The nature of radiative processes in Gamma-Ray Bursts

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Palaiseau - April 12th, 2017

OUTLINE

- Observations of prompt and afterglow emission in GRBs
- Standard model: open issues and problems
- Polarization of prompt and afterglow radiation: the theory
- Polarization measurements of prompt and afterglow radiation
- GRBs @ MeV

The basic picture: observations

EMISSION	ENERGY RANGE	DURATION
Prompt	keV-MeV	0.1-10^3 s

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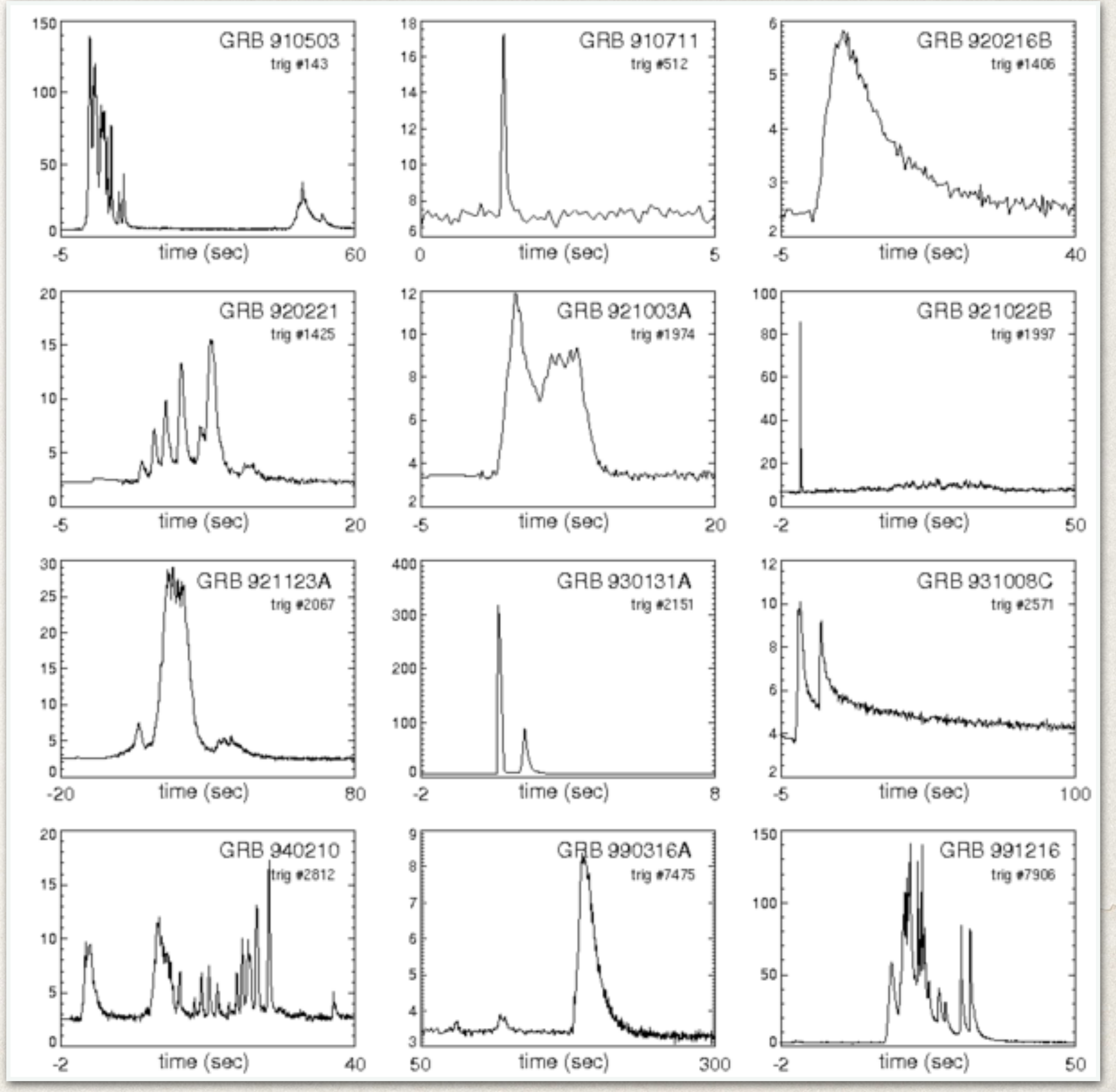
Light curves



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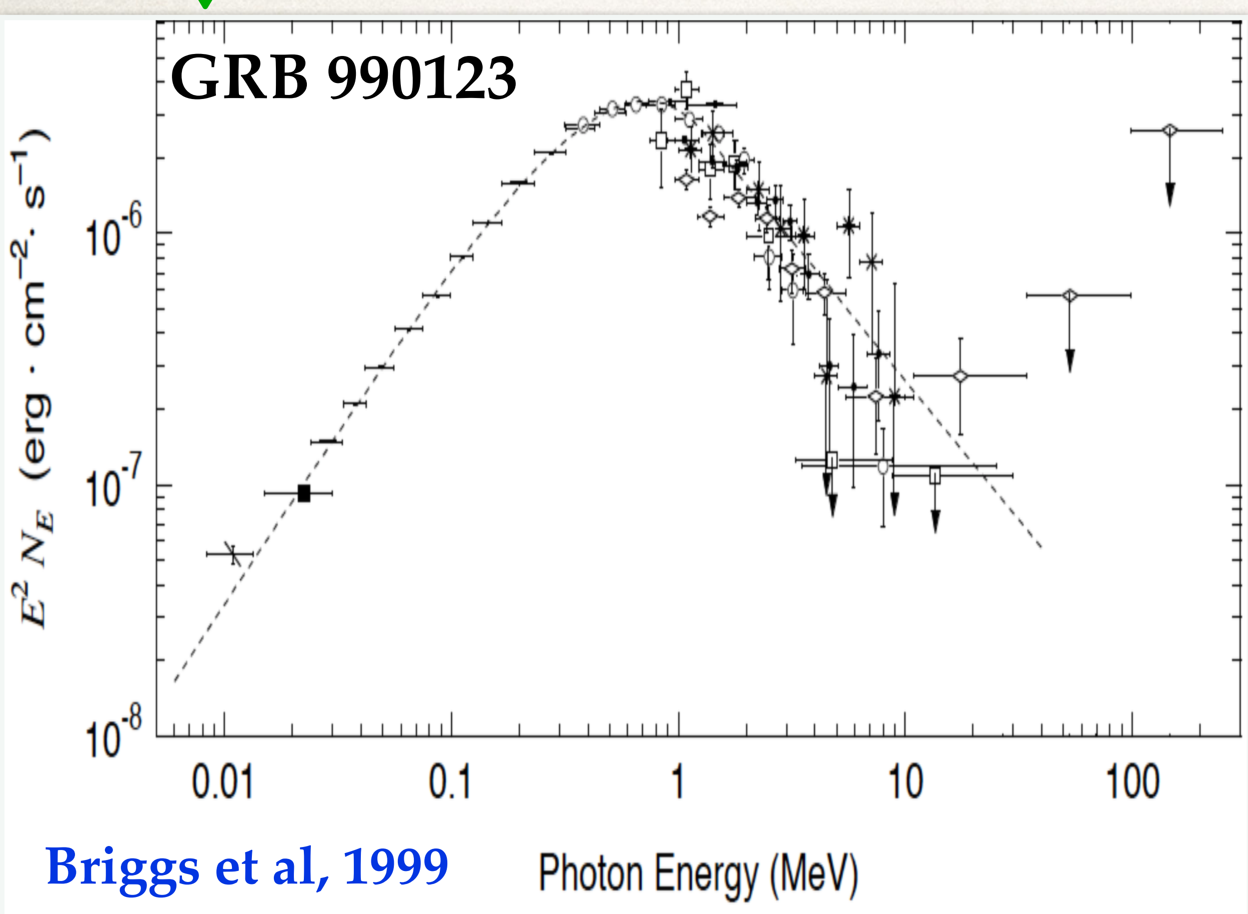
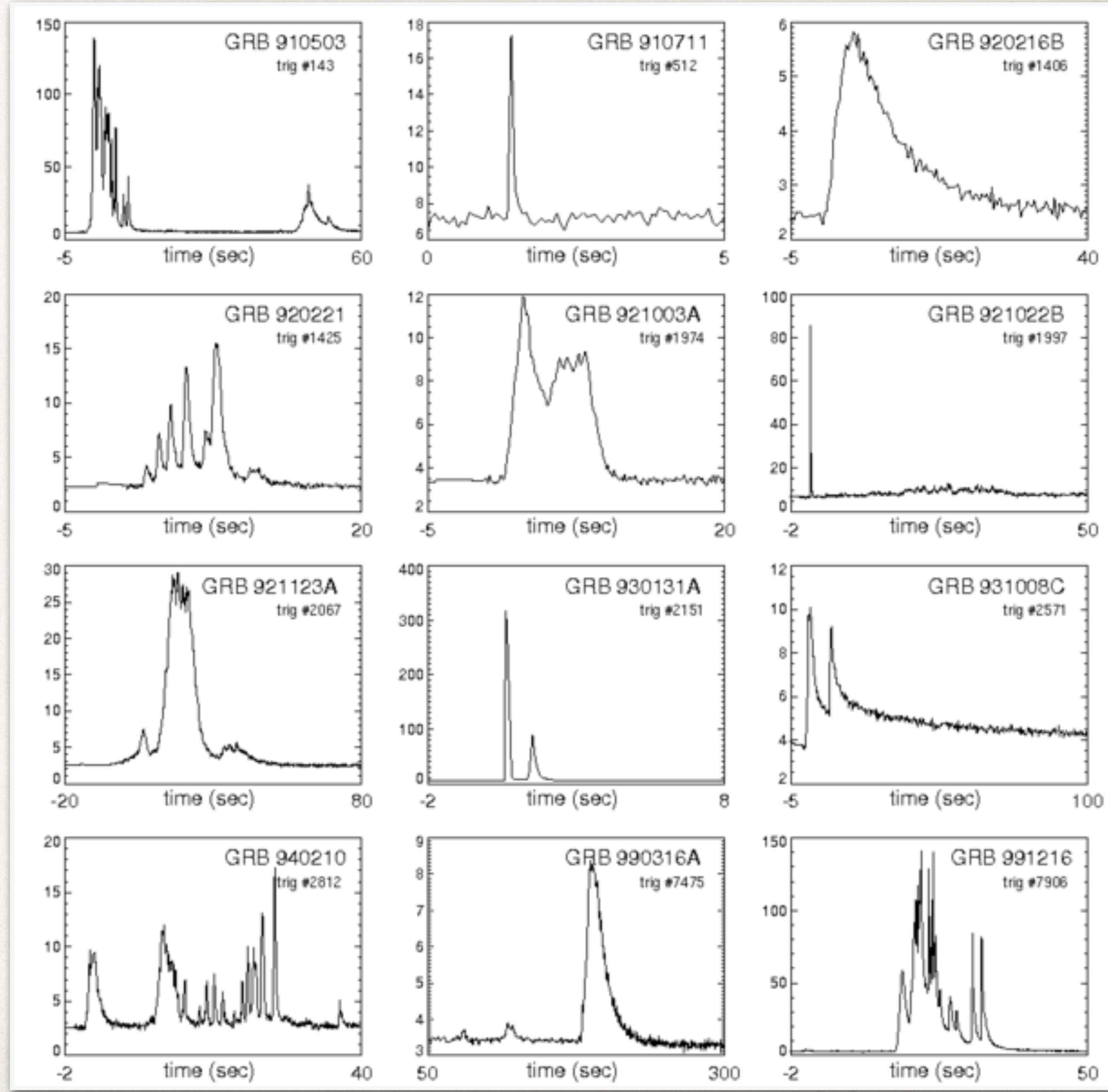
Light curves

Spectra





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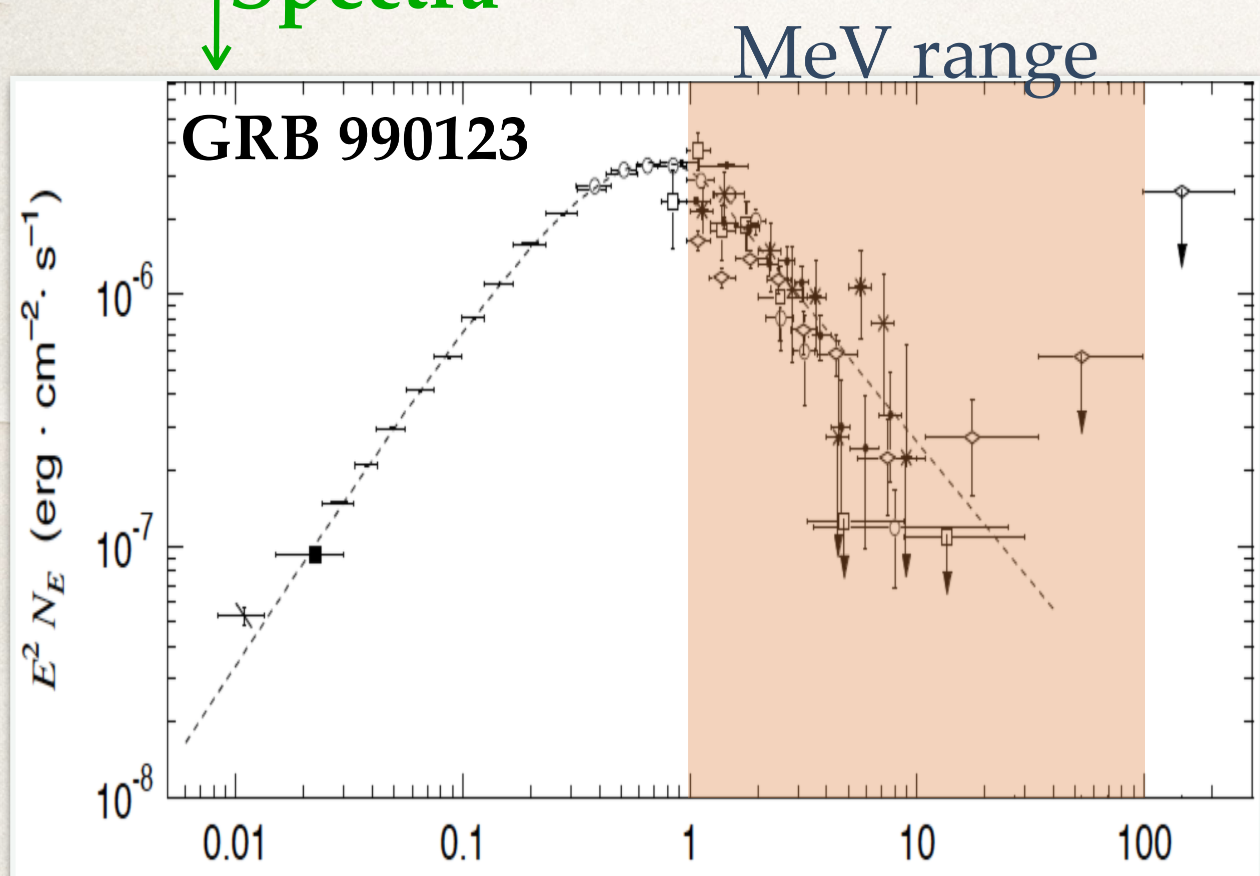
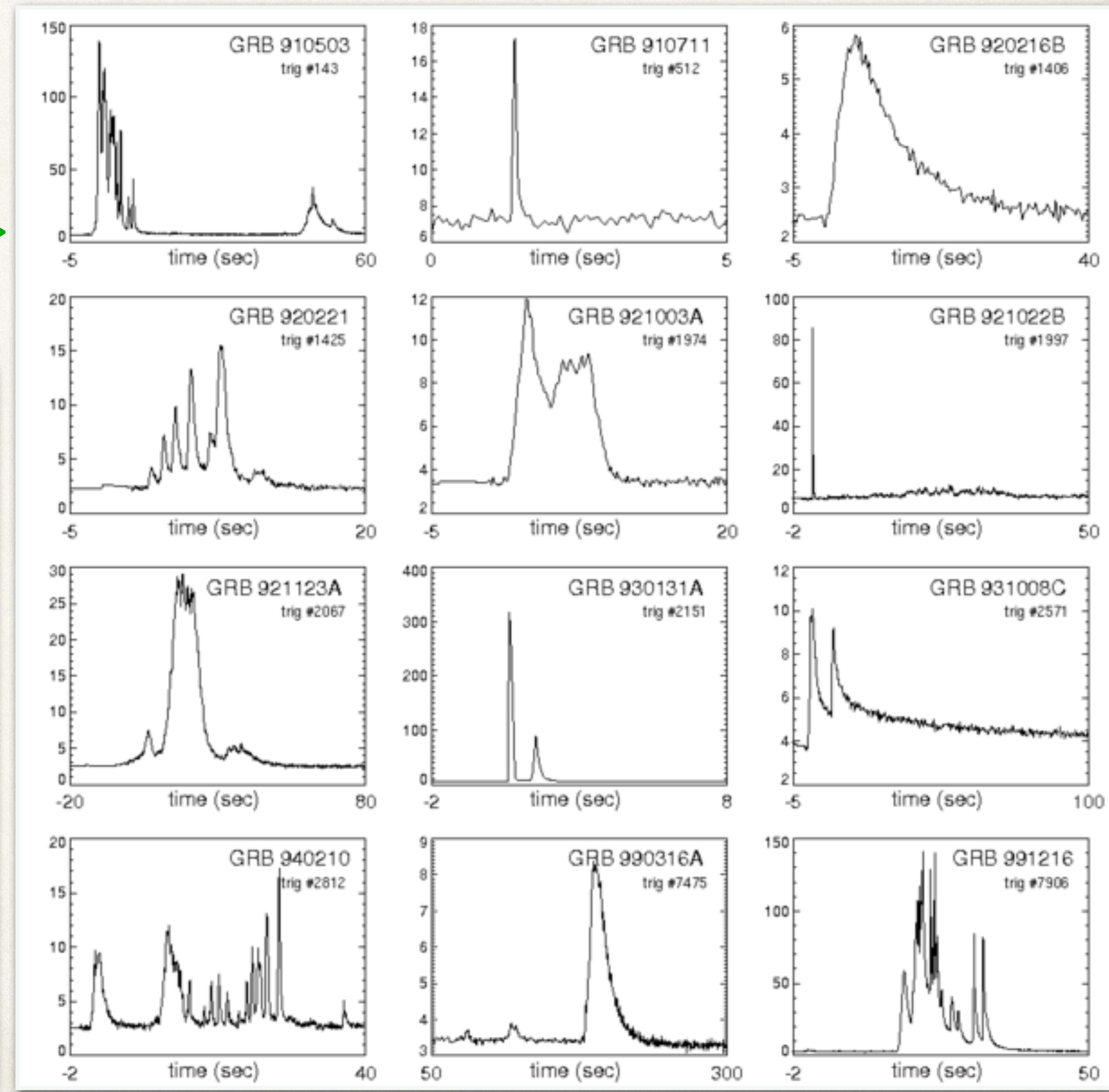


Briggs et al, 1999



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EMISSION	ENERGY RANGE	DURATION
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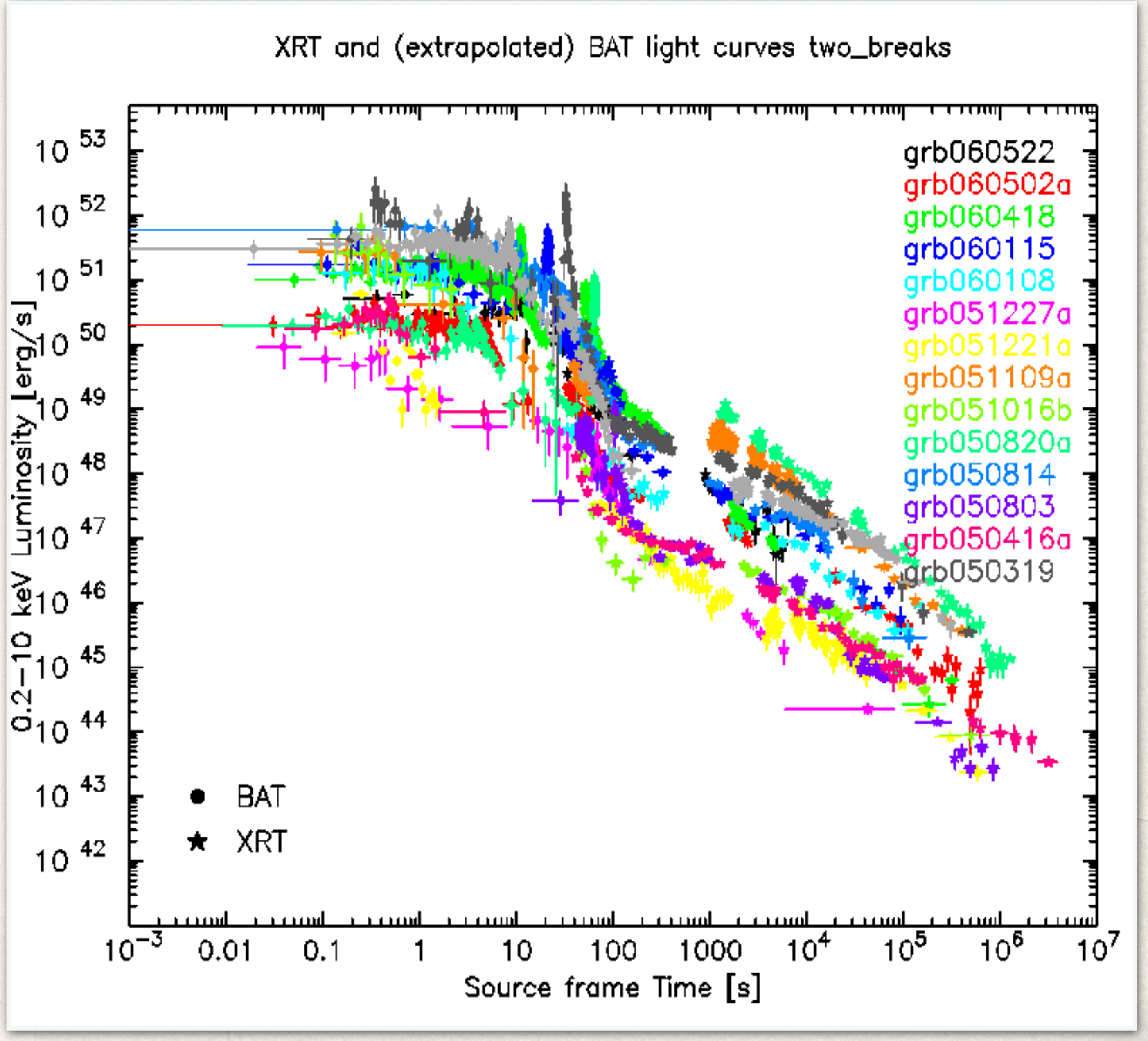

