Heavy particle creation due to the r-process in kilonova

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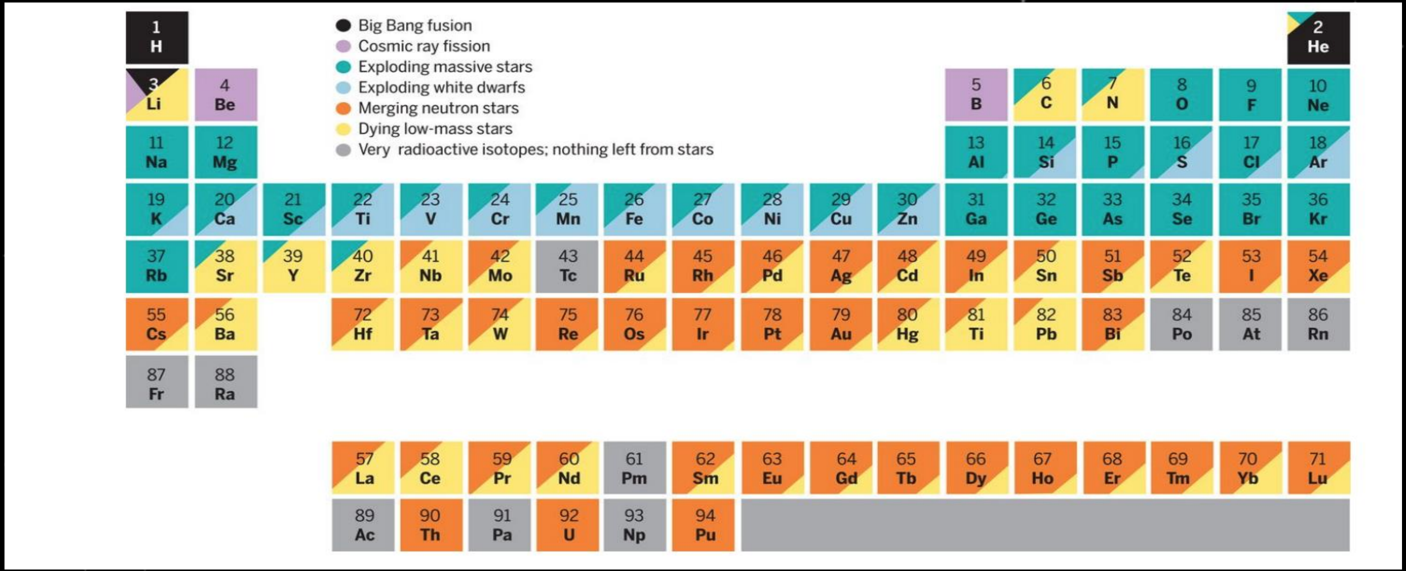
The envolving composition of the universe



Spectroscopic modelling of astrophysical mergers and kilonovae 2023-06-09 | Journal article DOI: 10.1126/sciadv.adi1405

kilonova

Diffusion time

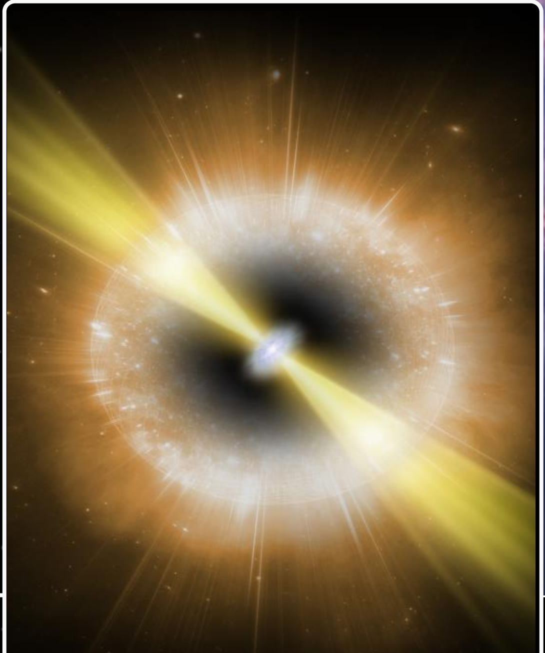
$$\boxed{t_{\mathrm{d}} = \frac{B\kappa M_{\mathrm{ej}}}{cR}}$$

