# MeV gamma rays from NSMs: a distinct signature of fission


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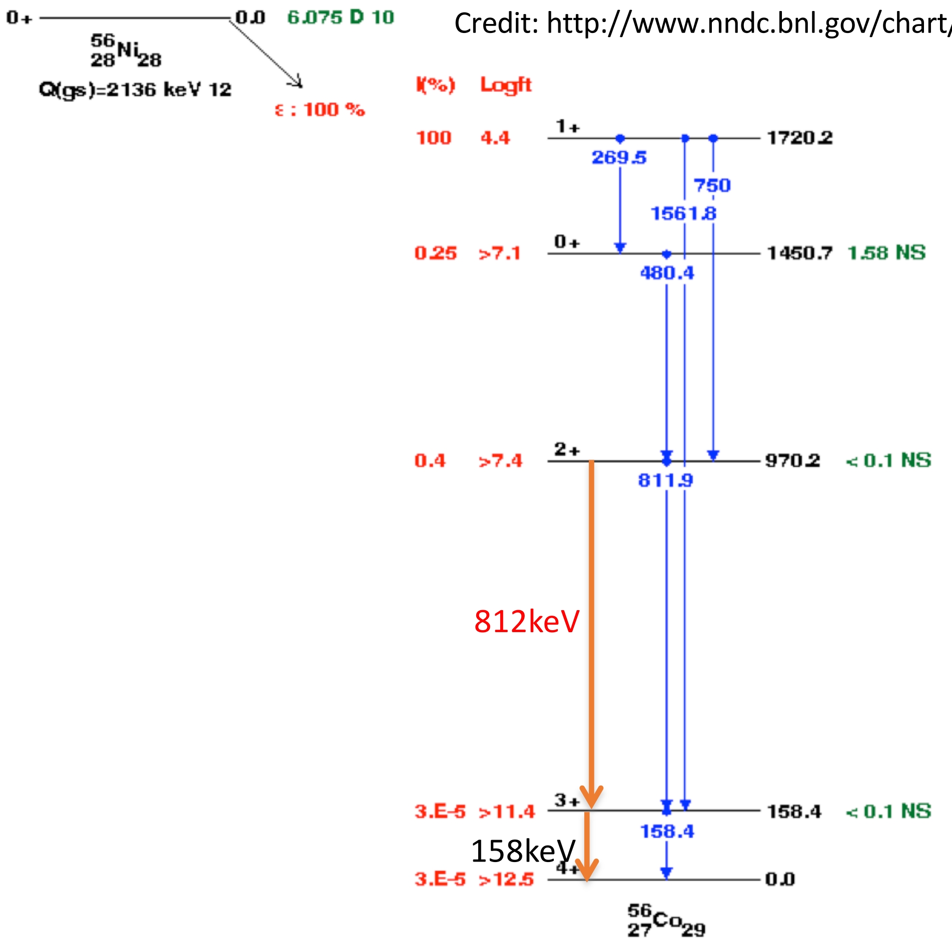
arXiv:2008.03335

# MeV Gamma rays (<~10MeV) from nucleosynthesis

- Gammas from radioactive decays:
  - ✓Alpha decay
  - ✓Beta decay
  - ✓Nuclear reactions like neutron capture, nuclear fission, nuclear fusion
  - ✓Nuclear isomers
- Example: $^{56}$Ni decay chains

$$^{56}Ni \xrightarrow{t_{mean}=8.8\,days} {}^{56}Co+\gamma$$

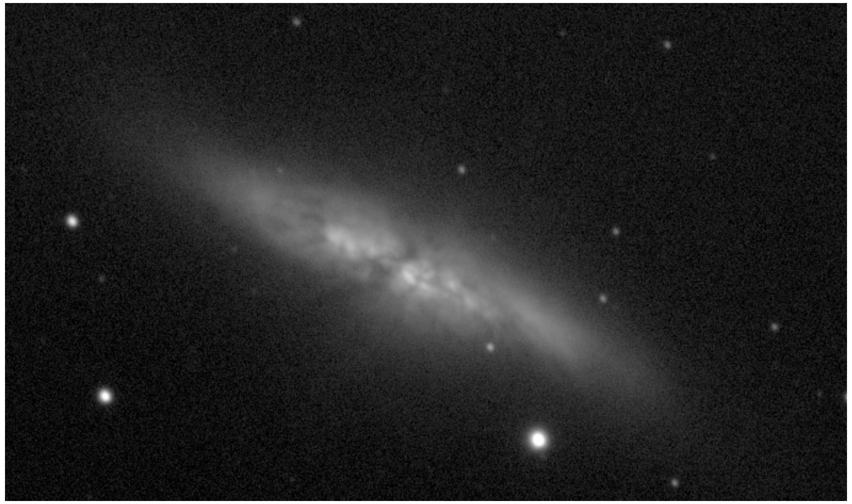
$$^{56}Co \xrightarrow{t_{mean}=111.3\,days} {}^{56}Fe+\gamma$$




Credit: http://www.nndc.bnl.gov/chart/

# MeV gamma rays from supernovae

- Type Ia SN:
  - SN2014J in M82 with distance 3.5 Mpc, by INTEGRAL, both $^{56}$Ni and $^{56}$Co lines seen →indicate the presence of surface $^{56}$Ni
- Core collapse SN:
  - SN1987A in the Large Magellanic Cloud with distance 51.4 kpc, by Solar Maximum Mission satellite, $^{56}$Co lines detected →indicate an opaque ejecta



SN2014J in M82

Credit: UCL/University of London Observatory/Steve Fossey/Ben Cooke/Guy Pollack/Matthew Wilde/Thomas Wright

SN1987A in LMC
Credit: ESO

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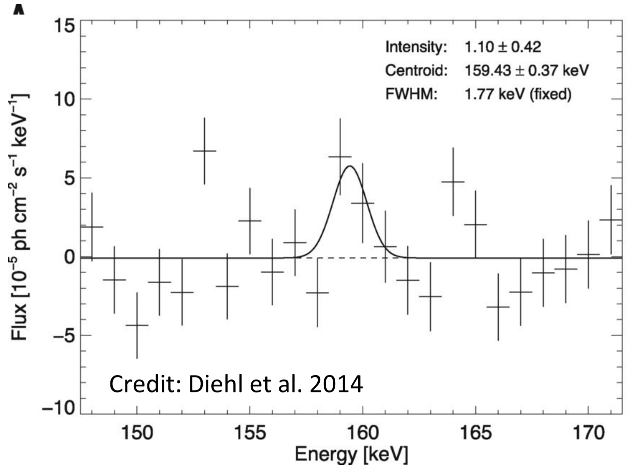
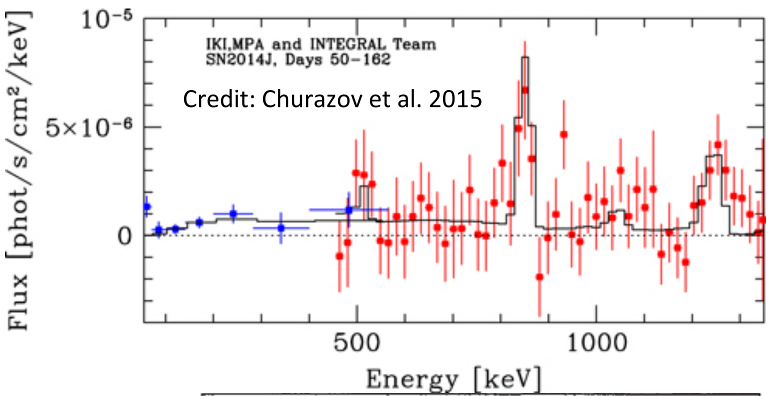
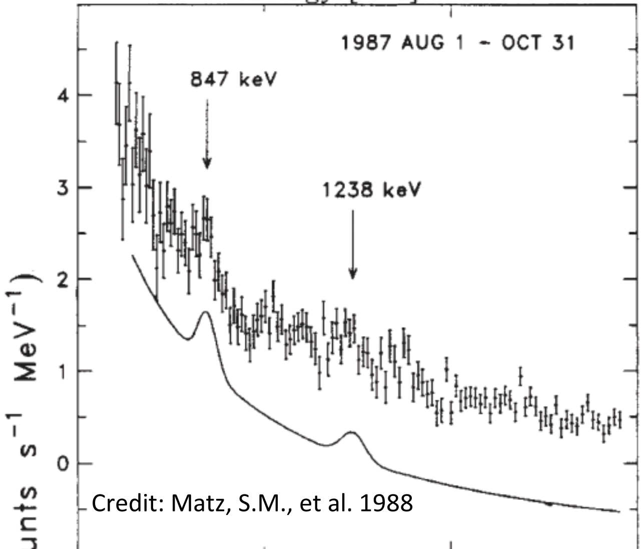
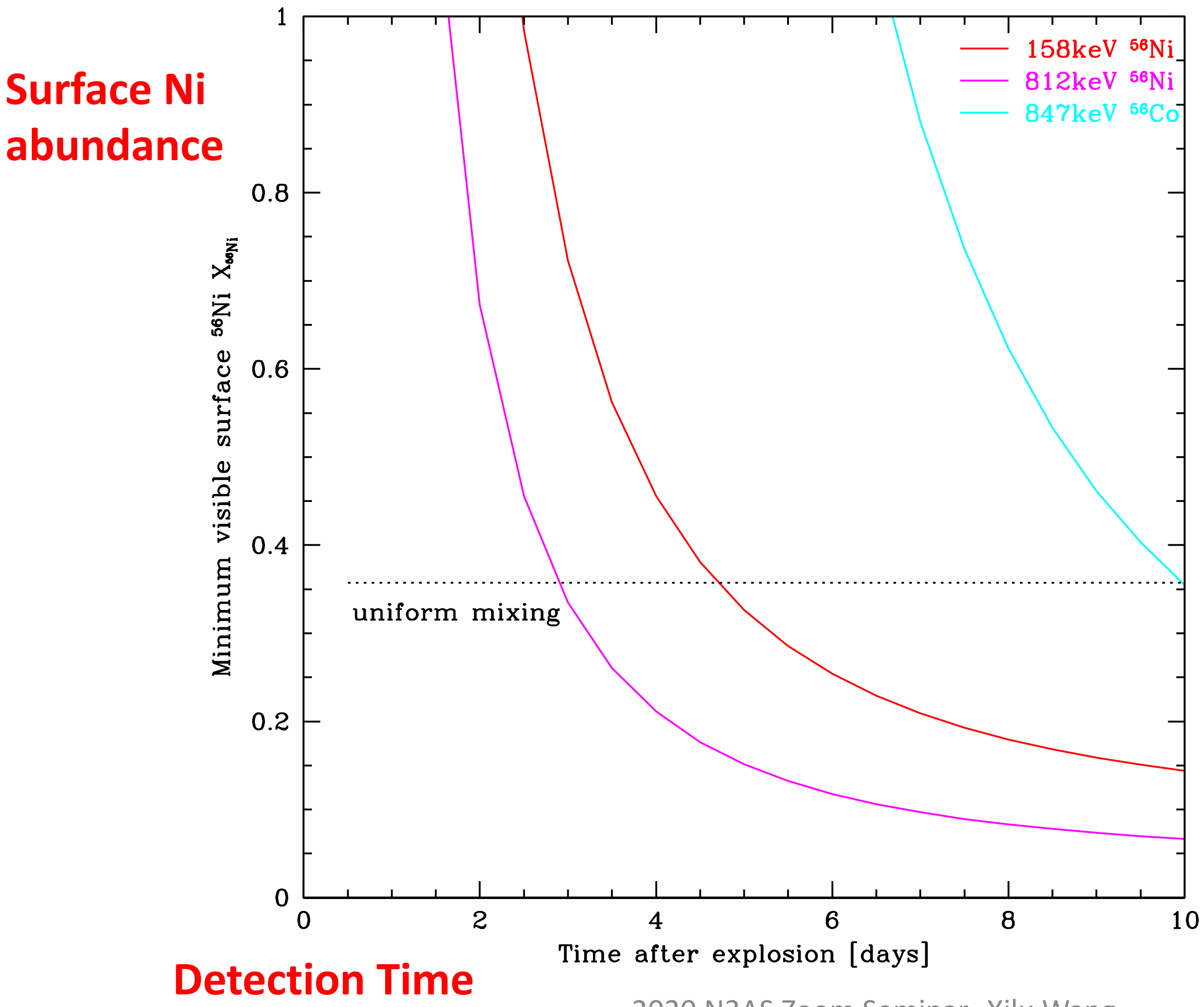


