Gravitational Wave Probes of Fundamental Physics

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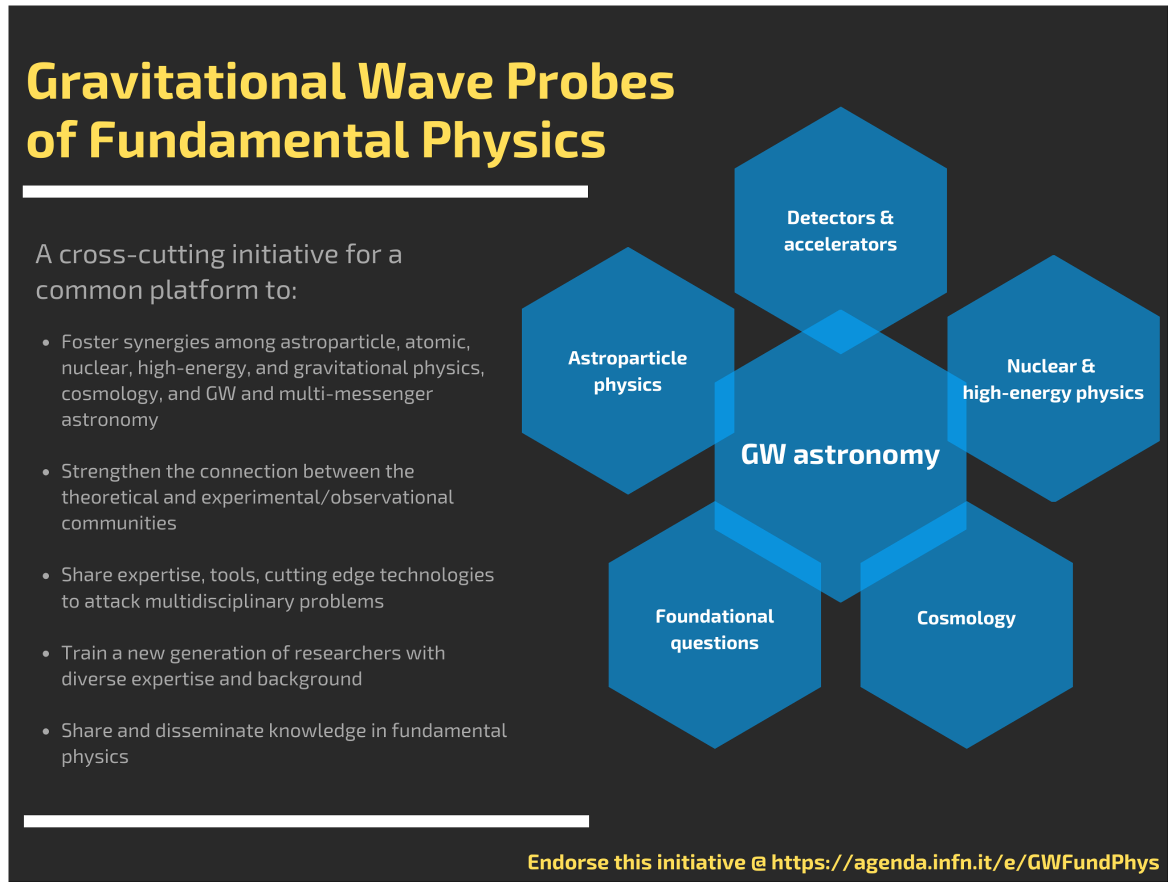
Rafael Porto (DESY - DE)

Antonio Riotto (Geneve U. - CH)

Stephan Rosswog (Stockholm U. - SWE)

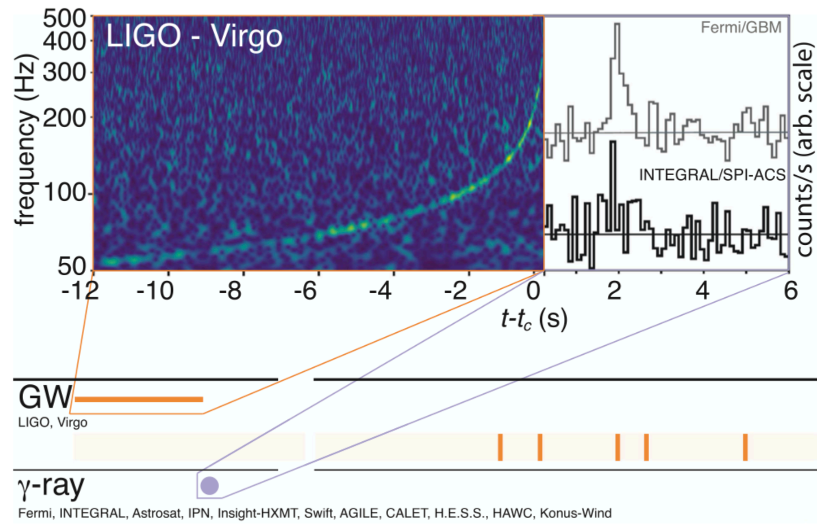


"Recording a GW […] has never been a big motivation for LIGO, the motivation has always been to open a new window to the Universe"

– Kip Thorne (BBC interview, 2016)

Multi-messenger astronomy

More by Samaya Nissanke



- GW170817 17 Aug 2017 12:41:04 UTC
  First detection of a binary neutron star mergers through gravitational waves

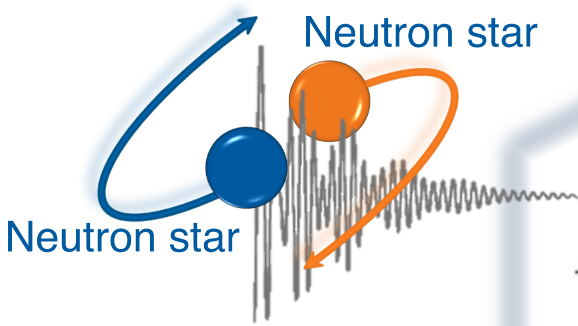
  LIGO + VIRGO, PRL 119 (2017) 1611001

- GRB 170817A ~1,7 s later
  Observation of the same event through electromagnetic waves (gamma-ray burst)

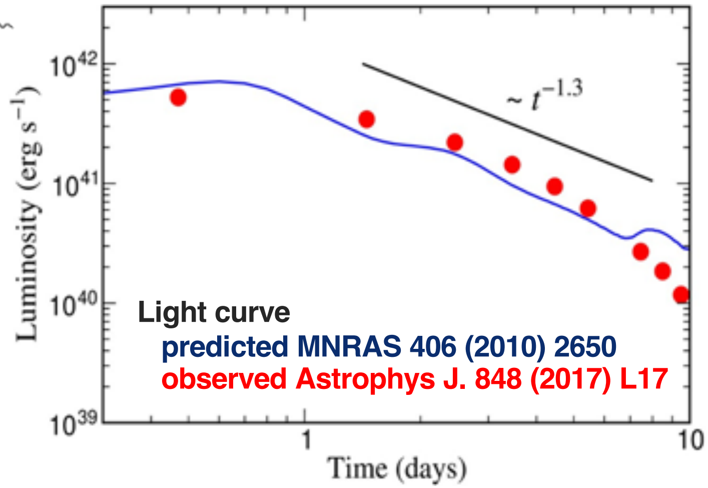
  Fermi GBM + INTEGRAL + LIGO + Virgo, Astrophys.J.Lett. 848 (2017)

Gravitational wave signal depends critically on nuclear equation of state (EoS)

More by Stephan Rosswog

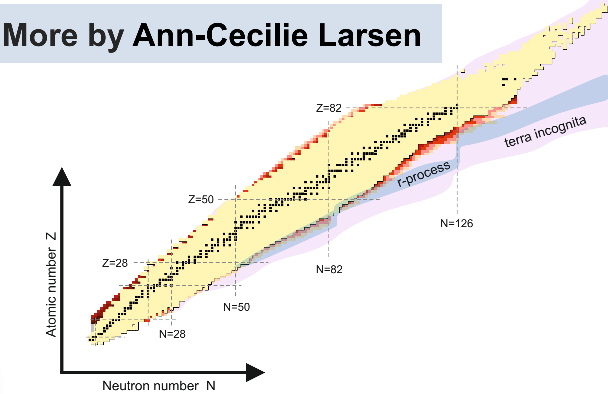


Nuclear, atomic high-energy physics



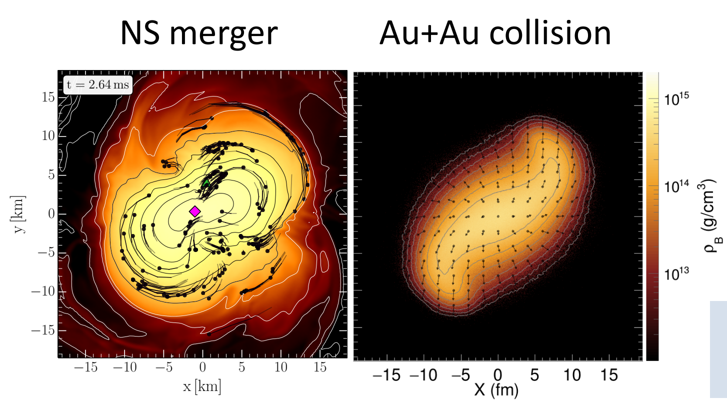
and their role in multi-messenger astronomy

More by Ann-Cecilie Larsen

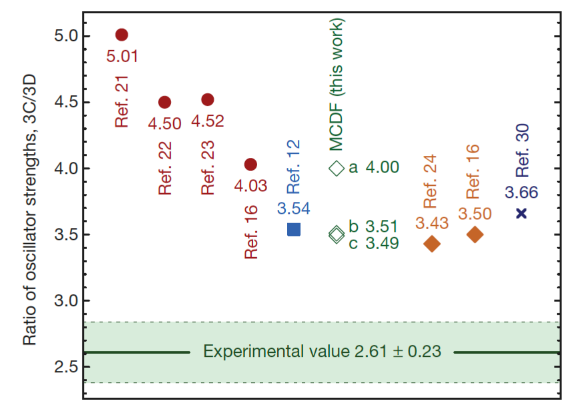


Production cite of heavy elements in cosmos (driven by nuclear physics r-process)

Study the EoS in the laboratory using high-energy heavy-ion collisions



More by Alexander Kalweit, Aleksi Kurkela

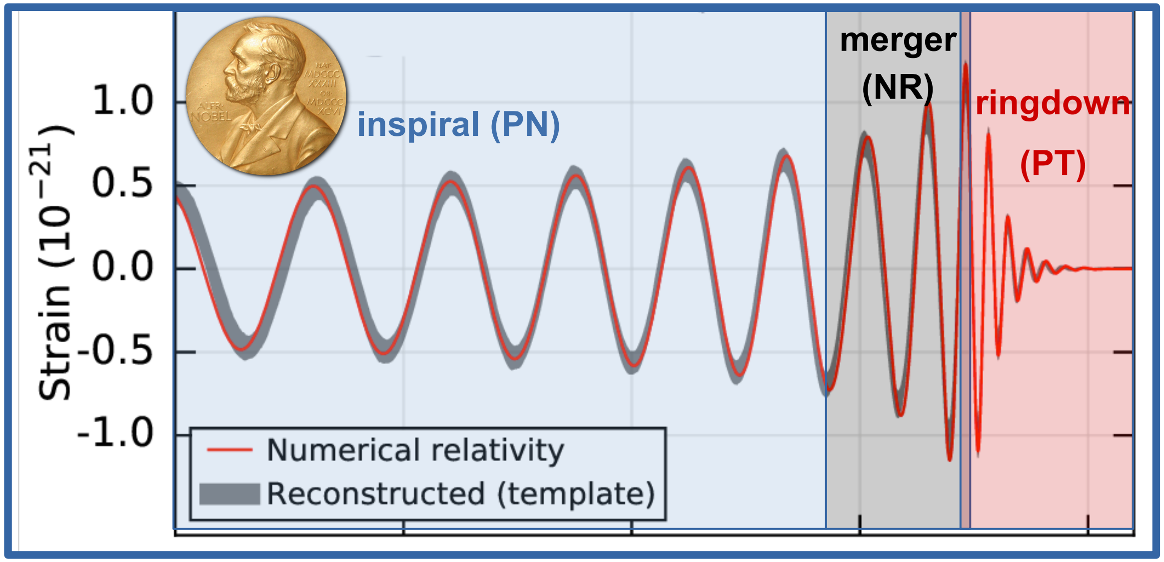


Spectral lines of highly charged atoms reveals composition in the ejecta (lack of atomic data!)

