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Exploring The Parameter Space of High Energy Stellar Explosions

Taylor Jacovich

A. J. van der Horst, D. Patnaude, P. Beniamini, S. Nagataki, S. H. Lee,
C. Badenes, D. Milisavljevic, P. Slane

Introduction

Outline

- Motivation: Big Data and Target of Opportunity (ToO) Observations
- The Physics of High Energy Stellar Explosions
- Mapping Parameter Space
- Using Observations to Constrain Parameter Space

Introduction

Big Data and The Next Generation of Observations

- **All Sky Surveys**
  - Vera Rubin Observatory (LSST)
  - Square Kilometre Array (SKA)
- **Multimessenger Detections**
  - LIGO/VIRGO/KAGRA
  - ICECUBE
  - LISA
- **High Cadence ToO Follow-up**
  - Rapid radio follow-up
  - Rapid multi-messenger follow-up
- **High Resolution X-ray Spectroscopy**
  - XRISM, ATHENA, LYNX

NOTICE: Next Slide contains some flashing images.

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Introduction

A Quick Primer

Figure: ZTF

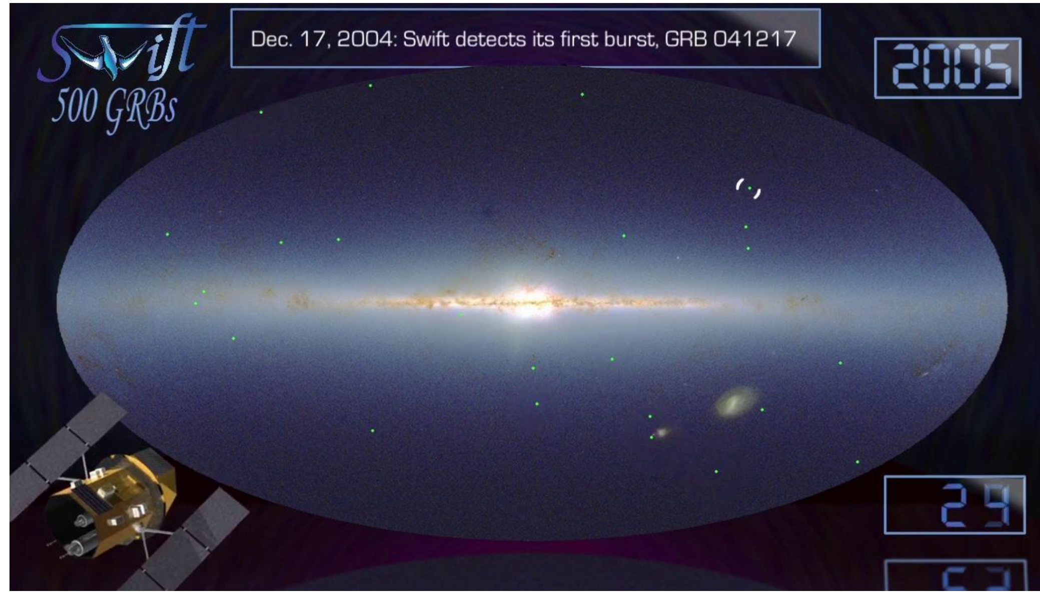

Figure: NASA/GSFC

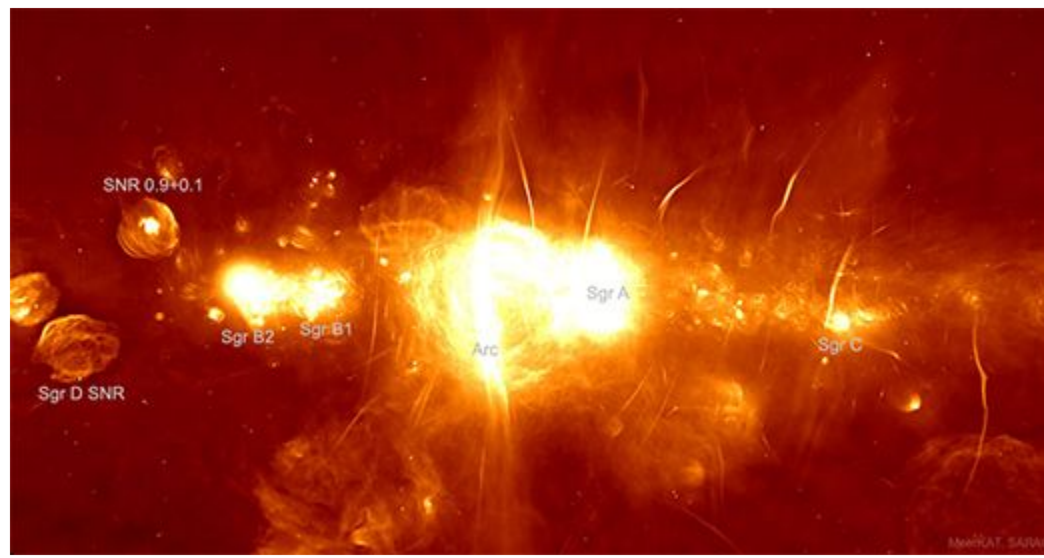

Figure: SARAO

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GRB Afterglows

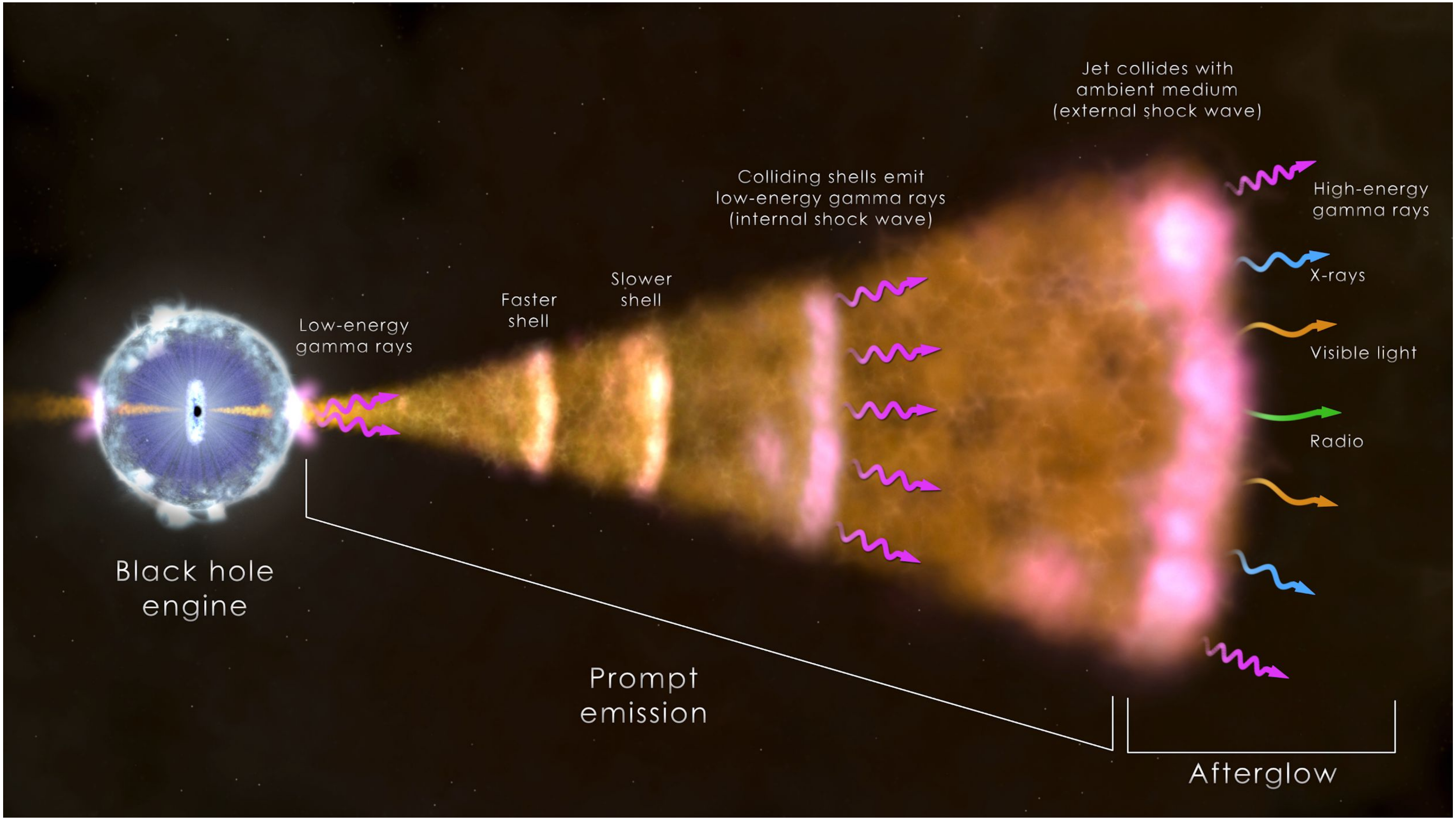

Figure: NASA GSFC

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Introduction

GRB Afterglow Modeling

- Dynamical Models
  - Relativistic blast wave (eg. Rees et al. 1992)
  - Scale-free hydrodynamics (eg. van Eerten et al. 2012)
- Emission Mechanisms
  - Synchrotron emission
  - Synchrotron-Self Compton (SSC, Inverse-Compton)
  - Other non-thermal and thermal mechanisms

Afterglow modelers tend to pair their favorite dynamical model with synchrotron emission

Invoke SSC when synchrotron-only fails

Should be included consistently for modeling afterglows as a class of objects.

Synchrotron-Self Compton Emission (SSC)

The Basics

- Up-scattering of synchrotron photons
- Same Lorentz factor dependence as synchrotron
  - Increased electron cooling (lower γ_c)
  - Increased emission near $\sim min(\gamma_c, \gamma_m)^2 \nu$
- Well established in the theoretical literature (eg. Sari & Esin 2001, Nakar et al. 2009)
- Hinted at by modelers (eg. Chandra et al. 2007, Nava et al. 2014, Beniamini et al. 2015)
  - Deployed **when modelers feel it is needed**
  - Causes shifts in afterglow parameters

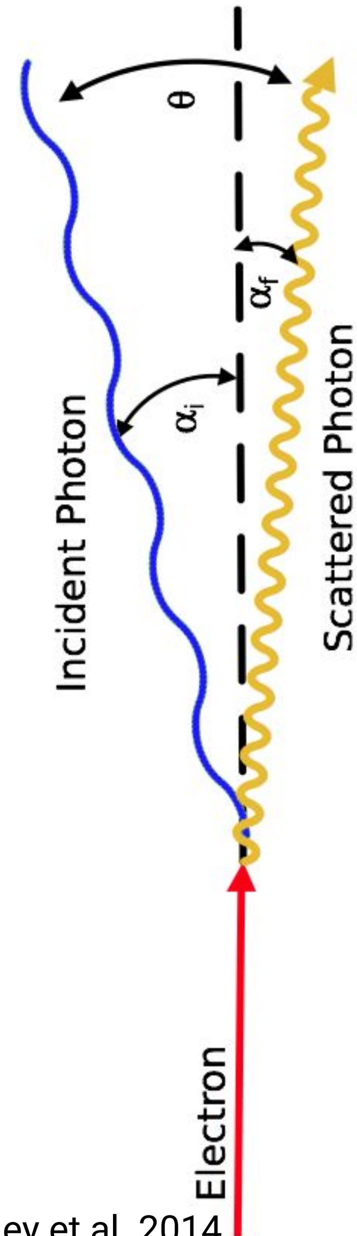

Figure: Ertley et al. 2014

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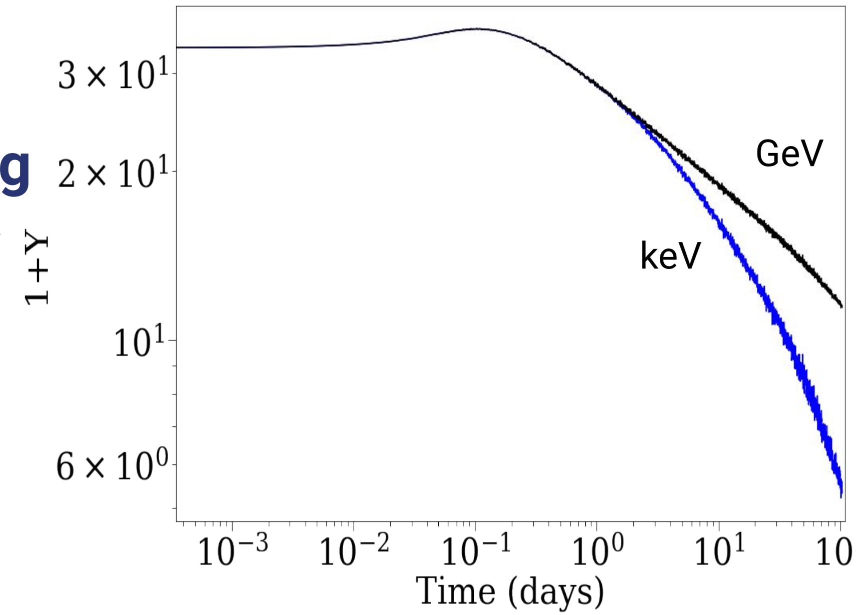
Implementation

Elastic (Thomson) Photon Scattering

- Adds a second term to electron cooling equation, *Y*

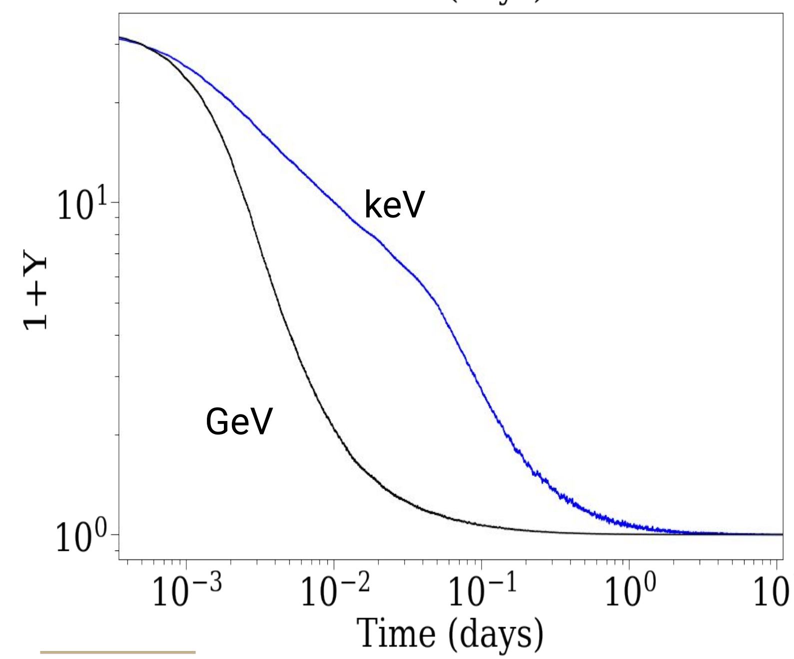
$$\gamma_c^s = (1+Y)\gamma_c$$

- Yields one self-consistent solution for each regime



Inelastic Photon Scattering (Klein-Nishina)

- Photons with energies above m_ec^2 no longer scatter efficiently
- Description of *Y* is more complex
- Additional dependence on photon energy