Time to peak

$$\boxed{t_{\mathrm{peak}} \equiv \left(\frac{3M\kappa}{4\pi\beta v c}\right)^{1/2} \approx 1.6\mathrm{d}\left(\frac{M}{10^{-2}M_{\odot}}\right)^{1/2}\left(\frac{v}{0.1\mathrm{c}}\right)^{-1/2}\left(\frac{\kappa}{1\mathrm{cm}^2\mathrm{g}^{-1}}\right)^{1/2}}$$

R-process

1. Neutron Capture
2. Neutron-Rich Environment
3. Beta Decay
4. Formation of Heavy Elements



Electromagnetic Counterparts of Compact Object Mergers Powered by the Radioactive Decay of R-process Nuclei arXiv:1001.5029v2

Toy Model

distribution of mass

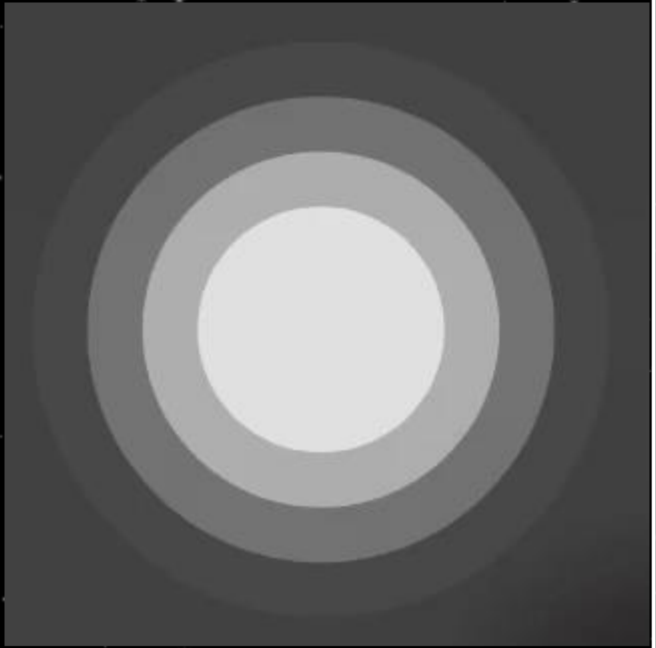
We approximate the distribution of mass with velocity greater than a value v as a power-law

$$M_\alpha = M\left(\frac{v}{v0}\right)^{-\beta}$$

diffusion timescale

radiation escapes from the mass layer M_α on the diffusion timescale

$$t_{d,v} \approx \frac{3M_\alpha k_\alpha}{4\pi\beta R_\alpha c} = \frac{M_\alpha^{\frac{4}{3}} k_\alpha}{4\pi M^{\frac{1}{3}} v_0 tc}$$



radiation peaks

$$t_{d,v} = t = \frac{R}{v}$$

Living Reviews in Relativity “kilonova “(2020) 23:1 https://doi.org/10.1007/s41114-019-0024-0

blackbody emission

Under the idealization of blackbody emission, the temperature of the thermal emission is:

$$\boxed{T_{\mathrm{eff}} = \left(\frac{L_{\mathrm{tot}}}{4\pi\sigma R_{\mathrm{ph}}^2}\right)^{1/4}}$$

