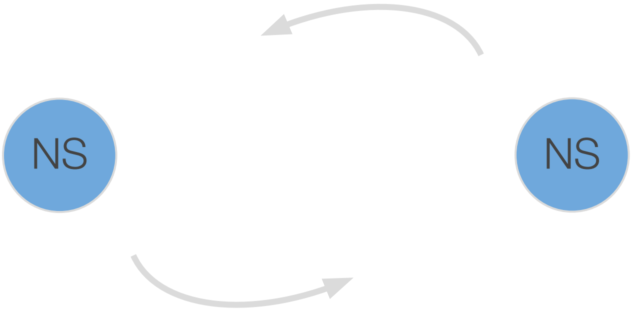
Electromagnetic Counterparts of Neutron Star Mergers: Signatures of Heavy r-Process Nucleosynthesis

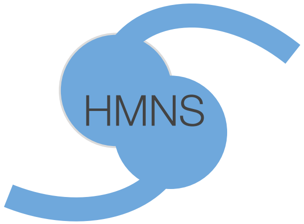
Andreas Flörs
GSI Darmstadt

European Research Council
Established by the European Commission

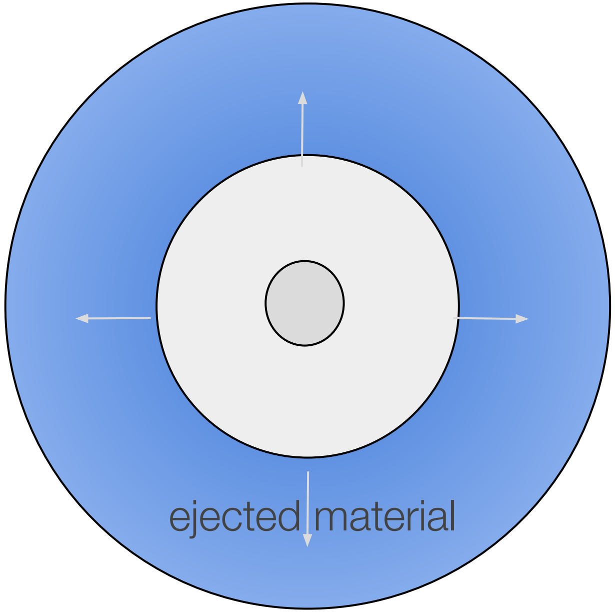
Signatures of Heavy r-Process Nucleosynthesis



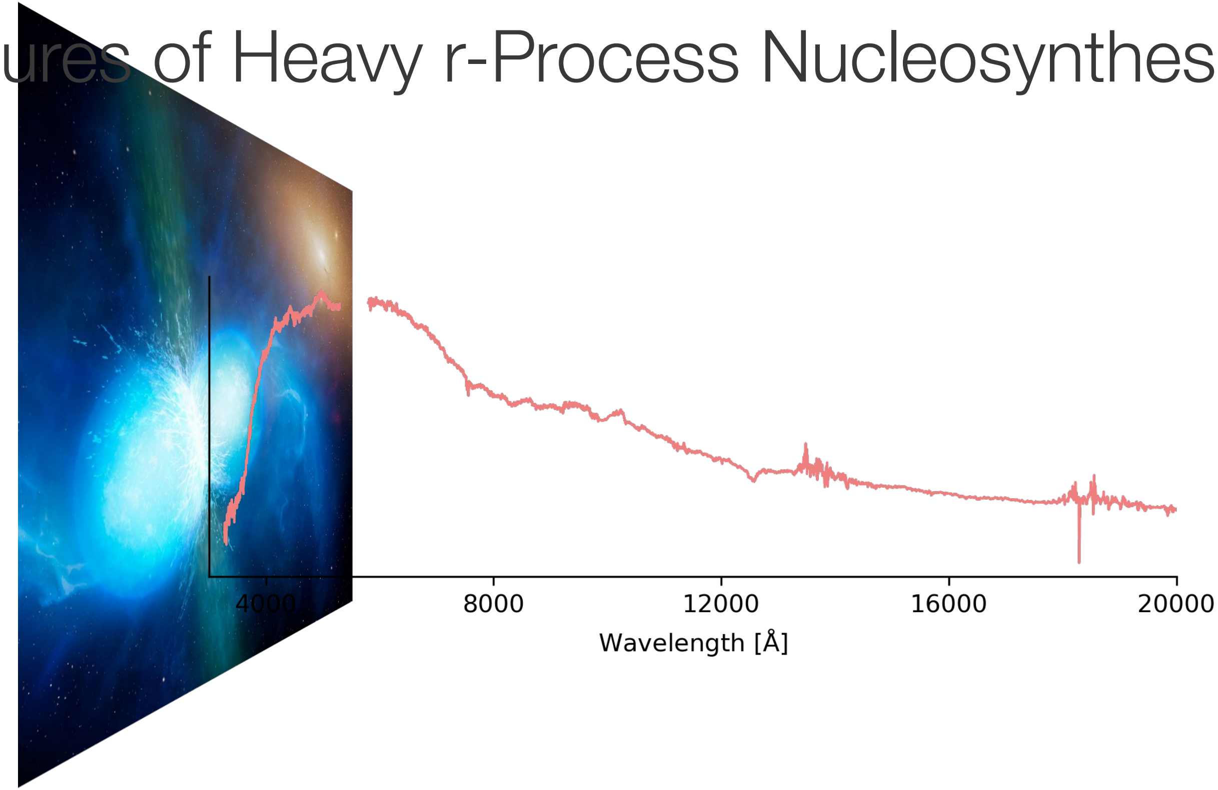
Signatures of Heavy r-Process Nucleosynthesis



