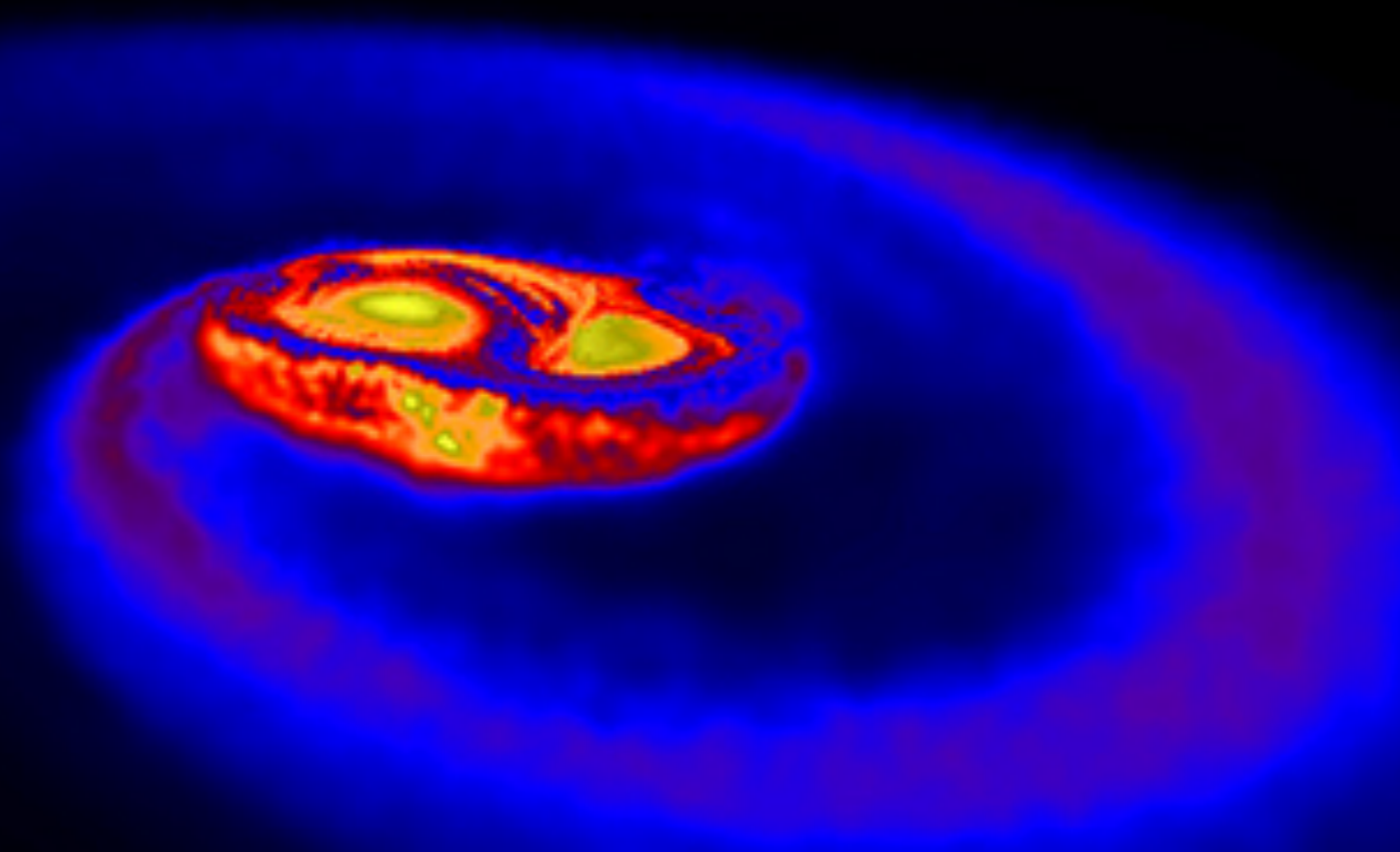




Silvia Piranomonte
INAF - Osservatorio Astronomico di Roma



IR emission from GW sources



Credits: Rosswog

COME TO THE IR SIDE

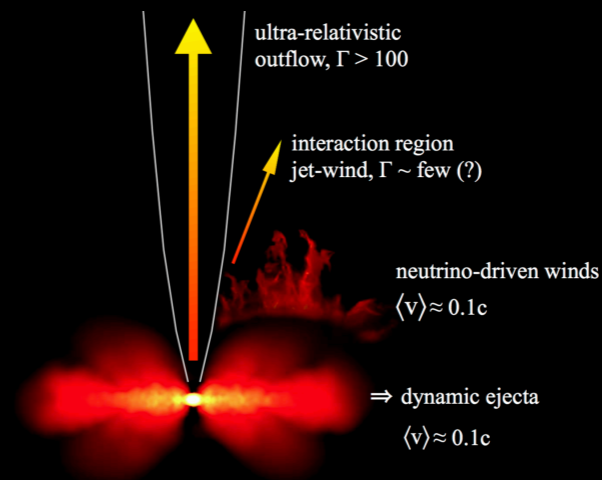
NS-NS / NS-BH mergers: Collimated EM emission from Short GRBs



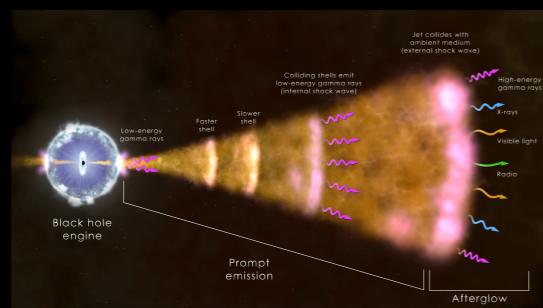
Short GRBs WITH
a detectable optical/
IR counterpart
(afterglow)

NS-NS / NS-BH mergers: Optical/**NIR** isotropic emissions

Kilonova or
Macronova



Core collapse of massive stars: Long GRBs, Low Luminosity GRBs and Supernovae



Long Gamma Ray Burst
with detectable **IR**
counterpart

COME TO THE IR SIDE

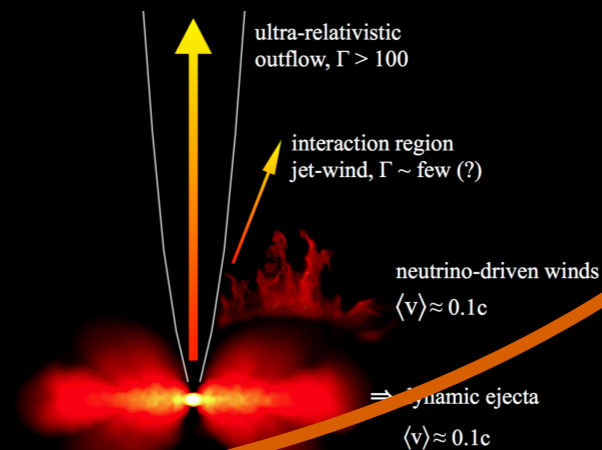
NS-NS / NS-BH mergers: Collimated EM emission from Short GRBs



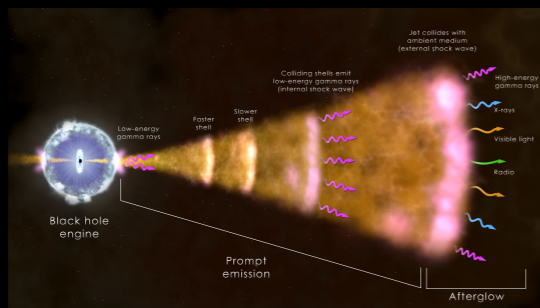
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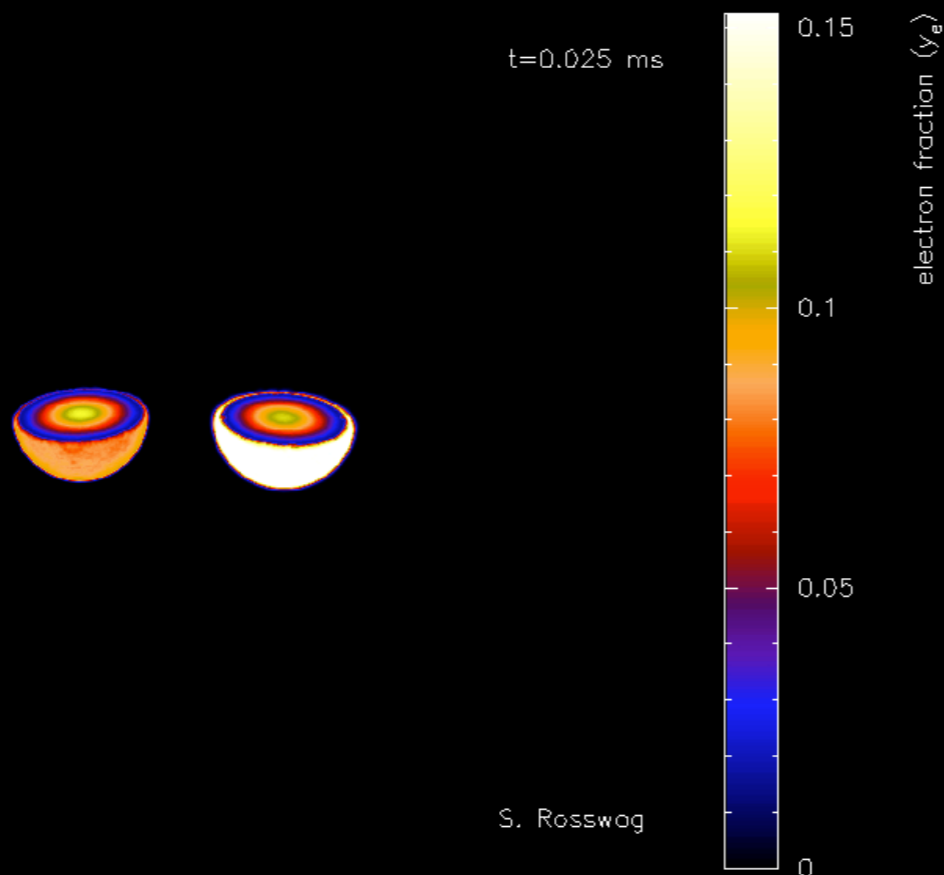


