Gamma-Ray Bursts as sources of Neutrinos and other Messengers

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@ EWASS, Prague, June 2017

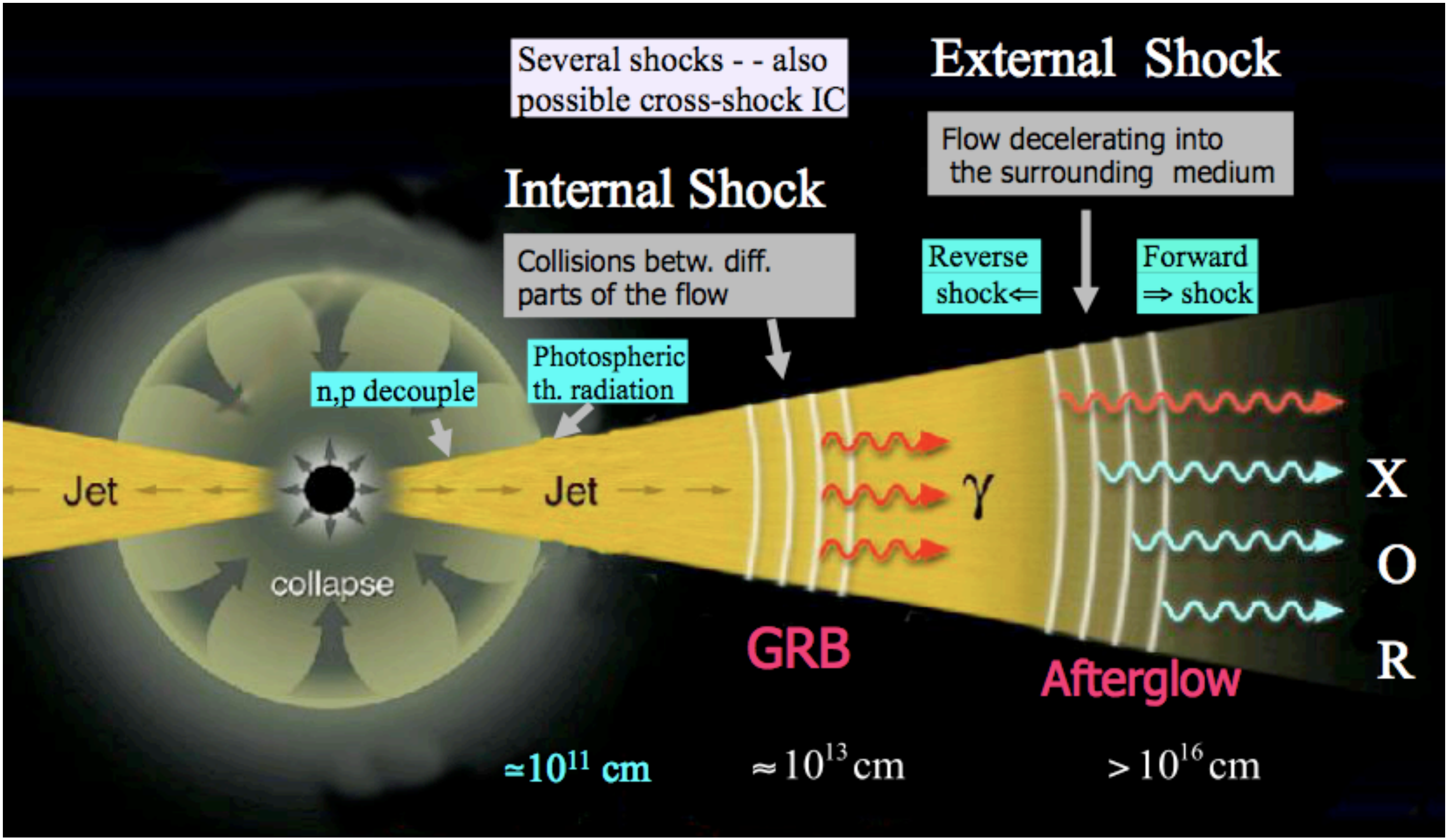
UHE Cosmic rays, VHE neutrinos & Gravitational waves

from

Gamma-Ray Bursts

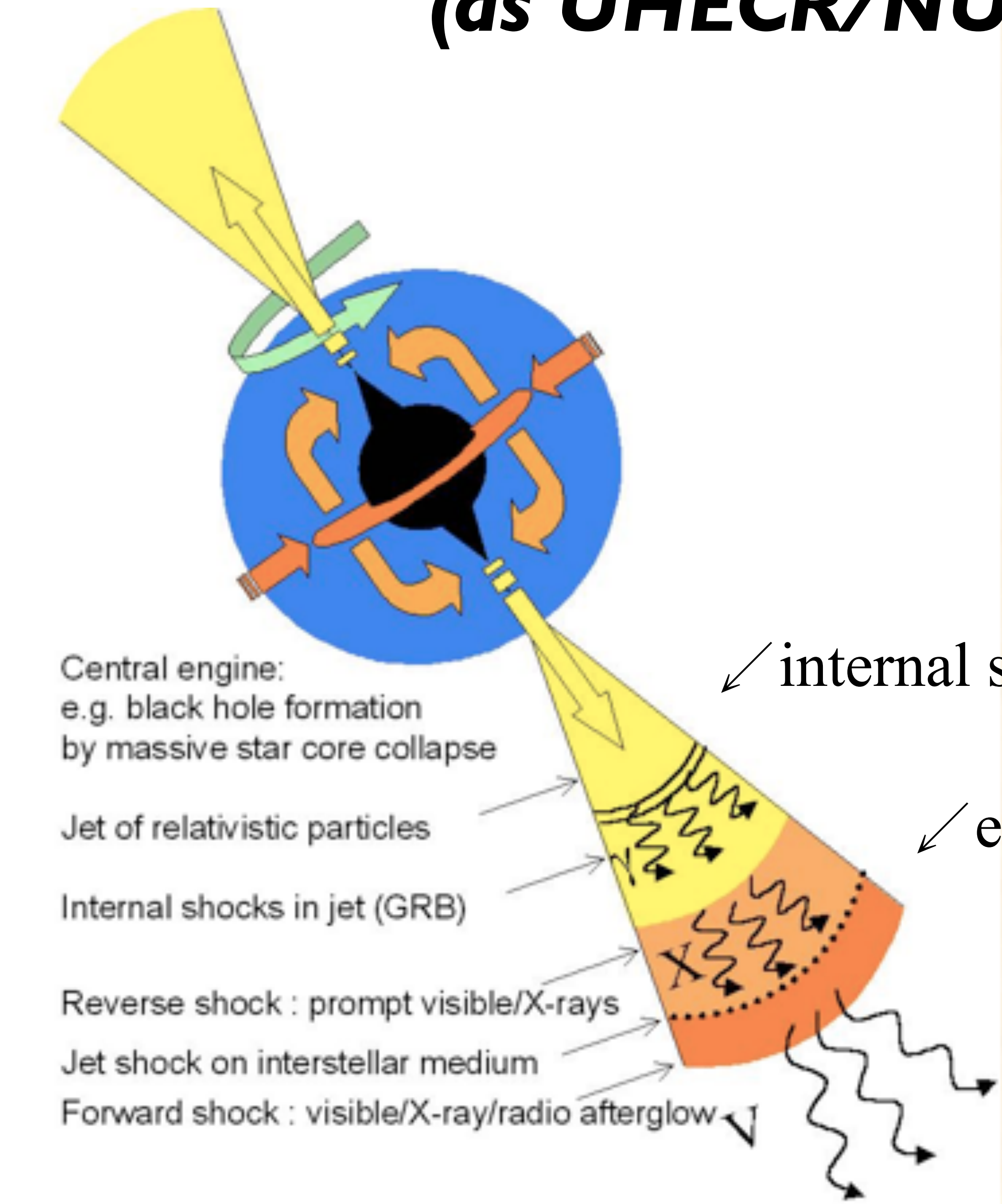
→ ***are expected and very probable***

GRB "Standard Model"



Standard(+) Model of GRB

(as UHECR/NU source)



↙ internal shocks

↙ external shock

Int. & ext. shocks, ***do*** Fermi-accelerate electrons, and make e,B →*γ* (*leptonic*);

So then …

same shocks must must accel. protons too (right?) → ***CRs*** ***and*** pγ→***ν***, ***γ*** (***hadronic***)

pp or pγ neutrino production

$$p + p/\gamma \rightarrow N + \pi^{\pm} + \pi^0 + ...$$

$$\begin{aligned} \pi^+ &\rightarrow \mu^+ + \nu_\mu \ , \\ &\quad\ \mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu \end{aligned}$$

$$K^+ \rightarrow \mu^+ + \nu_\mu$$

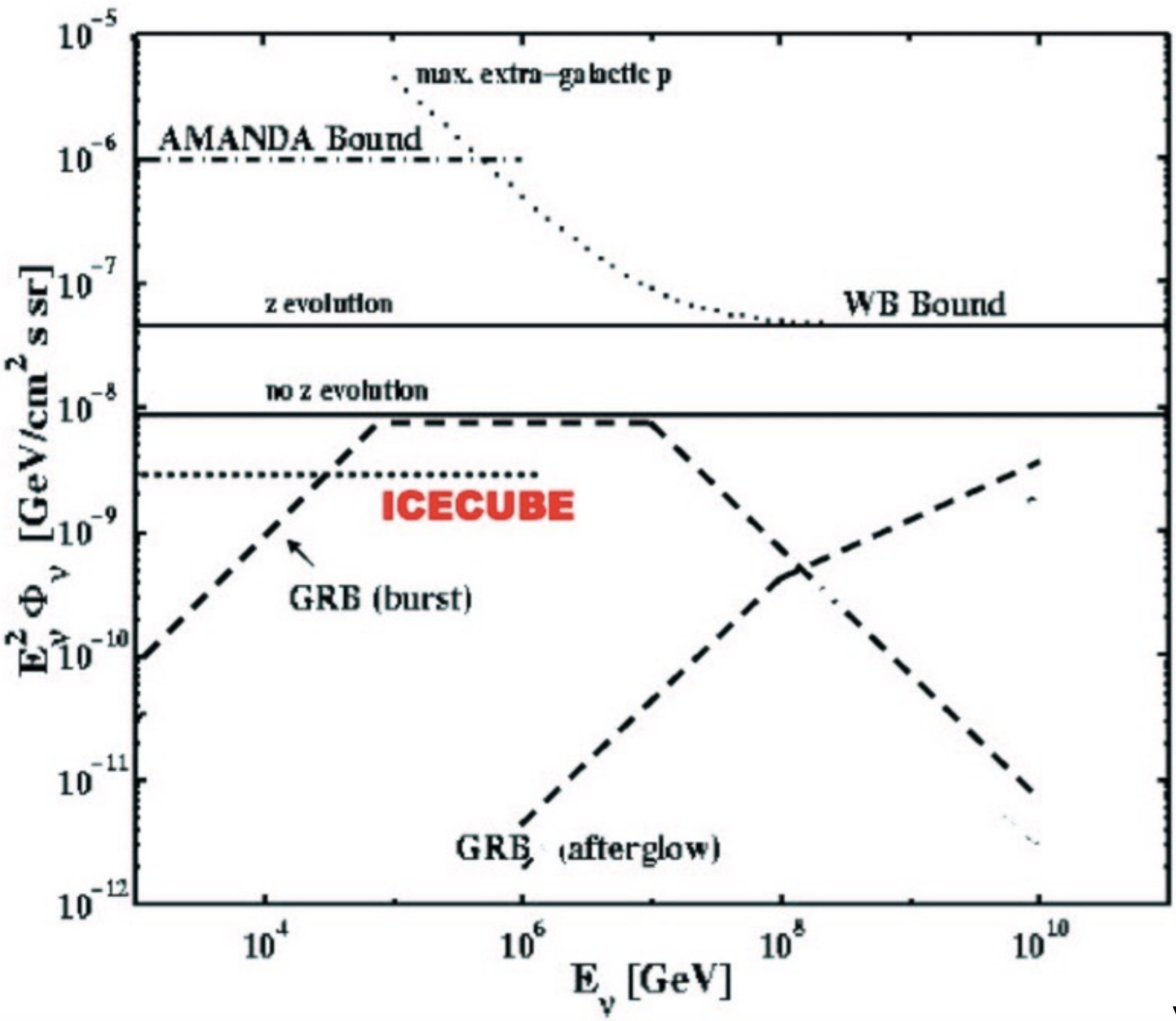
$$n \rightarrow p + e^- + \bar{\nu}_e$$

$$\begin{aligned} \pi^- &\rightarrow \mu^- + \bar{\nu}_\mu \ , \\ &\quad\ \mu^- \rightarrow e^- + \bar{\nu}_e + \nu_\mu \end{aligned}$$

$$\pi^0 \rightarrow \gamma + \gamma$$

- Both ν_e and ν_μ are produced by charged pion decay,
- γ-ray photons are produced by neutral pion decay

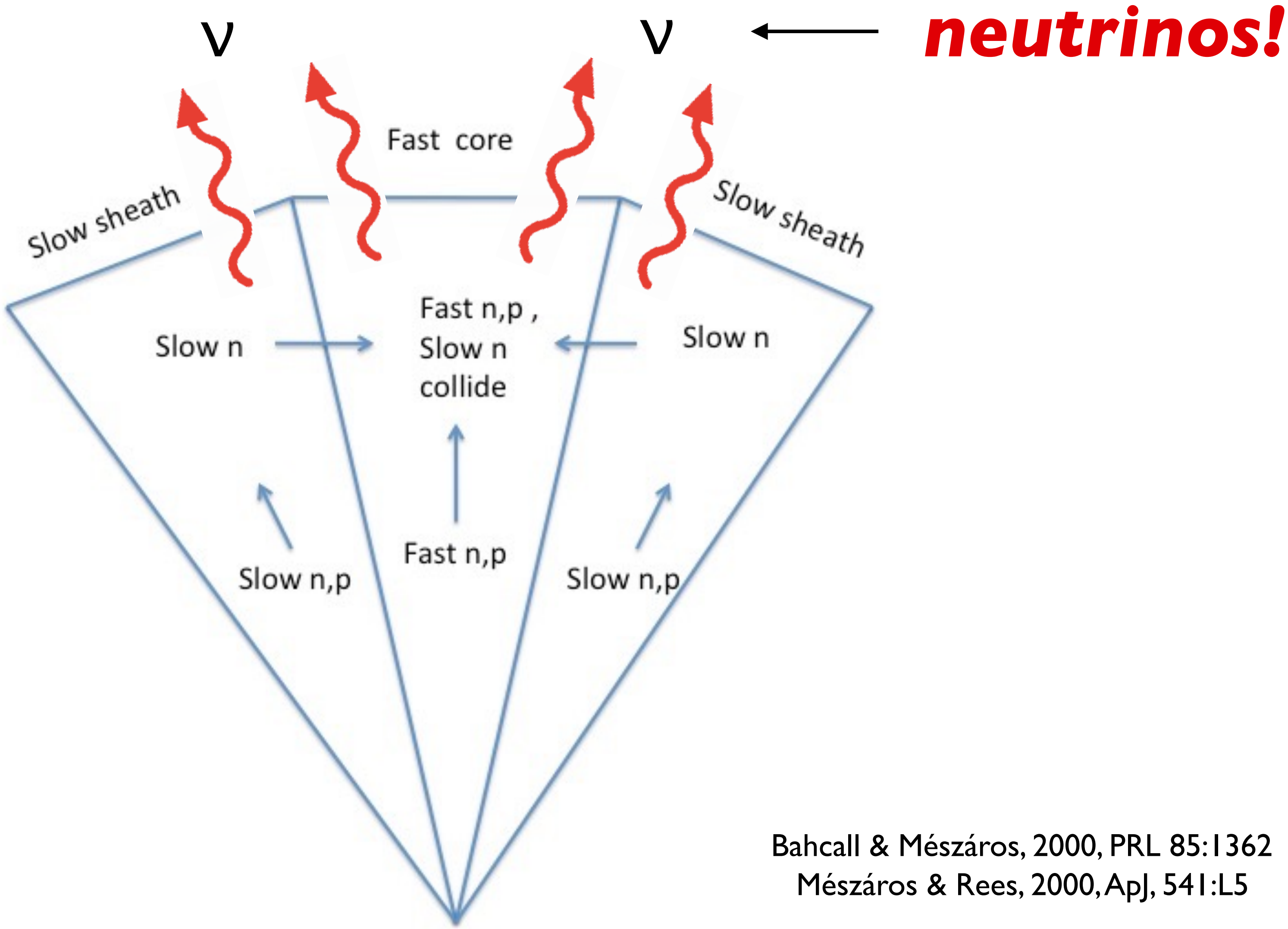
Original WB nu-spectrum



- Internal shocks
- CR Fermi accel.
- $p\Upsilon \rightarrow \pi \rightarrow \nu$
- Broken Υ PL $\rightarrow$ broken ν PL
- Flux ν ~ flux Υ

Waxman & Bahcall 1997

Decoupling of p-n (inelastic coll.): radially or transversally



Bahcall & Mészáros, 2000, PRL 85:1362
Mészáros & Rees, 2000, ApJ, 541:L5

Evidence for relativistic hadronic secondaries in GRB γ-emisslon?

