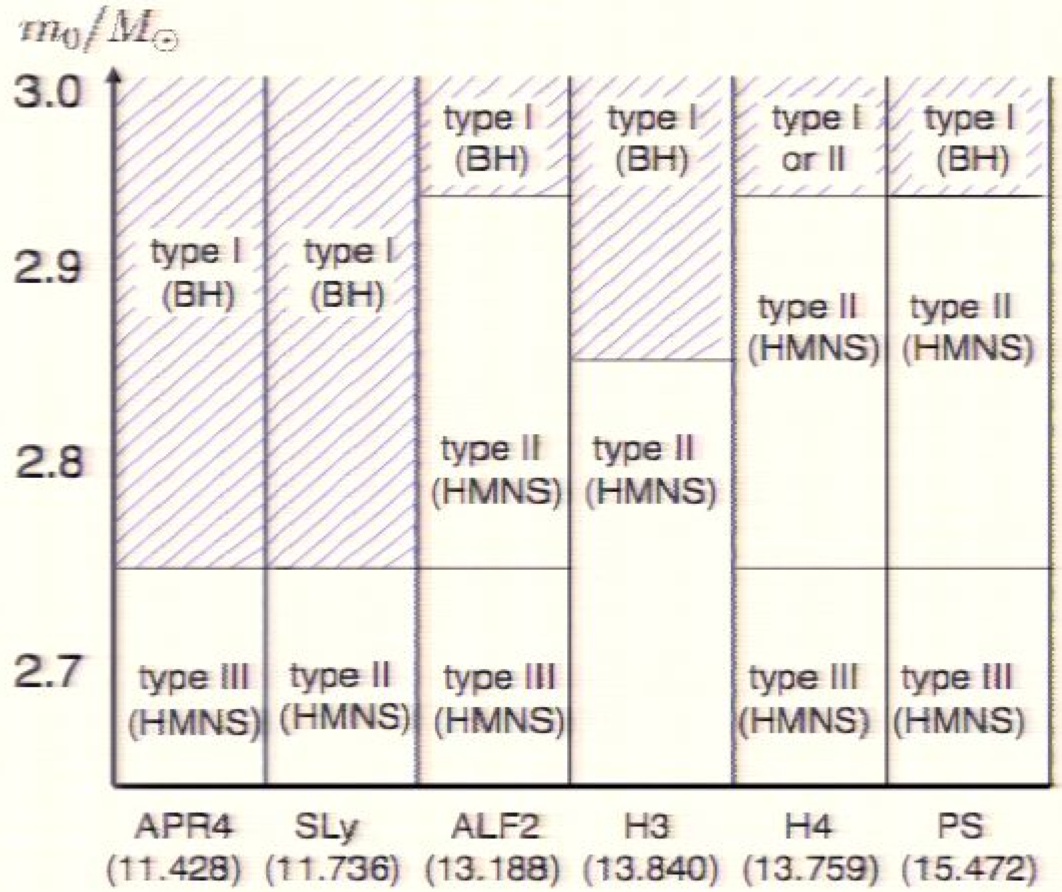
Impact of cold EOS on HMNS and torus formation: Hotokezaka et al 201



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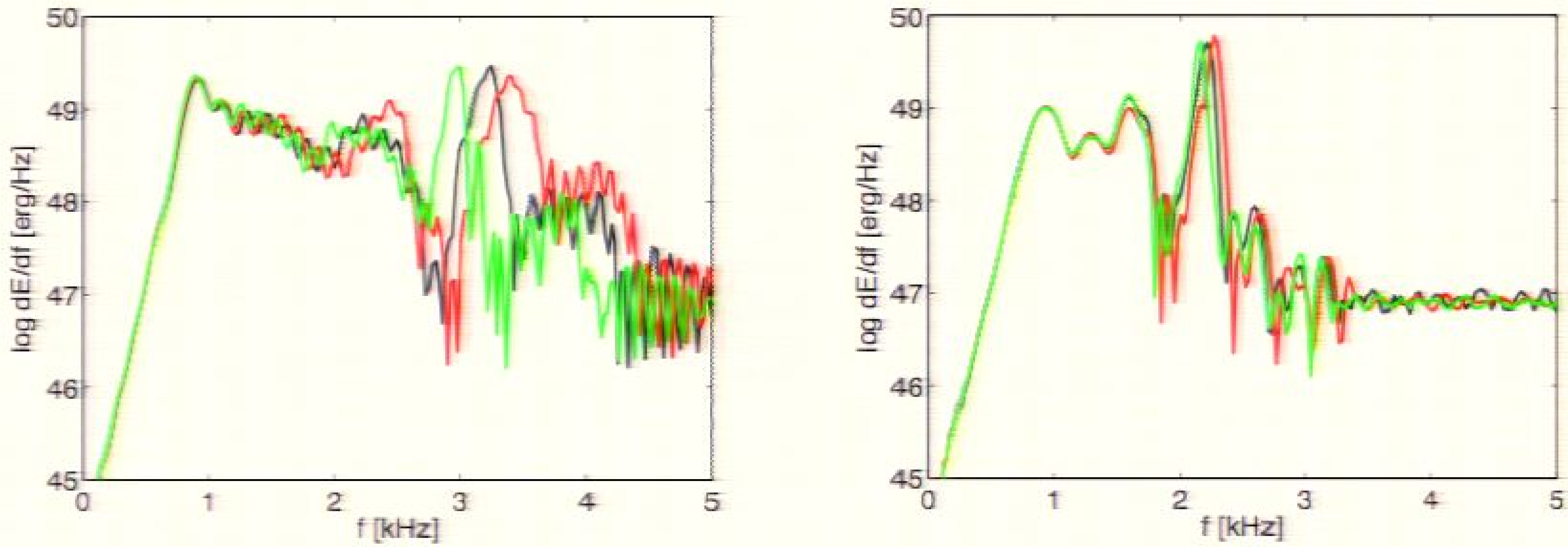