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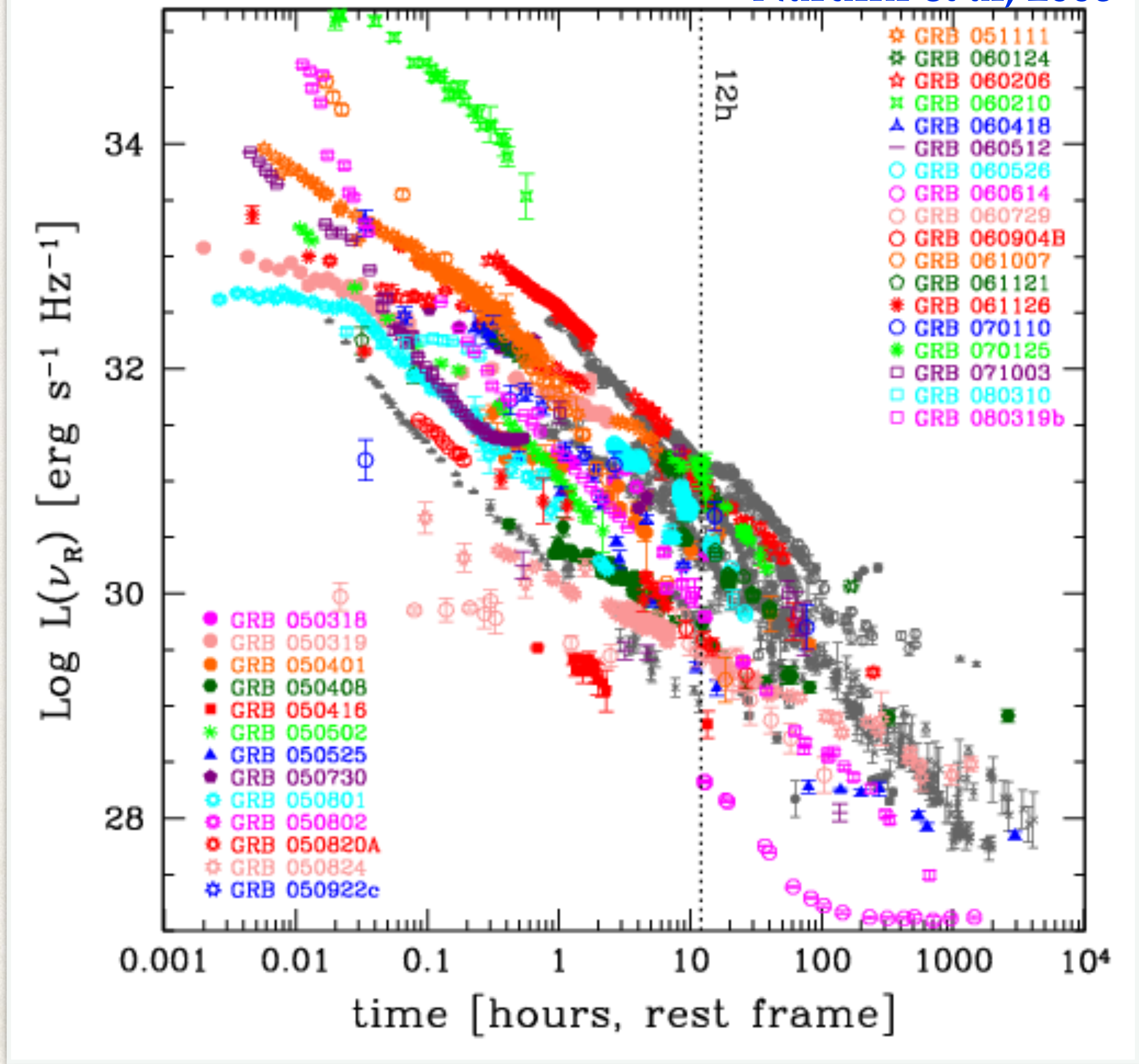
Nardini et al, 2008



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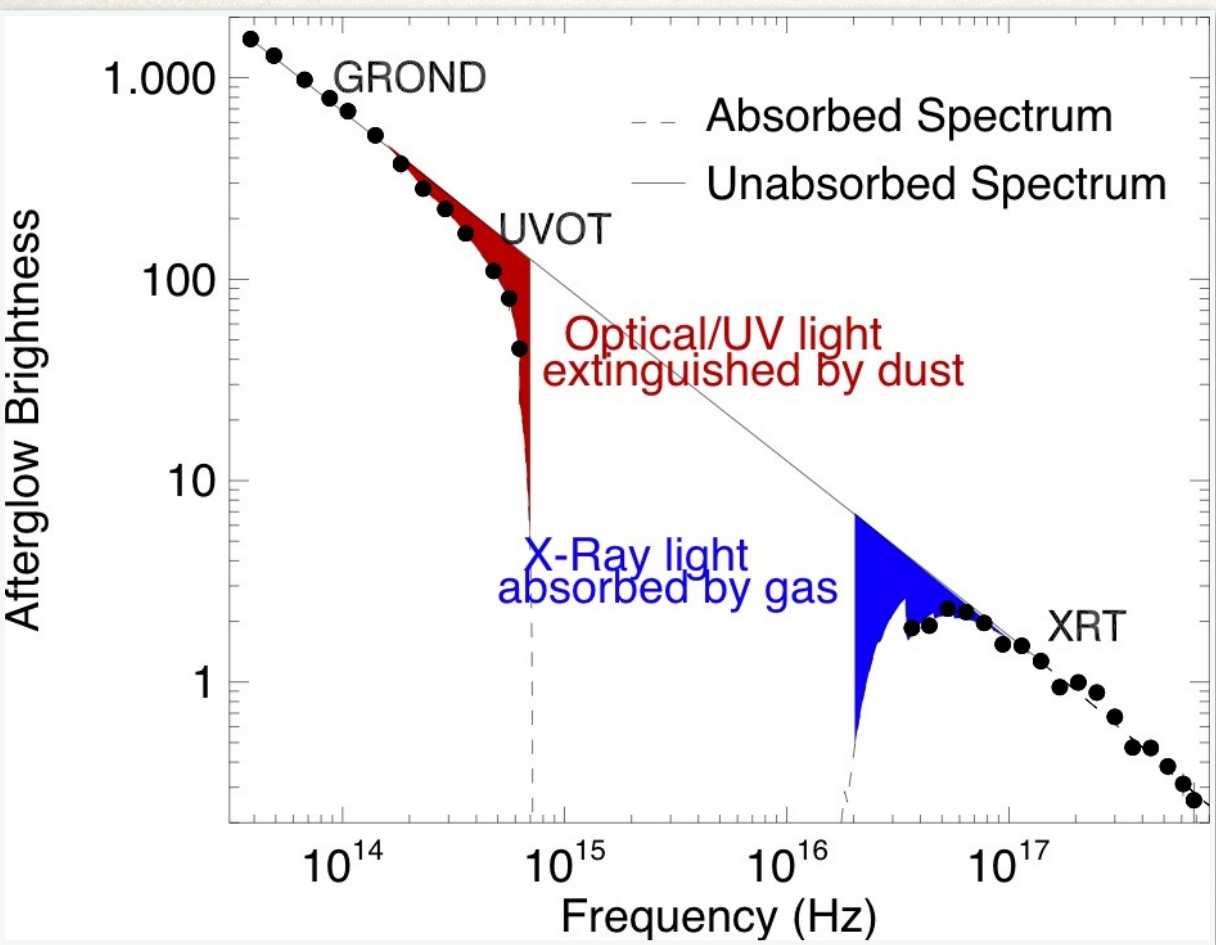
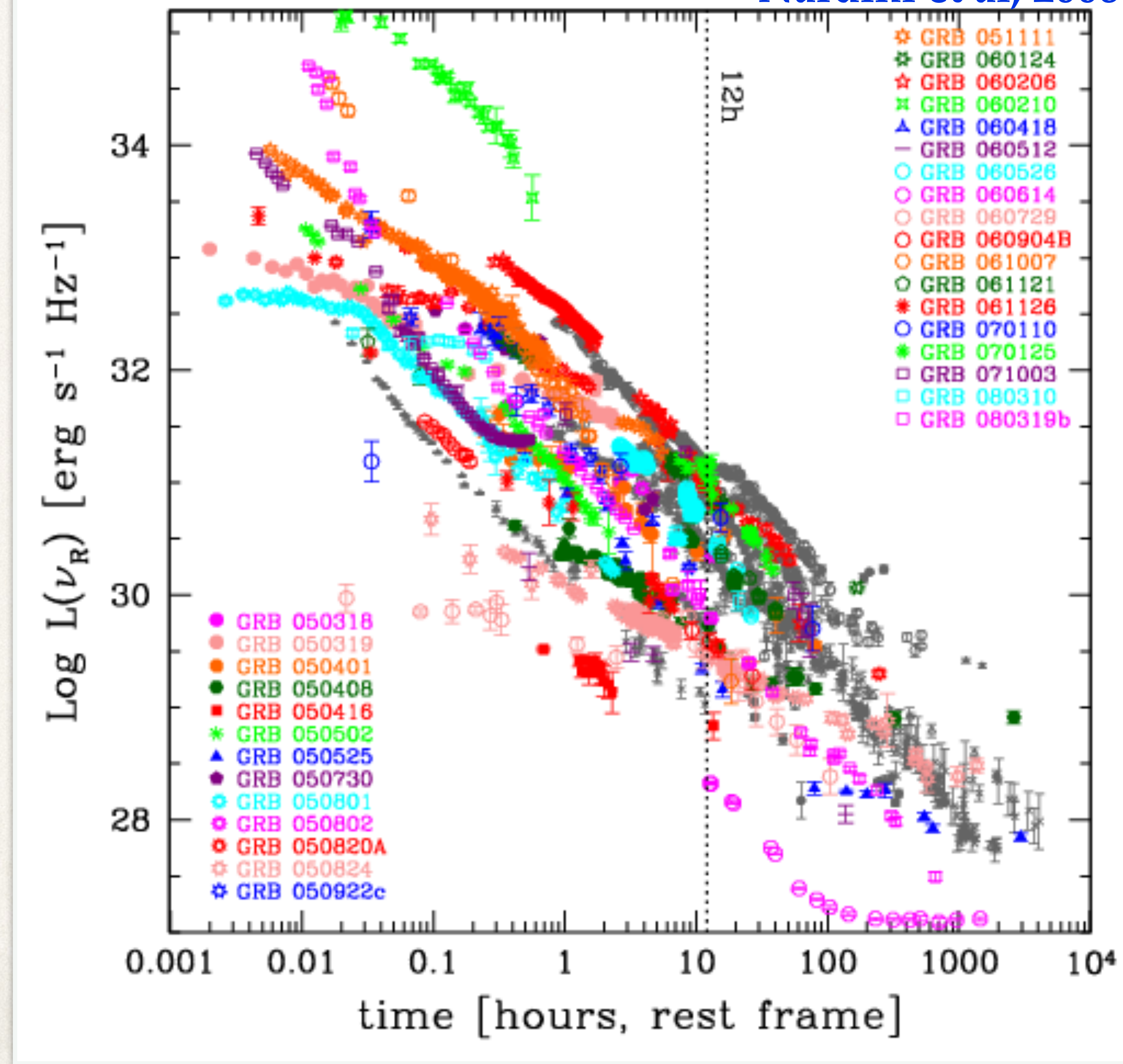


Nardini et al, 2008



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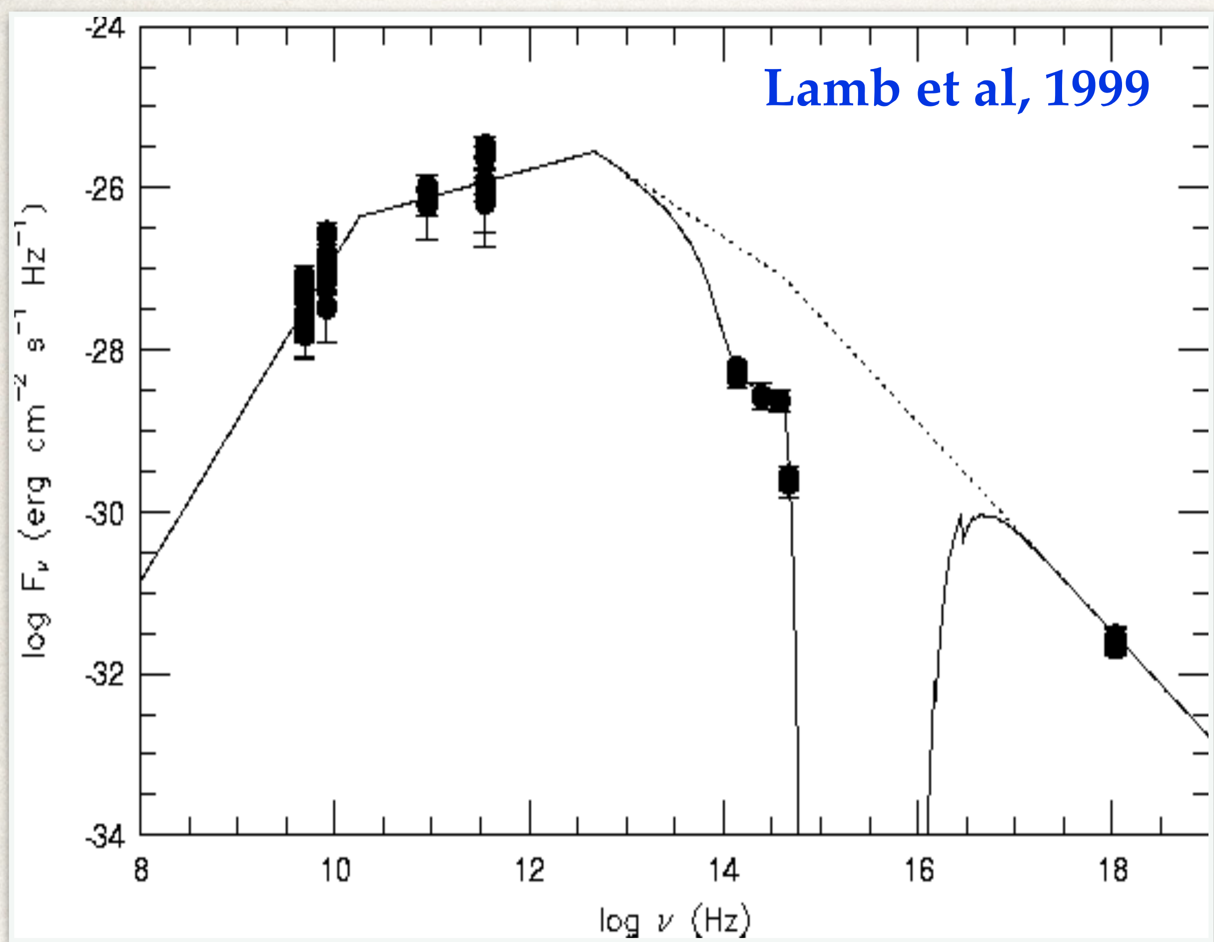

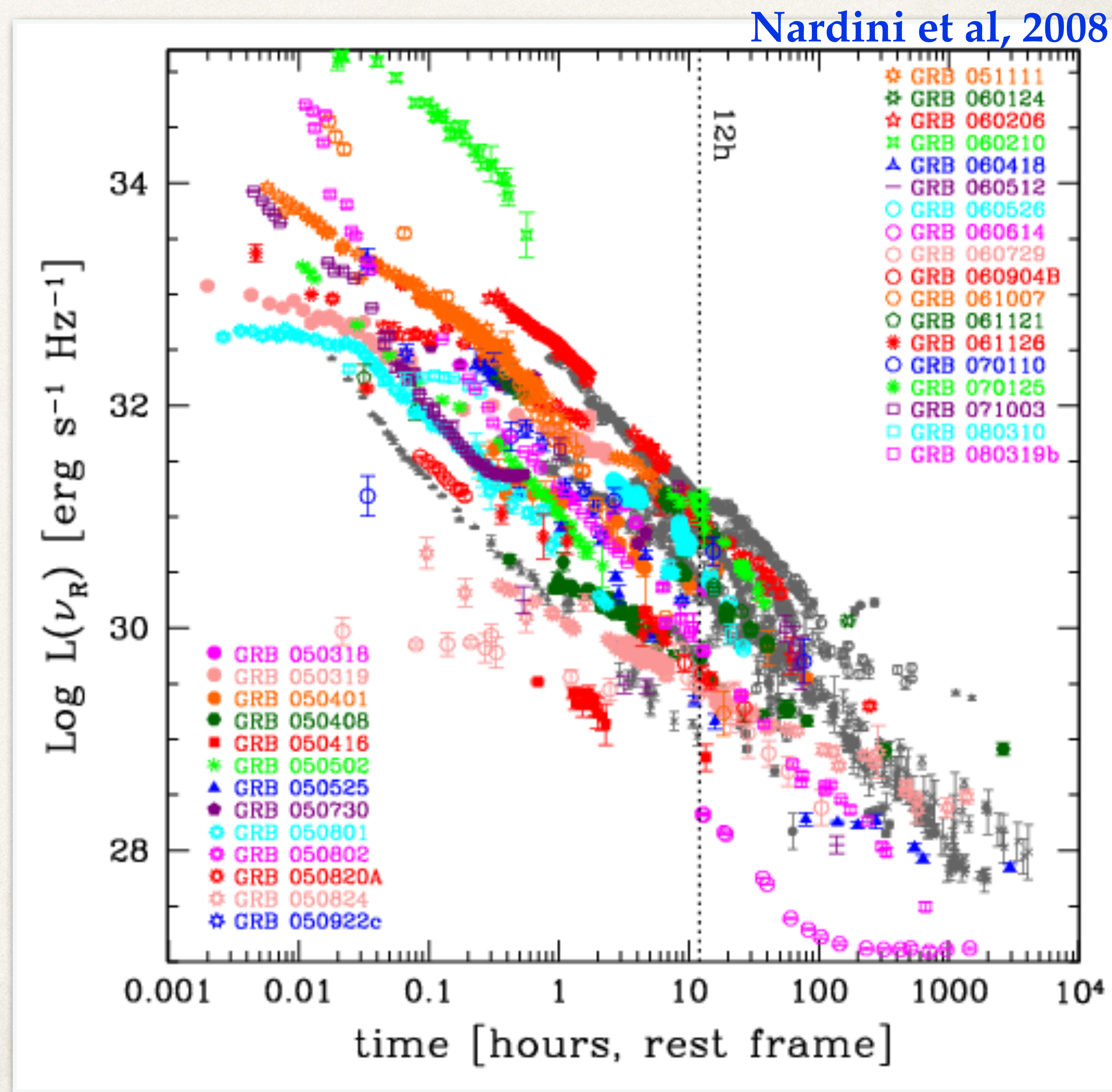

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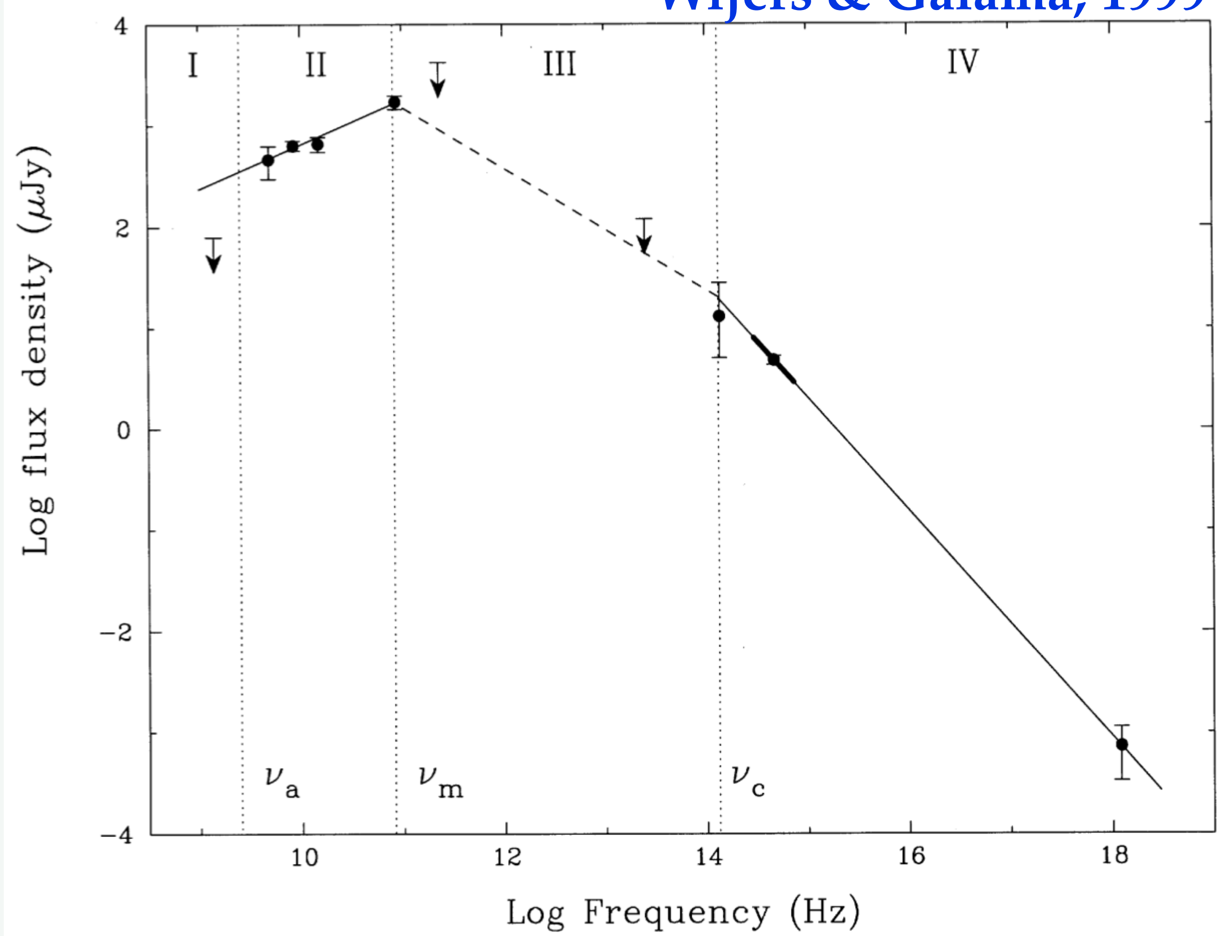
Wijers & Galama, 1999



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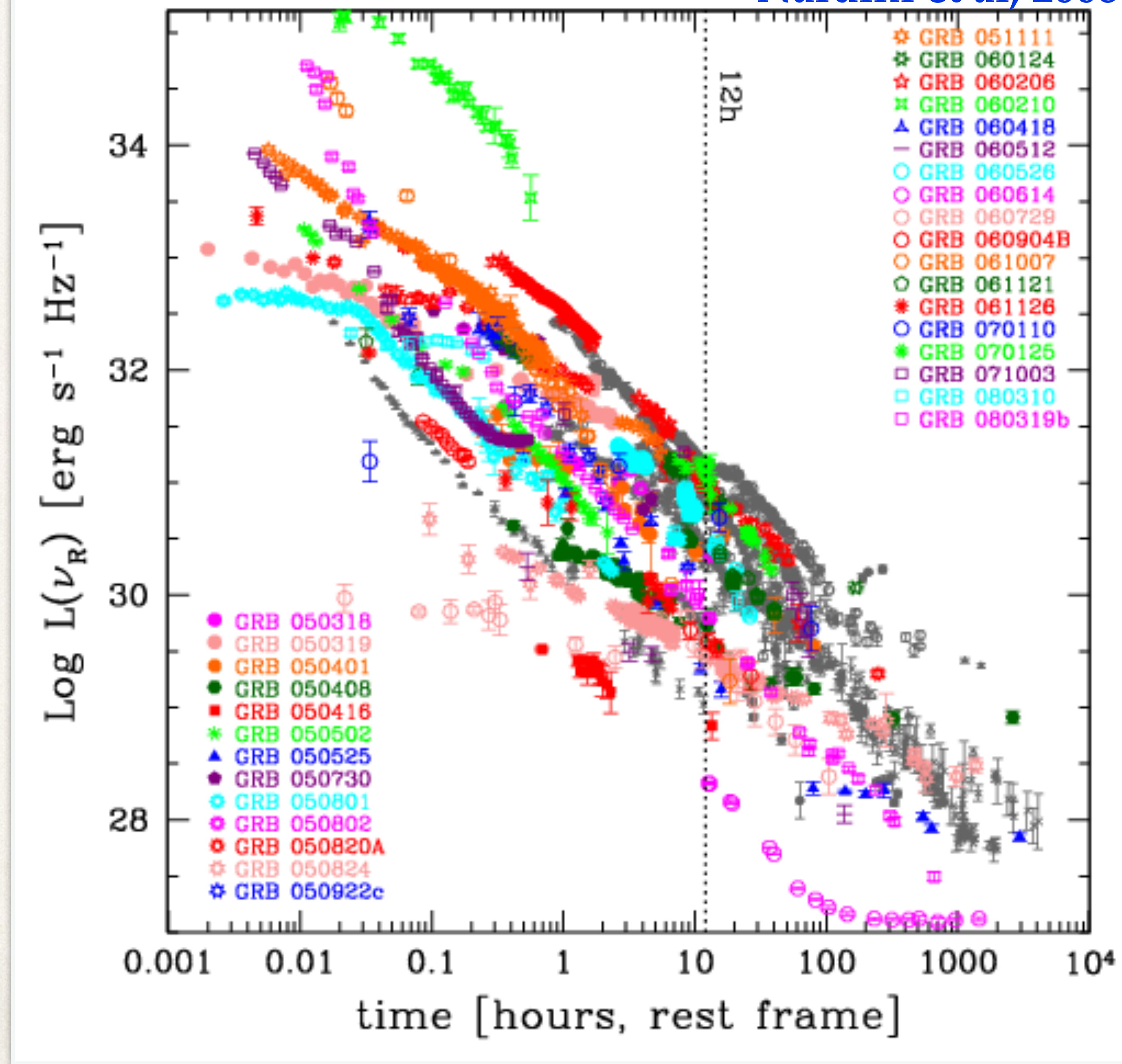