Signatures of Heavy r-Process Nucleosynthesis

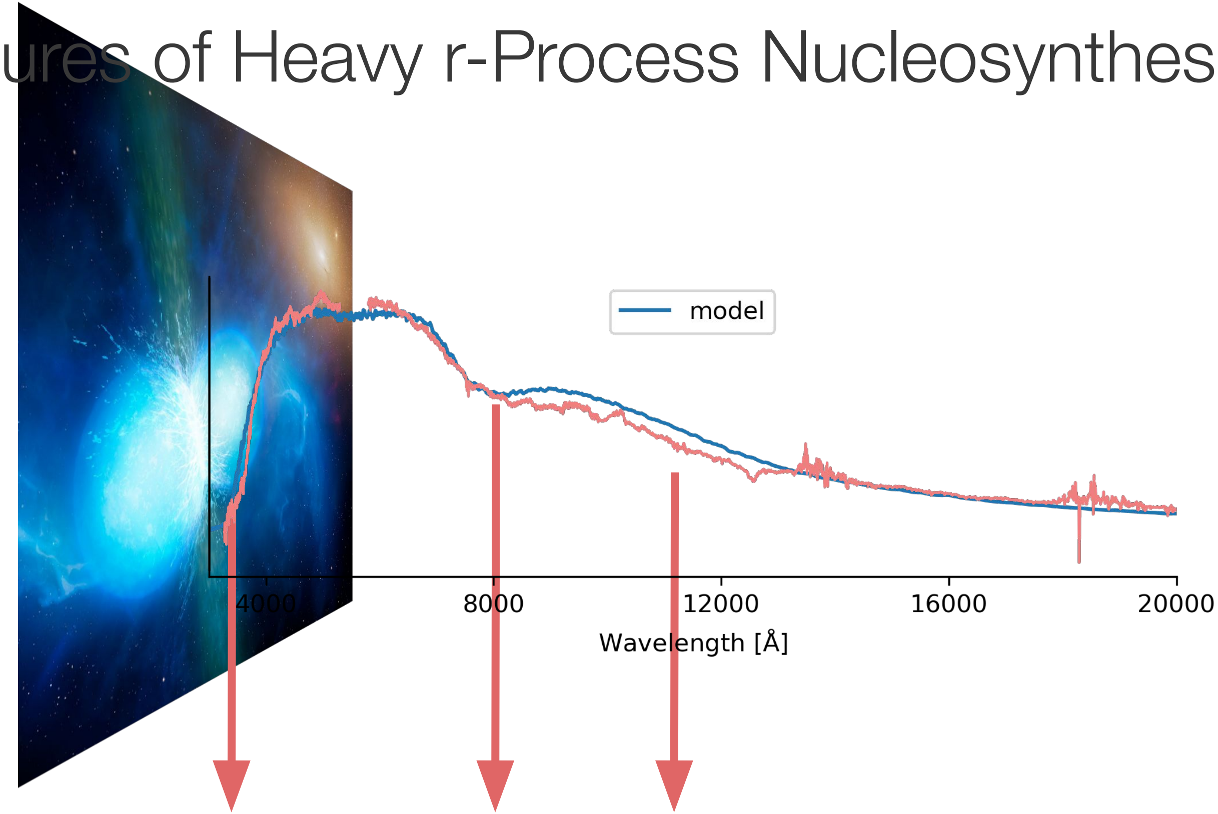


Signatures of Heavy r-Process Nucleosynthesis



ESO/VLT

Signatures of Heavy r-Process Nucleosynthesis



ESO/VLT

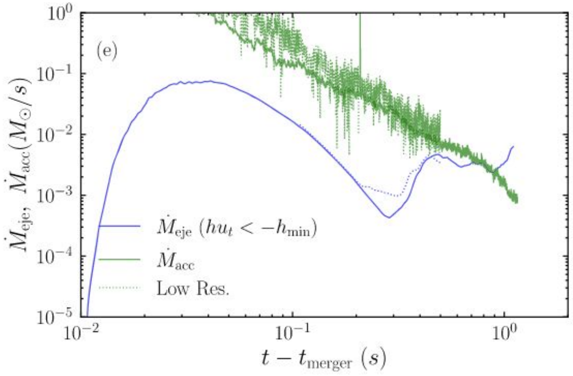
spectral signatures of r-process material?

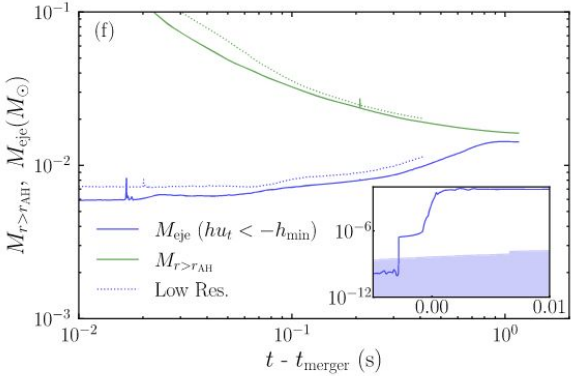
Requirements: Merger Models, Nucleosynthesis, **Atomic Opacities, Radiative Transfer**

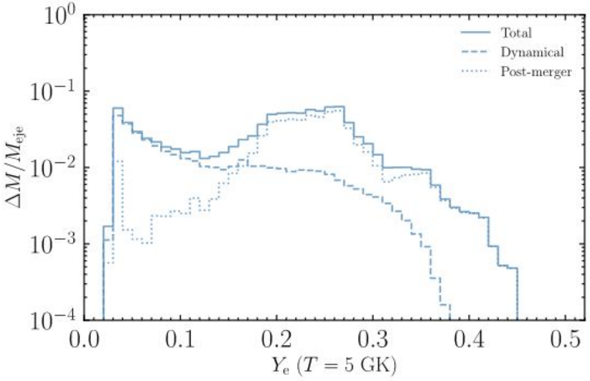
Long-duration merger simulations

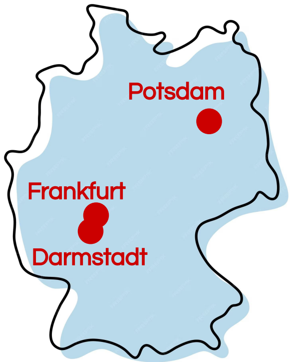
Kiuchi+2023

- Long duration merger models extremely important to obtain all ejecta components
- Homologous expansion?
- Timescale of dynamical ejecta ~few ms, for postmerger ejecta ~few s



