# Nuclear astrophysics theory in the era of multimessenger physics and radioactive beams

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North Carolina State University

With input from: Jutta Escher, Bob Fischer, Chris Fryer, Raph Hix, Luke Johns, Amy Lovell, Matt Mumpower, David Radice,Sanjay Reddy, Andrew Steiner, Rebecca Surman, Sherwood Richers, Ingo Tews, Nicole Vassh, Mike Zingale

# A few key questions

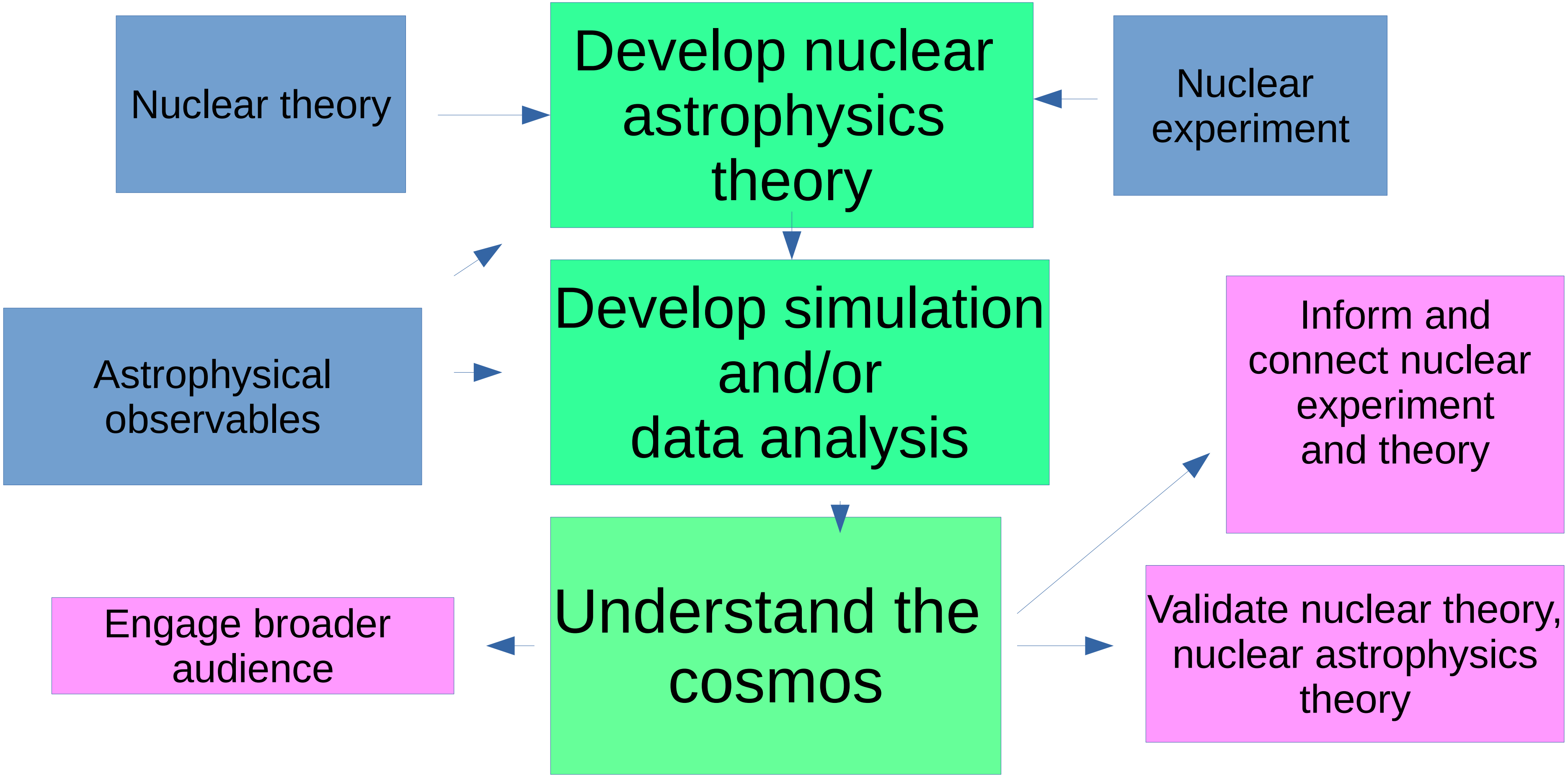
- What is the origin of the elements? e.g. Do the r-process elements we see on earth come from neutron star mergers? Collapsars? Other sites?
- What fundamental nuclear physics can we learn from the cosmos? e.g. What is the equation of state? What are the masses of nuclei off stability? Are there new particles beyond the standard model?
- How does nuclear physics govern the lives and deaths of stars? e.g. Does a given massive star end in a black hole or a neutron star at the end of its life?

# Two roles

Primary role: nuclear astrophysics theory is a core area of nuclear physics, addressing key questions

Secondary role: nuclear astrophysics theory adds value to many other areas in nuclear physics

# Nuclear astrophysics theory framework



Nuclear theory

Develop nuclear astrophysics theory

Nuclear experiment

Astrophysical observables

Develop simulation and/or data analysis

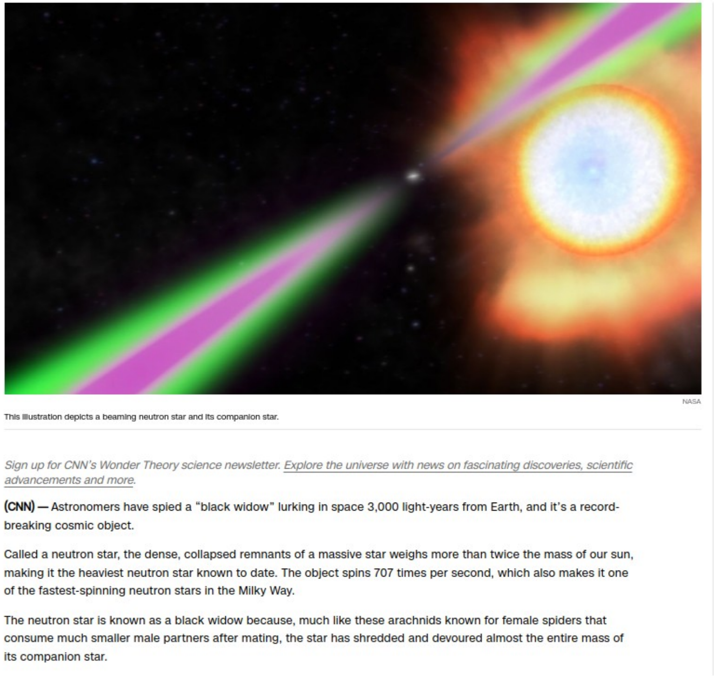
Inform and connect nuclear experiment and theory

Engage broader audience

Understand the cosmos

Validate nuclear theory, nuclear astrophysics theory

# Public fascination with the cosmos links nuclear physics to the public



NASA

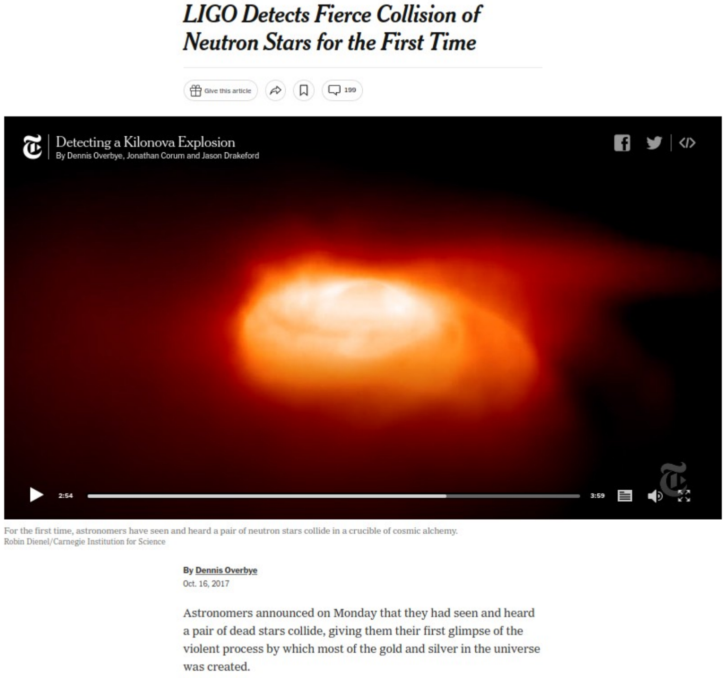
This illustration depicts a beaming neutron star and its companion star.

*Sign up for CNN's Wonder Theory science newsletter. Explore the universe with news on fascinating discoveries, scientific advancements and more.*

**(CNN) —** Astronomers have spied a "black widow" lurking in space 3,000 light-years from Earth, and it's a record-breaking cosmic object.

Called a neutron star, the dense, collapsed remnants of a massive star weighs more than twice the mass of our sun, making it the heaviest neutron star known to date. The object spins 707 times per second, which also makes it one of the fastest-spinning neutron stars in the Milky Way.

The neutron star is known as a black widow because, much like these arachnids known for female spiders that consume much smaller male partners after mating, the star has shredded and devoured almost the entire mass of its companion star.



*LIGO Detects Fierce Collision of Neutron Stars for the First Time*

For the first time, astronomers have seen and heard a pair of neutron stars collide in a crucible of cosmic alchemy.
Robin Dienel/Carnegie Institution for Science

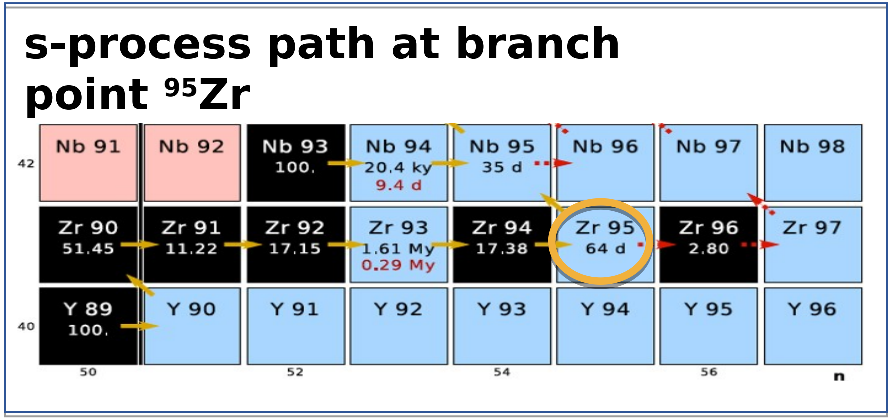
By Dennis Overbye
Oct. 16, 2017

Astronomers announced on Monday that they had seen and heard a pair of dead stars collide, giving them their first glimpse of the violent process by which most of the gold and silver in the universe was created.