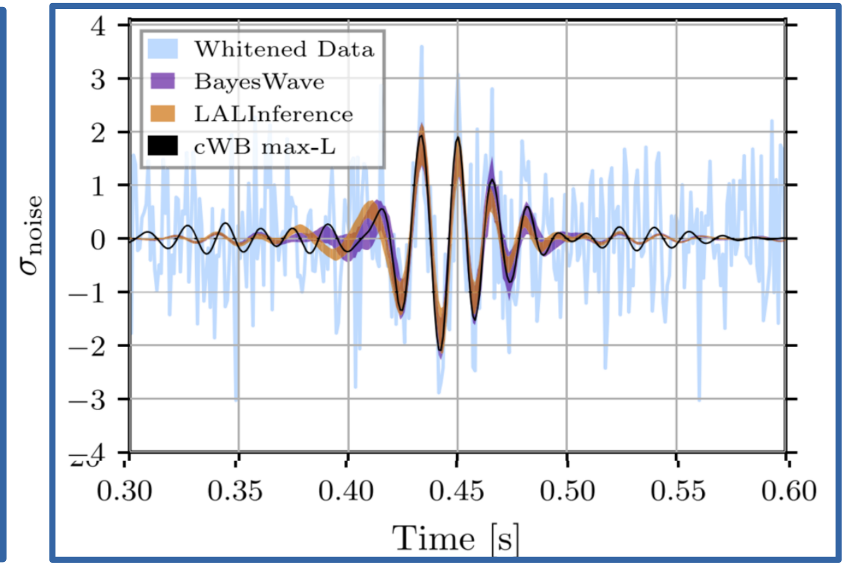
More by Sven Bernitt

GW events as labs for Fund Phys

In 5 yr GW astronomy has reshaped fundamental physics



[**GW150914** discovery paper: LVC, PRL 116, 061102 (2016)]

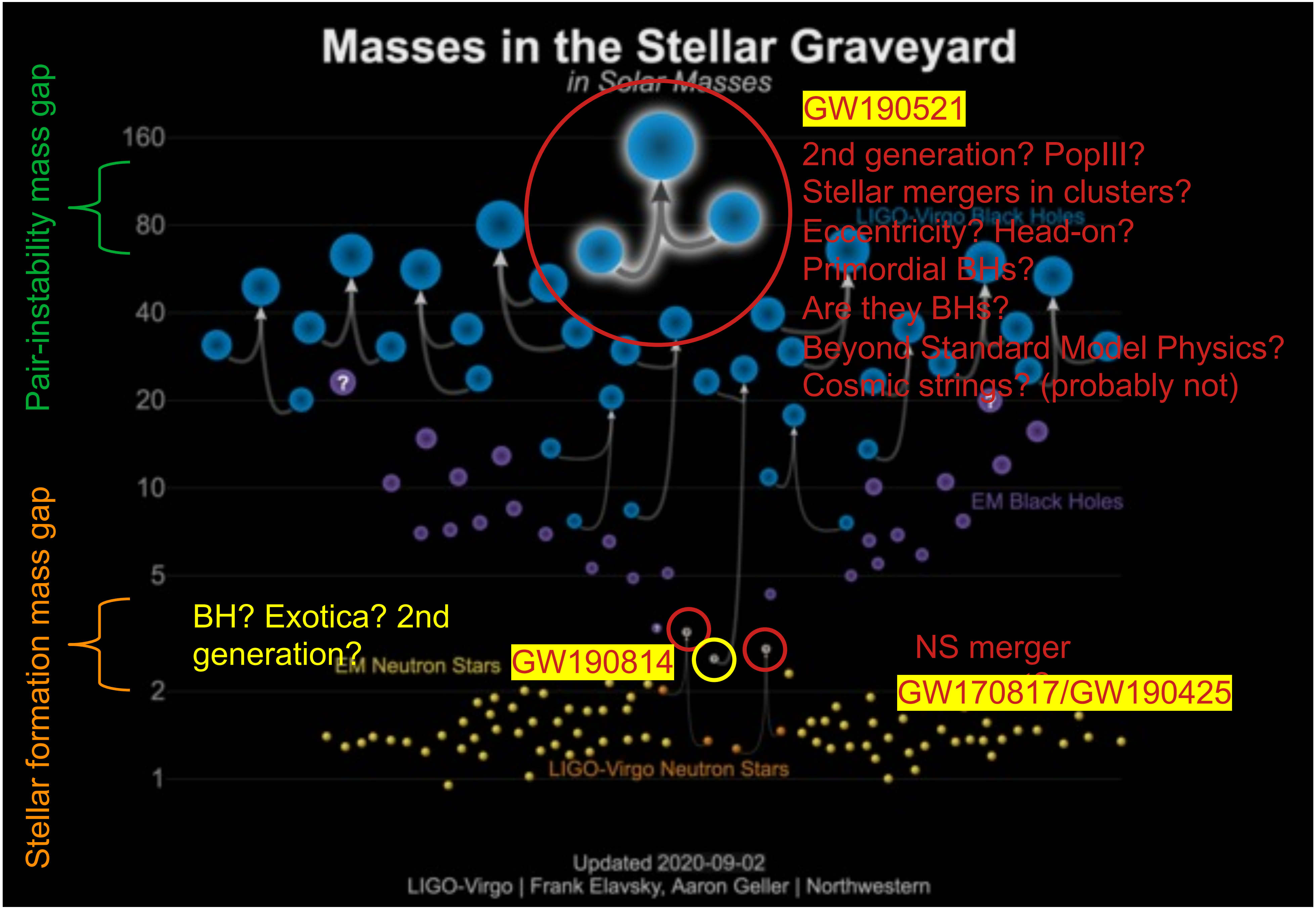


[**GW190521** discovery paper: LVKC, PRL 125 101102 (2020)]

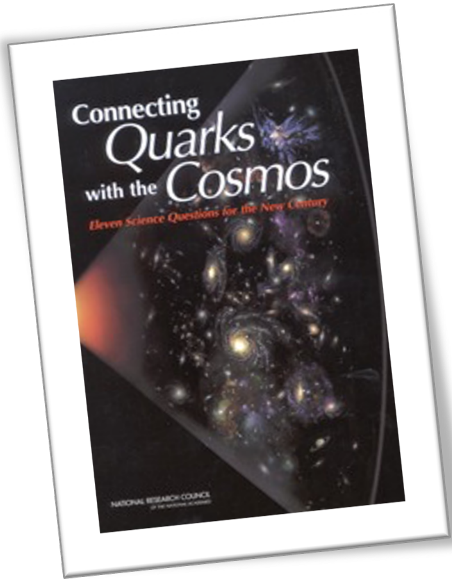
- New physics beyond General Relativity?
- How/where do BHs form? Are they classical BHs? **More by V. Cardoso**
- Hints of quantum gravity at the horizon? **More by R. Emparan**
- New sources: signatures of dark-matter environment **More by G. Bertone**
- New sources: stochastic bkg, GW signatures of inflation? **More by A. Riotto**
- Advanced GW modelling is crucial (esp. for ET and LISA) → tools from hep

More by R. Porto

The case of GW190521

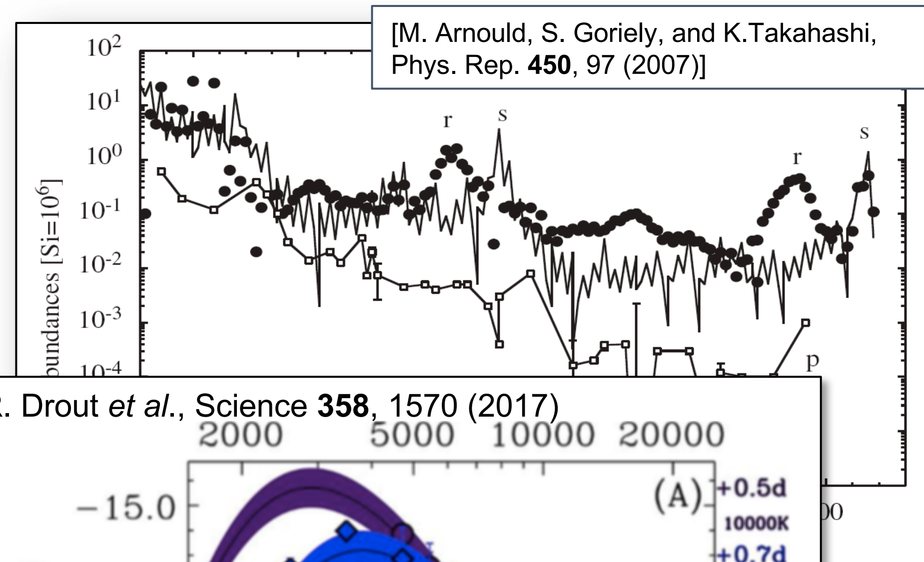


Synergy with nuclear physics

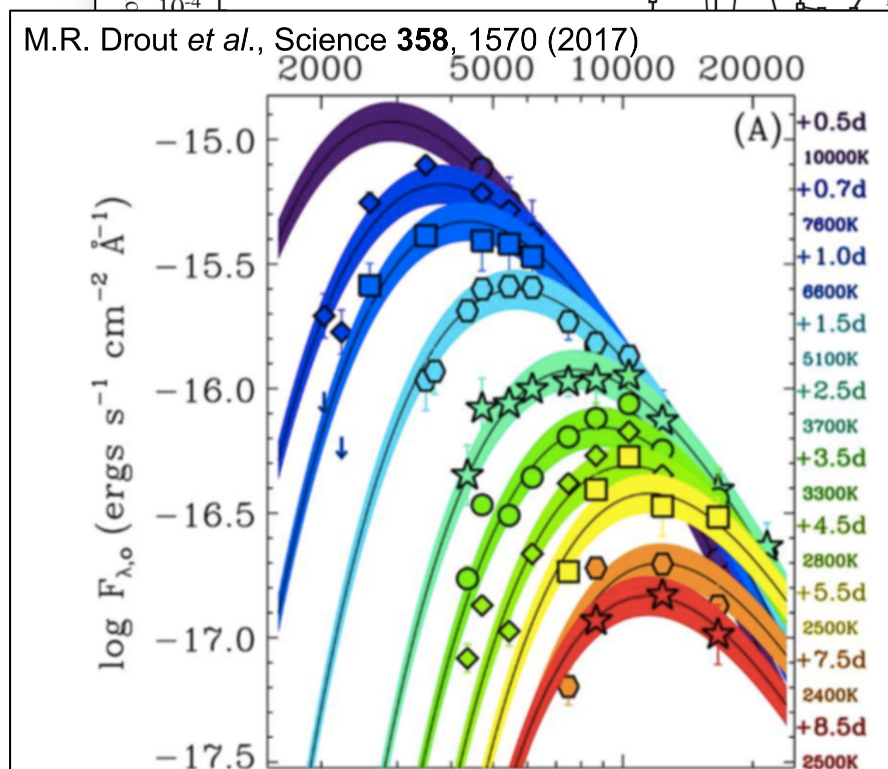


"How Were the Elements from Iron to Uranium Made?"
Eleven Science Questions for the New Century

Rapid neutron-capture process (r-process): requires extremely high neutron flux (>10^{20} cm^{-3})



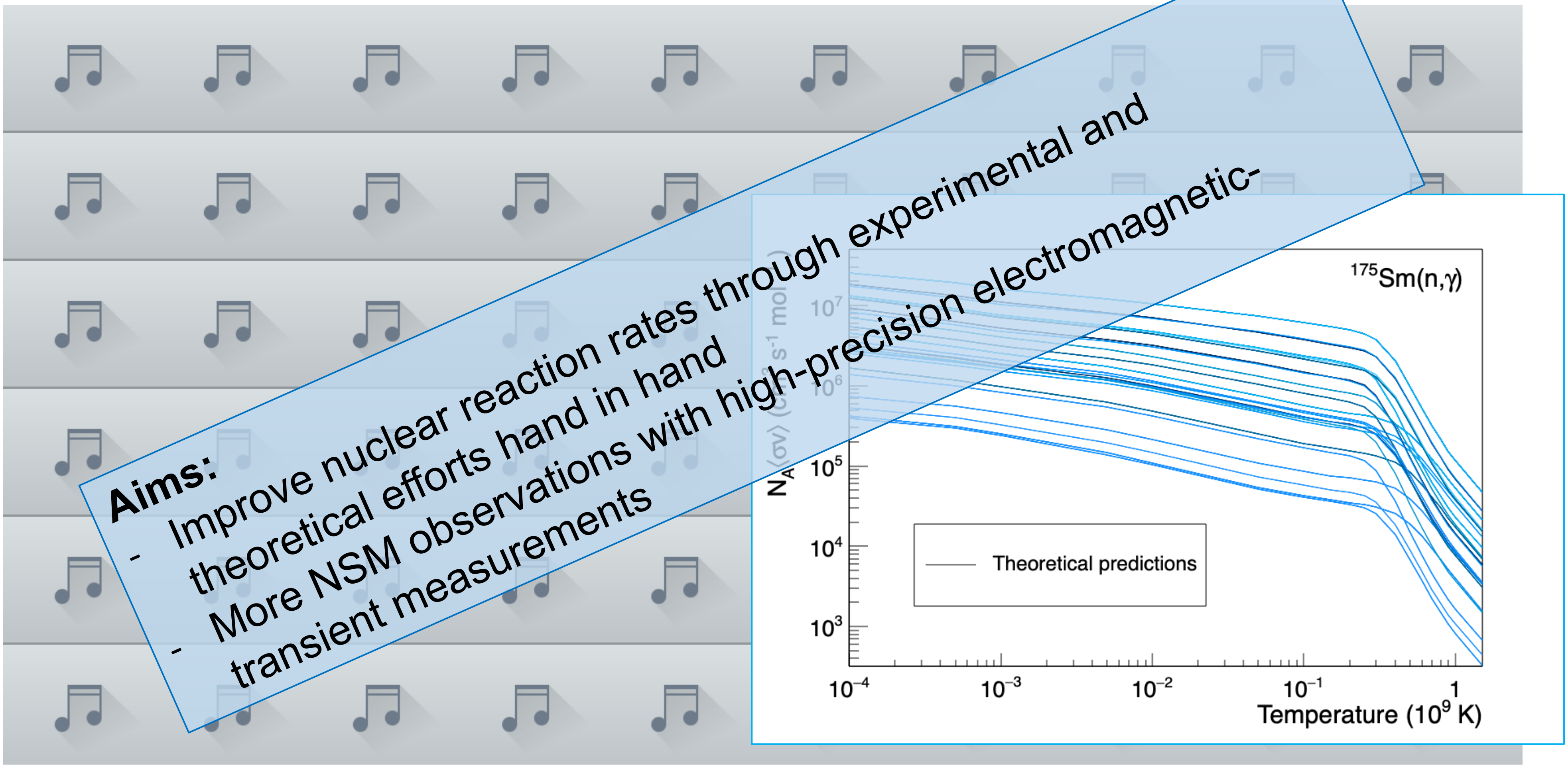
GW170817: confirmed that heavy elements are produced in neutron-star collisions!