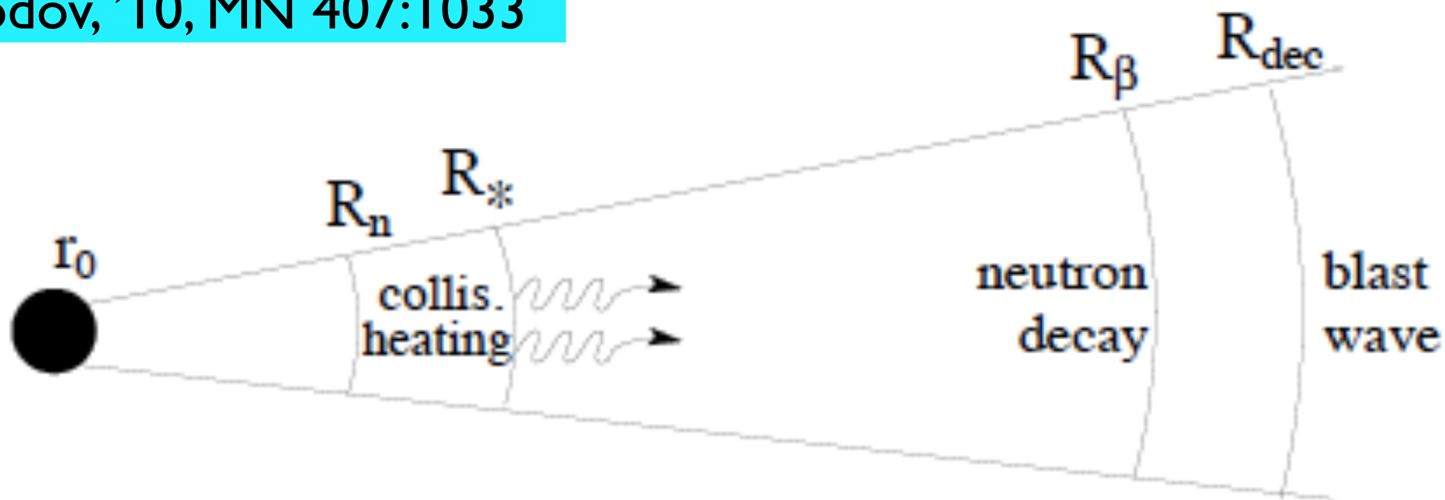
- ***YES***

- Hadrons ***solve*** the radiative efficiency and the Υ-spectrum issues in ***photospheres***
- They also solve this for ***internal shocks***
- And of course, if electrons are accelerated, why would hadrons ***not*** be accelerated?

A hadronic "thermal" photosphere PL spectrum?

p-n collisions in sub-photosphere

Beloborodov, '10, MN 407:1033

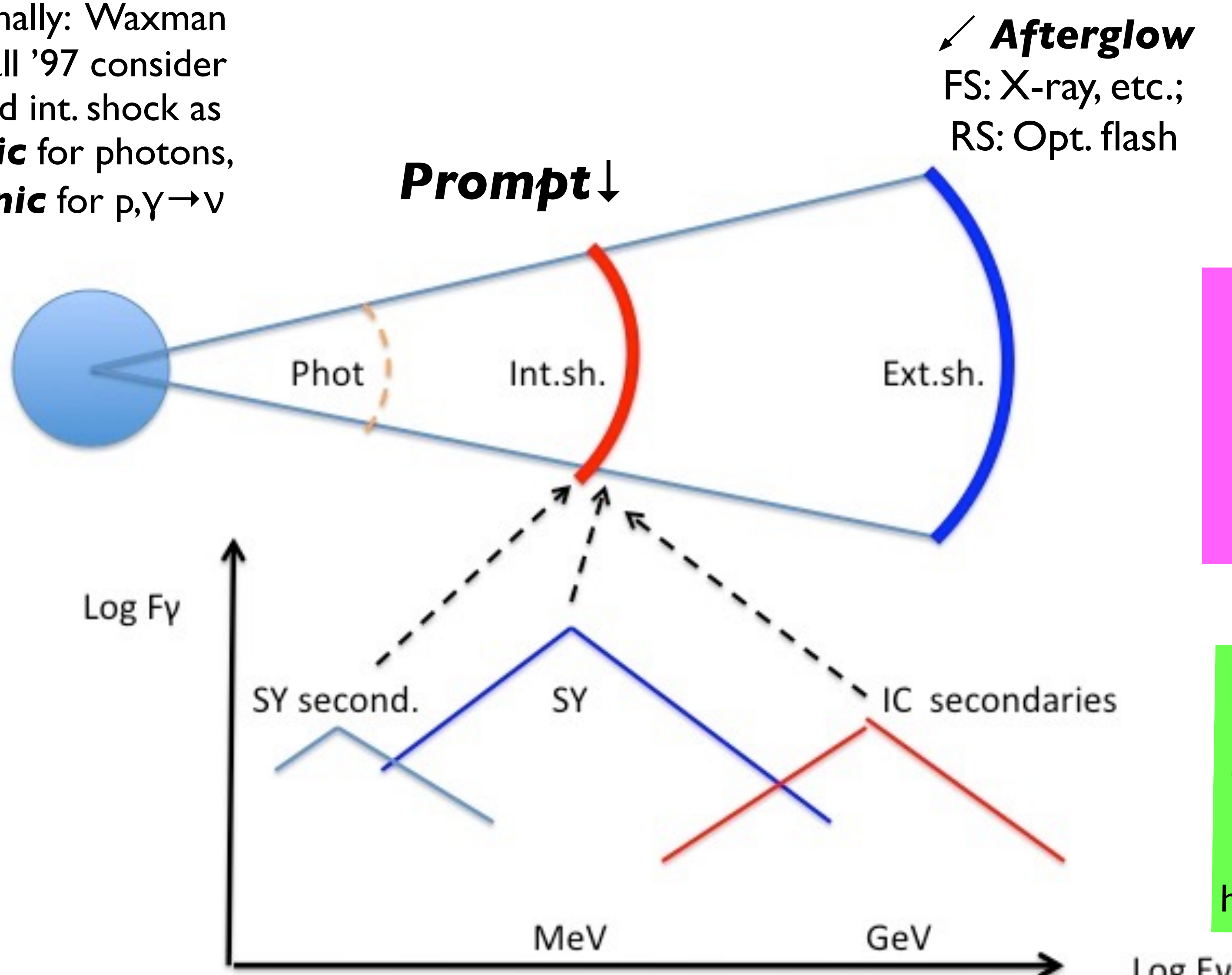


- Long history: Derishev-Kocharovsky 89, Bahcall-Meszaros 00, Rossi et al 04, etc
- Either p-n decoupling or internal colls. → relative p-n streaming, inelastic colls.
- Highly ***effective dissipation*** (involves baryons directly)- can get >50% effic'y
- Sub-photospheric dissipation can give strong photospheric component

Self-consistent hadronic int. shock

Calculate ***self-consistent*** CR proton, photon & neutrino spectra

- Originally: Waxman & Bahcall '97 consider standard int. shock as ***leptonic*** for photons, ***hadronic*** for p,γ→ν



New Feature:

***Hadron accel. + photomeson* → "dissipation"**
→inject copious ***relativistic sec'y leptons***

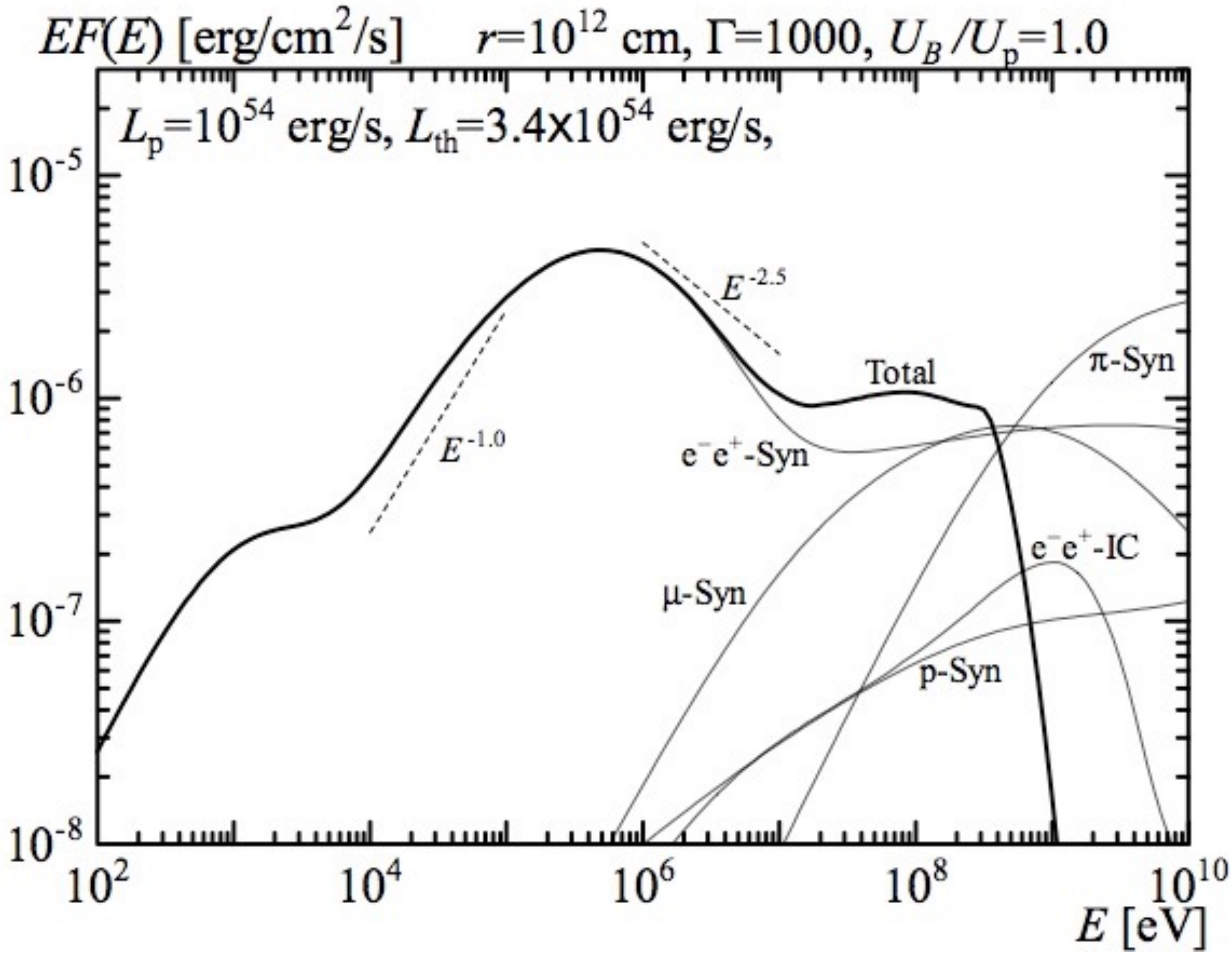
- ↙ Asano & PM, 09-12 on, calculate second'y ***photons*** & second'y ***neutrinos*** from both original & hadronic sec'y leptons

also: Murase et al, 2012, ApJ 746:164

IS w. hadronic cascades: γ

(Time indep.)

Murase, Asano, Terasawa & Mészáros'12, ApJ746:164

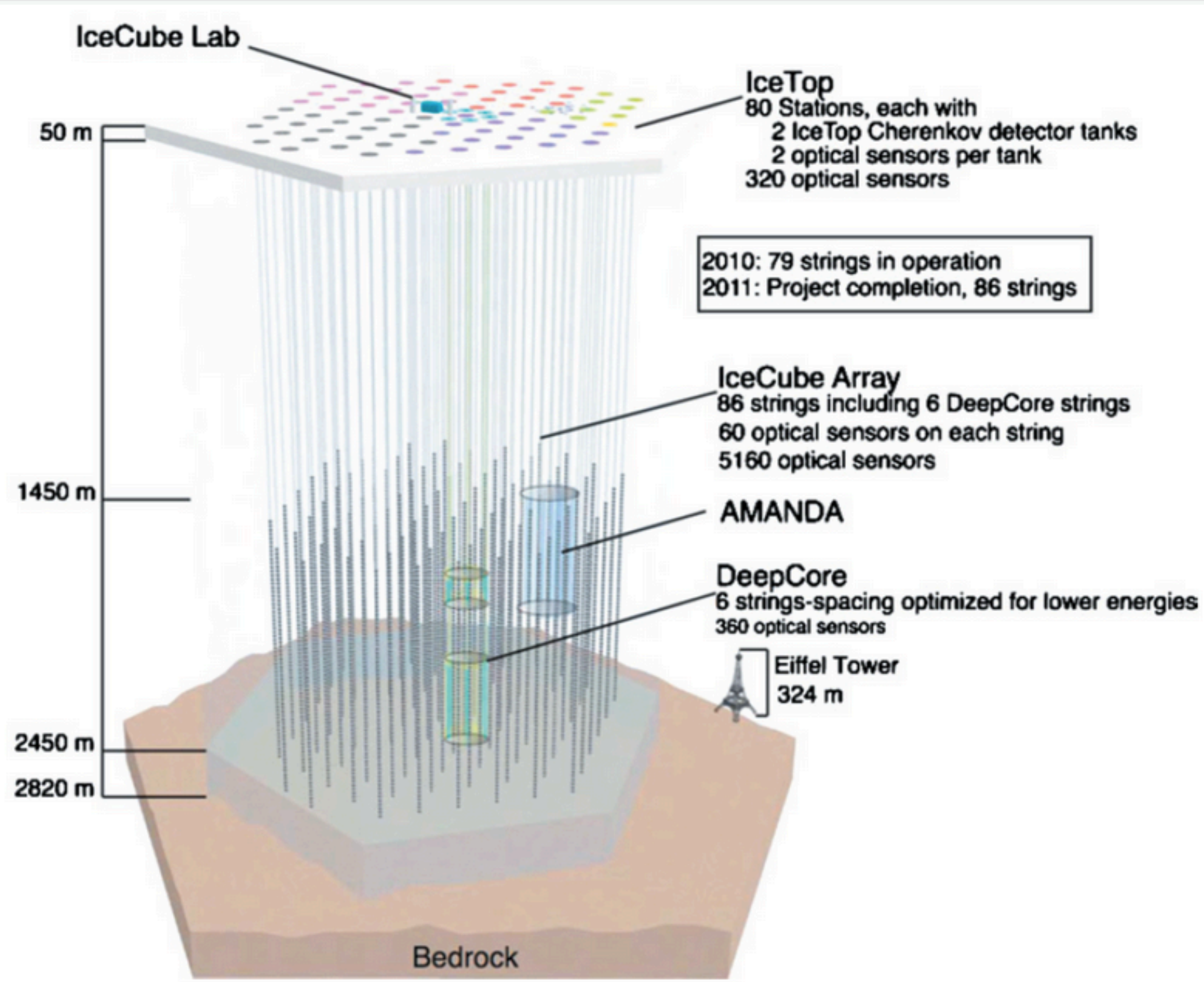


- Time-indep. shocks
- Self-generated Band MeV sp. (Fermi 2 in IS)
- Good low-en and hi-en Band slopes
- "2nd comp." at GeV energies

Confront with observations:

IceCube data on astrophysical VHE νs

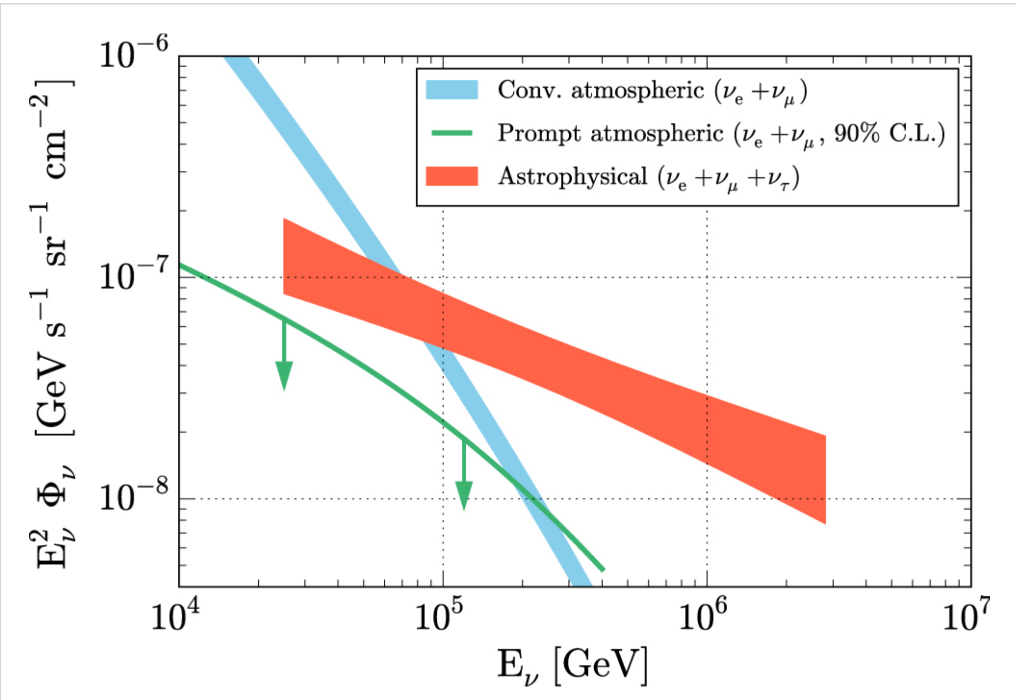
IceCube

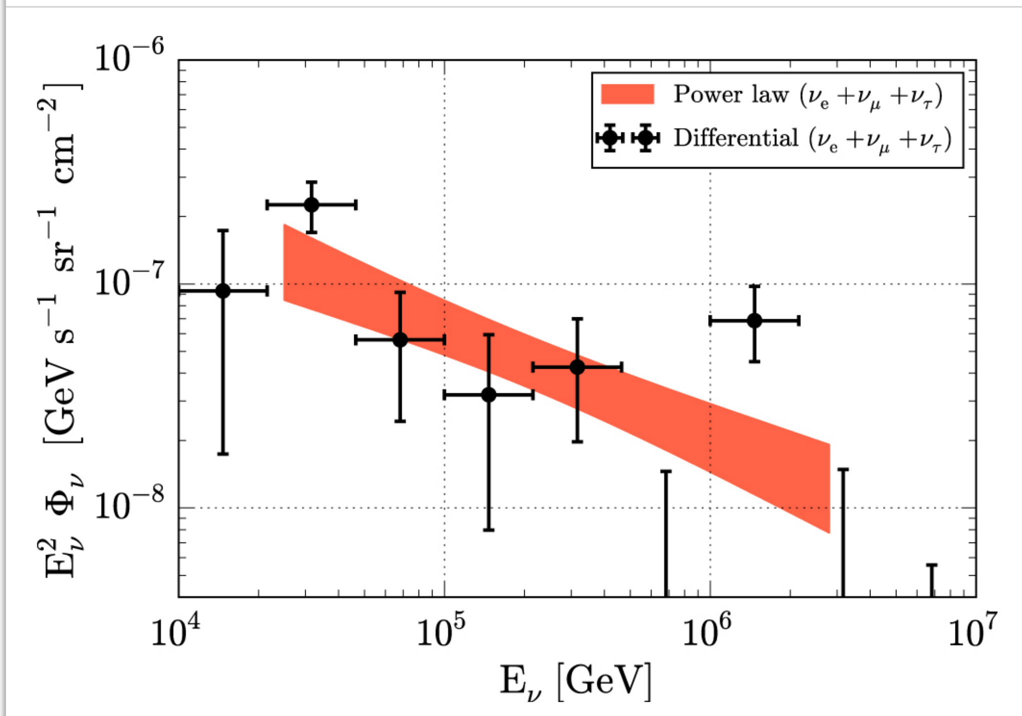


- The IceCube (IC) neutrino observatory is located at the Antarctic pole and has been at full operating capacity since 2011.
- Neutrinos produce charged particles when they interact with ice molecules. The Cherenkov radiation from these particles are observed by the optical sensors.
- Sensitive to two types of signals:
  - Charged current (CC) muon interactions are seen as track-like events
  - CC electron and tau interactions, and all neutral current (NC) interactions are seen as cascades

1 GTon instrumented volume, US$ 300M (30c/Ton)

- There is strong evidence for a diffuse, astrophysical flux of neutrinos with energies between 25 TeV and 2.8 PeV.
- The measured flux is well fit (at the 3.8σ level) by a soft power-law with index -2.50 ± 0.09 and an all-flavor flux of ~ 7 x 10^{-8} GeV cm^{-2} s^{-1} sr^{-1} at 100 TeV.
- Sources of the neutrino flux are unknown.

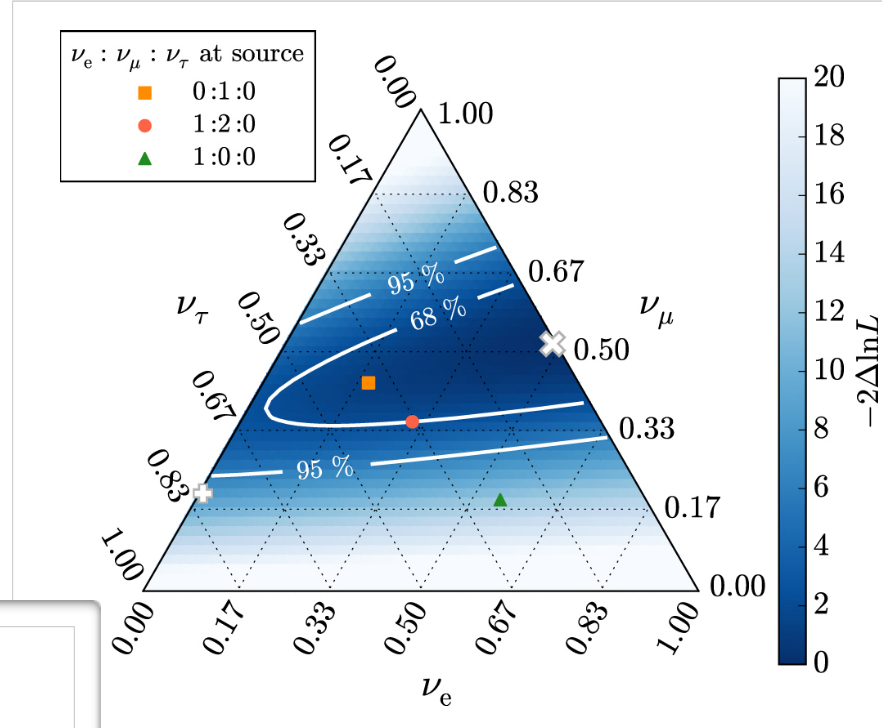


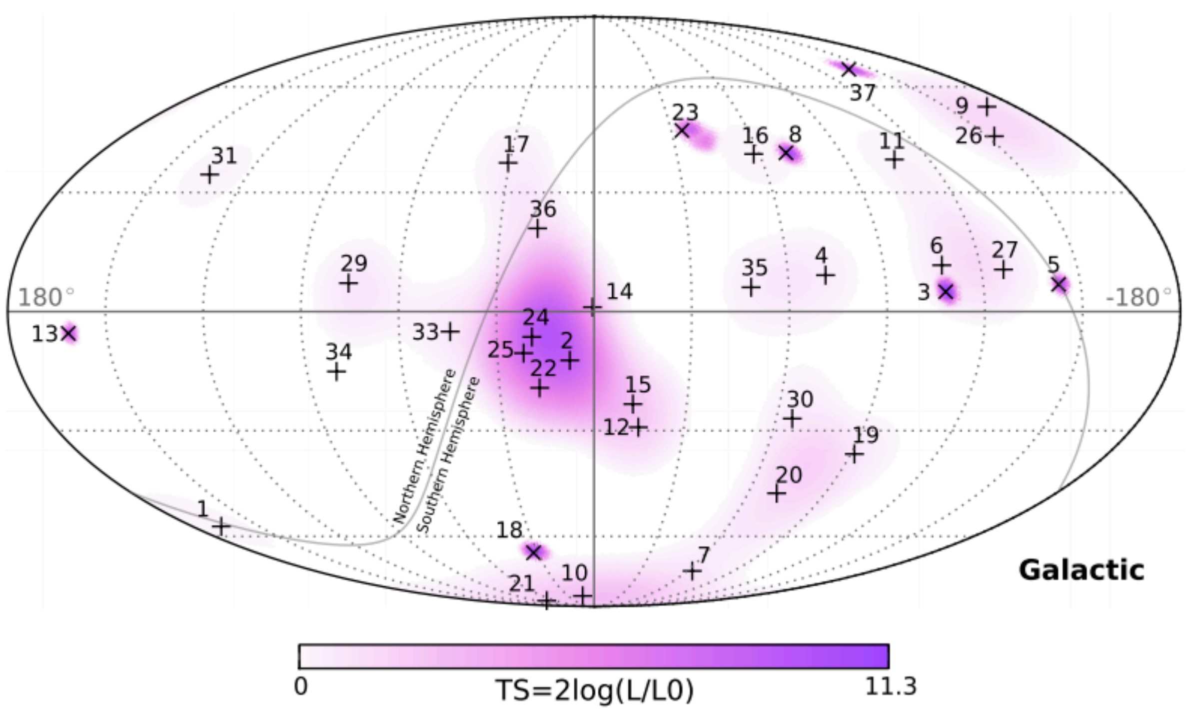


Aartsen, M.G. et al. ApJ 809, 98 (2015)

- There is increasing evidence for an extra-galactic origin for the observed neutrinos

- The measured flavor ratio (ν_e:ν_μ:ν_τ) is consistent with oscillation over cosmological distances (>100 Mpc)





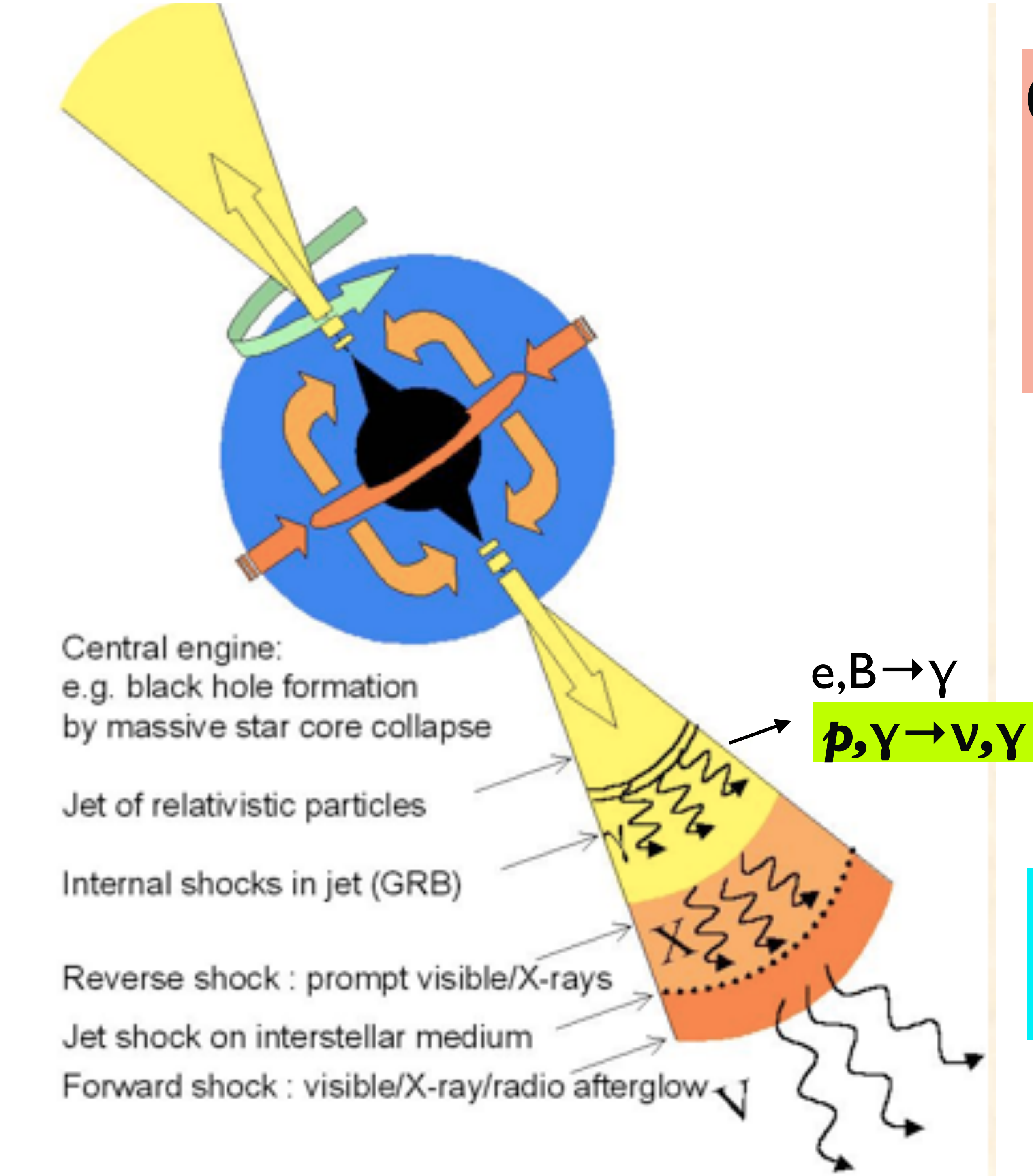
- The neutrino arrival directions are consistent with isotropically distributed sources

→No obvious sources!

[A] Classical GRBs?

- IceCube finds that <1% of the "classical" EM-observed GRBs can be contributing to this observed neutrino flux (e.g. arrival times)
- Classical GRBs are associated with core-collapse SNe Ic; the classical model used is that relativistic jet penetrates expanding stellar envelope
- Jet undergoes shocks outside envelope, Fermi accelerates both electrons (synchrotron $\rightarrow$ MeV γ-rays) and protons ($p,\gamma \rightarrow \pi^+ \rightarrow \nu$ @ TeV energies)

→ **NOT Classical GRBs !**



Conventional collapsar GRB model

- If $L_p/L_\gamma \sim 10$, expect that $L_\nu/L_\gamma \sim 1$,
- ***but*** IC3 observ.: → such high L_ν seems ***disproven***

That is, for standard internal shock model where γ and CR produced in same IS shocks

(IC3 team, 2015, ApJL, 805: L5)

Classical GRBs: low γ-optical depth →no hiding!