# Using gamma-ray detection to explore surface $^{56}$Ni mixing




Early time SNIa signal: optically thick

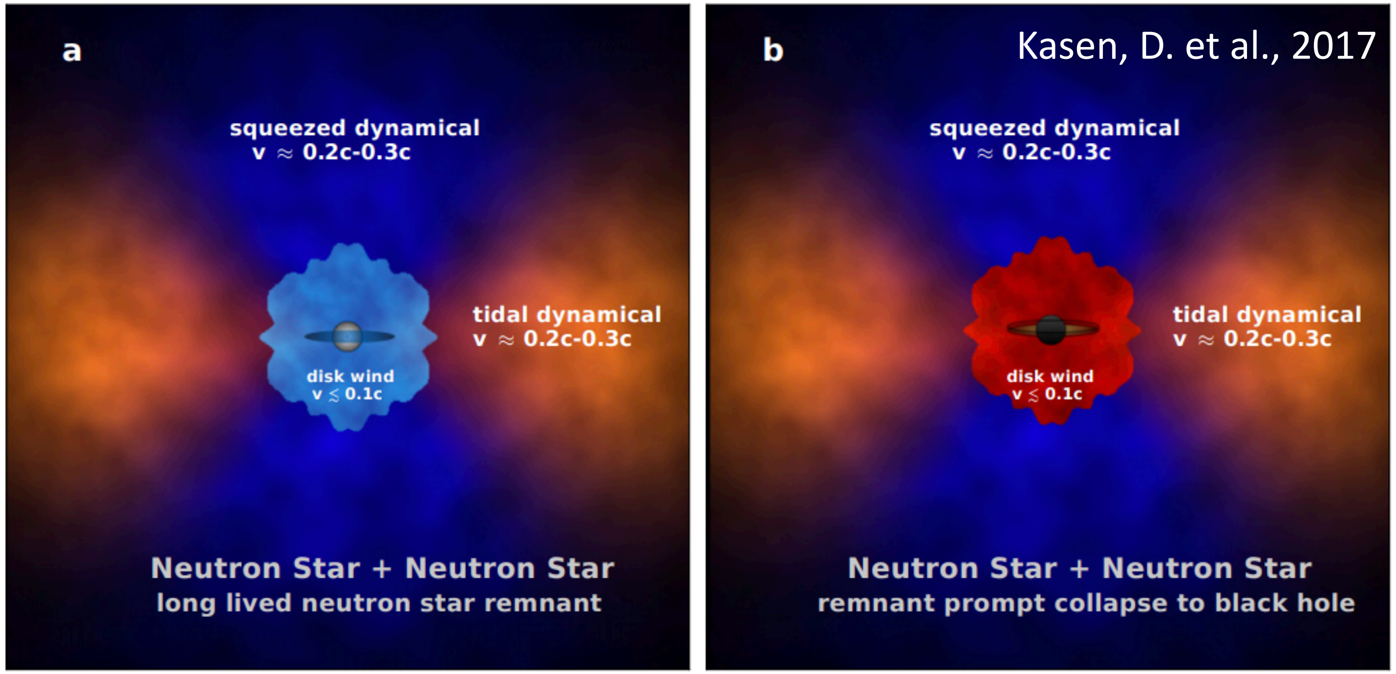
$$\Phi_{Ni}(E_i,t) = \frac{b_{E_i} X_{Ni}}{4 A_{Ni} Y_e \sigma} \frac{a^2(t)}{D^2} \frac{e^{-t/\tau_{Ni}}}{\tau_{Ni}}$$