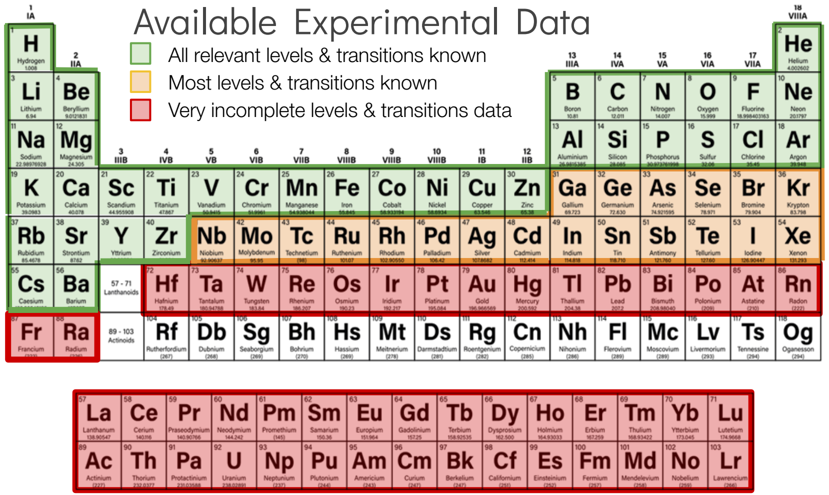


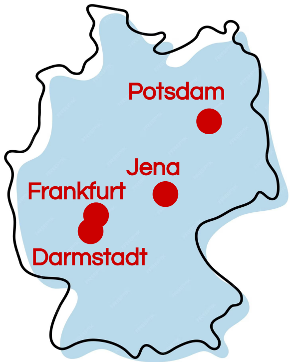




The atomic data landscape in 2022

- Only one complete atomic opacity database available (Tanaka+2019, Gaigalas+2020)
- Completeness over accuracy!
- NLTE atomic data for few species (Hotokezaka+2021)
- Several groups working on additional atomic opacity calculations: GSI, Jena

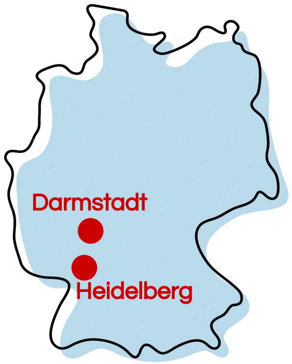




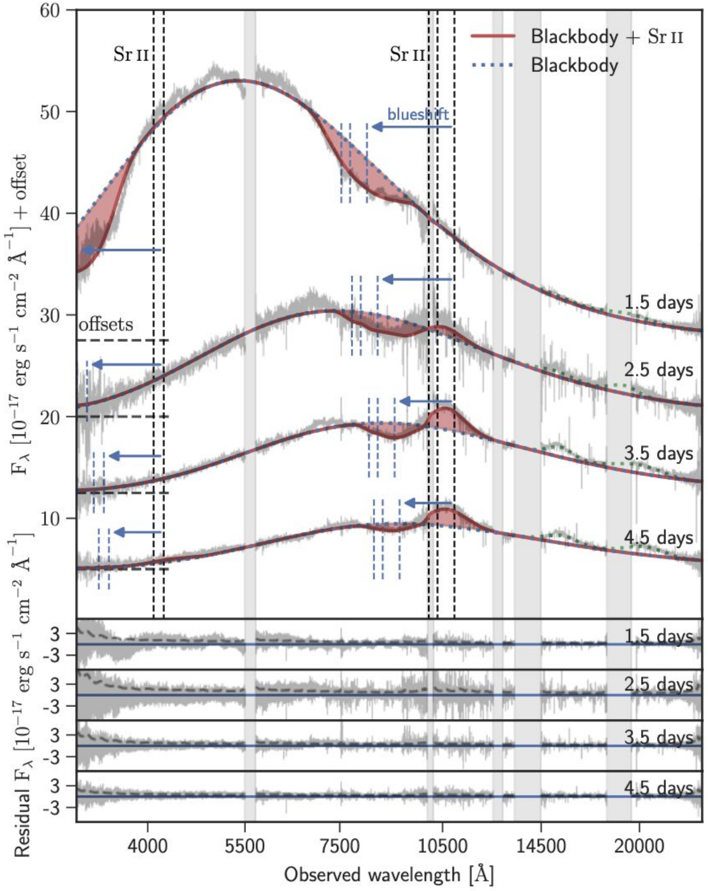
The State of the Field Two Years Ago

Radiative Transfer & Spectral Signatures

- ❑ Spectra are explained with blackbody emission
- ❑ Additional features visible at various KN epochs
- ❑ Identification of a single element - strontium (Watson+2019)
- ❑ Where are the heavy r-process elements?
- ❑ Incomplete atomic data



