High-Energy Multimessenger Transients

Kohta Murase (PSU/IAS/YITP)

November 30 2022

Neutrinos in the MM Era

PENNSTATE

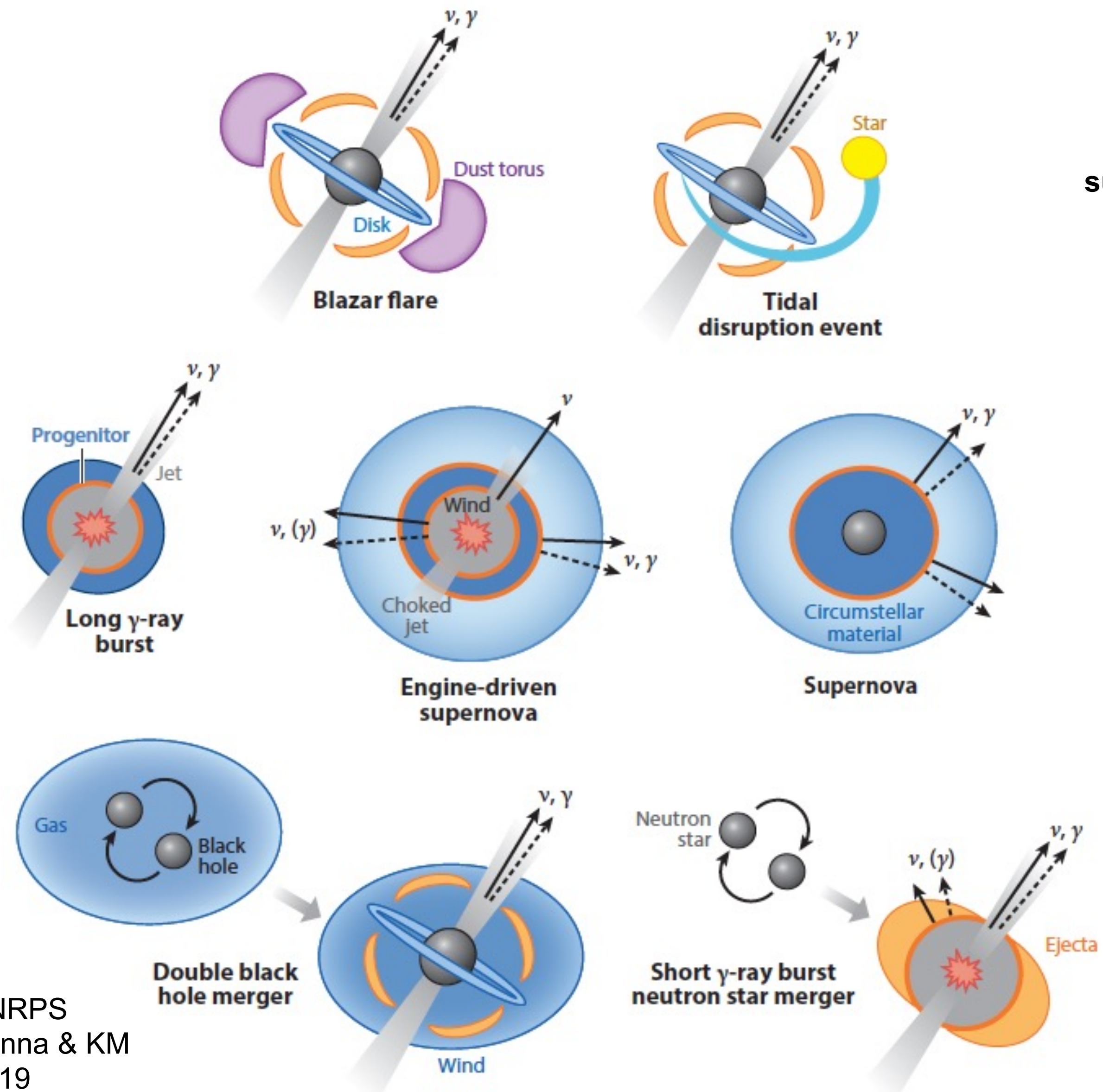
1855

AMON

Astrophysical Multimessenger Observatory Network

NSF

Diversity of High-Energy Transients



supermassive black holes

massive stellar deaths

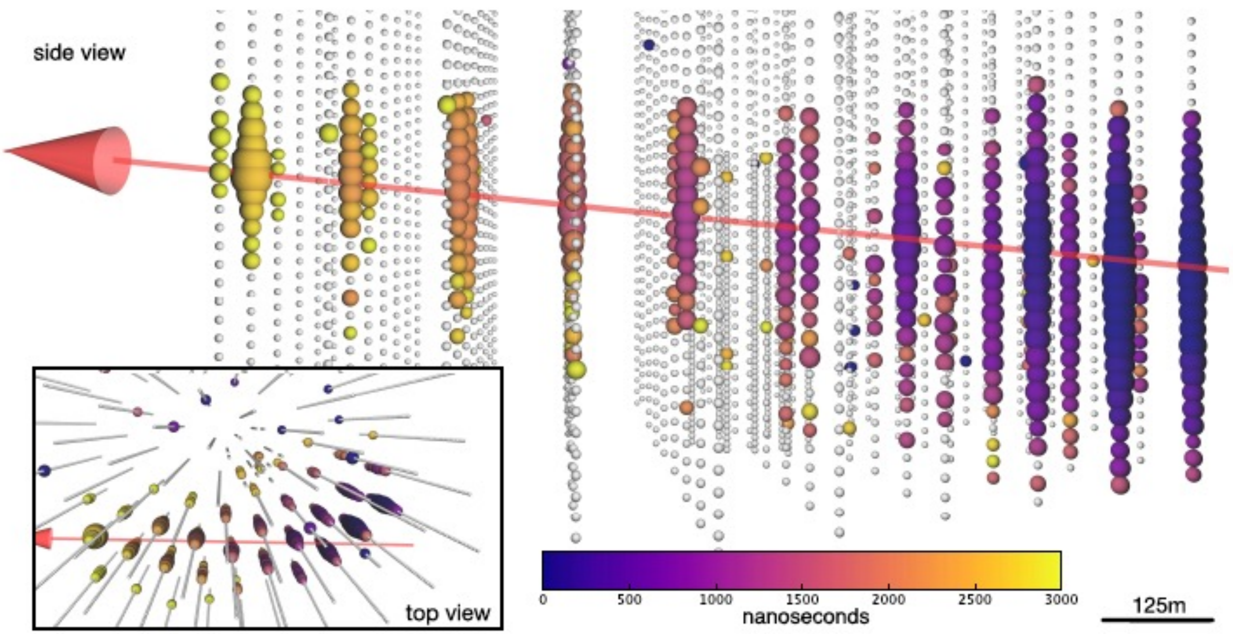
compact mergers
(promising GW sources)

KM & Bartos 19 ANRPS
Meszaros, Fox, Hanna & KM
Nature Rev. Phys. 19

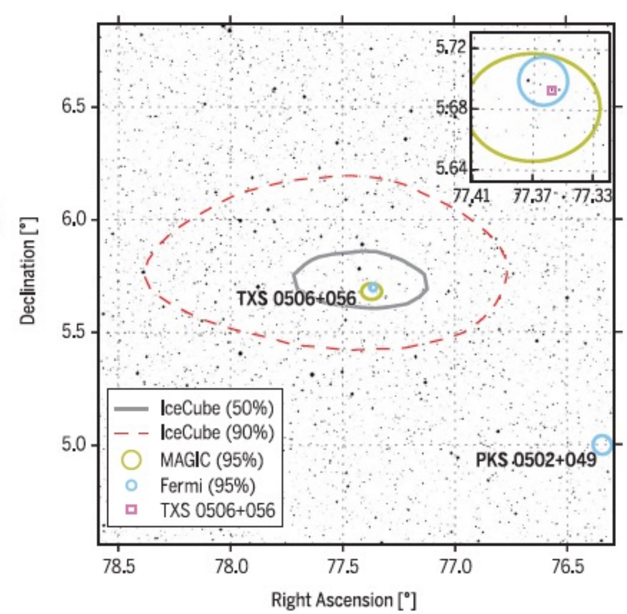
Why Transients?

1. Pointing & timing → reducing atmospheric backgrounds
2. Dominant sources ≠ brightest sources
3. Viable as the dominant origin & environments may be dense
4. Flares/bursts → more target γs → enhanced ν production

→ Good opportunities to find rare bright transients even now



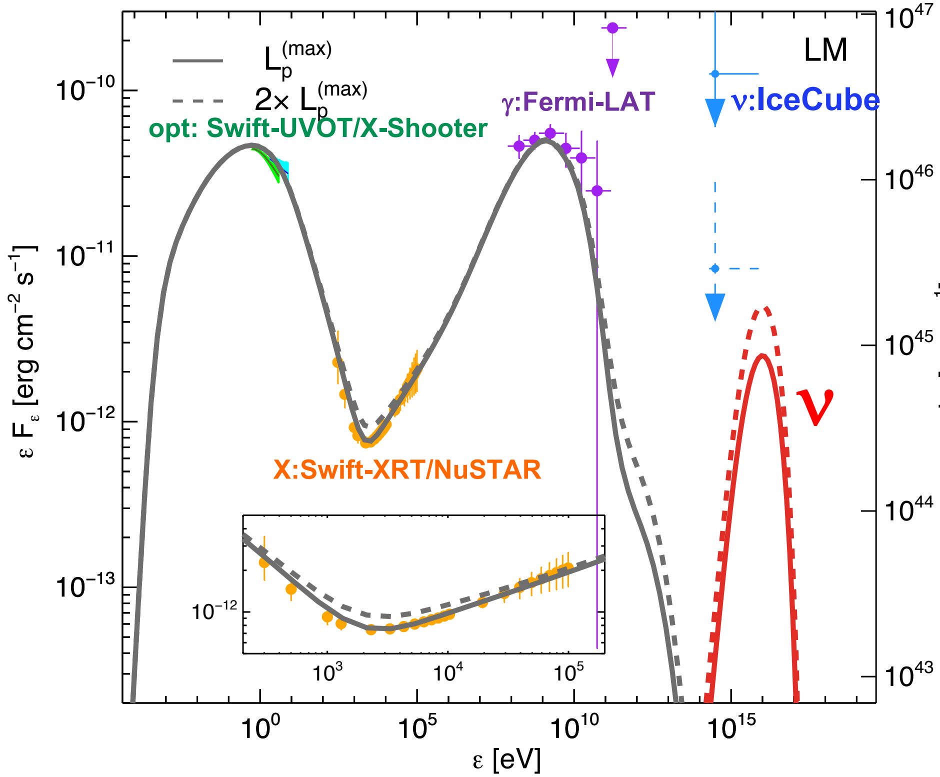
IceCube 2018 Science



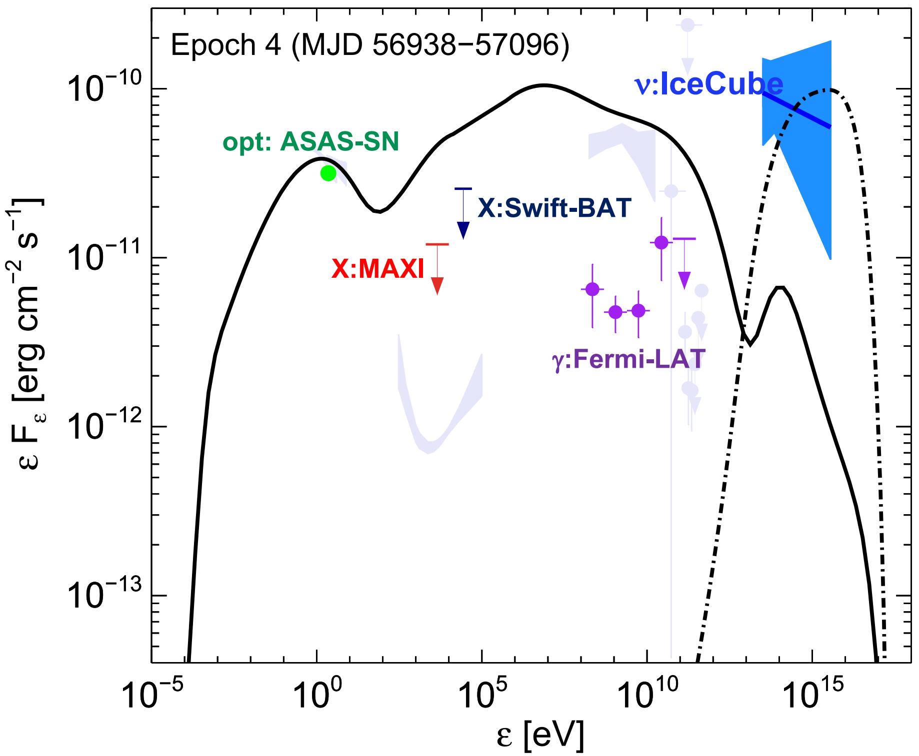
Demonstrating the Power of Multi-Messenger Approaches

$p\gamma \rightarrow \nu, \gamma + e$ **electromagnetic energy must appear at keV-MeV**

2017 multi-messenger flare
Keivani, KM et al. 18 ApJ



2014-2015 neutrino flare
Petropoulou, KM et al. 20 ApJ

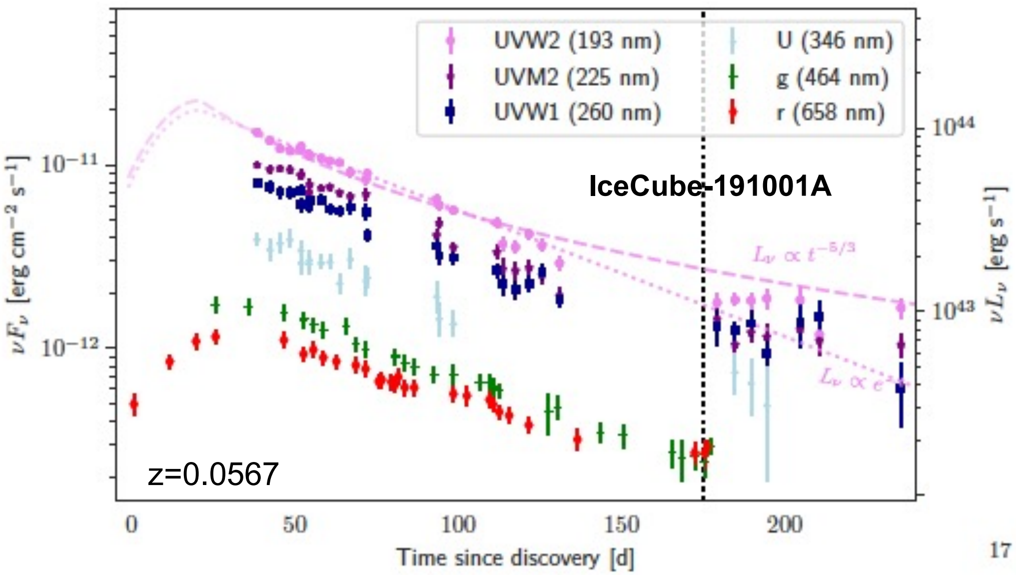


Puzzling: standard single-zone models do NOT give a concordance picture

More coincidences…? see also KM, Oikonomou & Petropoulou 18, Ansoldi+ 18, Cerutti+ 19, Gao+ 19, Rodriguez+ 19, Reimer+ 19

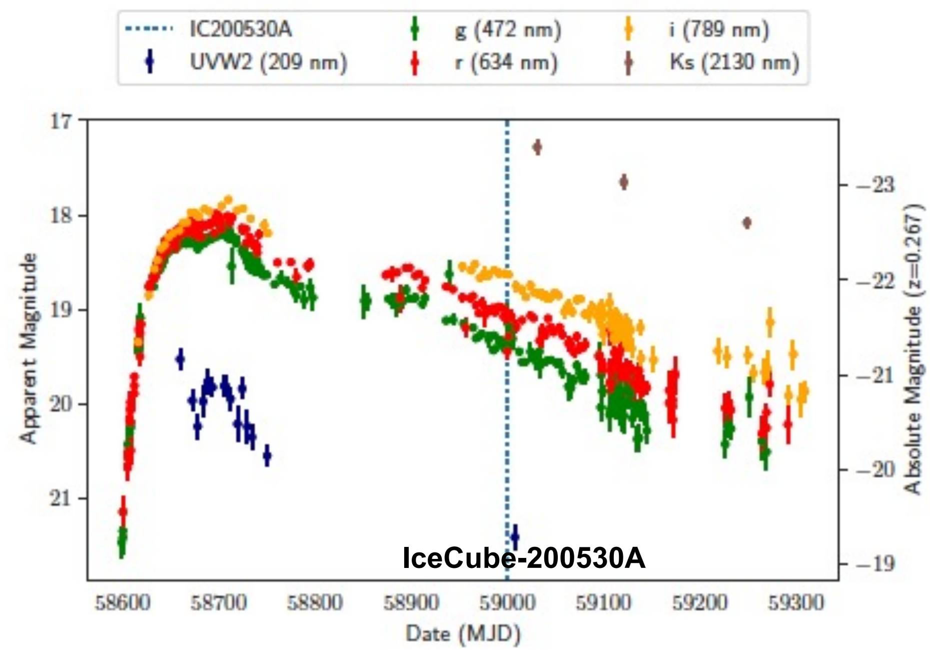
Coincidences w. Optical Transients

ZTF neutrino-followup program (24 until September 2021)