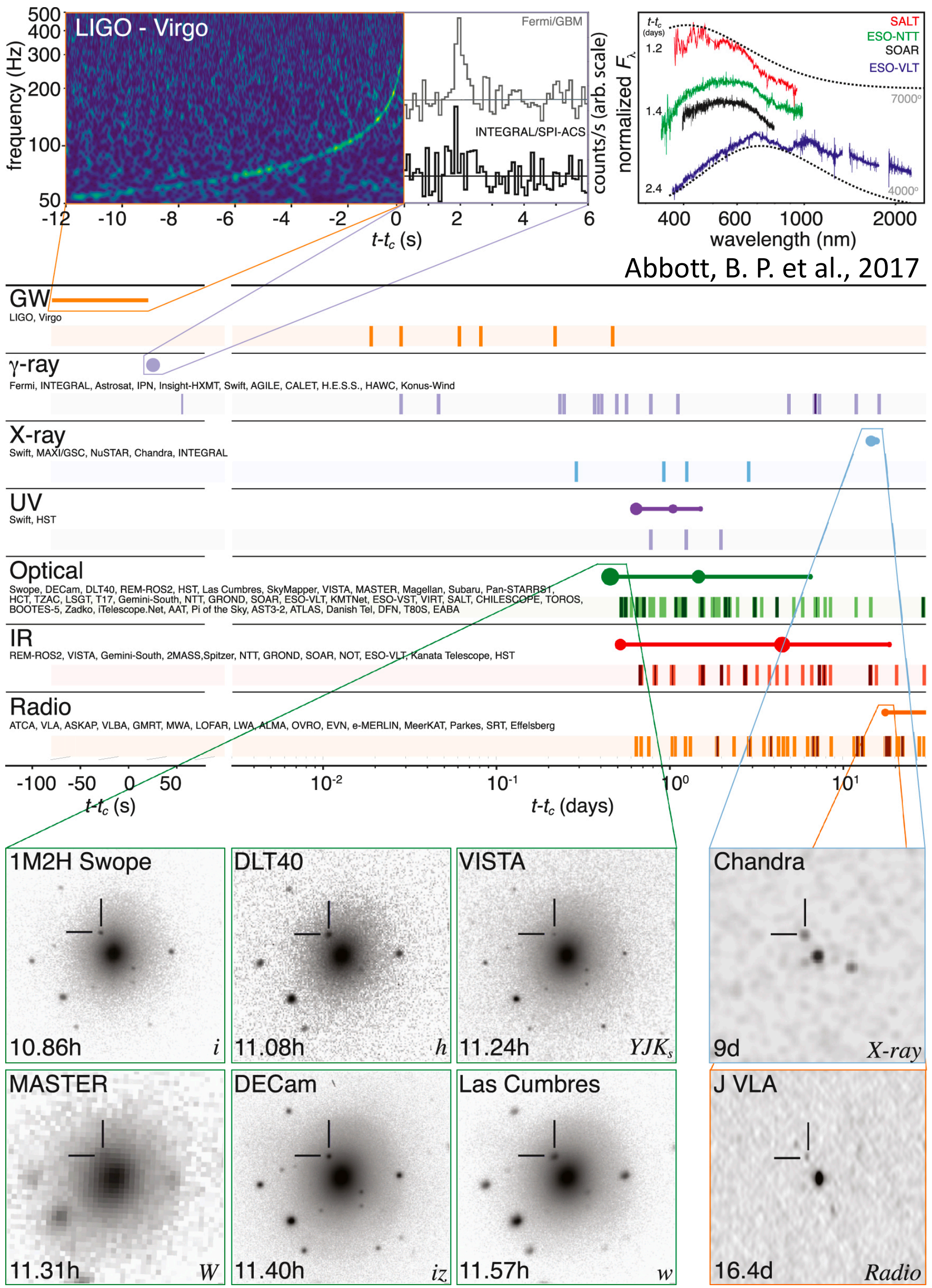
$$\sim \Phi_{background}(E_i)$$

X. Wang, B. Fields, & A. Lien, 2019, MNRAS, 486, 2910, arXiv:1904.04310

# Neutron star mergers

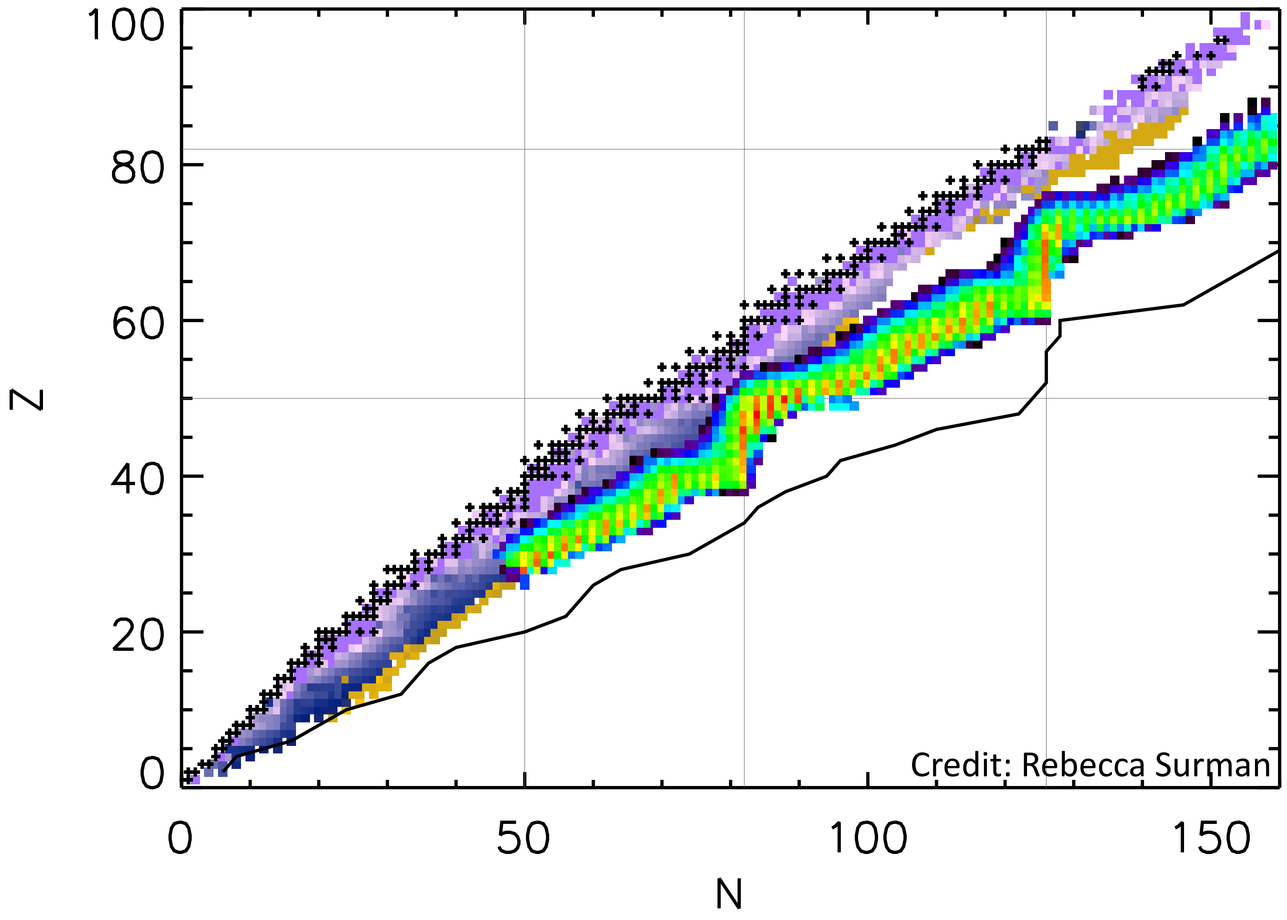
- GW170817: multi-wavelength observation
- r-process nucleosynthesis sites
- Matter ejected at high velocity: <$v$>~0.1$c$-0.3$c$



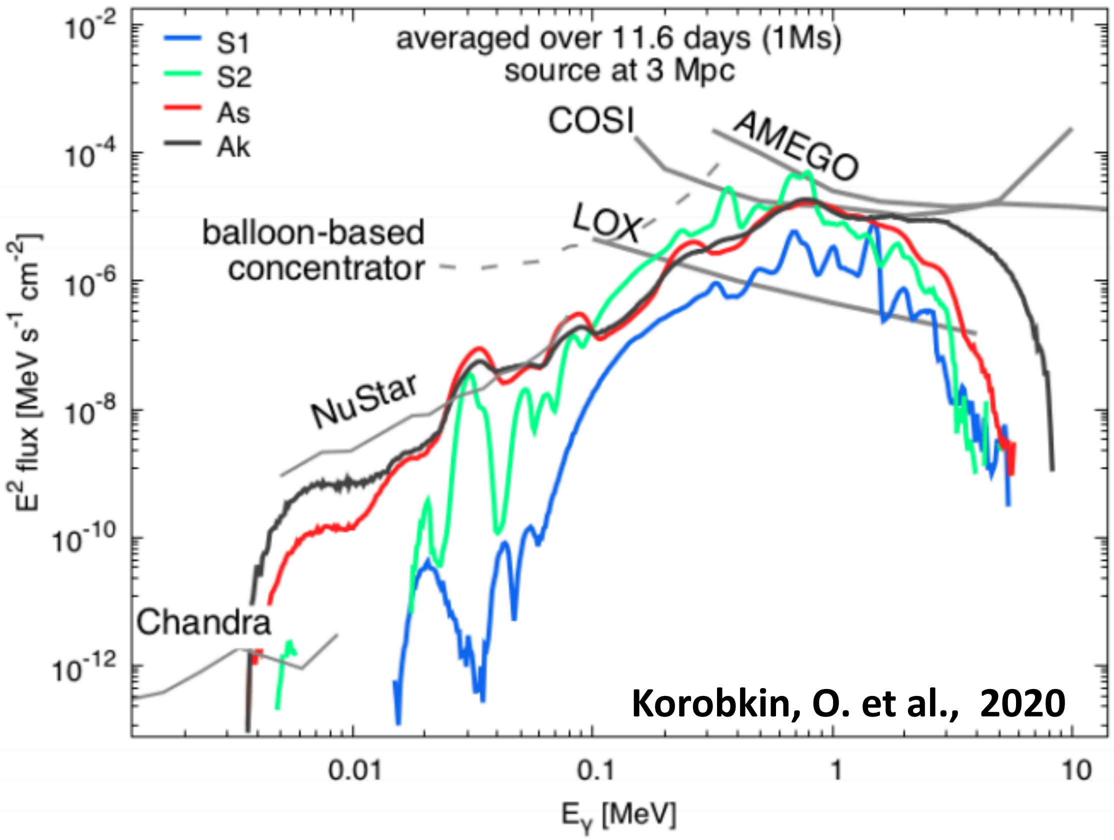



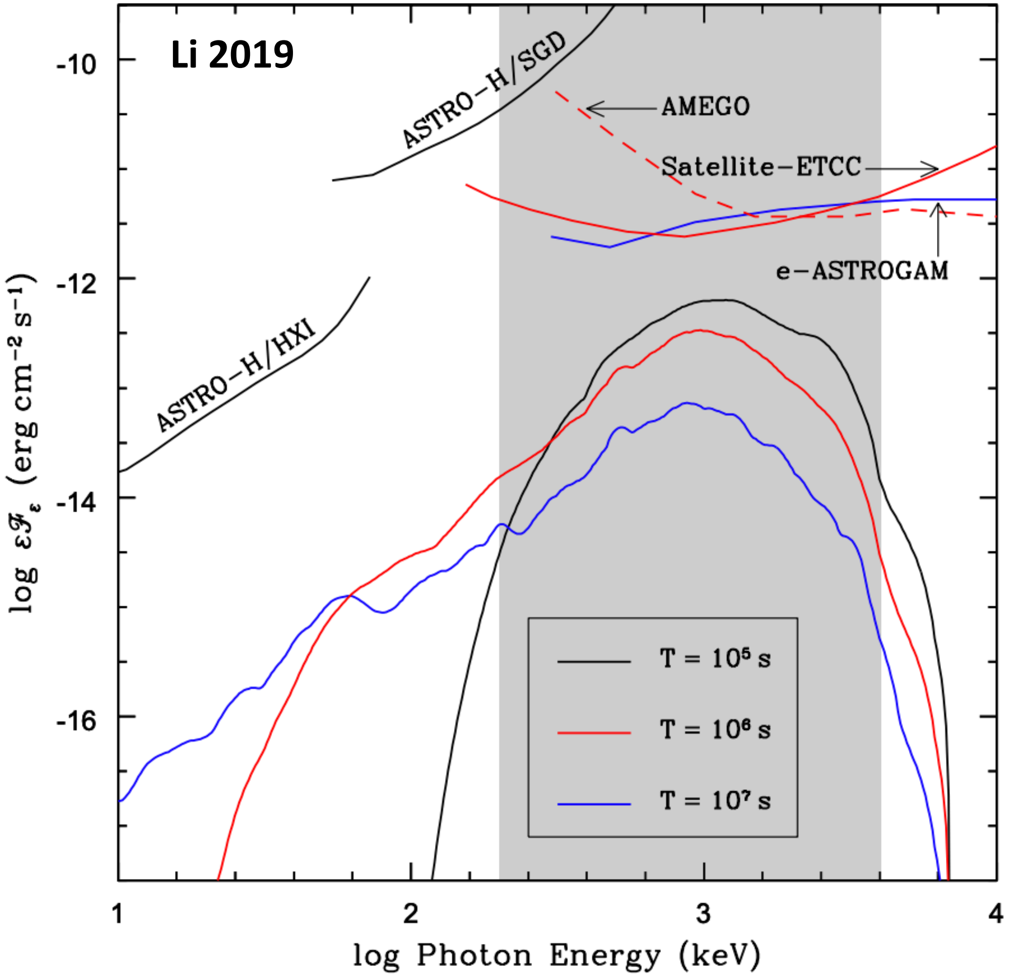
# r-process nucleosynthesis

- Rapid neutron-capture process (r process):
  - ✓Create ~half of the nuclei heavier than iron
  - ✓Thousands of nuclei far from stability are created and decay via alpha decay, beta decay and fission



