The Multimessenger View of Galaxy and Compact Binary Mergers

Chengchao Yuan

Ph.D. candidate of Physics

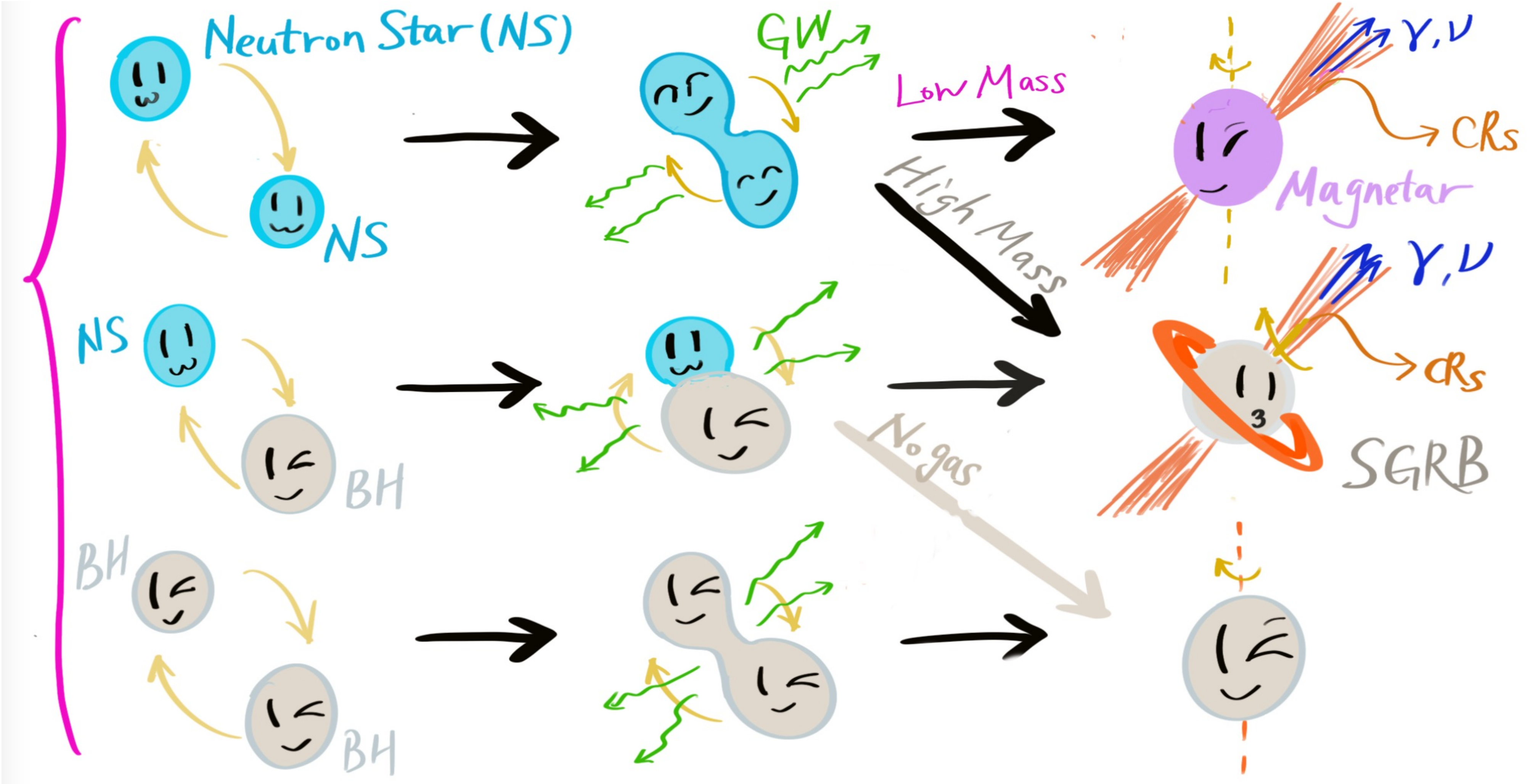
Penn State

Columbia University, HEP Seminar

December 8, 2021

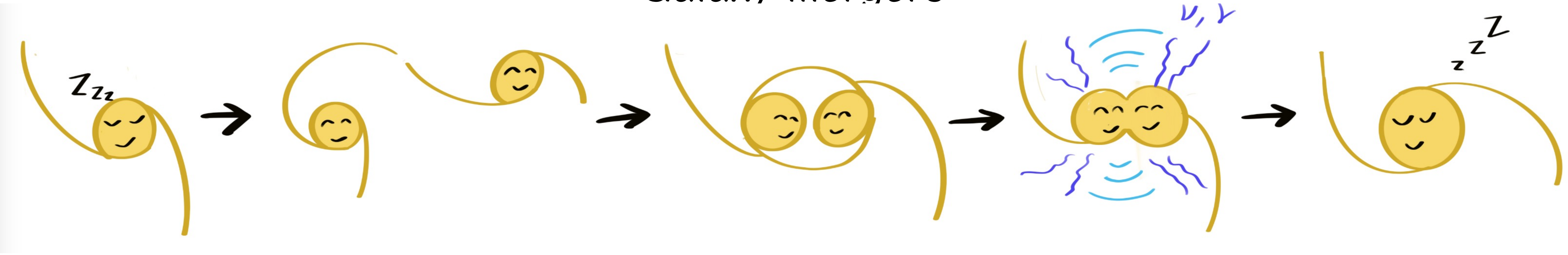
A Sketch of Astrophysical Mergers

Stellar-mass compact binary mergers: NS-NS, NS-BH, and BH-BH

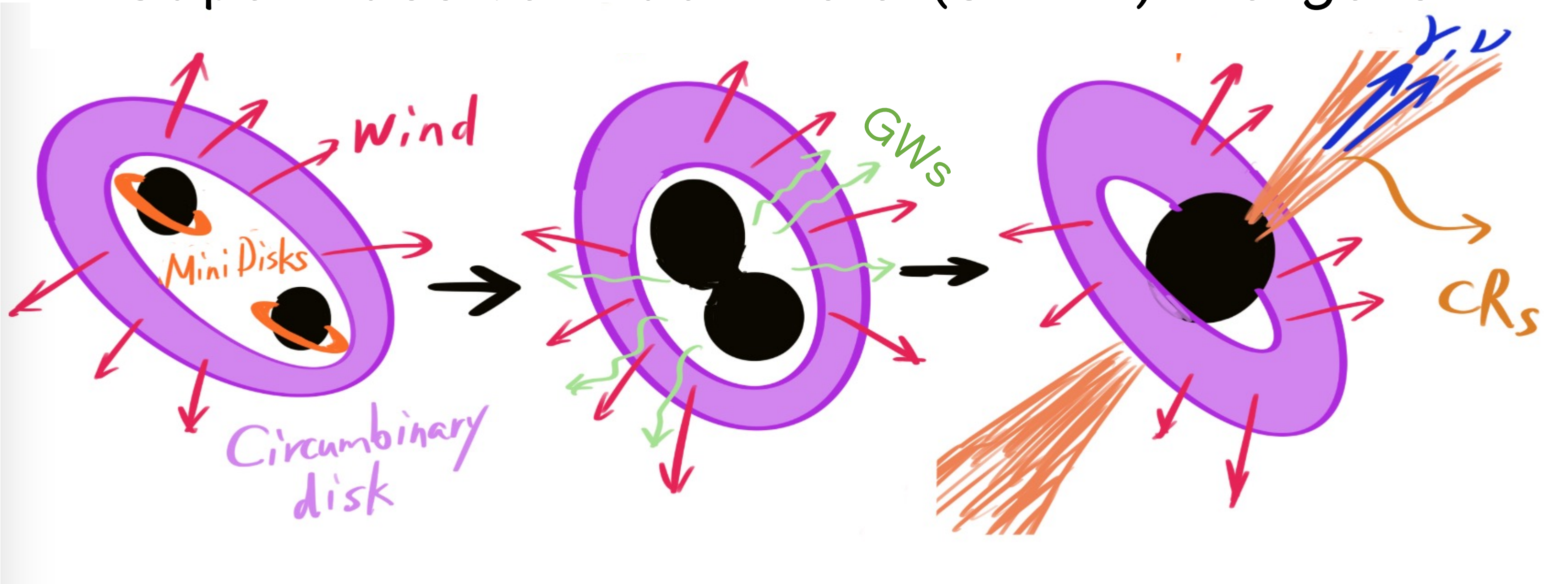


A Sketch of Astrophysical Mergers

Galaxy mergers

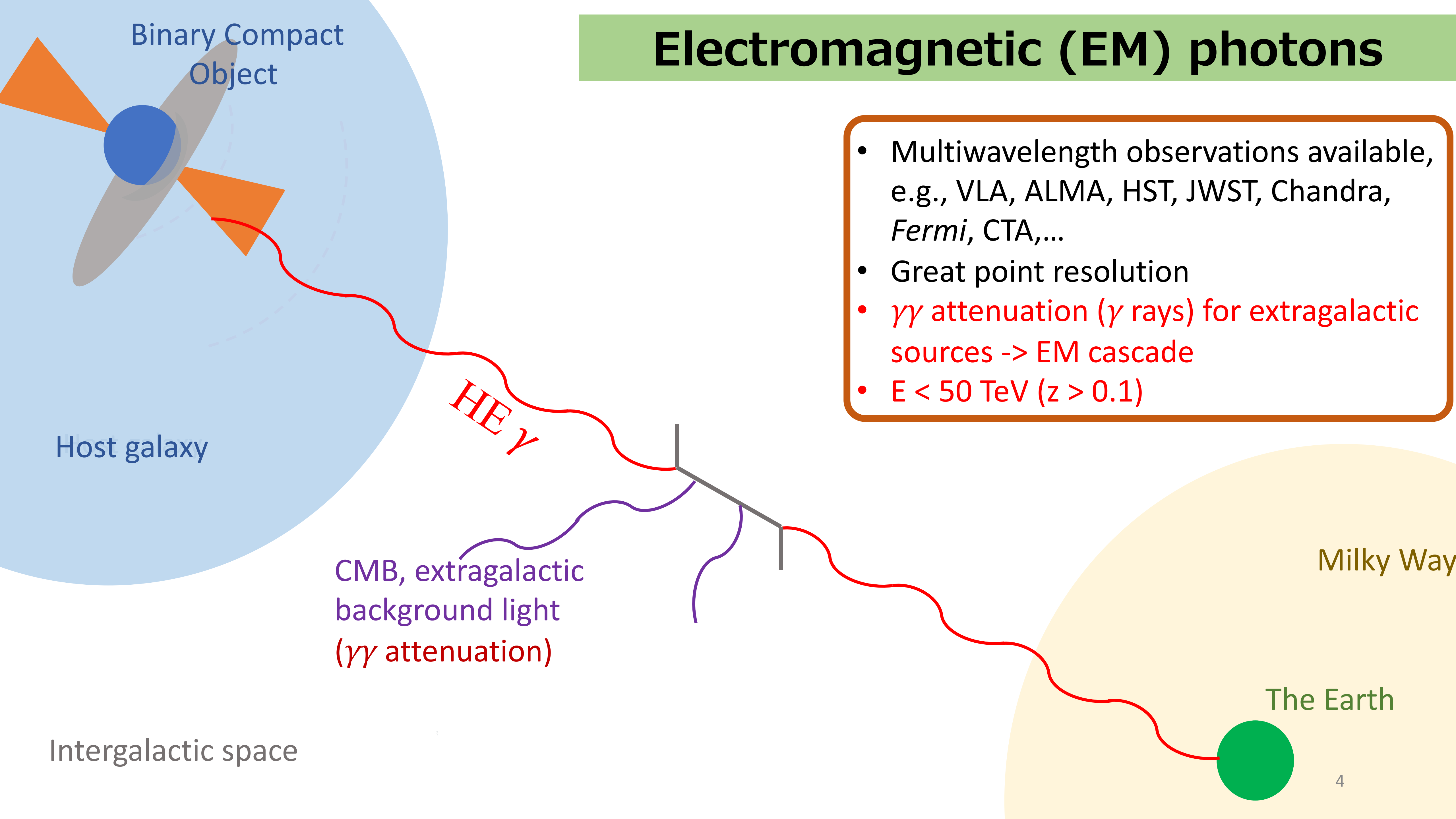


Supermassive Black Hole (SMBH) mergers

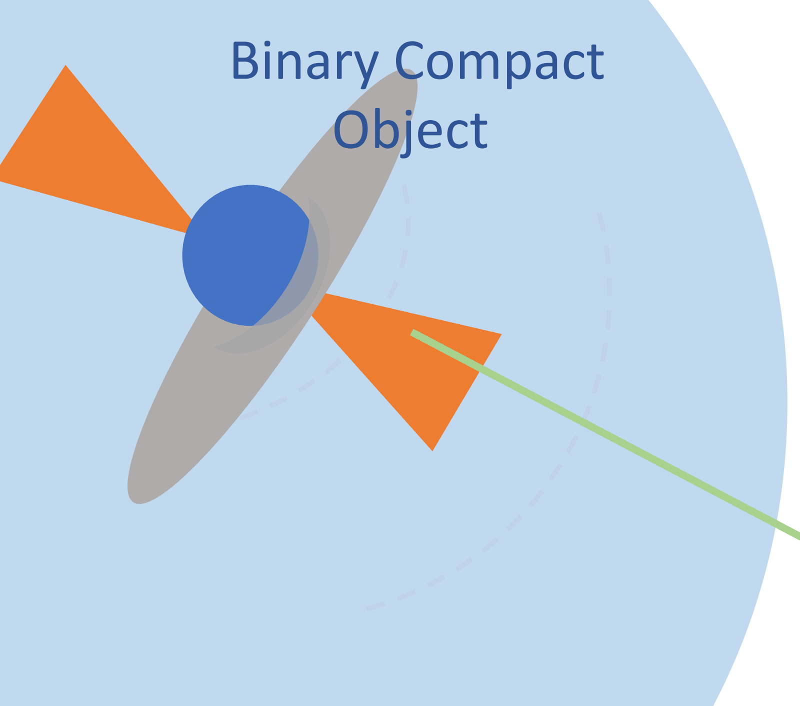


Electromagnetic (EM) photons

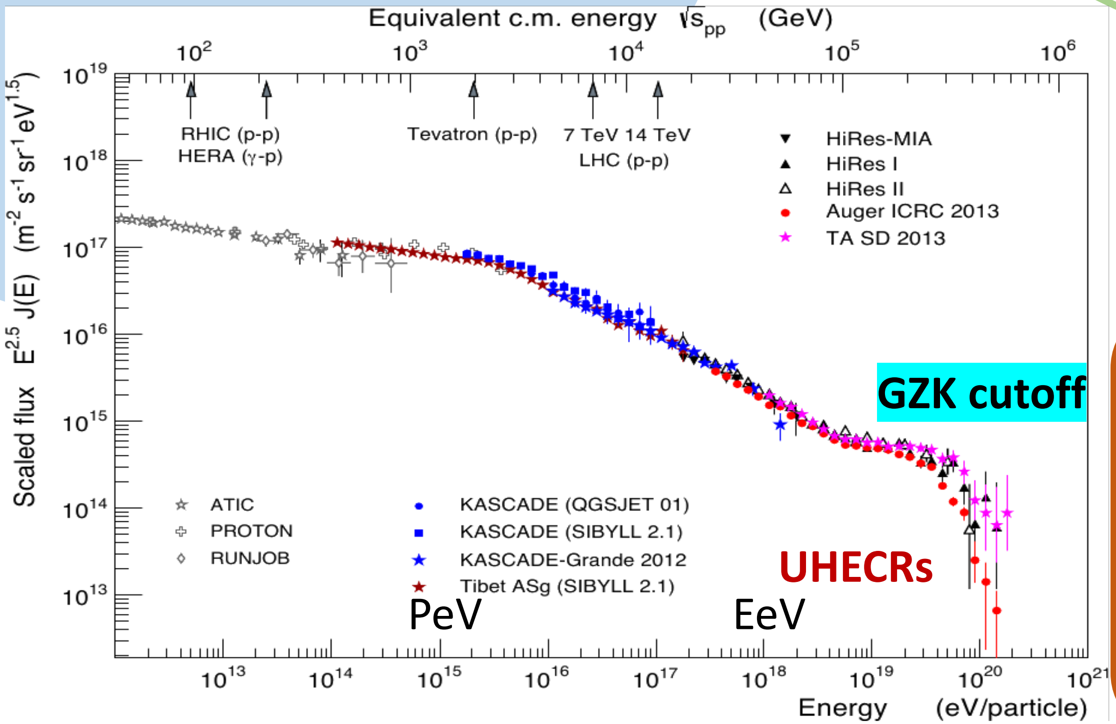
- Multiwavelength observations available, e.g., VLA, ALMA, HST, JWST, Chandra, *Fermi*, CTA,…
- Great point resolution
- $\gamma\gamma$ attenuation (γ rays) for extragalactic sources -> EM cascade
- E < 50 TeV (z > 0.1)



Cosmic rays (CRs)



"a radiation of high penetrating power enters the atmosphere from above"

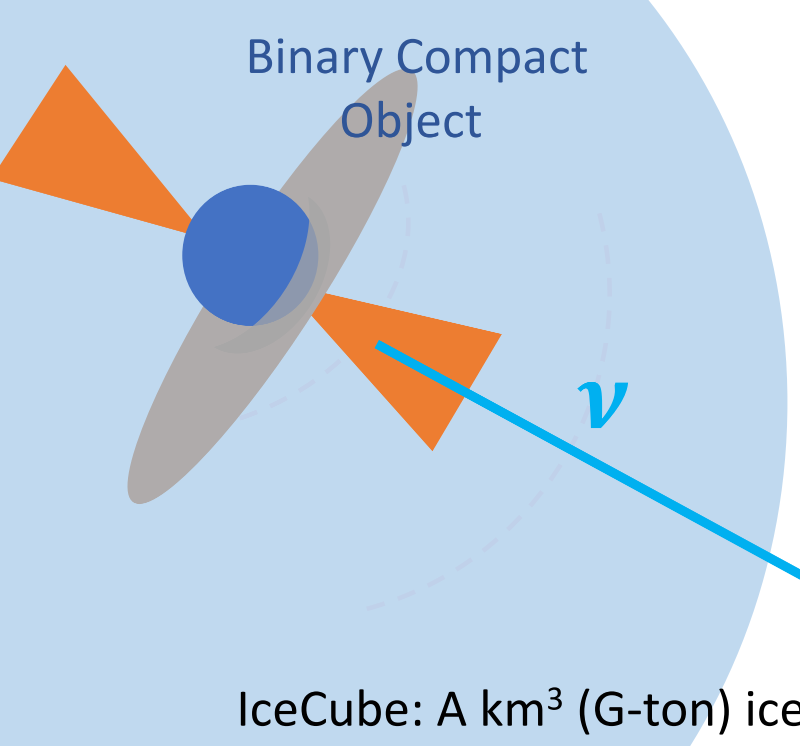


Greisen–Zatsepin–Kuzmin (GZK) cutoff

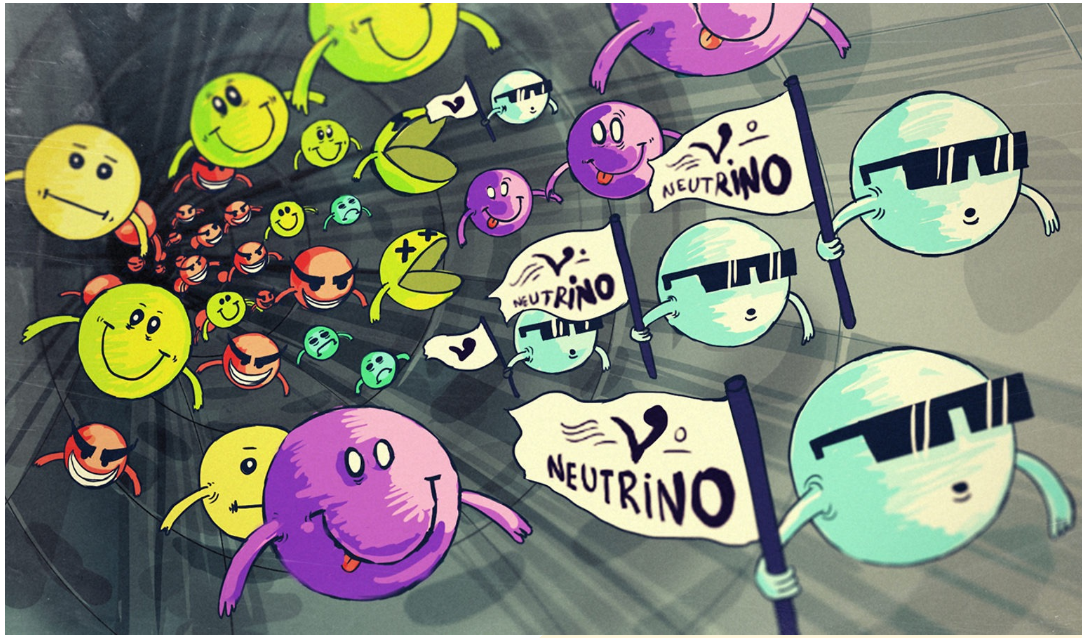
$$\gamma_{\rm CMB} + p \to \Delta^+ \to p + \pi^0,$$
$$\gamma_{\rm CMB} + p \to \Delta^+ \to n + \pi^+.$$

