Kilonova Spectra in the NLTE Regime

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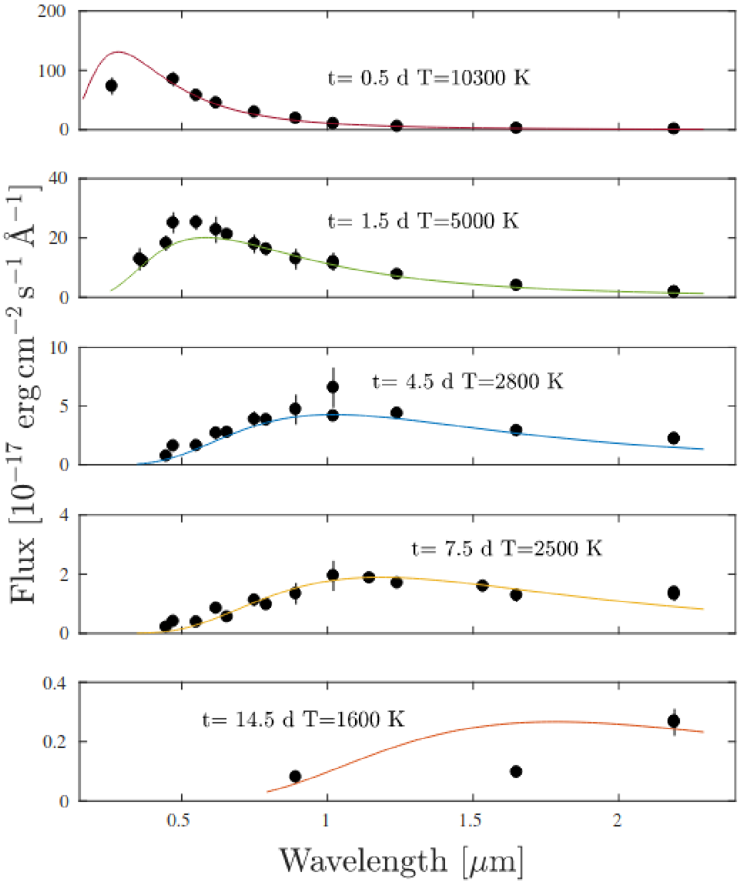
The Kilonova: LTE to NLTE

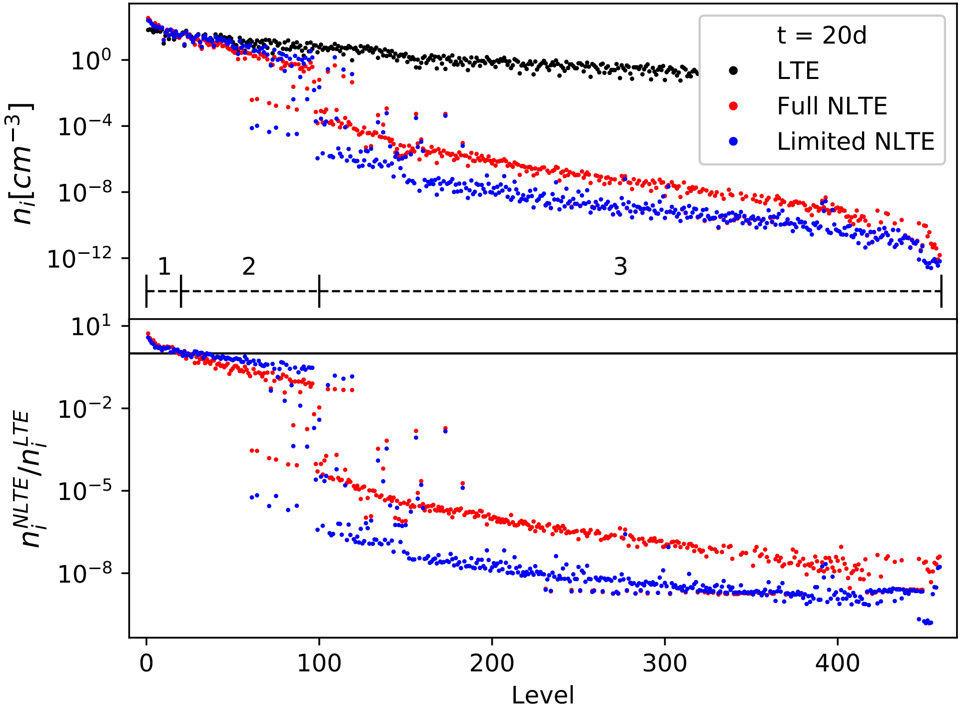
- Initially, the ejecta are extremely hot and dense
  - Ejecta are in local thermodynamic equilibrium (LTE) conditions
- Emission is thermal, and optical depth is high
- Rapidly move to NLTE regime as ejecta expand