⇒ *Need "hidden" neutrino sources ?*

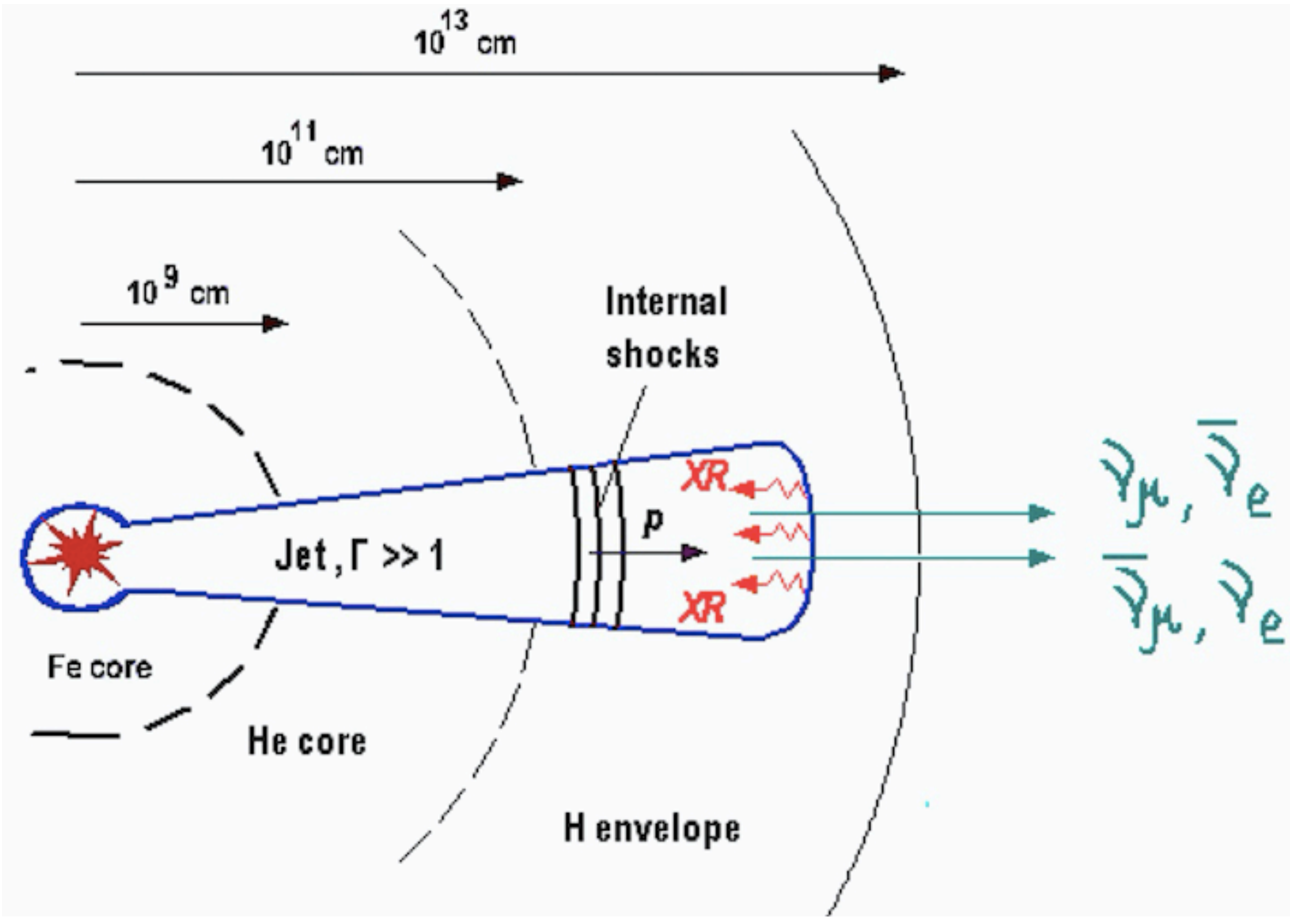
- Hidden in the sense of "low or no EM"
- E.g., high optical depth (Thomson kills)?
- Or, e.g., high distances (redshift kills)?

Possibility

↓

High optical depth,

[A] choked GRBs

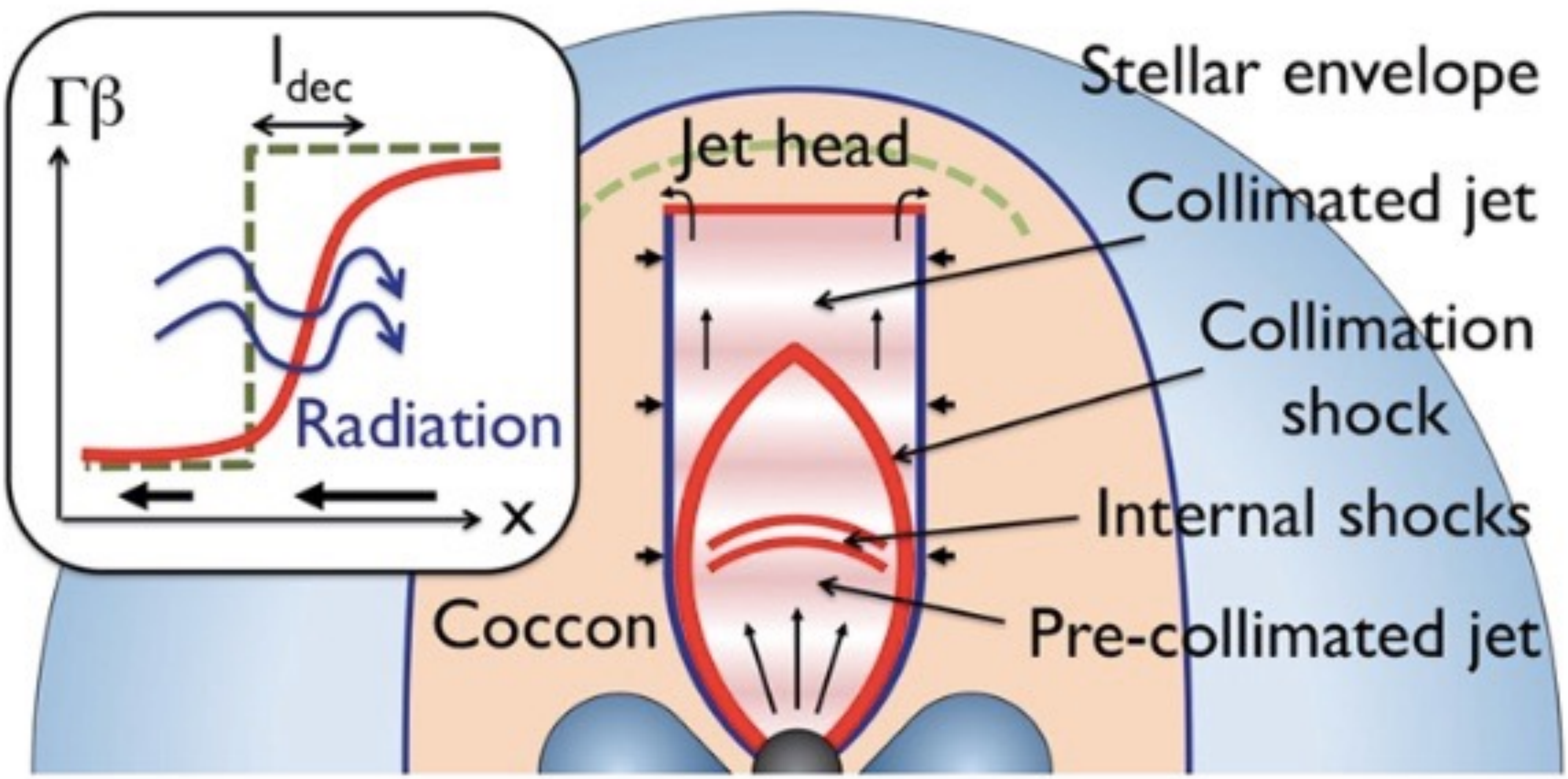


Choked, or buried and later emergent jets

Mészáros &Waxman, 2001, PRL, 87:1102

Star-penetrating jets

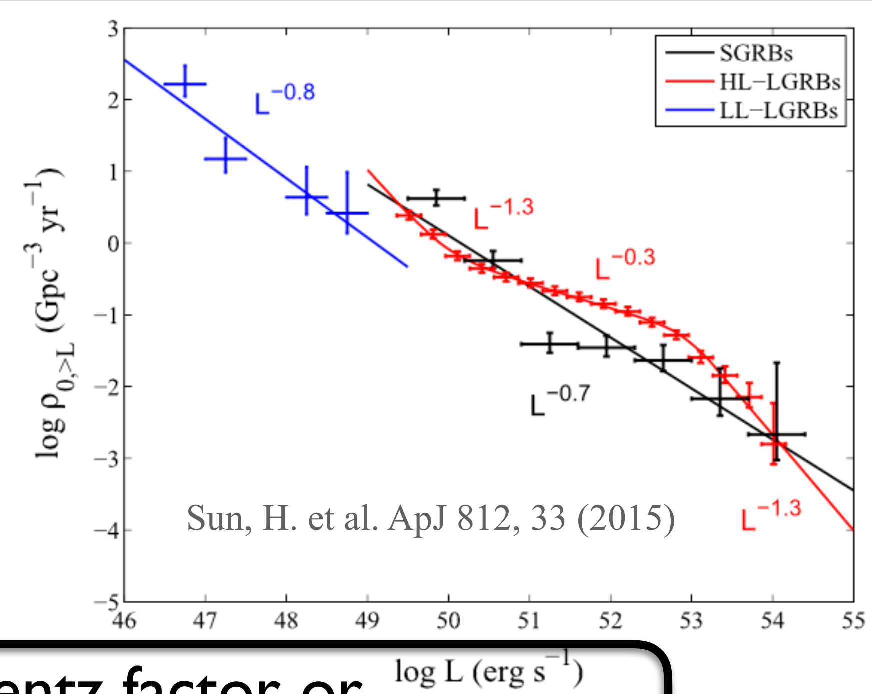
Mizuta & Ioka '13, ApJ, 777:162
Bromberg+, '11, ApJ, 740:100
Mészáros, Rees'01, ApJL 556:L37



[A] generically : LLGRBs

- Low luminosity GRBs (LLGRBs) have $L_\gamma \sim 10^{-2}$ - 10^{-3} ***smaller,*** but are are ~100x more ***numerous***

- Prompt emission can be up to 10^3 s, with smooth light curves



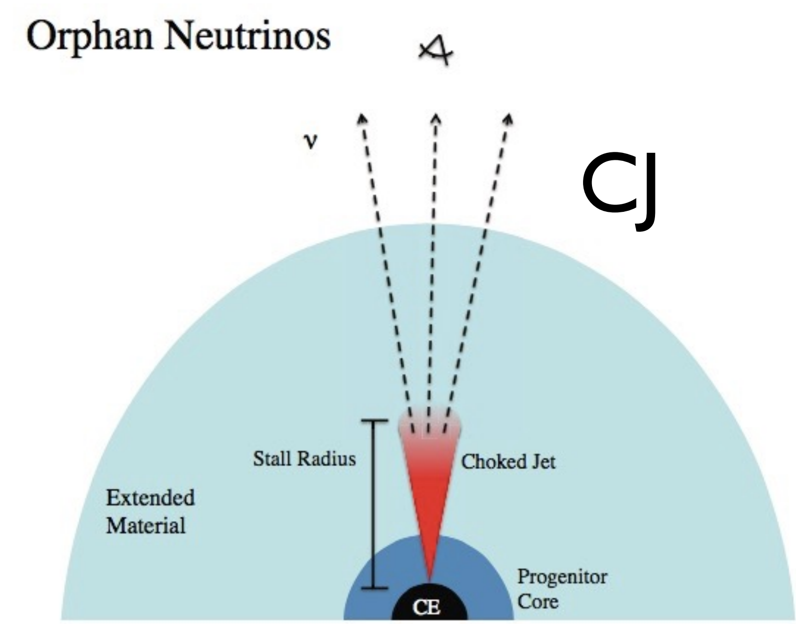
These may be:

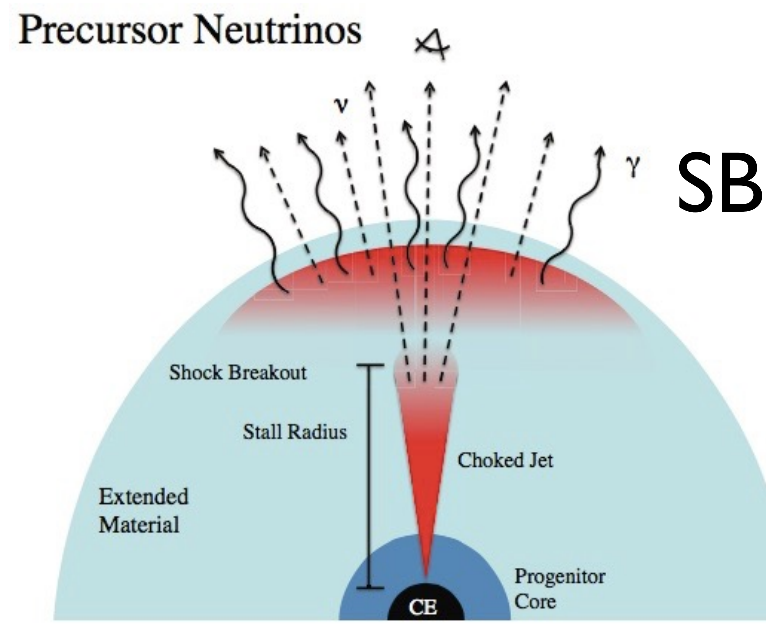
- (a) emergent jets (***EJ***) of lower Lorentz factor, or
  (b) jets barely emerging - shock breakout (***SB***), or
  (c) choked jets (***CJ***) which did not emerge…
  ….jet kinetic luminosity may be ~ comparable in all 3 cases

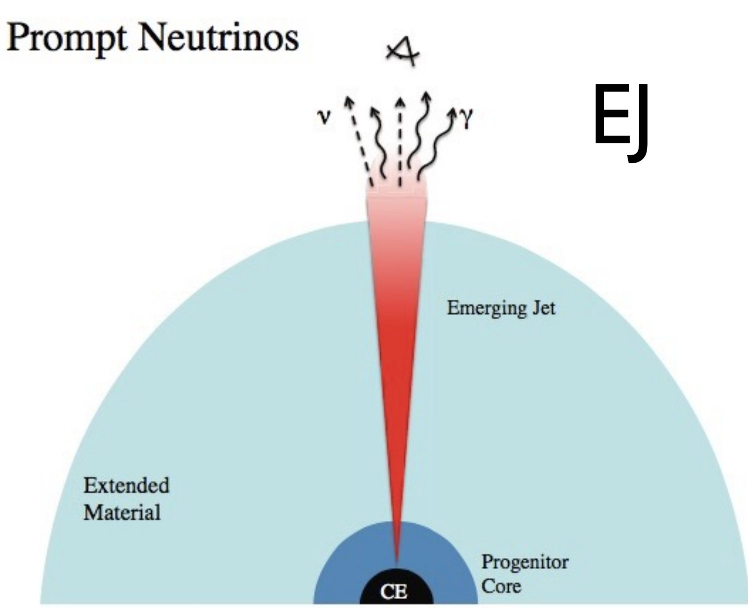
- All 3 cases: expect ***low L$_\gamma$***, do not trigger EM detector unless nearby

→EM hidden, or inconspicuous

From Choked to Emergent Jets as Hidden Neutrino Sources







Senno, Murase, Mészáros, (2016) PRD, 93, 083003

Other previous work on choked GRBs:

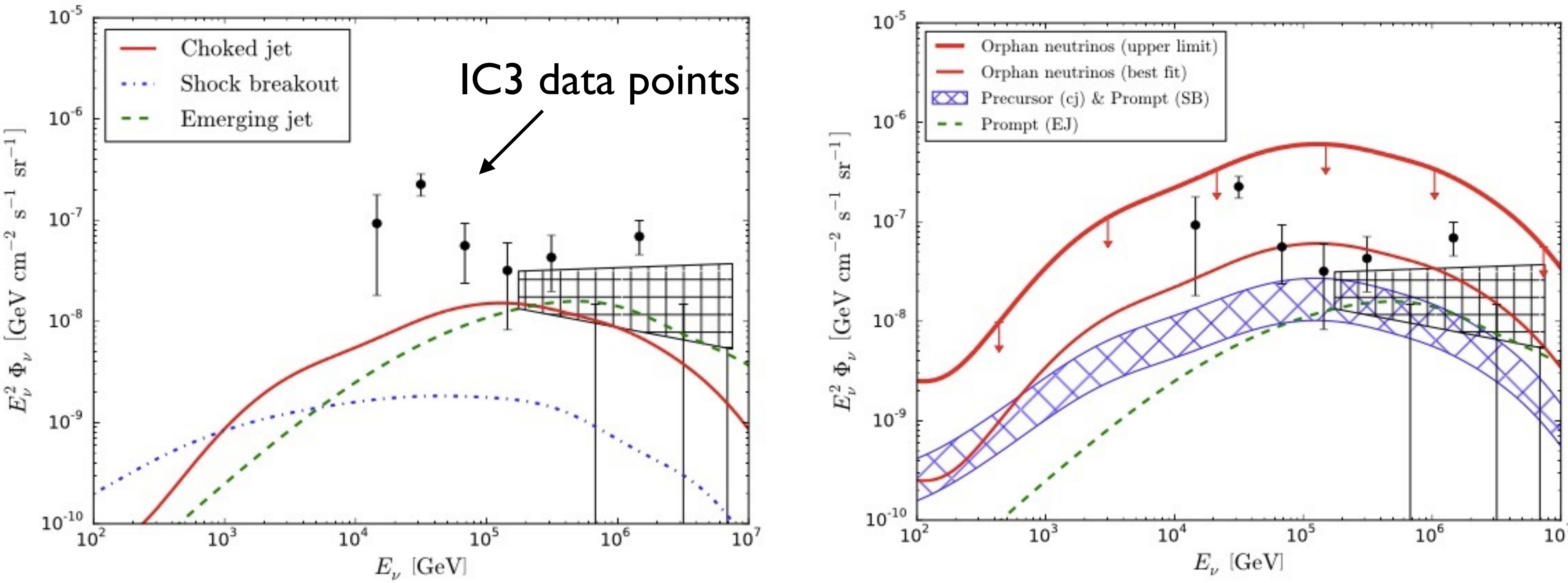
Mészáros &Waxman 2001, PRL 87, 171102

Waxman, Campana & PM 2006, ApJ 667, 351

Murase & Ioka, 2013, PRL 111, 121102

Nakar, 2015, ApJ 807, 172, etc.