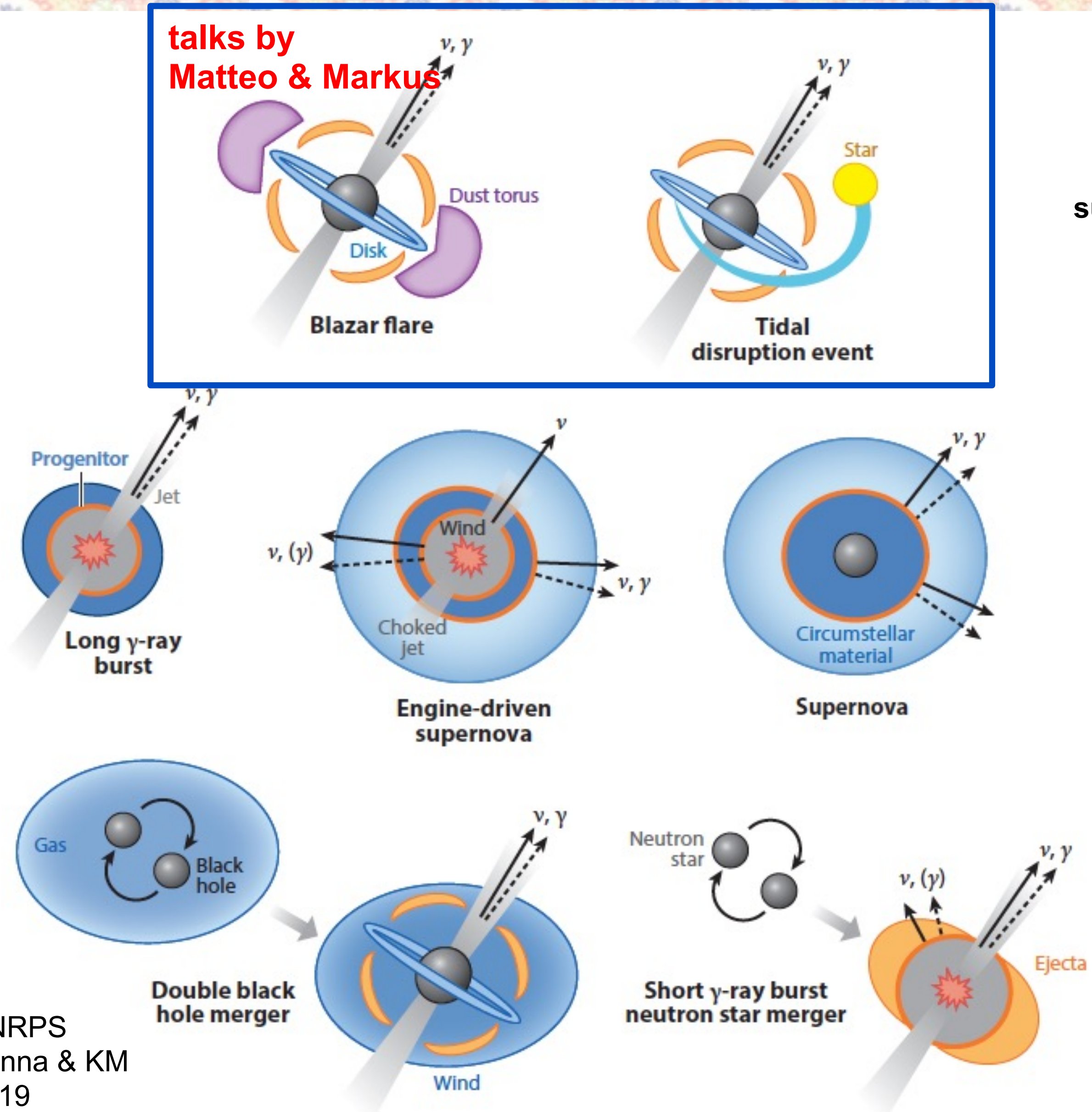
IceCube-191001A
& AT 2019dsg
(Stein+ 21 Nature Astron.)

IceCube-200530A
& AT 2019fdr
(Reusch+ KM 22 PRL)



Both are rare optical transients
(>3σ) with strong radio emission

Diversity of High-Energy Transients



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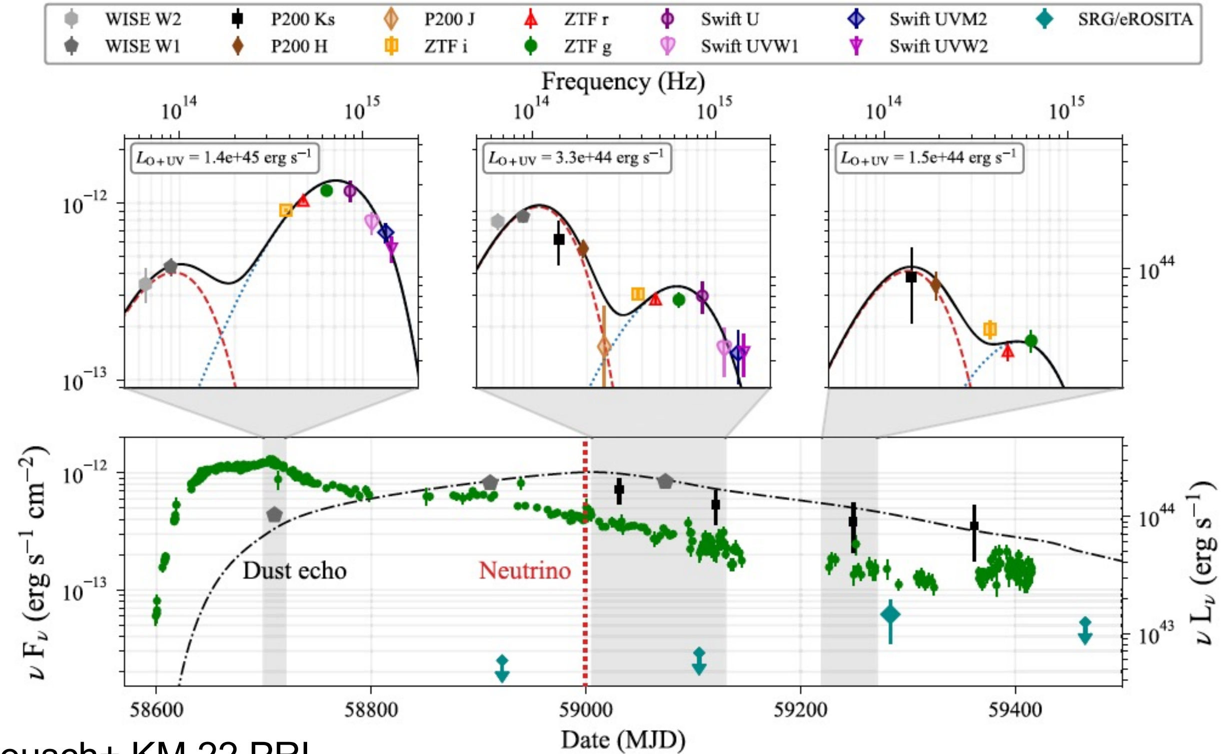
Nature Rev. Phys. 19



Reusch+ KM 22 PRL

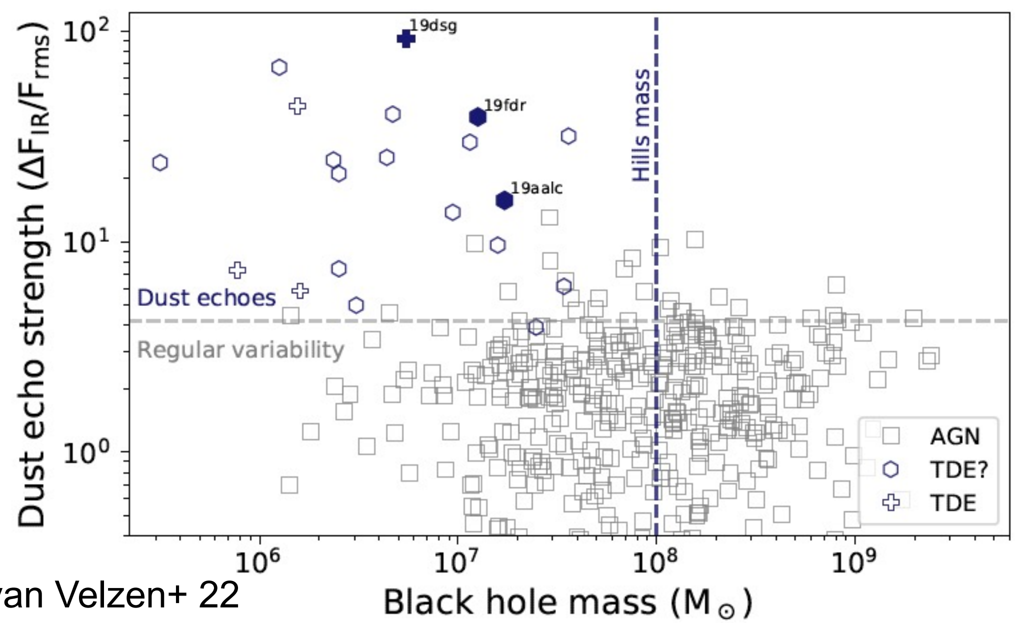
AT 2019fdr

E_{OUV}=3.4x10^{52} erg

E_ν < 10^{53} erg

Commonalities

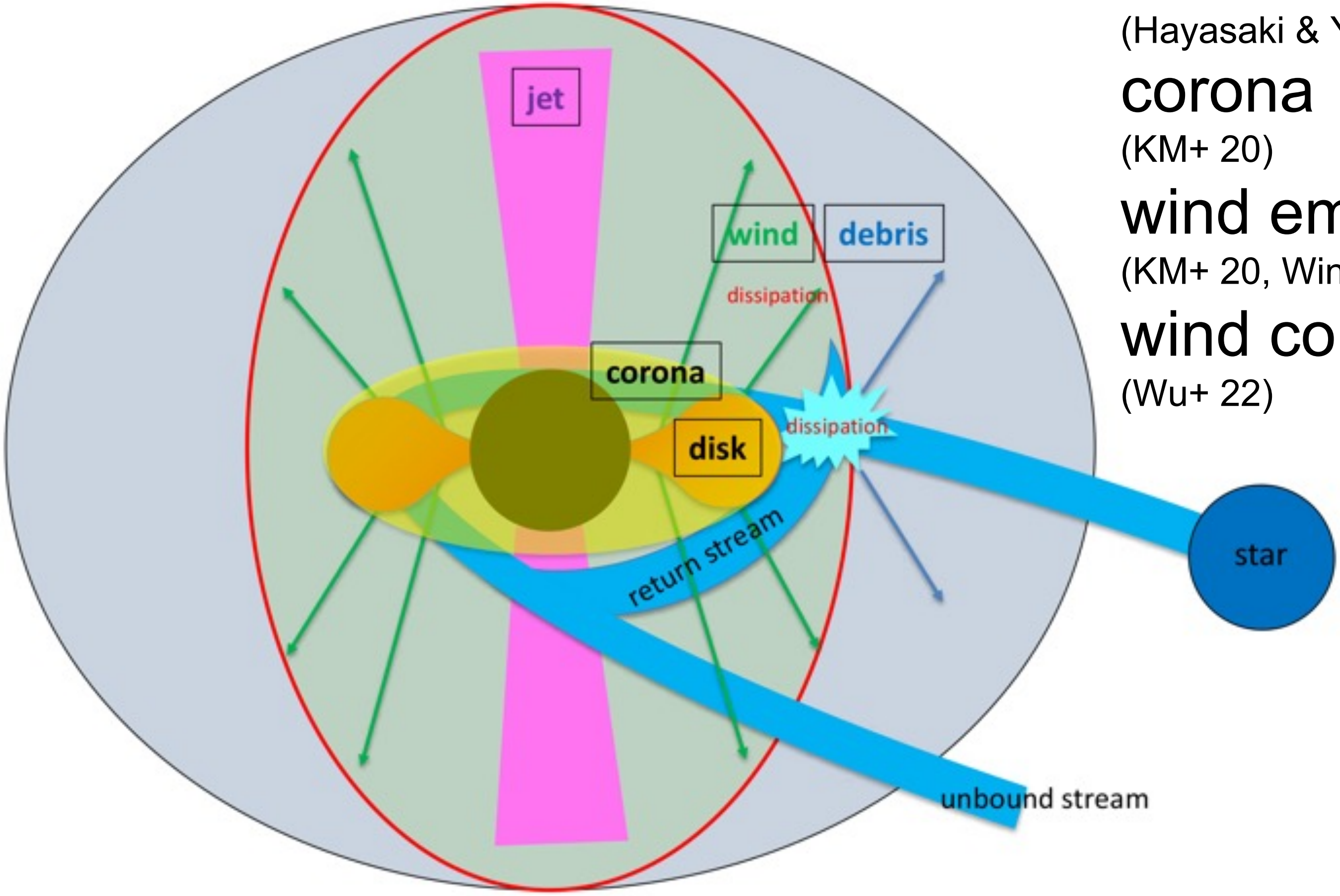
- Brightest TDEs
- Dust echoes
- Radio
- Soft x-rays



van Velzen+ 22

- Correlation w. dust echoes (63 samples; ~3.7σ)
- One more candidate found **AT 2019aalc** (highest IR flux)
- Controversial interpretations

HE Neutrinos from TDEs



successful/hidden jets
(Wang+16, Senno, KM & Meszaros 17
KM+ 20, Lunardini & Winter 17, 21)

RIAF disk
(Hayasaki & Yamazaki 19, KM+ 20)

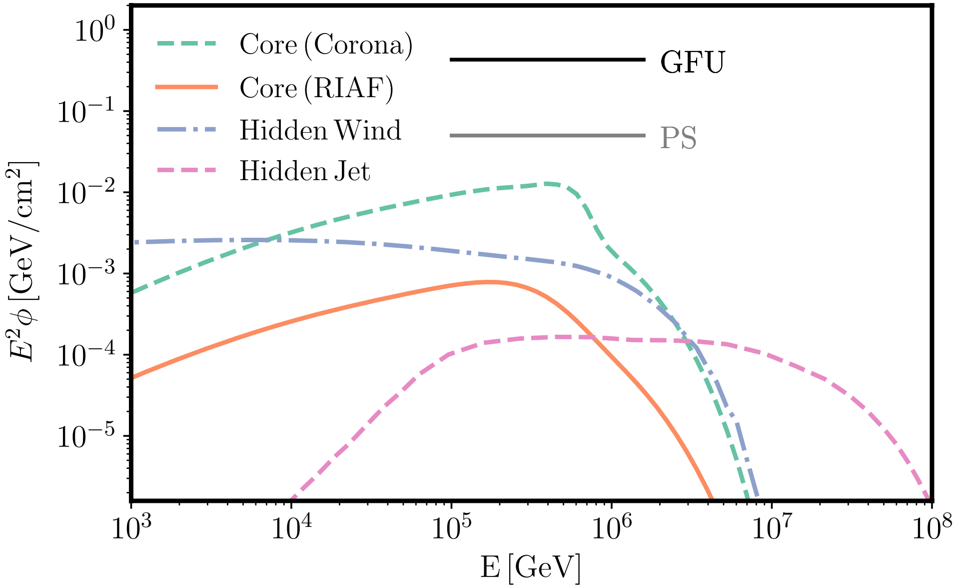
corona
(KM+ 20)

wind embedded in debris
(KM+ 20, Winter & Lunardini 22)

wind colliding w. clouds
(Wu+ 22)

Implications for AT2019dsg & AT2019fdr

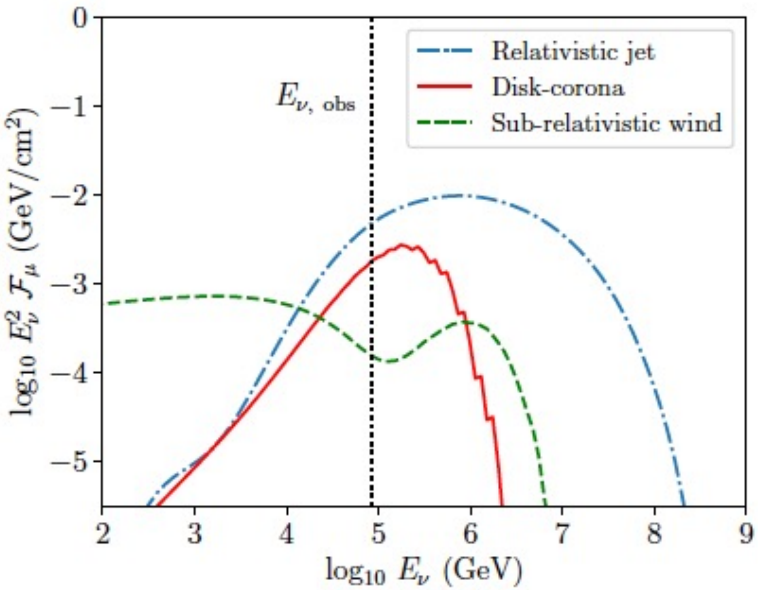
AT 2019dsg



KM+ 20 ApJ

Model	$\mathcal{N}_{\nu_\mu}$(> 100 TeV)	
	Point Source	GFU
Core (Corona)	9×10^{-2}	1×10^{-2}
Core (RIAF)	3×10^{-3}	3×10^{-4}
Hidden Wind	9×10^{-3}	1×10^{-3}
Hidden Jet	1×10^{-3}	3×10^{-4}

AT 2019fdr



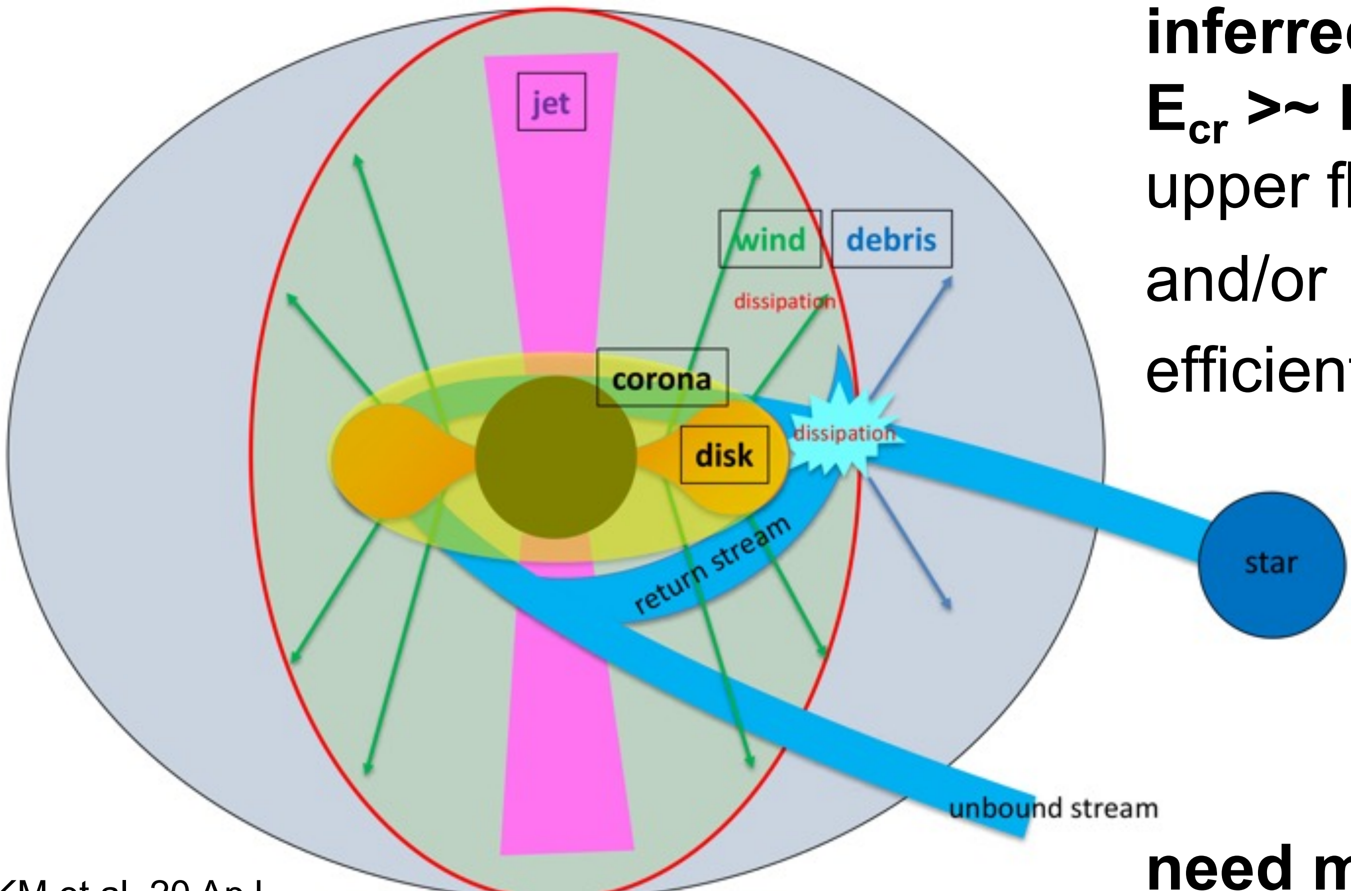
Reusch+ KM 22 PRL

N_ν ~ 0.01-0.1 events (alert)

no evidence of jets

Neutrinos from Black Hole "Flares"?