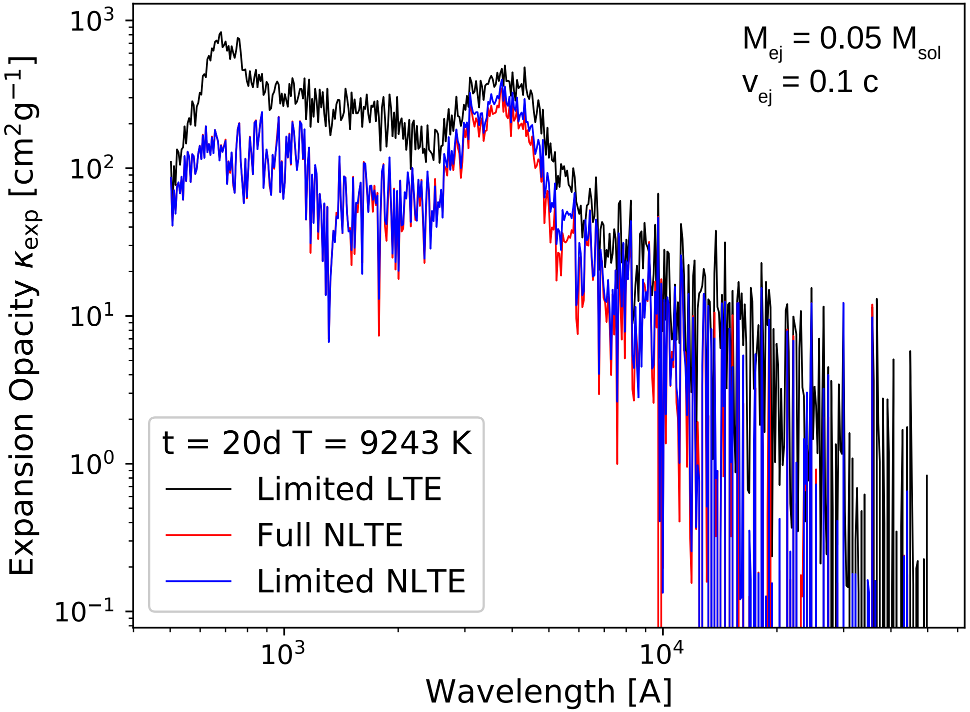
Source: Waxman et al. 2018

LTE vs NLTE: Visualisation

Excitation: Boltzmann vs rate equations



Effect on Expansion Opacity



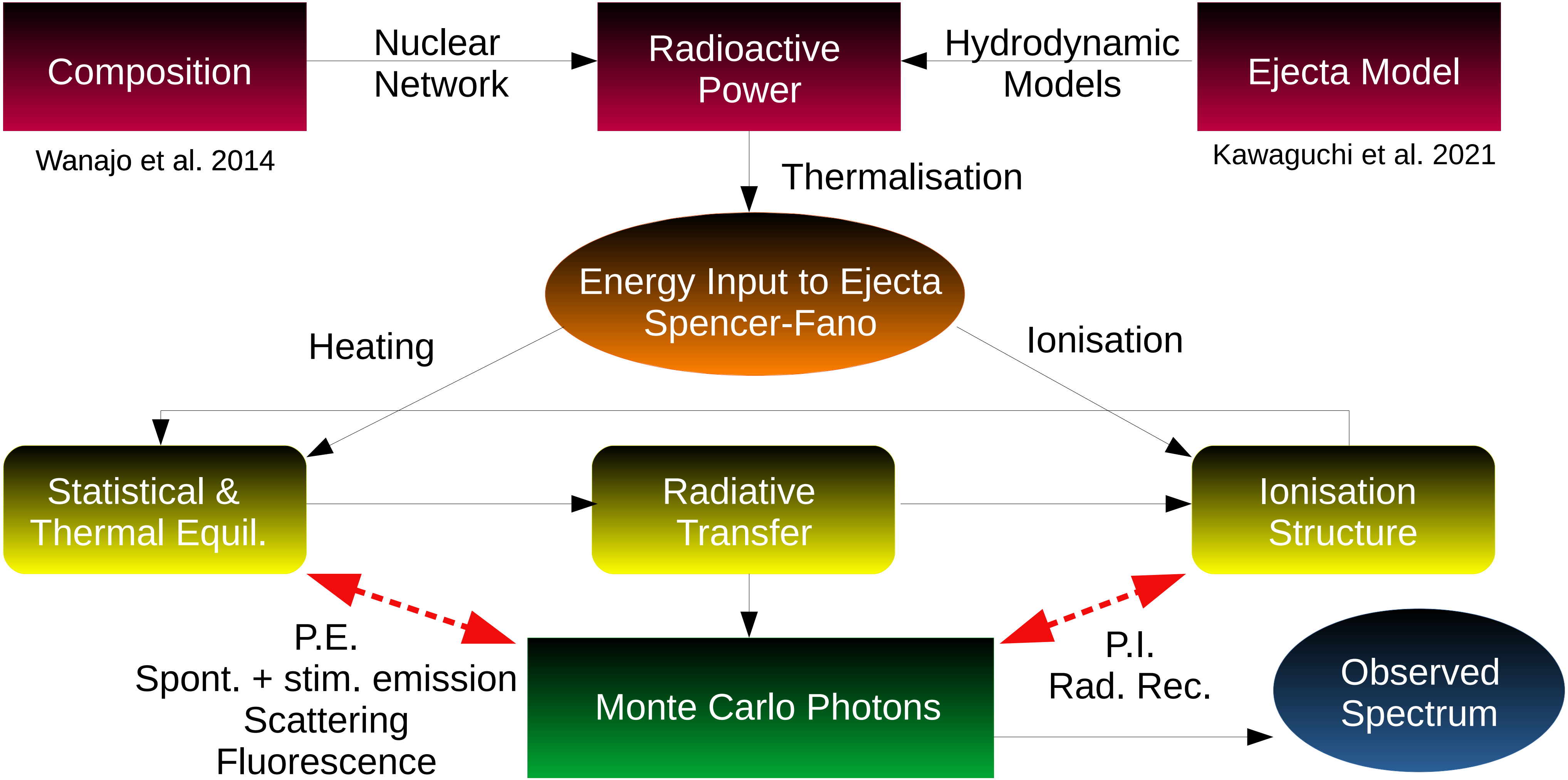
- Temperature: increasing in NLTE (e.g. Hotokezaka+ 2021, Pognan+ 2022a)
- Ionisation structure: Saha favours 1 or 2 ions, NLTE structure more complex

KN Modelling with SUMO (SUpernova MOnte Carlo Code)

Jerkstrand 2011,
Jerkstrand et al. 2012

- 1D NLTE Monte Carlo spectral synthesis code
- Theoretical r-process atomic data (levels and lines*) for Cu - U up to triply ionised from FAC (Jon Grumer, Uppsala University)
  - Including M1 and E2 lines -> found to affect temperature solution
  - Sr II levels calibrated to NIST, Y I first 8 levels only
- Line by line radiative transfer -> full fluorescence and resonance scattering modelled
- Want to produce spectra with detailed physics in the NLTE regime, 5 – 20 days

*Details of atomic data for cross-sections, rates in supplementary slides ;)



Composition

Nuclear
Network

Radioactive
Power

Hydrodynamic
Models

Ejecta Model

Wanajo et al. 2014

Kawaguchi et al. 2021

Thermalisation

Energy Input to Ejecta
Spencer-Fano

Heating

Ionisation

Statistical &
Thermal Equil.

Radiative
Transfer

Ionisation
Structure

P.E.
Spont. + stim. emission
Scattering
Fluorescence

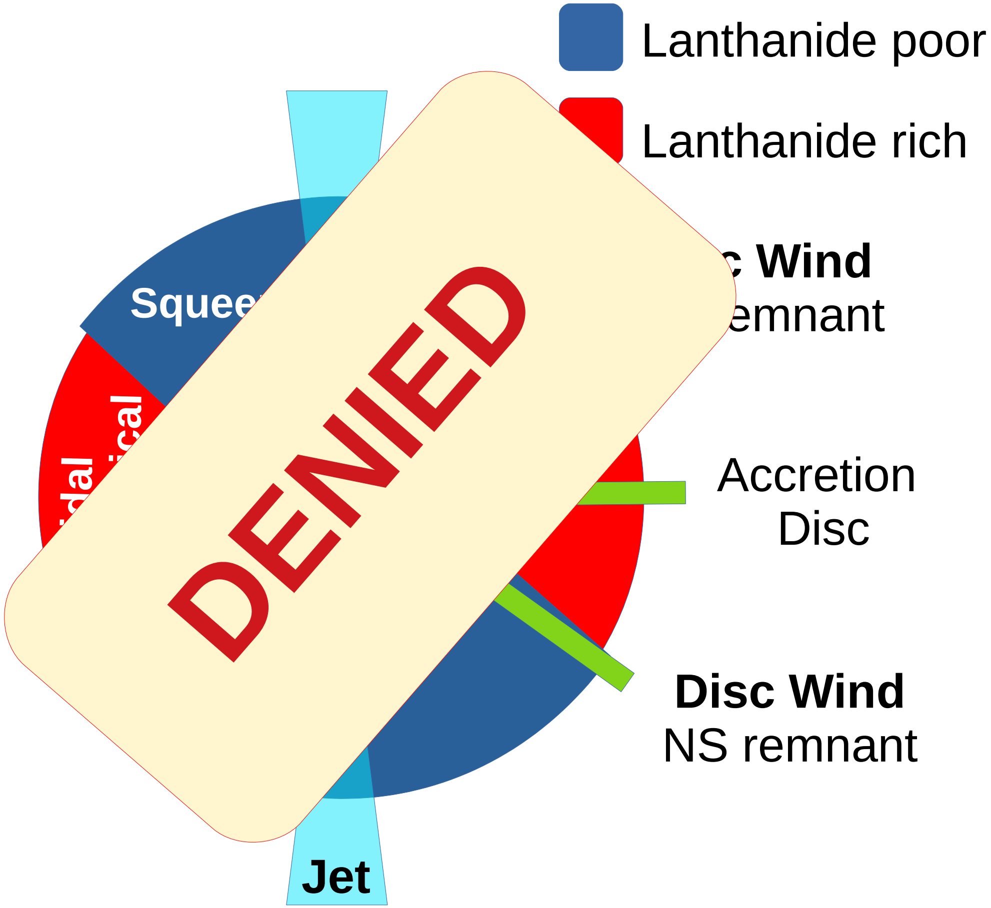
Monte Carlo Photons

P.I.
Rad. Rec.

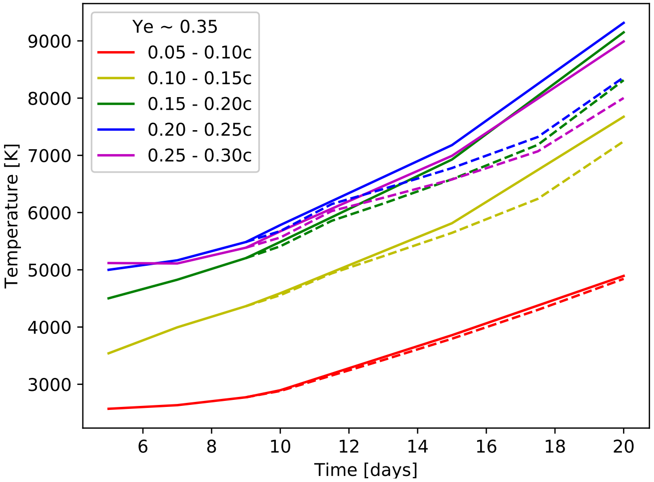
Observed
Spectrum

Ejecta Models

- Density profile ~ r^{-4}
  - Based on hydro models of Kawaguchi+ 2021
- Total ejecta mass: 0.05 M_{sol}
- Ejecta velocity: 0.05 - 0.3 c
- Homologously expanding, from 5 to 20 days after merger
- Homogeneous compositions and decay power for Y_e ~ 0.35, 0.25, 0.15
  - From the calculations of Wanajo+ 2014



