Multi-messengers from quasar outflows

Xiawei Wang
(advised by Prof. Avi Loeb)

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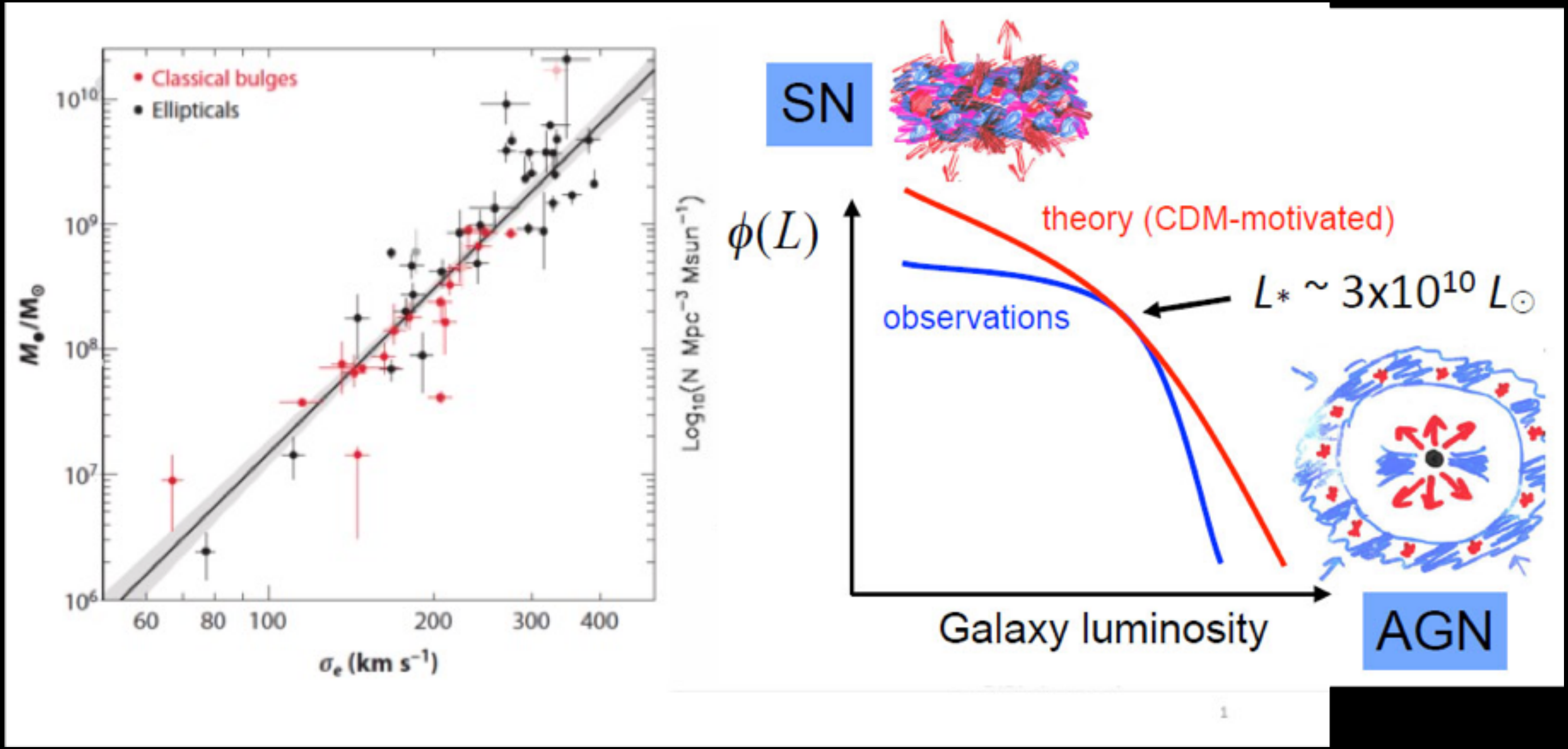
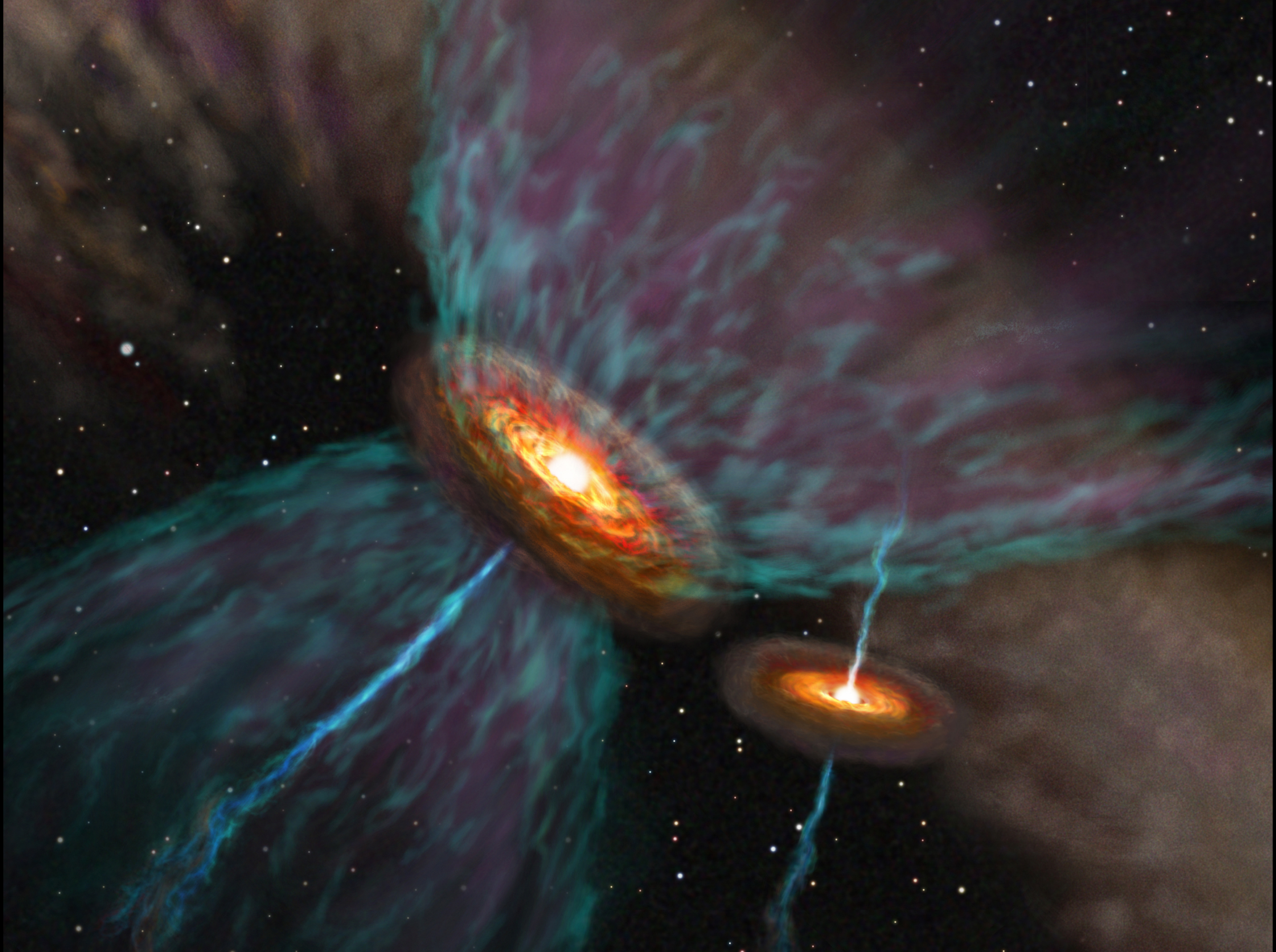
IPA conference