Synergy with nuclear physics

Nucleosynthesis network calculations: ≈ 7 000 nuclei and ≈ 70 000 reaction rates

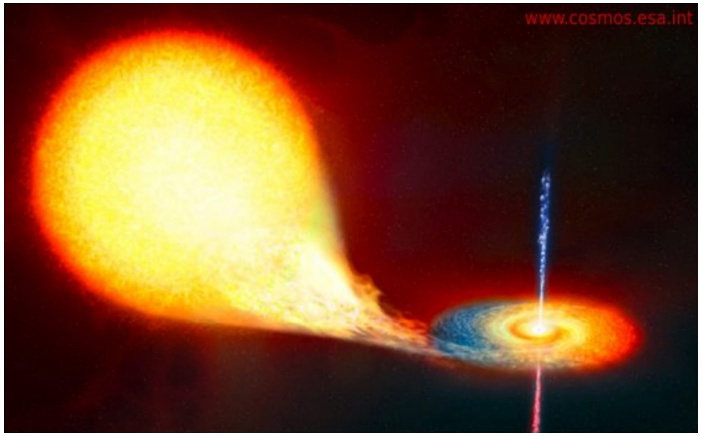
Jonas Lippuner, Skynet network code https://jonaslippuner.com/research/skynet/



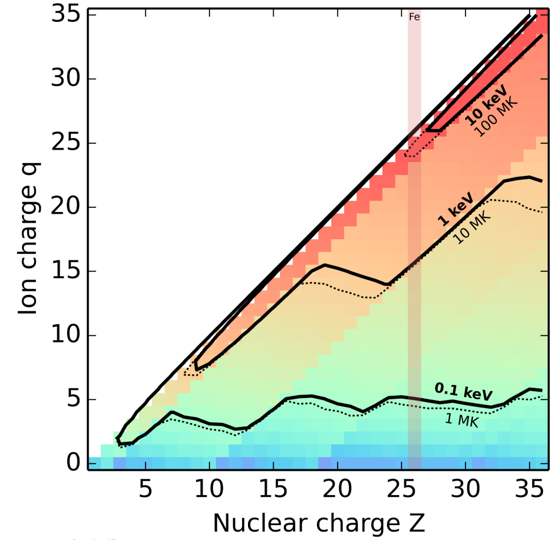
Aims:
- Improve nuclear reaction rates through experimental and theoretical efforts hand in hand
- More NSM observations with high-precision electromagnetic-transient measurements

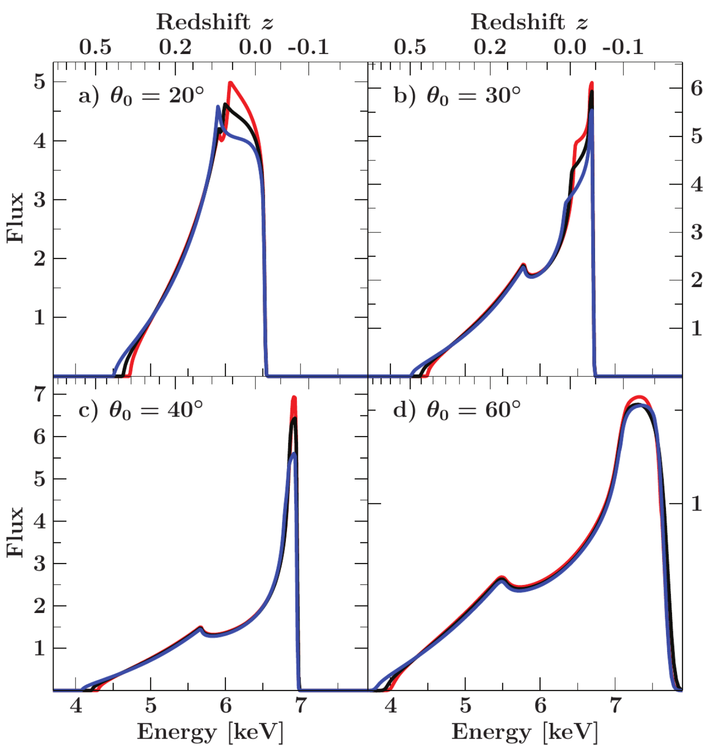
However: nuclear physics input is very uncertain (orders of magnitude)!
GW170817 is so far the only NSM with a measured «afterglow»

Synergy with Atomic Physics

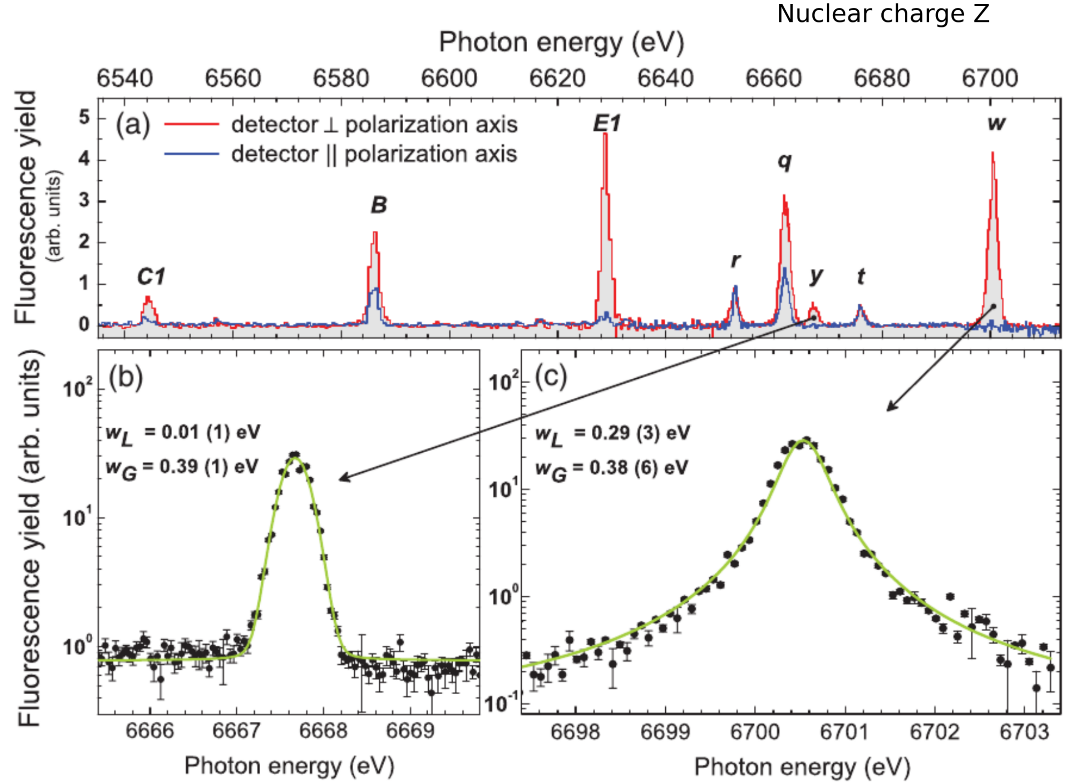


- **Spectral features from atomic processes** contain information about **state** (temperatures, densities, etc.) and **dynamics** (velocities, etc.) of matter
- **Highly charged ions** in extreme environments emit **x-rays**





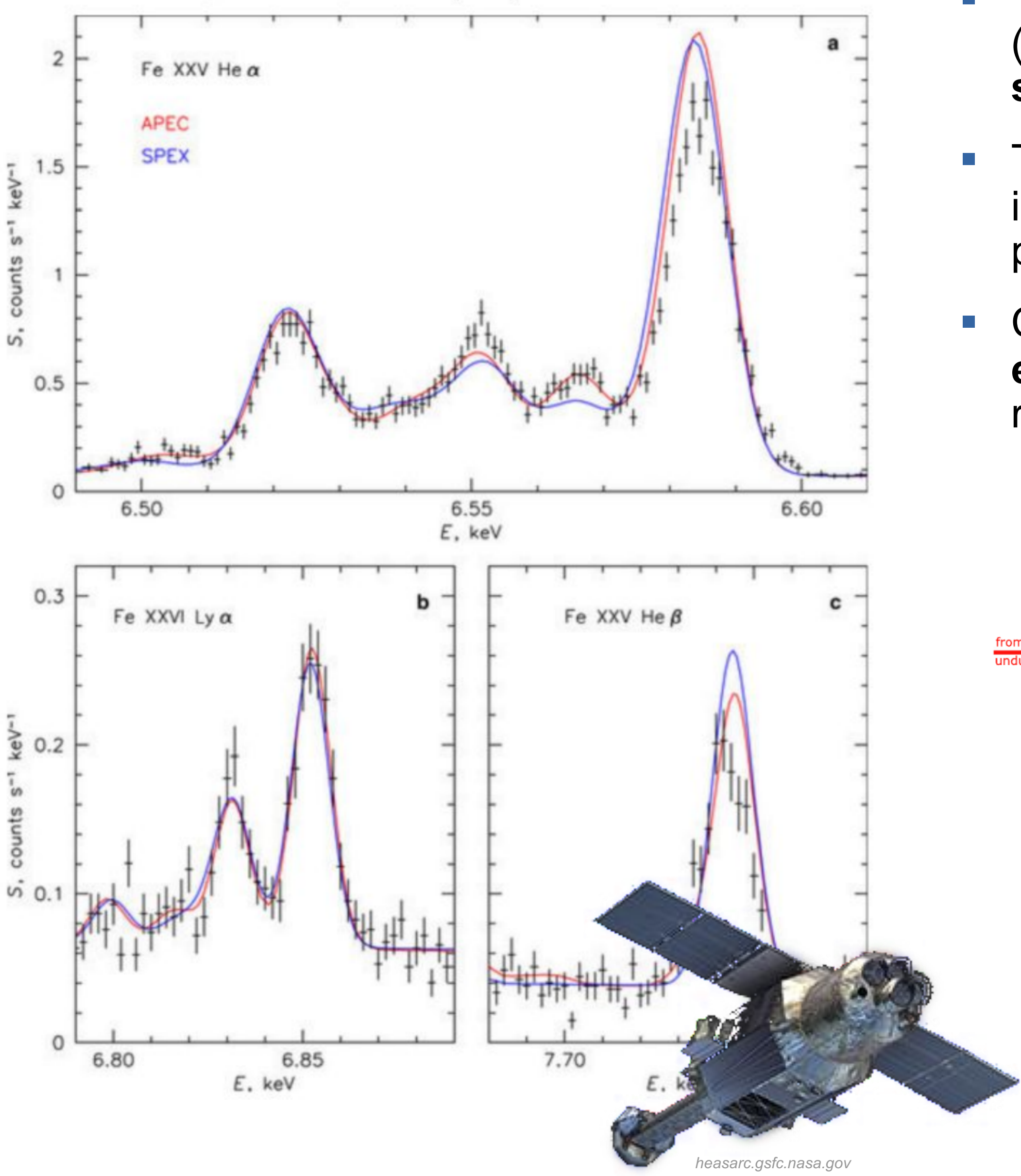
T. Dauser *et al.*, MNRAS **409**, 1534-1540 (2010)



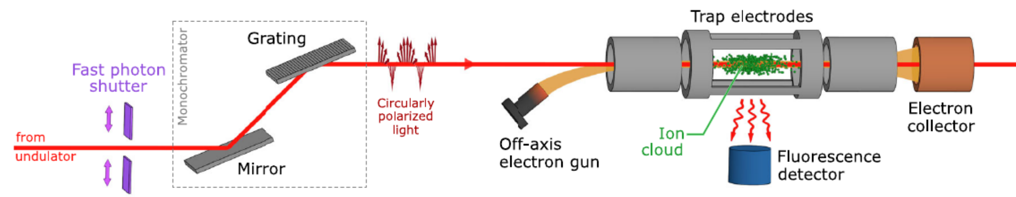
J. K. Rudolph et al., PRL 111, 103002 (2013).

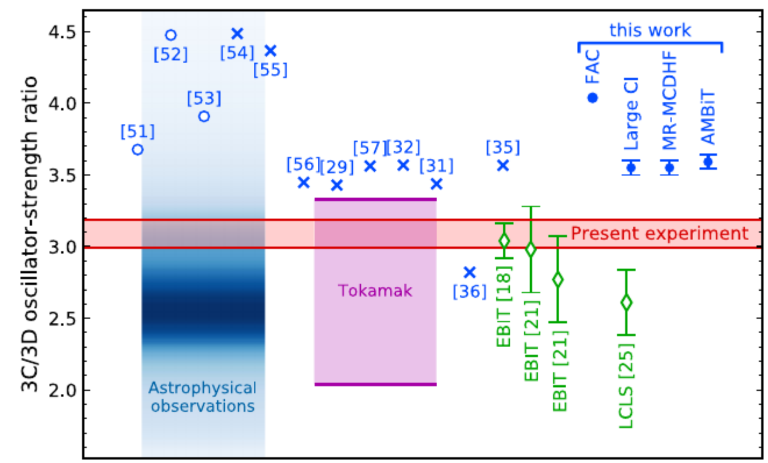
Synergy with Atomic Physics

Hitomi collaboration, Nature **551**, 478–480 (2017).



