Neutrinos and gravity: multimessenger scenarios

Cecilia Lunardini

Arizona State University

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Introduction

neutrinos and GW in the next 50 years

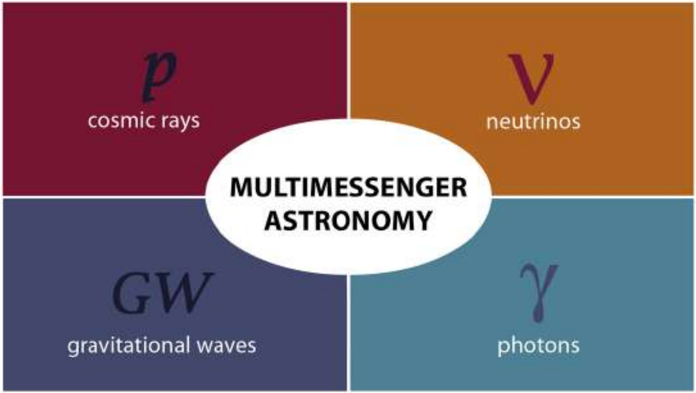
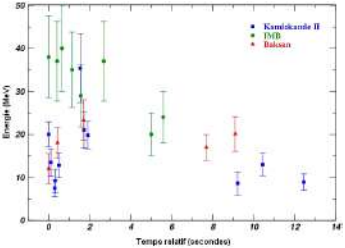


fig. adapted from IceCube collaboration;
article on https://theconversation.com

1987: astronomy triggers supernova neutrino detection

- SN1987A: astronomy provided time window, mass, position and distance of star
- $\mathcal{O}(10)$ MeV neutrino burst found in archival data, confirmed basic supernova physics

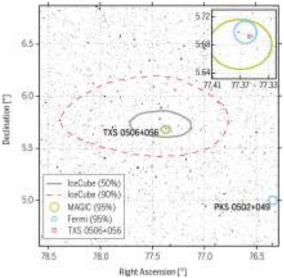


Bionta et al., PRL 58,1987, Hirata et al., PRL 58,1987, Alekseev et al. JETP Lett. 45 (1987)

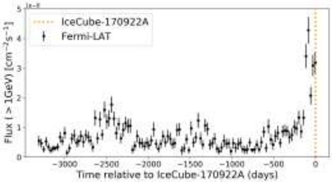
for figs, see http://astro.berkeley.edu/b̃metzger/sn1987a.html

2017: neutrino triggers astronomy observation of AGN flare

- IceCube: observed ~ 290 TeV neutrino provided time and direction
- Fermi-LAT, MAGIC, AGILE, ASAS-SN, HAWC, H.E.S.S and INTEGRAL observed flaring Active Galactic Nucleus



Aartsen et al., Science 361 (2018) 6398, eaat1378



Fermi-LAT Coll., ApJ 846, 2017; fig. from A. Franckowiak, talk at Mainz, 2018

2017: Gravitational waves trigger kilonova/GRB observation

- LIGO-Virgo observation of Neutron-Star binary merger provided localization and timing
- gamma ray follow up discovered kilonova/GRB
    - evidence of r-process nucleosynthesis

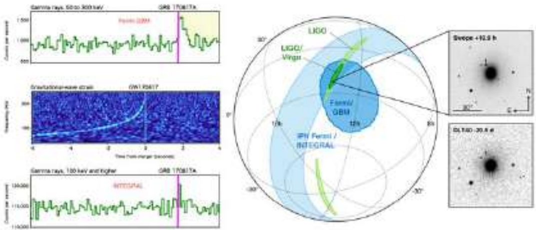


fig. from DeAngelis and Mallamaci, Eur.Phys.J.Plus 133 (2018) 324

Abbott et al. (LIGO and Virgo collab.) Phys. Rev. Lett. 119, 161101 2017
Goldstein et al., Astrophys.J.Lett. 848 (2017);
Savchenko et al., Astrophys.J.Lett. 848 (2017).

Still missing: neutrinos + GW

- several coincidences of neutrinos, photons and cosmic rays have been claimed
- **no** robust neutrino-GW association

The future of GW: opening the sub-Hz regime

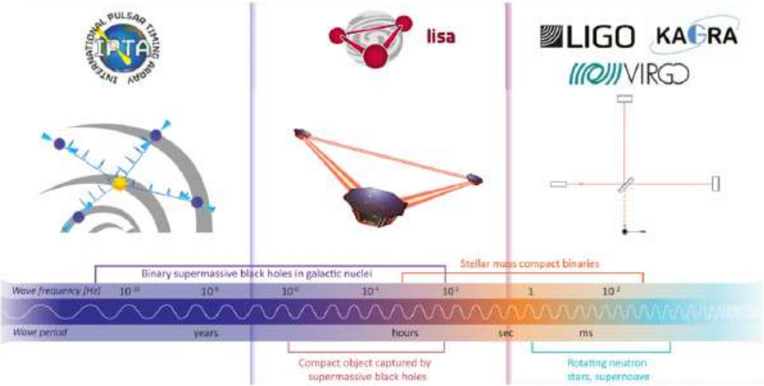


fig. LIGO/Sonoma State University/A Simonnet;
article on https://www.innovationnewsnetwork.com

The future of neutrino observatories: larger, cleaner

- $\mathcal{O}(10)$ kt *low background* detectors
    - liquid scintillator, liquid argon
- from 10 kt to Mt mass
- growth of Km^3 detectors
    - Km3NeT, IceCube Gen2, Bajkal, etc.

Towards Mt mass: **HyperKamiokande**

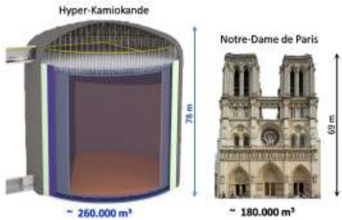
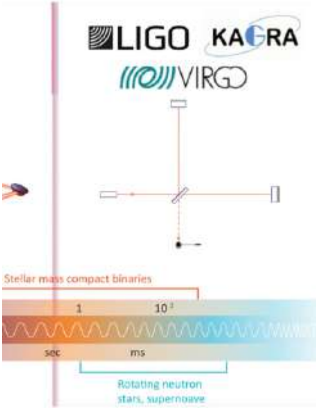


fig: from IN2P3/CNRS

better signal/background ratio, larger distances of sensitivity, larger energy window, better energy resolution

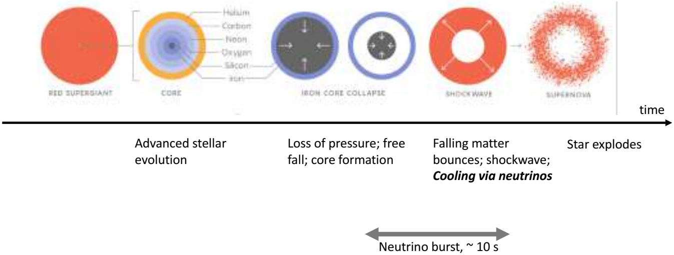
Scenarios for the future:

