Jets from Compact Binary Mergers:

Electromagnetic Counterparts to Gravitational Wave Sources

Gavin P Lamb

Supervisor: *Shiho Kobayashi*

Gavin P Lamb - 8 November 2016 - YITP, Kyoto, Japan

Outline

Part 1: Introduction

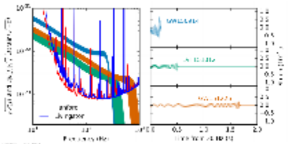
- Compact binary mergers and EM counterparts
- Jets from accreting black-hole systems
- GRBs

Part 2: Low-Lorentz Factor Jets

- Lorentz factor distribution and prompt suppression
- Monte Carlo simulation
- Results
- On-going/future work

Compact Binary Mergers

- A binary system where the components are neutron stars (NS) or BHs
- Inspiral and merger due to GW radiation
- NS-NS, BH-NS, and BH-BH*



*no expected EM counterpart, although Loeb+ 2016; Perna+ 2016; Woosley+ 2016; Morsony+ 2016; Kokoru & Silk 2016; Li+ 2016; Zhu & Wang 2016; Zhang+ 2016; Connaughton+ 2016; Yamazaki+ 2016; etc.

Next GW Breakthrough(?)

BH-NS or NS-NS merger

- For BH-NS - first(?) confirmed detection*
- NS-NS, BH-NS - EM counterparts expected
- Multi-messenger astronomy!

Gravitational Waves

- General relativity
- EOS

Electromagnetic Counterparts

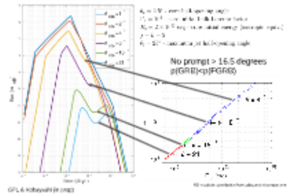
- Macronova; r-process, dynamical ejecta
- Jet dynamics; launch time, acceleration constraints, opening angle, structure, Lorentz factor distribution

Neutrinos/Cosmic-rays

- Particle energetics and acceleration

*analysis of GRB130603B supports BH-NS as progenitor (Hotokezaka+ 2013)

Afterglow from Structured Jets



No prompt > 16.5 degrees

p(GRB)<p(FGRB)

GPL & Kobayashi (in prep)

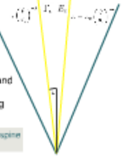
Structured Jets from Compact Binary Mergers

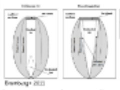
Core is uniform

Wings have structure e.g. Postnov+ 2001, Rossi+ 2002

Nature of the prompt and afterglow emission depend on the opening angle

Jet structure may vary e.g. spine and sheath, Gaussian, etc.





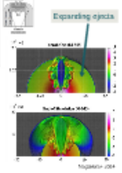
Bromberg+ 2011

Jet penetrates the expanding ejecta - becomes collimated

Jet breaks out of cocoon

- ~12 degrees
- Additional structure

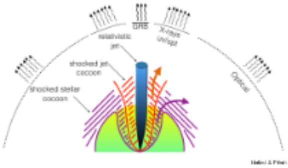
So far, only considered uniform jets!



Nagakura+ 2014

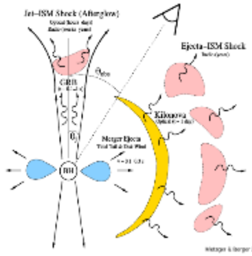
Cocoon Emission

- Jet punches through ejecta - cocoon forms
- Cocoon collimates jet (Bromberg+ 2011)
- Cocoon shock emission; X-ray, UV/optical?



Nakar & Piran 2016

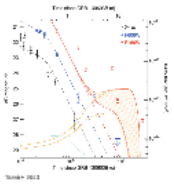
EM Counterparts to NS(BH)-NS Merger



Metzger & Berger 2012

Macronova

On-axis!

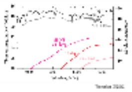


Tanvir+ 2013

Off-axis?

- 22 magnitude at 200 Mpc
- Peak ~1 day

{ *Are macronova as bright off-axis as they are on?* }



Tanaka 2016

Summary

- GW triggered search could reveal hidden low Γ population of merger jets
- Detection/non-detection will constrain Γ distribution for SGRBs
- Features in afterglow of local GW counterparts will constrain jet structure
- Low Γ components or jets are good candidates as EM counterparts to GW sources

Low-Γ Jets from Compact Stellar Mergers*

- More frequent than SGRBs given a power-law Γ-distribution
- X-ray, optical and radio afterglow are bright
- Peaking 0.1-10 days for X-ray and optical
- Peaking from 10 days for radio
- **Good candidates for EM counterpart searches**

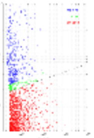
*http://adsabs.harvard.edu/abs/2016ApJ...829..112L arXiv:1605.02769

X-ray Flashes

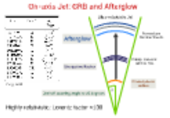
Some bursts may appear as X-ray flashes (XRF) or X-ray rich GRBs

- Select bursts that have the prompt spectrum cut-off at 100 keV

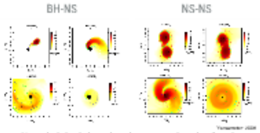
These bursts would appear as brief, <2 s flashes with maximum spectral energy <100 keV. The peak energy for these bursts is



On-axis Jet: GRB and Afterglow



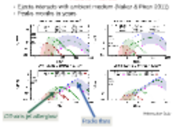
Highly relativistic: Lorentz factor >100



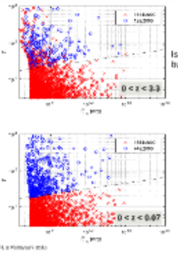
Numerical simulations show that mergers launch sub and mildly relativistic ejecta e.g. Rosswog+ 2000; Ruffert+ 2001; Yamamoto+ 2008; Kiuchi+ 2010; etc.

Merger ejecta -
NS-NS: isotropic
BH-NS: semi-isotropic → **Form accretion disk!**

Radio Flares



G. P. Lamb - 8 November 2016 - YITP, Kyoto



BLUE: detected
RED: undetected

Isotropic equivalent jet kinetic energy vs bulk Lorentz factor

2000 on-axis merger jets

- 91% of events undetected or failed GRBs; at cosmological distances
- 78% of events failed GRBs; within LIGO face-on NS-NS detection limit (~300 Mpc)

A significant fraction of mergers result in failed GRBs

GPL & Kobayashi 2016

Estimate the Rate of Failed GRBs

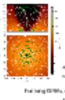
Rate of SGRBs, within LIGO detection volume?

Swift rate of SGRBs with z ~ 0.63*
Swift field of view ~ 2 sr
All-sky rate of SGRBs with z ~ 0.18
Fraction of *Swift* SGRBs with z ~ 0.25
All-sky rate of SGRBs with/without z ~ **0.75** per year

For a=1.75, 78% failed
All-sky rate of failed SGRBs ~ 2.6 per year

*Metzger & Berger 2012

Jet Opening Angle



Jet half-opening angle:

25 degrees ~30% on-axis
16 degrees ~13% on-axis
8 degrees ~4% on-axis

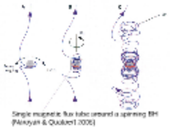
For failed GRBs from low-Γ jets, the fraction of on-axis jets could be higher than SGRBs

Jets from Accreting BH Systems

Jet launch mechanism:

- Blandford-Znajek (1977)
- Neutrino annihilation (e.g. Popham+ 1999)

Blandford-Znajek



Single magnetic flux tube around a spinning BH (Maruyan & Quataert 2006)

Requires:

- Spinning BH
- Large scale magnetic field (magnetized disk)

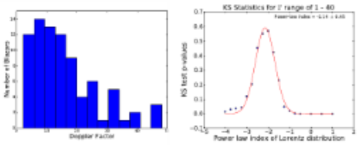
Note: BZ mechanism has been used to explain extended emission in SGRBs, and as a potential EM counterpart (Nakamura+ 2014)

Neutrino Annihilation

Energetically inefficient for GRBs - see Lei+ 2013, Liu+ 2015, Just+ 2016 etc.

Lorentz Factor Distribution in Astrophysical Jets

Lower values dominate the Γ distribution in AGN/Blazar jets (Lister+ 1997 2009; Saikia+ 2016)



Saikia+ 2016

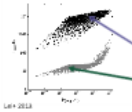
Distribution given by a negative index power-law:

$$N(\Gamma) \propto \Gamma^{-a}$$

Bulk Lorentz Factor

Bulk Lorentz factor (Γ) is difficult to constrain for GRBs (especially short GRBs)

Estimate from afterglow peak i.e. deceleration



Lei+ 2013

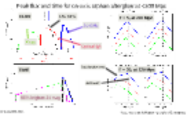
- Typically 10s to 1000s
- Efficiency of baryon loading can constrain

Max. Γ

Min. Γ - estimated via neutron loading only; expected to be lower if all contributions considered

Afterglow from Failed GRBs

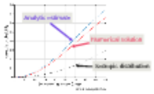
On-Axis Orphan Afterglow



Given a GW Detection

The probability the source is face-on is higher than for an isotropic distribution

- GW polarization components depend on inclination
- Strongest on-axis



Monte Carlo

- Using negative index power-law Γ distribution; a=1.75
- Wanderman & Piran 2015 redshift and energy distribution for short GRBs
- *Swift* detection band and sensitivity; 15-150 keV, >0.2 photons per second per square centimeter

Estimate the fraction of events with detectable prompt emission

- redshift and luminosity distribution

$$R_{\rm GRB}(z) \propto \begin{cases} e^{(z-0.9)/0.39} & z \leq 0.9 \\ e^{-(z-0.9)/0.26} & z > 0.9 \end{cases}$$

$$\Phi(L_\gamma) \propto \begin{cases} L_\gamma^{-1} & L_\gamma \leq 2 \times 10^{52}\ {\rm erg\ s^{-1}} \\ L_\gamma^{-2} & L_\gamma > 2 \times 10^{52}\ {\rm erg\ s^{-1}} \end{cases}$$

- limits/parameters

$$1 \leq \Gamma \leq 10^3$$

$$a = 1.75$$

$$10^{48}\ {\rm erg\ s^{-1}} \leq L_\gamma \leq 10^{53}\ {\rm erg\ s^{-1}}$$

Thermalization

Prompt photons will be Compton down-scattered and/or thermalized depending on depth below photosphere

- Depends on optical depth at dissipation radius

$$\tau_d = (R_p/R_d)^2$$

- Condition for efficient thermalization

$$\tau_d \geq \frac{m_e c^2}{k_B \phi_{BS}}$$

electron temperature at dissipation radius

If satisfied, spectral peak becomes the black-body peak energy

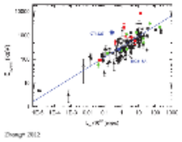
Otherwise, pair production limits the maximum energy, and

$$E_{\rm max} \simeq 511(\Gamma/\tau_d)\ {\rm keV}$$

Prompt emission will be suppressed; peaking at lower energies and becoming more thermal

Prompt Emission Spectrum

- Assumed to follow broken power law
- Spectral peak is correlated (Yonetoku+ 2004; Ghirlanda+ 2009)
- Holds for long and short (Zhang+ 2012)



Zhang+ 2012

For a low-Γ jets, spectral peak is shifted as the prompt luminosity

Low-Γ Jets

Energy density in outflow evolves* as

$$e \propto R^{-8/3}$$

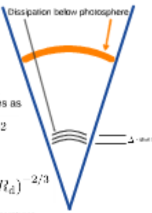
The prompt emission injected below the photosphere evolves as

$$L_\gamma \Delta / c \propto e R^2 \Delta \Gamma^2$$

Thus, at the photosphere

$$L_{\gamma,R_d} = L_{\gamma,R_p} \left(R_p/R_d\right)^{-2/3}$$

*for constant Γ and sub-relativistic temperatures



Γ in GRB Jets

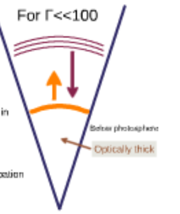
Dissipation radius estimated from min. variability timescale of prompt gamma-rays

$$R_d = c\delta t \Gamma^2$$

Photospheric radius: conservative estimate made by considering electrons associated with baryons in the jet

$$R_p \propto \left(E/\Gamma\right)^{1/2}$$

Conditions require Γ~100 for dissipation above the photosphere



Jets from Compact Binary Mergers:

Electromagnetic Counterparts to Gravitational Wave Sources

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Nuclear Physics, Compact Stars, and Compact Star Mergers 2016
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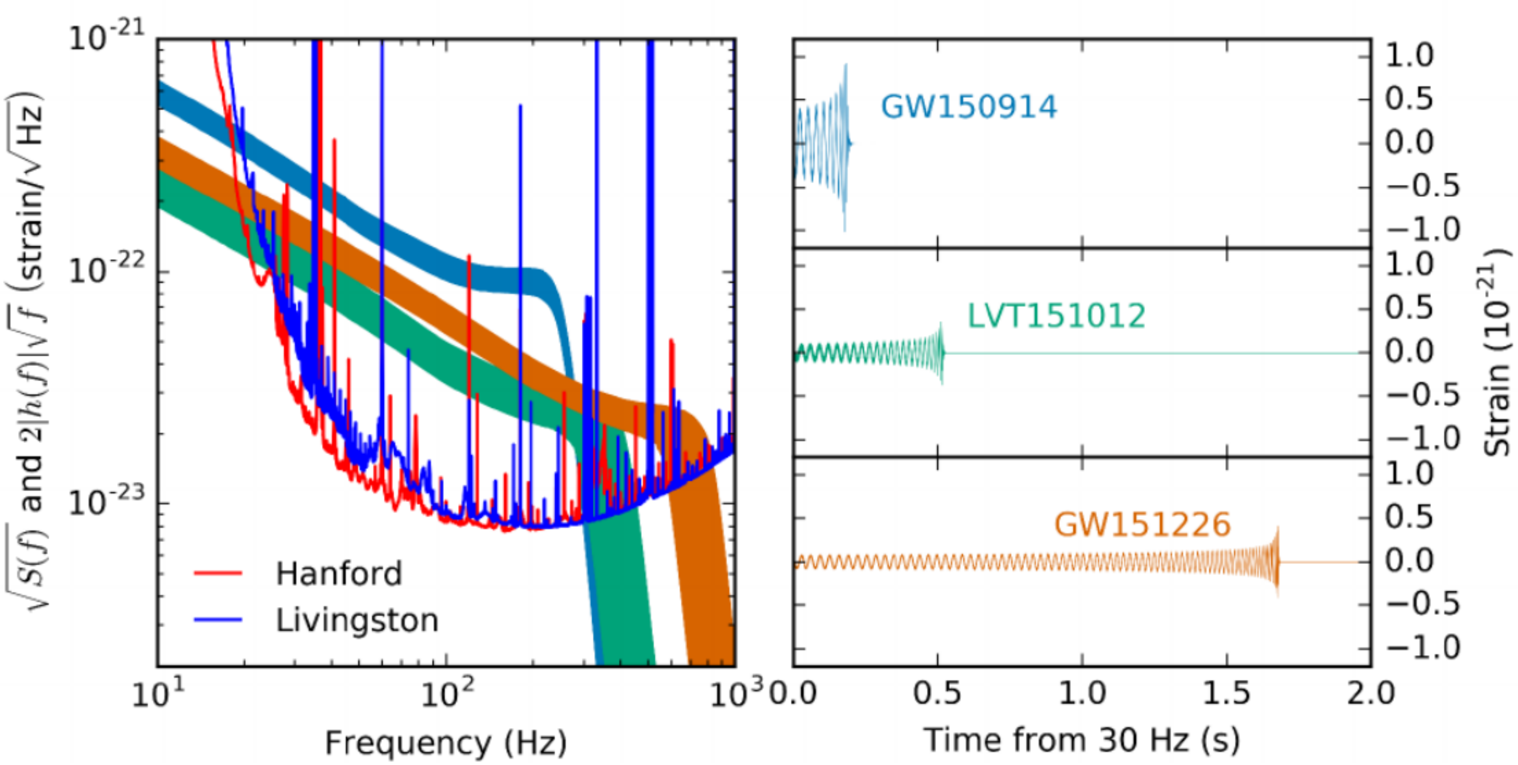

LIGO/Virgo Col. 2016

*no expected EM counterpart, although Loeb+ 2016; Perna+ 2016; Woosley+ 2016; Morsony+ 2016; Kotera & Silk 2016; Li+ 2016; Zhu & Wang 2016; Zhang+ 2016; Connaughton+ 2016; Yamazaki+ 2016; etc.

