Title: A nuclear physics - multi-messenger astronomy analysis of binary neutron star mergers - Tim Dietrich

Speakers: Tim Dietrich

Series: Strong Gravity

Date: May 27, 2021 - 1:00 PM

URL: http://pirsa.org/21050025

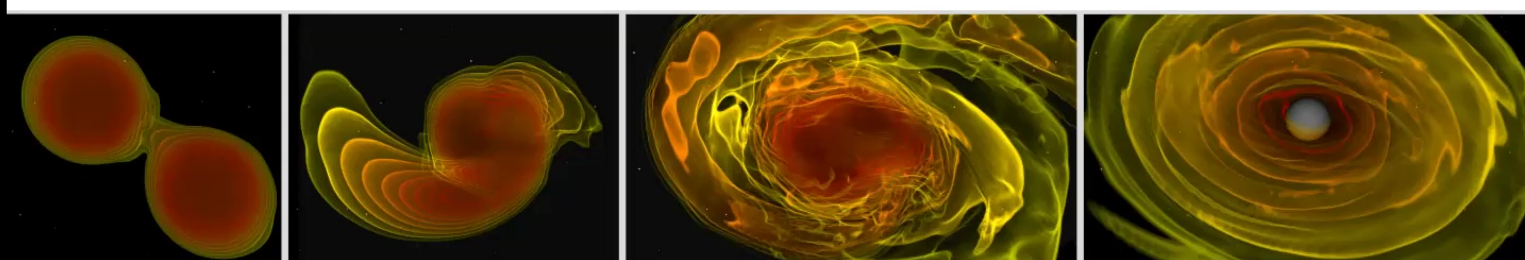
Abstract: We discuss how we can use numerical-relativity simulations to derive gravitational-wave and electromagnetic models describing the binary neutron star coalescence. We show how these models can be used within a multi-messenger framework to derive new constraints on the neutron-star equation of state and the Hubble constant. For this purpose, we analyze the gravitational wave signal GW170817 and its electromagnetic counterparts AT2017gfo and GRB170817A, together with X-ray observations by NICER, radio observations of massive pulsars, and nuclear theory computations. Similarly, we also discuss that a non-detection of a kilonova for the second binary neutron-star merger detection GW190425 placed constraints on the properties of the system.

Zoom Link: https://pitp.zoom.us/j/99911822549?pwd=NXNNMWJVOUhMTGJSSGYwWUN2NEcxQT09

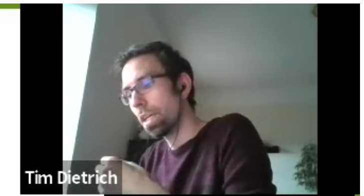
A nuclear physics - multi-messenger astronomy analysis of binary neutron star mergers

Tim Dietrich
University of Potsdam
Max Planck Institute for Gravitational Physics

LSC
LIGO Scientific Collaboration



27th of May 2021



Why study neutron stars?

Nuclear physics

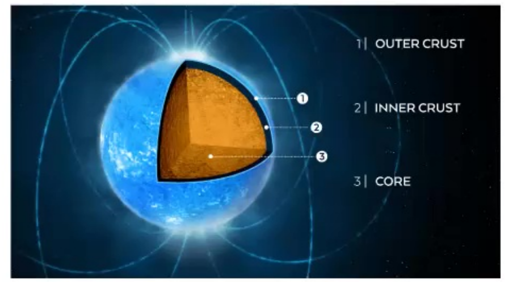
Equation of state of supranuclear matter

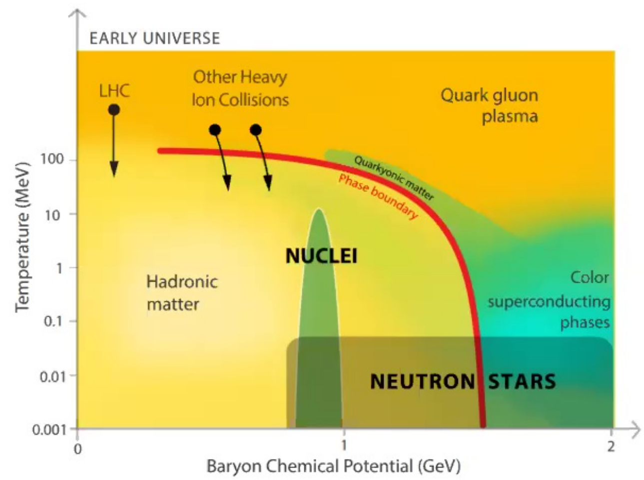
Gravitational Wave Astronomy

Source properties and binary population

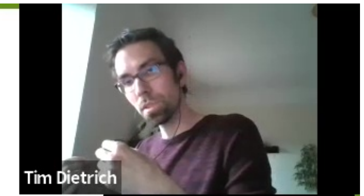
High-energy astrophysics

sGRBs and heavy element formation





Rev.Mod.Phys. 88 (2016) no.2, 021001



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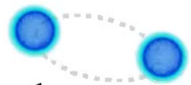

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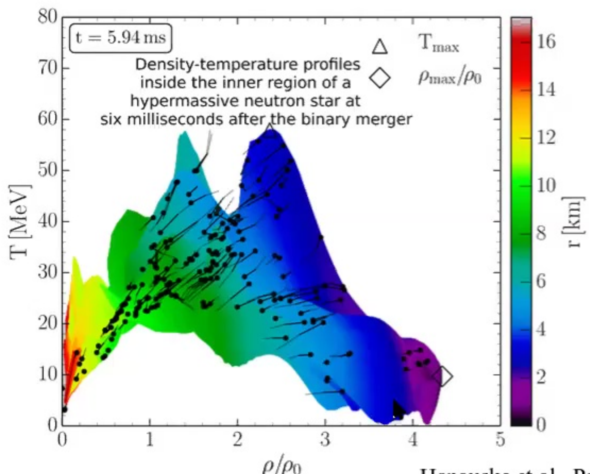
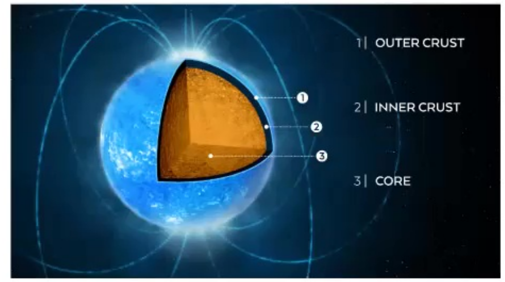
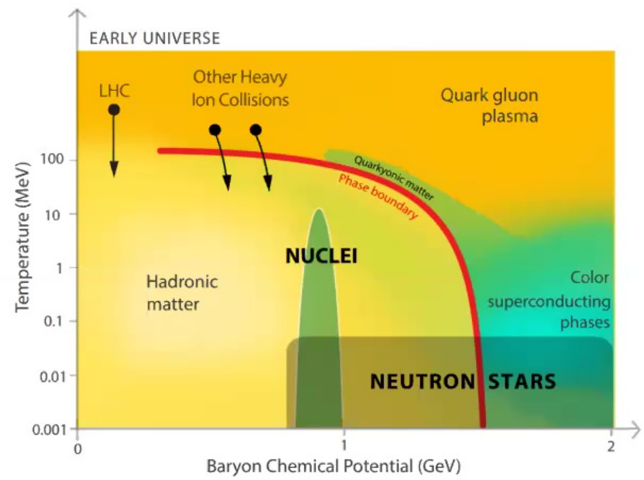


Hanauske et al., Particles 2019, 2(1), 44-56





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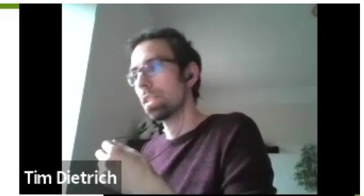

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Equation of state of supra

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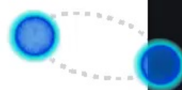

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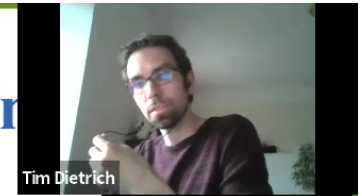

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Source properties and binary population

High-energy astrophysics

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Tests of General Relativity, Cosmology, …

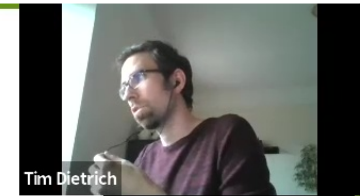
How to study neutron star binaries?

Modeling:

Numerical Relativity

Observation:

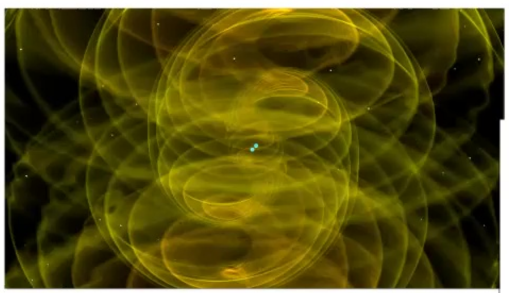
The multi-messenger picture



The multi-messenger picture

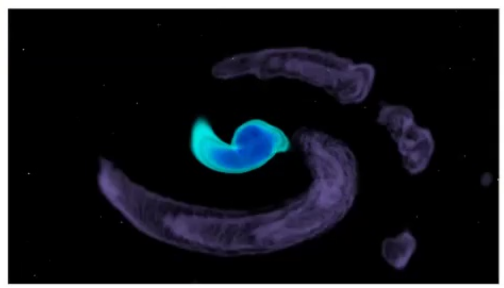
Gravitational Waves

- -inspiral
- -postmerger

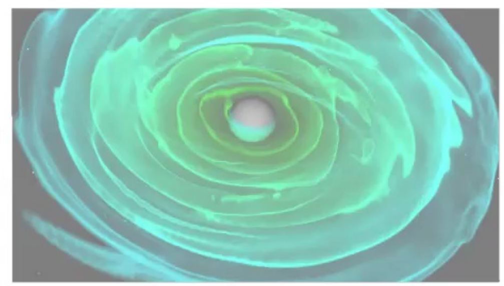


Electromagnetic Waves

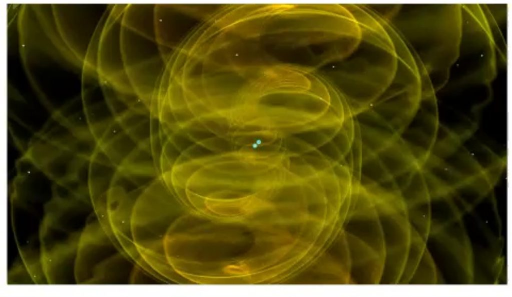
- -kilo/macronovae (optical/UV/IR)
- -short GRB
- -X-ray and radio flares

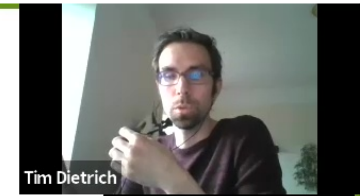


Neutrinos

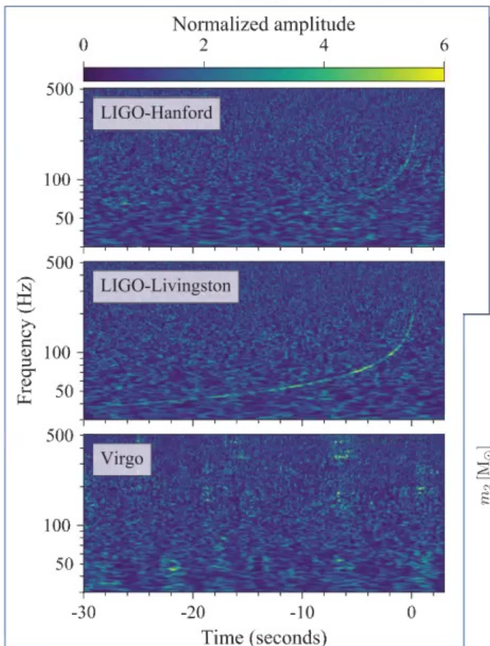


Gravitational Waves

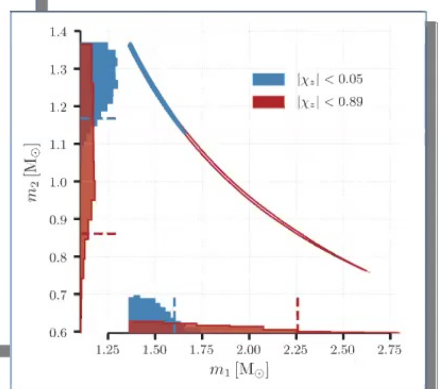




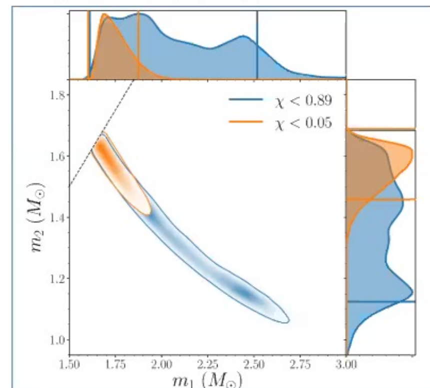
GW170817



PRL 119, 161101 (2017)



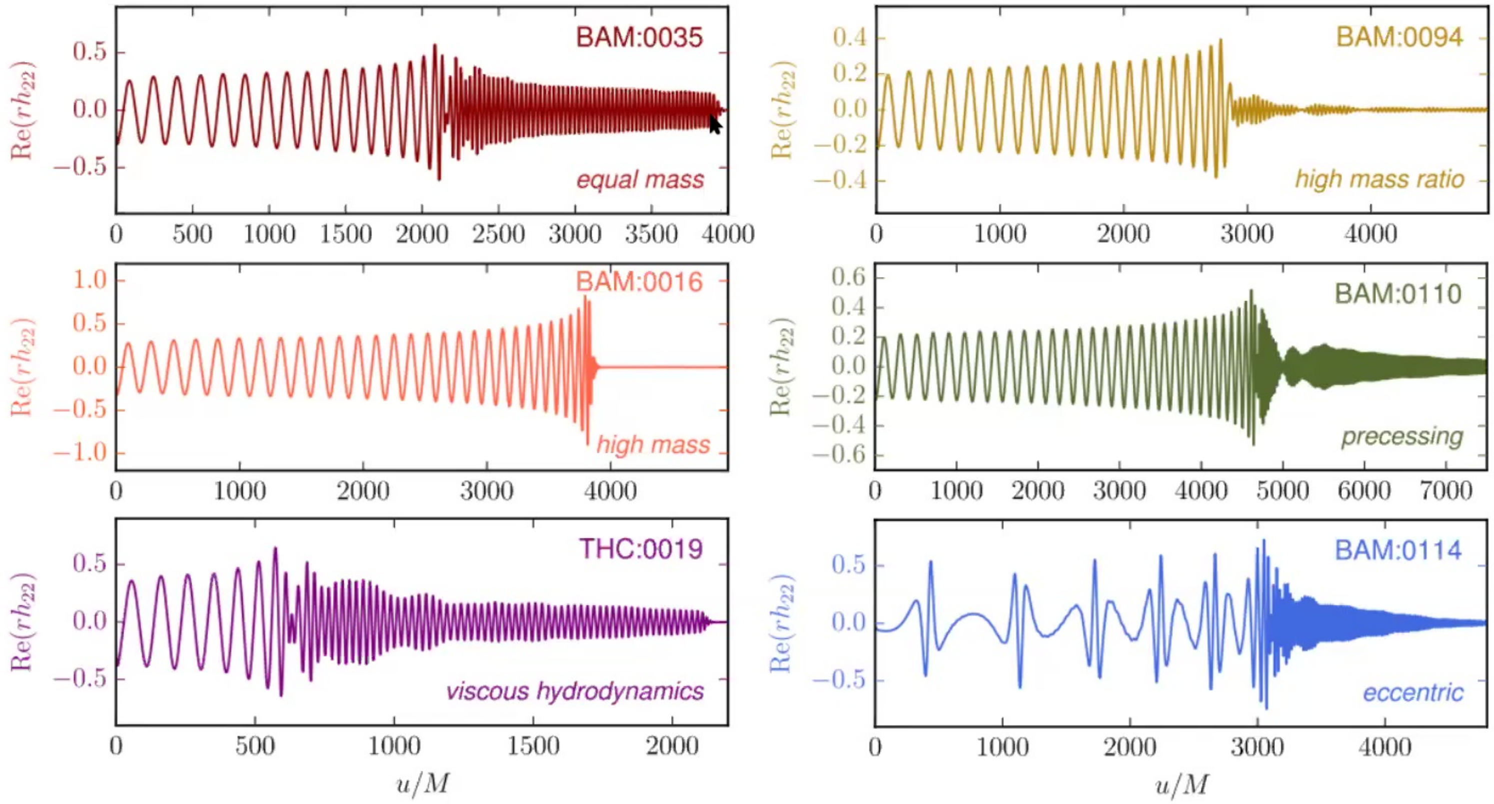
GW190425



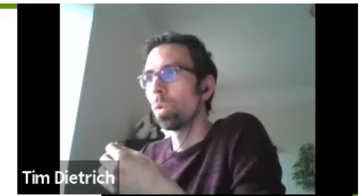
APJL 892 (2020)

GW170817 was just the beginning …
and *GW190425* proved our expectations wrong

Simulation variety:



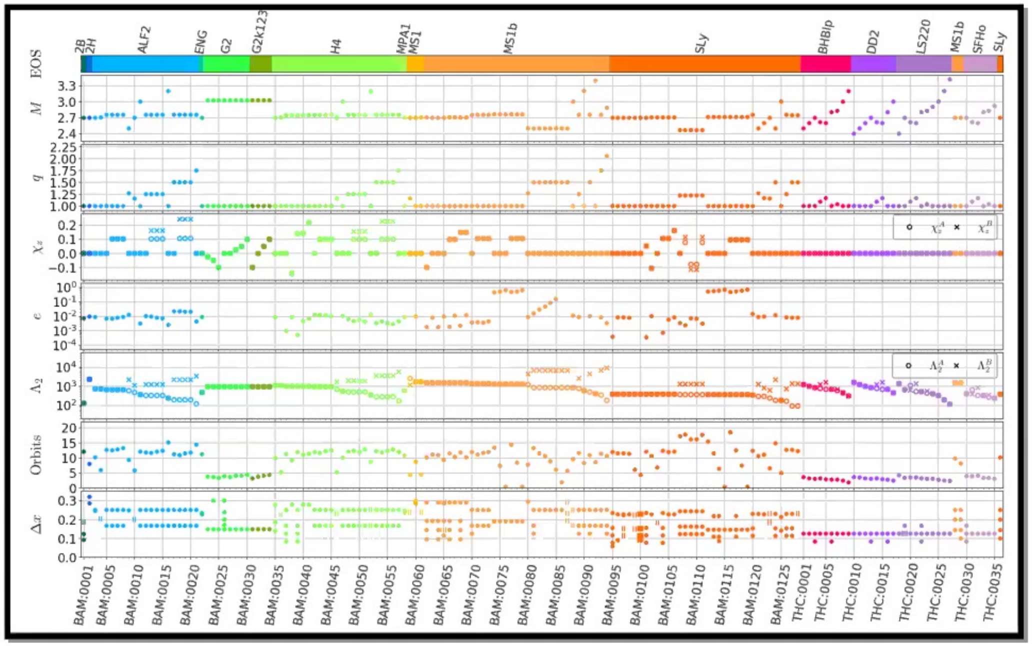
TD et al, CQG 35 (2018) 24LT01

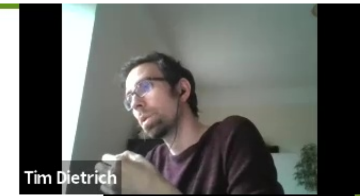


BNS database

http://www.computational-relativity.org/

TD et al, CQG 35 (2018) 24LT01





- first publicly available database for BNSs
- about 400 individual simulations
- more than 300 simulations done with BAM
- more than 450 million CPUhs

(c) Lino Mirgeler (dpa)

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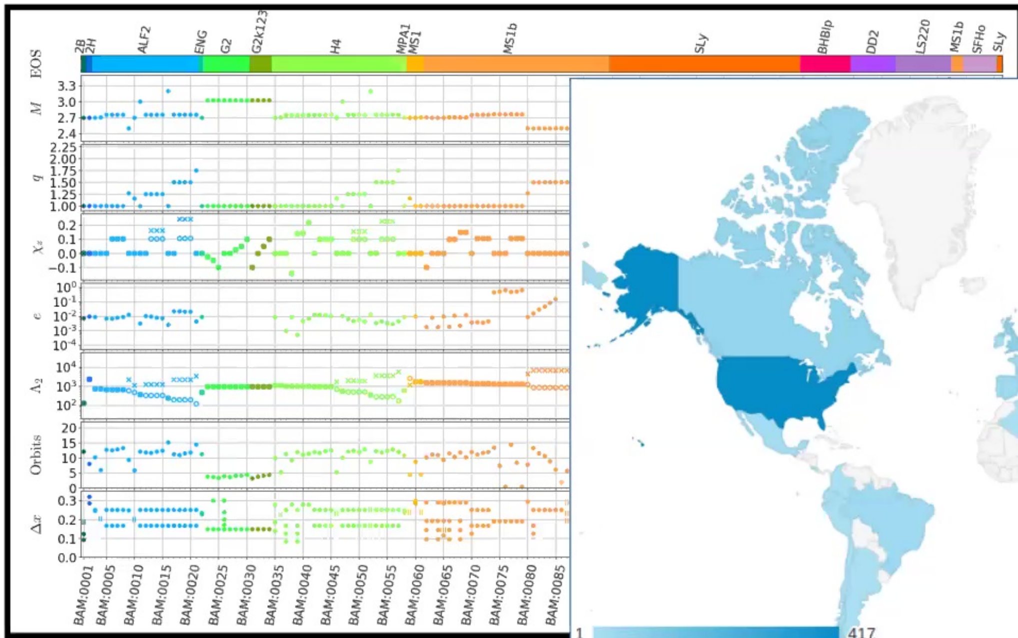