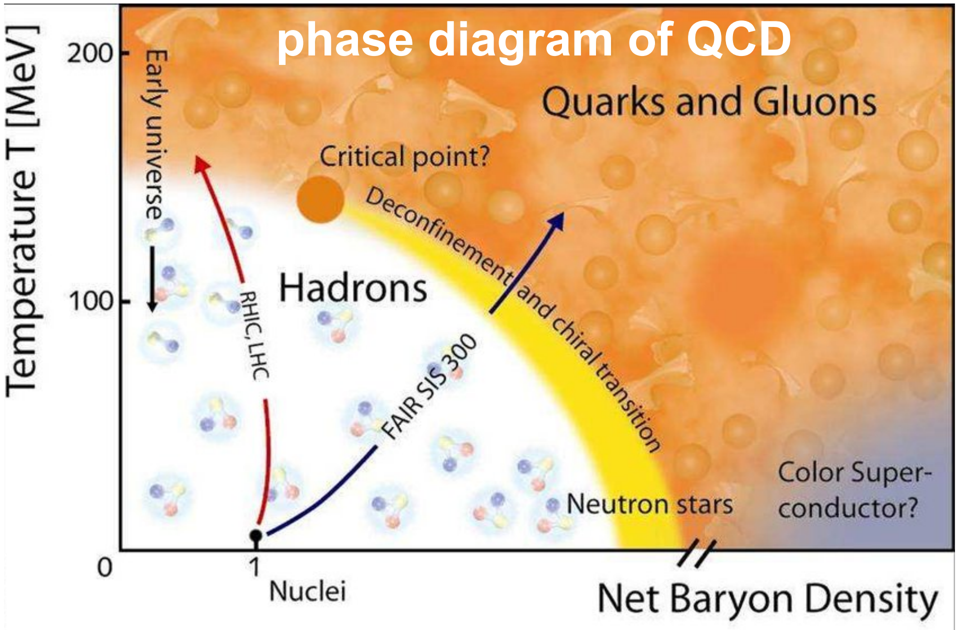
- The next generation of **x-ray observatories** (XRISM, Athena) will feature much **higher spectral resolution** than the current one
- Todays most sophisticated **spectral models** are insufficient, lacking **atomic data**, with some processes not included
- Combined efforts from astronomers, **laboratory experiments** and **atomic-structure theory** are required

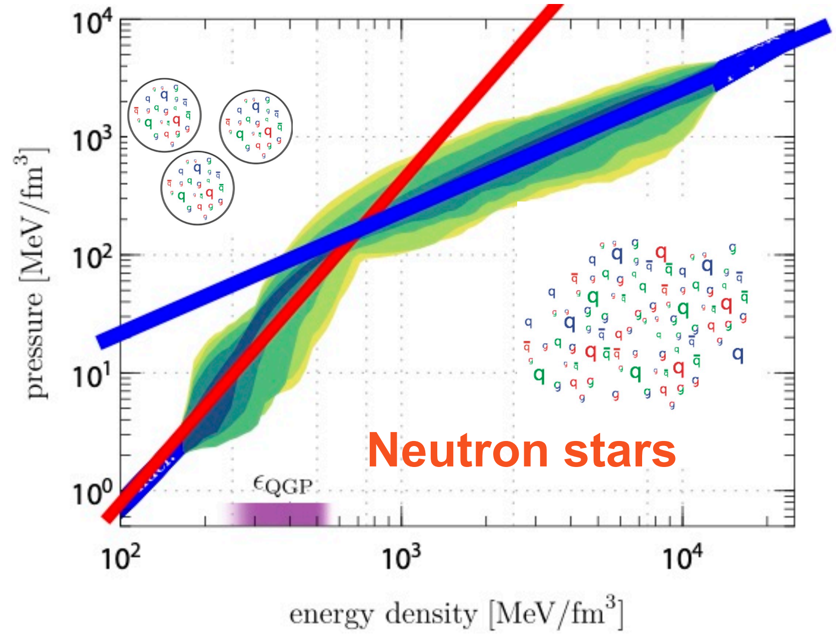




S. Kühn *et al.*, PRL **124**, 225001 (2020).

Quark matter in Neutron Stars





Heavy-ion collisions study how in extreme densities nuclear matter melts to **Quark Matter**

Conditions in the cores of Neutron Stars resemble the environment in heavy-ion collisions:

Is there Quark Matter in neutron stars?

Gravitational wave observations can determine:

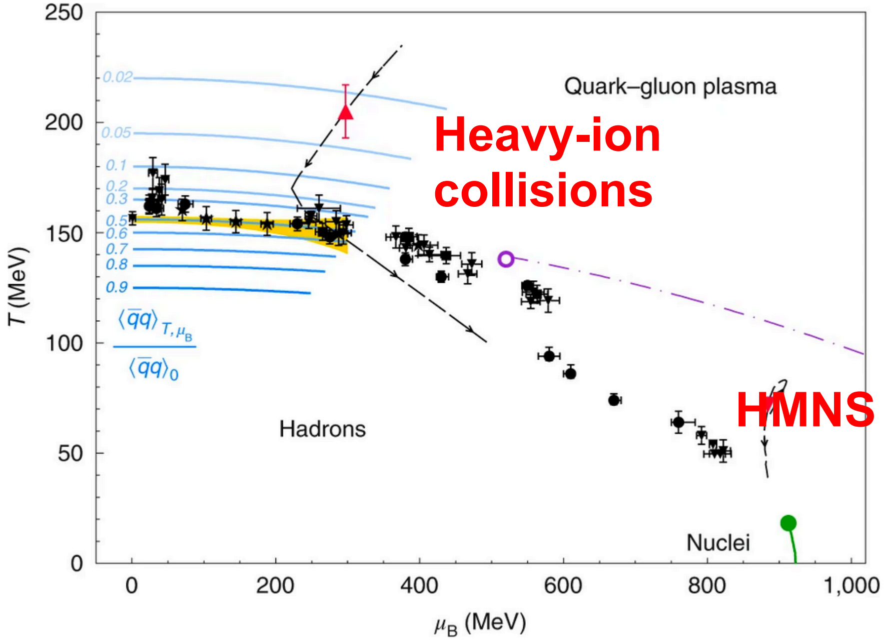
- Is there hyperons or ***deconfined*** Quark Matter in neutron stars?
- Does Quark Matter exist in exotic phase? Color superconductor, Crystalline phase, ...?

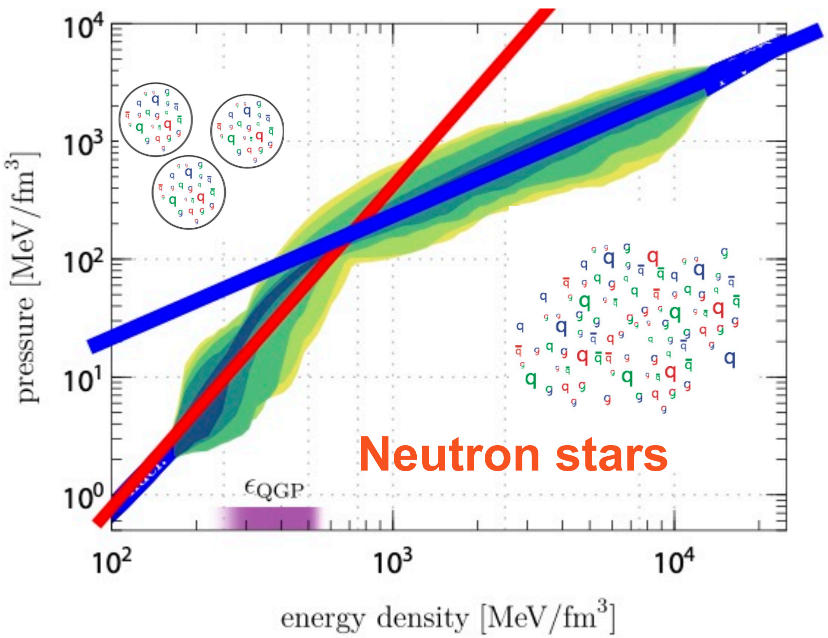
→ Both heavy-ion collisions and gravitational waves explore the **phase diagram of QCD**.

Strong synergy with the theory of heavy-ion theory community (Methods, calculations, tools..)

Quark matter in Neutron Stars

HADES Collab., Nature Phys. 15 (2019) 10, 1040-1045
A. Andronic et al., Nature 561 (2018) no.7723





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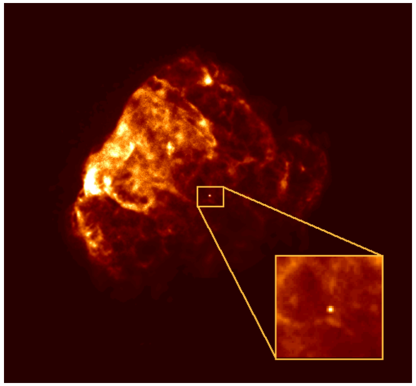
GWs & simulations: bounds on EoS

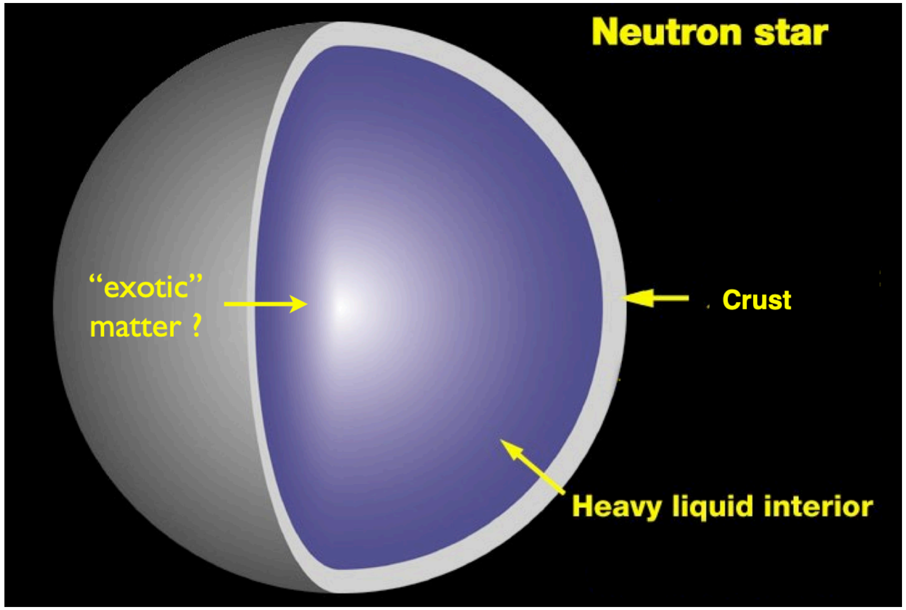


- Neutron stars:
  mass: ~ 1.4 solar masses
  radius: ~ 12 km
  } average density $\rho_{av} \approx 4x10^{14}$ g/cm^3
  > nuclear saturation density

- Dynamical timescale: $t_{dyn} = (G\,\rho_{av})^{-1/2} \approx 0.2$ ms $\Longrightarrow$ GW frequencies
  (~oscillation frequencies)
  few kHz

- Equation of State (EoS) $\Longrightarrow$ structure of neutron stars $\Longrightarrow$ GW fequencies

- Structure of neutron stars



composition:

crust: "iron-like" nuclei

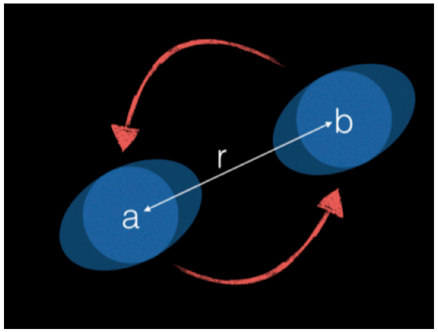
bulk: neutrons, protons,
electrons, muons

"core": likely "exotic"
- hyperons?
- quark matter?
- …

} new phases of matter?

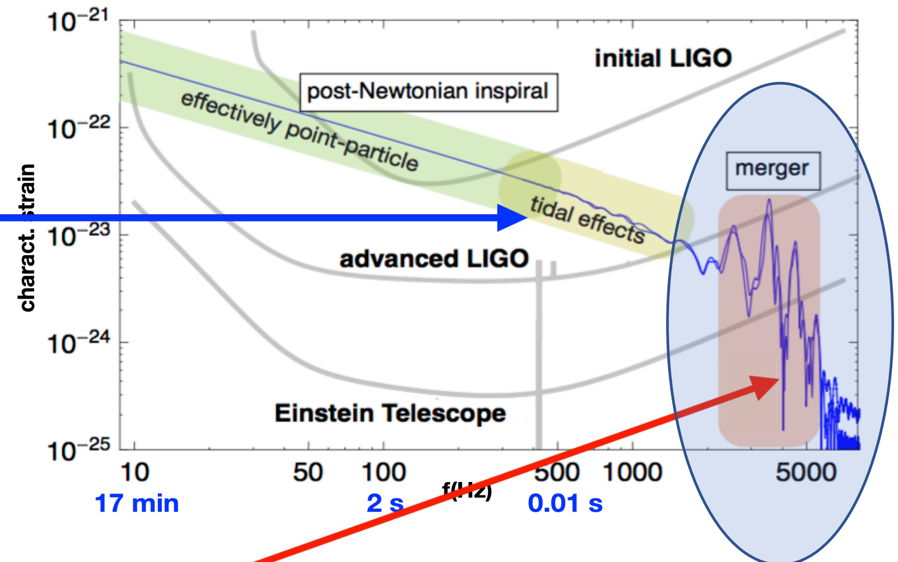
GWs & simulations: bounds on EoS

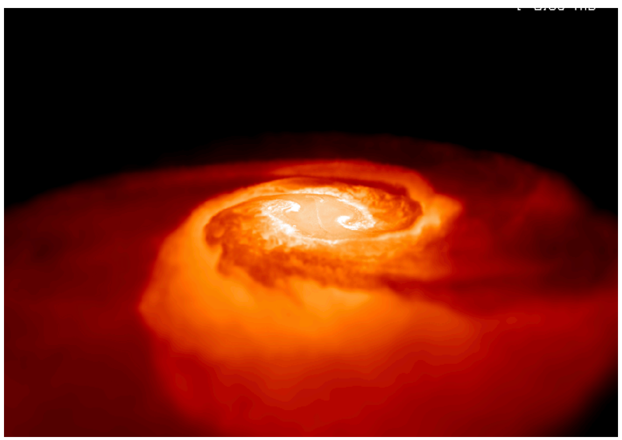
How can GWs constrain nuclear matter properties?