CNN on heaviest neutron star

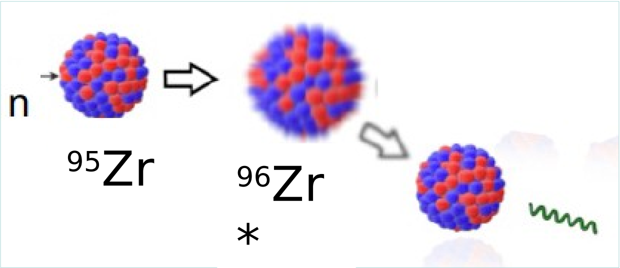
New York Times on r-process elements

# Value added: ties together experiment and theory

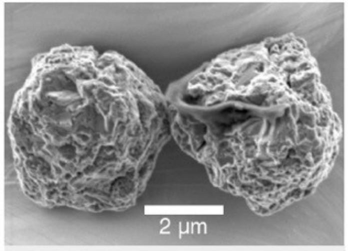


**s-process path at branch point $^{95}$Zr**

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| 42 | Nb 91 | Nb 92 | Nb 93<br>100. | Nb 94<br>20.4 ky<br>9.4 d | Nb 95<br>35 d | Nb 96 | Nb 97 | Nb 98 |
| | Zr 90<br>51.45 | Zr 91<br>11.22 | Zr 92<br>17.15 | Zr 93<br>1.61 My<br>0.29 My | Zr 94<br>17.38 | Zr 95<br>64 d | Zr 96<br>2.80 | Zr 97 |
| 40 | Y 89<br>100. | Y 90 | Y 91 | Y 92 | Y 93 | Y 94 | Y 95 | Y 96 |
| | 50 | | 52 | | 54 | | 56 | n |



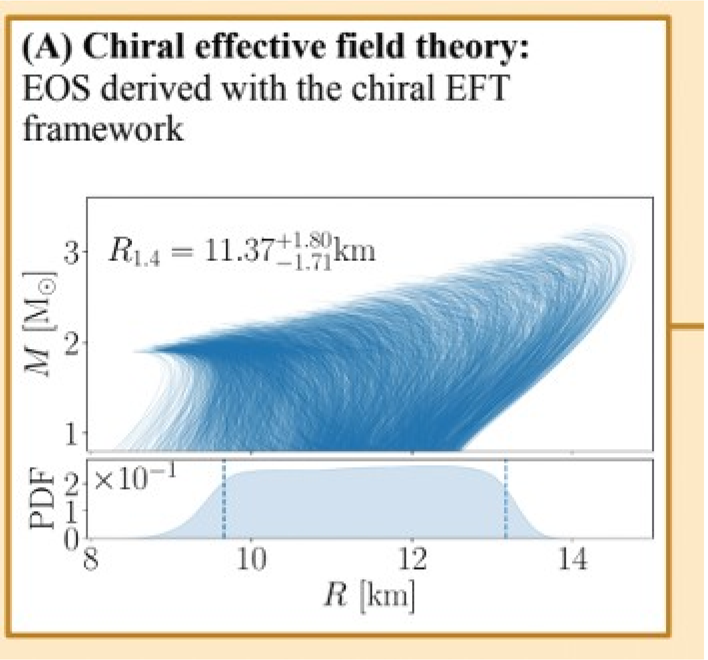
Presolar grains



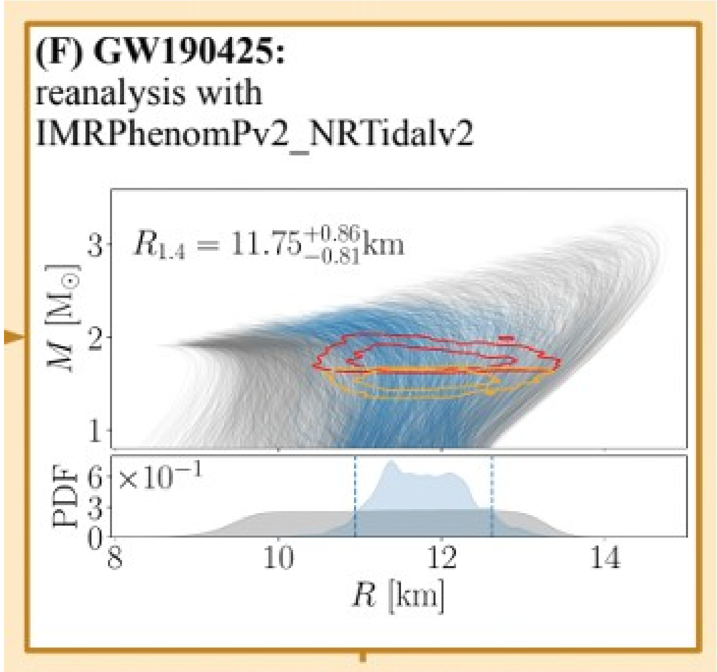
**Reaction theory is key to determining reliable cross sections**

Figures from Jutta Escher

# Value added: validate nuclear experiment/ theory with astrophysical observables



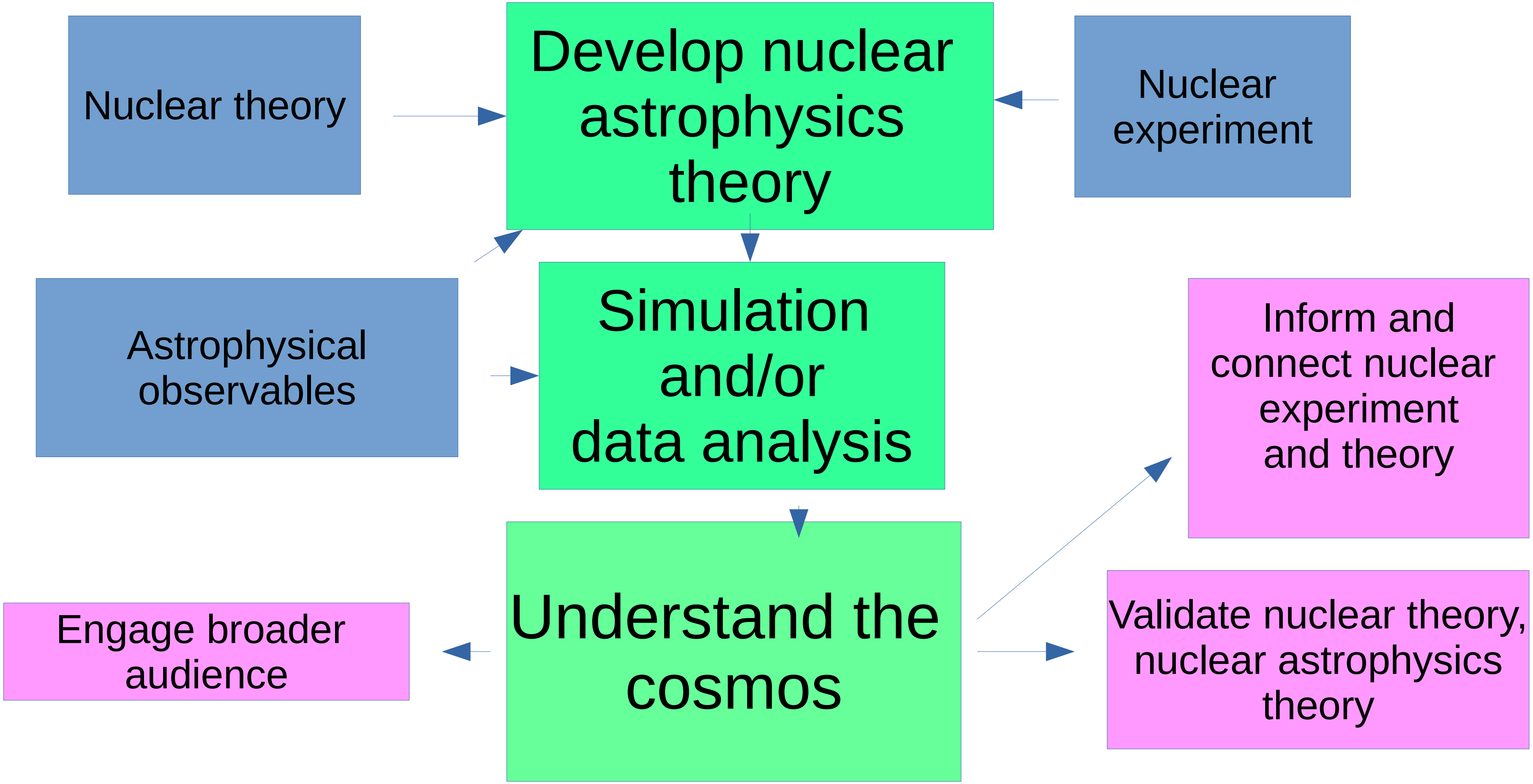
**(A) Chiral effective field theory:**
EOS derived with the chiral EFT framework



**(F) GW190425:**
reanalysis with
IMRPhenomPv2_NRTidalv2

Using astronomical observables to constrain the equation of state, figures from I. Tews

# Nuclear astrophysics theory framework



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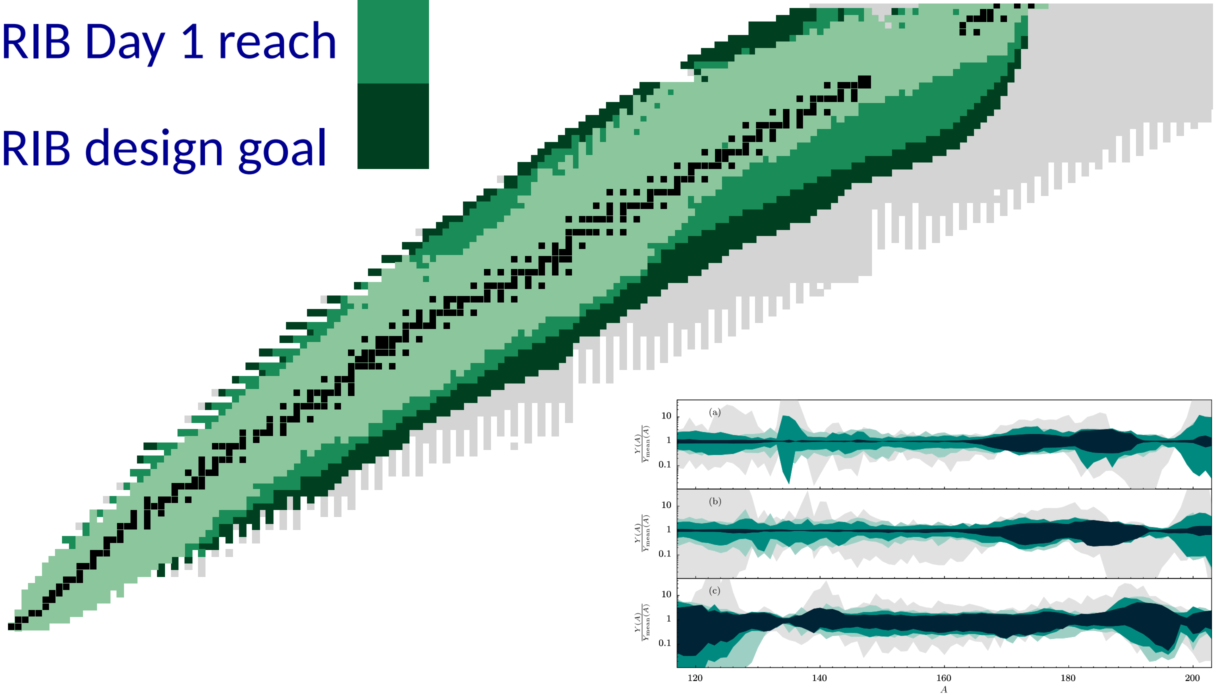
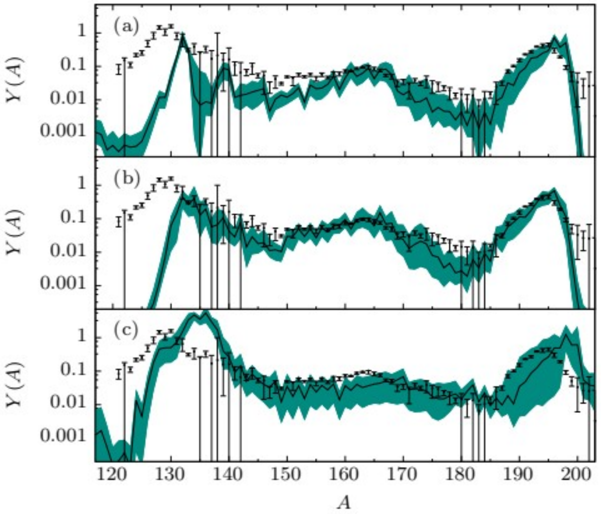
# Nuclear experiments: e.g. radioactive beams