Results: Thermodynamics



High Ye, low power

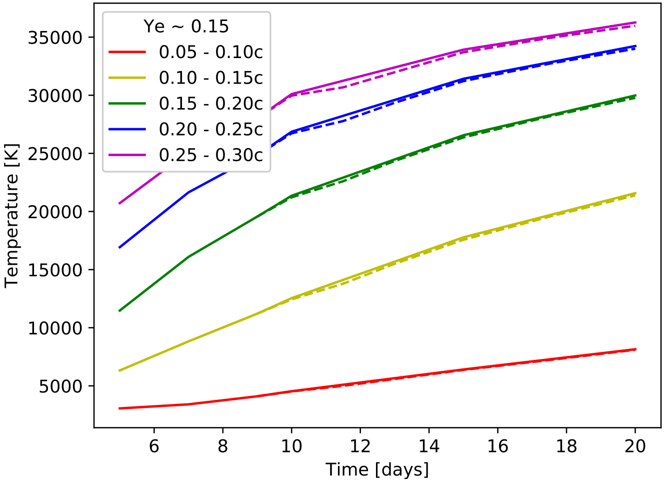
$X_e \sim 0.7 – 1.8$

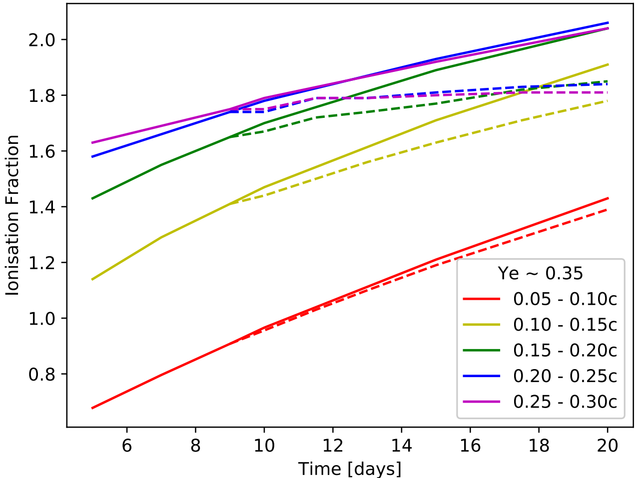
More ionised

Hotter

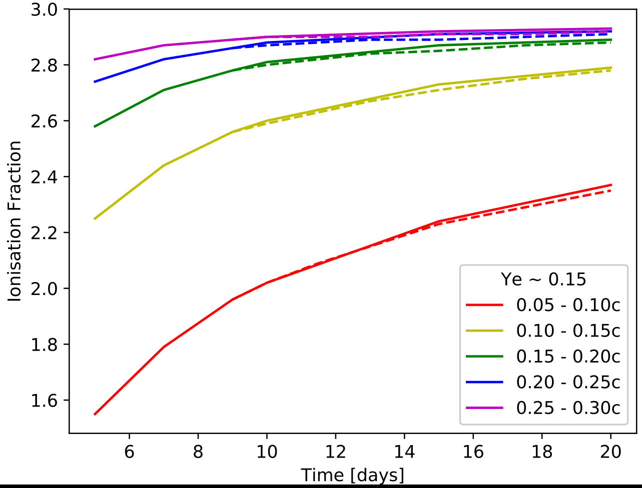
Low Ye, high power

$X_e \sim 1.5 – 2.9$



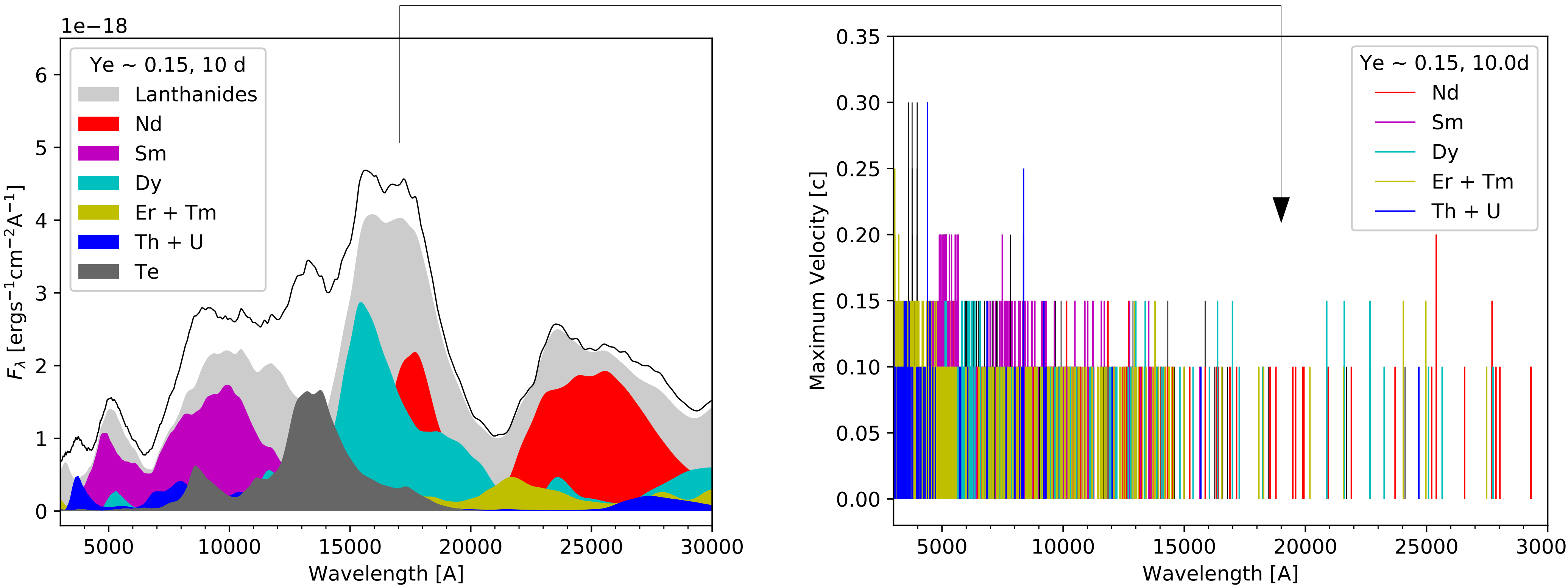


All ionisation stages from neutral to triply ionised play a role



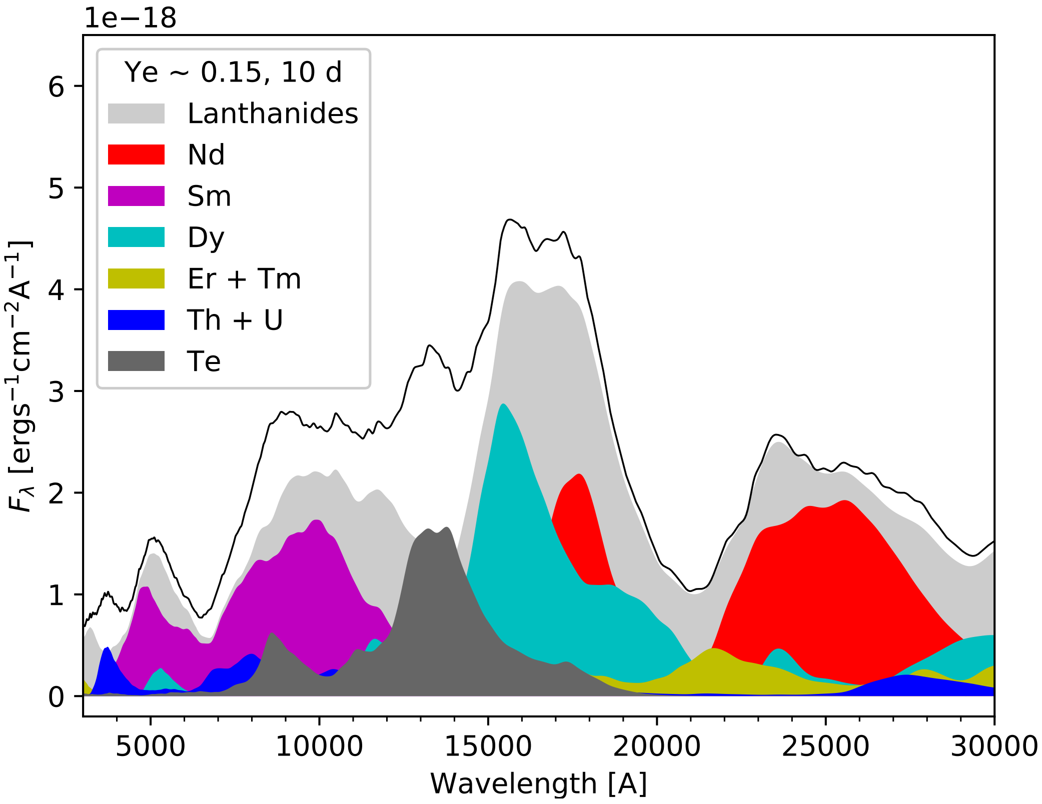
$Y_e \sim 0.15$: Lanthanide Party

Partial escape window

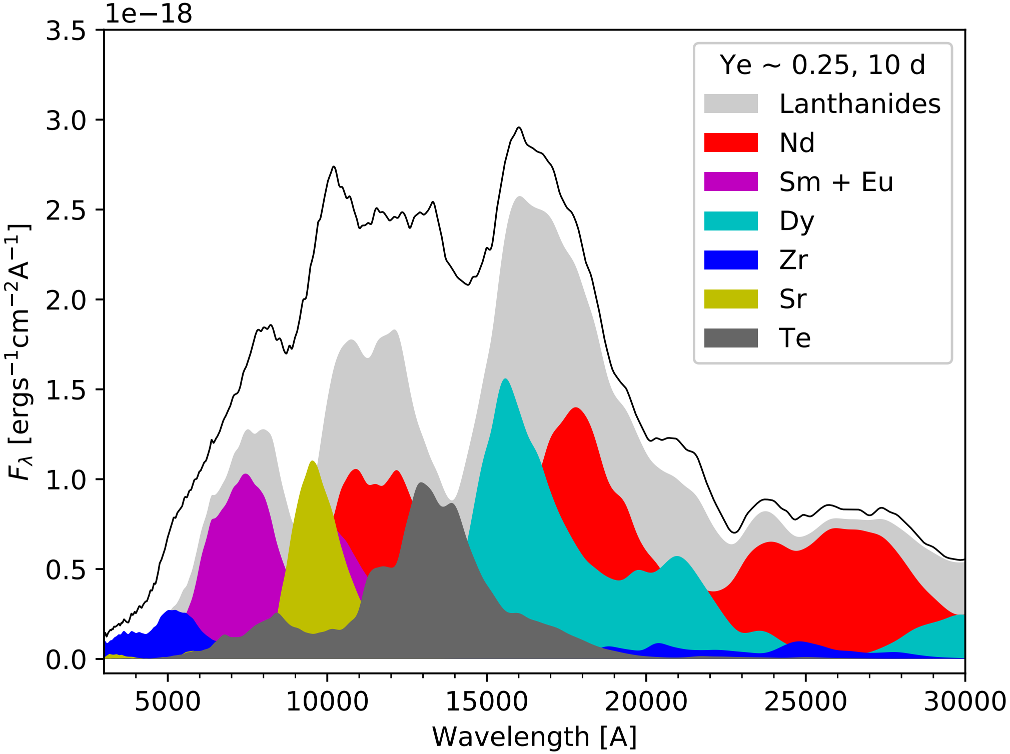