Quasar outflows

AGN feedback

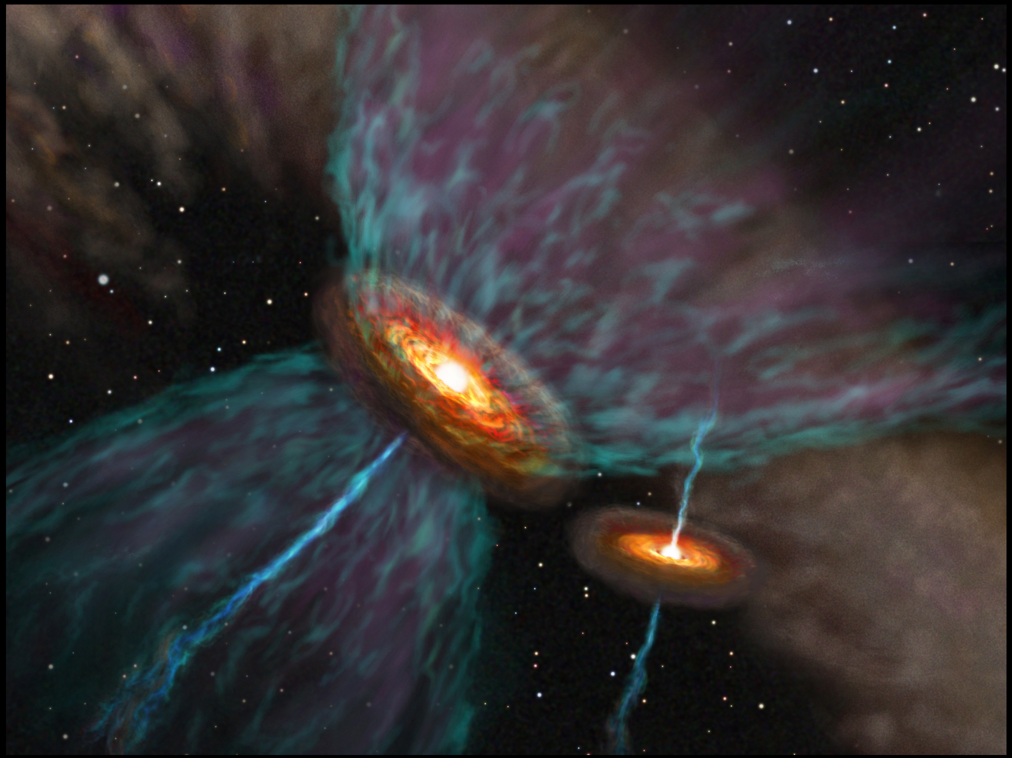
Regulate black hole growth & may quench star formation