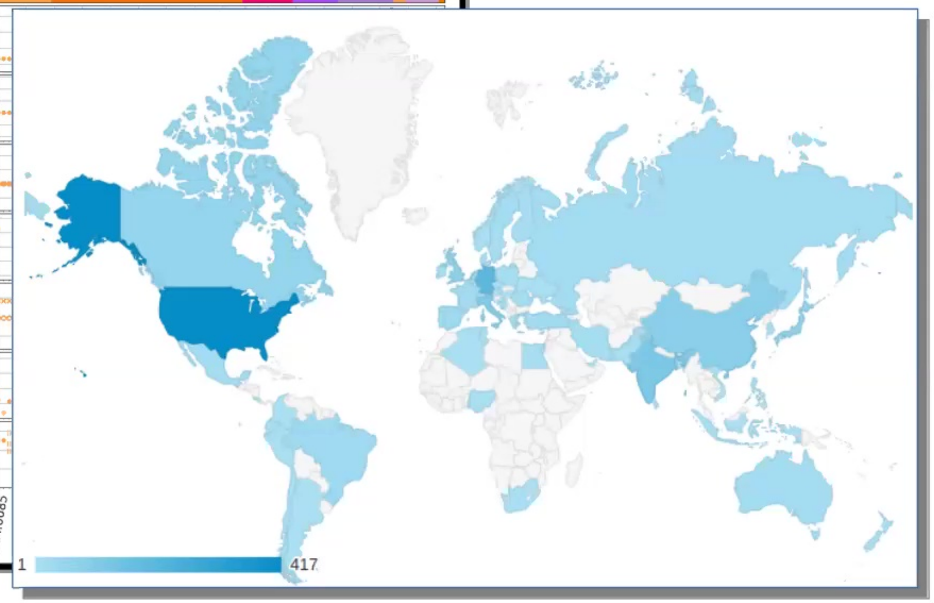

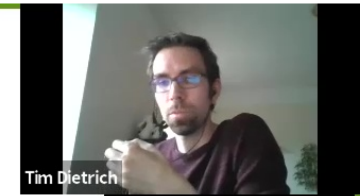

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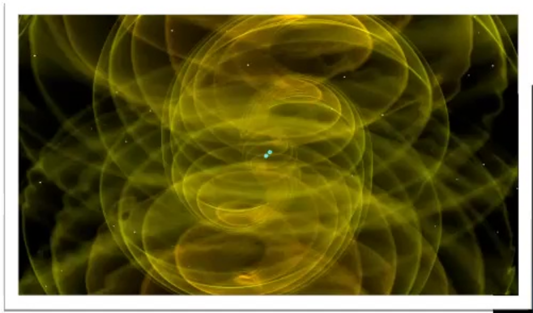
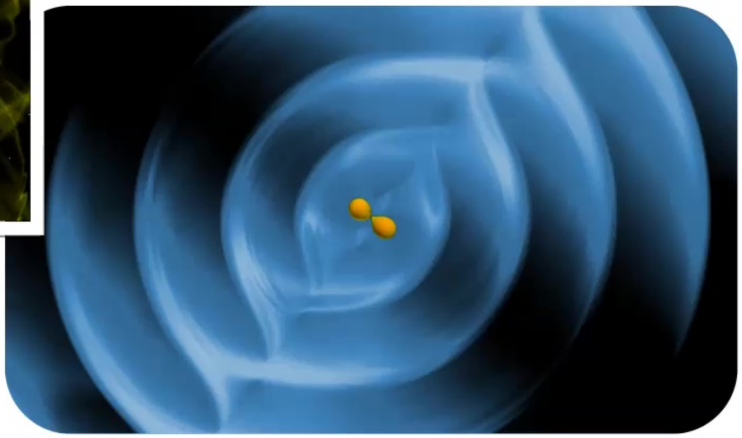
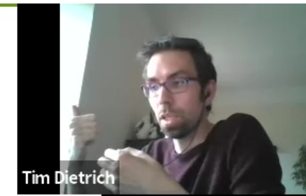
Real Life: Gravitational-Wave Astronomy

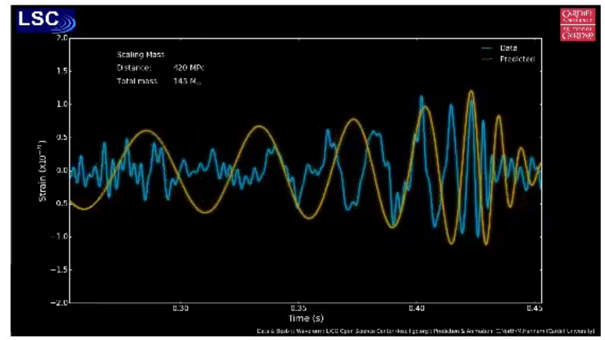






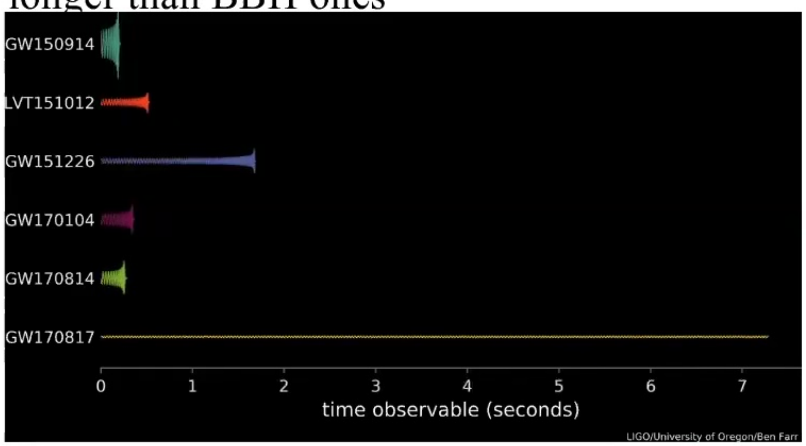
Real Life: Gravitational Waves

hundreds of millions of templates need to be evaluated to interpret data



(c) M.Hannam, C. North

BNS signals significantly longer than BBH ones



https://www.youtube.com/watch?v=vTeAFAGpfso

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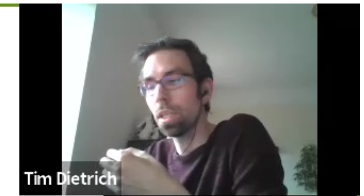

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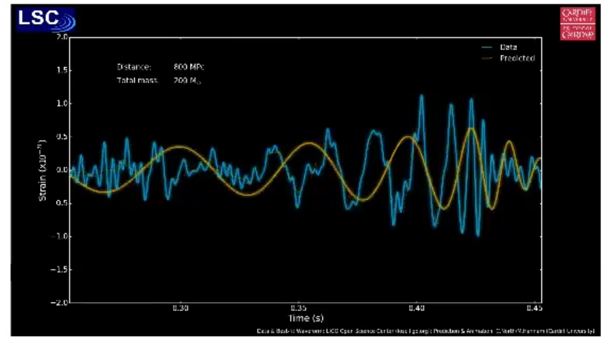

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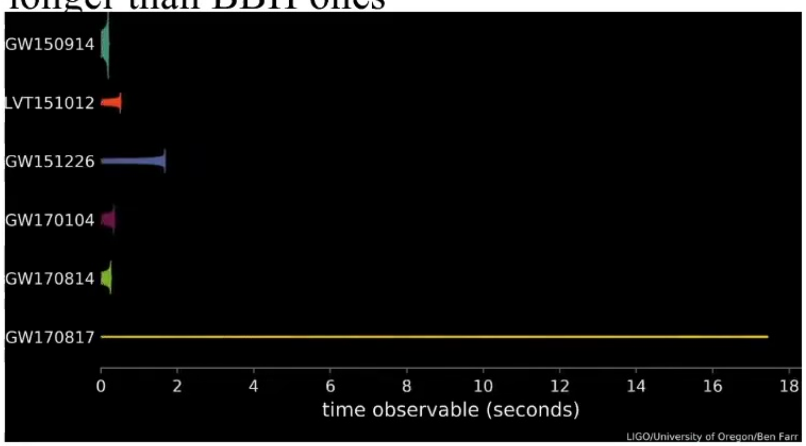

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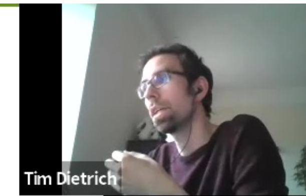

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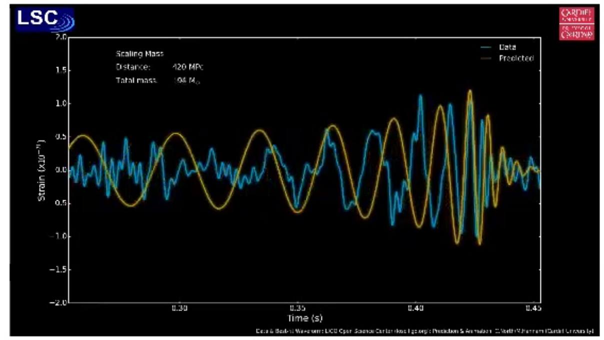

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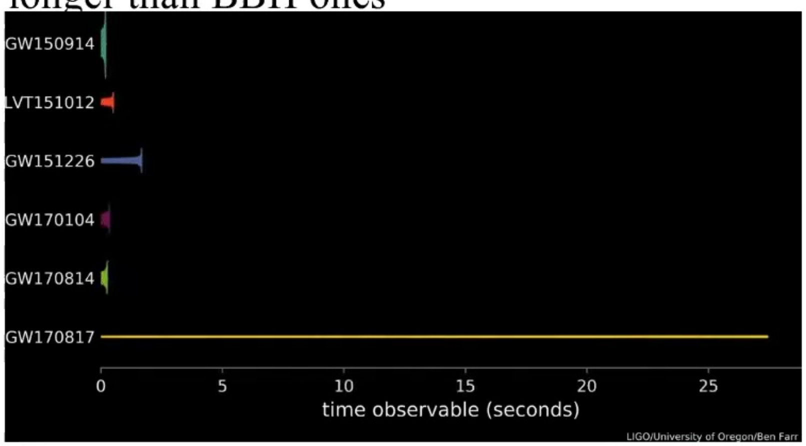

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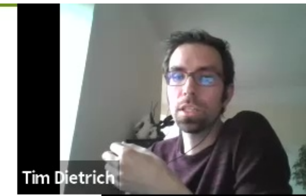

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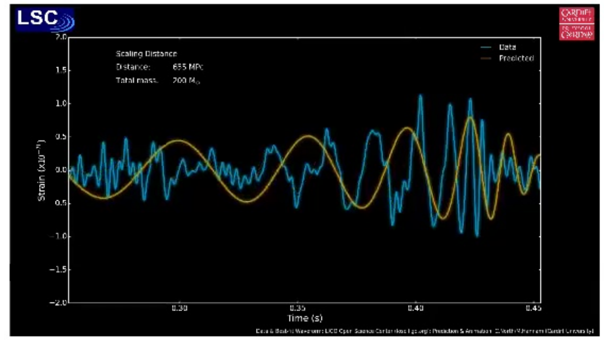

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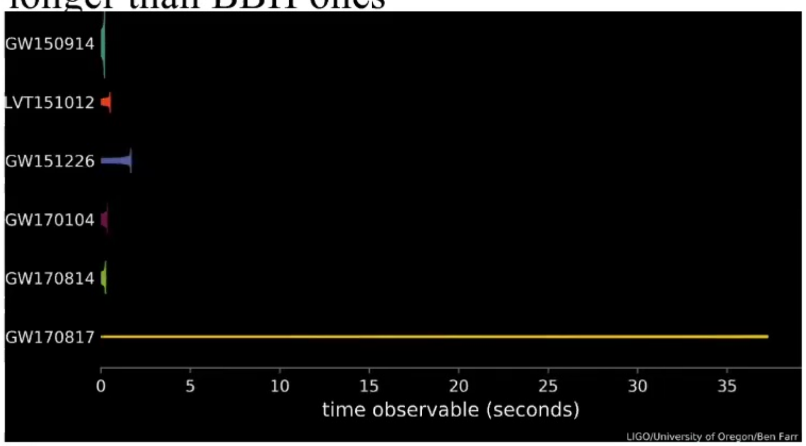

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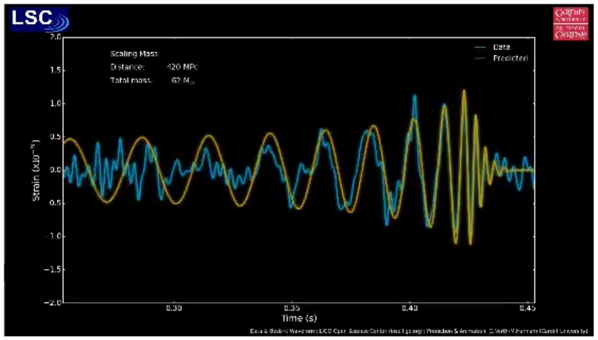

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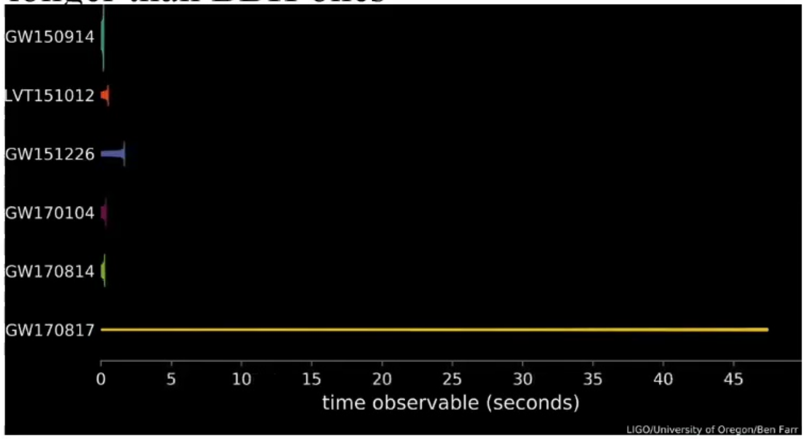

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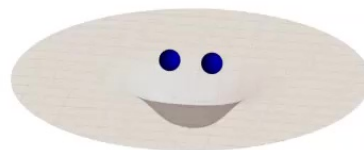
Inspiral waveforms

Numerical Relativity Simulations

+ solve Einstein equations
+ predictions of postmerger
– only the last orbits
– SUPER slow



Post-Newtonian Theory

+ fast to compute
– inaccurate near merger

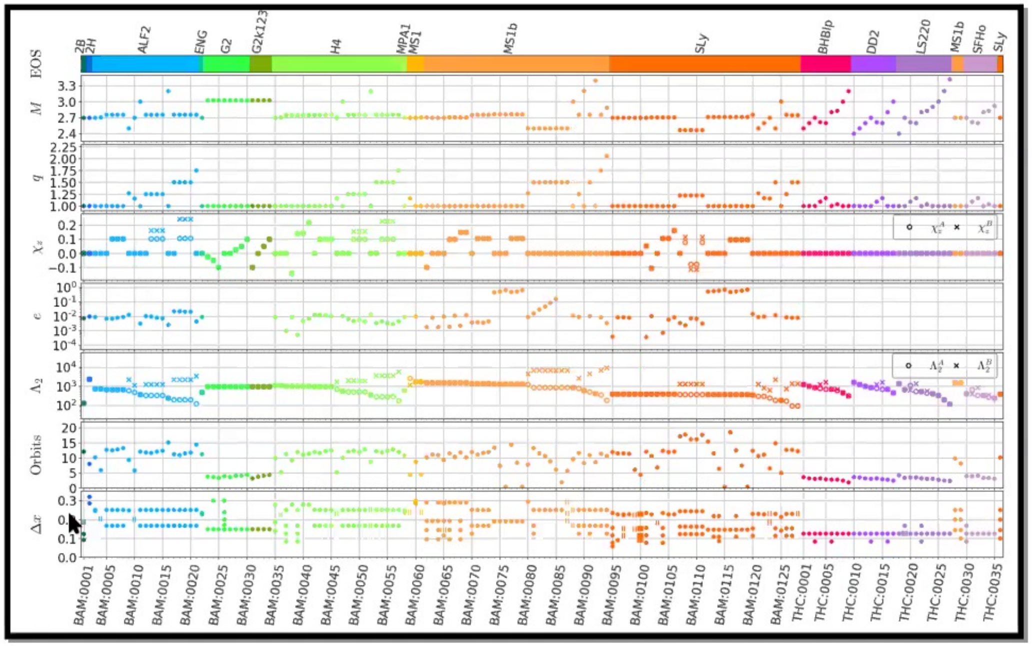
Effective-one-body Formalism

+ agree well with most NR data
– slow to compute

BNS database

http://www.computational-relativity.org/

TD et al, CQG 35 (2018) 24LT01



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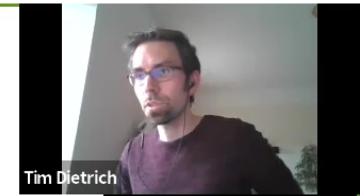

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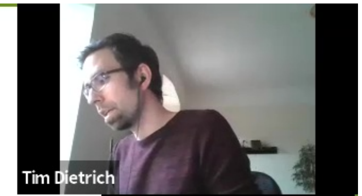

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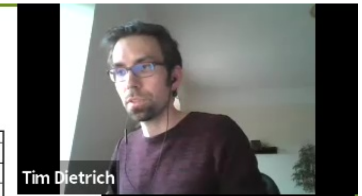
TD et al., (2017) PRD96,121501

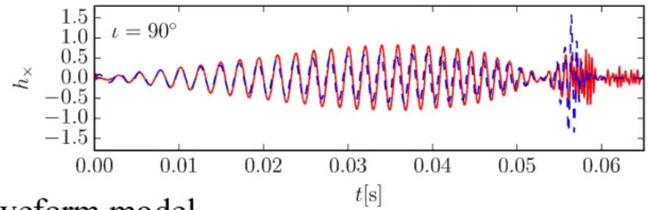
Phenomenological tides (NRTidal)

+ combination of PN/EOB/NR
+ accurate until merger
– just a fit

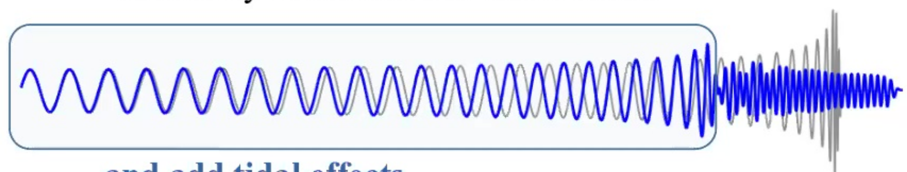
Phenomenological model: NRTidal



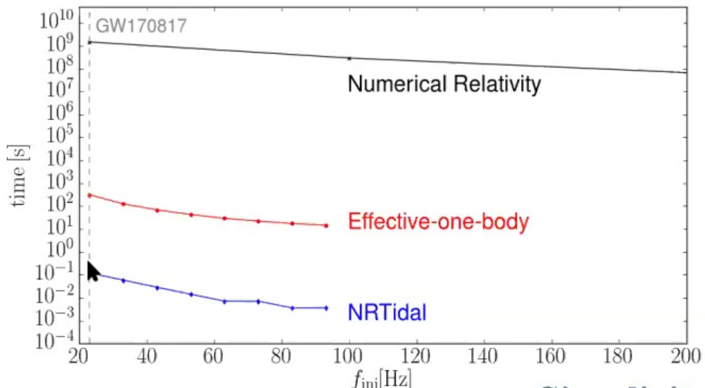
$$\phi_{\rm tides} = -c_{\rm Newt} \frac{\kappa_{\rm eff}}{\nu} \hat{\omega}^{5/3} \mathbf{P}(\hat{\omega})$$

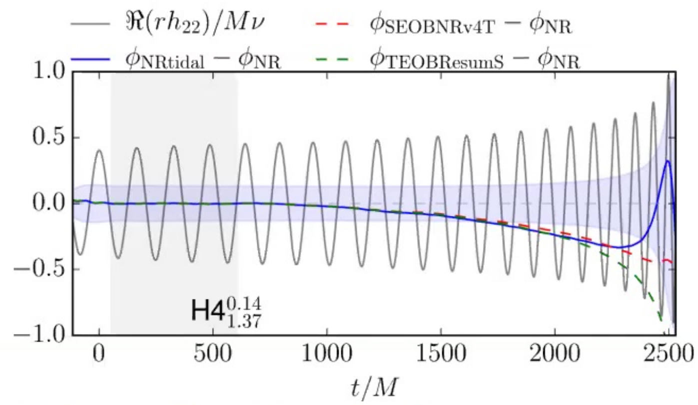


use binary black hole waveform model



and add tidal effects

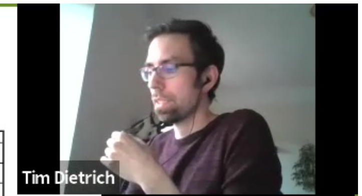


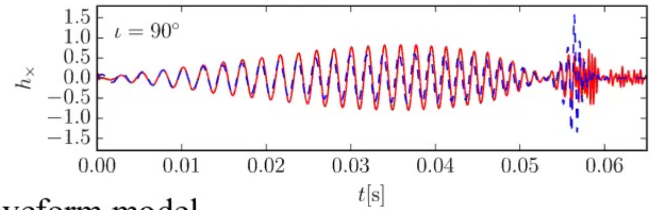


Simplicity + **Universality** +**Speed** + **Accuracy**

Phenomenological model: NRTidal

$$\phi_{\rm tides} = -c_{\rm Newt} \frac{\kappa_{\rm eff}}{\nu} \hat{\omega}^{5/3} \mathbf{P}(\hat{\omega})$$





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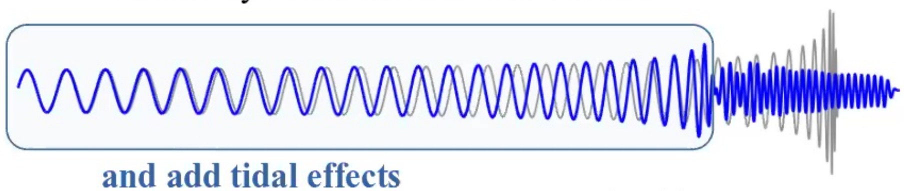