The flux density of the source at photon frequency ν is given by

$$\boxed{F_\nu(t) = \frac{2\pi h\nu^3}{c^2}\frac{1}{\exp[h\nu/kT_{\mathrm{eff}}(t)]-1}\frac{R_{\mathrm{ph}}^2(t)}{D^2},}$$

evolves of thermal energy

$$\frac{dE}{dt} = \dot{E}_{\mathrm{nuc}} - L - P\frac{dV}{dt} = \dot{E}_{\mathrm{nuc}} - \frac{E}{t_{\mathrm{diff}}} - \frac{E}{t},$$

At a minimum, the ejecta is heated by the radioactive decay of heavy r-process nuclei. This occurs at a rate

$$\dot{E}_{\mathrm{nuc}} = \delta M_v X_{r,v} \dot{e}_r(t),$$

$$\dot{e}_r = 4 \times 10^{18} \epsilon_{th,v} (0.5 - \pi^{-1} \arctan[(t - t_0)/\sigma])^{1.3} \ \mathrm{erg s^{-1}\ g^{-1}},$$

$$\begin{aligned} L_{\mathrm{peak}} &\approx M\dot{e}_r(t_{\mathrm{peak}}) \\ &\approx 10^{41} \mathrm{erg s^{-1}} \left(\frac{\epsilon_{th,v}}{0.5}\right)\left(\frac{M}{10^{-2}M_\odot}\right)^{0.35}\left(\frac{v}{0.1c}\right)^{0.65}\left(\frac{\kappa}{1\mathrm{cm^2 g^{-1}}}\right)^{-0.65}. \end{aligned}$$

arxive: 1512.05435v1 Electromagnetic Signatures of Neutron Star Mergers in the Advanced LIGO Era

flux density transformation:

$$I = \mathcal{D}^3 I'$$

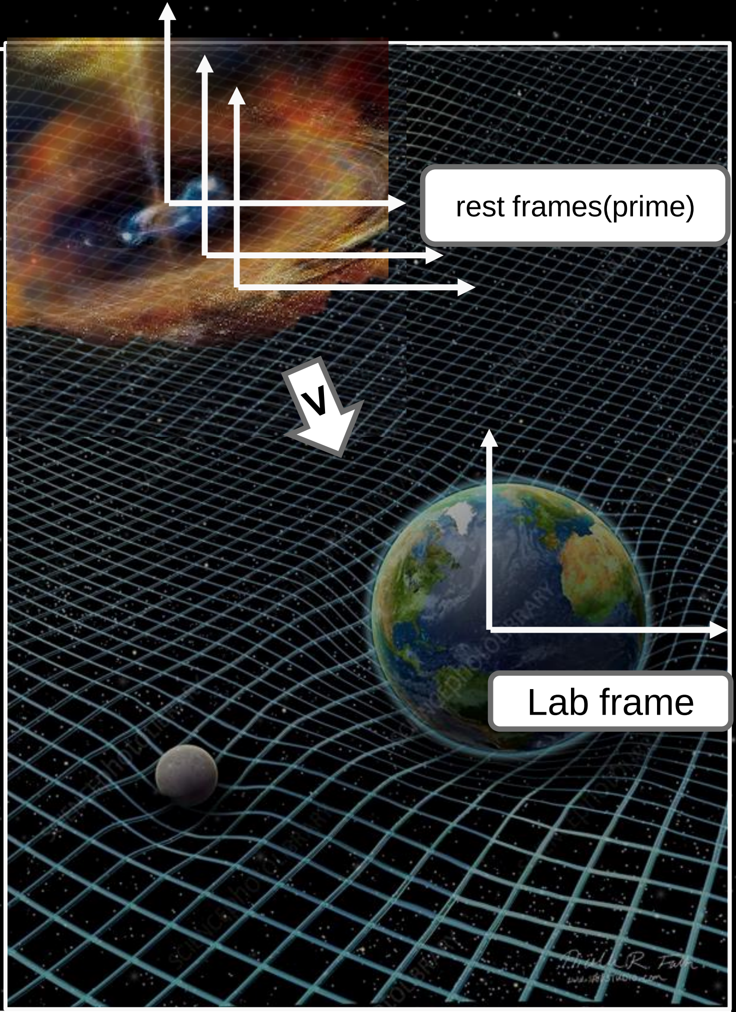
$$\Gamma = (1-\beta^2)^{-1/2}$$

$$\mathcal{D} = \frac{1}{\Gamma(1-\beta\mu)}$$

The specific intensity is inversely proportional to the square distance,
then we have the flux received at P is