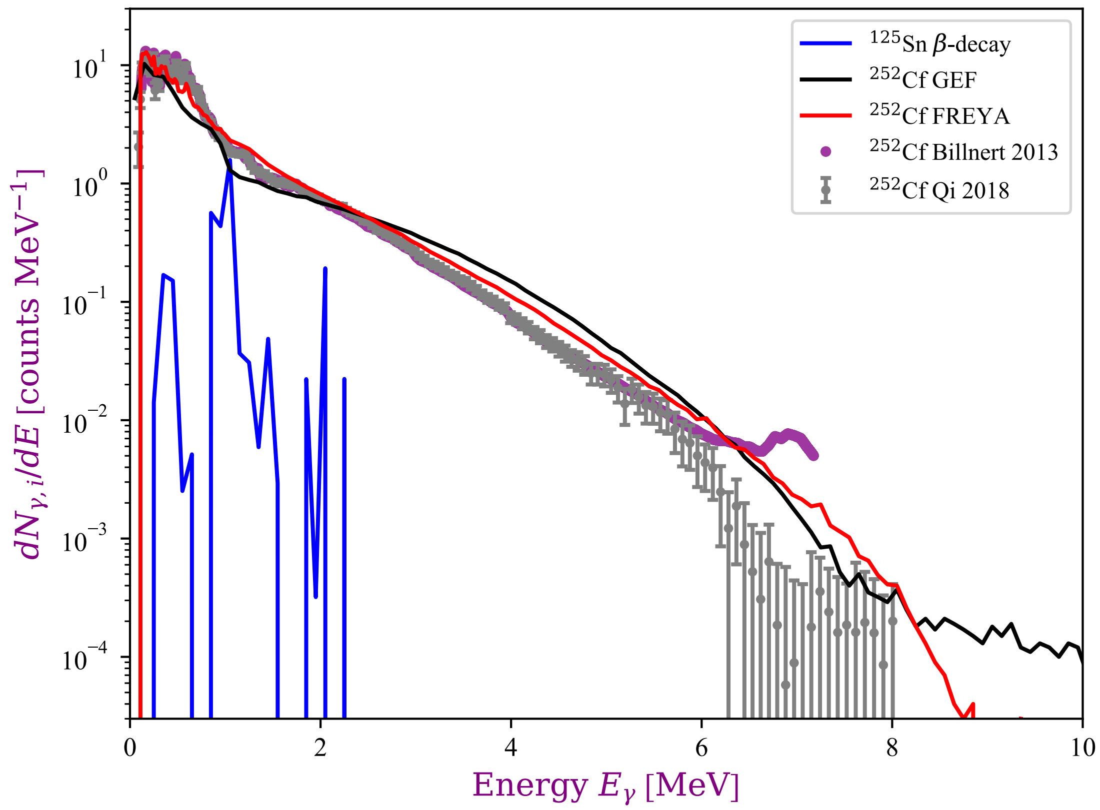
# Previous studies in NSM gamma rays



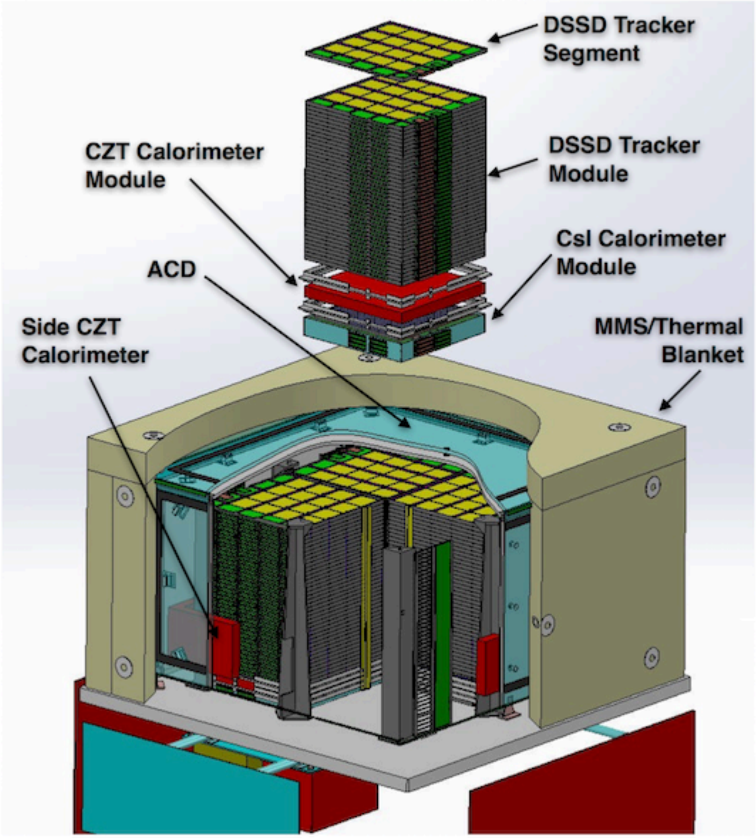
# MeV gamma rays from neutron star mergers

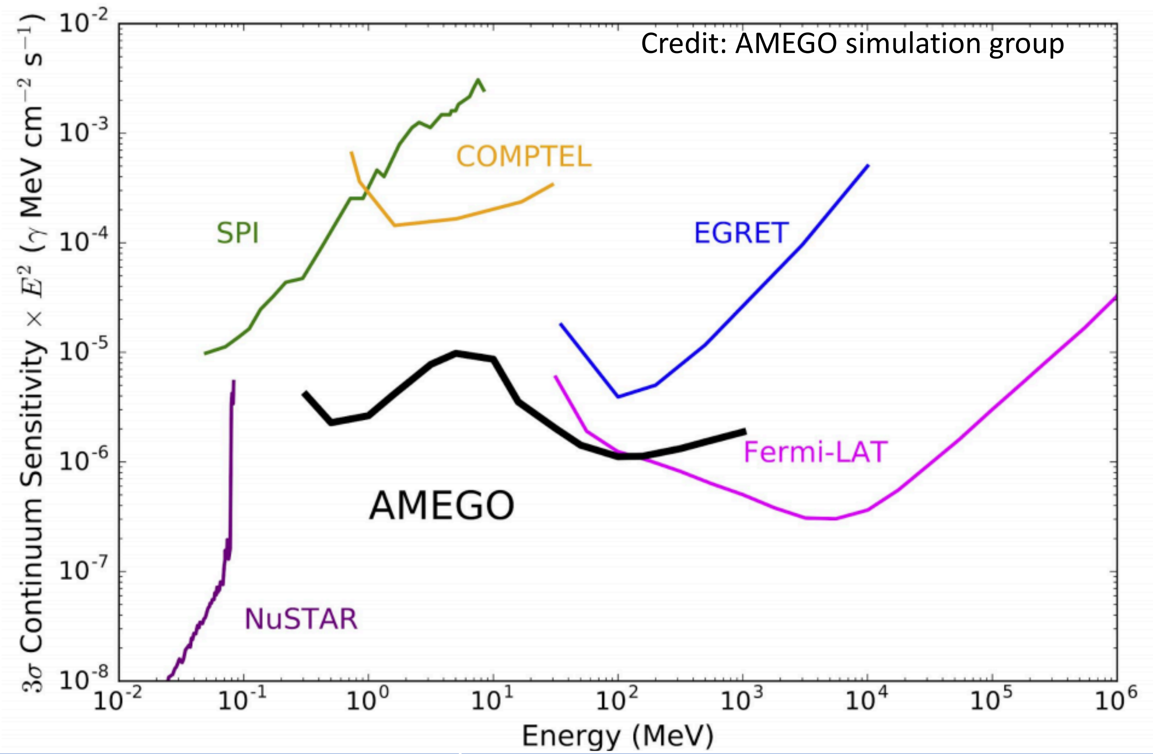
- Prompt gamma-ray photons emitted from r-process:
  - Beta decays, experimental data from ENDF/B-VIII.03 (Brown et al. 2018), theoretical calculations from LANL work (Korobkin et al., 2020)
  - Fission, theoretical calculation from GEF (Schmidt et al. 2016) and FREYA (Vogt & Randrup 2017) as in Vassh et al., 2019.




**Wang, X., et al. 2020 arXiv:2008.03335**

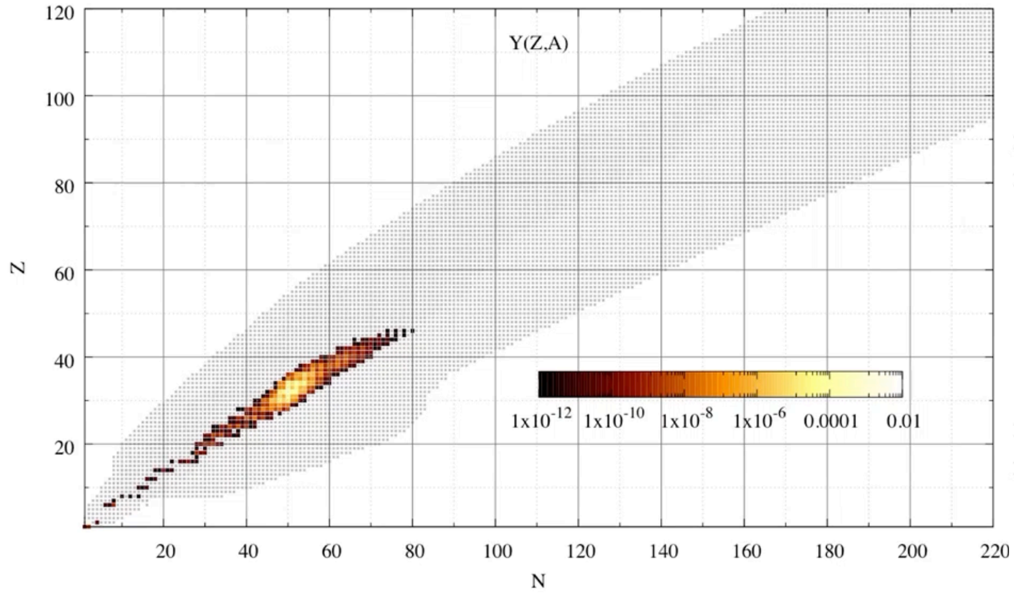
# AMEGO--All-sky Medium Energy Gamma-ray Observatory

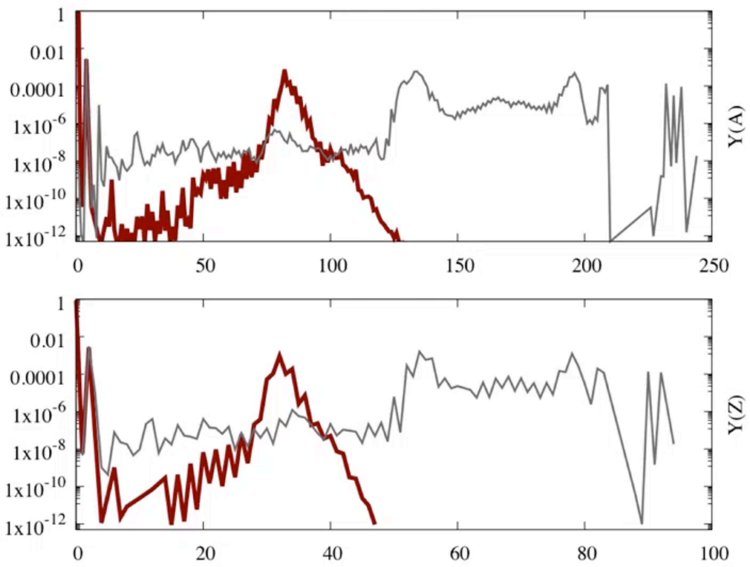


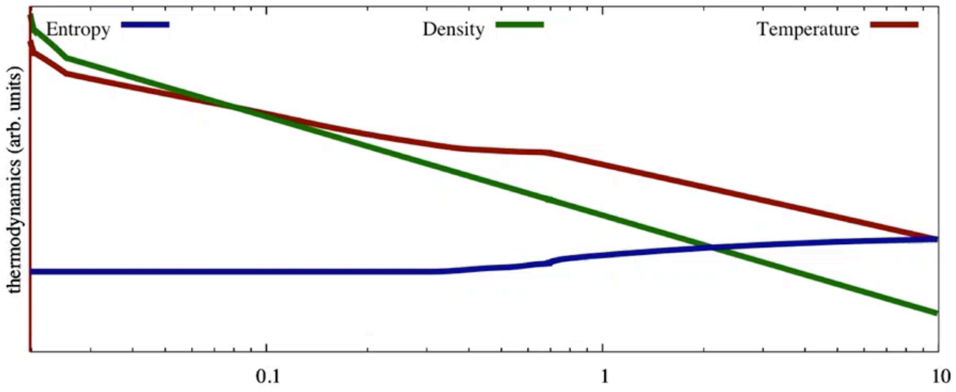




| PARAMETER | CAPABILITY |
|---|---|
| Energy range | ~200 keV to >10 GeV |
| Continuum sensitivity (MeV $s^{-1}$ $cm^{-2}$) | $4x10^{-6}$(1 MeV); $4.8x10^{-6}$(10 MeV); $1x10^{-6}$(100 MeV) |
| Field of view | 2.5 steradian |
| Energy resolution | <1% below 2 MeV; 1-5% at 2-100 MeV; ~10% at 1 GeV |
| Angular resolution | 3° (1 MeV), 10° (10 MeV) |