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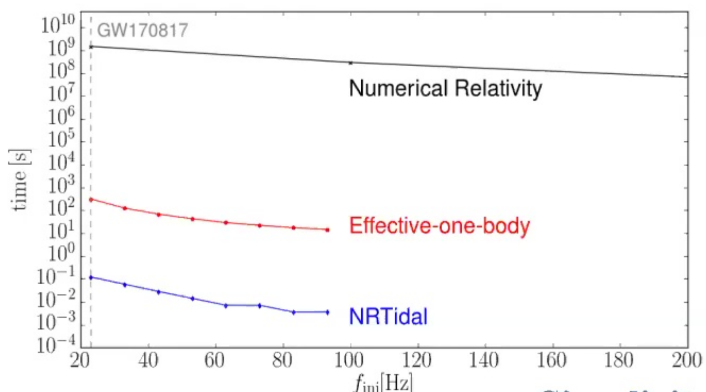
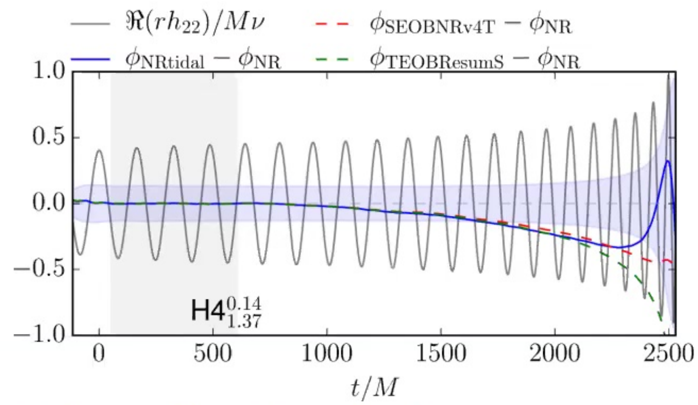




Simplicity + Universality +Speed + Accuracy

NRTidalv2 now available

TD et al., PRD100 (2019), 044003

NRTidal-based models for BHNSs:

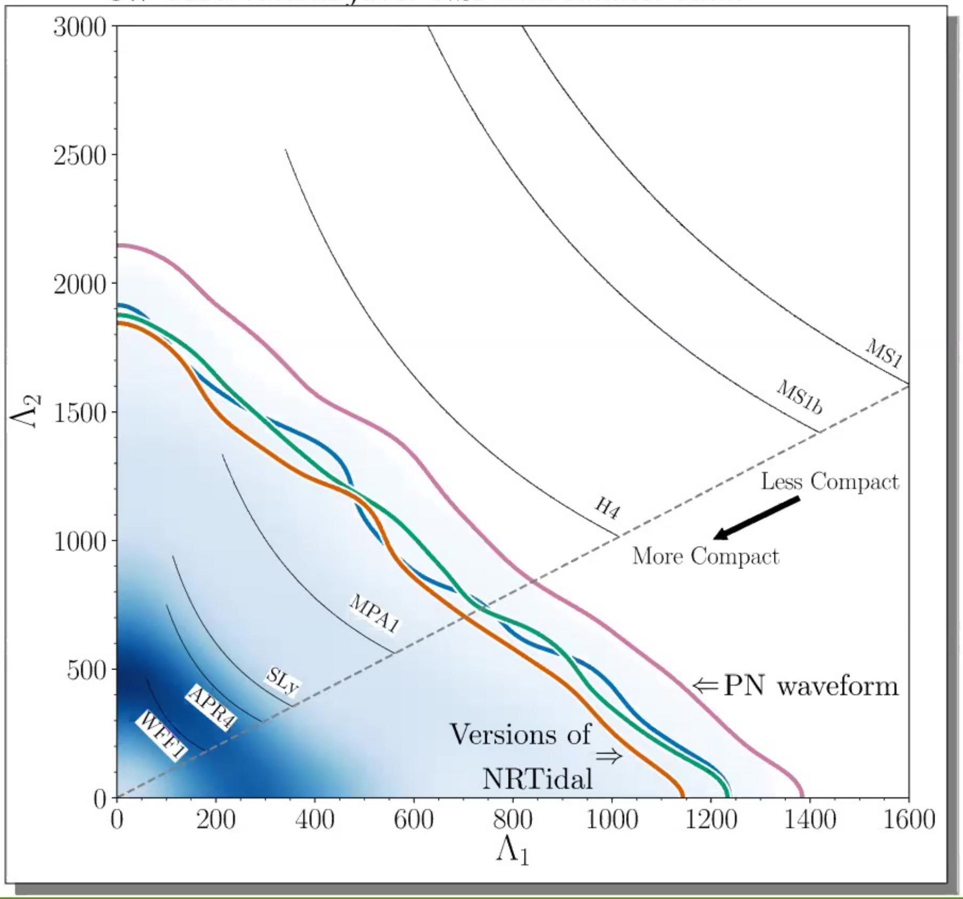
Thompson et al., PRD 101 (2020) 12, 124059

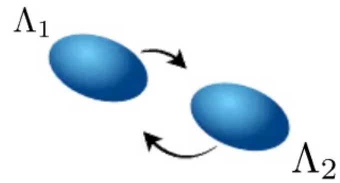
Matas et al., PRD 102 (2020) 4, 043023

Application: GW170817 – Tidal Effects

Determine the Equation of State

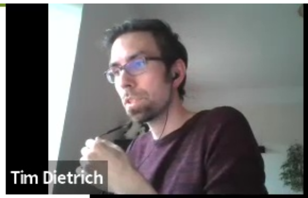
GW observations favor NSs with smaller radii





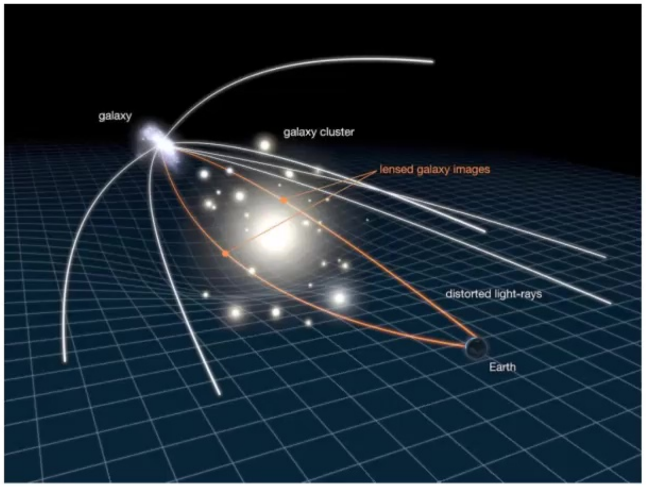
Λ determines tidal deformability

Phys.Rev. X9 (2019) 011001

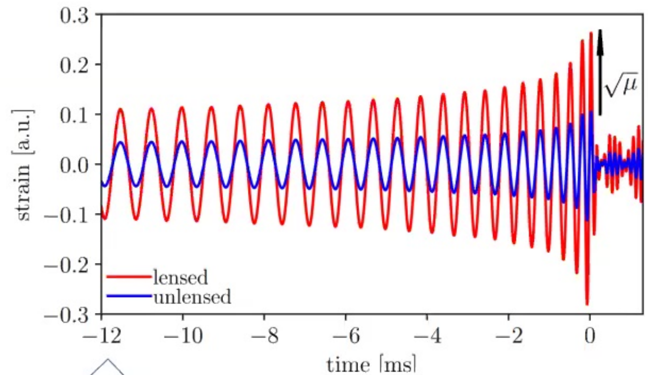


Application: Lensed or not-lensed that is the question.

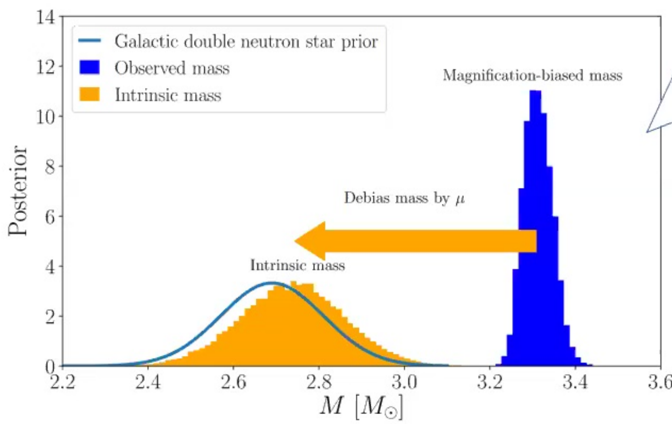
Pang, Hannuksela, TD, Pagano, Harry, MNRAS 10.109



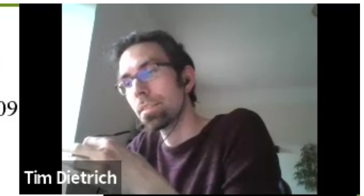
(c) NASA/ESA

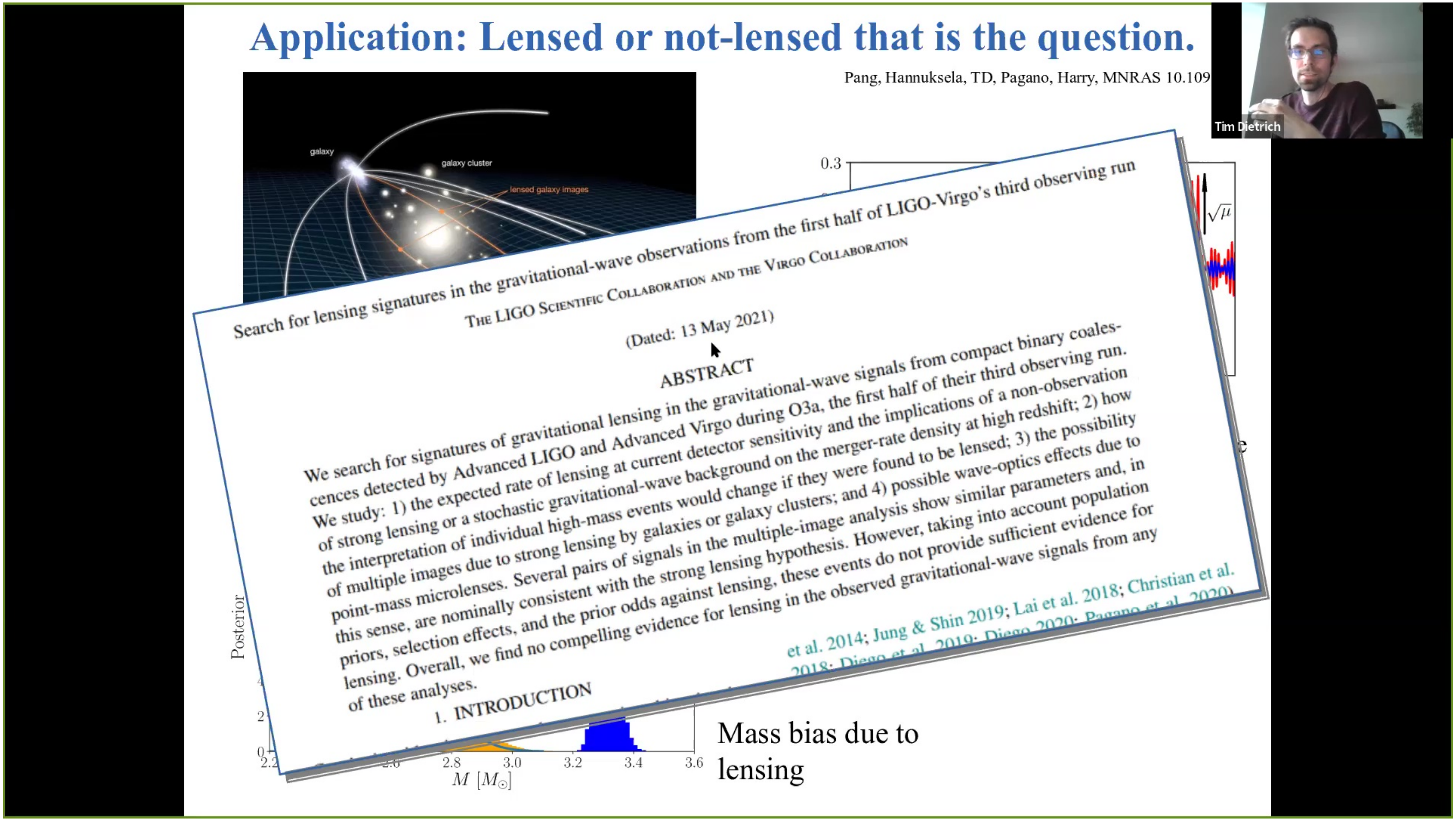


lensing changes the magnitude but not the phase evolution



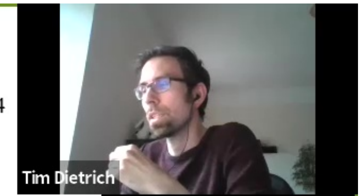
Mass bias due to lensing

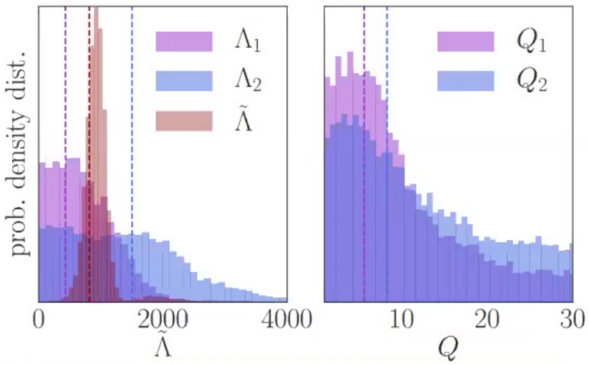



Application: Lensed or not-lensed that is the question.
Pang, Hannuksela, TD, Pagano, Harry, MNRAS 10.109
Tim Dietrich
galaxy
galaxy cluster
lensed galaxy images
Search for lensing signatures in the gravitational-wave observations from the first half of LIGO-Virgo's third observing run
THE LIGO SCIENTIFIC COLLABORATION AND THE VIRGO COLLABORATION
(Dated: 13 May 2021)
ABSTRACT
We search for signatures of gravitational lensing in the gravitational-wave signals from compact binary coalescences detected by Advanced LIGO and Advanced Virgo during O3a, the first half of their third observing run. We study: 1) the expected rate of lensing at current detector sensitivity and the implications of a non-observation of strong lensing or a stochastic gravitational-wave background on the merger-rate density at high redshift; 2) how the interpretation of individual high-mass events would change if they were found to be lensed; 3) the possibility of multiple images due to strong lensing by galaxies or galaxy clusters; and 4) possible wave-optics effects due to point-mass microlenses. Several pairs of signals in the multiple-image analysis show similar parameters and, in this sense, are nominally consistent with the strong lensing hypothesis. However, taking into account population priors, selection effects, and the prior odds against lensing, these events do not provide sufficient evidence for lensing. Overall, we find no compelling evidence for lensing in the observed gravitational-wave signals from any of these analyses.
1. INTRODUCTION
et al. 2014; Jung & Shin 2019; Lai et al. 2018; Christian et al.
0.3
$\sqrt{\mu}$
Posterior
2
0
2.2
2.8
3.0
3.2
3.4
3.6
$M\ [M_\odot]$
Mass bias due to lensing

Application: Measuring Q-Love with GW data

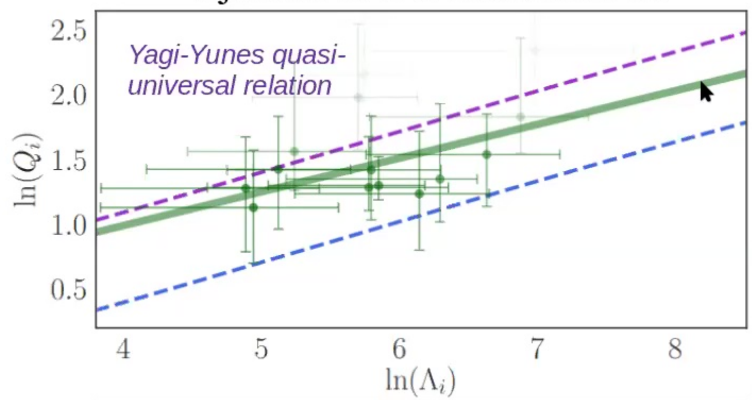
Samajdar & TD, PRD 101 (2020) 12, 124014

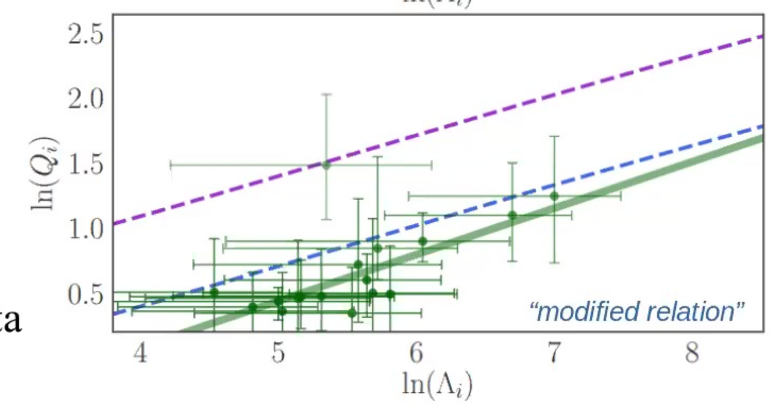




single source

injection of 120 sources for ET

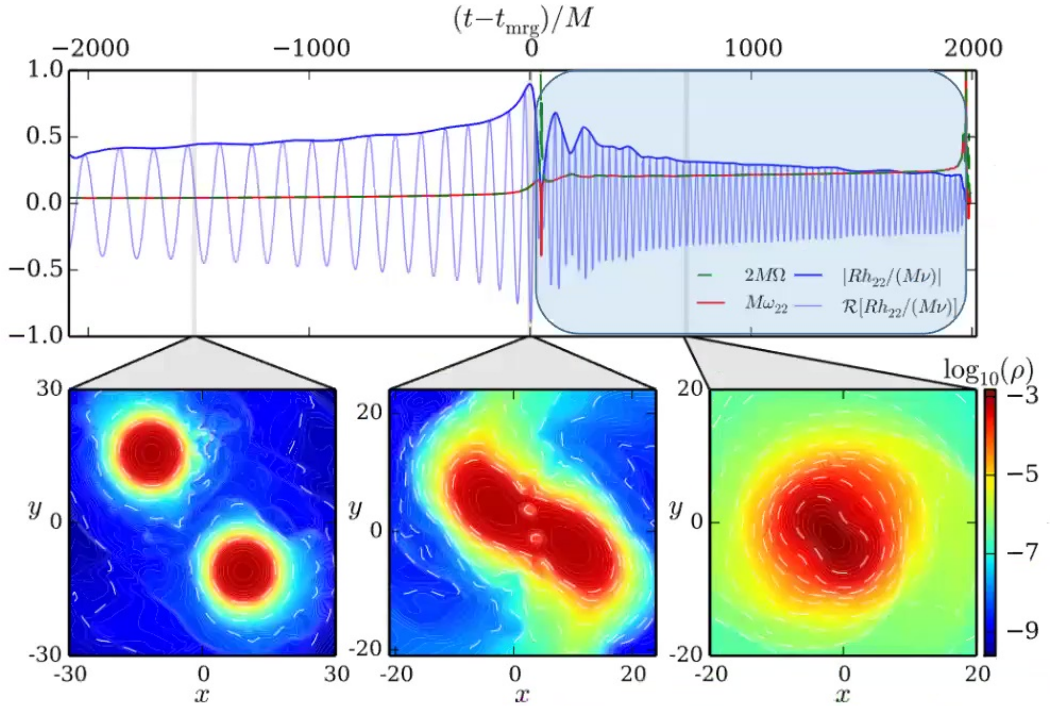




Measurement of Love-Q relation from the GW data

Gravitational Waves: Postmerger

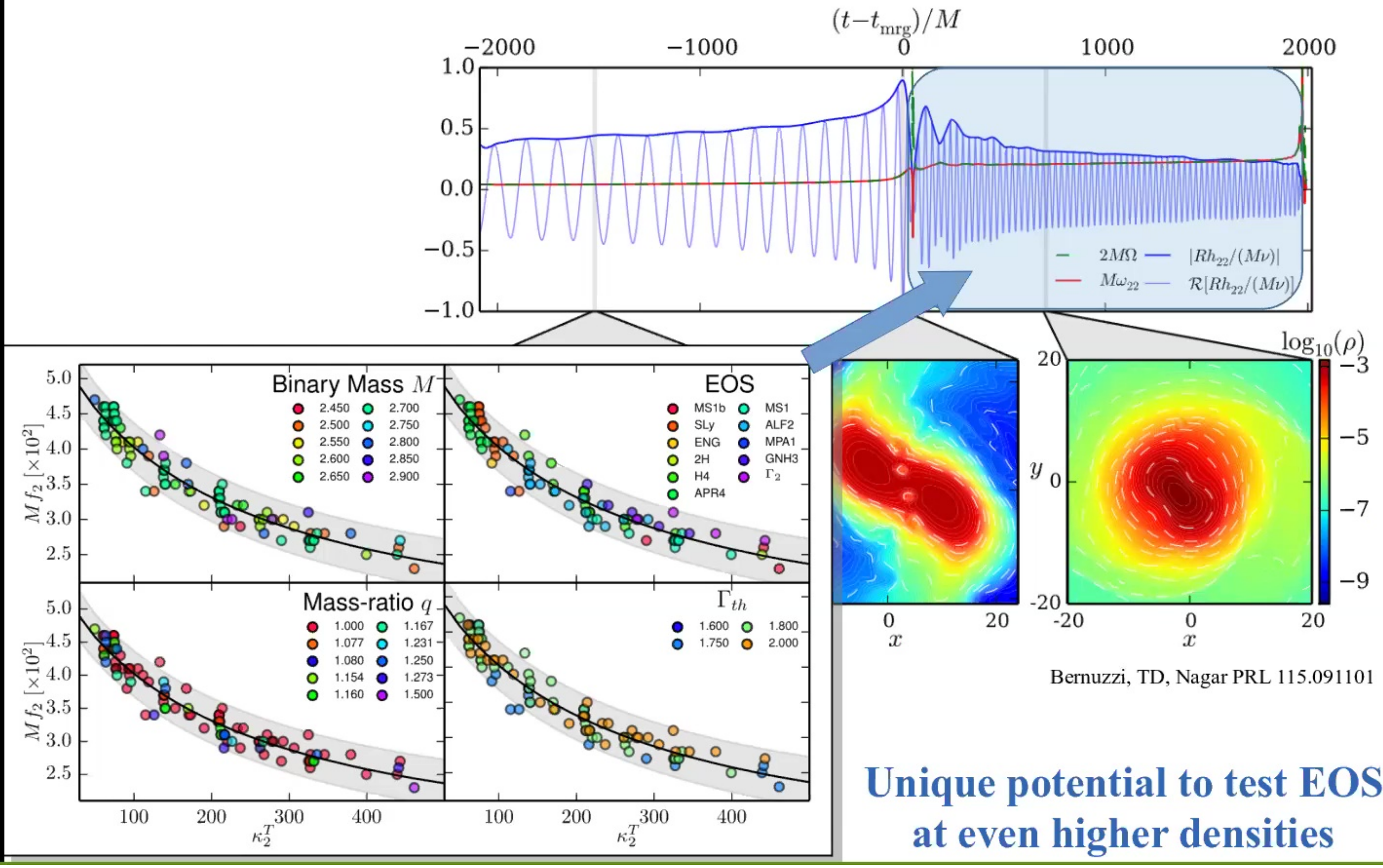
postmerger signal at higher frequencies with low chances of detection