Choked jet, shock breakout & emergent jet ν-spectra



May do the job - LLGRBs produce practically no IGB ⇒ hidden ✔

Senno, Murase, Mészáros, PRD, 93, 083003

Conclusions for GRB νs

- At least ***two*** possible interpretations for the ***IceCube INB*** & the ***Fermi IGB***
- One are ***LLGRBs*** (act as "hidden sources") ***[A]***
- The other are ***HNe/SNe*** (they are "hidden" if their strongest contribution is at ***high z***)
- No need for blazars (they would not be "hidden")
- Normal (classical) ***GRB***s with Fermi 2nd CRs in ≠ shocks than the γs can be GZK ***UHECR*** sources ***without*** violating IceCube - see below, ***[B]***

Moving on:
Can GRBs explain [B]
GZK UHECRs ?

3 main objections:

- (1) If spectral index is ***p*=2** (Fermi 1st order) $\Rightarrow$GRB CR energy budget $>10^{52}$ - 10^{53} , too high
- (2) If ***assume same*** shocks accelerate ***CRs*** (and do p,$\gamma\rightarrow\nu$) as those producing obs. **γ*-rays***: $\Rightarrow$GRBs in Swift time windows ***over-produce*** **ν's**
- (3) IceCube stacking analysis: $\leq$ ***1%*** of UHENUs can be coming from Swift EM-triggered GRBs

Consider objection (1):

- (1) If spectral index is ***p*=2** (Fermi 1st order) ⇒GRB CR energy budget $>10^{52}$ -10^{53} too high

Possible solution to (1): harder slope

(Asano & Mészáros, 2016, PRD 94, 023005)

Consider Fermi **2nd** : stochastic acceleration

- May be expected in turbulence in relativistic jet outflow, induced by:
- E.g., RT in decelerating outflow (ext. shock), or KH in shear flow (say boundary of jet-cocoon), or Richtmyer-Meshkov in IS, etc.
- Also, turbulence can enhance mag. reconn., which also can lead to Fermi 2nd

Evol. of proton en.distr.(i)

$$\frac{\partial N(\varepsilon,t)}{\partial t} = \frac{\partial}{\partial \varepsilon}\left[D(\varepsilon)\frac{\partial N(\varepsilon,t)}{\partial \varepsilon}\right] - \frac{\partial}{\partial \varepsilon}\left[\frac{2D(\varepsilon)}{\varepsilon}N(\varepsilon,t)\right] + \dot{N}_{\rm inj}(\varepsilon,t),$$

at $t = 0$ with $\dot{N}_{\rm inj}(\varepsilon,t) \equiv N_0\delta(\varepsilon-\varepsilon_0)\delta(t)$ (impulsive)

$$N_{\rm G}(\varepsilon,t) = \frac{N_0}{2\varepsilon_0\sqrt{\pi K t}}\sqrt{\frac{\varepsilon}{\varepsilon_0}}\exp\left(-\frac{9}{4}Kt - \frac{(\ln\frac{\varepsilon}{\varepsilon_0})^2}{4Kt}\right)$$

Evol. of proton en.distr.(iii)

with the variable
$$X_\pm \equiv \frac{3Kt \pm \left|\ln \frac{\varepsilon}{\varepsilon_0}\right|}{2\sqrt{Kt}}, \tag{14}$$

For $\varepsilon \geq \varepsilon_0$, the spectrum can be rewritten as

$$N(\varepsilon, t) = \frac{\dot{N}_0}{6K\varepsilon}\left[1 + \mathrm{erf}(X_-) - \left(\frac{\varepsilon}{\varepsilon_0}\right)^3 \mathrm{erfc}(X_+)\right], \tag{15}$$

where $\mathrm{erfc}(x) \equiv 1 - \mathrm{erf}(x)$ is the complementary error function. On the other hand, the distribution for $\varepsilon \leq \varepsilon_0$ is approximated by a steady solution

$$N(\varepsilon, t) \simeq \frac{\dot{N}_0}{3K\varepsilon_0}\left(\frac{\varepsilon}{\varepsilon_0}\right)^2. \tag{16}$$

Model CR spectra (i)

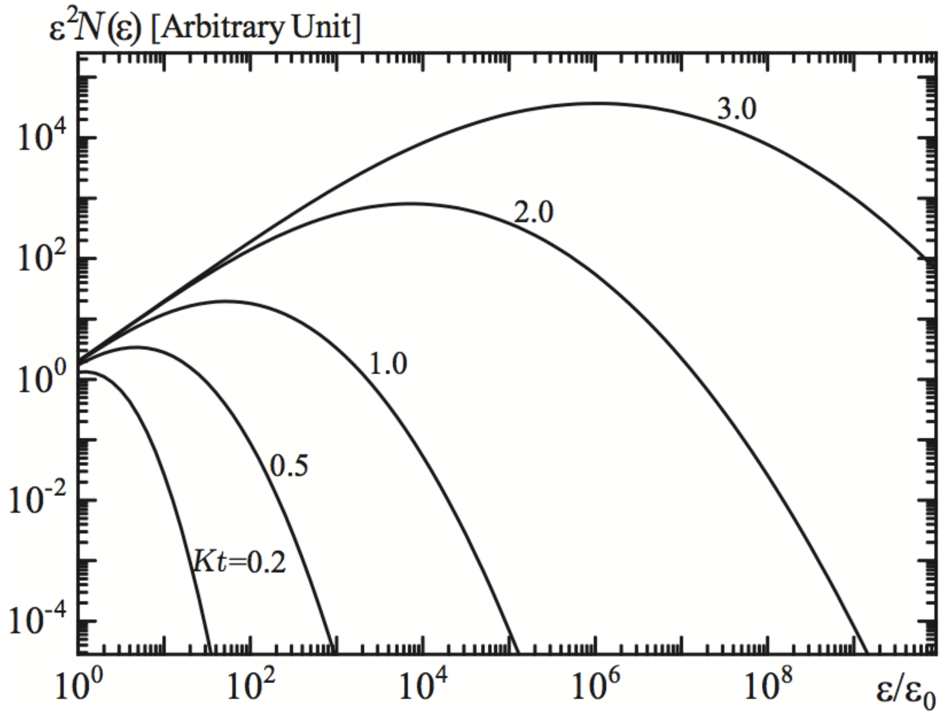


FIG. 1. Evolution of the particle energy distribution expressed by Eq. (15).

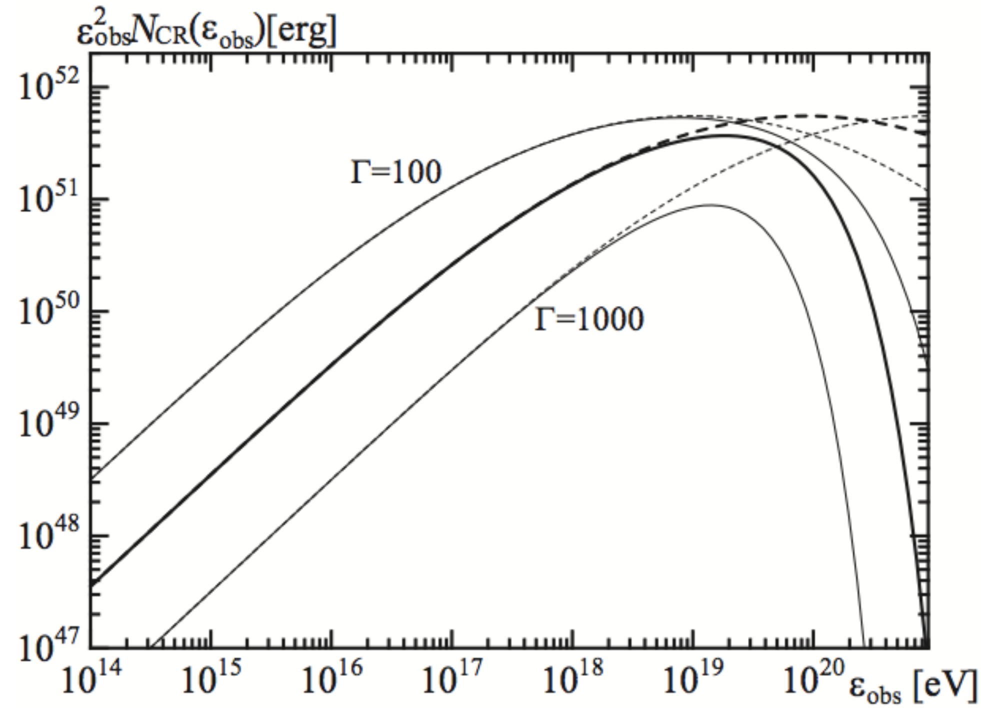


FIG. 2. Model spectra of the UHECRs escaping from a GRB. The thick lines are the spectrum for the parameters $L_{52} = \Gamma_{300} = f_B = f_{CR} = \xi_{0.1} = 1$, while the thin lines show the spectra with the same parameters but for different values of Γ. The dashed lines are the spectra neglecting the exponential cut-off due to the maximum energy determined by the eddy size.

so that

- Below ε_{max} this Fermi 2nd order gives a ***much harder*** spectrum than the usual one of p=2 for Fermi 1st.

- Total energy needed down to ε_{min} is ***much less*** than with p=2

(Harder e^- spectra from Fermi 2nd, see, e.g, Bykov & Mészáros, 1996, ApJ(Lett)461, L37; or Murase, et al, 2013, ApJ, 746, 164)

Model CR spectra (ii)

$$\phi(L_\gamma) \propto \begin{cases} \left(\frac{L_\gamma}{L_*}\right)^{-0.17} & \text{for } L_\gamma \le L_* \\ \left(\frac{L_\gamma}{L_*}\right)^{-1.44} & \text{for } L_\gamma > L_* \end{cases}$$

TABLE I. Model parameters.

Model	A	B	C	D
f_{CR}	10	10	U.M.[a]	U.M.
Γ	300	$72.1 L_{52}^{0.49}$	300	$72.1 L_{52}^{0.49}$
LLC[b]	30.0%	45.8%	92.3%	100%

[a] Universal CR luminosity model expressed in Eq. (24)
[b] The UHECR contribution from GRBs with $L \le L_*$ at $10^{18.5}$ eV (Low Luminosity Contribution).

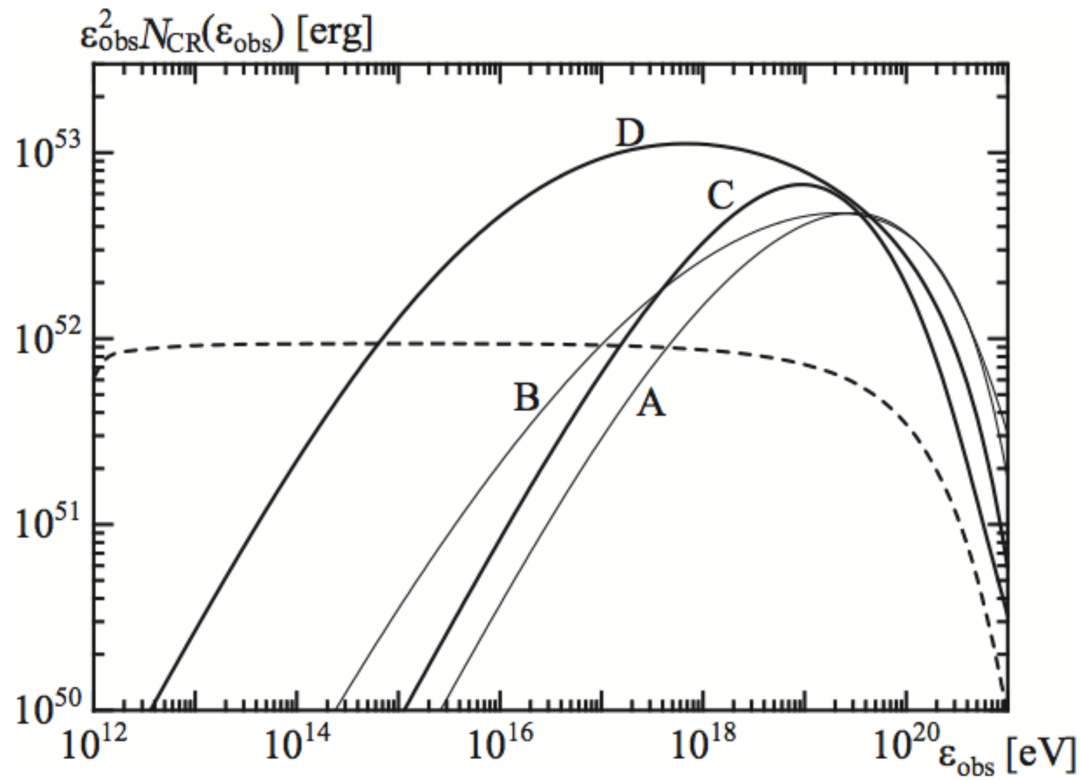


FIG. 3. The average UHECR spectra per burst for the parameter sets shown in Table I. The thin lines are for the models A and B, while the thick lines are for the models C and D. The dashed line is the average UHECR spectrum for the shock acceleration model adopted in Asano and Mészáros [22], in which $f_{CR} = 10$, $f_B = 0.1$, and $\Gamma_{300} = 1$ with the same luminosity function.

What about the other objections?

- (2) If ***assume same*** shocks accelerate ***CRs*** (and do $p,\gamma \to \nu$) as those which produce the ***γ-rays***: $\Rightarrow$GRBs in Swift time windows ***over-produce ν's***(2)

- (3) IceCube stacking analysis: $\leq$ ***1%*** of UHENUs can be coming from Swift EM-triggered GRBs

Possible solution to (2,3) :

$\neq$ CR & γ regions

(Asano & Mészáros, 2016, PRD 94, 023005)

Accel. site & ν-production

- The **accelerating shock** (***CRs, νs)*** could be, e.g., external shock:

$$R_{\rm dec} = \left(\frac{3E_{\rm tot}}{4\pi n m_{\rm p} c^2 \Gamma^2}\right)^{1/3}$$
$$\simeq 1.46 \times 10^{17} n_0 \left(\frac{E_{\rm tot}}{10^{53.5}\ {\rm erg}}\right)^{1/3} \left(\frac{\Gamma}{127}\right)^{-2/3} {\rm cm},$$

Or could be a larger radius internal shock, e.g.

$R_{is} = 2\, c\, \Gamma^2\, \Delta t \gtrsim 10^{16}\, (\Gamma/127)^2\, (\Delta t/10s)$ cm

- ***But*** the bulk of ***photon radiation (γs)*** could be from a ≠ **region,** e.g. from a **photosphere**,

$R_{ph} = (dM/dt)\kappa/4\pi c\Gamma^2) \sim 6 \times 10^{12}\, L_{52}\, (\Gamma/127)^{-3}$ cm,

(i.e., way below the CR, ν production region)

so that...