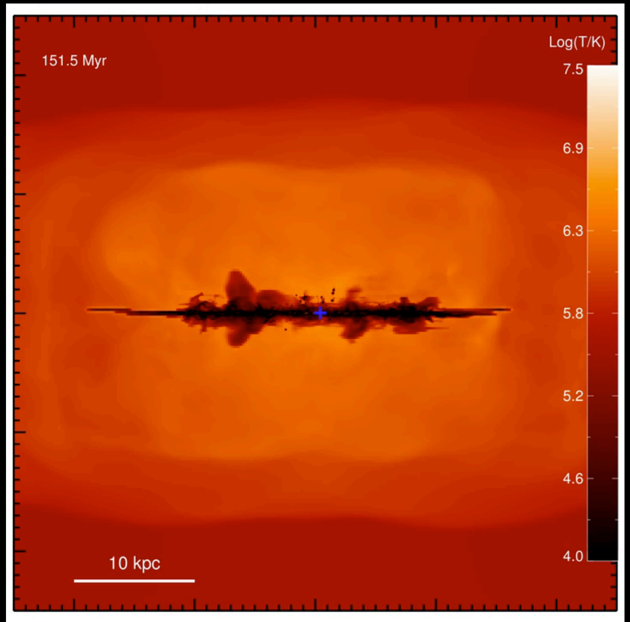




Observational evidence:

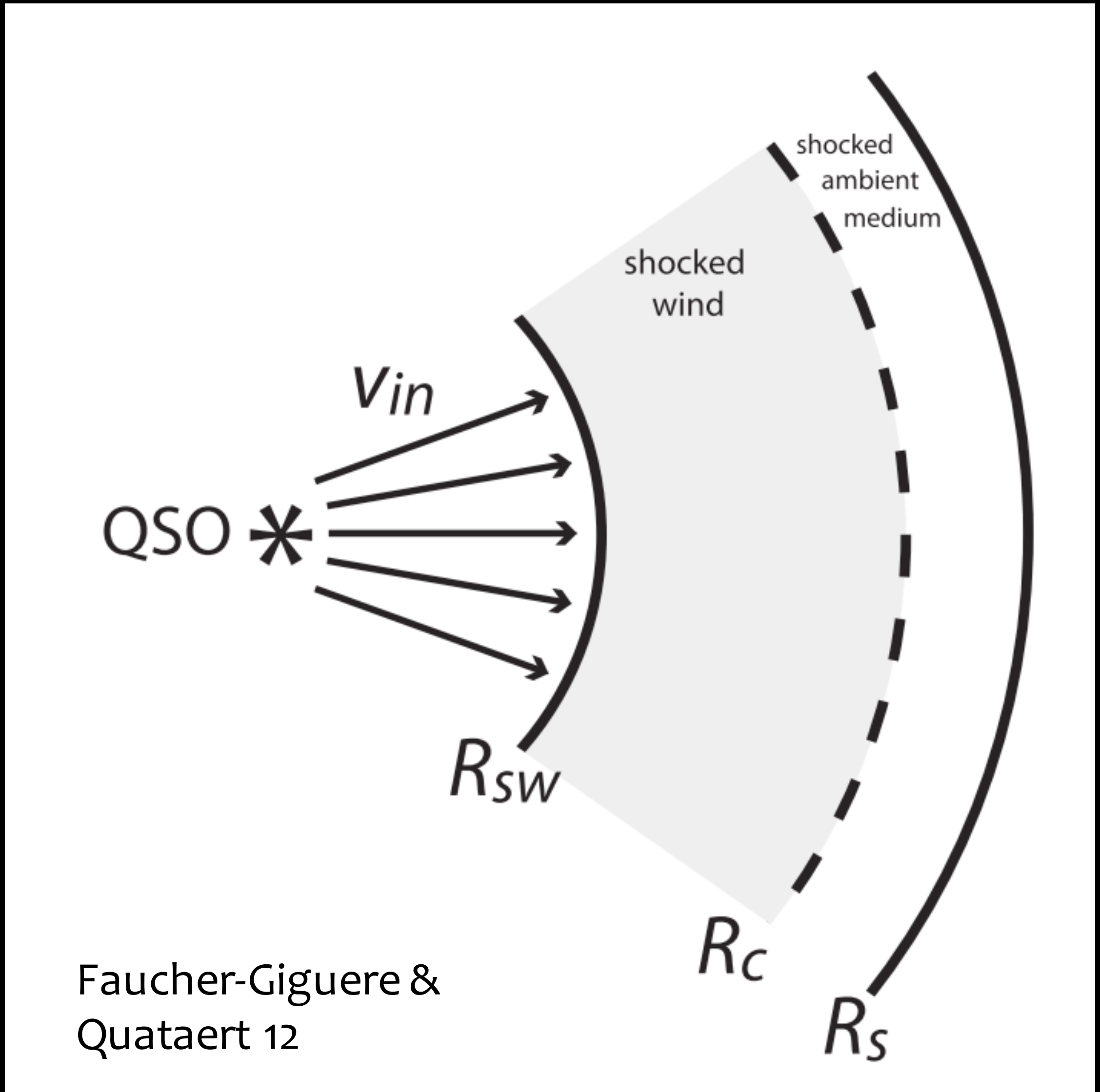
- Broad absorption lines in quasars
  Ganguly+07, Zakamska & Greene14, Arav+15
- Multi-phase outflows in nearby ultraluminous infrared galaxies (ULIRGs) and quasars
  Sturm+11, Cicone+14, Tombesi+15
- Post-starburst galaxies
  Tripp+11