Bernuzzi, TD, Nagar PRL 115.091101

Gravitational Waves: Postmerger

postmerger signal at higher frequencies with low chances of detection

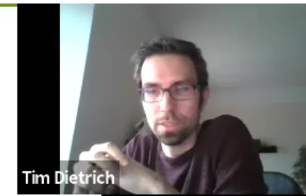


Bernuzzi, TD, Nagar PRL 115.091101

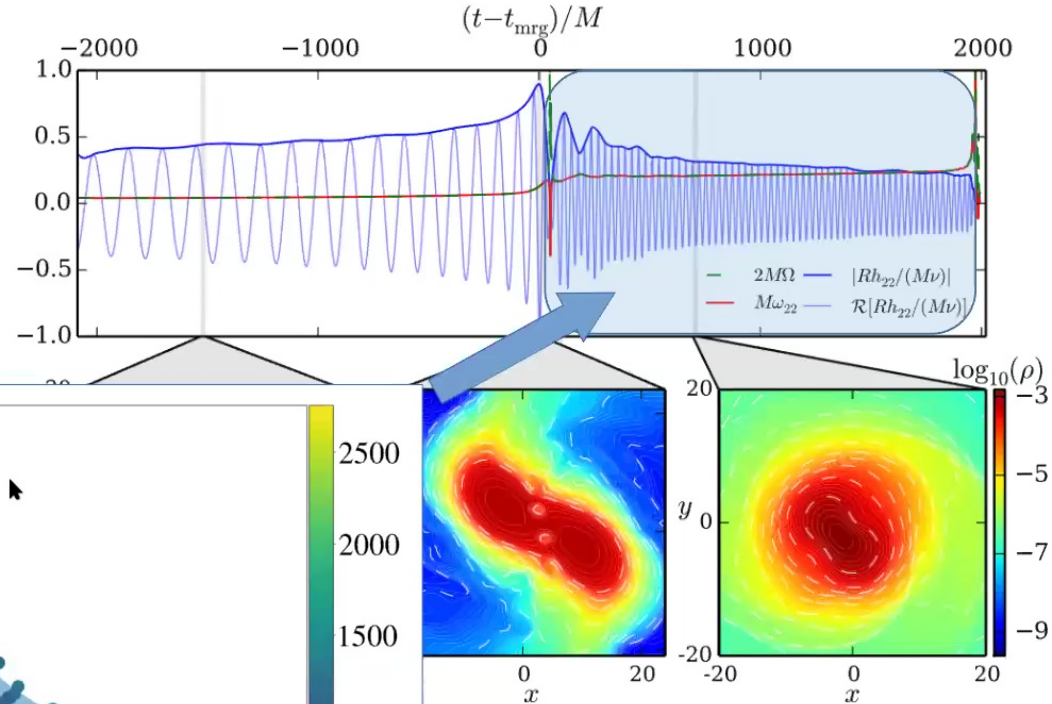
Unique potential to test EOS at even higher densities

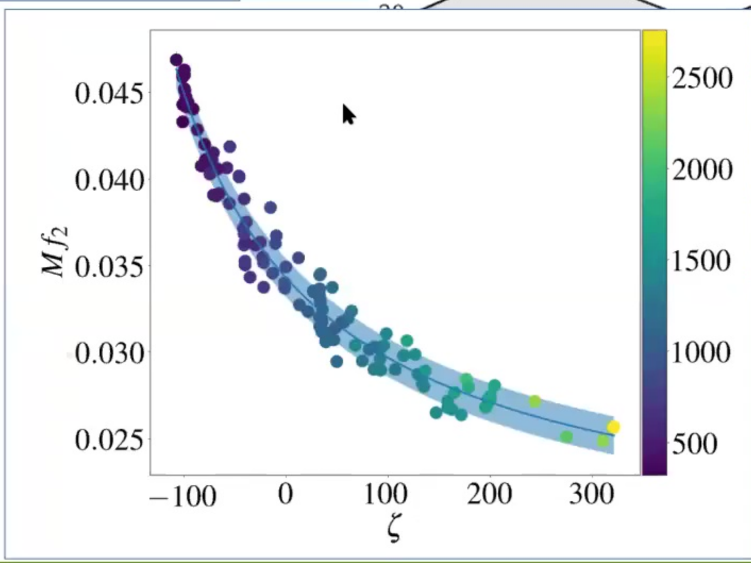
Gravitational Waves: Postmerger

postmerger signal at higher frequencies with low chances of detection



$$\zeta = \kappa^{\mathrm{T}}_{\mathrm{eff}} + a\frac{M}{M_{\mathrm{TOV}}}$$



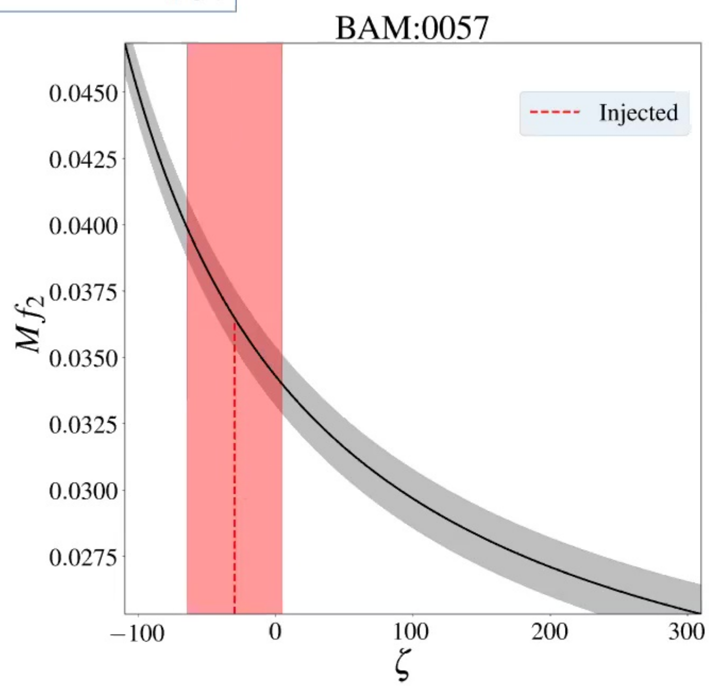


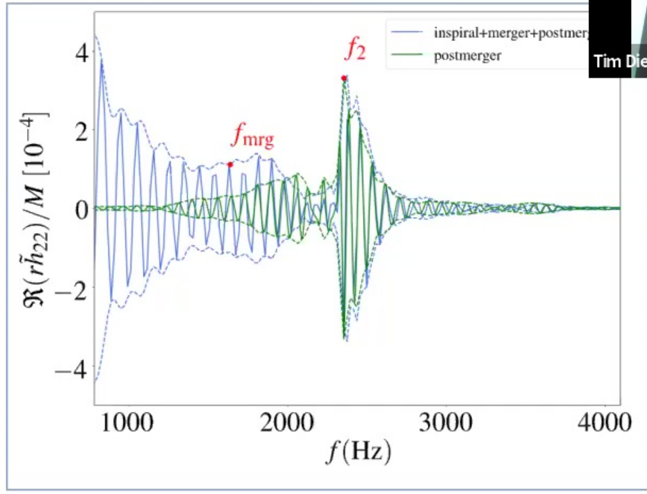
Tsang, TD, Van den Broeck, PRD100 (2019), 044047

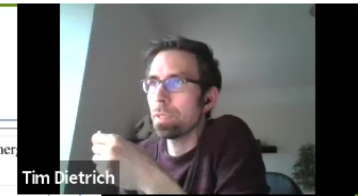
Unique potential to test EOS at even higher densities

Gravitational Waves: Postmerger

$$\zeta = \kappa^{\mathrm{T}}_{\mathrm{eff}} + a\frac{M}{M_{\mathrm{TOV}}}$$



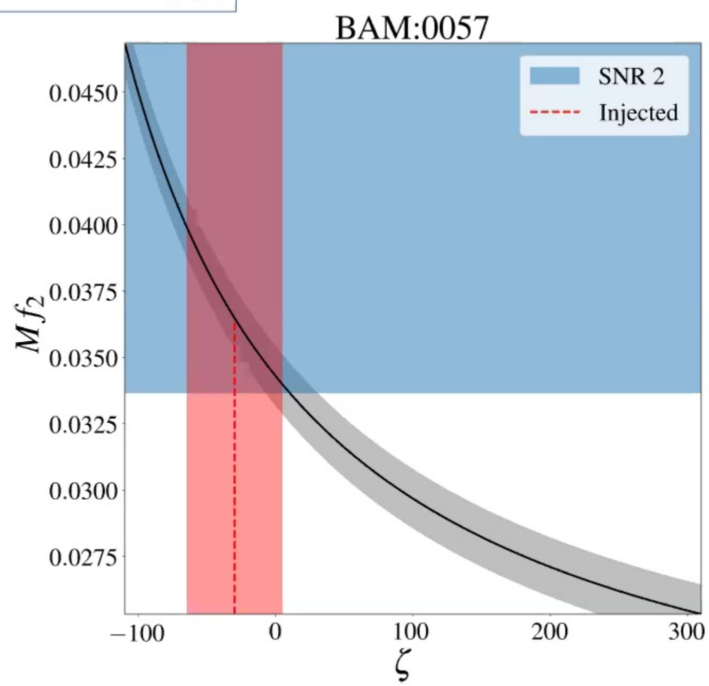


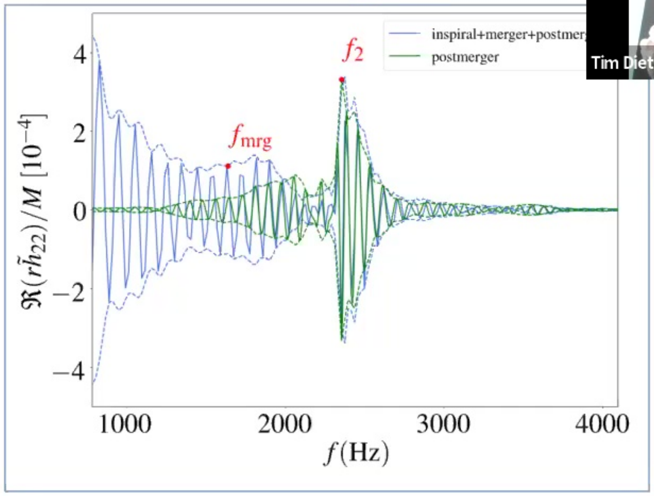


Tsang, TD, Van den Broeck, PRD100 (2019), 044047

Gravitational Waves: Postmerger

$$\zeta = \kappa_{\text{eff}}^{\text{T}} + a\frac{M}{M_{\text{TOV}}}$$





Tsang, TD, Van den Broeck, PRD100 (2019), 044047

Gravitational Waves: Postmerger

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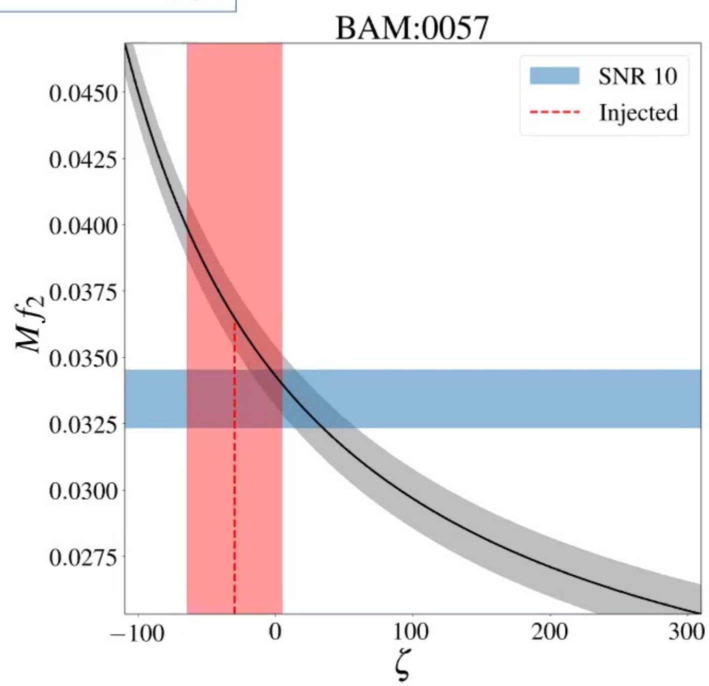
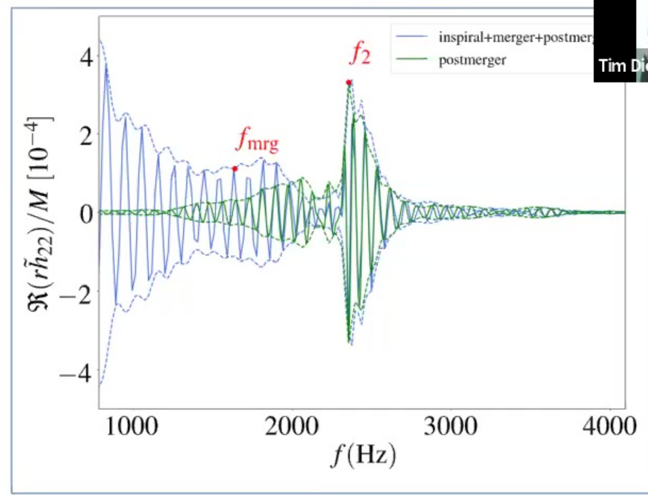
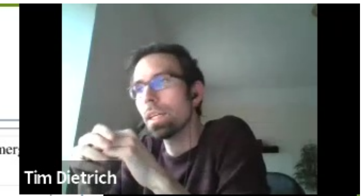
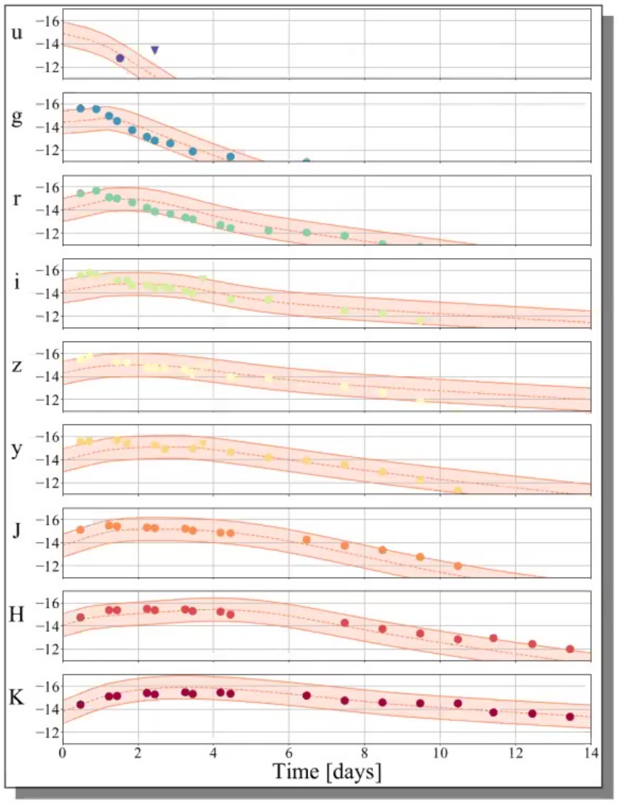


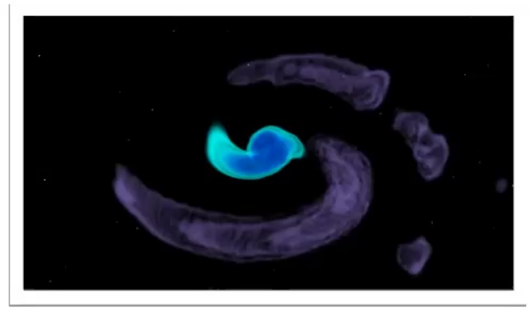


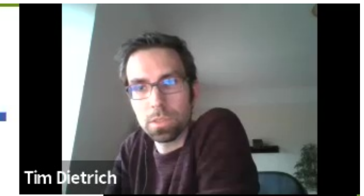


Tsang, TD, Van den Broeck, PRD100 (2019), 044047

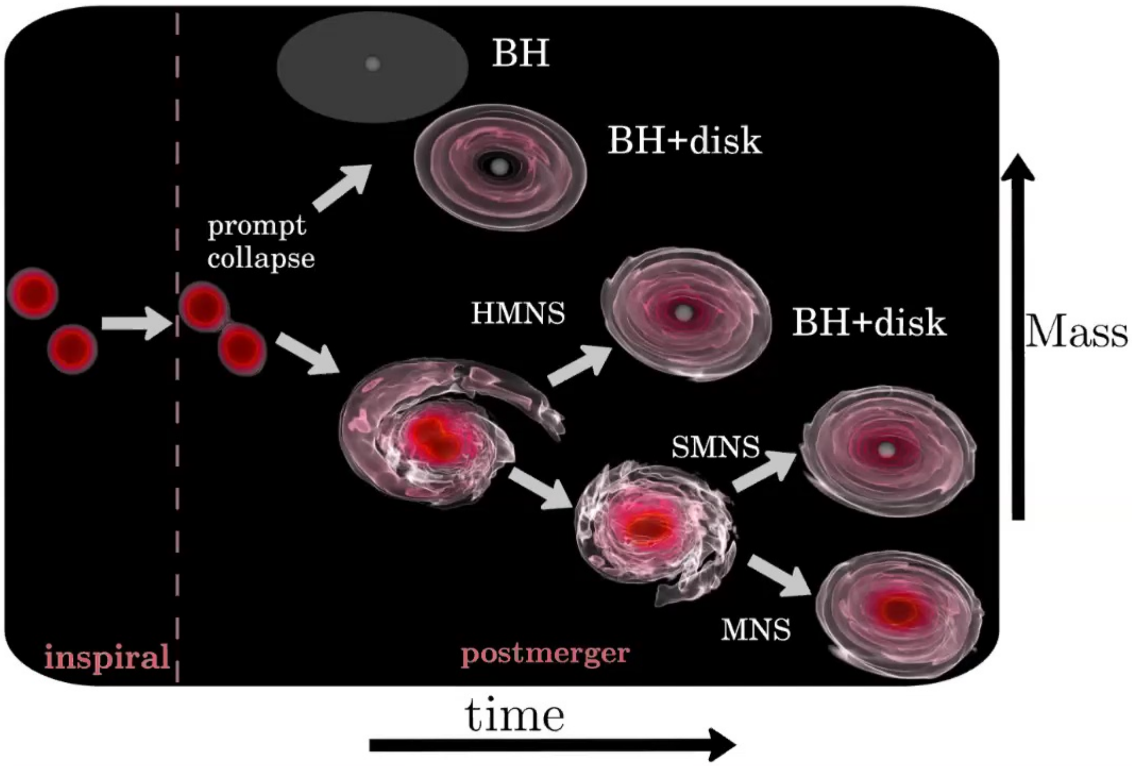
Electromagnetic Signals and Multi-messenger Astronomy