# r process simulation with PRISM




Cold, neutron-rich dynamical ejecta from an NSM event

PRISM: Trevor Sprouse (ND) & Matthew Mumpower (LANL)

# MeV gamma rays from neutron star mergers

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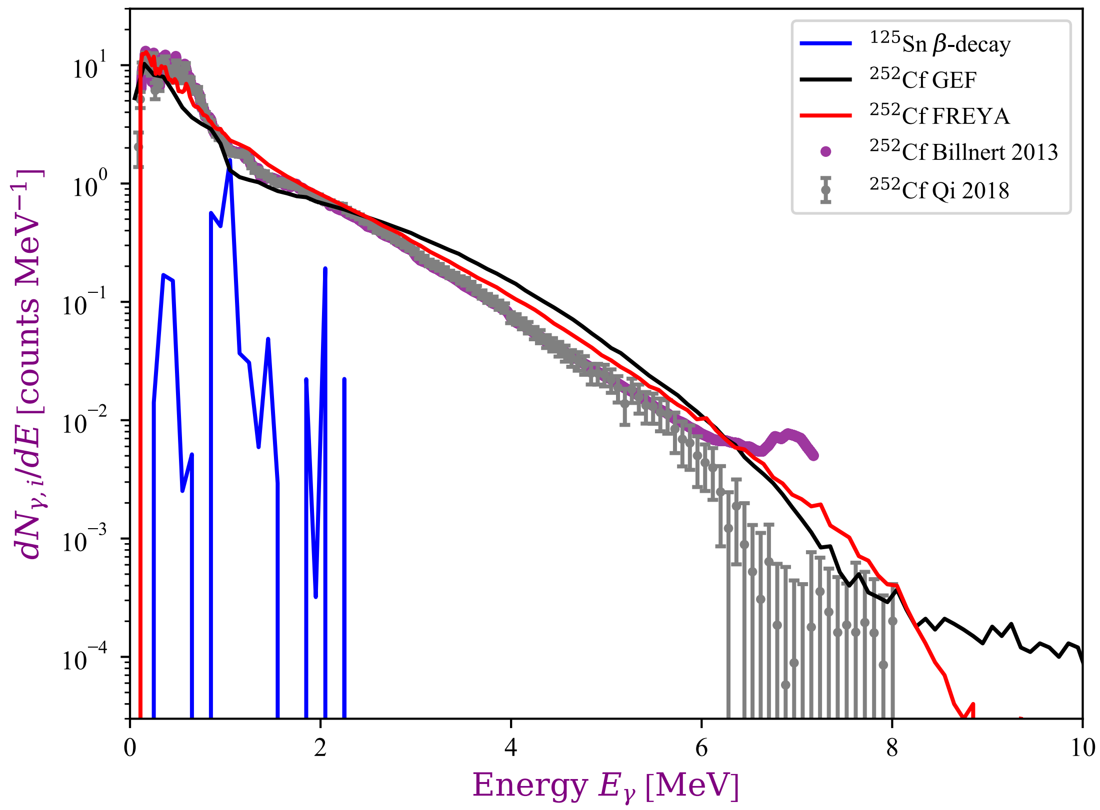
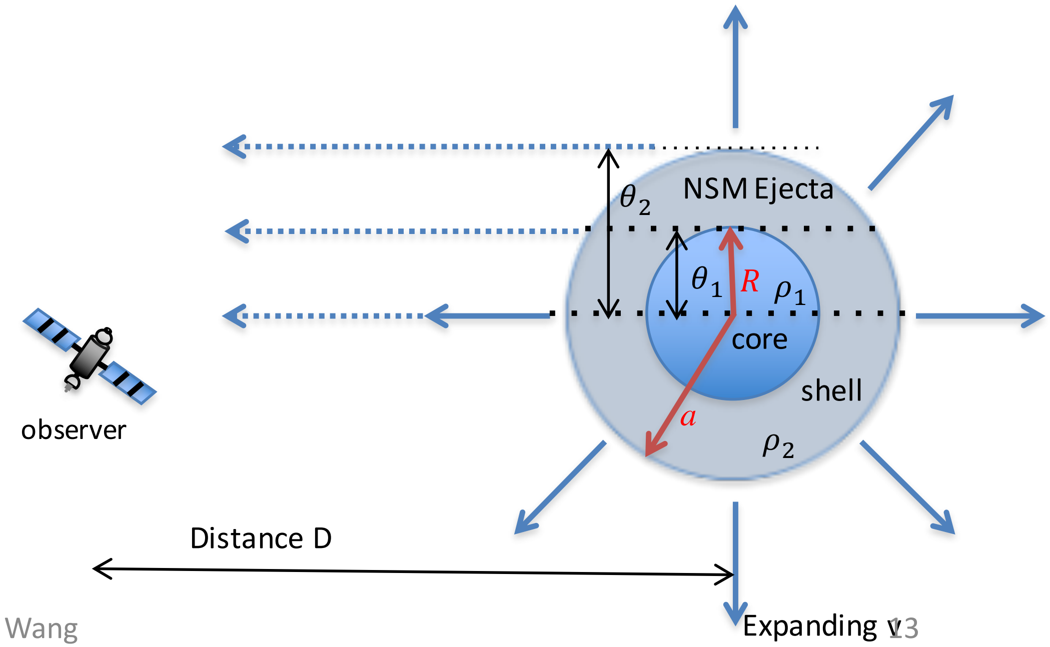



**Wang, X., et al. 2020**
**arXiv:2008.03335**

# Radiation transfer calculation

- Semi-analytical gamma-ray radiation transfer calculation adapted from Wang, X., et al 2019, MNRAS, 486, 2910
- Late time signal: when fission starts to dominate over beta decay in gamma-ray emissions; when the ejecta becomes optically thin
- Uniform ejecta: dense core + less dense
  - ✓$M_{ej}$=0.01 $M_{\odot}$, $f_{shell}$=0.1
  - ✓$\rho_1 = 2\times10^{10}$g/cm³, $\rho_2 = 2\times10^{7}$g/cm³
- Homologous expansion: $v_0$=0.3c, $v \propto r$
- A Galactic event: D=10 kpc



# Radiation transfer calculation

- The prompt emitted gamma ray photons from an r-process ejecta:

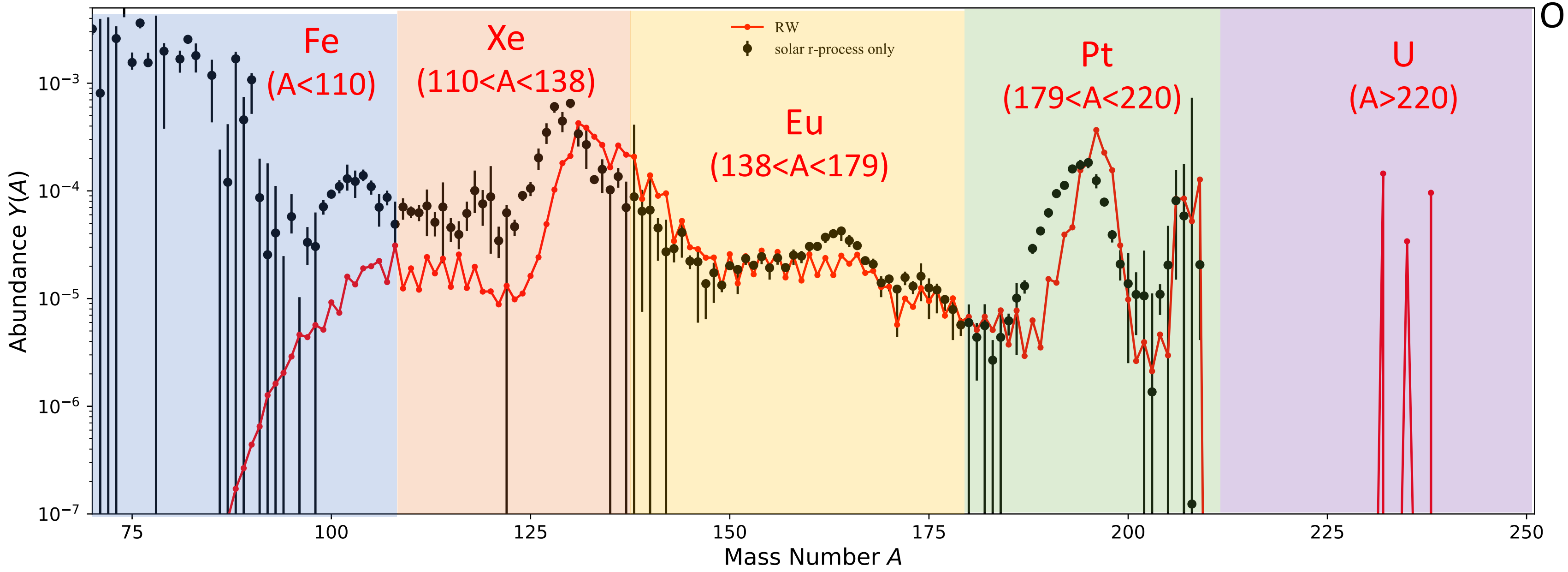
  $$L_{\gamma,emitted} = (M_{ej}/m_p)\sum_i dN_{\gamma,i}(E)/dEdt$$

- Get the observed intensity $I_E$ by solving the radiative transfer equation $\frac{dI_E}{dl} = -\alpha(E)I_E + j_E$, with absorption coefficient $\alpha(E) = \rho\kappa(E)$, $\kappa(E)$ is the opacity for gamma-ray photons propagating through the r-process ejecta. The source term $j_E = L_{\gamma,emitted}/4\pi\mathrm{V}$.
- The total observed flux then is $F_E = \int I_E cos\theta d\Omega$
- Doppler shift effect is included.