Core collapse supernovae



Core collapse supenovae: a mini-review

Credit: Lucy Reading-Ikkanda/Quanta Magazine



Advanced stellar evolution

Loss of pressure; free fall; core formation

Falling matter bounces; shockwave; ***Cooling via neutrinos***

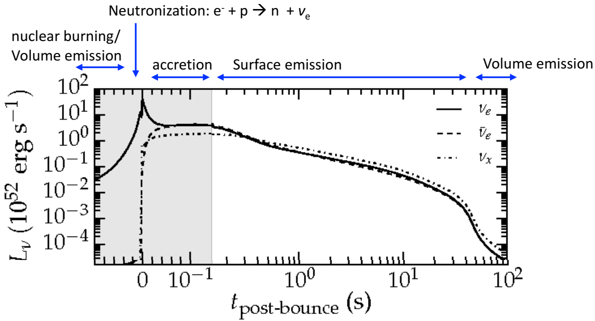
Star explodes

Neutrino burst, ~ 10 s

Stellar death: core collapse

- neutrinos emitted thermally, $\langle E \rangle \simeq 10 - 18$ MeV, radius $R \simeq 100$ Km.
- $E_{tot} \sim 3\ 10^{53}$ ergs emitted in $\mathcal{O}(10)$ s burst.

Phases of neutrino emission: $L_\nu(t)$



Neutronization: $e^- + p \rightarrow n + \nu_e$

nuclear burning/ Volume emission

accretion

Surface emission

Volume emission

fig. from Roberts and Reddy, Handbook of Supernovae, Springer Intl., 2017

- accretion phase: $t \sim 0.003 - 0.5$ s: shockwave is stalled
- cooling phase: $t \sim 0.5 - 40$ s : shockwave re-energized by neutrino energy deposition, launches

GW from core collapse

$f = \mathcal{O}(10^2)$ Hz; observable at LIGO for galactic SN

- **g-mode** : oscillations of protoneutron star (PNS)
- **SASI** (Standing Accretion Shock Instability): large scale sloshing motion of stalled shock front

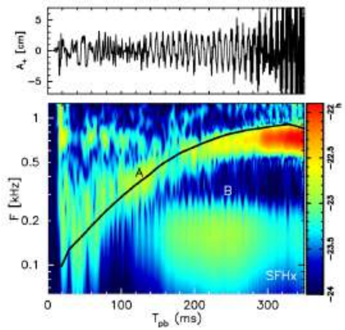
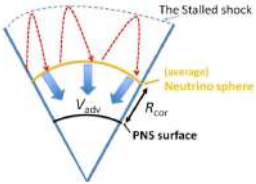


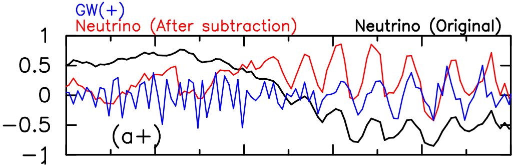
fig. from Kuroda, Kotake and Takiwaki, 2016 ApJL 829 L14

A: g-mode B: SASI

Probing the near-core dynamics: SASI

- Neutrino count at detector oscillates due to SASI
- nu-GW hase shift due to distance between nu-sphere and PNS surface





Kuroda, Kotake, Hayama and Takami, ApJ, 851:62, 2017

References

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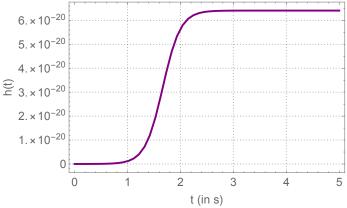
  C. Ott, Class.Quant.Grav. 26 (2009) 063001

  Mirizzi, Tamborra, Janka, Saviano and Scholberg, Riv.Nuovo Cim. 39 (2016) 1-2, 1-112

  Kotake et al., Adv.Astron. 2012 (2012), 428757

The gravitational memory of supernova neutrinos

- a *permanent* distortion of the local space time metric
  - due to *anisotropic* matter/energy emission



$$\boxed{h^{xx}_{TT} = h(t) = \frac{2G}{rc^4}\int_{-\infty}^{t-r/c} dt' L_\nu(t')\alpha(t')}$$

- emission timescale $\Delta t \sim O(10)$ s $\rightarrow$ sub-Hz scale
  - promising for future Deci-Hz detectors!

Probing the near-core dynamics: anisotropy

$$\alpha(t) = \frac{1}{L_\nu(t)} \int_{4\pi} d\Omega' \ \Psi(\vartheta', \varphi') \ \frac{dL_\nu(\Omega', t)}{d\Omega'}$$

develops during accretion, due to convection and SASI

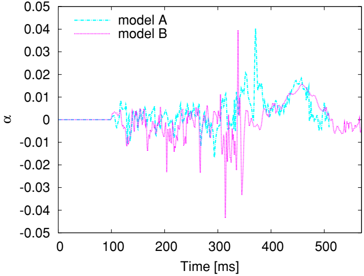


fig. from Kotake, Iwakami, Ohnishi and Yamada, Astrophys. J. 704 (2009) 951

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Turner, Nature 274 (1978) 565.
M. Favata, The gravitational-wave memory effect, Class. Quant. Grav. 27 (2010) 084036

- numerical results and phenomenological works

Burrows and Hayes, PRL 76 (1996) 352
Mueller and Janka, AAP 317 (1997) 140.
Kotake, Iwakami, Ohnishi and Yamada, ApJ 704 (2009) 951
Muller, Janka and Wongwathanarat, Astron. Astrophys. 537 (2012) A63
Yakunin et al., PRD92 (2015) 084040
Vartanyan and Burrows, ApJ 901 (2020) 108
Li, Fuller and Kishimoto, PRD98 (2018) 023002

Building a phenomenological model

M. Mukhopadhyay, C. Cardona and CL, JCAP 07 (2021), 055

- toy $L_\nu(t)$: global shape (only valid locally) :

$$L_\nu(t) = \lambda + \beta \ \exp\left(-\chi\, t\right) \ ,$$

- toy $\alpha(t)$: multi-Gaussian+constant:

$$\alpha(t) = \kappa + \sum_{j=1}^{N} \xi_j \ \exp\left(-\frac{(t-\gamma_j)^2}{2\sigma_j^2}\right) \ ,$$