Core collapse of massive stars: Long GRBs, Low Luminosity GRBs and Supernovae



Long Gamma Ray Burst
with detectable **IR**
counterpart

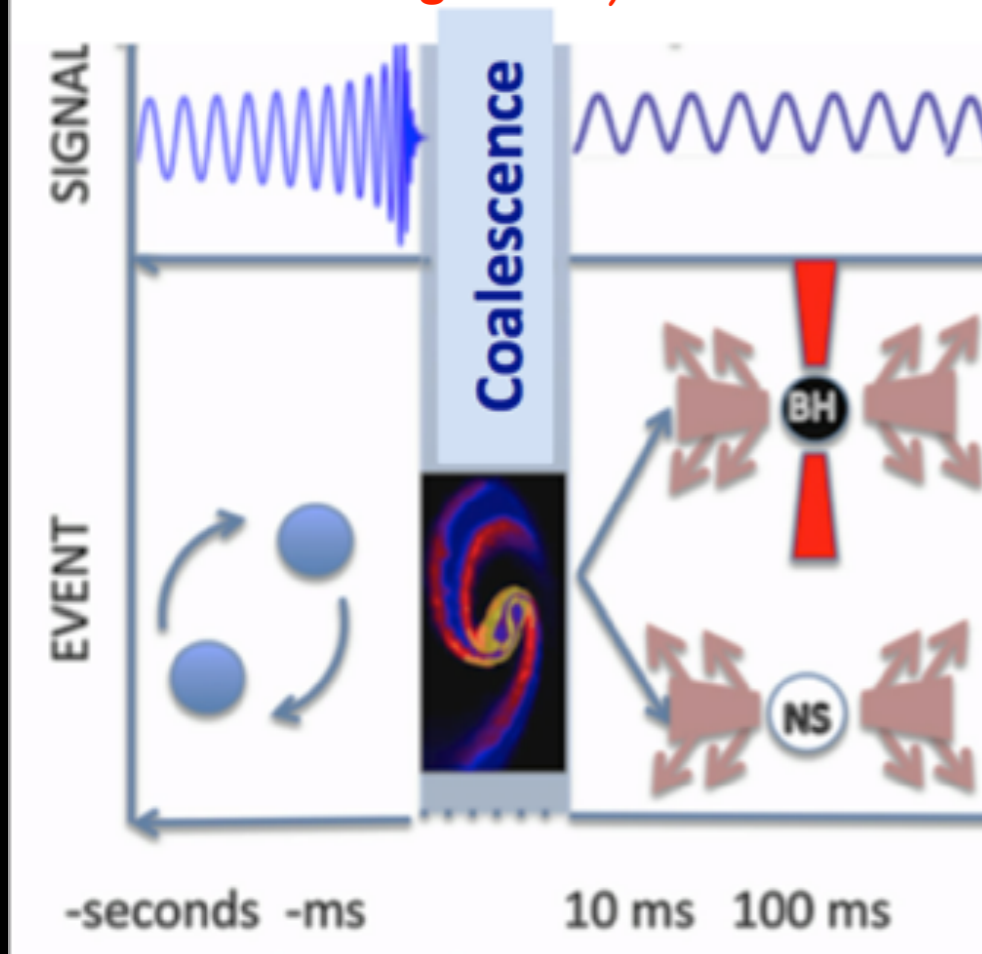
NS-NS NS-BH Merger



- ✓ prime candidates to be detected by terrestrial gravitational wave detectors.
- ✓ They likely are the 'engine' behind short **gamma-ray bursts**.
- ✓ They likely produce the **heaviest elements** (such as platinum or gold) in the cosmos.
- ✓ The radioactive decay of freshly synthesized, heavy elements causes an **electromagnetic transient ("macronova/kilonova")** that accompanies the expected gravitational wave signal.

EM emission: Compact Binary Coalescence (CBC) systems

Fernandez & Metzger 2016, ARNPS 66



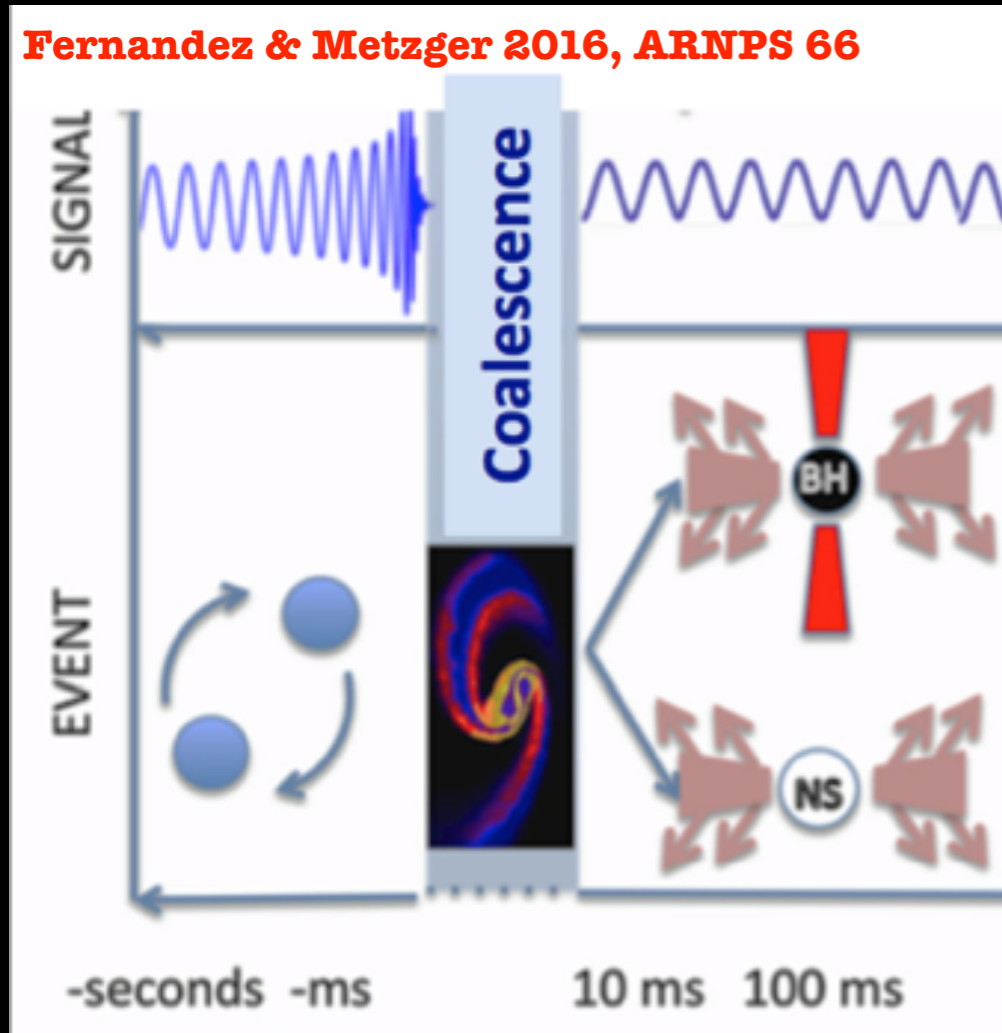
- Mass ejected by tidal forces: dynamically unbound matter
- Ejected mass gravitationally bound to the central remnant
—> accretion disk
- Final remnant: 90% of the initial binary mass

NS-NS: unbound mass of $10^{(-4)}$ - $10^{(-2)}$ Mo ejected at 0.1-0.3c

NS-BH: unbound mass up to 0.1Mo

**Dynamical
phase: tidal
effects**

EM emission: Compact Binary Coalescence (CBC) systems



Ejected material
gravitationally bound from
the central remnant → fall
back or circularize into an
accretion disk