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EMISSION	ENERGY RANGE	DURATION
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‣ High Energy	0.1-100 GeV	1 - 10^4 s

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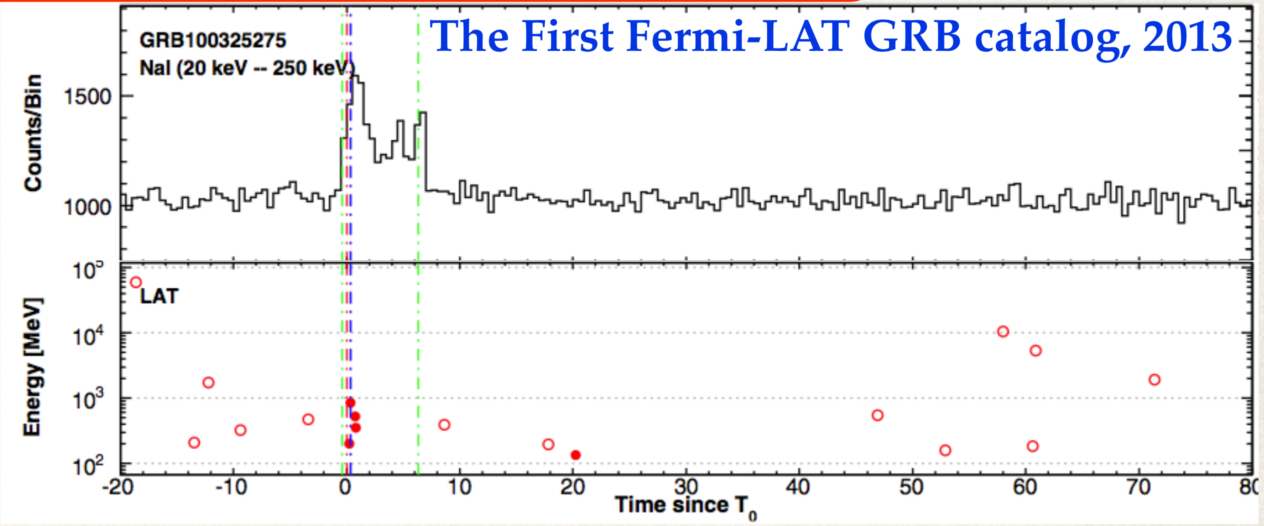

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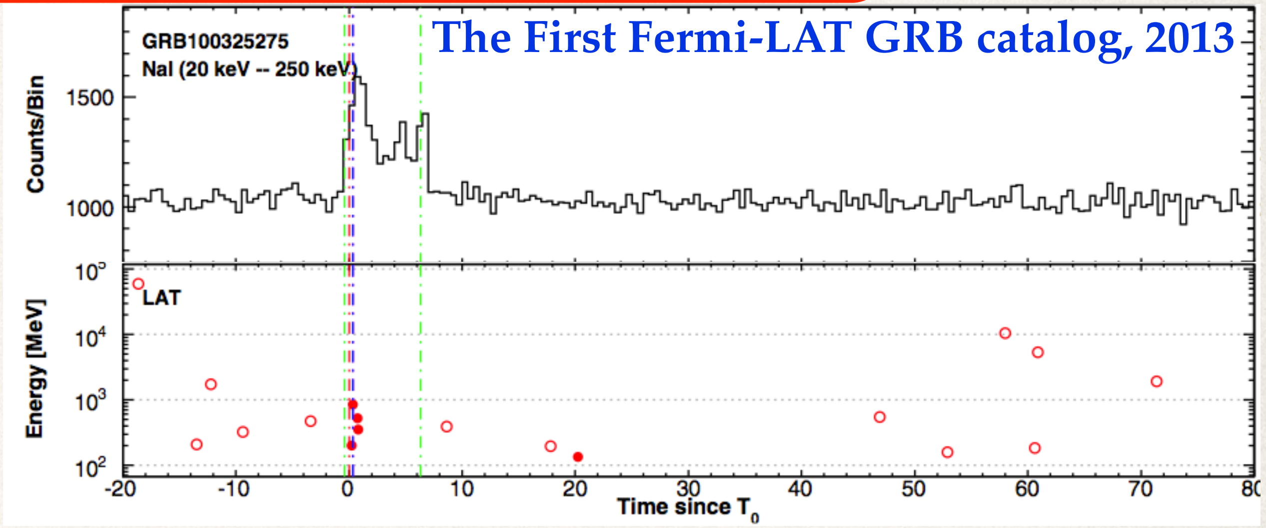

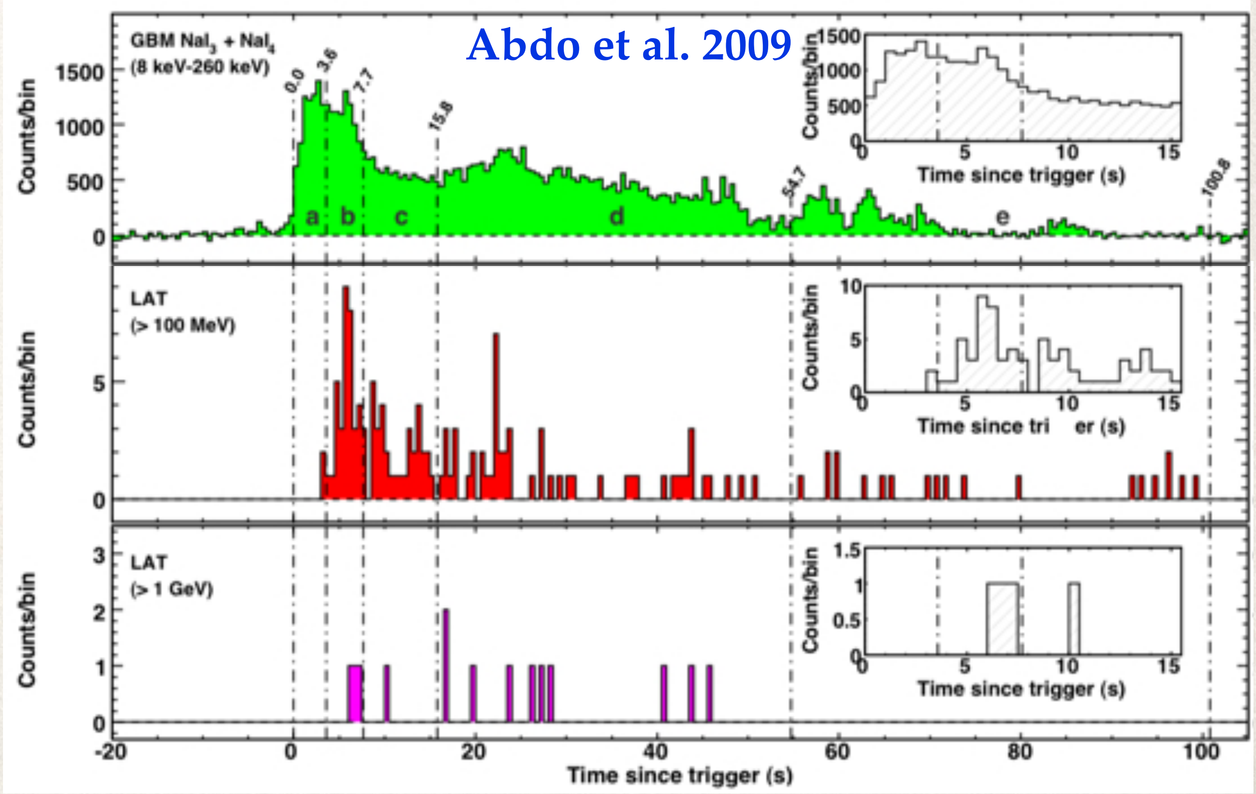

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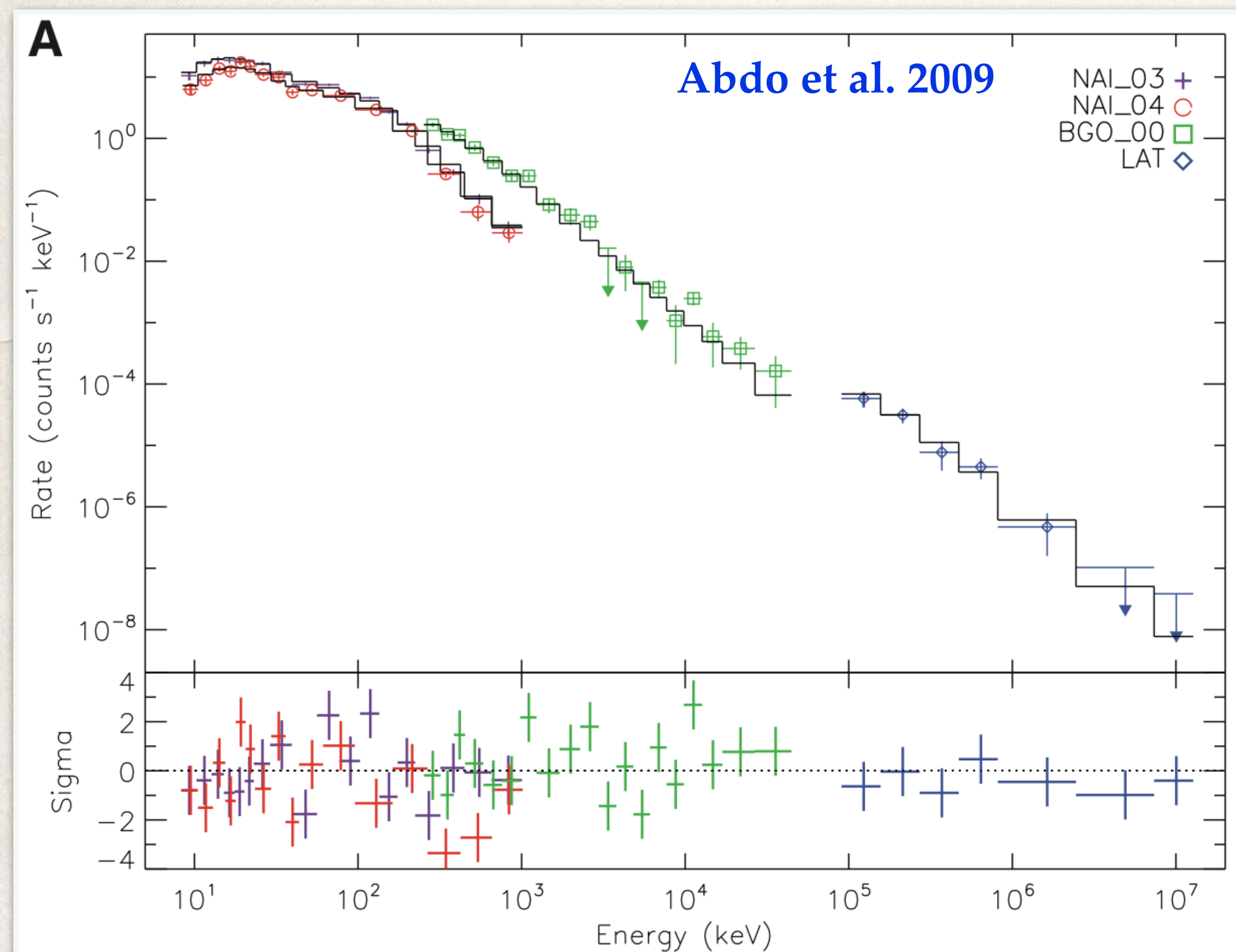

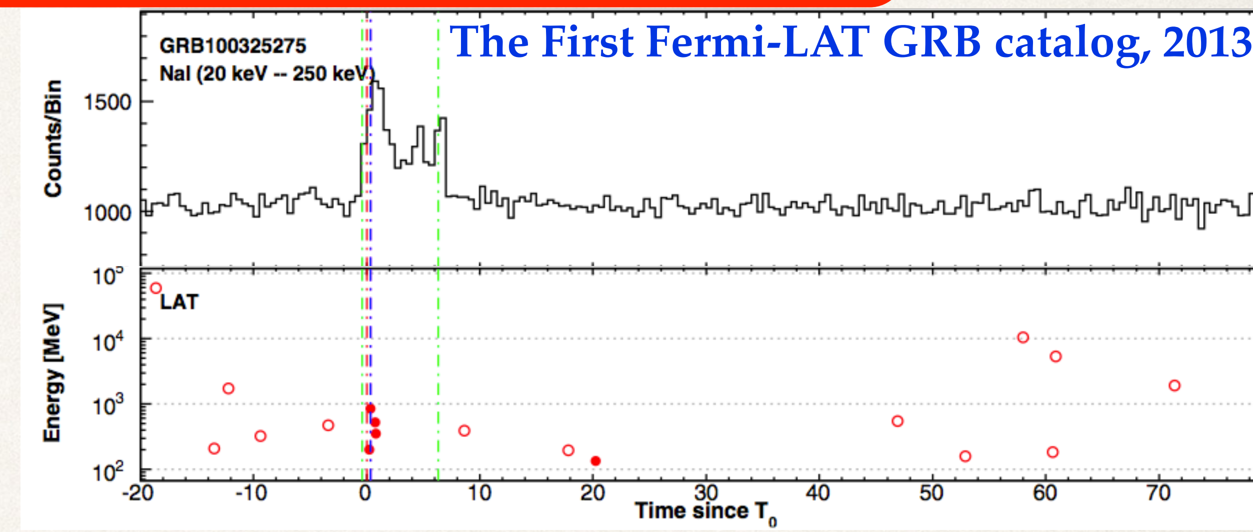

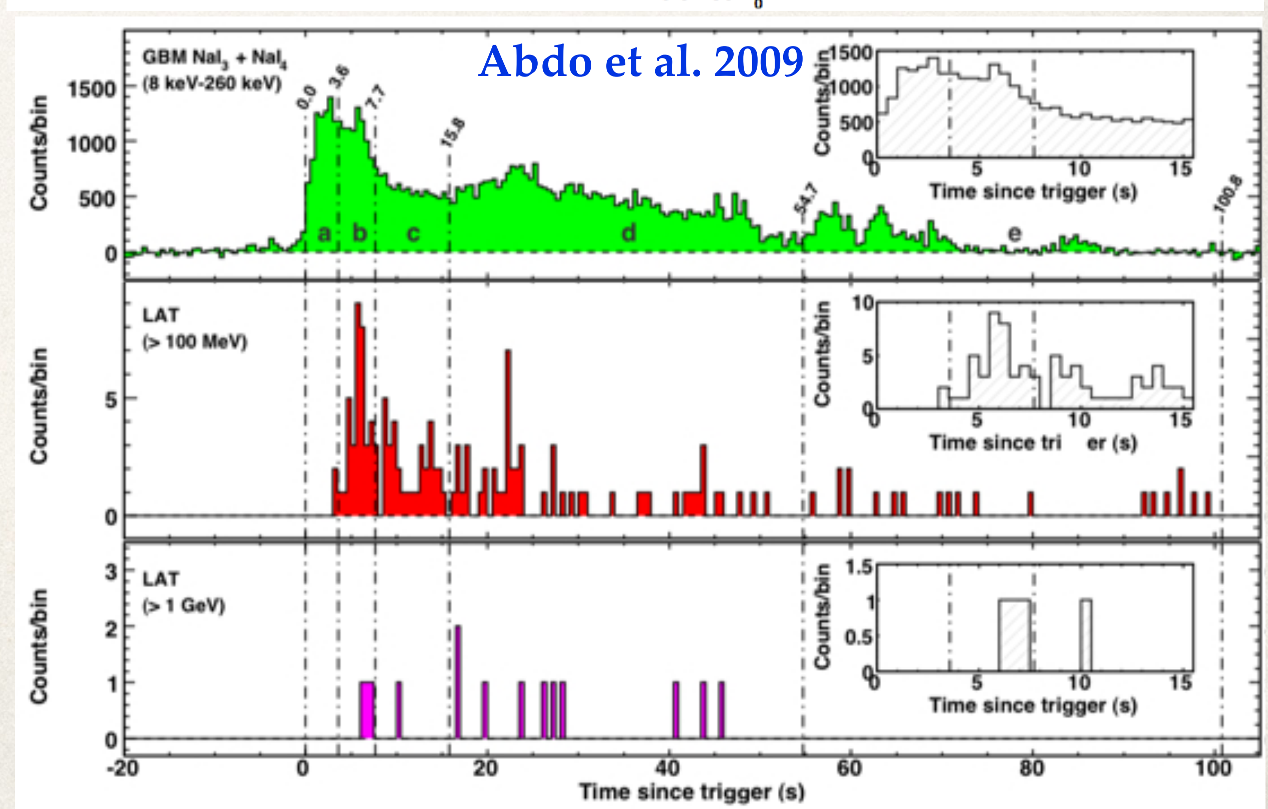

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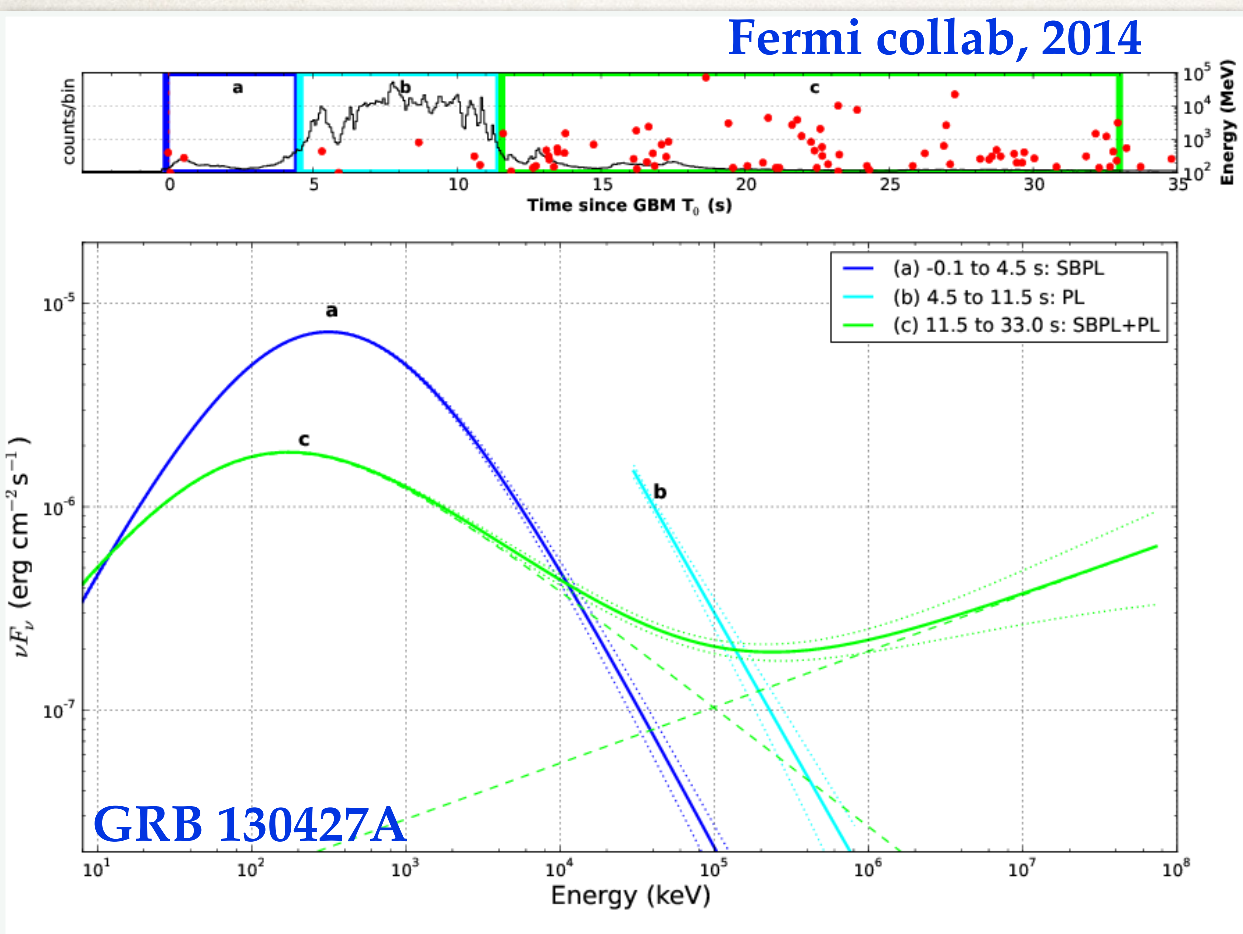

