Electromagnetic Counterparts

S. R. Kulkarni

Limitations

- No exotic channels made with no physical models considered
  - Not worth discussing
- Plausible models but very uncertain signal strength also not considered
  - Burst of radio emission following merger but before black hole is formed
  - Burst of radio waves preceding the coalescence (Jupiter & Io)

Organization

I. New developments in radio astronomy

II. Rates: diverse outcomes

III. Radio emission

IV. UV/optical/NIR/MIR emission: Kilo- & macro-nova

V. New facilities (early times): ZTF & ULTRASAT

NEW DEVELOPMENTS IN RADIO ASTRONOMY

High Speed Radio Mapping Machines

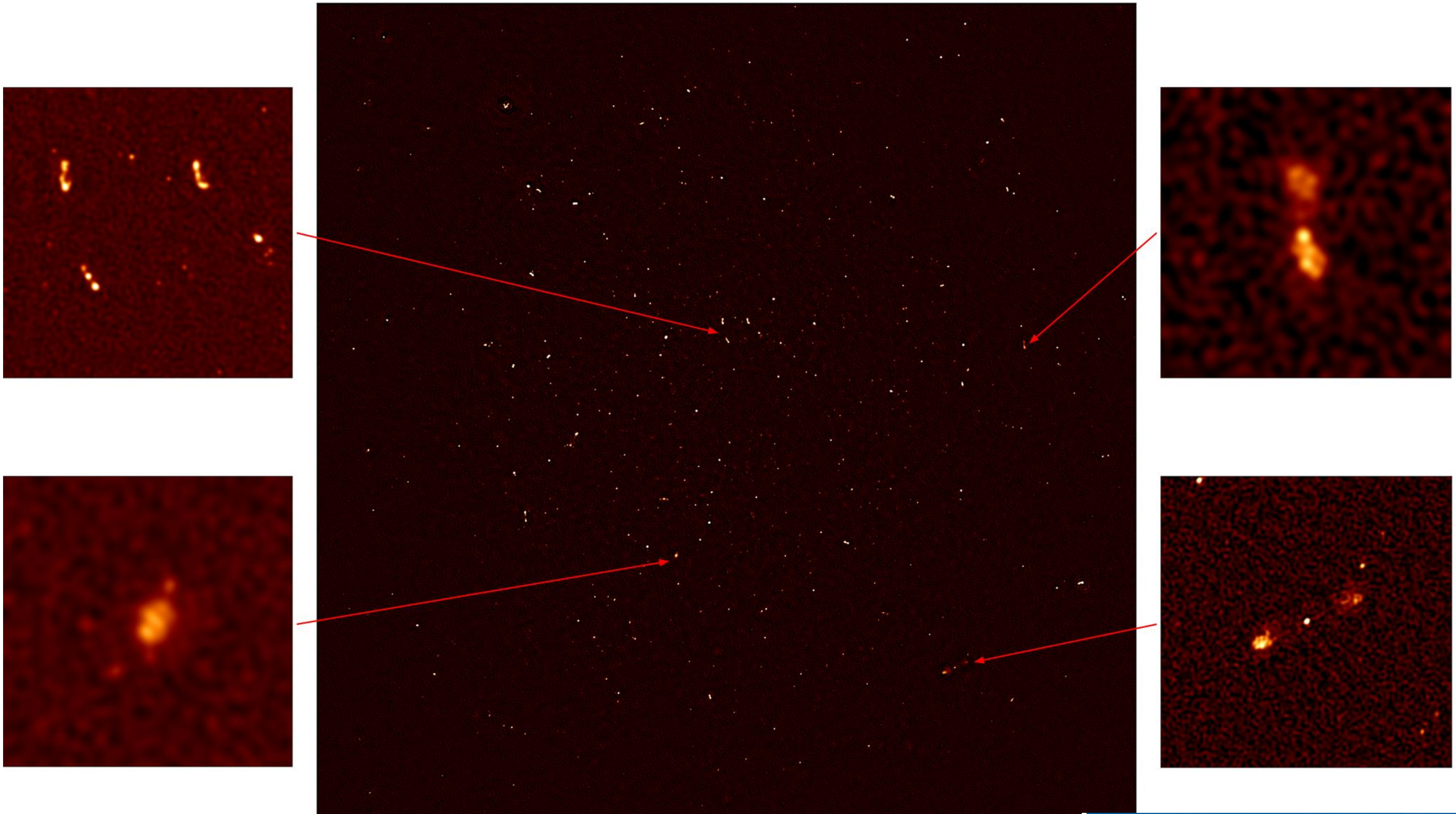
- The refurbished Very Large Array
  - On-the-fly-mapping (OTFM)
- Development of “LNSD” (large N, small diameter) arrays
  - MeerKAT
- Phased Array Feeds
  - ASKAP
  - APERTIF

Radio background: Mapping Speed

- F_{lim} … limiting flux density (mJy)
- SNR (say 5 or 8)
- η … aperture efficiency
- A … total collecting area of the array
- D … diameter of the array
- B … bandwidth

$$\mathcal{S} = \frac{B}{\eta_c \pi}\left(\frac{F_{lim}}{SNR}\right)^2\left(\frac{\lambda}{D}\right)^2\left(\frac{\eta_s A}{k_B T_{sys}}\right)^2$$

MeerKAT (LNSD)

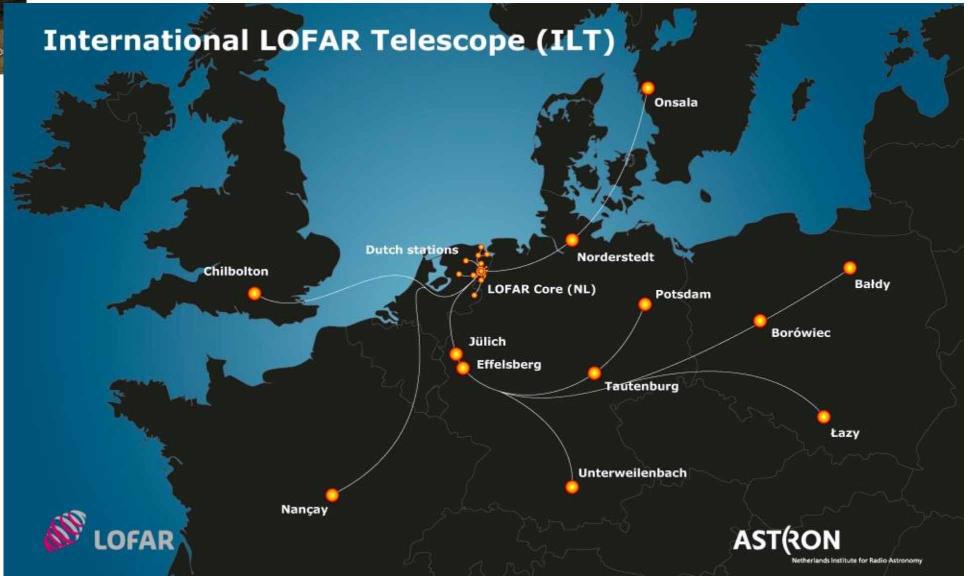


Commissioning observations: 10° from South Celestial Pole
16 antennas, 0.9--1.67 GHz, 7.5 hr integration time
Image: 7” resolution, 12 μJy rms

Image credits: SKA South Africa

LOFAR


2011 © AEROPHOTO EELD


International LOFAR Telescope (ILT)
Onsala
Dutch stations
Chilbolton
Norderstedt
LOFAR Core (NL)
Potsdam
Bałdy
Borówiec
Jülich
Effelsberg
Tautenburg
Łazy
Unterweilenbach
Nançay
LOFAR
ASTRON
Netherlands Institute for Radio Astronomy