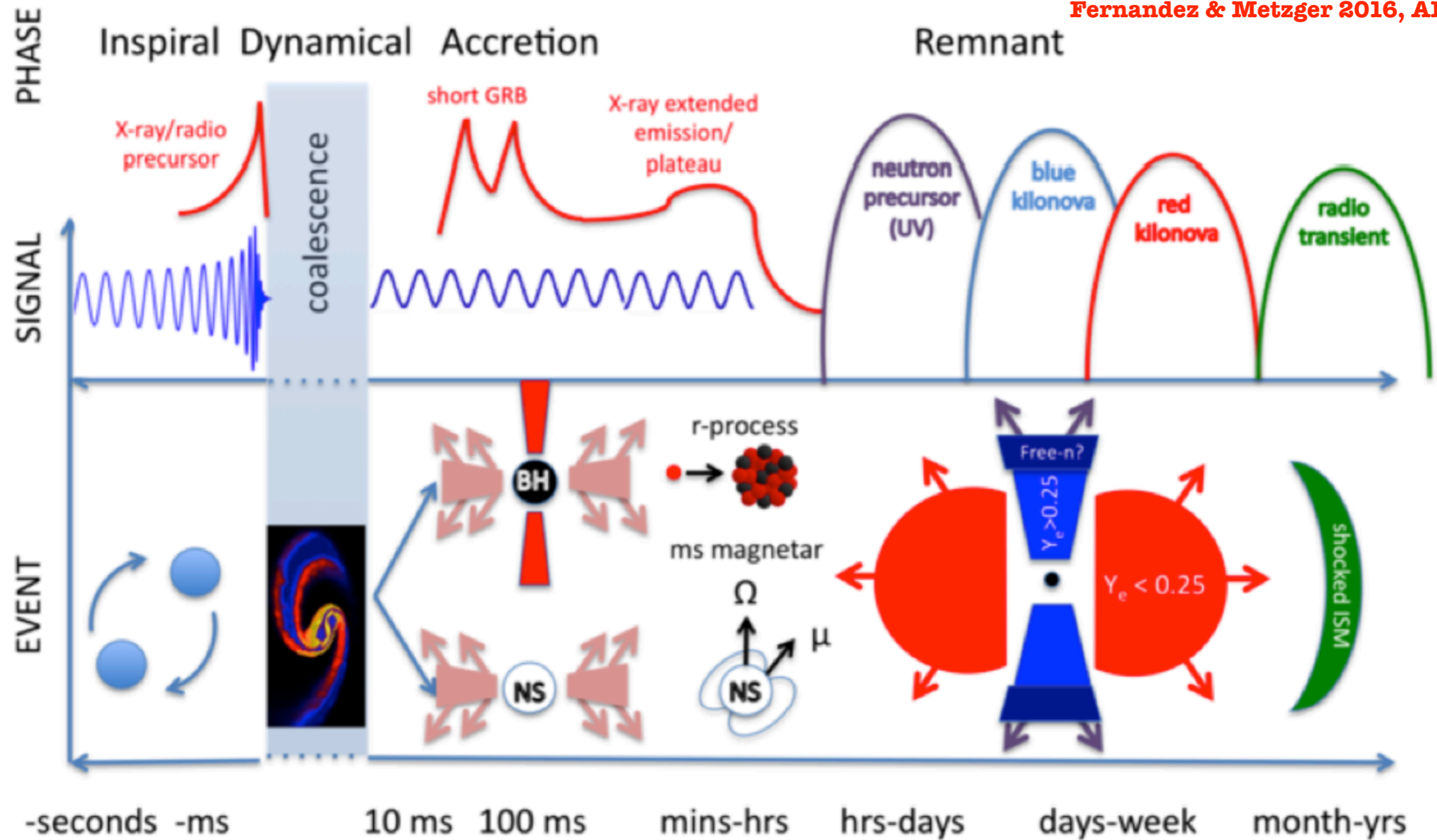
Disk mass up to 0.3 M_{\odot}

Outflow mass and geometry
influence the EM emission

Accretion phase:
BH-Torus →
relativistic jets

NS-NS NS-BH Merger: a global picture

Fernandez & Metzger 2016, ARNPS 66

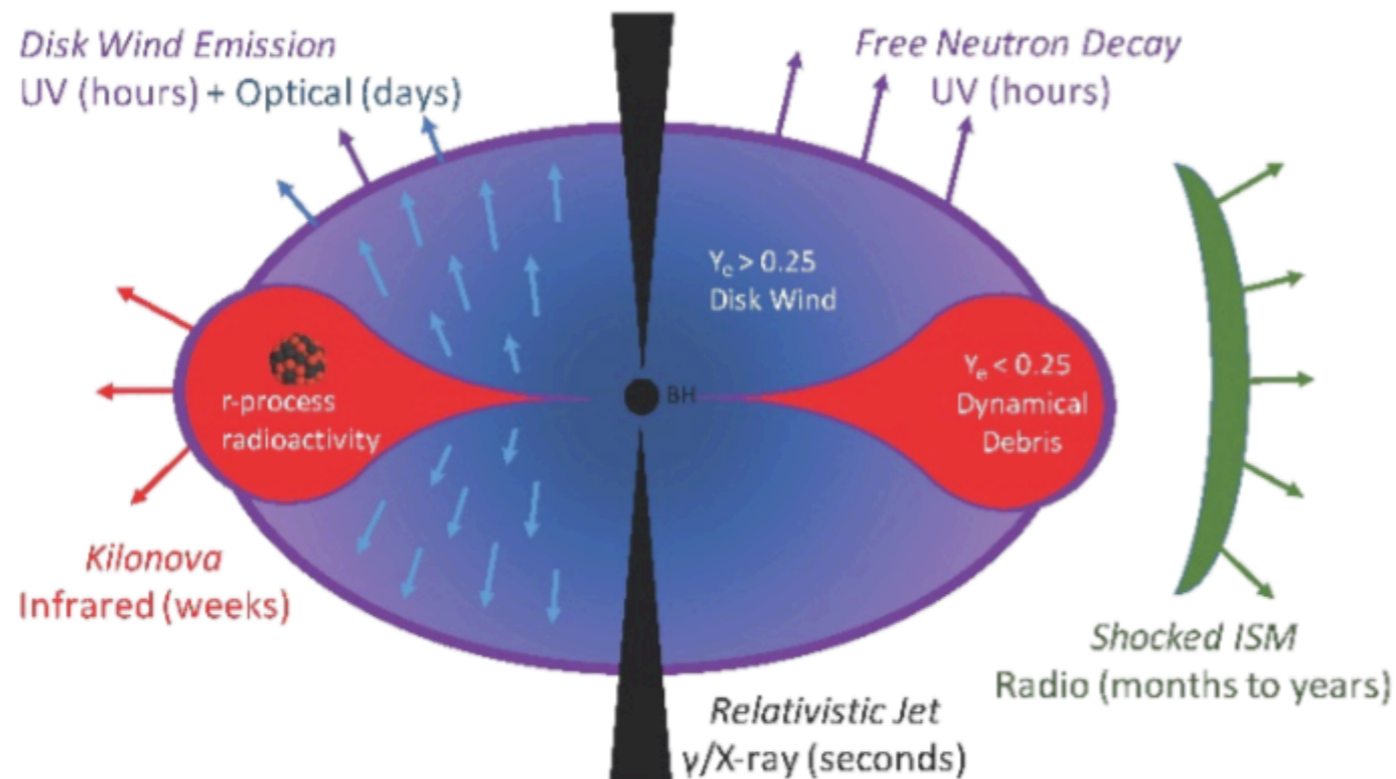
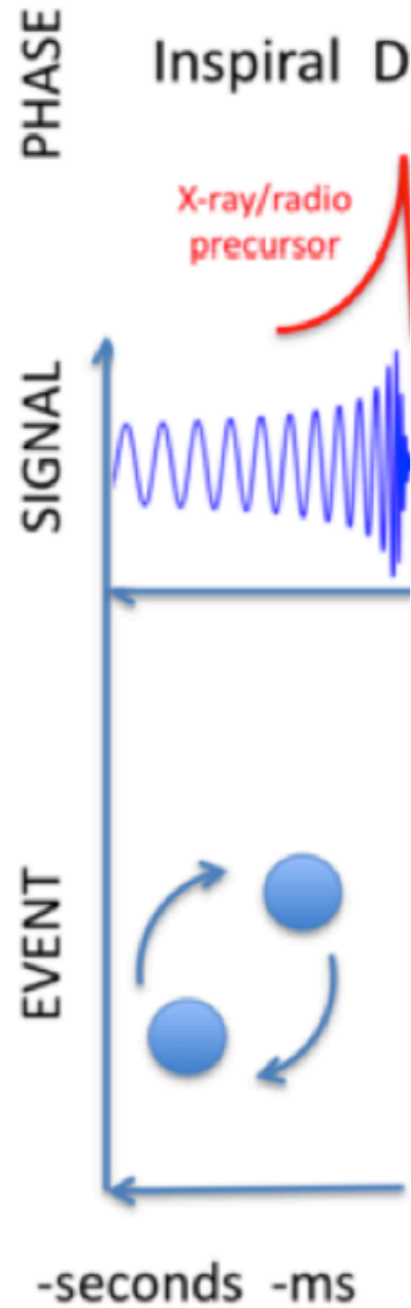