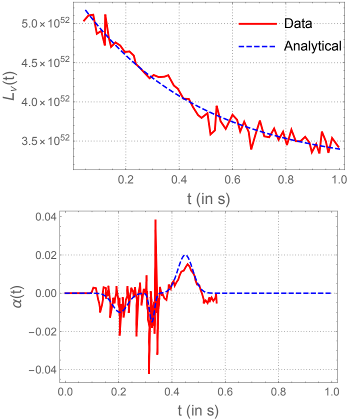
- result: analytical $h(t)$

$$h(t) = \sum_{j=1}^{N} \left\{ \left[h_{1j} \left(\mathrm{erf}\left(\rho_j \ \tau_{1j}\right) + \mathrm{erf}\left(\rho_j (t-\tau_{1j})\right) \right) \right] + \left[h_{2j} \left(\mathrm{erf}\left(\rho_j \ \tau_{2j}\right) + \mathrm{erf}\left(\rho_j (t-\tau_{2j})\right) \right) \right] \right\}$$
$$+ \left[h_3 \left(\frac{\beta}{\chi} \left(1 - \exp\left(-t\chi\right)\right) + \lambda t \right) \right] ,$$

$$\begin{aligned}\tilde{h}(f) \quad &= \textstyle\sum_{j=1}^{N} \left[\left(h_{1j}\, \frac{i}{\pi f} \exp\left(\frac{-\pi^2 f^2}{\rho_j^2}\right) \exp\left(i 2\pi f \tau_{1j}\right) \right) + \left(h_{2j}\, \frac{i}{\pi f} \exp\left(\frac{-\pi^2 f^2}{\rho_j^2}\right) \exp\left(i 2\pi f \tau_{2j}\right) \right) \right] \\ &\qquad + \left(\sqrt{2\pi}\; h_3\, \frac{\beta}{\chi} \left(\frac{1}{i2\pi f} - \frac{1}{-\chi + i2\pi f} \right) \right),\end{aligned}$$

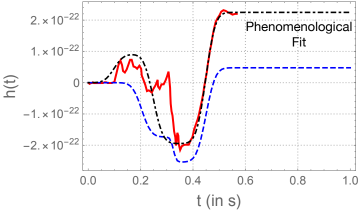
$$\begin{aligned}
h_{1j} &= \frac{2G}{rc^4}\sqrt{\frac{\pi}{2}}\beta\xi_j\sigma_j \exp\left(\frac{\chi}{2}(-2\gamma_j + \sigma_j^2\chi)\right) , \\
\rho_j &= \frac{1}{\sqrt{2}\sigma_j} , \\
\tau_{1j} &= \gamma_j - \sigma_j^2\chi , \\
h_{2j} &= \frac{2G}{rc^4}\sqrt{\frac{\pi}{2}}\lambda\xi_j\sigma_j , \\
\tau_{2j} &= \gamma_j , \\
h_3 &= \frac{2G}{rc^4}\kappa .
\end{aligned}$$

Comparison with numerical results



top data: Vartanyan and Burrows, Astrophys. J. 901 (2020) 108 ; **bottom** data: Kotake, Iwakami, Ohnishi and Yamada, Astrophys. J. 704 (2009) 951.

- toy model reproduces low frequency trends (relevant for Deci-Hz detectors)

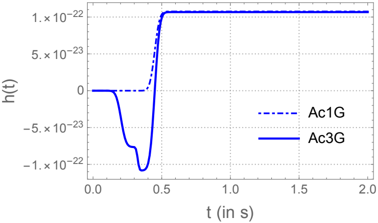


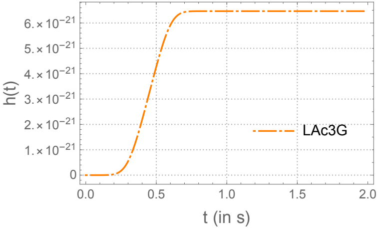
Data: Kotake, Iwakami, Ohnishi and Yamada, Astrophys. J. 704 (2009) 951.

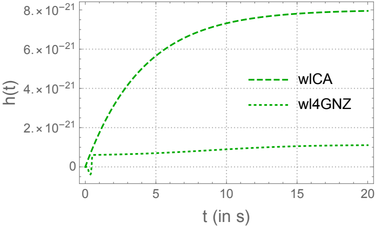
- toy $h(t)$ reproduces numerical result
    - dashed: computed from $L(t)$ and $\alpha(t)$
    - dot-dashed: toy formula for $h(t)$ with effective parameters

Case studies

A- and LA- : anisotropy in accretion phase only ;
w- : anisotropy is non-zero throughout
(D=10 kpc)

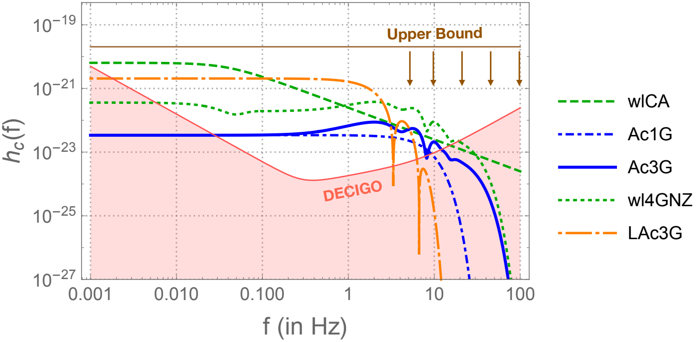






Detectability

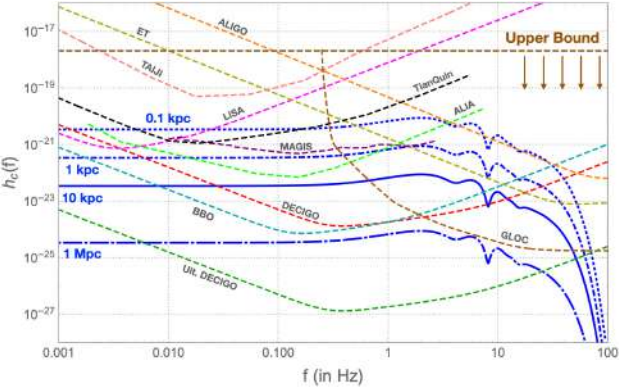
$h_c(f) \equiv 2f|\tilde{h}(f)|$ ($\tilde{h}$: Fourier transform)
A- and LA- : anisotropy in accretion phase only ;
w- : anisotropy is non-zero throughout
(D=10 kpc)



Detectable even in most pessimistic cases!

Summary of detection prospects

Accretion only model, Ac3G. Note sensitivity up to Mpc distance and beyond!

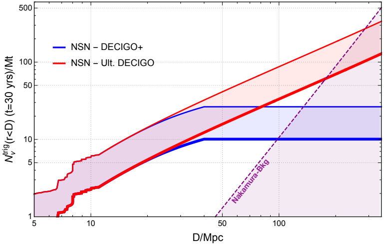


New: memory-triggered neutrino searches?

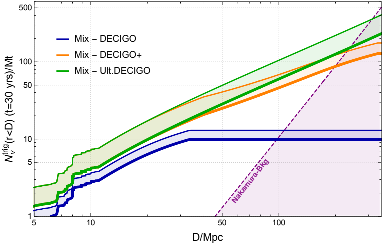
M. Mukhopadhyay, Z. Lin and CL, to appear soon

- detecting neutrinos in *time coincidence* with memory
  - background-free SN neutrino sample from local universe
  - requires O(10) improvement in noise at DECIGO
  - complementary to diffuse (cosmological) flux
    - learn neutrino spectrum of SNe in *local* universe
    - study correlation with star's mass, type, etc.