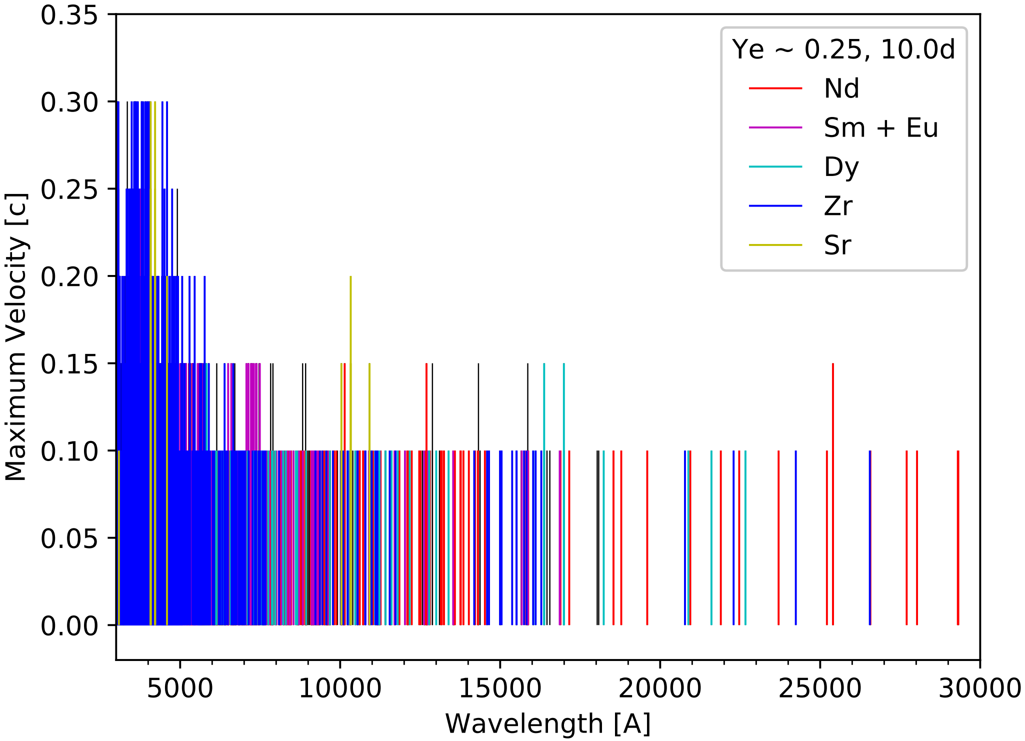
Te III: where is the 2.1 micron line?

- Some Te emission, but believed to be inaccurate
- Te III 2.1 micron line exists in our data at 2.2 micron, with A-value accurate
  - But collision strength from Axelrod 1980 ~ 0.01, vs measurement of ~5!
  - Reduced emissivity: 10^{38} erg s^{-1} vs 10^{39} erg s^{-1}
- E1 absorption lines present around 2.2 micron can absorb
- 10d -> densities still too high for forbidden emission lines?