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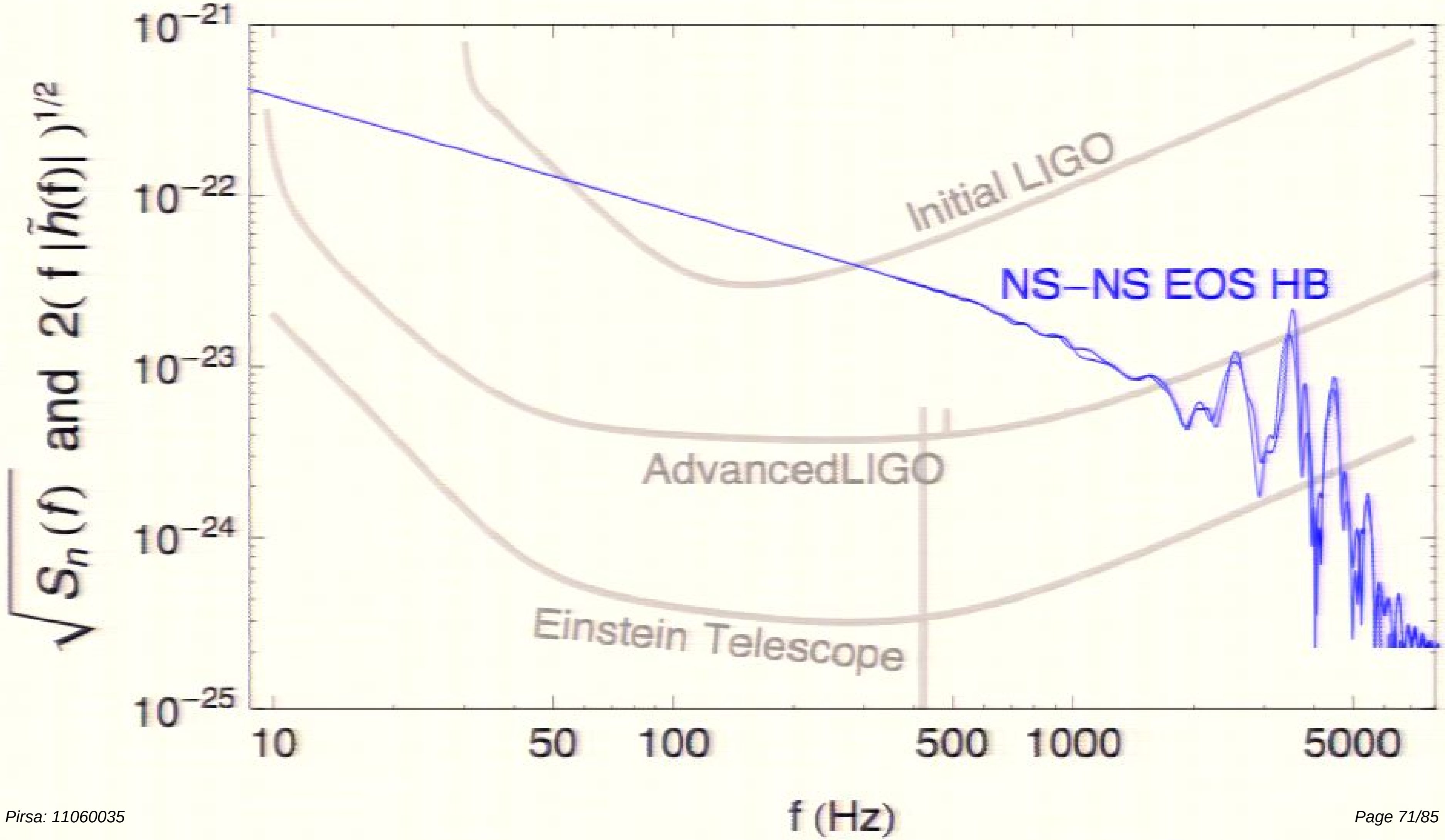
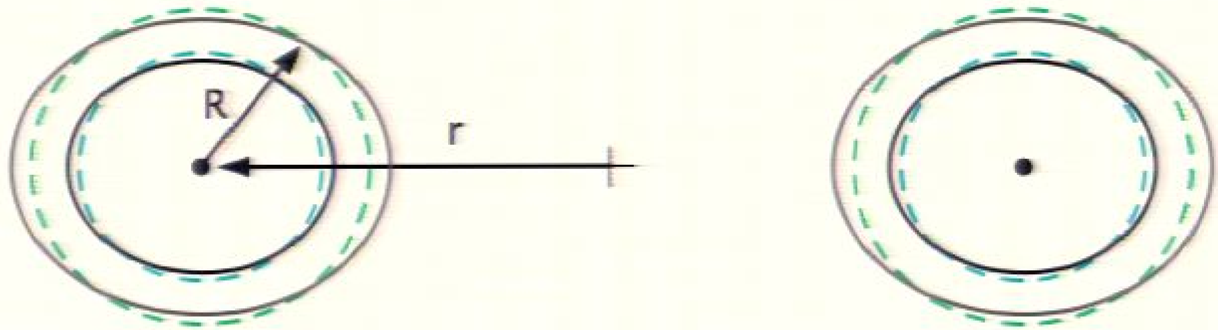
Numerical simulation of binary neutron stars

SACRA and Whisky codes, multiple resolutions
(codes compared in arxiv:1007.1754)



Effect of matter on inspiral

Incorporate first order tidal correction to post-Newtonian waveform



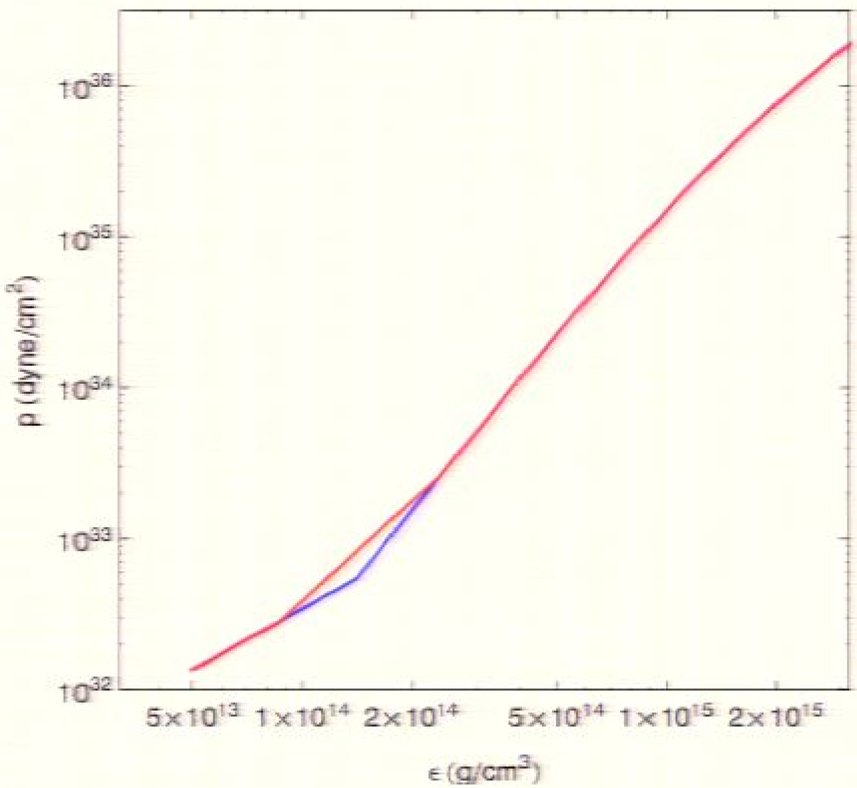
$$E = -\frac{1}{2}\left(\frac{Gm\mu}{r}\right)\left(1 + [\mathrm{PN}] - \frac{1}{2} Q^1_{ij}\mathcal{E}^2_{ij} + 2 \leftrightarrow 1\right)$$