LOFAR 150 MHz

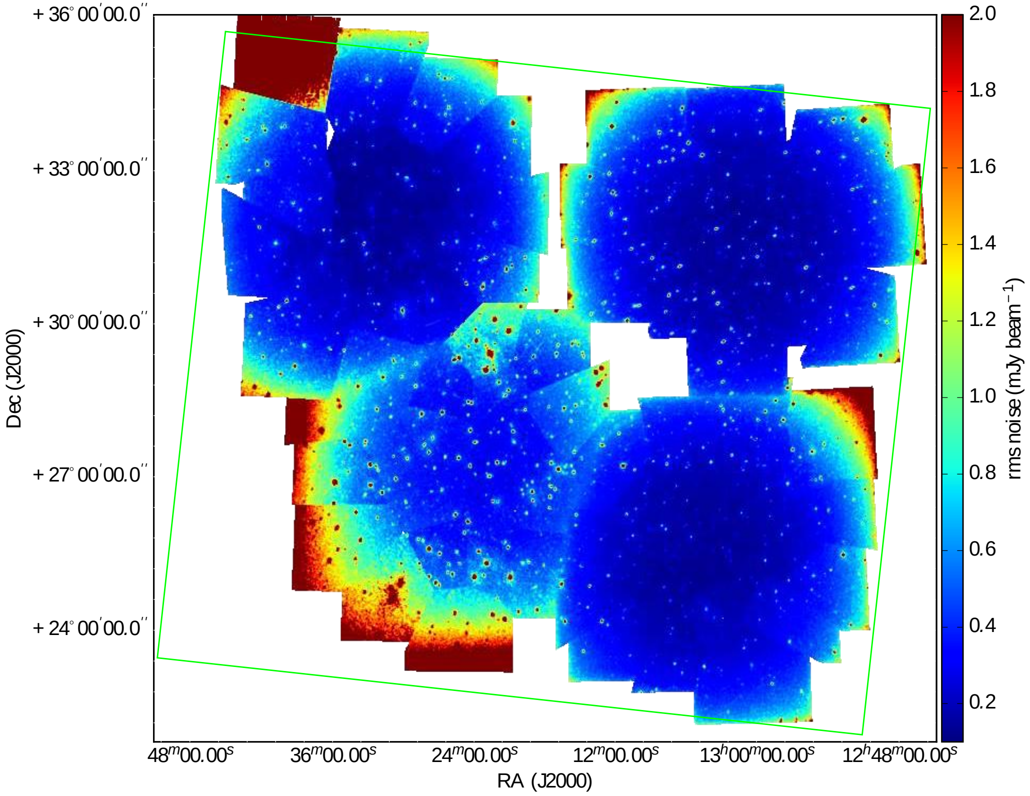


Figure 2. Map showing the sky coverage and rms values of the four fields, constructed as described in the text. Colour levels run from 100 μJy to 2 mJy beam^{-1}. The green square shows the approximate boundary of the *Herschel* survey. The LOFAR survey is deeper (in rms terms) than FIRST, the previous most sensitive radio survey of this area, in the blue regions of the image. The many ‘point sources’ in the image are the result of dynamic range limitations around bright objects, rather than the objects themselves: the pixel size in this image is 20 arcsec, significantly larger than the image resolution.

Focal Plane Arrays

APERTIF: Westerbork, NL

RATES

Rates

- Galactic NS-NS coalescence rate
  - 10^2 Gpc^{-3} yr^{-1} (Phinney)
  - 3.6×10^2 Gpc^{-3} yr^{-1} (Kim)
- Short Hard Burst (SHB)
  - [3 27] Gpc^{-3} yr^{-1} (observed & corrected for low luminosity)
  - ~10^3 Gpc^{-3} yr^{-1} (beaming corrected)
- Core Collapse Sne
  - 2×10^5 Gpc^{-3} yr^{-1}

- LSC O1 limits (95% CL)

  $< 1.26 \times 10^4$ Gpc^{-3} yr^{-1} (ns-ns)
  $< 3.6 \times 10^3$ Gpc^{-3} yr^{-1} (ns-bh)
  2-600 Gpc^{-3} yr^{-1} (bh-bh)

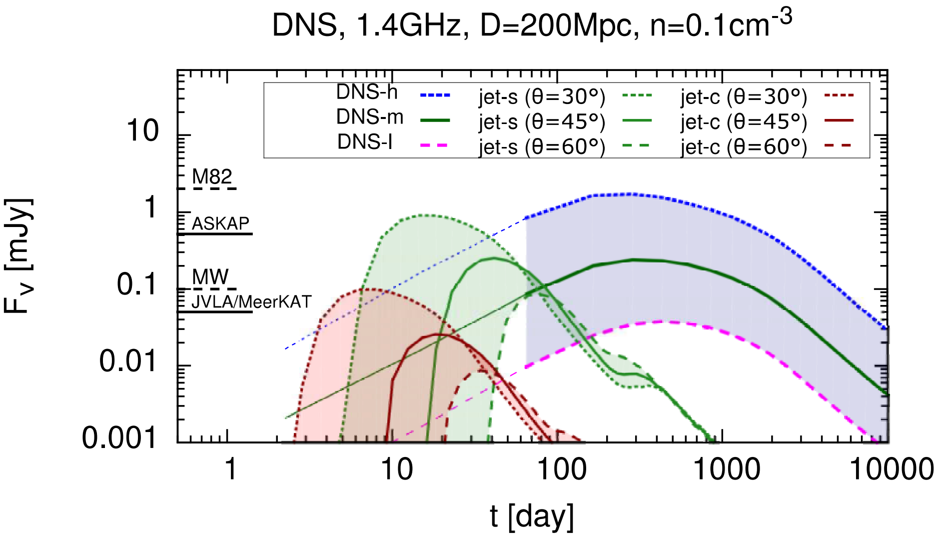
1. *We know no Galactic bh-ns system (informative?)*
2. *Looking at the range in rates, KEEP AN OPEN MIND FOR DIVERSE OUTCOMES*

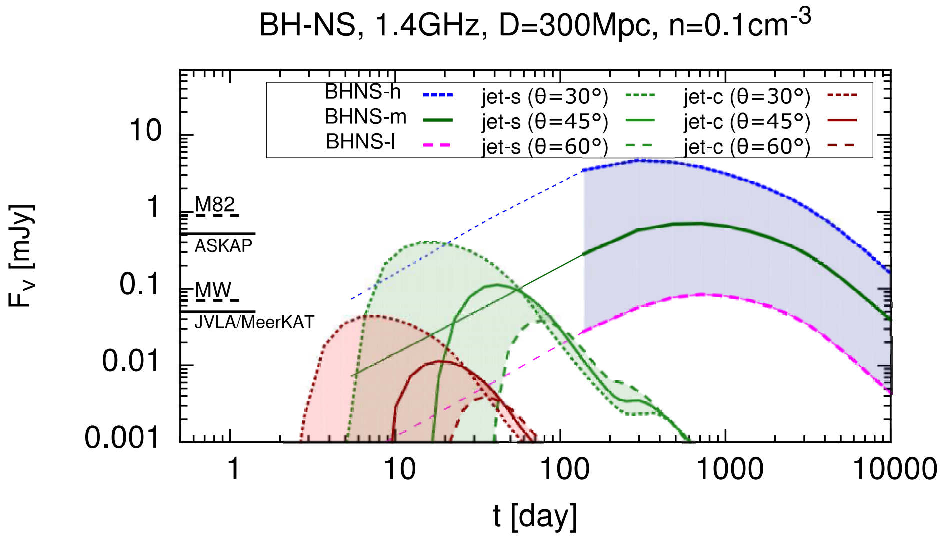
RADIO EMISSION: FORWARD SHOCK, ORPHAN AFTERGLOW