Cutoff energy: 5×10^{19} eV (50 EeV)
Energy-loss distance: ~100 Mpc

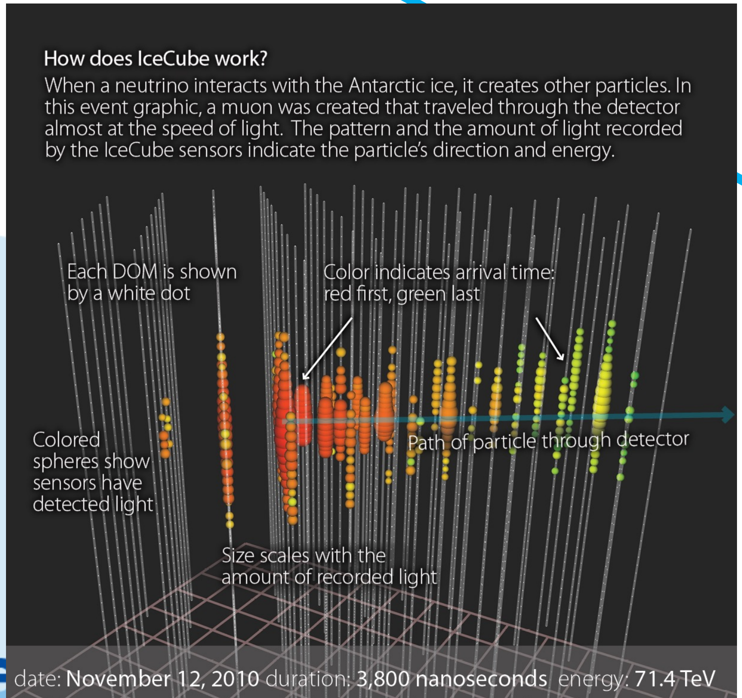
High-Energy (HE) Neutrinos

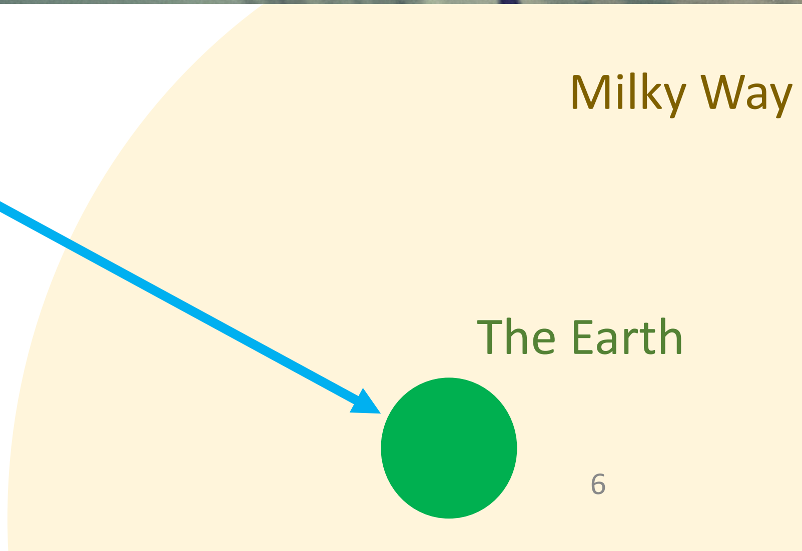


Astrophysical neutrino beam



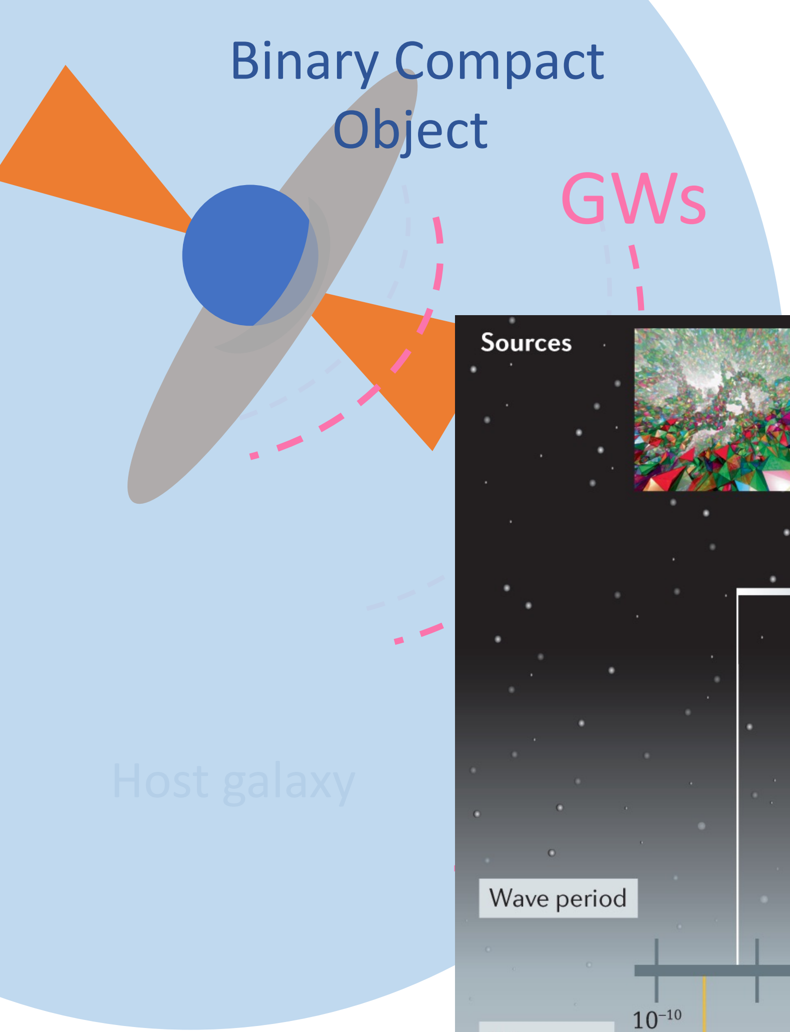
IceCube: A km^3 (G-ton) ice Cherenkov detector



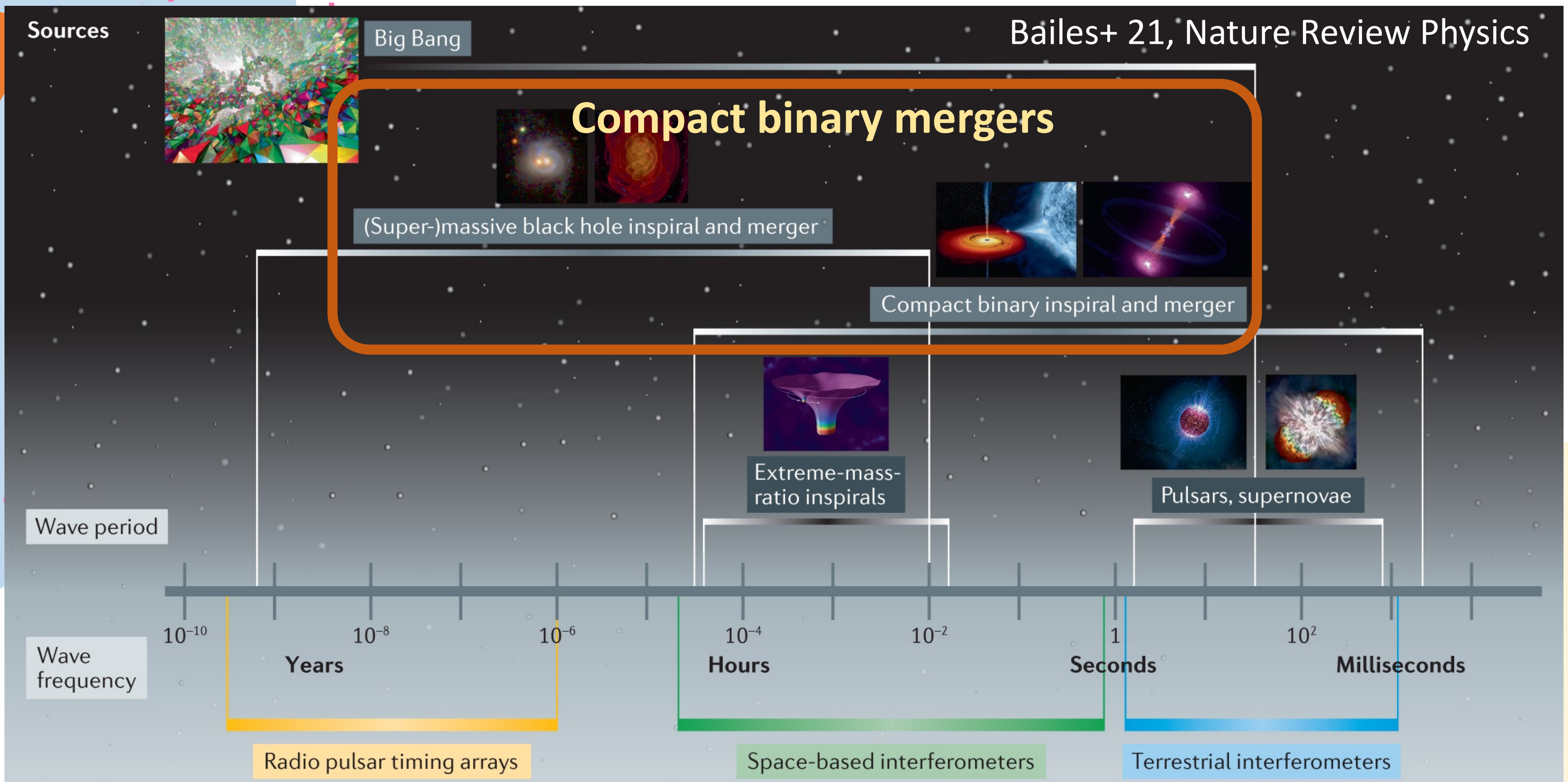


Source: higgstan

GWs



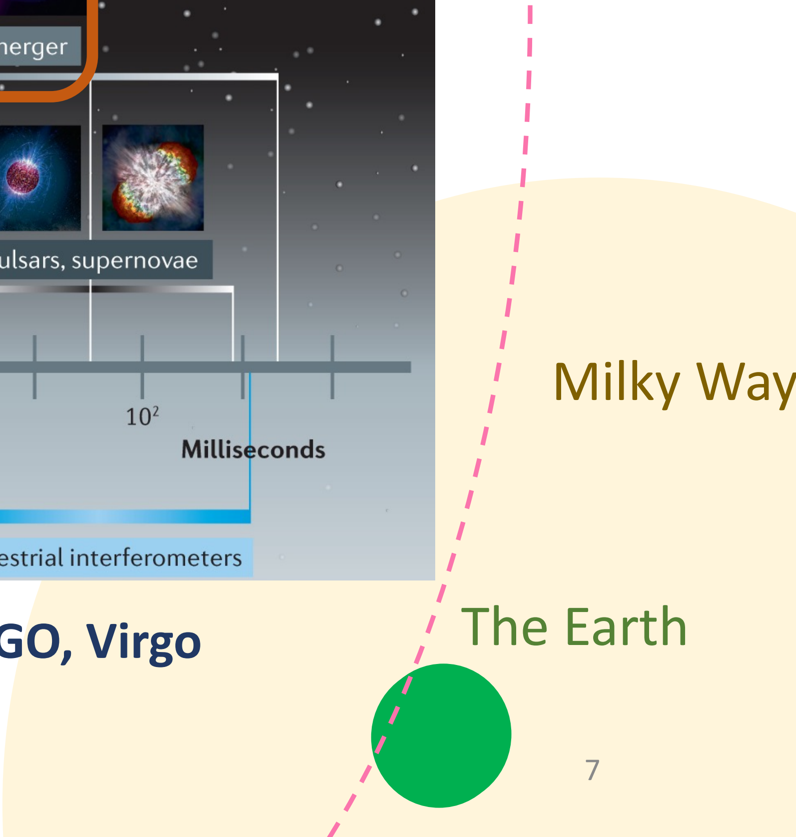
And then there were four!



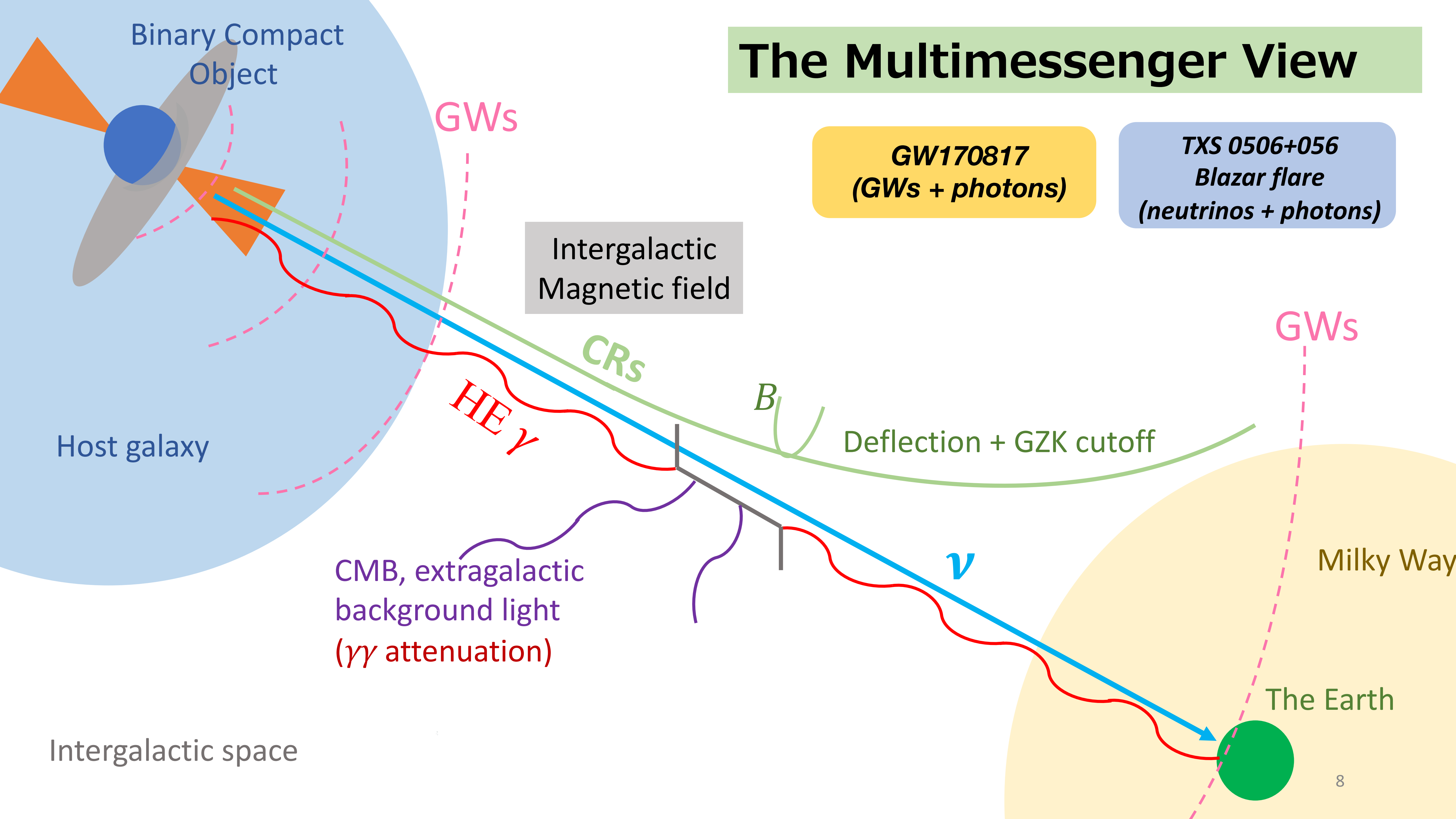
Pulsar Telescope Array (PTA)

Laser Interferometer Space Antenna (LISA)

LIGO, Virgo



The Multimessenger View



Outline

Part 1: Galaxy/cluster mergers

- contribution to the IceCube diffuse neutrino background
- Secondary radio and X-ray emission

Part 2: Supermassive black hole mergers

- Post-merger jet-induced neutrino emission
- EM counterpart

Part 3: Short GRBs embedded in AGN disks

- Physical picture
- Extended gamma-ray emission

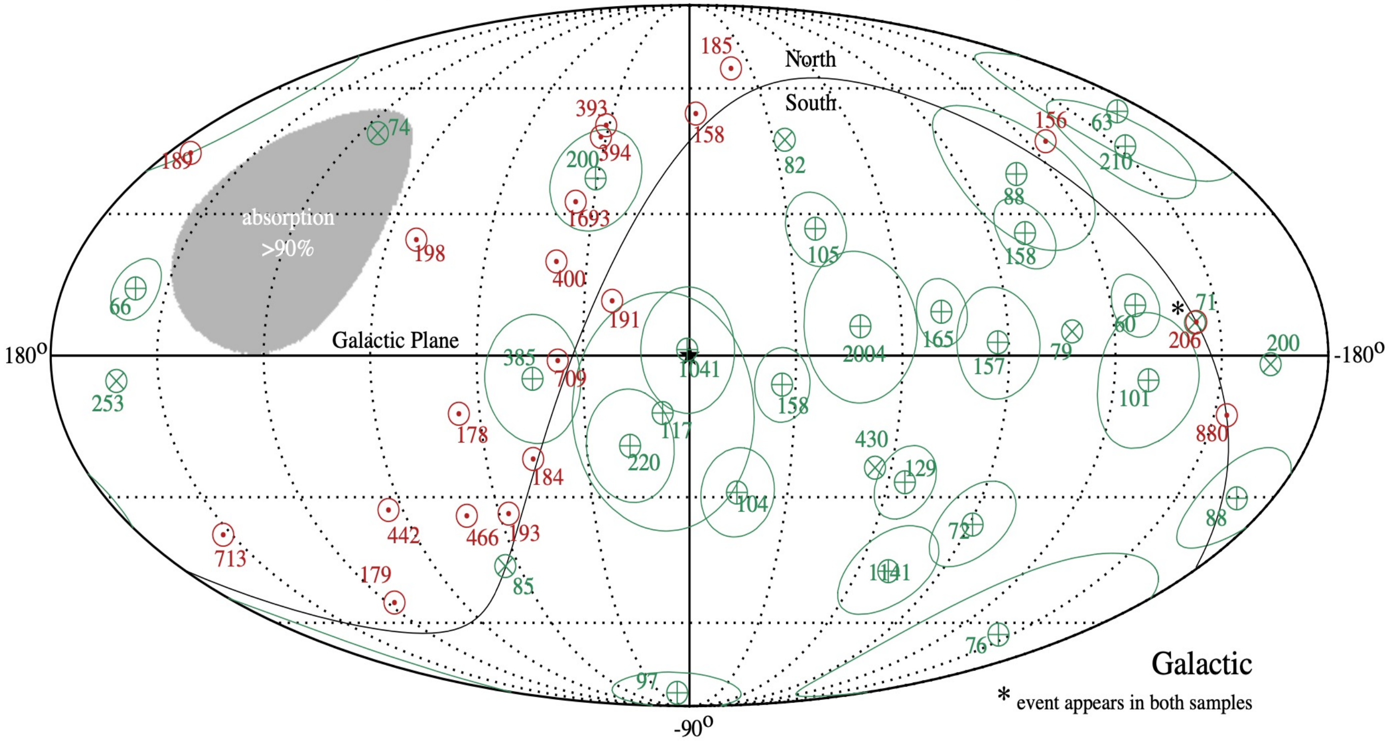
Part 4: The future

HE Diffuse Neutrino Background

origins & mechanisms: new mystery in astroparticle physics

Mostly isotropic -> Extragalactic origin

HESE 4yr with $E_{dep} > 60$ TeV (green) / Classical $\nu_\mu + \bar{\nu}_\mu$ 2yr with $E_\mu > 50$ TeV (red)



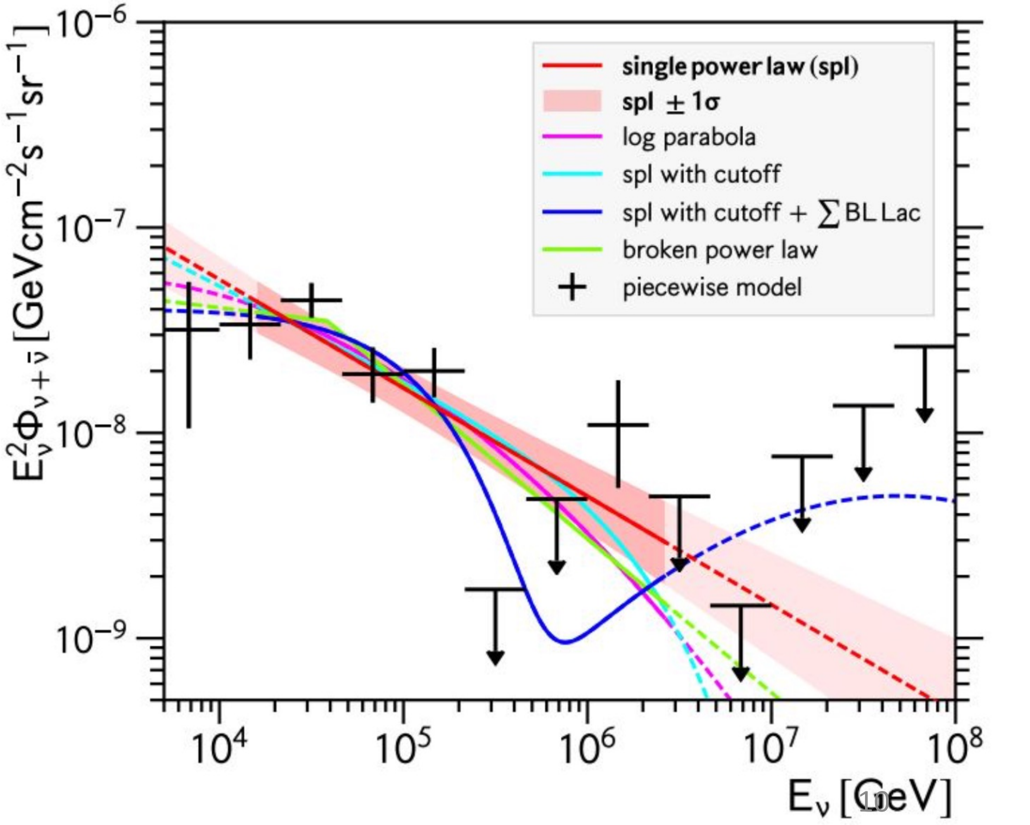
Credit: IceCube Collaboration

-*pp* or *p*γ?

-connection to UHECRs? -connection to γ rays?

-new physics?

-two components?