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BH-NS or NS-NS merger

- For BH-NS - first(?) confirmed detection*
- NS-NS, BH-NS - EM counterparts expected
- Multi-messenger astronomy!

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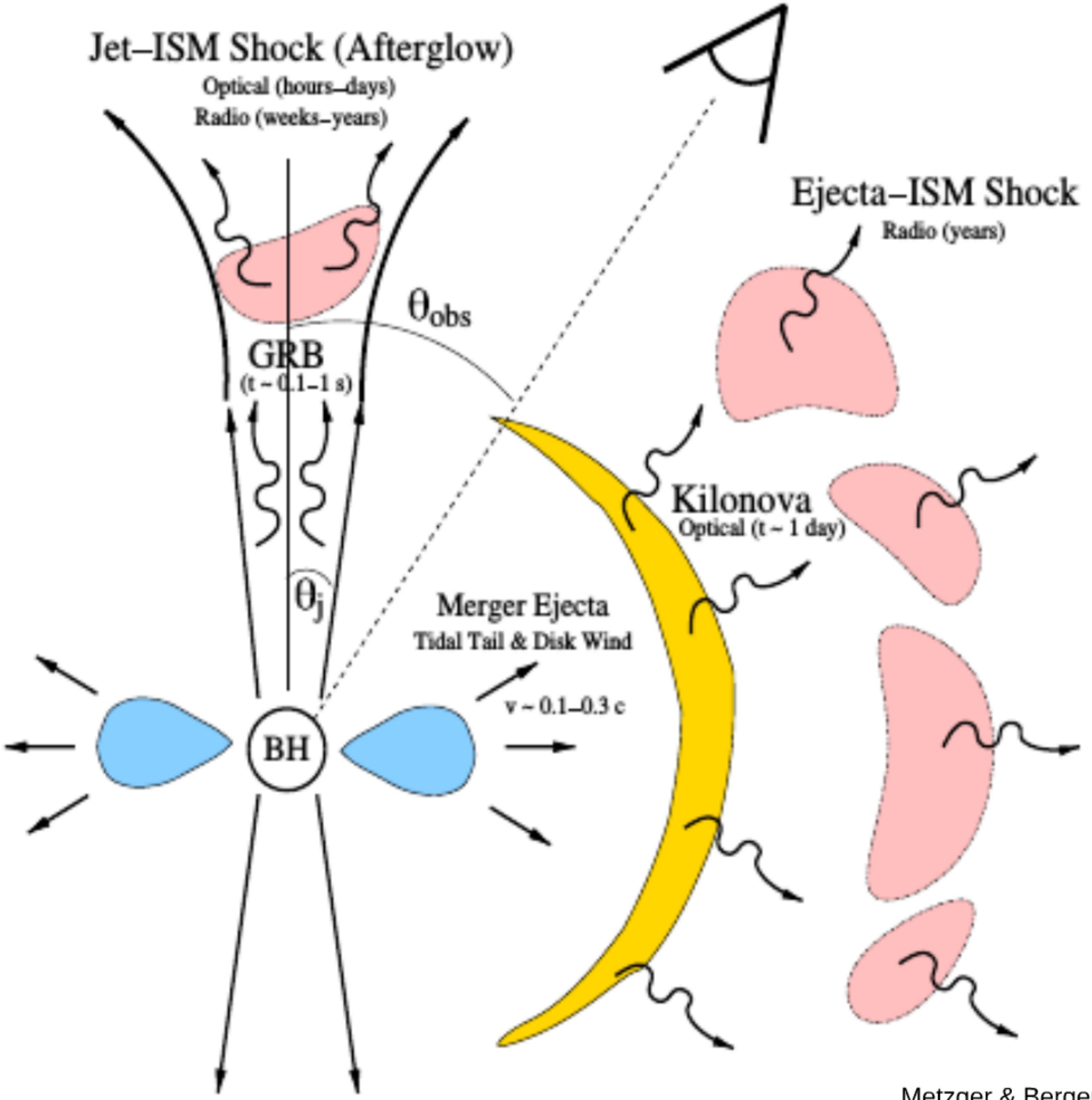
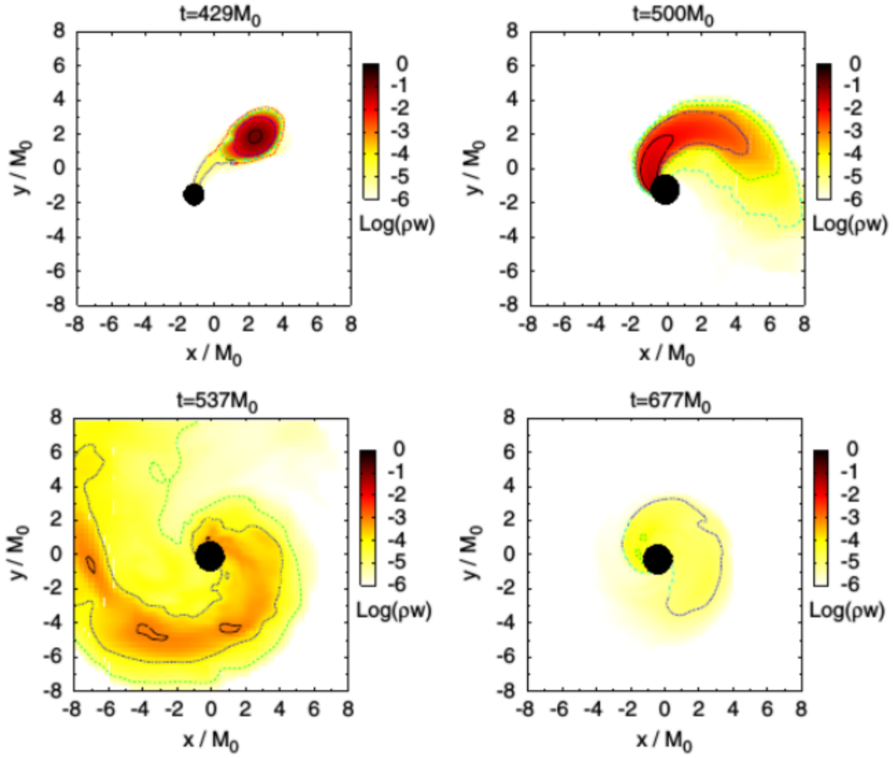
EM Counterparts to NS(BH)-NS Merger

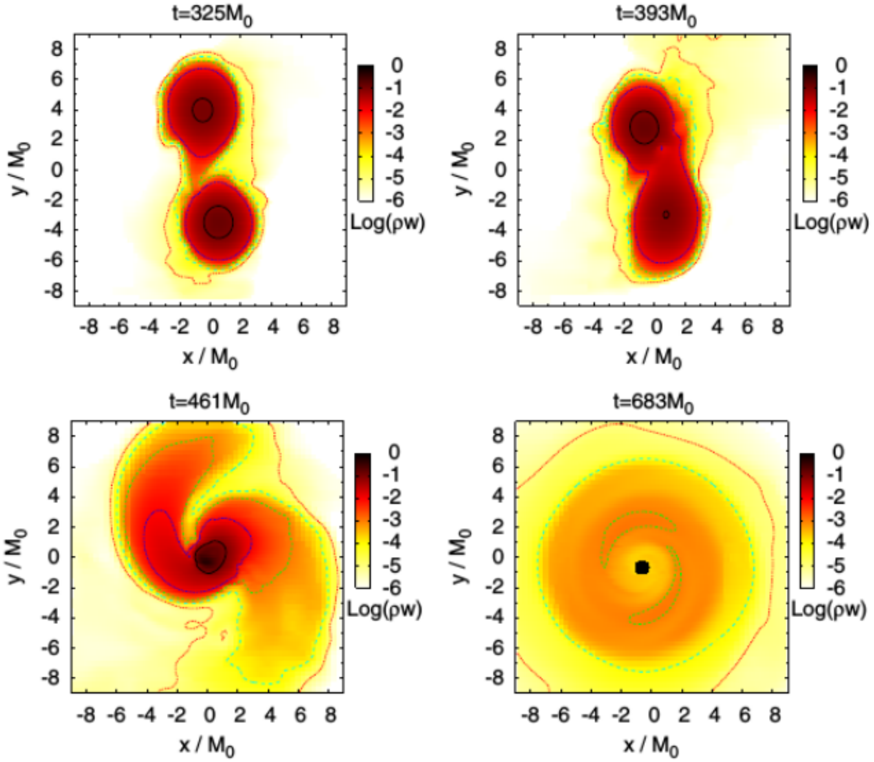


Metzger & Berger 2012

BH-NS



NS-NS



Yamamoto+ 2008

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Merger ejecta -
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BH-NS: semi-isotropic

→ **Form accretion disk!**

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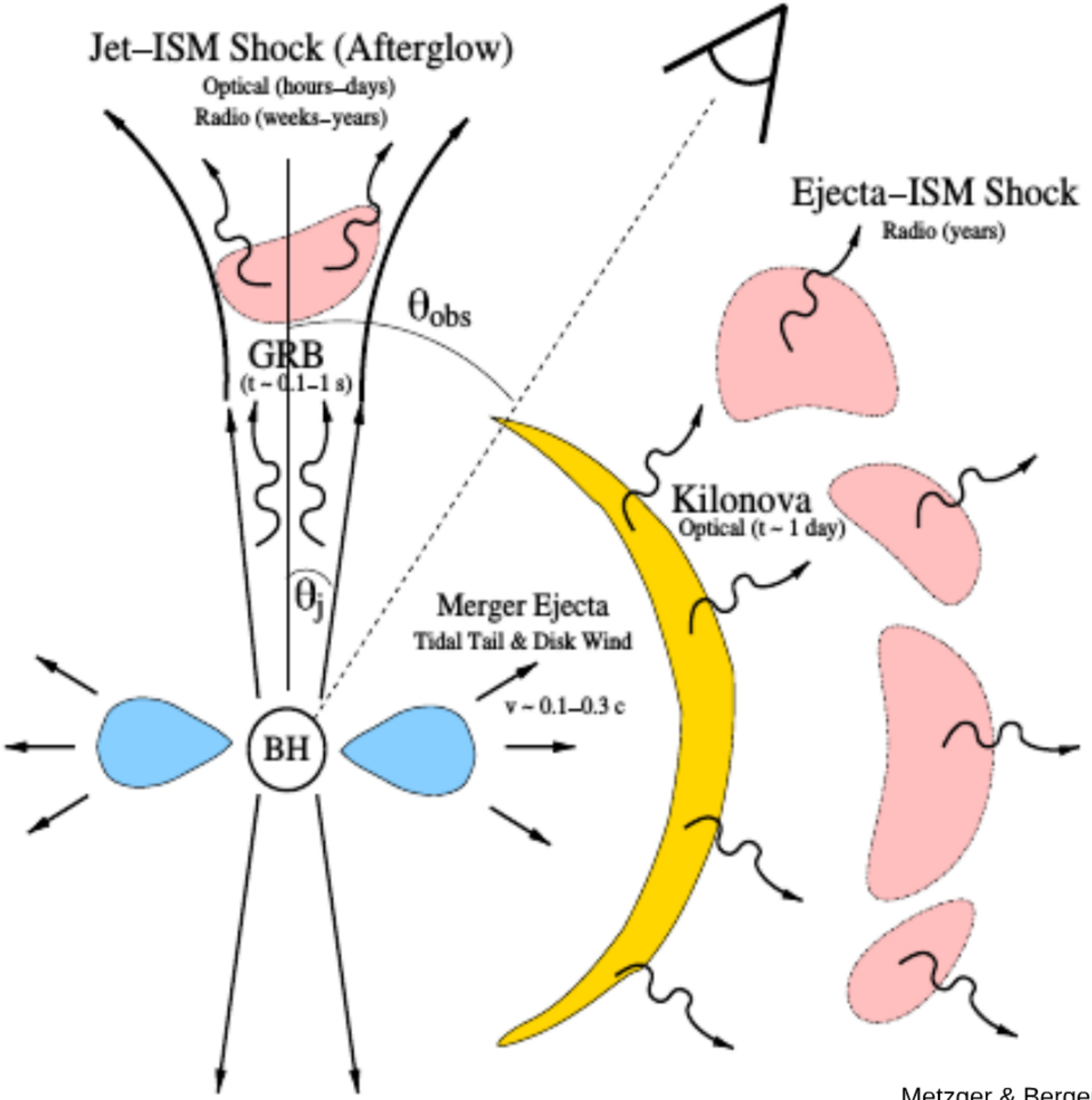
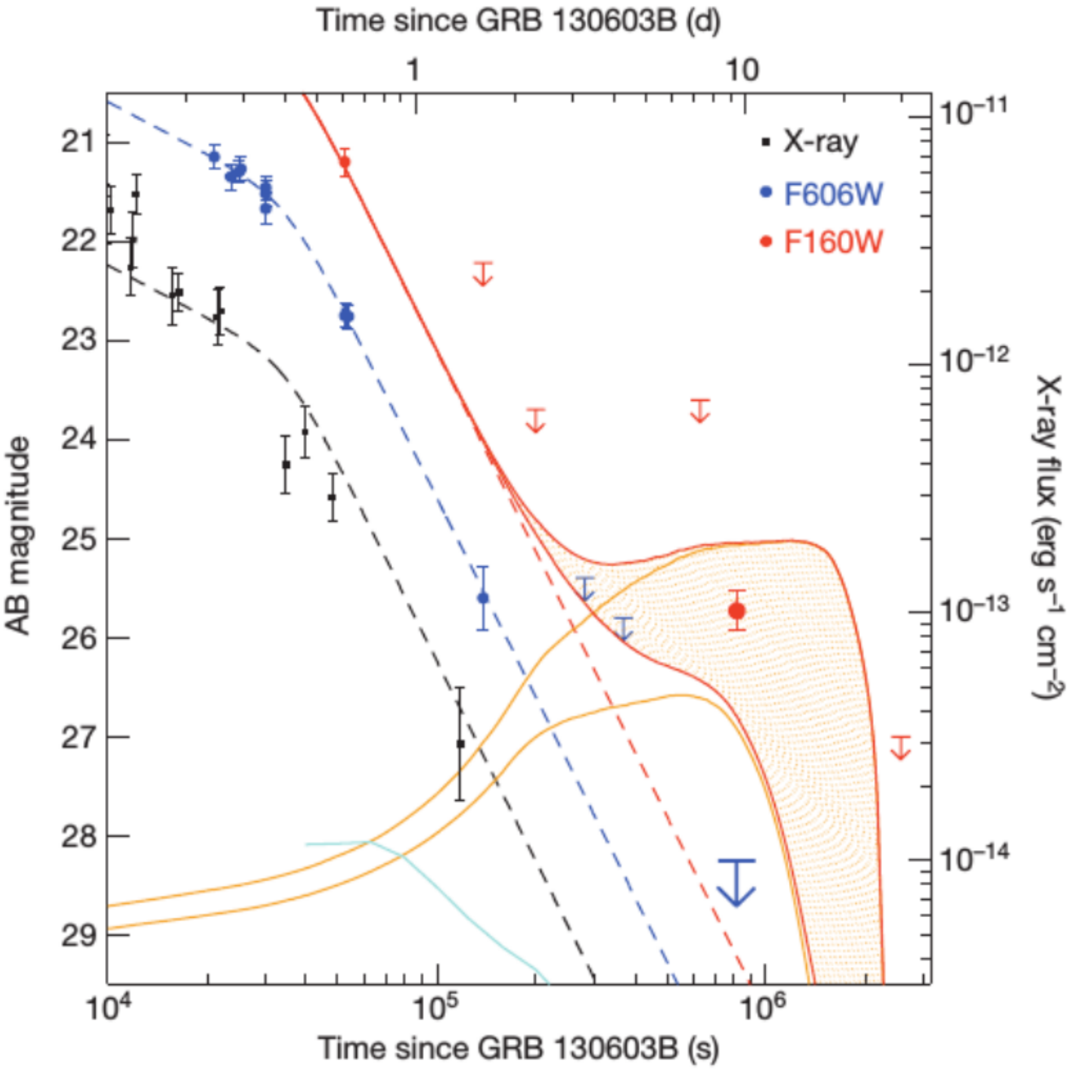