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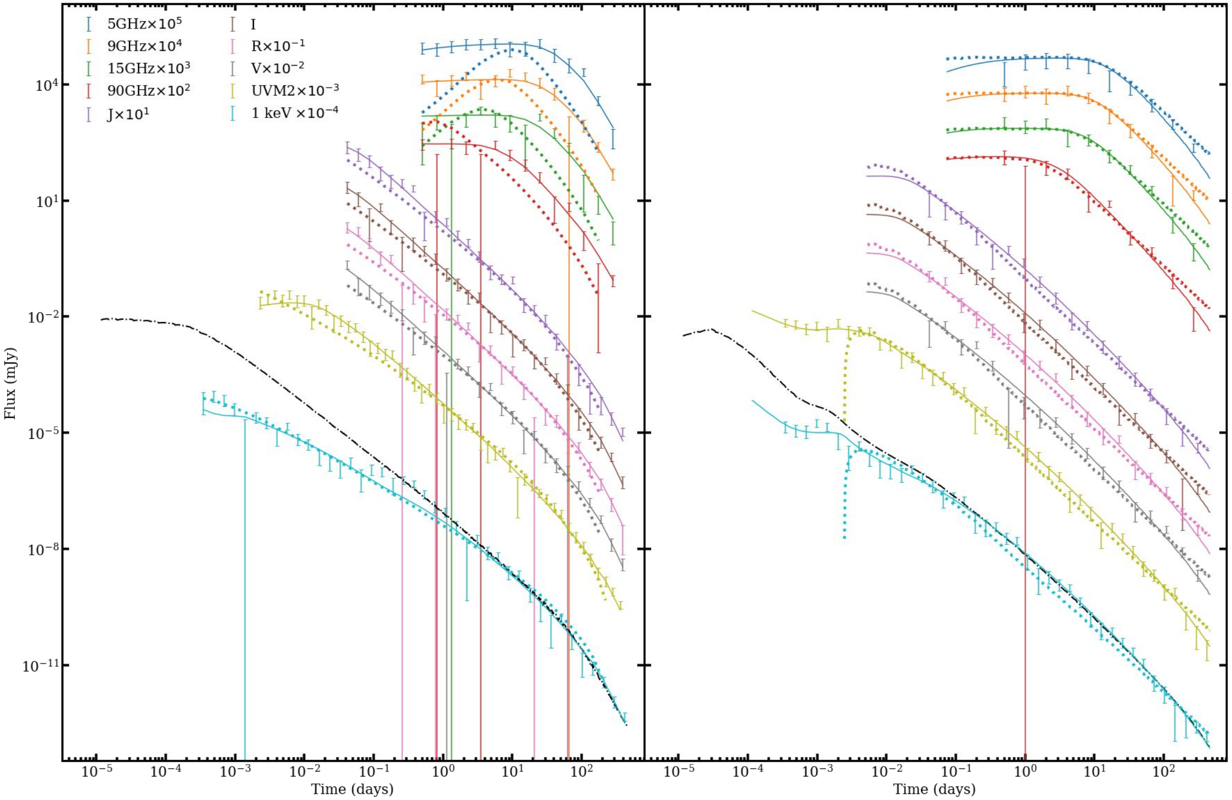
Iterative Fitting

- Quantifying SSC effects requires fitting synthetic datasets
- Synchrotron-only fits quantify systematic errors in parameters
- SSC fits examine parameter recovery

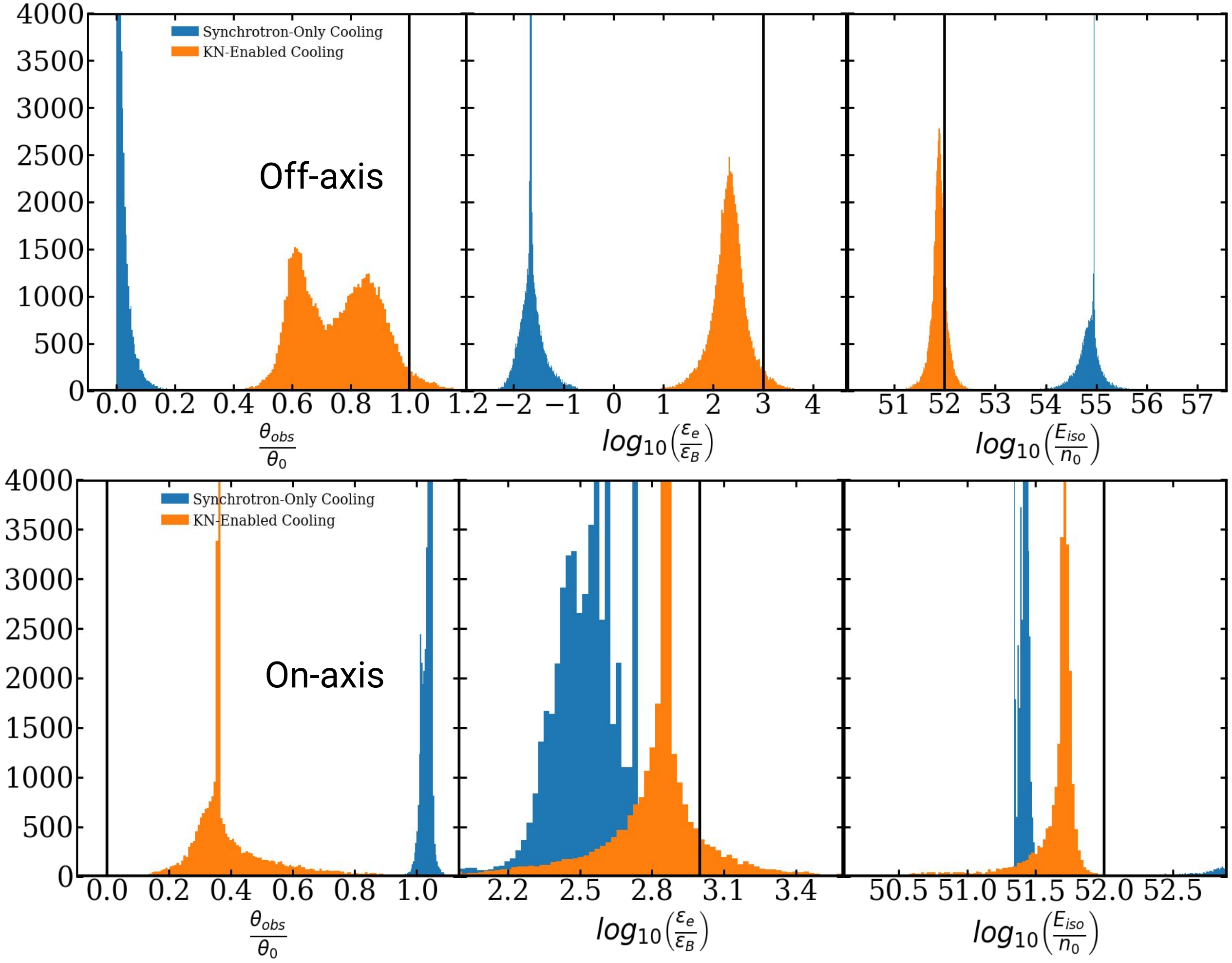


On-axis

Off-axis

- Simulated dataset from a wind (k=2) medium
- Broadband ~250 data points

Iterative Fitting



- SSC fit better recovers parameters
- Fitting Algorithm does struggle to fully recover inputs

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Iterative Fitting of GRB Afterglows

DownHill Simplex+Simulated Annealing

- Finite temperature fitting
    - χ^2 fit statistic
- Convergence issues due to complexity of parameter space

MultiNest Fitting

- Simultaneous multiple parameter search
    - Bayesian Inference
- Testing for better fit convergence (ongoing)
- Considering better parallelization

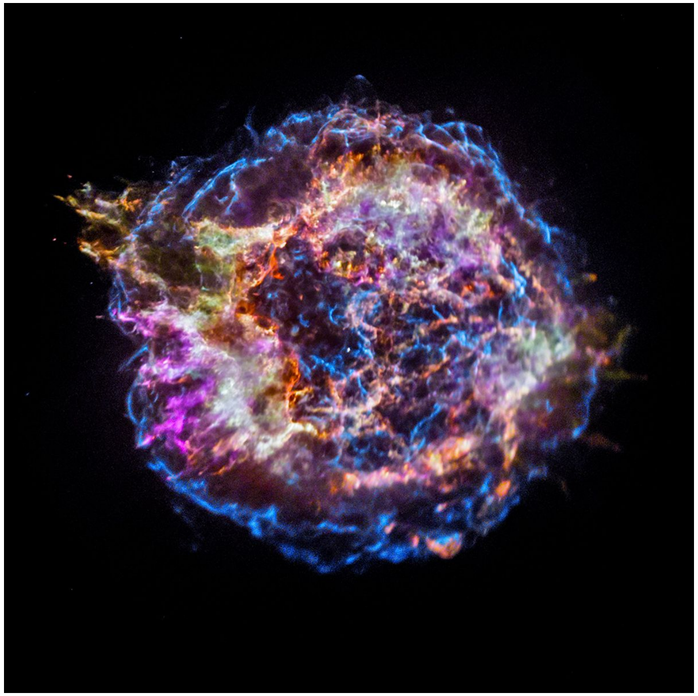
Now onto Supernova Remnants

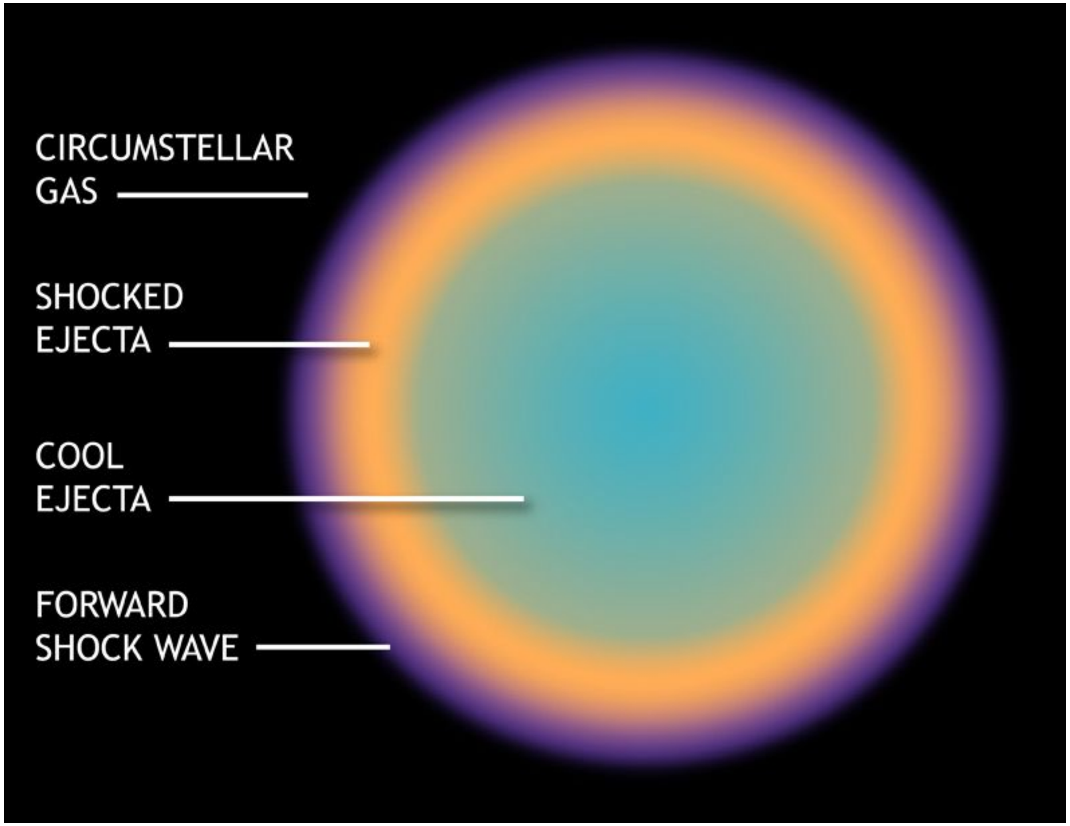
- The Same modeling framework can be applied to understanding supernovae and their remnants

  SNe are more numerous than GRBs

- In the galactic neighborhood
  - Resolved 3D Structure

- Interplay between progenitor and CSM





Figures: NASA CXC/SAO

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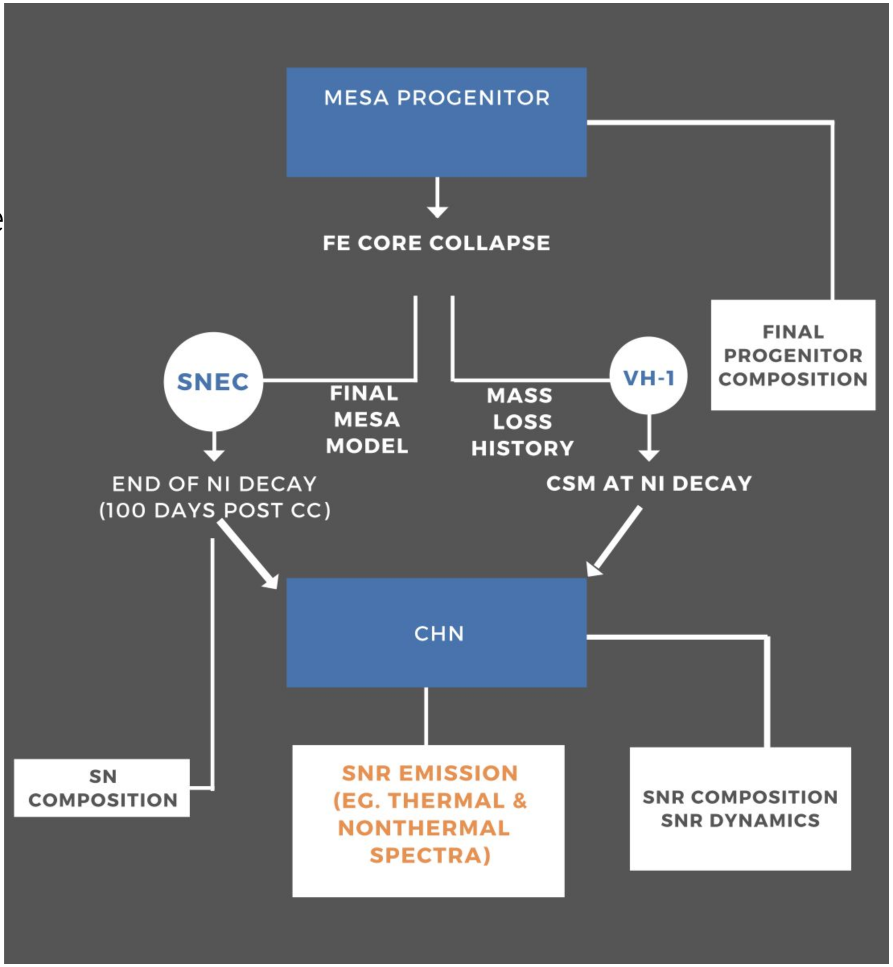
Introduction

Why Progenitor Modeling?