- AT 2019dsg, AT 2019fdr, AT 2019aalc: TDE "candidates"
- TDE and AGN ν emission may share common mechanisms (e.g., corona model for NGC 1068)

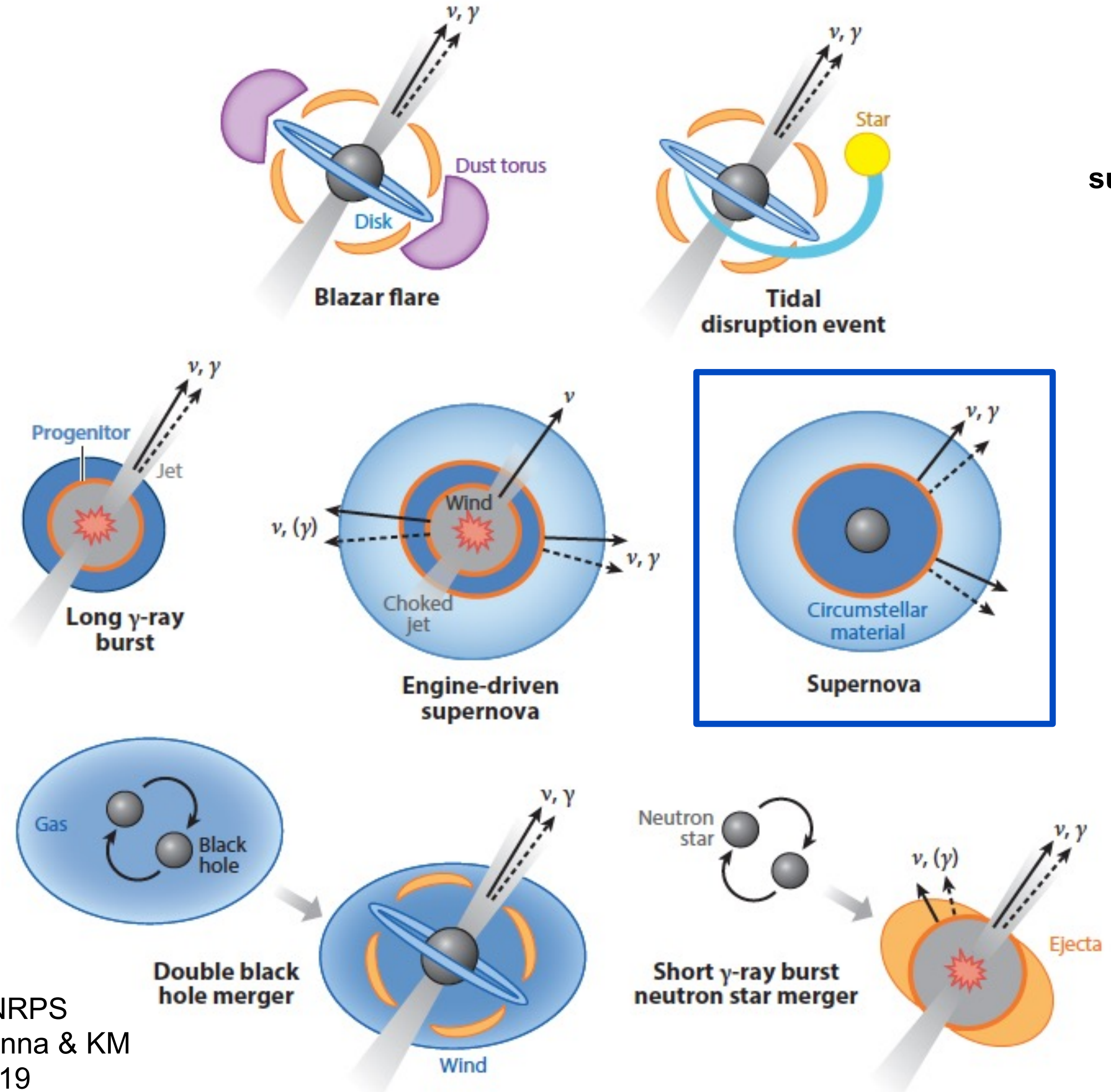


KM et al. 20 ApJ

inferred CR energy
E_{cr} >~ E_{OUV}
upper fluctuation
and/or
efficient CR acceleration

need more searches…

Diversity of High-Energy Transients



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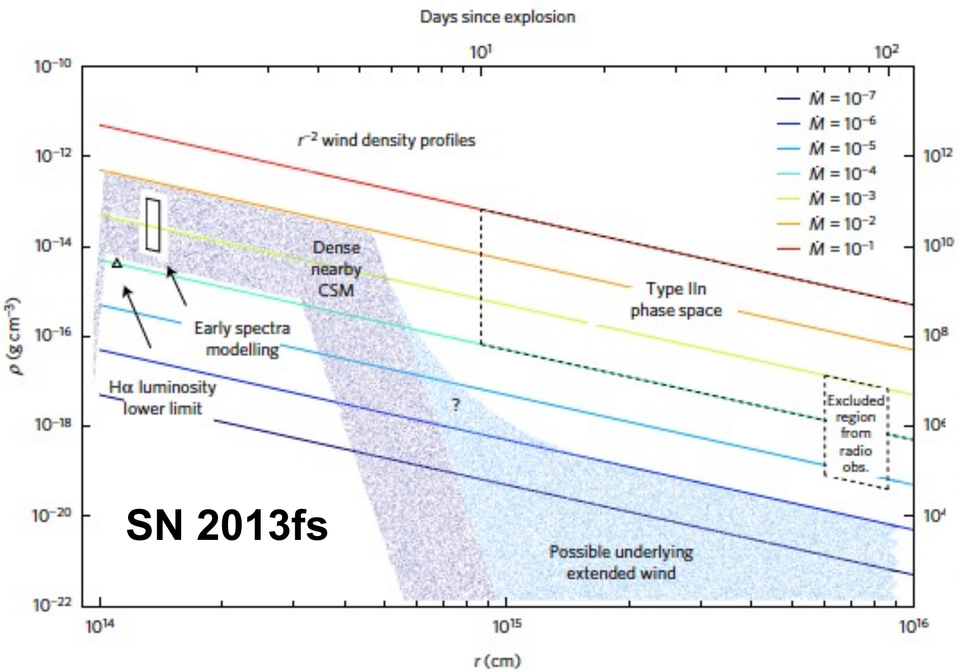
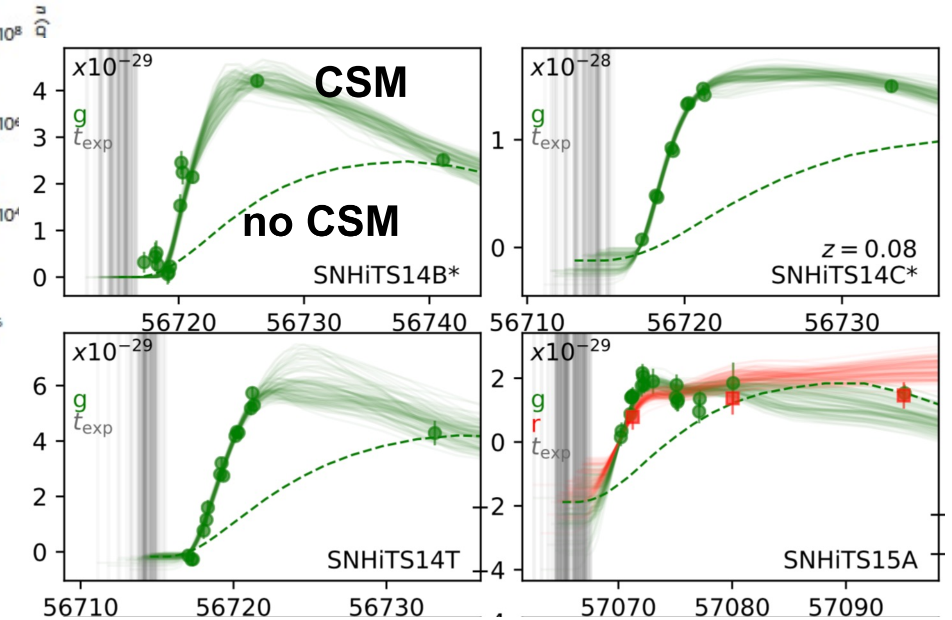
Nature Rev. Phys. 19

Evidence for Dense Material around Progenitors



early spectroscopy
(Yaron+ 16 Nature Phys.)

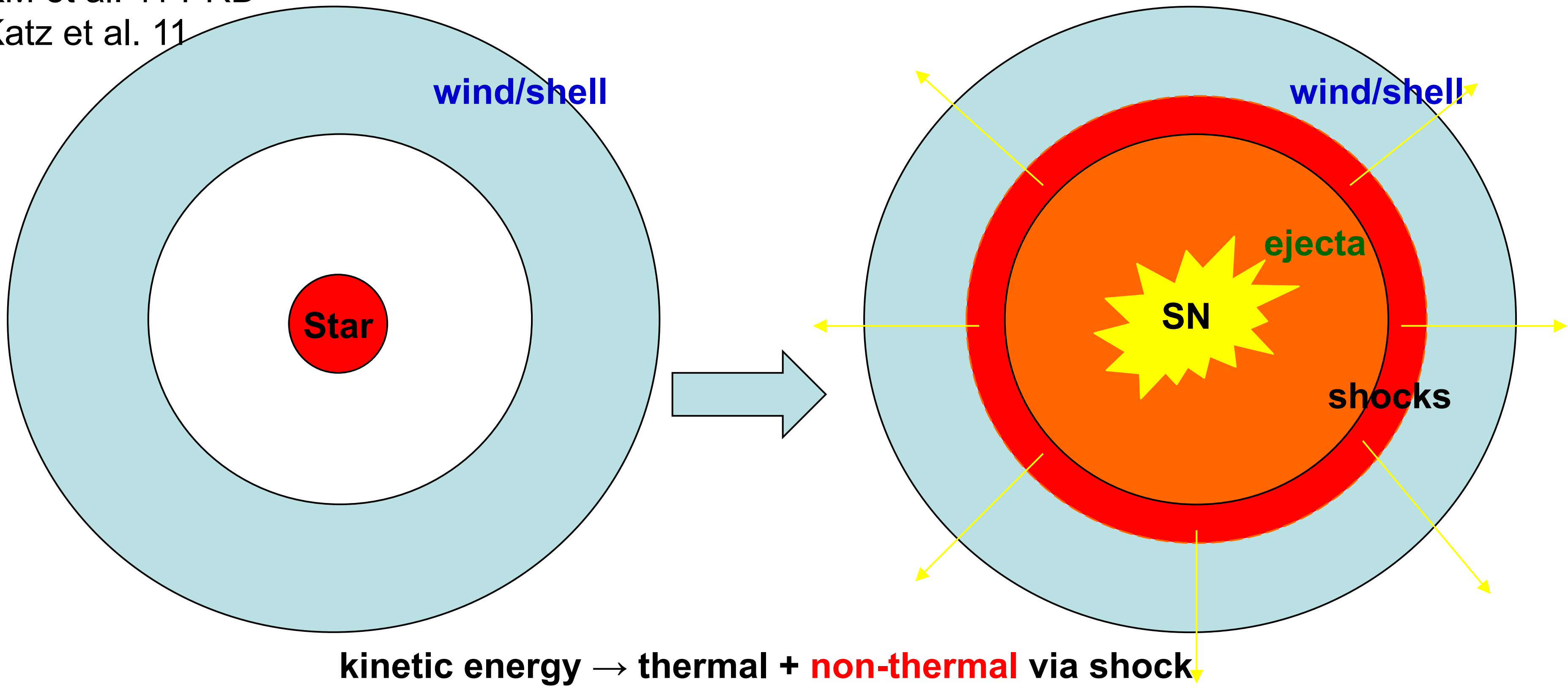


light curve modeling
(Forster+ 18 Nature Astronomy
see also Morozova+ 17 ApJ)

- **Known to exist for Type IIn SNe** (M_{cs}~0.1-10 M_{sun})
- **May be common even for Type II-P SNe**
  dM_{cs}/dt~10^{-3}-10^{-1} M_{sun} yr^{-1} (>> 3×10^{-6} M_{sun} yr^{-1} for RSG)

Interacting Supernovae

KM et al. 11 PRD
Katz et al. 11



kinetic energy → thermal + non-thermal via shock

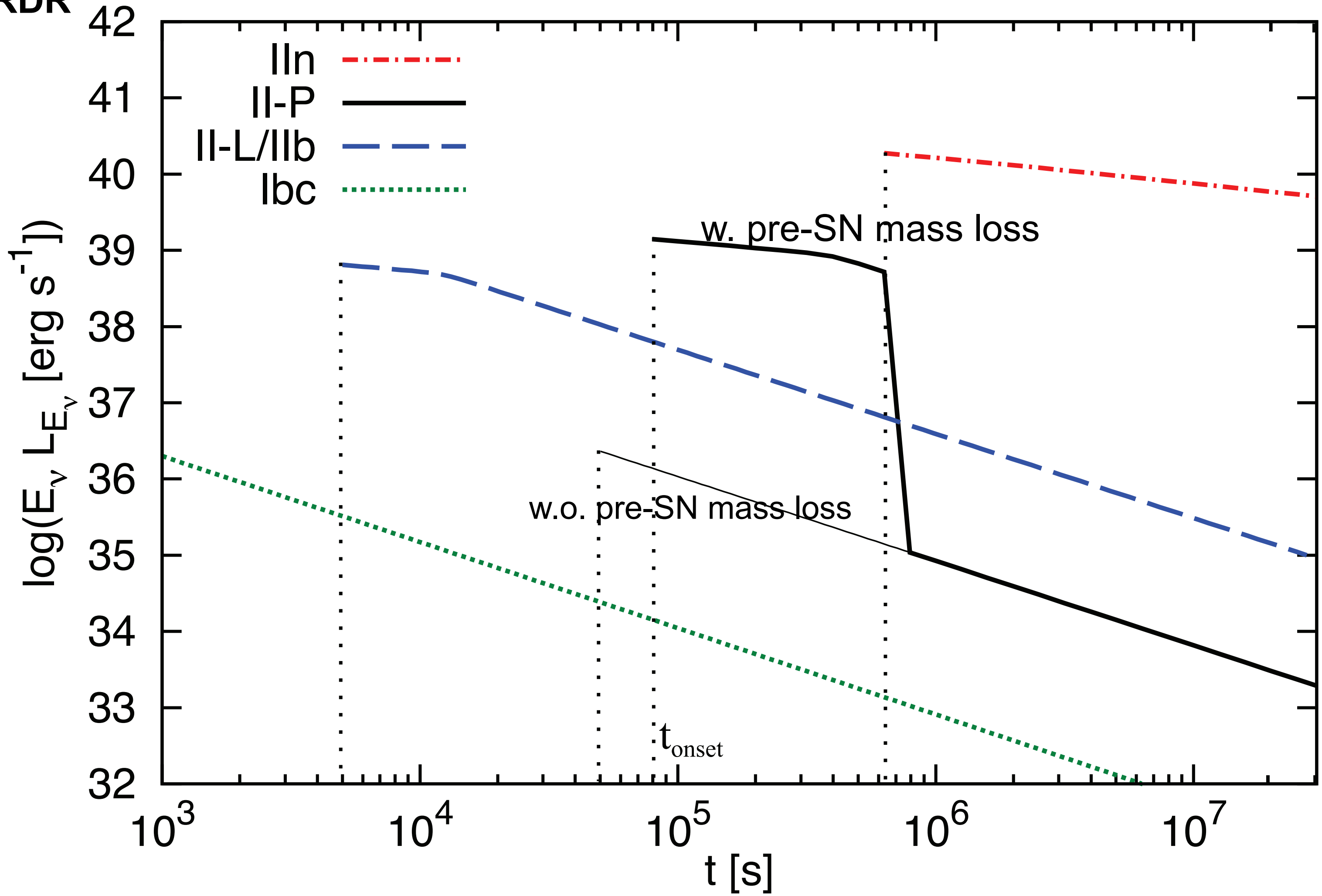
$$p + p \rightarrow N\pi + X$$

$$\pi^{\pm} \rightarrow \nu_{\mu} + \bar{\nu}_{\mu} + \nu_{e}(\bar{\nu}_{e}) + e^{\pm}$$
$$\pi^{0} \rightarrow \gamma + \gamma$$

dense environments = efficient ν emitters (calorimeters)