Metzger & Berger 2012

Macronova

On-axis!



Tanvir+ 2013

Off-axis?

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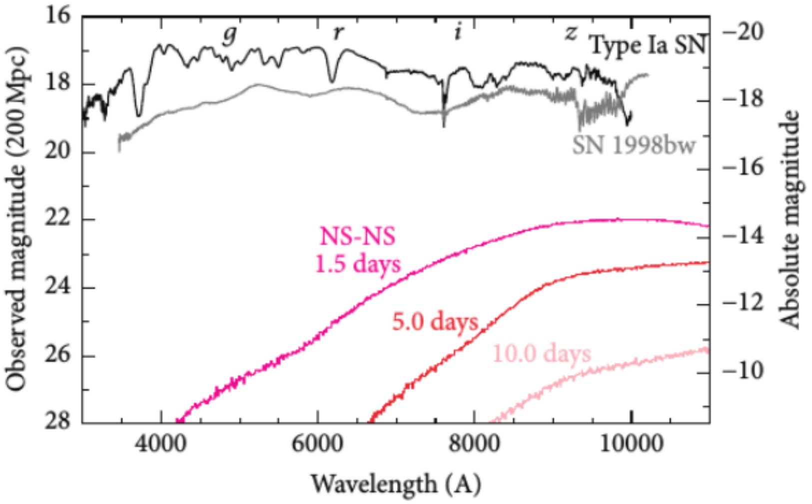
- Peak ~1 day

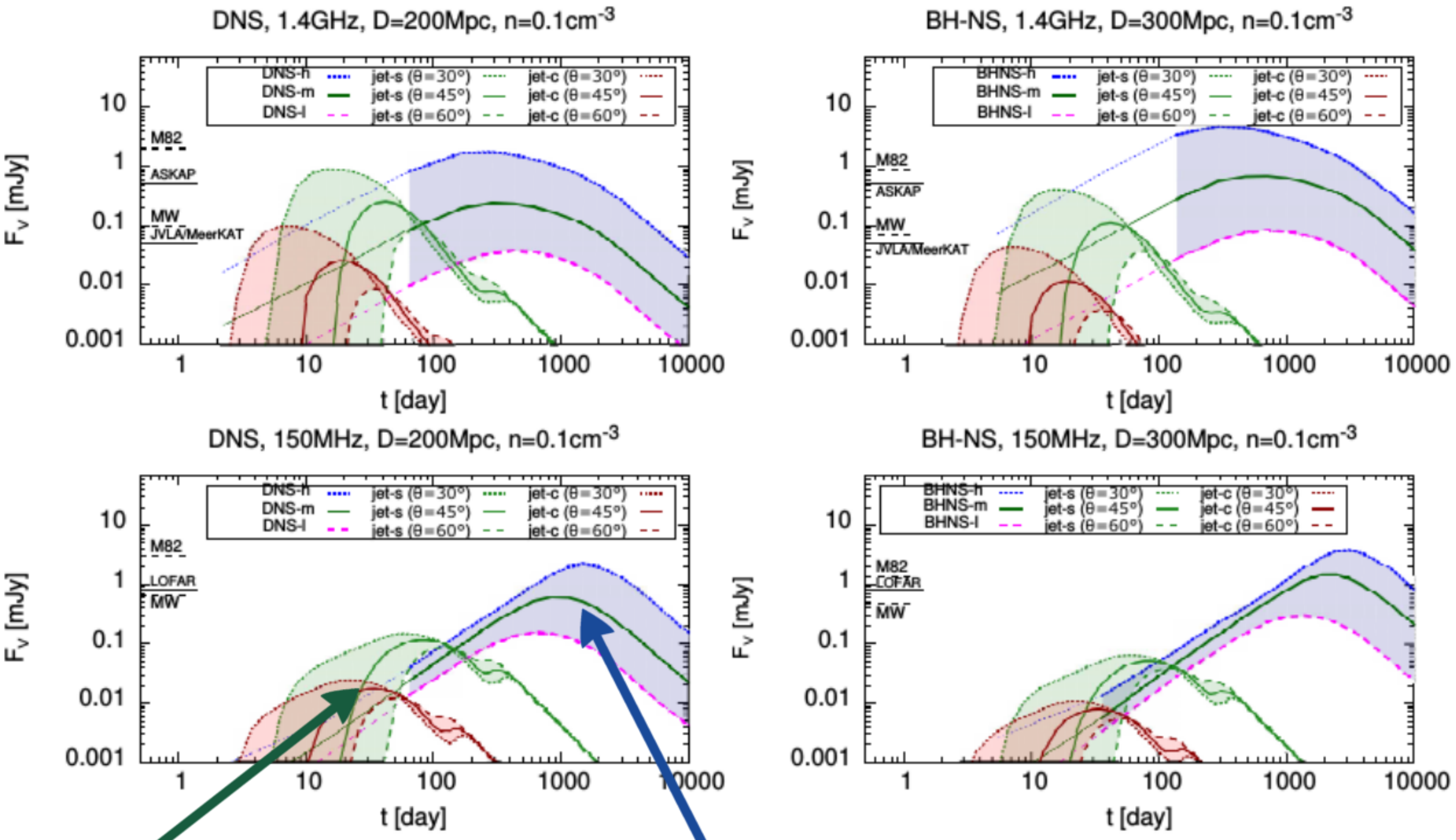
{ *Are macronova as bright off-axis as they are on?* }



Tanaka 2016

Radio Flares

- Ejecta interacts with ambient medium (Nakar & Piran 2011)
- Peaks months to years