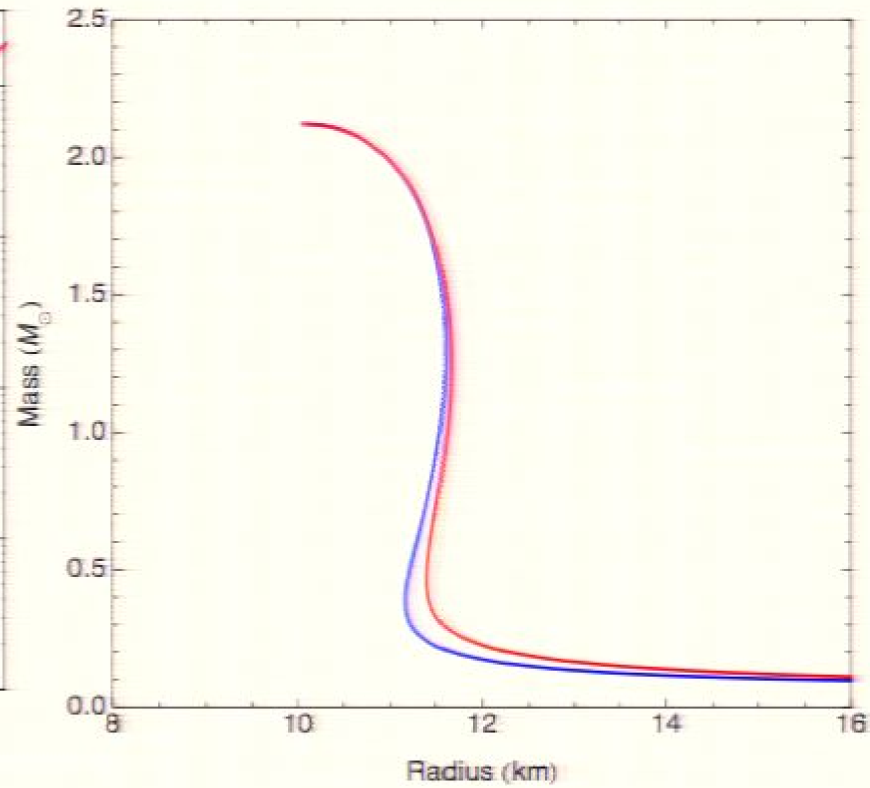
$$\dot{E}_{GW} = -\frac{32}{5}\frac{c^5}{G}\left(\frac{\mu}{m}\right)^2\left(\frac{Gm}{c^2 r}\right)^5\left(1 + [\mathrm{PN}] + \frac{1}{5}\langle \dddot{Q}^1_{ij}\dddot{Q}^1_{ij}\rangle + 2 \leftrightarrow 1\right)$$

$m = m_1 + m_2$
$\mu = m_1 m_2 / m$

Evolve orbit using balance of
luminosity and orbital energy
Flanagan and Hinderer 2008

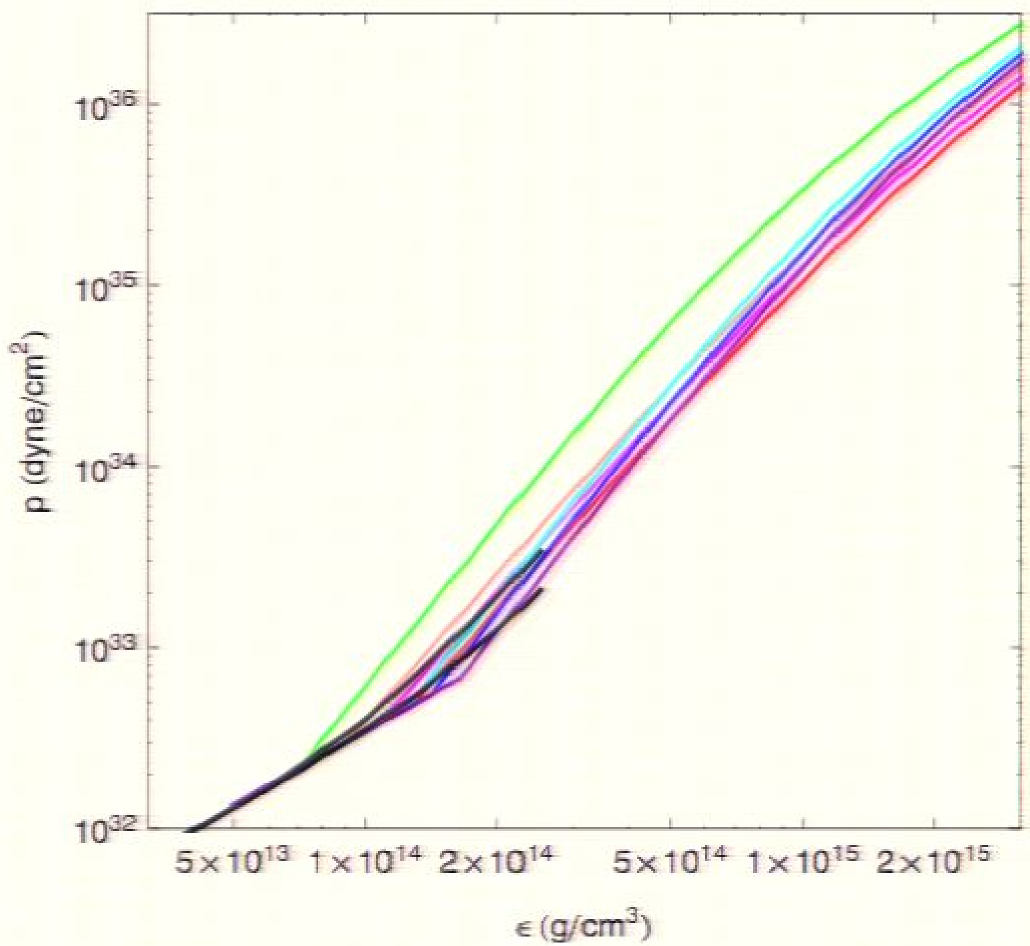
Effect of low density EOS on relevant characteristics





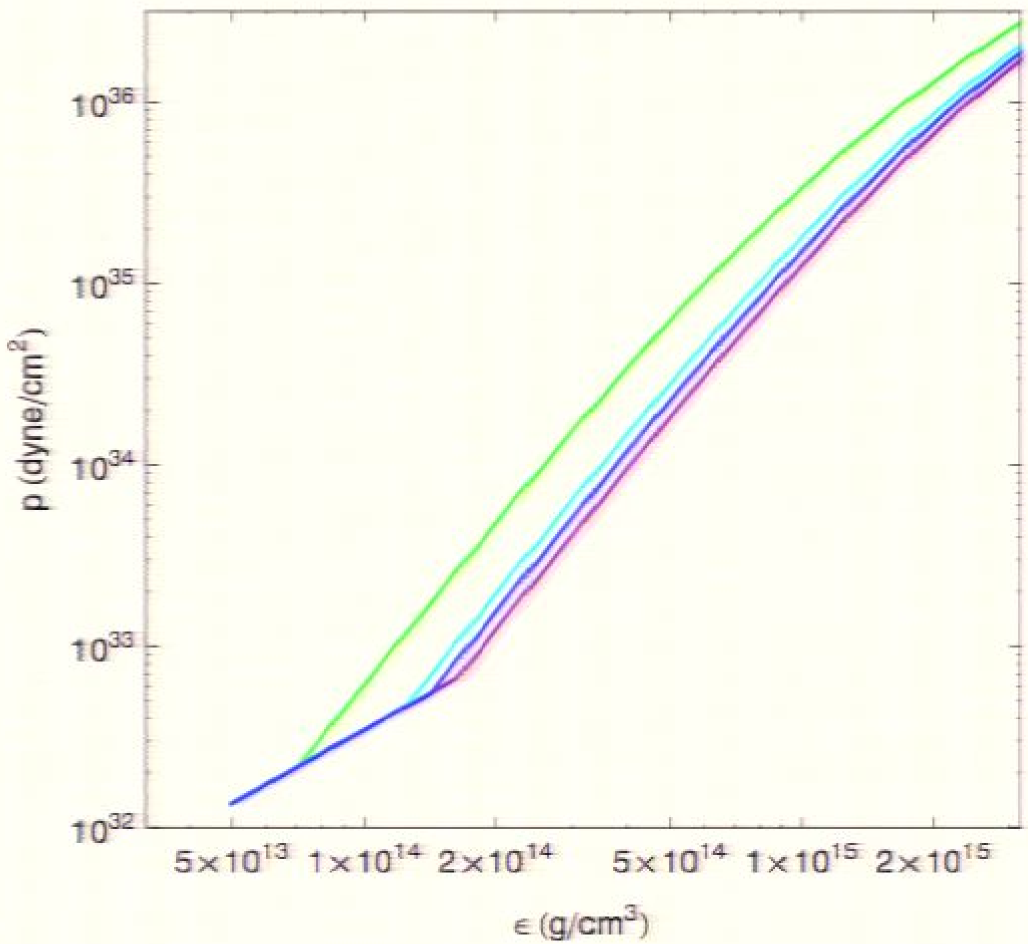
What about nuclear physics constraints?