Hydrodynamics

Hydrodynamics



Faucher-Giguere & Quataert 12

Hydro equations (Furlanetto & Loeb 01, Wang & Loeb 15)

$$\frac{d^2 R_\mathrm{s}}{dt^2} = \frac{4\pi R_\mathrm{s}^2}{M_\mathrm{s}}(P_\mathrm{t} - P_0) - \frac{G M_\mathrm{tot}}{R_\mathrm{s}^2} - \frac{v_\mathrm{s}}{M_\mathrm{s}}\frac{dM_\mathrm{s}}{dt} \ ,$$

$$\frac{dM_\mathrm{s}}{dt} = 4\pi m_\mathrm{p} n_\mathrm{ISM} R_\mathrm{s}^2 v_\mathrm{s} \ ,$$

$$\frac{dP_\mathrm{t}}{dt} = \frac{\Lambda}{2\pi R_\mathrm{s}^3} - 5 P_\mathrm{t}\frac{v_\mathrm{s}}{R_\mathrm{s}} \ ,$$

$$\Lambda = L_\mathrm{in} - L_\mathrm{ff} - L_\mathrm{IC} - L_\mathrm{syn} - L_\mathrm{p} \ ,$$

spherical symmetry

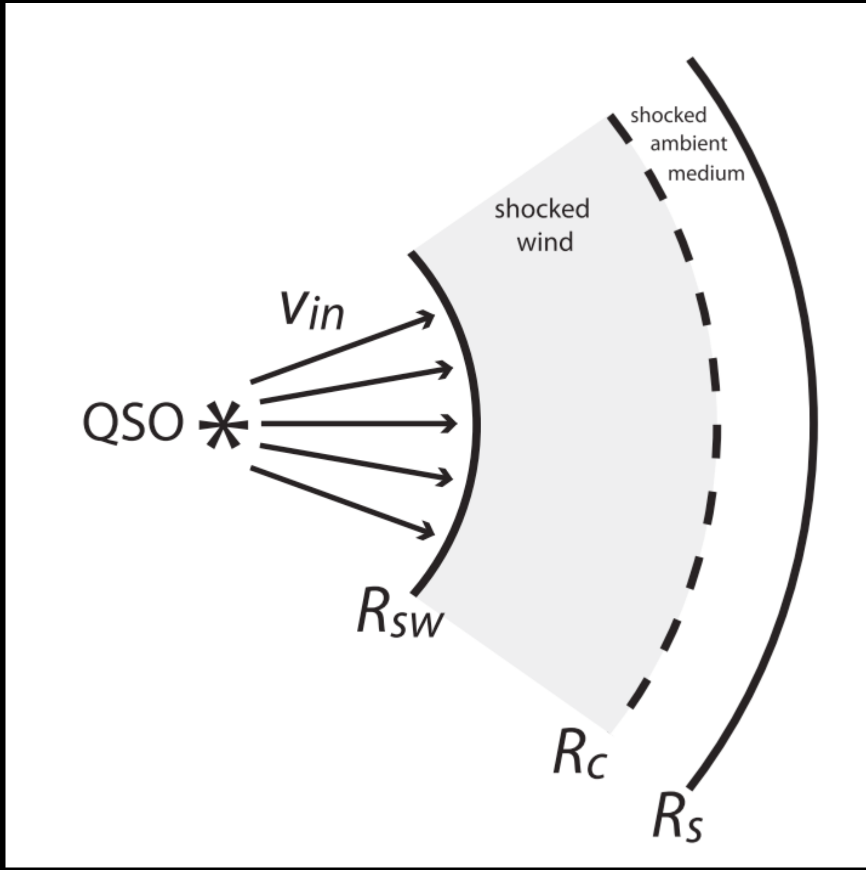
Gas density profile (Wang & Loeb 15)