NS-NS NS-BH Merger: a global picture

Metzger 2016, ARNPS 66

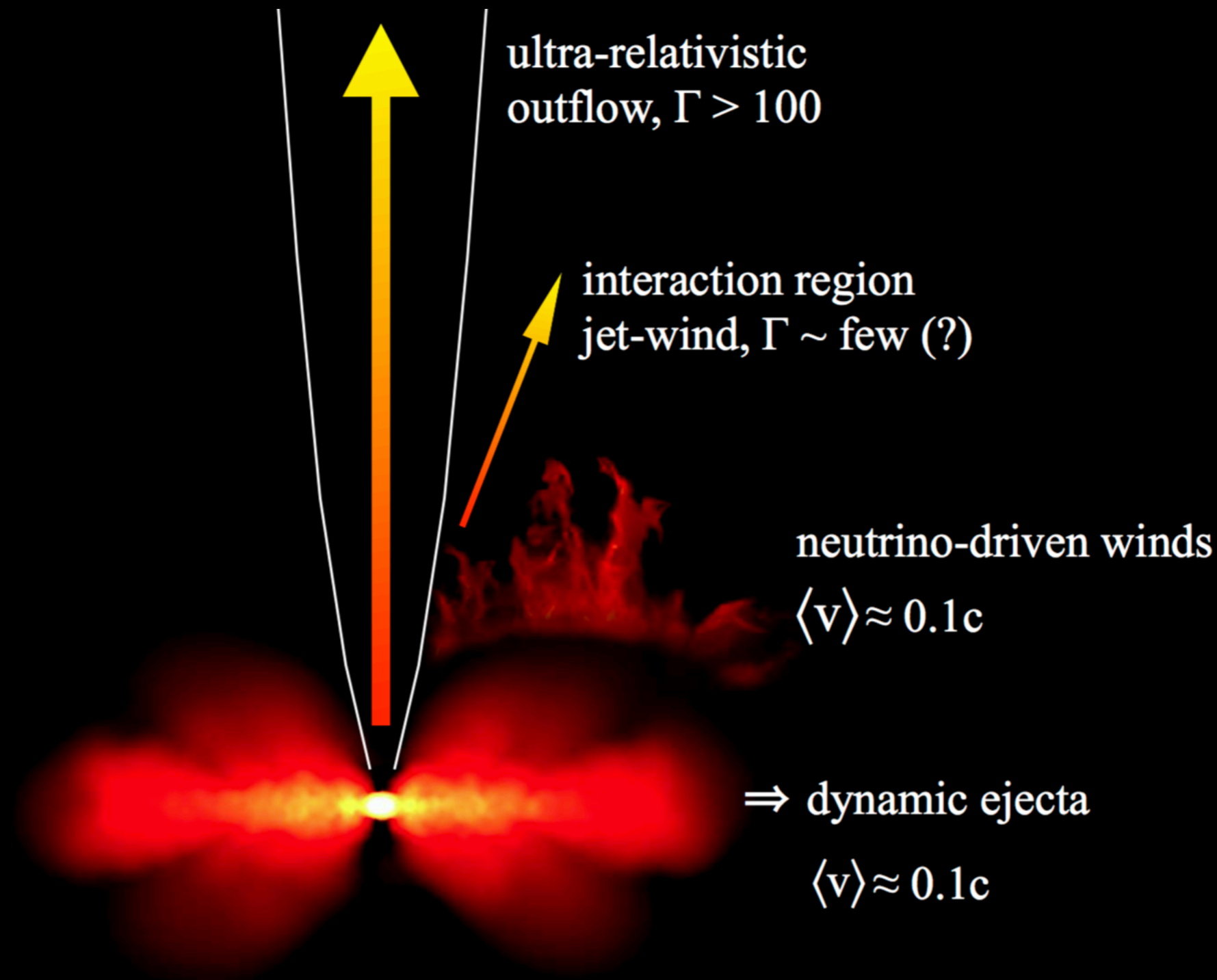
Radioactive decay heats the ejecta

-> optical- NIR thermal radiation



Isotropic EM- counterpart

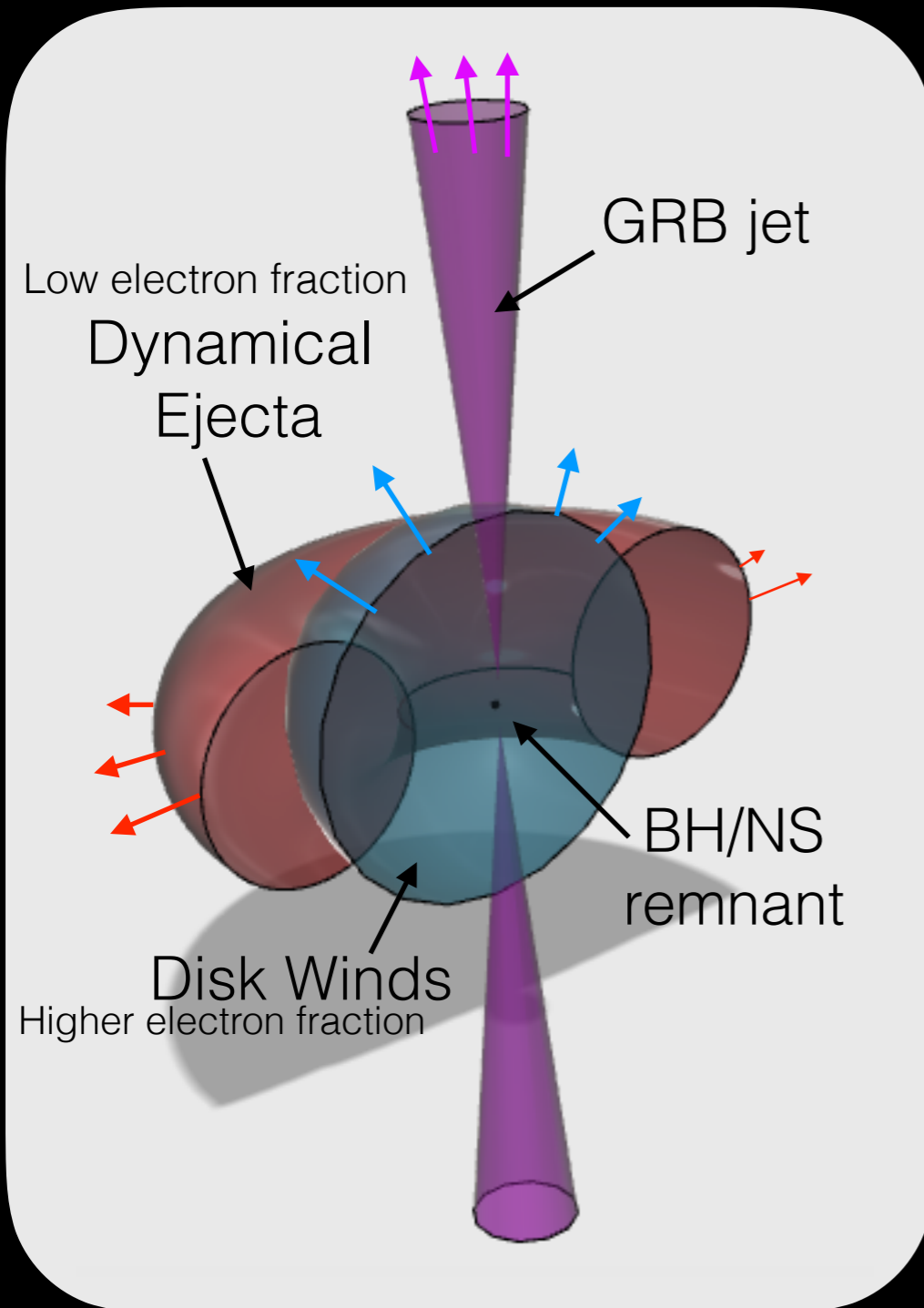
Macronovae: radioactively powered electromagnetic transients from compact binary mergers



Credits: Rosswog

Morphology of the Ejecta

(Two different channels)



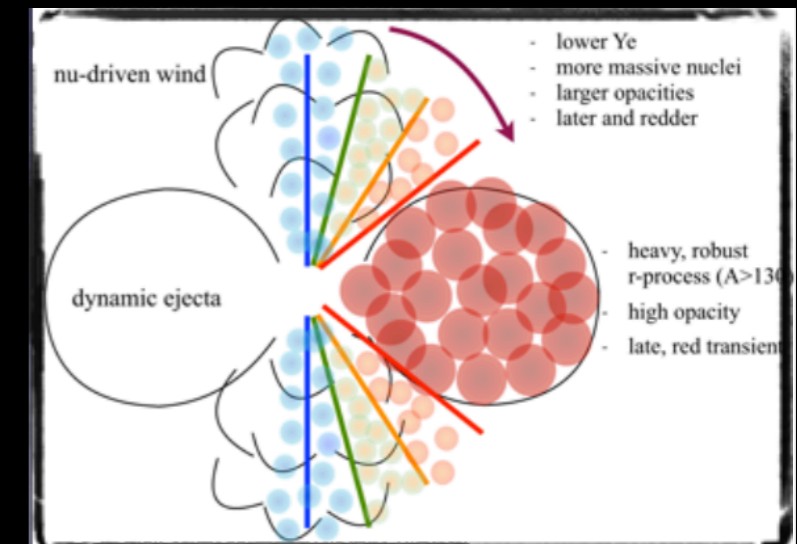
Courtesy of S. Ascenzi

Dynamical Ejecta

unbound by hydrodynamic interaction and gravitational torques

Red Macronova

Peaks at days - 1 week after the merger



Disk Winds

neutrino absorption, magnetically launched winds or accretion disk matter that becomes unbound by viscous and nuclear heating

Blue Macronova

Peaks at 1 day after the merger

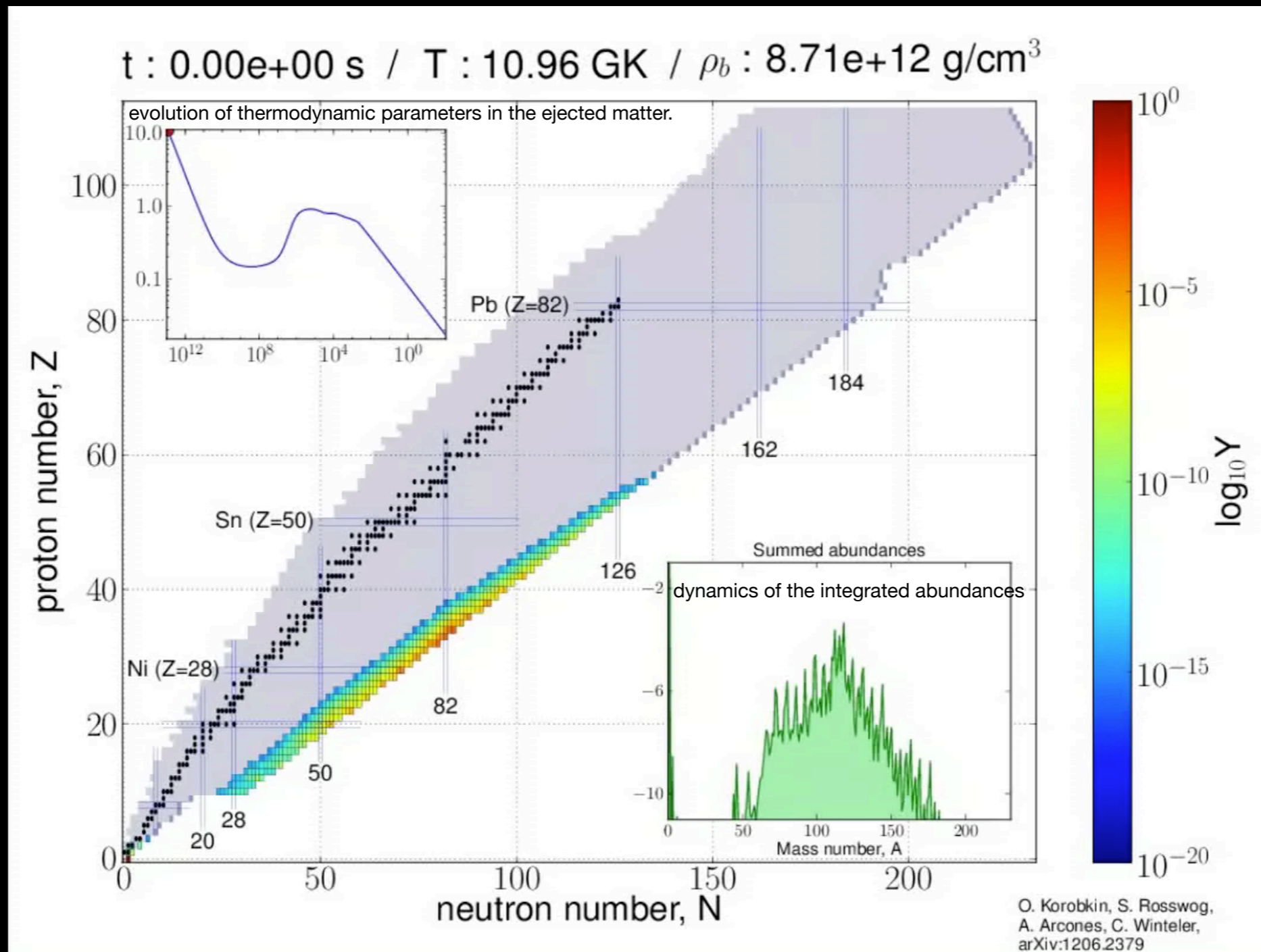
2-3 magnitude brighter than the red macronova