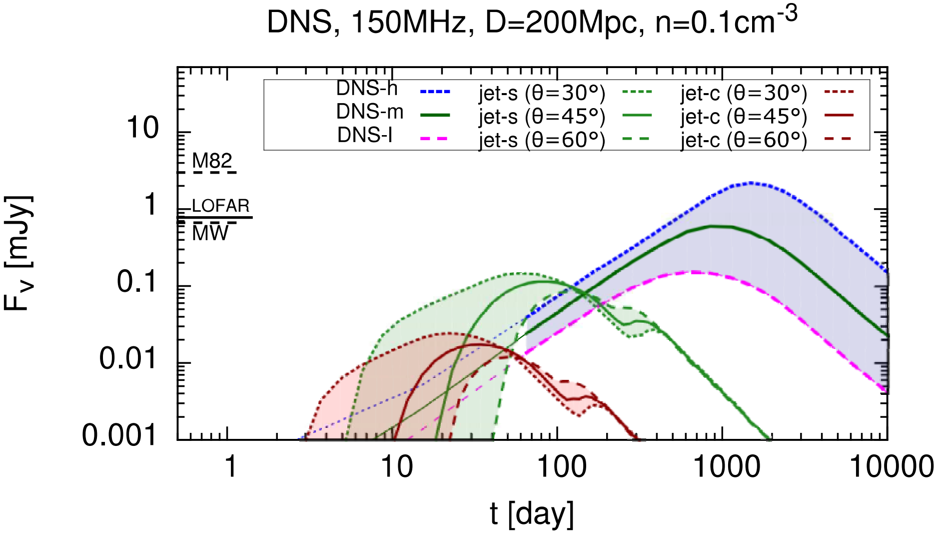
Forward shock

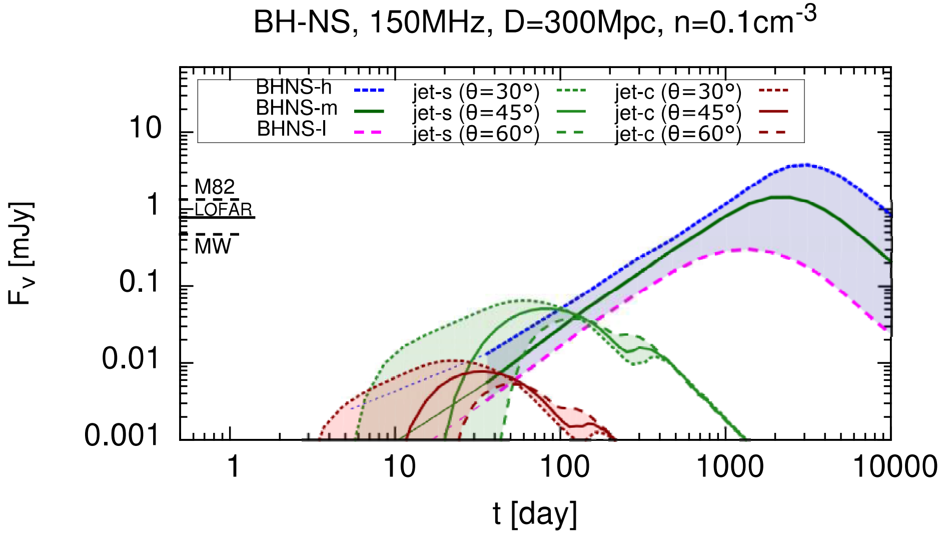
- Ejecta rams into interstellar matter
- After sweeping up a few times its mass settles into self-similar solution (Sedov phase)
  - Post-shocked gas is heated (but radiates poorly)
  - Electrons are accelerated in post-shock gas
  - Magnetic fields are apparently generated
  - Radio afterglow emission is produced (as in SN, GRB afterglow)