$N \sim 10 - 400$ neutrino events in 1 Mt water Cherenkov detector in 30 years



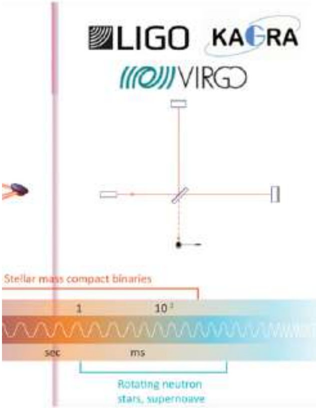
Baseline (conservative) memory scenario



Optimistic memory scenario (some failed SNe?)

Scenarios for the future:

Binary mergers



Matter-rich mergers as neutrino sources

Binary Neutron Star (BNS) or neutron star-black hole (NS-BH)

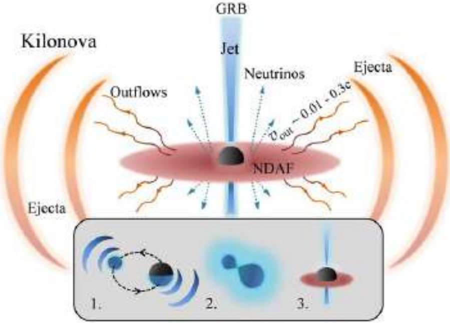


fig. from Yi et al., MNRAS 476, 1, 2018, 683.

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  Fujibayashi, Sekiguchi, Kiuchi, and Shibata, ApJ 846, 114 (2017). 12
  Lippuner, et al., MNRAS 472, 904 (2017).
- phenomenology
  Caballero, McLaughlin and Surman, PRD80, 123004 (2009)
  Schilbach, Caballero, and McLaughlin (2018), arXiv: 1808.03627
  Kyutoku and Kashiyama, PRD97, 103001 (2018).

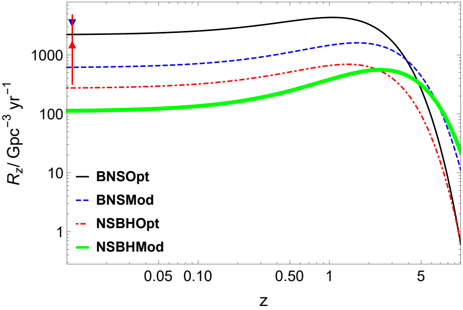
Thermal neutrinos from post-merger phase

- Lower energy budget than SNe: $E^{\nu}_{merger} \sim 0.1 E^{\nu}_{CCNS}$
- E^{ν}_{merger} larger for larger disk mass and for longer-lived, more massive remnant

$T_{99}(s)$	$\mathcal{E}_{\bar{\nu}_e}(10^{51} erg)$	$\langle E_{\bar{\nu}_e}\rangle (MeV)$	type	remnant	Ref.
0.58	4.4	18	BNS	HMNS	J.Lippuner(2017)
0.40	2.0	16.5	BNS	BH	
0.30	1.8	15.4	NSBH	BH	
0.10	1.0	17.8	BNS	BH	O.Just(2015)
0.27	11.2	16	NSBH	BH	
0.99	14	10	BNS	HMNS	S.Fujibayashi(2017)
0.58	40	20	BNS	HMNS	Y.Sekiguchi(2011)
0.08	19.8	24	NSBH	BH	H.T.Janka (1999)
0.16	23.2	28	NSBH	BH	

Merger rates

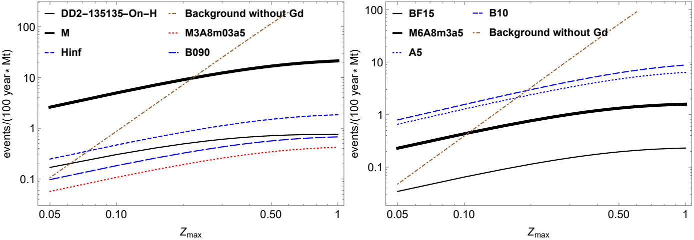
Lower rate than SNe: $R_{merger} \sim (10^{-3} - 10^{-2}) R_{CCNS}$



Mapelli and Giacobbo, MNRAS 479, 4391 (2018) ; Eldridge, Stanway, and Tang, MNRAS 482, 870 (2019).

GW-triggered detection possible!

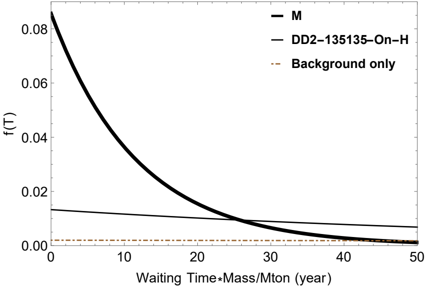
- background abatement is key
- requires Mt mass and decades of operation



Kyutoku and Kashiyama, PRD97, 103001 (2018).

Z. Lin and CL, PRD 101 (2020) 2, 023016

- time of first detection can discriminate between models
- results in 2 decades!

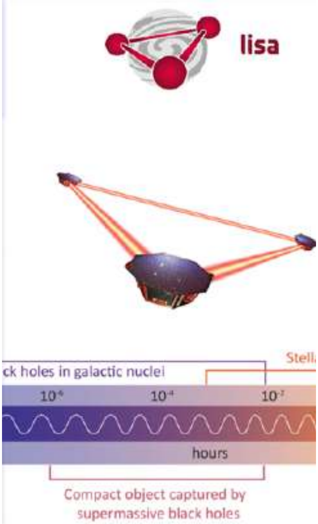


Kyutoku and Kashiyama, PRD97, 103001 (2018).

Z. Lin and CL, PRD 101 (2020) 2, 023016

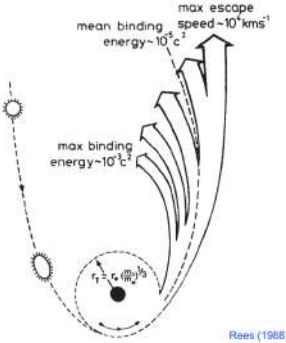
Scenarios for the future:

Tidal Disruption Events



A tidal disruption event (TDE)

- a star-supermassive BH merger
    - $m \simeq M_\odot$, $M \simeq (10^5 - 10^7)\ M_\odot$
- if M$\lesssim 10^{7.2}\ \ M_\odot$, and $r < r_T$ the star is shredded by tidal forces



Rees (1988)

TDE as gravitational wave sources

- TDEs have not been detected in GW
- detectable signal predicted for sub-Hz interferometers (LISA, etc.)
    - amplitude and avg. frequency increase with penetration factor ($\beta = r/r_T$)