Tidal deformability Λ
⟹ accelerates inspiral
⟹ constraints on
COLD, nuclear matter
($T \approx 0$, $\rho \approx \rho_{NS}$)

Gravitational wave sweeping through detector band (2 x1.4 $M_\odot$)

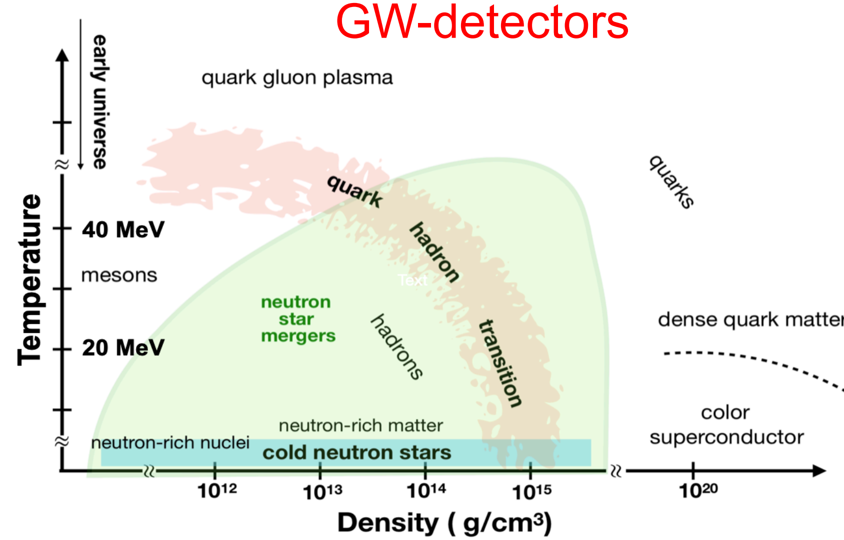




Post-merger GW-frequencies:
observations +
multi-physics simulations

⟹ constraints on
HOT, nuclear matter
($T \approx 60$ MeV, $\rho > \rho_{NS}$, $Y_e \approx 0.02 .. 0.4$)

Target of 3rd Generation GW-detectors



⟹ neutron star mergers cover a broad region in the QCD phase diagram, complementary to heavy ion collisions

Multi-messenger astronomy

Opportunities: GW+EM are new opportunities for astronomy and cosmology

- What are the intrinsic nature of compact objects?
- How and where do BH-BH/NS-BH/NS-BH form?
- How do compact object mergers probe and drive the evolution of the Universe?
- How do the fundamental laws of physics interact with each other in strong-field gravity?

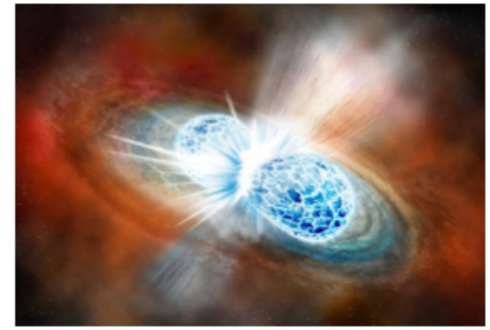
Challenges: combining GW+EM

- Detection of GW (strains ~ 10^{-21}) & EM (different timescales)
- Modelling GW + EM simultaneously (microphysics)
- Interpretation (astrophysics, fundamental physics and cosmology)

Chemical enrichment in the Universe

Binary stellar evolution & the fate of massive stars

High energy astrophysics

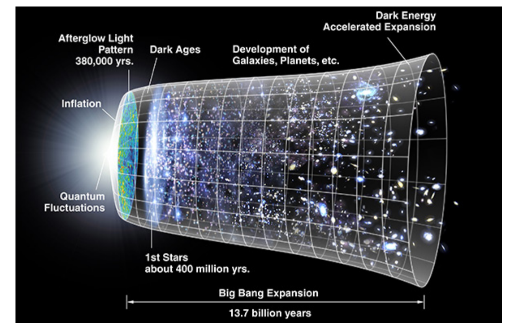


<u>Joint GW and EM measurements</u>: masses, spins, composition of neutron stars & outflows, magnetic fields …

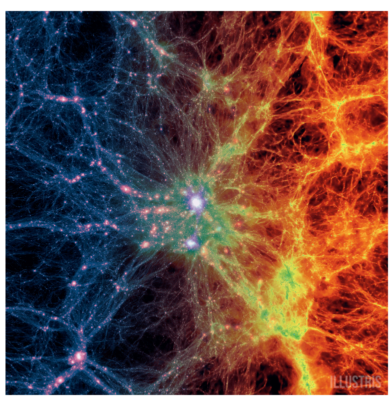
Challenge: obtaining EM, Analysis and Interpretation

Time-domain Astronomy

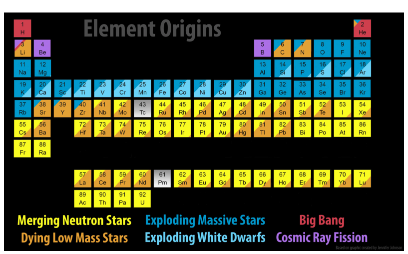
Cosmology



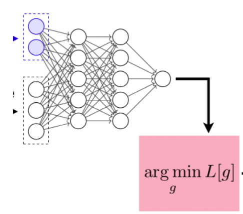
Large Scale Structure



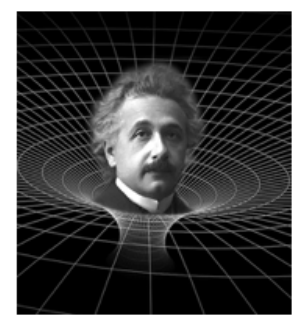
Nuclear Physics



Data theory, big data and machine learning

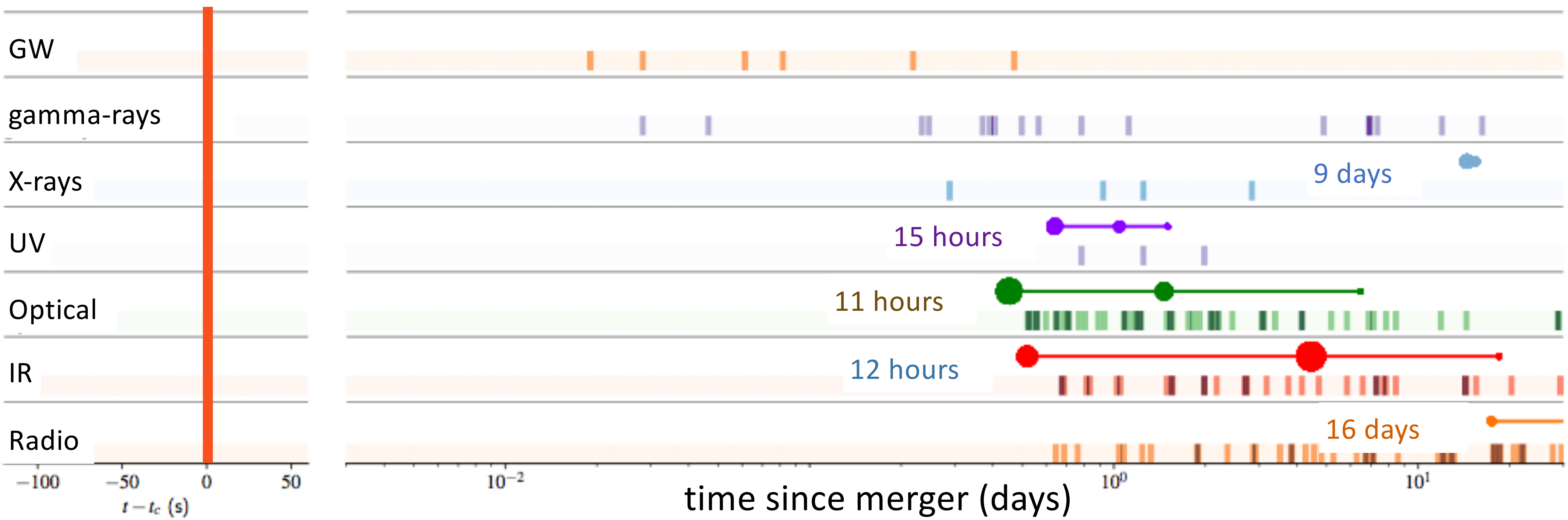


General Relativity and Beyond the Standard Model Physics



Key Challenge: the first month(s) of multi-messenger observations of GW170817

adapted from LIGO, Virgo, EM partners + ApJ 848 L12 (2017)



Global ground and space-based effort:
70+ teams, 100+ instruments, over 3500 co-authors

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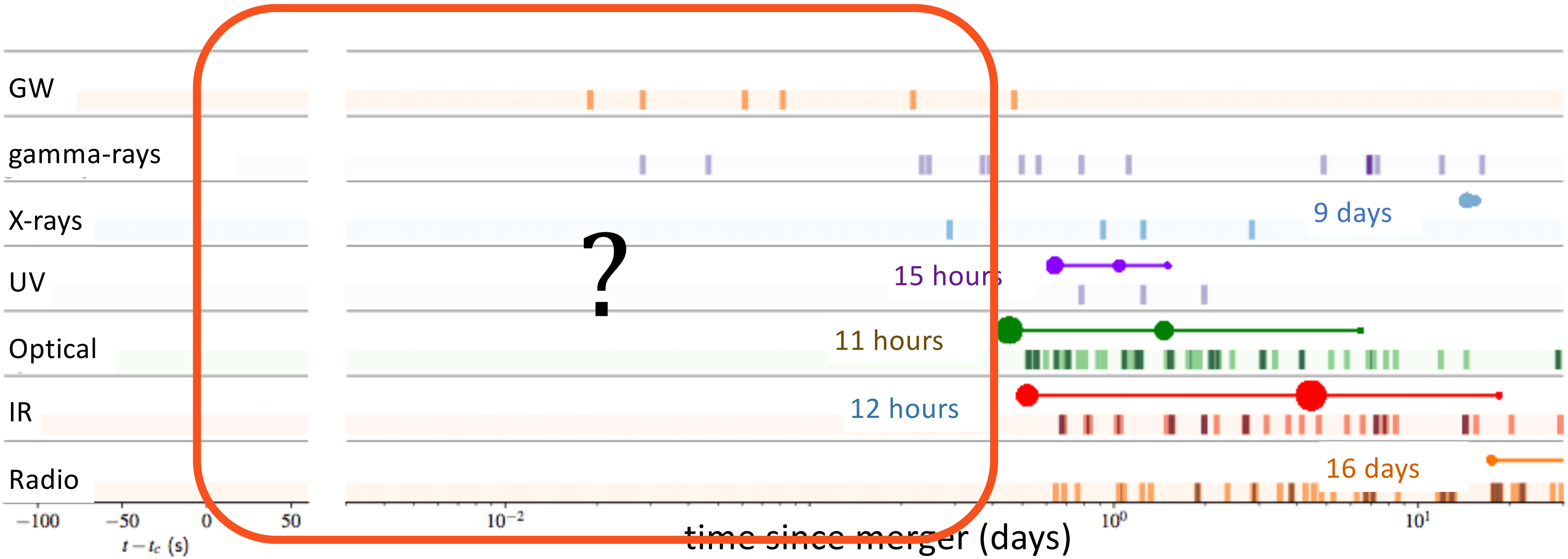

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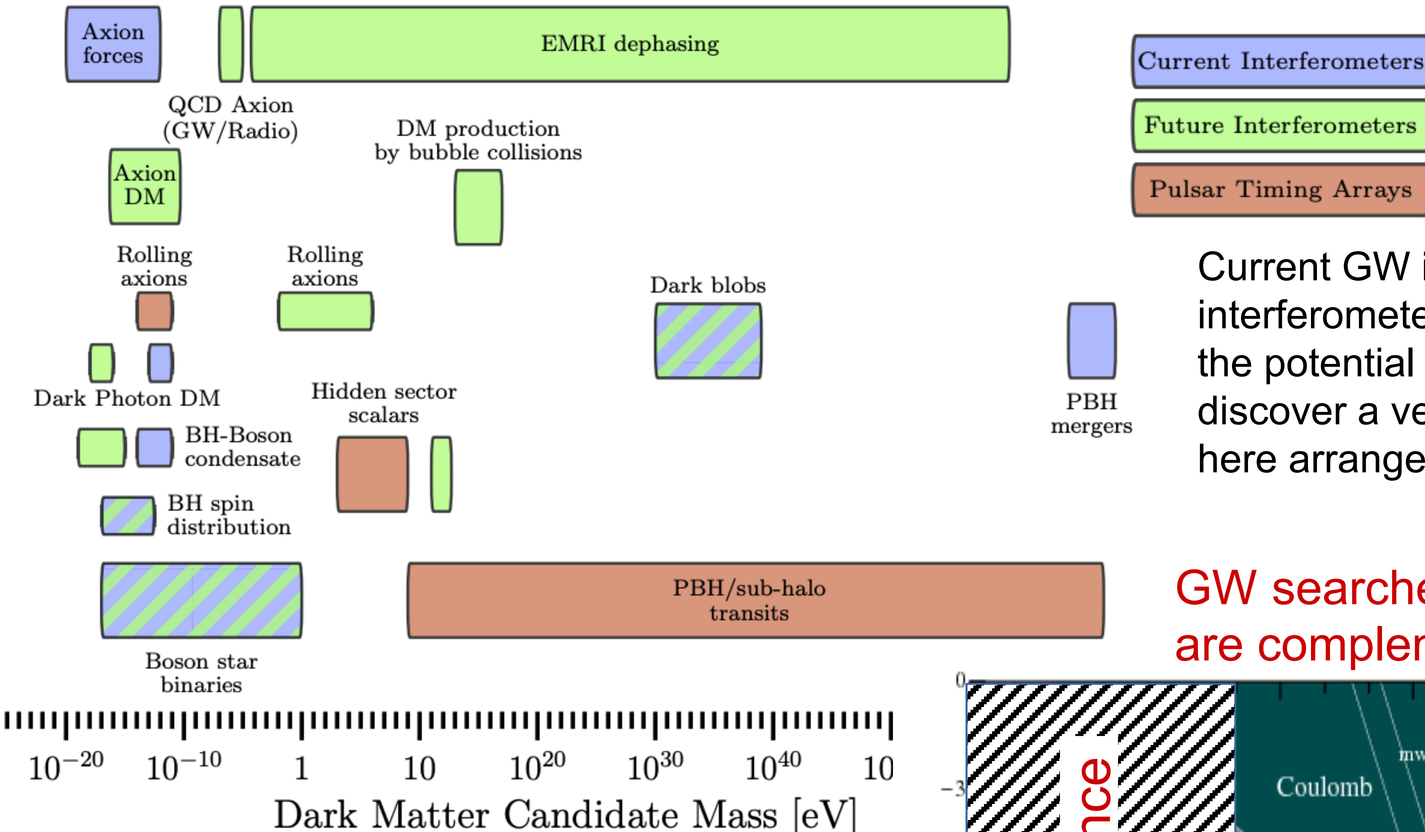
GW probes of Dark Matter