Neutrino efficiency is reduced

- First, if γ emission is short, photons may have escaped before outer shocks occur
$\Rightarrow$ no pγ

- Even if duration is longer than $(R/c\Gamma^2)$, photon density will be much diluted, and
$\Rightarrow$ pγ efficiency is significantly reduced

Diffuse CR-NU spectrum

$$R_{\rm GRB}(z) \propto (1+z)^{2.1} \text{ for } z \leq 3.0 \text{ and } \propto (1+z)^{-1.4} \text{ for } z > 3.0$$

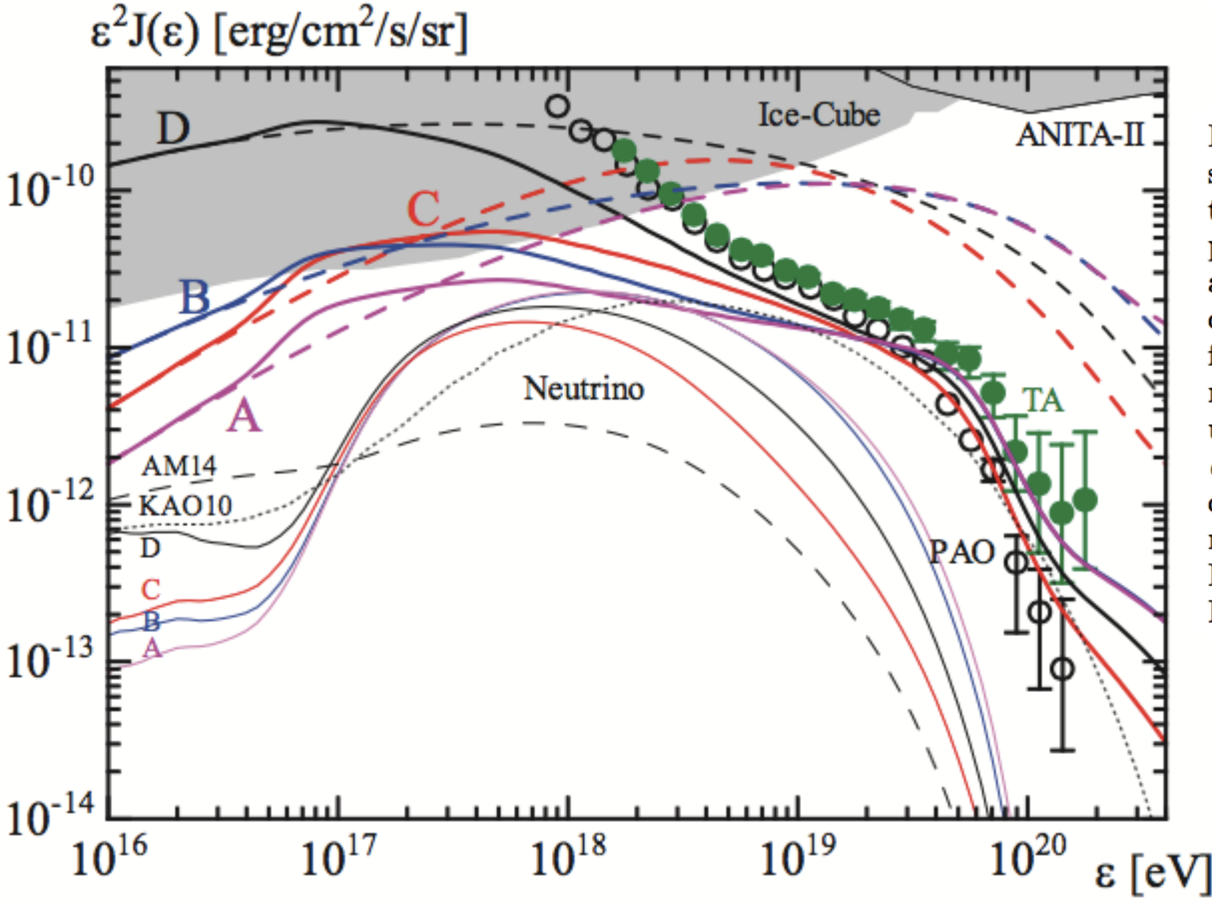


FIG. 4. The diffuse UHECR spectra for models A–D (thick solid lines). The thick dashed lines are spectra neglecting the effects of photomeson production and Bethe–Heitler pair production. The observed data for the UHECR intensities are taken from Schulz [78] for Pierre Auger observatory (open circles) and Abu-Zayyad *et al.* [79] for Telescope Array (green filled circles). The thin lines show the all-flavour cosmogenic neutrino intensities for the models A–D, which are below the upper limits (grey shaded area) by IceCube taken from Heinze *et al.* [80] based on Ishihara [81], and ANITA-II [82]. For comparison, we also plot the model spectra of the cosmogenic neutrinos by Kotera *et al.* [83] (thin dotted line, denoted as KAO10) and prompt plus cosmogenic neutrinos by Asano and Mészáros [22] (thin dashed line, denoted as AM14).

(Asano & Mészáros, 2016, PRD 94, 023005)

Can explain 10^{19}-10^{20} eV CRs and IceCube constraint so:

[B] CONCLUSION for GRB UHECRs

- *Classical GRBs may:*
- Provide the 10^{18}-10^{20} eV UHECR flux
- Not requiring excessive energy $(L_p/L_\gamma) \leq 10$
- Maintaining observed γ-ray (Band) spectrum
- Satisfying (amply) the IceCube neutrino limits

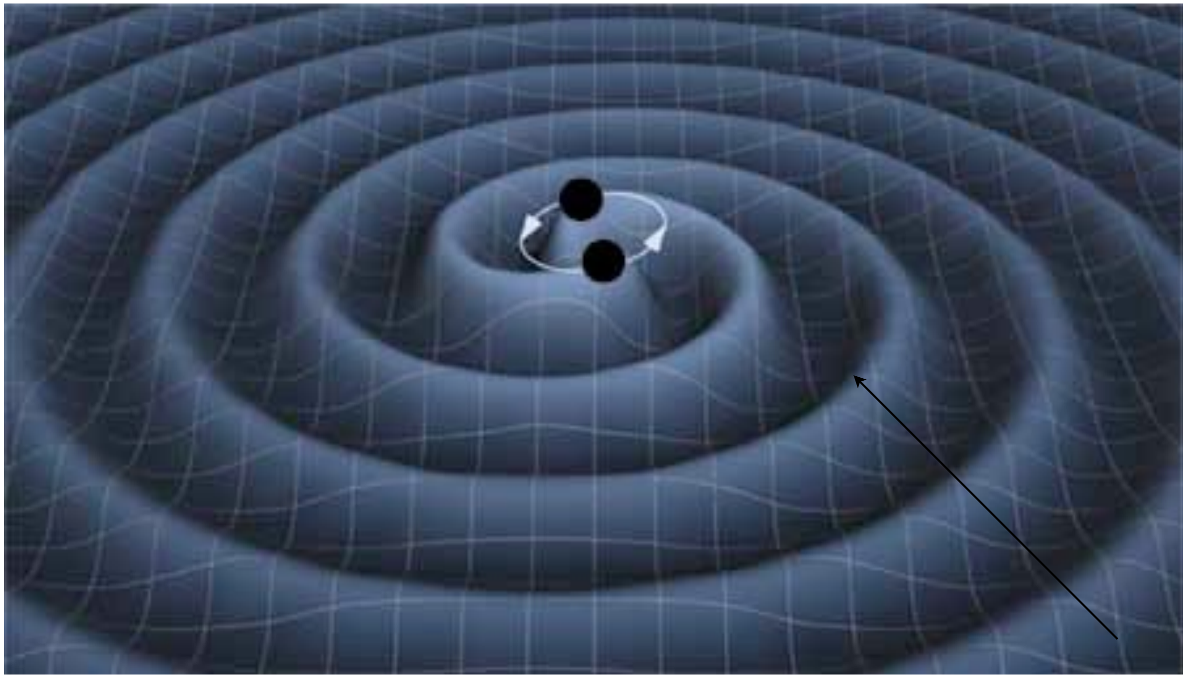
a third multi-messenger:

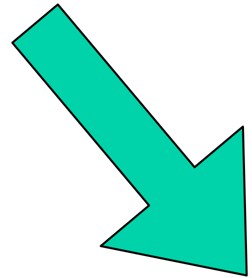
GRB are likely to emit [C]

GWs

(at least the SGRBs, if they are compact binary mergers)

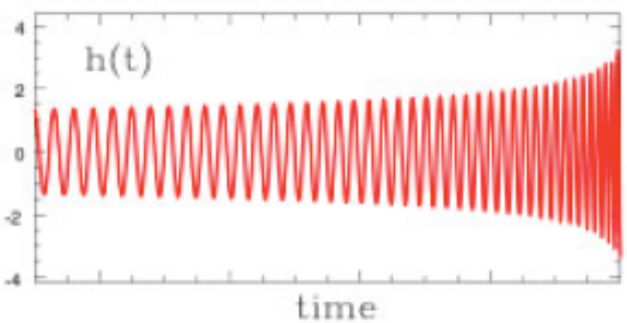
Short GRB- DNS inspiral





GWs

Last few minutes of BNS inspiral signal has a "chirp" waveform in frequency range 40 Hz ~ 2 kHz



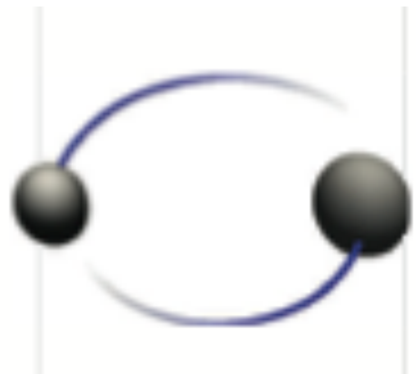
If SGRB are indeed DNS or BH-NS mergers, A-LIGO/A-VIRGO should find few/year

Simple astrophysical GRB GW model:

either bin.merger or collapsar:
⇒ as if blobs orbiting

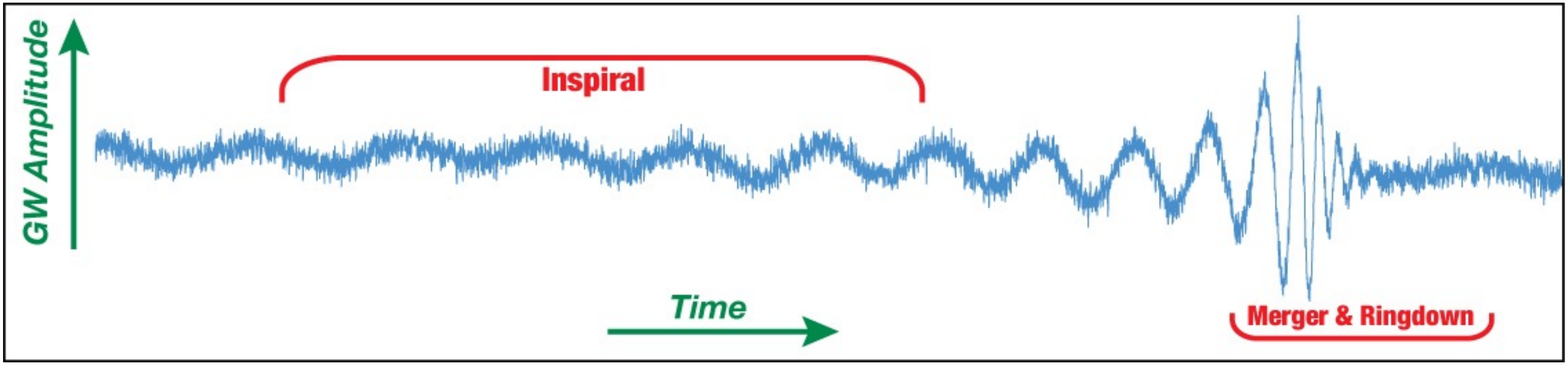
(fast rot. → instab. → blobs → merge ;

or: double NS, NS/BH: blobs → merge)

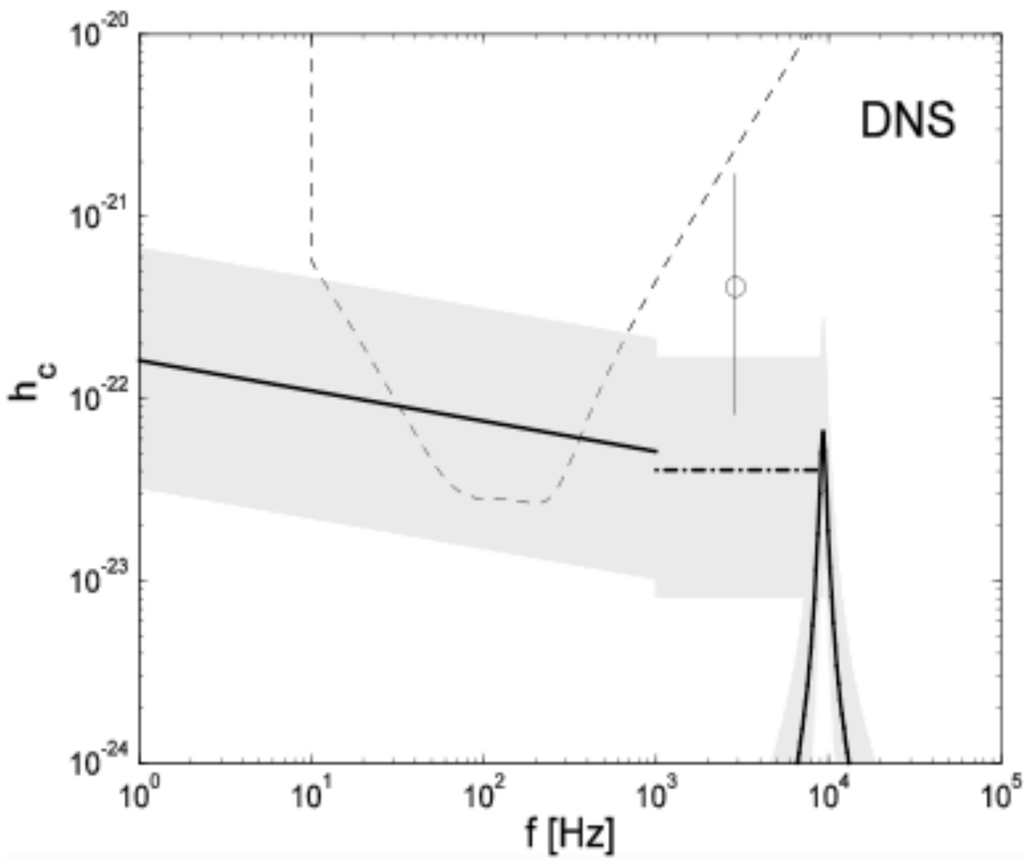


3 Phases of Rotating Collapse

- In-spiral (binaries, or core blobs)
- Merger - central condensation + disk, subject to instabilities (again blobs?)
- Ring-down



GRB Progenitor GW Signals: DNS



Dashed: LIGO II sensitivity

Double neutron star

Charact. Strain h_c

D (avg) =220 Mpc,

$m_1=m_2=1.4\ M_\odot$

$a=0.98$, $e_m=0.05$,

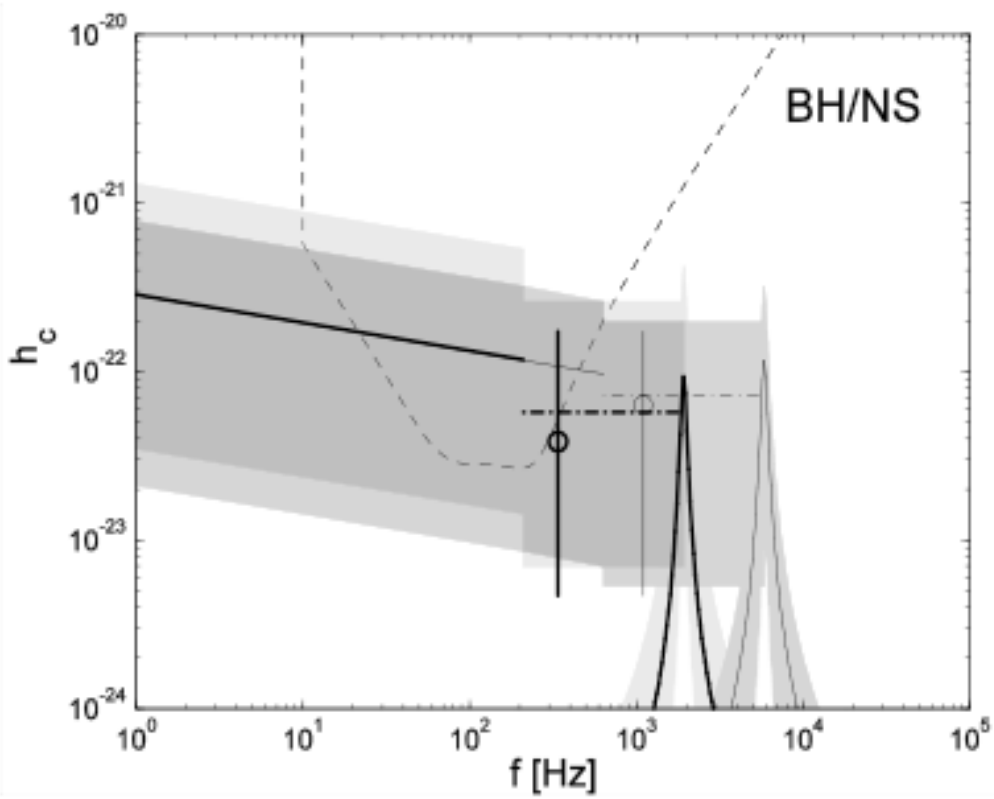
$m=m'=2.8\ M_\odot$, $N=10$,

$e_r=0.01$

Solid: inspiral; Dot-dash: merger;
Circle (bar inst); Spike: ring-down);
Shaded region: rate/distance uncertainty

Kobayashi & Mészáros, 02, ApJ 589:861

GRB Progenitor GW Signals: BHNS



Solid: inspiral; Dot-dash: merger; circle (bar inst); spike: ring-down); shaded region: rate/dist uncertainty
Dashed: LIGO II noise $[f\, S_h(f)]^{1/2}$

Black hole-neutron star

thin: =170Mpc,
m_1=3.0 $M_\odot$, m_2=1.4 $M_\odot$,
m=0.5 $M_\odot$, m'=4 $M_\odot$
thick: d=280Mpc,
m_1=12 $M_\odot$, m_2=1.4 $M_\odot$
m=0.5 $M_\odot$, m'=13 $M_\odot$;
Both: a=0.98, e_m=0.05,
N=10, e_r =0.01

aLIGO exp. BNS det.