Neutrino Light Curve

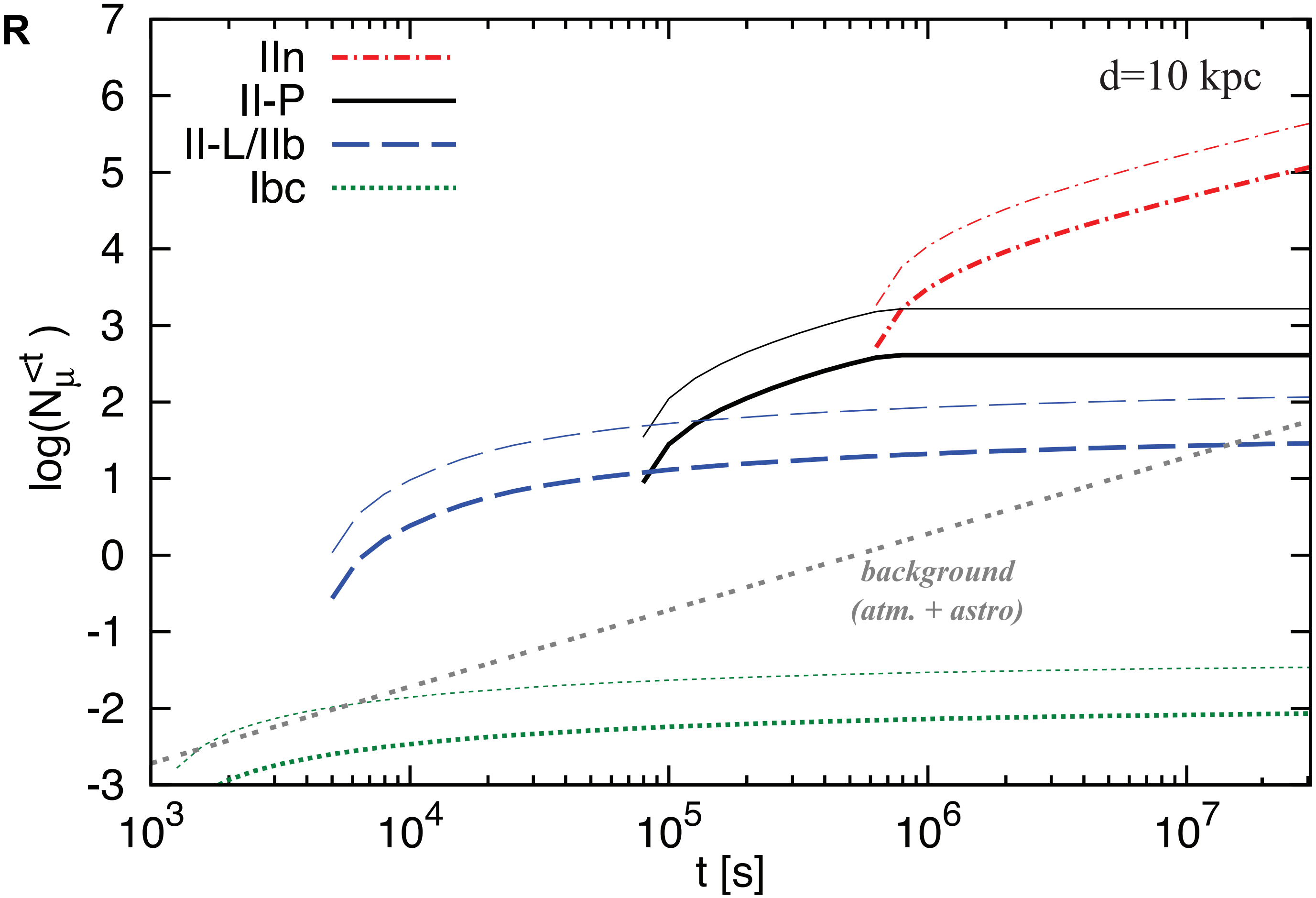
KM 18 PRDR



slowly declining light curves while pion production efficiency ~ 1

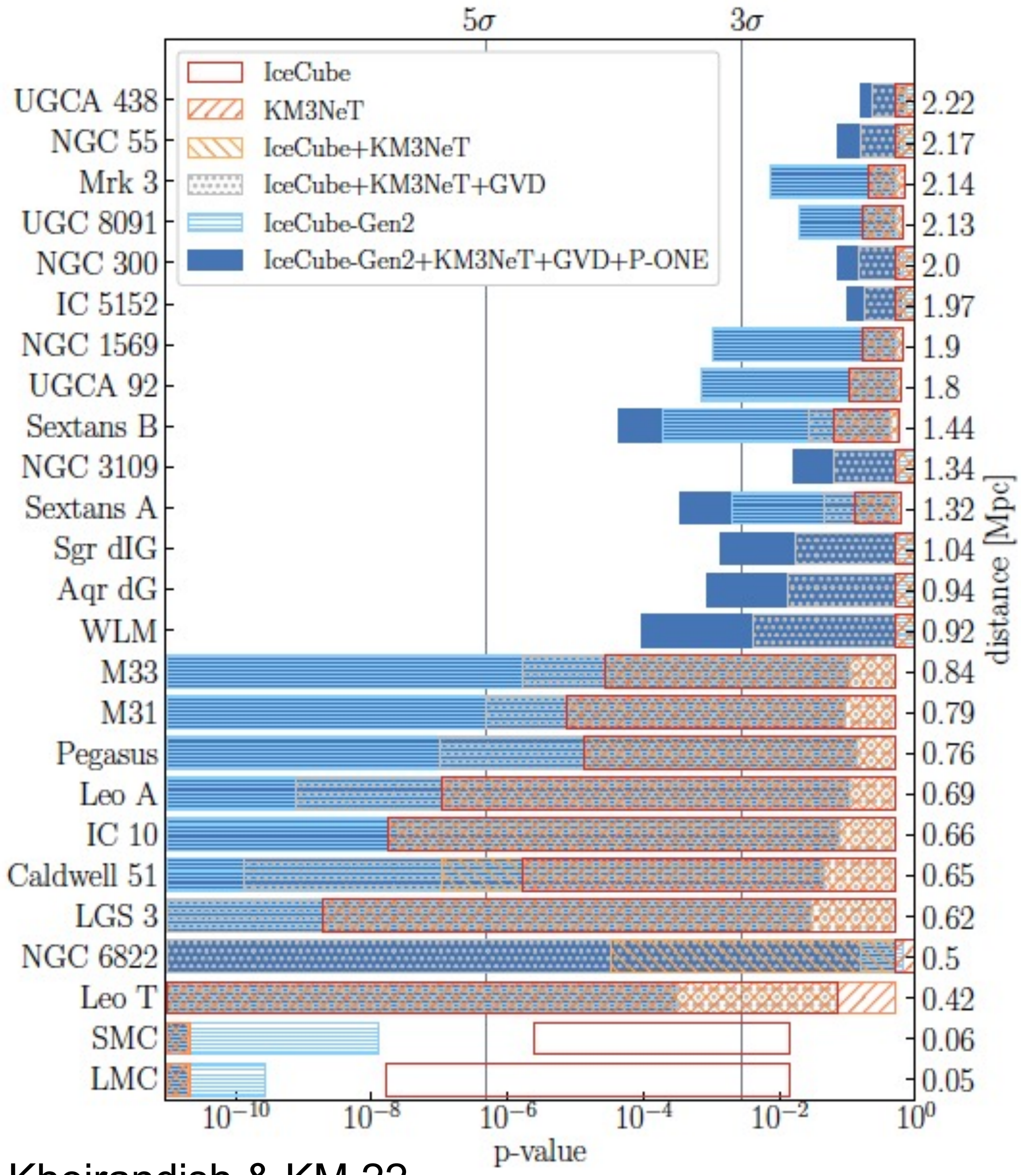
Next Galactic Supernova?

KM 18 PRDR



- Type II: ~100-1000 events of TeV ν from the next Galactic SN
  ex. Betelgeuse: ~10^3-3×10^6 events, Eta Carinae: ~10^5-3×10^6 events
- SNe as “multi-messenger” & “multi-energy” neutrino source
- “Real-time" detection of CR acceleration, testing Pevatrons, neutrino physics

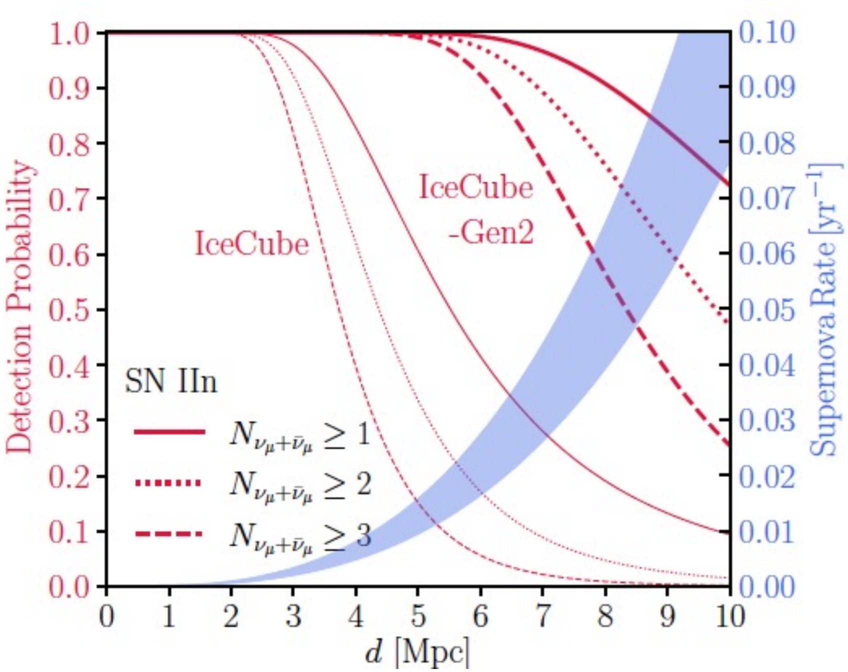
Detectability of Minibursts



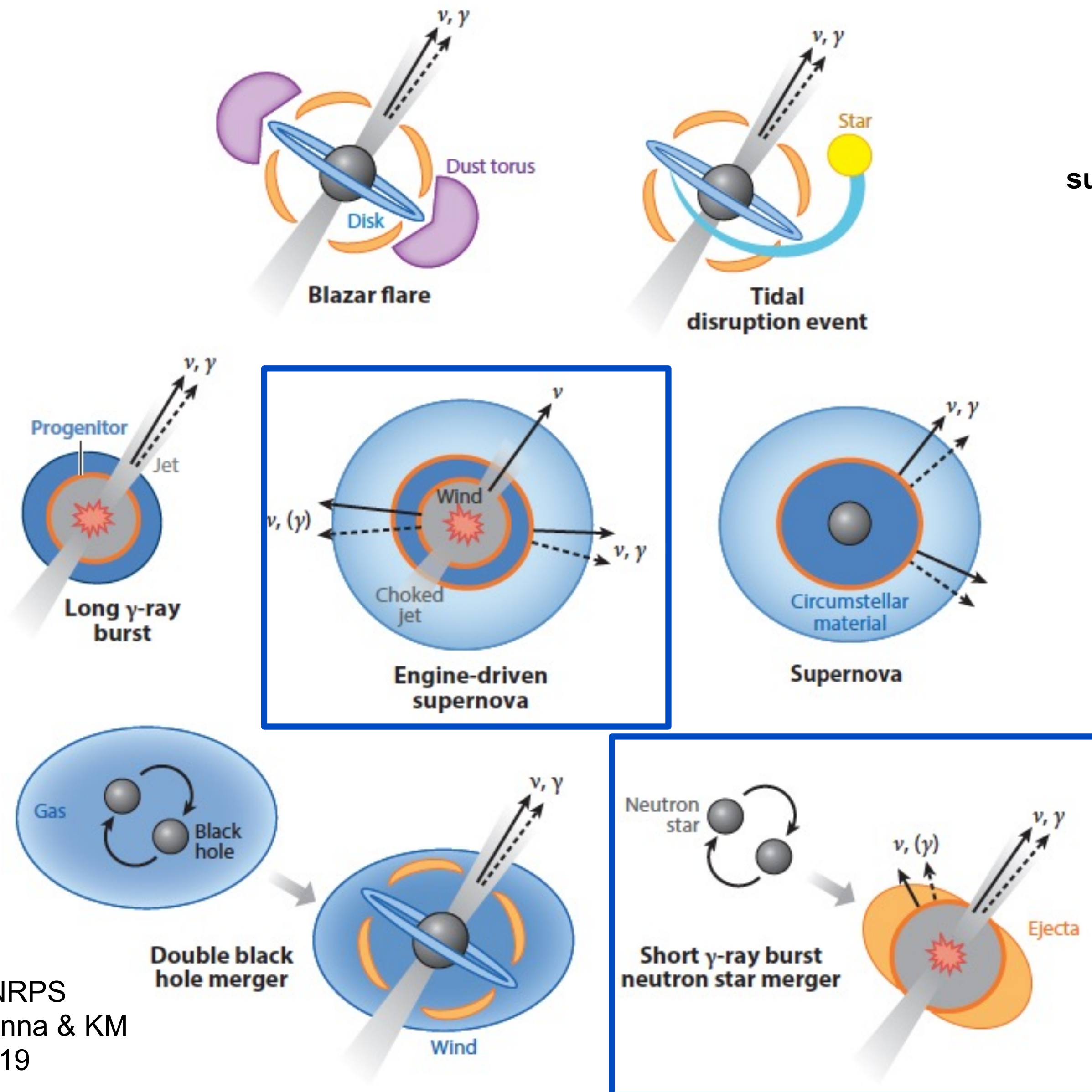
Kheirandish & KM 22

- CCSN rate enhancement in local galaxies (ex. Ando+ 05 PRL)
- Neutrino telescope networks are beneficial for nearby SNe at Mpc
- II-P: detectable up to ~3-4 Mpc
  IIn: detectable up to ~10 Mpc

see also Erin's talk



Diversity of High-Energy Transients



supermassive black holes

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KM & Bartos 19 ANRPS
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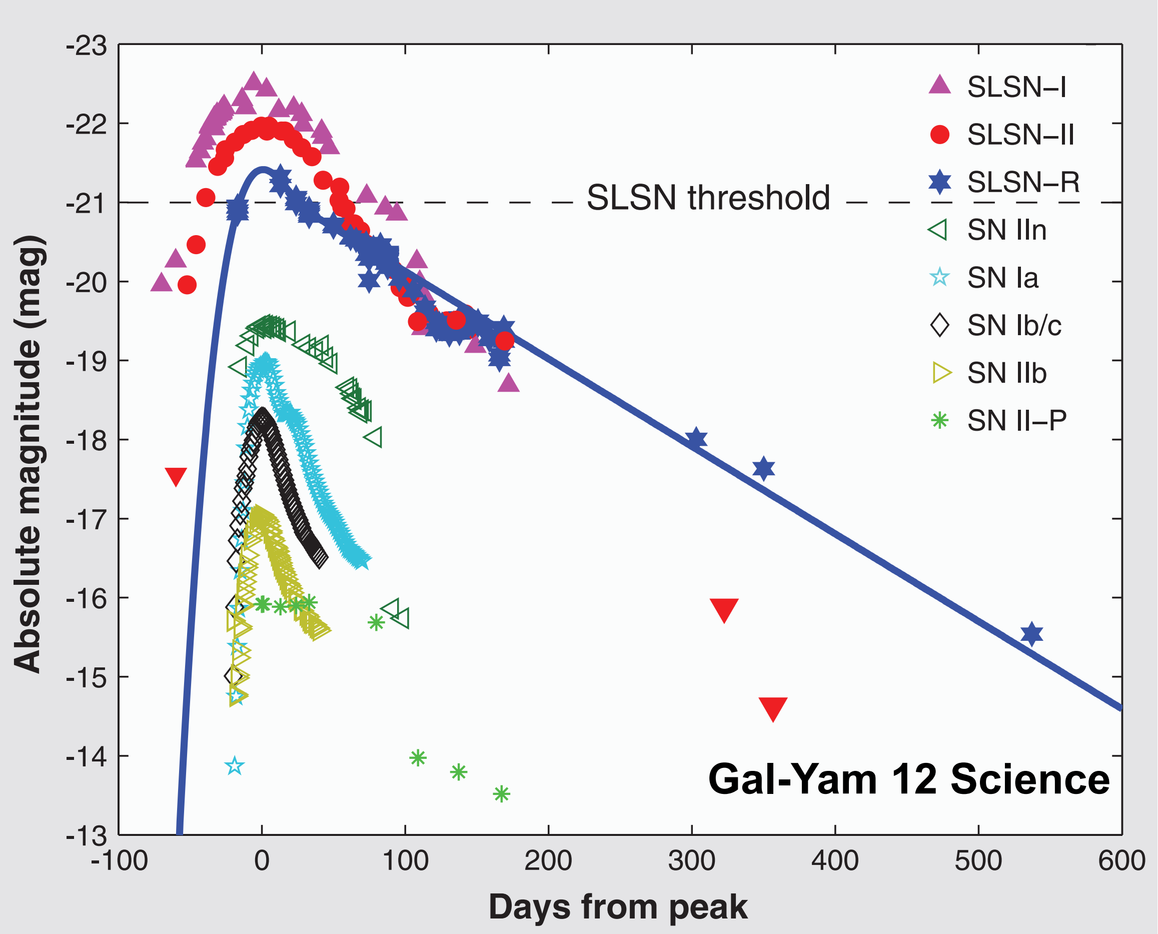
Nature Rev. Phys. 19