- Remnant, supernova, and progenitor evolution are connected
  - Each aspect depends on the prior ones
  - SNe energetics dictate composition and outflow
  - Stellar mass loss dictates Circumstellar environme



- Stellar parameter spaces is quite large
  - Not all parts of parameter space are physical or produce physical results
  - many mechanisms uncertain
  - high degree of parameter degeneracy

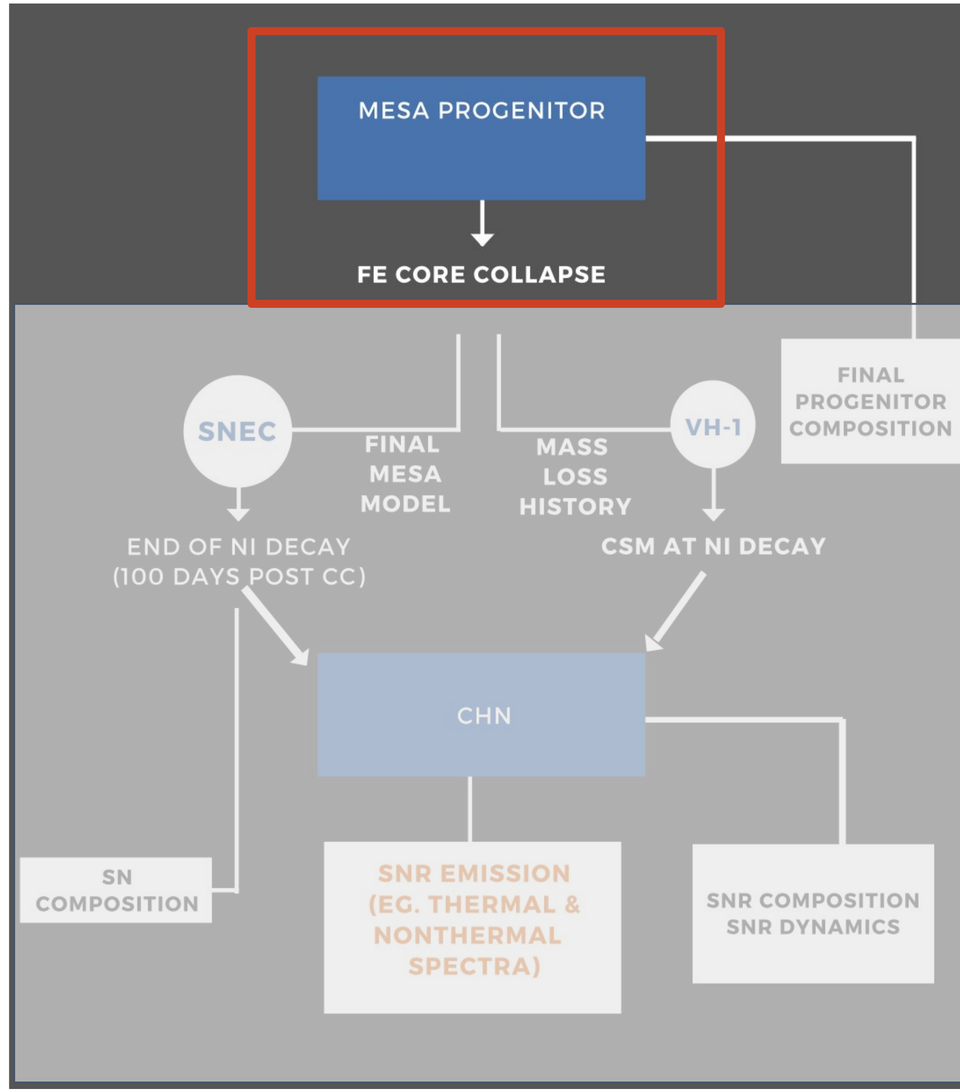
MESA Progenitor Models

Methodology

- Dense coverage of stellar parameter space
  - 0.1 $M_\odot$ mass resolution (9.5-30.0) $M_\odot$
  - intermediate models
  - multiple wind schemes
  - Composition profile data
  - self-contained git repos

- started from MESA test suite case **make_pre_ccsne**
  - provides a default set of inlists
  - modified to include rotation and increase mass resolution
  - Evolved to Fe core collapse

$$(v_{infall} > 10^5 km/s)$$



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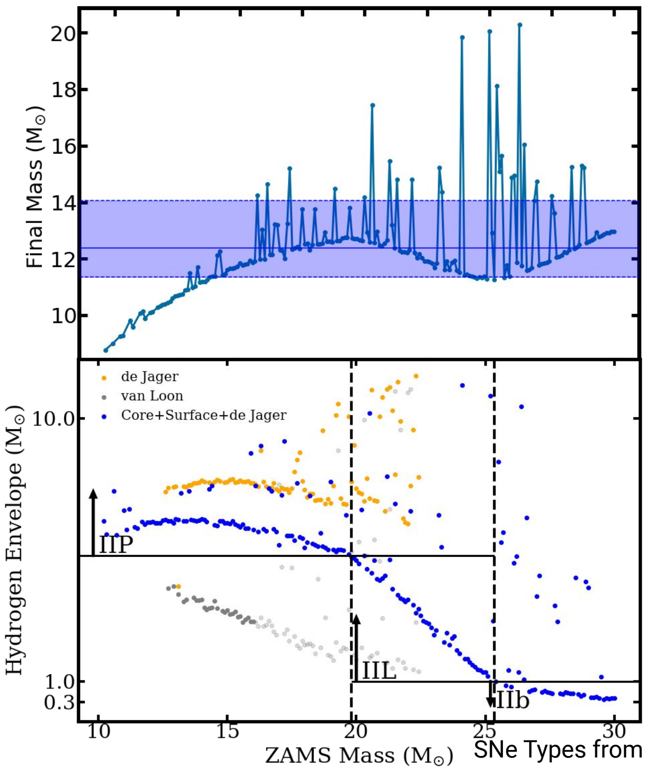
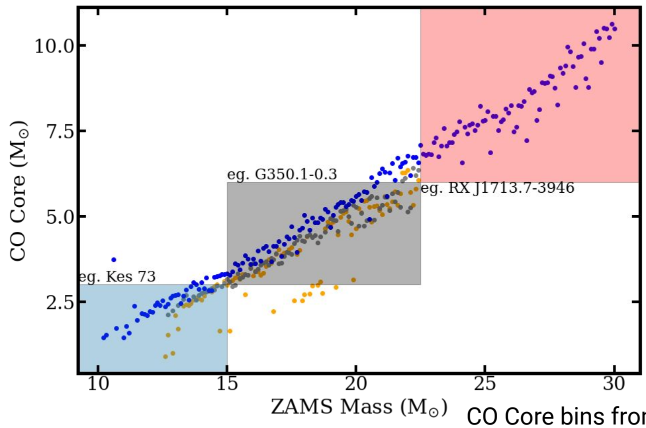
Young Remnants from ChN

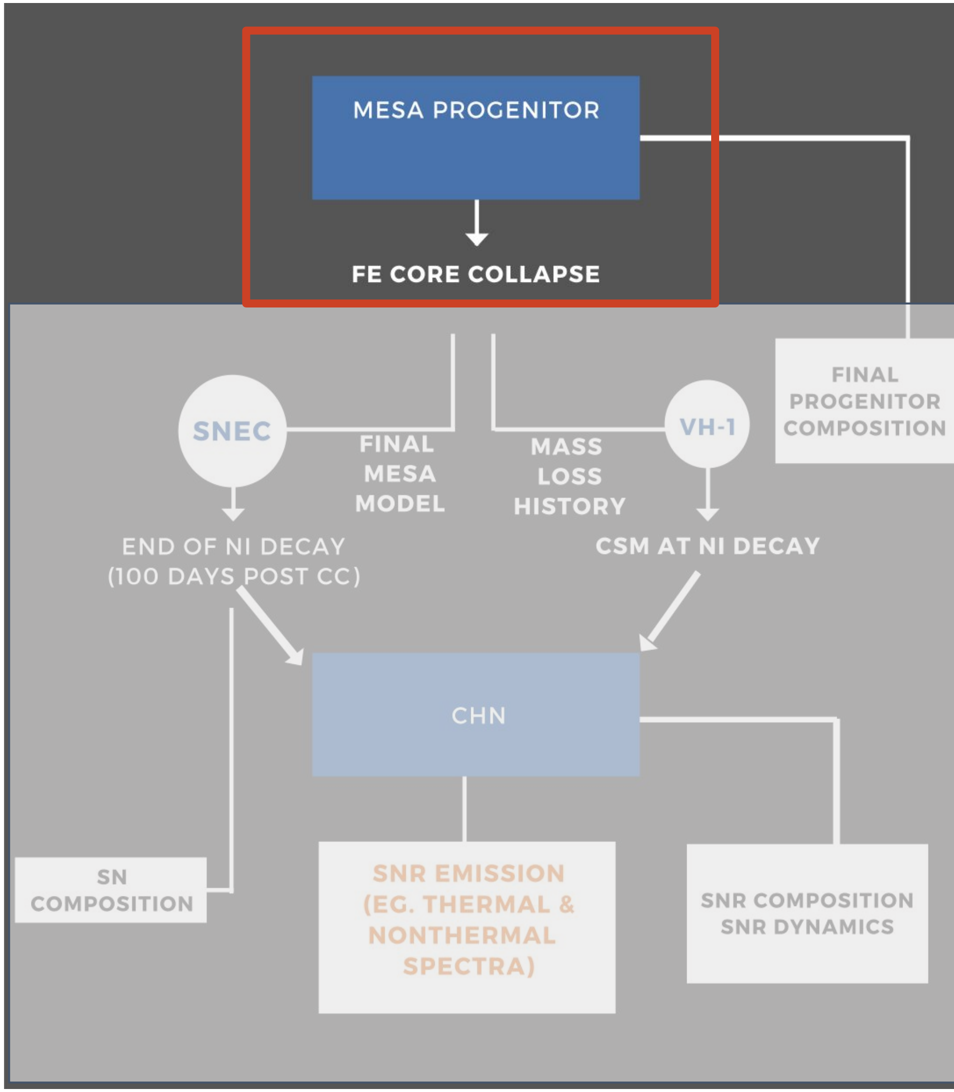
Methodology and Progenitor Grid



SNe Types from Nomoto et al. 1996



CO Core bins from Katsuda et al. 2018



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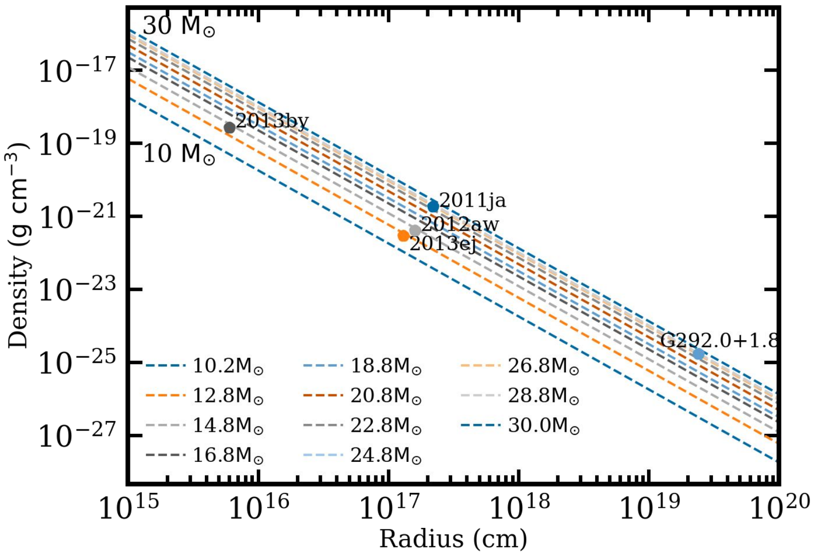
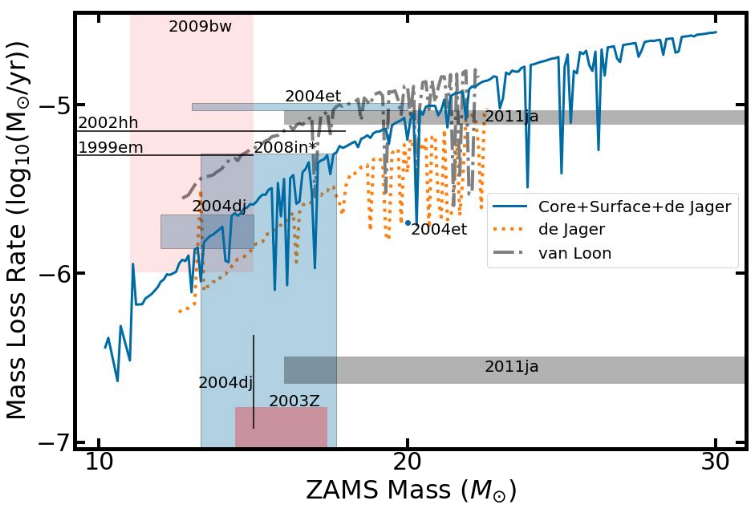
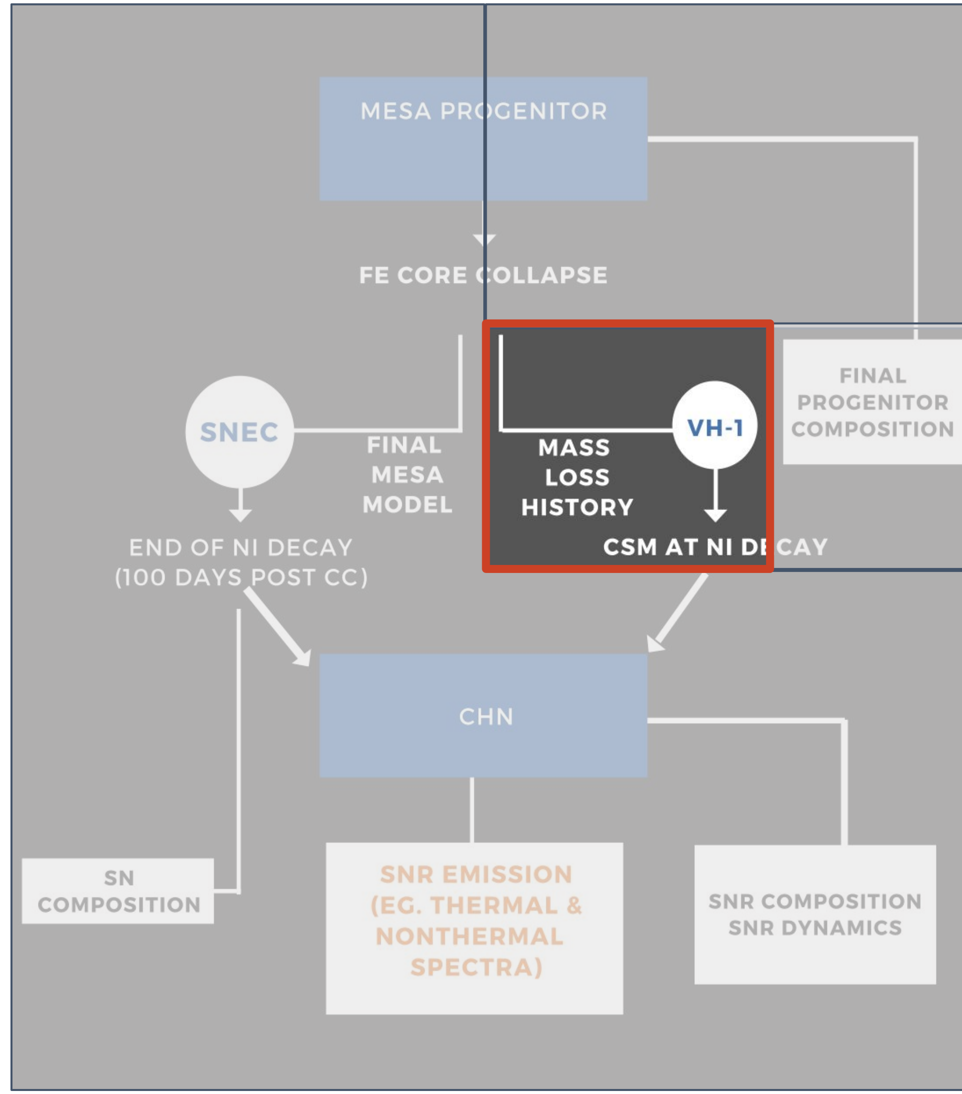




SNe Types from Nomoto et al. 1996



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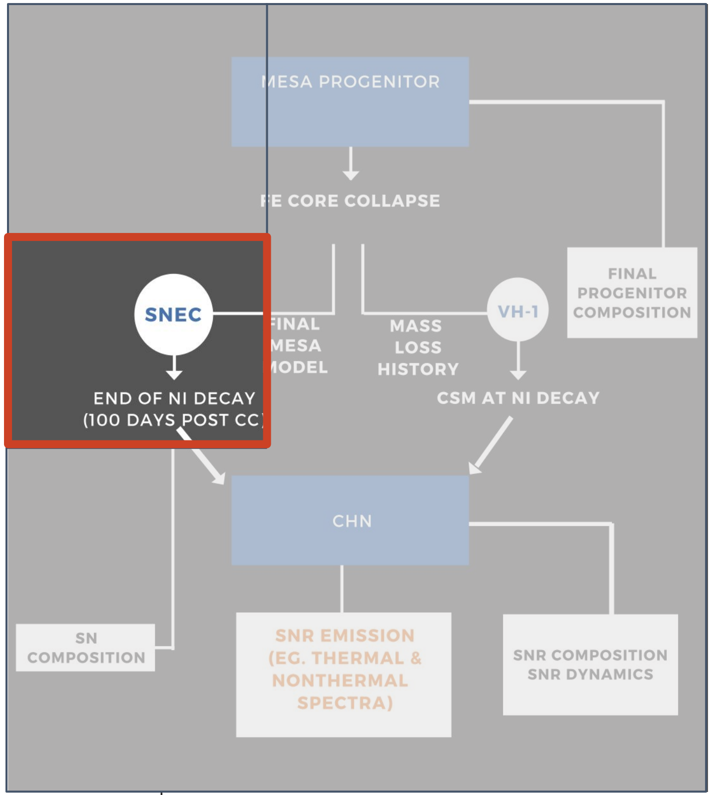
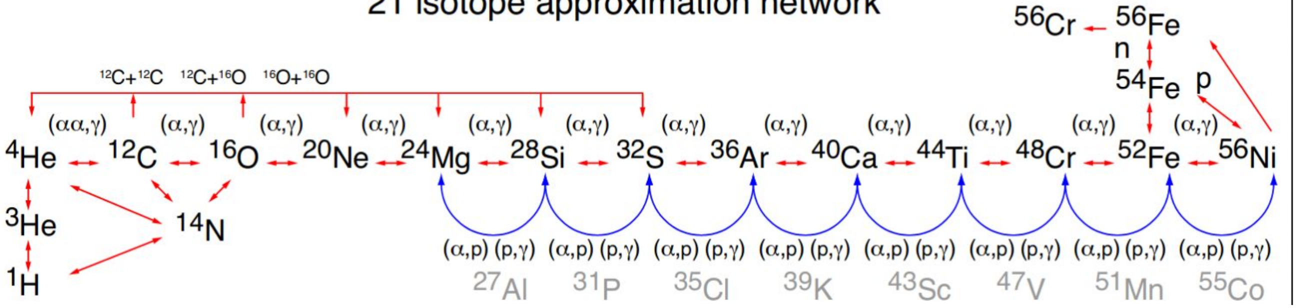
Supernova Modeling with SNEC