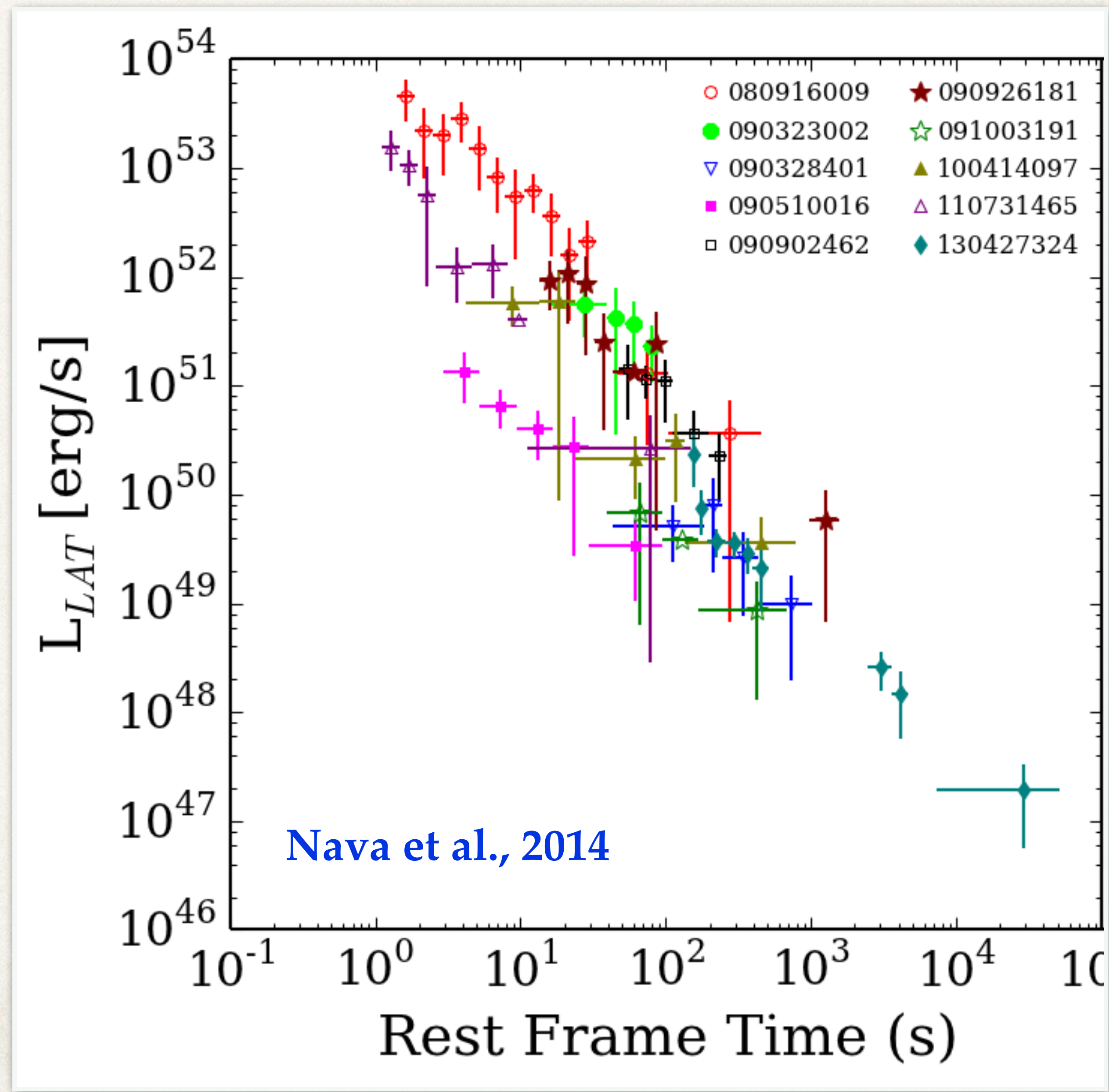

The basic picture: the standard model

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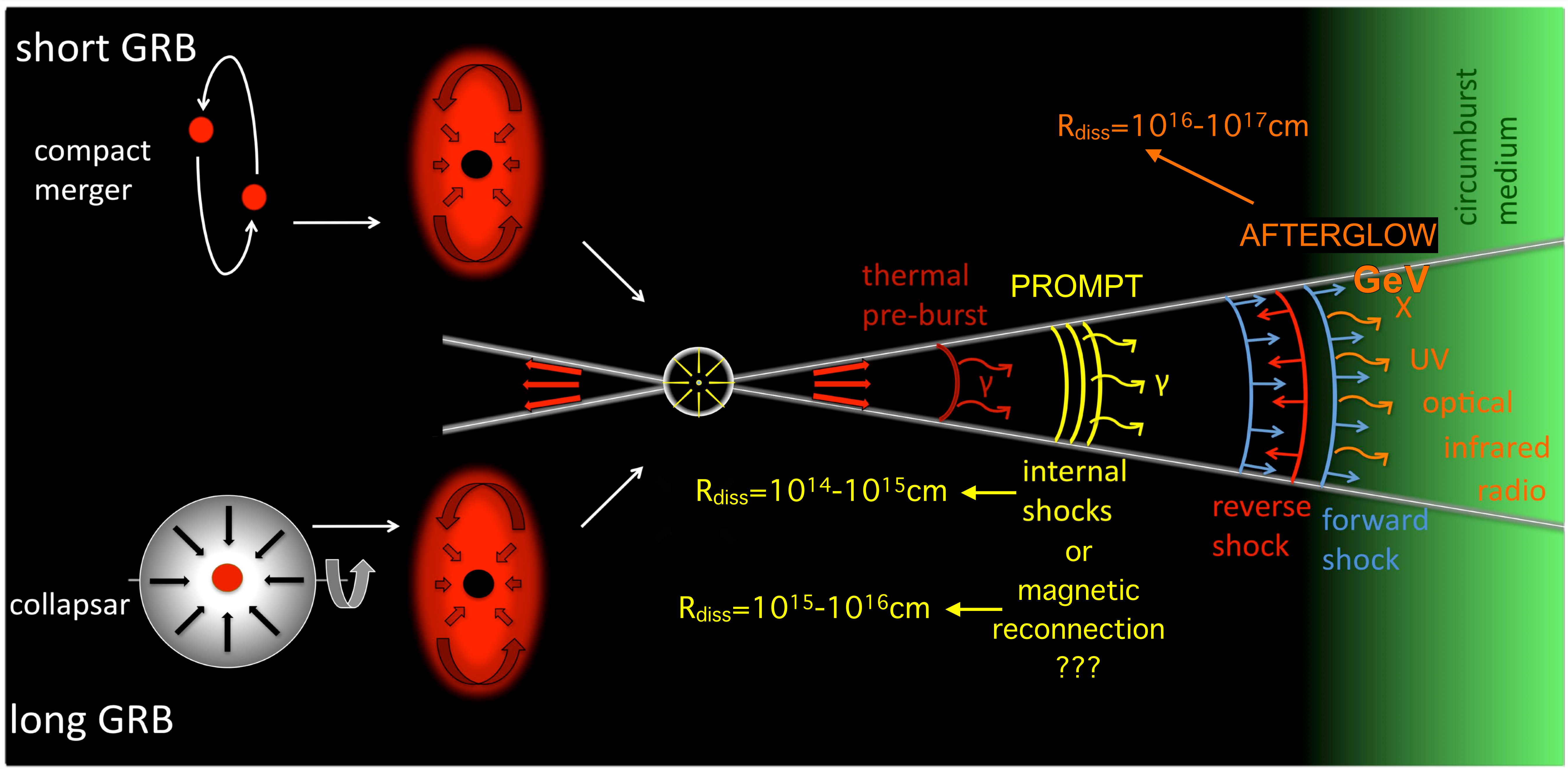

The basic picture: open issues

...... = unknown physics/quantities that can be constrained with further observations

	Dissipation mechanism	Radiation process(es)
Prompt	? Internal Shocks? ? Magnetic reconnection?	? Synchrotron? ? Inverse Compton? ? Thermal contribution?
Afterglow	✓external shocks	✓synchrotron ? contribution from reverse shock?
High-Energy	same as prompt	same as prompt (+SSC)
	✓external shocks	✓synchrotron + SSC

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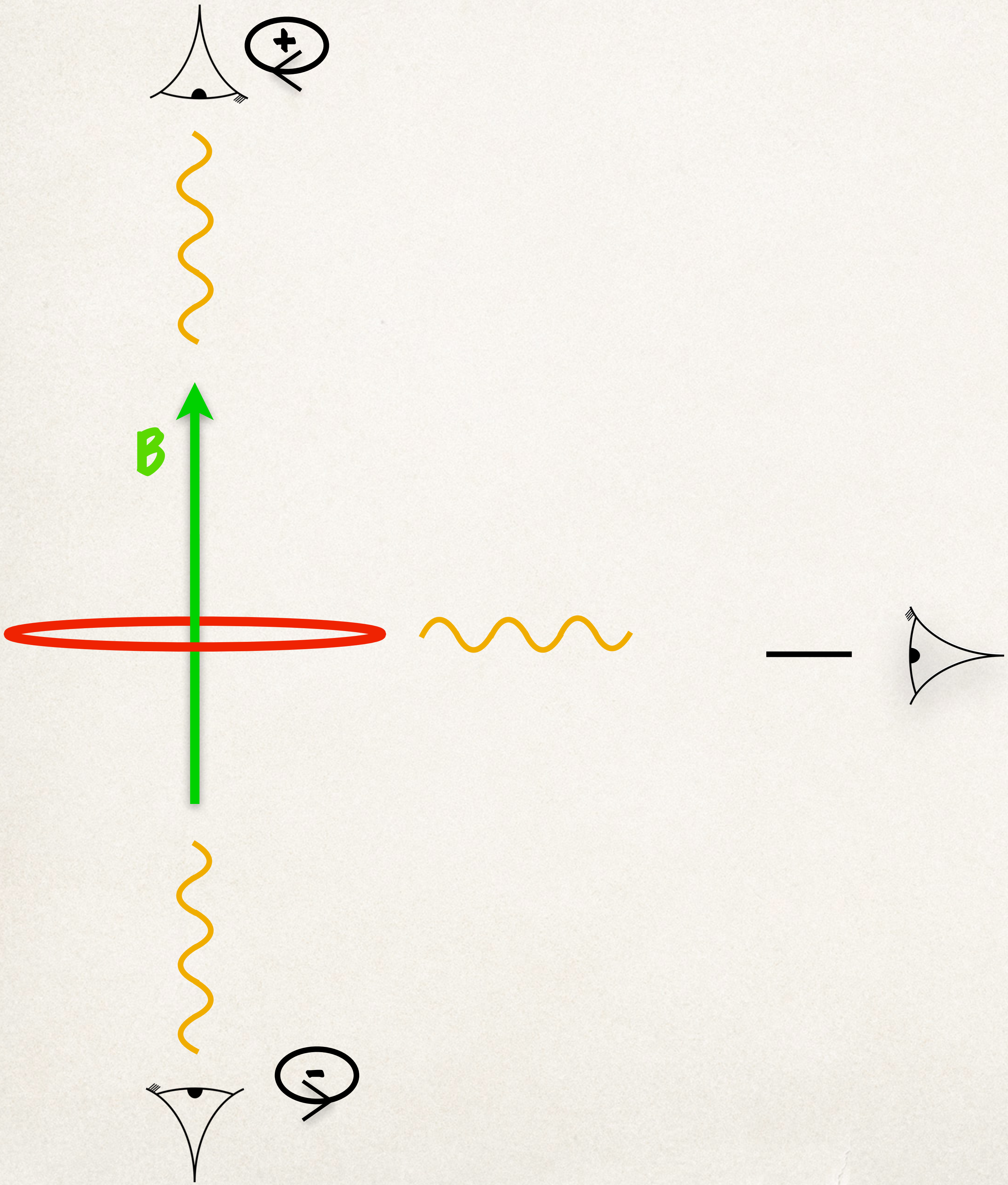
High-Energy	same as prompt	same as prompt (+SSC)
	✓external shocks	✓synchrotron + SSC $\boxed{\text{relativistic shocks}}$

Polarization of prompt and afterglow radiation: theory

Theoretical predictions

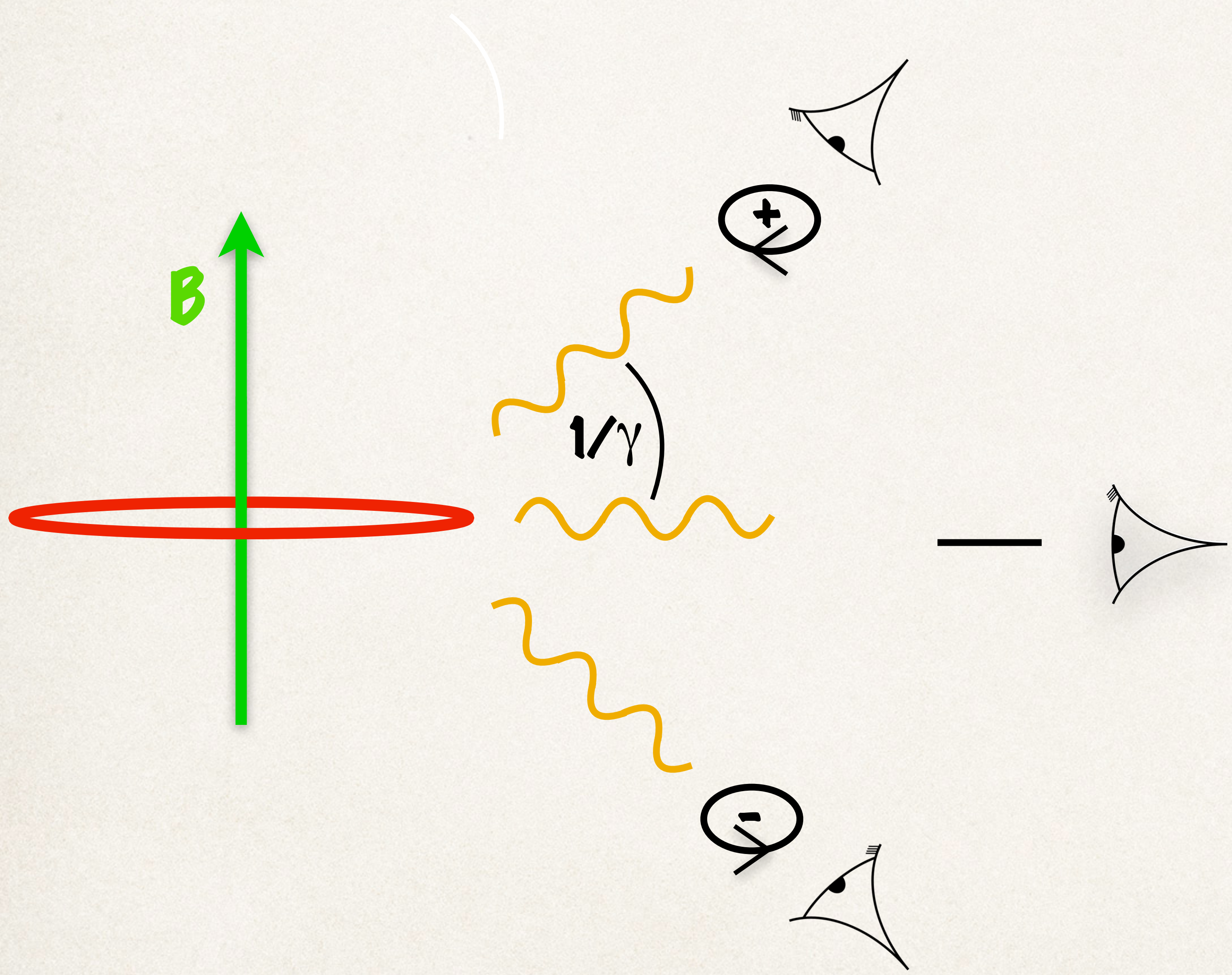
- Basic synchrotron theory
- + B configuration (Jet? Shocks?)
- + relativistic motion of radiating matter (beaming)
- + curvature of the emitting surface
- + conical geometry of the ejecta
- + line of sight

Non-relativistic case



Westfold 1959
Legg & Westfold 1968
Sazonov 1969, 1972

Relativistic case: synchrotron radiation



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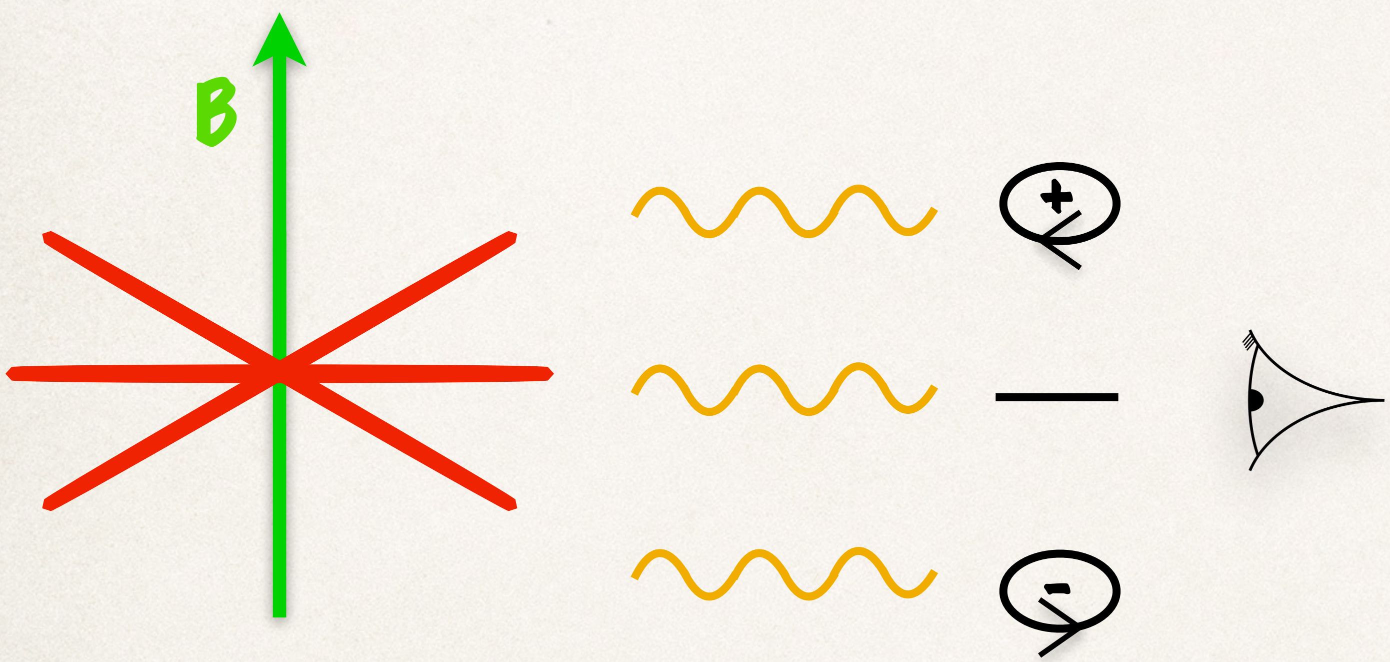

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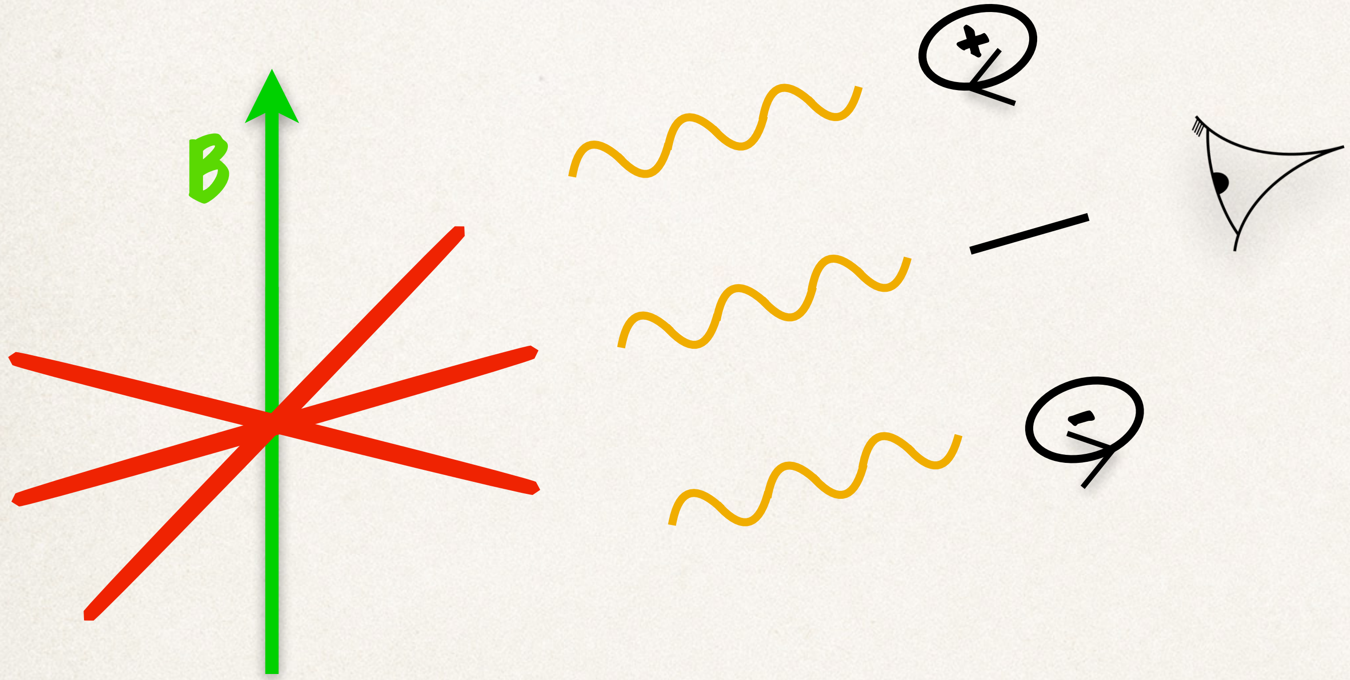

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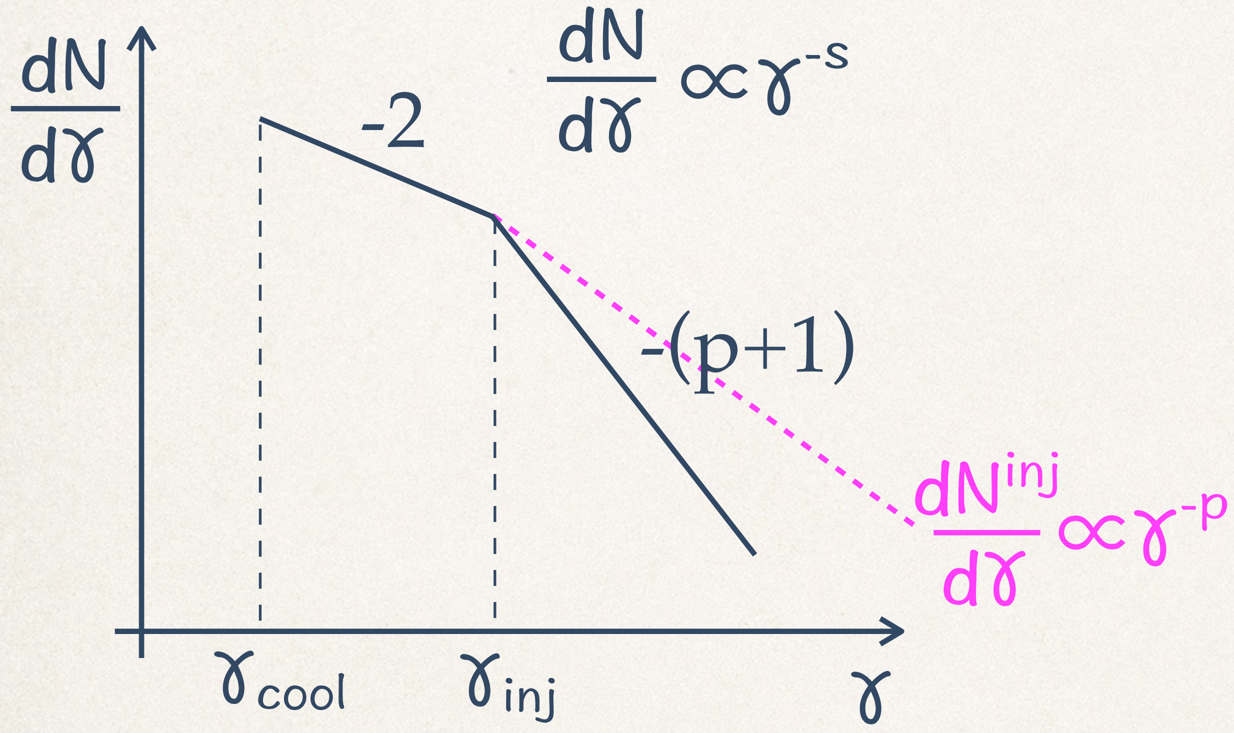
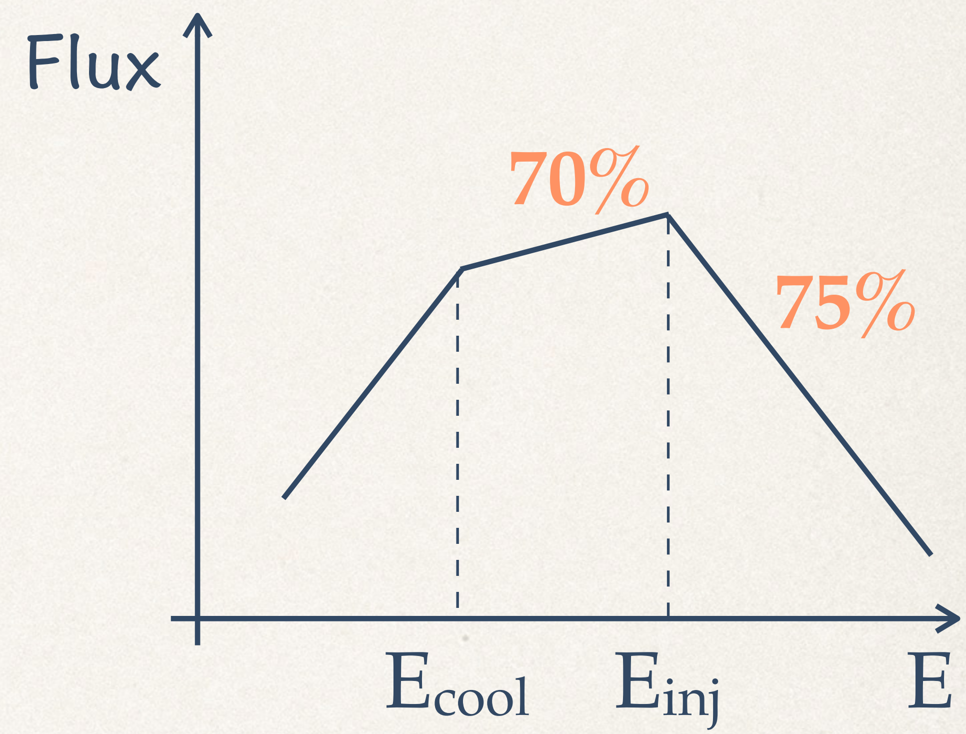
Synchrotron