IceCube collaboration, 2020 PRL

HE Diffuse Neutrino Background: Origins

Photohadronic ($p\gamma$): luminous bursts

e.g. relativistic jets

Gamma-ray bursts (GRBs), active galactic nuclei (AGN) jets/cores, cosmogenic

Hadronuclear (pp): CR reservoirs

e.g. extensive dense regions

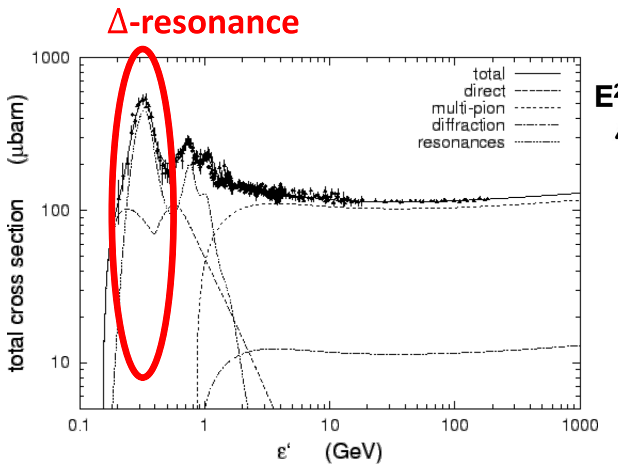
Supernova/hypernova remnants, galaxies and clusters

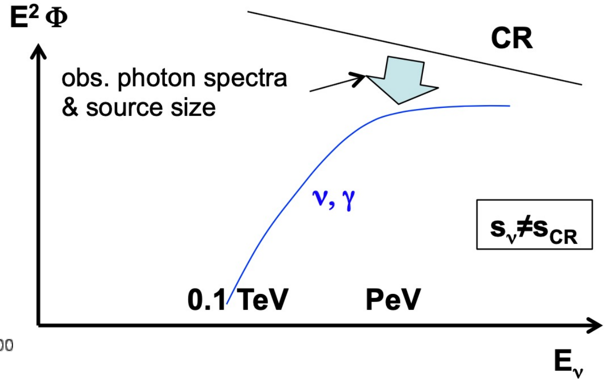
$$p + \gamma \rightarrow \pi + X$$

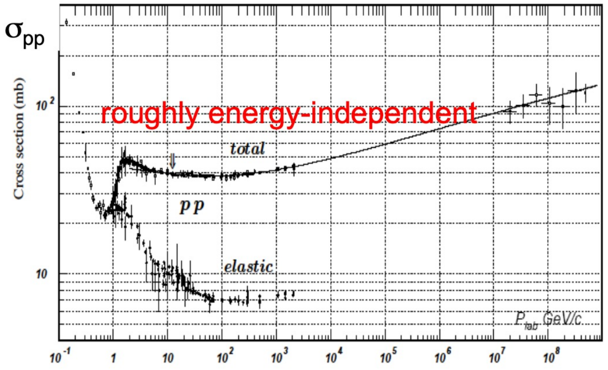
$$\pi^{\pm} \rightarrow \mu^{\pm} + \nu_{\mu}(\bar{\nu}_{\mu}), \;\; \mu^{\pm} \rightarrow e^{\pm} + \bar{\nu}_{\mu}(\nu_{\mu}) + \nu_e(\bar{\nu}_e)$$

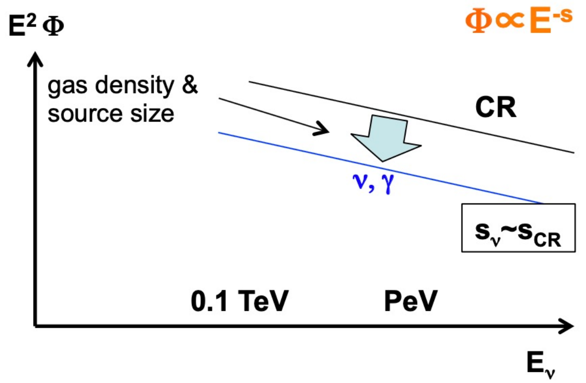
$$\pi^0 \rightarrow \gamma + \gamma$$

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









Flux/energy relations between γ-ray, ν and CRs

$$\mathbf{pp} \text{ collision } \;\; \pi^+ : \pi^- : \pi^0 \approx 1:1:1, \;\; \varepsilon_\nu Q_{\varepsilon_\nu} \approx \frac{1}{2}\varepsilon_p Q_{\varepsilon_p}, \;\; \varepsilon_\gamma Q_{\varepsilon_\gamma} \approx \frac{2}{3}\varepsilon_\nu Q_{\varepsilon_\nu}$$

Neutrino: $E_\nu = 0.04 - 0.05\, E_p$

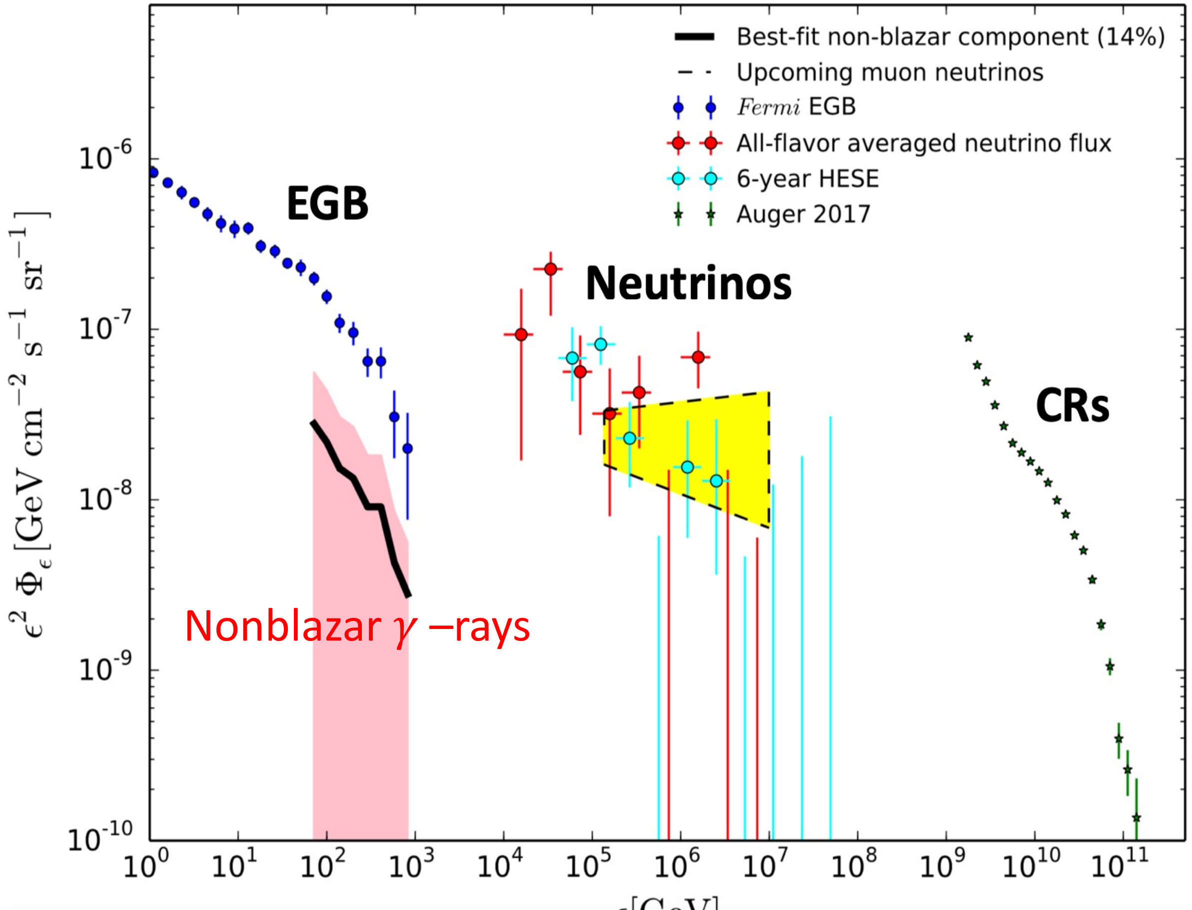
$$\mathbf{p}\gamma \text{ collision } \;\; \pi^+ : \pi^- : \pi^0 \approx 1:1:2, \;\; \varepsilon_\nu Q_{\varepsilon_\nu} \approx \frac{3}{8}\varepsilon_p Q_{\varepsilon_p}, \;\; \varepsilon_\gamma Q_{\varepsilon_\gamma} \approx \frac{4}{3}\varepsilon_\nu Q_{\varepsilon_\nu}$$

Gamma-ray: $E_\gamma = 0.08 - 0.1\, E_p$

Extragalactic γ-ray background (EGB) constraints

pγ/pp -> neutrinos, γ –rays **-> diffuse ν background + extragalactic γ-ray background (EGB)**

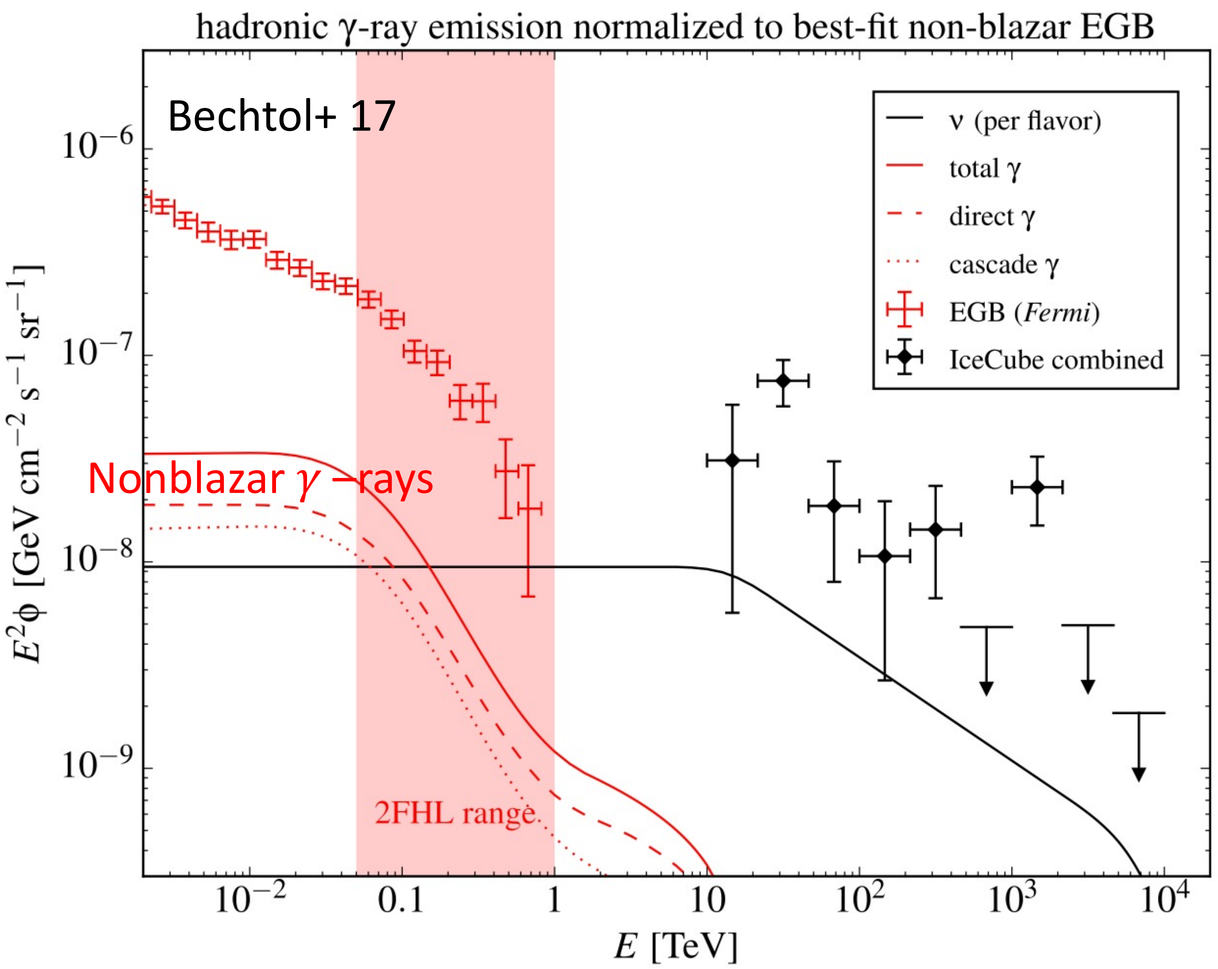
- **Blazars account for 86^{+16}_{-14} % of the total EGB flux** (Ackermann+ 2016)
- **but are not the dominant source of IceCube diffuse ν background.** (Aartsen+17 …)

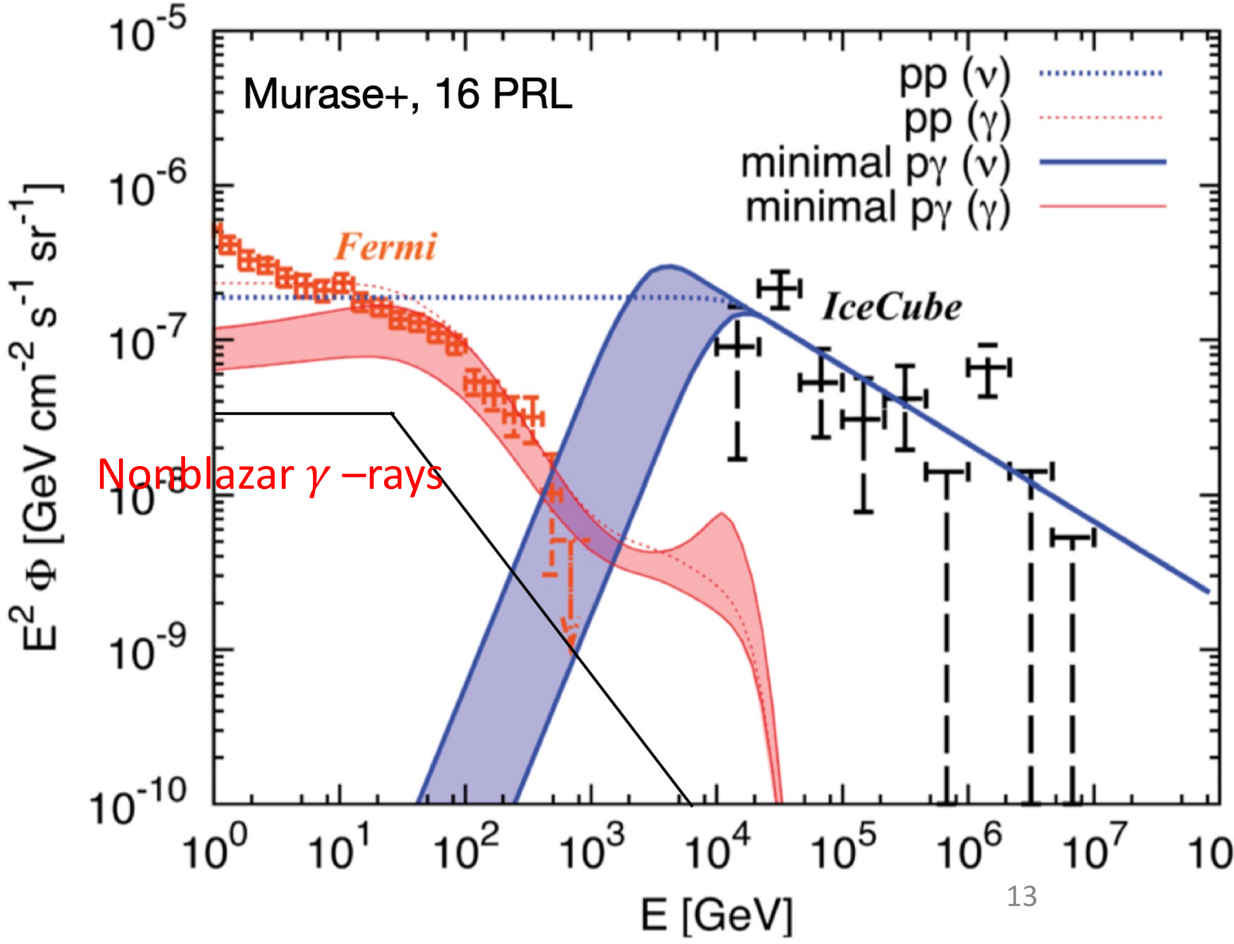


Sources that contribute significantly to IC diff. νs but are not very bright in the γ-ray sky are wanted!

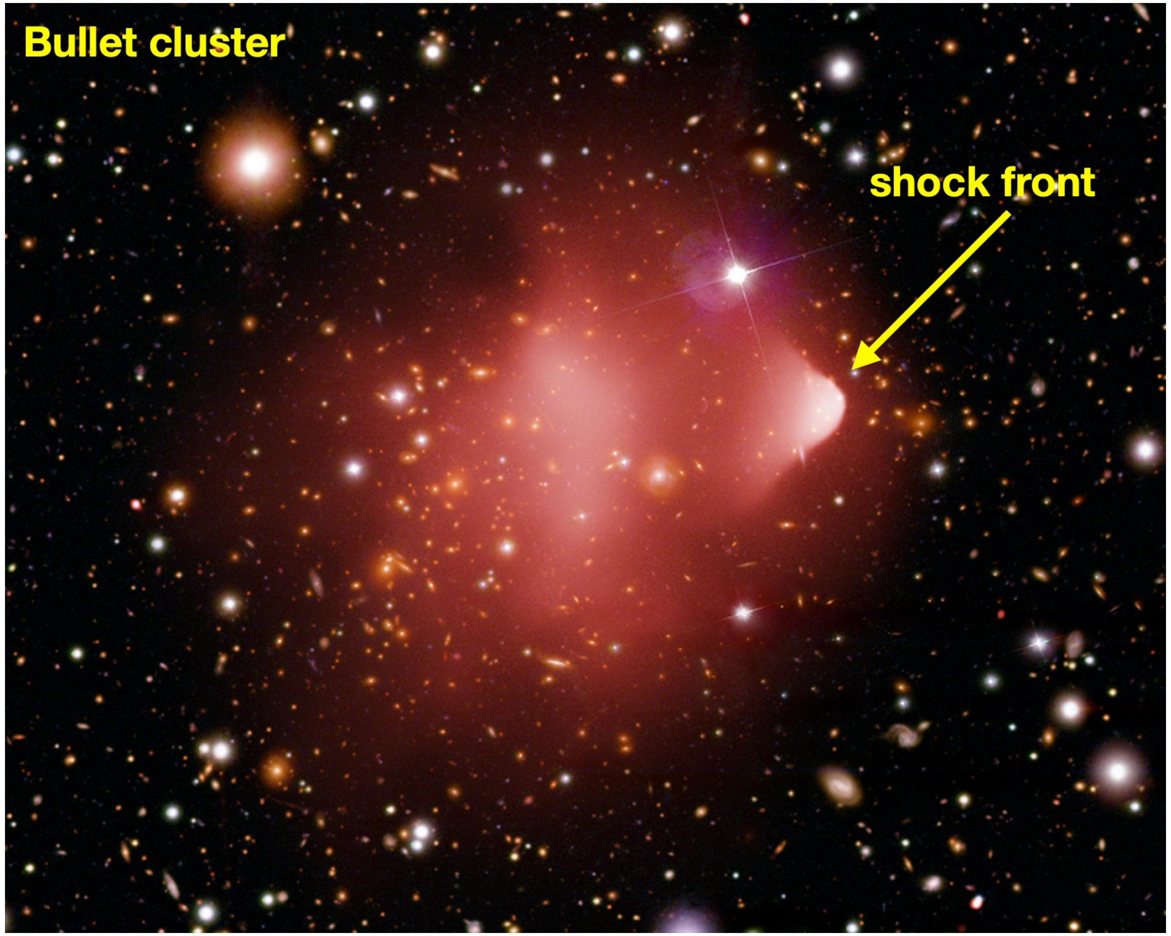
Extragalactic γ-ray background (EGB) constraints

- **Starforming galaxies are disfavored as the main source of IceCube diff. neutrinos**
- **"Hidden" (high γ-ray opacity) sources or high-redshift objects are needed (galaxy mergers?)**

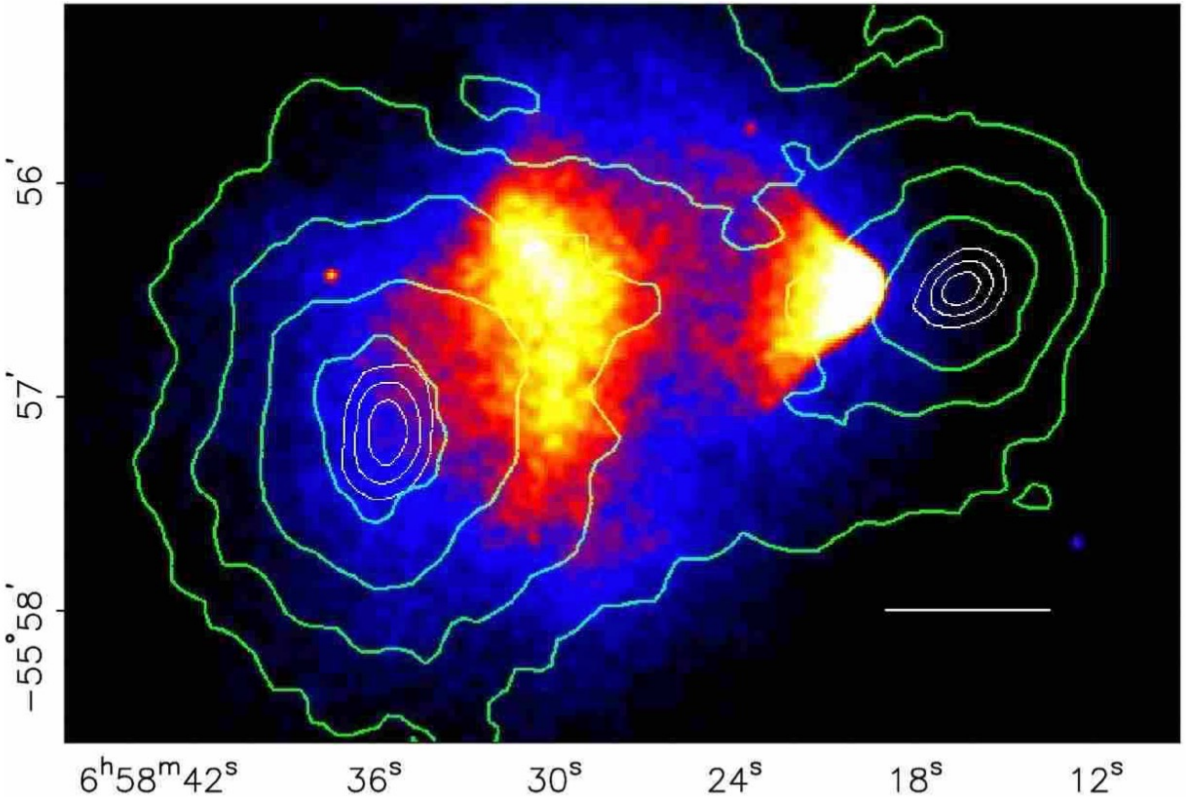




Galaxy/Cluster Mergers



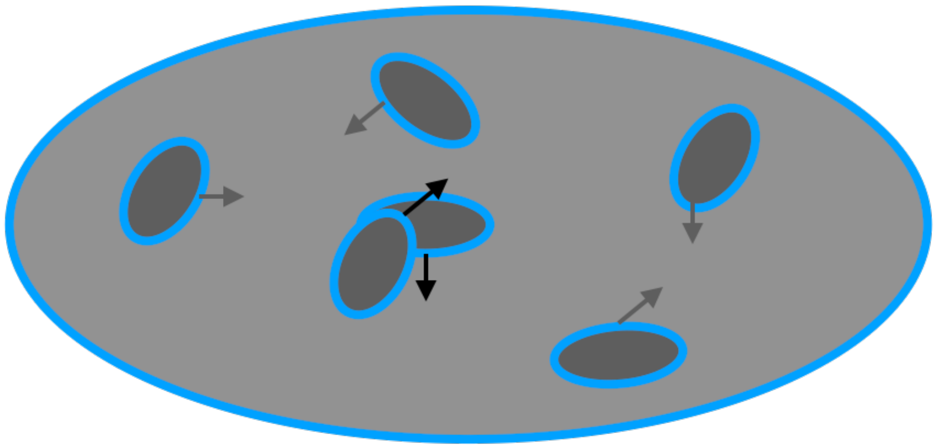
Clowe+ 04



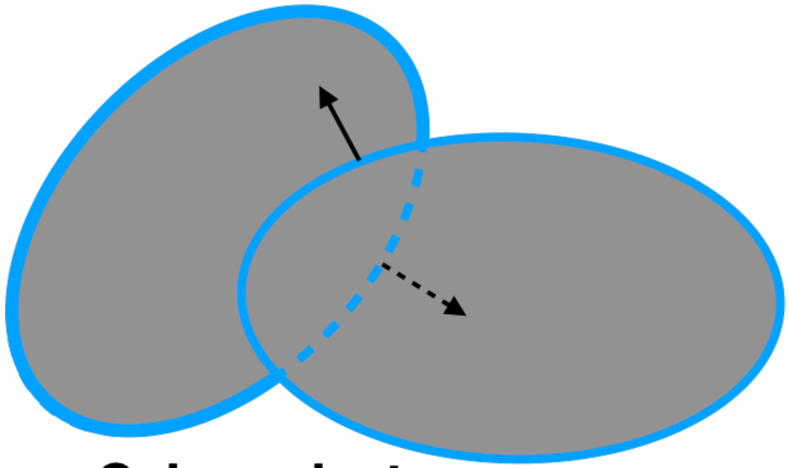
Galaxy/Cluster Mergers: Physical Picture