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}

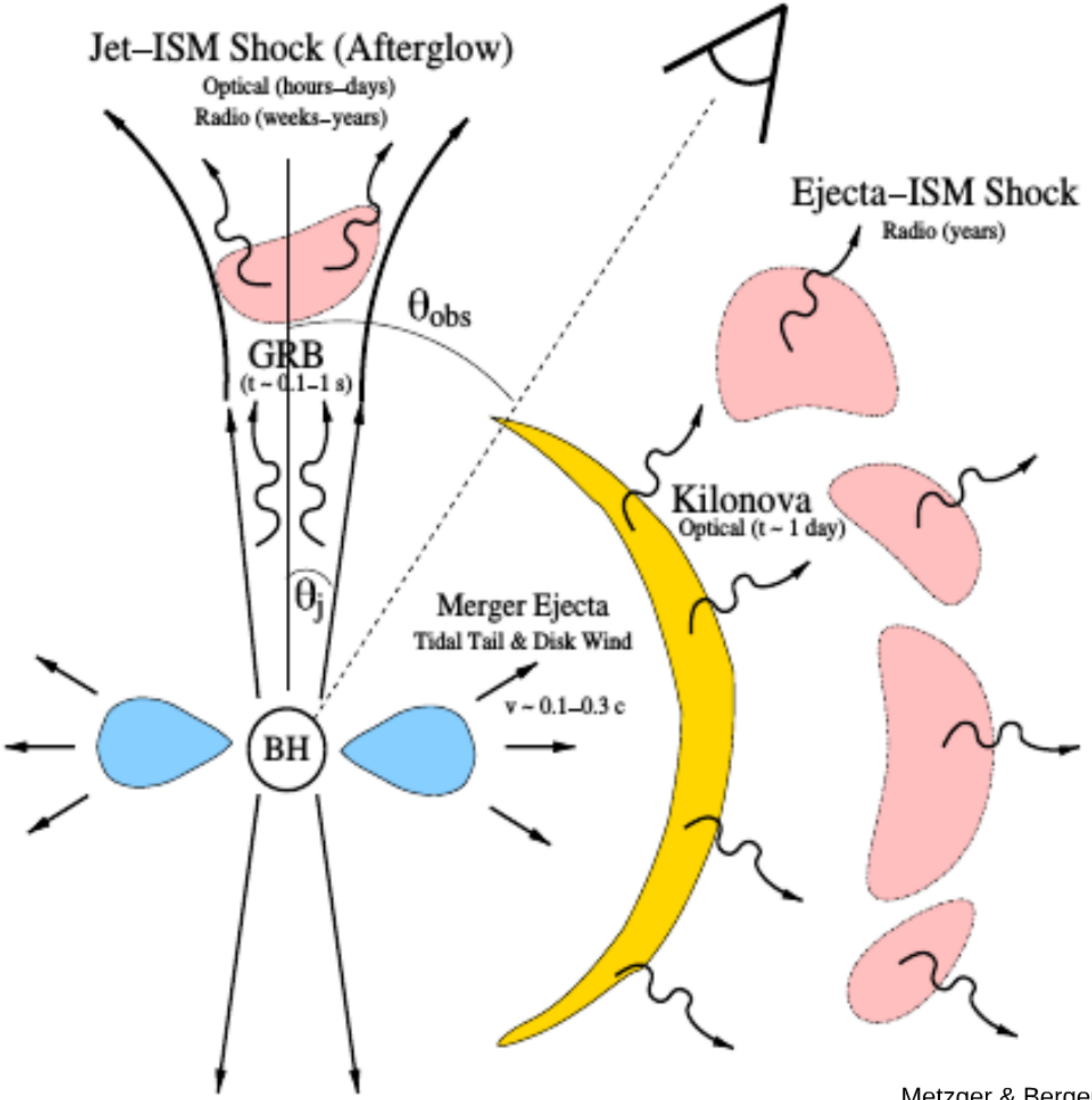
BH-NS, 150MHz, D=300Mpc, n=0.1cm^{-3}

Hotokezaka+ 2016

Off-axis jet afterglow

Radio flare

EM Counterparts to NS(BH)-NS Merger



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Cocoon Emission

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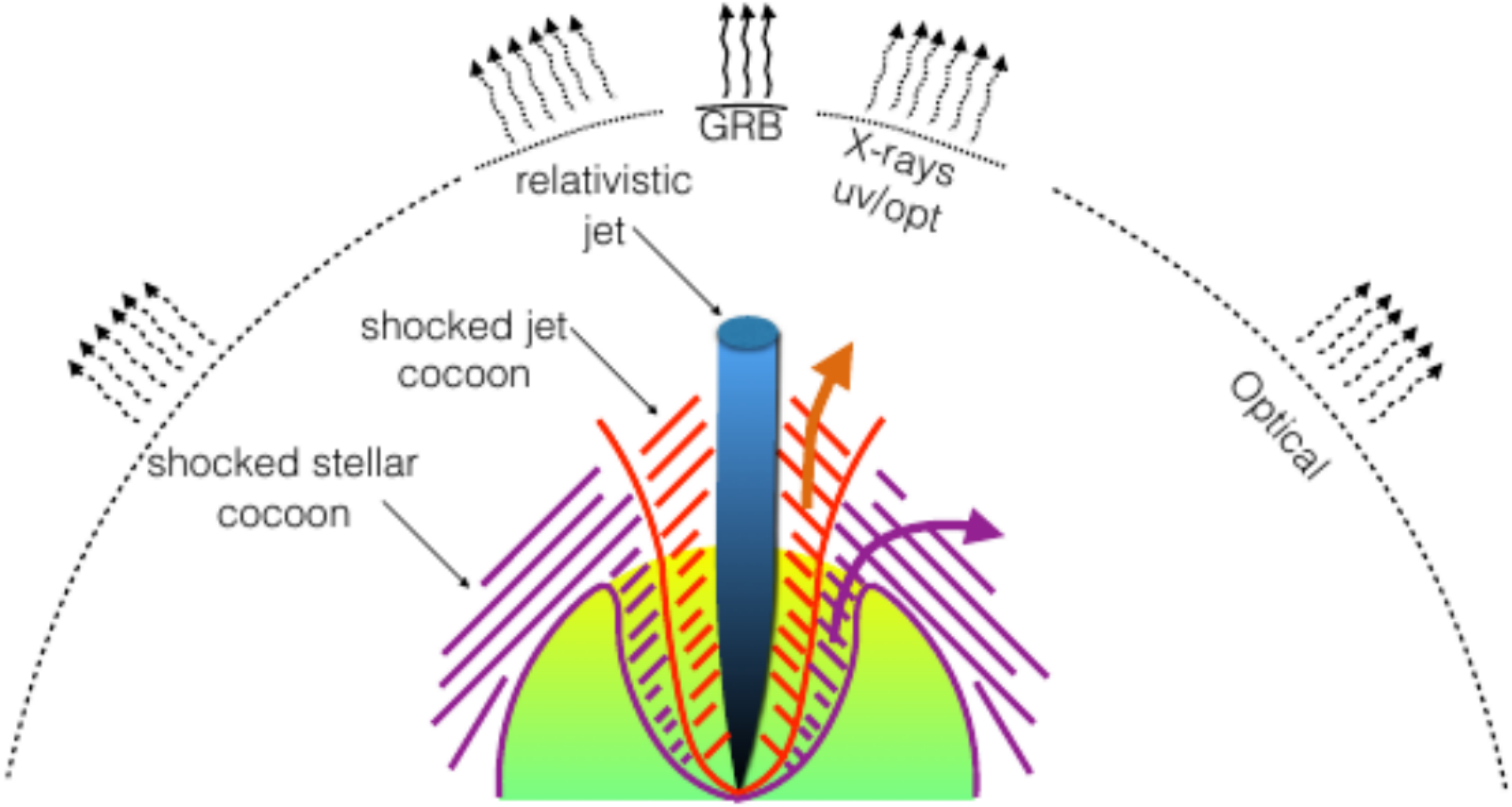
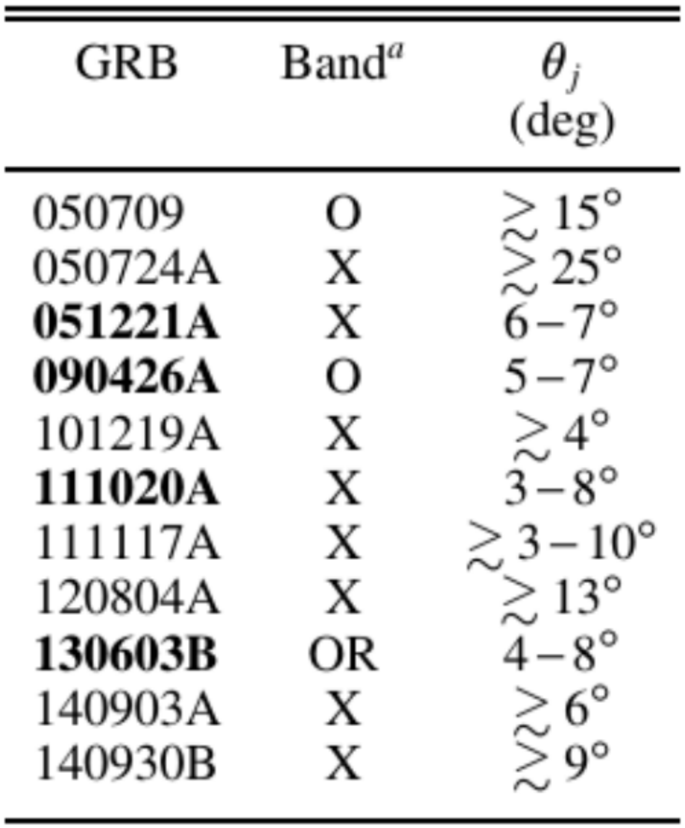
- Cocoon shock emission; X-ray, UV/optical?



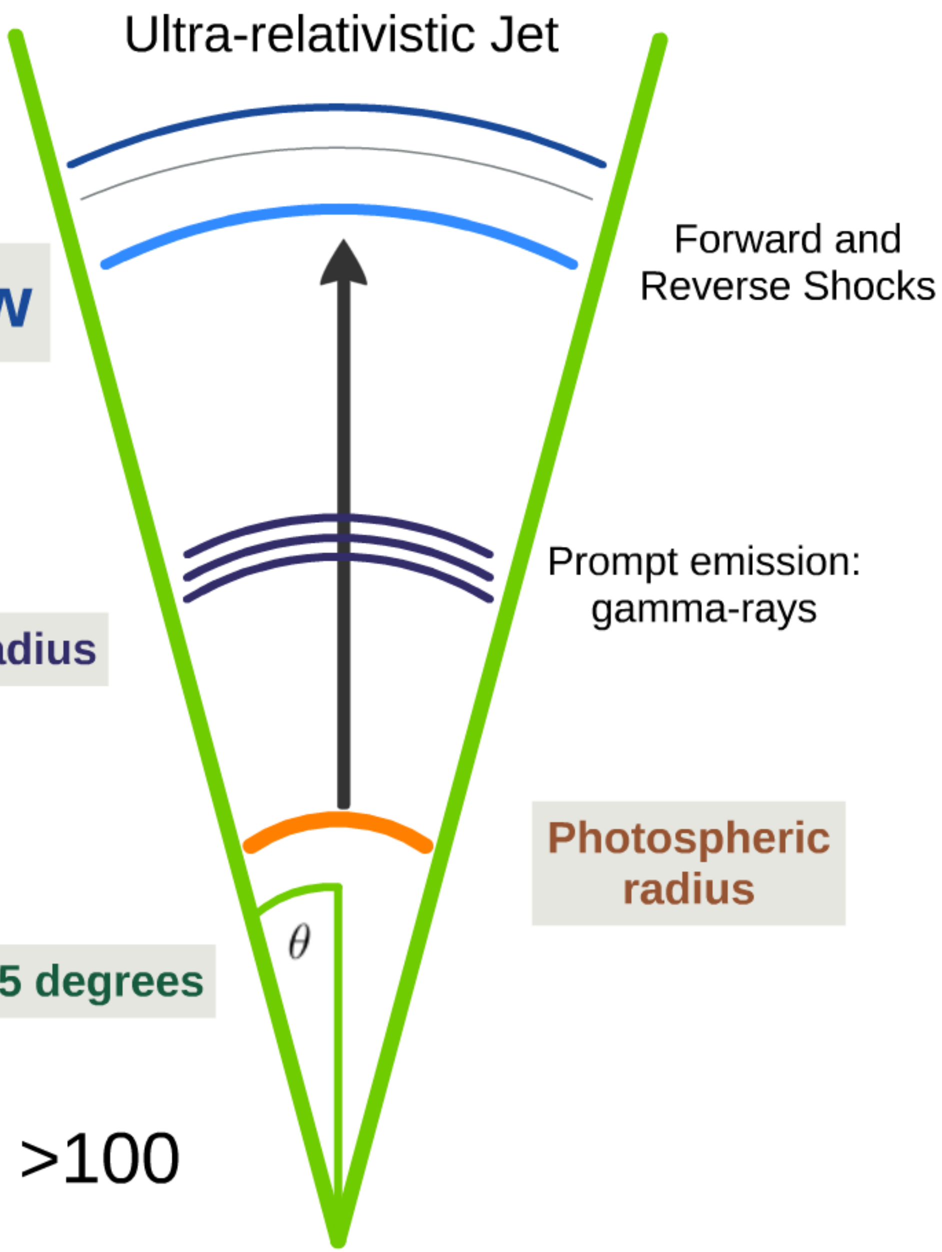
Nakar & Piran 2016

On-axis Jet: GRB and Afterglow



GRB	Band^a	θ_j (deg)
050709	O	$\gtrsim 15^\circ$
050724A	X	$\gtrsim 25^\circ$
051221A	X	$6-7^\circ$
090426A	O	$5-7^\circ$
101219A	X	$\gtrsim 4^\circ$
111020A	X	$3-8^\circ$
111117A	X	$\gtrsim 3-10^\circ$
120804A	X	$\gtrsim 13^\circ$
130603B	OR	$4-8^\circ$
140903A	X	$\gtrsim 6^\circ$
140930B	X	$\gtrsim 9^\circ$

Fong+ 2015



Afterglow

Dissipative Radius

Photospheric radius

Jet half opening angle to 25 degrees

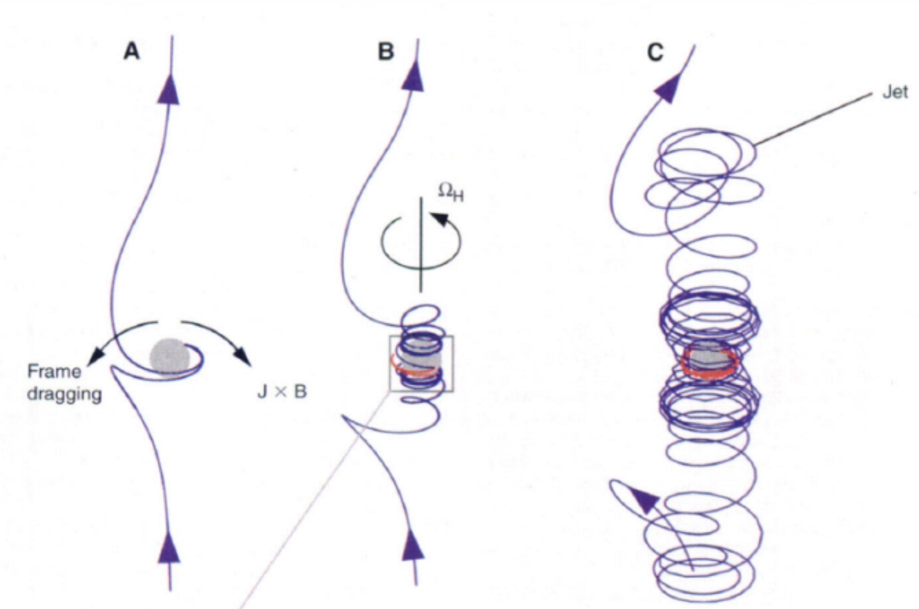
Highly relativistic: Lorentz factor >100

Jets from Accreting BH Systems

Jet launch mechanism:

- Blandford-Znajek (1977)
- Neutrino annihilation (e.g. Popham+ 1999)

Blandford-Znajek



Single magnetic flux tube around a spinning BH (Narayan & Quataert 2005)

Requires:

- Spinning BH
- Large scale magnetic field (magnetized disk)

Note: BZ mechanism has been used to explain extended emission in SGRBs, and as a potential EM counterpart (Nakamura+ 2014)

Neutrino Annihilation

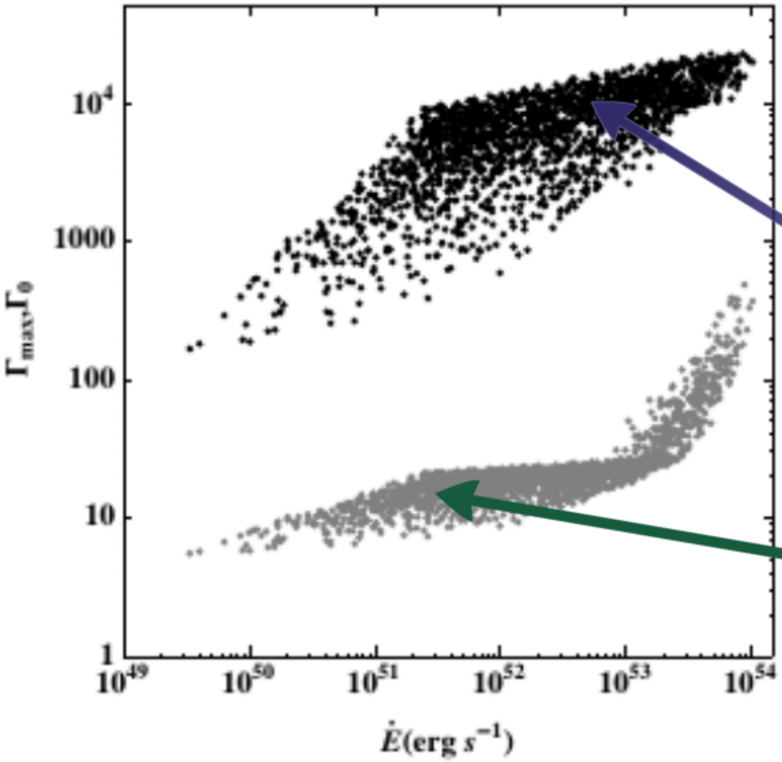
Energetically inefficient for GRBs - see Lei+ 2013, Liu+ 2015, Just+ 2016 etc.