SNEC Models

- All successful MESA models were piped into SNEC
- Models were exploded with 0.8 and 1.5 foe Thermal Bomb
- Mass cut was varied from 1.4 to 1.6 $M_\odot$
- spread was varied from 0.038 to 0.08 $M_\odot$
- Models were evolved to 100 days
- Burning occurs in SNEC (approx21)



21 isotope approximation network



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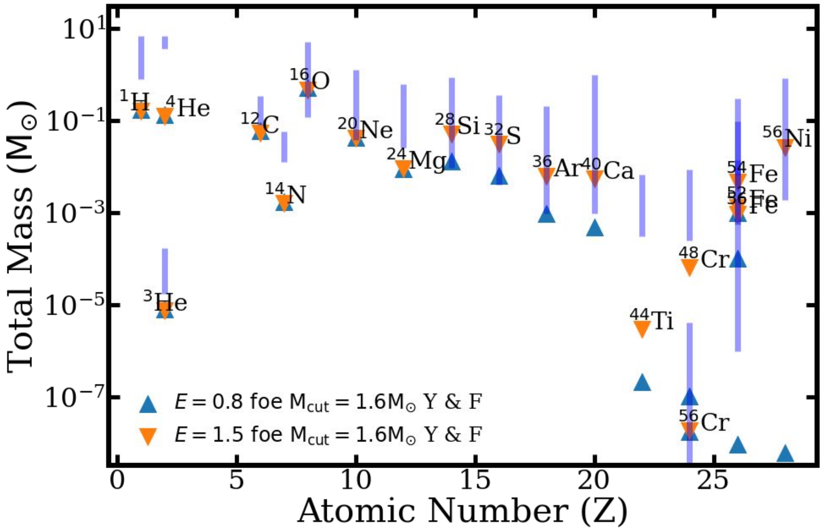
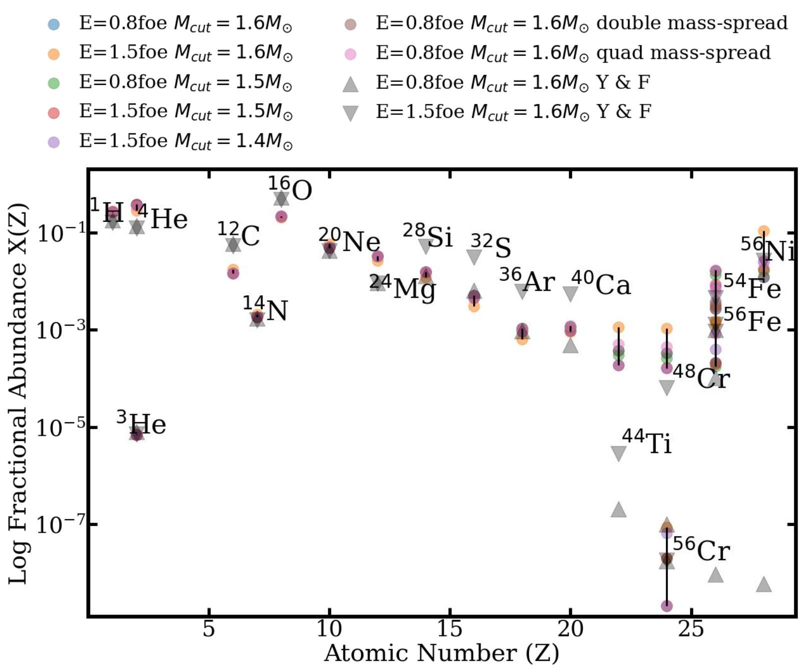
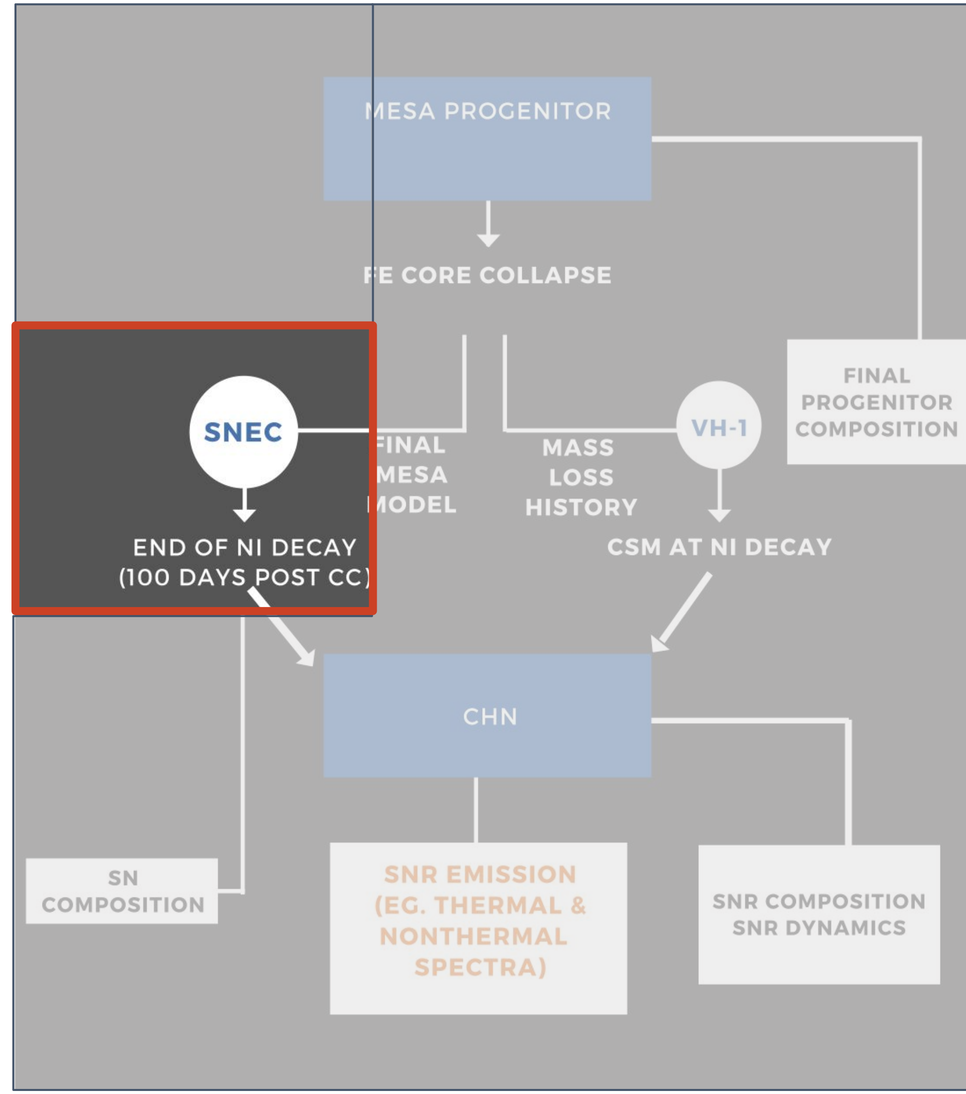
Young Remnants from ChN

Methodology and Progenitor Grid







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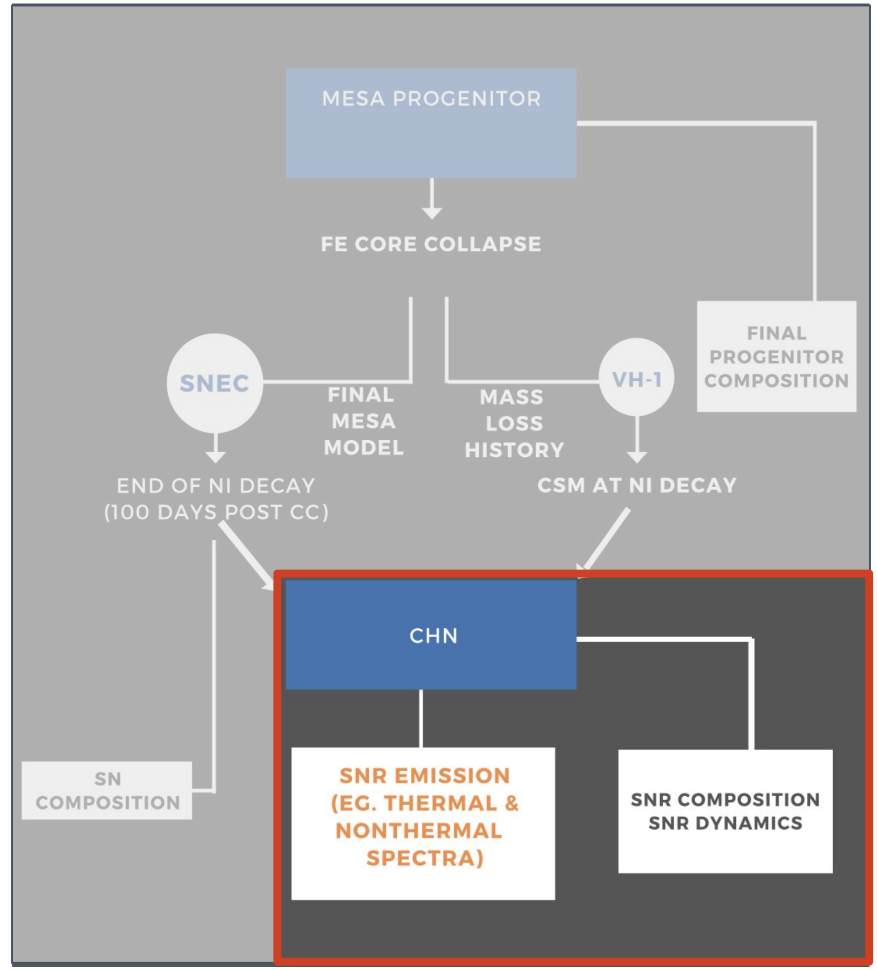
Supernova Remnant Modeling with ChN

ChN Models

- All successful SNEC models were piped into ChN
  - Merged with wind CSM
- Simulated from ~180 days to 7000 years post CC
  - 1D hydrodynamics
  - Full NEI calculation (linked to atomDB)
- Dynamics and Composition
  - Ionization as a function of radius/time
  - shock velocities
- SNR Emission
  - Thermal Spectra with Line Emission
  - Nonthermal Spectra



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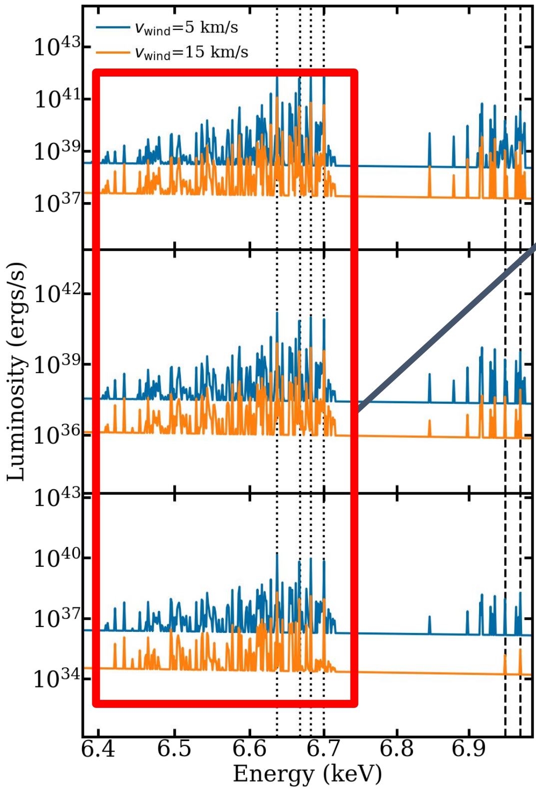
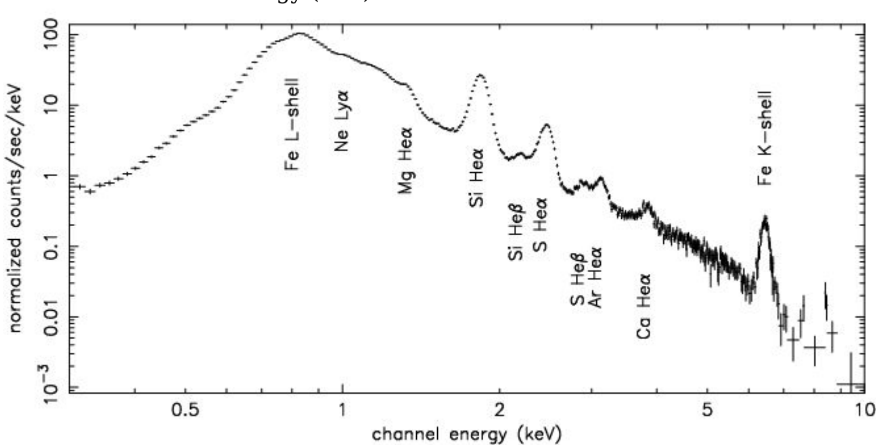
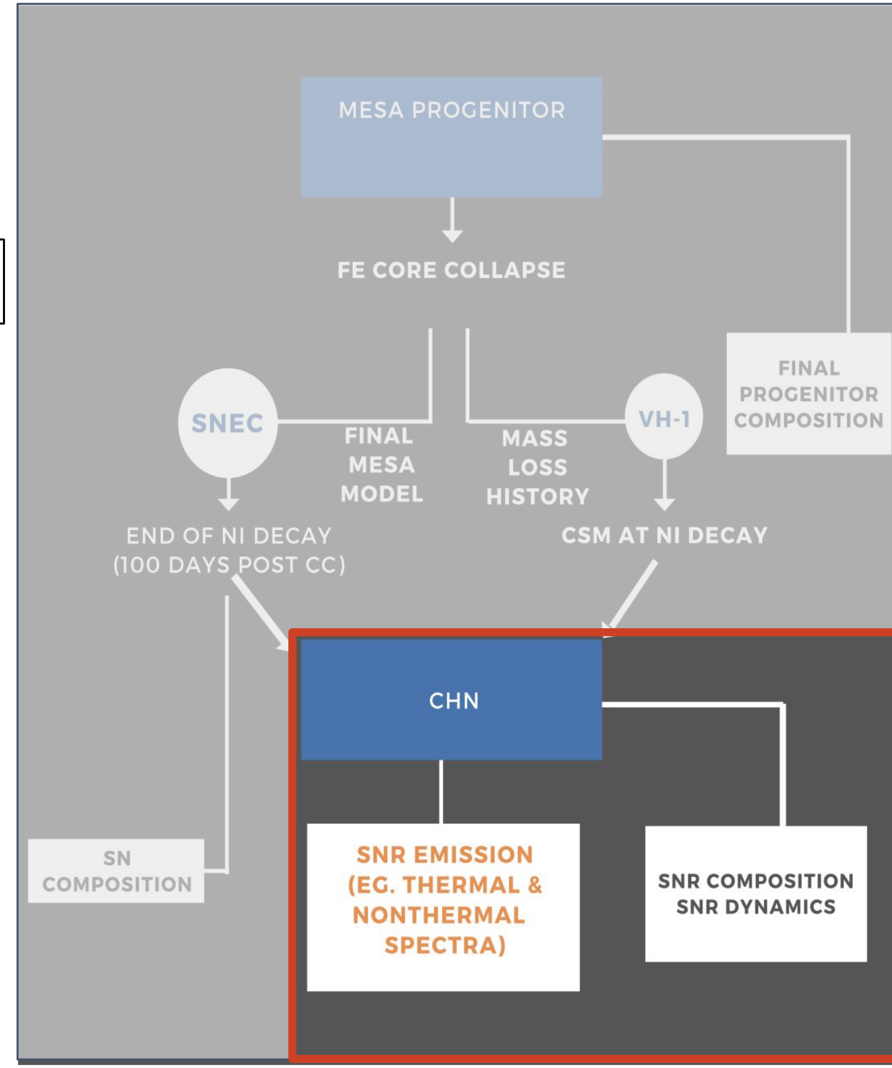
Methodology and Progenitor Grid