Polarization of synchrotron radiation

energy distribution of radiating e⁻



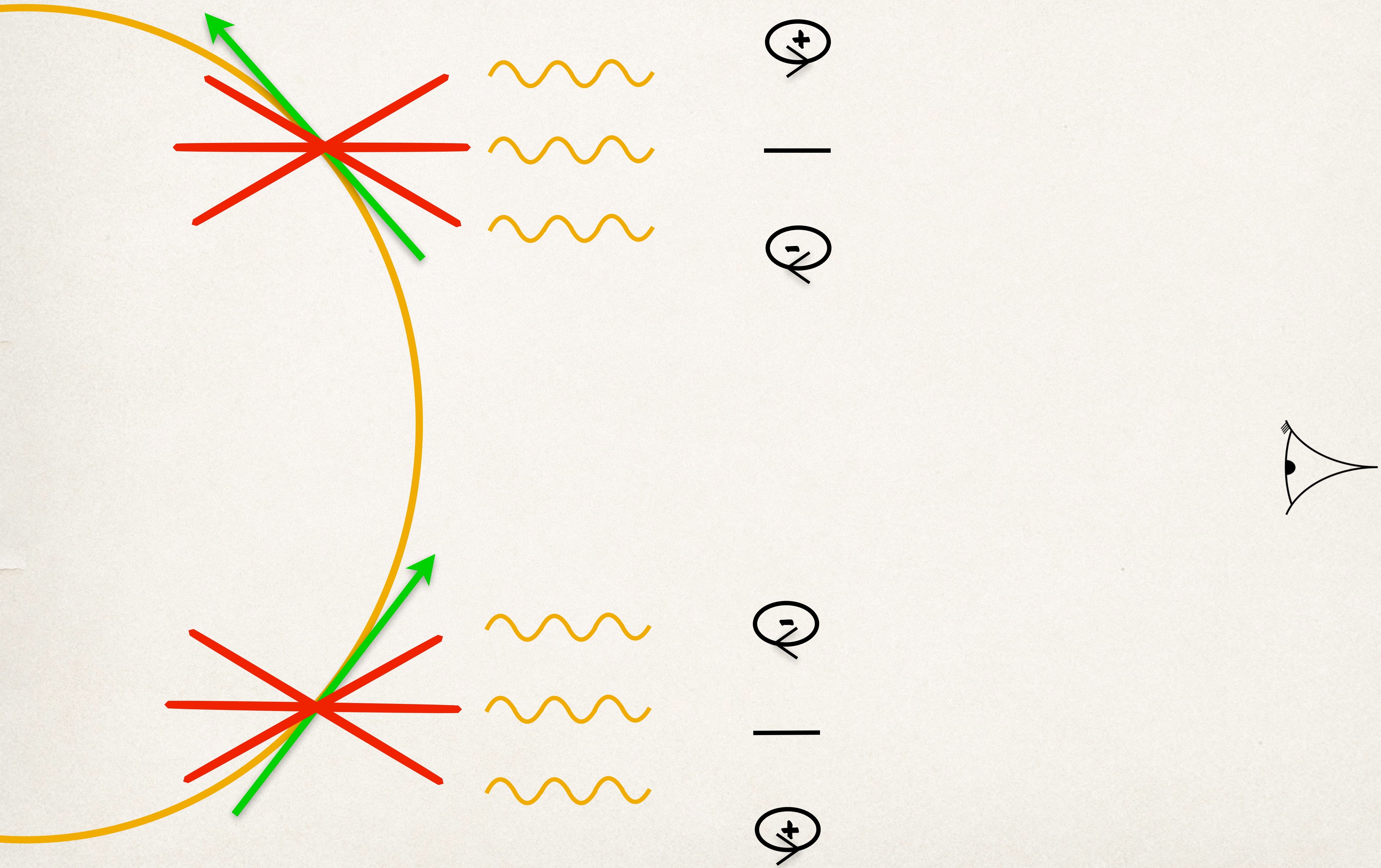
photon spectrum



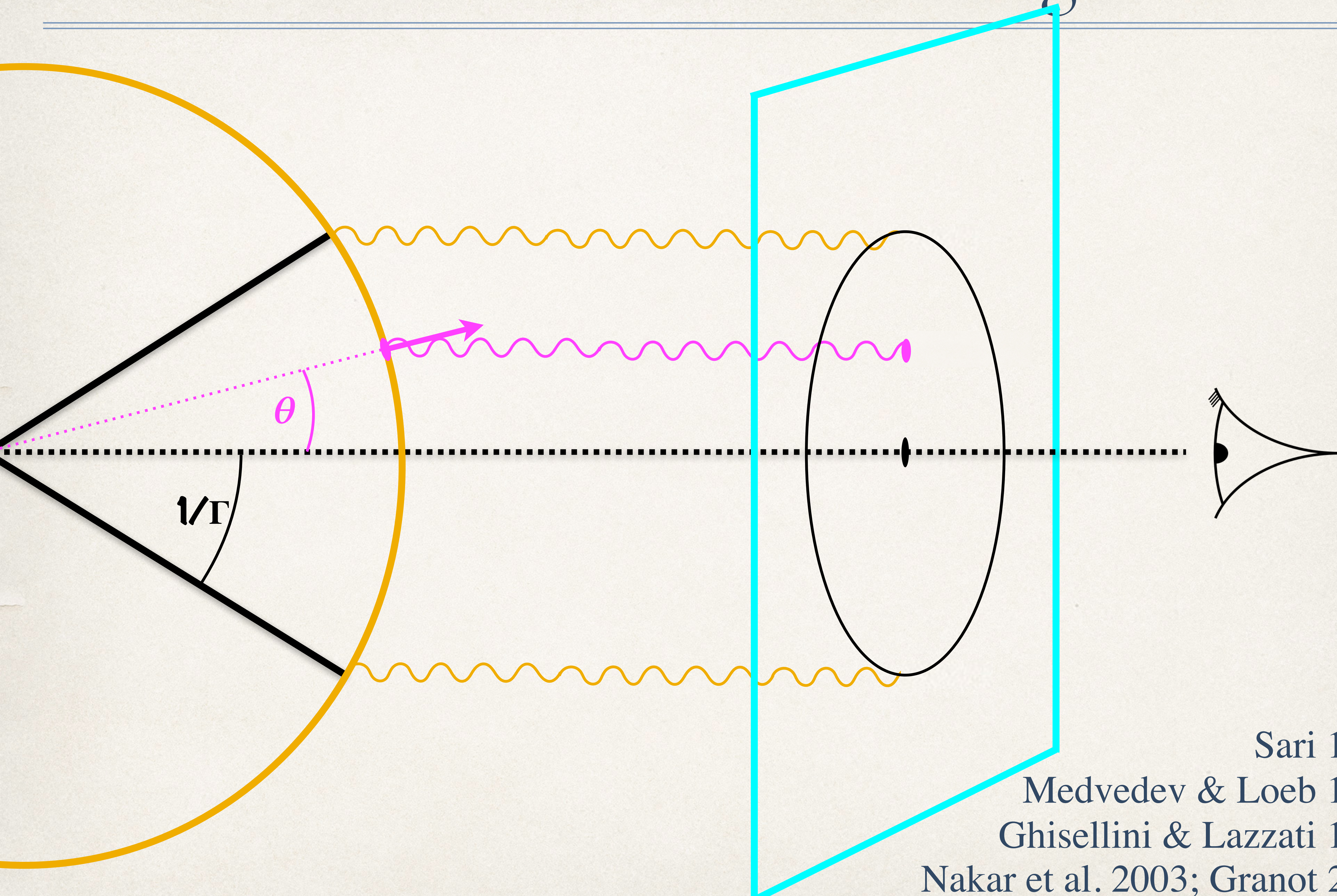
$$\boxed{\Pi_{syn} = \frac{(s+1)}{(s+7/3)}}$$

Rybicki & Lightman, 1986

Spherical emitting surface



Relativistic motion: beaming



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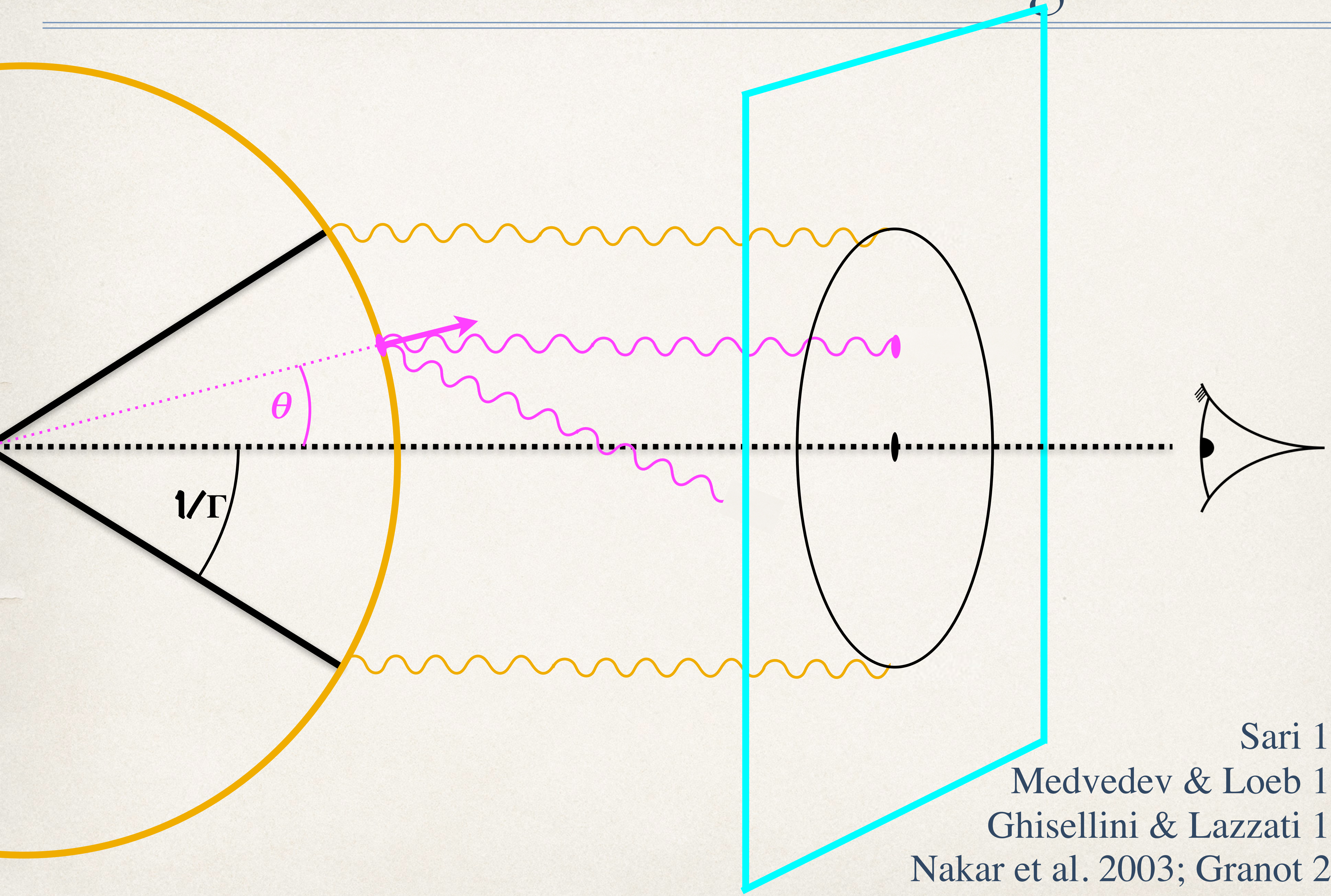

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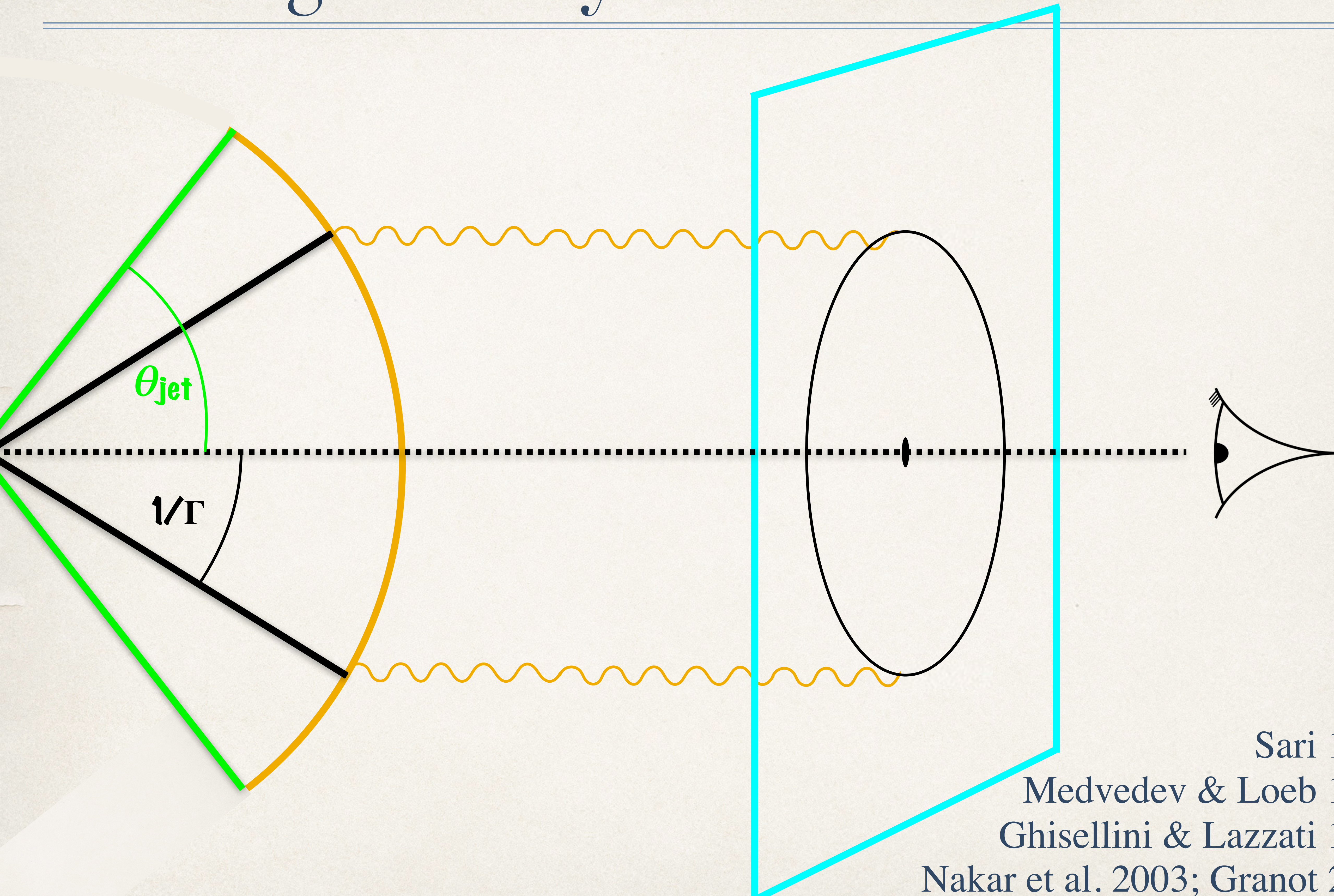
Jetted geometry



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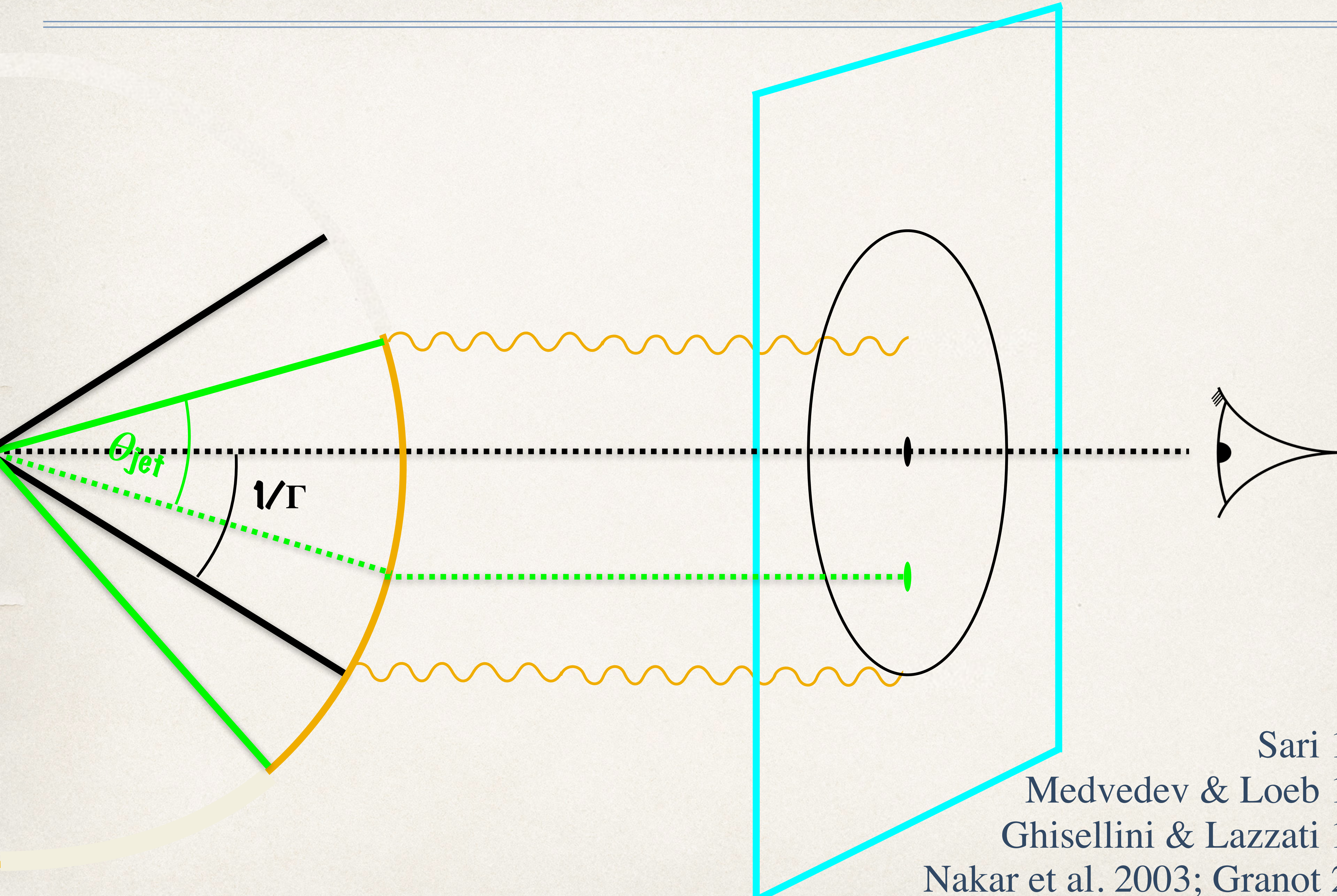
Jet seen off-axis



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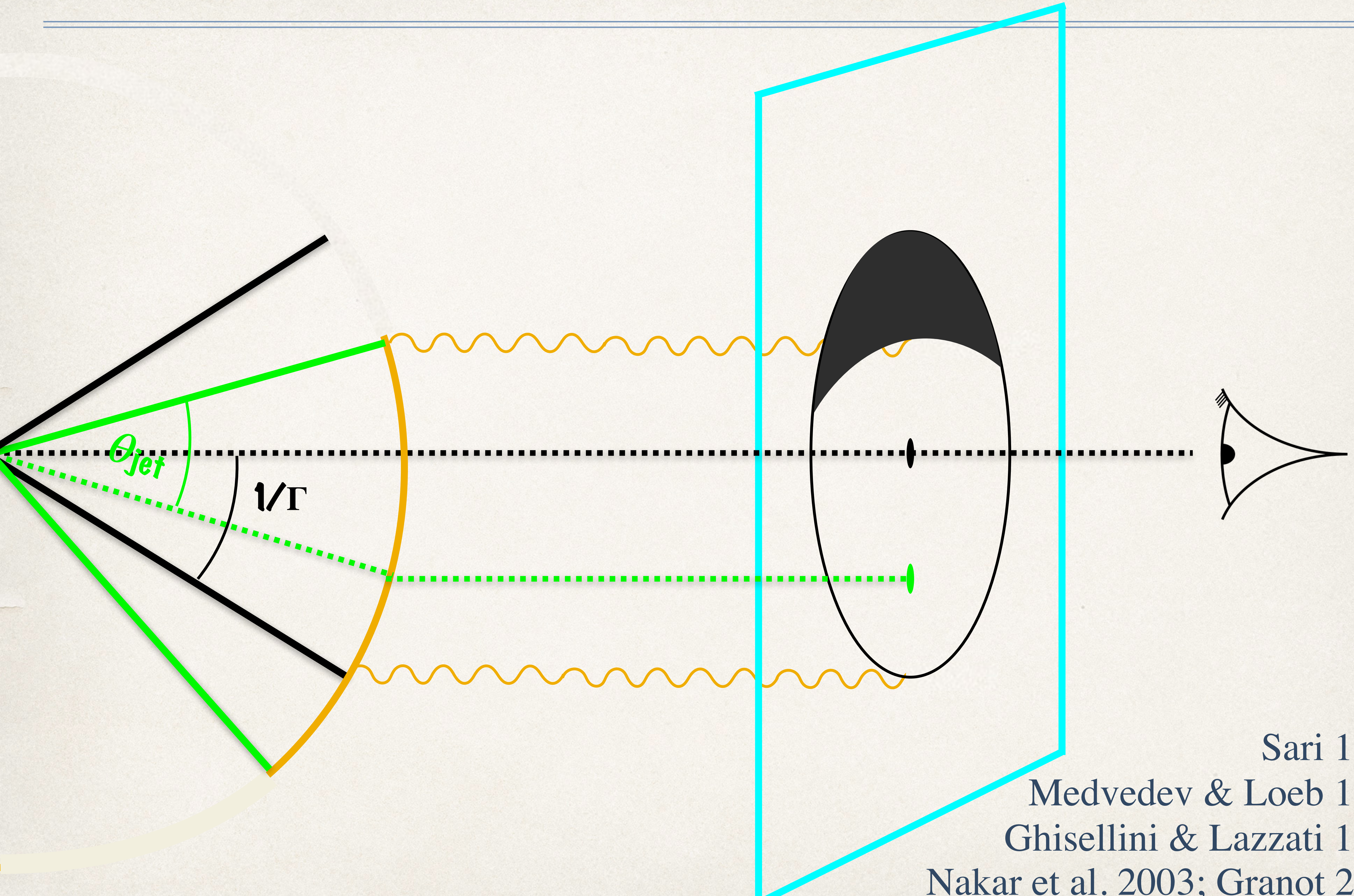