AME 2016 🟩

FRIB Day 1 reach 🟩

FRIB design goal 🟩





← Grey – current uncertainty

Figures from Sprouse et al 2019 and R. Surman

# Nuclear theory: e.g. DFT with machine learning and AI

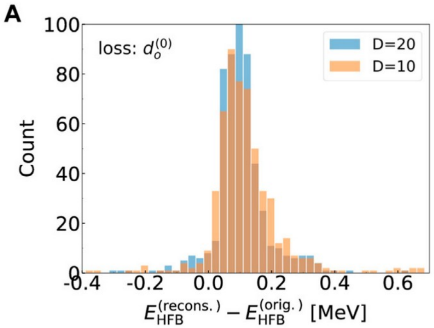
**ML/AI for DFT**

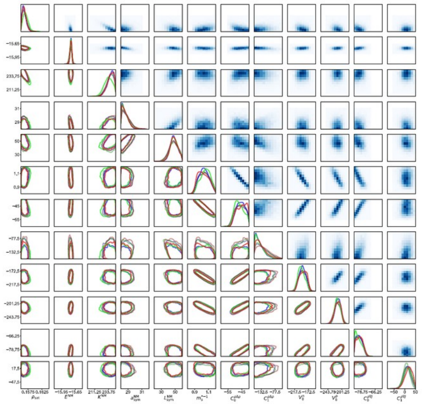
Schunck et al, JpG **47**, 074001 (2022)

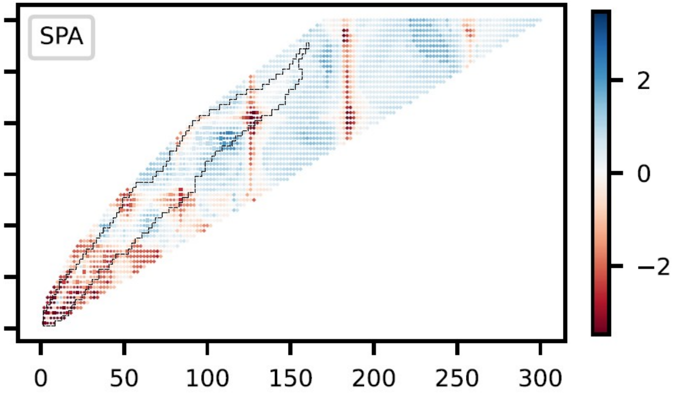
**Bayesian UQ**

Navarro Perez et al., PLB **47**, 074001 (2022)

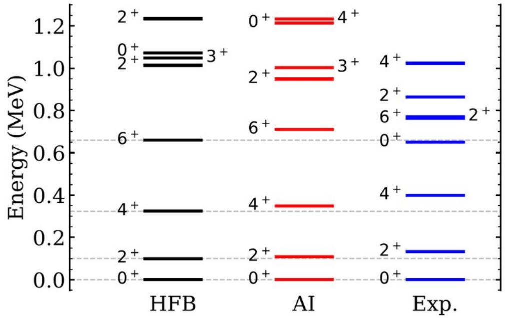
Verriere et al., Front. Phys. **10**, 1 (2022)

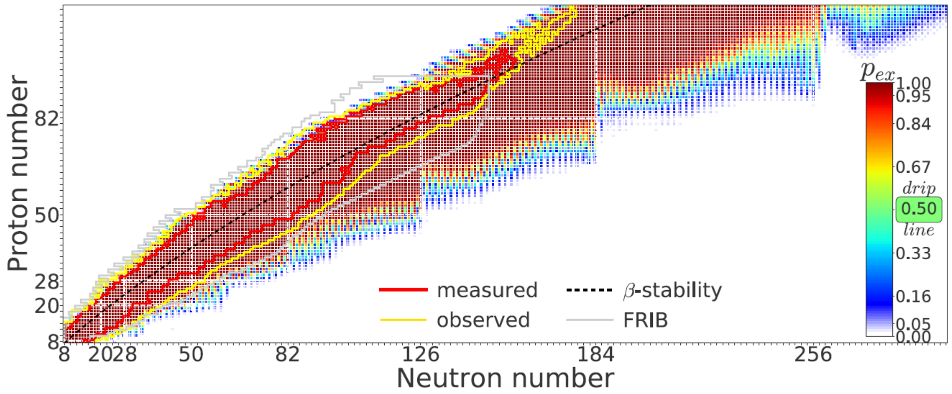






Lasseri et al., PRL **124**, 162502 (2020)

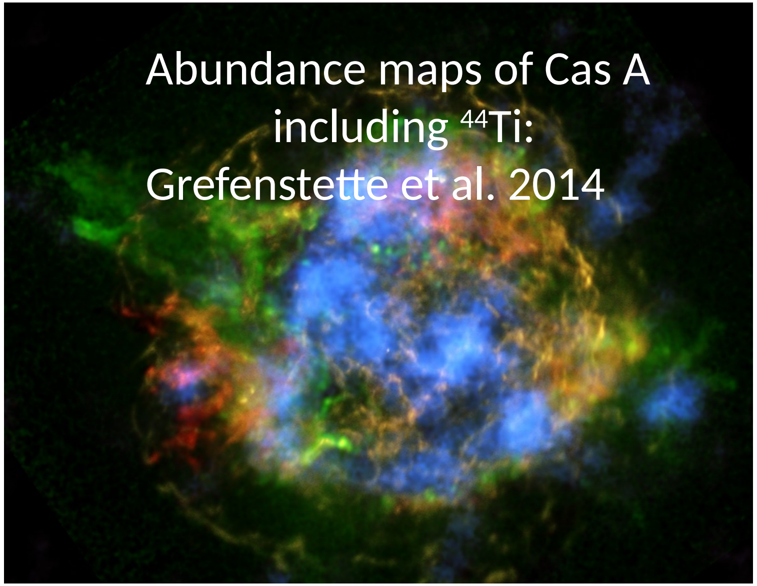




Neufcourt et al.,
PRC **101**, 044307
(2020)

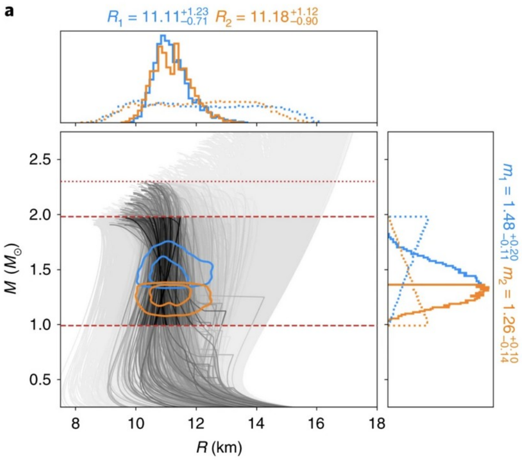
Slide from adapted from
N. Schunck, A. Lovell

# Astrophysical observations tie nuclear physics to astronomy



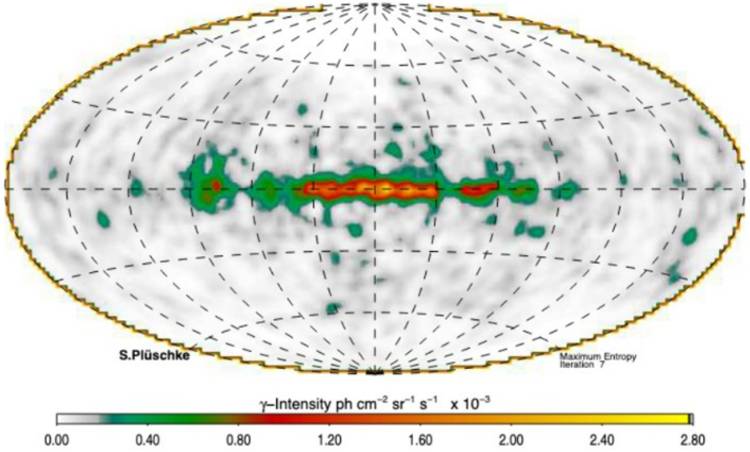
Abundance maps of Cas A including $^{44}$Ti: Grefenstette et al. 2014

- Transients
  - Gravitational Waves: Probes of the EOS (LVK)
  - Neutrinos: EOS and Neutrino physics (DUNE, JUNO, Super-K, Hyper-K)
  - UVOIR spectra