Comparison with Hebeler et al EOS constraint:



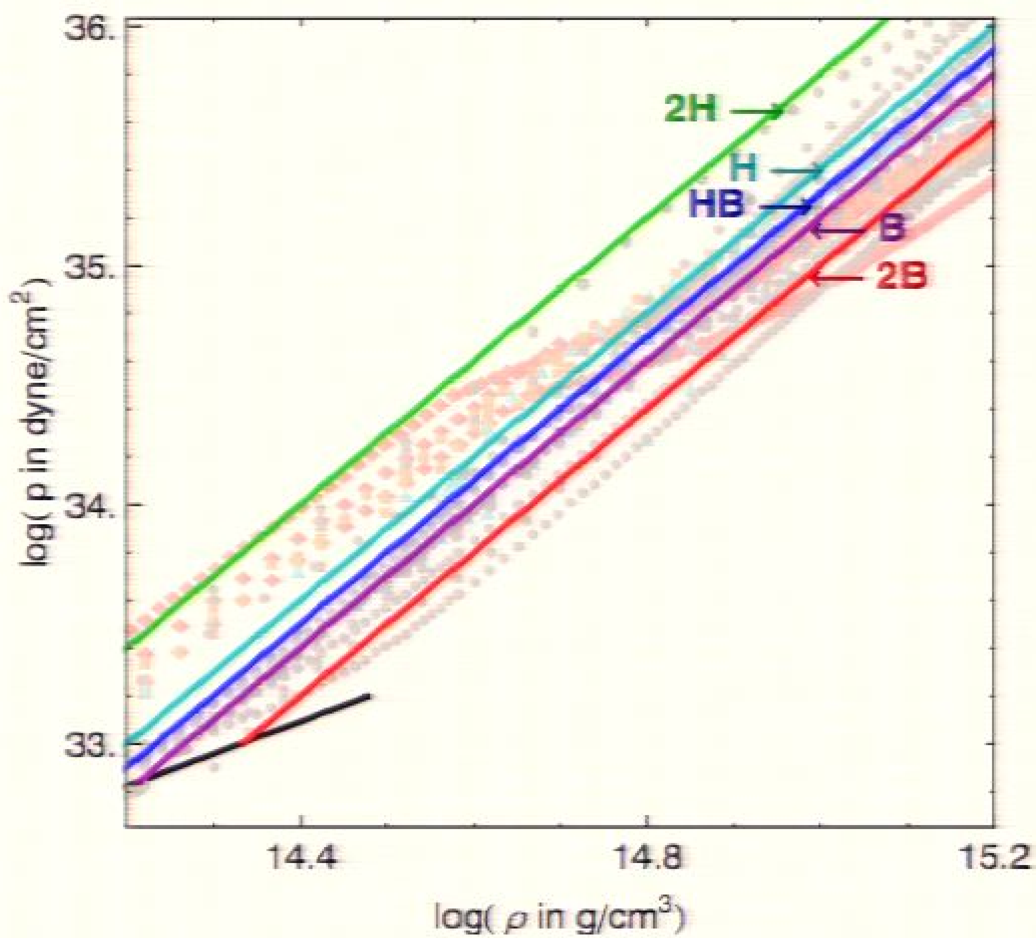
How relevant are these choices with astrophysical constraints?

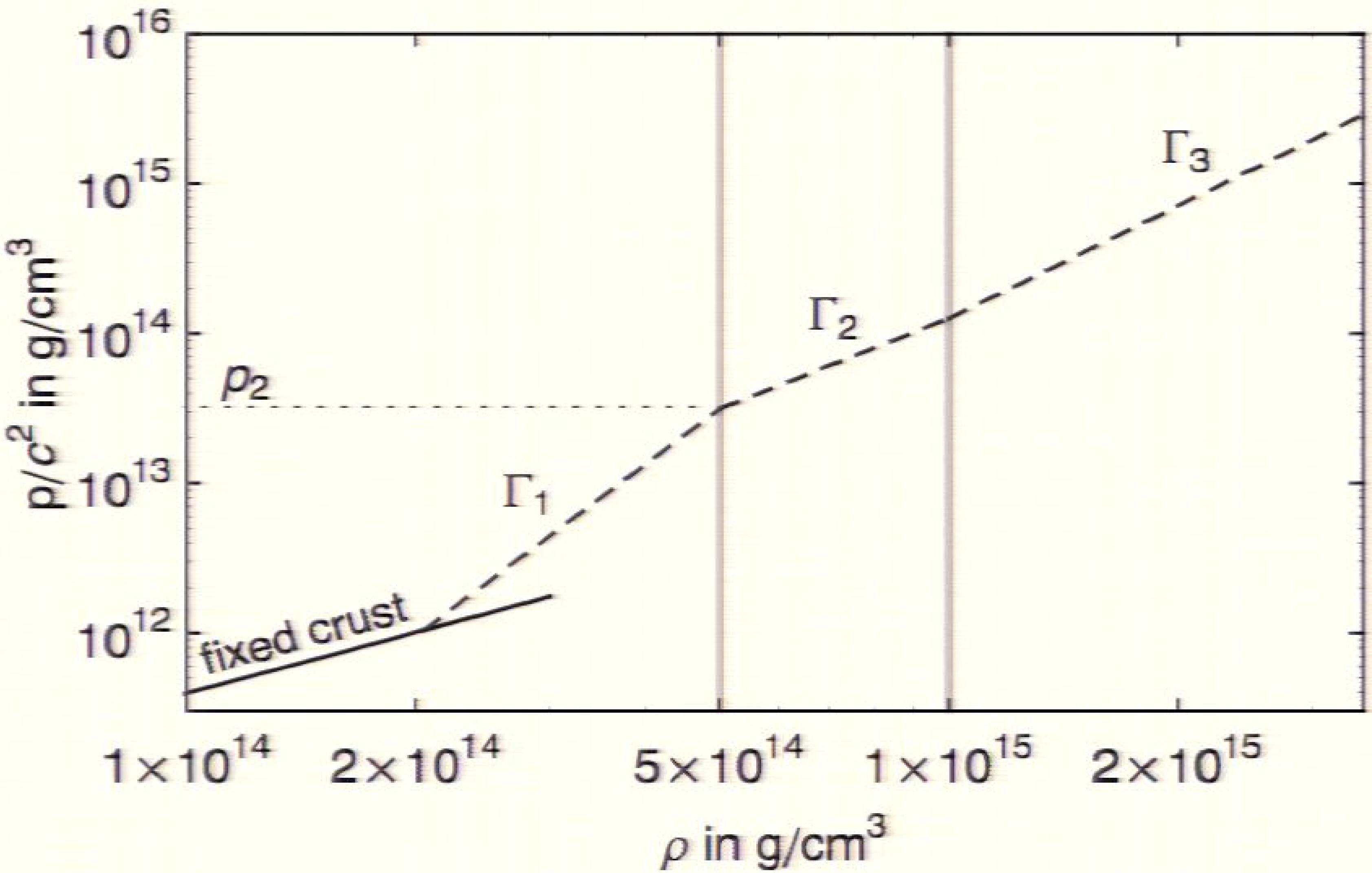
Current set of waveforms: vary pressure p