$$F_\nu = \int_0^1 \frac{R^2}{D_L^2}\mathcal{D}^3 I' \mu d\mu$$

$$R' = \Gamma \mathrm{R}$$



Equal Arrival time surface

A photon emitted at (t,μ) will arrive the observer at

$$t_{\mathrm{arr}} = \frac{D_L - R\mu}{c} + t$$

$$\Gamma - 1 = \Gamma_0 \left(\frac{R}{R_0}\right)^{-\alpha}$$

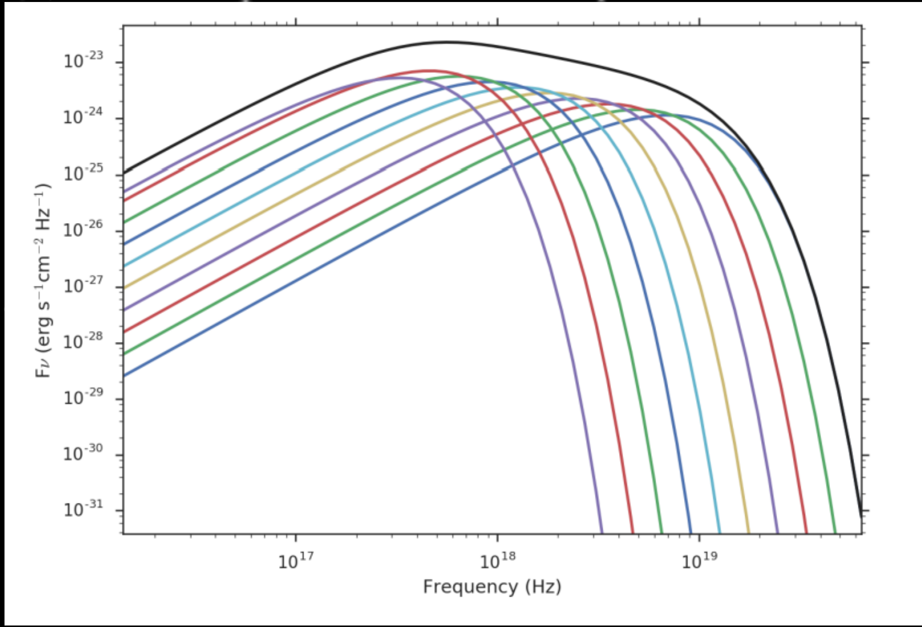
$$R = R(t_{arr}, \mu)$$

Reproducing the code

```python
# for a given set of initial value, compute radius R(t),
# Lorentz factor and velocity in the laboratory frame.
def _R(t0,R0,G0):
    t = np.logspace(np.log10(t0), np.log10(tMax), nTime, endpoint=True)
    dt = t[1:]-t[:-1]

    ### Radius R(t), Lorentz factor G[t] and Velocity B[t]
    R = np.zeros([len(t)])
    G = np.zeros([len(t)])
    B = np.zeros([len(t)])
    R[0] = R0
    G[0] = G0
    B[0] = np.sqrt(1-G0**(-2))
    for i in range(len(t)-1):
        R[i+1] = R[i]+ B[i]*c*dt[i]
        G[i+1] = G0*(R[i+1]/R[0])**(a)+1
        B[i+1] = np.sqrt(1-G[i+1]**(-2))
    return t,dt,R,G,B

# find the equal arrival time surface R(tarr,mu)
def _EATS(tarr,t0,R0,G0,linear=False):

    t,dt,R,G,B = _R(t0,R0,G0)
    mu = 1-np.logspace(-5,0, nAngel, endpoint=True)
    if linear == True:
        mu = 1-np.linspace(0,1, nAngel, endpoint=True)
    dmu = mu[:-1]-mu[1:]
    dmu = np.insert(dmu, 0, dmu[0])
    EATS = []
    for j in range(len(mu)):
        diff = np.abs(tarr-t+R*mu[j]/c)
        minIndex = np.argmin(diff)
        if diff[minIndex]/tarr < rTol:
            EATS.append([tarr,mu[j],dmu[j],t[minIndex],R[minIndex],\
```