GW observations Capano et al. 2020

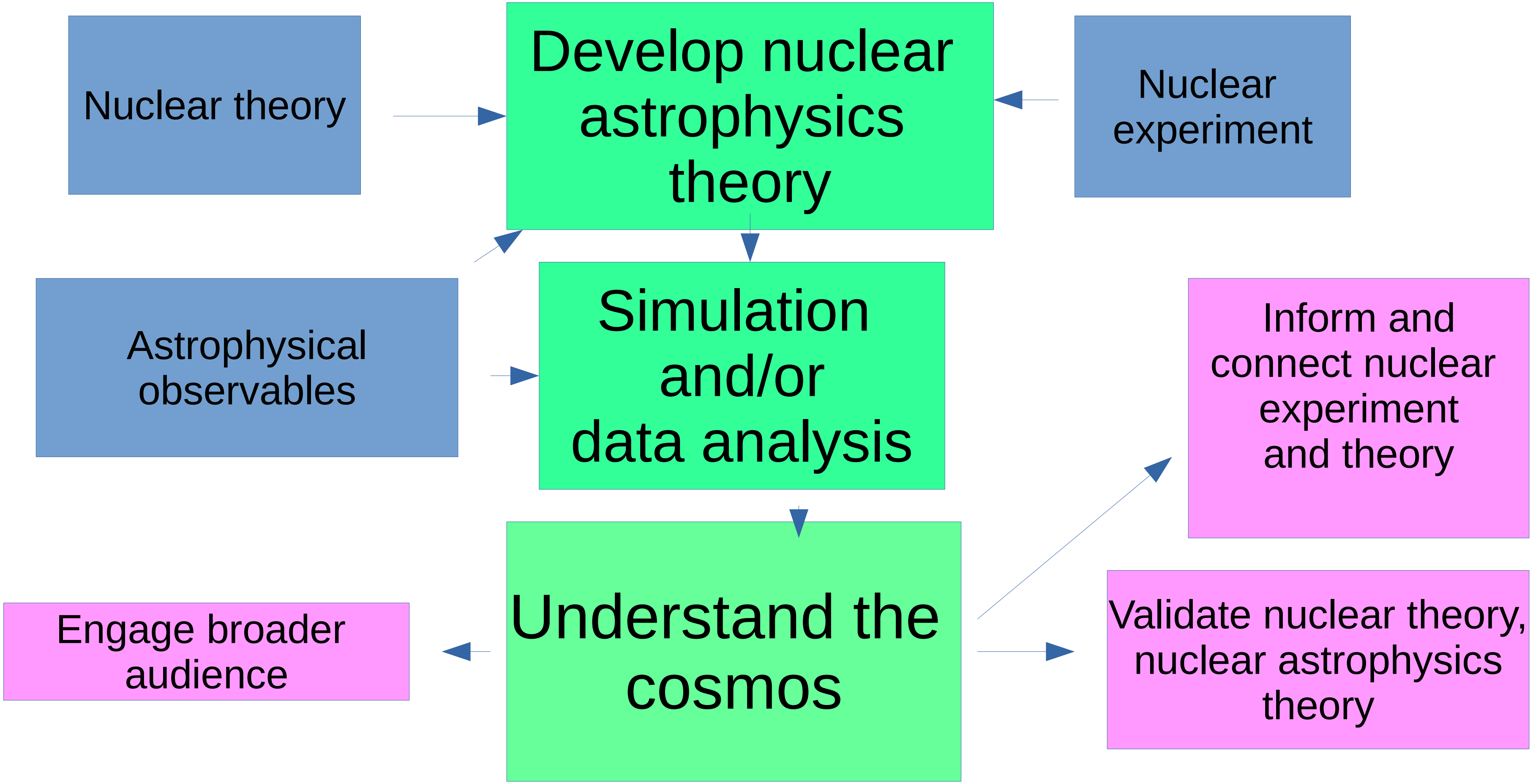
- Nucleosynthetic Yields:
  - SN and Mergers: Radioactive $^{44}$Ti
  - Galactic Distribution of Isotopes: $^{26}$Al, $^{60}$Fe, ..
  - Galactic Chemical Evolution (Dust, Stars)



COMPTEL Map of Radioactive Isotopes

Slide adapted from C. Fryer

# Nuclear astrophysics theory framework



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# Element synthesis last decade: some r-process was made in a BNS merger

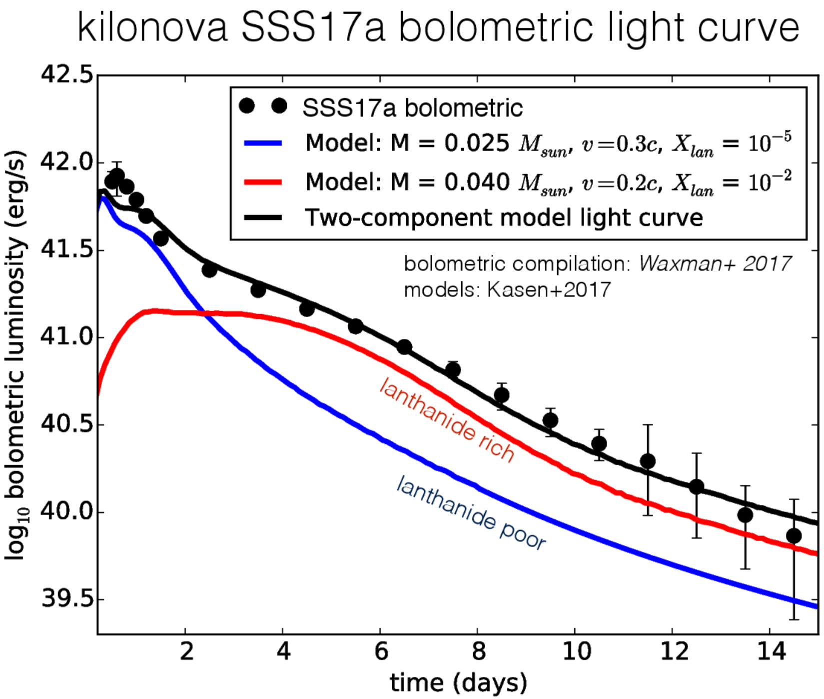
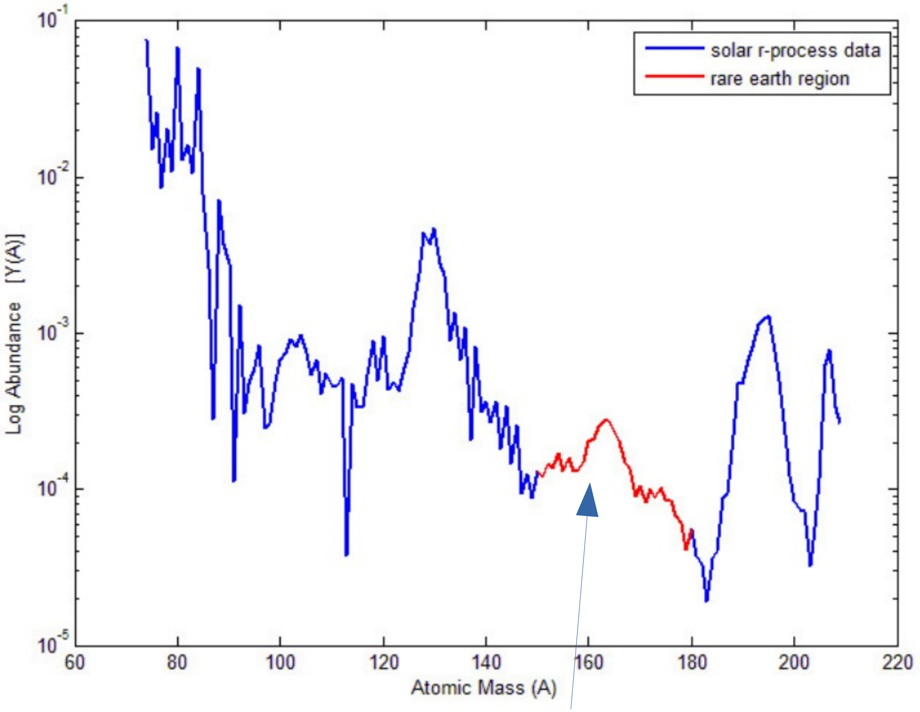
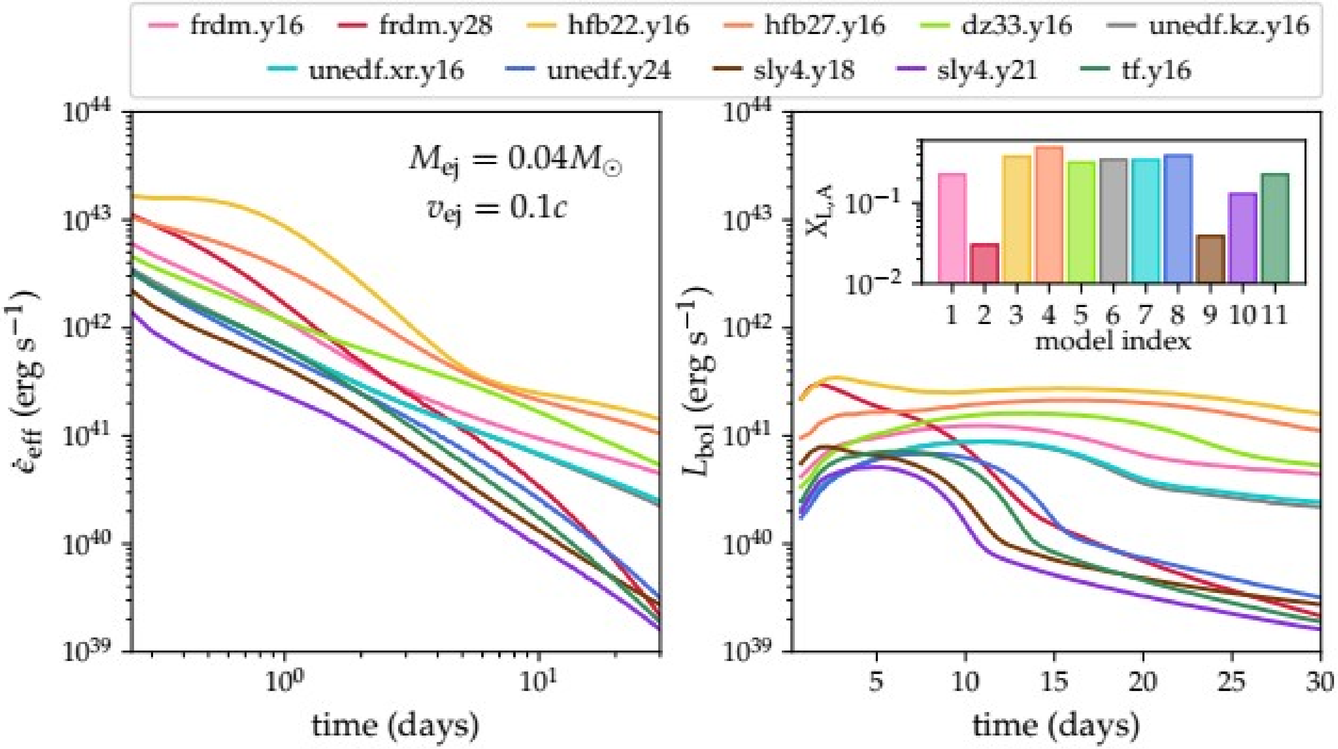