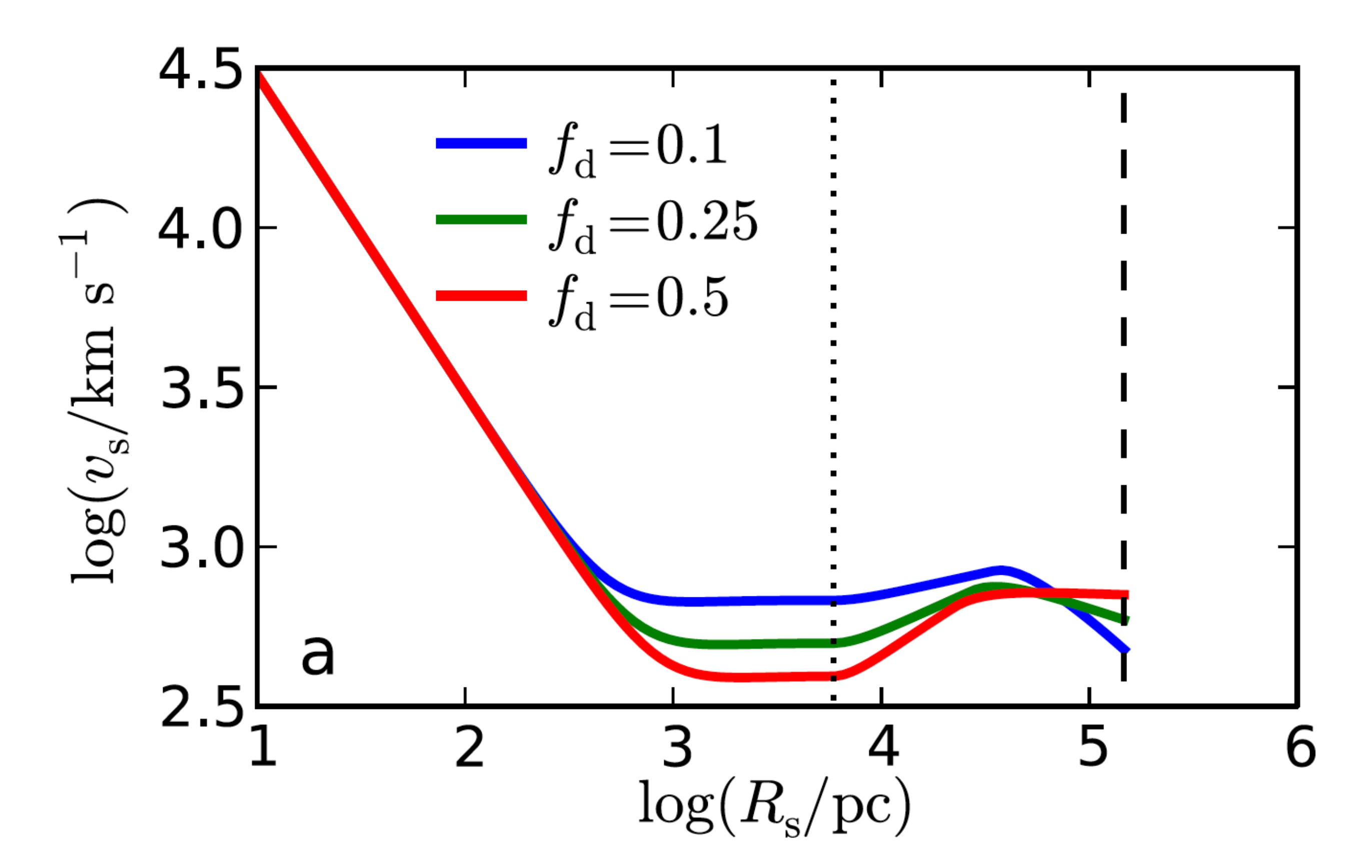
$$\rho_\mathrm{pl}(R) = \begin{cases} C_\mathrm{d}\ R^{\boxed{-\alpha}} & (R \le R_\mathrm{disc}) \\ C_\mathrm{h}\ R^{\boxed{-\beta}} & (R_\mathrm{disc} < R \le R_\mathrm{vir}), \end{cases}$$