Nakar & Piran


DNS, 1.4GHz, D=200Mpc, n=0.1cm^{-3}


BH-NS, 1.4GHz, D=300Mpc, n=0.1cm^{-3}

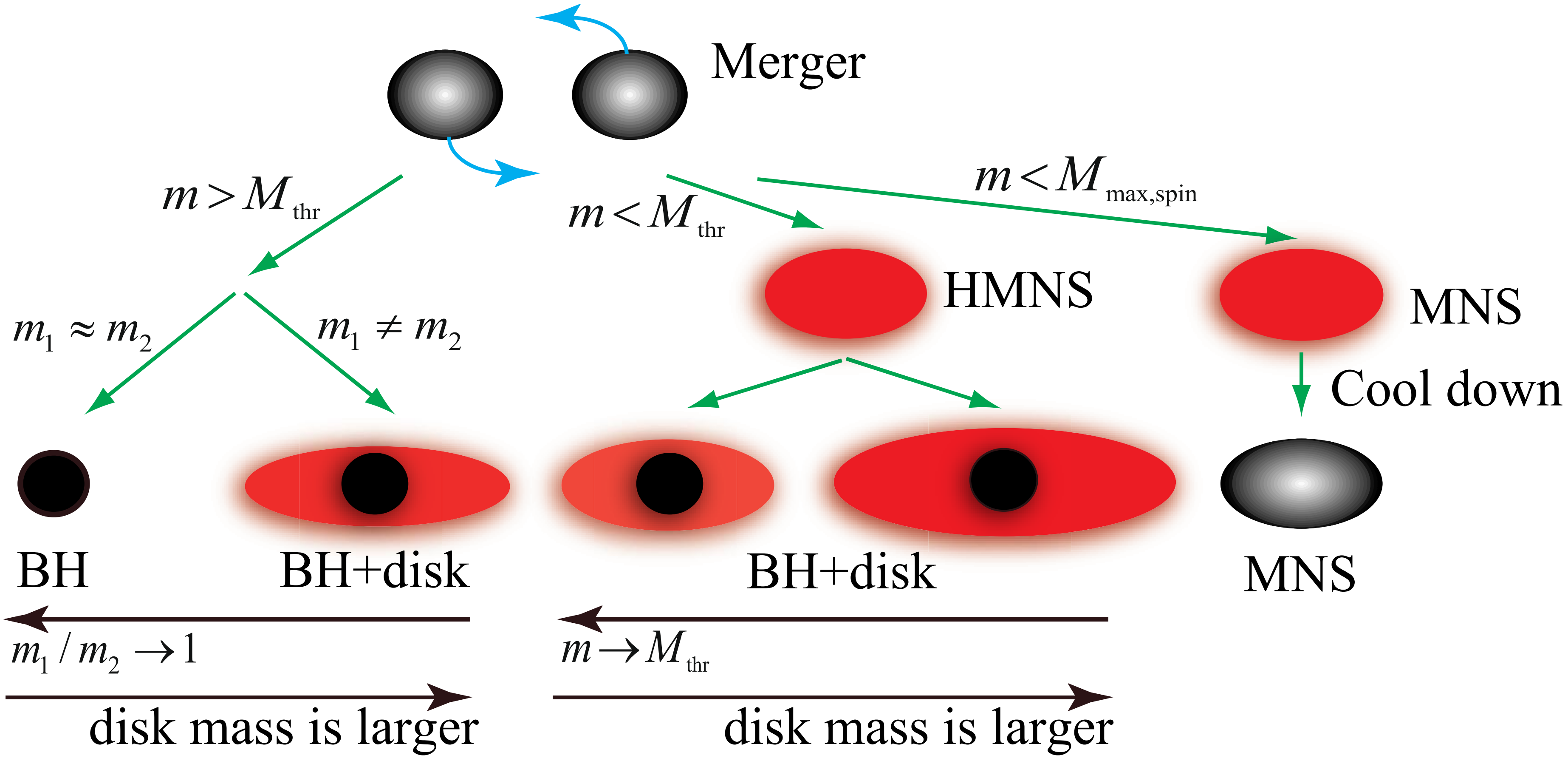

DNS, 150MHz, D=200Mpc, n=0.1cm^{-3}


BH-NS, 150MHz, D=300Mpc, n=0.1cm^{-3}

Hotokezaka+

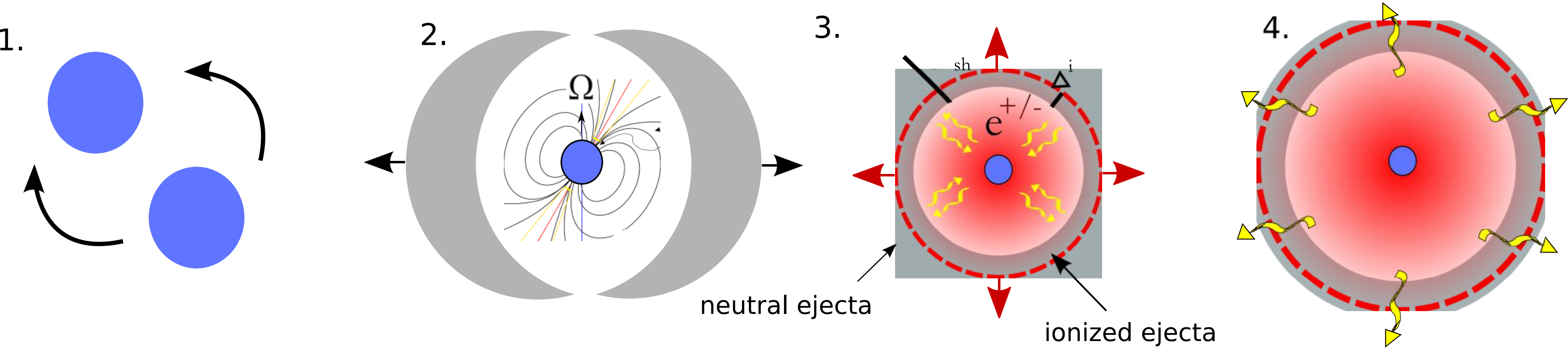
DIVERSE OUTCOMES?

EOS is uncertain



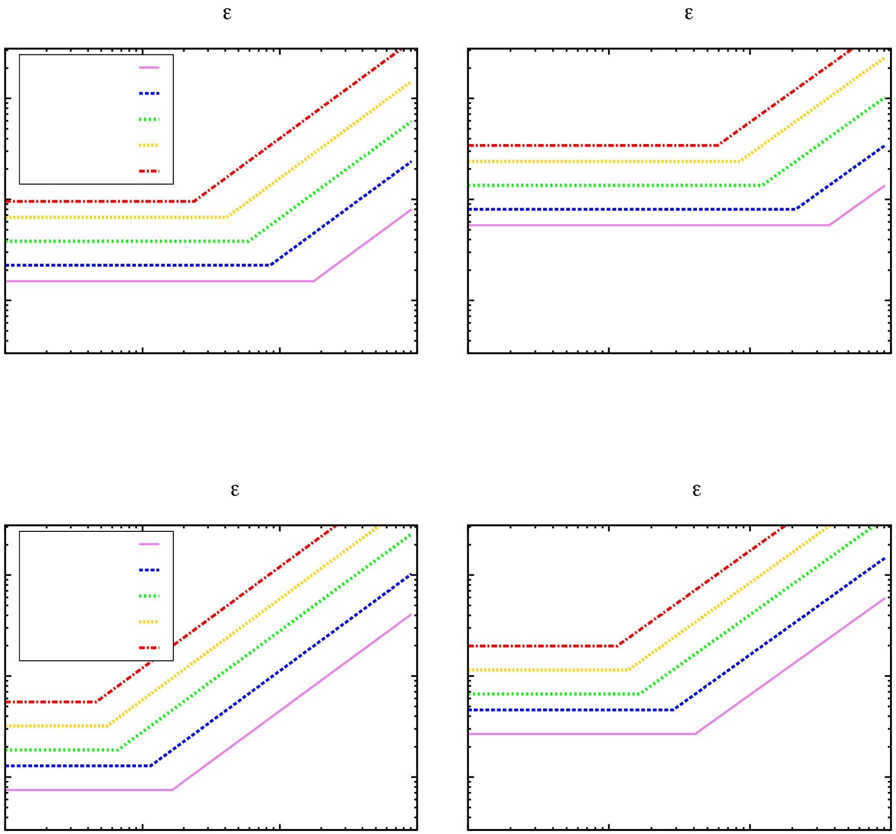
Hotokezaka, Shibata+

Formation of MNS (Magnetar)



Piro & Kullkarni
Metzger & Piro

Late time radio searches (VLA)



Horesh et al.   Fong et al.

KILO-NOVA, MACRO-NOVA

The total heat of the system is due to the electrons (density, n_e), ions (density, n_i) and photons:

$$E/V = \frac{3}{2}n_i(Z+1)kT + aT^4, \tag{2}$$

where $V = 4\pi/3R^3$, $N_i = M_{\rm ej}/(Am_H)$, $n_i = N_i/V$, $n_e = Zn_i$ and m_H is the mass of a hydrogen atom. For future reference, the total number of particles is $N = N_i(Z+1)$. This heat store has gains and losses described by

$$\dot{E} = \varepsilon(t) - L(t) - 4\pi R(t)^2 P v(t) \tag{3}$$

where $L(t)$ is the luminosity radiated at the surface. P is the total (electron, ion and photon) pressure and is

$$P = n_i(Z+1)kT + aT^4/3. \tag{4}$$

As explained earlier, the ejecta gain speed rapidly from expansion (the $4\pi R^2 P v_s$ work term). Thus, following the initial acceleration phase, the radius can be expected to increase linearly with time:

$$R(t) = R_0 + v_s t; \tag{5}$$

With this (reasonable) assumption of coasting we avoid solving the momentum equation.

Heating by Decay of Ni^{56}

- Nickel decay results in 1.72 MeV gamma-rays.
- A few scatterings are needed to transfer bulk of the energy to electrons
- Unlike ordinary SN, the ejecta become transparent to gamma-rays before 6 days.