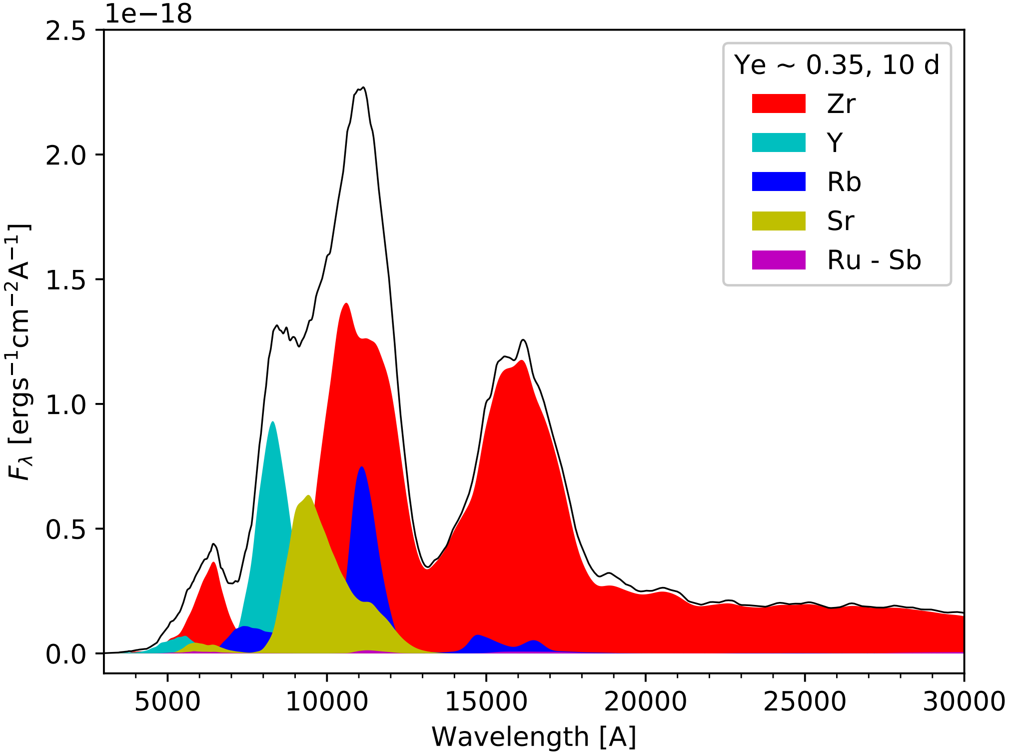


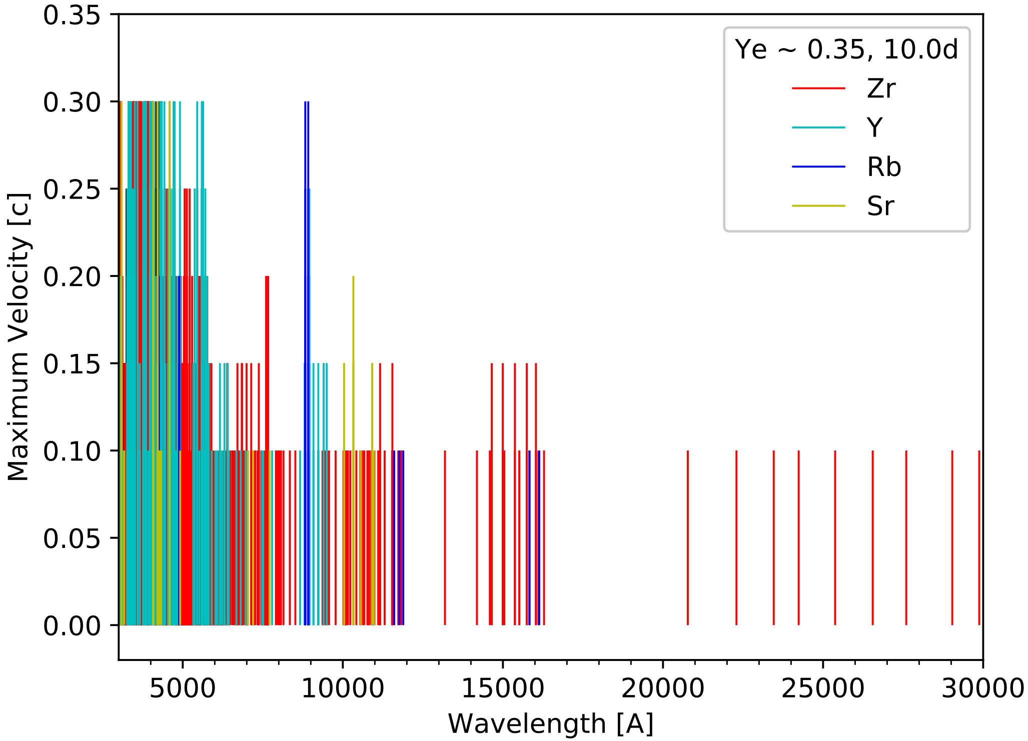
$Y_e \sim 0.25$: The Middle Ground





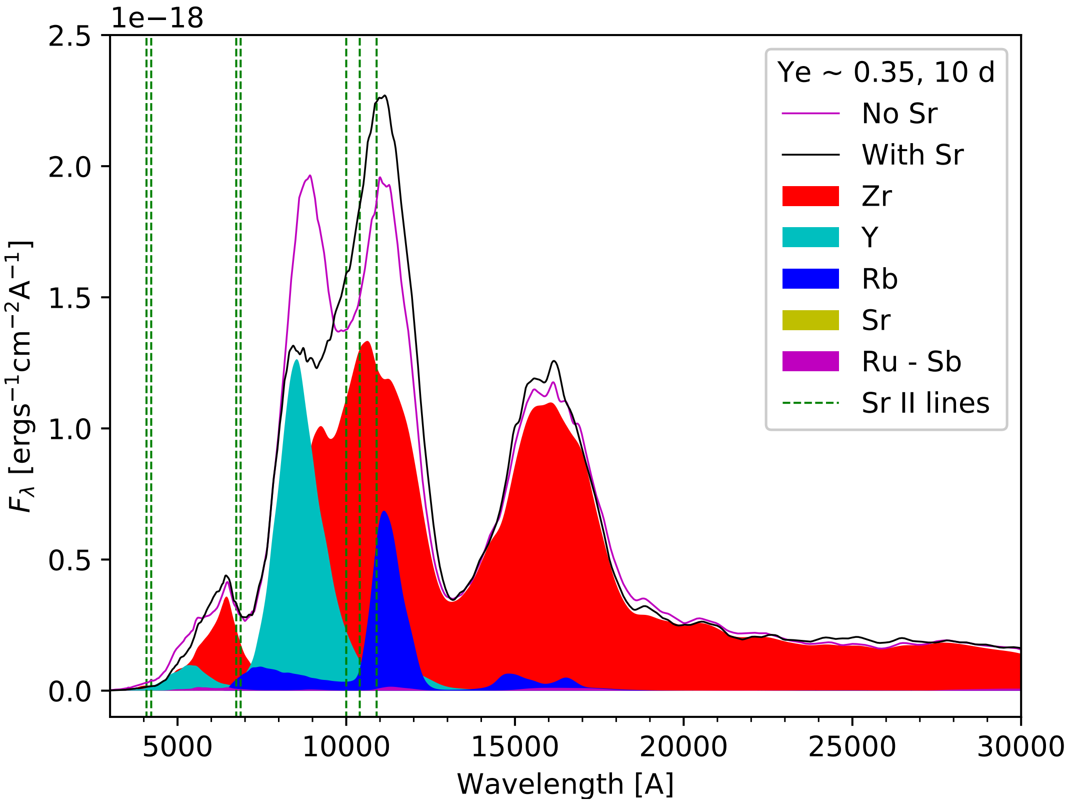
$Y_e \sim 0.35$: The First Peak





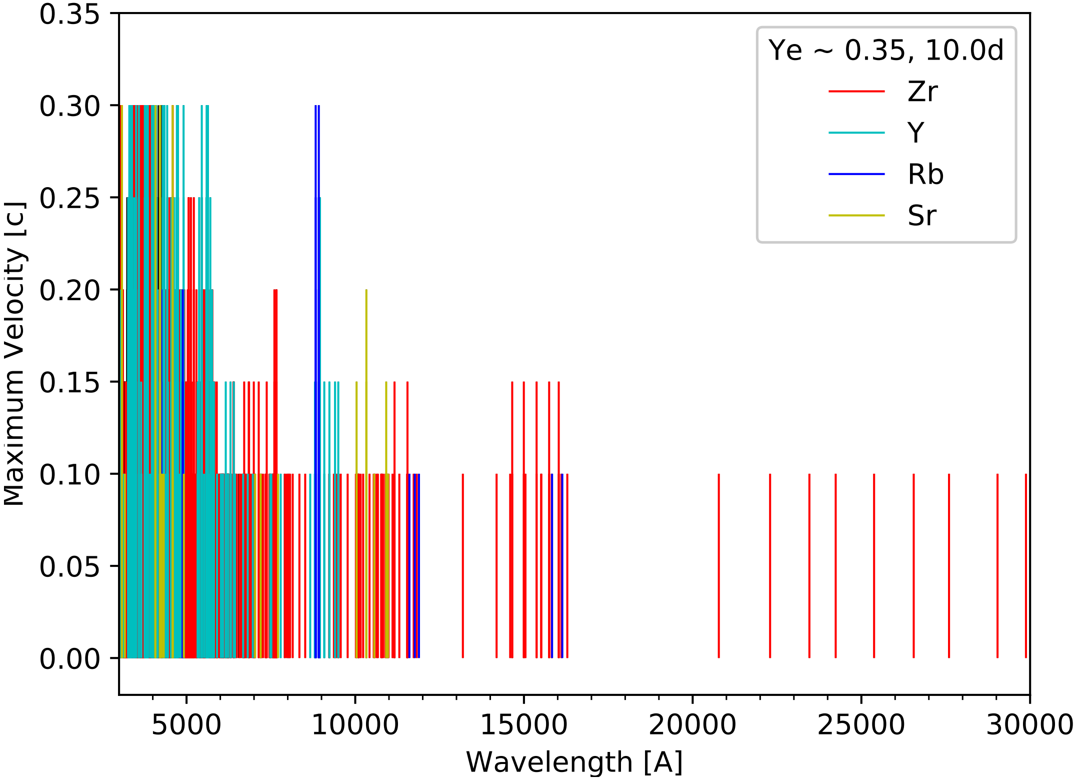
Y_e ~ 0.35: Role of Sr II

- Sr II 1 micron triplet has large impact on spectrum
- Also minor effects on thermodynamic state of ejecta
  - Sr II 4000 angstrom doublet a key cooling transition



Y_e ~ 0.35: Diagnosis of Sr II

- Sr II 1 micron triplet not only thick lines in area
- We see ~1 micron emission without Sr in the model (or He)
- Sr II P-Cygni at 1 micron likely, but are there other contributors?