Luminous Supernovae as Long-Duration Transients

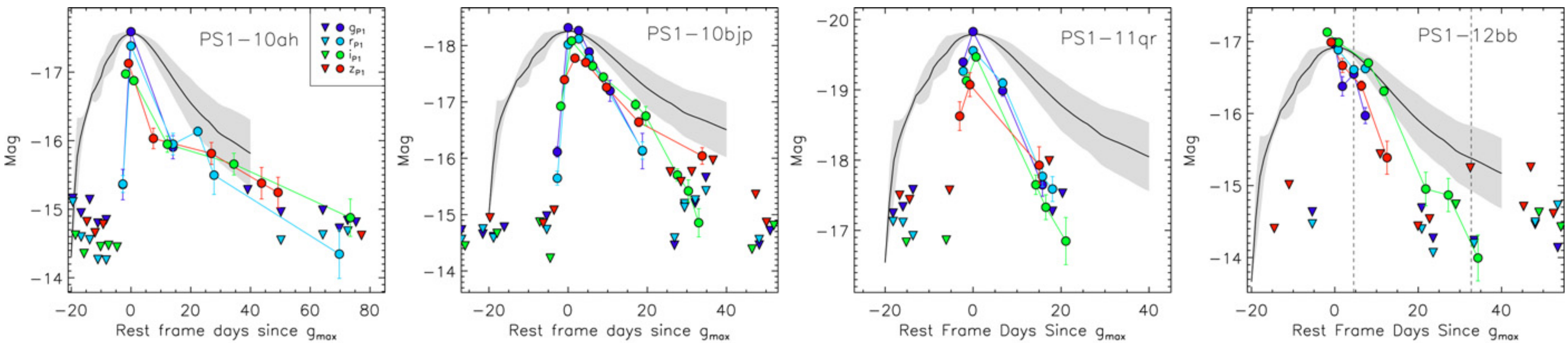


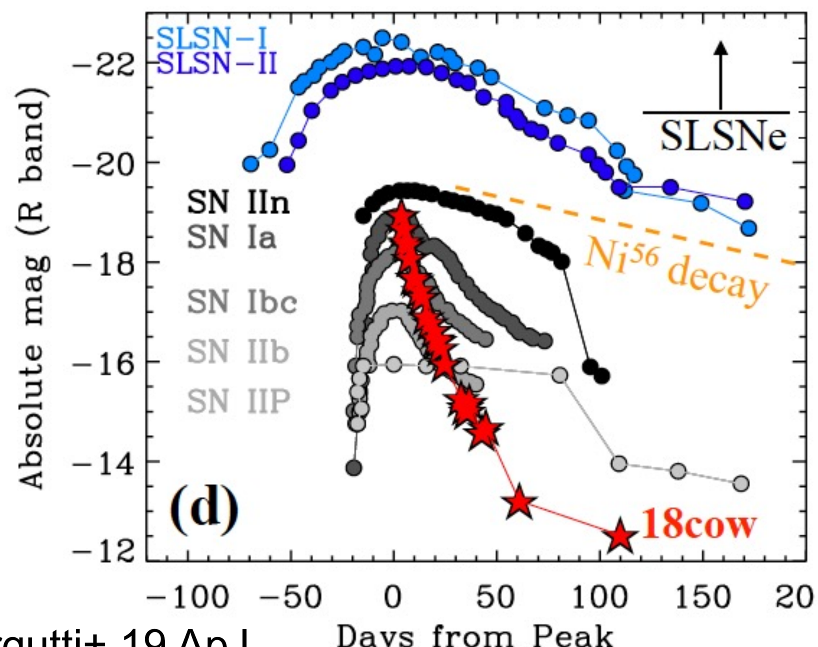
Luminous SNe explanations w. radioactivity for I and II often have difficulty

- SLSN-I (hydrogen poor) – energy injection by engine?
- SLSN-II (hydrogen) – circumstellar material interaction

Fast Blue Optical Transients

Drout+ 14 (see also Arcavi+ 13 etc)





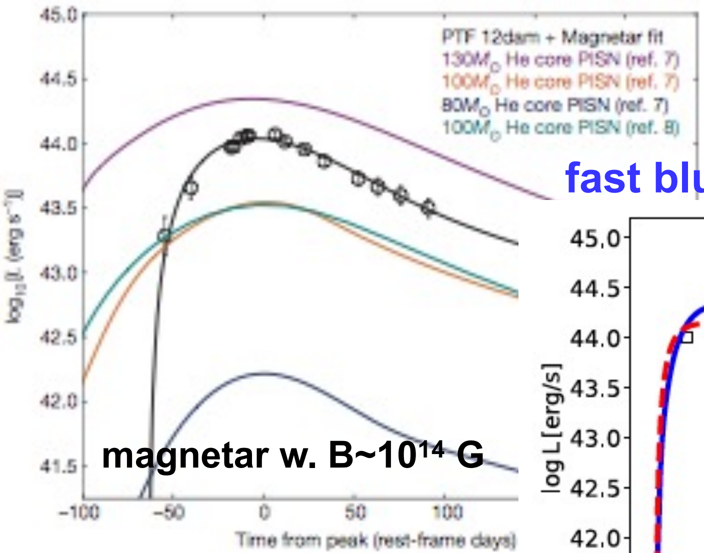
Margutti+ 19 ApJ

- Rapidly evolving (<10 day)
- Luminous & bright
- T ~ a fewx10^4 K (blue)
- Unlikely to be Ni-powered
- Star-forming region
- ~4-7% of core-collapse SNe (not so rare)

Pulsar/Magnetar-Driven Supernovae

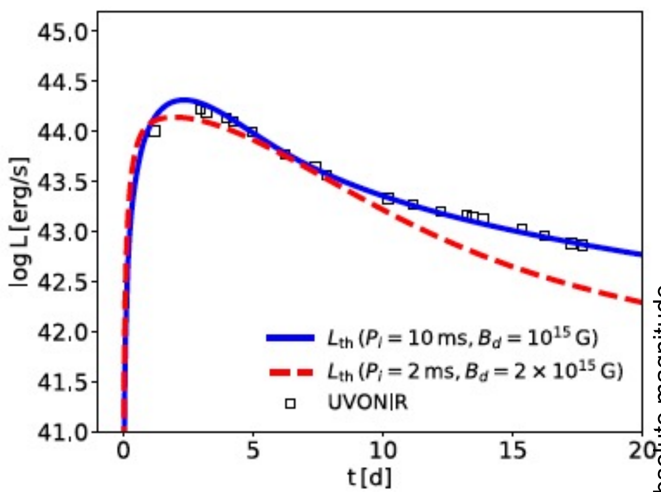
"Rapidly rotating pulsars" are popularly invoked to explain some SNe Ibc

super-luminous supernova (SLSN)



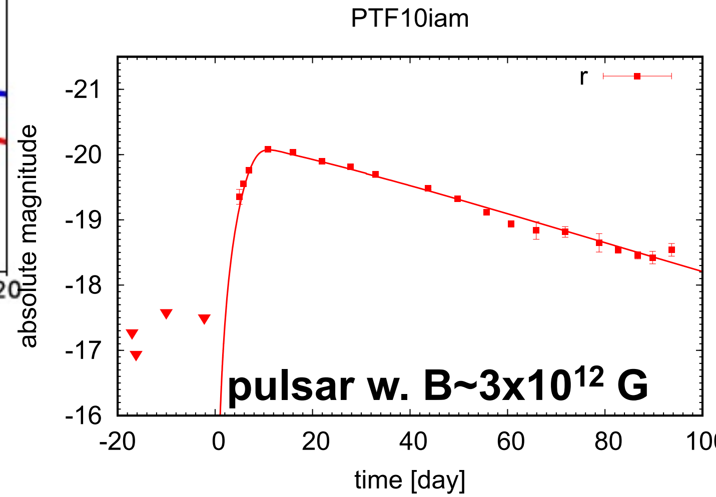
Nicholl et al. 13 Nature

fast blue optical transient (FBOT)



Fang, Metzger, KM+ 19 ApJ

ultra-stripped supernova (USSN)

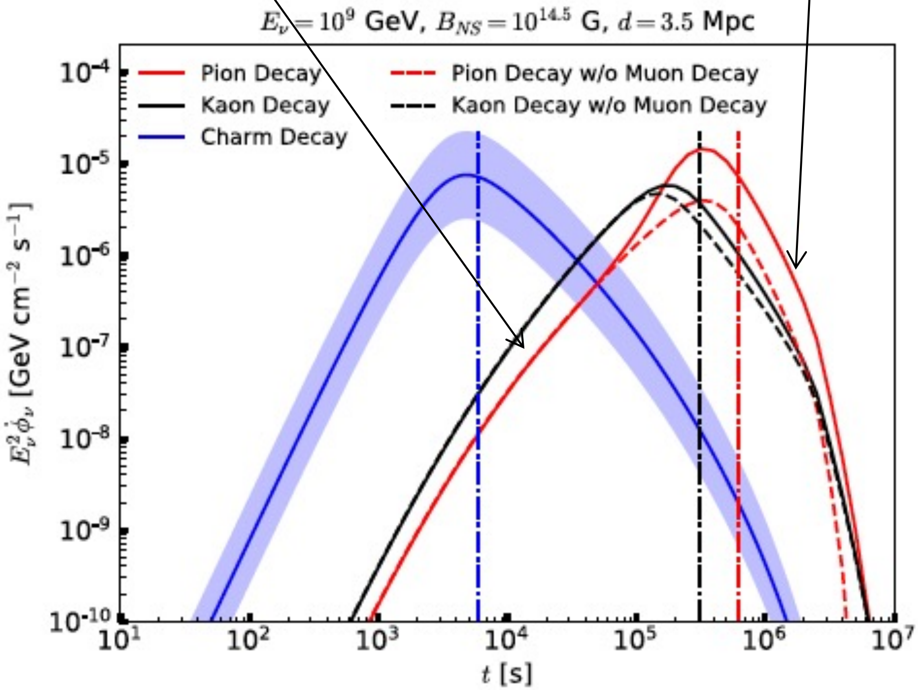


Hotokezaka, Kashiyama & KM 17 ApJ

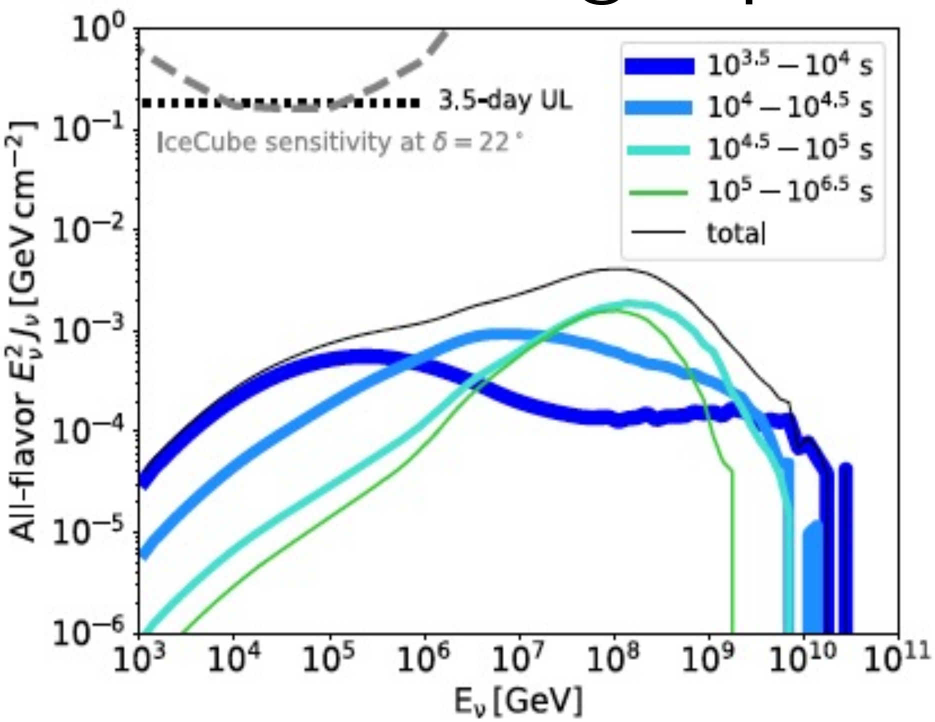
requirement: rotation energy is converted into thermal energy

HE Neutrinos from Pulsar/Magnetar-Driven SNe

- (UHE) CRs could be accelerated via magnetic dissipation in the wind zone
- Efficient ν production should occur in hour-day-week time scales
– ν signals arrive earlier (ν alerts): followed by supernova optical emission



Carpio, KM, Reno, Sarcevic & Stasto 20 PRD
see also KM, Meszaros & Zhang 09 PRD



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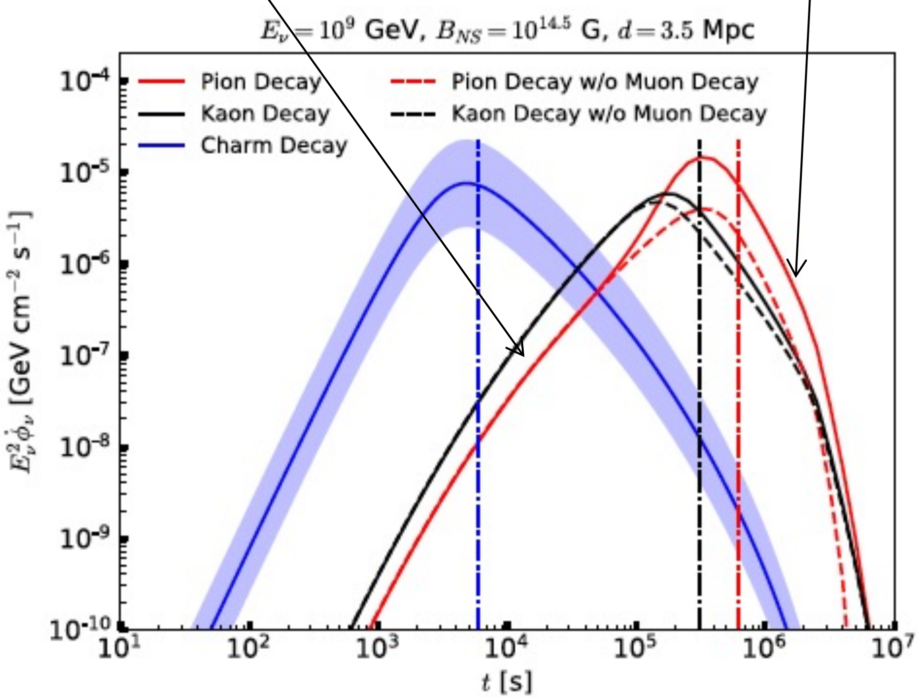
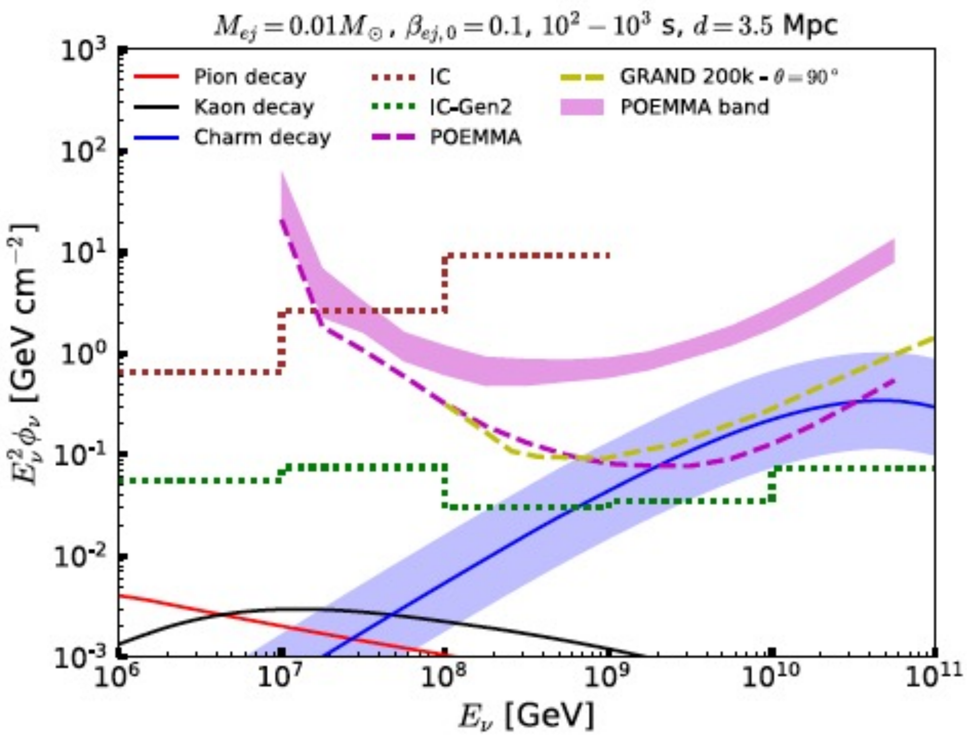
flux suppression due to hadronic cooling of mesons