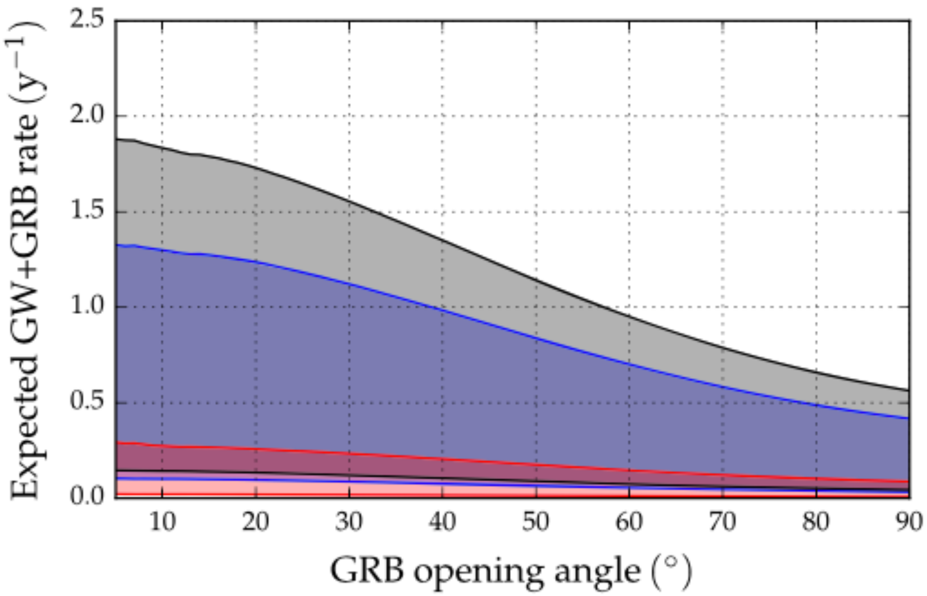


Figure 2. Expected rate of observed gravitational wave–GRB signals when the LIGO and Virgo detectors are operating at their design sensitivity. We take the intrinsic short GRB rate to be in the range $(1\text{–}10) \times 10^{-9}\,\mathrm{Mpc}^{-3}\,\mathrm{yr}^{-1}$ and assume that BNS are the progenitor source of all short GRBs. The gray region shows the range of expected rates with all-sky GRB coverage. The observed rate increases with a small opening angle as the systems are close to face on and thus have the maximum gravitational wave emission. The blue region shows the expected rate for joint observations with *Fermi* GBM and the red region for *Swift* BAT. For preferred opening angles (less than 30°) we expect to see at least one GRB per year in coincidence with *Fermi* GBM.

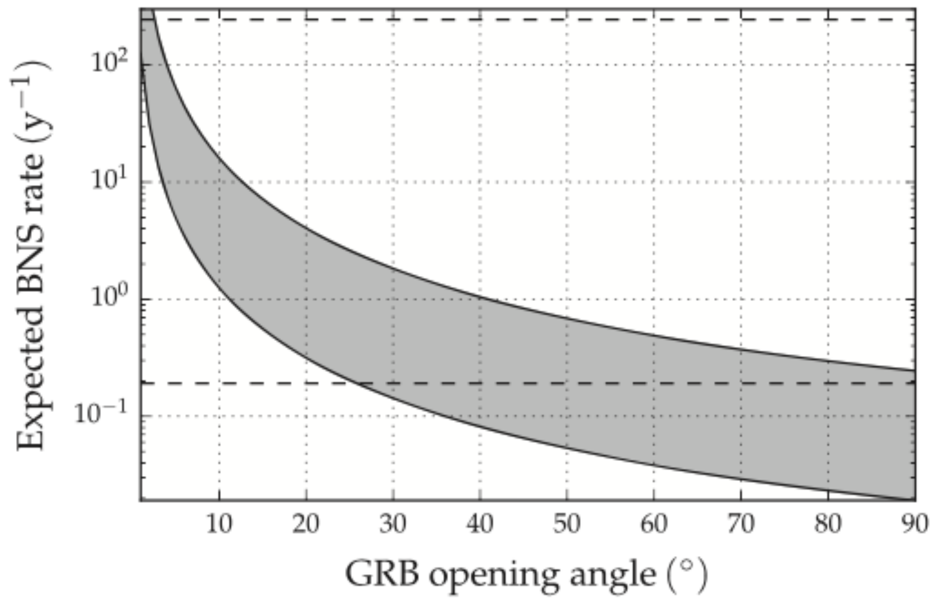
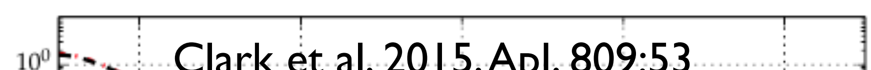


Figure 3. Expected rate of observed BNS signals when the LIGO and Virgo detectors are operating at their design sensitivity. We take the intrinsic GRB rate to be in the range $110 \times 10^{-9}\,\mathrm{Mpc}^{-3}\,\mathrm{yr}^{-1}$. The rate increases with smaller opening angles as this implies a greater fraction of sources which are not observed as GRBs. The horizontal lines bound the predicted number of observations based upon estimates of BNS rates. At the largest opening angles, only the higher GRB rates are consistent with the BNS predictions.



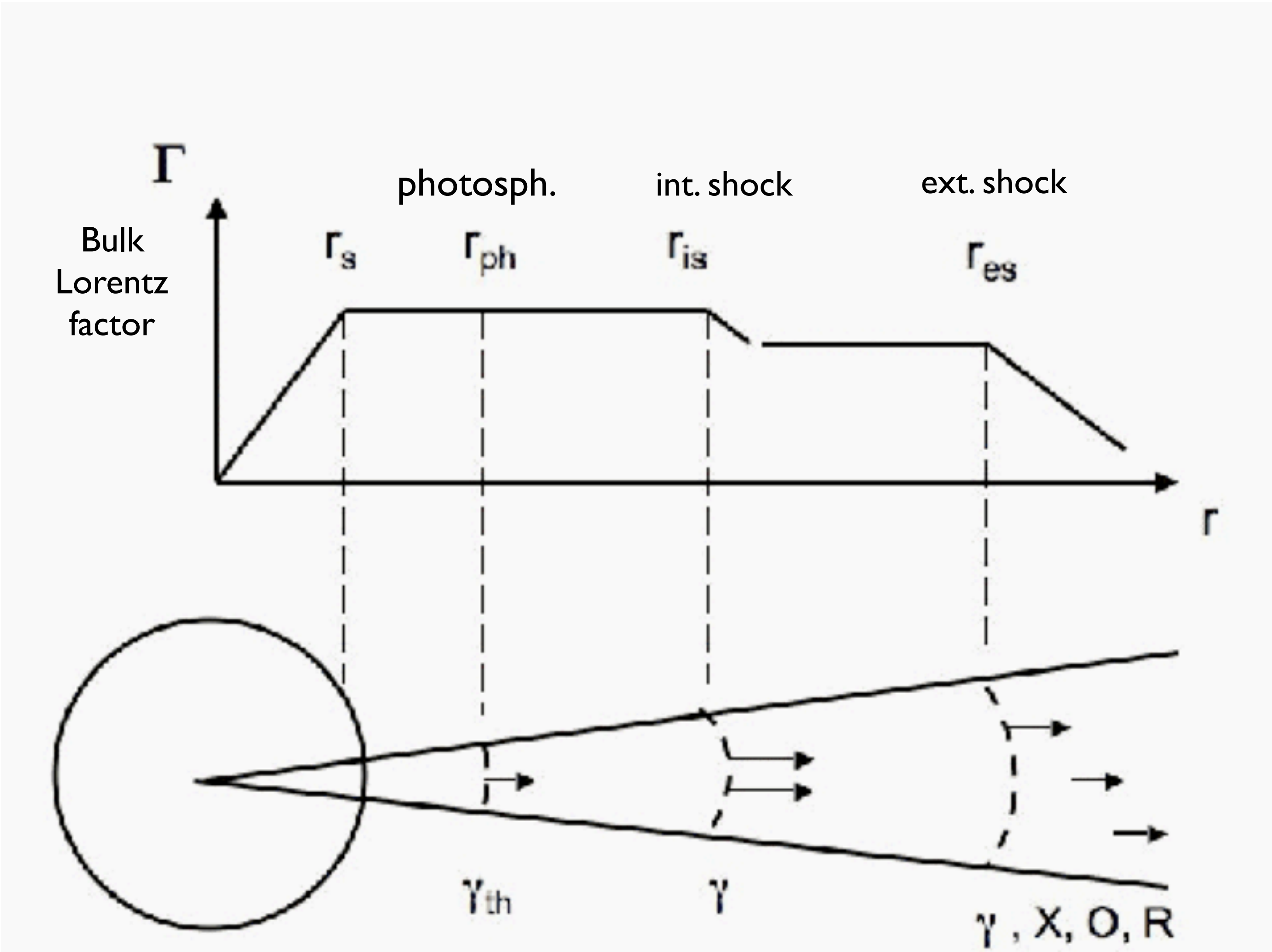
Clark et al, 2015, ApJ, 809:53

Current status:

- **GWs from BH-BH detected !**
- **[C] are waiting for BH-NS or NS-NS GW detections .....**

Thanks!

Photosphere-Int.Sh.-Ext.Sh.



possible γ-emission from 3 zones: photosphere, IS, ES

What can cause Photospheric Dissipation ?

- MHD reconnection, accel. → rel. $e^{\pm}$, γ
- Shocks @ photosphere (& below, above) → same
- ***p-n*** decoupling (⊥, ||), ***inelastic nuclear*** collisions → relativistic $e^{\pm}$, γ
- Magnetic reconnection, $e^{\pm}$, ***p^{+} acceleration*** → relativistic $e^{\pm}$, γ, ν

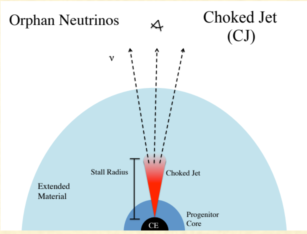
IS w. hadronic cascades, I

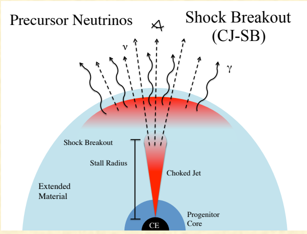
(Time indep.)

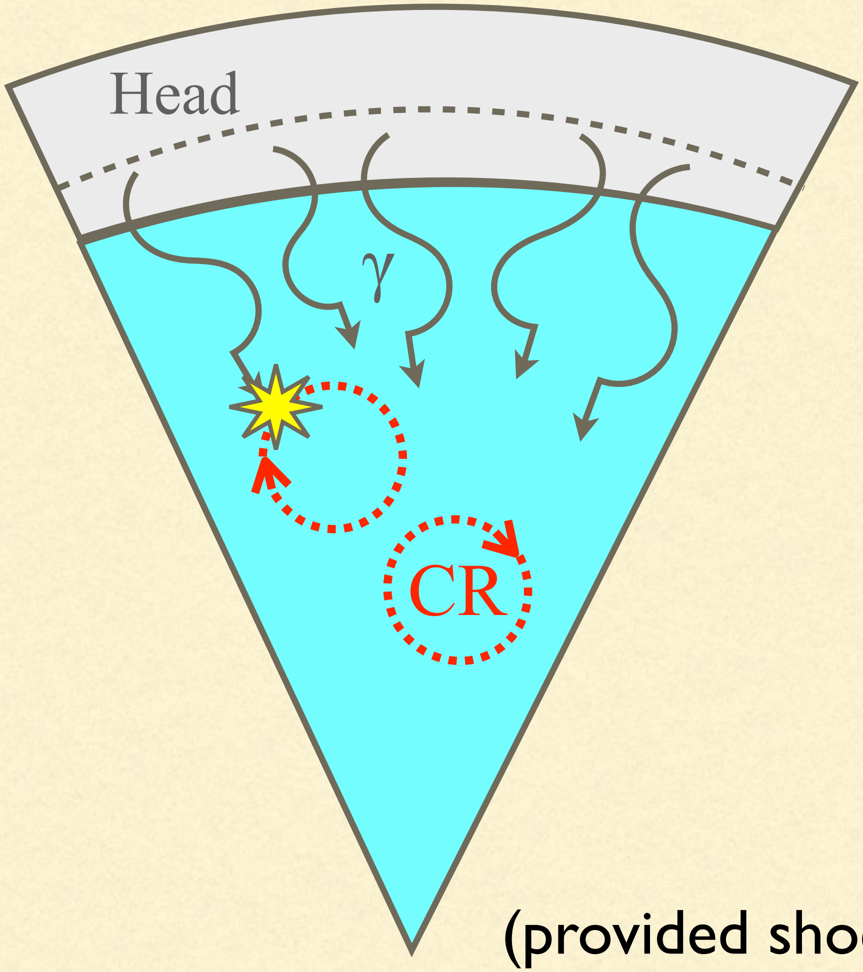
Murase, Asano, Terasawa & PM'12, ApJ746:164

- Assume dissipation region at R_0 (photosphere, IS, etc.)
- Inject Fermi (1st ord) accelerated e^-, p^+ , spectrum~E^{-2}
- Allow cool, subject to ***Sy, IC, pair-form., photomeson***
- Secondary leptons are ***reaccelerated*** by scattering on turbulence/MHD waves behind shocks
- Modulo some plausible assumptions about mag. field growth, turbulence, etc, reaccelerated lepton spectrum leads to a ***self-consistent*** "Band" photon spectrum plus a ***2nd hard*** high en. power law, ~ similar to Fermi LAT.
- ***Good radiative*** efficiency, IceCube ✔, **but** not up to GZK (time-indep.; if do time-dep., Asano-PM'14, get GZK as well)

CJ NEUTRINOS FROM pγ INTERACTIONS







- The plasma surrounding the jet is optically thick
- The dominant photon field for pγ interactions is from photons generated in the jet head

$$kT_j \simeq 5.3 \text{ keV } \Gamma_{\text{rel},1.2}$$

$$U_{\gamma,j} \sim \Gamma_{\text{rel}}^2 U_{\gamma,h}$$

(provided shocks NOT radiation dominated, i.e. LLGRBs)