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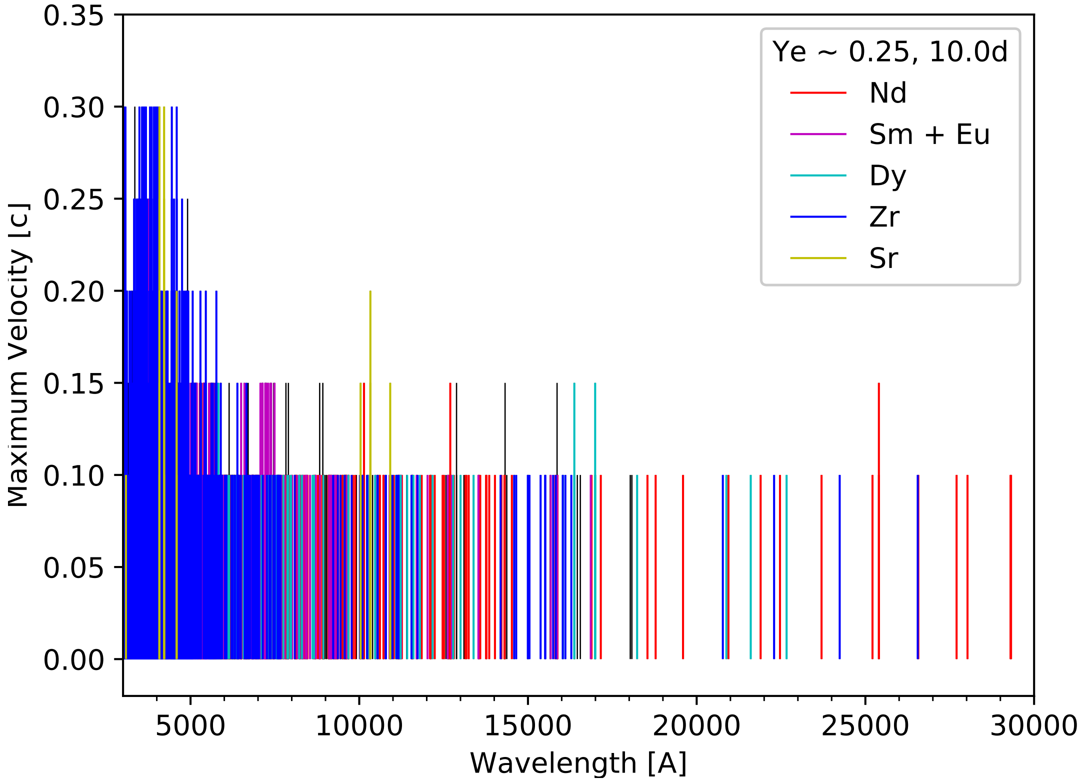
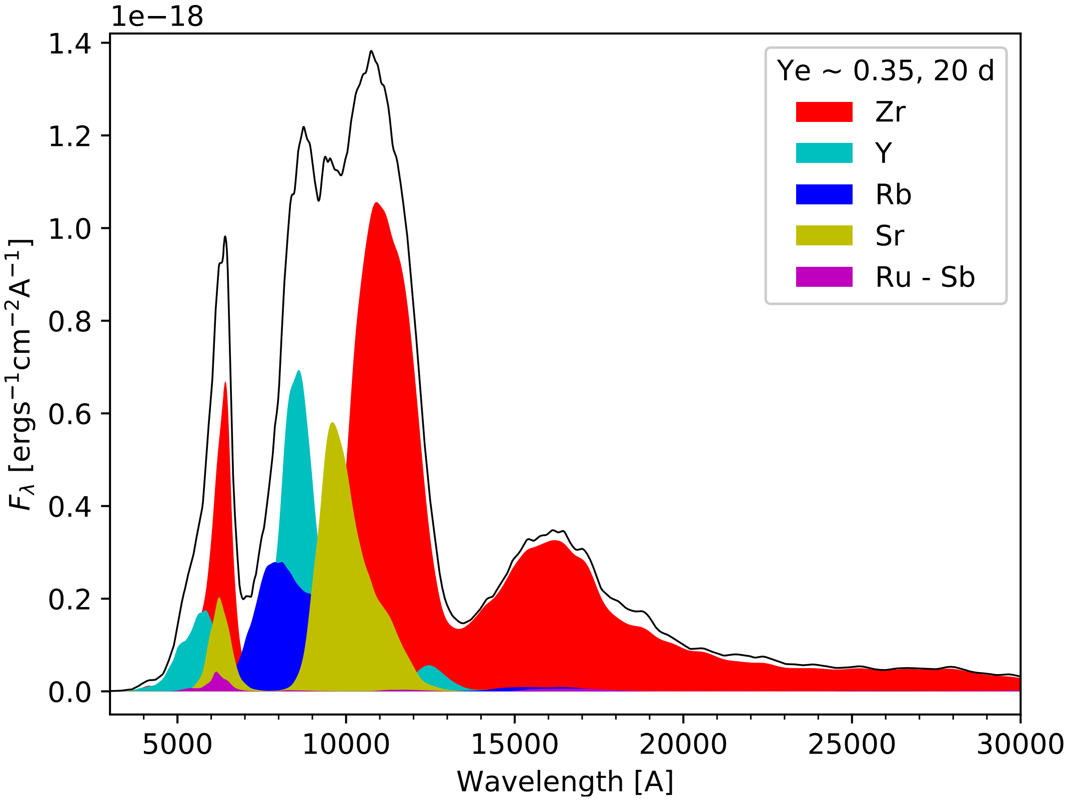


Y_e ~ 0.35: Rb I doublet n=2,3 -> 1

- Rb I doublet at 8900 angstrom (7900 real wavelength)
  - Optically thick up to 0.3c even up to 20 days
- Produce partial P-Cygni like feature
  - Alternative candidate for ~7600 angstrom P-Cygni in At2017gfo?



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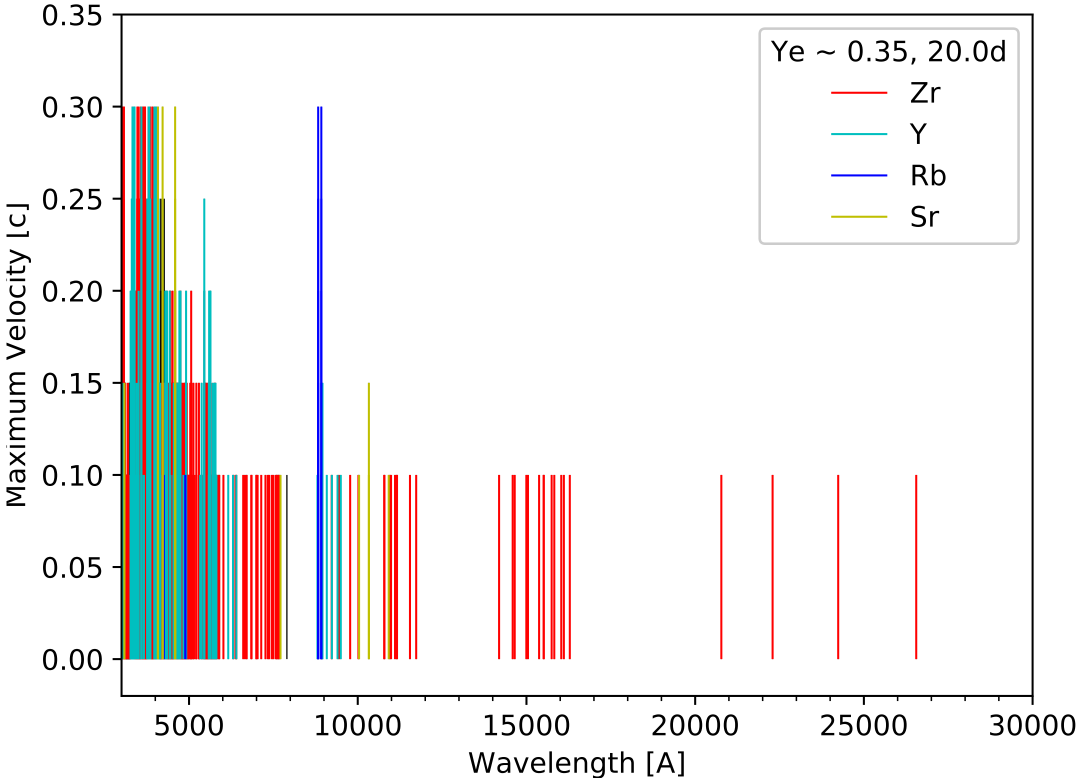
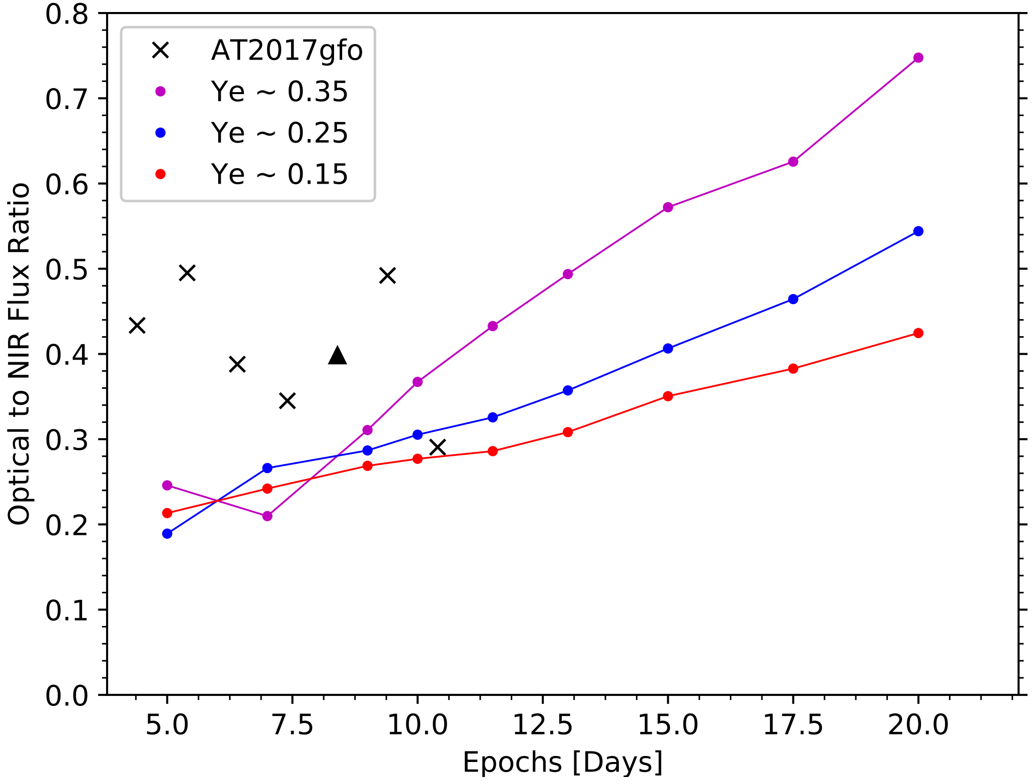


Evolution: Optical to NIR flux

- Adjacent colour bands (e.g. *r-i*, *i-z* ...) affected by change of individual features
  - Find relatively flat colour evolution
  - Gauge broader ‘colour’ evolution by flux ratios
- Models get *bluer* with time?