Galaxy/cluster mergers: ✓

- **Strong shocks**
  CR acceleration + *pp* interaction -> HE ν
- **Strong redshift evolution**
  cosmic $\gamma\gamma$ attenuation with EBL/CMB suppresses γ-ray flux



Galaxy mergers



Galaxy cluster mergers

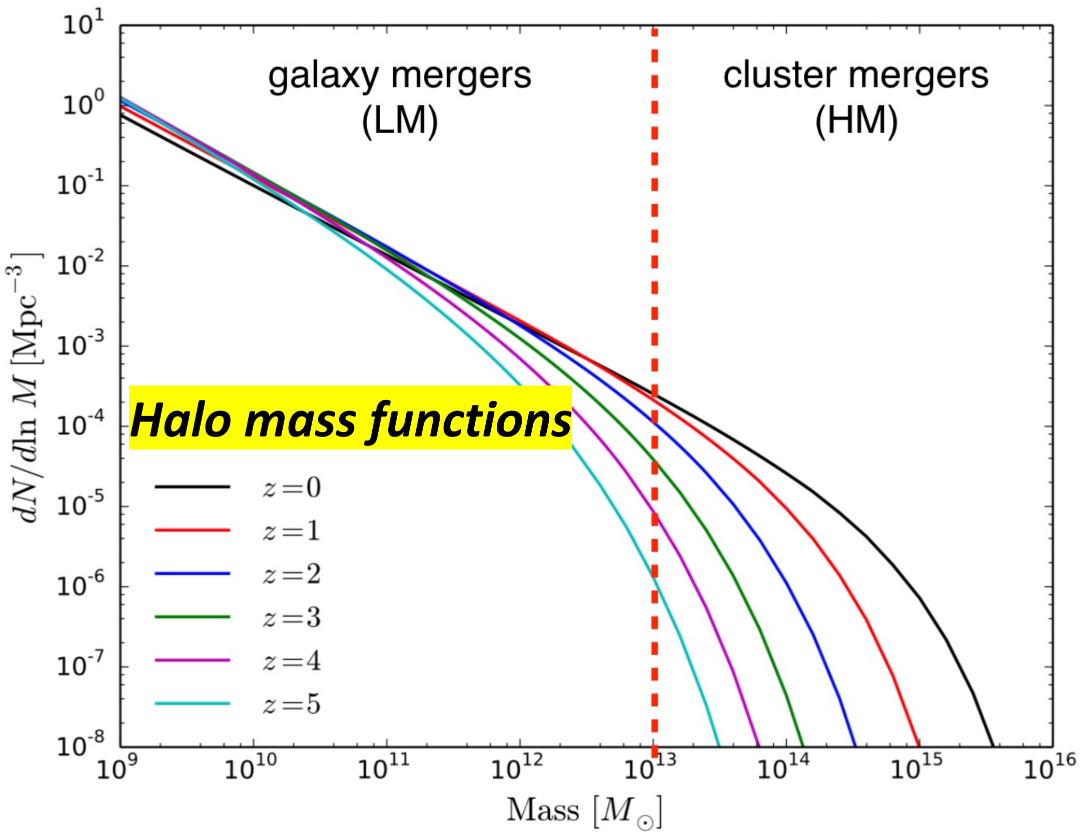
Galaxy/Cluster Mergers: CR intensity

Total CR injection power at z (galaxy mergers + cluster mergers)

$$\varepsilon_p Q_{\varepsilon_p}(z) = \frac{E_{\rm merger}}{t_{age}\mathfrak{C}} = \epsilon_p \mathfrak{C}^{-1} \int_{M_{\rm min}}^{M_{\rm max}} dM \left[\frac{1}{2}\xi_{\rm g}(M,z) M v_s^2\right] \frac{dN_h}{dM}\frac{P(M,z)}{t_{age}}$$

Merger rate

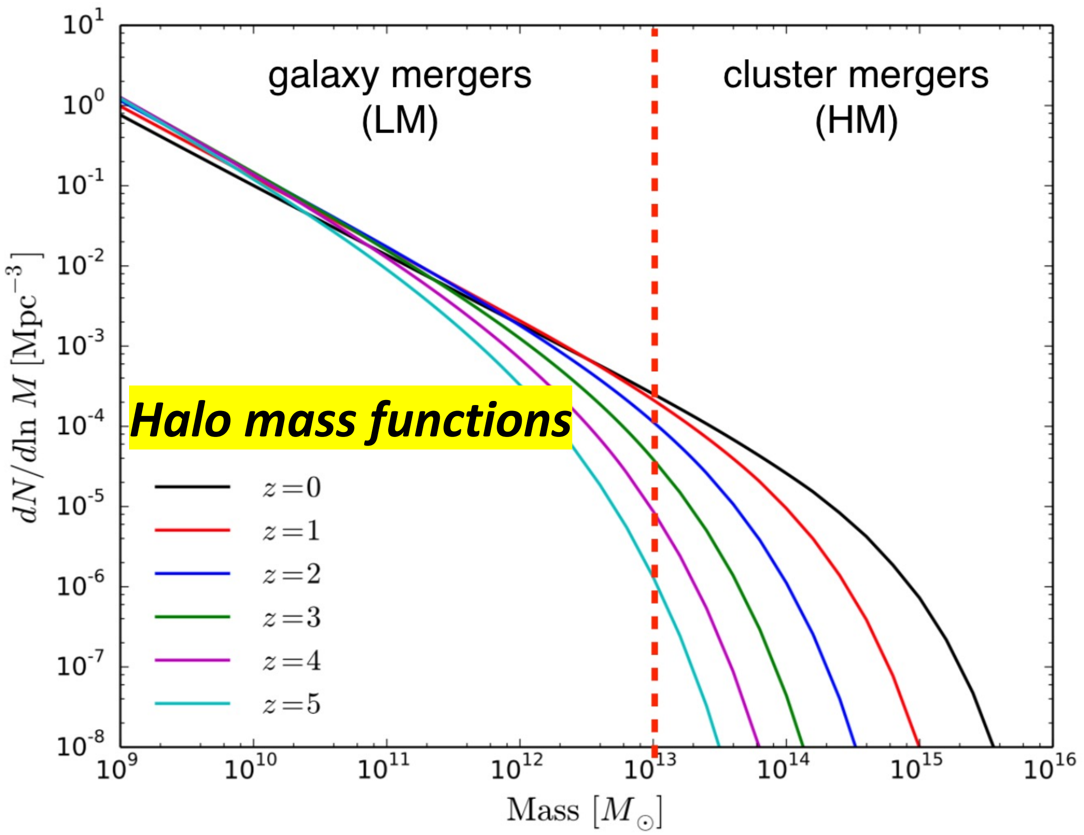
Shock energy

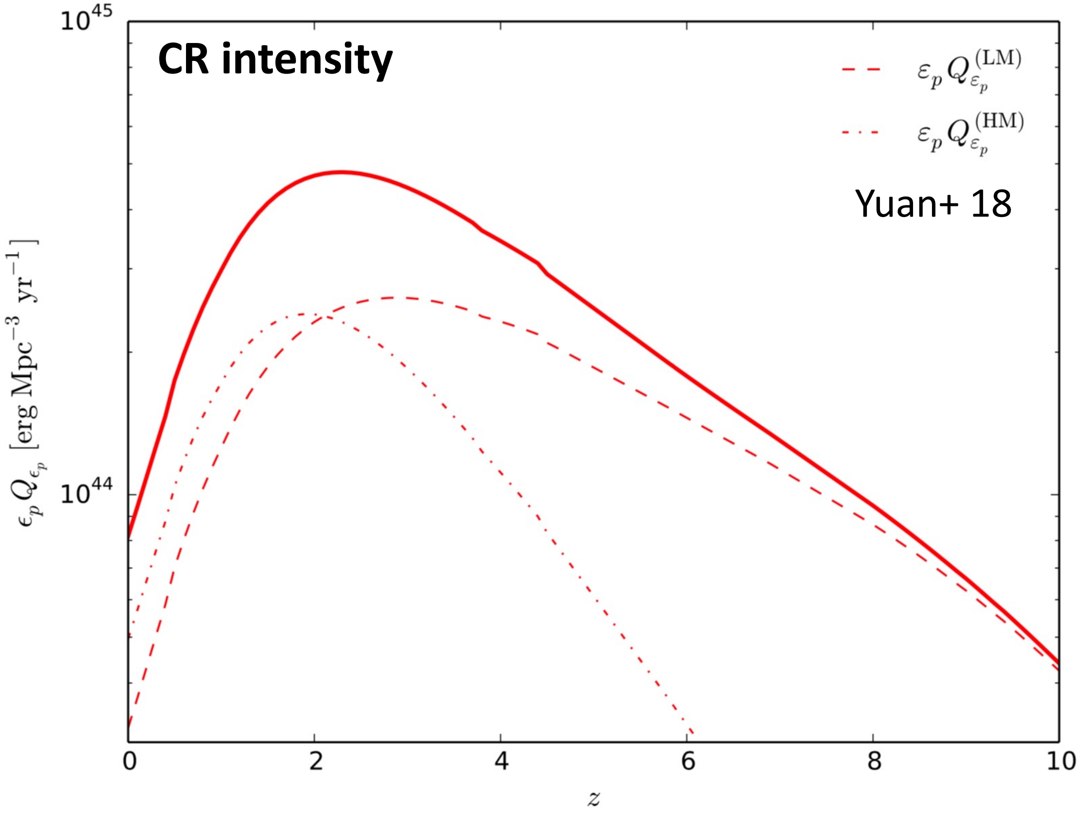


Galaxy/Cluster Mergers: CR intensity

Total CR injection power density at z (galaxy mergers + cluster mergers)

$$\varepsilon_p Q_{\varepsilon_p}(z) = \frac{E_{\rm merger}}{t_{age}\mathfrak{C}} = \epsilon_p \mathfrak{C}^{-1} \int_{M_{\rm min}}^{M_{\rm max}} dM \left[\frac{1}{2}\xi_{\rm g}(M,z) M v_s^2\right] \frac{dN_h}{dM}\frac{P(M,z)}{t_{age}}$$





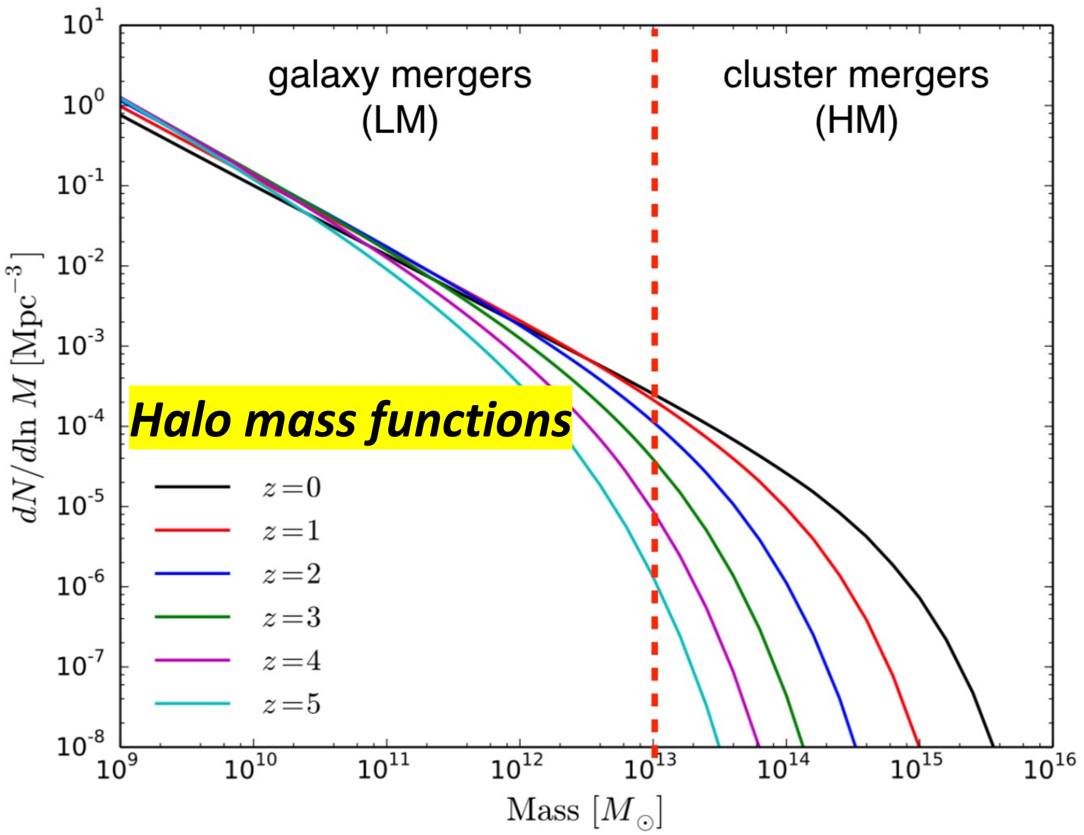
Galaxy/Cluster Mergers: CR intensity

Total CR injection power at z (galaxy mergers + cluster mergers)

$$\varepsilon_p Q_{\varepsilon_p}(z) = \frac{E_{\rm merger}}{t_{age}\mathcal{C}} = \epsilon_p \mathcal{C}^{-1} \int_{M_{\rm min}}^{M_{\rm max}} dM \left[\frac{1}{2}\xi_{\rm g}(M,z) M v_s^2\right] \frac{dN_h}{dM}\frac{P(M,z)}{t_{age}}$$

Merger rate

Shock energy



pp interaction efficiency $f_{pp} \sim \kappa_{pp} c n \sigma_{pp} \min[t_{\rm dyn}, t_{\rm diffuse}]$

Neutrino intensity -

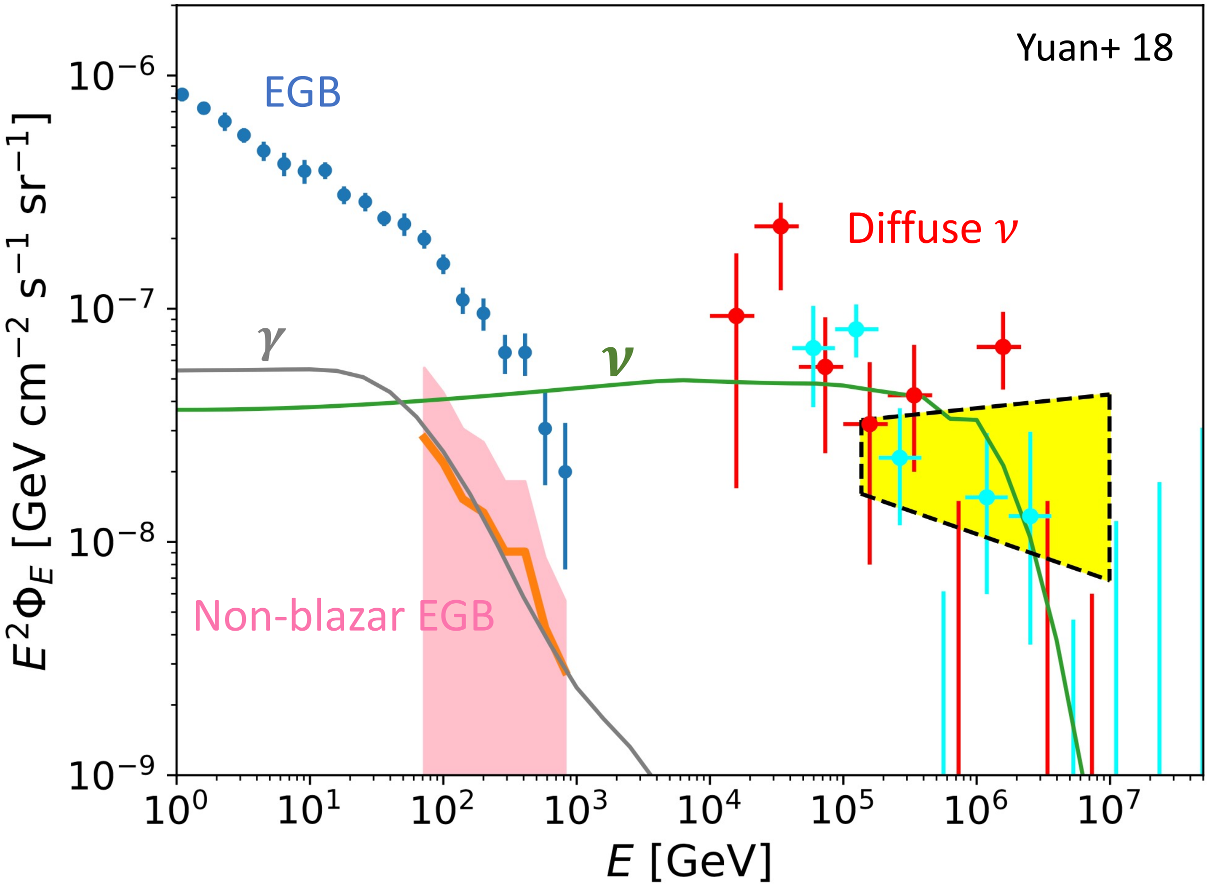
Galaxy component: $\varepsilon_\nu Q^{(\rm g)}_{\varepsilon_\nu} = \frac{1}{2}(1 - e^{-f^{\rm g}_{pp}})\varepsilon_p Q^{(\rm LM)}_{\varepsilon_p}$

Cluster component: $\varepsilon_\nu Q^{(\rm cl)}_{\varepsilon_\nu} = \frac{1}{2}[(1 - e^{-f^{\rm cl}_{pp}})\varepsilon_p Q^{(\rm HM)}_{\varepsilon_p} + \eta(1 - e^{-f^{\rm cl}_{pp}}) e^{-f^{\rm g}_{pp}} \varepsilon_p Q^{(\rm LM)}_{\varepsilon_p}],$

subdominant
Galaxy CRs escaped to clusters

Galaxy/Cluster Mergers: Diffuse γ, ν Backgrounds

- Galaxy/cluster mergers can be promising PeV neutrino emitters **without violating the existing Fermi γ-ray constraints on the nonblazar component of EGB**



Galaxy/Cluster Mergers: Secondary EM Emission

pp collision -> secondary *e⁻/e⁺* (+galactic mag. field) -> observable radio/X-ray emission (via **synchrotron + synchrotron self-Compton**)

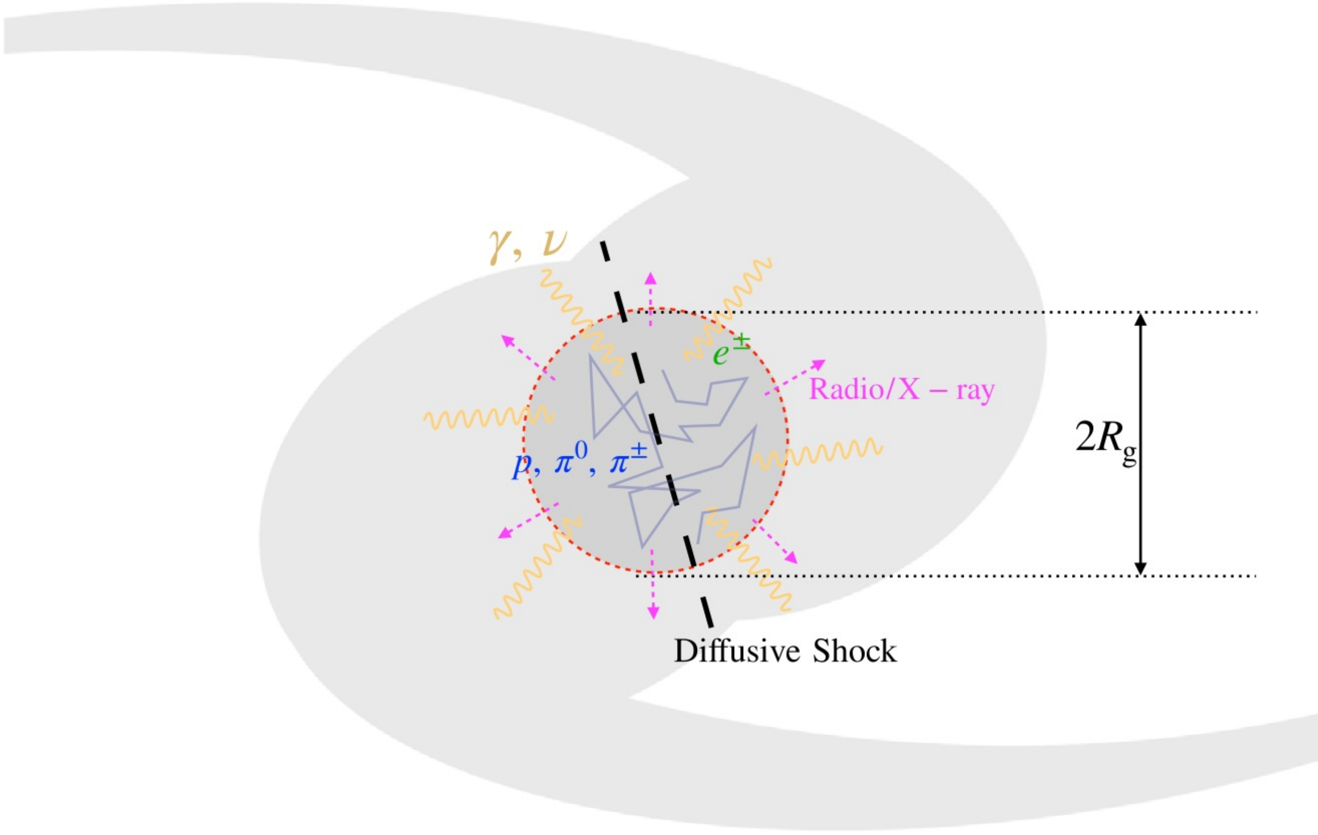
Emission from secondary particles more efficient than accelerated primary electrons

$$\frac{\mathcal{E}_{e,\mathrm{primary}}}{\mathcal{E}_{e,\mathrm{sec}}} \simeq \frac{6\epsilon_e}{\min[1, f_{pp,\mathrm{g}}]\,\epsilon_p} \lesssim 10^{-1},$$

$$K_{e/p} = \epsilon_e/\epsilon_p \sim 10^{-4}\text{–}10^{-2}$$

(Jones 11; Caprioli 12)

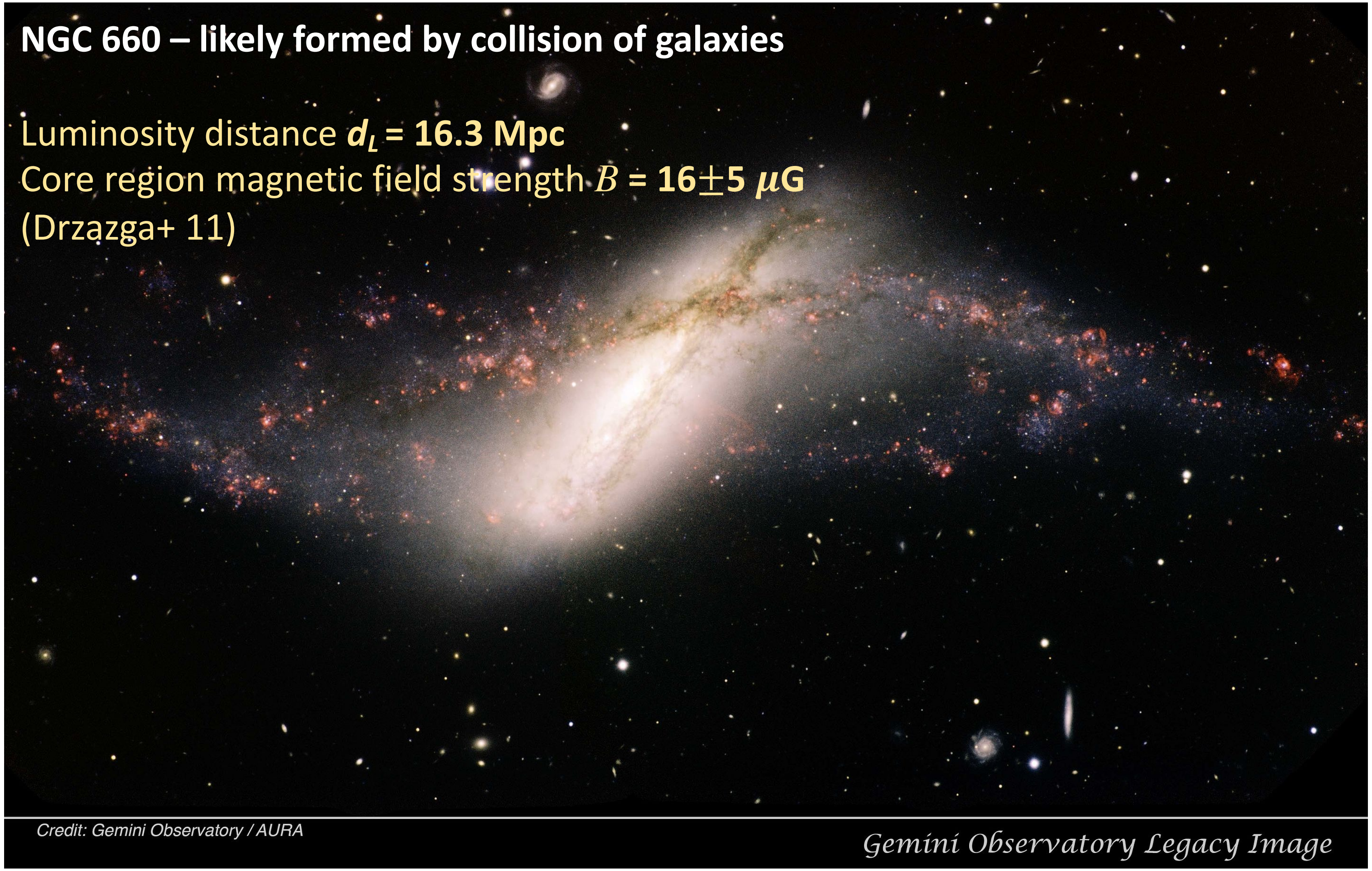
ϵ_p , ϵ_e are CR and electron acc. efficiency.