spin-down



low-mass NS-NS merger



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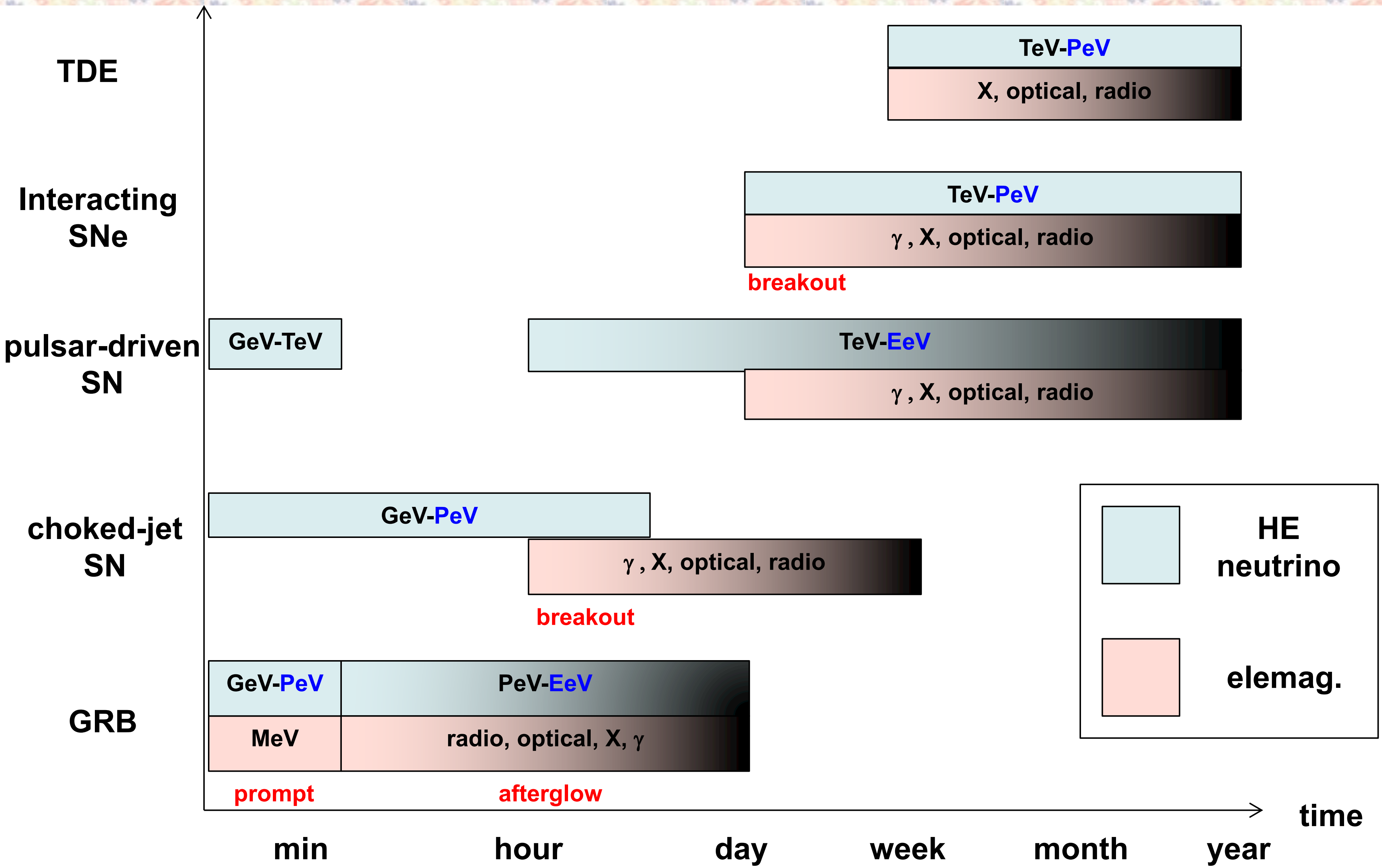
Long-Duration TeV-EeV vs Short-Duration GeV-TeV



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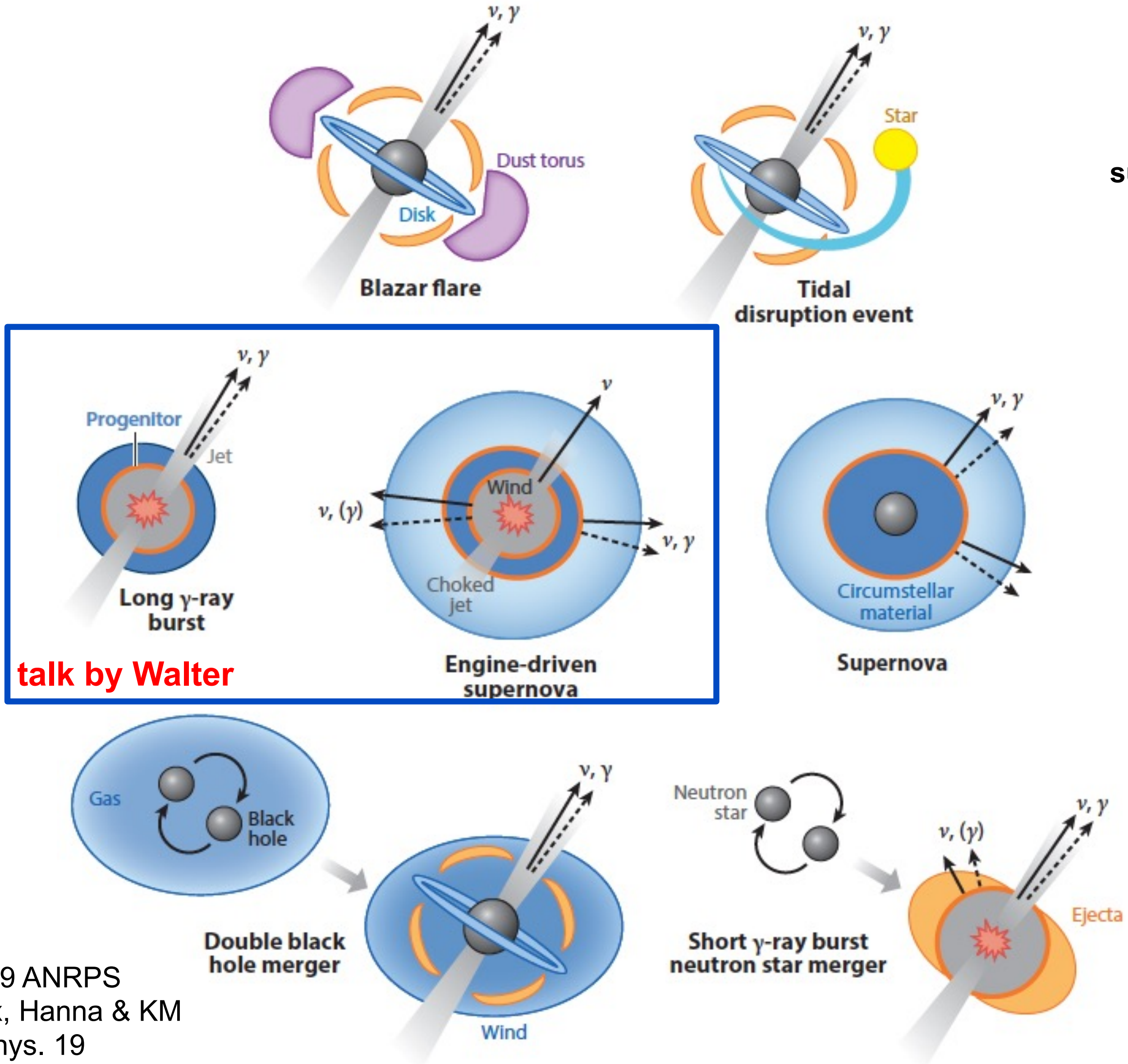

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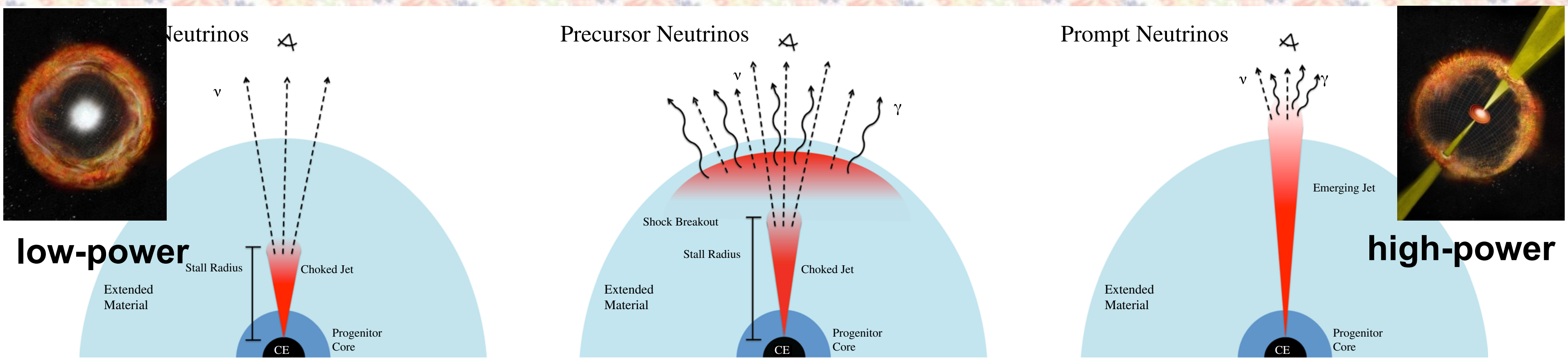
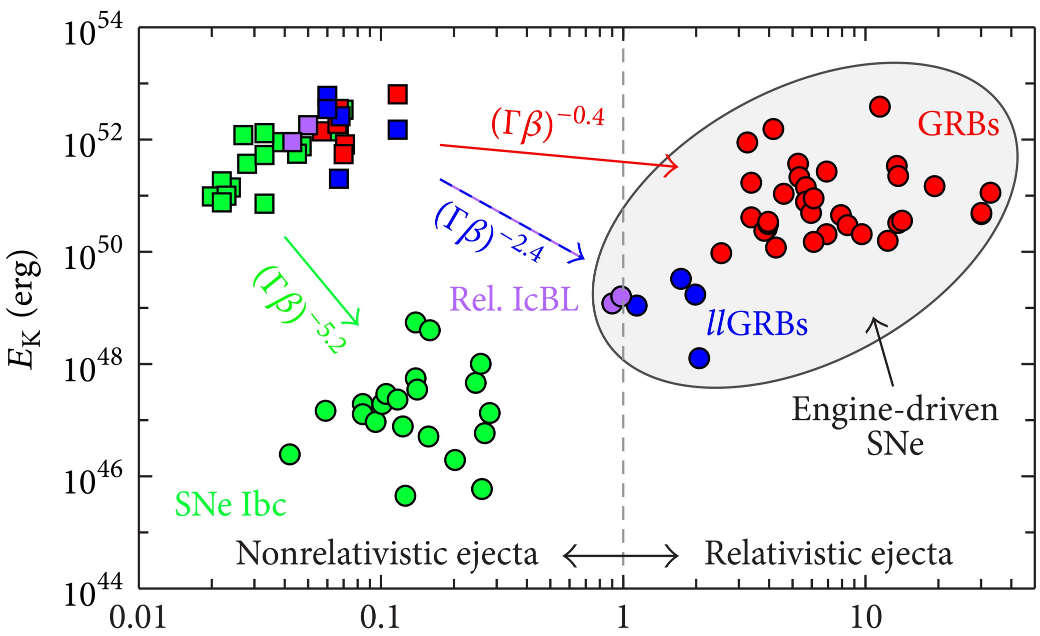
KM & Bartos 19 ANRPS
Meszaros, Fox, Hanna & KM Nature Rev. Phys. 19

HE Neutrinos from Choked Jets in Type Ibc SNe



from Senno, KM & Meszaros 16 PRD



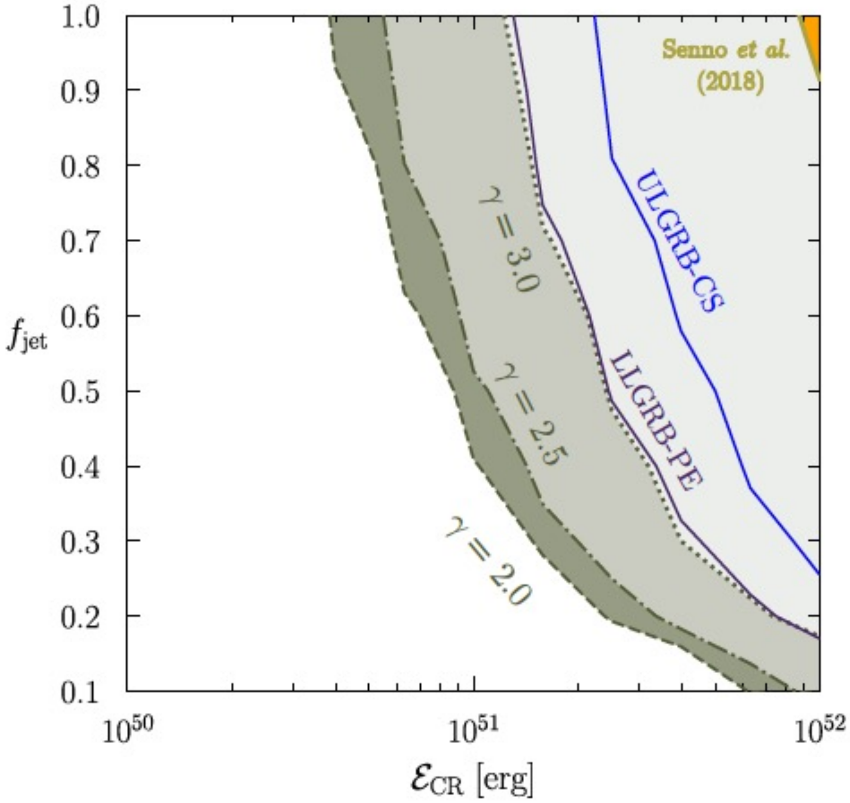
from Cano+ 17 Adv. Ast.

- Marginally choked jets: trans-relativistic SNe & low-luminosity (LL) GRBs
  (Toma+07, Nakar 15, Irwin & Chevalier 16)

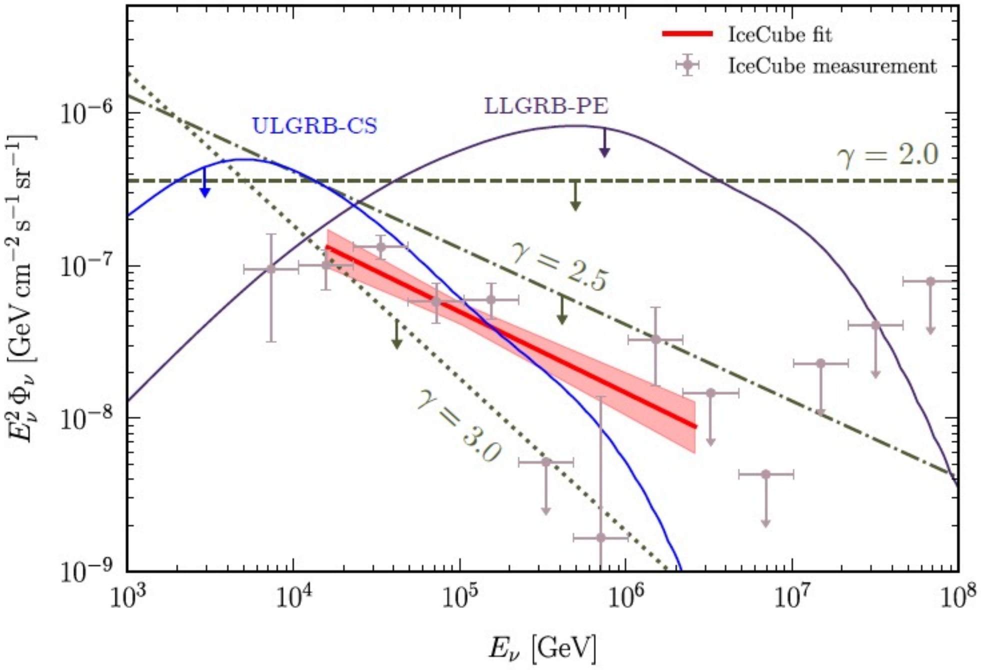
- Low-power choked jets may contribute to the IceCube flux with GRB stacking limits evaded
  (KM+ 06 ApJL, Gupta & Zhang 07 APh, KM & Ioka 13 PRL, Denton & Tamborra 18 ApJ Carpio & KM 20 PRD)

Powerful Stacking Searches

Stacking analyses on 386 SNe Ibc w. 10 yr IceCube data



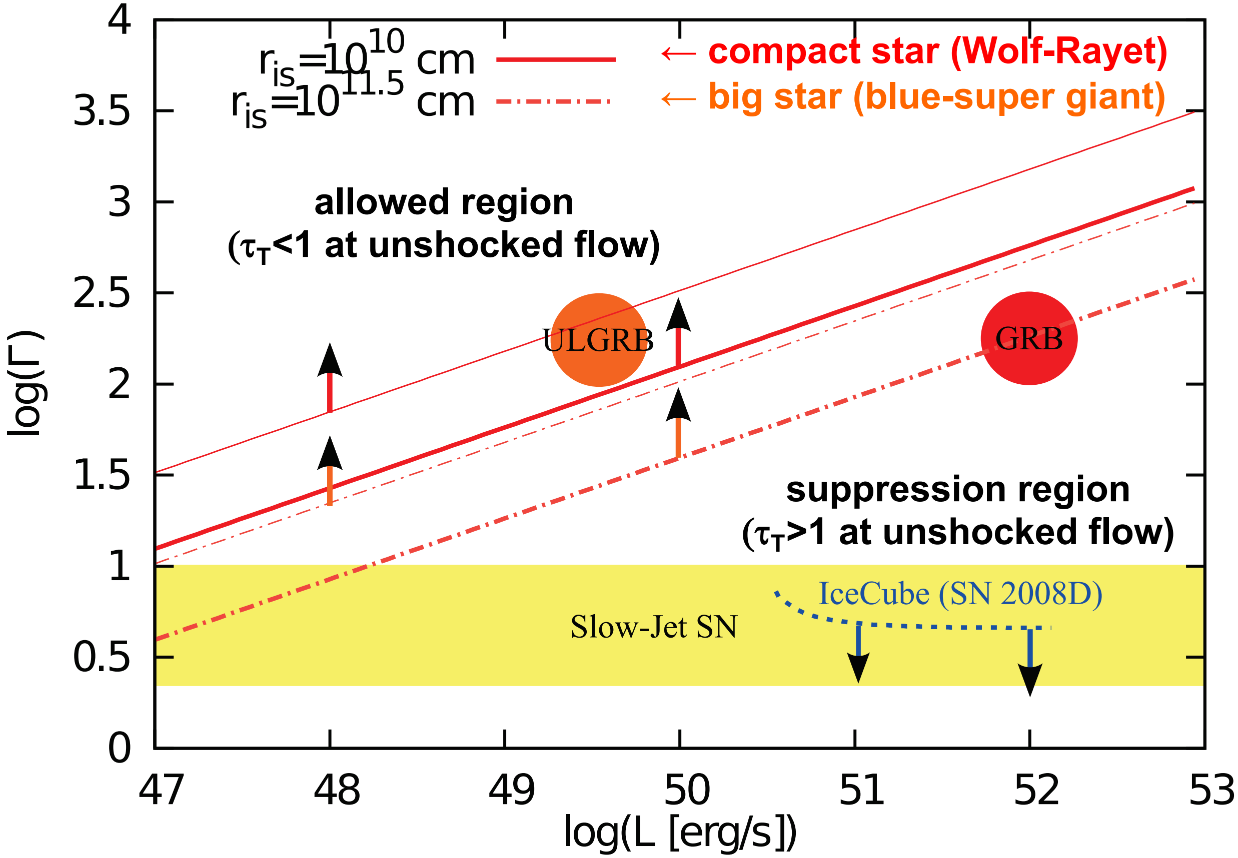
Chang, Zhou, Km & Kamionkowski 22
see also Senno, KM & Meszaros 18 JCAP
Esmaili & KM 18 JCAP