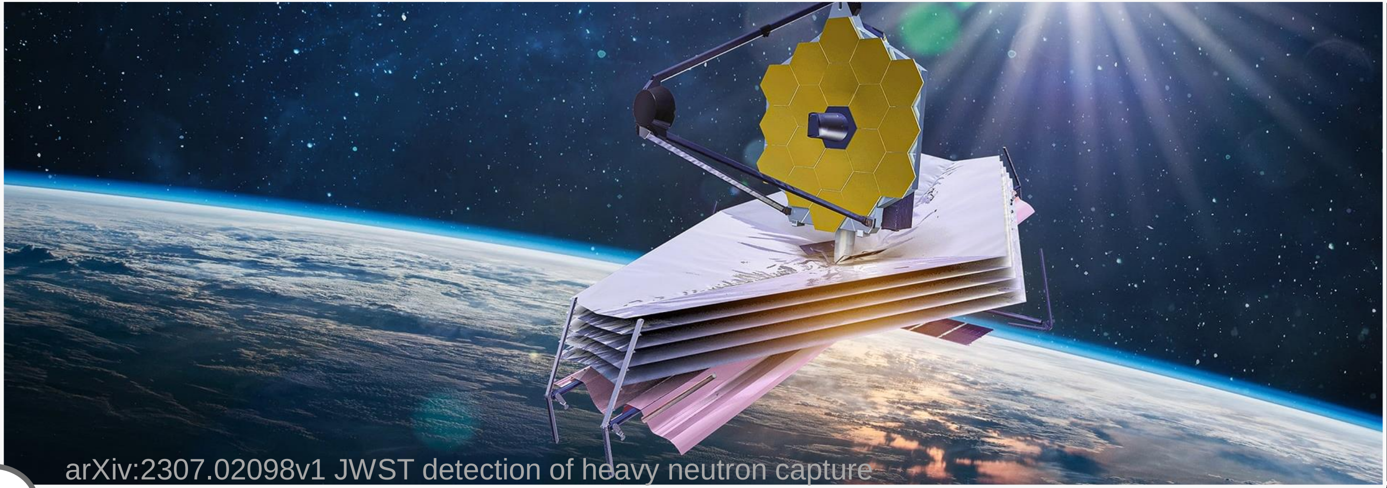
```python
# compute Fnu at different nu and integrate to have F from a equal arrival time surface
def _F(tarr,t0,R0,G0,T0,linear=False):

    # Test to find range of nu
    nu = np.logspace(8,23,15, endpoint=True)
    dnu = -nu[:-1]+nu[1:]
    dnu=np.append(dnu,dnu[-1])
    Fnu = np.asarray([_Fnu(tarr,nui,t0,R0,G0,T0,linear) for nui in nu])

    # computing Fnu
    maxIndex = np.argmax(Fnu)
    nu = np.logspace(np.log10(nu[maxIndex])-3.5,np.log10(nu[maxIndex])+1.5,nF, endpoint=True)
    dnu = -nu[:-1]+nu[1:]
    dnu=np.append(dnu,dnu[-1])
    Fnu = np.asarray([_Fnu(tarr,nui,t0,R0,G0,T0) for nui in nu])

    # sum up all Fnu*du
    FnuDnu = Fnu*dnu
    F = FnuDnu.sum()


    # compute initial parameters of effective temperature and radius
    # Teff = peak frequency/2.821
    maxIndex = np.argmax(Fnu)
    Teff = nu[maxIndex]*hzToK/2.821
    Reff =  DL*(2*F/(sigma*Teff**4))**(1/2)


    # fitting
    model = modeling.models.BlackBody1D(temperature=Teff*u.Kelvin,bolometric_flux=F*u.erg/u.cm/u.cm/u.s)
    fit = modeling.fitting.LevMarLSQFitter()
    model = fit(model, nu*u.Hz, Fnu*u.erg/u.cm/u.cm/u.s/u.Hz)
```