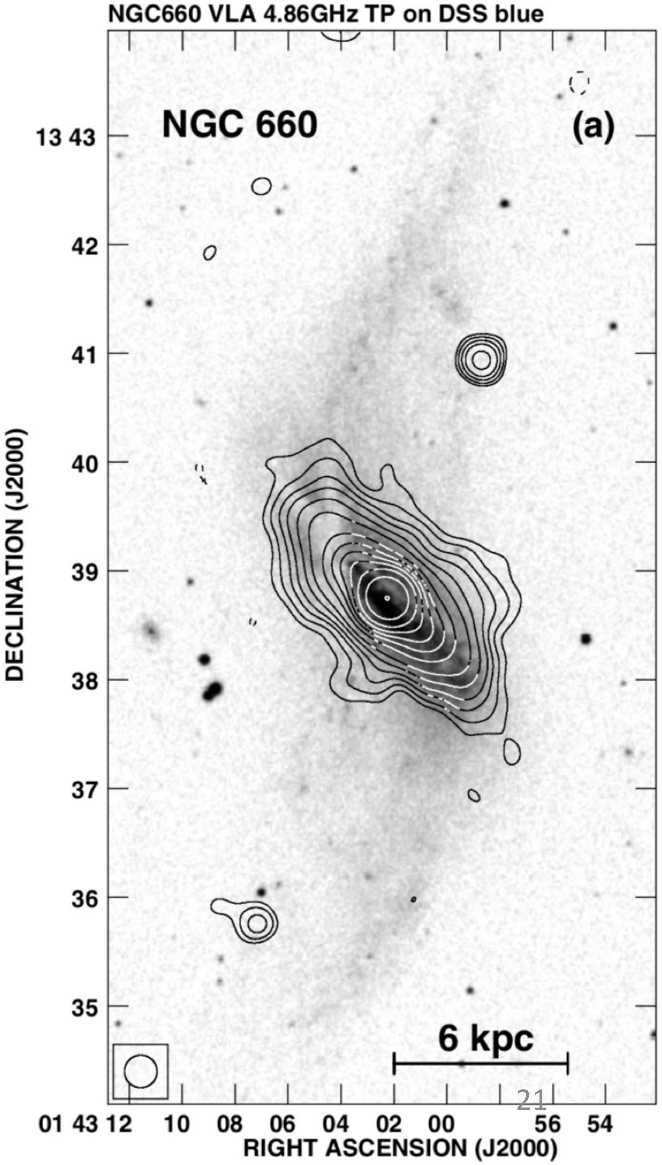


Application to NGC 660

NGC 660 – likely formed by collision of galaxies

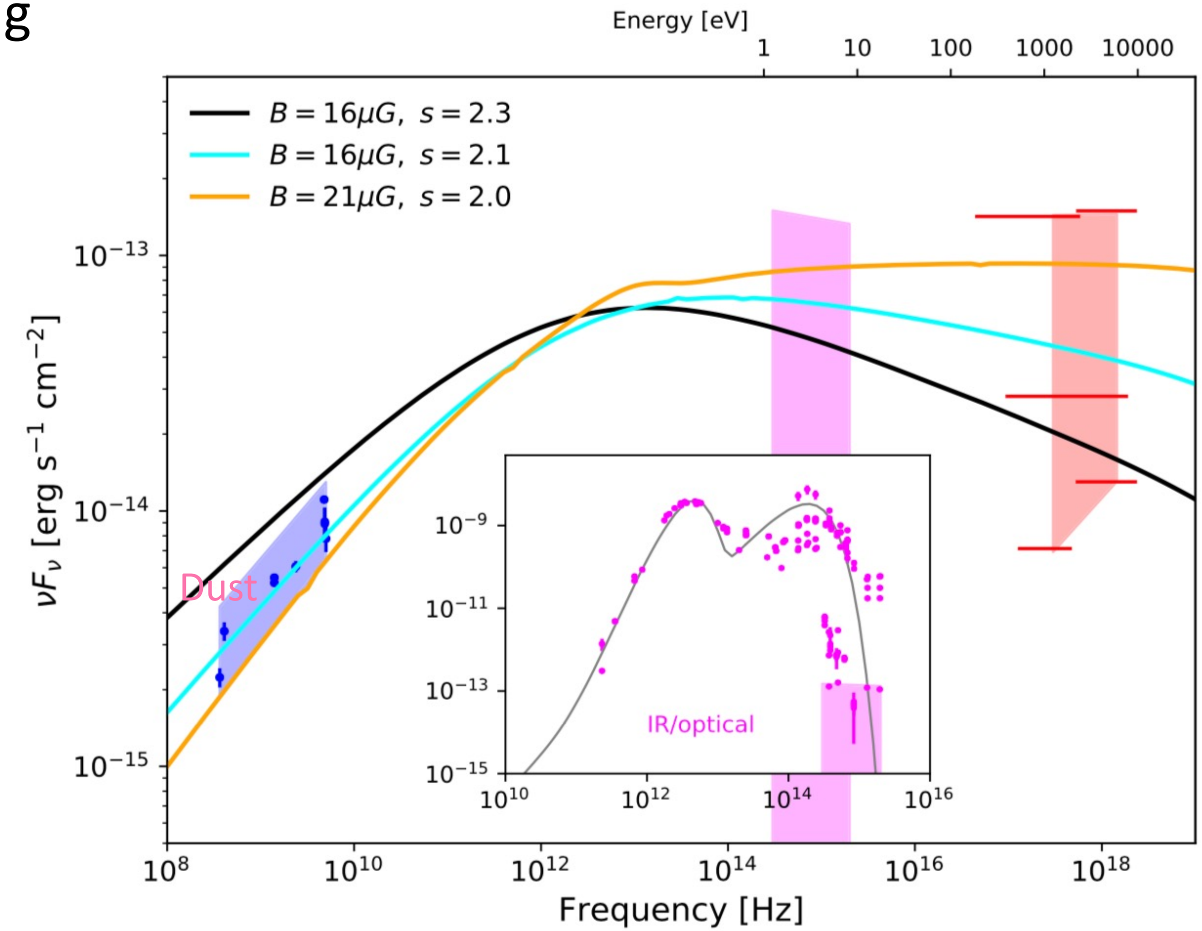
Luminosity distance $\boldsymbol{d_L}$ **= 16.3 Mpc**
Core region magnetic field strength B **= 16$\pm$5 μG**
(Drzazga+ 11)





NGC 660: Secondary EM Emission Scenario

NGC 660 SED fitting

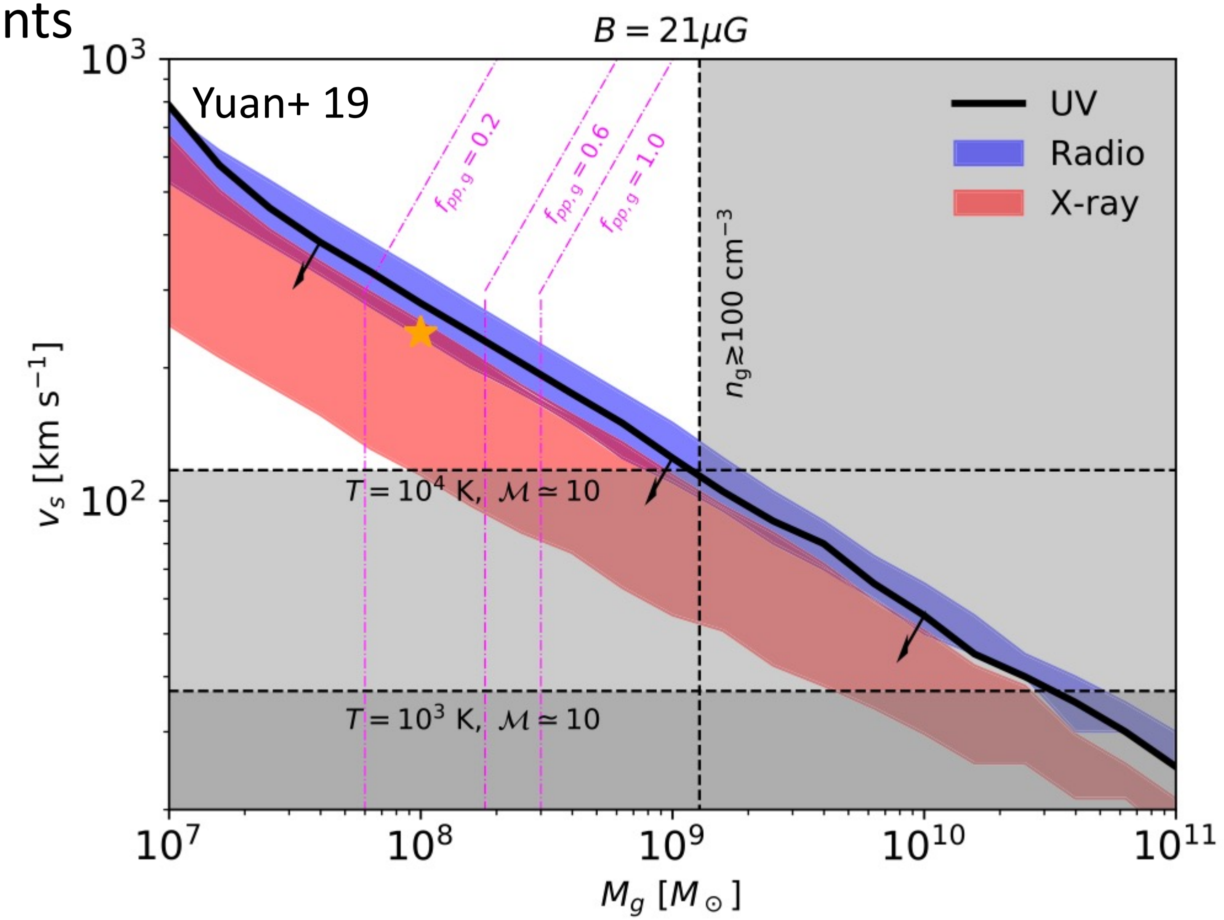


Yuan+ 19 ApJ 878:76

- This scenario can explain the radio and X-ray fluxes of merging galaxies such as **NGC 660**.
- **Stringent constraints** on gas mass, shock velocity, mag. field, and the CR spectral index.

NGC 660: Secondary EM Emission Scenario

Parameter constraints

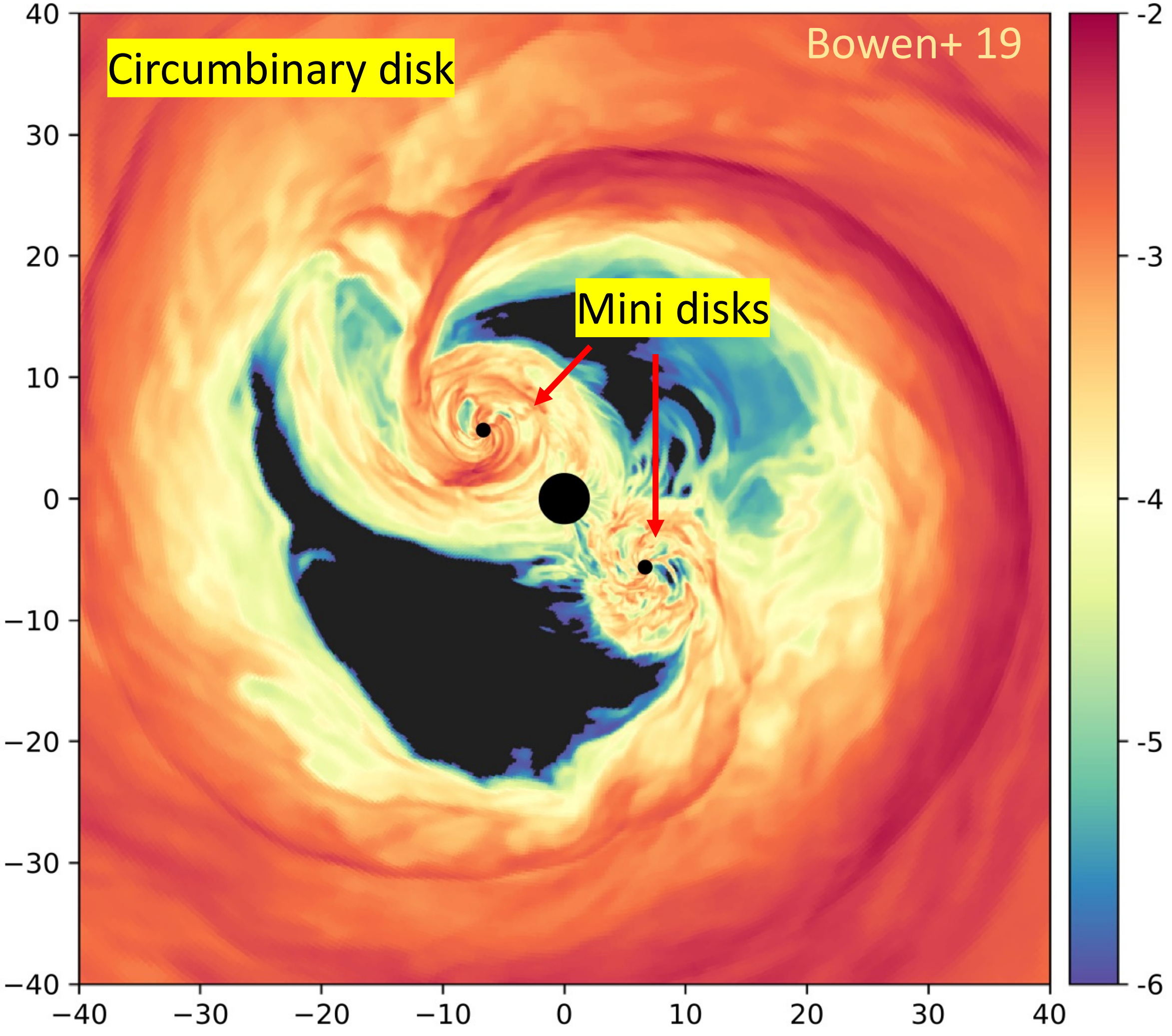


- This scenario can explain the radio and X-ray fluxes of merging galaxies such as **NGC 660**.
- **Stringent constraints** on gas mass, shock velocity, mag. field, and the CR spectral index.

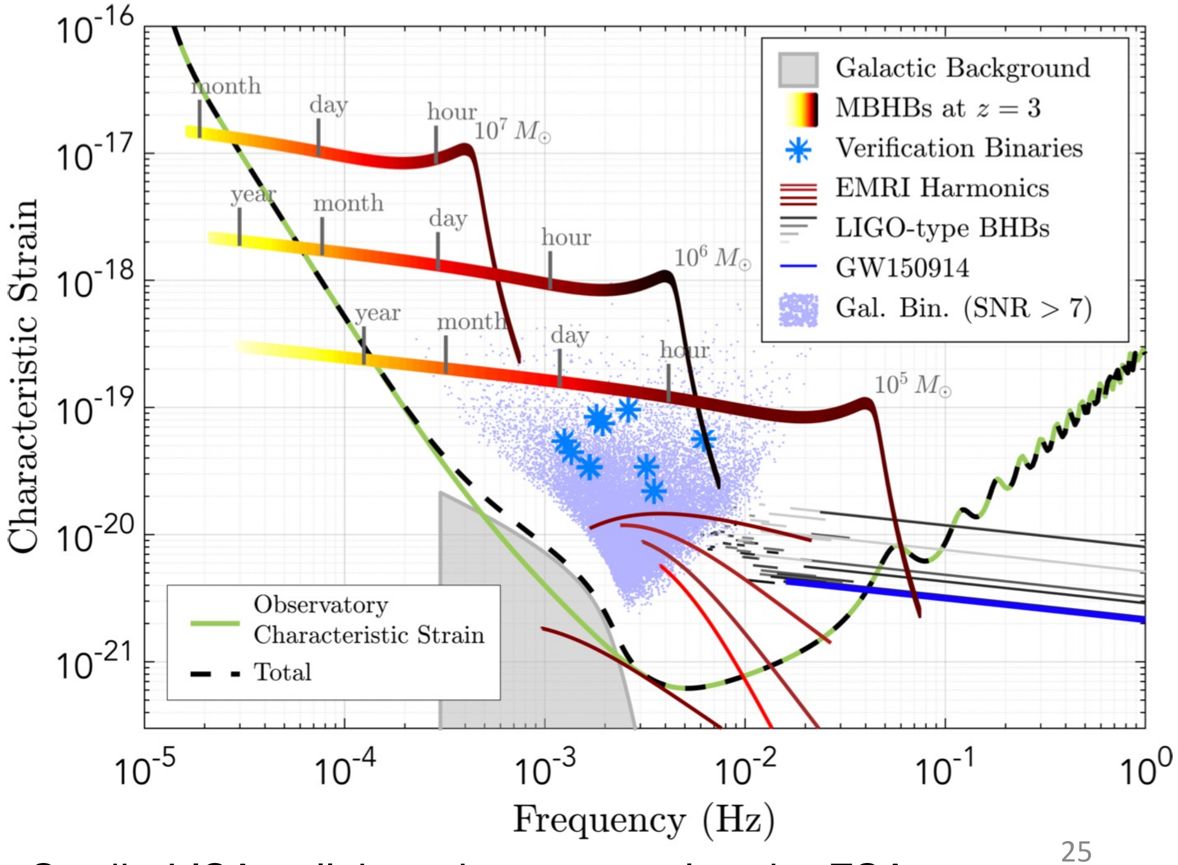
Summary of Part 1

- Galaxy and cluster mergers can explain a significant portion of IceCube diffuse neutrino flux.
- High-z CR injections alleviate the tension between the non-blazar EGB and the IceCube neutrinos.
- Synchrotron and SSC emissions from secondary e^-/e^+ pairs can explain the radio and X-ray fluxes of merging galaxies such as NGC 660 (and NGC 3256 , not shown in this talk).
- In this secondary emission scenario, we can constrain the gas mass, shock velocity, magnetic field, and the CR spectral index s of these systems.