Systematically vary equations of state for simulations

A limited number of simulations are feasible (particularly for long inspiral
Try to cover parameter space:

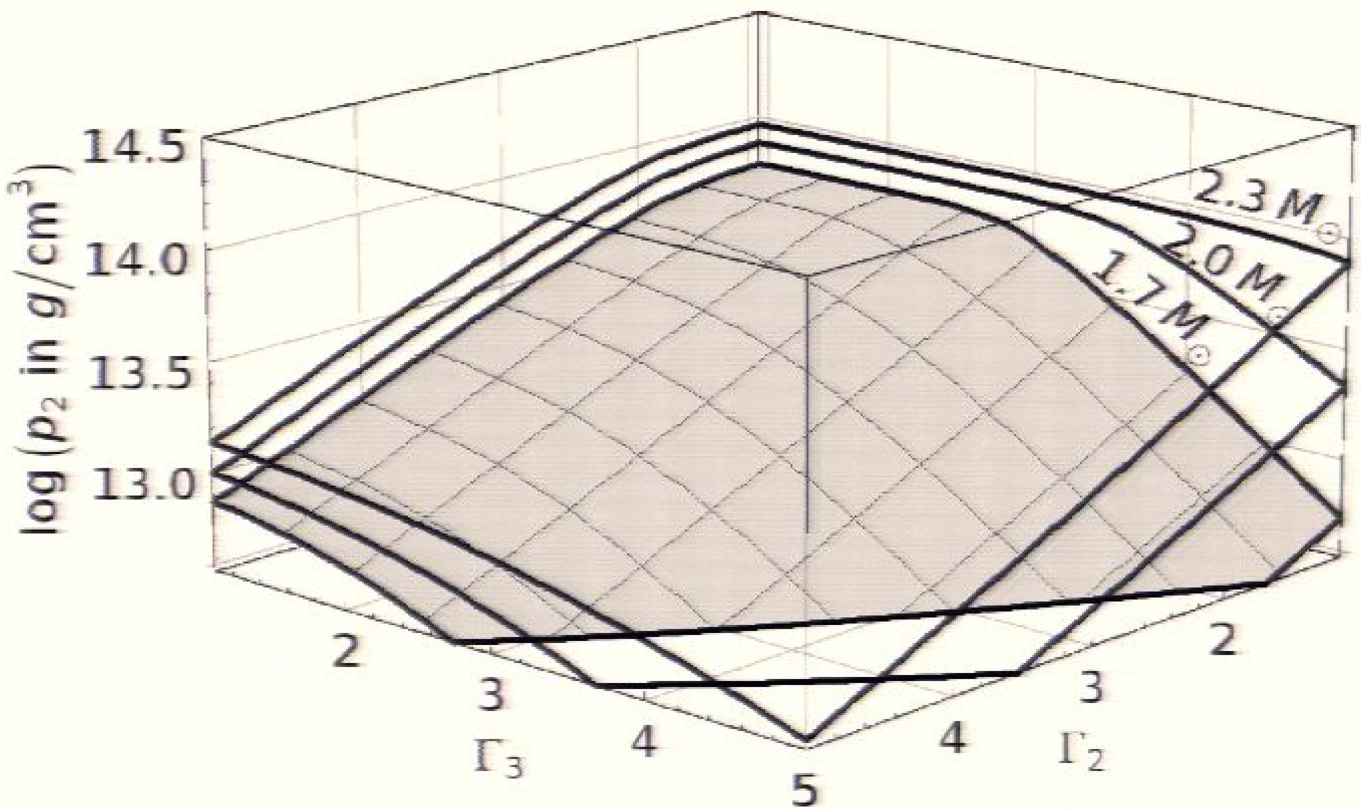




10^{16}
10^{15}
10^{14}
10^{13}
10^{12}
p/c^2 in g/cm^3
Γ_3
Γ_2
p_2
Γ_1
fixed crust
1×10^{14}
2×10^{14}
5×10^{14}
1×10^{15}
2×10^{15}
ρ in g/cm^3