# Opacity for gamma-ray photons

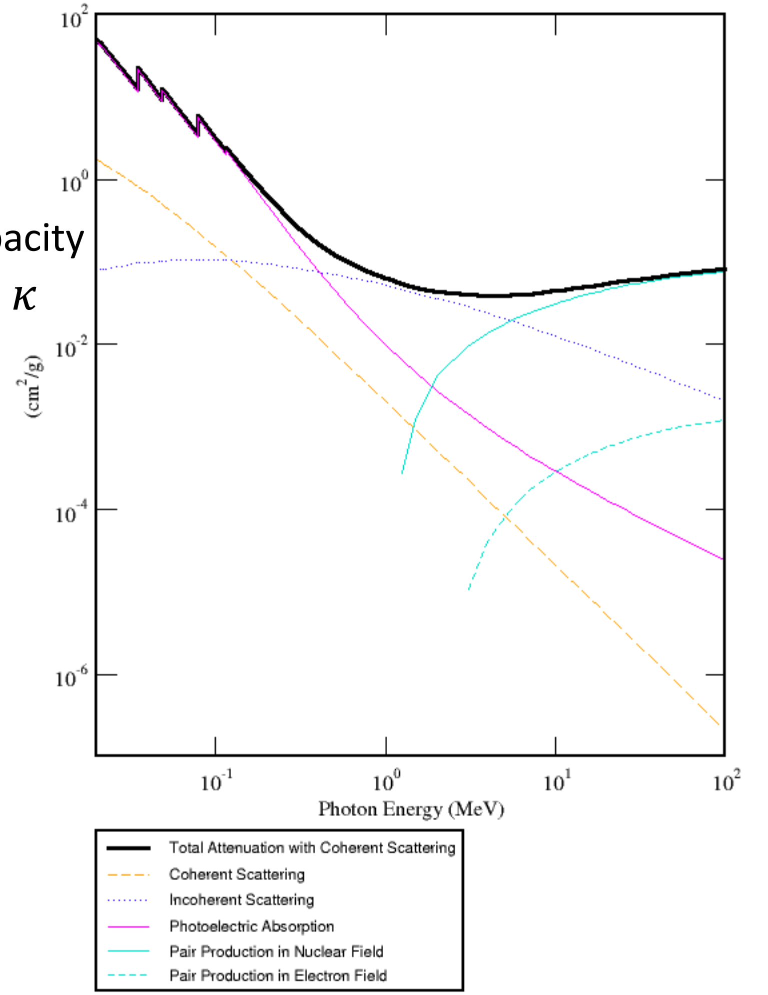
- Based on the ejecta composition

e.g., dynamical ejecta with FRLDM fission barrier:




Opacity

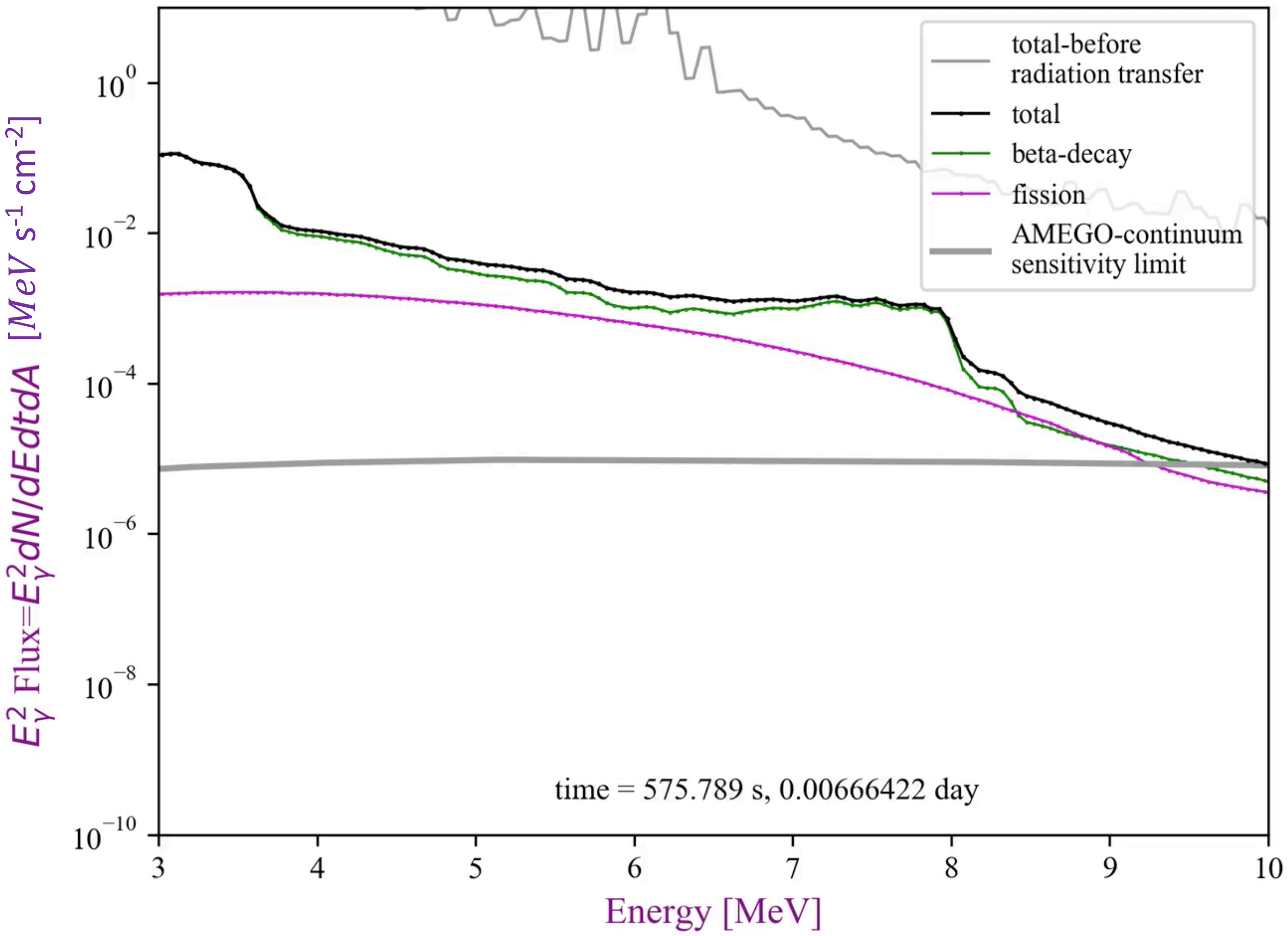
$\kappa$




- NIST XCOM: Photon Cross Sections Database (1keV-100 GeV)
  - incoherent (Compton) scattering, coherent (Rayleigh) scattering, photoelectric absorption, and pair production in the field of the atomic nucleus and in the field of the atomic electrons.