Part 2: SMBH Mergers



Laser Interferometer Space Antenna (LISA)



Credit: LISA collaboration proposal to the ESA

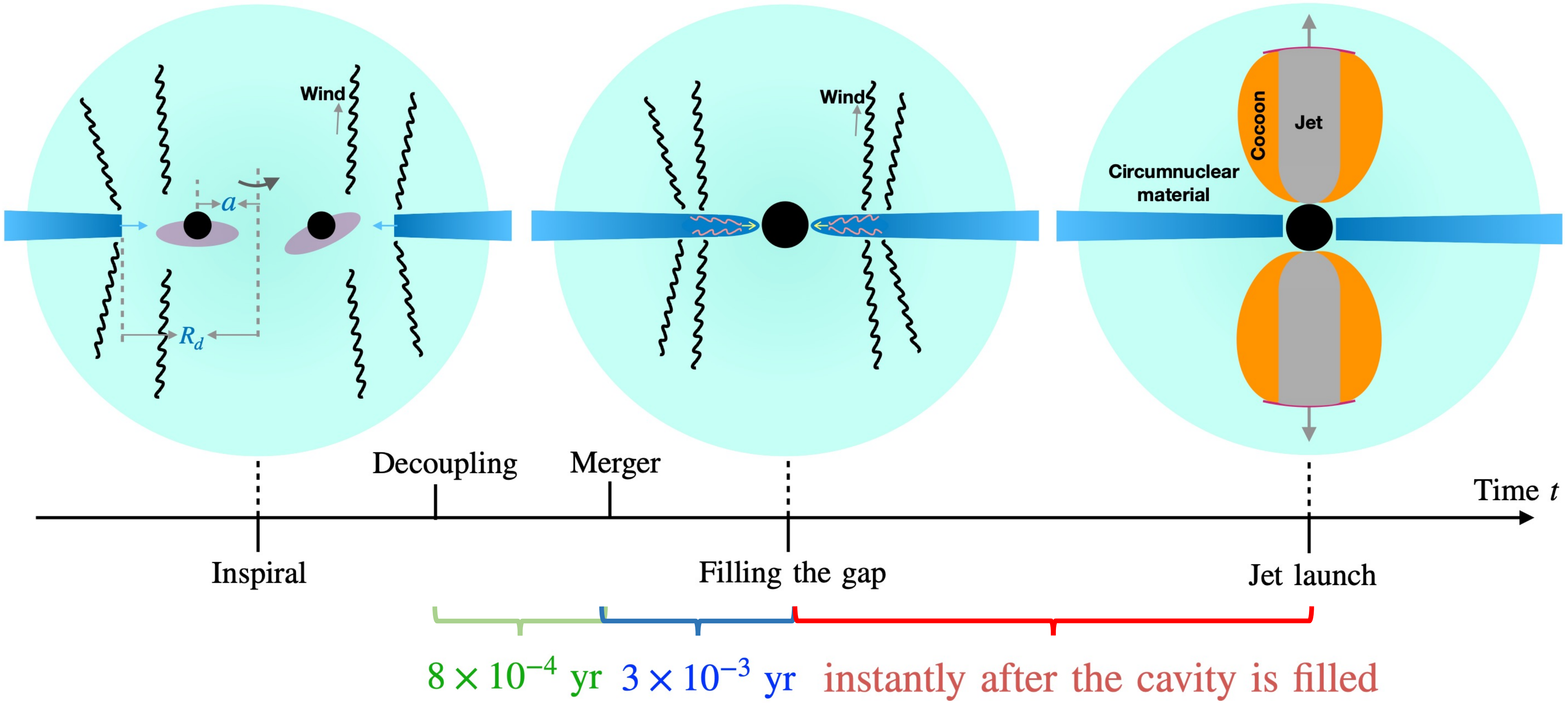
Yuan, Murase, Kimura, Meszaros 20 PRD 102.083013

ν from SMBH Mergers: Physical Picture

Merger -> circumnuclear gas bubble (wind) + jet (BZ mechanism) -> internal, collimation, forward and reverse shocks -> **VHE CRs, PeV neutrinos**

Time lag between GW burst and jet launch: **10^{-3}-10^{-2} yr**

Scaleheight $h = 0.01$(thin disk) $-$ 0.3(thick disk)



ν from SMBH Mergers: Jet Structure

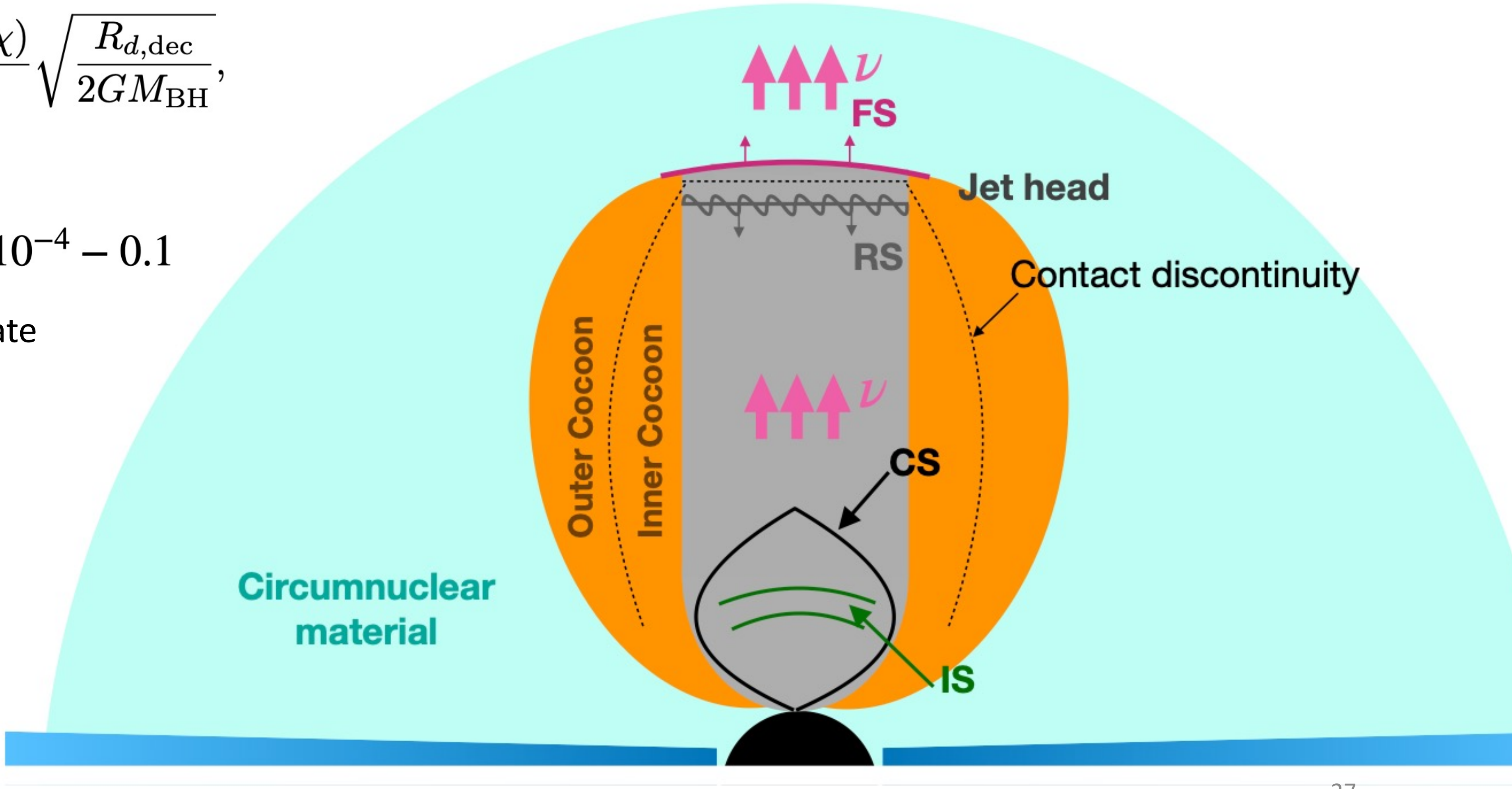
Wind density

$$\varrho_w(r) = \frac{\eta_w \dot{M}_{\rm BH}(1+\chi)}{4\pi r^2}\sqrt{\frac{R_{d,\rm dec}}{2GM_{\rm BH}}},$$

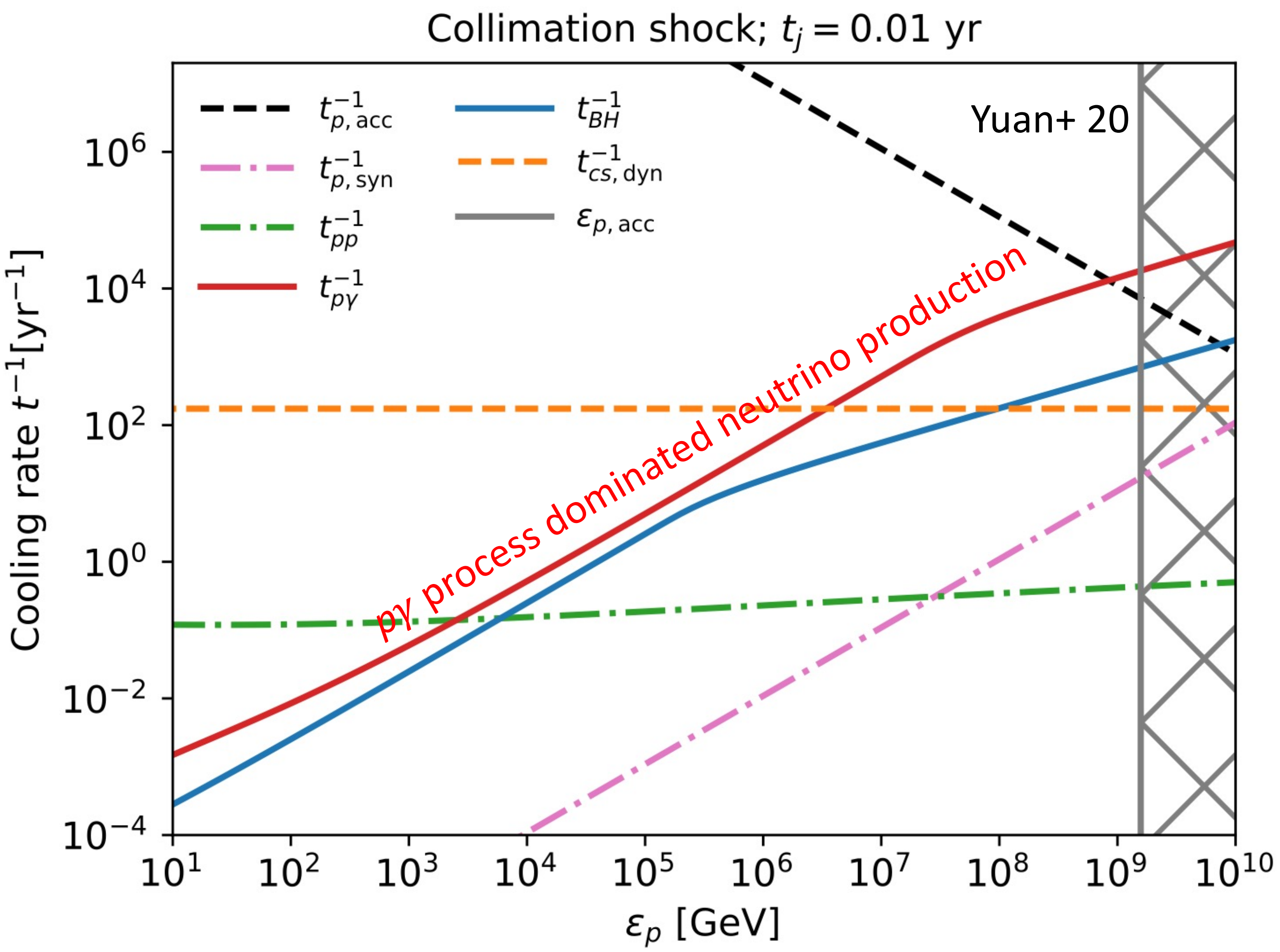
The parameter

$$\eta_w = \dot{M}_w/\dot{M}_{\rm SMBH} \sim 10^{-4} - 0.1$$

depends on accretion rate



ν from SMBH Mergers: Interaction Rates



ν from SMBH Mergers: CR Acceleration

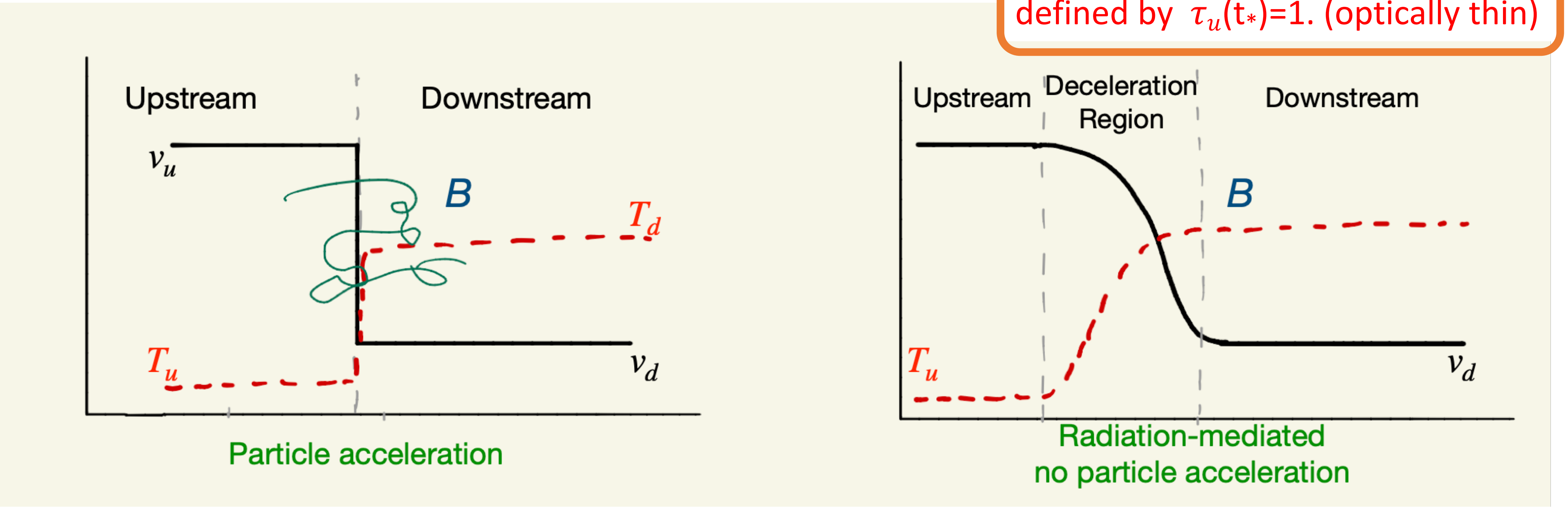
Conditions for particle acceleration

- Shock is **NOT radiation-mediated** -> strong discontinuity -> efficient acceleration

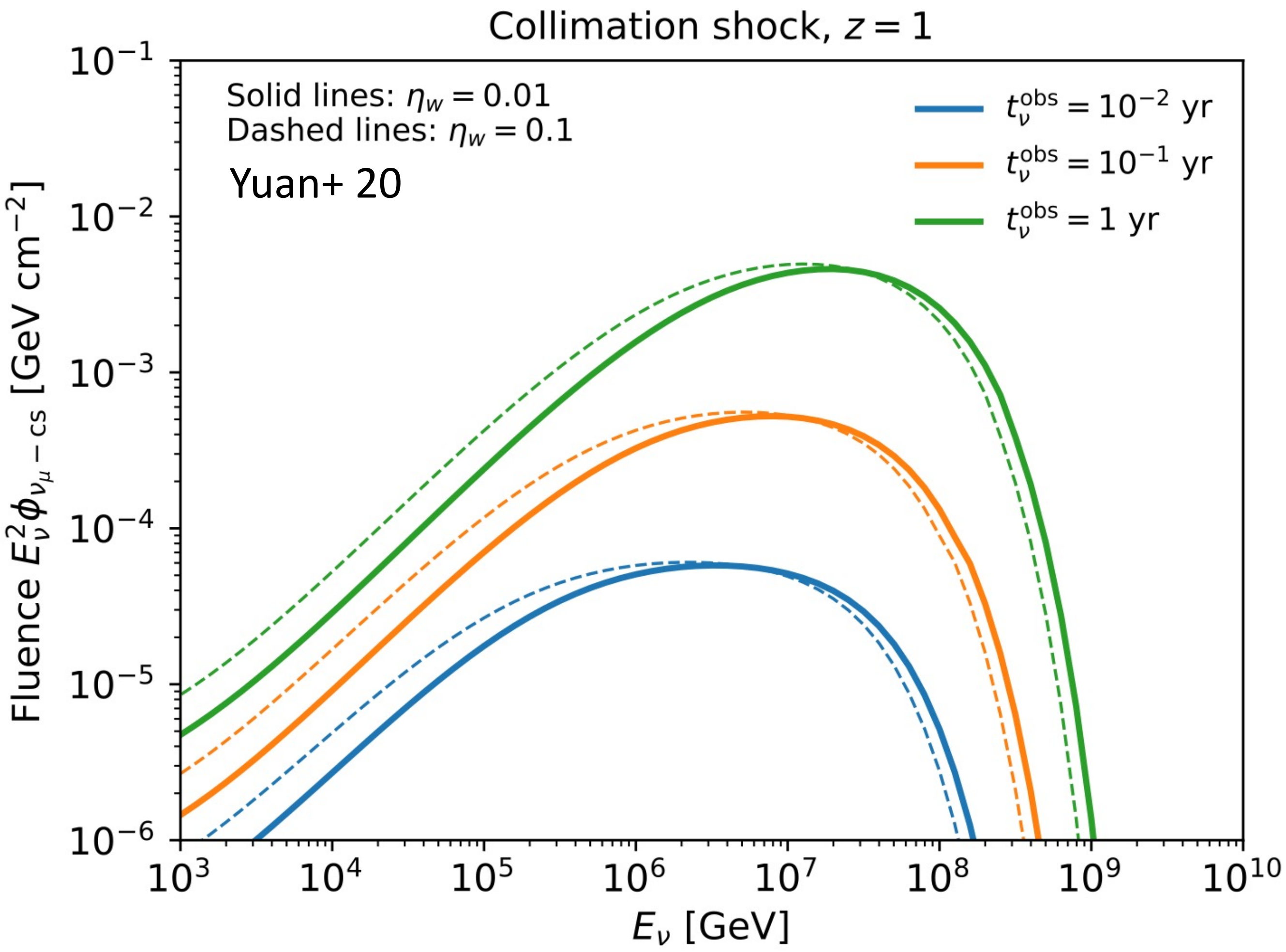
$$\tau_u = n_u \sigma_T l_u \lesssim \min[1, \Pi(\Gamma_{\rm sh})]$$

- n_u comoving number density of upstream materials, l_u comoving length of upstream, Π: e^+/e^- enrichment

Neutrino emission onset time t_*, defined by $\tau_u(t_*)=1$. (optically thin)



ν from SMBH Mergers: Fluences



$$M_{\rm SMBH} = 10^6 M_\odot$$

Optimistic case

- Super-Eddington accretion rate

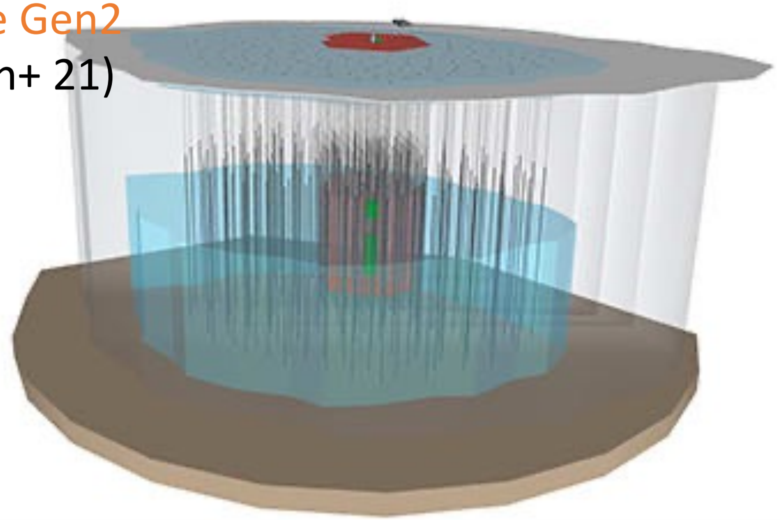
$$\dot{m} = \dot{M}_{\rm SMBH}/\dot{M}_{\rm Edd} = 10$$

- Efficient baryon loading

$$\epsilon_p = L_{\rm CR}/L_{k,j} \sim 0.5$$

νs from SMBH Mergers: Detectability

IceCube Gen2
(Aartsen+ 21)



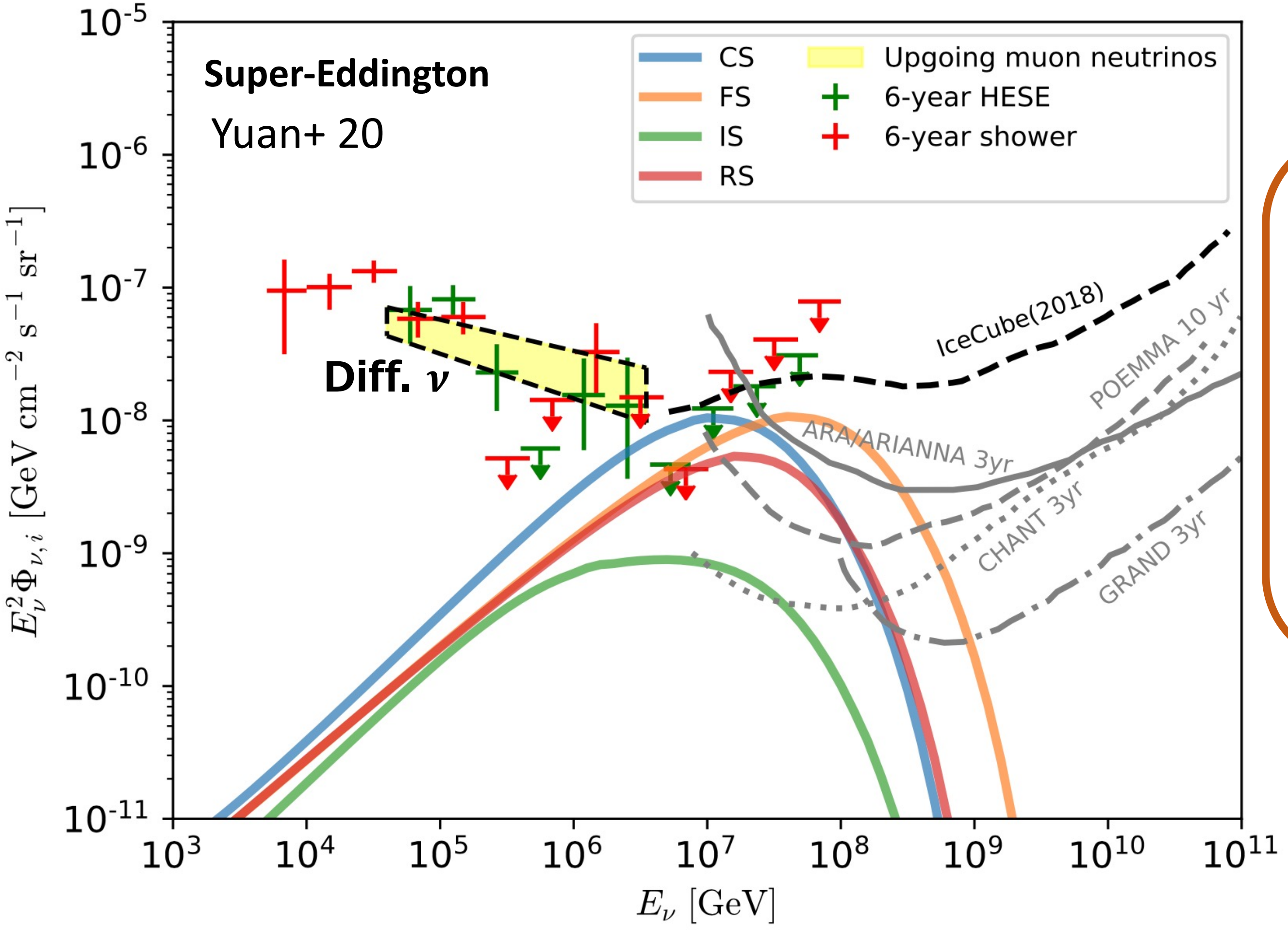
Optimistic case (super-Edd.): **IceCube Gen2 + LISA coincident detection rate ∼1-2 per decade**;
Challenging for sub-Edd. cases.