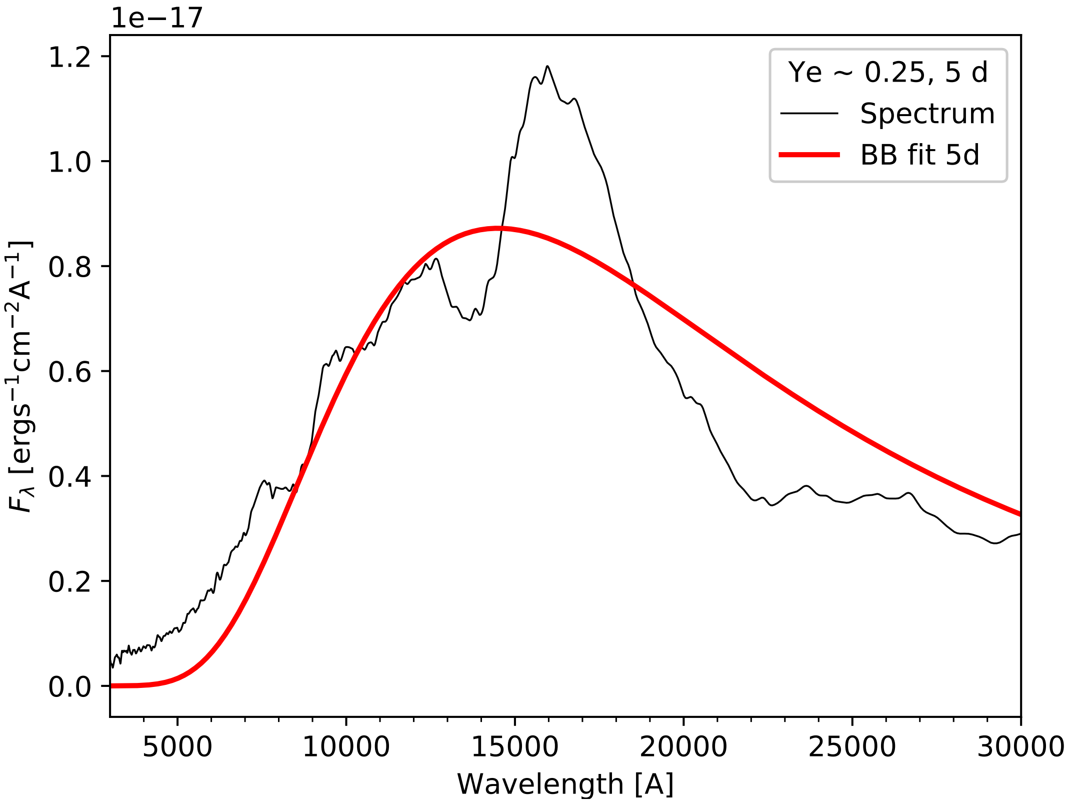


Fluorescence and Scattering

- Early times: high UV/optical opacity from line blanketing forces photons to fluoresce/scatter redwards
- As time progresses, T increases, optical depth decreases:
  - Bluer photons are more able to escape
- Homogeneous compositions get bluer:
  - Implications for multi-component KN in real objects

Observable: SED Temperature

- Results imply fitting blackbody to SED may not be physically meaningful
- Fluorescence/scattering change radiation temperature from gas temperature
  - $T_{rad} \sim 2000$ K
  - $T_{gas} \sim 4000 – 12\,000$ K



Summary: Key messages

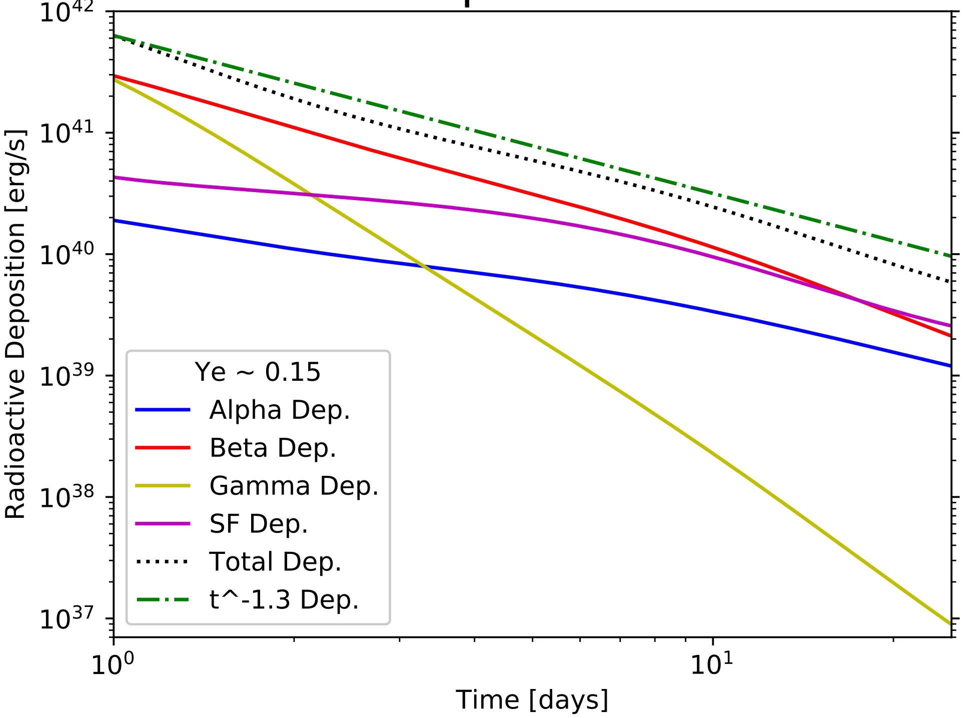
- Have produced 1D, homogeneous composition NLTE spectra for 5 – 20 days
  - Features emerge in wavelength windows of reduced optical depth
- Key elements in lanthanide-free ejecta: Rb, Sr, Y, Zr
  - Lanthanides dominate otherwise: Nd, Dy, Sm
- Fluorescence and scattering play key roles in spectral formation in 5 – 20 day period
  - Ejecta are *not* optically thin in this period -> the optically thin, thermal nebular phase may occur later
  - SED temperature is not representative of gas temperature
- Models tend to get *bluer* with time, unlike AT2017gfo:
  - Temperature is generally increasing in the NLTE regime
  - Optical depth continues to drop, allowing bluer photons to escape

Thank you for listening!