Fig from Dan Kasen



Neutrons captured out to the rare earths

# Next decade: fission, alpha decay signatures can be identified in future kilonovae



Barnes et al 2022

# Neutron star merger last decade (observations!!) paradigm shift: there are different types of ejecta

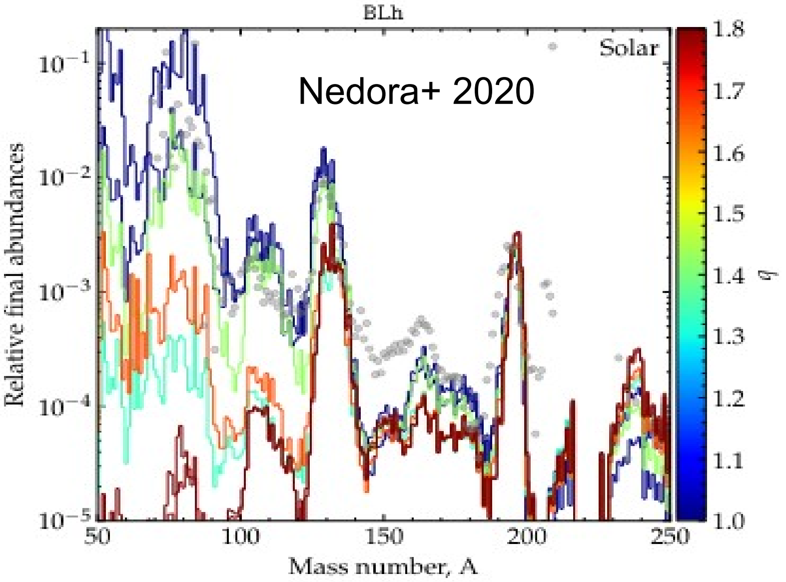
**Progress in the last ten years**

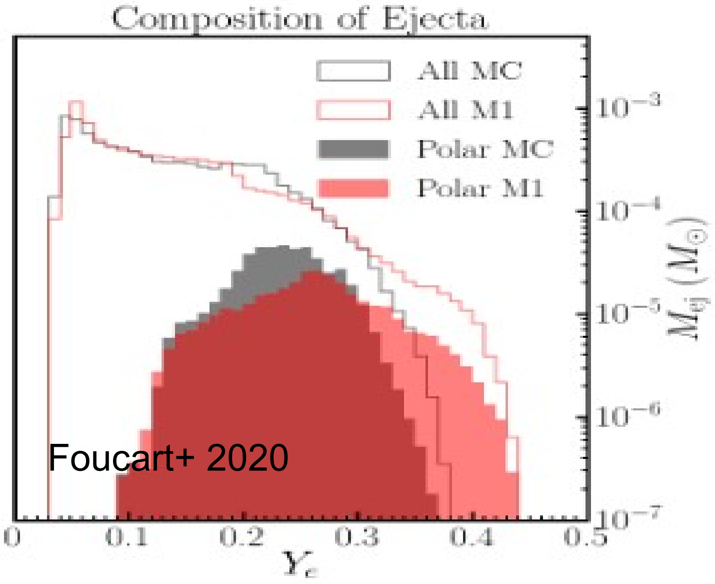
- Dynamical-spacetime, 3D, GRMHD with advanced microphysics
- Neutrino transport (M1 and Monte Carlo)
- Subgrid turbulence models

**Next ten years**

- Non-equilibrium effects in dense matter
- End-to-end simulations: from inspiral, through merger, wind phase, and kilonova
- Nuclear reactions
- Neutrino quantum-kinetics
- Embedding of ML models into the simulations

Slide from D. Radice

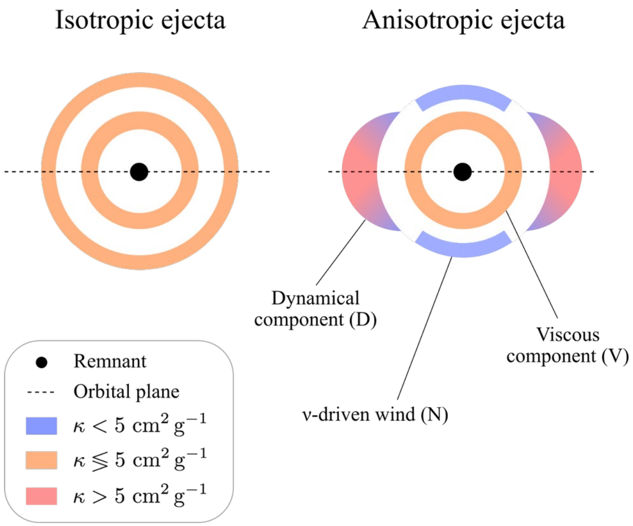




# Neutron star merger simulation, next decade: connecting the different “messengers” with simulations

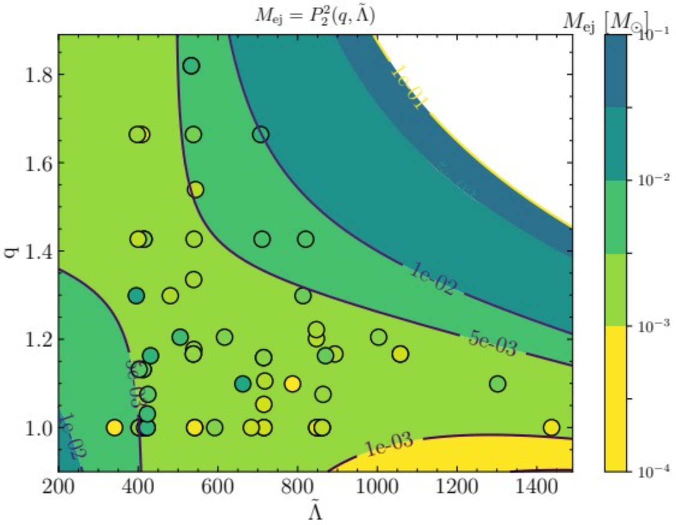
$$P[\theta|d] \sim P[\theta]P[d|\theta] = P[\theta]P[d_{\rm GW}|\theta]P[d_{\rm EM}|\theta]$$

NR informed GW modeling and data analysis



kilonova modeling

NR simulations



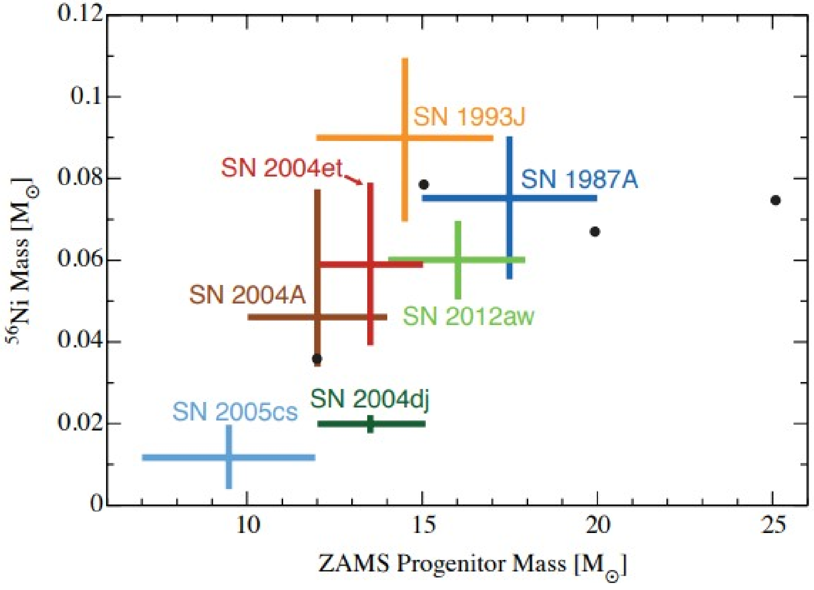
Perego+ 2017

Slide from D. Radice

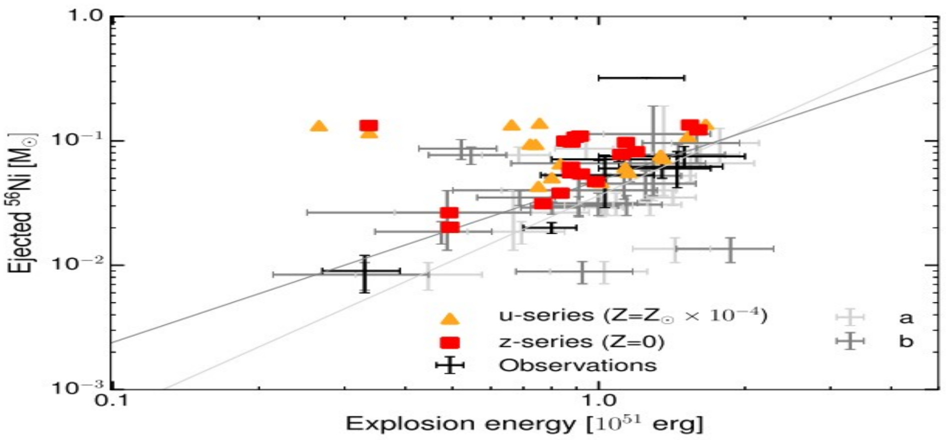
Nedora+ 2022

# Achievement of the last decade: core collapse supernovae simulation

Recent progress: success of the neutrino heating mechanism tested against light curve data

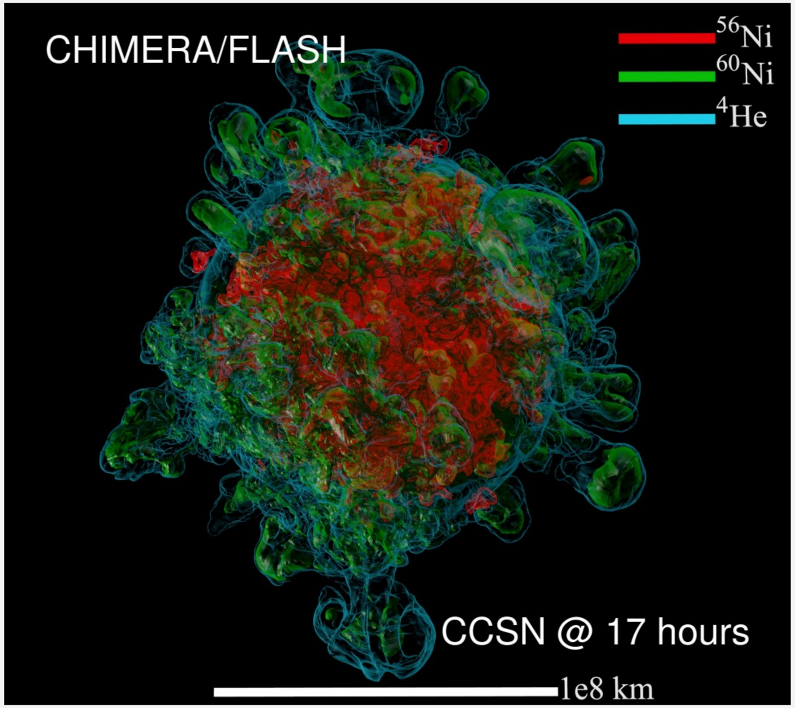


Bruenn et al 2016



Ebinger et al 2020

# Next Decade's Core-Collapse Supernova Promise



1) Compare to quantitative observations.