D=20 Mpc; $M = 10^6\ M_\odot$; solar type star

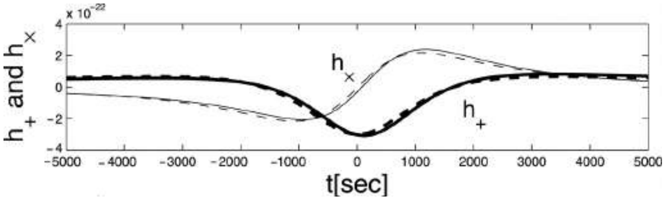


fig. from Kobayashi et al 2004 ApJ 615 855

photons and neutrinos from TDEs

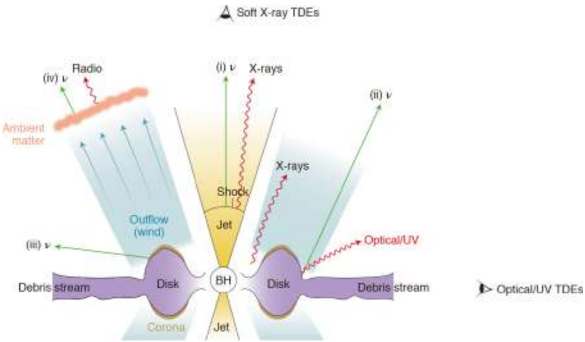


fig. from K. Hayasaki, Nat. Astron. (2021)

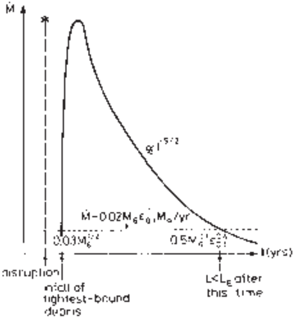
- **accretion disk**: from star's debris; cools in Optical-UV and X-rays
- **outflow**: $v \simeq 0.1c$; emits at radio wavelengths
- **jet**: $v \sim c$, hadron-rich, can form for extreme accretion rates
- high energy neutrinos can come from disk, outflow, jet

A year long transient

Main luminosity scale:

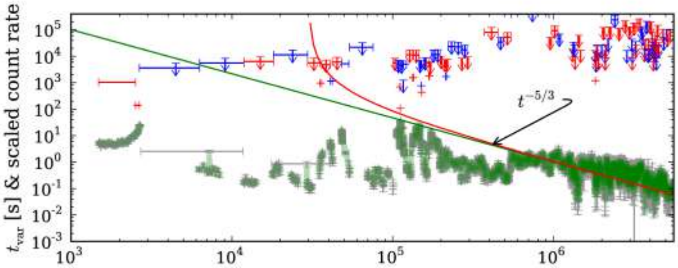
$$L_{\rm Edd} \simeq 1.3\ 10^{44}\ {\rm erg\ s}^{-1} \left(\frac{M}{10^6\ M_\odot}\right)$$

- photon/neutrino flare fades when $\dot{M} < L_{Edd}$ ($\dot{M}$ = mass accretion rate)
    - typical duration $\Delta T \sim \mathcal{O}(0.1 - 1)$ yr



Observations

- $\sim$ 90 candidate TDEs observed
  - most are consistent with thermal emission
  - 3 show evidence of jets (*hard* X-ray spectrum)



Best known *jetted* TDE, Swift J1644+57, Burrows et al., *Nature* **476** (2011) 421

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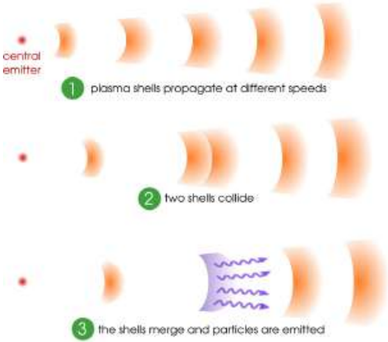
  De Colle et al, *Astrophys. J.* **760** (2012) 103.
  Stone and Metzger, *Mon. Not. Roy. Astron. Soc.* **455** (2016), no. 1 859–883
  Kochanek, `arXiv:1601.06787`.
- Observations
  Komossa, *JHEAp* **7** (2015) 148–157.
  Burrows et al., *Nature* **476** (2011) 421
  Cenko et al., *Astrophys. J.* **753** (2012) 77
  Brown, et al., *Mon. Not. Roy. Astron. Soc.* **452** (2015), no. 4 4297–4306.

- GW predictions
  Kobayashi et al 2004 ApJ 615 855
  Stone, et al., 2020, SSR, 216, 35
  Toscani Rossi and Lodato, 2020, MNRAS, 498, 507
- Connection to Cosmic Rays
  Farrar and Gruzinov, *Astrophys. J.* **693** (2009) 329–332.
  Farrar and Piran, `arXiv:1411.0704`.
  Pfeffer, Kovetz, and Kamionkowski, `arXiv:1512.04959`.
- Connection to HE neutrinos
  Murase 2008, AIP conference series; Murase & Takami 2009, ICRC conference proceedings
  X.-Y. Wang, et al., *Phys. Rev.* **D84** (2011) 081301.
  X.-Y. Wang and R.-Y. Liu, *Phys. Rev.* **D93** (2016), no. 8 083005.
  Dai and Fang, MNRAS 469 (2017) 2, 1354-1359
  Senno, Murase and Meszaros, ApJ 838 (2017) 1, 3
  Lunardini and Winter, PRD 95 (2017) 12, 123001
  Fang, Metzger, Vurm, Aydi & Chomiuk, arXiv:2007.15742
  Hayasaki & Yamazaki, ApJ, 886 114 (2019)
  Winter and Lunardini, arXiv:2005.06097
  Murase, Kimura, Zhang, Oikonomou & Petropoulou, arXiv:2005.08937

High energy neutrinos from TDE jets

Particle acceleration in internal shocks:



Neutrinos from $\pi^{\pm}$ decay chain:

$$p + \gamma \to \pi^{+} + anything, \quad \pi^{+} \to \mu^{+} + \nu_{\mu}, \quad \mu^{+} \to e^{+} + \nu_{e} + \bar{\nu}_{\mu}$$

Bustamante, Baerwald, Murase and Winter, Nat. Comm. 6, 6783 (2015)

Analytics: Δ-resonance approximation

X.-Y. Wang, et al., *Phys. Rev.* **D84** (2011) 081301

- $\nu_\mu + \bar{\nu}_\mu$ and $\nu_e + \bar{\nu}_e$ fluence (no oscillations):

$$\begin{aligned} E^2 F^0_\mu(E) &= \frac{1}{32\pi d_L^2} \frac{E_X \xi_p}{\ln\left(E_{p,\mathrm{max}}/E_{p,\mathrm{min}}\right)} f_{p\gamma} \zeta_\pi (1+\zeta_\mu) \ , \\ E^2 F^0_e(E) &= \frac{1}{32\pi d_L^2} \frac{E_X \xi_p}{\ln\left(E_{p,\mathrm{max}}/E_{p,\mathrm{min}}\right)} f_{p\gamma} \zeta_\pi \zeta_\mu \ . \end{aligned}$$