- Present constraints: $E_{cr}<10^{51}$-10^{52} erg (if all SNe emit νs)
- Future: readily improved w. more SNe (especially w. Rubin)
- Be careful about the completeness of representative population

"Radiation Constraints" on Non-thermal Neutrino Production

KM & Ioka 13 PRL



Thomson optical depth

$$\tau_T = n_e \sigma_T \Delta \propto L\Gamma^{-2}$$

L: kinetic luminosity

Γ: Jet Lorentz factor

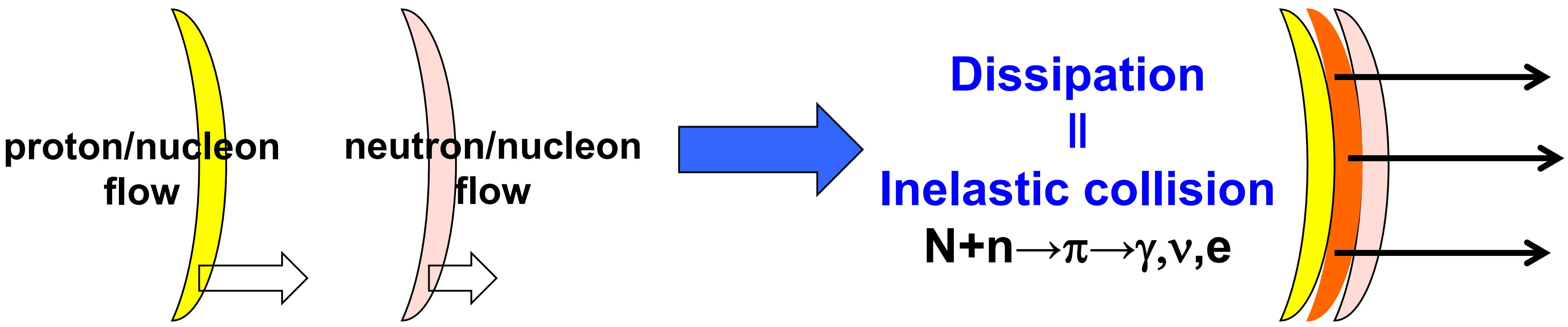
- Lower-power is better
- Extended material is better

⇒ **suppressed in typical GRB jets and powerful slow jets**

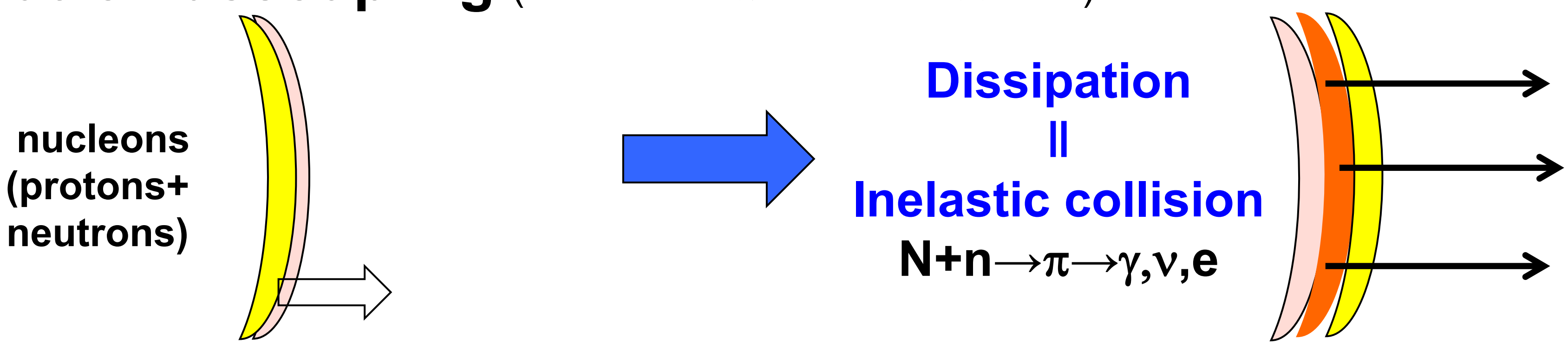
e.g., KM & Ioka 13, Gottlieb & Globus 21
Bhattacharya, Carpio, KM+ 22

Relativistic Neutrons Dissipate via Inelastic np Collisions

Collision w. neutrons (ex. Meszaros & Rees 00 ApJ, KM+ 13 PRL, Bartos+ 13 PRL)



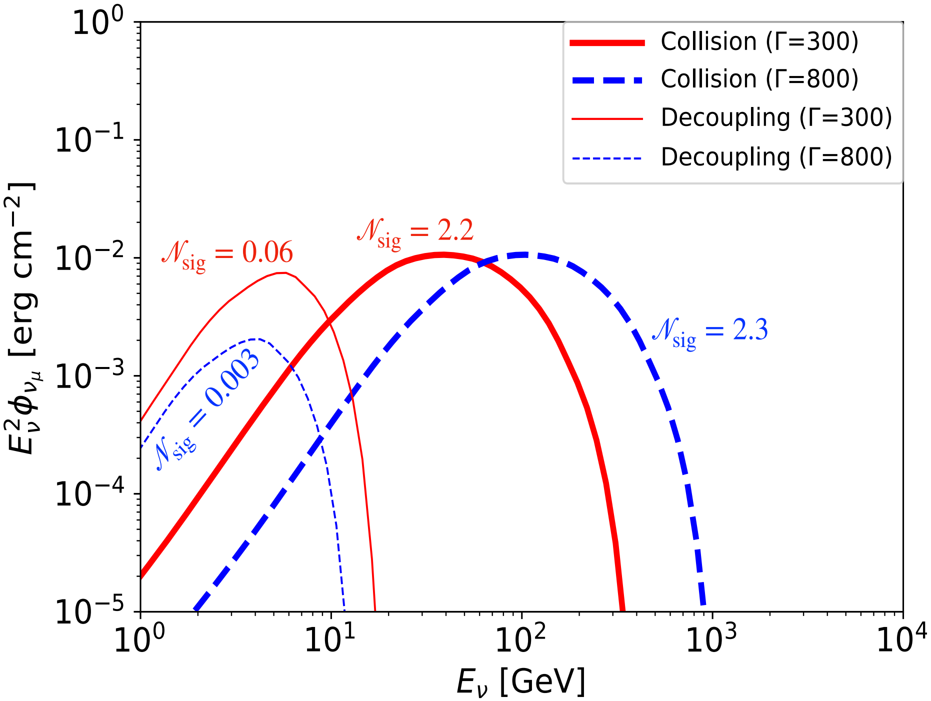
Neutron decoupling (ex. Bahcall & Meszaros 00 PRL)

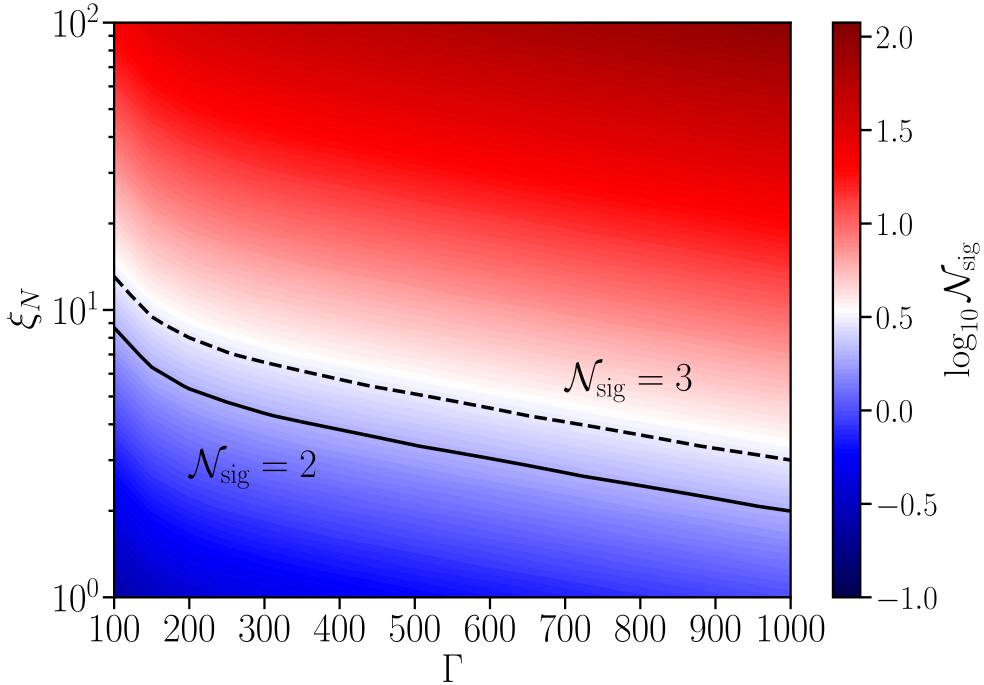


Subphotospheric GeV-TeV ν

GRB 221009A

KM+ 22 ApJL





- Collision model predicts a few signal events
- Detectability is comparable w. ~10 year stacking searches
- Not "yet" constrained by IceCube limits
- Probes of jet composition and dissipation mechanism

What Do We Need?

Targets: long-duration HE ν/short-duration GeV-TeV ν transients

- Multimessenger coincident searches (e.g., AMON events) would be powerful for subthreshold events
- Neutrino multiplet followups would also be useful

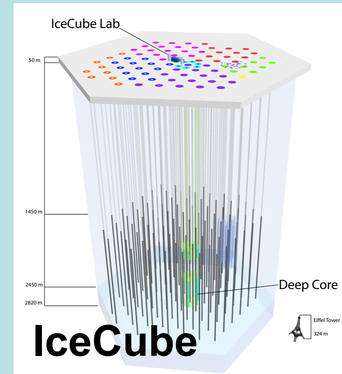
- Optical: spectroscopic information is relevant (SN brokers would be useful)
- Better hard X/γ-ray sky monitors needed (ex. >~10 times better than Swift for LL GRBs)
- Coincidences w. UV transients also help (ex. ULTRASAT)
- Radio facilities also help (ex. DSA-2000, ngVLA)

Ongoing "Multi-Messenger" Attempts

Light (electromagnetic)

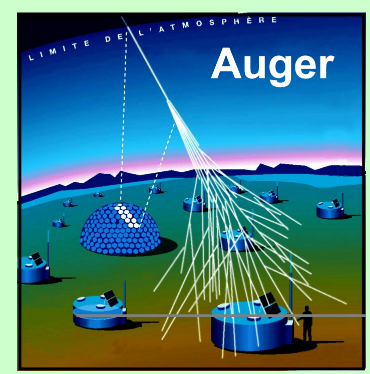
- **AMON**
- **SciMMA**
- **Astro-Colibri**

Neutrino (weak force)



Gravitational wave (gravity)

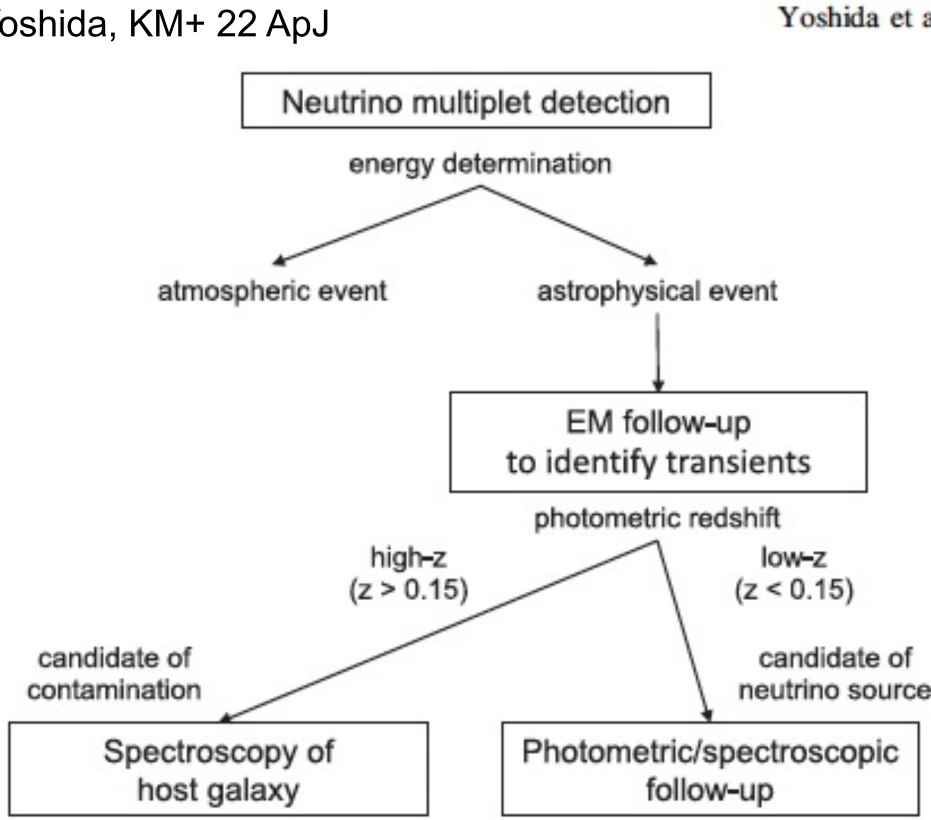
Cosmic-ray (strong force)

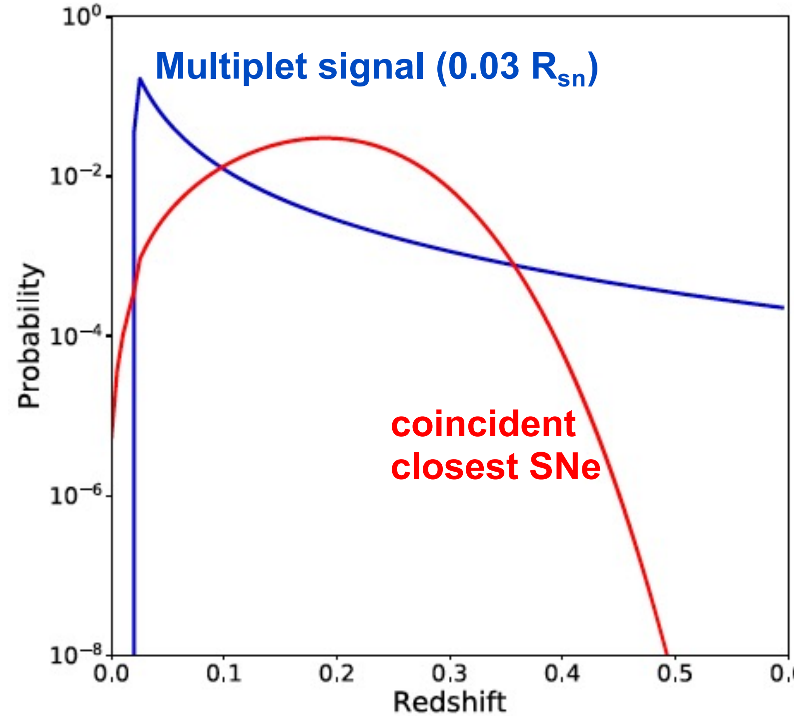


Don't miss interesting ν & GW events

- **Realtime coincident searches**
- **Prompt data-sharing for follow-ups**

Yoshida, KM+ 22 ApJ

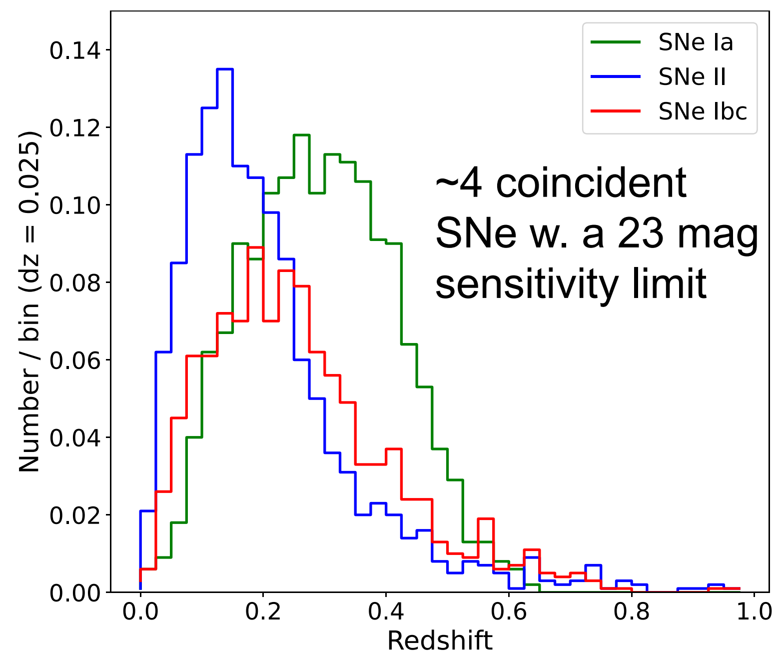




- Need for long-duration multiplet alerts
  lower FAR (< 1/yr)
  likely to be low redshifts if SN-like

- Discriminating optical transients is a key

- Sensitivity: ~(30-3000) Gpc^{-3} yr^{-1}
  more improved w. KM3Net/IceCube-Gen2



What Do We Need?