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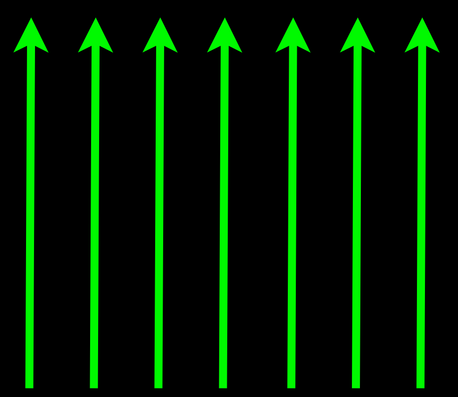
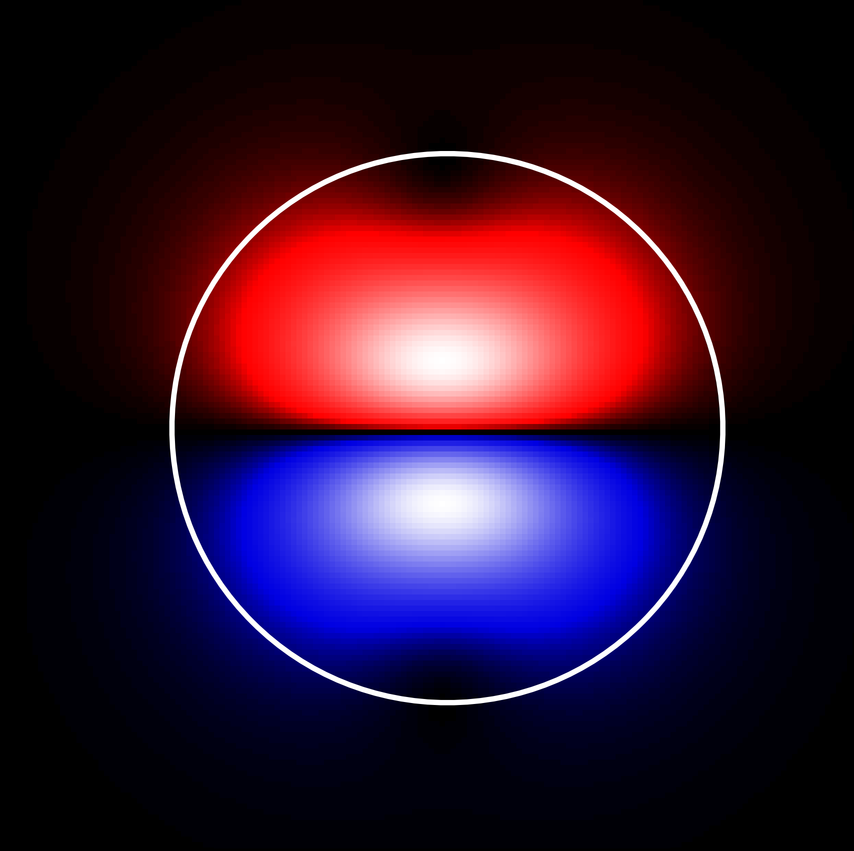
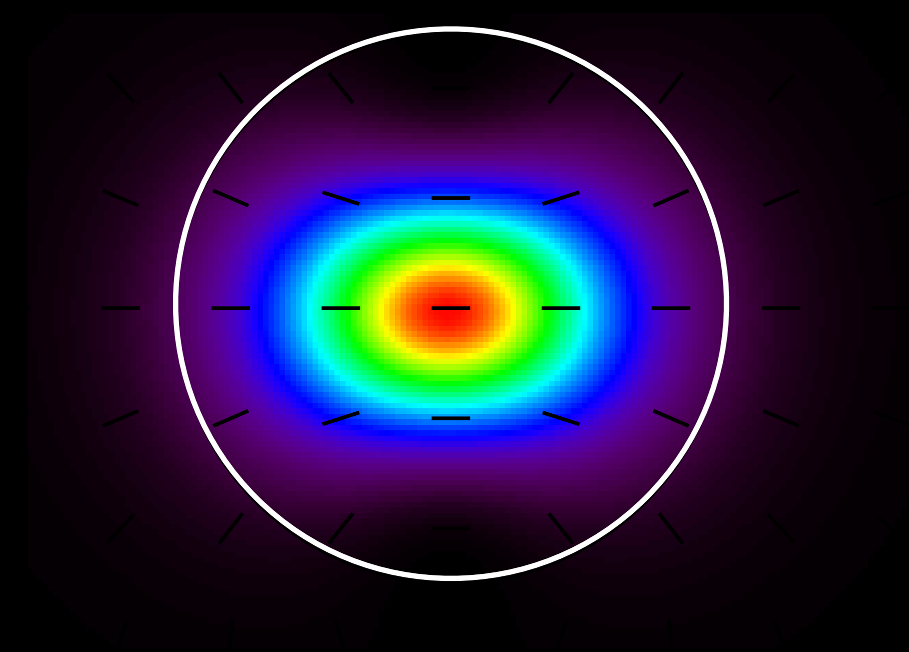
Uniform B in the plane of the shock



Circular



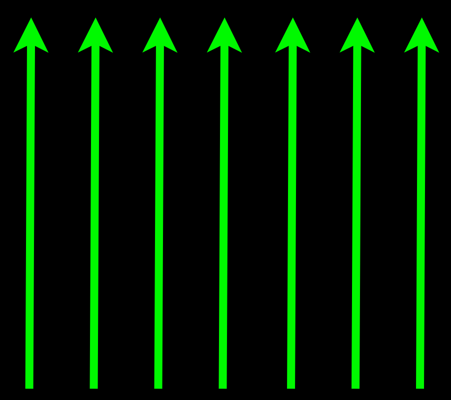
Linear

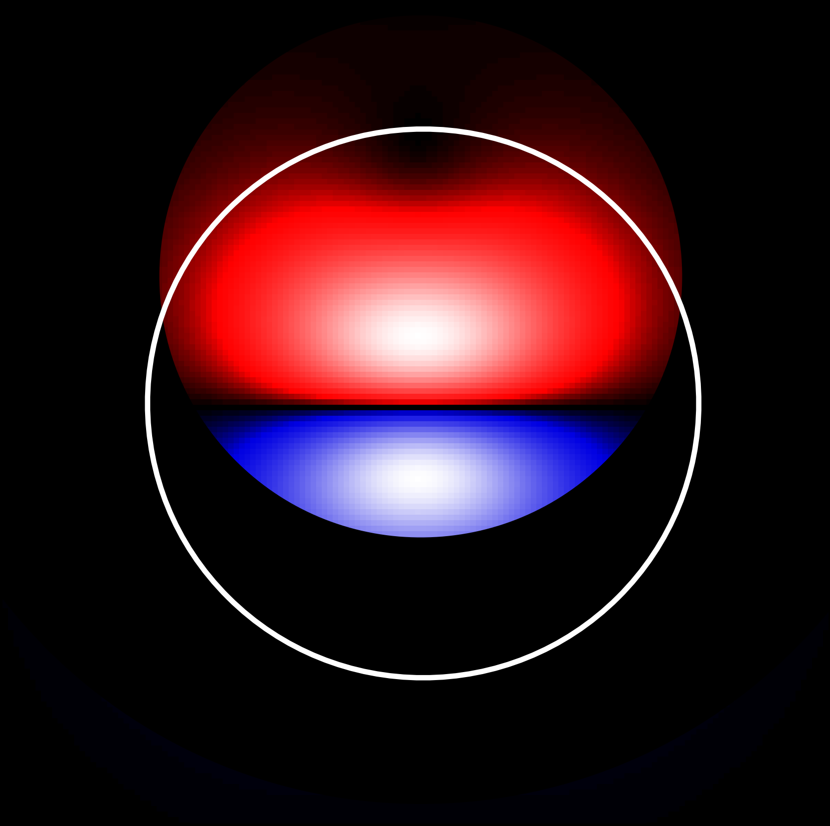
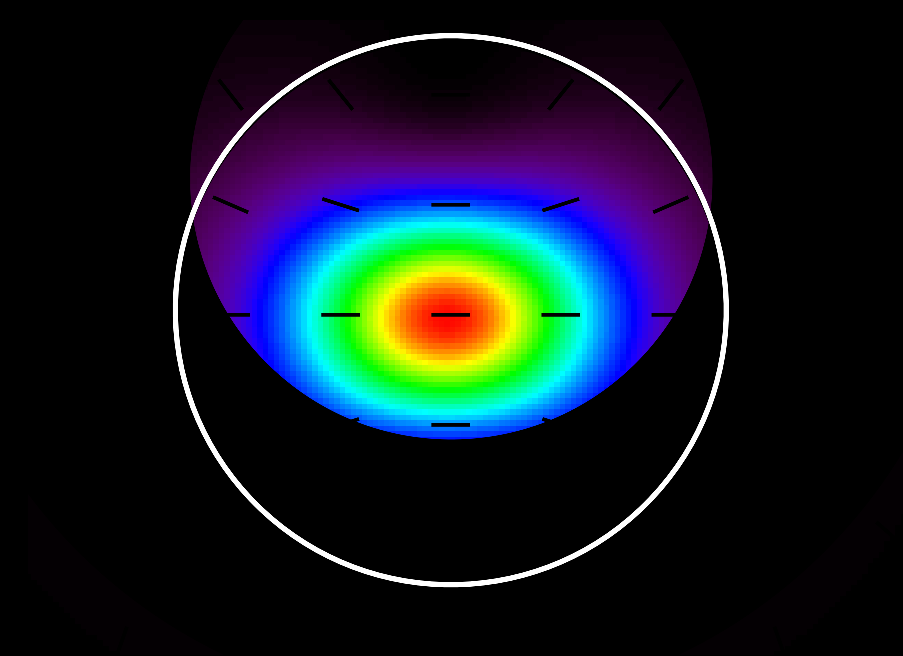


$\theta_j >> 1/\Gamma$ | 0 | 0.61

Nava, Nakar & Piran 2015

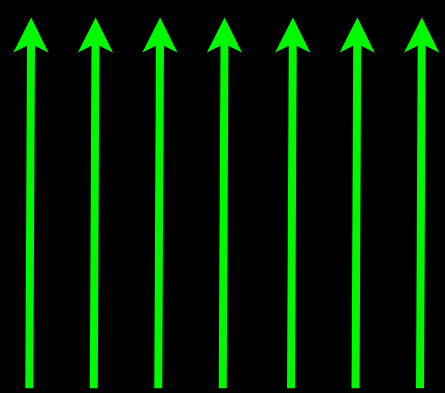
Uniform B in the plane of the shock

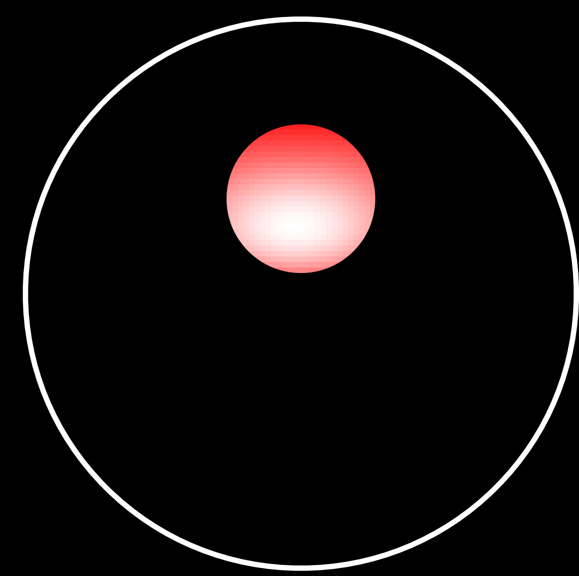


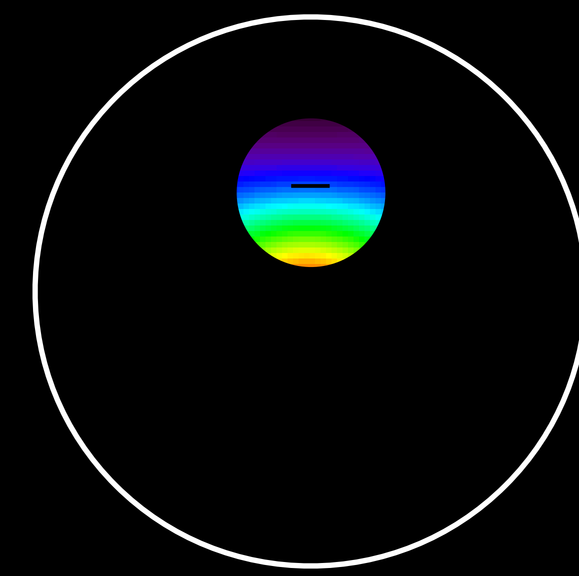
	Circular	Linear
		
$\theta_j >> 1/\Gamma$	0	0.61
$\theta_j = 1/\Gamma$	0 - 0.35/γ	0.61 - 0.67

Nava, Nakar & Piran 2015

Uniform B in the plane of the shock



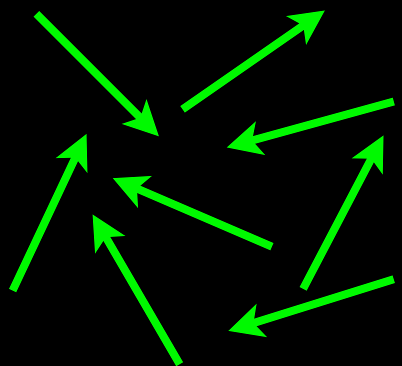


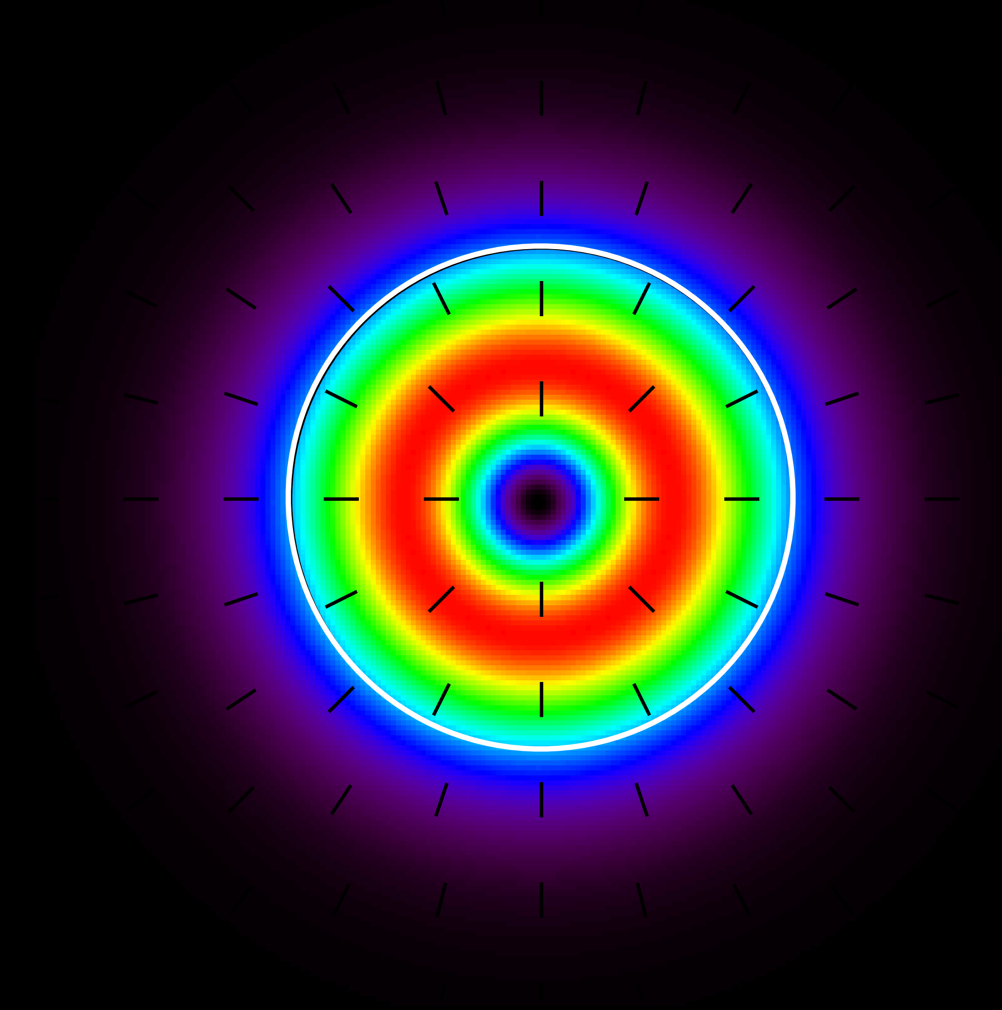


	Circular	Linear
$\theta_j >> 1/\Gamma$	0	0.61
$\theta_j = 1/\Gamma$	$0 - 0.35/\gamma$	0.61 - 0.67
$\theta_j = 1/3\Gamma$	$0 - 0.33/\gamma$	0.71 - 0.72

Nava, Nakar & Piran 2015

Random B (in the plane of the shock)





	Circular	Linear
$\theta_j >> 1/\Gamma$		0
$\theta_j = 1/\Gamma$		0 - 0.1

Nava, Nakar & Piran 2015

General expectations: Prompt vs Afterglow

Prompt

Uniform B (relevant B is from the jet — shocks are adding a tangled component)

⇩

High level of polarization

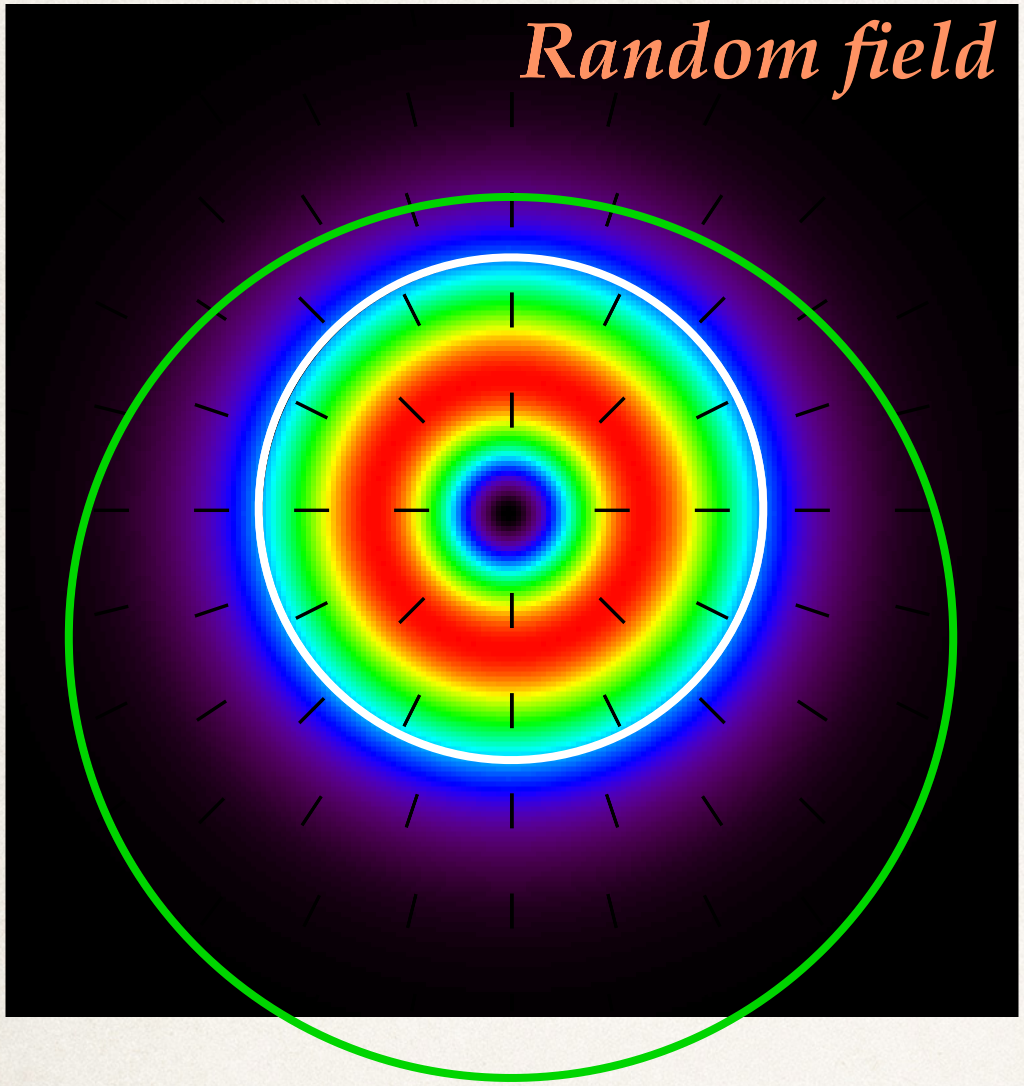
Afterglow

- *Forward shock*: tangled B (relevant B is the one generated at the shock)
- *Reverse shock*: ordered B (jet)

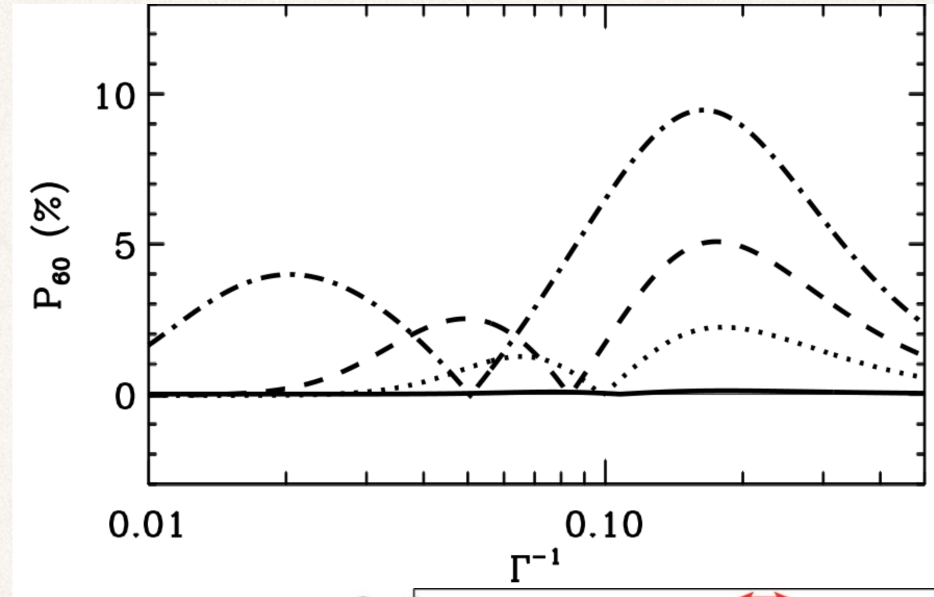
⇩

- *Forward shock*: low level of polarization
- *Reverse shock*: higher level of polarization