THE ASTROPHYSICAL JOURNAL, 775:18 (9pp), 2013 September 20

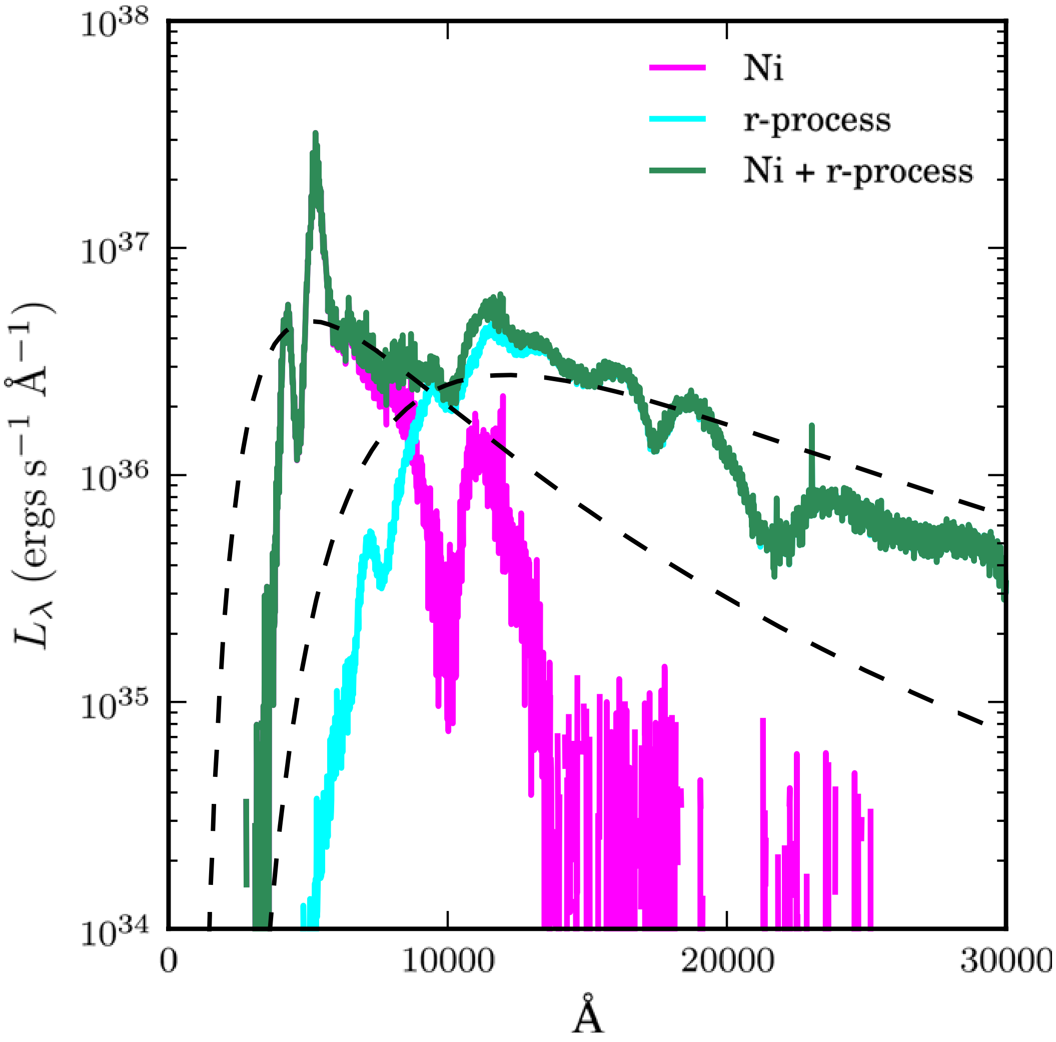
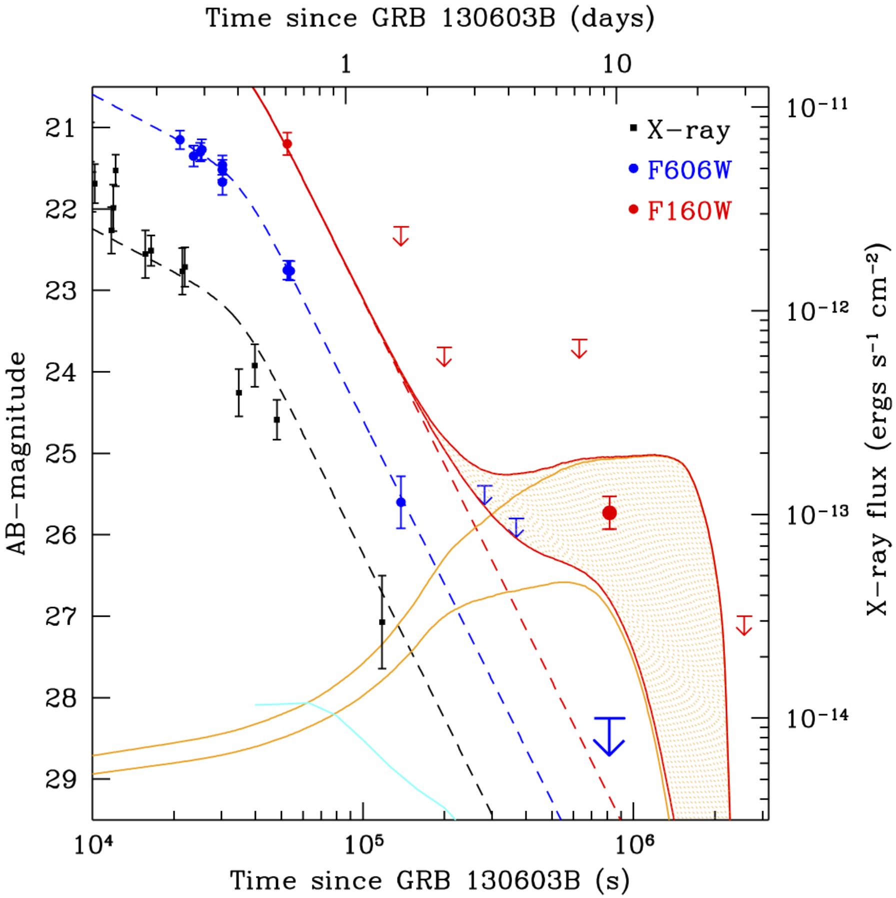


Figure 10. A combined ^{56}Ni and *r*-process spectrum at $t = 7$ days, taking $M_{\rm ni} = M_{\rm rp} = 10^{-2}\,M_\odot$. The peak at blue wavelengths is due to the ^{56}Ni, while the *r*-process material supplies the red and infrared emission. The best-fit blackbody curves to the individual spectra are overplotted in dashed black lines ($T_{\rm ni} \simeq 5700$ K, $T_{\rm rp} \simeq 2400$ K). The combined spectrum generally resembles a superposition of two blackbodies at different temperatures.

(A color version of this figure is available in the online journal.)

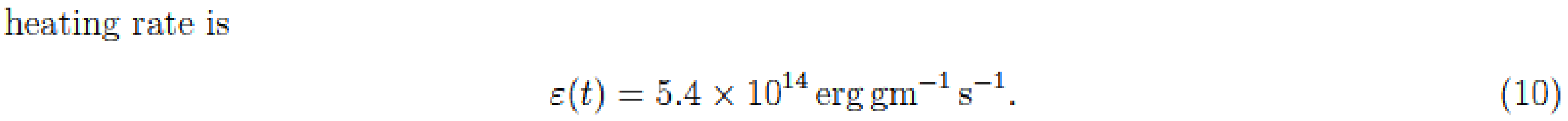
Barnes & Kasen

Detection?



Tanvir et al.   Berger et al.