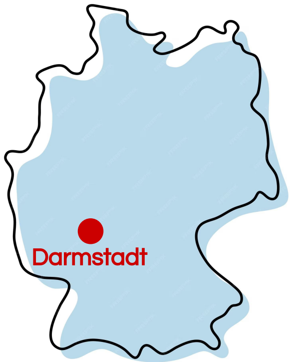
Watson+2019

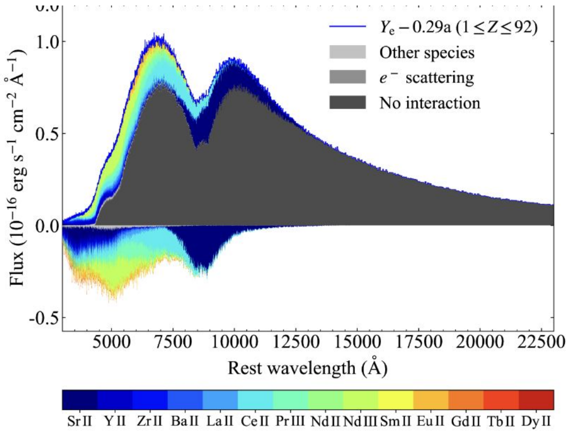


The State of the Field Two Years Ago

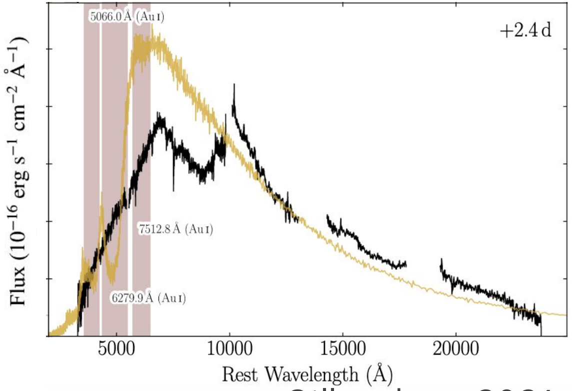
Radiative Transfer & Spectral Signatures

- ❑ Exploration of signatures of heavy elements: Pt, Au, Ba, Lanthanides
- ❑ Blackbody + few P-Cygni features places strong constraints on the presence of heavy r-process material
- ❑ But: Many simplifications and Approximations are used to derive these results!





Gillanders+2022

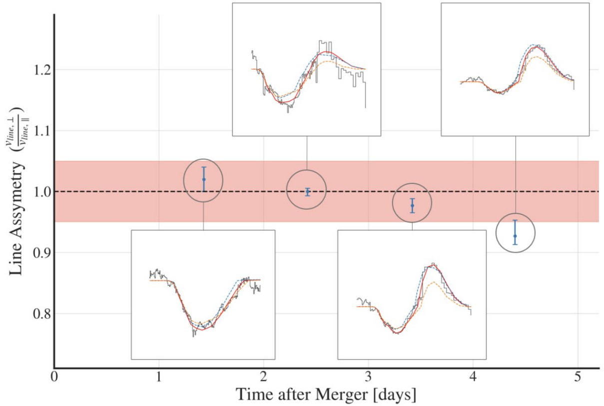


Gillanders+2021

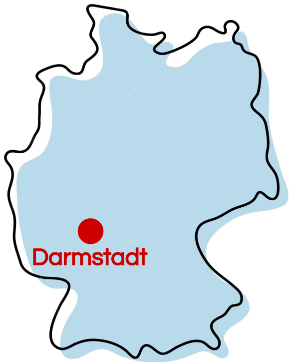
Kilonova Geometry

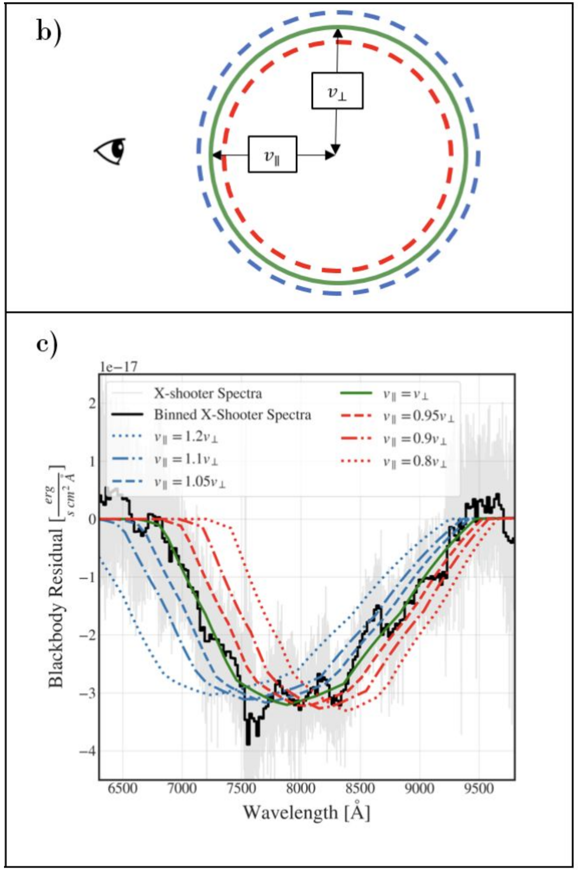
Sneppen+2023

A Spherical Kilonova?



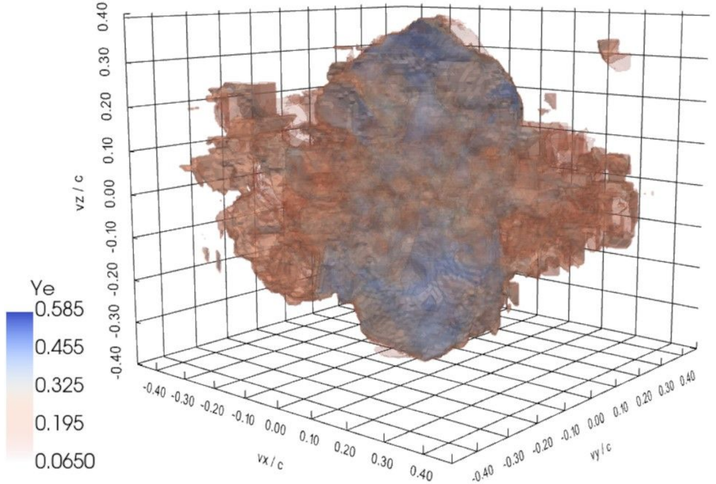
- ❑ Radial velocity from line position
- ❑ Tangential velocity from emitting area
- ❑ Both velocities agree extremely well
  → AT2017gfo was highly spherical
- ❑ Difficult for theory
  → merger geometry is axis-symmetric