$\alpha = 2$ (isothermal)
β determined by baryonic disk fraction f_d

Parameters: f_d, M_h, z

Hydrodynamics

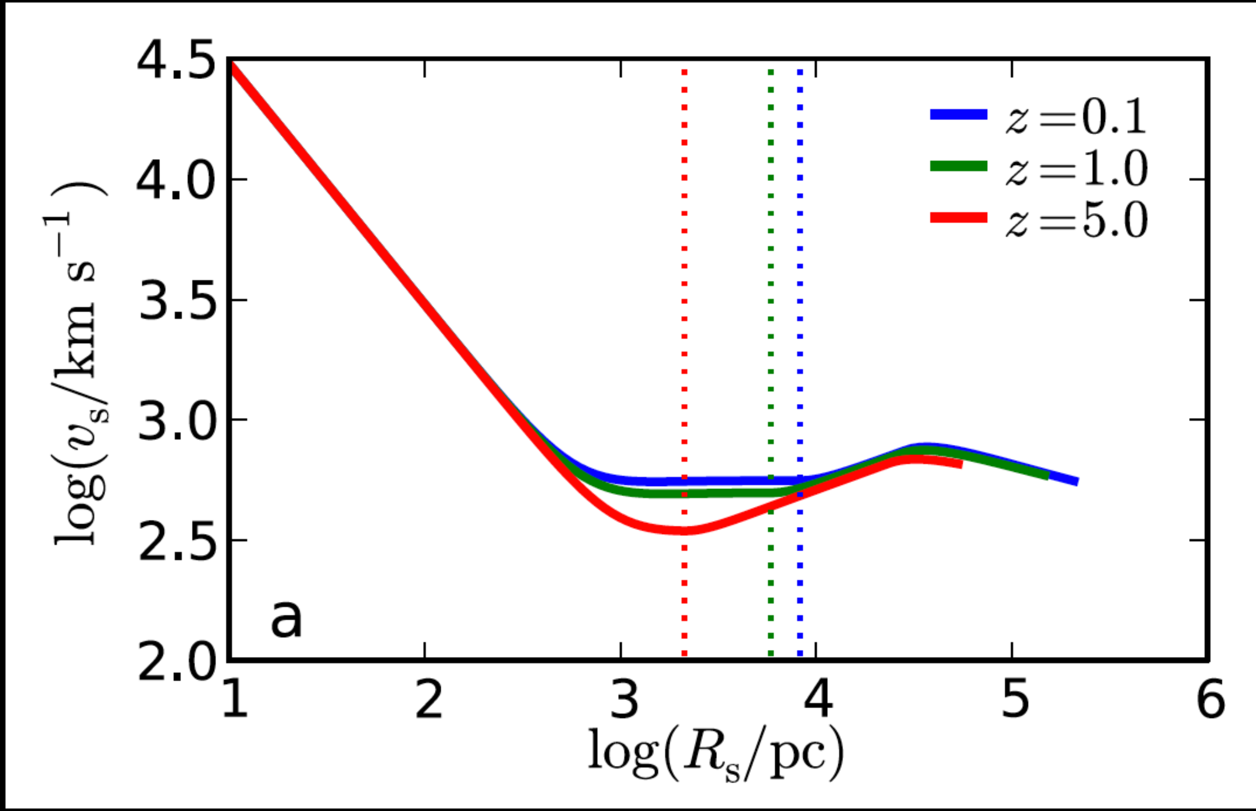




Faucher-Giguere & Quataert 12

Wang & Loeb 15

Hydrodynamics



Wang & Loeb 15

Non-thermal emission from **electrons** accelerated in the forward shock (similarly to **SN remnants**):

- Synchrotron
- Inverse Compton:
  - Quasar's radiation field
  - CMB photons (important at high z)

Detectability:

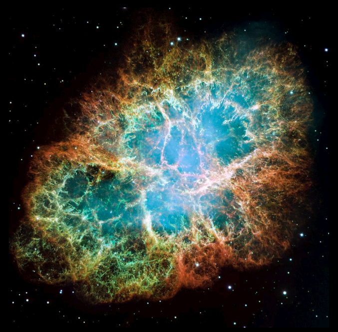
- Detectable at multi-wavelengths
- Radio signal can be detected up to z~5

Ultra High Energy Cosmic Rays

Gamma-rays

Neutrinos

Outflow shock



Analogous to SN shocks

Multi-messengers

Gamma-rays

Wang & Loeb, Nat. Phys., 2016, 12, 1116

Hadronic emission

- Power-law distribution of accelerated protons:

$$N_p \sim E_p^{-\Gamma_p}$$

- Neutral pion decay via proton-proton collision:

$$p + p \rightarrow \pi^0 \rightarrow 2\gamma$$

- Magnetic field estimated by equi-partition

(Prescriptions following Kelner+06, Aharonian & Atoyan 00)