Afterglow: temporal evolution

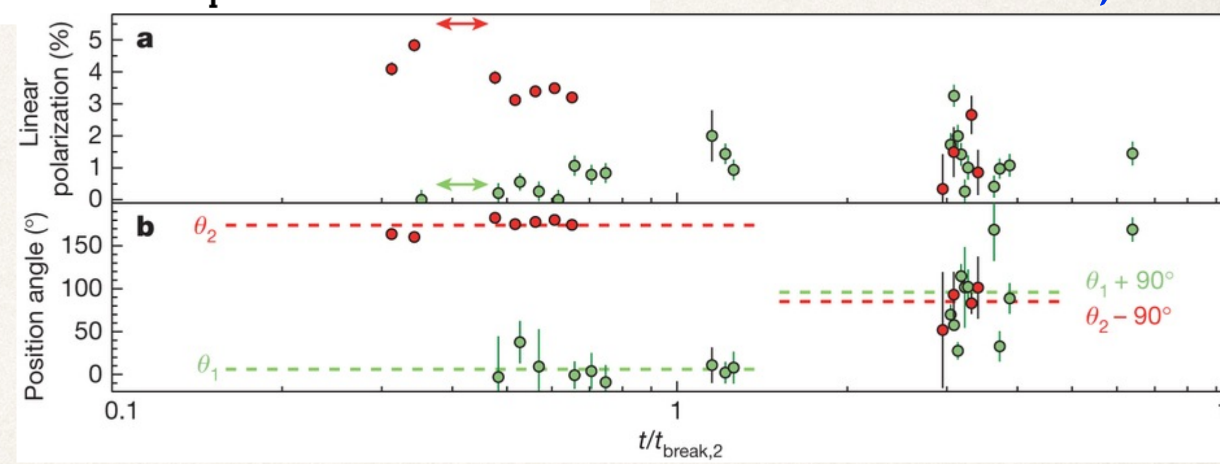


Ghisellini & Lazzati 1999



Random field

Wiersema et al., 2014

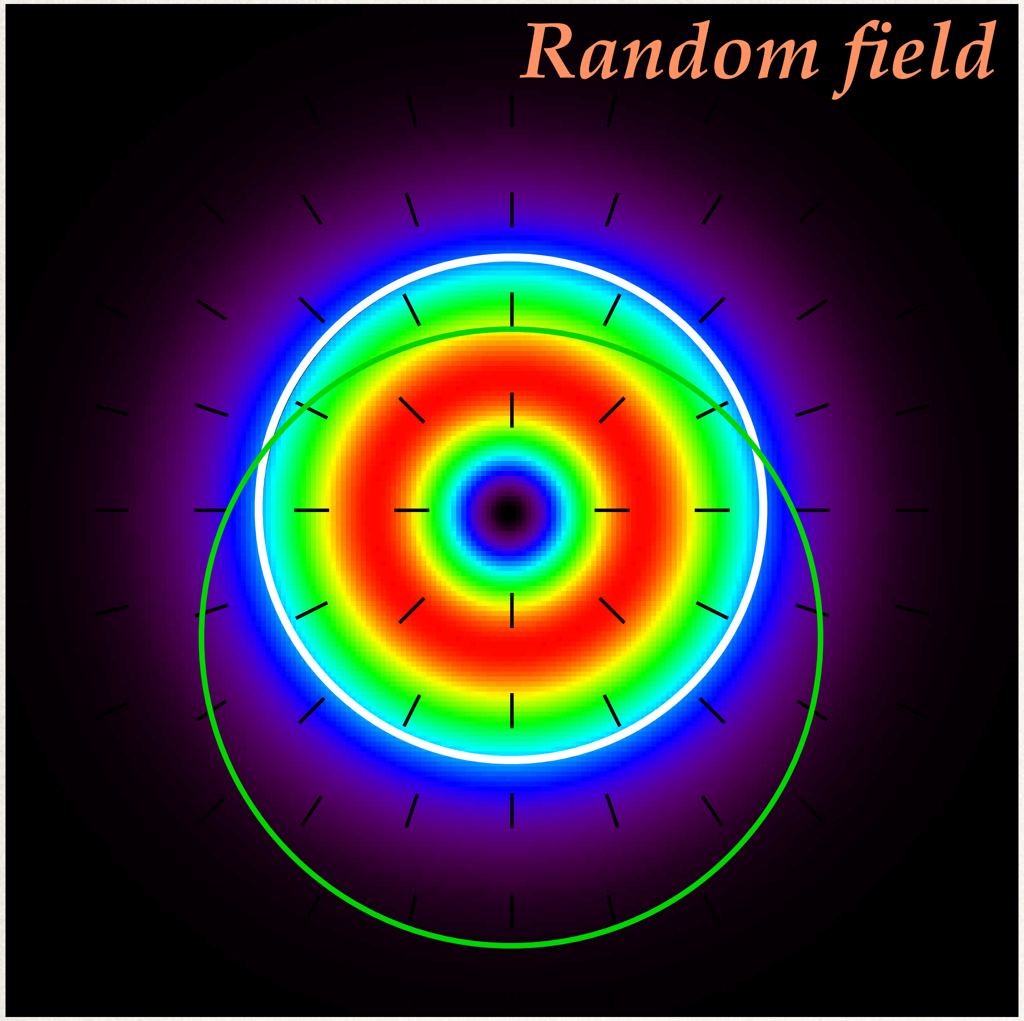


Different temporal evolutions of Π and P.A. are predicted in different models:

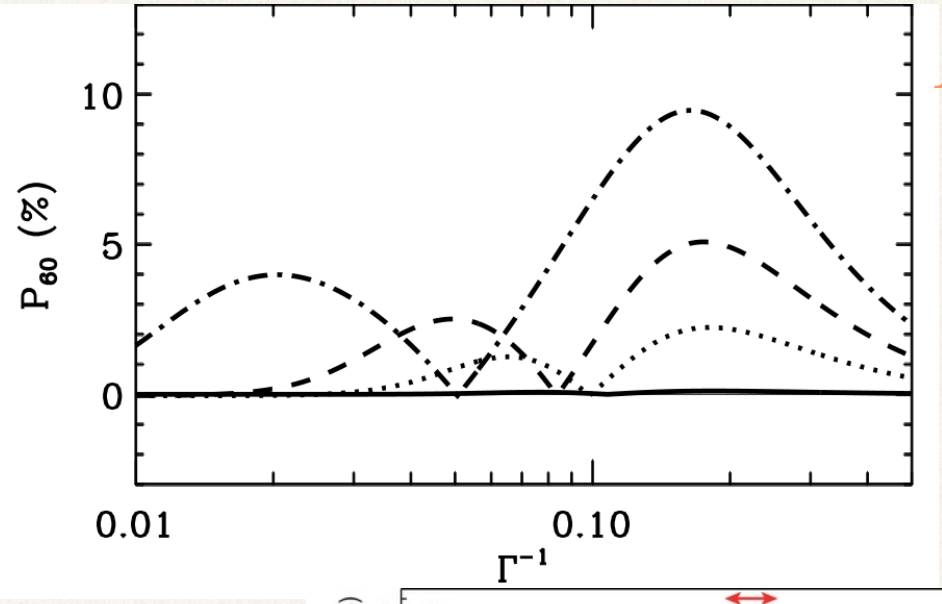
Random field + ordered component (Granot & Konigl 2003)

Structured jets (Rossi et al. 2004)

Afterglow: temporal evolution



Ghisellini & Lazzati 1999



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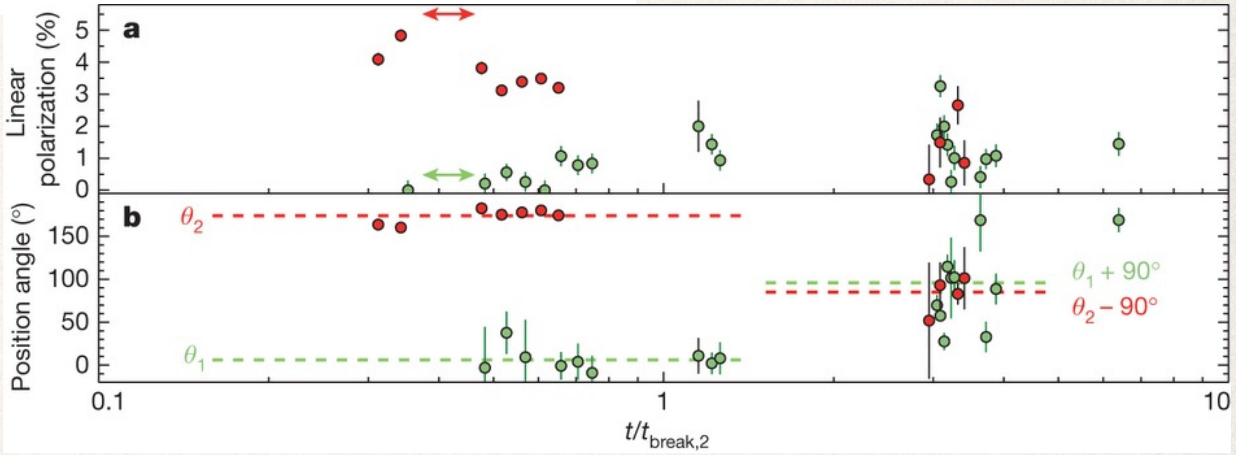
Wiersema et al., 2014



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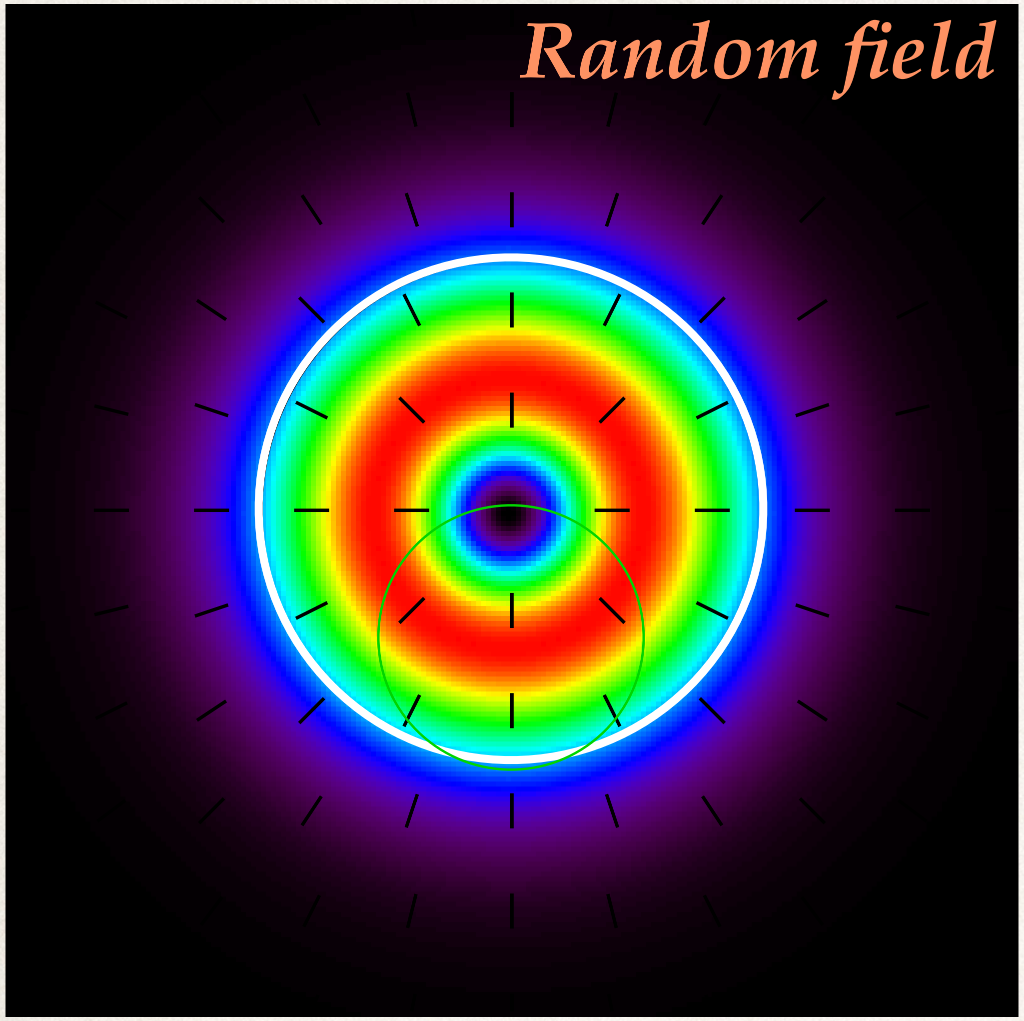

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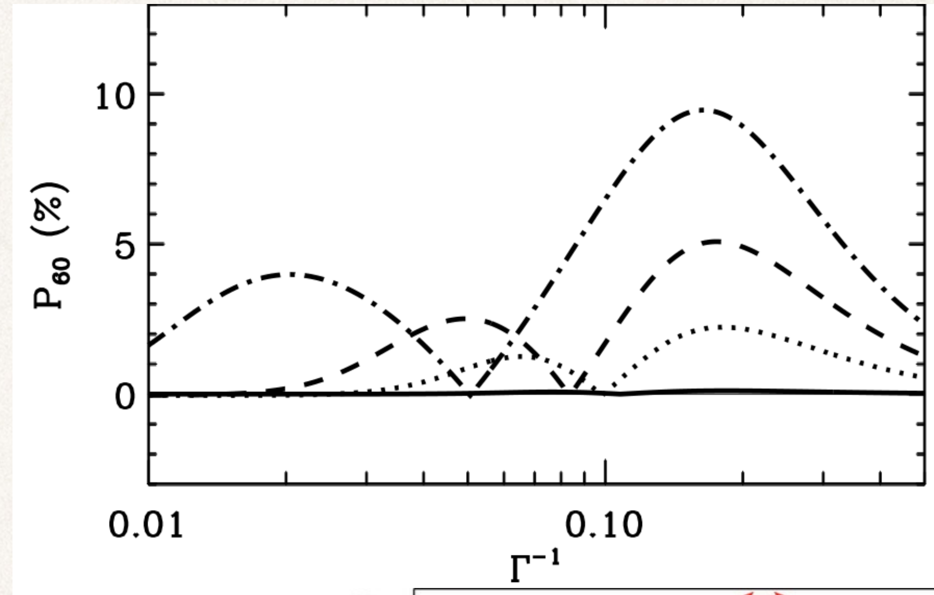
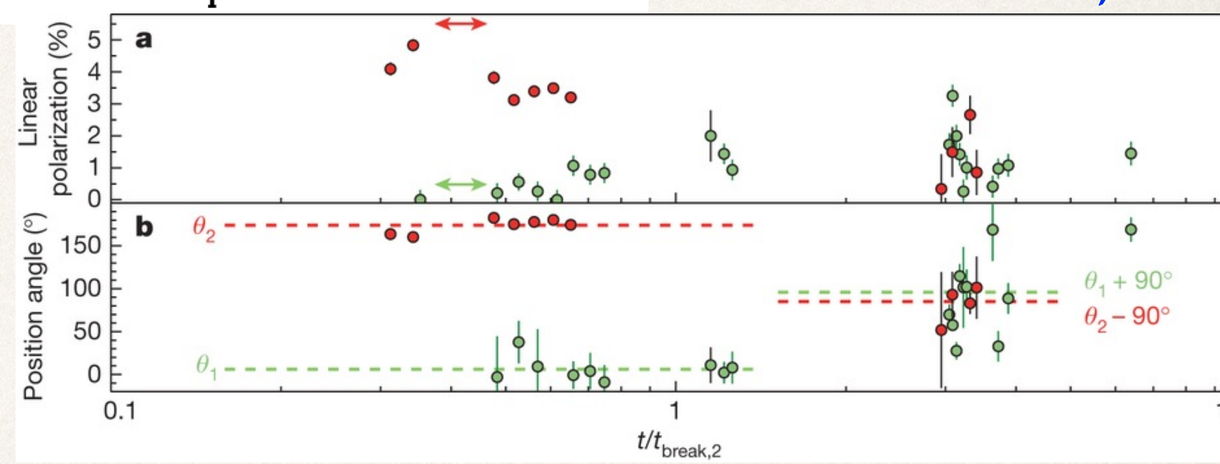


Random field

Wiersema et al., 2014



Different temporal evolutions of Π and P.A. are predicted in different models:

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Polarization of prompt and afterglow radiation: measurements

PROMPT — observations

Adapted from Covino & Götz, 2016

GRB name	Polarization	Peak energy [keV]	Fluence [erg cm	Energy range	Redshift	Instrument
021206	80+-20% [compatible with 0]		1.6x10	0.15-2 MeV		RHESSI
930131	>35%					BATSE
960924	>50%					BATSE
041219	65+-26%	201	2.5X10	20-200 keV	0.31	IBIS
061122	>60%	188	2.0X10	20-200 keV	1.33	IBIS
100826	27+-11%	606	3.0X10	20keV-10MeV	0.71-6.84	GAP
110301A	70+-22%	107	3.6X10	10keV-1MeV	0.21-1.09	GAP
110721	84	393	3.5X10	10keV-1MeV	0.45-3.12	GAP
140206	>48%	98	2.0X10	15-350 keV	2.739	IBIS

[1] Pol dependency of differential cross section for Compton scattering
[2] On board *CGRO*. Method: Scattering of gamma-ray photons by the Earth atmosphere
[3] Imager on board *INTEGRAL*, used as Compton Polarimeter
[4] Spectrometer on board *INTEGRAL*. Method: Compton scattering
[5] GRB Polarimeter on board *IKAROS*. Method: anisotropy of differential of Klein-Nishina cross section

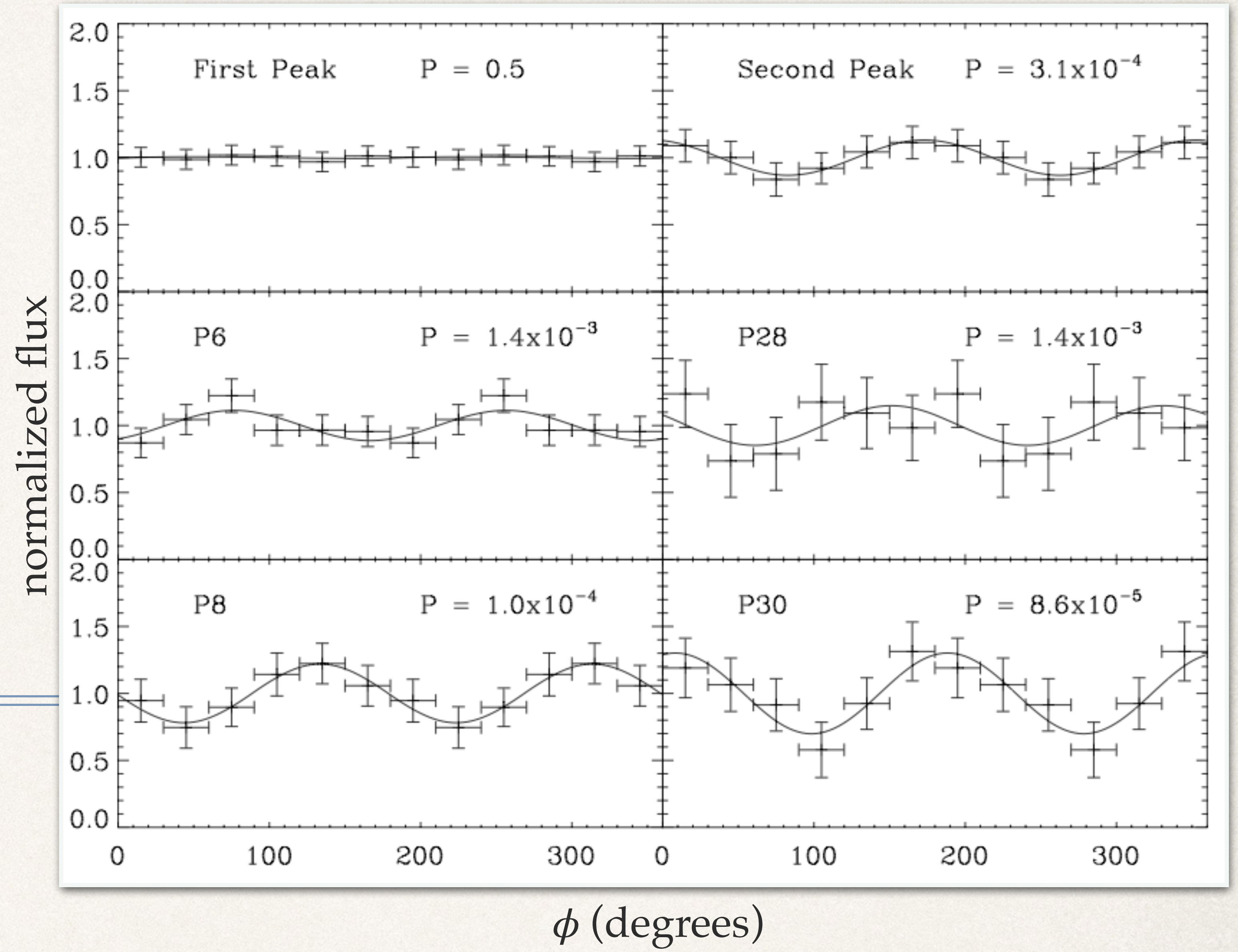
PROMPT — 041219A *(from Götz et al. 2009)*

differential cross section

$$\frac{d\sigma}{d\Omega} = \frac{r_0^2}{2}\left(\frac{E'}{E_0}\right)^2\left(\frac{E'}{E_0} + \frac{E_0}{E'} - 2\sin^2\theta\cos^2\phi\right)$$

angle distribution

$$N(\phi) = S[1 + a_0 \cos 2(\phi - \phi_0)]$$



Polarization Results for the Different Time Intervals

Name	Π %	P.A. (deg)
First peak	<4	. . .
Second peak	43 ± 25	38 ± 16
P6	22 ± 13	121 ± 17
P8	65 ± 26	88 ± 12
P9	61 ± 25	105 ± 18
P28	42 ± 42	106 ± 37
P30	90 ± 36	54 ± 11

Time-resolved analysis shows evidence of temporal variation of polarization level Π and polarization angle (P.A.)