Output light curve of model

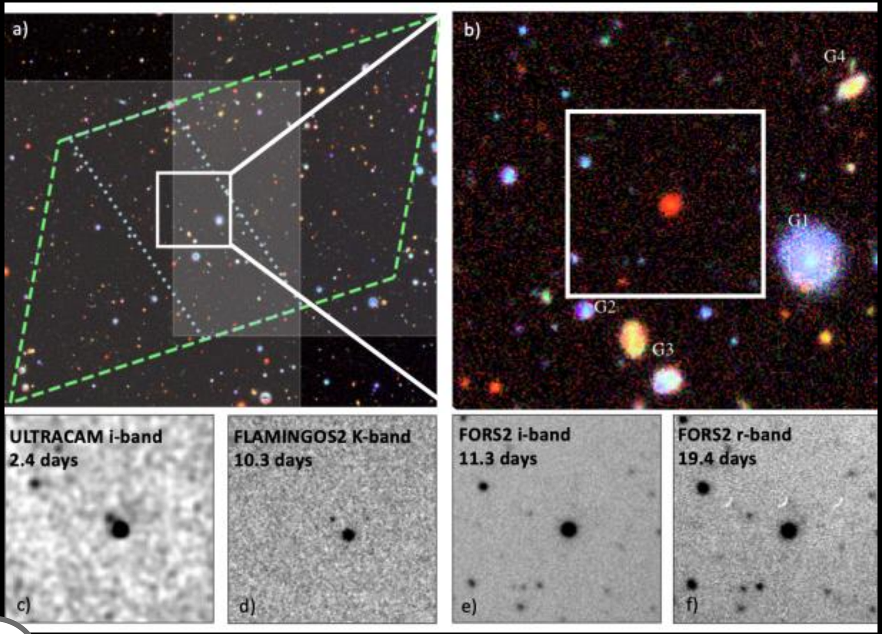


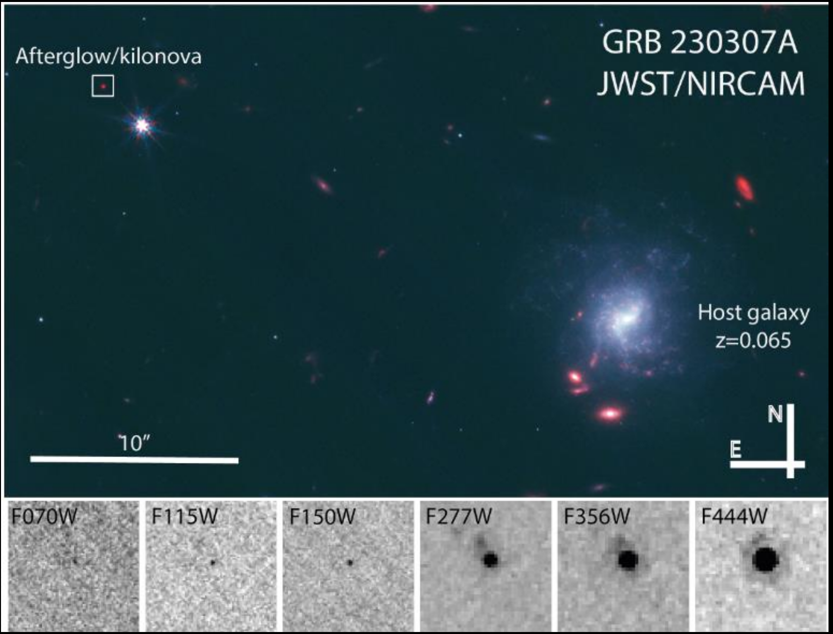
JWST observes

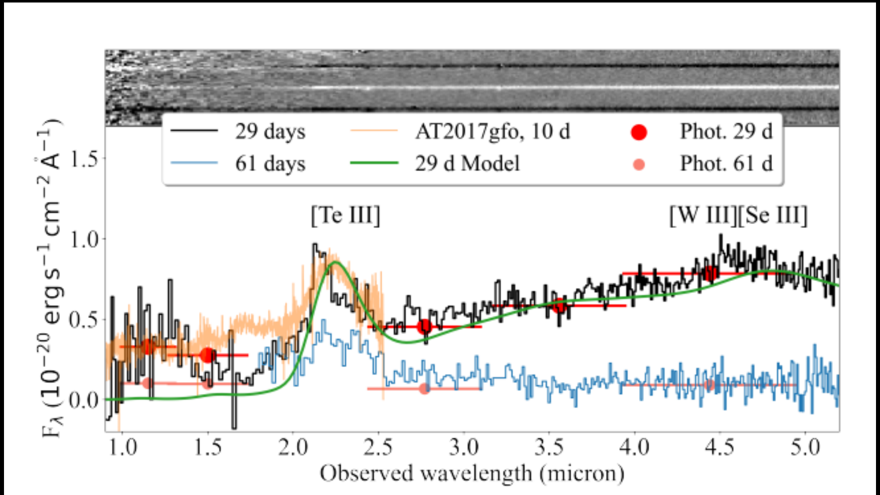
The GRB that led the team to the kilonova source, designated as GRB 230307A, was initially detected by NASA’s Fermi Gamma-ray Space Telescope on March 7, 