Neutrino detection rate $\dot{N}_{\nu,i}$ for SMBH mergers within the LISA detection range $z \lesssim 6$ [yr^{-1}] — Yuan+ 20

	Optimistic parameters $\dot{m}=10,\ L_{k,j}\simeq 3.4\times10^{46}$ erg s^{-1}, $\epsilon_p=0.5,\ h=0.3$			Conservative parameters $\dot{m}=0.1,\ L_{k,j}\simeq 3.4\times10^{44}$ erg s^{-1}, $\epsilon_p=0.5,\ h=0.01$		
Scenario	IC (up+hor)	IC (down)	IC-Gen2 (up+hor)	IC (up+hor)	IC (down)	IC-Gen2 (up+hor)
CS	0.019	0.014	0.16	8.2×10^{-5}	4.3×10^{-5}	3.7×10^{-4}
IS	9.1×10^{-4}	7.8×10^{-4}	4.2×10^{-3}	1.7×10^{-6}	1.3×10^{-6}	9.5×10^{-6}
FS	2.6×10^{-3}	1.8×10^{-3}	0.013	9.6×10^{-5}	7.2×10^{-5}	4.1×10^{-4}
RS	0.011	8.4×10^{-3}	0.044	3.5×10^{-4}	1.9×10^{-4}	2.1×10^{-3}

Super-Eddington — **Sub-Eddington**

νs from SMBH Mergers: Diff. ν Background

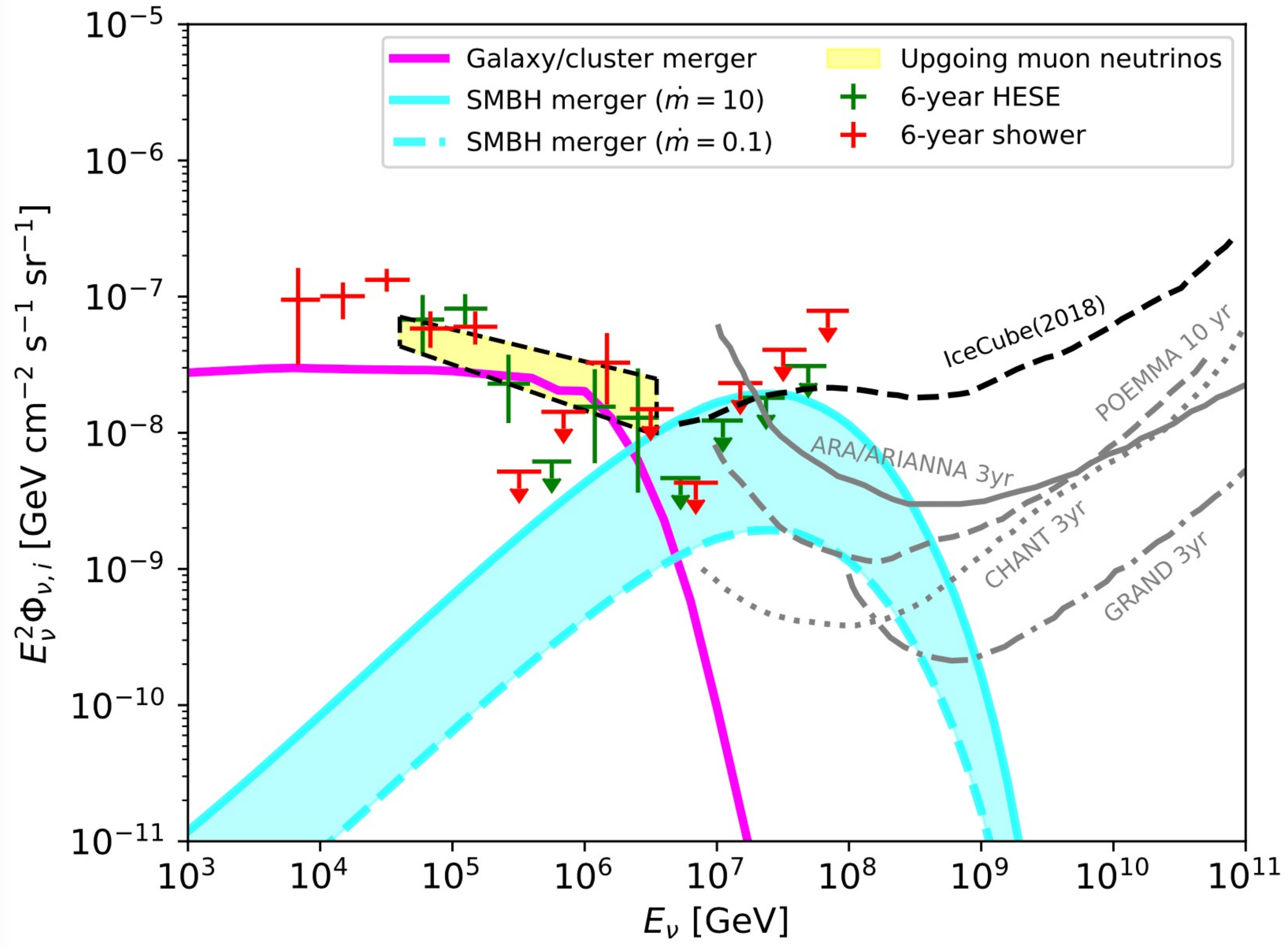


Optimistic cases can explain a significant potion of diffuse ν in the 1-100 PeV energy range.
(10% IC diff. neutrinos for sub-Eddington cases)

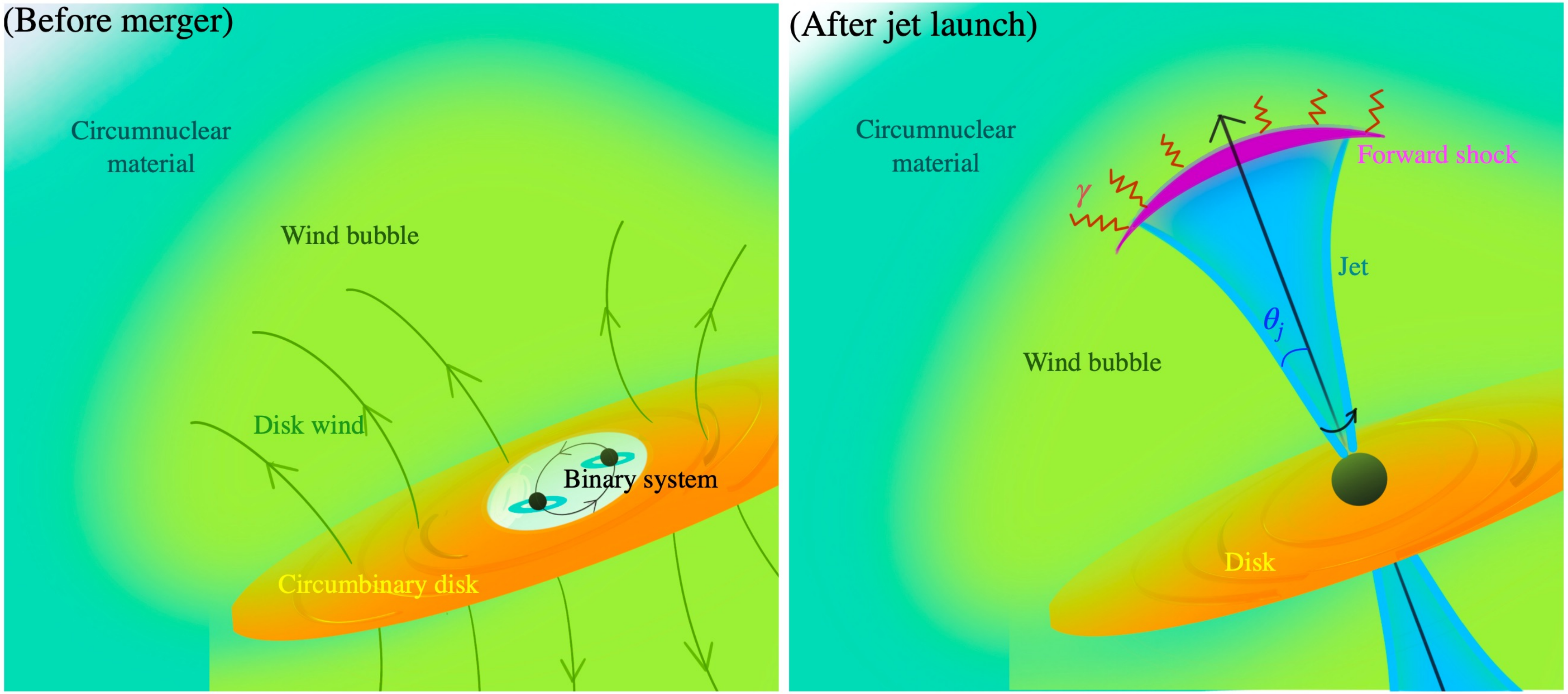
Can be tested by next-gen ν detectors.

Caveat: all mergers are assumed to be identical
(increase SMBH mass -> powerful emission + lower rate)

Galaxy/Cluster Mergers + SMBH Mergers



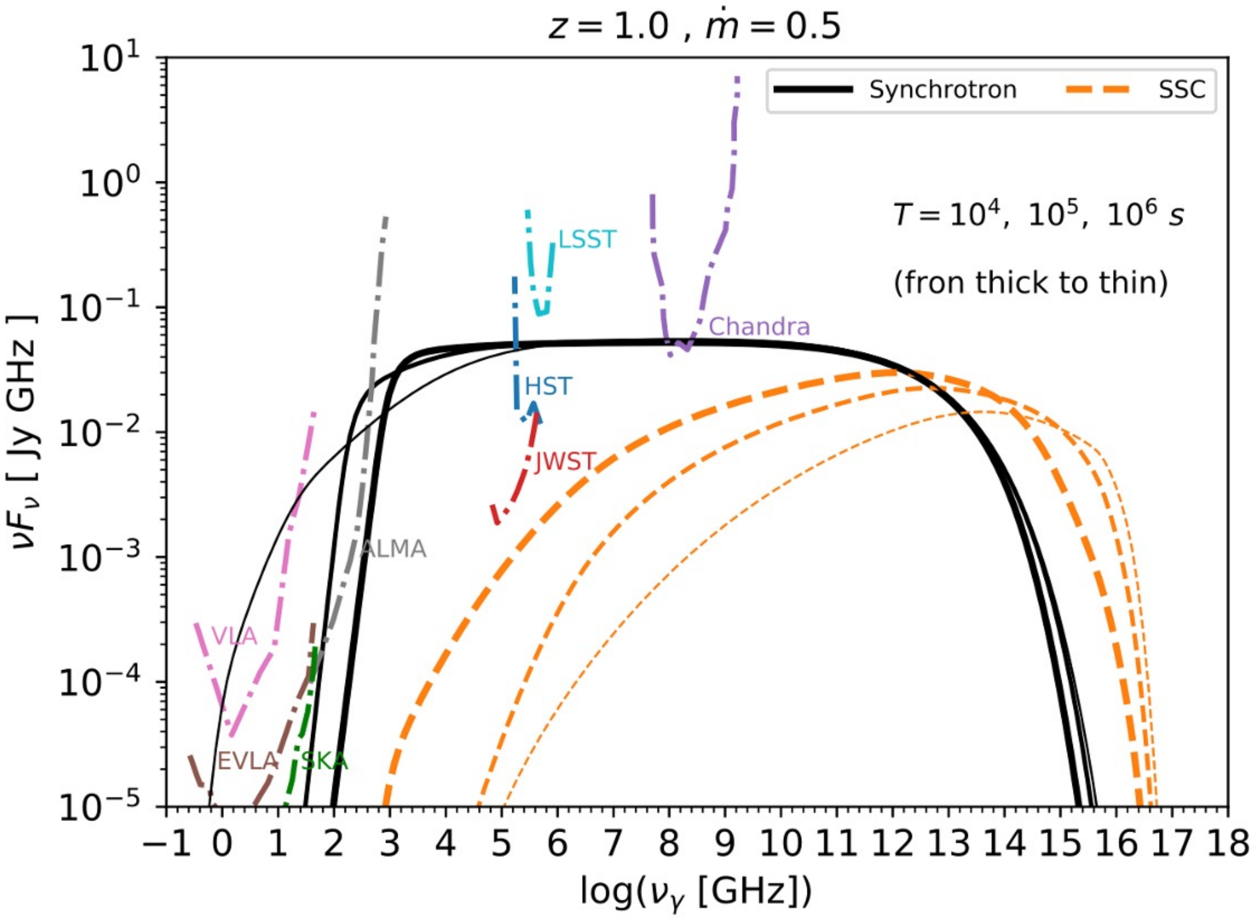
SMBH Mergers: EM Counterpart



- Inside the pre-merger wind bubble (disk-driven winds), the jet is mild relativistic $\boldsymbol{\Gamma \sim 2.0}$

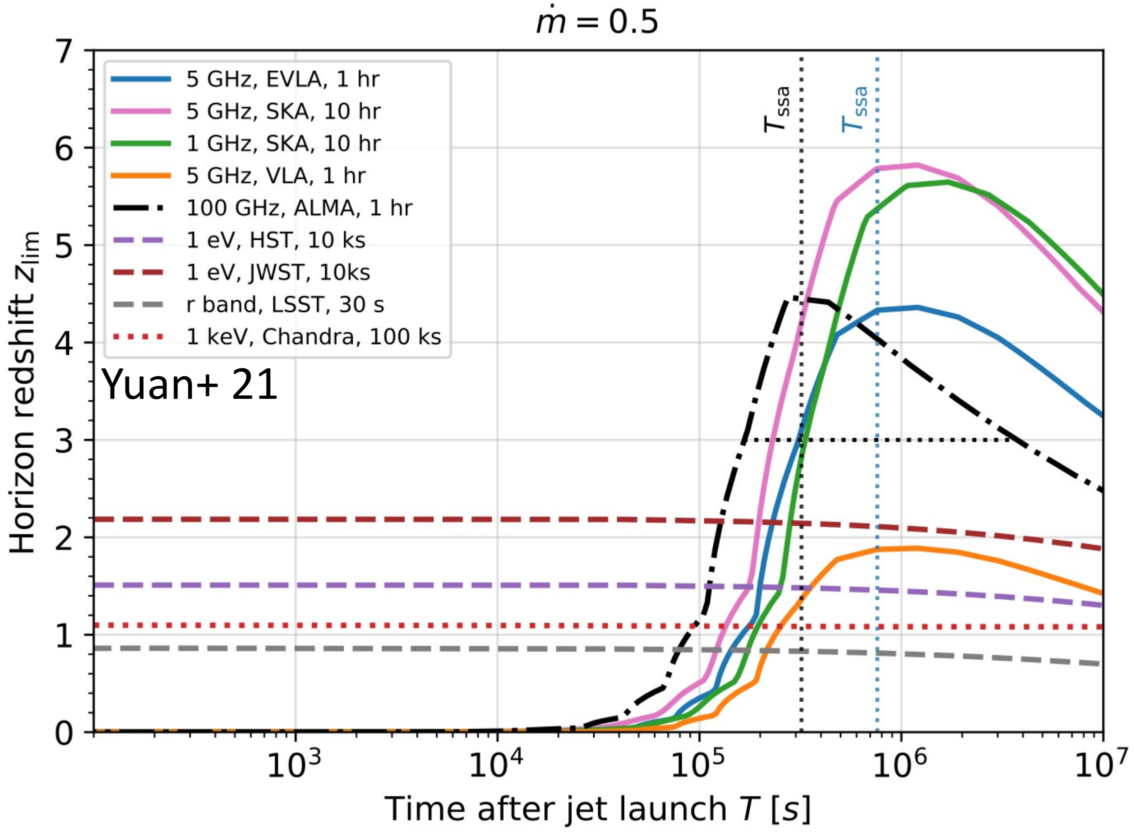
Yuan, Murase, B.T. Zhang, Kimura, Meszaros 21 ApJL 911 L15

SMBH Mergers: EM Counterpart



- **EM counterpart: synchrotron+synchrotron self Compton**
- Early radio emission is suppressed by **synchrotron self-absorption (SSA)**

SMBH Mergers: EM Counterpart



- Early radio emission is suppressed by **synchrotron self-absorption (SSA)**
- **EM (syn.+SSC)** signals are detectable up to the detection horizon of LISA, **(1-10)f_b per year**
- **Initial observation with** large FOV telescopes (SKA, LSST) can guide narrow FOV detectors.

Summary of Part 2

- Month-to-year high-energy neutrino emission from the post- merger jet after the gravitational wave event is detectable by IceCube-Gen2 within approximately five to ten years of operation in optimistic cases

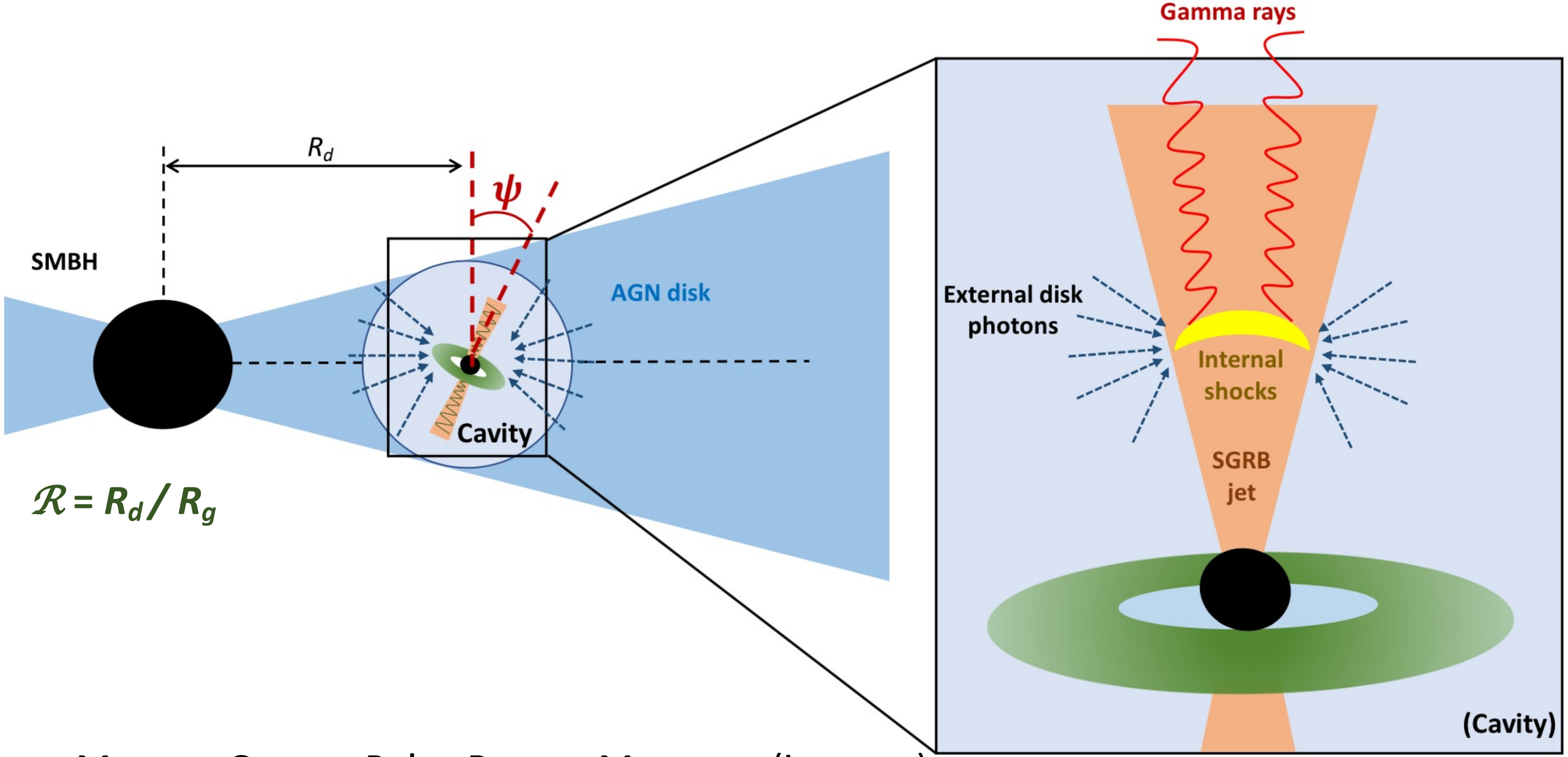
- A significant fraction of the observed very high-energy (> 1 PeV) IceCube neutrinos could originate from them in the optimistic cases.

- SMBH mergers can produce slowly fading transients with duration from months to years after the coalescence

- Jet-induced EM signals from SMBH mergers are detectable by optical telescopes up to the detection horizon LISA (z=2-6).

Short GRBs in AGN Disks: Configuration

- A subpopulation of short GRBs occurs in the AGN accretion disks **near a migration trap (20-1000 R_g)**.
- Winds from compact binary (highly super-Eddington) -> **low-density cavity** -> **successful GRB jets**
- Non-thermal electrons -> **syn. + SSC + external inverse Compton (EIC, upscattered disk photons)**

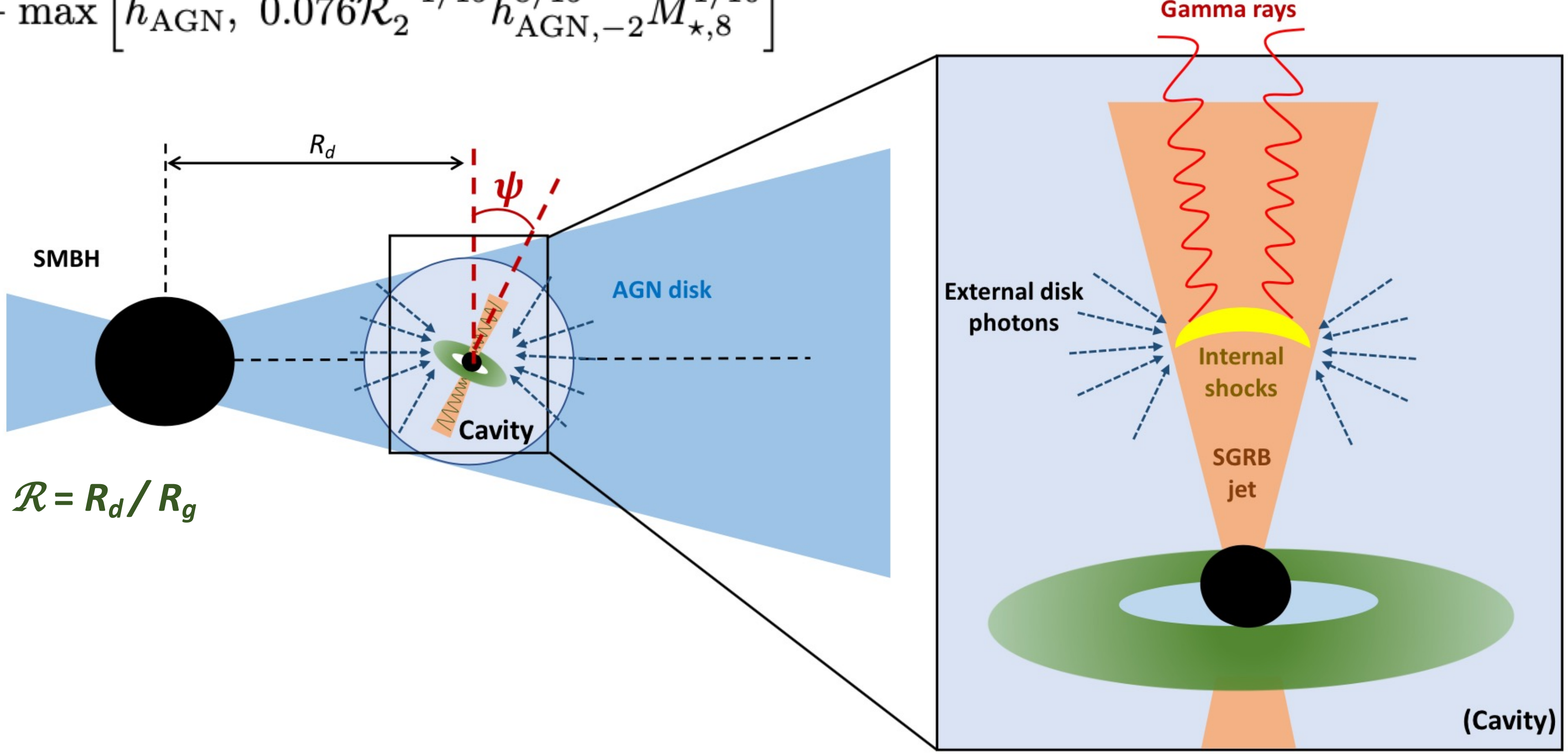


Yuan, Murase, Guetta, Pe'er, Bartos, Meszaros (in prep.)