- Growing sense of 'crisis' in the dark-matter particle community
- Absence of evidence for the most popular DM candidates (WIMPs, axions, sterile neutrinos)
- Need to diversify experimental effort & incorporate astro surveys and GW observations!
- Tremendous advances in our understanding are likely with GW probes of DM

From White Paper "GW probes of DM", 1907.10610

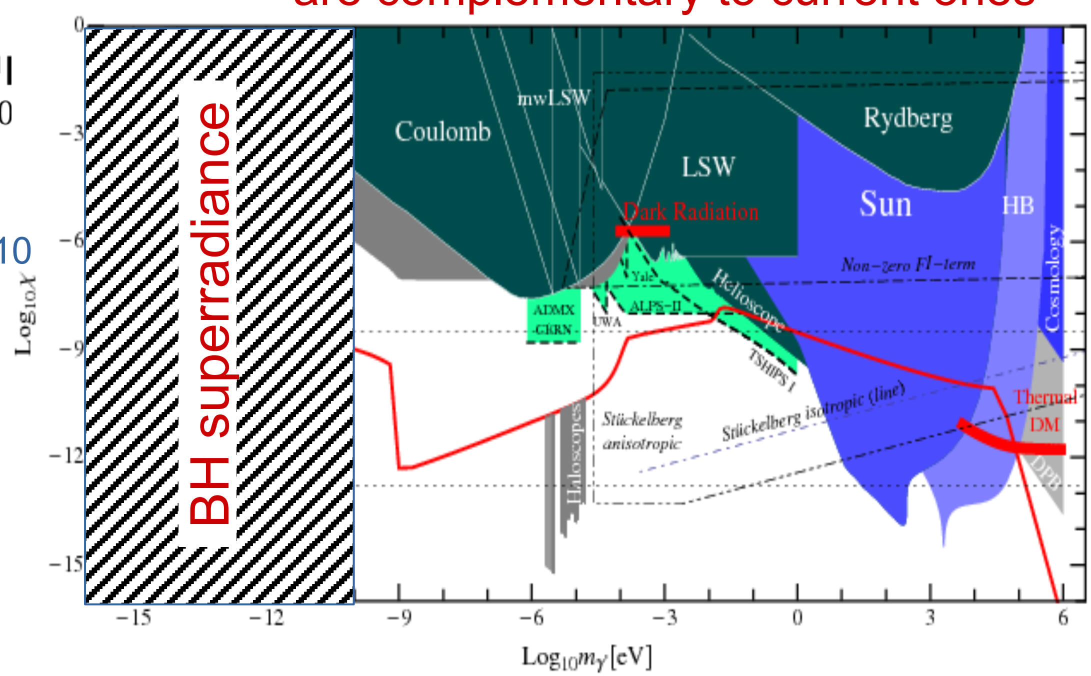
GW probes of Dark Matter



Current GW interferometers, future interferometers and Pulsar Timing Arrays have the potential to set stringent constraints or discover a very wide range of DM models, here arranged by candidate mass

From White Paper "GW probes of DM", 1907.10610

GW searches for axions & dark photons are complementary to current ones



Nature of compact objects

"In my entire scientific life, extending over forty-five years, the most shattering experience has been the realization that an exact solution of Einstein's equations of general relativity provides the absolutely exact representation of untold numbers of black holes that populate the universe."

S. Chandrasekhar, The Nora and Edward Ryerson lecture, Chicago April 22 1975

BH seeds, demography...
(how many, where, how?)

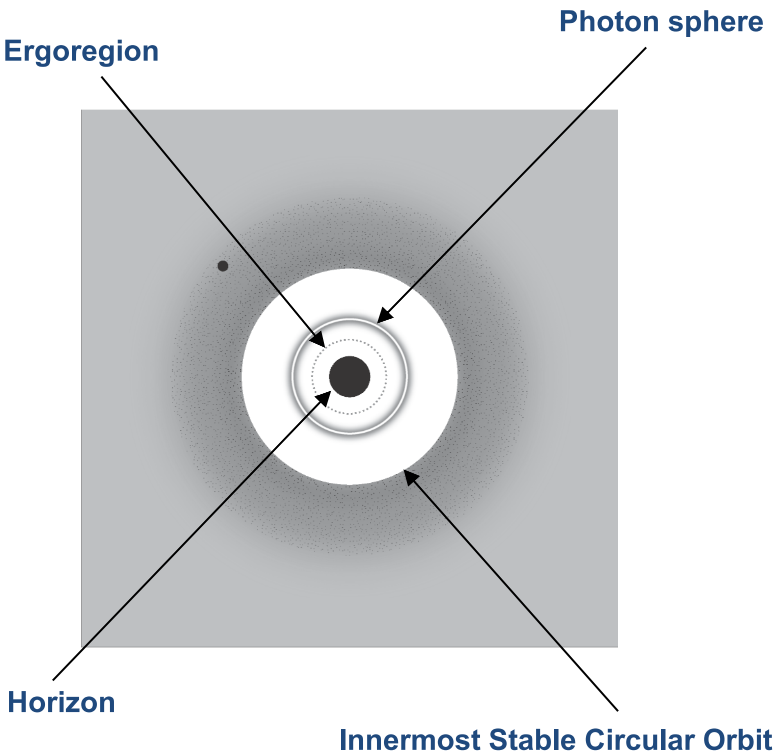
Environment around compact objects

Evidence for photon surfaces, ergoregions

Tests of the Kerr paradigm, spectroscopy

Black holes as new particle detectors

Do black holes exist?



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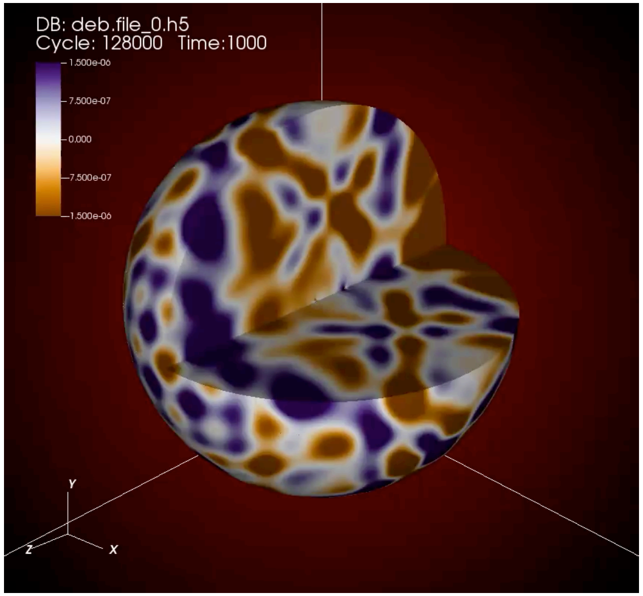


Nature of compact objects

"The crushing of matter to infinite density by infinite tidal gravitation forces is a phenomenon with which one cannot live comfortably. From a purely philosophical standpoint it is difficult to believe that physical singularities are a fundamental and unavoidable feature of our universe [...] one is inclined to discard or modify that theory rather than accept the suggestion that the singularity actually occurs in nature."

Kip Thorne, Relativistic Stellar Structure and Dynamics (1966)

"*Extraordinary claims require extraordinary evidence.*"

Carl Sagan

BH exterior is pathology-free, interior is not.

Quantum effects not fully understood. Information paradox and unresolved singularities point to deep inconsistencies in understanding of GR and QM. Non-local physics?

Tacitly assumed quantum effects at Planck scales. Planck scale could be significantly lower. Even if not, many orders of magnitude standing, surprises can hide.

Dark matter exists, and interacts gravitationally. Are dark, compact objects simply DM "clumps"?

Physics is experimental science. We can test exterior. Aim to quantify evidence for horizons. Similar to quantifying equivalence principle.

Connection to string theory and hep

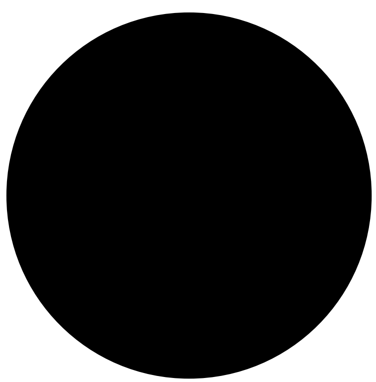
- String theory as an **idea-generating framework**
- String length much shorter than probed by GW observations – *not direct evidence of strings*
- Provides basis to many speculative ideas discussed in this presentation
  - refinements, constraints, and specific realizations

Connection to string theory and hep

- Fundamental nature of black hole horizons

  BH info problem

  - No-BH hypothesis:
    - firewalls, fuzzballs, microstate geometries
  - String effects in *echoes, shadows,* and *memories*



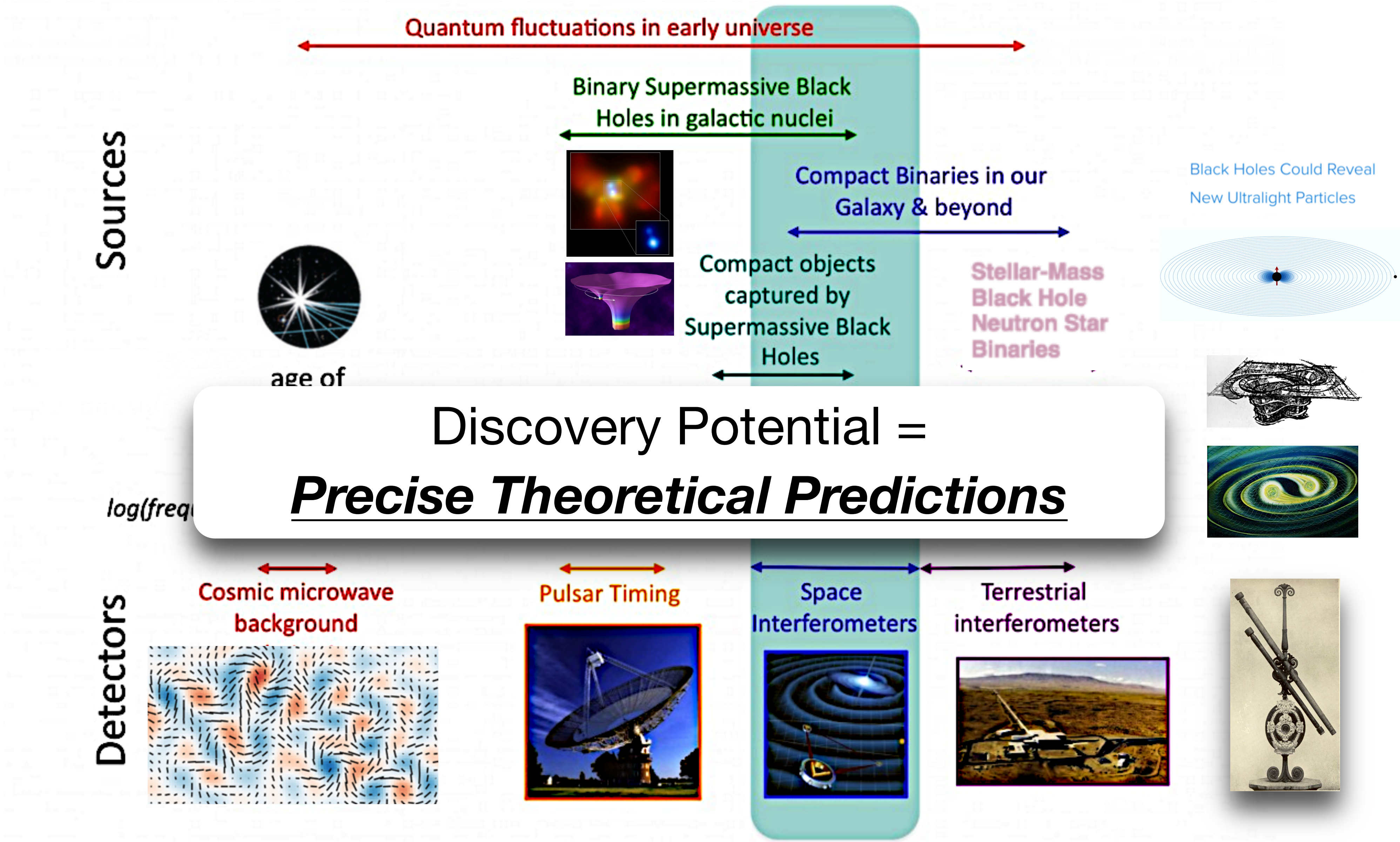
?