2023, and stands as the second-brightest GRB ever observed.

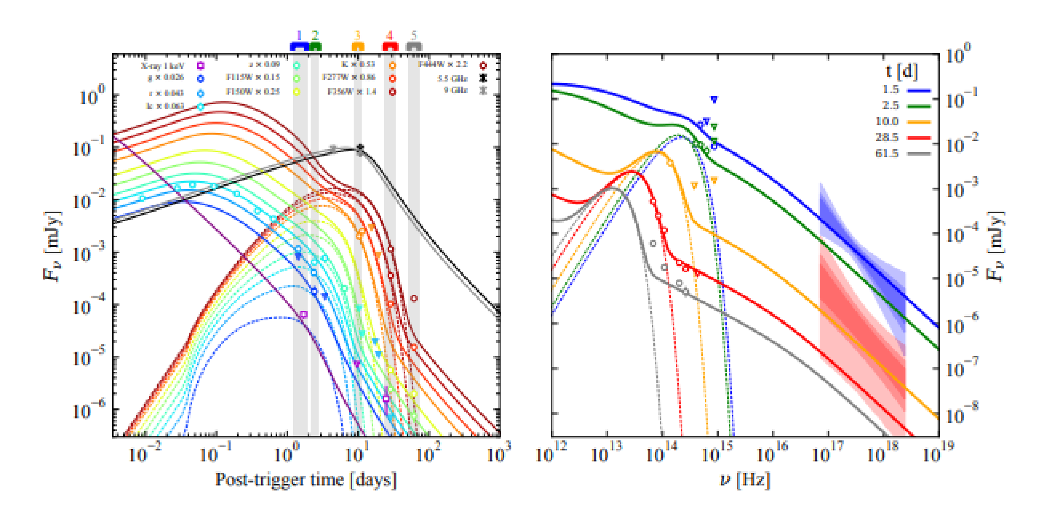


arXiv:2307.02098v1 JWST detection of heavy neutron capture elements in a compact object merger


a)
b)
G1
G2
G3
G4
ULTRACAM i-band
2.4 days
c)
FLAMINGOS2 K-band
10.3 days
d)
FORS2 i-band
11.3 days
e)
FORS2 r-band
19.4 days
f)