Short GRBs in AGN Disks: Cavity Formation

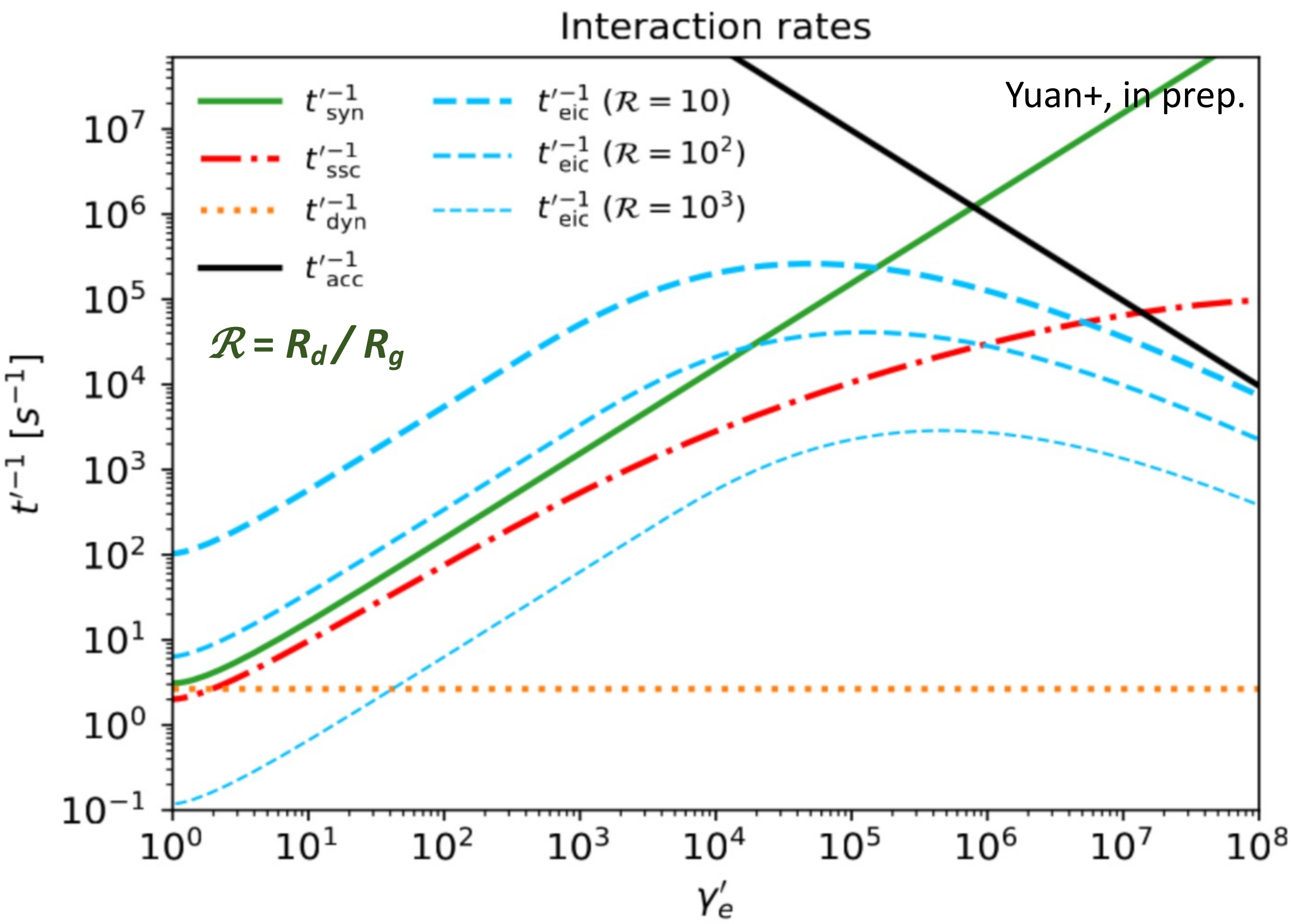
Compact binaries + dense AGN disk -> highly super-Eddington accretion rate -> strong wind -> low-density cavity (**condition $\psi < \psi_c$**)

$$\psi_c \simeq \frac{\pi}{2} - \max\left[h_{\rm AGN},\ 0.076\mathcal{R}_2^{-1/15} h_{{\rm AGN},-2}^{8/15} M_{\star,8}^{1/10}\right]$$



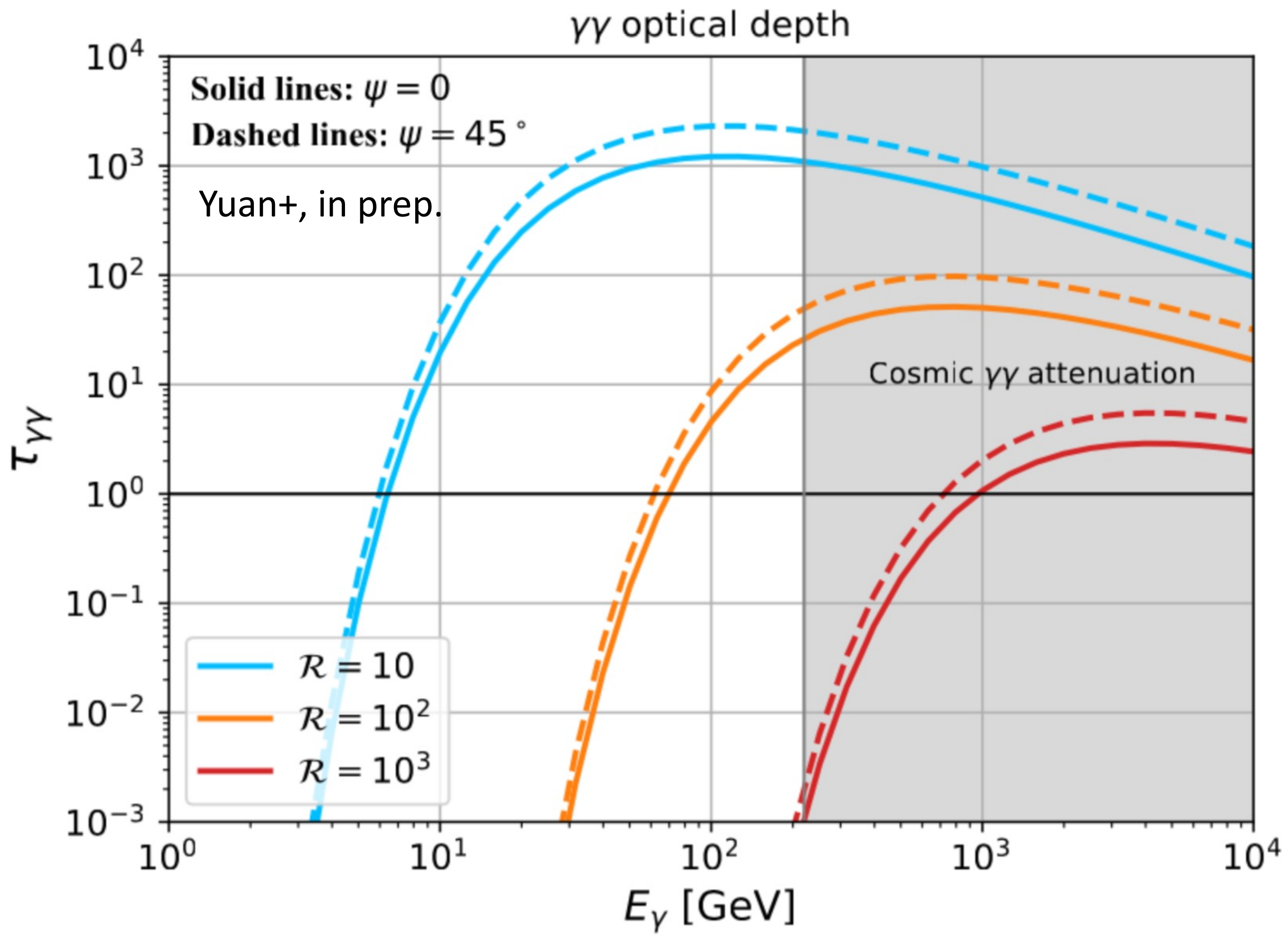
Short GRBs in AGN Disks: Interaction Rates

- Close to SMBH (< $100R_g$) EIC (upscattered disk photons) dominates the γ-ray flux



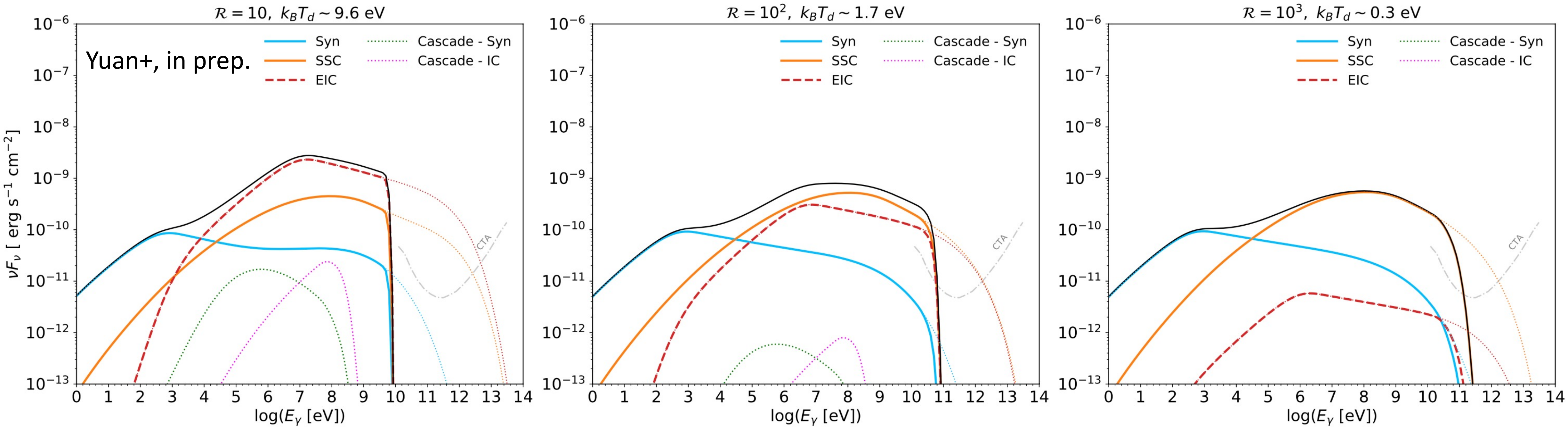
Short GRBs in AGN Disks: Disk Photon Absorption

- γ-ray (>100 GeV) suppressed by $\gamma\gamma$ attenuation (γ-ray + thermal disk photons) -> cascade emission in AGN disk



Short GRBs in AGN Disks: Gamma Ray Spectra

- Extended emission: $\boldsymbol{L_{k,iso}} \sim \mathbf{10^{48.5}}$ **erg/s, z=1, duration $\mathbf{10^2}$-$\mathbf{10^3}$ s, $\boldsymbol{\Gamma \sim 50}$**
- **HE cutoff:** $\gamma\gamma$ attenuation with disk photons; **Cascade – subdominant**
- Close to SMBH (low R_d): more EIC flux, stronger HE cutoff

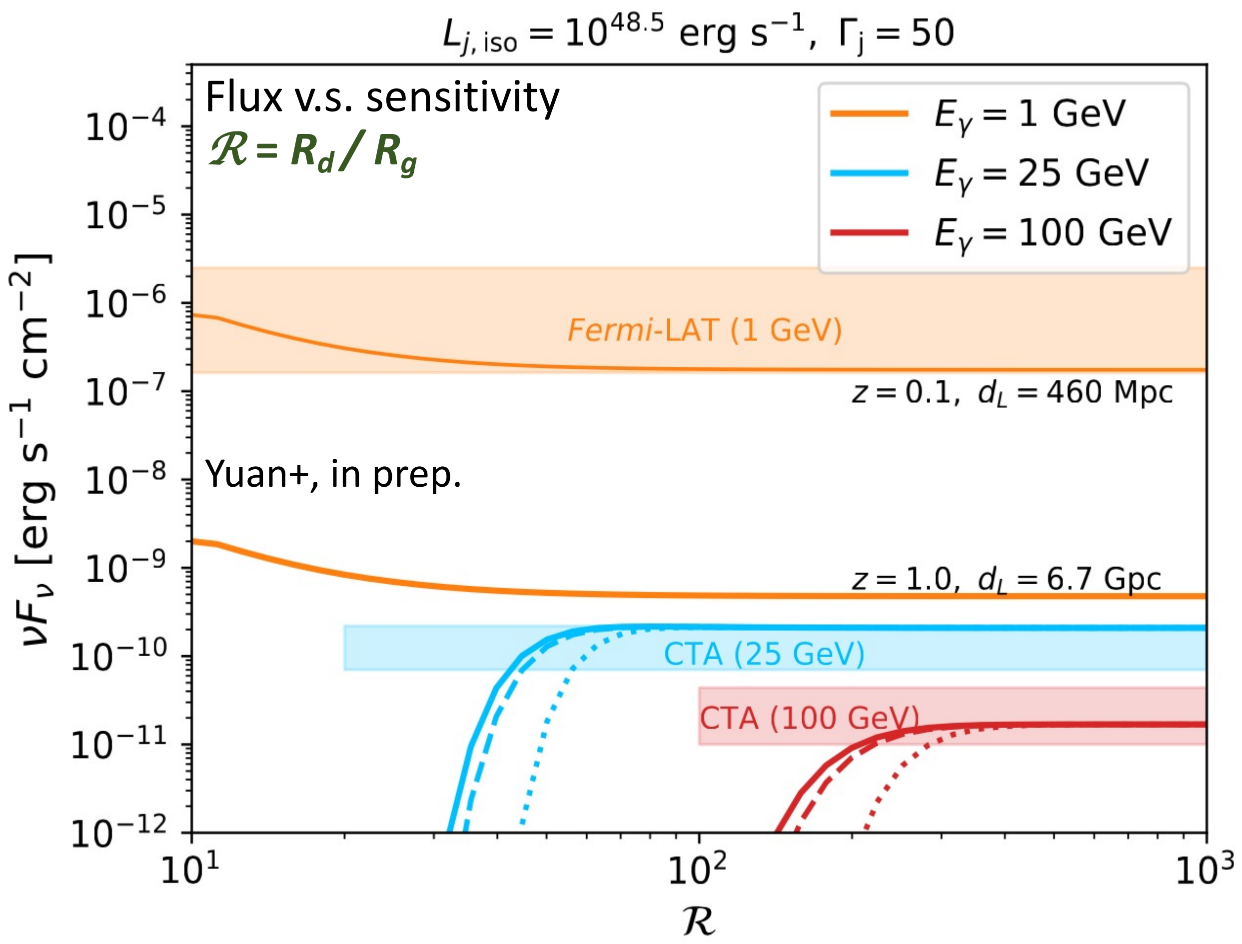


Short GRBs in AGN Disks: Implications

- 25 GeV - 100 GeV: **detectable for CTA upto *z* = 1.0 if R>100**
- **Gamma-ray (CTA) + GW (LIGO) joint detection rate**

$$\dot{R}^{(L)}_{\rm SGRB-AGN} = f_{\rm EE} f_b f_{\rm L,BCO/BBH} \dot{R}_{\rm L,BBH} \sim (2.5 \times 10^{-3} - 0.35)\theta^2_{j,-1}\ {\rm yr}^{-1}.$$

- $\dot{R}_{L,BBH} \sim 20{\rm yr}^{-1}$: LIGO detection rate of embedded BH mergers (Bartos+ 17)
- Detectable in the decade-long observations



Summary of Part 3

- A low-density cavity can be formed in the migration traps, leading to the embedded mergers producing successful GRB jets.

- Thermal photons from the AGN disks contribute to the EIC component and initiate electromagnetic cascades when the γ-rays escape from the jets and propagate in the disks.

- EIC component would dominate the GeV emission if the compact binary object is close to the SMBH.

- The future CTA will be able to detect its 25 −100 GeV emission out to a redshift $z = 1.0$, as well as being able to detect the on-axis extended emission simultaneously with GWs in within one decade.

- Results for neutrino emission from embedded SGRBs are on the way.

The Future

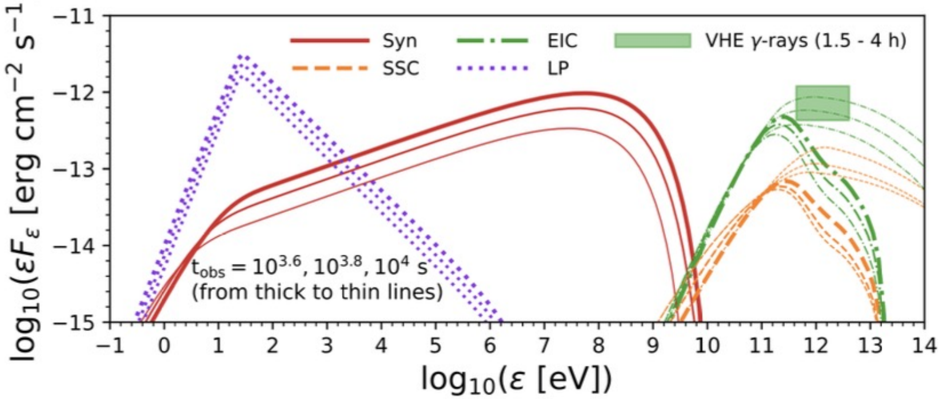
Theoretically

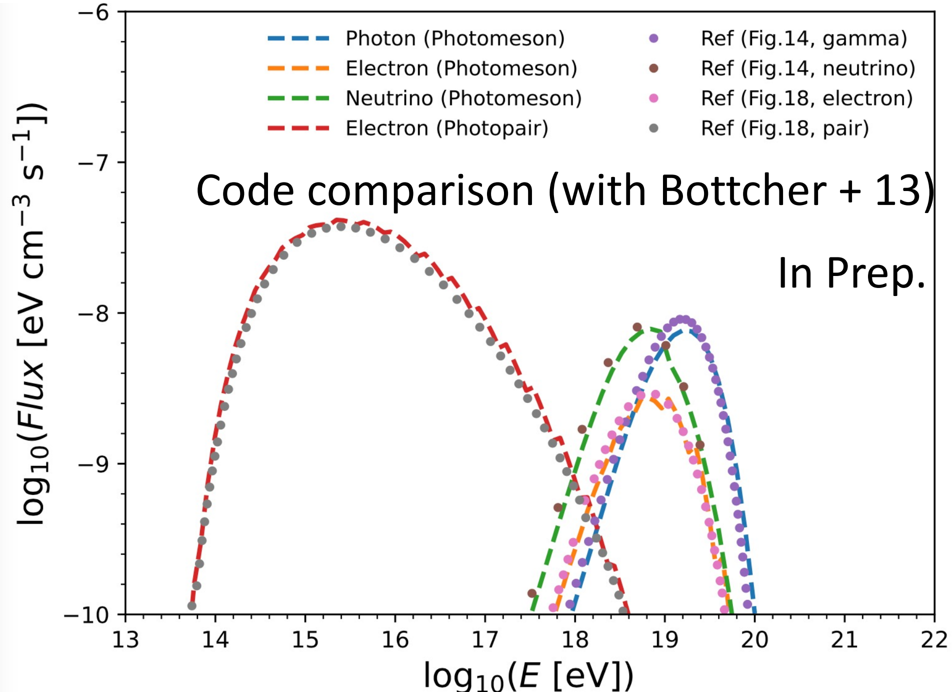
Hybrid models (leptonic + hadronic)
- Blazar SED fitting
- VHE (>TeV) gamma-rays from GRBs obs. by MAGIC, VERITAS, H.E.S.S., ...

Multi-zone time-dependent scenarios
- Environment (external photon fields)
- Time-dependent cascade
- Particle transport/diffusion, radiation transfer in different sites (e.g., jet shocks, cocoon, winds)

Astrophysical Multimessenger Emission Synthesizer (AMES, under development)
- Written in C++ and python
- CR acc., transport, radiation/particle interactions/propagation,…
- AGNs, GRBs, supernovae, galaxies, dark matter, TDEs …

Apply to GRB 160821B (B. T. Zhang+ 21)





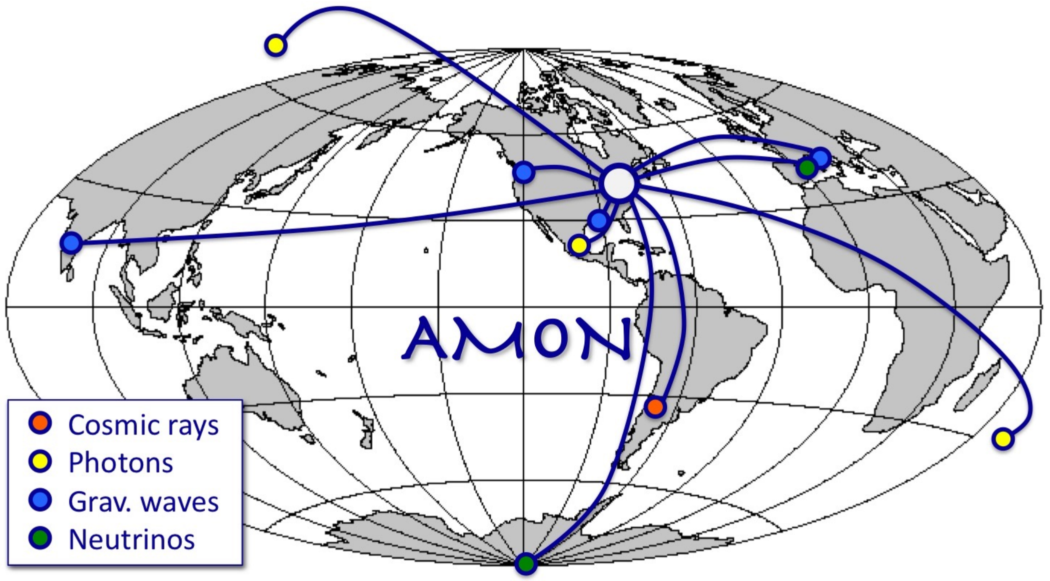
The Future

Extraordinary claims require extraordinary evidence. – Carl Sagan

Observationally

New and powerful detectors

- ν : PINGU, IceCube-Gen2, KM3NeT, GRAND, …
- EM: CTA, LHAASO, SVOM, LSST, SKA, …
- GW: LIGO upgrades, PTA, eLISA, Einstein Teles., …
- CRs: AUGER upgrades, LHAASO, POEMMA, …



Multimessenger Programs

Astrophysical Multimessenger Observatory Network (AMON)

- Improve combined sensitivity
- Enable rapid follow-up obs. and correlation analysis

Scalable Cyberinfrastructure to support Multi-Messenger Astrophysics (SCiMMA)

- To rapidly handle, combine, and analyze the very large-scale distributed data from all the types of astronomical measurements.

Thanks!