Bulk Lorentz Factor

Bulk Lorentz factor (Γ) is difficult to constrain for GRBs (especially short GRBs)

Estimate from afterglow peak i.e. deceleration

$$\Gamma \propto E^{1/8} n^{-1/8} t_{\mathrm{dec}}^{-3/8}$$



Lei+ 2013

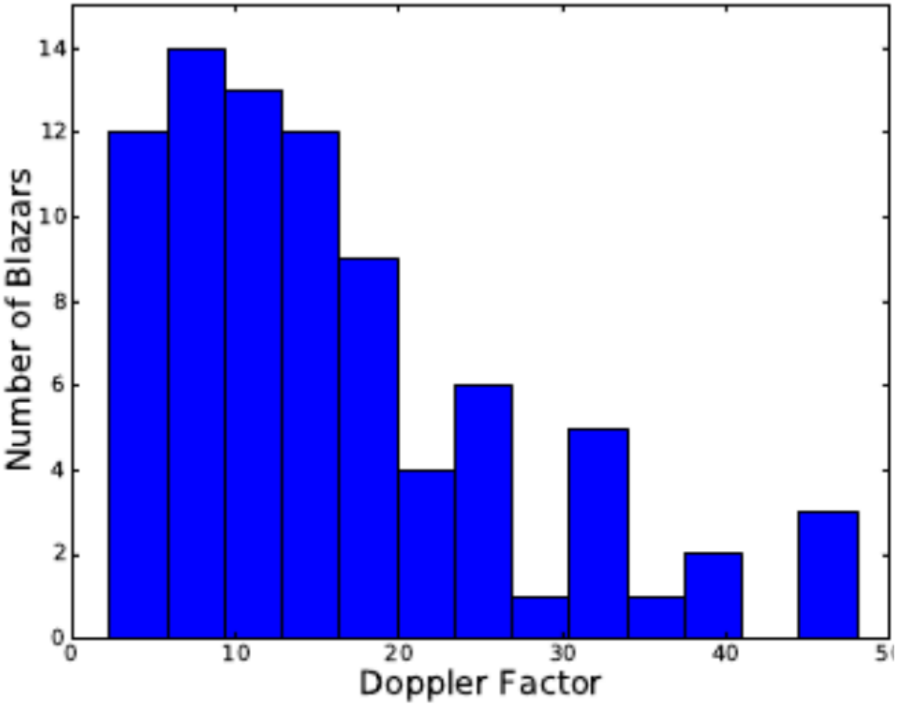
- Typically 10s to 1000s
- Efficiency of baryon loading can constrain

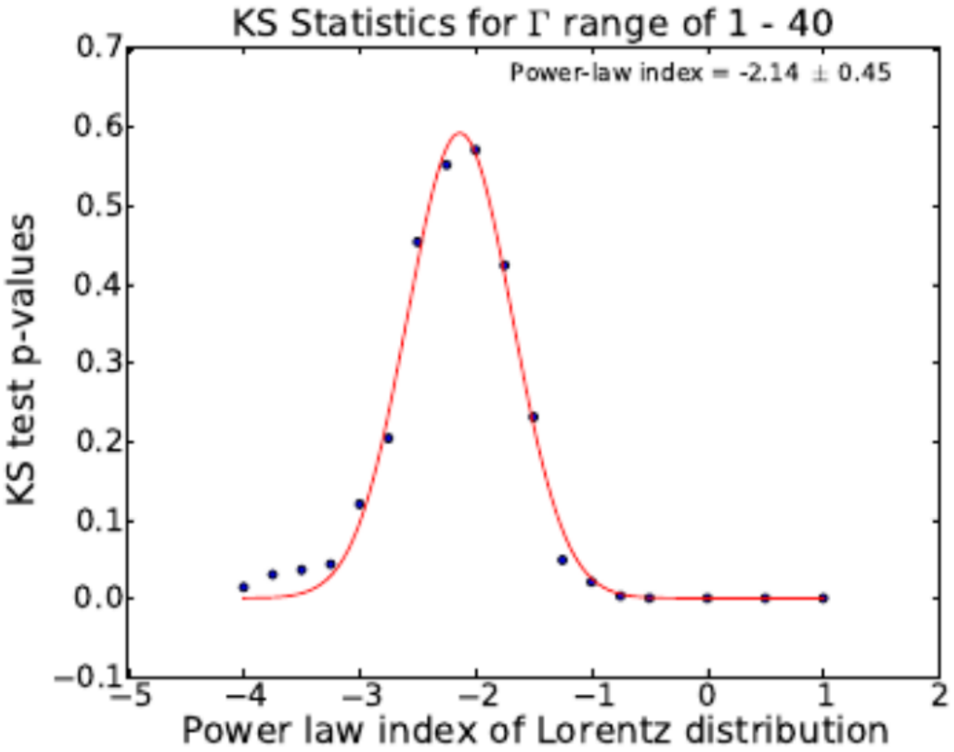
Max. Γ

Min. Γ - estimated via neutron loading only; expected to be lower if all contributions considered

Lorentz Factor Distribution in Astrophysical Jets

Lower values dominate the Γ distribution in AGN/Blazar jets (Lister+ 1997 2009; Saikia+ 2016)





Saikia+ 2016

Distribution given by a negative index power-law:

$$N\left(\Gamma\right) \propto \Gamma^{-a}$$

Γ in GRB Jets

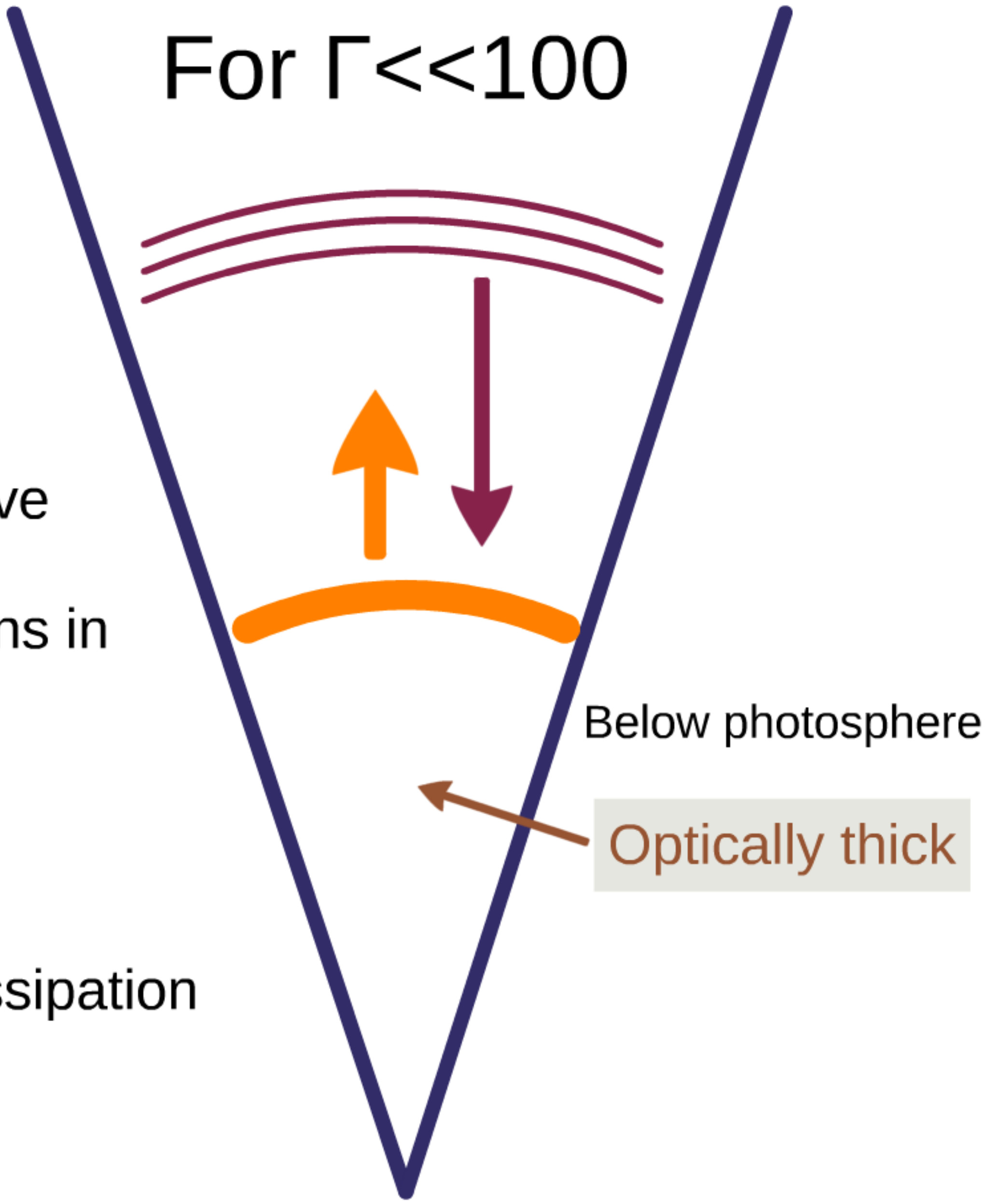
Dissipation radius estimated from min. variability timescale of prompt gamma-rays

$$R_\mathrm{d} = c\delta t\Gamma^2$$

Photospheric radius; conservative estimate made by considering electrons associated with baryons in the jet

$$R_\mathrm{p} \propto (E/\Gamma)^{1/2}$$

Conditions require Γ~100 for dissipation above the photosphere



Low-Γ Jets

Energy density in outflow evolves* as

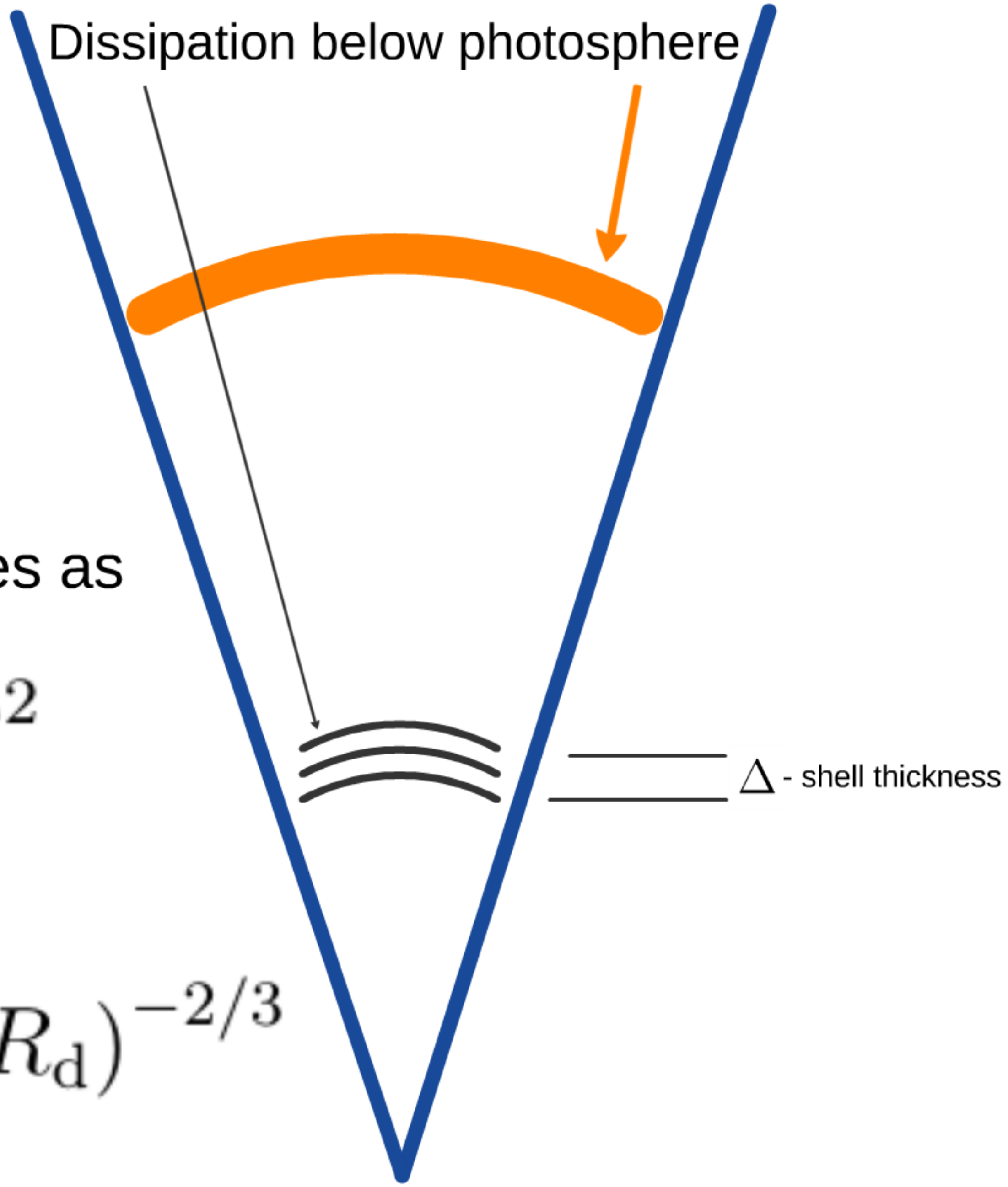
$$e \propto R^{-8/3}$$

The prompt emission injected below the photosphere evolves as

$$L_\gamma \Delta / c \propto e R^2 \Delta \Gamma^2$$

Thus, at the photosphere

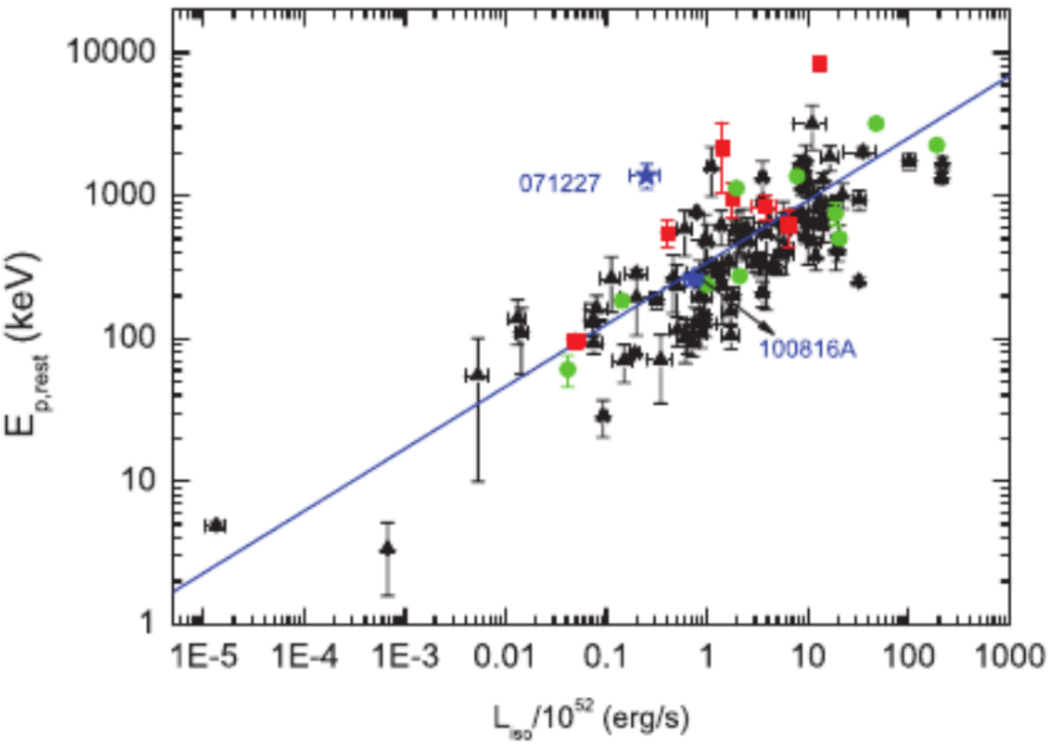
$$L_{\gamma,R_\mathrm{d}} = L_{\gamma,R_\mathrm{p}} \left(R_\mathrm{p}/R_\mathrm{d}\right)^{-2/3}$$