https://www.nist.gov/pml/xcom-photon-cross-sections-database

# MeV gamma-ray spectrum evolution



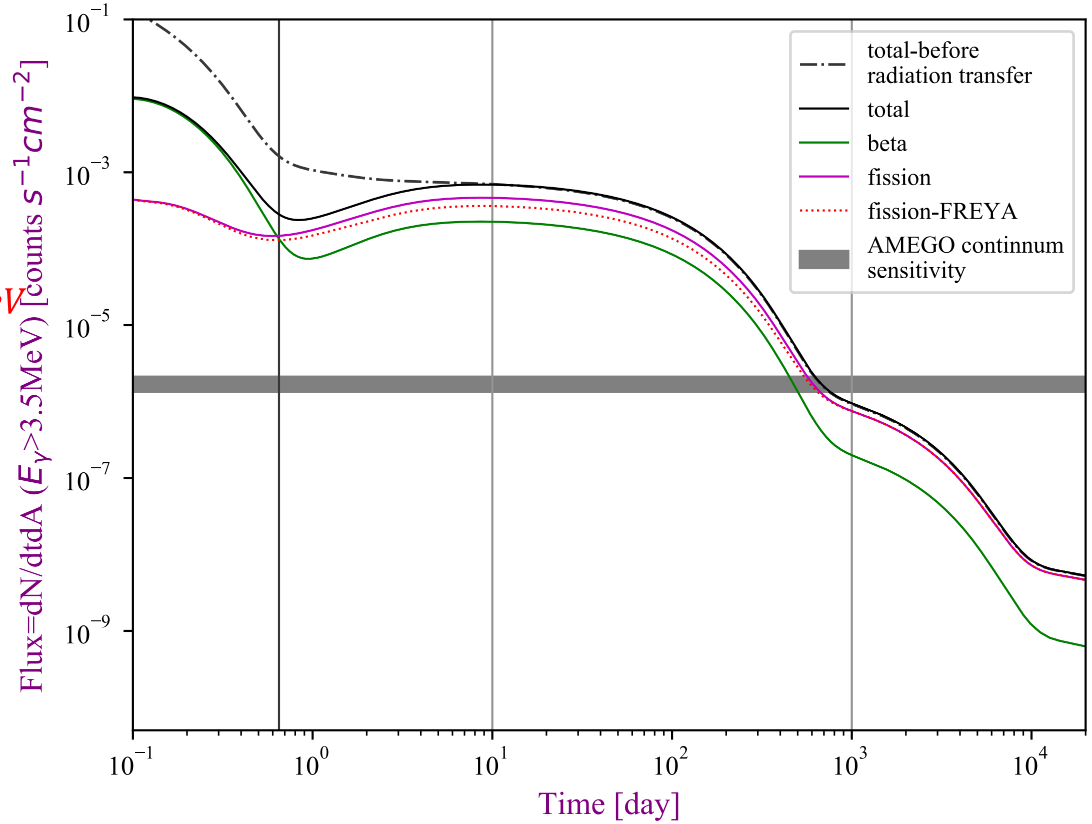

$$Y_e = \frac{n_e}{n_b} \sim 0.015$$

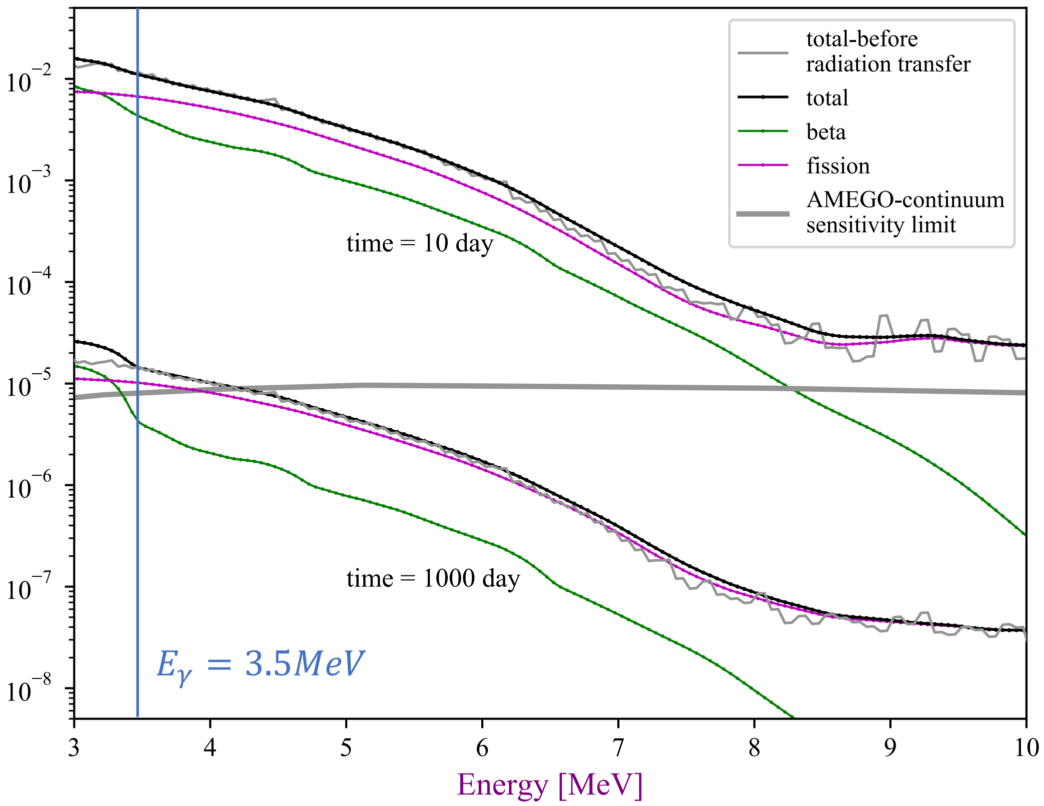
Very neutron rich dynamical ejecta from Rosswog et al., 2013, Piran et al., 2013. Nuclear data based on FRDM and FRLDM nuclear models

**Wang, X., et al. 2020 arXiv:2008.03335**

# MeV light curve and late-time spectra

Flux at
$E_\gamma > 3.5MeV$

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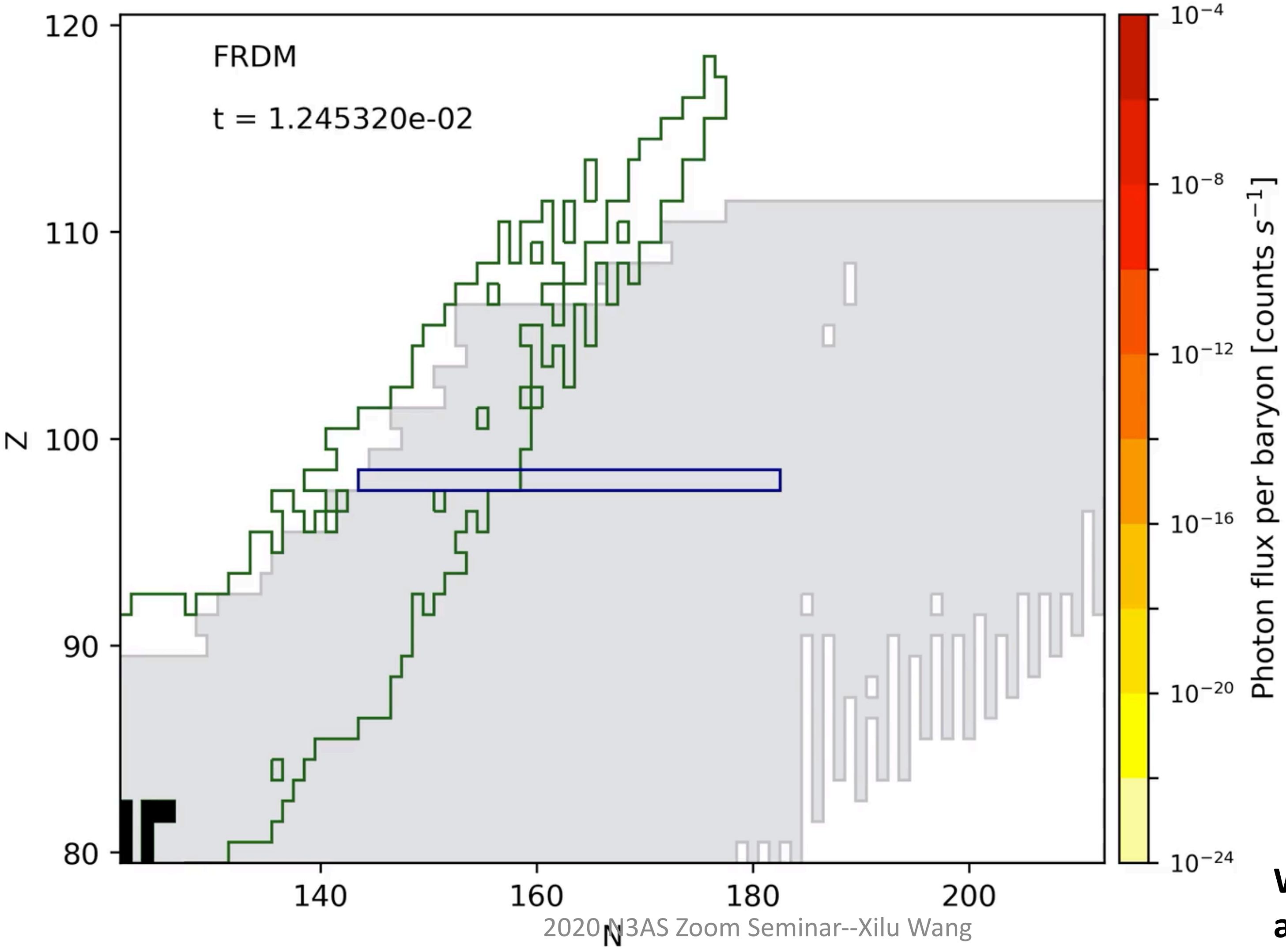
# Contributions from individual fissioning nuclei

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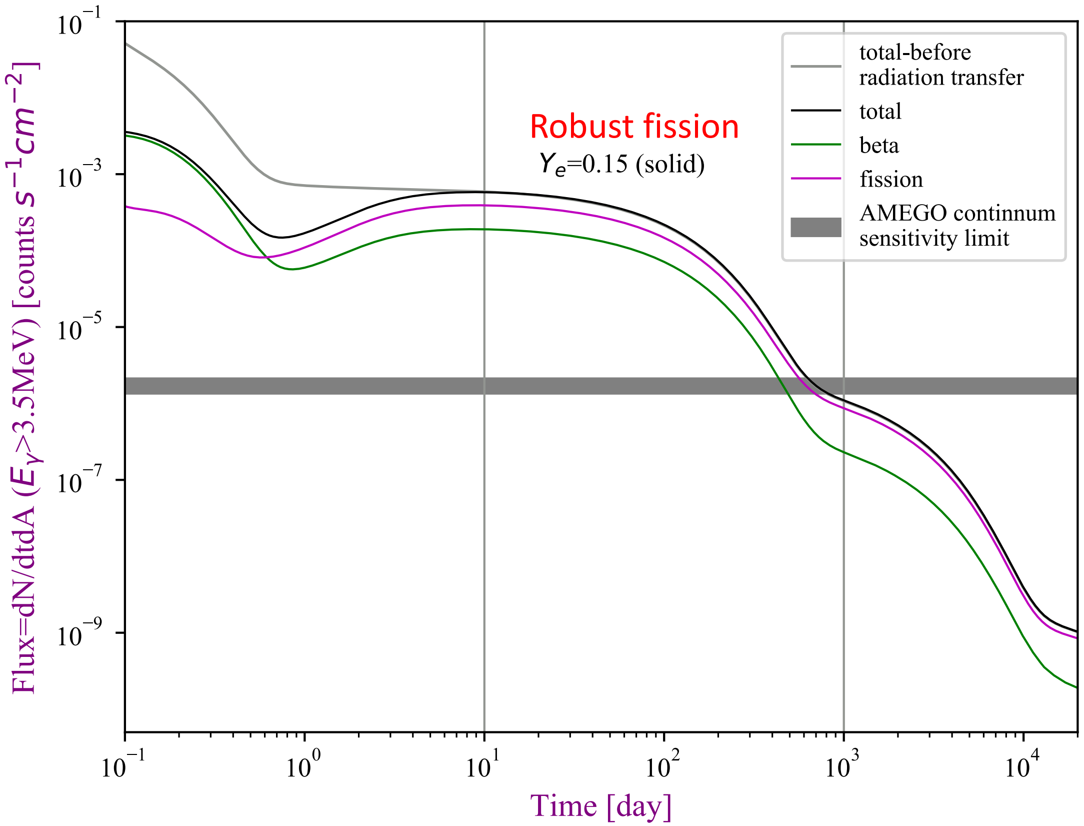
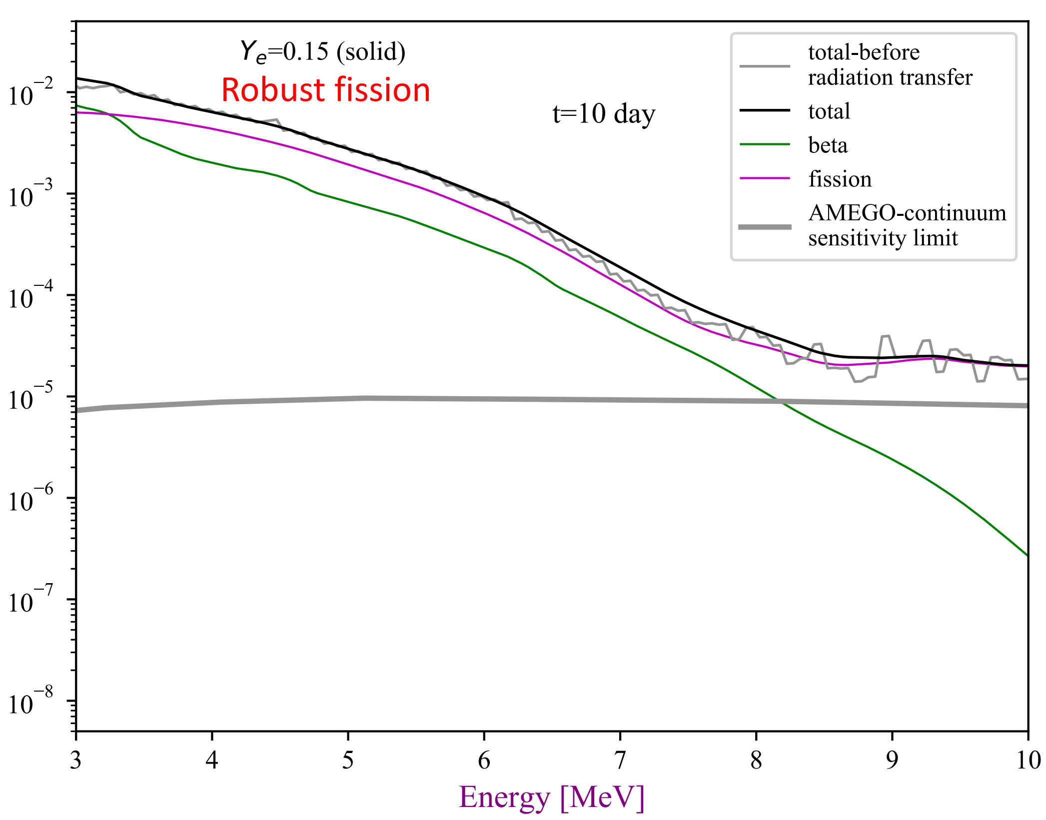
# Variations on neutron-richness and the participation of fission