Fe-K shell emission





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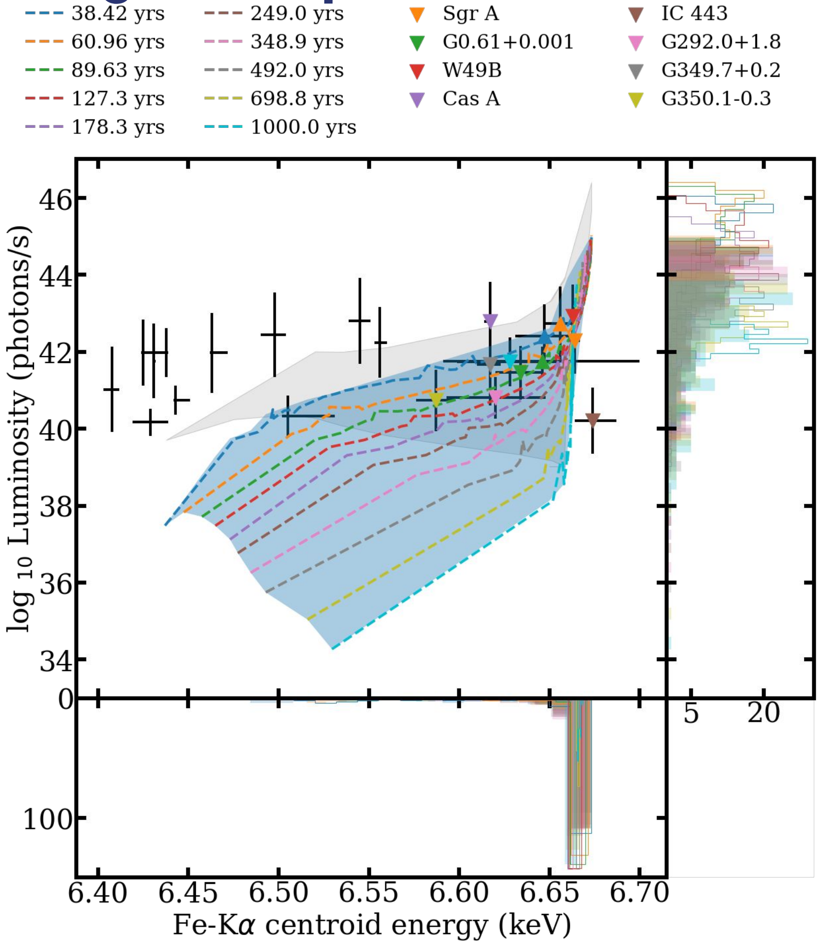
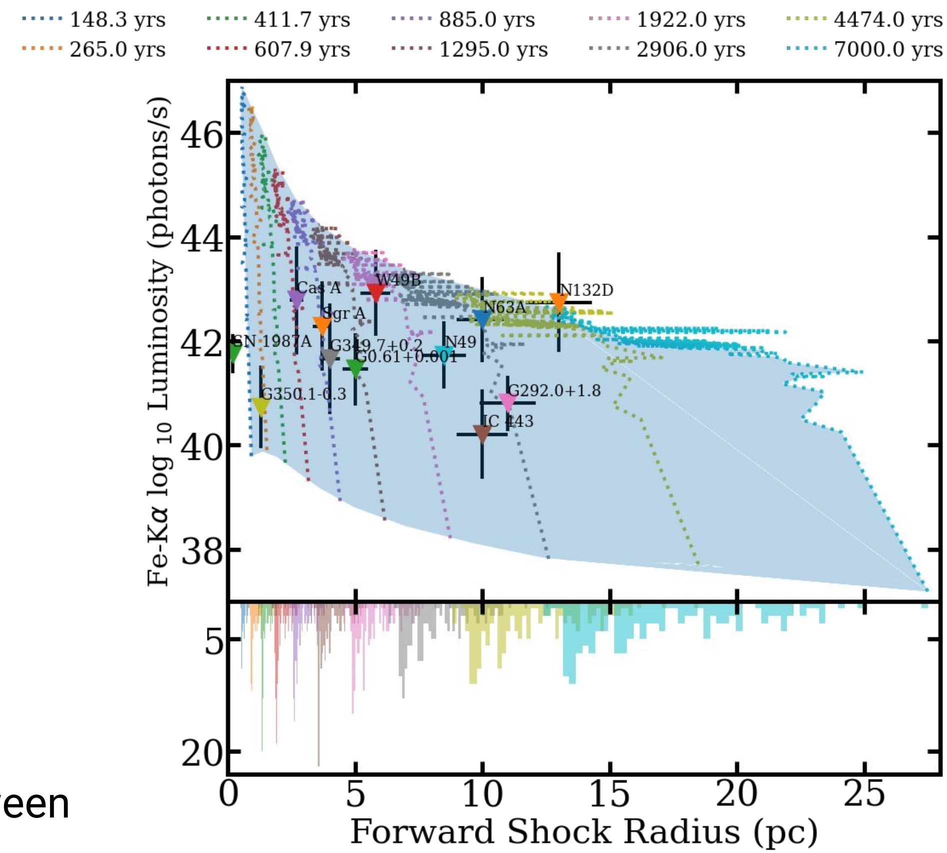
Young Remnants from ChN

Integrated Spectra Metrics: Fe-K Centroids





- Fe-K can be used to discriminate between Core-collapse and Type Ia progenitors
    - Our models broadly overlap with observation
    - All models assume wind CSM, so not applicable to all CC data plotted above

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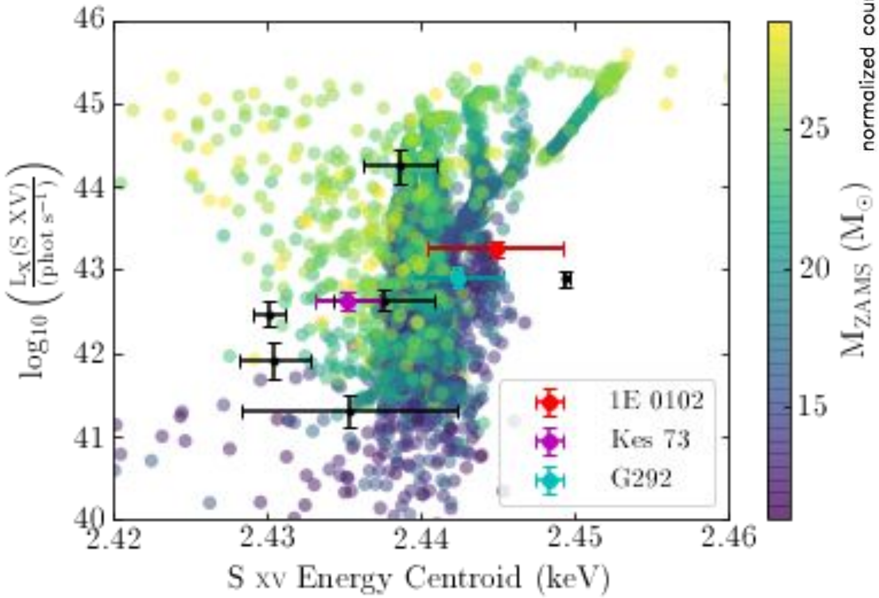
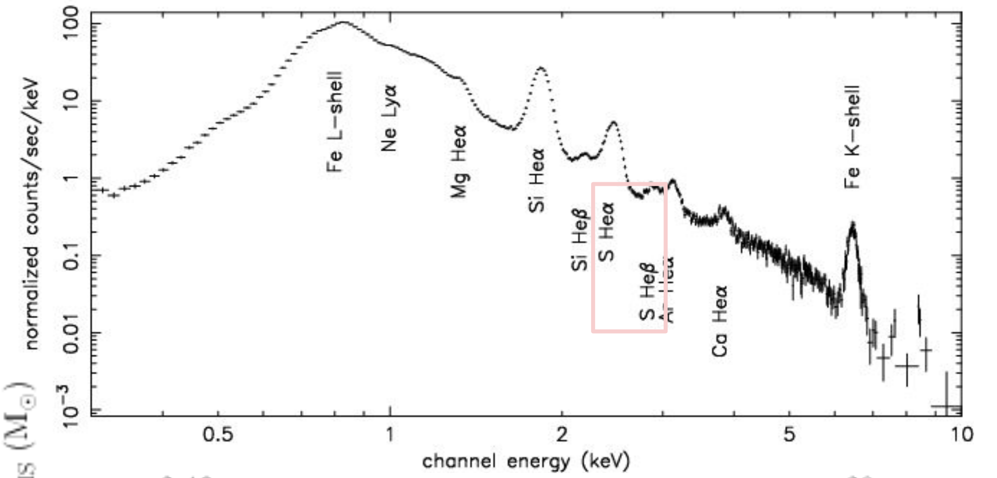
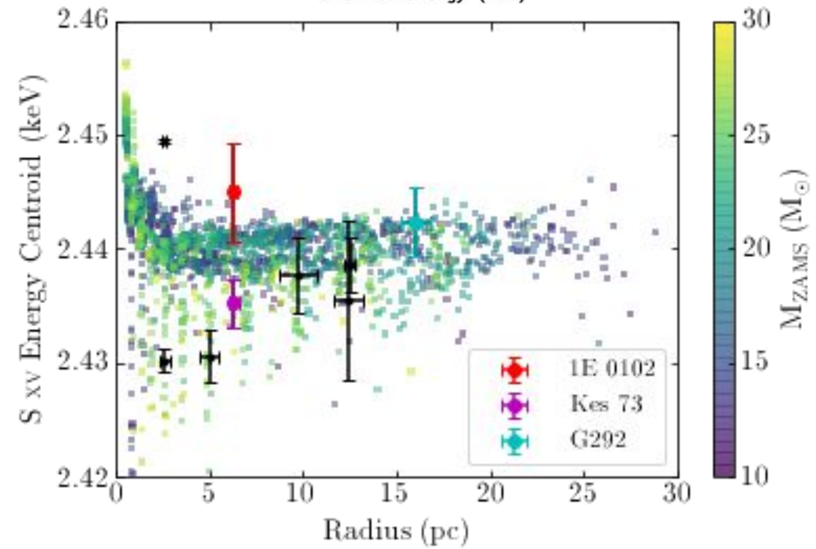
Integrated Spectra Metrics: He-Like S Centroids







•S centroids can also be used in remnants with low Fe emission

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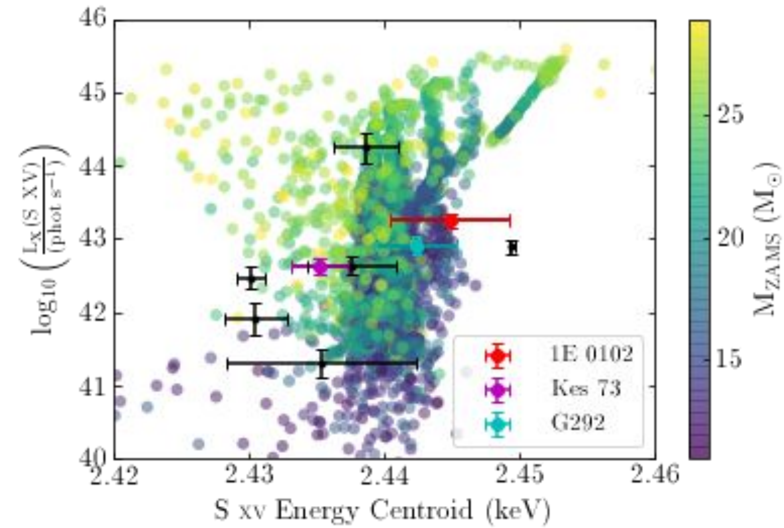
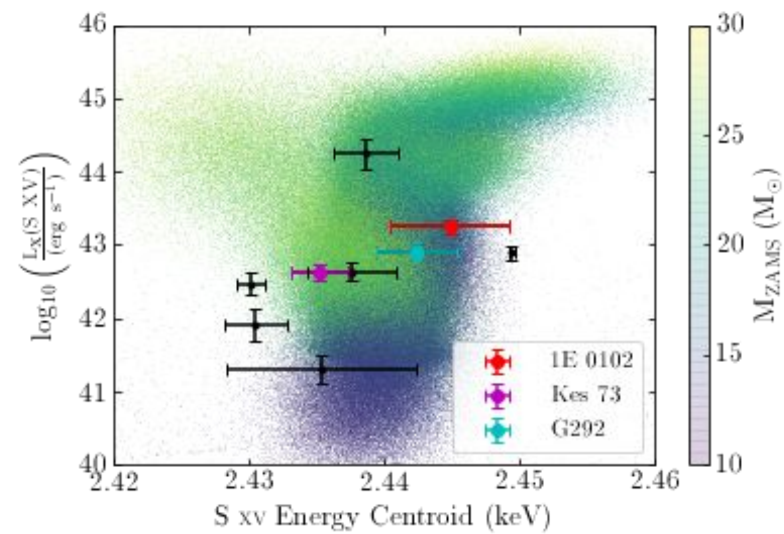
Young Remnants from ChN

Gaussian Mixture Model (GMM) Sampling

- Sparse Model Parameter Space
  - Changes between Progenitor inputs are small
    - Wasteful to simulate finer mass resolution
    - No useful information gain
  - Time Domain is sparse, but smooth
    - Remnant dynamics evolve slowly on larger timescales
    - Wind models evolve smoothly
- Generate Observational Parameter Space
  - Chandra ASIC Centroid Measurements
    - He-like S fit in xspec
  - Gaussian Mixture Model of Centroid values and Model parameters
    - number of gaussians selected by minimizing the Bayesian Information Criterion (BIC)
    - Mixture maintains relative density while increasing number of samples
    - Fills in gaps in parameter space