Connection to string theory and hep

- From the string landscape
  - Modified gravity theories
  - Ultralight scalars: axiverse in string theory & hep

- Applied holographic principle
  - holographic equations of state for neutron stars
  - rapidly rotating black holes: *conformal symmetry in the sky*

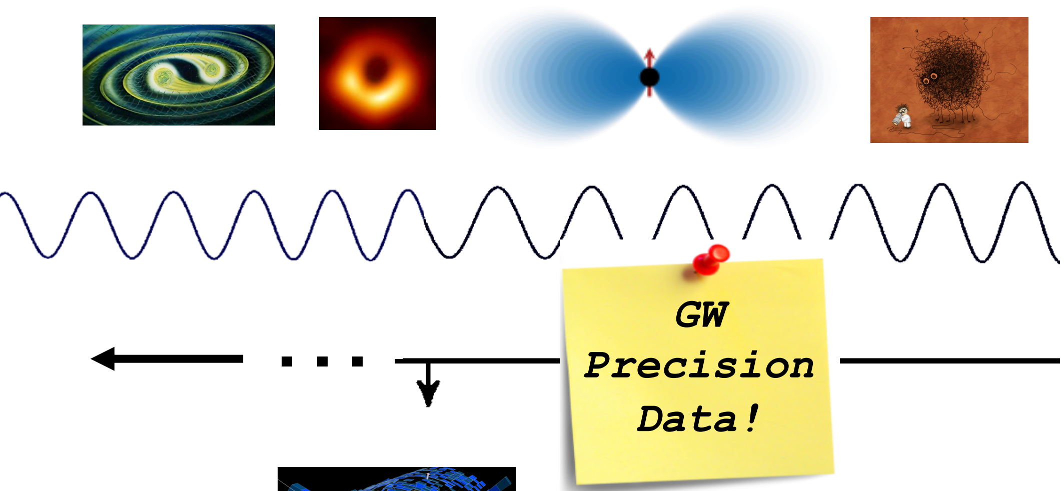
The Gravitational Wave Spectrum

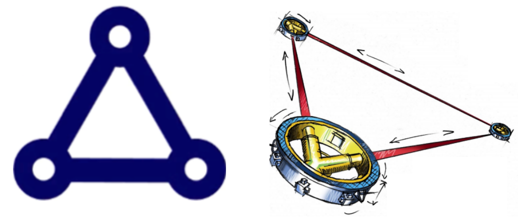


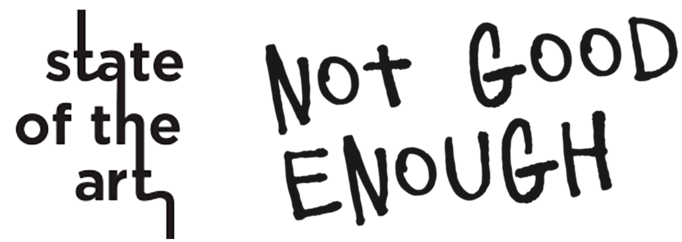
Discovery Potential =

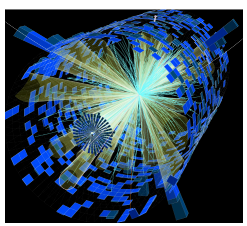
Precise Theoretical Predictions

Theoretical uncertainties dominate over planned empirical reach!



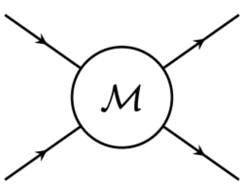


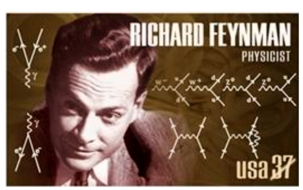




$$\frac{\dot{\omega}}{\omega^2} = \frac{96}{5}\nu x^{5/2}\left\{1 + \overbrace{\cdots + [\cdots] x^{7/2}}\right\}$$

Modern tools from collider physics!



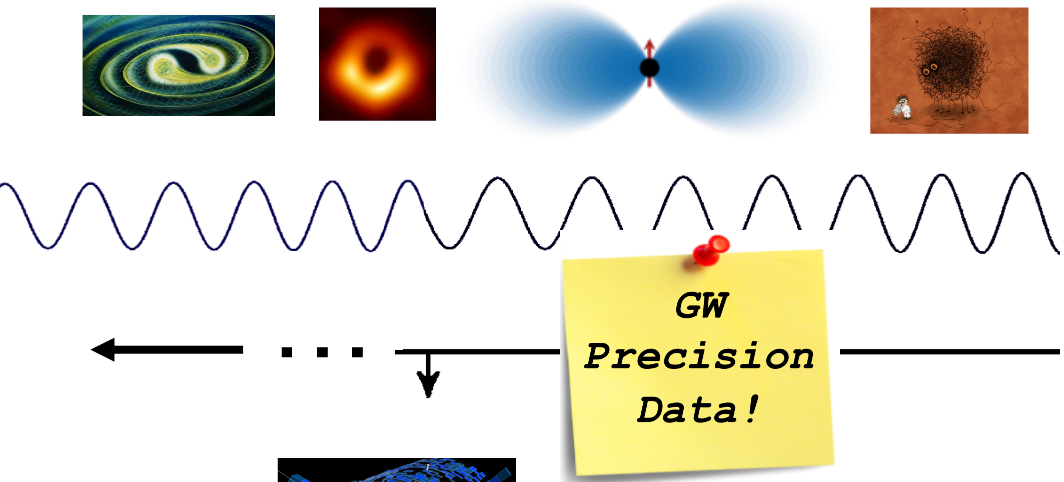


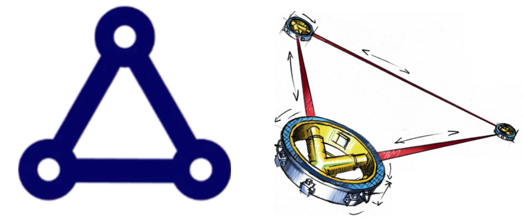
"Waveforms will be far more complex and carry more information than expected. Improved modeling will be needed for extracting the GW's information"

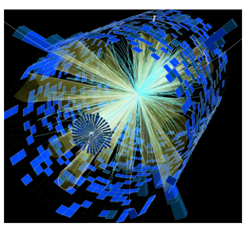
Kip Thorne 'Last 3 minutes' **1993**

20+ years prior to first detection!

Are we ready for the future?

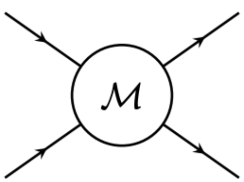


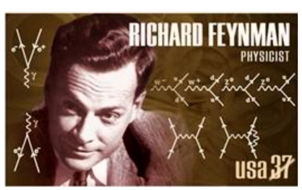




$$\frac{\dot{\omega}}{\omega^2} = \frac{96}{5}\nu x^{5/2}$$

Modern tools from collider physics!





"Waveforms will be far more complex and carry more information than expected. Improved modeling will be needed for extracting the GW's information"

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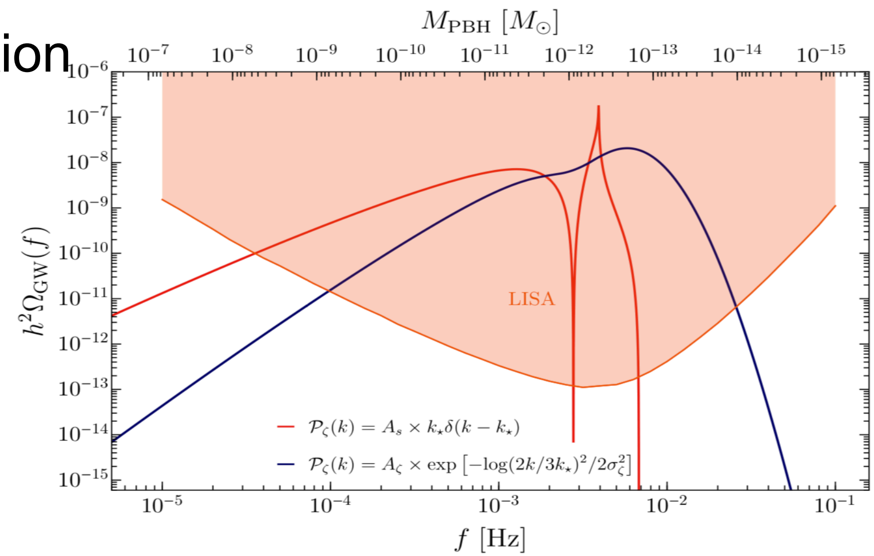
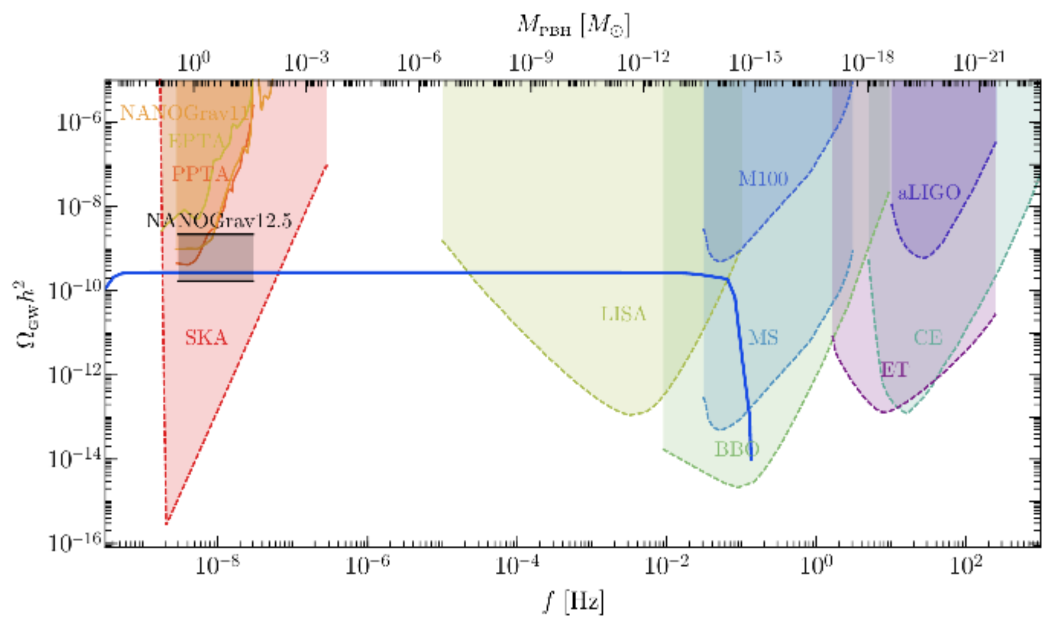
20+ years prior to first detection!

GW Searches for PBHs

- Testing PBHs at their birth
  - Emission of GWs at PBH formation



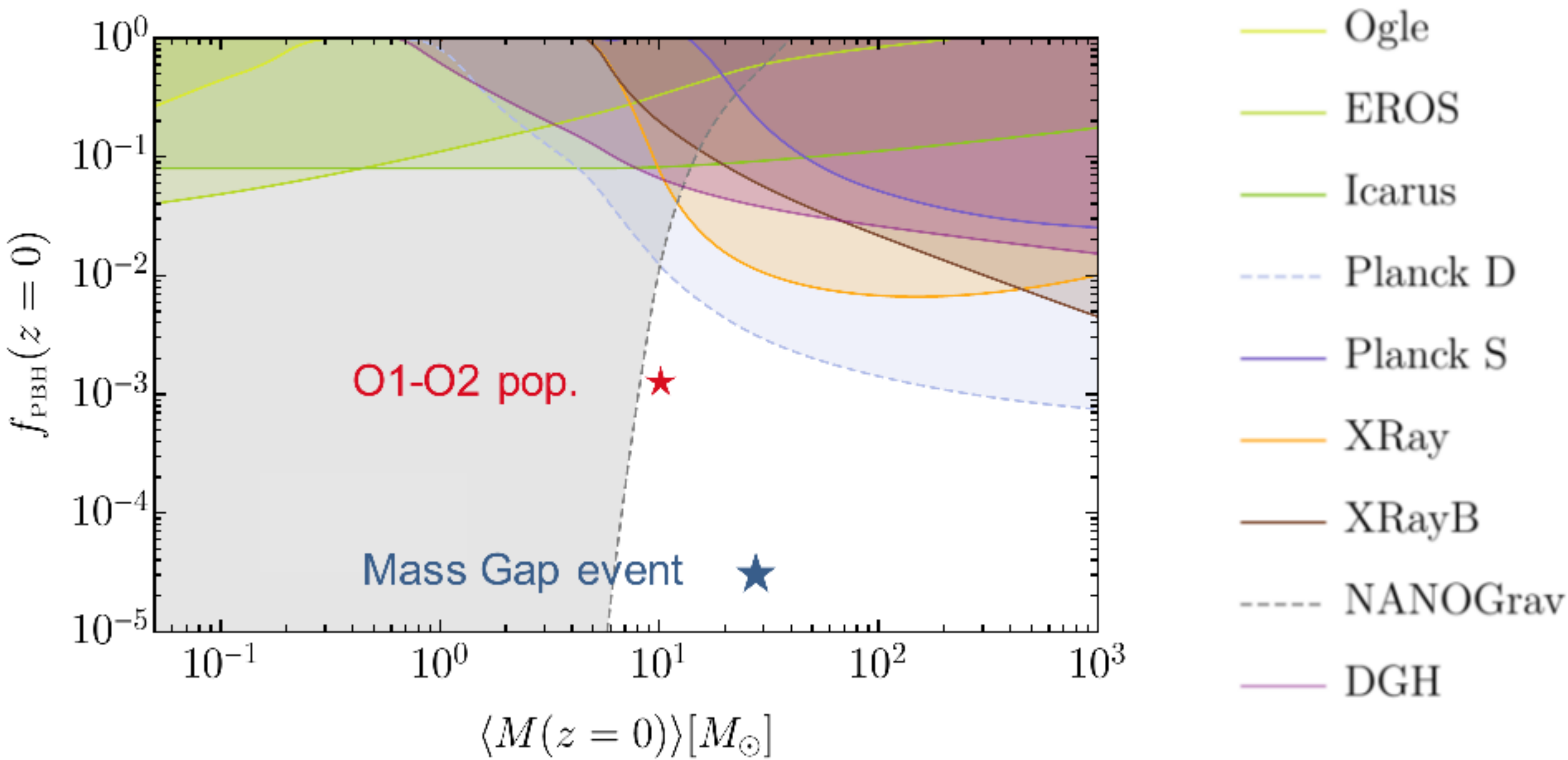
$$f = 3\,\mathrm{mHz}\left(\frac{M_{\mathrm{PBH}}}{10^{-12}M_\odot}\right)^2$$



NANOGrav 12.5 yr data already explained with PBHs as DM?