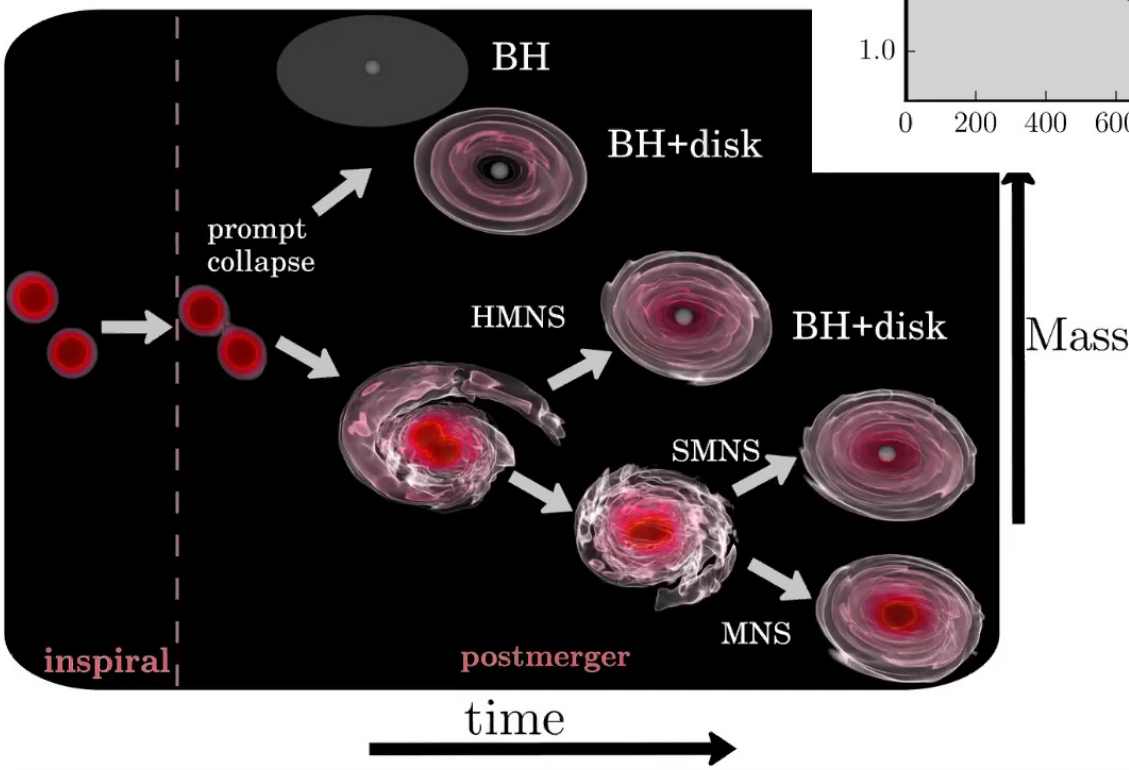


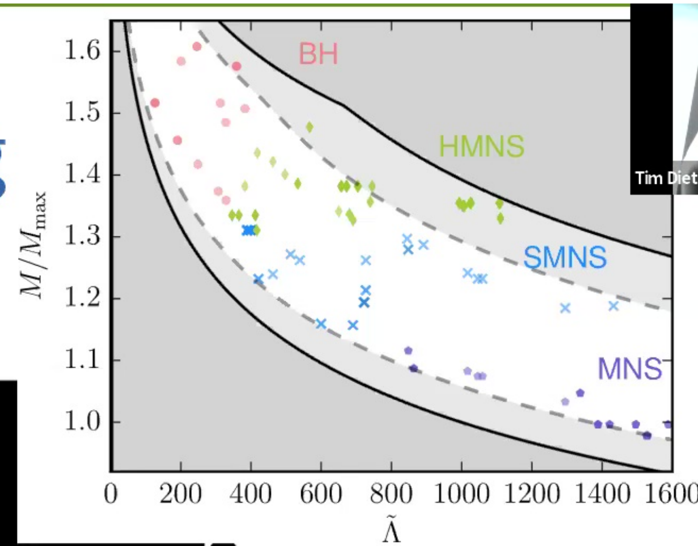


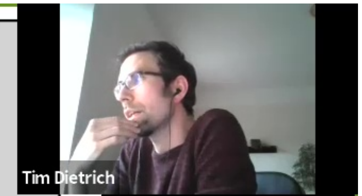
Incorporating NR results



Incorporating







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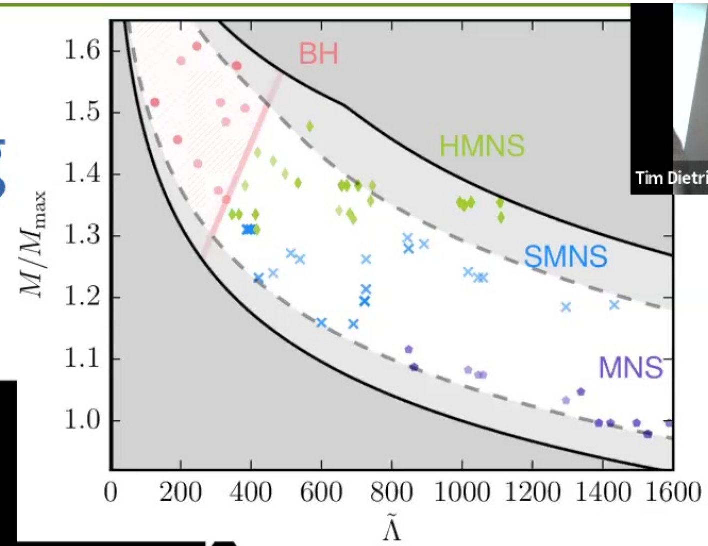

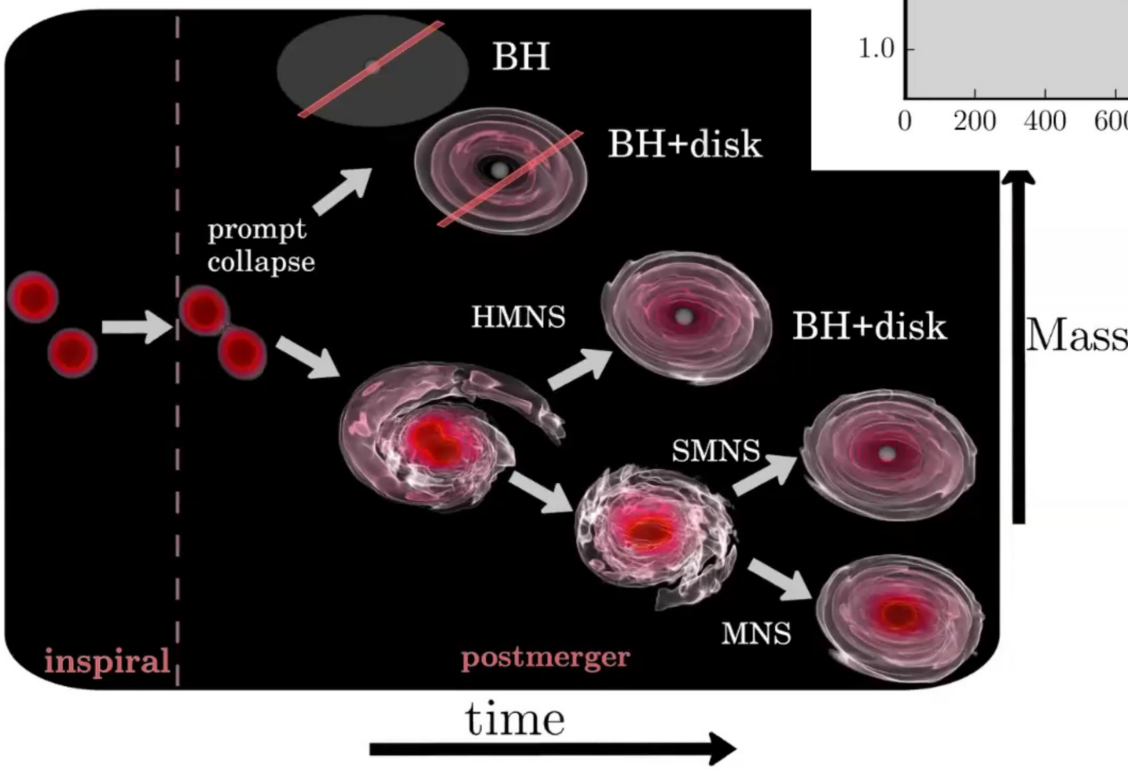

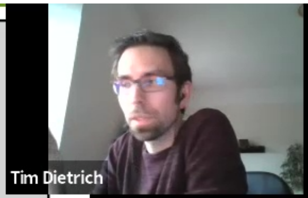

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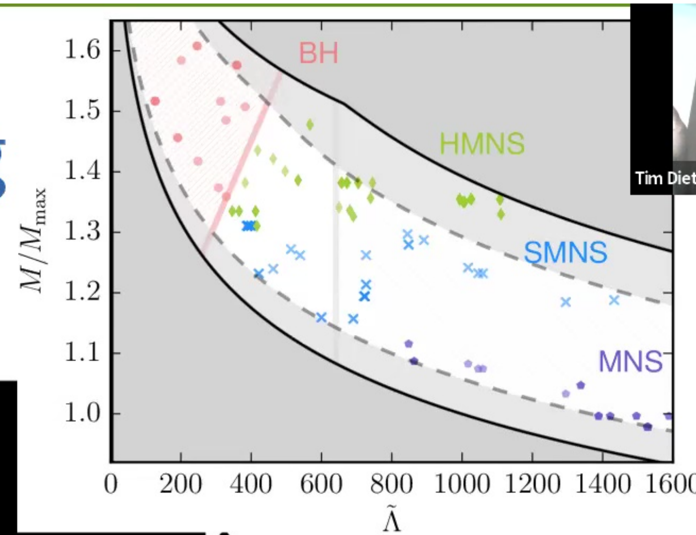
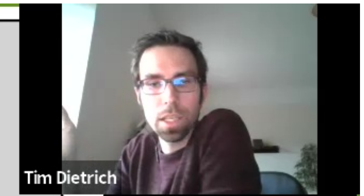
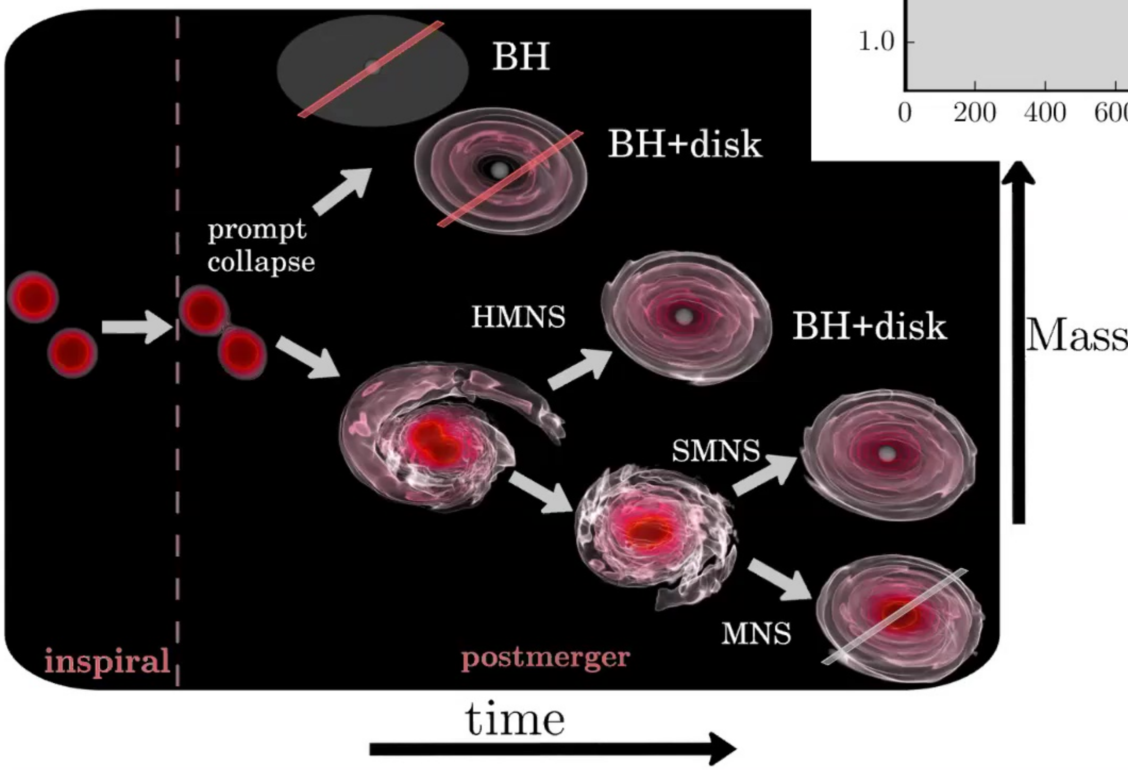
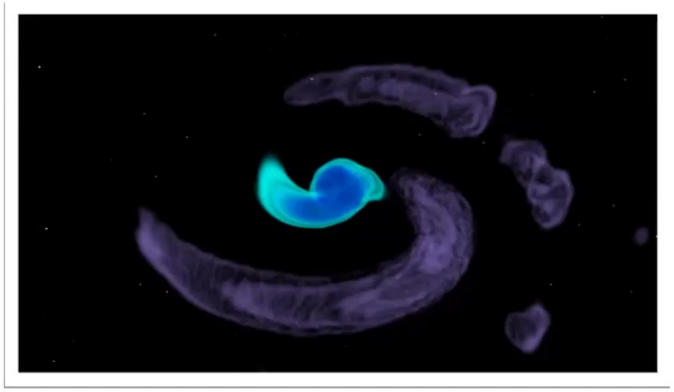


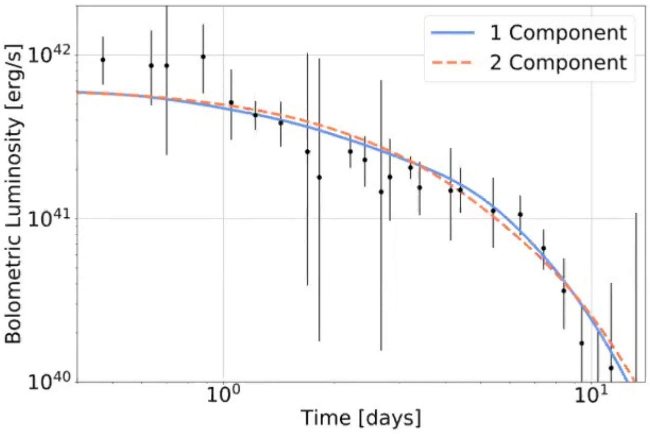




EM Signals – Kilonova

- neutron rich ejecta produce heavy r-process elements
- pseudo-black body radiation from r-process elements
- mergers are major sites for the formation of heavy elements

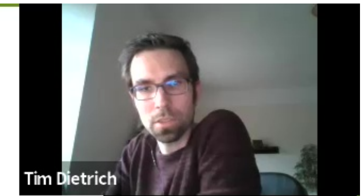




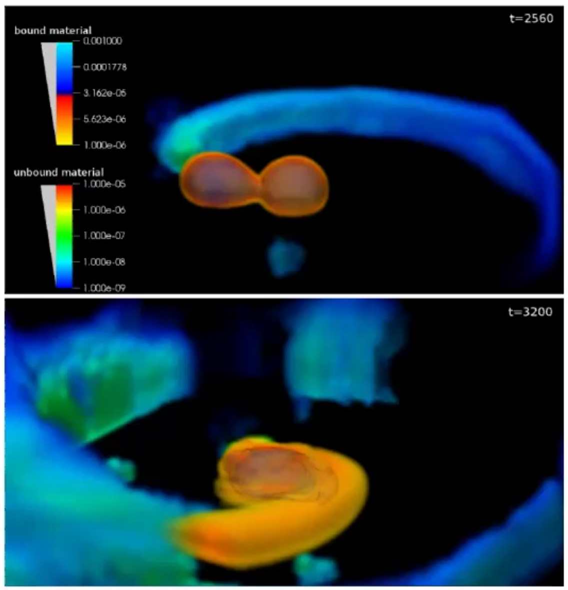
Coughlin, TD, et al., MNRAS/sty2174

Incorporating NR results

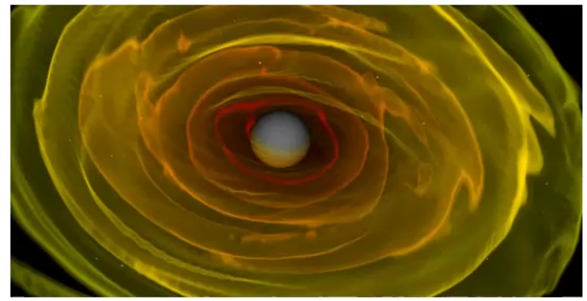
Predictions about ejecta mass and compositions

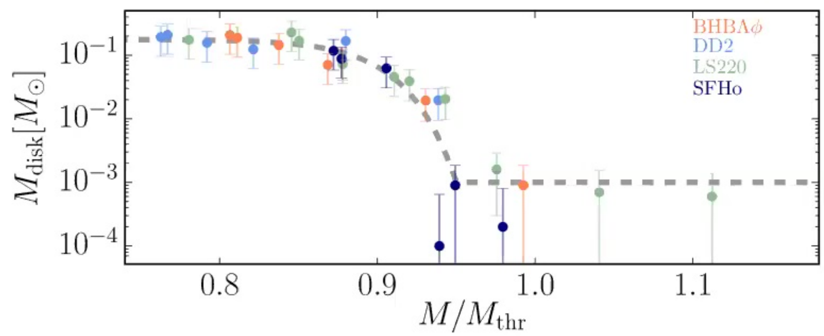


dynamical ejecta



disk winds





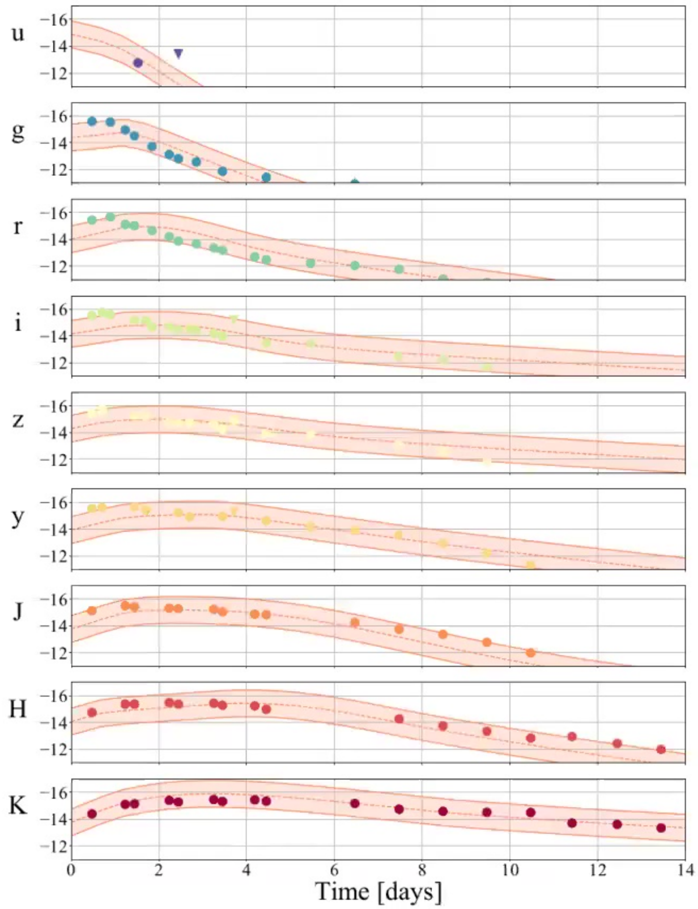
Combine predictions with radiative transfer simulations

Kasen et al., Nature 551

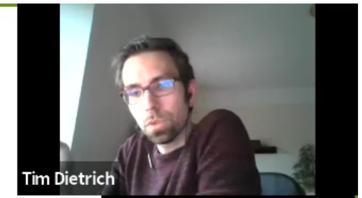
EM Signals
Kilonova

Coughlin, TD, et al., MNRAS/sty2174

Photometric lightcurves



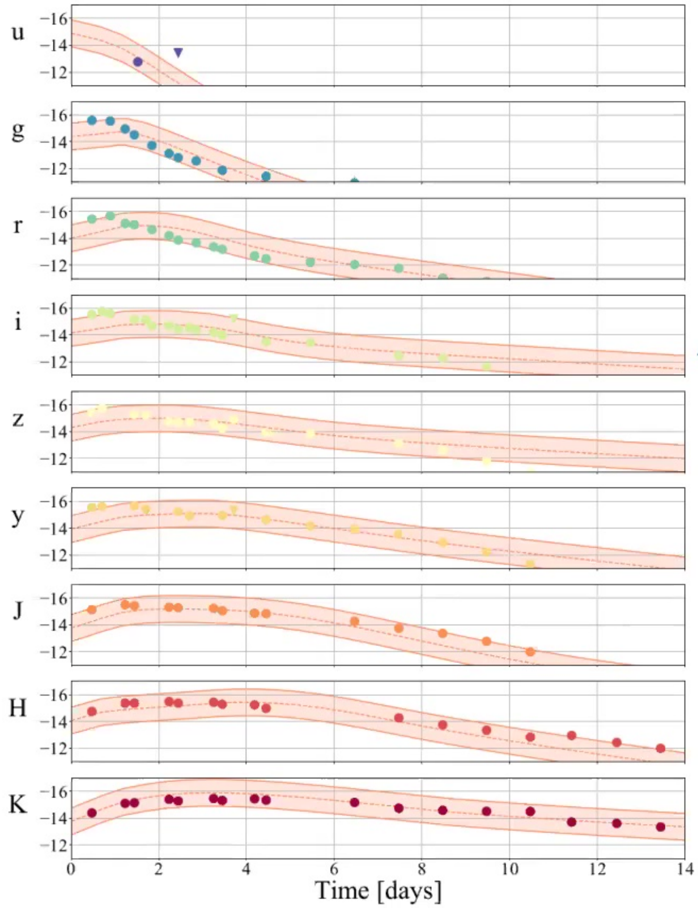
Full radiative transfer simulation linked to Gaussian Process Regression to access full parameter space