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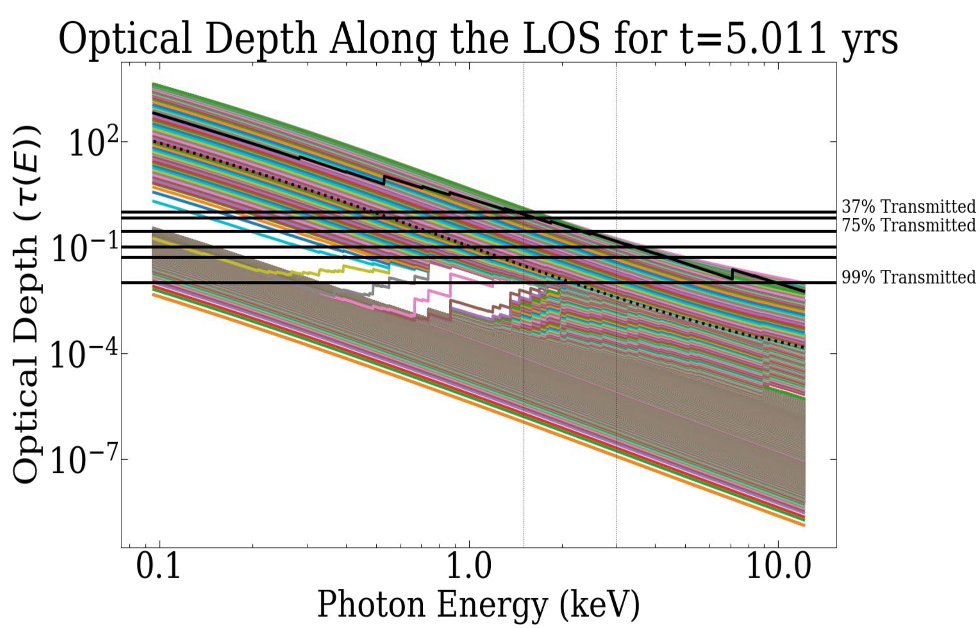
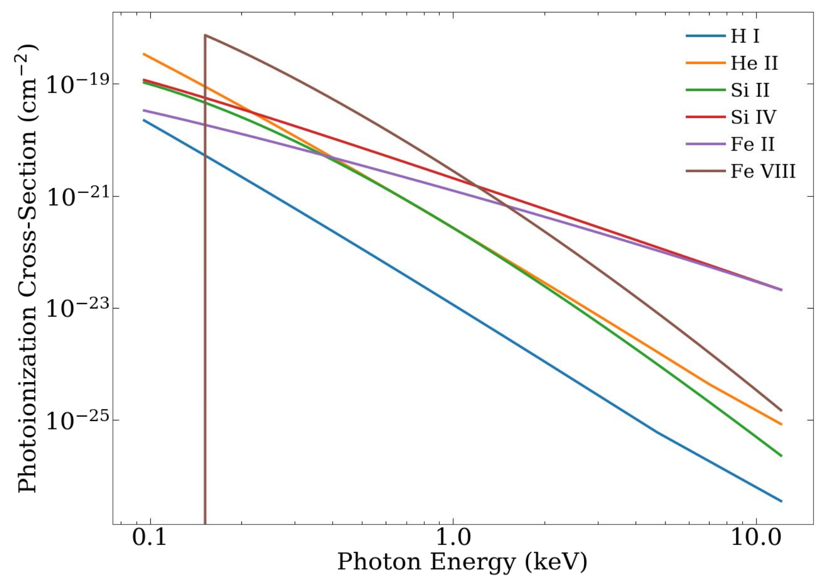
Young Remnants from ChN

Line of Sight Effects: Absorption

- Suppresses emission mainly from far-side of remnant
  - Actual absorption depends on
    - LOS distance
    - Density
    - Ionization State
  - Absorption calculated following Wilms et. al. (2000) method for ISM
    - Abundances pulled from ChN for each ion
    - photoionization cross-sections pulled from ATOMDB

$$\sigma_{\rm gas} = \sum_{Z,i} A_Z \times a_{Z,i} \times (1 - \beta_{Z,i}) \times \sigma_{\rm bf}(Z, i) \,, \qquad (3)$$





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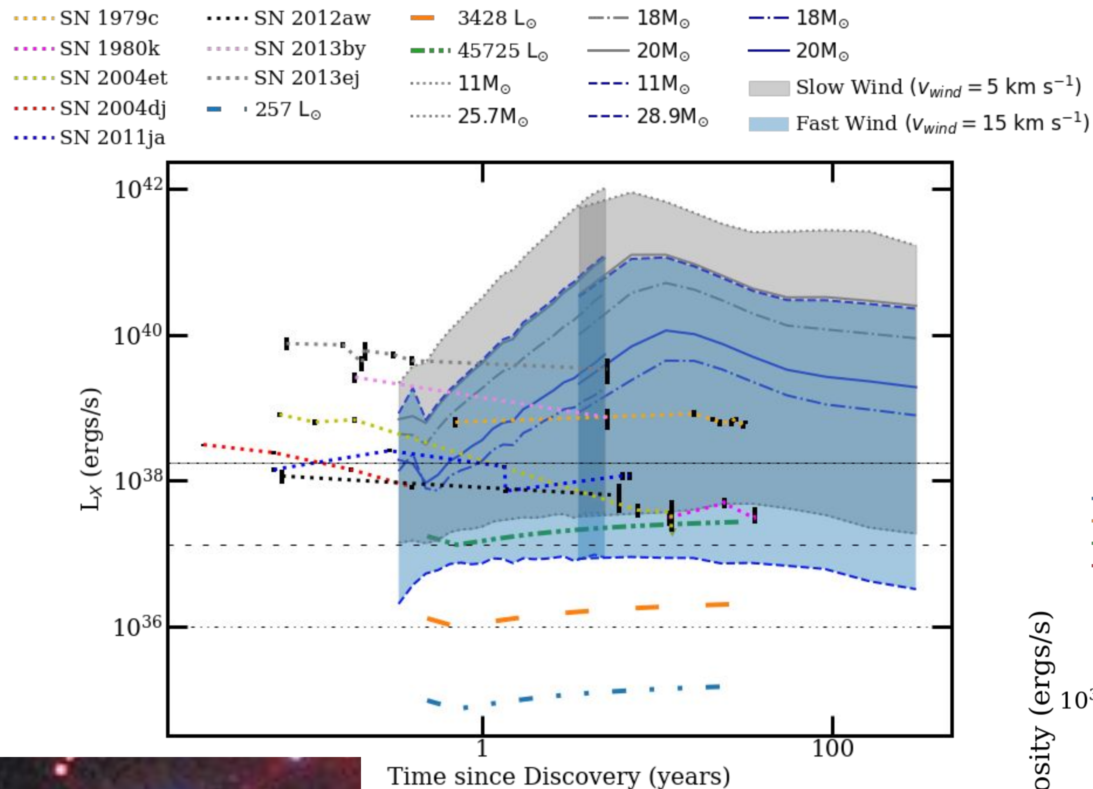
Young Remnants from ChN

Absorption and The PWNe



- Shock emission can reasonably explain late-time SNe emission
- Absorbed PWNe emission follows a similar trend

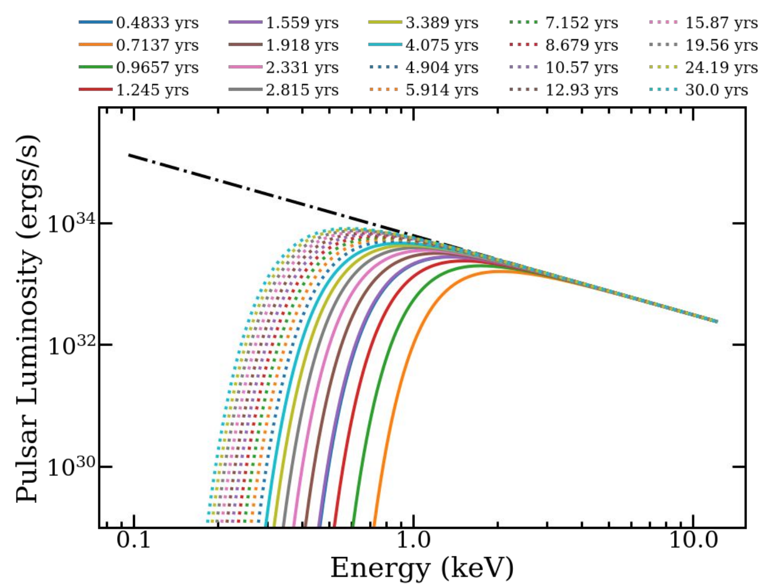


Figure: NASA STScI

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Expanding the ChN Parameter Space

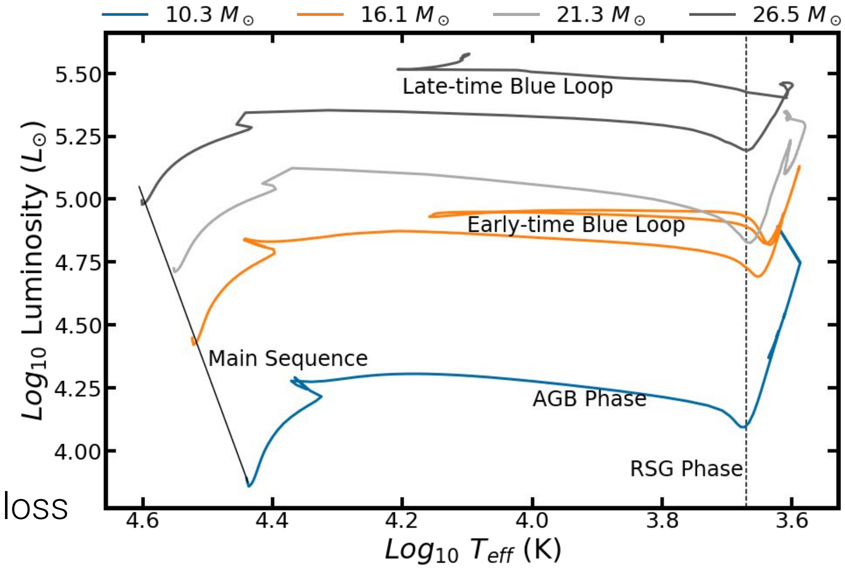
Additional CSM models

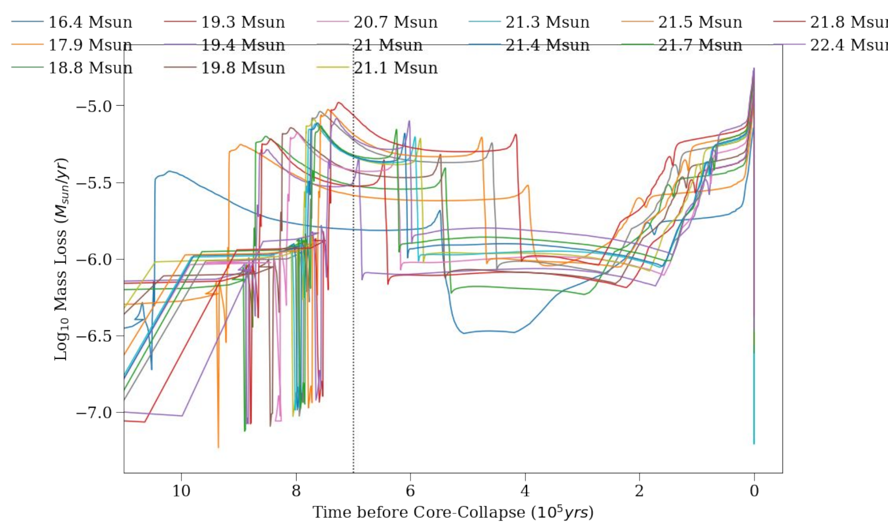
- Blue Loop modeling
    - Early time blue loop

      Explode as RSG, larger H envelope
    - Late time blue loop

      Explode as YSG/BSG, minimal H envelope
    - Period of higher velocity winds with lower mass loss

      Complicates CSM
- Wave Driven Mass Loss
    - can drive mass loss episodes (~0.1 $M_\odot$/yr)
    - Dependent on stellar composition





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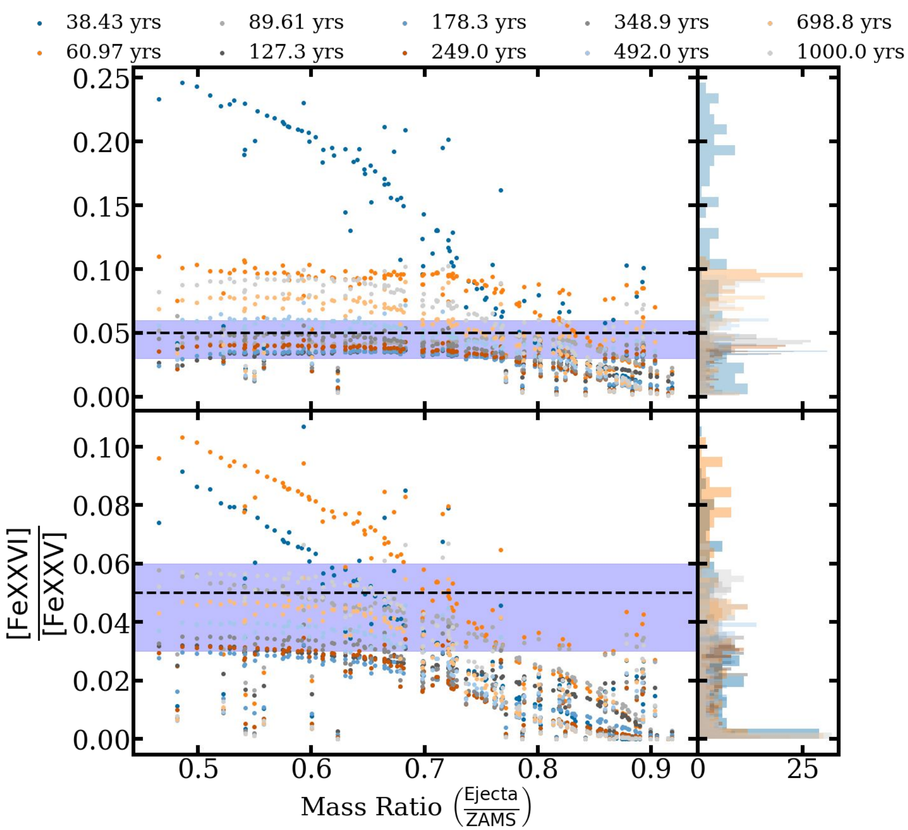
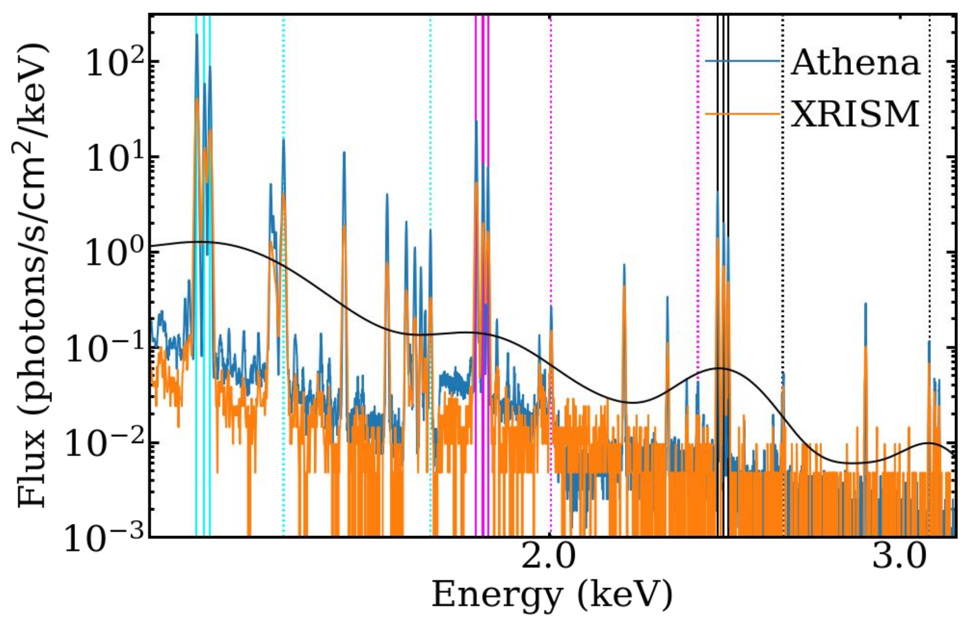
Expanding the ChN Parameter Space

Working with the Next Generation of X-ray Instruments

- X-ray Microcalorimeters
  - Great spectral resolution (~5-10 eV)
  - Low spatial resolution (remnants become point sources beyond ~10kpc)

Additional work required to understand remnant structure from integrated spectra.