- pion production efficiency:

$$\begin{aligned} f_{p\gamma} &\simeq 0.35 \left(\frac{L_X}{10^{47.5}\ \mathrm{erg\, s^{-1}}} \right) \left(\frac{\Gamma}{10} \right)^{-4} \left(\frac{t_v}{10^2\ \mathrm{s}} \right)^{-1} \left(\frac{\epsilon_b}{\mathrm{KeV}} \right)^{-1} \\ &\times \begin{cases} (E_p/E_{pb})^{\beta-1} & \mathrm{for} \quad E_p < E_{p,\mathrm{br}} \\ (E_p/E_{pb})^{\alpha-1} & \mathrm{for} \quad E_p \geq E_{p,\mathrm{br}} \end{cases} \end{aligned}$$

$$E_{p,\mathrm{br}} = 1.5\ 10^7 \mathrm{GeV} \ \left(\frac{\Gamma}{10}\right)^2 \left(\frac{1\ \mathrm{KeV}}{\epsilon_{X,\mathrm{br}}}\right)$$

- damping due to $\pi^\pm$ and $\mu^\pm$ cooling before decay:

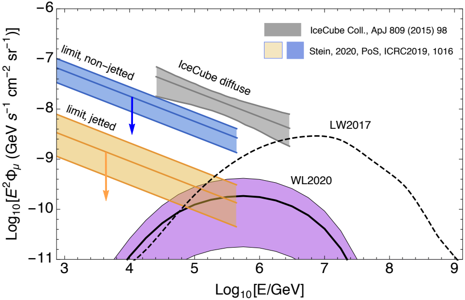
$$\left\{ \begin{array}{ll} \zeta_\pi = 1 & \text{for } E_\pi \lesssim E_{\pi,\mathrm{br}} \\ \zeta_\pi \propto E_\pi^{-2} & \text{for } E_\pi \gtrsim E_{\pi,\mathrm{br}} \end{array} \right. \qquad \left\{ \begin{array}{ll} \zeta_\mu = 1 & \text{for } E_\mu \lesssim E_{\mu,\mathrm{br}} \\ \zeta_\mu \propto E_\mu^{-2} & \text{for } E_\mu \gtrsim E_{\mu,\mathrm{br}} \end{array} \right.$$

$$E_{\pi,\mathrm{br}} \simeq 5.8 \times 10^8 \ \mathrm{GeV} \left(\frac{L_X}{10^{47.5} \ \mathrm{erg\,s^{-1}}} \right)^{-\frac{1}{2}} \left(\frac{\xi_B}{1} \right)^{-\frac{1}{2}} \left(\frac{\Gamma}{10} \right)^4 \left(\frac{t_v}{10^2 \ s} \right)$$

$$E_{\mu,\mathrm{br}} \simeq 3.1 \times 10^7 \ \mathrm{GeV} \left(\frac{L_X}{10^{47.5} \ \mathrm{erg\,s^{-1}}} \right)^{-\frac{1}{2}} \left(\frac{\xi_B}{1} \right)^{-\frac{1}{2}} \left(\frac{\Gamma}{10} \right)^4 \left(\frac{t_v}{10^2 \ s} \right)$$

Bounds from IceCube

TDEs contribute to up to $\sim 26\%$ of the diffuse astrophysical flux at IceCube.

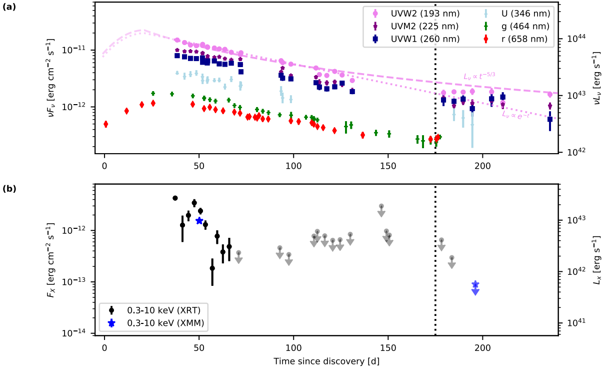


R. Stein, PoS ICRC2019, 1016 (2020)

A neutrino-TDE coincidence

- TDE AT2019dsg ("Bran Stark") is likely the source of the IceCube neutrino IC191001A ($E \sim 200$ TeV)
  - discovered in follow up search with the Zwicky Trasient Facility (ZTF)
  - p-value of 0.2% to 0.5% of random association; $\sim 3\sigma$ significance.

R. Stein et al., Nat Astron 5, 510-518 (2021)

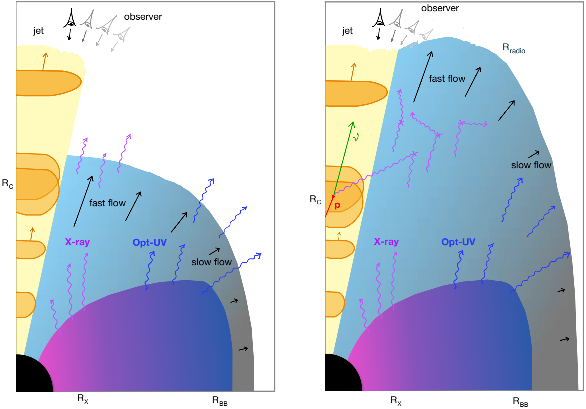


- L_{BB} exponential (or power-law) decay ($\tau \sim 60$ days), late time flattening
- L_X *faster* exponential decay ($\tau \sim 10$ days), upper limits only at late times
- *150 days delay* between the neutrino event and the photon peak

van Velzen, et al., arXiv:2001.01409, R. Stein et al., Nat Astron 5, 510-518 (2021)

A concordance *jetted* model: concept

Walter Winter and Cecilia Lunardini, arXiv:2005.06097



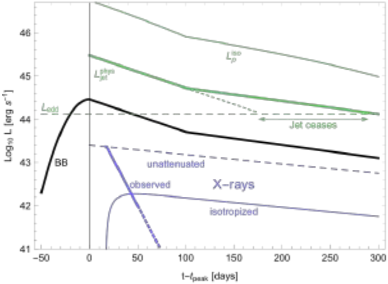
Left: early times ($t \lesssim 17 days$); Right: late times ($t \gtrsim 17 days$)

Main features, motivation

- *Idea: direct link between late time X-ray and neutrino emission*
    - fast dimming in X-rays suggests increasingly strong absorption
    - the same absorption could favor neutrino production at late times, *if the backscattered X-rays photons are the targets for $p\gamma$ scattering!*
- uses scalings with BH mass from Unified TDE Model, which matches the data for $M \simeq 10^6\ M_\odot$

Dai, McKinney, Roth, Ramirez-Ruiz, & Miller, Astrophys. J. 859, L20 (2018)