Integrated gamma-ray background

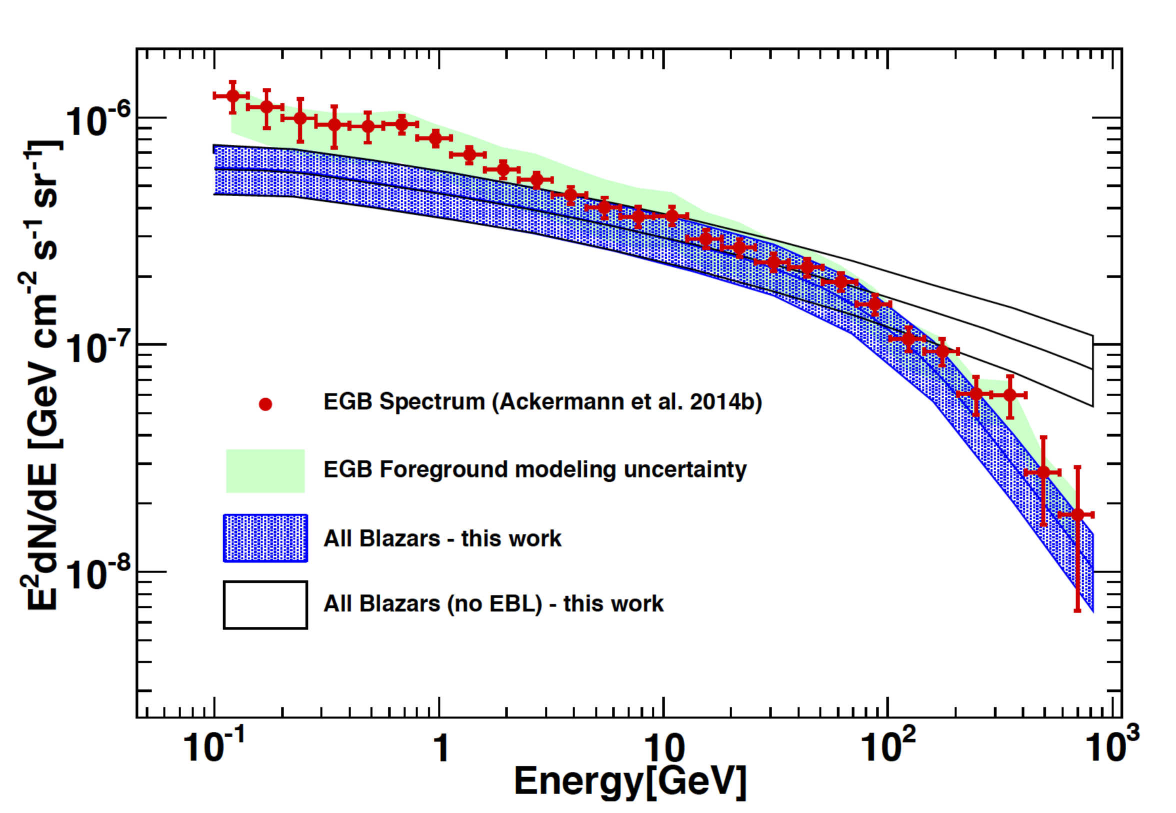
$$I(E_\gamma) = \iint \Phi(L_{\mathrm{bol}}, z) \frac{\overline{L}_\gamma(E'_\gamma, L_{\mathrm{bol}}, z)}{4\pi D_{\mathrm{L}}^2(z)} \exp[-\tau_{\gamma\gamma}(E'_\gamma, z)] \times \frac{\mathrm{d}V}{\mathrm{d}z\,\mathrm{d}\Omega}\,\mathrm{d}\log L_{\mathrm{bol}}\,\mathrm{d}z$$

Free parameters:

- f_{kin} -- fraction of L_{bol} injected into the outflow ~ 1-5 %
- ϵ_{nt} -- fraction of the shock kinetic energy used to accelerate protons ~10%