   Requires detailed nucleosynthesis

   Requires end-to-end simulations — from formation of elements until the new elements become observable

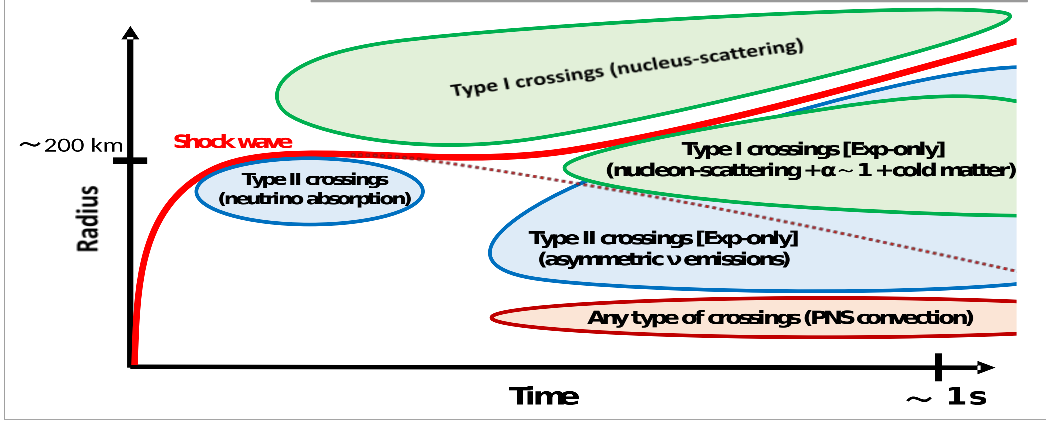
2) Understand how details of stellar structure and binarity manifest in supernovae. Requires more models

3) Model the full massive star menagerie: Long GRBs with SN, SN that form Magnetars, Electron-Capture SN, Super-luminous SN and new things Vera Rubin (Telescope) will find.

   Requires better physics (neutrino oscillations, full GR, better Equation of State and neutrino opacities, …)

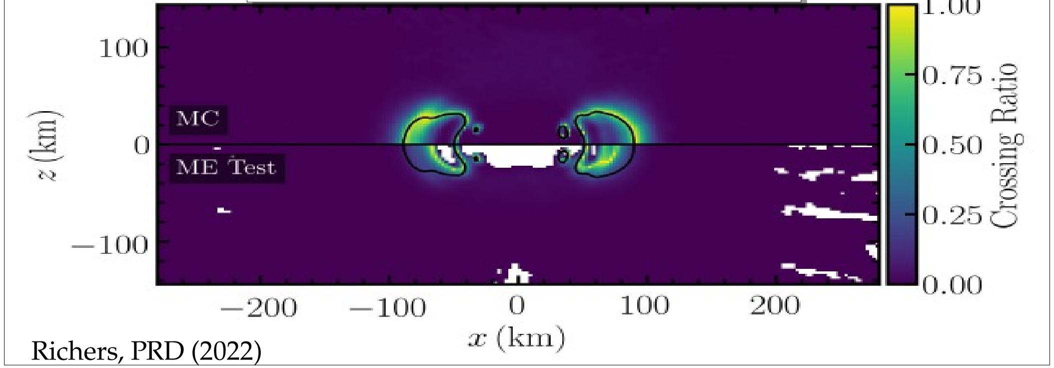
# Neutrino achievement of the last decade: neutrino flavor instabilities in supernovae and mergers occur much deeper than previously realized → affects our core questions

**Fast instabilities** in a typical CCSN
(*“crossing”* = *unstable*)



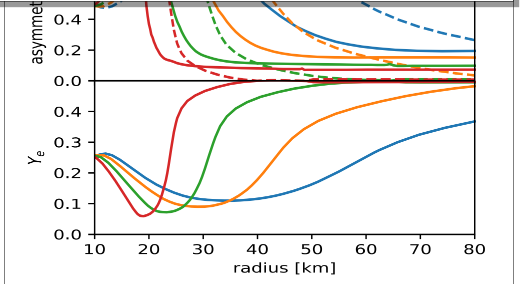
Nagakura, Burrows, Johns, & Fuller, PRD (2021)

**Fast instabilities** in a NSM



Richers, PRD (2022)

**Collisional instabilities** in a CCSN
(*unstable where dashed > solid*)

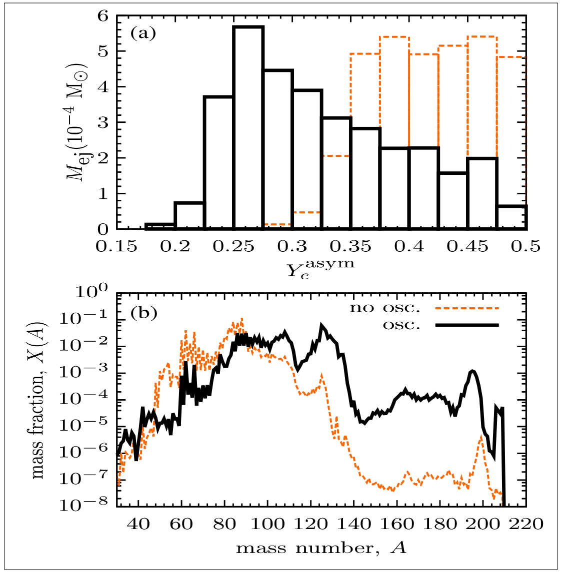


Xiong et al., 2210.08254

**Slide adapted from Luke Johns, Einstein Fellow @ Berkeley**

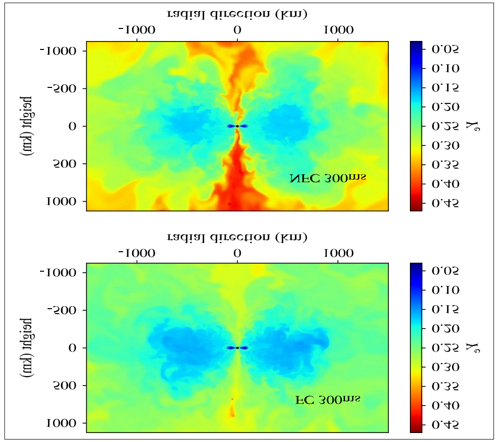
# Next decade: **Neutrino Quantum Kinetics**, Evaluate role in **dynamics & nucleosynthesis**.

Preliminary results suggest that instabilities can significantly enhance *r*-process yields in post-merger outflows.



Wu, Tamborra, Just, & Janka, PRD (2017)

Now we need calculations that
(1) have **more complete oscillation physics**,
(2) cover **a variety of progenitors/conditions**,
(3) predict **more observables** (neutrino signals, kilonova light curves, dynamical effects).

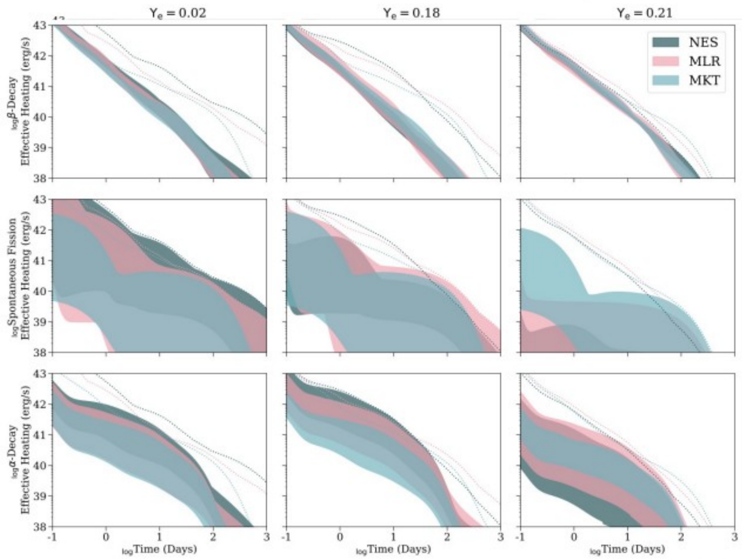


Li & Siegel, PRL (2021)

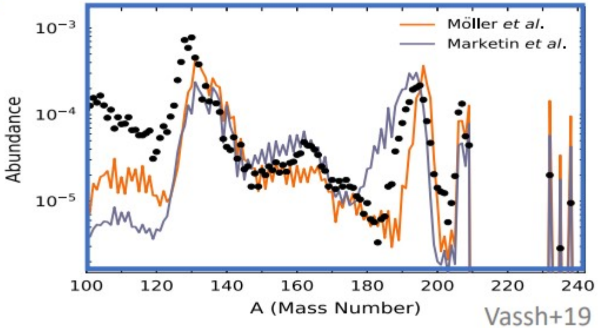
**Slide adapted from Luke Johns, S. Richers**

# Element synthesis and global theories of beta decay: achievement → uncertainties identified, next decade → improve predictive power of element synthesis

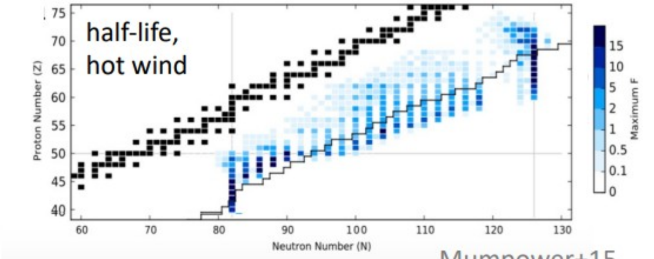
Heating rates for NSM light curves given 3 different $\beta$-decay models



Lund+22



Vassh+19



Mumpower+15

* *r*-process calculations sensitive to **$\beta$-strength functions**, **$Q_\beta$-values**, **half-lives**, **$P_n$ values**, and **$\beta$-gamma spectra**

Slide adapted from N. Vassh

# Surrogate reactions provide viable method to extract neutron capture rates

Slide from J Escher

Determining capture rates for unstable nuclei directly is hard

- Short-lived target make measurements difficult to impossible
- Hauser-Feshbach (HF) calculations lack predictive power away from stability

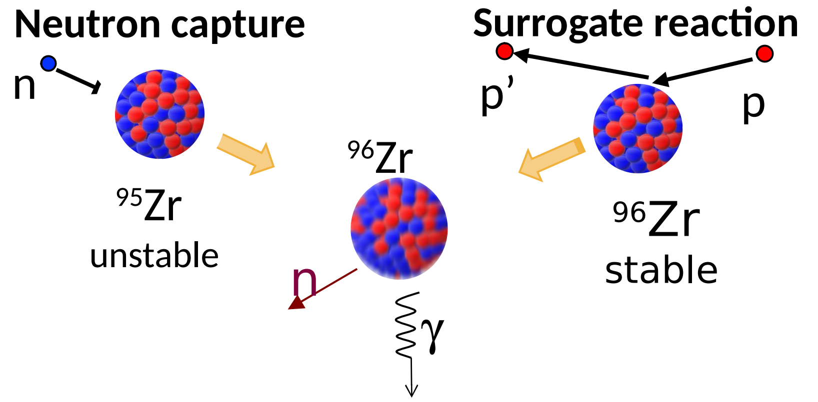
Surrogate reactions provide a solution

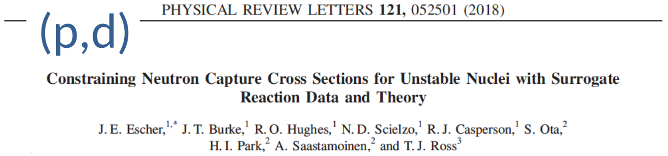
- A transfer or inelastic scattering experiment produces the compound nucleus and the decay is measured
- Advanced reaction theory turns this data into constraints for calculations of the desired neutron capture rate

Status:

- Capture cross sections have been obtained from surrogate reactions using (p,d) and (d,p) transfers and inelastic scattering.
- Cross sections for capture involving isomers have been obtained.
- Future: inverse-kinematics, fission.