CR-nu-ph. spectrum single GRB

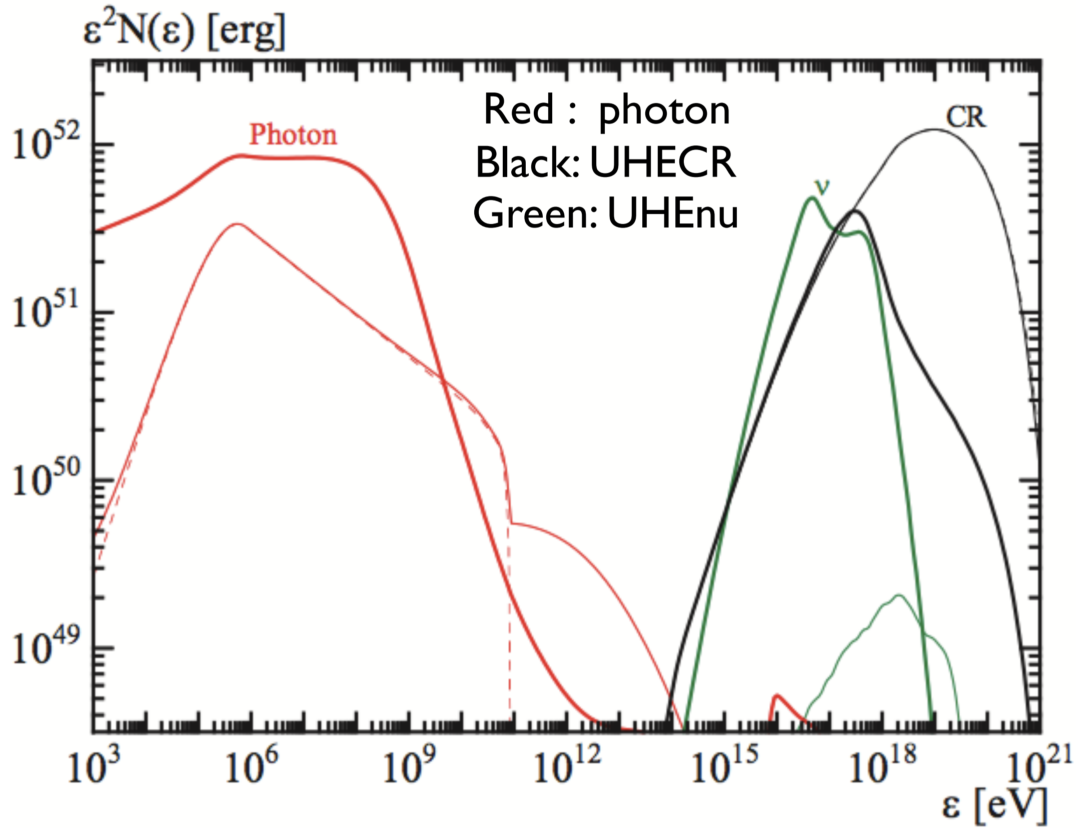
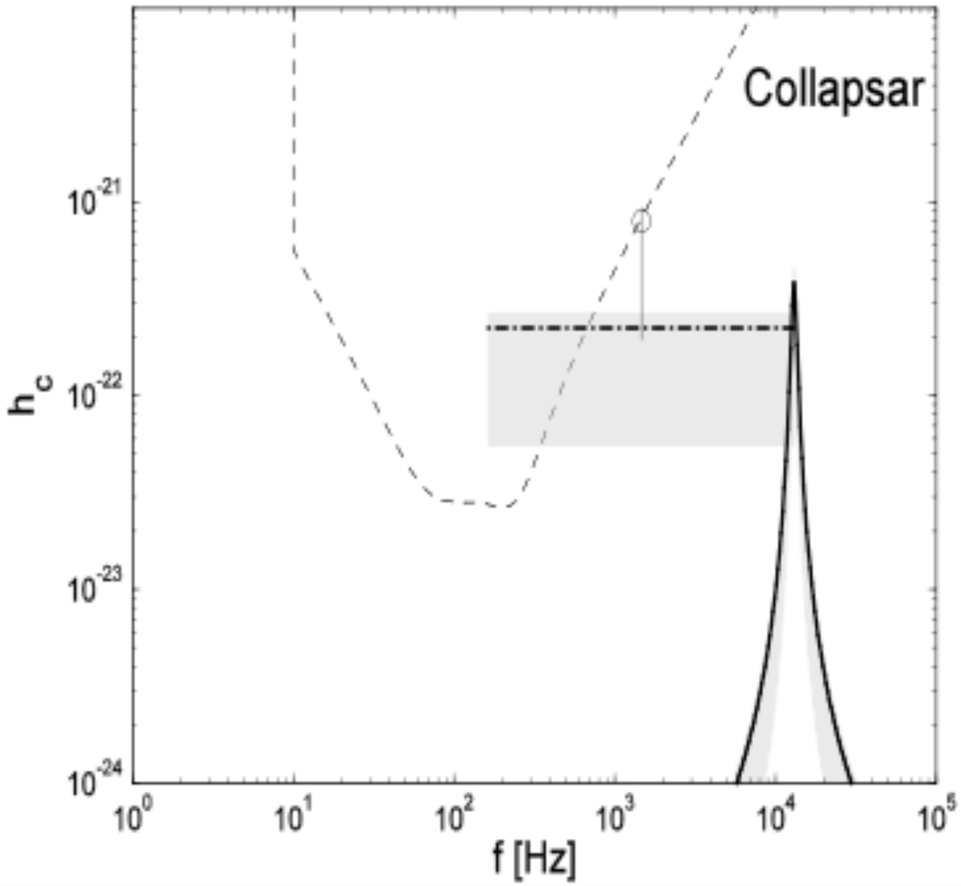


FIG. 5. The final photon (red), cosmic-ray (black), and neutrino (green) spectra from a GRB with $E_\gamma = 2 \times 10^{52}$ erg and $\Gamma = 127$. The assumed radii of the UHECR acceleration site are 10^{15} cm (thick line), 10^{16} cm (thin line), and 10^{17} cm (dashed line), respectively. The dashed lines for photon and cosmic-ray mostly overlap with the thin lines. The photon spectrum for 10^{17} cm is almost the input shape of the Band function. The dashed line for neutrino is far below the plot range of this figure.

(Asano & Mészáros, 2016, PRD 94, 023005)

- $R_{CR}=10^{15}$ (thick), 10^{16} (thin), 10^{17} (dashed)
- $R_{CR}=10^{15}$ (thick) can be ruled out, because: (1) RCR photons overwhelm input Band and wrong shape, and (2) too much neutrino
- R_{CR}=,10^{16} (thin), and 10^{17} (dashed) satisfy all constraints ✔✔

GRB Progenitor GW Signals: Collapsar



Collapsar w. core breakup, bar inst.

(optimistic numbers!)

d=270 Mpc,

$m_1=m_2=1\ M_\odot$, a=0.98,

e_m =0.05,

merge at $r=10^7$ cm;

$m=1\ M_\odot$, $m'= 3\ M_\odot$,

N=10, e_r =0.01

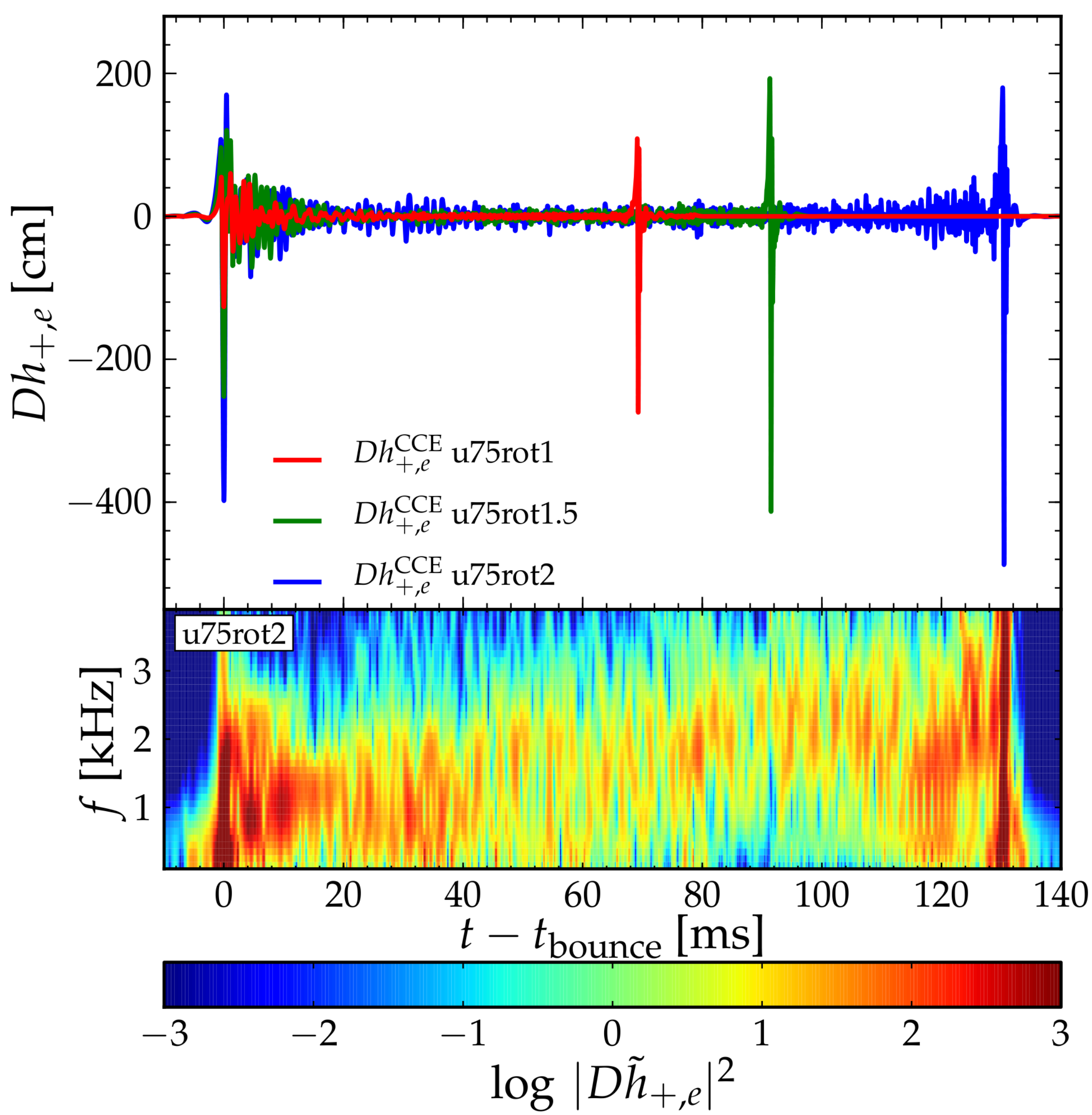
Dashed: LIGO II noise $[f\ S_h(f)]^{1/2}$

Kobayashi & Mészáros 02, ApJ 589, 861

Solid: inspiral; dot-dash: merger;
circle :bar inst; spike: ring-down);
shaded : rate/dist uncertainty

Collapsar GRB GW

C. Ott et al, 2011, PRL106:161103



Chaotic infall: very small quadrupole

← Model u75rot2

Use 75 M⊙ rot. prog.model Woosley-Heger 02, 10-4 Zsun, 3+1 GR calculation

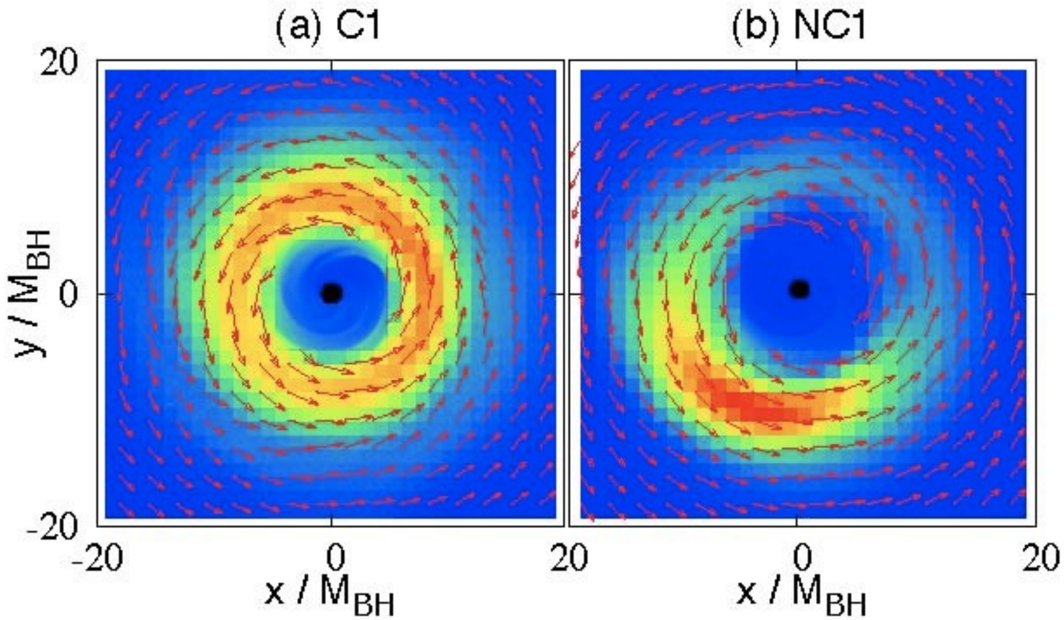
E_{GW}=3.4 10^{-7} M⊙ , f_c=807 Hz

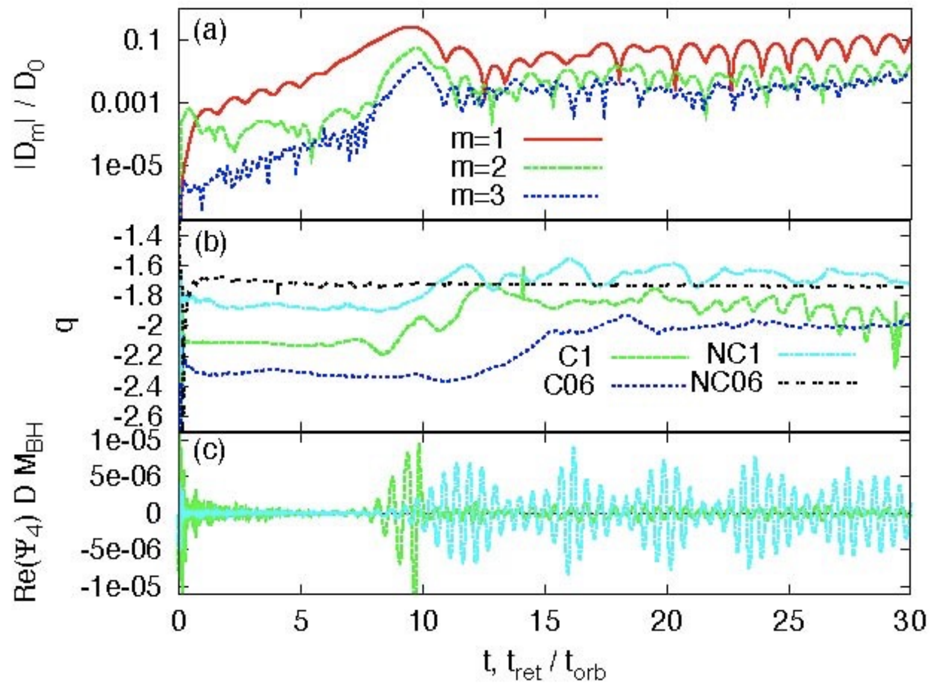
Undetectable unless in Milky Way

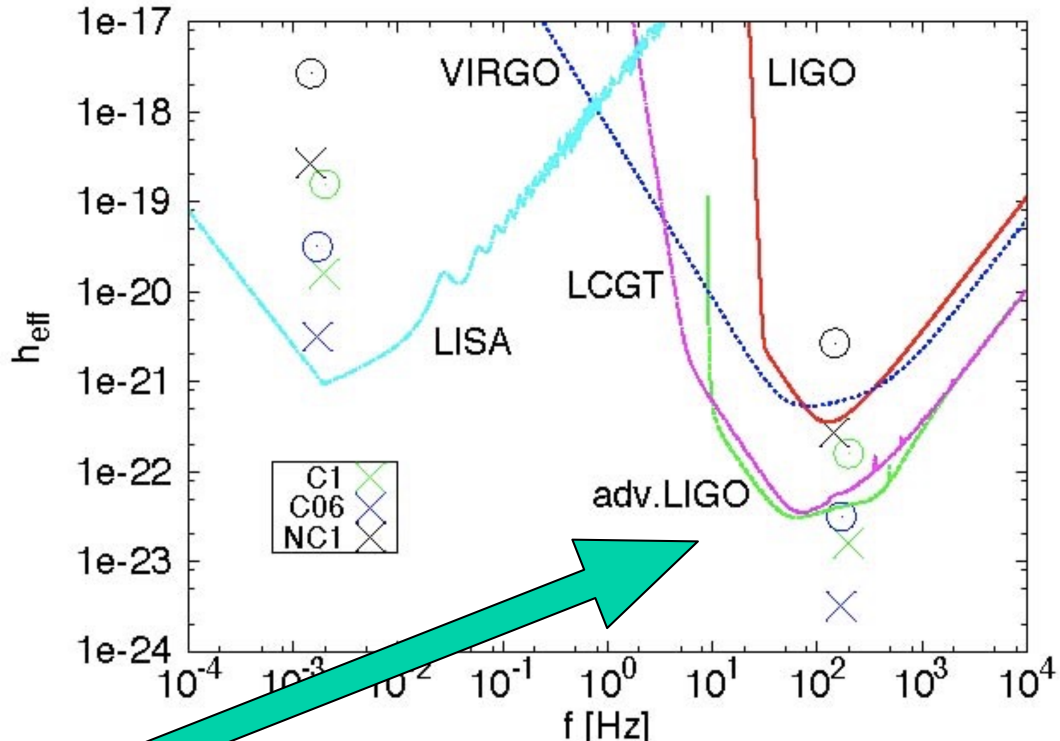
But:

BH-torus in GRB collapsar : Papaloizu-Pringle instability: big quadrupole

Kiuchi, Shibata et al, 2011, PRL 106:251102







Detectable at 100 Mpc…? But no template…