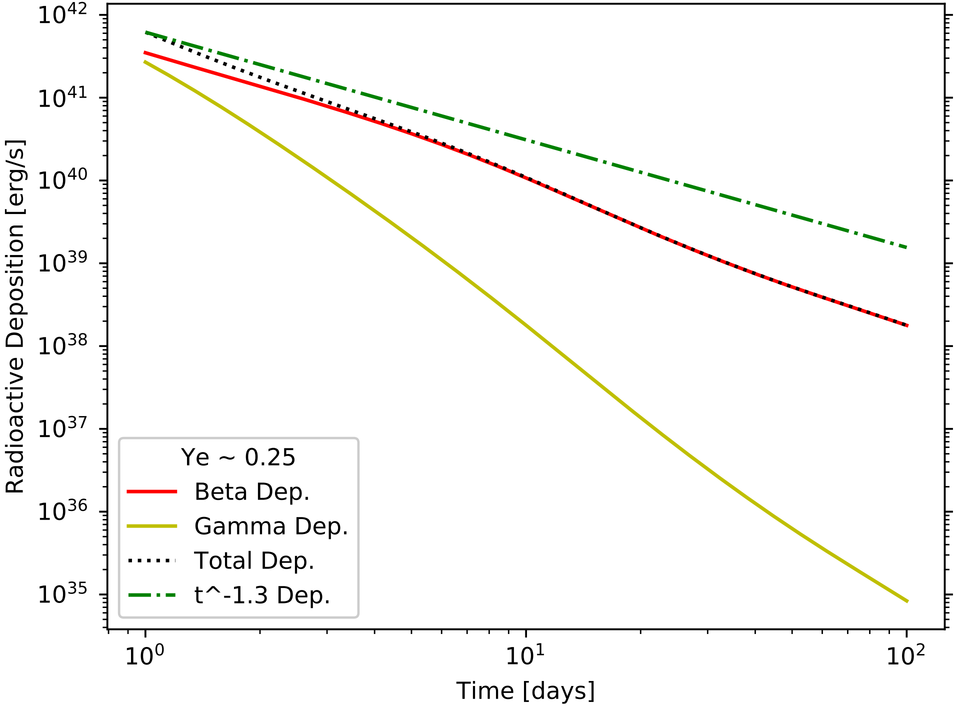
Supplementary Slides

Energy Deposition: Visualised

$Y_e \sim 0.15$: fission and alpha decay important



$Y_e \geq 0.25$: beta decay dominates energy deposition

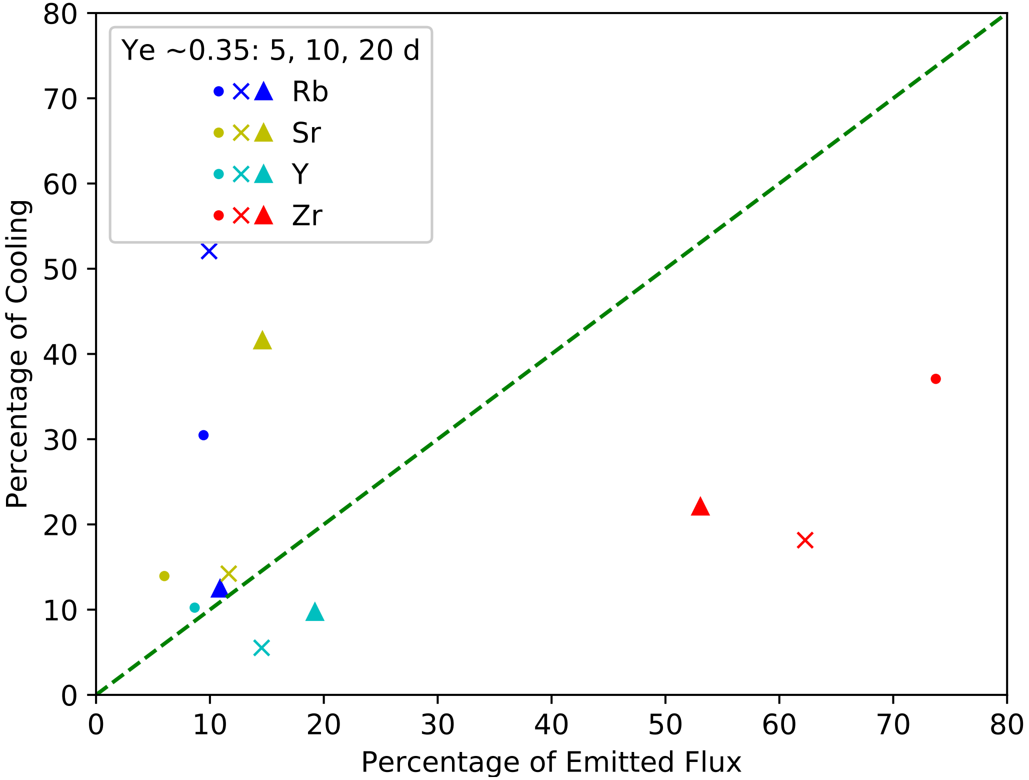


Atomic Data in NLTE

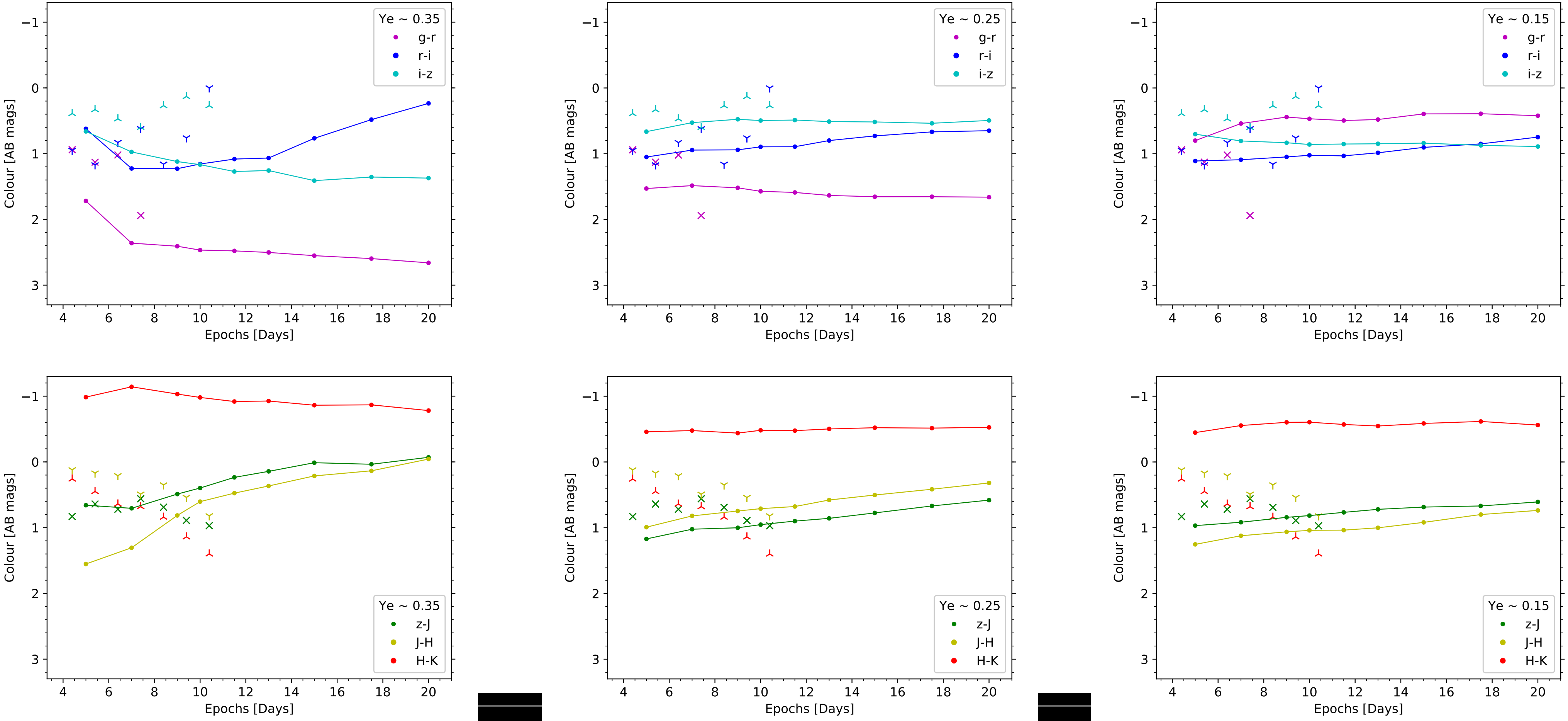
- Energy degradation by Spencer-Fano
  - NT cross-sections -> Lotz 1967 formula
- Excitation: collision strengths
  - Van Regemorter for allowed, $f_{osc} >= 10^{-3}$
  - Axelrod 1980 for forbidden, $f_{osc} < 10^{-3}$
- Ionisation:
  - PI cross sections: hydrogenic for first 50 levels
  - Recombination: constant rate 10^{-11} cm^3s^{-1}
- Please give us more data! We will pay you... in dinner/drinks

Cooling vs Scattering/Fluorescence

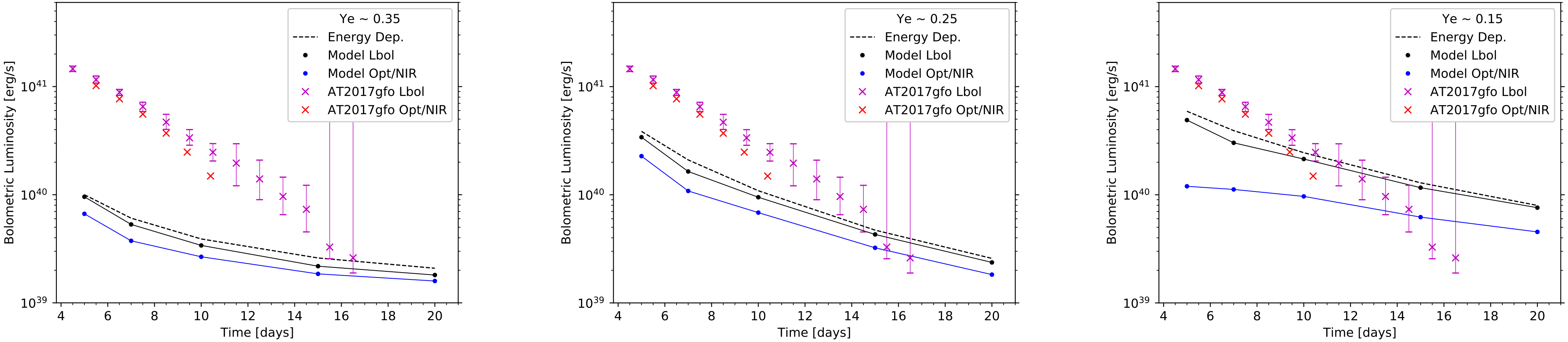
- Cooling emission: rad. deexcitation after collisional excitation
- Fluorescence: rad. deexcitation after rad. excitation, by other channels
- Resonance Scattering: rad. deexcitation after rad. excitation, by same channel
- Combined with cooling logs, can gauge which process is driving emission feature



grizJHK colours



Bolometric Light Curves



- LCs appear dim compared to AT2017gfo
- Several possible explanations:
  - Y_e ~ 0.35 model has naturally low power -> should have low luminosity
  - Stationarity approximation in rad. transfer -> no diffusion effects modelled, which can bolometric LC in 5 – 20 day period
  - Photon degradation from many scattering interactions due to co-moving frame transformations