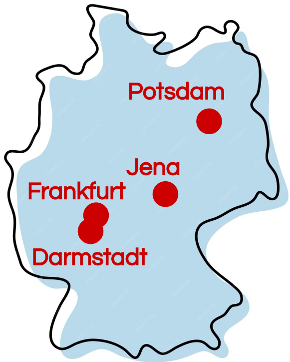


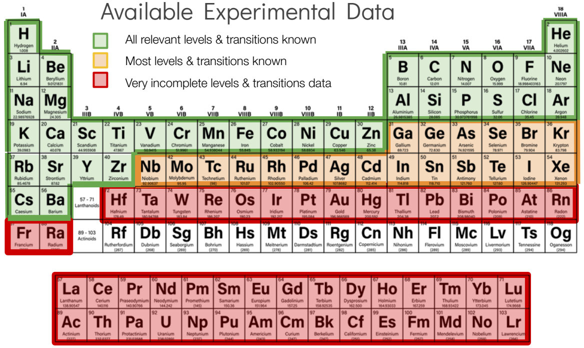
Ways to move forward

- ❑ Calibrated transition data for lanthanides
- ❑ Use merger models instead of analytical description
- ❑ Take decay energy deposition rate into account
- ❑ 2D/3D radiative transfer
- ❑ Line-by-line opacity



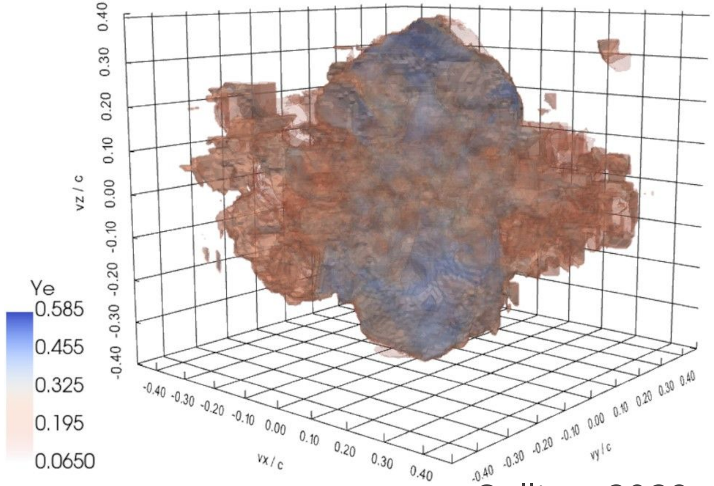
Collins+2023



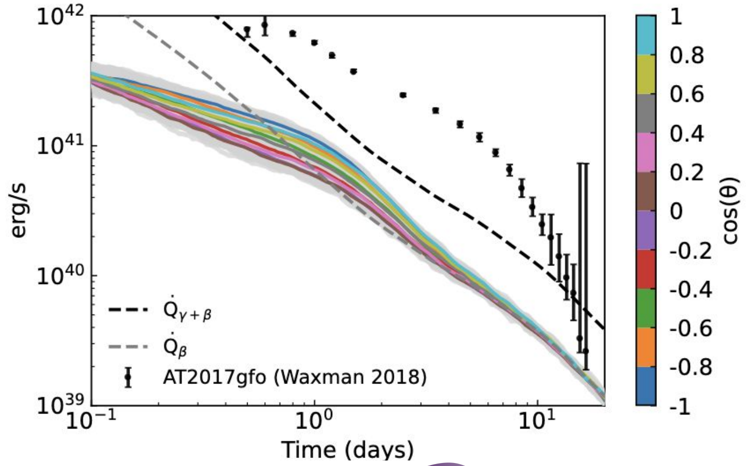


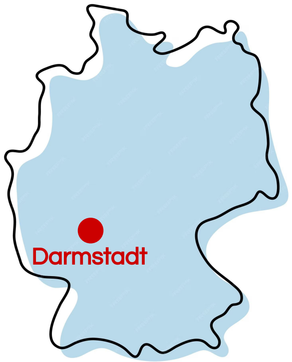
3D Radiative Transfer: Light Curves

- ❑ Neutron Star Mergers are a 3D phenomenon!
- ❑ But why do 1D models yield such good fits?
- ❑ Collins+2023: First 3D radiative transfer simulation from hydrodynamical merger model
- ❑ Still uses wavelength independent opacities
- ❑ merger simulations → nuclear network calculation → 3D radiative transfer
- ❑ Consistent connection between theory and observations: Ejected mass, velocity structure, r-process pattern