GRB 230307A
JWST/NIRCAM
Afterglow/kilonova
Host galaxy
z=0.065
10″
N
E
F070W
F115W
F150W
F277W
F356W
F444W


29 days
61 days
AT2017gfo, 10 d
29 d Model
Phot. 29 d
Phot. 61 d
[Te III]
[W III][Se III]
F$_\lambda$ (10^{-20} erg s^{-1} cm^{-2} Å^{-1})
Observed wavelength (micron)


F_ν [mJy]
Post-trigger time [days]
t [d]
1.5
2.5
10.0
28.5
61.5
ν [Hz]

JWST Data:

$$\epsilon = 0.5 \qquad \mathrm{M} = 0.03\mathrm{M}\odot \qquad v = 0.08c \qquad k = 100(cm^2 g^{-1})$$

Our model

$$L_{\text{peak}} \approx M\dot{e}_r(t_{\text{peak}})$$

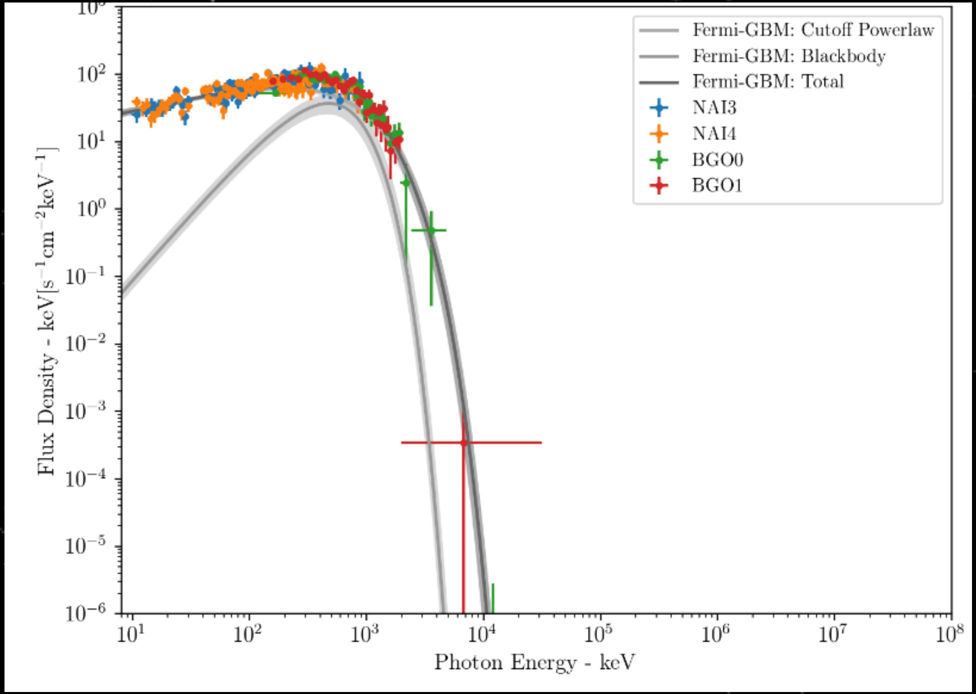
$$\approx 10^{41}\text{ergs}^{-1}\left(\frac{\epsilon_{th,v}}{0.5}\right)\left(\frac{M}{10^{-2}M_\odot}\right)^{0.35}\left(\frac{v}{0.1\text{c}}\right)^{0.65}\left(\frac{\kappa}{1\text{cm}^2\text{g}^{-1}}\right)^{-0.65}.$$

$$L_{\text{peak}} \approx 6.38 \times 10^{39}.$$

JWST

$$L_{\text{peak}} \approx 5 \times 10^{39}.$$

Model vs data



Thanks!