*for constant Γ and sub-relativistic temperatures

Prompt Emission Spectrum

- Assumed to follow broken power law
- Spectral peak is correlated (Yonetoku+ 2004; Ghirlanda+ 2009)
- Holds for long and short (Zhang+ 2012)



Zhang+ 2012

$$E_p \sim 300 \left(\frac{L_\gamma}{10^{52}\mathrm{erg\ s}^{-1}} \right)^{2/5} \ \mathrm{keV}$$

For a low-Γ jets, spectral peak is shifted as the prompt luminosity

$$E_{p,R_\mathrm{d}} = E_{p,R_\mathrm{p}} \left(R_\mathrm{p}/R_\mathrm{d}\right)^{-2/3}$$

Thermalization

Prompt photons will be Compton down-scattered and/or thermalized depending on depth below photosphere

- Depends on optical depth at dissipation radius

$$\tau_{\rm d} \equiv (R_{\rm p}/R_{\rm d})^2$$

- Condition for efficient thermalization

$$\tau_{\rm d} \geq \frac{m_e c^2}{k_B \phi_{BB}}$$

electron temperature at dissipation radius

If satisfied, spectral peak becomes the black-body peak energy

Otherwise, pair production limits the maximum energy, and

$$E_{\rm max} \simeq 511(\Gamma/\tau_{\rm d})\ {\rm keV}$$

Prompt emission will be suppressed; peaking at lower energies and becoming more thermal

Monte Carlo

- Using negative index power-law Γ distribution; a=1.75
- Wanderman & Piran 2015 redshift and energy distribution for short GRBs
- *Swift* detection band and sensitivity; 15-150 keV, >0.2 photons per second per square centimeter

Estimate the fraction of events with detectable prompt emission

- redshift and luminosity distribution

$$R_{\mathrm{SGRB}}(z) \propto \begin{cases} e^{(z-0.9)/0.39} & z \leq 0.9 \\ e^{-(z-0.9)/0.26} & z > 0.9 \end{cases}$$

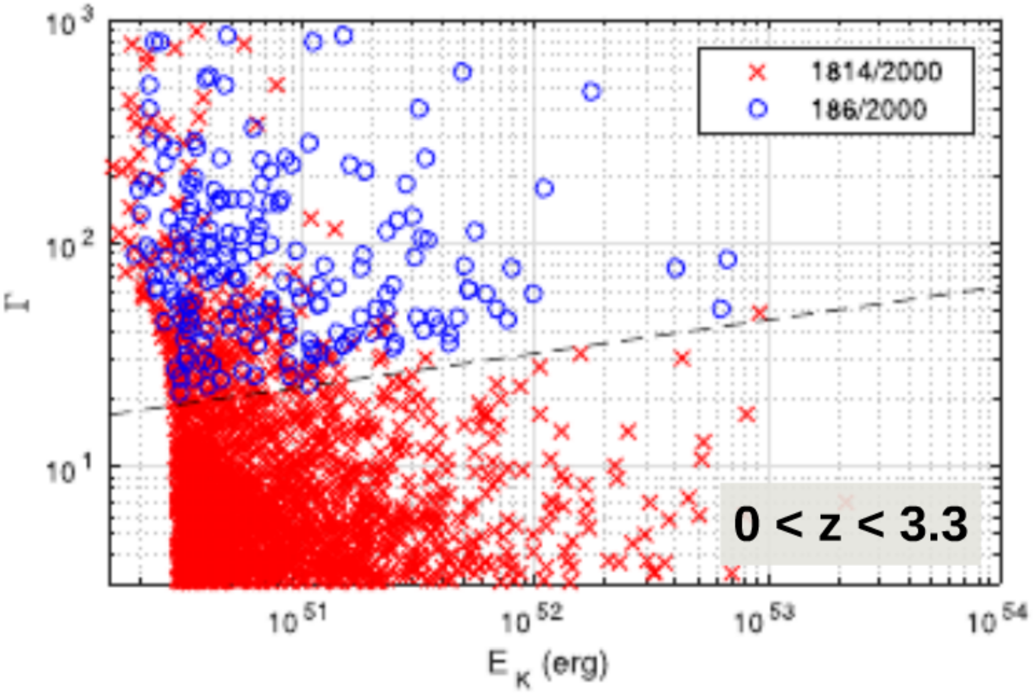
$$\Phi(L_\gamma) \propto \begin{cases} L_\gamma^{-1} & L_\gamma \leq 2 \times 10^{52}\ \mathrm{erg\ s^{-1}} \\ L_\gamma^{-2} & L_\gamma > 2 \times 10^{52}\ \mathrm{erg\ s^{-1}} \end{cases}$$

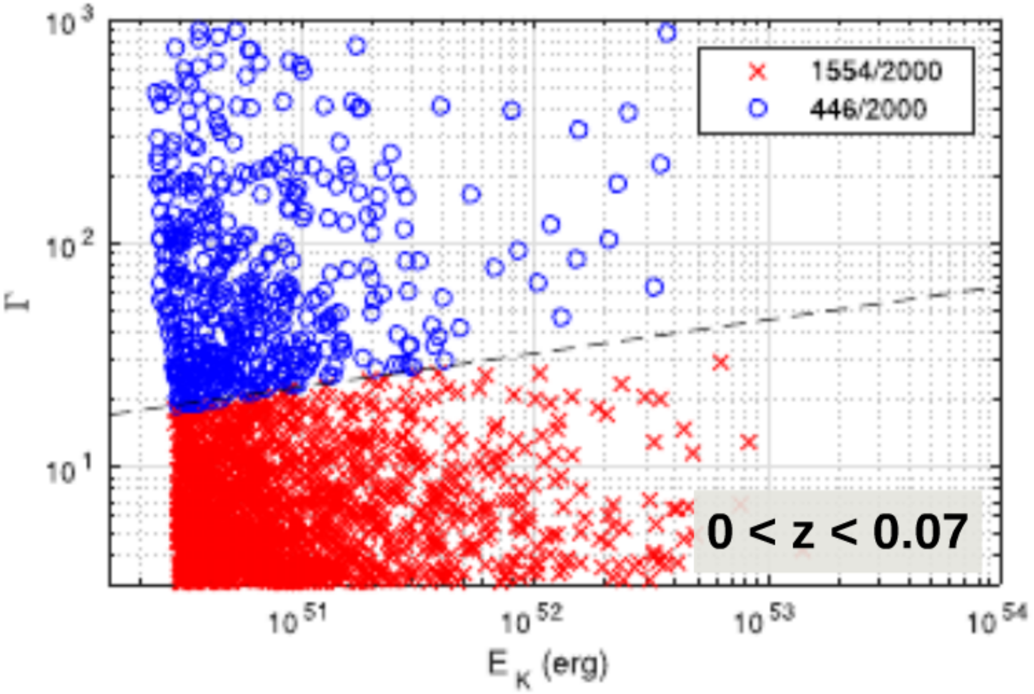
- limits/parameters

$$3 \leq \Gamma \leq 10^3$$

$$a = 1.75$$

$$10^{50}\ \mathrm{erg\ s^{-1}} \leq L_\gamma \leq 10^{53}\ \mathrm{erg\ s^{-1}}$$





BLUE: detected

RED: undetected

Isotropic equivalent jet kinetic energy vs bulk Lorentz factor

2000 on-axis merger jets

- 91% of events undetected or failed GRBs; at cosmological distances
- 78% of events failed GRBs; within LIGO face-on NS-NS detection limit (~300 Mpc)

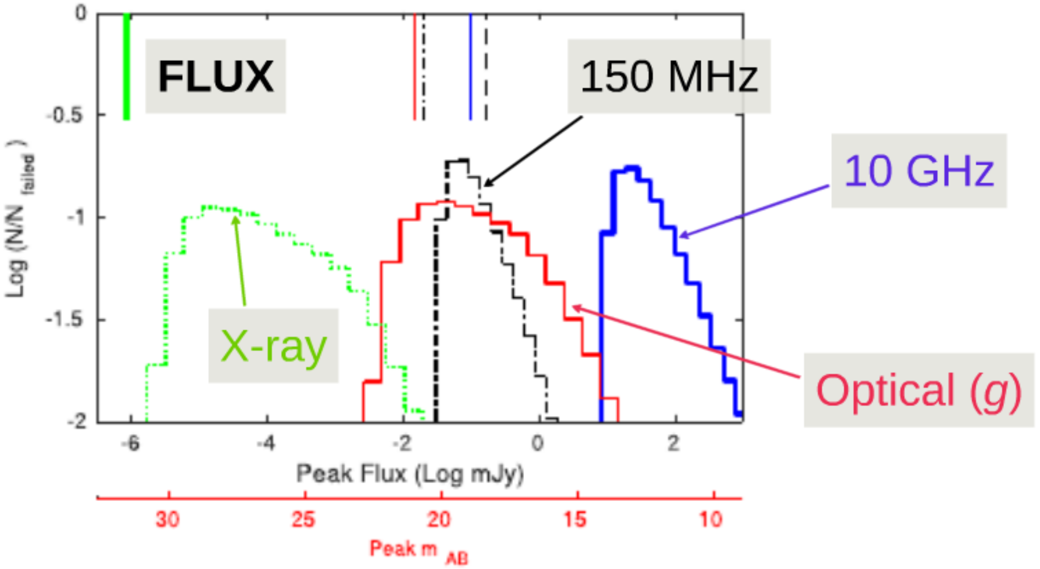
A significant fraction of mergers result in failed GRBs