Targets: long-duration HE ν/short-duration GeV-TeV ν transients

- Multimessenger coincident searches (e.g., AMON events) would be powerful for subthreshold events
- Neutrino multiplet followups would also be useful

- Optical: spectroscopic information is relevant (SN brokers would be useful)
- Better hard X/γ-ray sky monitors needed (ex. >~10 times better than Swift for LL GRBs)
- Coincidences w. UV transients also help (ex. ULTRASAT)
- Radio facilities also help (ex. DSA-2000, ngVLA)

Summary

Transients
some hints, the power of multimessenger approaches

TDEs
Intriguing coincidences
Common mechanisms between AGN and TDEs?

Supernovae
Galactic SN: multi-energy ν source (>10-100 HE νs in IceCube)
Nearby SNe within a few Mpc: neutrino telescope networks

Jet-driven SNe
Stacking searches w. more samples and future neutrino detectors
GeV-TeV νs from neutron-loaded outflows

Compact binary mergers
ν-GW coincidence would need Gen2-like detectors

Strategic multi-messenger searches
Better X-ray/γ-ray monitors, optical/infrared surveys (w. spectroscopy)

from Murase's talk
@ Neutrino 2014

WANTED

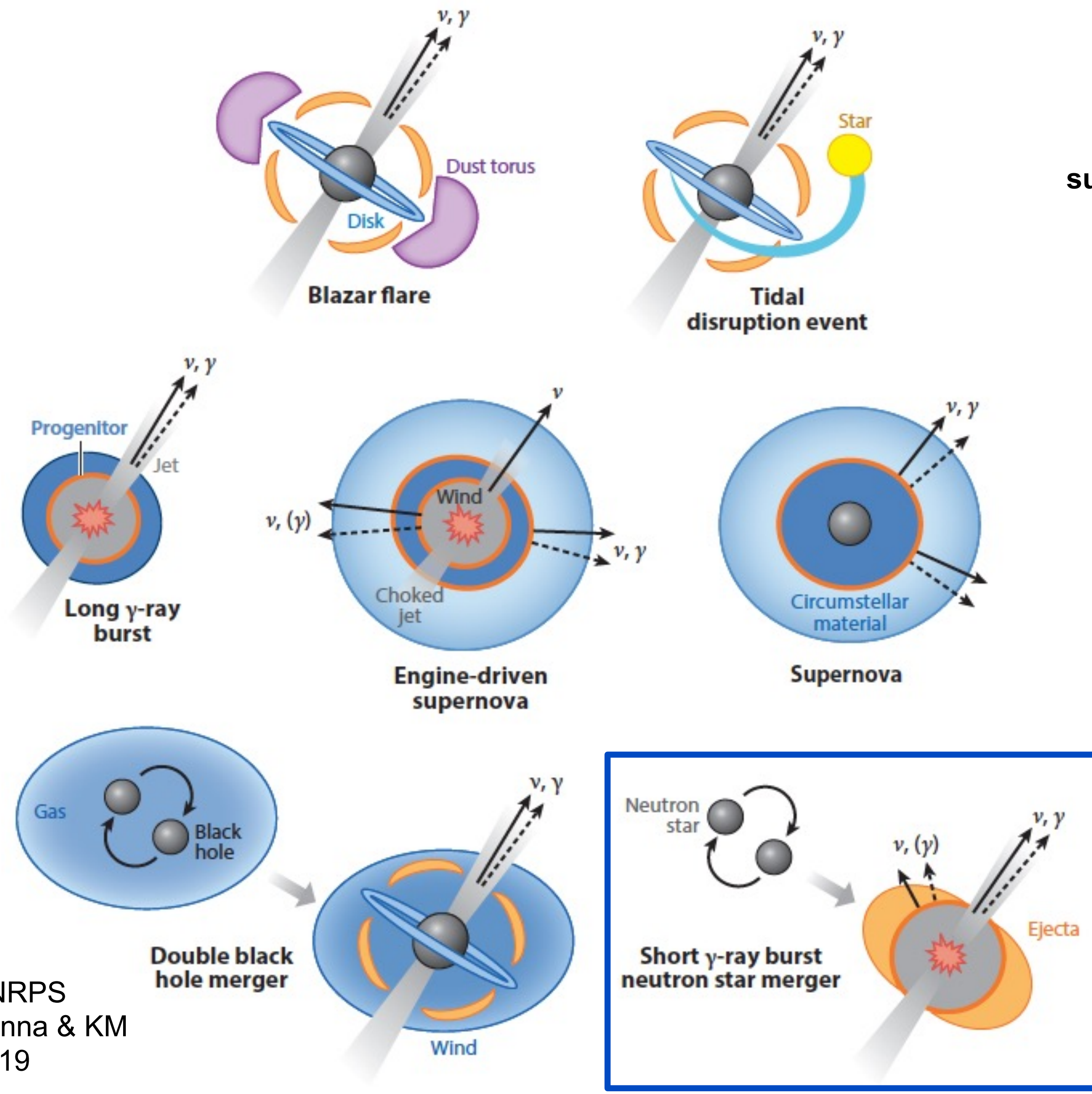
~~Diffuse or A~~ssociated

ν

- Source identification may not be easy
  (ex. starbursts: horizon of an average sourc TXS, TDEs)
- promising cases: "bright transients (GRBs, AGN flares)",
  "rare bright sources (powerful AGN)", "Galactic sources"
- Not guaranteed but rem NGC 1068 e success of γ-ray astrophysics

Backup Slides

Diversity of High-Energy Transients



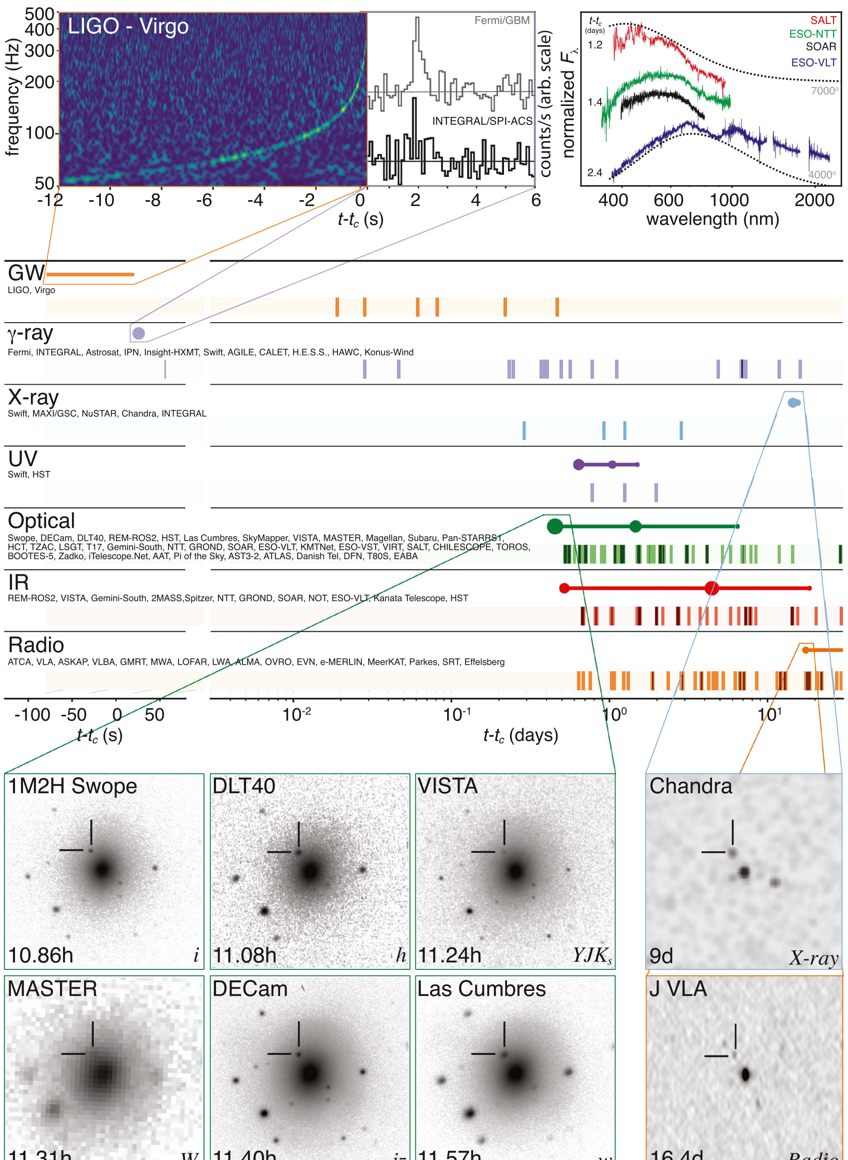
supermassive black holes

massive stellar deaths

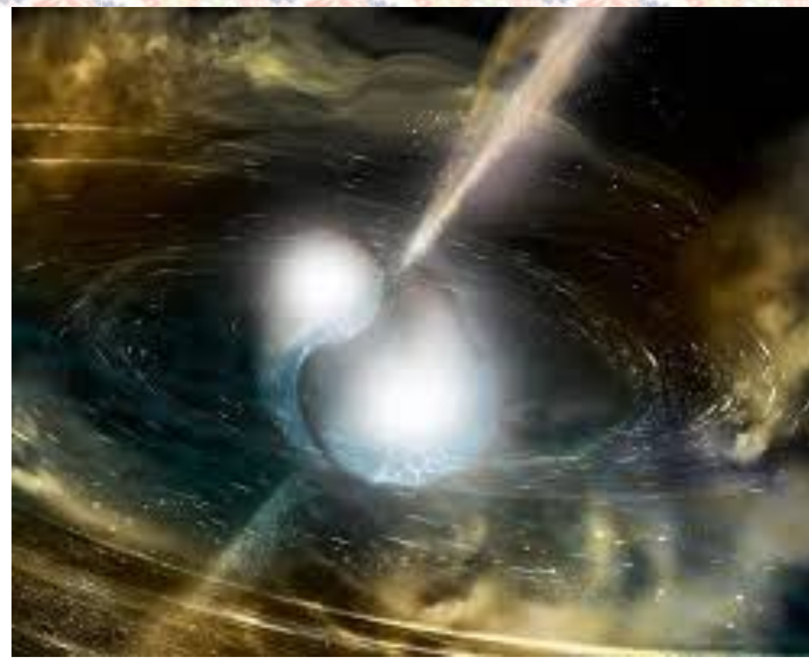
compact mergers
(promising GW sources)

KM & Bartos 19 ANRPS
Meszaros, Fox, Hanna & KM
Nature Rev. Phys. 19

Discovery of Binary Neutron Star Merger (2017)



Abbott et al. 2017 ApJL

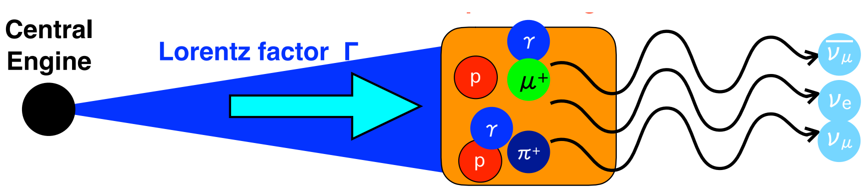


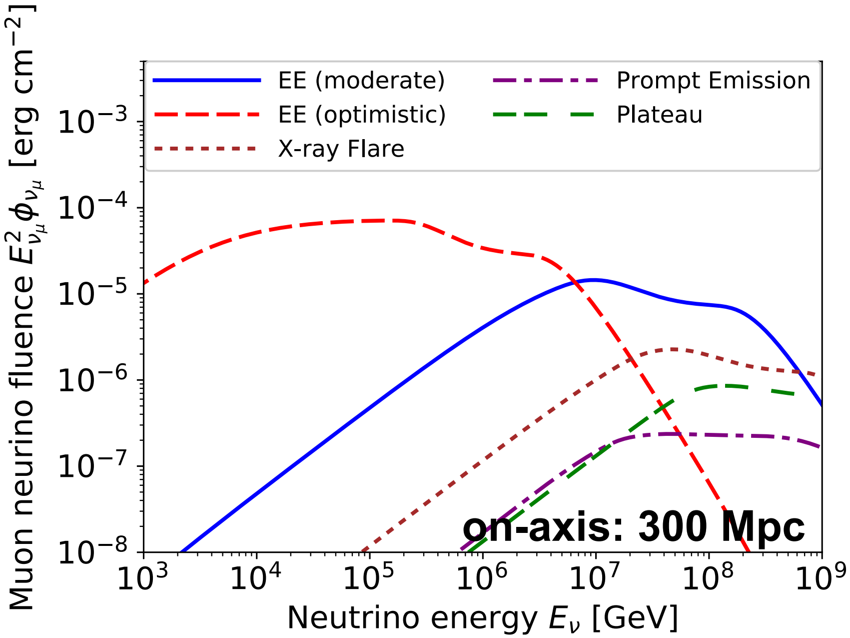
concordance picture

- **gravitational wave**
- **gamma-ray burst**
- **kilonova/macronova**
- **X-ray/radio afterglow**

Coincident Detection w. Gravitational Waves?

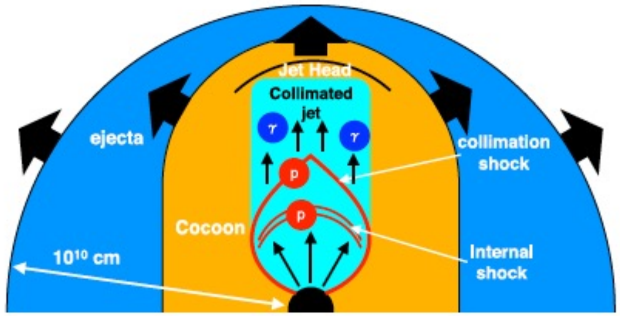
Kimura, KM, Meszaros & Kiuchi 17 ApJL
(cf. Waxman & Bahcall 97 PRL for prompt
KM & Nagataki 06 PRL for X-ray flares)

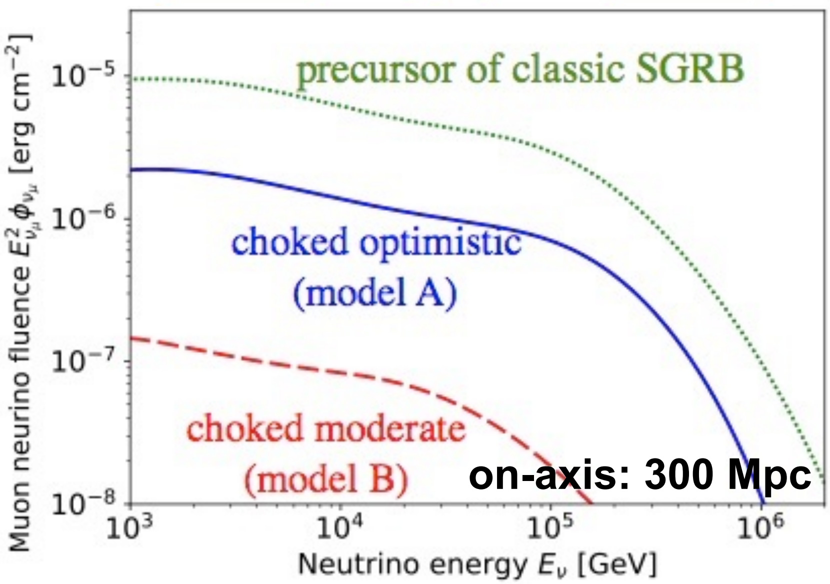




extended emission:
< 2-5 events in 10 years w. Gen2

Kimura, KM, Bartos, Ioka+ 18 PRD
(cf. KM & Ioka 13 PRL for massive stars)

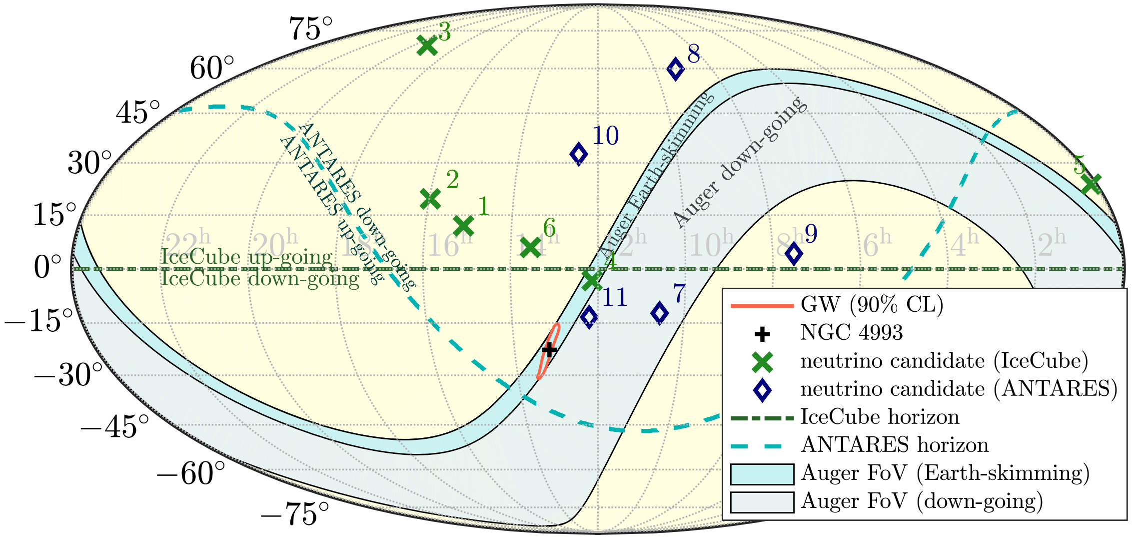




< 1-3 bursts in 10 years w. Gen2

Current Limits on HE Neutrinos from NS Mergers

ANTARES, IceCube, Auger, & LIGO-Virgo ApJL 17



theoretical models

short GRB jets

(Kimura, KM, Meszaros & Kiuchi 17 ApJL)

(see also Biehl et al. 18 MNRAS
Ahlers & Halser 19 MNRAS)

long-lived magnetar in the ejecta

(not supported for GW170817)

(Fang & Metzger 17 ApJ)