R-Process Nucleosynthesis

basic reactions:

a) n-capture: $n + (Z,A) \Rightarrow (Z,A+1)$

b) β -decay: $(Z,A) \Rightarrow (Z+1,A) + e + \bar{\nu}_e$



R-Process Nucleosynthesis

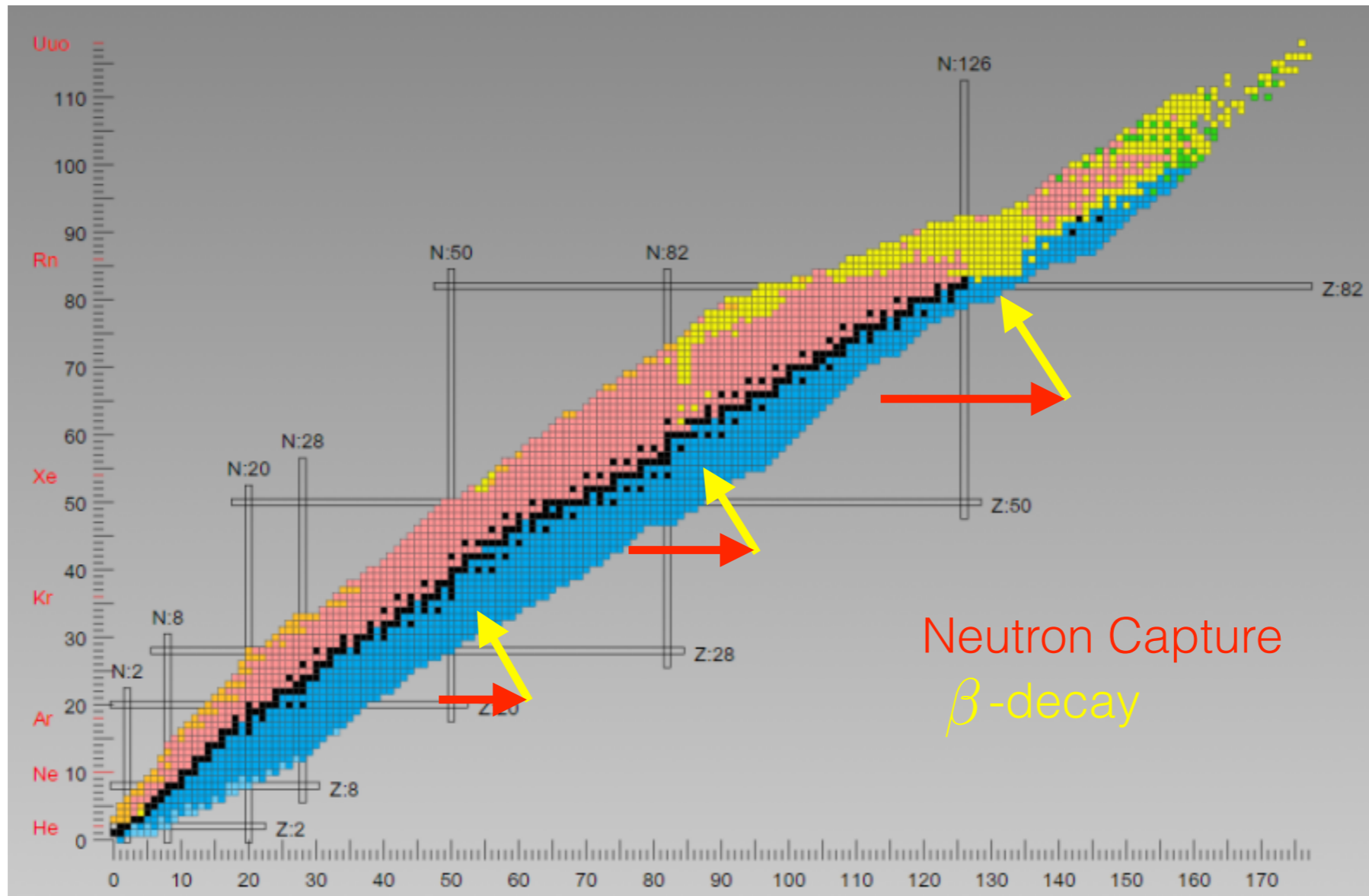
basic reactions:

a)

b)

Chart of Nuclides

Proton Number



Neutron Number

neutron number, N

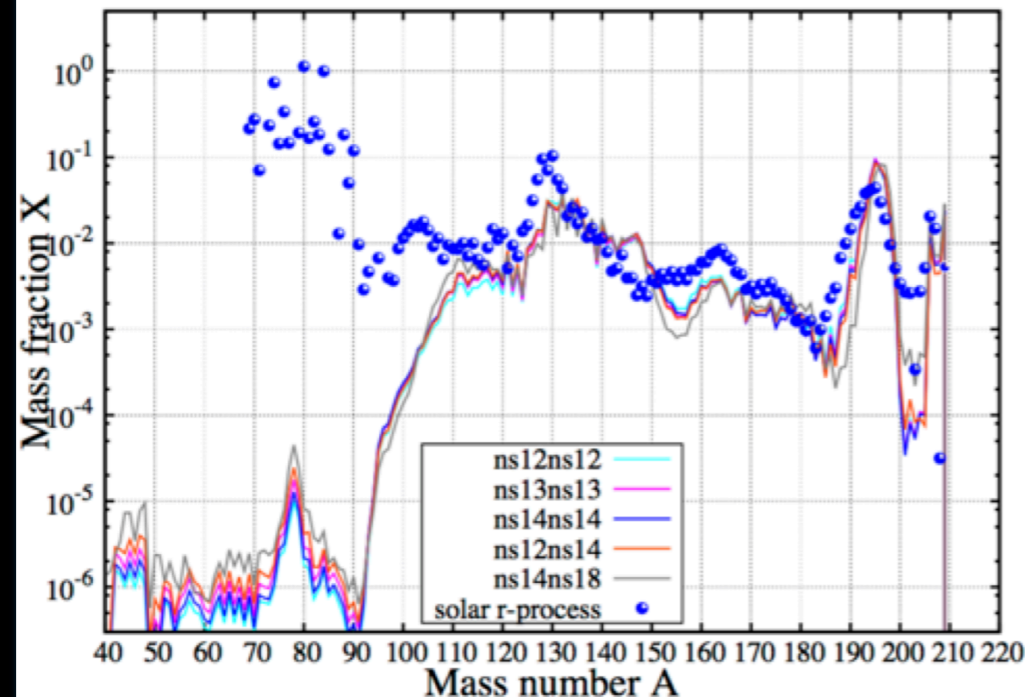
A. Arcones, C. Winteler,
arXiv:1206.2379

R-Process Nucleosynthesis

Nucleosynthesis for dynamic ejecta

(Rosswog et al. 2017)

low Y_e (≈ 0.1)



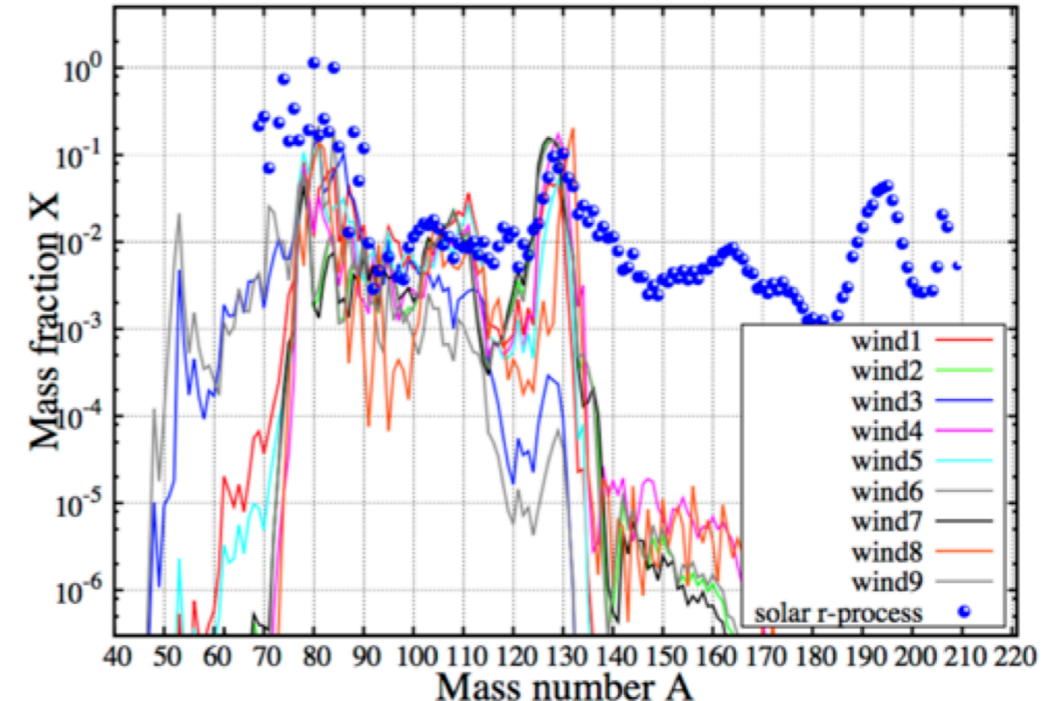
- the heaviest elements, $A > 130$
- robustly producing the “platinum peak” at $A = 195$