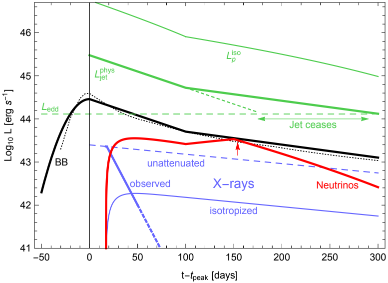
Input time profiles



- L_{BB} and jet luminosities: from observation or Unified model scalings
- X-ray unattenuated: from slim disk simulations

  Wen, Jonker, Stone, Zabludoff, Psaltis, arXiv:2003.12583
- X-ray isotropized: assumed 10% photons backscattered at late times

Results: neutrino luminosity

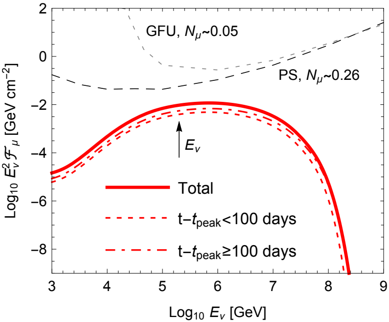


- numerical calculation done with NeuCosmA code

  see Lunardini and Winter, arXiv:1612.03160, and refs. therein.

- double peak in L_ν due to interplay of decline of $L_X^{isotr.}$ and decrease of R_C (i.e., increase in neutrino production efficiency) → *reproduces late time neutrino detection!*

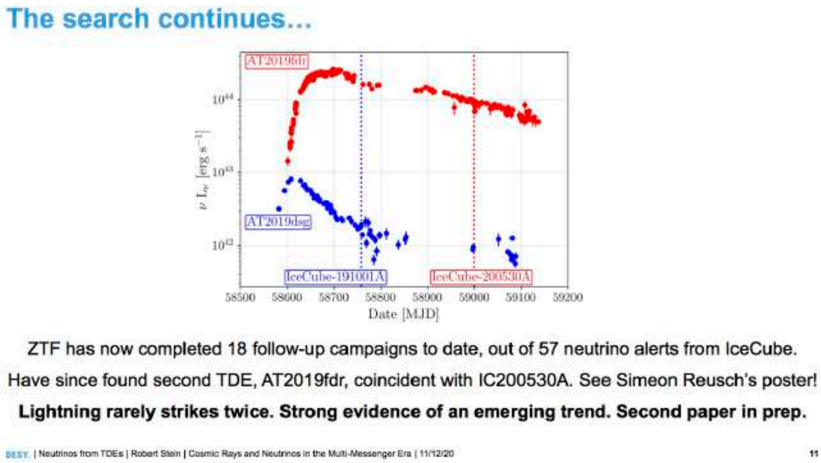
Neutrino fluence and expected number of events



GFU: gamma-ray follow-up effective area ; PS: point source effective area

- good agreement with likely neutrino energy
- number of predicted events: $N_\mu \sim 0.05 - 0.26$ depending on effective detector area used

New: a second neutrino-TDE association!



The search continues...

ZTF has now completed 18 follow-up campaigns to date, out of 57 neutrino alerts from IceCube.

Have since found second TDE, AT2019fdr, coincident with IC200530A. See Simeon Reusch's poster!

Lightning rarely strikes twice. Strong evidence of an emerging trend. Second paper in prep.

DESY. | Neutrinos from TDEs | Robert Stein | Cosmic Rays and Neutrinos in the Multi-Messenger Era | 11/12/20 11

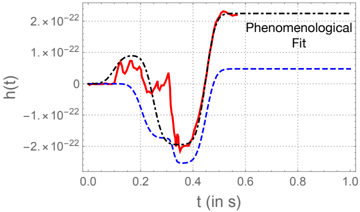
Discussion and conclusions

Detectability

- neutrino and GW observatories are now providing frequent, high quality **alerts** to the multimessenger astronomy community
  - power discoveries, thanks to real-time, pointing and precise timing
- upcoming **sub-Hz** GW detectors and **Mt-scale** neutrino observatories will lead to joint discoveries, which may require decades of running.
  - Core collapse supernovae, stellar-mass compact object mergers, Tidal Disruption Events

What physics can we learn? Core collapse supernovae

- galactic SN: correlations in time structure of GW and ν signals
  - probe large scale dynamics near collapsed core (SASI, emission anisotropy)
- diffuse, O(10-100) neutrinos from SNe in local universe
  - Complementary to cosmological flux
  - Can extract spectrum parameters, study SN sub-populations (failed SNe?)

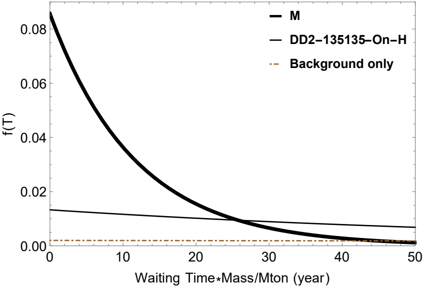


joint fit of memory signal and ν burst will measure anisotropy parameter

What physics can we learn? Binary mergers

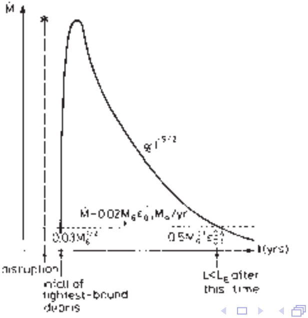
Even with a single detection, we can

- confirm the presence of at least one neutron star in the binary
- distinguish between models using time of first detection
  - constrain the mass and lifetime of remnant, mass of accretion disk

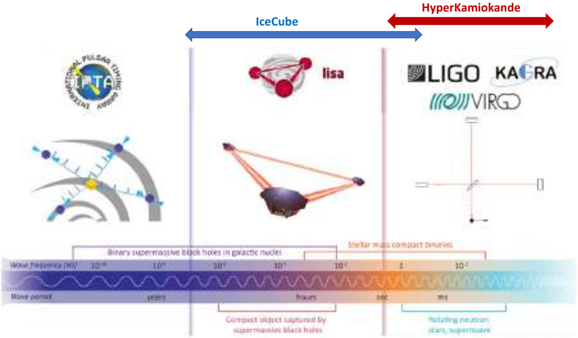


What physics can we learn? Tidal Disruption Event

- exclude alternative interpretations of flare (AGN activity, etc.)
    - test the rate of TDEs
- test jet hypothesis
- estimate $L_{Edd} \propto M$, complementary estimate of BH mass
    - constrain BH mass distribution, currently very uncertain at $M \lesssim 10^6\ M_\odot$.



Looking forward to the next 50 years of discoveries!

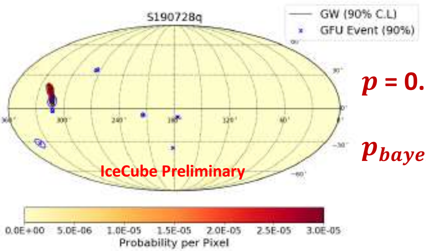


Thank you!