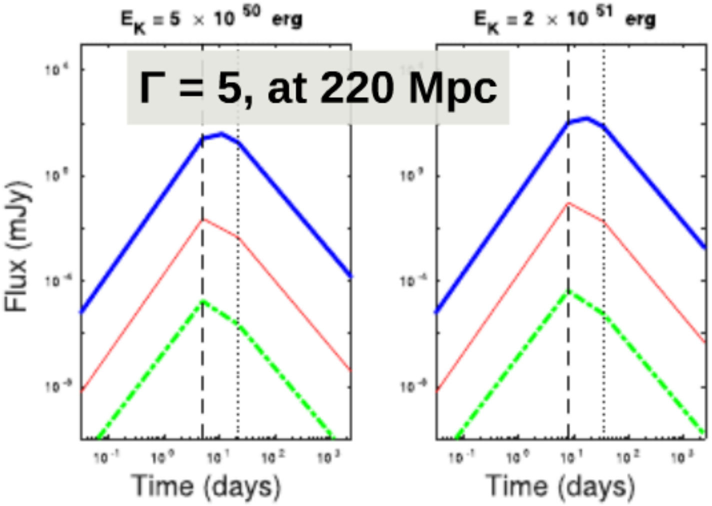
GPL & Kobayashi 2016

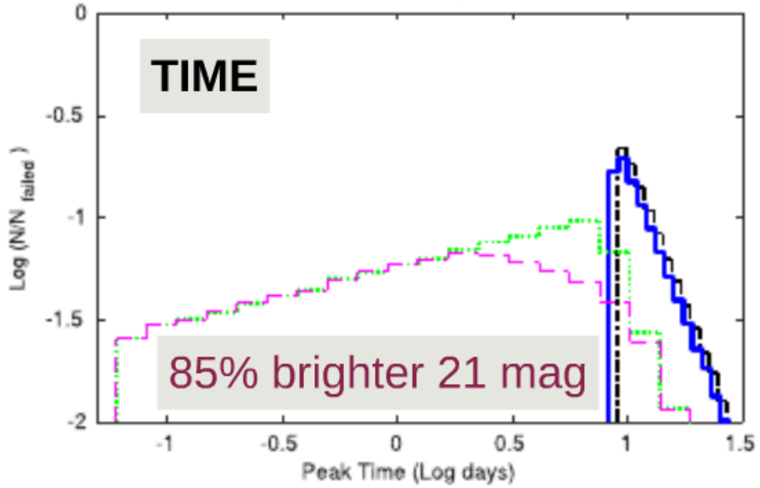
Afterglow from Failed GRBs

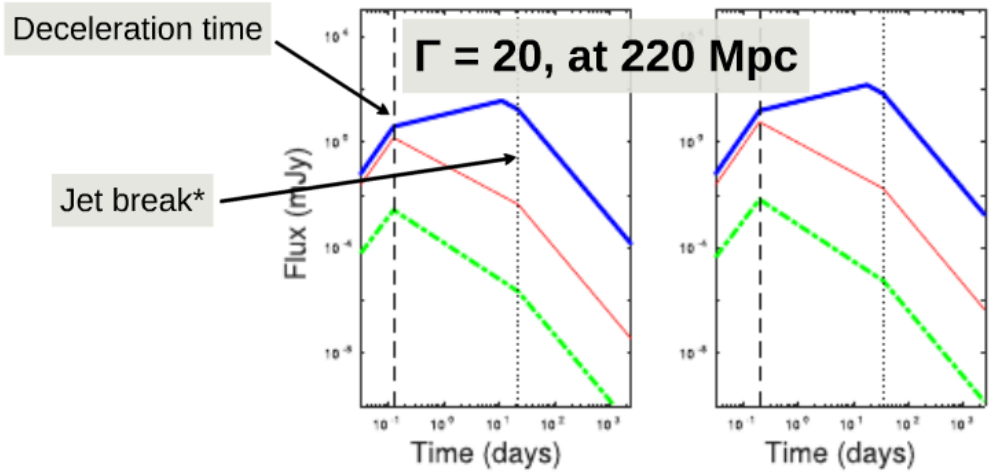
On-Axis Orphan Afterglow

Peak flux and time for on-axis orphan afterglow at <300 Mpc









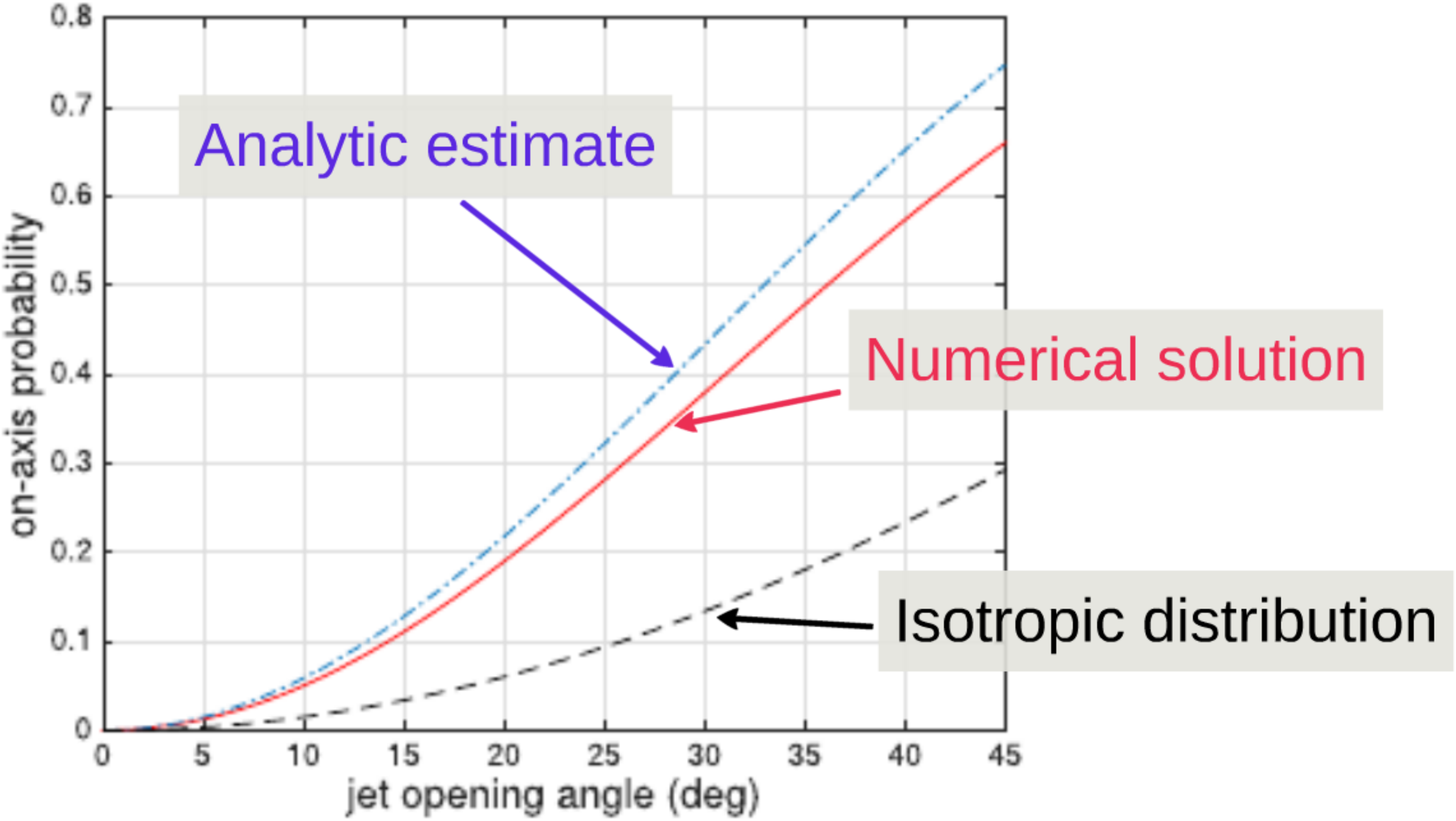
GPL & Kobayashi 2016

*assumed a jet half-opening angle of 20 degrees

Given a GW Detection

The probability the source is face-on is higher than for an isotropic distribution

- GW polarization components depend on inclination
- Strongest on-axis



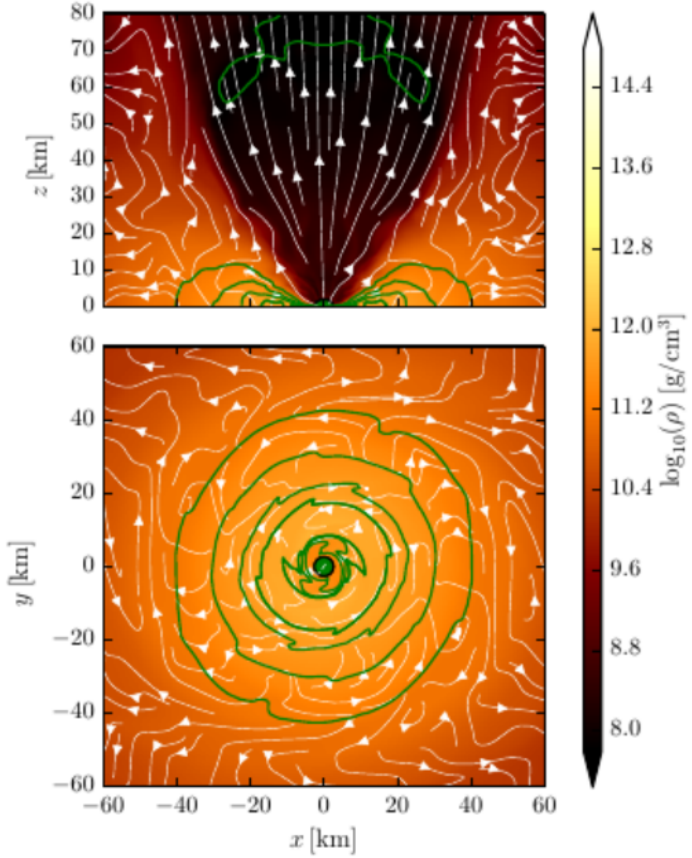
Analytic estimate

Numerical solution

Isotropic distribution

GPL & Kobayashi 2016

Jet Opening Angle



Jet half-opening angle:

25 degrees ~30% on-axis
16 degrees ~13% on-axis
8 degrees ~4% on-axis

Jet structure indicated by RMHD simulations (Dionysopoulou+ 2015)

Average from SGRB sample (Fong+ 2015)

For long GRBs, observations indicate a correlation*

$$\Gamma \propto \theta_j^{-k} \quad 0.3 \leq k \leq 2.7$$

For failed GRBs from low-Γ jets, the fraction of on-axis jets could be higher than SGRBs

*Kobayashi+ 2002; Panaitescu & Kumar 2002; Salmonson & Galama 2002; Ghirlanda+ 2013

Estimate the Rate of Failed GRBs

Rate of SGRBs, within LIGO detection volume?

Swift rate of SGBs with *z* ~ 0.03*
Swift field of view ~ 2 sr
All-sky rate of SGRBs with *z* ~ 0.19
Fraction of *Swift* SGRBs with *z* ~ 0.25
All-sky rate of SGRBs with/without *z* ~ **0.75** per year

For a=1.75, 78% failed.
All-sky rate of failed-SGRBs ~ **2.6** per year

*Metzger & Berger 2012

Low-Γ Jets from Compact Stellar Mergers*

- More frequent than SGRBs given a power-law Γ-distribution
- X-ray, optical and radio afterglow are bright
- Peaking 0.1-10 days for X-ray and optical
- Peaking from 10 days for radio

- **Good candidates for EM counterpart searches**

*http://adsabs.harvard.edu/abs/2016ApJ...829..112L arXiv:1605.02769

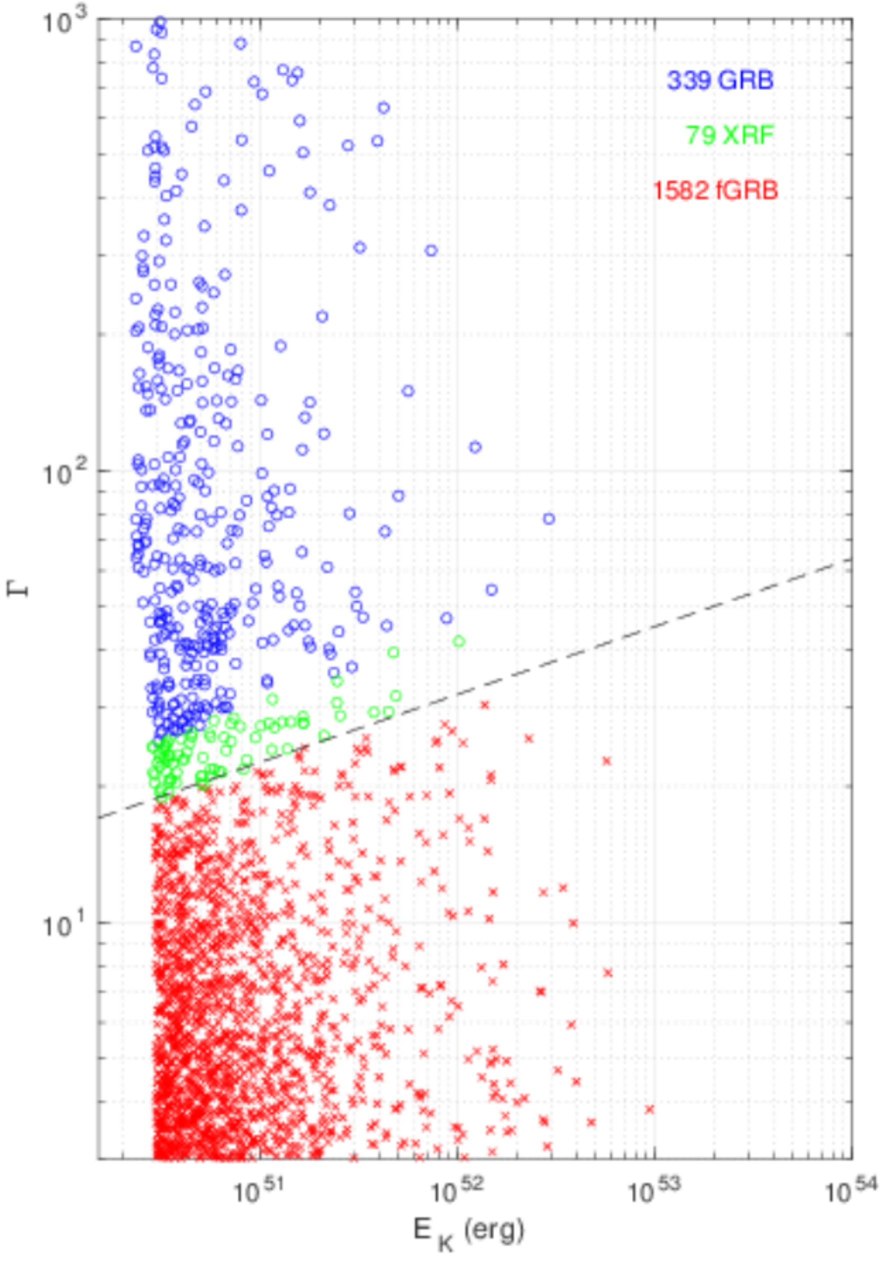
X-ray Flashes

Some bursts may appear as X-ray flashes (XRF) or X-ray rich GRBs

- Select bursts that have the prompt spectrum cut-off at 100 keV

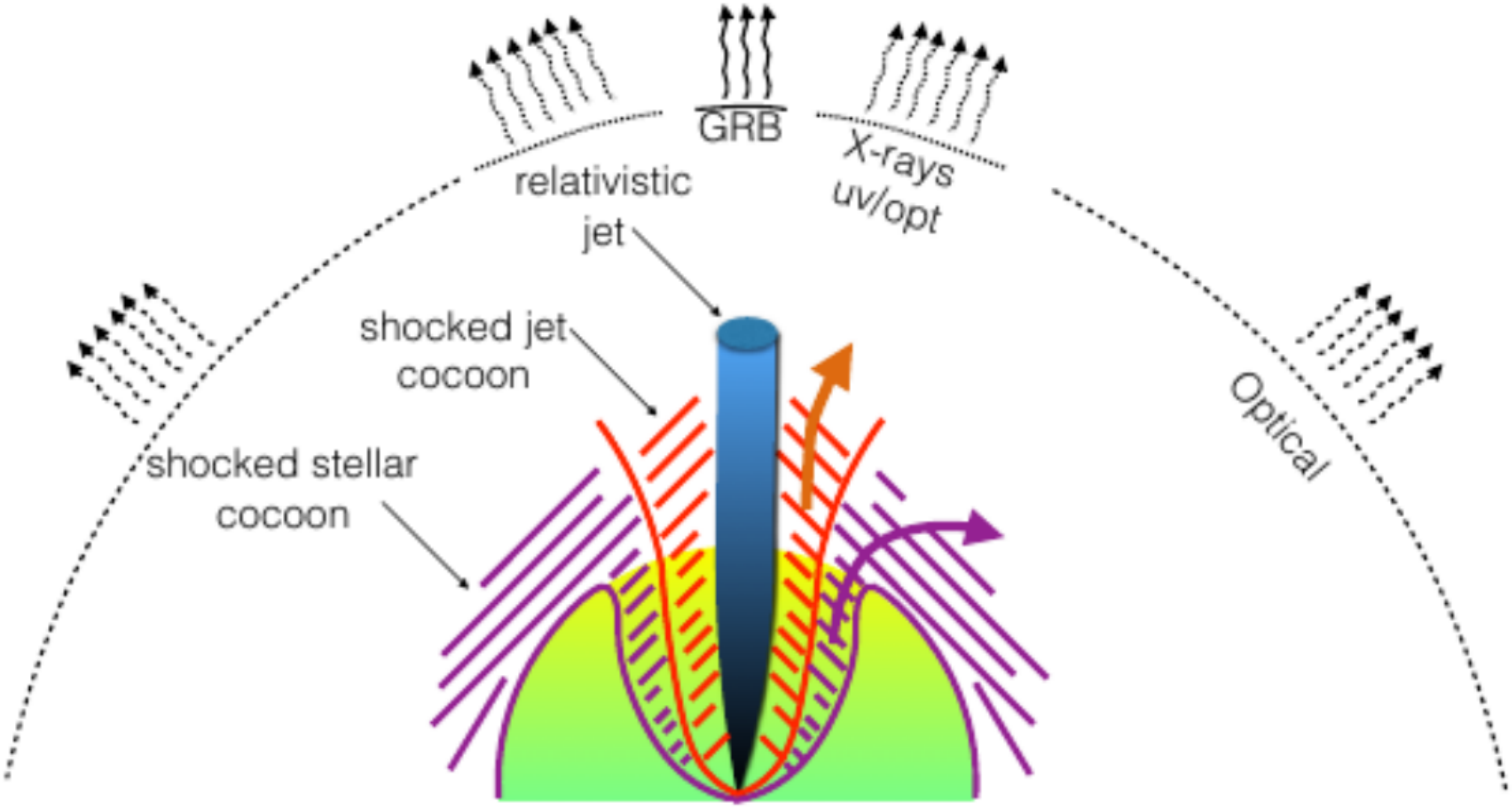
These bursts would appear as brief, <2 s flashes with maximum spectral energy <100 keV. The peak energy for these bursts is