Heating by Decay of Neutrons?



heating rate is

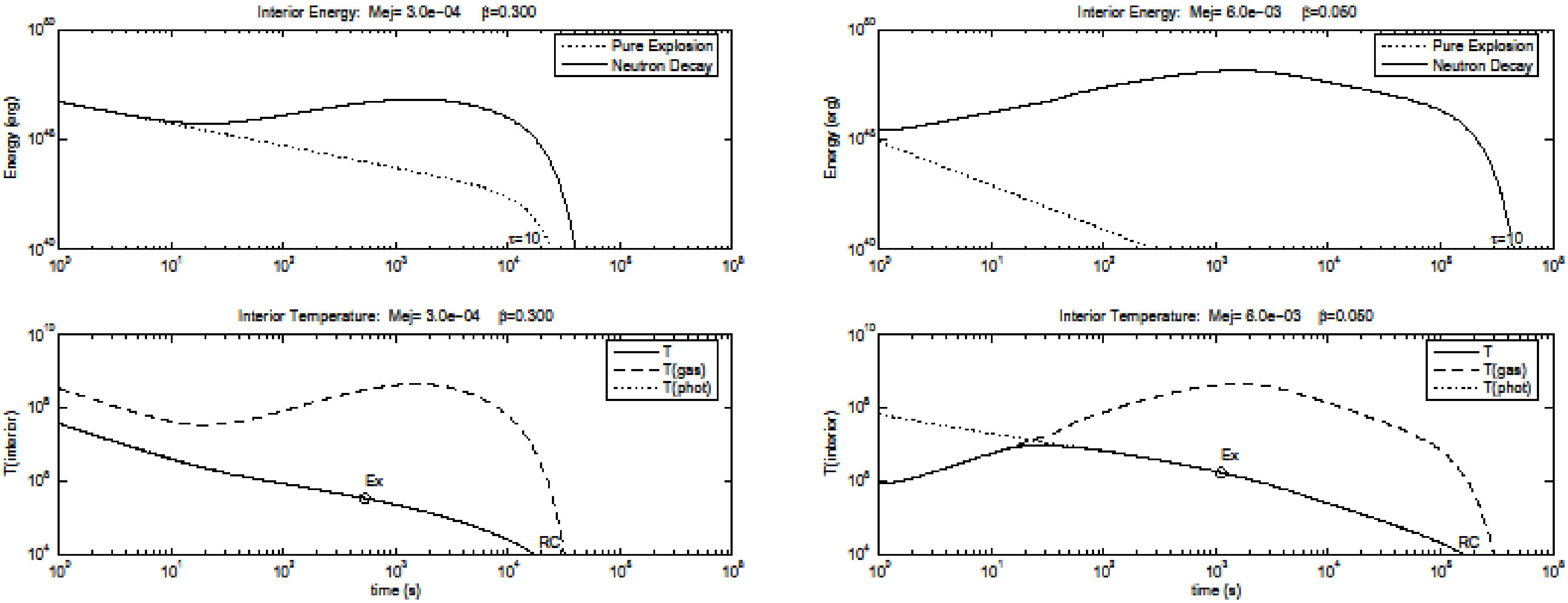
$$\varepsilon(t) = 5.4 \times 10^{14}\,\mathrm{erg\,gm^{-1}\,s^{-1}}. \tag{10}$$

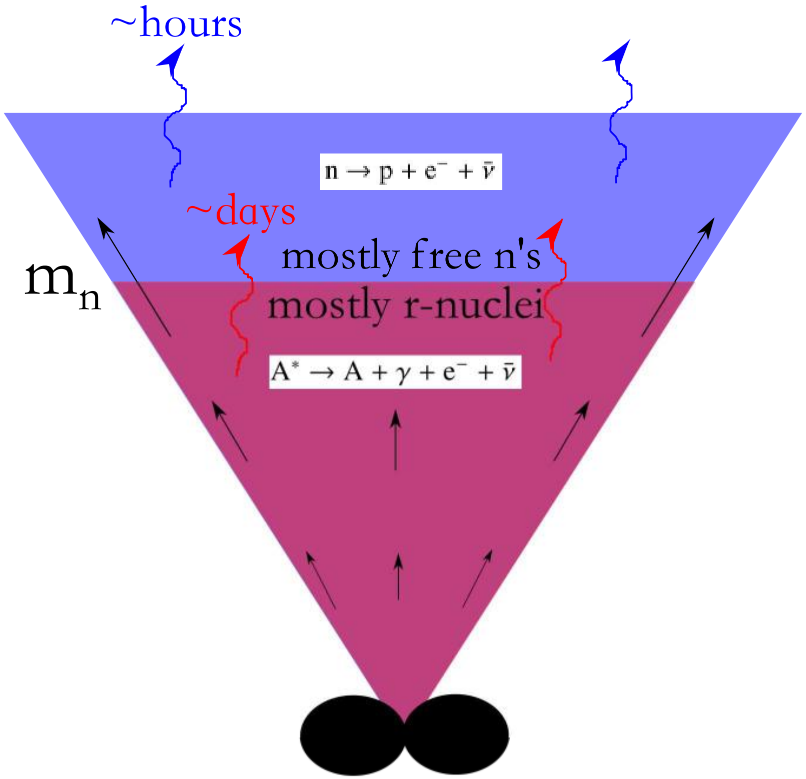
Even though half life is 10 minutes, neutron heating results in detectable signals.

Kulkarni 2005

Heating by Neutron Decay

8 *Kulkarni*





~hours

$n \rightarrow p + e^{-} + \bar{\nu}$

~days

m_n

mostly free n's

mostly r-nuclei

$A^{*} \rightarrow A + \gamma + e^{-} + \bar{\nu}$

$\propto$ $^{-\beta}$ □ □ $\beta \approx$

$<$ $\sim$ $^{-}$ $\odot$

$>$

$\lesssim$

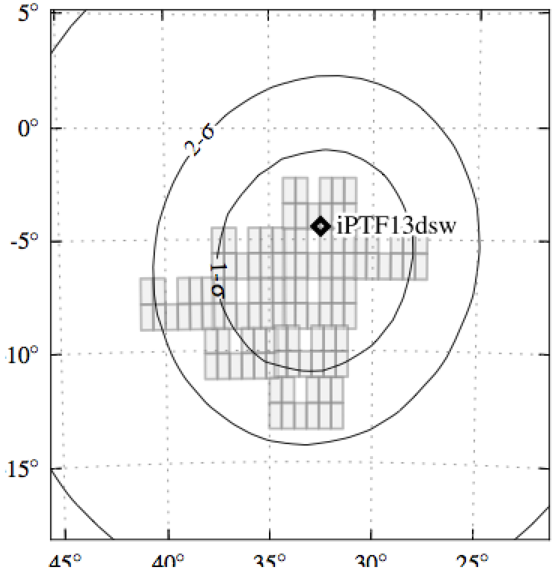
$\sim$

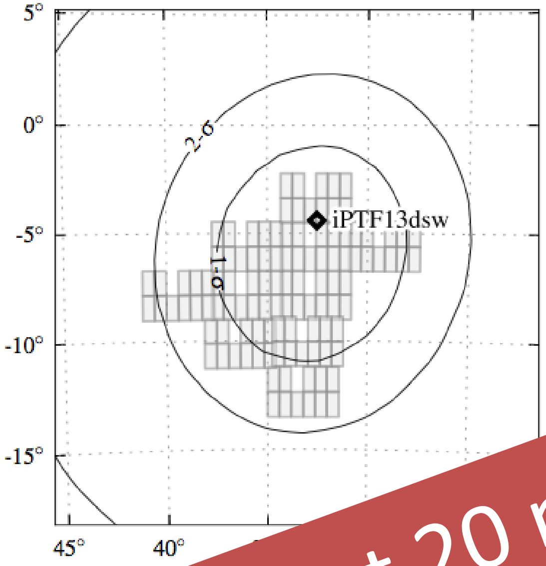
Metzger,Bauswein,...