Neutron capture on s-process branch point $^{95}$Zr from inelastic scattering




(p,d)

PHYSICAL REVIEW LETTERS **121,** 052501 (2018)

**Constraining Neutron Capture Cross Sections for Unstable Nuclei with Surrogate Reaction Data and Theory**

J. E. Escher,[1,*] J. T. Burke,[1] R. O. Hughes,[1] N. D. Scielzo,[1] R. J. Casperson,[1] S. Ota,[2] H. I. Park,[2] A. Saastamoinen,[2] and T. J. Ross[3]

# Achievements: Neutron stars

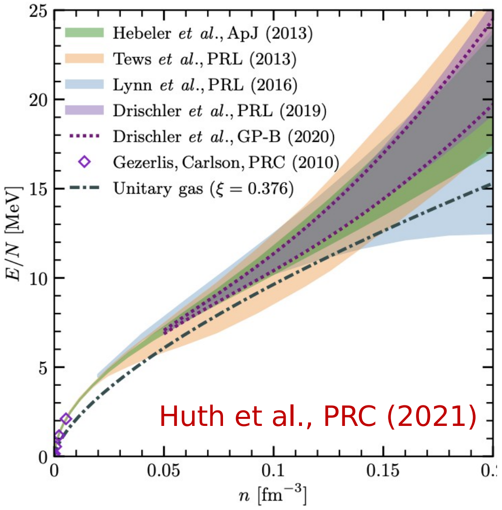
- Below $2n_{sat}$, nuclear theory constraints on EOS of **neutron-rich matter with UQ**
- Heaviest neutron star with **2.08(7) $M_{sol}$** observed in 2019, AT2019gfo provided estimate **$M_{max} \lesssim 2.3\,M_{sol}$**
- First-ever constraint on **tidal deformability** of neutron stars from GW170817:

$$\tilde{\Lambda}_{\mathrm{GW170817}} \leq 720$$

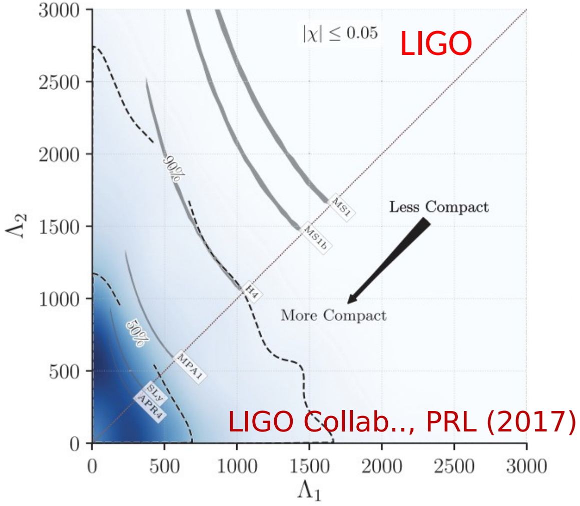
- Neutron Star Interior Composition Explorer (NICER) provided two NS **mass-radius measurements:**

$$R_{0030} = 13.02^{+1.24}_{-1.06}\mathrm{km}, \quad M_{0030} = 1.44^{+0.15}_{-0.14} M_{\odot}$$
$$R_{0740} = 13.7^{+2.6}_{-1.5}\mathrm{km}, \quad M_{0740} = 2.08 \pm 0.07 M_{\odot}$$

- Systematic combination of all these data

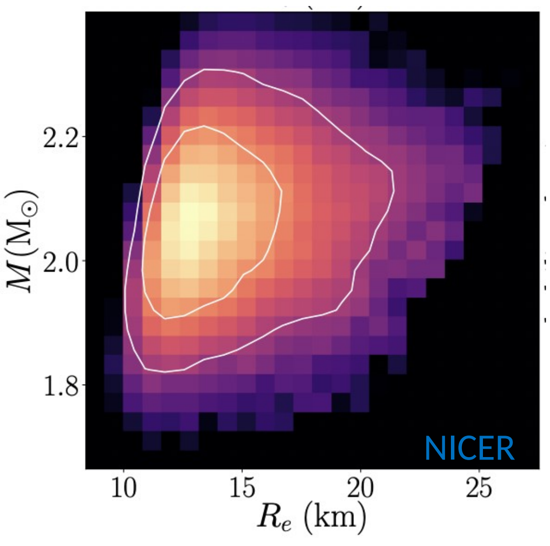


Huth et al., PRC (2021)



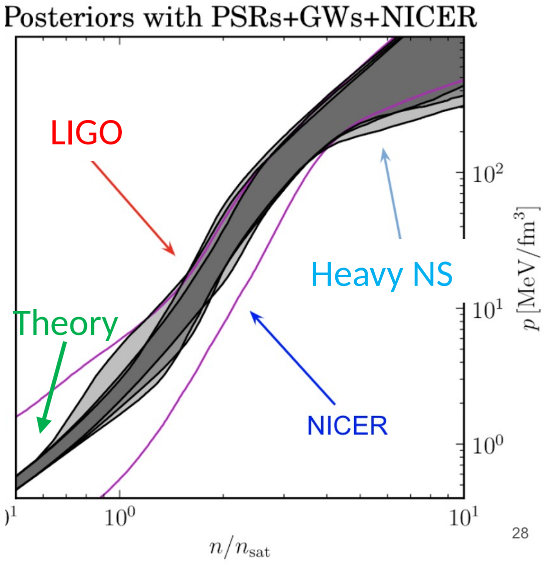
LIGO

LIGO Collab.., PRL (2017)



NICER

Miller et al., ApJ Lett (2021)



LIGO

Theory

Heavy NS

NICER

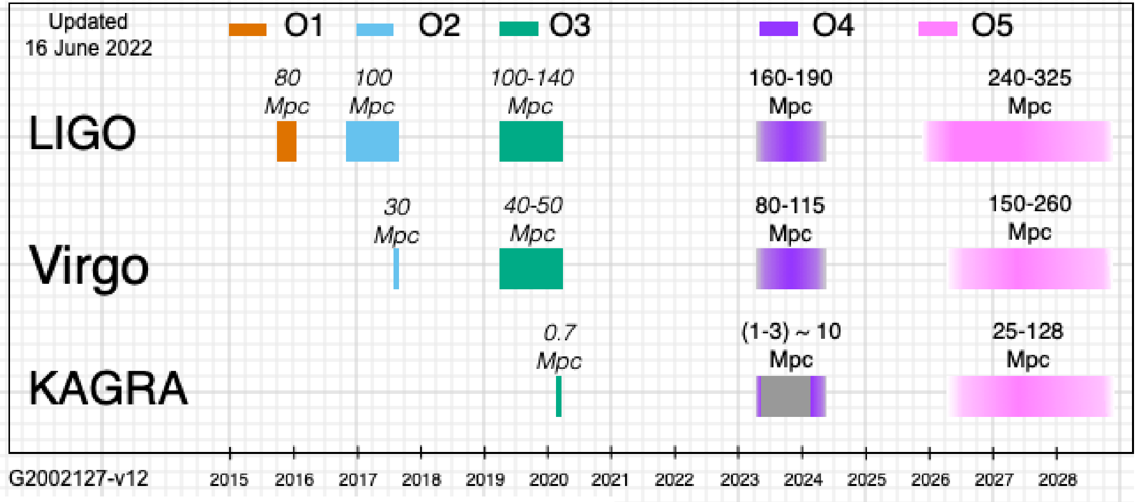
Essick et al., PRC (2020)

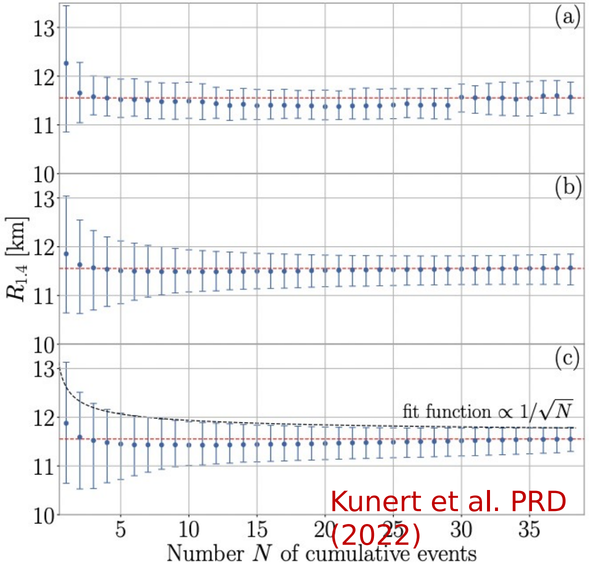
# Next decade:
# NS Golden Age

- Improved theory constraints on EOS: Combine EFT + Bayes + UQ
- New experimental constraints from FRIB, FAIR, RHIC. Improved neutron-skin measurements (MREX).
- Many more gravitational-wave signals from LIGO observing runs (O4 Spring 2023).
- NICER was extended for at least another 3 years.

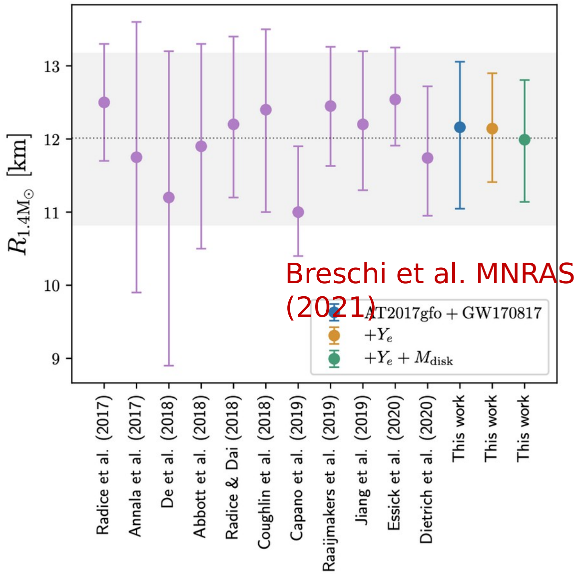
**EOS will be much better constrained in ten years!**

Slide from I. Tews





Kunert et al. PRD (2022)

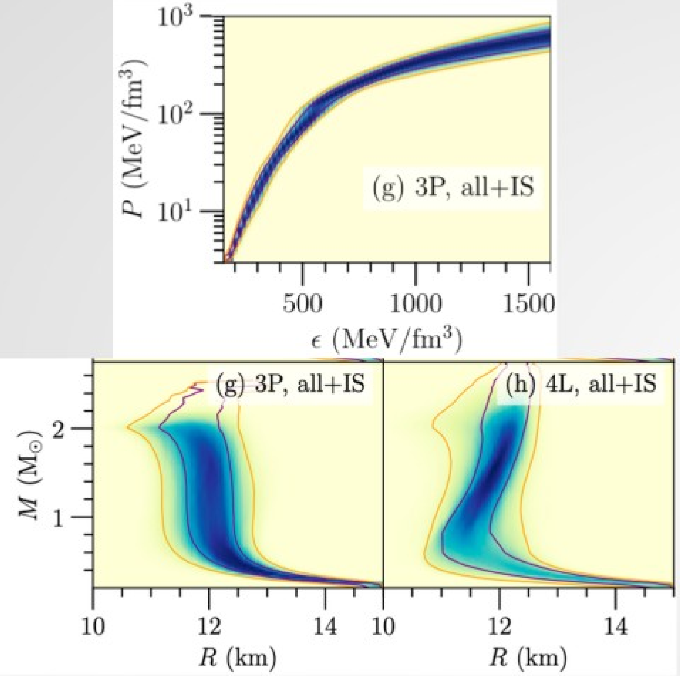


Breschi et al. MNRAS (2021)

?