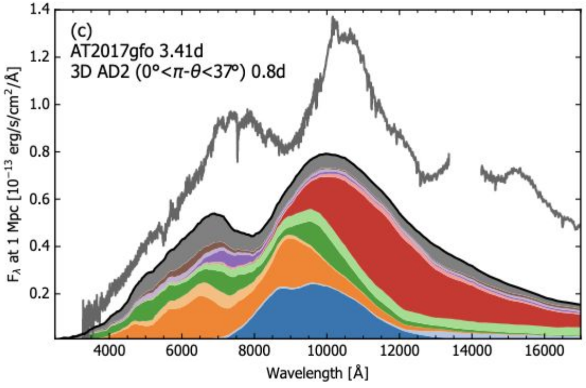
Collins+2023



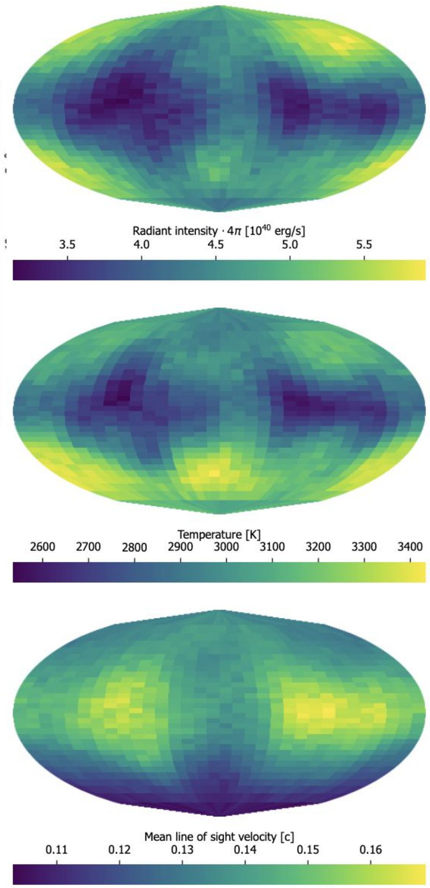


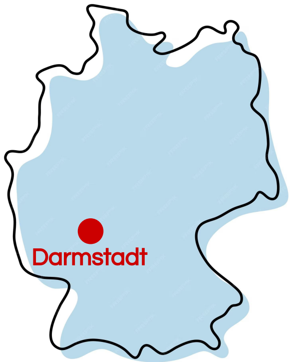
3D Radiative Transfer: Spectra

- Most self-consistent radiative transfer simulation
- Includes time-dependence, hydrodynamical merger model, nuclear decay network, 3D RT, detailed thermalisation treatment, line-by-line opacity
- Contribution of Sr, Zr, Y, Ce as inferred from 1D, but probably not the full picture
- Spectra extremely different between spherically averaged 1D and full 3D models



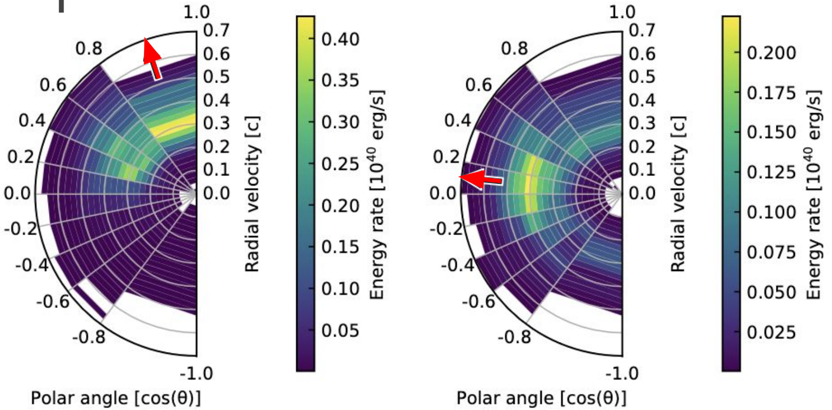
Shingles+2023



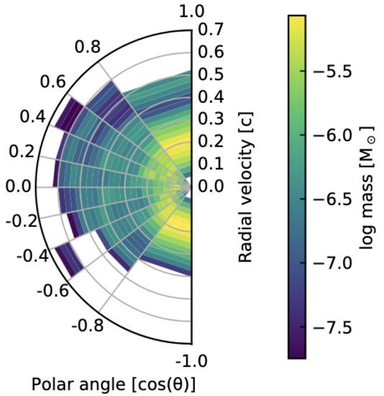


3D Radiative Transfer: A Not-So-Spherical Kilonova?

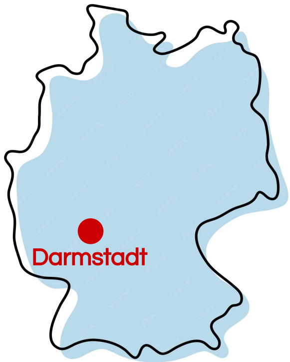
- 1D models of observed spectra indicate high degree of sphericity
- Difficult to verify method using observed spectra
- Use 3D spectra from Shingles+2023, apply method from Sneppen+2023
- Radiation observed in any line of sight is emitted from a broad region
  → decreases anisotropies
  → apparent sphericity
- Sphericity of radiation ≠ sphericity of ejecta