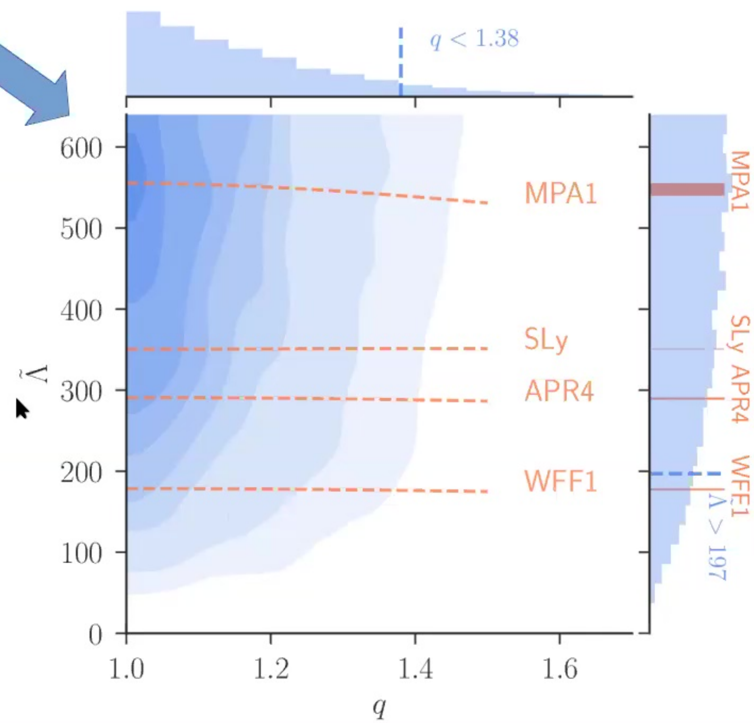
EM Signals Kilonova

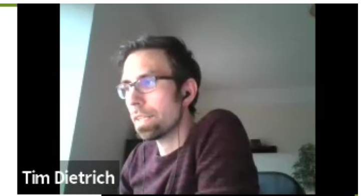
Coughlin, TD, et al., MNRAS/sty2174

Photometric lightcurves

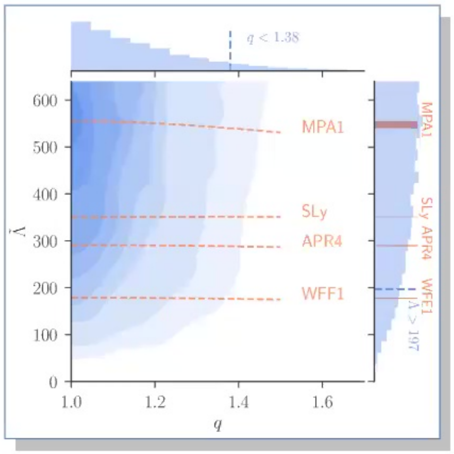


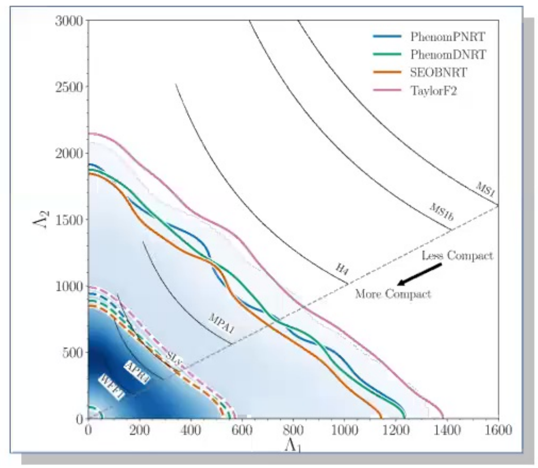
Full radiative transfer simulation linked to Gaussian Process Regression to access full parameter space

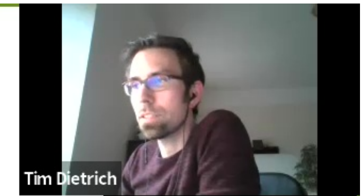


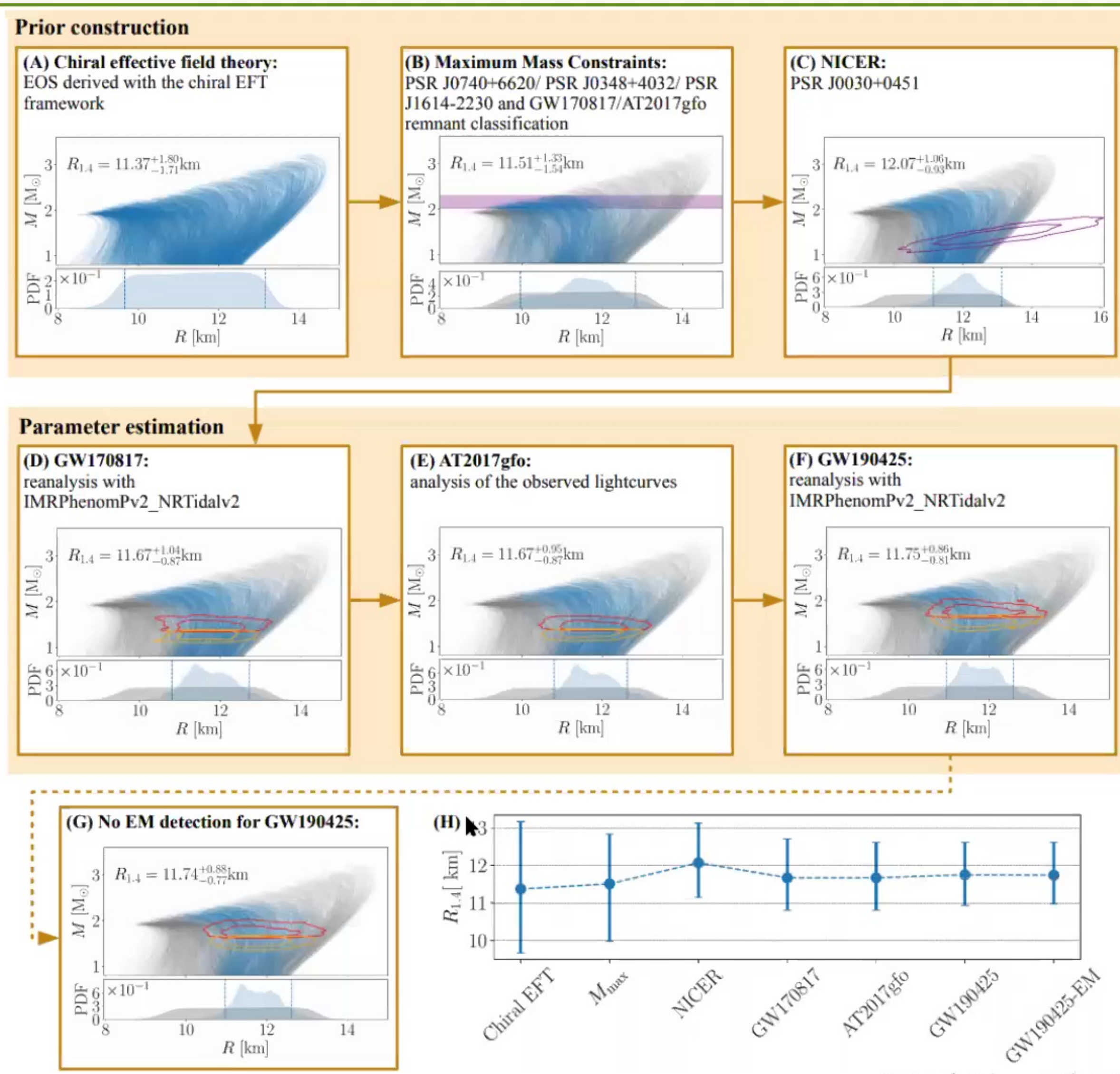


Fundamental physics with Multi-messenger astronomy

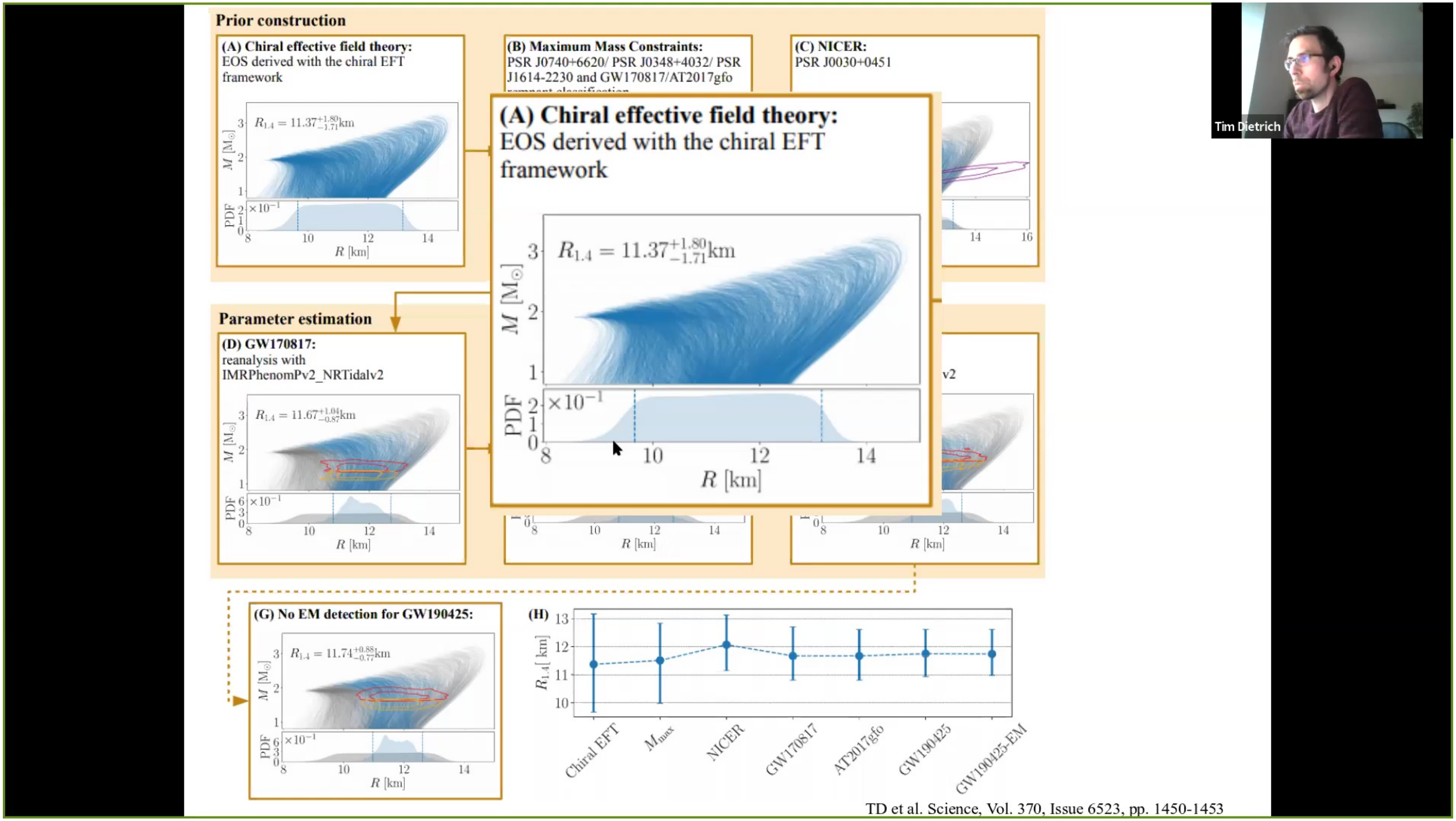




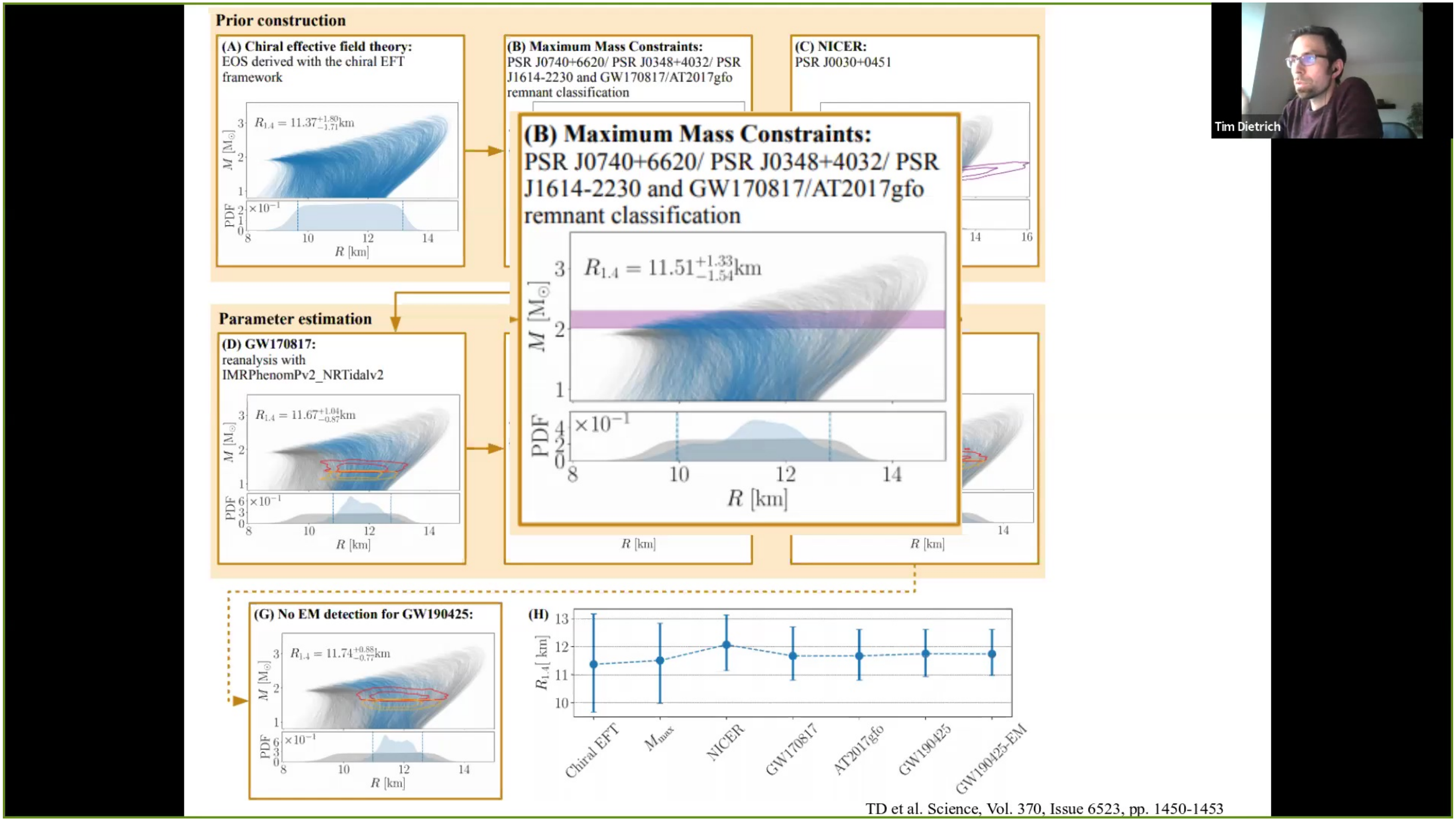




TD et al. Science, Vol. 370, Issue 6523, pp. 1450-1453



Prior construction
(A) Chiral effective field theory:
EOS derived with the chiral EFT framework
(B) Maximum Mass Constraints:
PSR J0740+6620/ PSR J0348+4032/ PSR J1614-2230 and GW170817/AT2017gfo
(C) NICER:
PSR J0030+0451
(A) Chiral effective field theory:
EOS derived with the chiral EFT framework
$R_{1.4} = 11.37^{+1.80}_{-1.71}$km
Parameter estimation
(D) GW170817:
reanalysis with IMRPhenomPv2_NRTidalv2
$R_{1.4} = 11.67^{+1.04}_{-0.87}$km
(G) No EM detection for GW190425:
$R_{1.4} = 11.74^{+0.88}_{-0.77}$km
(H)
Chiral EFT
M_{max}
NICER
GW170817
AT2017gfo
GW190425
GW190425-EM
TD et al. Science, Vol. 370, Issue 6523, pp. 1450-1453
Tim Dietrich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EOS derived with the chiral EFT framework
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(B) Maximum Mass Constraints:
PSR J0740+6620/ PSR J0348+4032/ PSR J1614-2230 and GW170817/AT2017gfo remnant classification
$R_{1.4} = 11.51^{+1.33}_{-1.54}$km
(C) NICER:
PSR J0030+0451
Parameter estimation
(D) GW170817:
reanalysis with IMRPhenomPv2_NRTidalv2
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Chiral EFT
M_{max}
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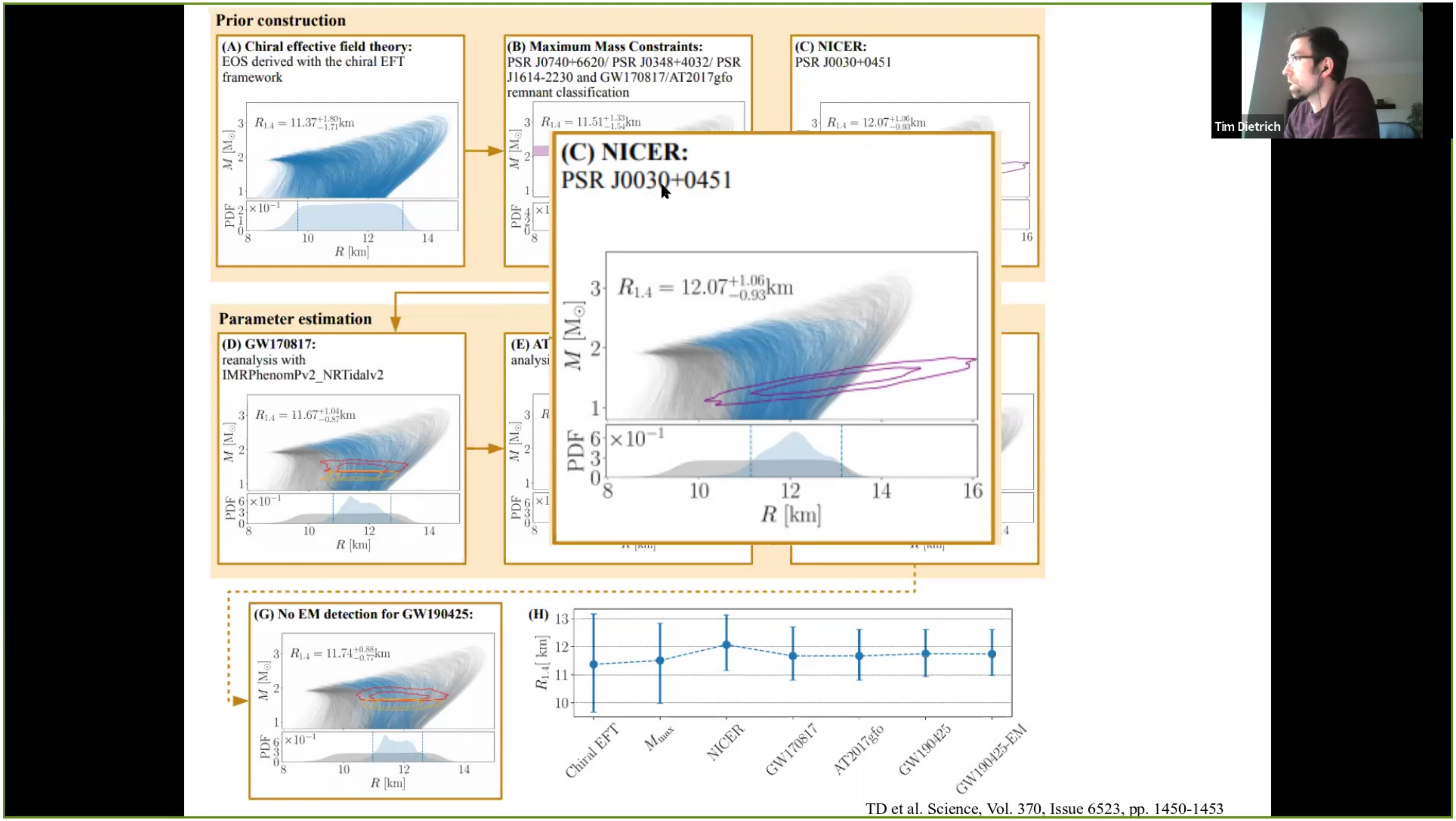
Tim Dietrich