**“strong r-process” - lanthanides -
large opacities $\kappa = 10 \text{ cm}^2/\text{g}$**

Nucleosynthesis for neutrino-driven winds

(Rosswog et al. 2017)

“large” Y_e (~ 0.3)



- lighter r-process elements, $A < 130$

**“Weak r-process” - no lanthanides -
moderate opacities $\kappa = 1 \text{ cm}^2/\text{g}$**

\Rightarrow together, they add up to the solar abundance pattern (blue dots)

Opacity

1

1A

1A

2

IIA

2A

3

IIIB

3B

4

IVB

4B

5

VB

5B

6

VIB

6B

7

VII B

7B

8

VIII

8

9

IB

1B

10

IIB

2B

11

IIIA

3A

12

IVA

4A

13

VA

5A

14

VIA

6A

15

VIIA

7A

16

VIIIA

8A

17

VIIIA

8A

18

VIIIA

8A

1

H

Hydrogen

[He]1s¹

2

He

Helium

[He]1s²

3

Li

Lithium

[He]2s¹

4

Be

Beryllium

[He]2s²

5

B

Boron

[He]2s²2p¹

6

C

Carbon

[He]2s²2p²

7

N

Nitrogen

[He]2s²2p³

8

O

Oxygen

[He]2s²2p⁴

9

F

Fluorine

[He]2s²2p⁵

10

Ne

Neon

[He]2s²2p⁶

11

Na

Sodium

[Ne]3s¹

12

Mg

Magnesium

[Ne]3s²

13

Al

Aluminum

[Ne]3s²3p¹

14

Si

Silicon

[Ne]3s²3p²

15

P

Phosphorus

[Ne]3s²3p³

16

S

Sulfur

[Ne]3s²3p⁴

17

Cl

Chlorine

[Ne]3s²3p⁵

18

Ar

Argon

[Ne]3s²3p⁶

19

K

Potassium

[Ar]4s¹

20

Ca

Calcium

[Ar]4s²

21

Sc

Scandium

[Ar]3d¹4s²

22

Ti

Titanium

[Ar]3d²4s²

23

V

Vanadium

[Ar]3d³4s²

24

Cr

Chromium

[Ar]3d⁵4s¹

25

Mn

Manganese

[Ar]3d⁵4s²

26

Fe

Iron

[Ar]3d⁶4s²

27

Co

Cobalt

[Ar]3d⁷4s²

28

Ni

Nickel

[Ar]3d⁸4s²

29

Cu

Copper

[Ar]3d¹⁰4s¹

30

Zn

Zinc

[Ar]3d¹⁰4s²

31

Ga

Gallium

[Ar]3d¹⁰4s²4p¹

32

Ge

Germanium

[Ar]3d¹⁰4s²4p²

33

As

Arsenic

[Ar]3d¹⁰4s²4p³

34

Se

Selenium

[Ar]3d¹⁰4s²4p⁴

35

Br

Bromine

[Ar]3d¹⁰4s²4p⁵

36

Kr

Krypton

[Ar]3d¹⁰4s²4p⁶

37

Rb

Rubidium

[Kr]5s¹

38

Sr

Strontium

[Kr]5s²

39

Y

Yttrium

[Kr]4d¹5s²

40

Zr

Zirconium

[Kr]4d²5s²

41

Nb

Niobium

[Kr]4d⁴5s¹

42

Mo

Molybdenum

[Kr]4d⁵5s¹

43

Tc

Technetium

[Kr]4d⁵5s²

44

Ru

Ruthenium

[Kr]4d⁷5s¹

45

Rh

Rhodium

[Kr]4d⁸5s¹

46

Pd

Palladium

[Kr]4d¹⁰

47

Ag

Silver

[Kr]4d¹⁰5s¹

48

Cd

Cadmium

[Kr]4d¹⁰5s²

49

In

Indium

[Kr]4d¹⁰5s²5p¹

50

Sn

Tin

[Kr]4d¹⁰5s²5p²

51

Sb

Antimony

[Kr]4d¹⁰5s²5p³

52

Te

Tellurium

[Kr]4d¹⁰5s²5p⁴

53

I

Iodine

[Kr]4d¹⁰5s²5p⁵

54

Xe

Xenon

[Kr]4d¹⁰5s²5p⁶

55

Cs

Cesium

[Xe]6s¹

56

Ba

Barium

[Xe]6s²

57-71

72

Hf

Hafnium

[Xe]4f¹⁴5d²6s²

73

Ta

Tantalum

[Xe]4f¹⁴5d³6s²

74

W

Tungsten

[Xe]4f¹⁴5d⁴6s²

75

Re

Rhenium

[Xe]4f¹⁴5d⁵6s²

76

Os

Osmium

[Xe]4f¹⁴5d⁶6s²

77

Ir

Iridium

[Xe]4f¹⁴5d⁷6s²

78

Pt

Platinum

[Xe]4f¹⁴5d⁹6s¹

79

Au

Gold

[Xe]4f¹⁴5d¹⁰6s¹

80

Hg

Mercury

[Xe]4f¹⁴5d¹⁰6s²

81

Tl

Thallium

[Xe]4f¹⁴5d¹⁰6s²6p¹

82

Pb

Lead

[Xe]4f¹⁴5d¹⁰6s²6p²

83

Bi

Bismuth

[Xe]4f¹⁴5d¹⁰6s²6p³

84

Po

Polonium

[Xe]4f¹⁴5d¹⁰6s²6p⁴

85

At

Astatine

[Xe]4f¹⁴5d¹⁰6s²6p⁵

86

Rn

Radon

[Xe]4f¹⁴5d¹⁰6s²6p⁶

87

Fr

Francium

[Rn]7s¹

88

Ra

Radium

[Rn]7s²

89-103

104

Rf

Rutherfordium

[Rn]5f¹⁴6d²7s²

105

Db

Dubnium

[Rn]5f¹⁴6d³7s²

106

Sg

Seaborgium

[Rn]5f¹⁴6d⁴7s²

107

Bh

Bohrium

[Rn]5f¹⁴6d⁵7s²

108

Hs

Hassium

[Rn]5f¹⁴6d⁶7s²

109

Mt

Meitnerium

[Rn]5f¹⁴6d⁷7s²

110

Ds

Darmstadtium

[Rn]5f¹⁴6d⁸7s²

111

Rg

Roentgenium

[Rn]5f¹⁴6d⁹7s²

112

Cn

Copernicium

[Rn]5f¹⁴6d¹⁰7s²

113

Uut

Ununtrium

[Rn]5f¹⁴6d¹⁰7s²7p¹

114

Fl

Flerovium

[Rn]5f¹⁴6d¹⁰7s²7p²

115

Uup

Ununpentium

[Rn]5f¹⁴6d¹⁰7s²7p³

116

Lv

Livermorium

[Rn]5f¹⁴6d¹⁰7s²7p⁴

117

Uus

Ununseptium

[Rn]5f¹⁴6d¹⁰7s²7p⁵

118

Uuo

Ununoctium

[Rn]5f¹⁴6d¹⁰7s²7p⁶

Lanthanide Series

Actinide Series

57

La

Lanthanum

[Xe]5d¹6s²

58

Ce

Cerium

[Xe]4f¹5d¹6s²

59

Pr

Praseodymium

[Xe]4f³6s²

60

Nd

Neodymium

[Xe]4f⁴6s²

61

Pm

Promethium

[Xe]4f⁵6s²

62

Sm

Samarium

[Xe]4f⁶6s²

63

Eu

Europium

[Xe]4f⁷6s²

64

Gd

Gadolinium

[Xe]4f⁷5d¹6s²

65

Tb

Terbium

[Xe]4f⁹6s²

66

Dy

Dysprosium

[Xe]4f¹⁰6s²

67

Ho

Holmium

[Xe]4f¹¹6s²

68

Er

Erbium

[Xe]4f¹²6s²

69

Tm

Thulium

[Xe]4f¹³6s²

70

Yb

Ytterbium

[Xe]4f¹⁴6s²

71

Lu

Lutetium

[Xe]4f¹⁴5d¹6s²

89

Ac

Actinium

[Rn]6d¹7s²

90

Th

Thorium

[Rn]6d²7s²

91

Pa

Protactinium

[Rn]5f²6d¹7s²

92

U

Uranium

[Rn]5f³6d¹7s²

93

Np

Neptunium

[Rn]5f⁴6d¹7s²

94

Pu

Plutonium

[Rn]5f⁶7s²

95

Am

Americium

[Rn]5f⁷7s²

96

Cm

Curium

[Rn]5f⁸6d¹7s²

97

Bk

Berkelium

[Rn]5f⁹7s²

98

Cf

Californium

[Rn]5f¹⁰7s²

99

Es

Einsteinium

[Rn]5f¹¹7s²

100

Fm

Fermium

[Rn]5f¹²7s²

101

Md

Mendelevium

[Rn]5f¹³7s²

102

No

Nobelium

[Rn]5f¹⁴7s²

103

Lr

Lawrencium

[Rn]5f¹⁴6d¹7s²

THESEUS WORKSHOP - NAPLES 5-6 OCT 2017

Macronova: Main Ingredients

k ← Opacity

m_{ej} ← Mass of the Ejecta

v_{ej} ← Velocity of the Ejecta

$$t_{peak} \simeq 4.9 \text{ days} \left(\frac{k}{10 \text{ cm}^2/\text{g}} \frac{m_{ej}}{0.01 M_{\odot}} \frac{0.1 c}{v_{ej}} \right)^{1/2}$$