Collins+2023

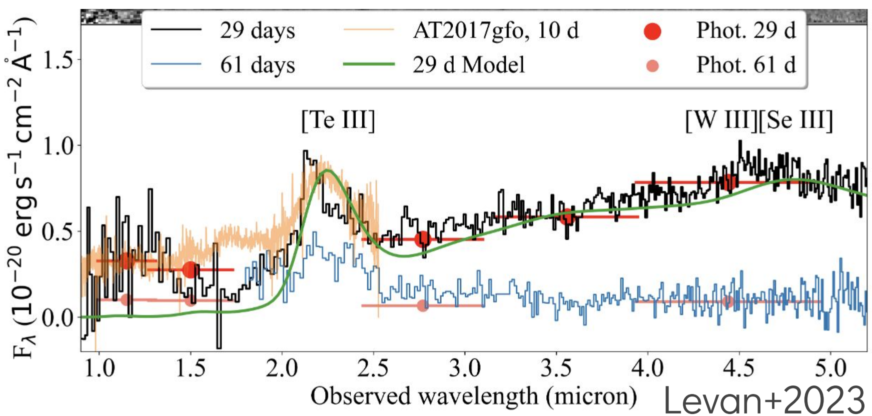


(b) Sr mass



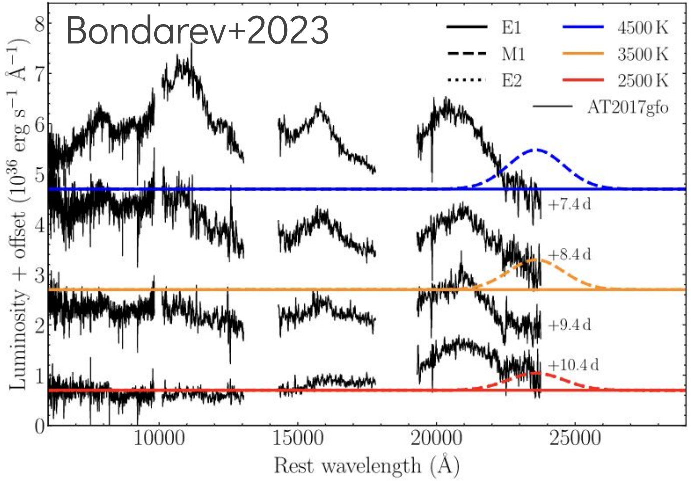
R-Process Atomic Structure

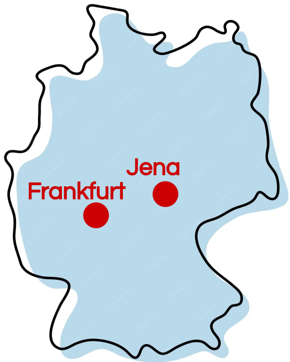
- The first observed kilonova with JWST!
- Nebular spectroscopy: extremely low density (10^6 cm^{-3}), low velocity
  → easier identification of features
- Mid-IR forbidden transitions
  → requires accurate data, not experimentally accessible
- New window for r-process nucleosynthe fingerprints



Levan+2023

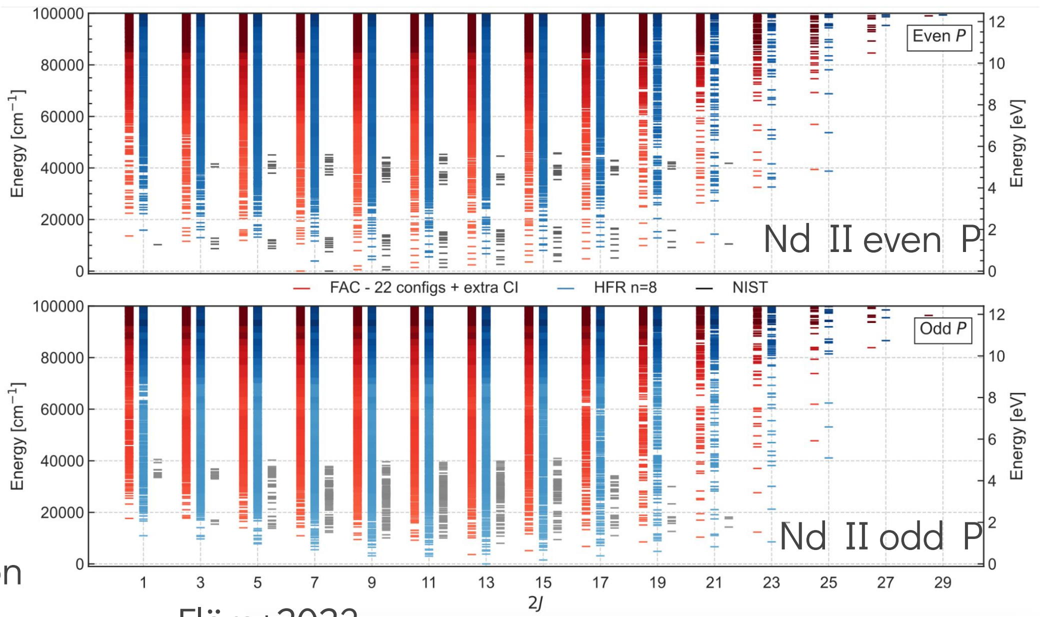
also Hotokezaka+2023



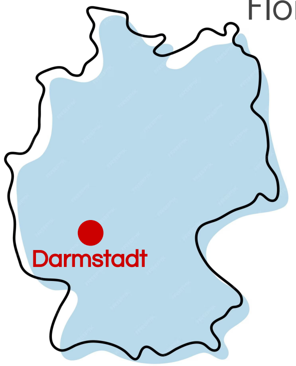


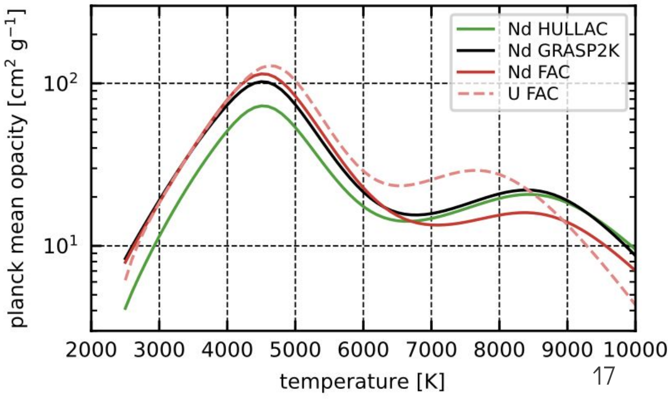
R-Process Atomic Structure

- Radiative transfer heavily relies on high-quality atomic data
- Atomic data for lanthanide sparse, for actinides not available
- We need complete ***and*** accurate data!
- Nd & U as test cases: importance of obtaining all relevant transitions & calibration to experimental data
- Computationally feasible to repeat for all lanthanides!