Prior construction
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EOS derived with the chiral EFT framework
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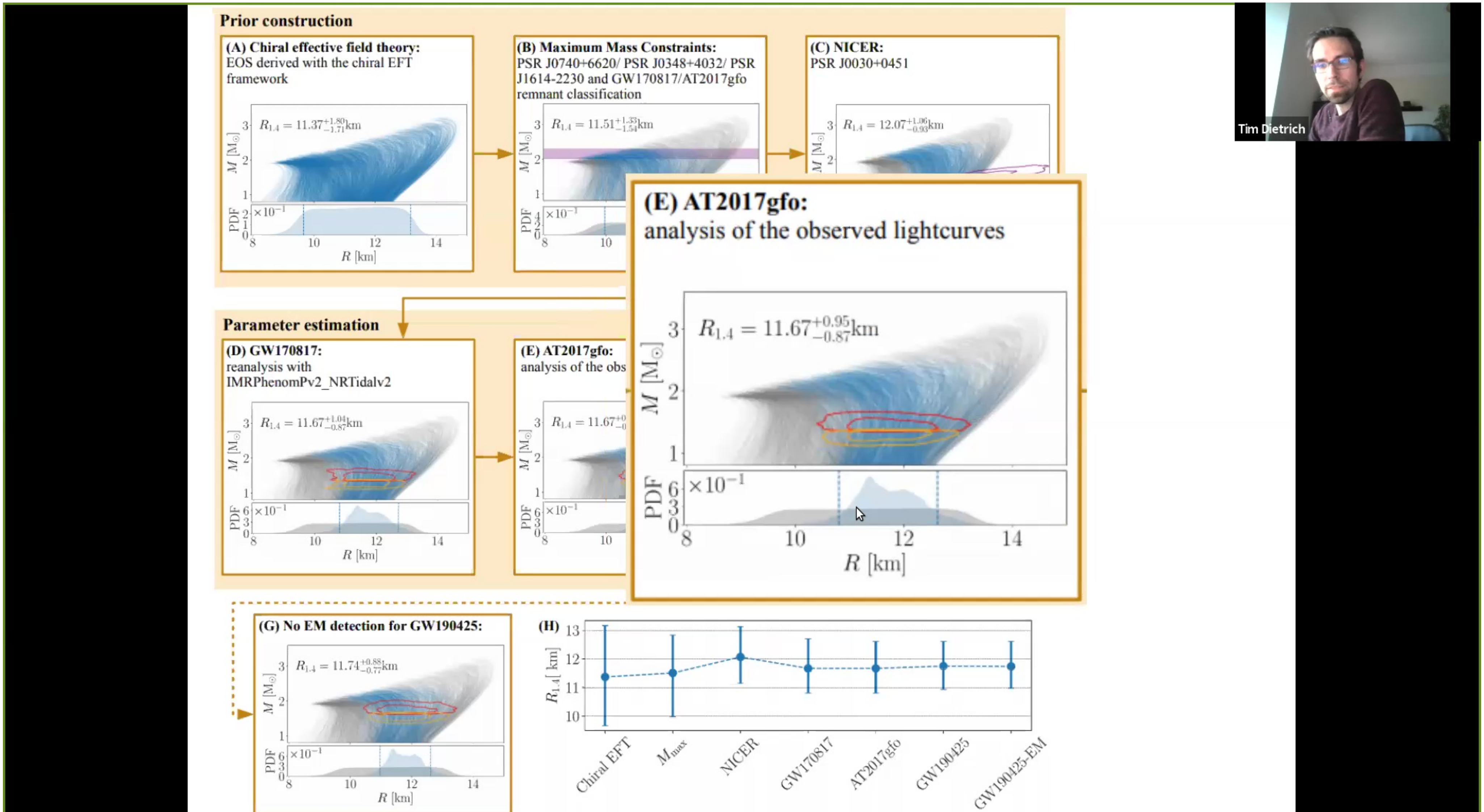
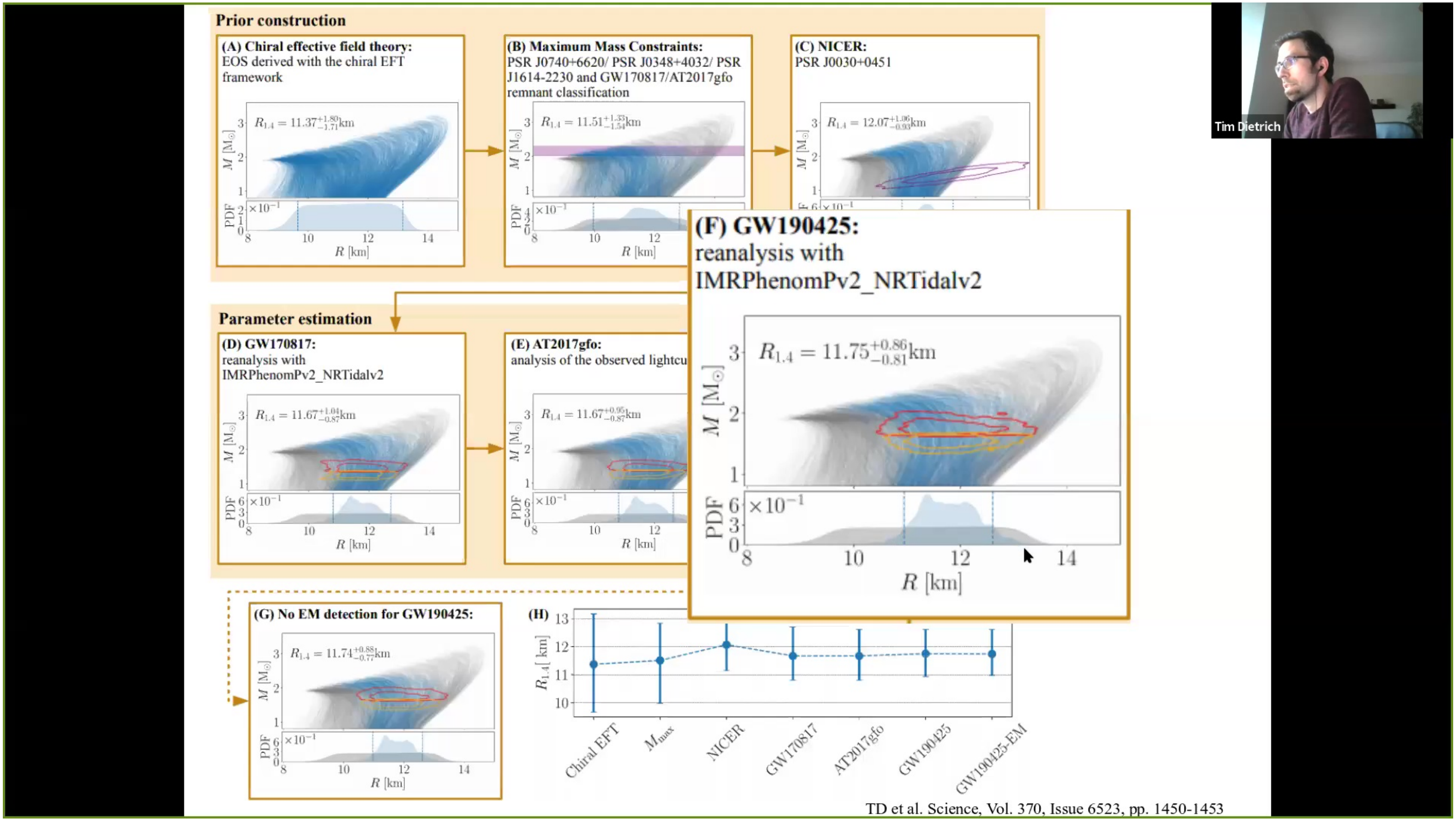
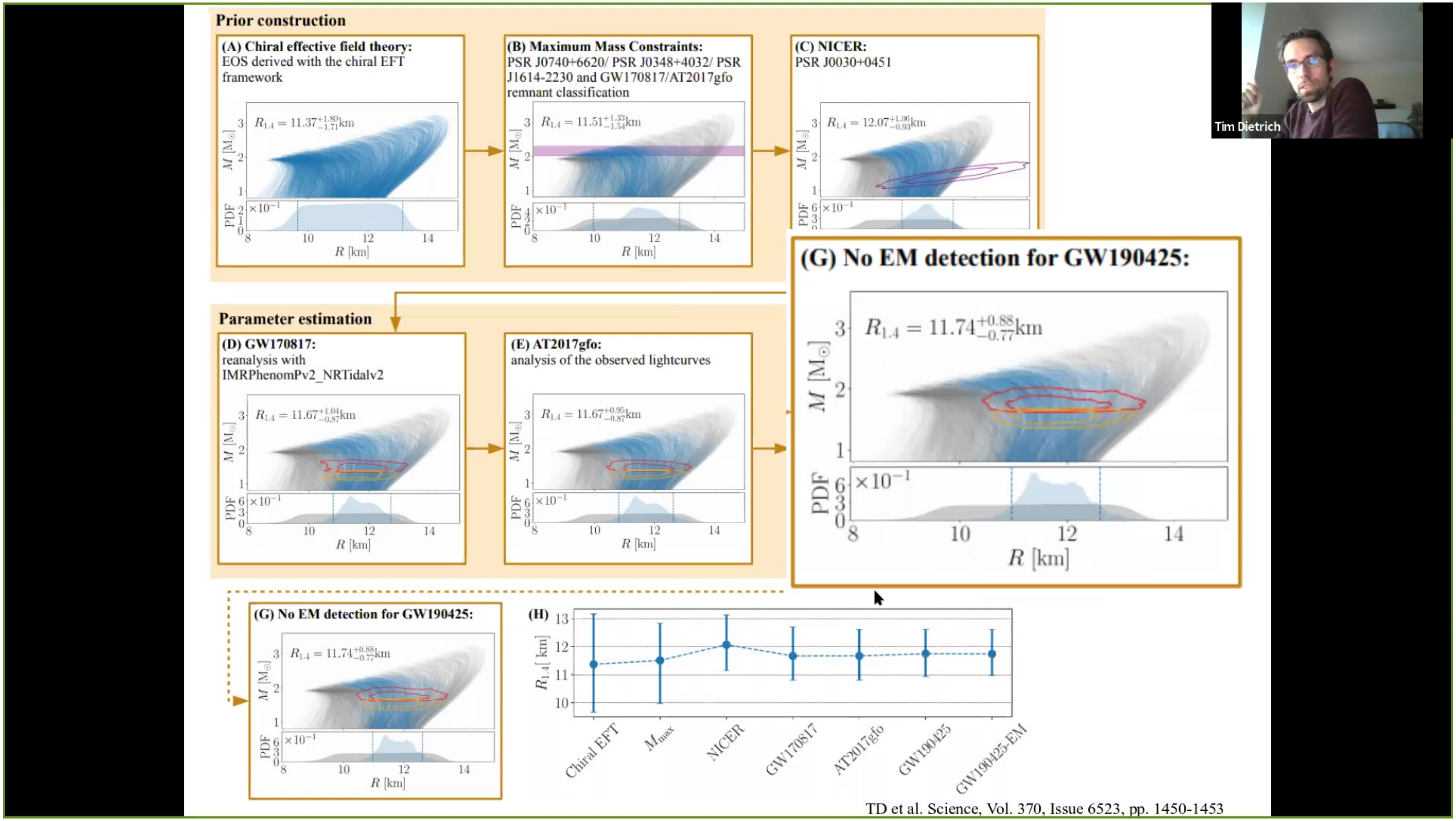
PSR J0740+6620/ PSR J0348+4032/ PSR J1614-2230 and GW170817/AT2017gfo remnant classification
(C) NICER:
PSR J0030+0451
$R_{1.4} = 12.07^{+1.06}_{-0.93}$km
M [$M_\odot$]
PDF
R [km]
Parameter estimation
(D) GW170817:
reanalysis with IMRPhenomPv2_NRTidalv2
$R_{1.4} = 11.67^{+1.04}_{-0.87}$km
(G) No EM detection for GW190425:
$R_{1.4} = 11.74^{+0.88}_{-0.77}$km
(H)
$R_{1.4}$ [km]
Chiral EFT
M_{max}
NICER
GW170817
AT2017gfo
GW190425
GW190425-EM
TD et al. Science, Vol. 370, Issue 6523, pp. 1450-1453
Tim Dietrich



TD et al. Science, Vol. 370, Issue 6523, pp. 1450-1453



Prior construction
(A) Chiral effective field theory:
EOS derived with the chiral EFT framework
(B) Maximum Mass Constraints:
PSR J0740+6620/ PSR J0348+4032/ PSR J1614-2230 and GW170817/AT2017gfo remnant classification
(C) NICER:
PSR J0030+0451
Parameter estimation
(D) GW170817:
reanalysis with IMRPhenomPv2_NRTidalv2
(E) AT2017gfo:
analysis of the observed lightcu
(F) GW190425:
reanalysis with IMRPhenomPv2_NRTidalv2
$R_{1.4} = 11.75^{+0.86}_{-0.81}$ km
(G) No EM detection for GW190425:
(H)
Chiral EFT
M_{max}
NICER
GW170817
AT2017gfo
GW190425
GW190425-EM
TD et al. Science, Vol. 370, Issue 6523, pp. 1450-1453
Tim Dietrich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reanalysis with IMRPhenomPv2_NRTidalv2
(E) AT2017gfo:
analysis of the observed lightcurves
(G) No EM detection for GW190425:
$R_{1.4} = 11.74^{+0.88}_{-0.77}$km
(H)
Chiral EFT
M_{max}
NICER
GW170817
AT2017gfo
GW190425
GW190425-EM
TD et al. Science, Vol. 370, Issue 6523, pp. 1450-1453
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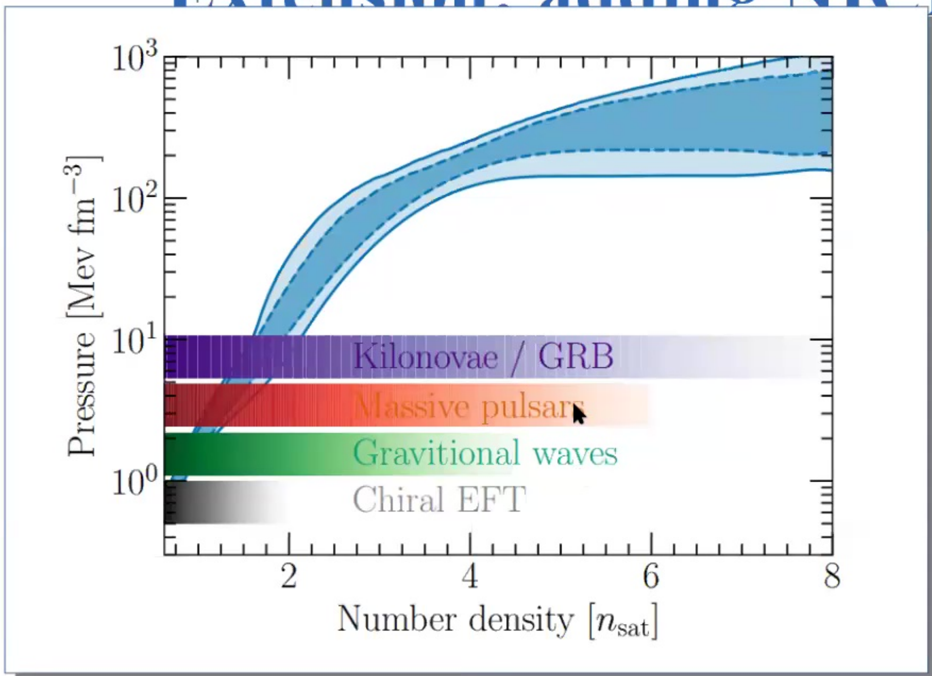
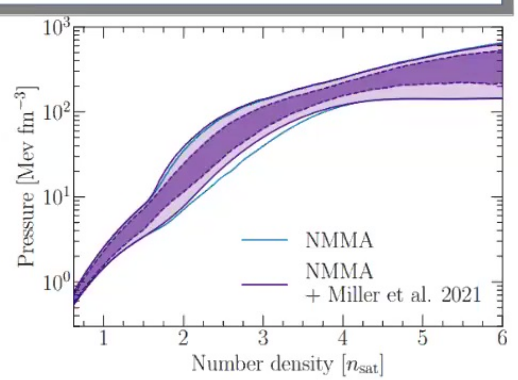
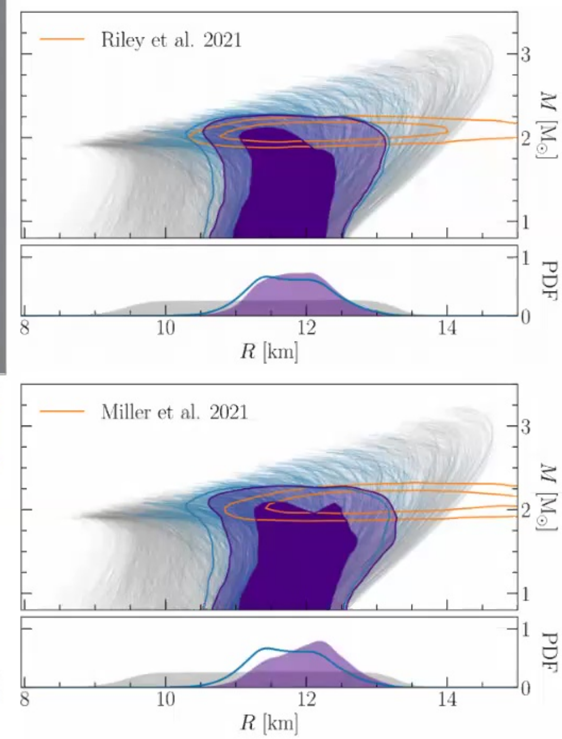
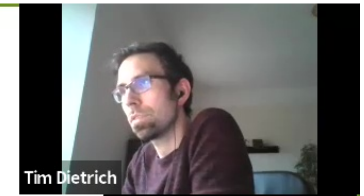
Extension: adding NICER & XMM ...ts









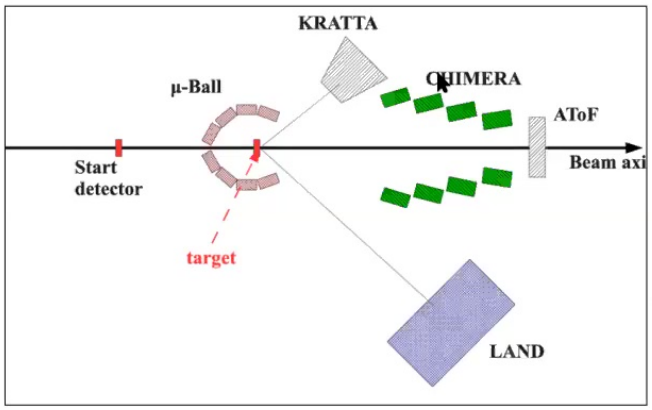
Pang et al., arxiv:2105.08688

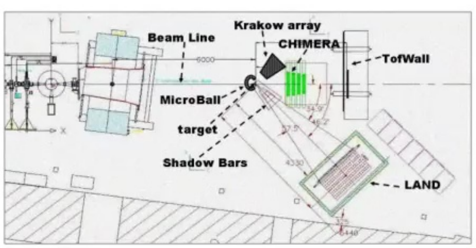
Ongoing studies (preliminary)

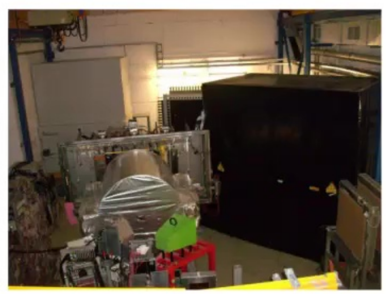
including experimental data from heavy ion collisions

Results of the ASY-EOS experiment at GSI: The symmetry energy at suprasaturation density

P. Russotto,[1] S. Gannon,[2] S. Kupny,[3] P. Lasko,[3] L. Acosta,[4,5] M. Adamczyk,[3] A. Al-Ajlan,[6] M. Al-Garawi,[7] S. Al-Homaidhi,[6] F. Amorini,[4] L. Auditore,[8,9] T. Aumann,[10,11] Y. Ayyad,[12] Z. Basrak,[13] J. Benlliure,[12] M. Boisioli,[14] K. Boretzky,[11] J. Brzychczyk,[3] A. Budzanowski,[15,*] C. Caesar,[10] G. Cardella,[1]

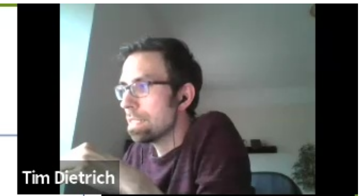






Russotto et al., J.Phys.Conf.Ser. 420 (2013)

Ongoing studies (preliminary)



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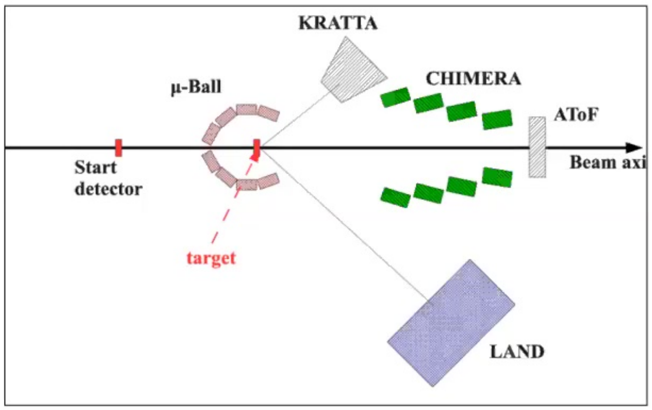


Total energy: $E(n,x) = E_{\rm SNM} + E_{\rm sym}\delta^2$

Asymmetry energy:

$$E_{\rm sym}(n) = E_{kin,0}\left(\frac{n}{n_0}\right)^{2/3} + E_{pot,0}\left(\frac{n}{n_0}\right)^{\gamma_{\rm asy}}$$

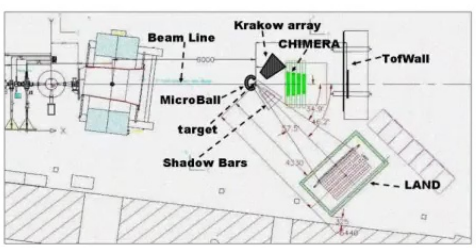
Parameters set by UrQMD model fitted to

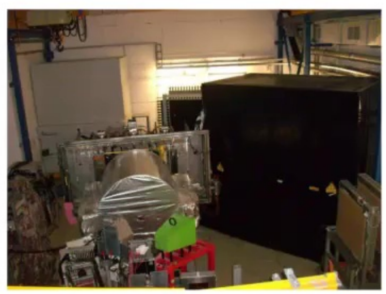
elliptic flow data from asyEOS experiment:

$$\gamma_{\rm asy} = 0.68 \pm 0.19 \quad \text{for} \quad E_{\rm sym} = 31 \text{ MeV}$$

$$\gamma_{\rm asy} = 0.72 \pm 0.19 \quad \text{for} \quad E_{\rm sym} = 34 \text{ MeV}$$

Pressure: $P = n^2 \dfrac{\partial E}{\partial n}$





Russotto et al., J.Phys.Conf.Ser. 420 (2013)

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ion collisions

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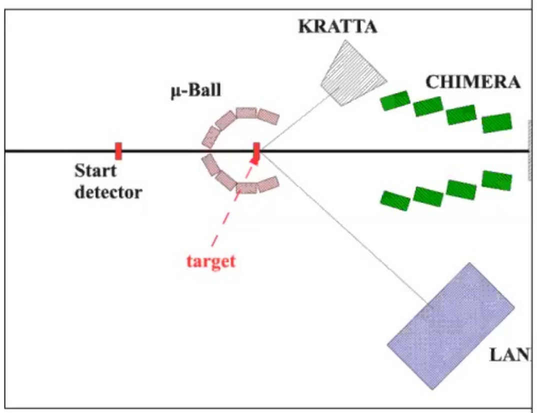