Constraints on a phenomenologically parametrized neutron-star equation of state

JR, B. Lackey, J. Friedman, B. Owen PRD 79 (2009) 124033



example: constraints from maximum mass

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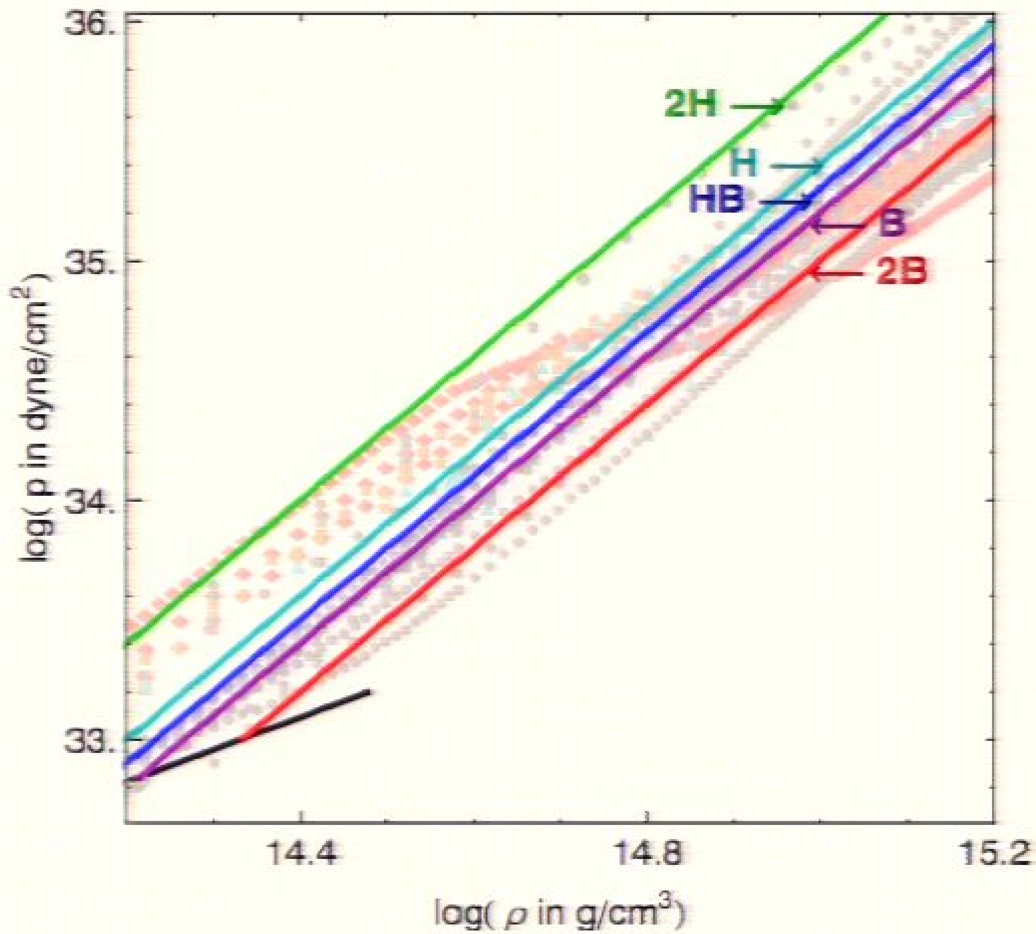
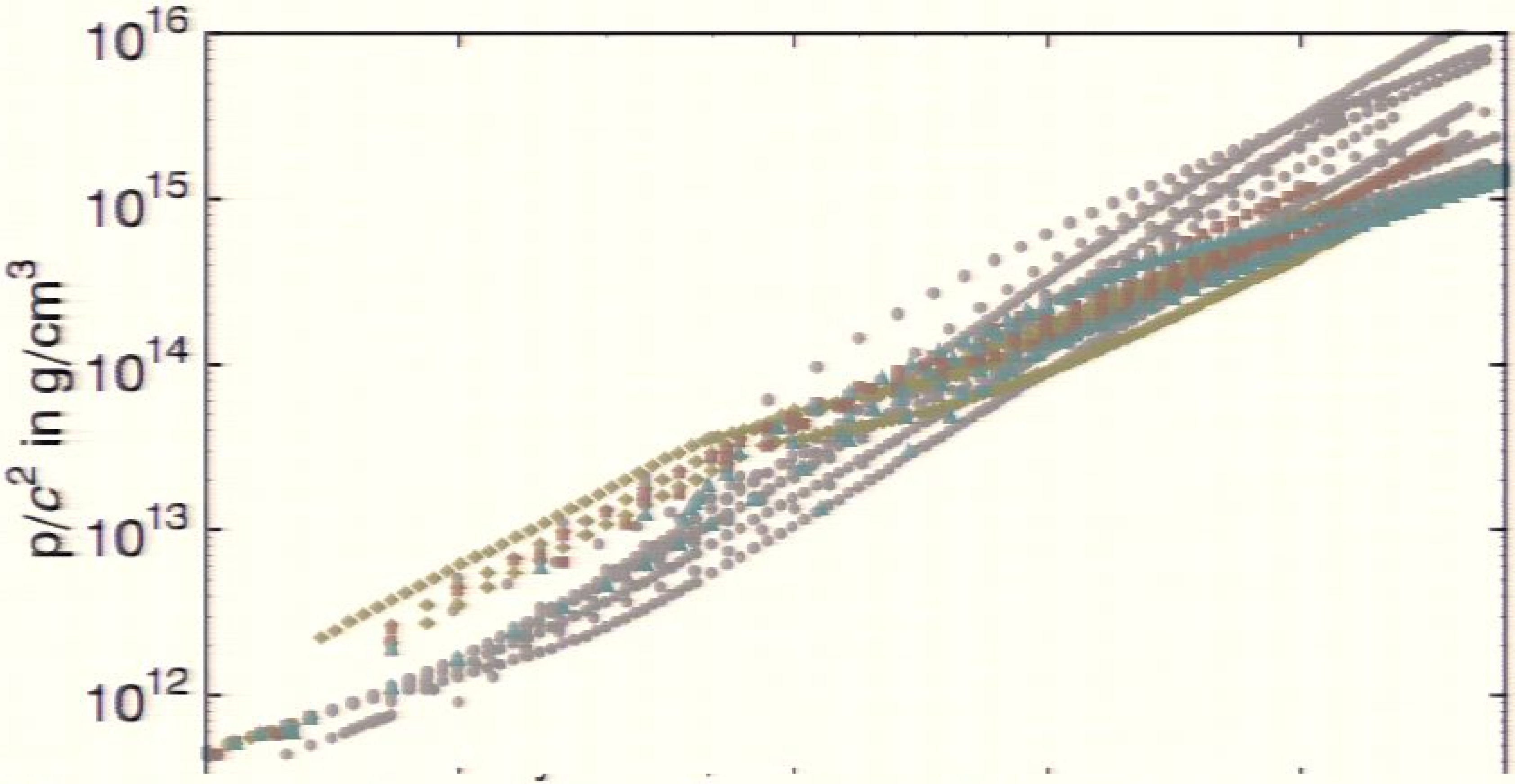
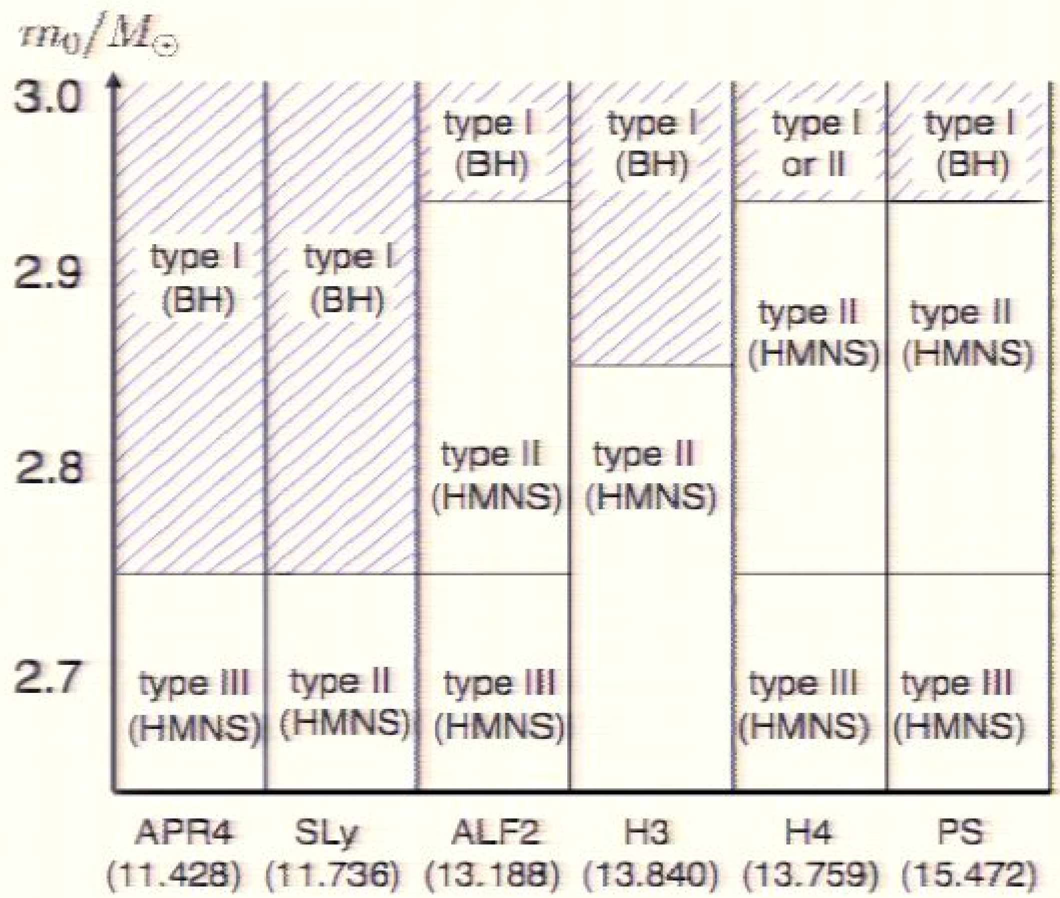