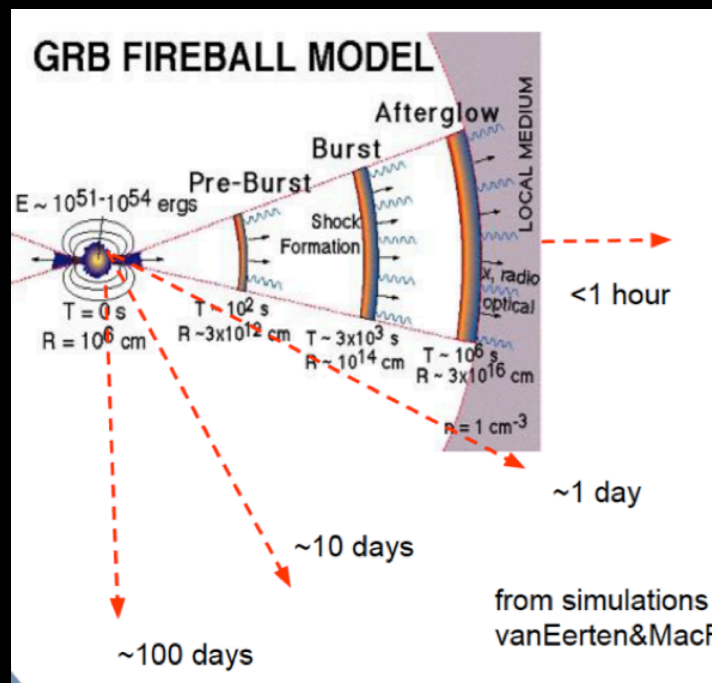
$$L_{peak} \simeq 2.5 \times 10^{40} \frac{\text{erg}}{\text{s}} \left(\frac{v_{ej}}{0.1 c} \frac{10 \text{ cm}^2/\text{g}}{k} \right)^{0.65} \left(\frac{m_{ej}}{0.01 M_{\odot}} \right)^{0.35}$$

(Grossman et al. 2014)

WHAT SHOULD WE EXPECT

NS-NS NS-BH Merger EM-Emission: SGRBs? Kilonove?

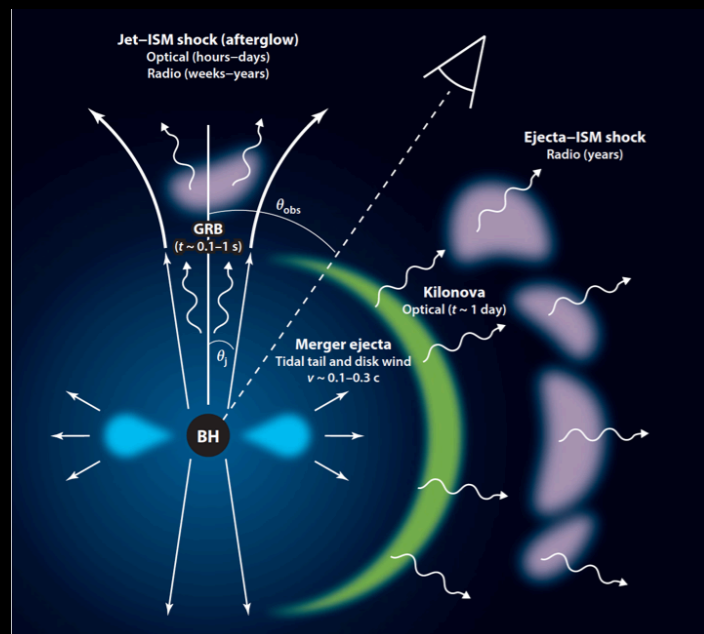
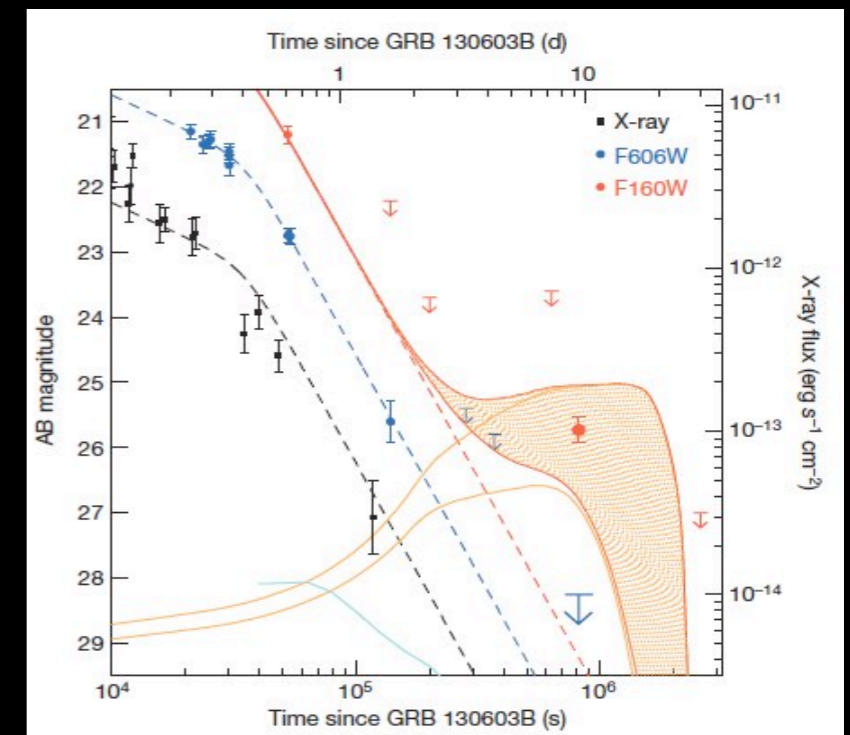
Models and Observations



* **SGRB on-axis emission**

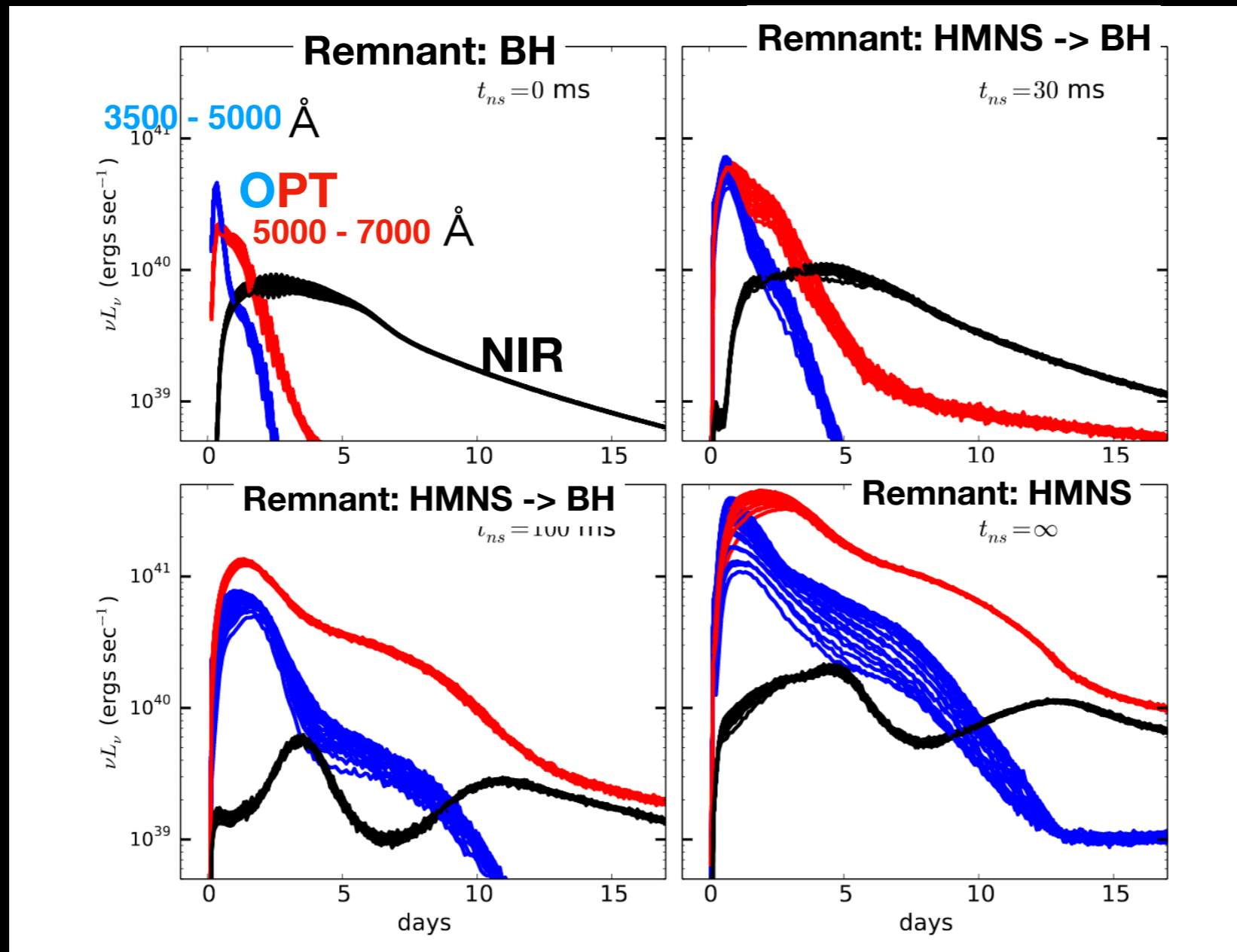
* **Evidence of kilonova emission**

* **Evidence of off-axis emission**



✓ GRB130603B Tanvir et al. 2013;
Berger et al. 2013
✓ GRB 060614 Yang et al. 2015
✓ GRB 050709 Jin et al. 2016