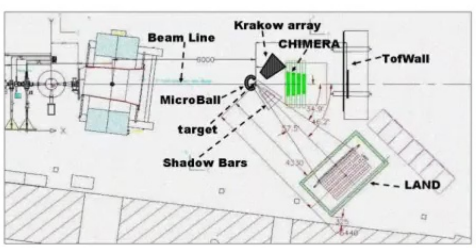

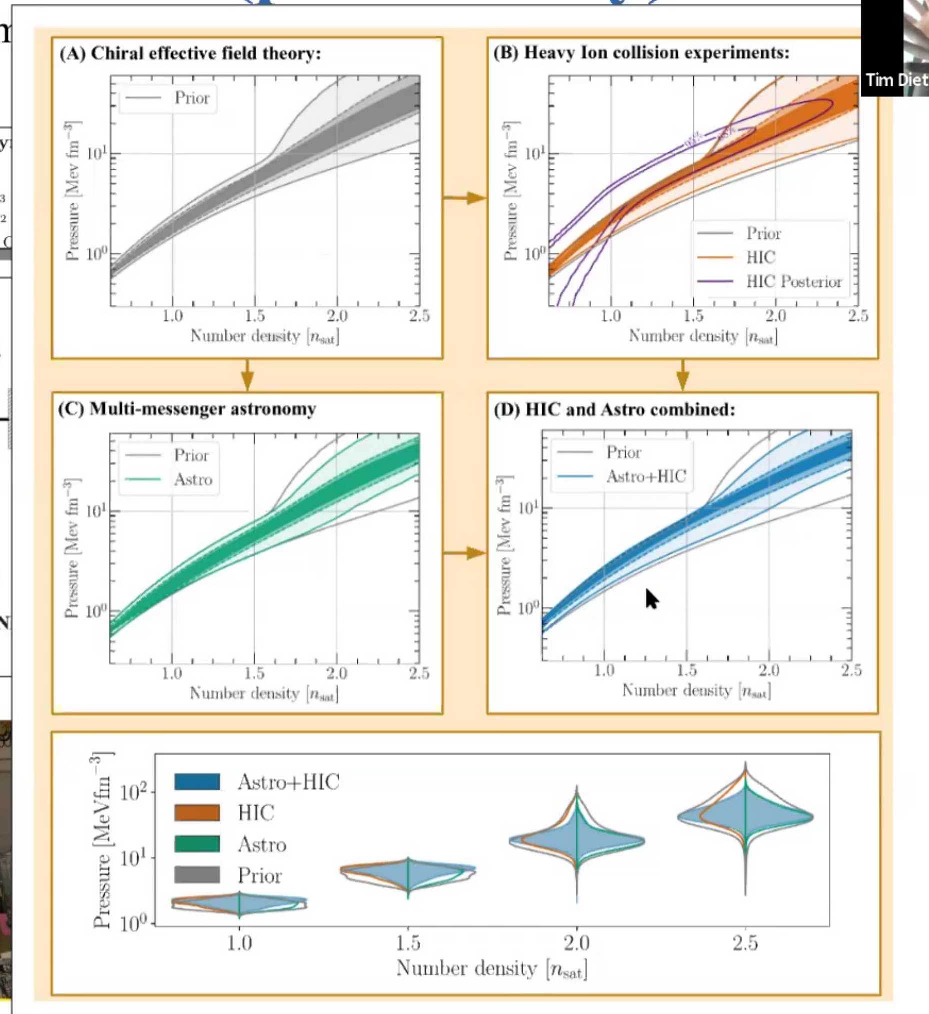

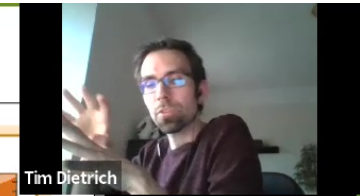

Russotto et al., J.Phys.Conf.Ser. 420 (2013)

Ongoing studies (preliminary)

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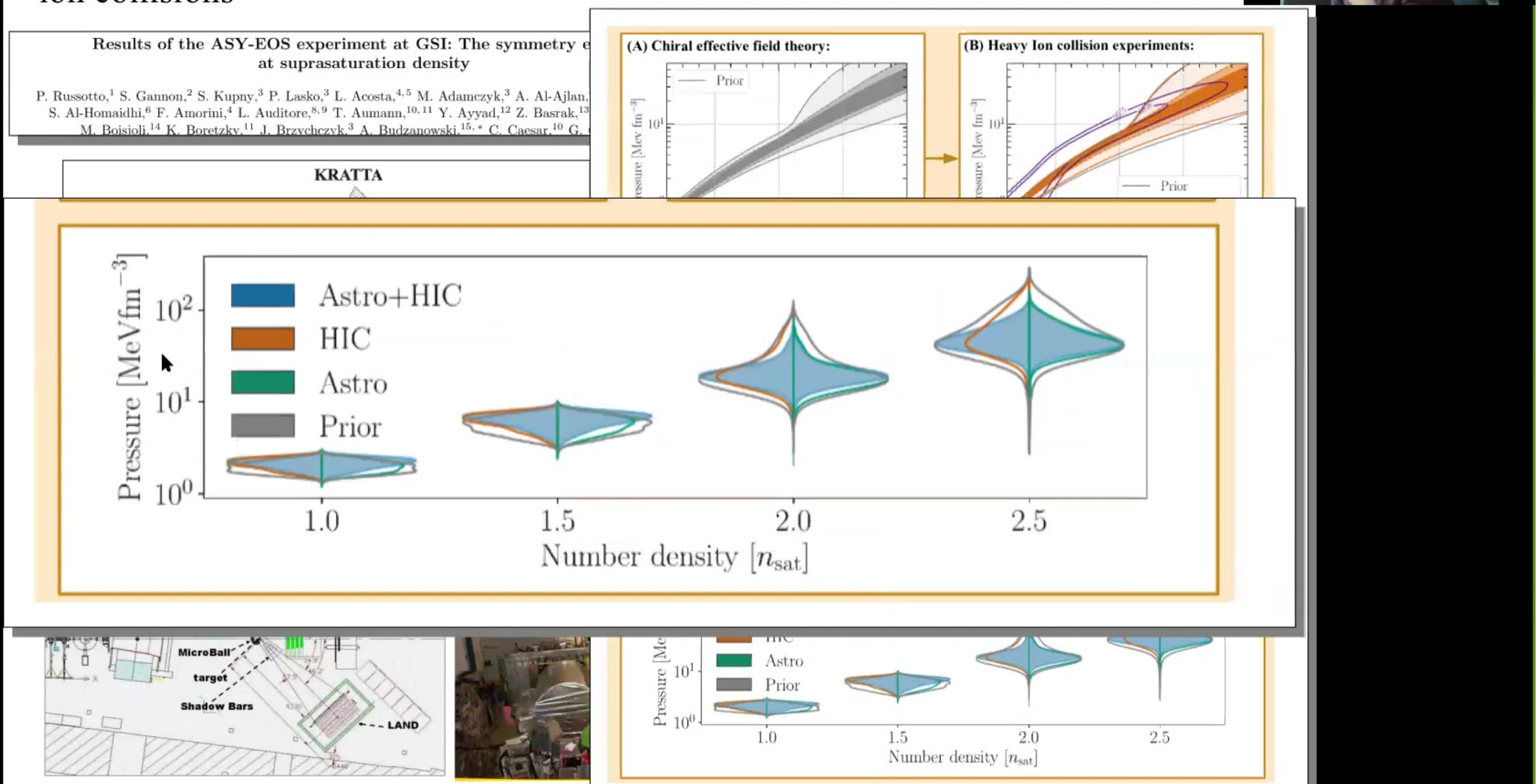

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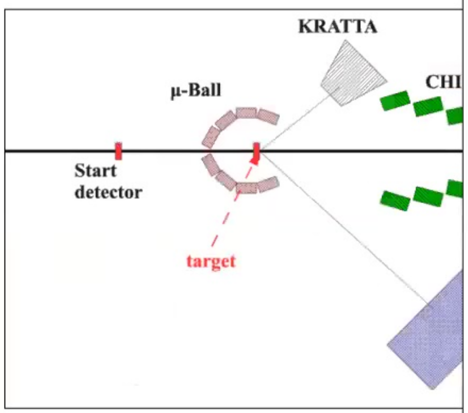
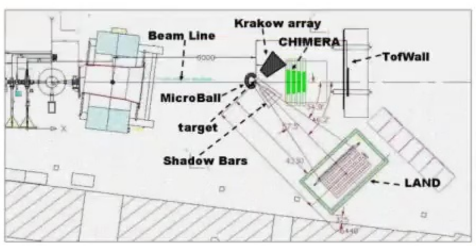
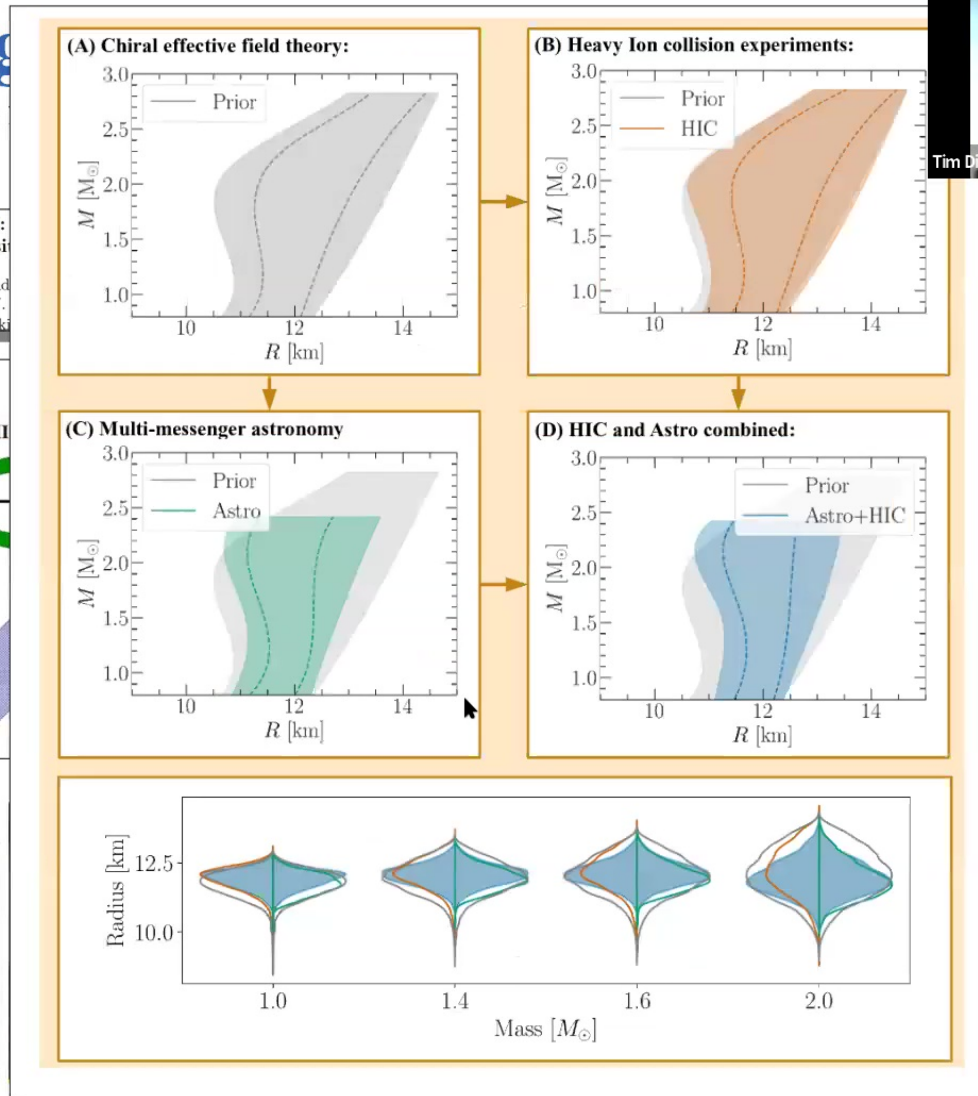
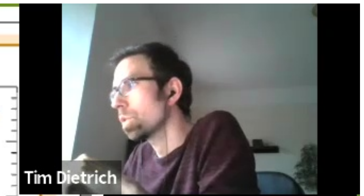


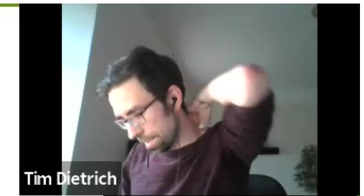


Russotto et al., J.Phys.Conf.Ser. 420 (2013)





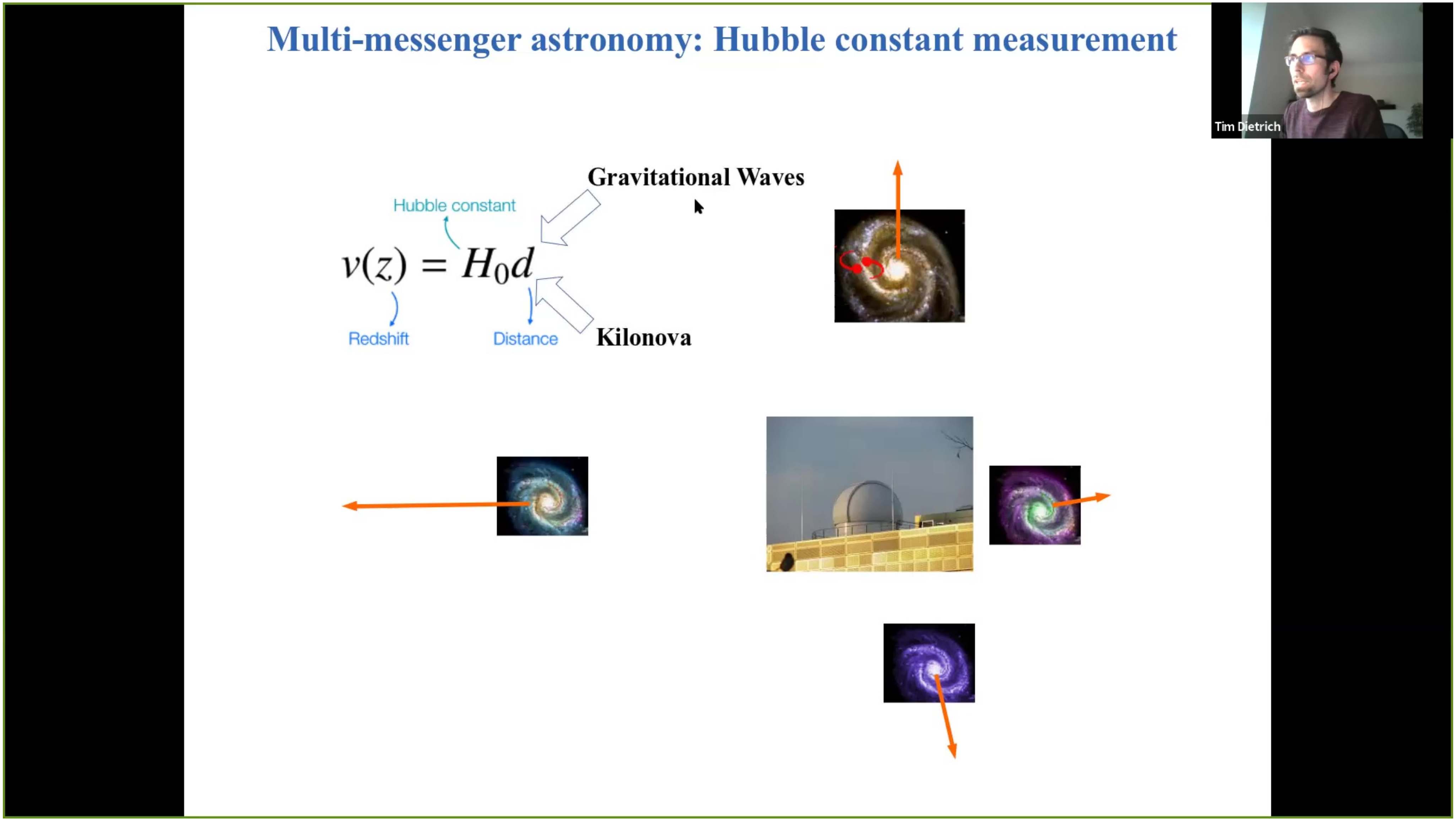
Multi-messenger astronomy: Hubble constant measurement



Hubble constant

$$v(z) = H_0 d$$

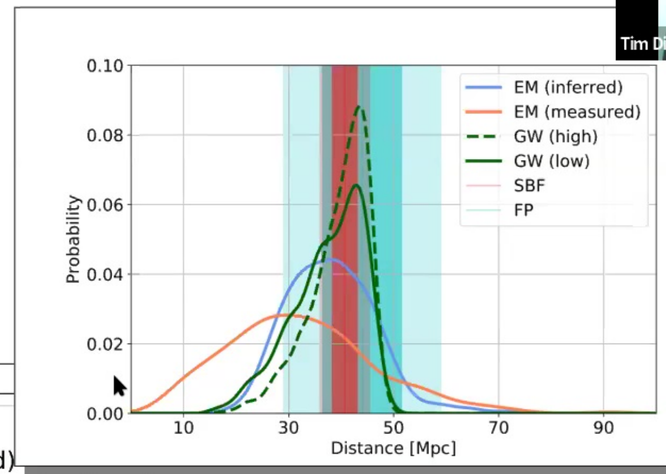
Redshift — Distance

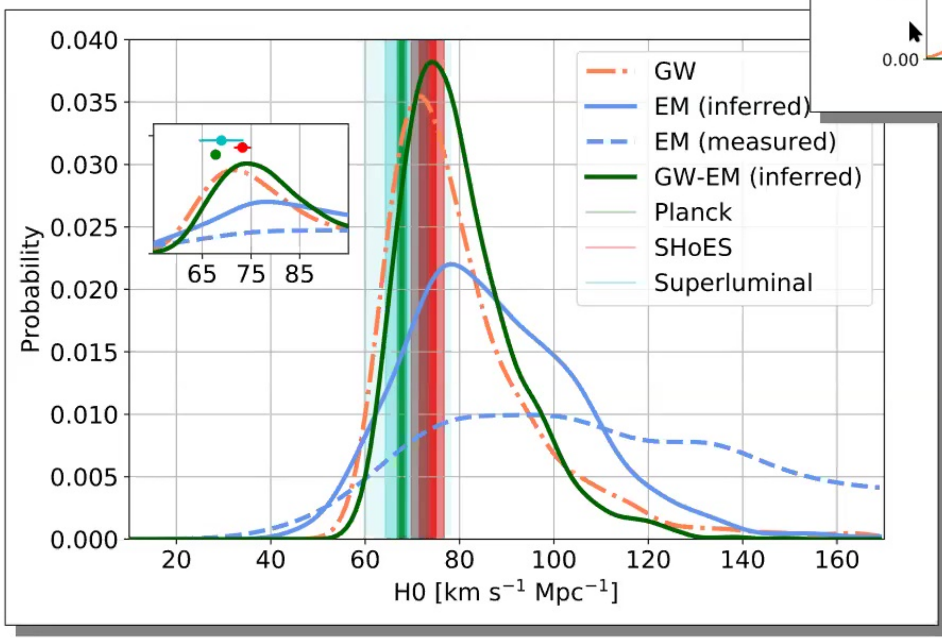

Multi-messenger astronomy: Hubble constant measurement
Tim Dietrich
Gravitational Waves
Hubble constant
$v(z) = H_0 d$
Redshift
Distance
Kilonova

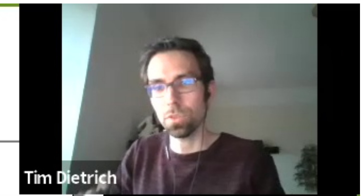
Multi-messenger astronomy: Hubble constant measurement

Coughlin, et al, PRR(R), 022006

Hubble constant measurement via standardization of kilonova lightcurves







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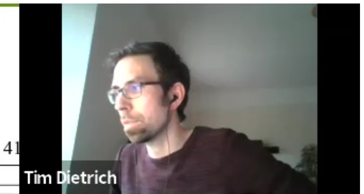
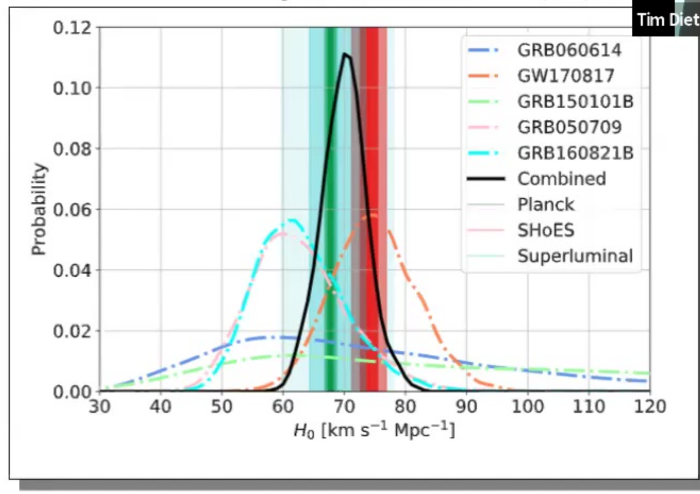
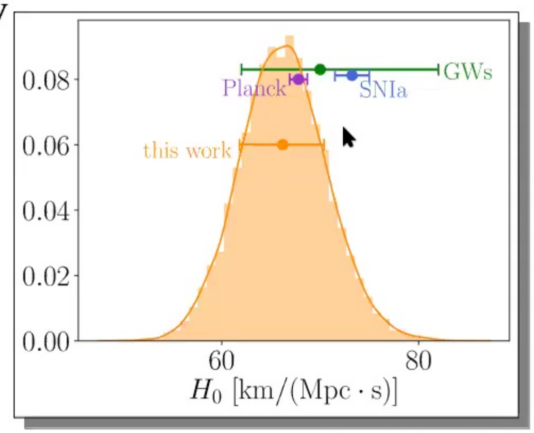


Coughlin, et al, Nature Commun. 11 (2020) 1, 41

Using previously observed kilonovae to improve measurement of the Hubble constant

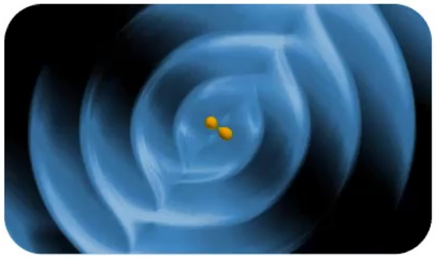


Alternatively: use again nuclear physics – multi-messenger astronomy



TD et al. Science, Vol. 370, Issue 6523, pp. 1450-1453

Summary



- numerical relativity BNS database with largest simulation variety
- development of NRTidal model
- predictions about kilonova signatures
- Bayesian analysis within a nuclear physics – multi-messenger framework
- Applications: *measuring tides, GW lensing, Q-Love relations, Hubble measurement, EOS measurement, probe of exotic compact objects*