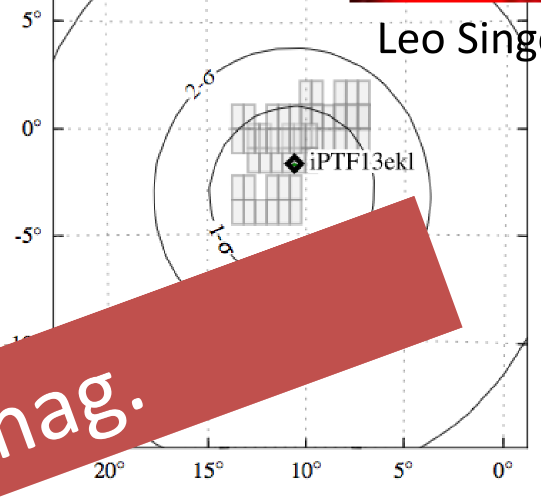
EARLY FOLLOW-UP (SAME NIGHT)

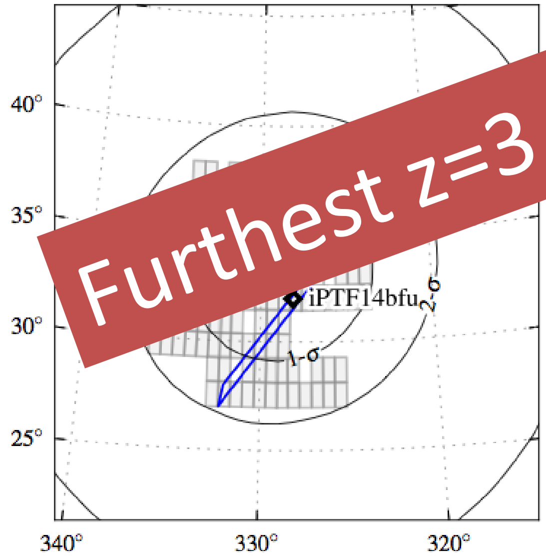
Needle in Haystack Found: Eight times

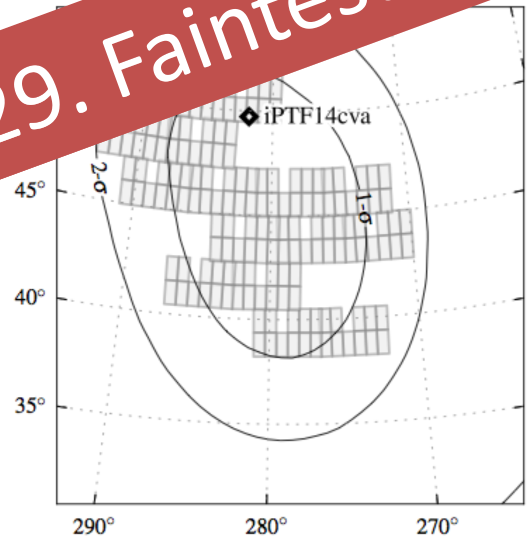
Leo Singer

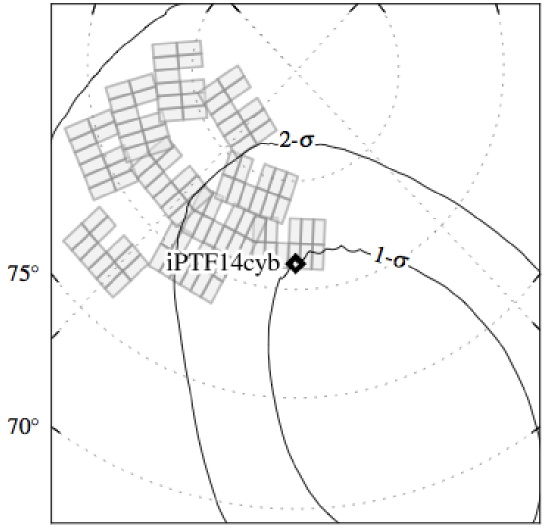










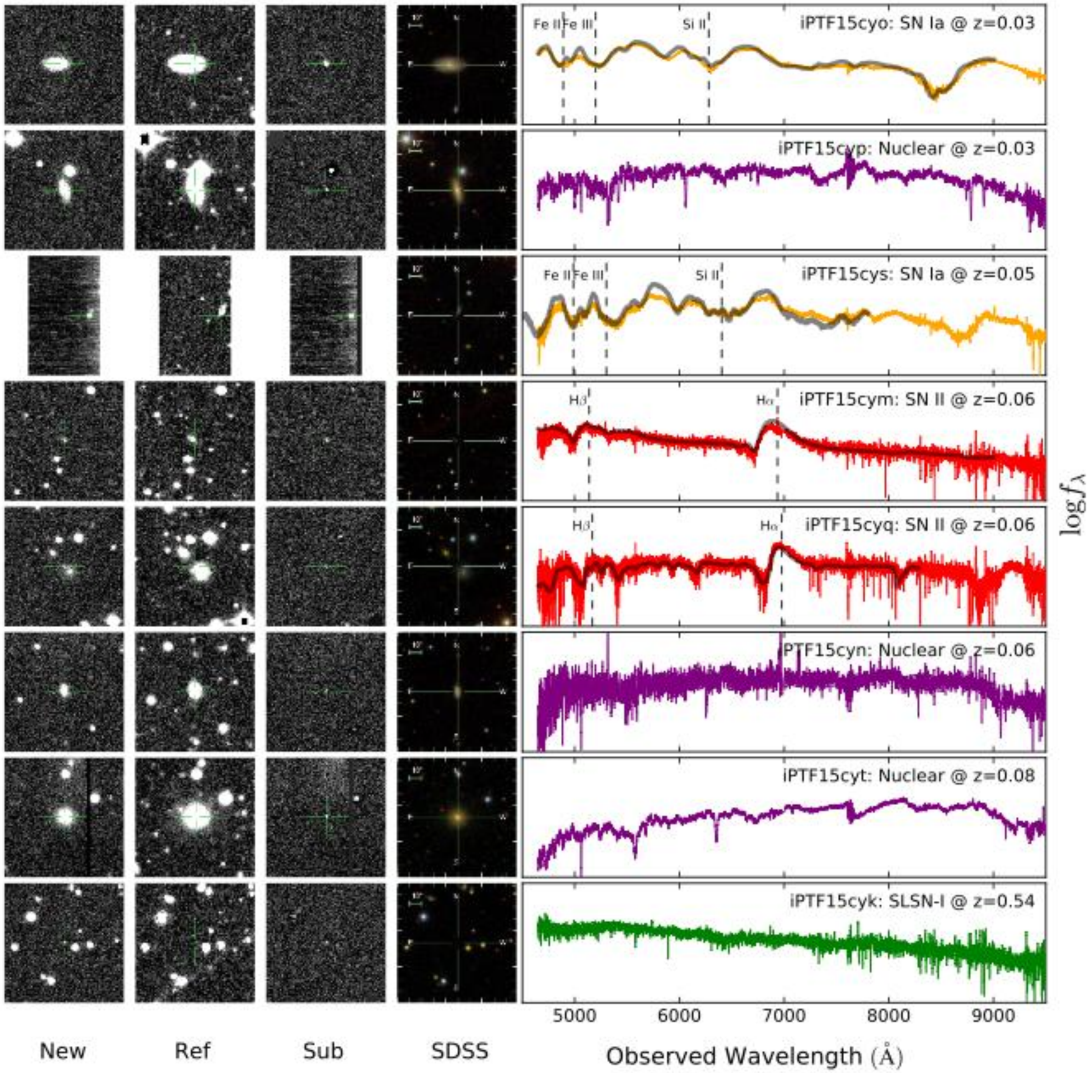


Furthest z=3.29. Faintest 20 mag.