Kilonova expected light curves



Kasen+2015

PRO: emitted in essentially all directions

CONS: likely weak, and will only be observable by the largest telescopes

OPTICAL COMPONENT (from disk outflow) : peaks at 1 day with $L=5-500 \times 10^{40}$ erg/s (r=19-24 mag at 200 Mpc)

NIR COMPONENT (from ejecta) : peaks at few up to 10 days with $L=0.1-1 \times 10^{40}$ erg/s

Kilonova expected spectra

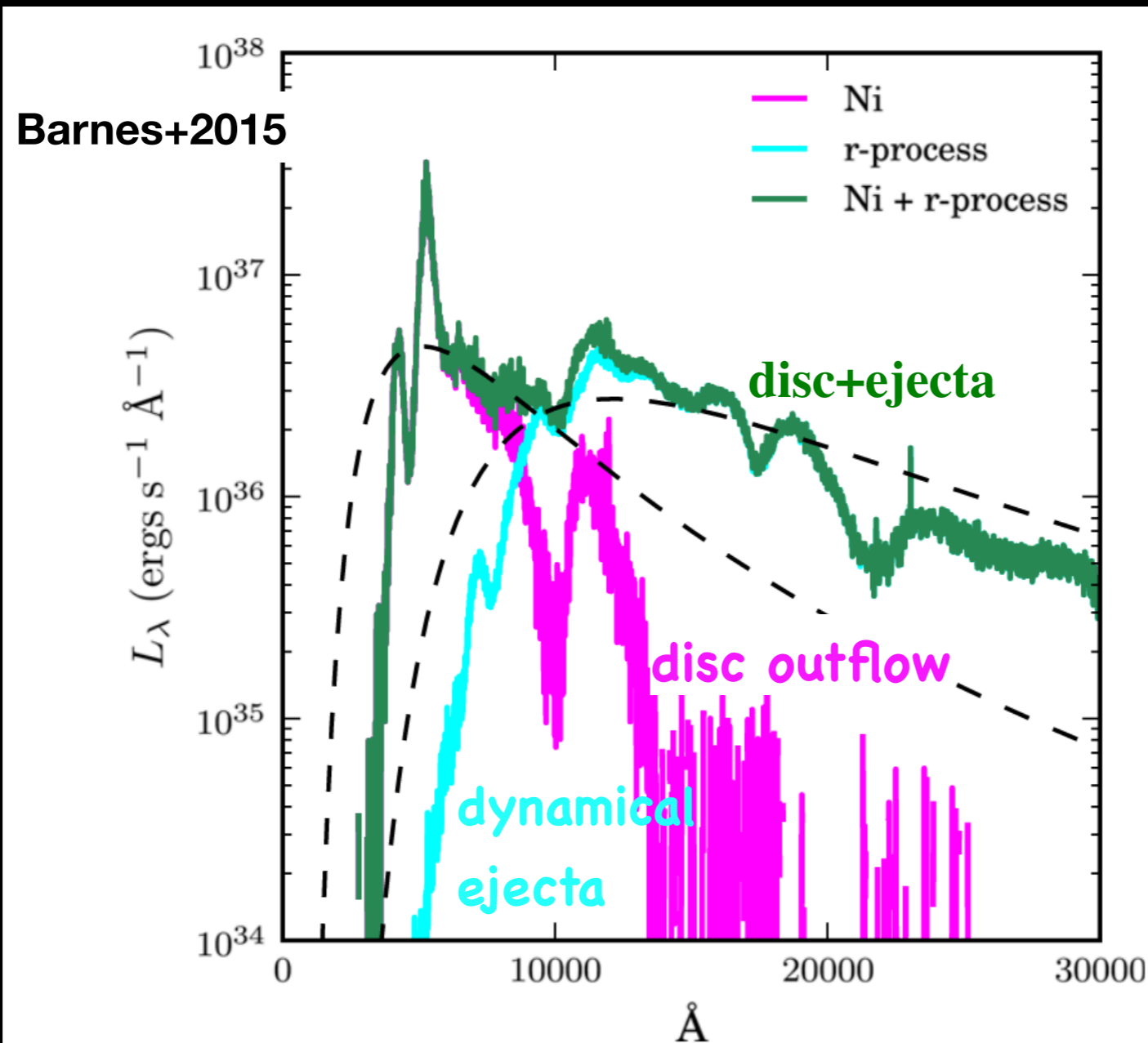


Figure 10. A combined ^{56}Ni and r -process spectrum at $t = 7$ days, taking $M_{\text{Ni}} = M_{\text{rp}} = 10^{-2} M_{\odot}$. The peak at blue wavelengths is due to the ^{56}Ni , while the r -process material supplies the red and infrared emission. The best-fit blackbody curves to the individual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

thermal (BB) spectra
which evolve from
optical to NIR due to
different opacities
predicted in the disc
outflows and in the
middle-relativistic
ejecta

COME TO THE IR SIDE WITH IRT

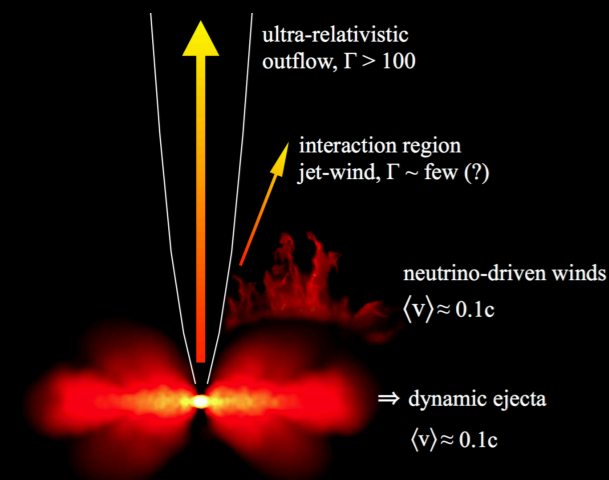
NS-NS / NS-BH mergers: Collimated EM emission from Short GRBs



IRT could point the SXI localized afterglow **within few minutes from the trigger**. If bright enough, spectroscopic observations could be performed **onboard**, thus providing **redshift estimates** and information on chemical composition of circumburst medium. In addition, precise sky coordinates will be disseminated to ground based telescopes to perform spectroscopic observations.

COME TO THE IR SIDE WITH IRT

NS-NS / NS-BH mergers: Optical/NIR and soft X-ray isotropic emissions

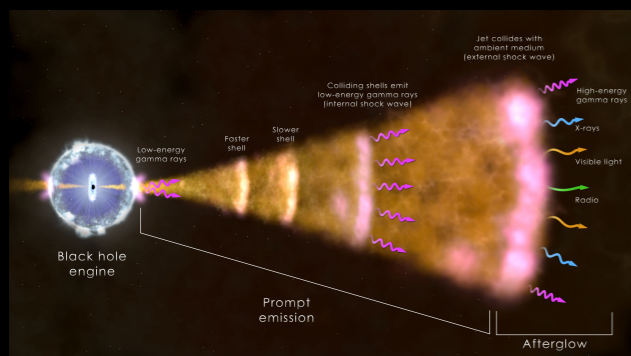


IRT OPTIMAL FOR KILONOVA IDENTIFICATION and to **disentangle different macronova components** due to its photometric and spectroscopic capabilities (light curves and spectra)

Core collapse of massive stars: Long GRBs, Low Luminosity GRBs and Supernovae

Off-axis X-ray afterglow detections ("orphan afterglows") can potentially increase the simultaneous GW+EM detection rate by a factor that strongly depends on the jet opening angle and the observer viewing angle.

THESEUS with IRT may also observe the appearance of a **NIR orphan afterglow few days after the reception of a GW signal** due to a collapsing massive star. In addition, the possible large number of low luminosity GRBs (**LLGRBs**) in the nearby Universe, expected to be up to 1000 times more numerous than long GRBs, will provide clear signatures in the GW detectors because of their much smaller distances with respect to long GRBs.



IRT/THESEUS IN THE 20s-30s

SKA 2025

Athena - 2028

JWST - 2018

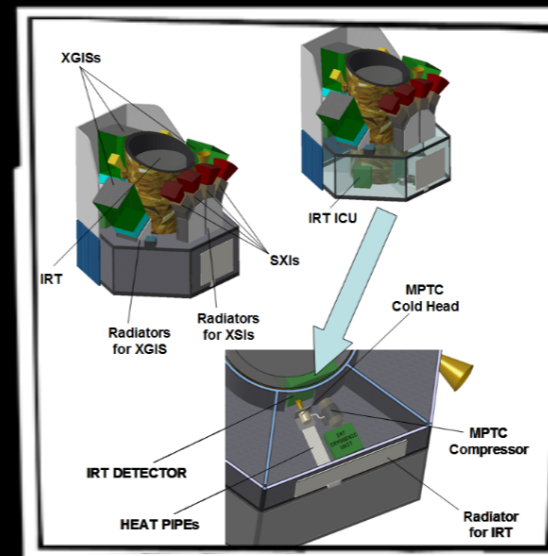
LSST - 2023

EELT - 2024

WFIRST - 2020

SVOM - 2021

Synergies between the **second-generation GW detector network** and several telescopes operating at different wavelengths such as **JWST, ATHENA, SVOM** and **WFIRST, zPTF** and **LSST, GMT, TMT** and **E-ELT** and the Square Kilometer Array (**SKA**) in the radio



THESEUS/IRT

THANKS!