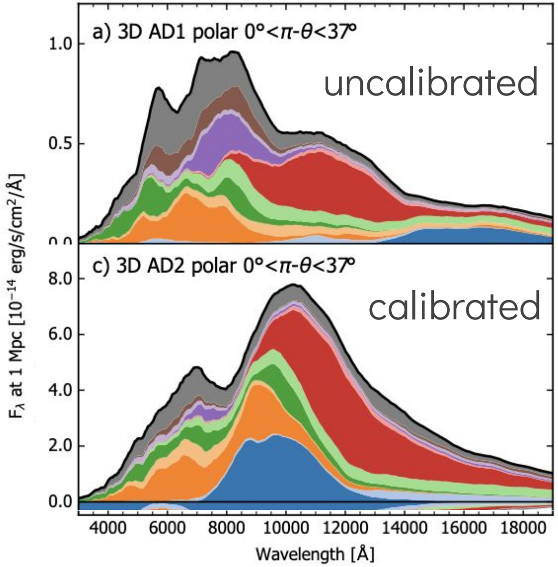
Flörs+2023



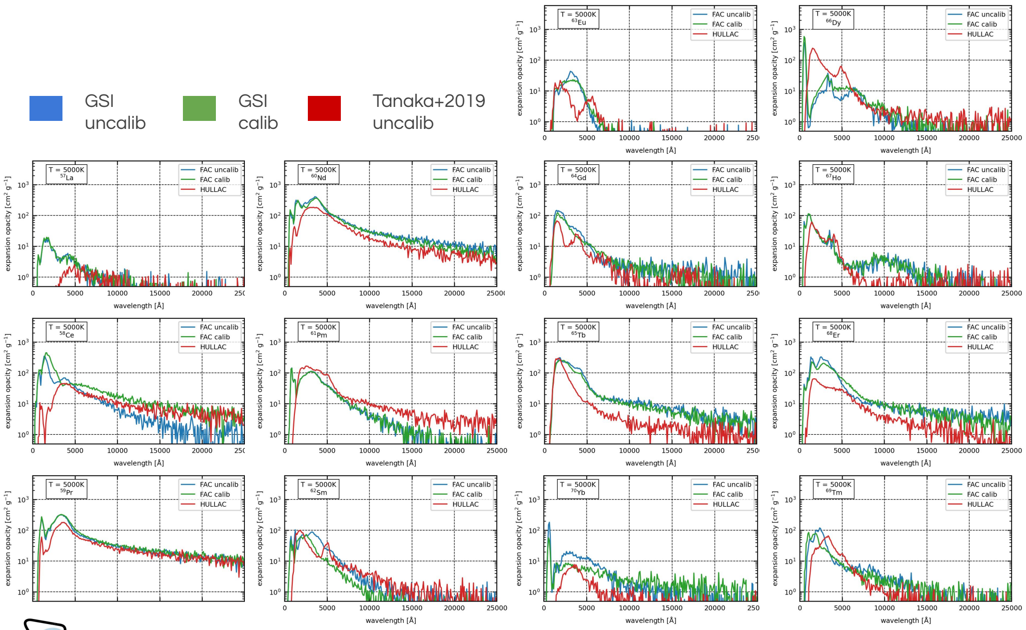


R-Process Atomic Structure

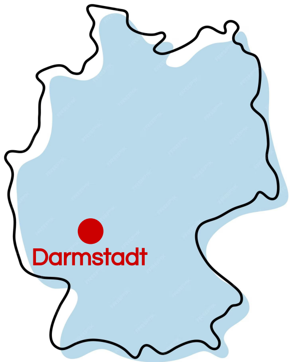
- All lanthanides are important for accurate radiative transfer modeling
- Inaccurate data from few ions can affect the radiative transfer solution as a whole



GSI uncalib | GSI calib | Tanaka+2019 uncalib



Flörs+ in prep



- Data will be made available after publication (Zenodo)

R-Process Atomic Structur

- Accuracy benchmark: La III infrared transitions
- Currently available dataset: wavelengths inaccurate, 500nm vs 1500nm
- GSI calibrated atomic data: test case accuracy ~20%

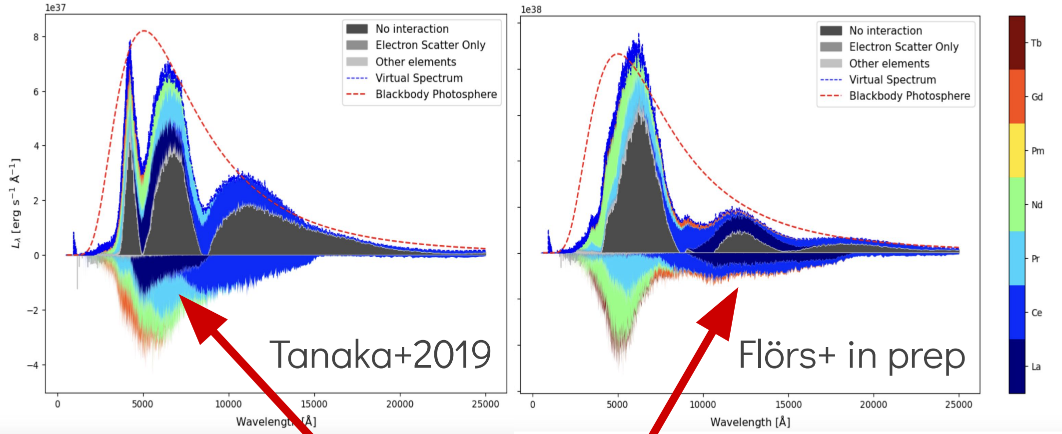


Table 3. Summary of calibrated lines for La III. We list only lines that adopt theoretical gf-values with $\lambda > 7000$ Å and $\log gf > -3$.

	$\lambda_{\rm vac}$[a] (Å)	$\lambda_{\rm air}$[b] (Å)	Lower level	$E_{\rm lower}$[c] (cm^{-1})	Upper level	$E_{\rm upper}$[d] (cm^{-1})	log gf[e]
La III	13898.270	13894.471	$5d\ ^2D_{3/2}$	0.00	$4f\ ^2F^o_{5/2}$	7195.14	−0.749
	14100.037	14096.183	$5d\ ^2D_{5/2}$	1603.23	$4f\ ^2F^o_{7/2}$	8695.41	−0.587
	17882.977	17878.094	$5d\ ^2D_{5/2}$	1603.23	$4f\ ^2F^o_{5/2}$	7195.14	−1.938

Outlook

- Many improvements in the last year!
- (Hopefully) many more mergers with LIGO/VIRGO
- Complete modeling pipeline:

  Merger models → r-process → radiative transfer
- Explore the merger landscape – diverse group
- NLTE radiative transfer

  → challenging but rewarding
- Actinide atomic data
- NLTE atomic data (collisional excitation, photoionisation, recombination)