# Observations and Theory for the EOS ⇒ NS-NS Merger Science

- Nuclear theory and multimessenger observations constrain the cold EOS:

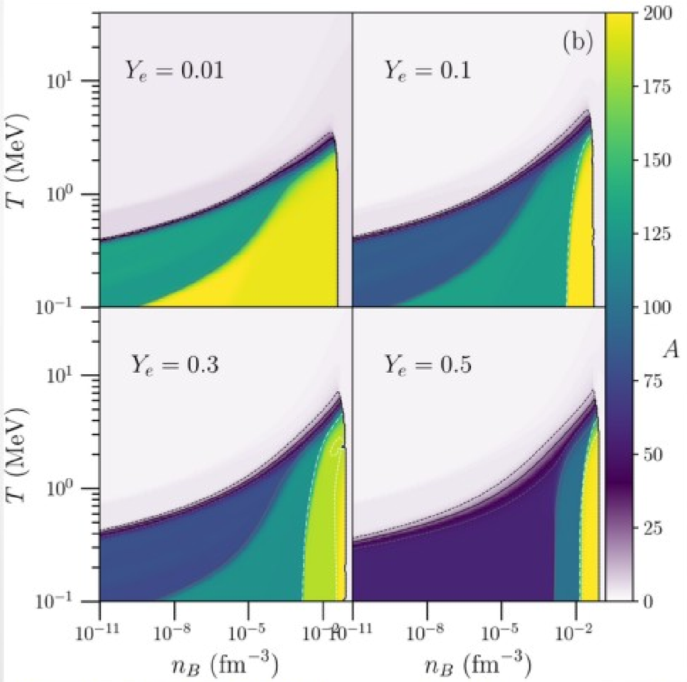


Al-Mamun et al., PRL (2021), see also De et al., PRL (2018)

- The shape of the M-R curve is not fully determined ⇔ the possible presence of a phase transition

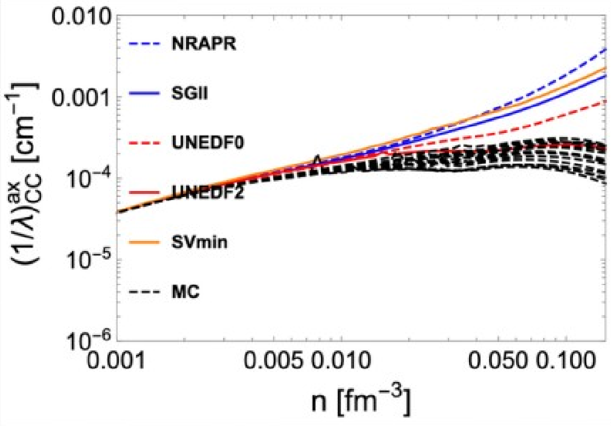
Slide from A. Steiner

- Using nuclear structure data, scattering phase shifts, NS observations, and chiral effective theory for merger simulations
- New equation of state tables with uncertainties:



Du et al. PRC (2021), see also Furusawa et al. NPA (2017) and Huth et al. PRC (2021)

- Begin quantifying the uncertainties in the neutrino inverse mean free path:

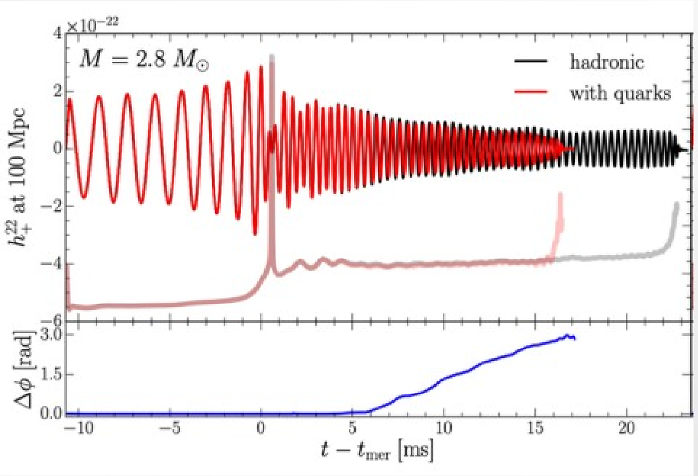


Lin et al. (2022), see also Roberts et al. (2017), Horowitz et al. PRC (2017), Alexandru et al. PRL (2021)

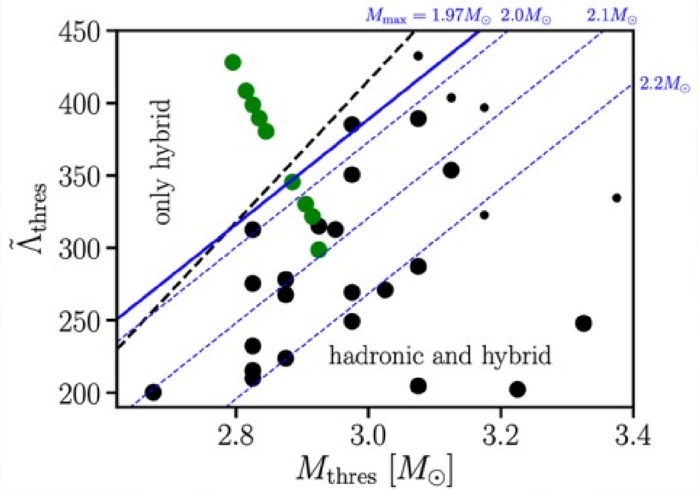
- Cosmic Explorer will accurately determine $P(\varepsilon)$ over a wide range of densities
- Simulations continue to make progress on neutrino physics, see also e.g. Foucart et al. ApJL (2020), Radice et al. (2022), Fernández et al. PRD (2022)

# Observations and Theory for the EOS ⇒ NS-NS Merger Science

- The future will go beyond the cold EOS:
    - composition
    - superfluidity and superconductivity
    - transport properties
    - neutrino cross sections
    - quark-hadron phase transition
    - the properties of nuclei in hot and dense matter



Most et al. PRL (2018)



Bauswein et al. PRL (2020)

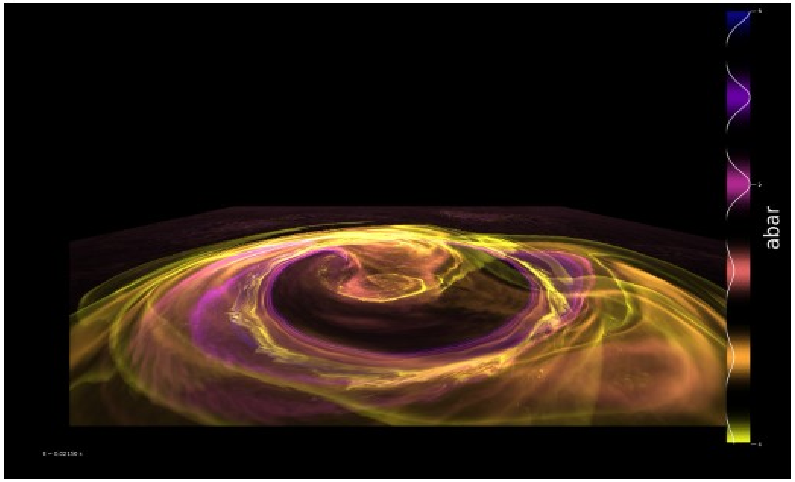
- (at left) Quark-hadron phase transition leaves an imprint on the GW signal
- (above) Determining the maximum mass from merger observations
- (above) Quark-hadron phase transition evident from maximum mass and tidal deformability

- We need simulations with uncertainty quantification to connect experimental data and astronomical observations to models of hot and dense matter
- Our theory work needs to be complimented with reproducible and well-documented software infrastructure
- Conclusion: From "Long Range Plan: Dense matter theory for heavy-ion collisions and neutron stars" (2211.02224) Interpreting: [FRIB, PREX, CREX, RHIC, LIGO, NICER] data fully will require significant coordinated efforts in dense matter theory beyond current levels and improved coordination among theorists, experimentalists, and observers.

Slide from A. Steiner

# Simulation: X-ray Bursts

- **Past decade: XRB models used various approximations:**
  - 1D spherical
  - 2D shallow water
  - 2/3D atmospheric hydrostatic
  - Boosted flame speeds / rotation rates
- **Today: resolve flame structure + use realistic nuclear physics**
  - Current generation of supercomputers essential



- **Next decade:**
  - Full star models of flame spreading + lightcurves

Slide from M. Zingale

# Progress Since Last NSAC Town Hall

## White dwarf physics

| | Observational / Experimental Progress | Modeling Progress | Open Questions |
|---|---|---|---|
| Supernova Ia Progenitors | Discover of Hypervelocity WDs by Gaia & Iax ex-companion LP 40-365 indicate that at least some SN Ia have double degenerate progenitors | Considerable effort on Helium-ignited double detonations and mergers | $^{44}$Ti probes helium burning, can observations accommodate amount of He burning in models? |
| Convection and Detonation / Novae | Observations reveal ubiquitous Nova GeV Emission<br>Laboratory Detonation Initiation | Low-Mach Number He Shells<br>Pre-explosion mixing of CNO in novae. | How does binarity impact Novae?<br>Can Nova be SN Ia/x Progenitors? |
| Nucleosynthesis, Synthetic Spectra & Light Curves | Observational Constraints from SN 2011fe<br>Observe Gamma rays from SN 2014J | Comparison of spectra and light curve calculations to observations highlights the importance of non-LTE | What can we learn from Early Spectra, Bumps?<br>What can we learn from the presence of stable Ni in Nebular Phase |
| Supernova Remnants | Searches for ex-companions associtated with SNRcontinue to<br>3C 397: near-$M_{Ch}$ SNR | 3D Hydrodynamical Models<br>3C 397 | Det. Mech. 3C 397? |

Slide adapted from B. Fischer

# Landscape in the last decade

N3AS Network for Neutrinos, Nuclear Astrophysics, and Symmetries
PHYSICS FRONTIER CENTER
NSF

Physics Frontier Center

NP3M

NSF theory Hub

FRIB Theory Alliance

Reactions, structure aspects

SciDAC Scientific Discovery through Advanced Computing

Scidac TEAMS (ended)

FIRE

DOE topical collaboration (ended)

JINA-CEE

PFC, exp, obs, th. (ended)

# Conclusions

Nuclear astrophysics theory is looking at some exciting times: lots of data coming! e.g. EOS constraints, r-process site constraints

Integrated approach is essential: e.g. simulations, neutrino QKEs, application of DFT/MI and reaction theory

Needed: people, computing