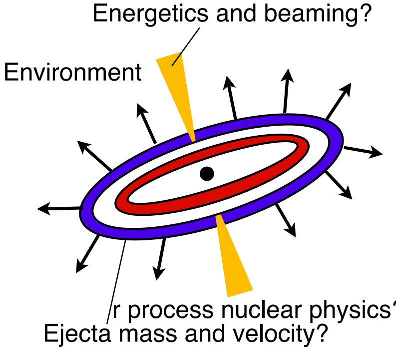
Singer et al. 2013, 2015 (PhDT)

GW150914:

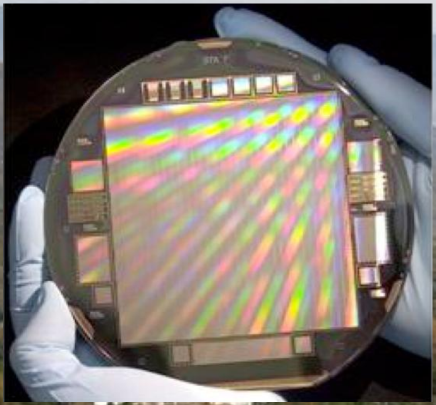
All candidates classified in 2 hours!



Kasliwal et al. 2016



Zwicky Transient Facility (ZTF)



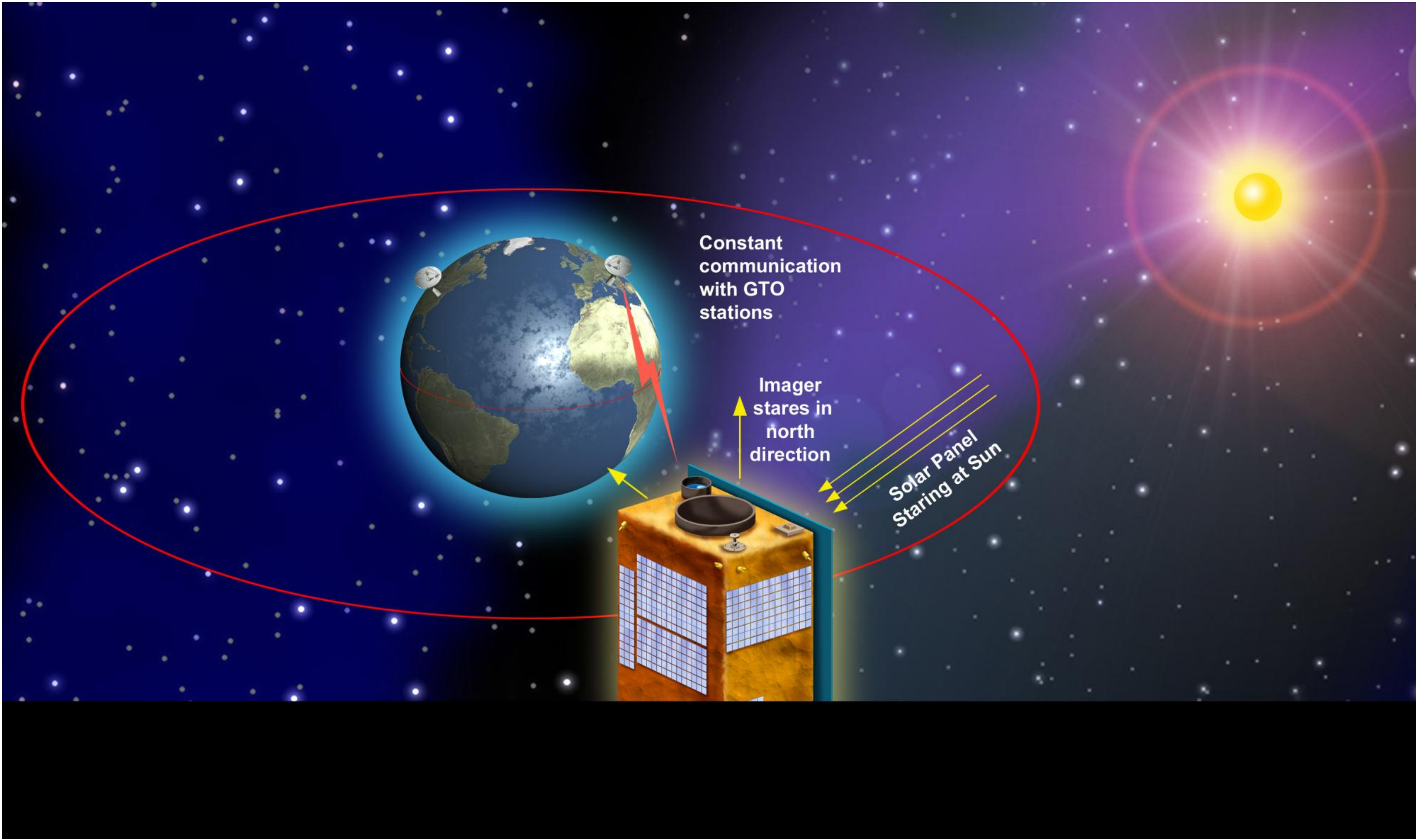
P48
Discovery
47 sq deg!
PI: S. Kulkarni
(2017)

P200:
Spectroscopy

P60
Classification
The SED Machine
PI: N. Konidaris
(2015)

Survey Speed of 3750 sq deg per hour!

ULTRASAT


Constant communication with GTO stations
Imager stares in north direction
Solar Panel Staring at Sun

Design & capabilities

- 33 cm f/1 Schmidt
- NUV band (220-280 nm)
- d-d CCD (QE~70%)
- Lim mag. 21.8 AB (3x300s; 5s)
  - 30 mag arcsec2 (in 3 months)
  - FWHM ~24”
- FOV: 235 deg2
  - Volumetric rate: ~380 X GALEX
  - ~12 X ZTF
  - ~0.2 LSST (but in NUV)

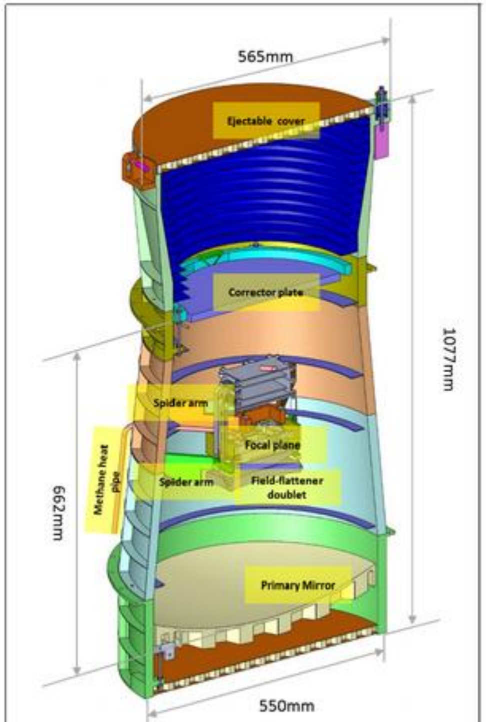


Figure E.1-1. Payload cut away showing the components; the control and power electronics boxes are attached to a spacecraft panel and not shown here. Different colors of the barrel indicate the separate segments of the structure.

What is ULTRASAT?

- Weizmann-Caltech led proposed small space mission (~$100M)
  - PIs: Waxman & Kulkarni
  - JPL, ISA, IAI, ElOp
- Exploring the UV transient sky
  - Designed to:
    - SN shock cooling and breakout discovery & alerts
    - Studying SN progenitors and physics
    - Search & alert for GW EM counterparts in the UV
    - Explore the transient sky (e.g., variability, TDE, GRB, QSO)