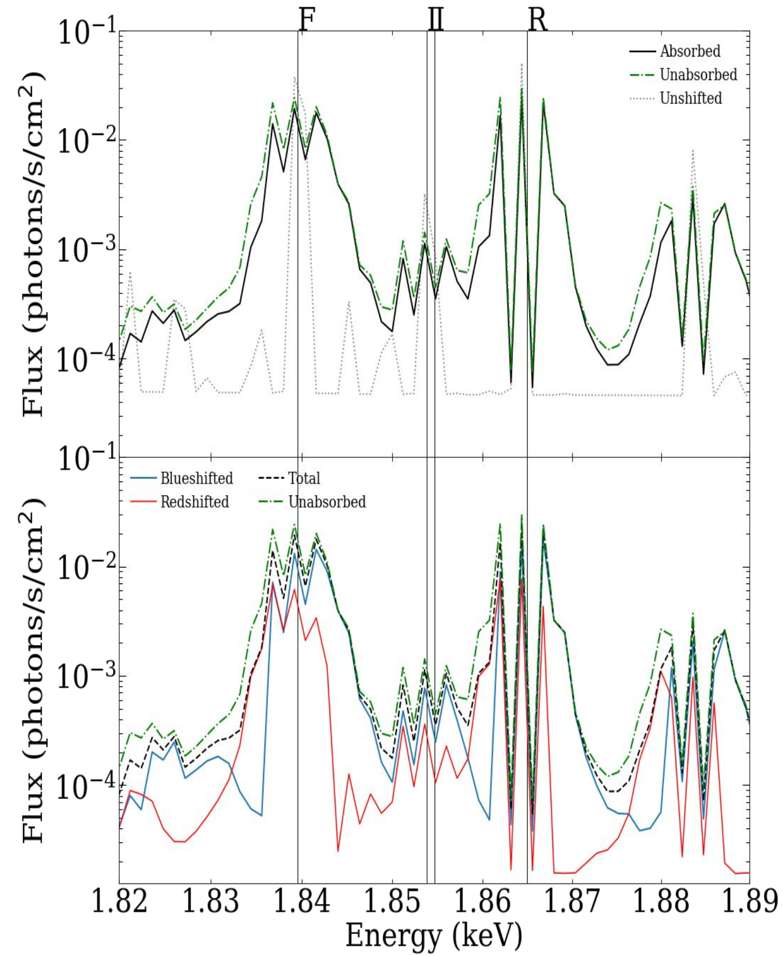
Expanding the ChN Parameter Space

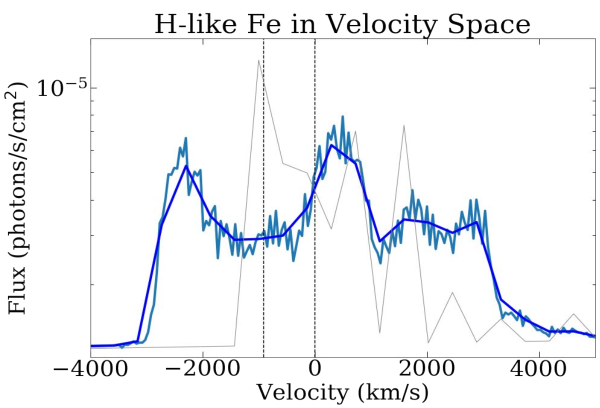
Absorption and Emission in Unresolved Remnants

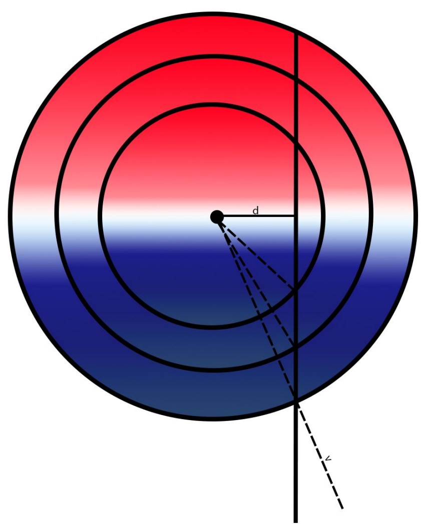
- Asymmetric Emission
  - Far side of remnant is redshifted, near side is blueshifted

    Far side will be more absorbed

- doppler shift varies depending on emitting cell and LOS
  - cell velocities decrease from FS to RS
  - component parallel to LOS varies based on distance from center







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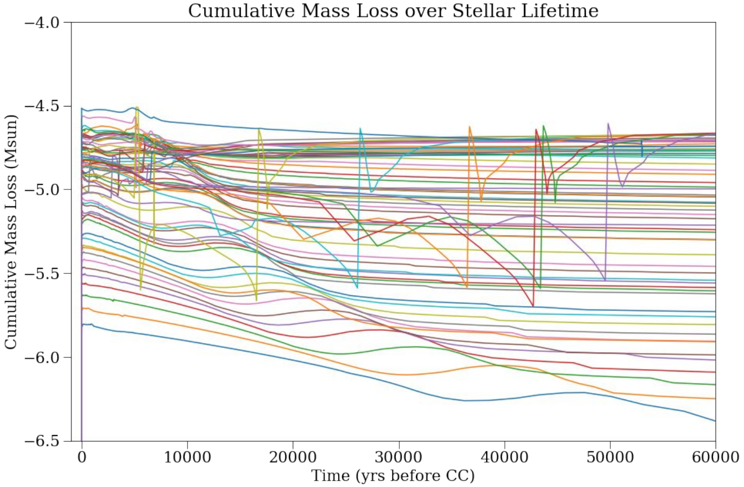
Summary and Future Work

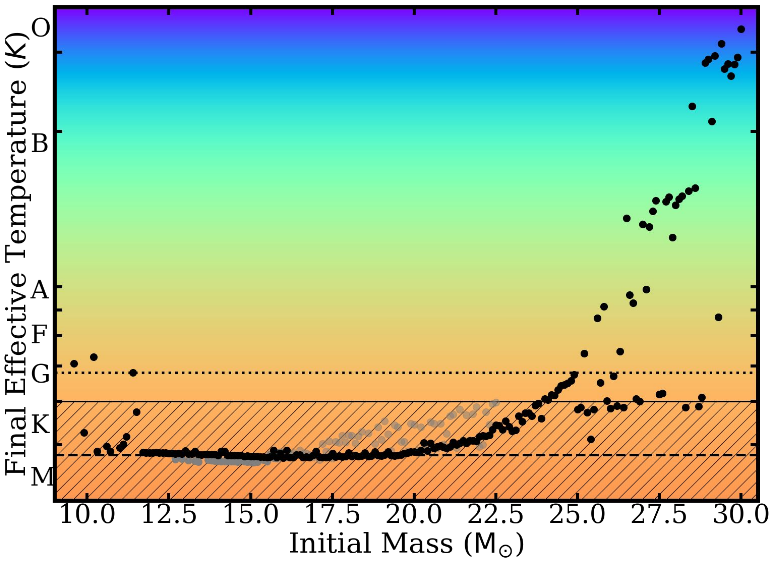
- SSC Cooling is an important contributor to GRB afterglow emission
  - Changes derived parameters compared to synchrotron-only modeling
  - **Needs no new fit parameters**
  - Need to apply to real data (ongoing)
- SNRs and progenitors are broadly consistent with observation
  - Ejecta mass similar across all models
  - H-envelope size consistent with expectations for SNe sub-types
  - RSG mass loss is detectable in the X-Ray spectra
    - Effects present in centroid energy and luminosity
- Remnant dynamics and absorption are important
  - can offer glimpse of structure for unresolved remnants
  - can set limits on when PWNe or CCO would be detectable
- Need to consider additional mass loss prescriptions
  - Implementing wave-driven mass loss
- Ib and Ic SNe mass loss mechanisms (The GRB/SNe connection!)

Extra Slides

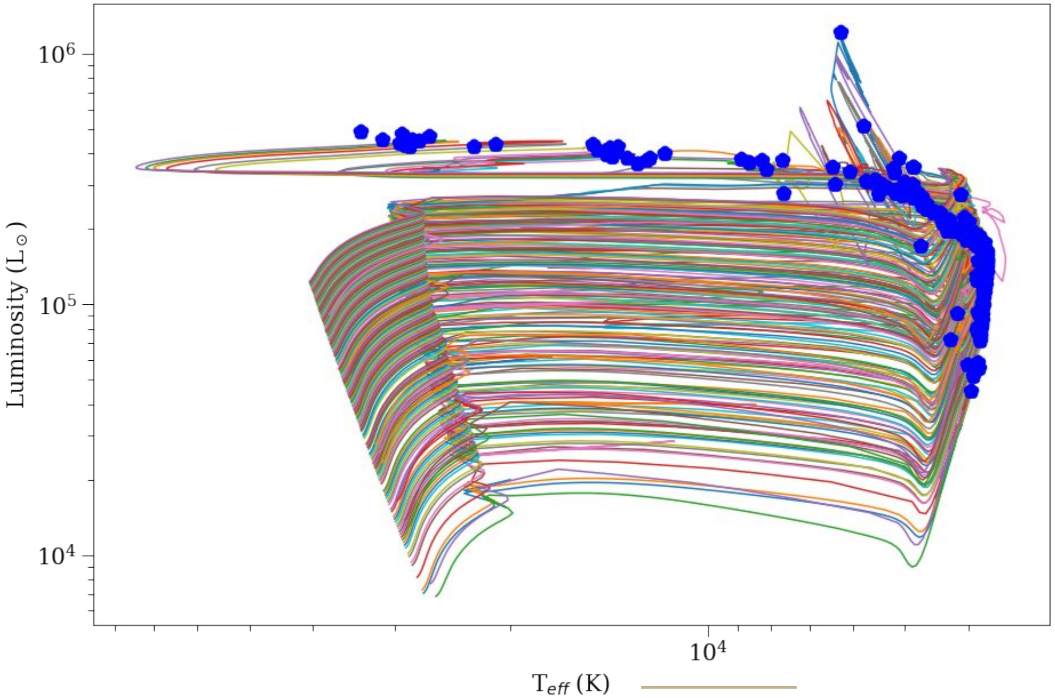
Extra Plots



Cumulative Mass Loss over Stellar Lifetime
Cumulative Mass Loss (Msun)
−4.0
−4.5
−5.0
−5.5
−6.0
−6.5
0
10000
20000
30000
40000
50000
60000
Time (yrs before CC)

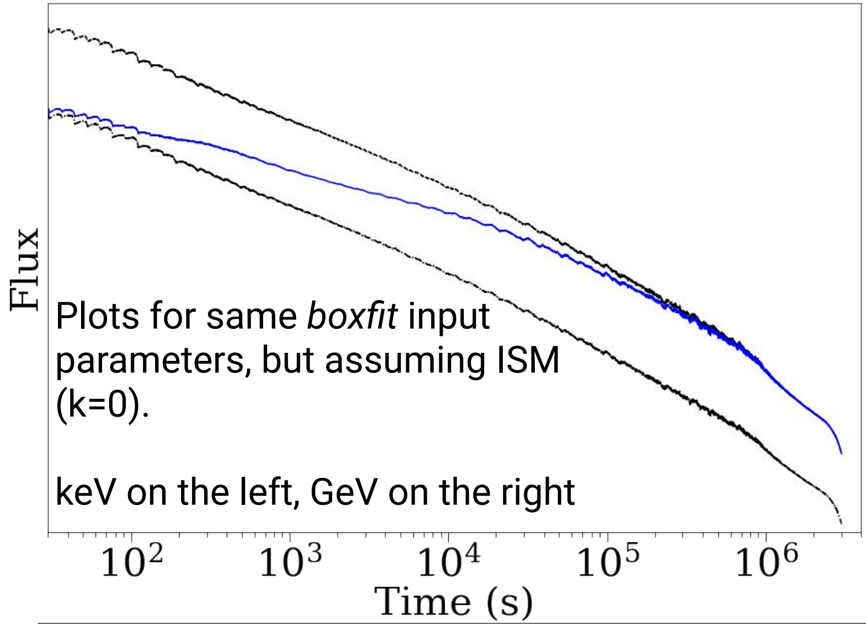


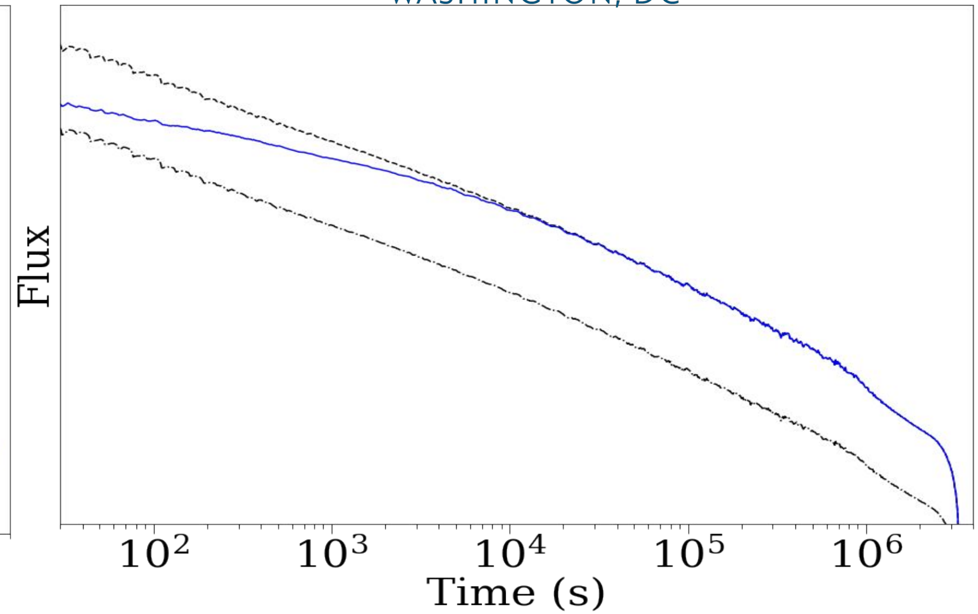
Final Effective Temperature (K)
O
B
A
F
G
K
M
10.0
12.5
15.0
17.5
20.0
22.5
25.0
27.5
30.0
Initial Mass (M⊙)

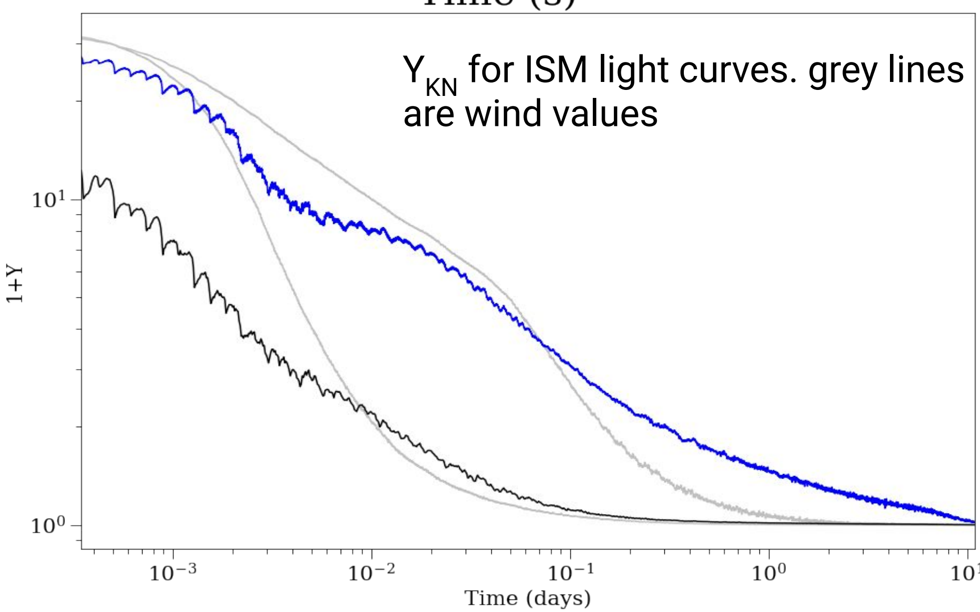


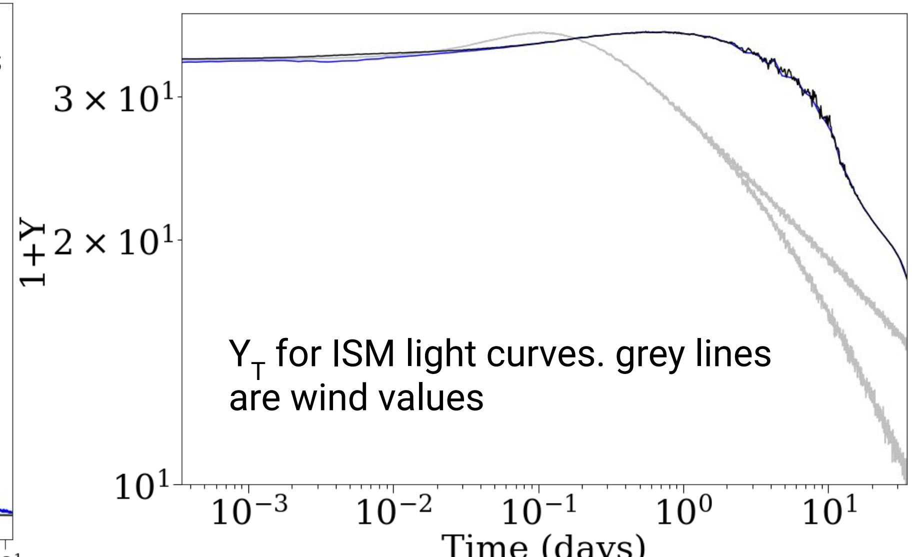
Luminosity (L⊙)
10^6
10^5
10^4
10^4
T_{eff} (K)