Low entropy parameterized outflow found in Radice et al., 2018, Just et al., 2015.
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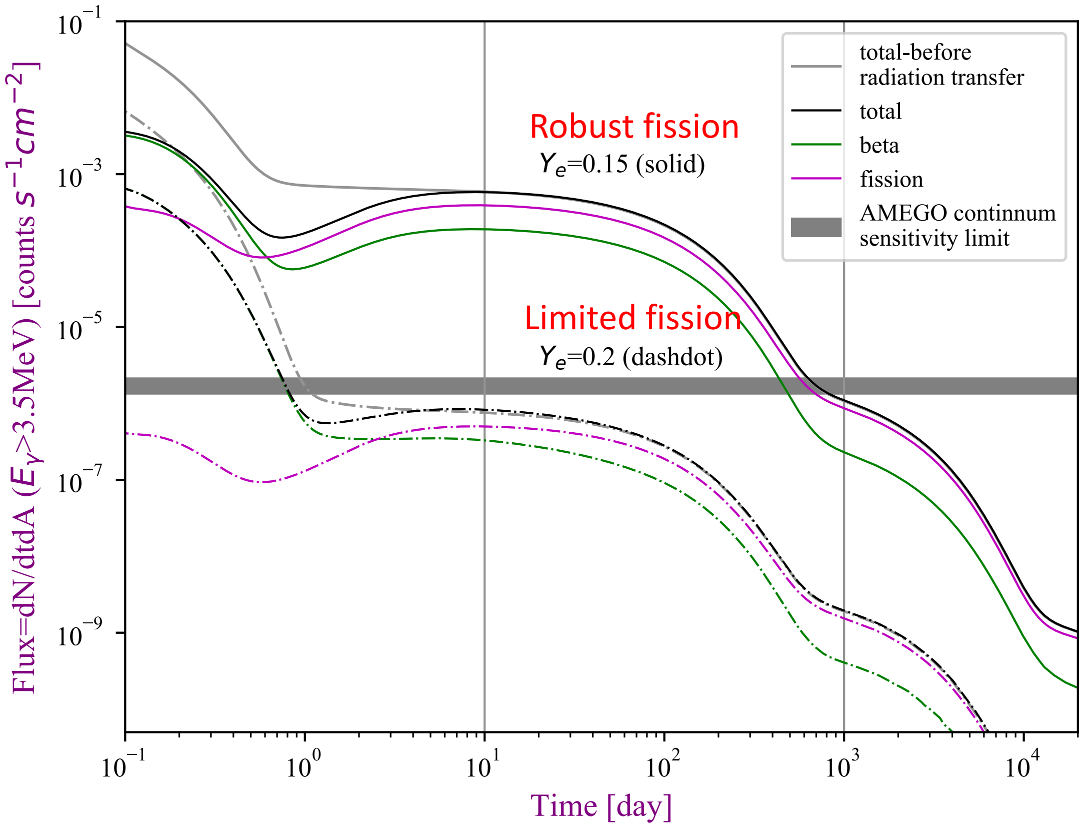


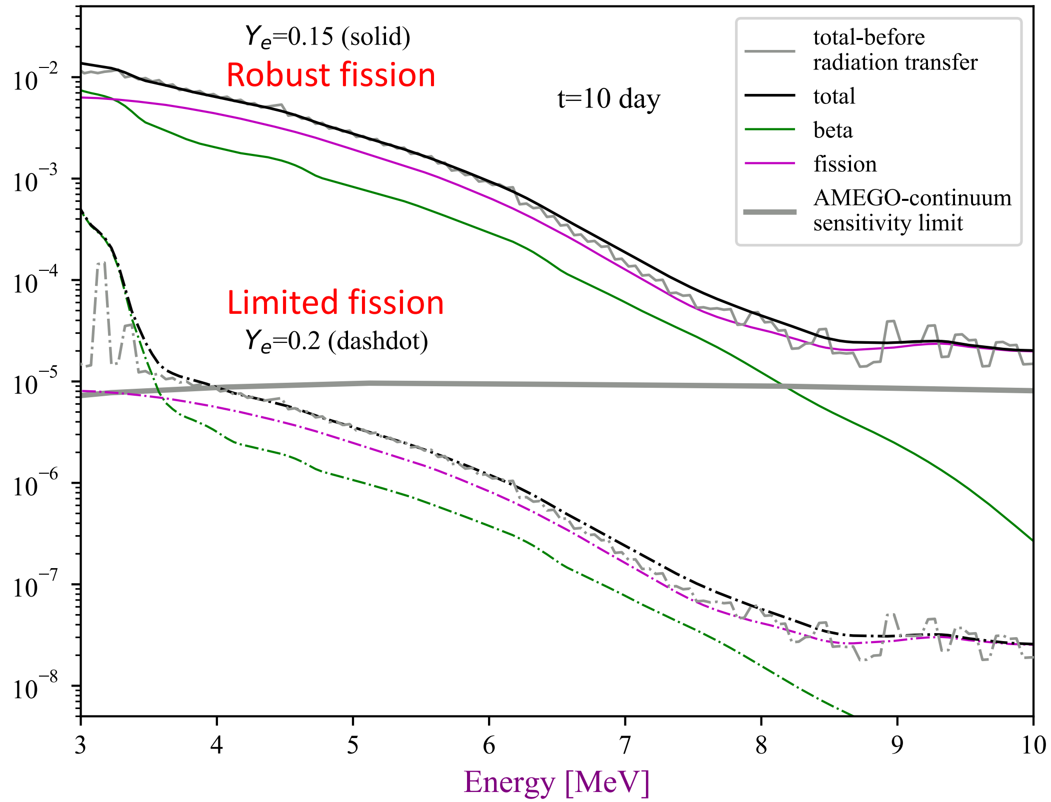


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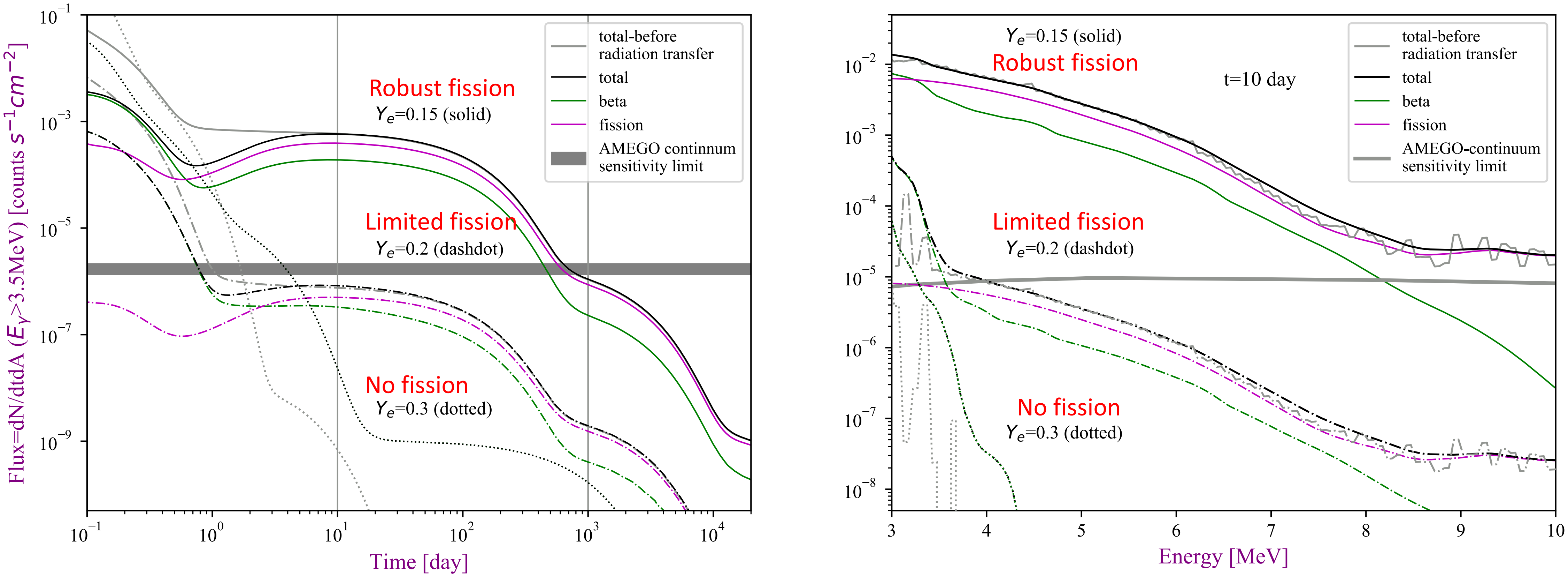


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# Summary

- We report a first estimate for the contributions of fission to a late-time MeV gamma-ray signal from a NSM, which is detectable by AMEGO for a galactic event.
- The gamma ray emissions above 3.5 MeV from fission dominate over beta decay signal at late time after several days.
- The MeV gamma ray signal at late time is sensitive to the degree which fissioning nuclei participates, which is determined by the nature of the astrophysical outflows.
- If a Galactic event happens, next generation gamma ray detectors like AMEGO would provide direct evidence for NSMs as a source of heavy, fissioning actinide elements.
- Followup work: a detailed investigation of the nuclear model dependence of the MeV fission gamma signature from NSMs.

- Thanks for attention! Questions?