νF_ν spectral peak energy $\sim 20 - 30$ keV

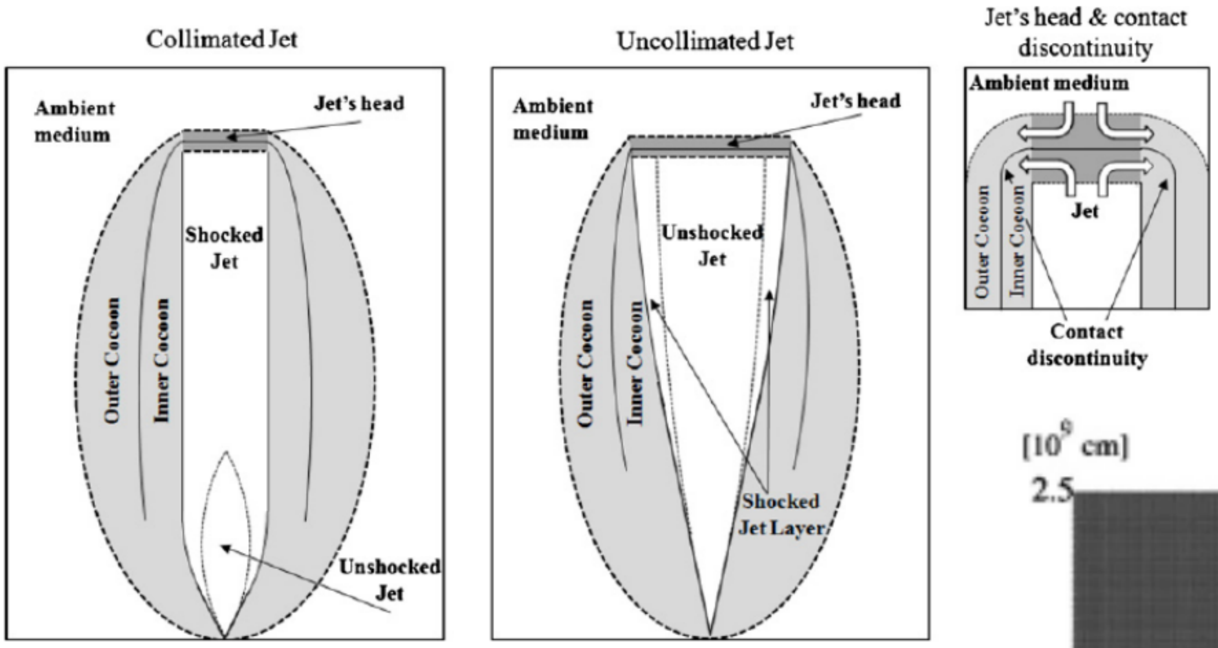


Cocoon Emission

- Jet punches through ejecta - cocoon forms
- Cocoon collimates jet (Bromberg+ 2011)
- Cocoon shock emission; X-ray, UV/optical?



Nakar & Piran 2016



Bromberg+ 2011

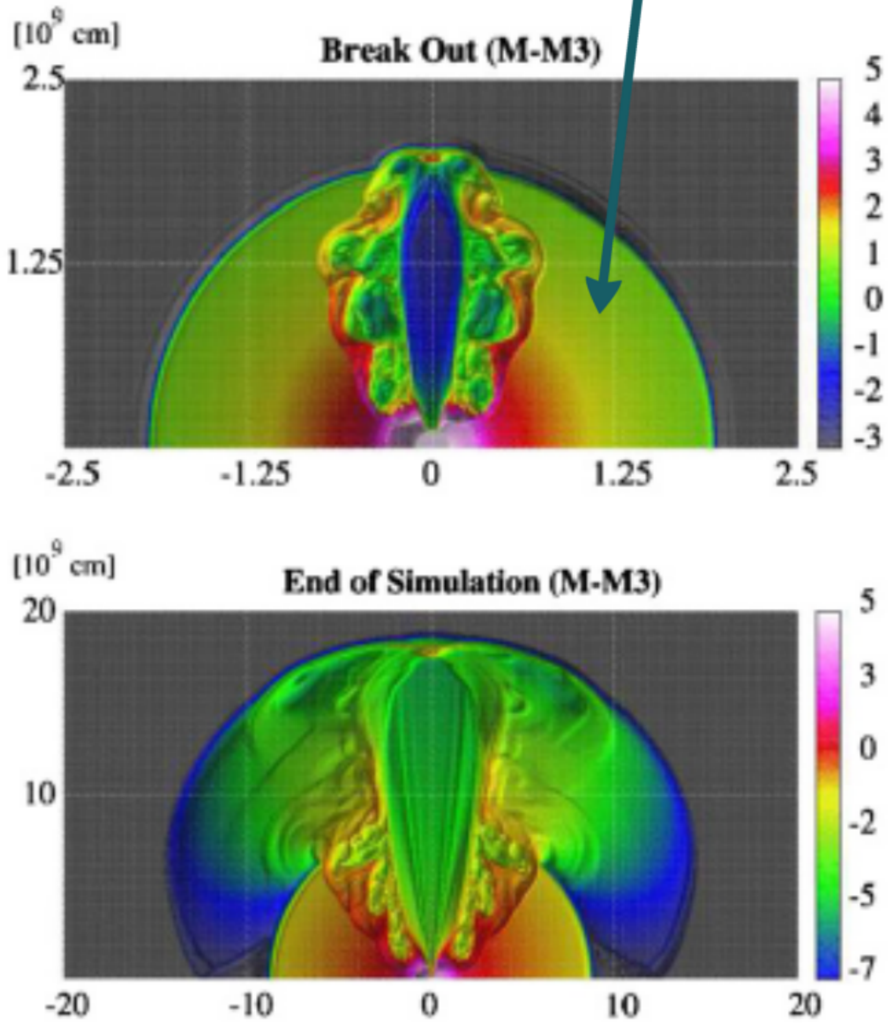
Jet penetrates the expanding ejecta - becomes collimated

Jet breaks out of cocoon

- ~12 degrees
- Additional structure

So far, only considered uniform jets!

Expanding ejecta



Nagakura+ 2014

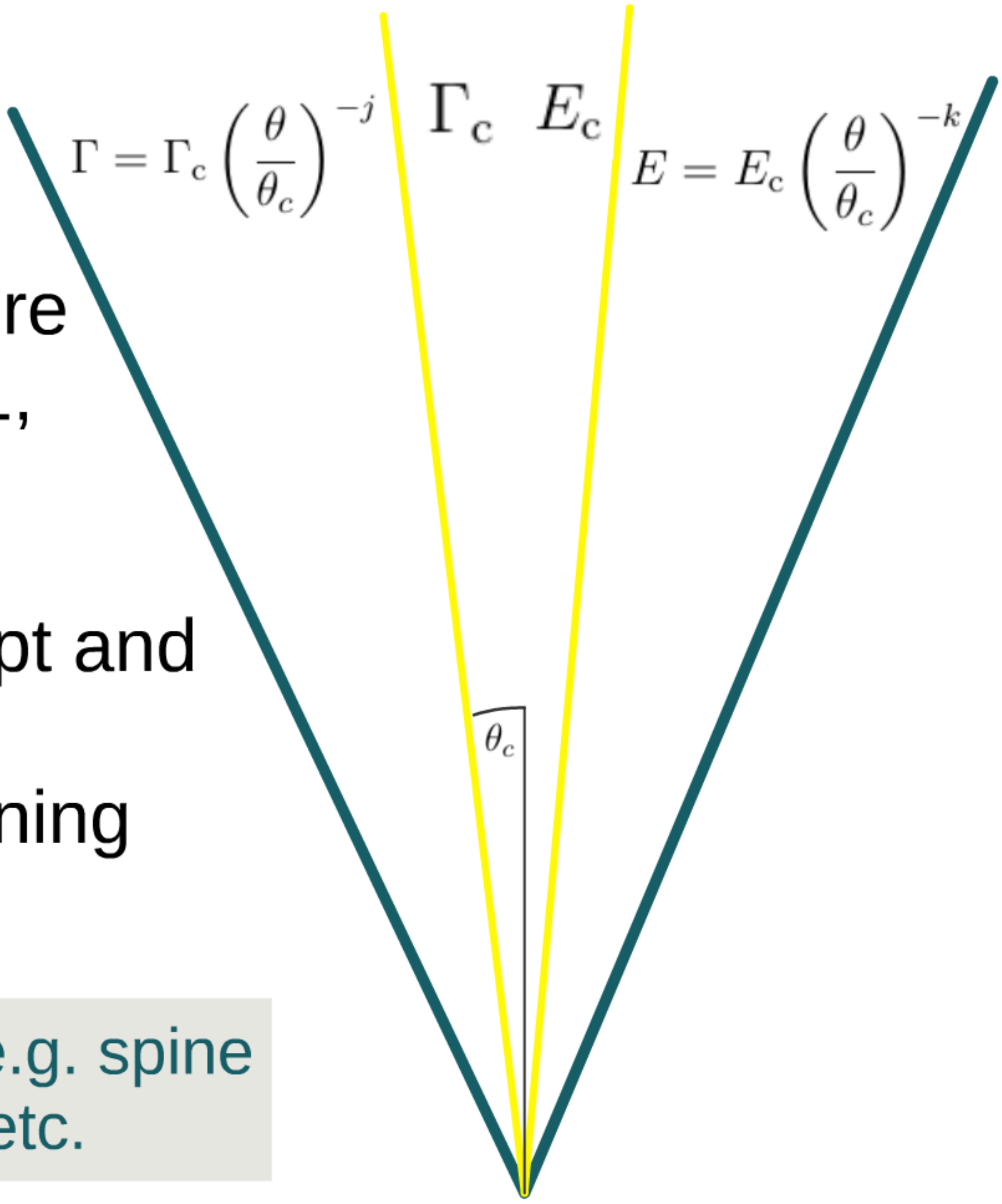
Structured Jets from Compact Binary Mergers

Core is uniform

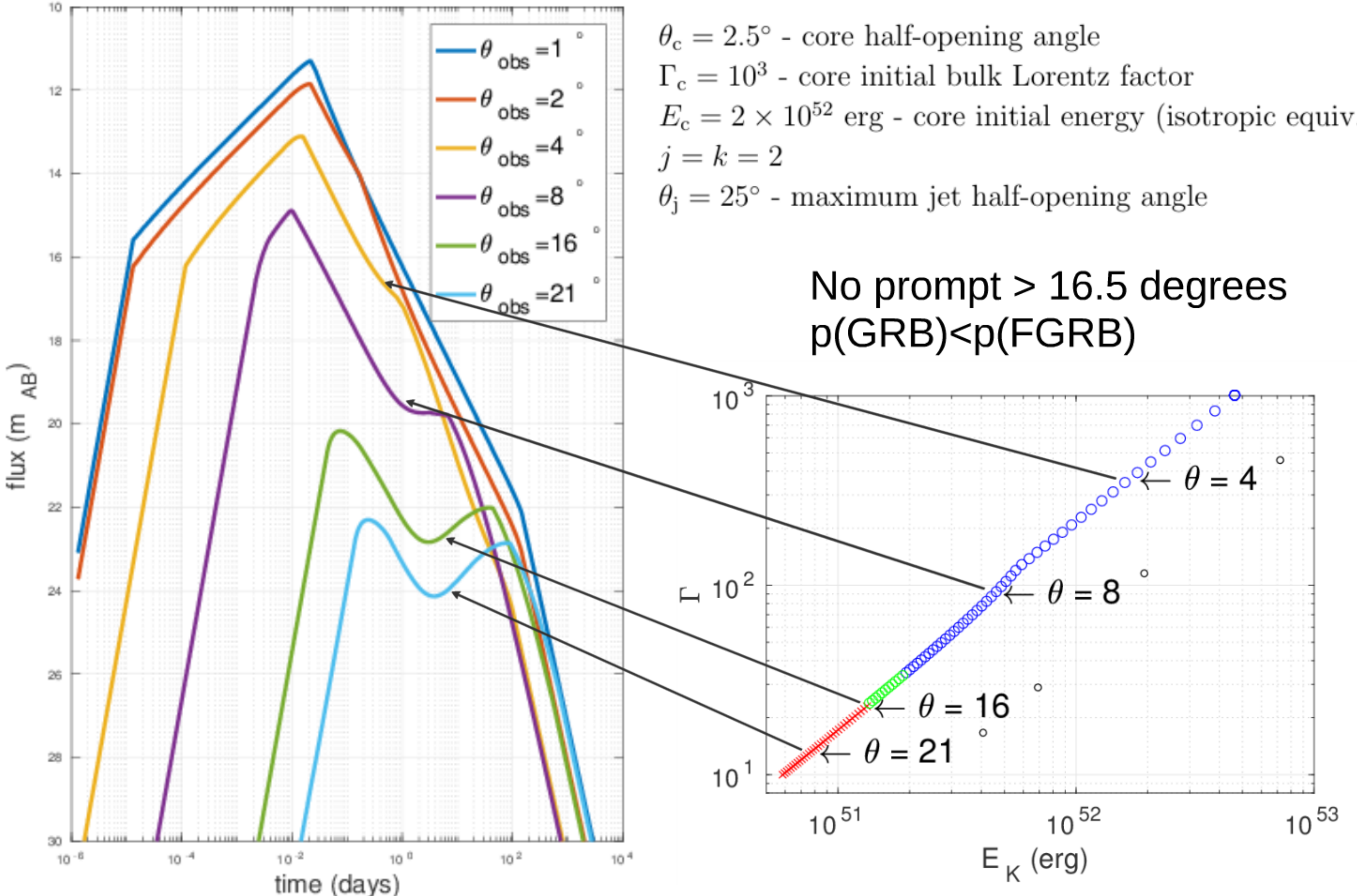
Wings have structure
e.g. Postnov+ 2001,
Rossi+ 2002

Nature of the prompt and afterglow emission depend on the opening angle

Jet structure may vary e.g. spine and sheath, Gaussian, etc.



Afterglow from Structured Jets



$\theta_c = 2.5°$ - core half-opening angle

$\Gamma_c = 10^3$ - core initial bulk Lorentz factor

$E_c = 2 \times 10^{52}$ erg - core initial energy (isotropic equiv.)

$j = k = 2$

$\theta_j = 25°$ - maximum jet half-opening angle

No prompt > 16.5 degrees
p(GRB)<p(FGRB)

NB: neglects contribution from adjacent jet components

GPL & Kobayashi (in prep)

Summary

- GW triggered search could reveal hidden low Γ population of merger jets
- Detection/non-detection will constrain Γ distribution for SGRBs
- Features in afterglow of local GW counterparts will constrain jet structure
- Low Γ components or jets are good candidates as EM counterparts to GW sources

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