Extra Plots


Flux
Plots for same *boxfit* input parameters, but assuming ISM (k=0).
keV on the left, GeV on the right
10^2 10^3 10^4 10^5 10^6
Time (s)

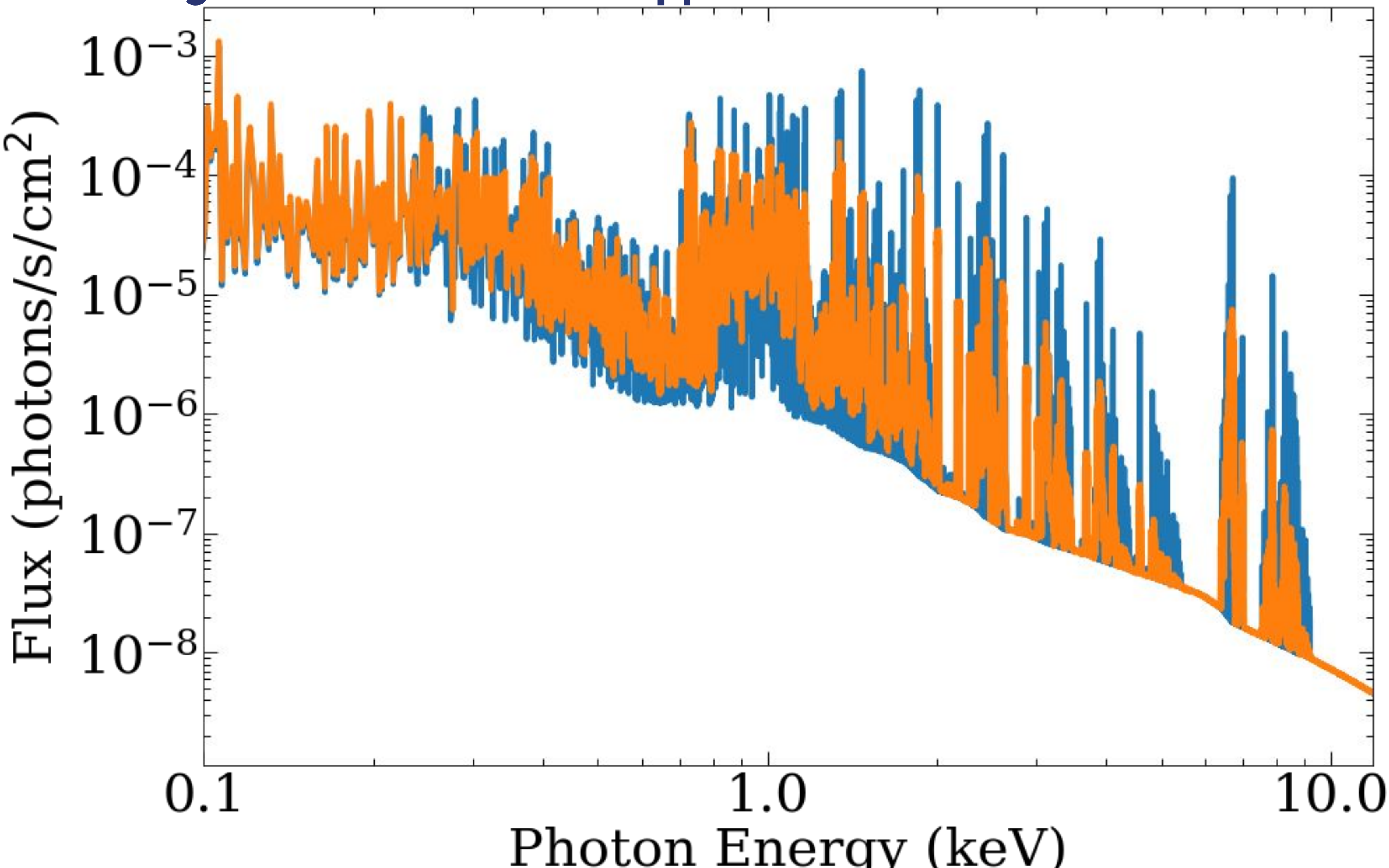

Flux
10^2 10^3 10^4 10^5 10^6
Time (s)


Y_{KN} for ISM light curves. grey lines are wind values
1+Y
10^1
10^0
10^{-3} 10^{-2} 10^{-1} 10^0 10^1
Time (days)

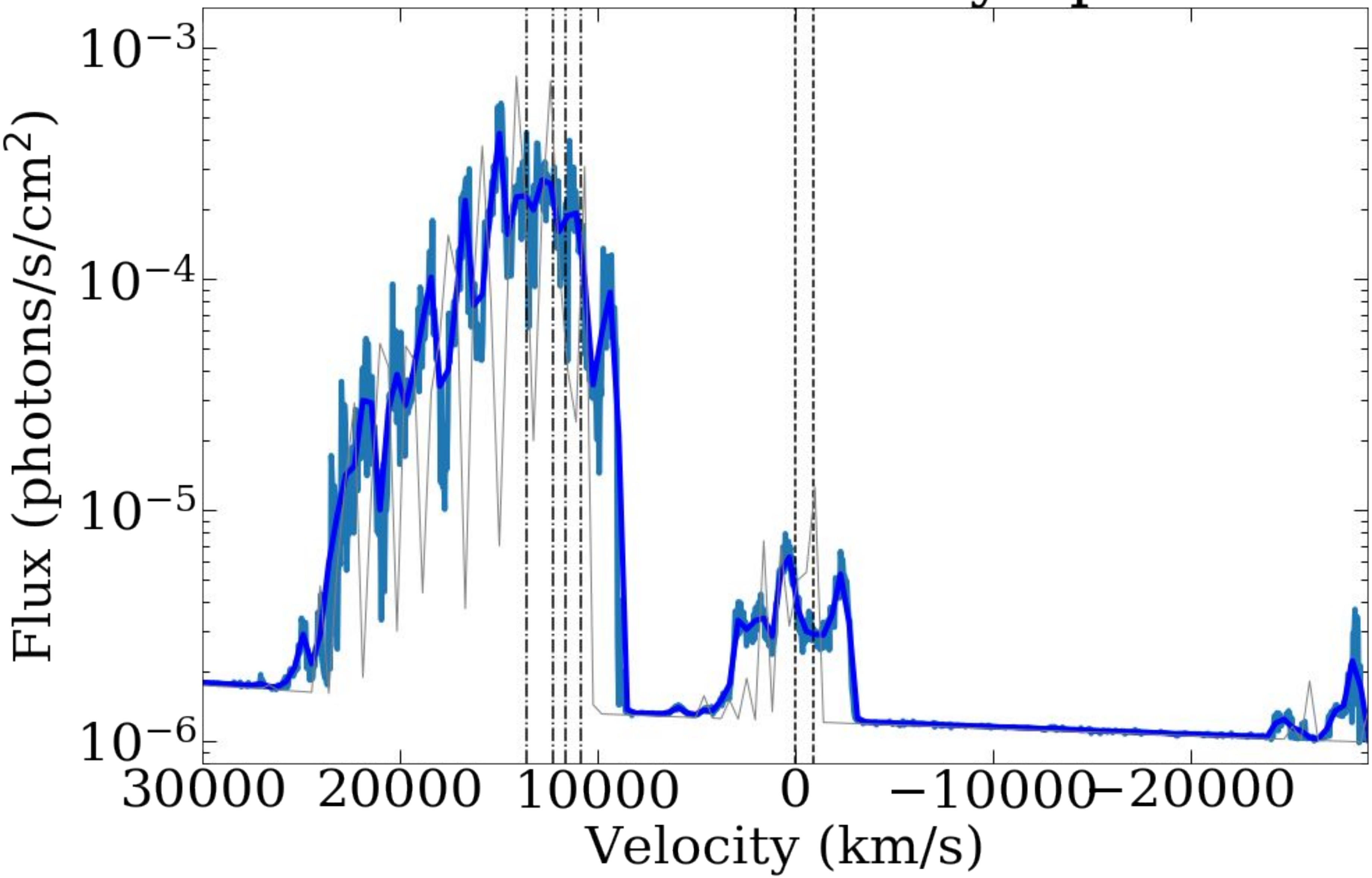

Y_T for ISM light curves. grey lines are wind values
1+Y
3×10^1
2×10^1
10^1
10^{-3} 10^{-2} 10^{-1} 10^0 10^1
Time (days)

Extra Slides:

Line of Sight Calculations III: Doppler Shift



H-like Fe in Velocity Space



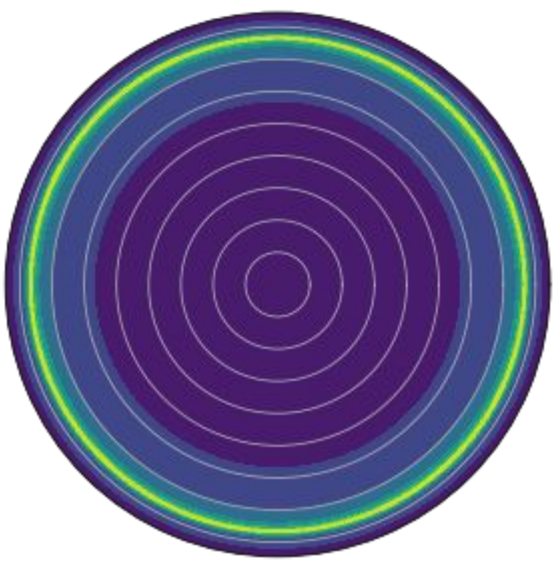
THE GEORGE WASHINGTON UNIVERSITY
WASHINGTON, DC

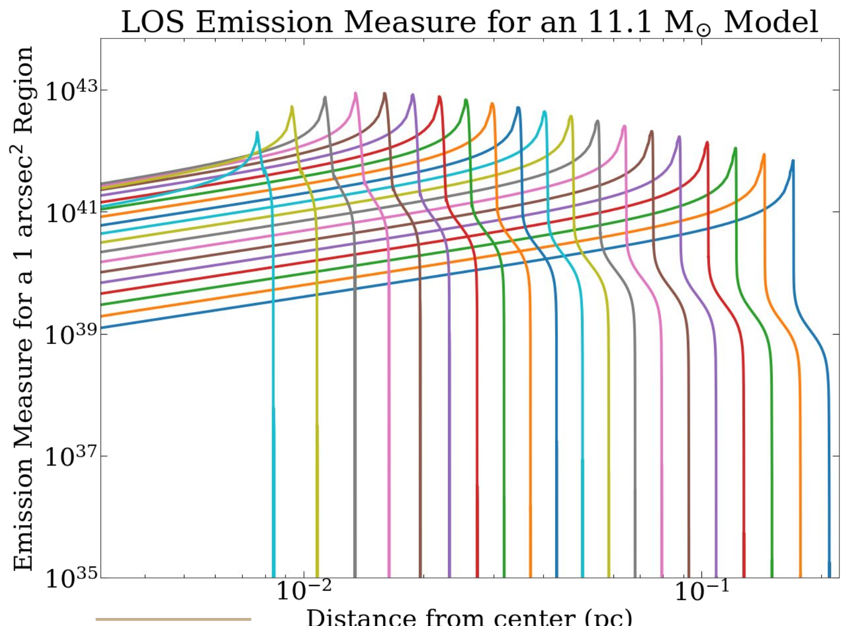
CENTER FOR ASTROPHYSICS
HARVARD & SMITHSONIAN

Young Remnants from ChN

Line of Sight Calculations

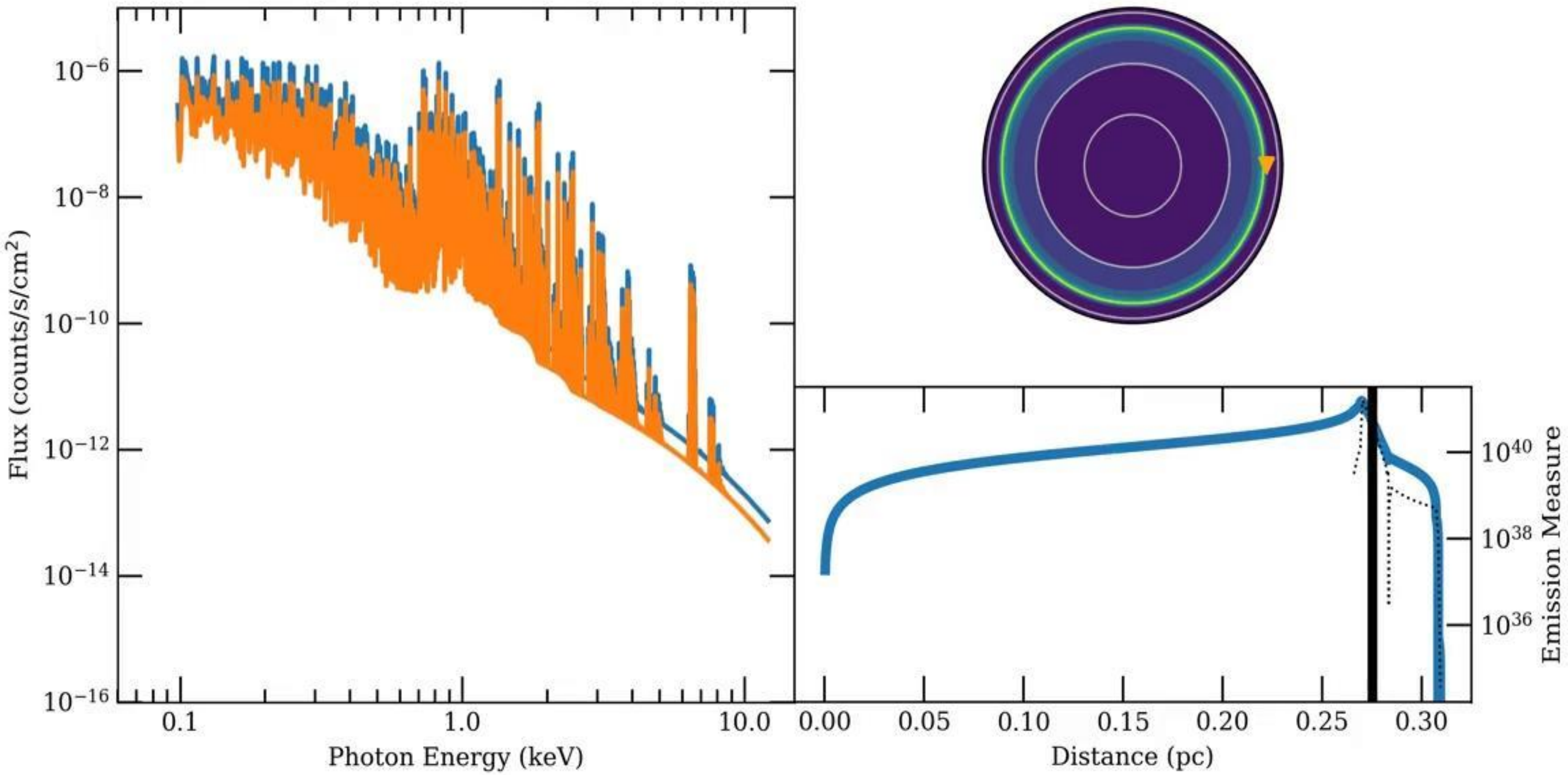
- Remnants are viewed as 2D projections
  - Spectra composed of “Pencil beam” passing through remnant
    Multiple shock regions contributing to emission
  - Intra-remnant absorption may become important
    Depends on optical depth of remnant
  - shock velocity vector changes along LOS
    Spectra have a redshifted and blueshifted component





Young Remnants from ChN

Line of Sight Calculations II: Absorption



Synchrotron-Self Compton Emission

Our Roadmap to Including SSC Cooling

- Define how SSC cooling affects the cooling Lorentz factor
- Determine analytic forms of the effect in all cooling regimes and at the transition
- Incorporate effects due to inelastic scattering at high energies (Klein-Nishina effects)
- Incorporate results into the afterglow modeling code *boxfit* (van Eerten et al. 2012)

Young Remnants from ChN

Line of Sight Calculations III: Doppler Shift