Candidate cold EOS in 2007



Waveform Analysis: Jolien Creighton, John Friedman

Impact of cold EOS on HMNS and torus formation: Hotokezaka et al 201



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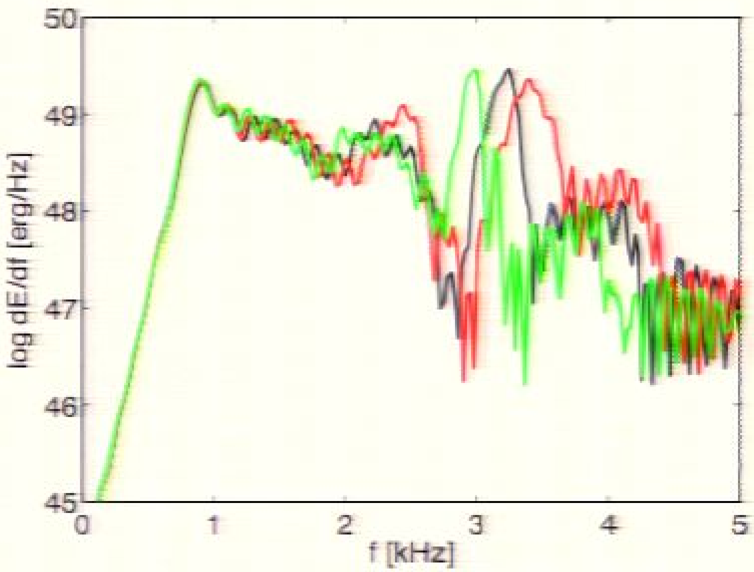

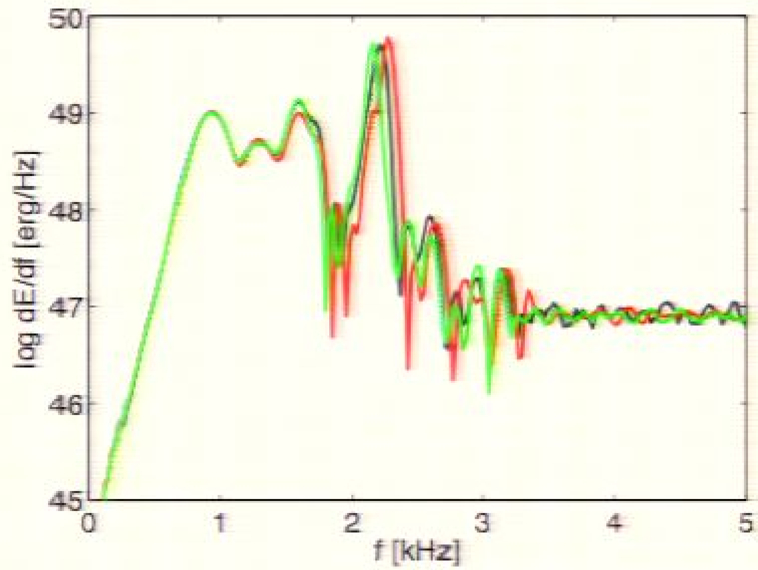

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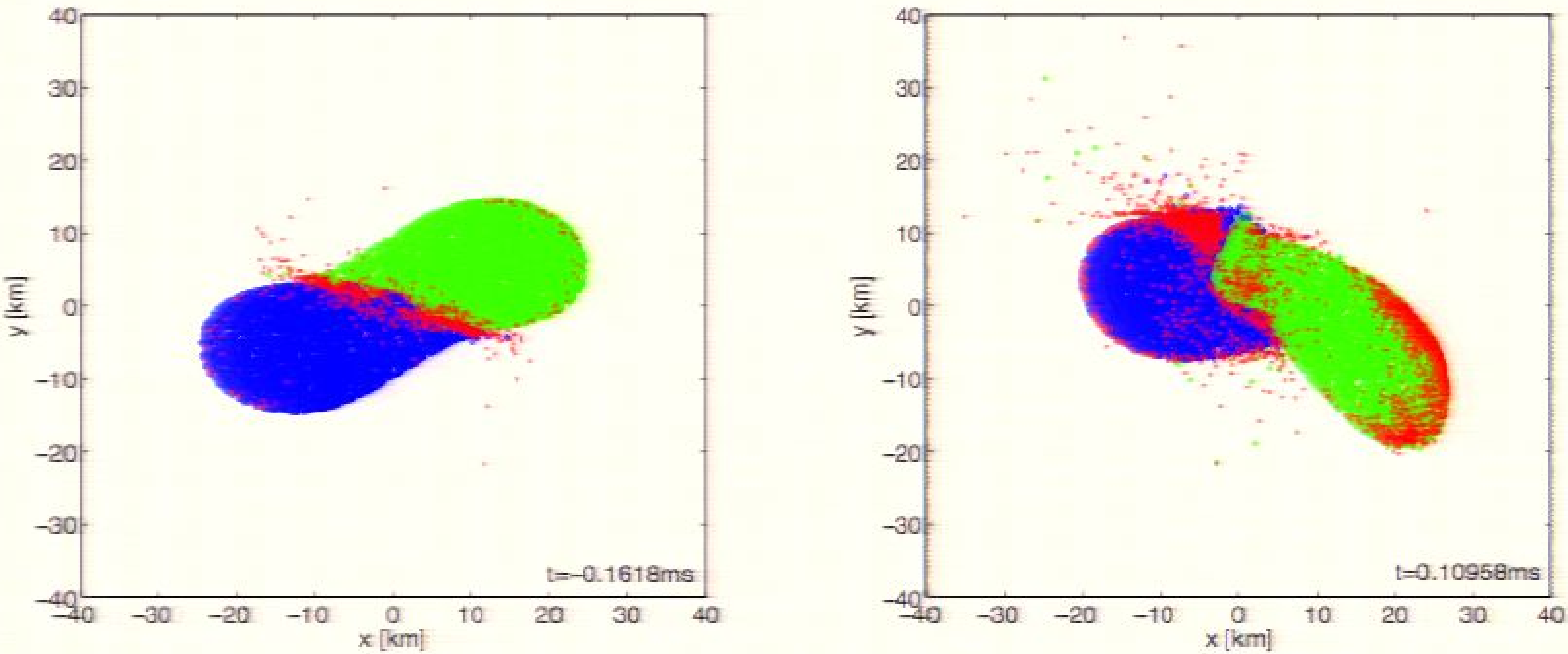