GW Searches for PBHs

- Testing PBHs at their late stages: BH mergers
  - LIGO/Virgo population + Mass Gap event GW190521

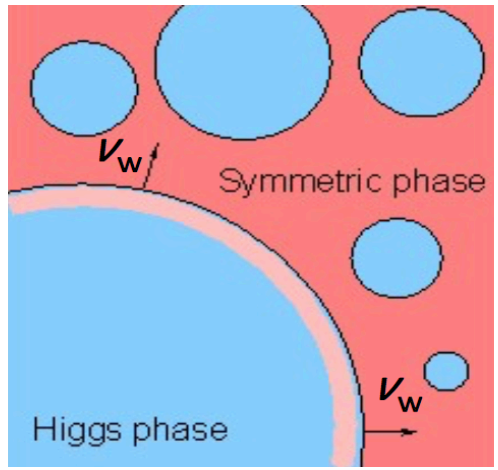


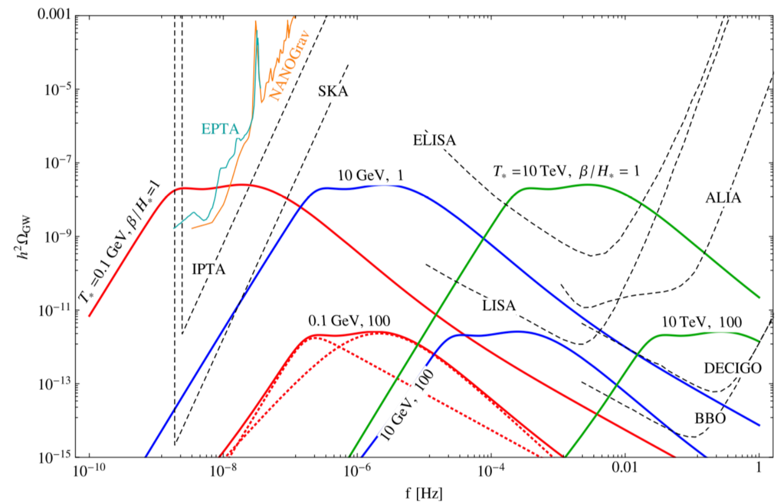
GWs probing the early Universe

GWs will probe early universe phenomena which would remain untestable

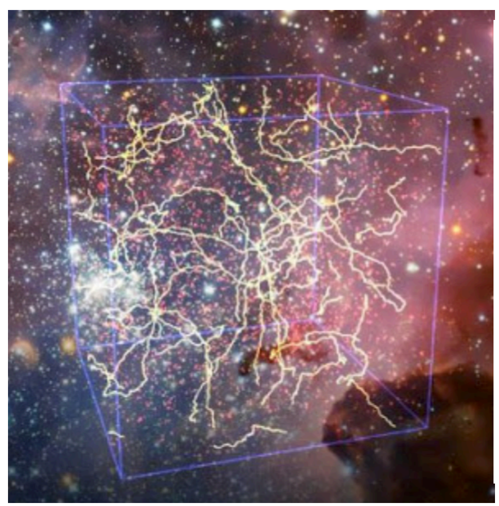
(beautiful connection to the origin of the baryon asymmetry of the universe)

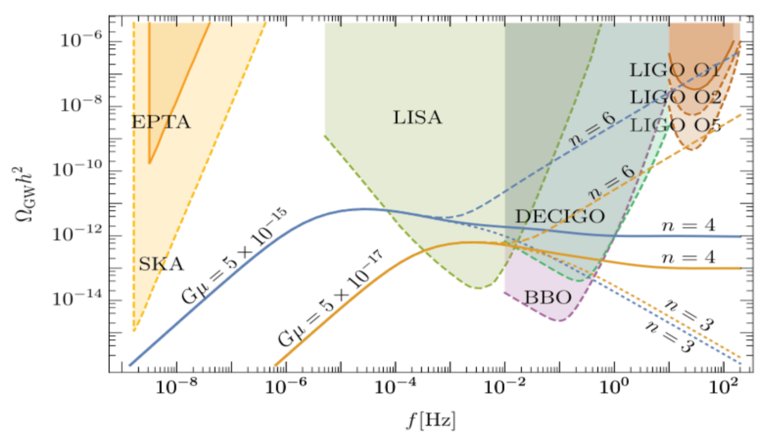
- Phase transitions





- Cosmic strings

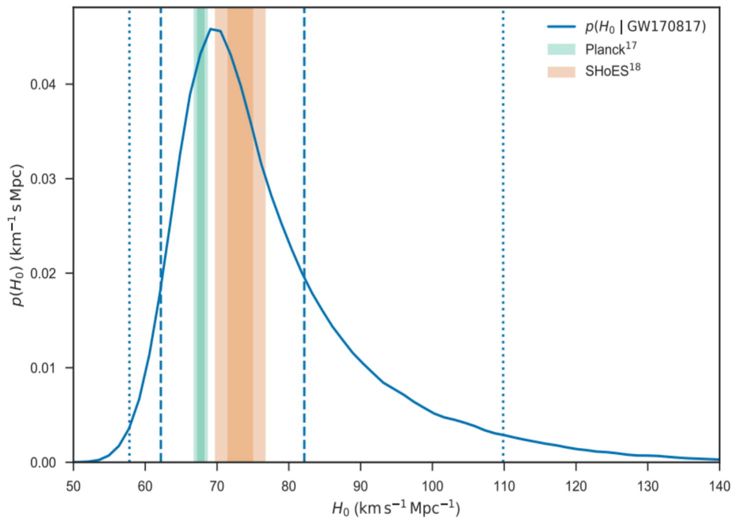


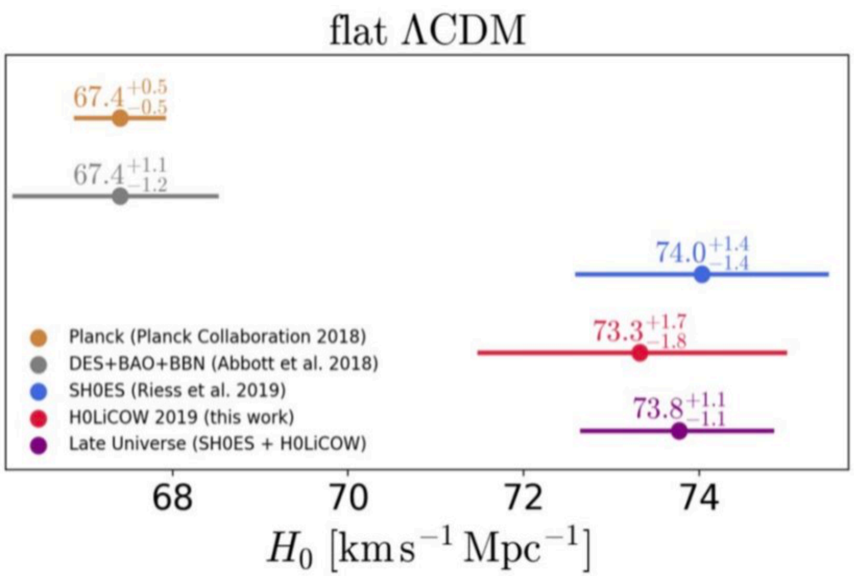


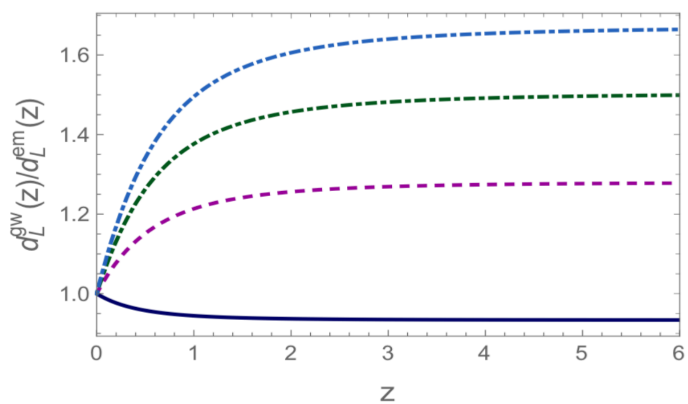
GWs probing the late Universe

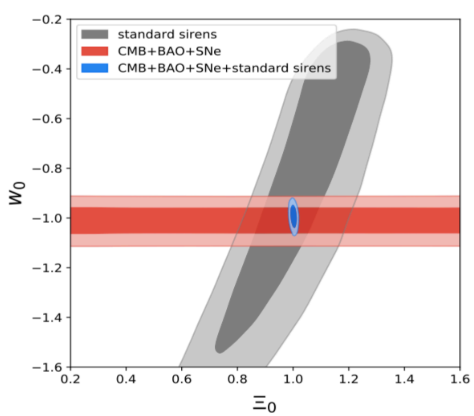
GWs will help understanding the nature of our late time universe: why does it accelerate, is there dark energy? Is gravity modified at large distances?

Fantastic new tool: coalescing binaries as standard sirens!









It's just the beginning

Science Case for the Einstein Telescope 1912.02622

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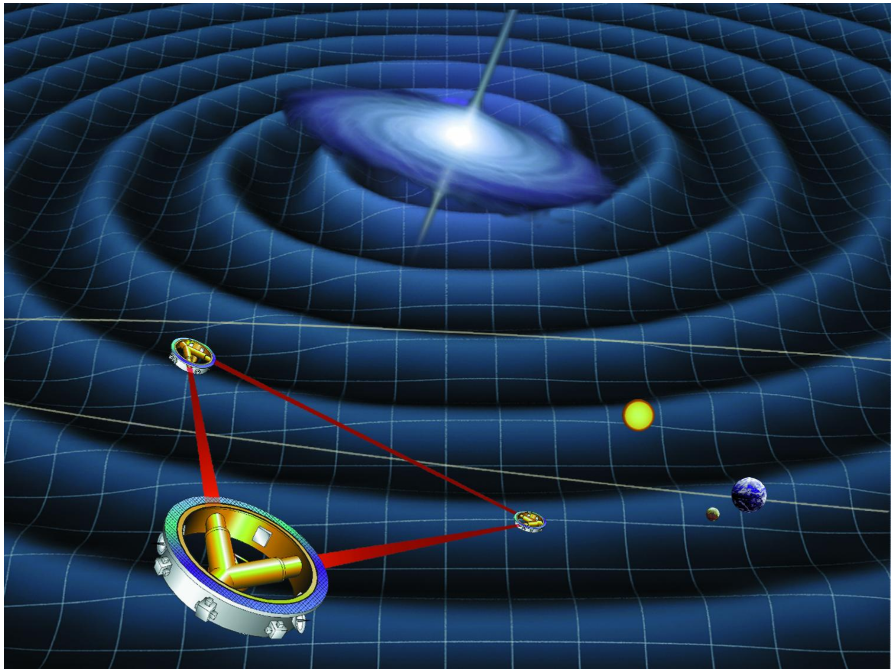

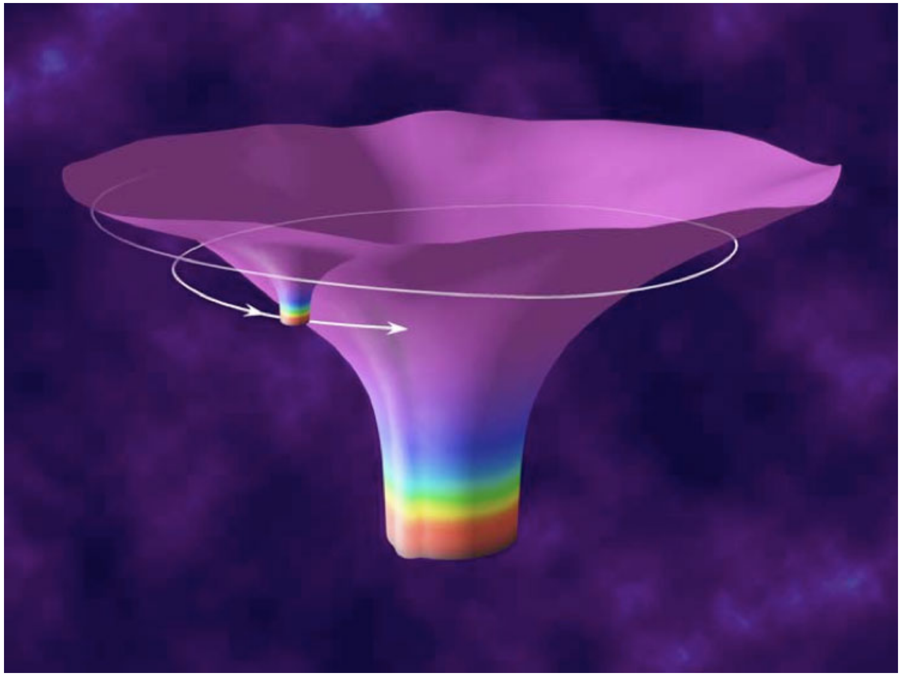

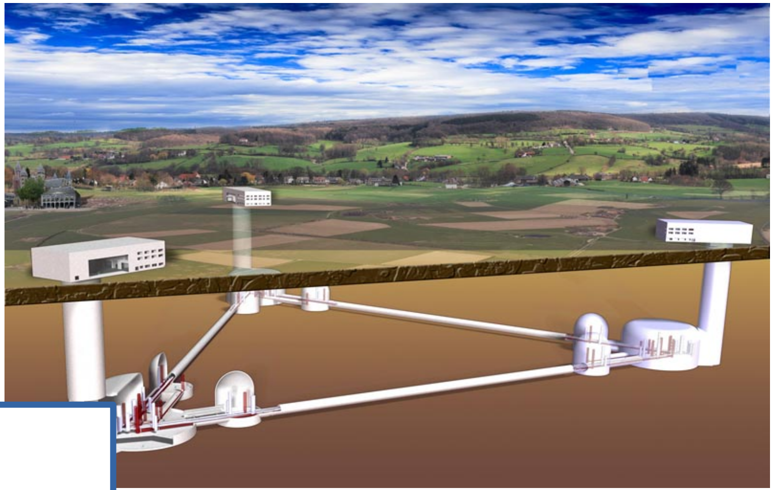

2001.09793 **Prospects for Fundamental Physics with LISA**

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Thank you for your attention!

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