Backup

Still missing: neutrinos + GW

- several coincidences of neutrinos, photons and cosmic rays have been claimed
- **no** robust neutrino-GW association

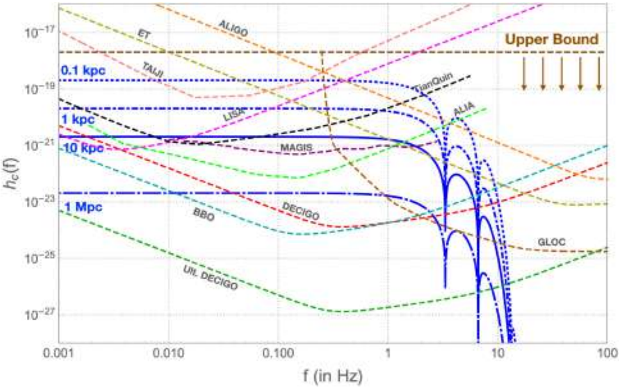


p = **0.0136**

p_{bayes} = **0.0102**

Most significant coincidence, from R. Hussain for IceCube coll., ICRC2019 conference
see also B. Zhang, Res.Notes AAS 3 (2019) 8, 114 for physical plausibility discussion

Longer accretion model, LAc3G.



- masses: $m \sim (0.1 - 2)\ M_\odot$, $M \sim (10^4 - 10^8)\ M_\odot$
- Tidal radius: where SMBH gravity $\simeq$ star's self gravity

$$\begin{aligned} r_t &= \left(\frac{2M}{m}\right)^{1/3} R \\ &\simeq 8.8 \times 10^{12}\,\mathrm{cm} \left(\frac{M}{10^6\ M_\odot}\right)^{1/3} \frac{R}{} \left(\frac{m}{M_\odot}\right)^{-1/3} \end{aligned}$$

- Schwarzschild radius

$$R_s = \frac{2MG}{c^2} \simeq 3 \times 10^{11}\,\mathrm{cm} \left(\frac{M}{10^6\ M_\odot}\right)$$

  - Condition for TDE: $r_t \gtrsim R_s \to M \lesssim M_{\max} \simeq 10^{7.2}\ \ M_\odot$

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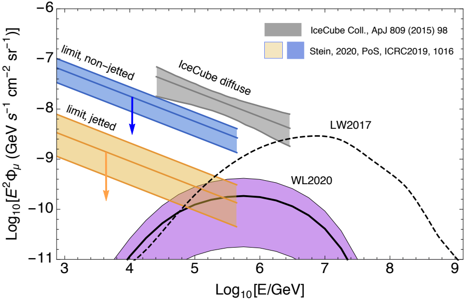


R. Stein, PoS ICRC2019, 1016 (2020)

AT2019dsg basic facts

$z \simeq 0.05$ ($d_L \simeq 230$ Mpc). Optical-UV, X-ray thermal spectra.

Optical-UV

$T_{\rm BB} = 3.35\,{\rm eV}$ $R_{\rm BB} \simeq 5\,10^{14}{\rm cm}$, $L_{\rm BB} = 2.88 \cdot 10^{44}\,{\rm erg\,s^{-1}}$

X-ray

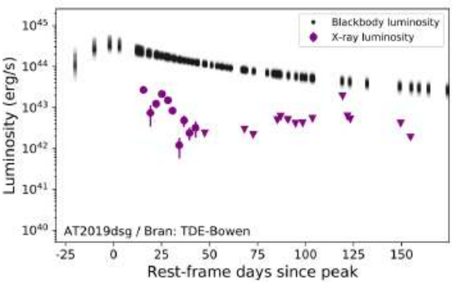
$T_X \sim 0.06$ keV, $R_X \sim 3 - 7\ 10^{11}$ cm,
$L_X \sim 2.5\ 10^{43}\ {\rm erg\,s^{-1}}$ ($[0.3 - 8]$ keV)
$L_X \sim 4\ 10^{44}\ {\rm erg\,s^{-1}}$ ($[0.1 - 10]$ keV).

Radio

radio emission nearly constant with increasing radius of emission $R_{\rm radio} = \mathcal{O}(10^{16})$ cm
(indication of mildly relativistic outflow)

van Velzen, et al., arXiv:2001.01409, R. Stein et al., Nat Astron 5, 510-518 (2021)

Time evolution



- L_{BB} exponential (or power-law) decay ($\tau \sim 60$ days), late time flattening
- L_X *faster* exponential decay ($\tau \sim 10$ days), upper limits only at late times

van Velzen, et al., arXiv:2001.01409, R. Stein et al., Nat Astron 5, 510-518 (2021)

- R_{BB} decreases slightly with time:

$$\frac{R_{BB}}{10^{14}\,\mathrm{cm}} \sim \begin{cases} 5.0\,\exp\left(-\frac{t-t_{\mathrm{peak}}}{109\,\mathrm{d}}\right) & ,\ t-t_{\mathrm{peak}} \leq 150\,\mathrm{d} \\ 1.3 & ,\ t-t_{\mathrm{peak}} > 150\,\mathrm{d}\,. \end{cases} \tag{1}$$

van Velzen, et al., arXiv:2001.01409

Technical slide: more detailed inputs

- **Jet parameters (inspired by Swift J1644+57 and AGNs):**
  - Lorentz factor: $\Gamma = 7$;
  - variability time scale: $t_v \sim 2\pi R_S/c \sim \mathcal{O}(10^2)$ s (for $M = 10^6\ M_\odot$);
  - collision radius $R_C \sim 2\Gamma^2 c t_v \sim$ *few* 10^{14} cm *(comparable to R_{BB}!)*
- **Time-evolving collision radius:**
  - Ansatz: $R_C \sim R_{BB}$ at all times, i.e., R_C decreases with time. → **increased neutrino production efficiency:** $f_\pi \propto R_C^{-2}$.
- **target photons:**
  - checked connection between X-ray energy (boosted) and neutrino energy: $E_X/\mathrm{keV} \simeq 0.025\,(E_\nu/\mathrm{PeV})^{-1}$
  - assumed same spectrum as primary for backscattered X-rays
  - checked that fast outflow overtakes R_C for realistic speeds ($v \sim 0.1 - 0.5\ c$)
  - checked basic consistency with Unified model using Thomson scattering optical depth

- **Hadronic content of jet:**
  - initial proton spectrum $\propto {E'}_p^{-2}$
  - verified Hillas criterion
  - $L_p^{iso} \simeq 2\Gamma^2 \epsilon L_{jet}^{phys}$ $(\epsilon = 0.2)$
  - require relatively large baryonic loading, from non-observation of (non-thermal) jet X-rays: $\xi_b \gtrsim 10^3 - 10^4$
- **magnetic field, etc.**
  - $\sim 1\%$ of jet kinetic energy in magnetic field, implies $B' \sim 10^2$ G.
  - included neutrino flavor oscillations
  - calculation done in discrete steps of $\Delta t = 1$ day