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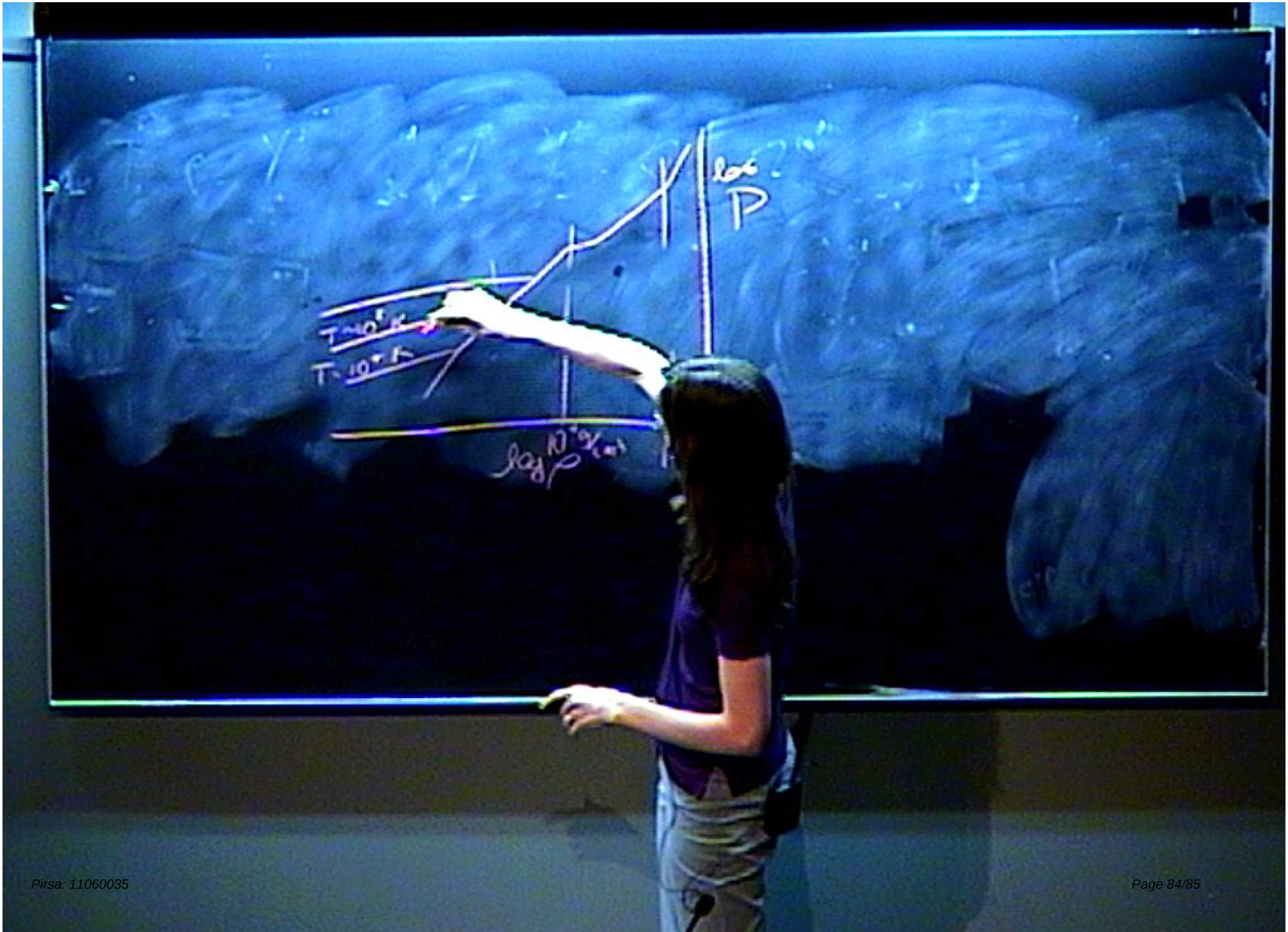
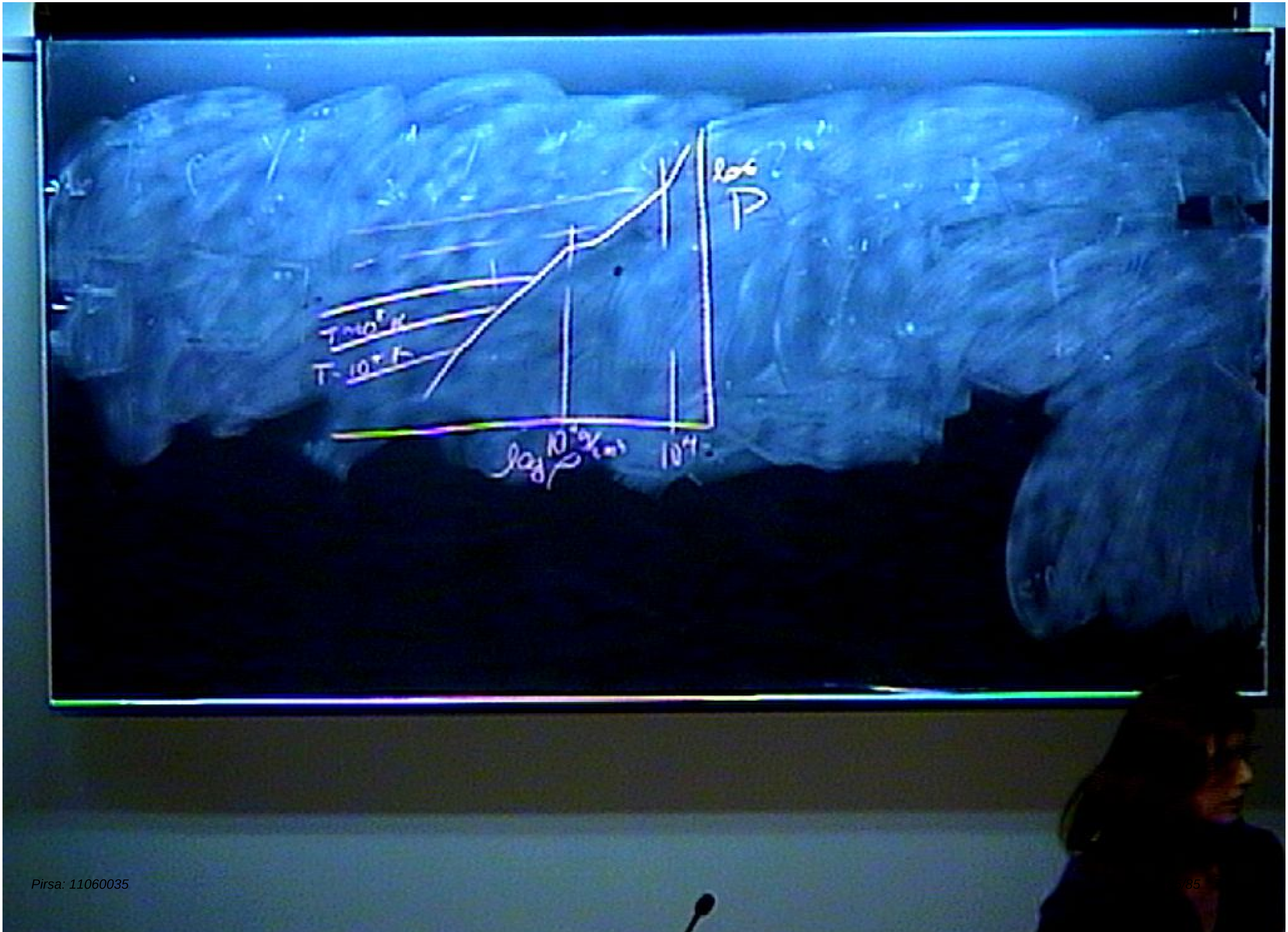

log P


log P
T~10⁵ K
T~10⁴ K
log ρ
10⁴ g/cm³
10⁴