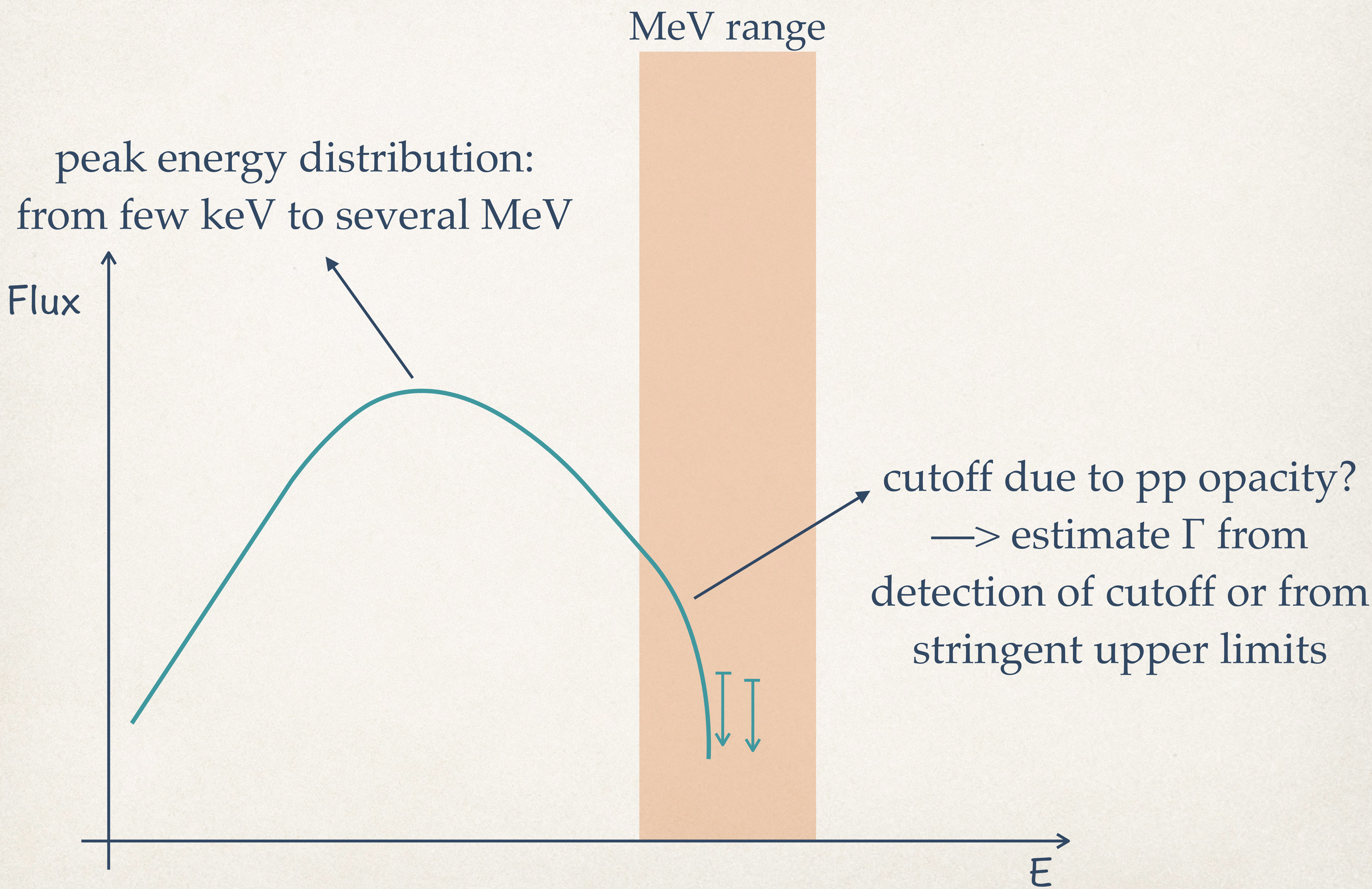
AFTERGLOW — observations (not complete)

Adapted from Covino & Götz, 2016

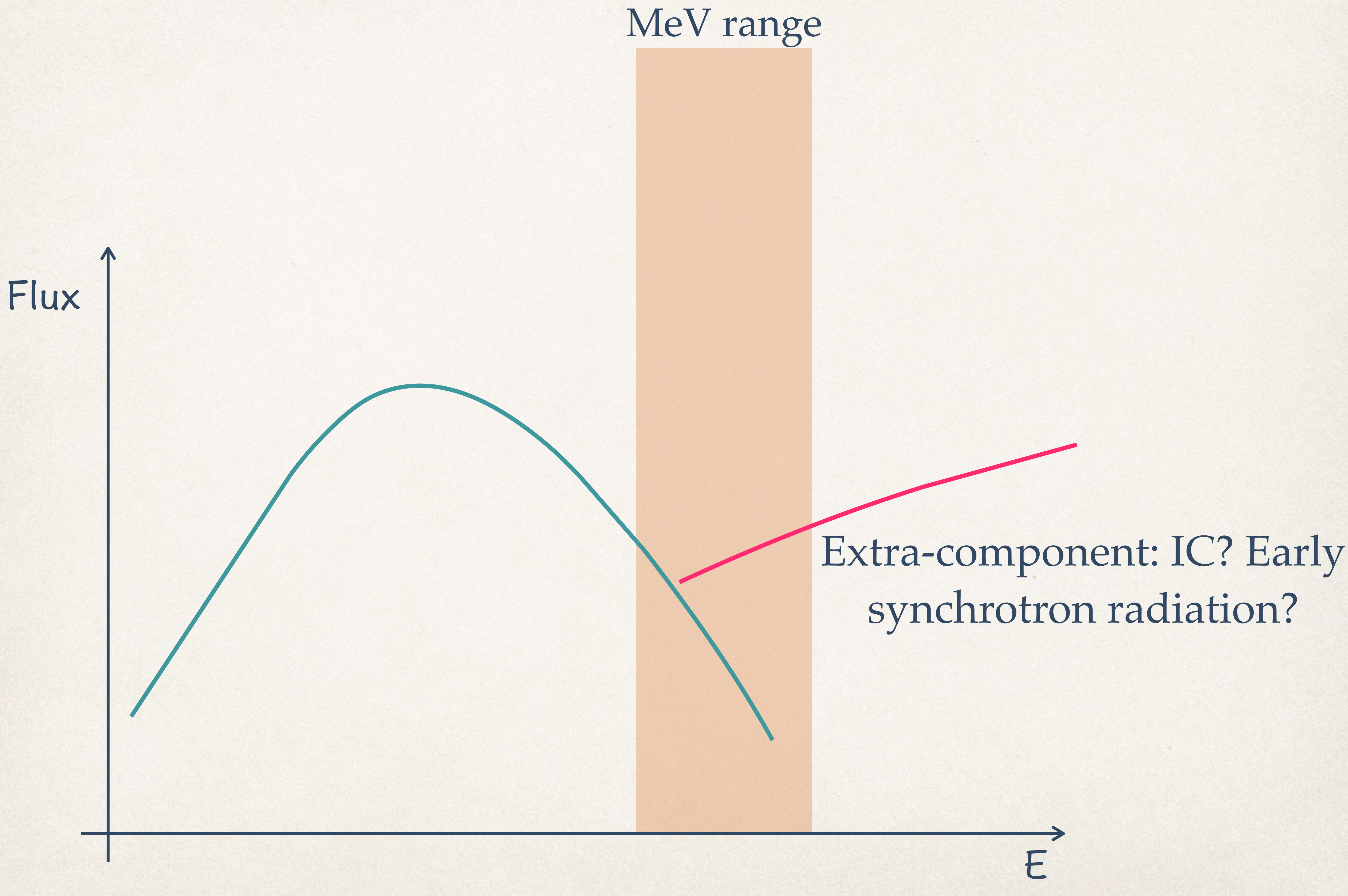
GRB name	Polarization	Time	Frequency	Instrument	Comments
980329 980703	<21% <8%	20 days 7 days	radio	VLA	
990123	<2.3%	18 hours	optical	NOT	
990510	1.7+-0.2 %	18-21 hours	optical	VLT	later meas. consistent with no variability
990712	1-3%	10-35 hours	optical		3 epochs, possible variability. PA constant
991216	<2.7%		optical	VLT	
020813	2%	5-8 hours		VLT	No change in the PA before and after jet break
030329	0.3-2.5%	one month	opt. and radio	VLT, NOT, VLBA	Strong variability of Π and PA
090102	10%	3 minutes	optical	LT	reverse shock
091018	up to 3%	0.13-2.3 days	optical	VLT	Possible rotation of PA by 90 degrees

GRBs at MeV energies

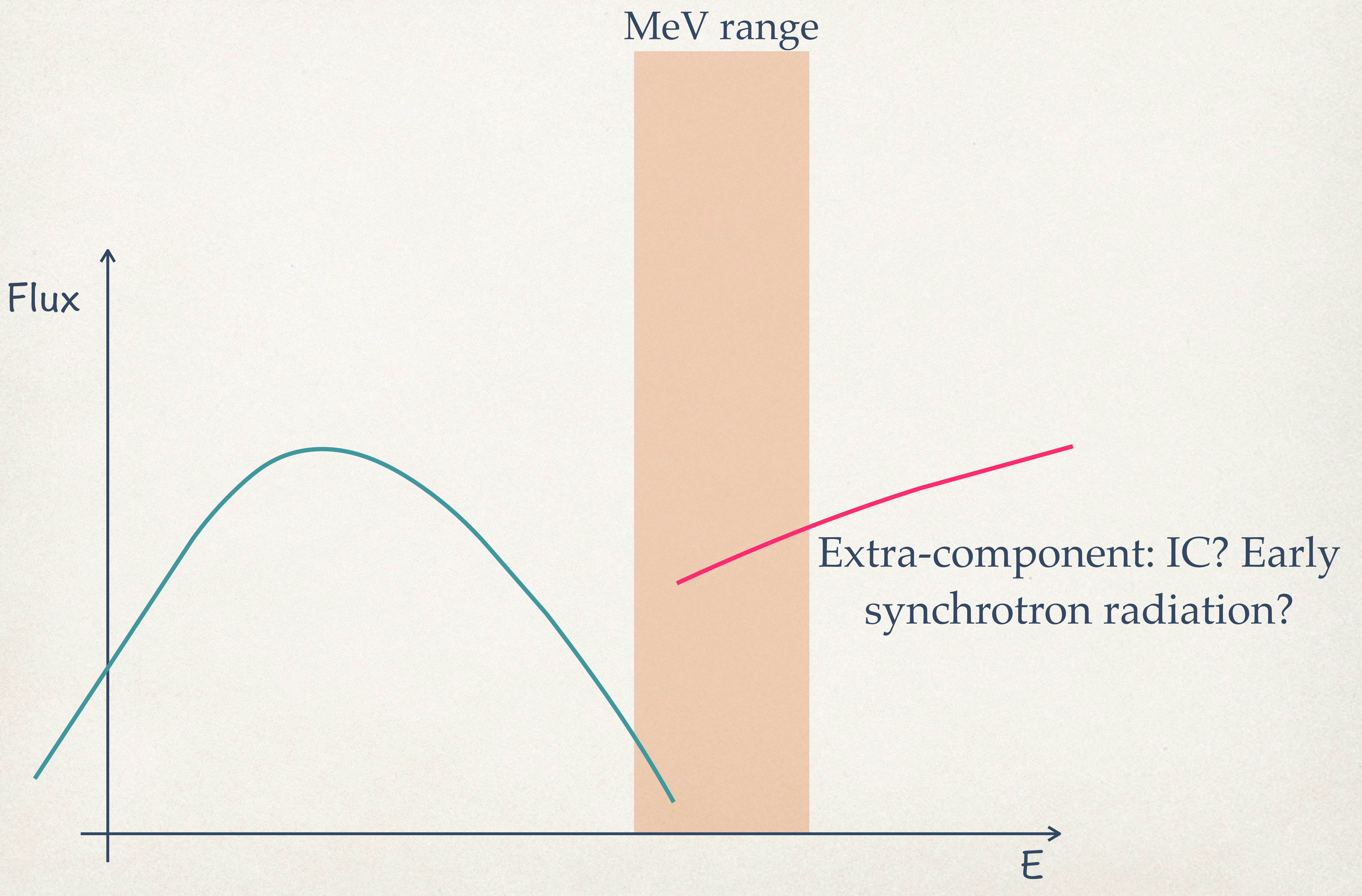
MeV energy range: early time



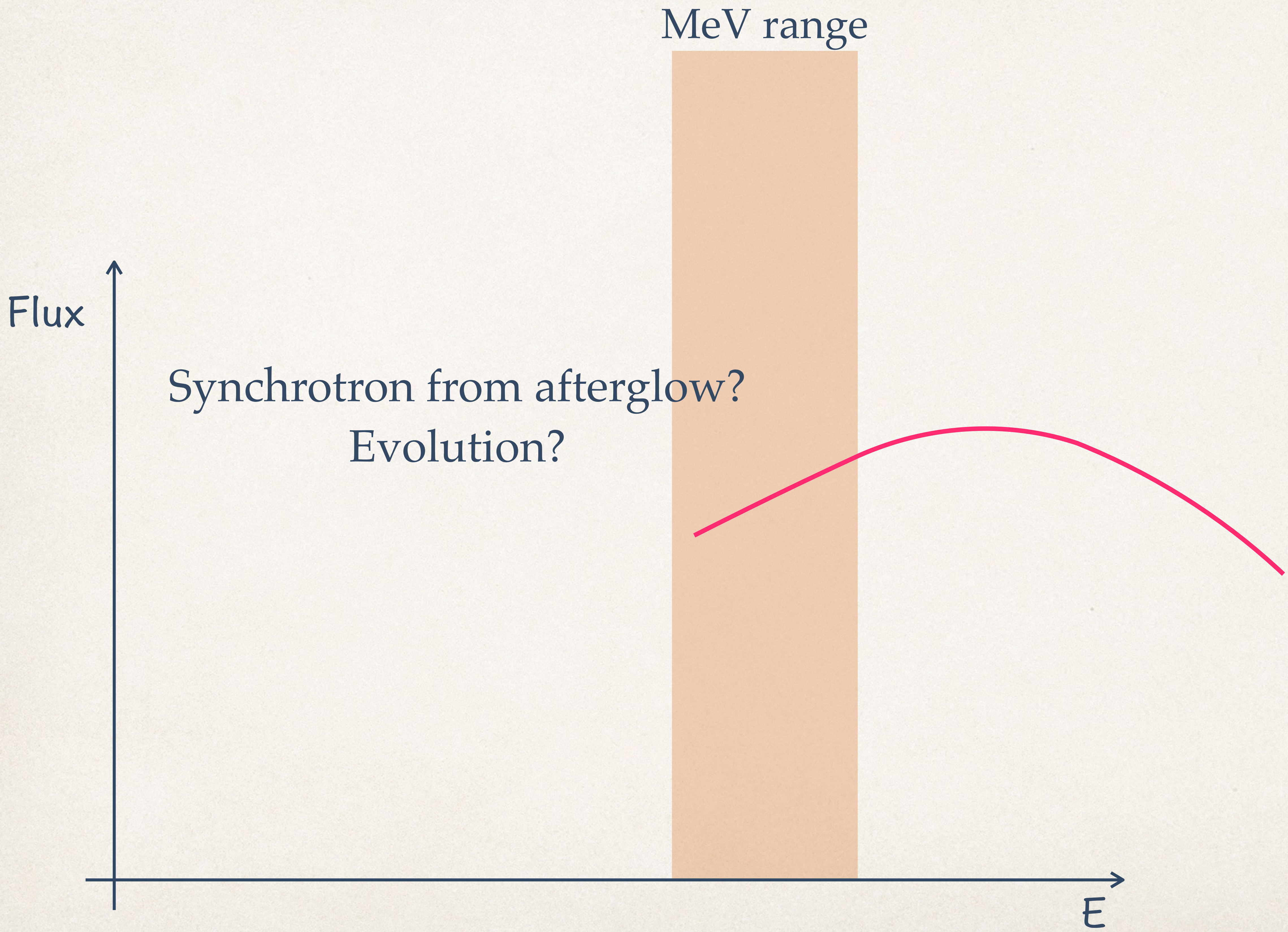
MeV energy range: intermediate times



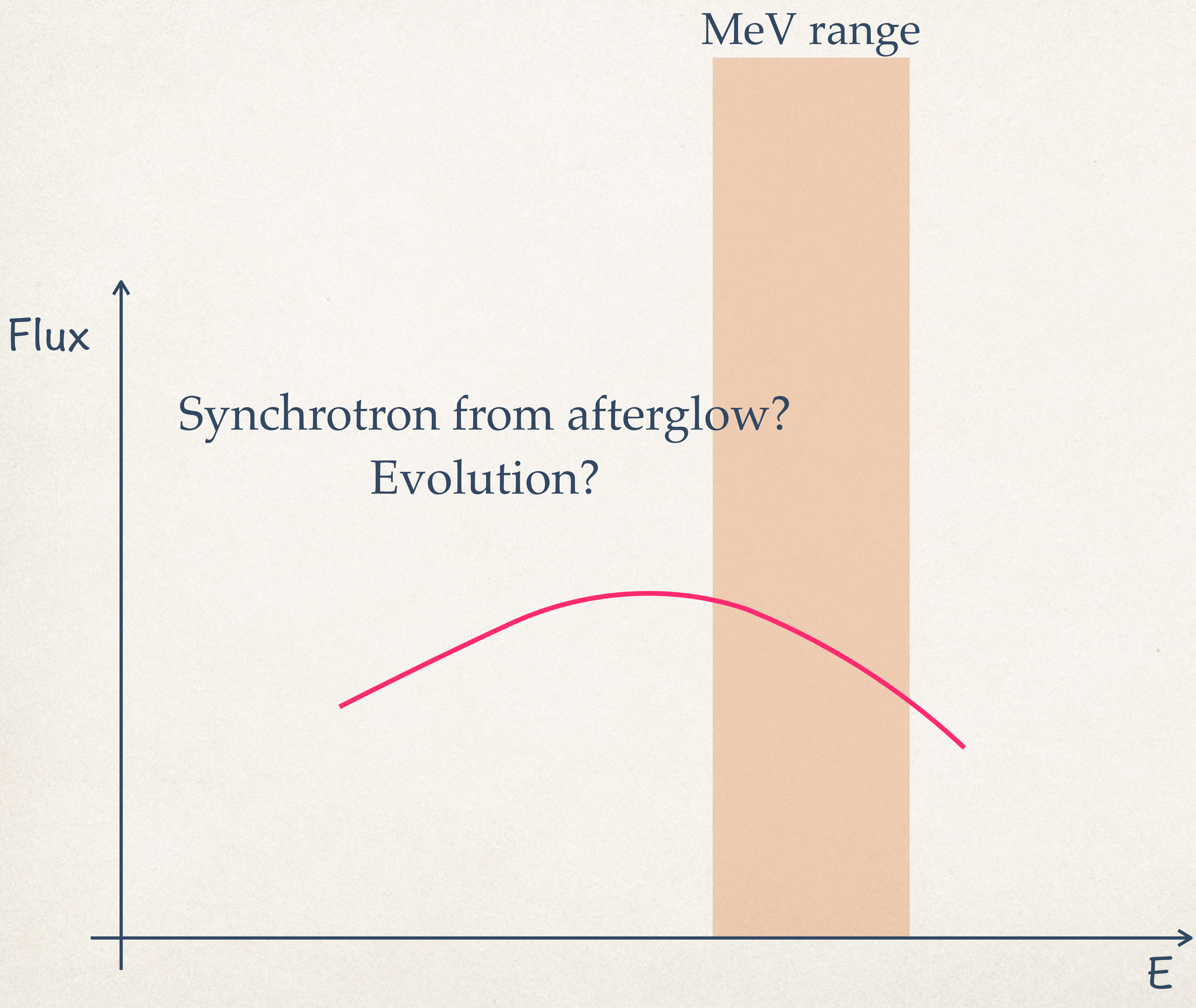
MeV energy range: intermediate times



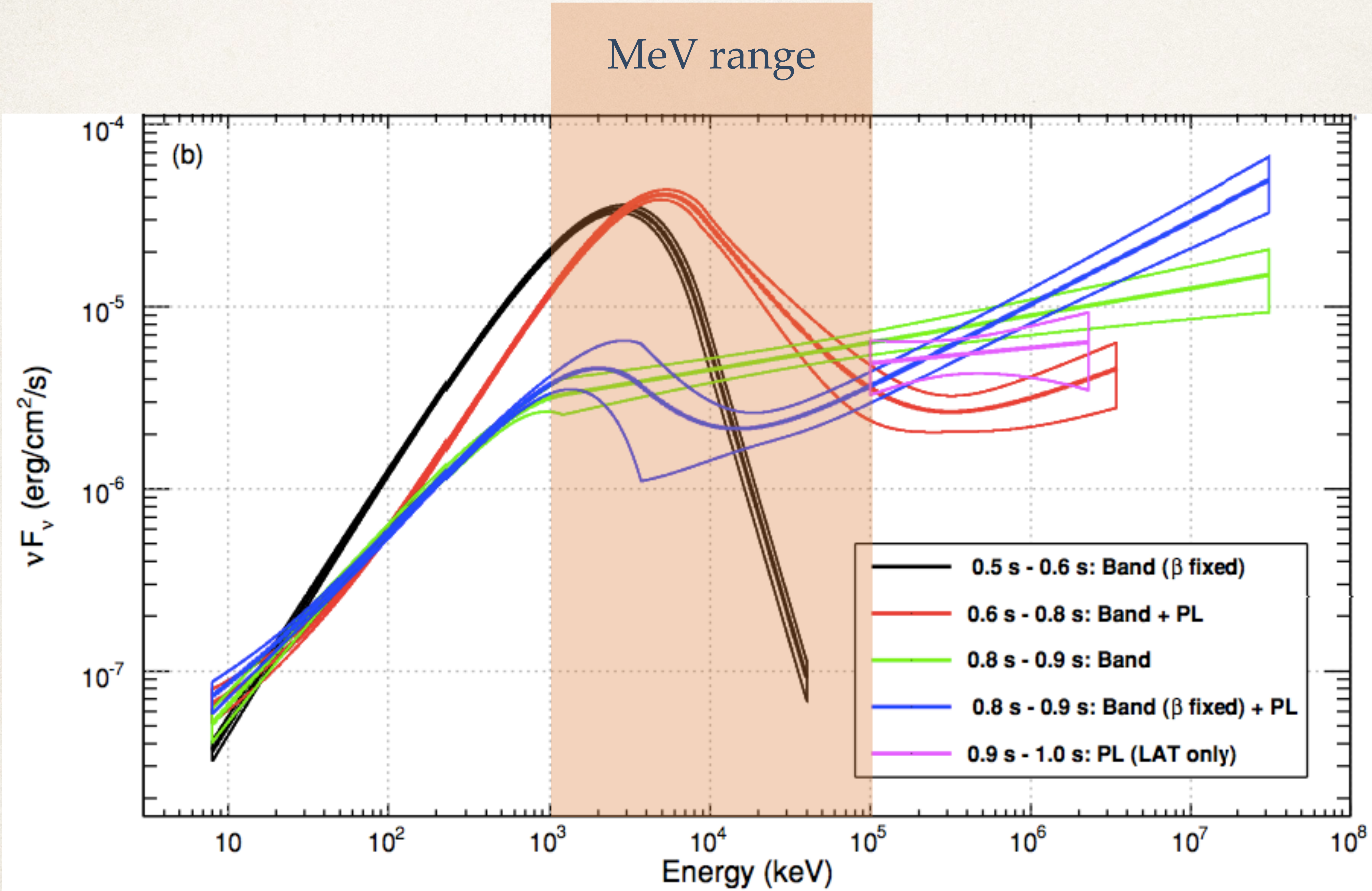
MeV energy range: late time (>100s)



MeV energy range: late time (>100s)



MeV energy range: an example



Conclusions (1)

Polarization measurements as complementary information on:

- jet composition
- jet structure
- magnetic field configuration
- geometry of the system
- particle acceleration
- radiative processes

Different models can predict similar polarization levels but different temporal evolution/variability of the polarization level and polarization angle. Measurements at different times are necessary to discriminate between different models

Conclusions (2)

MeV measurements can shed light on:

- cutoffs in the high-energy part of the prompt spectrum
- nature of prompt emission radiation mechanism
- transition from prompt to afterglow phase
- origin of long-lasting GeV radiation detected by the LAT and its temporal evolution
- early afterglow from forward shock