Gamma-rays

Extragalactic gamma-ray background

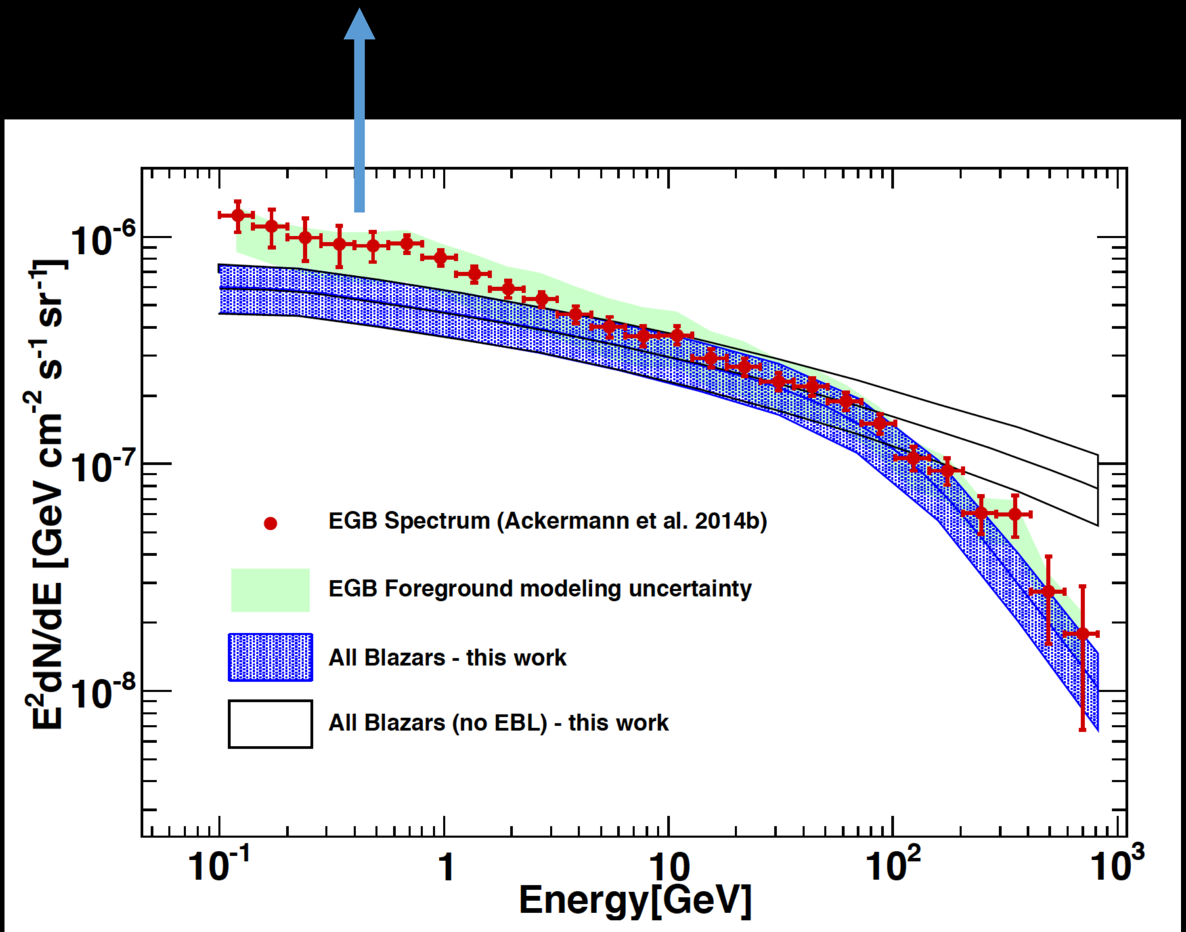


Ajello+ 15

Gamma-rays

Extragalactic gamma-ray background

Missing component!



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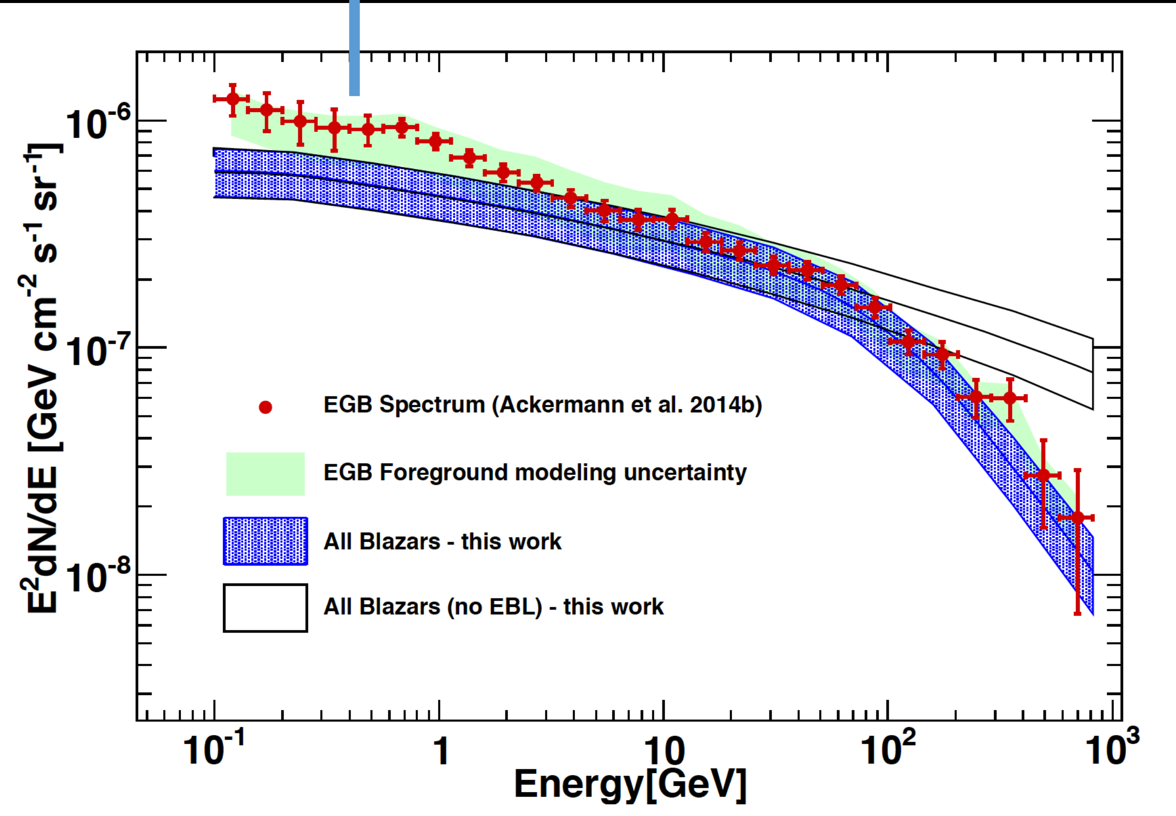

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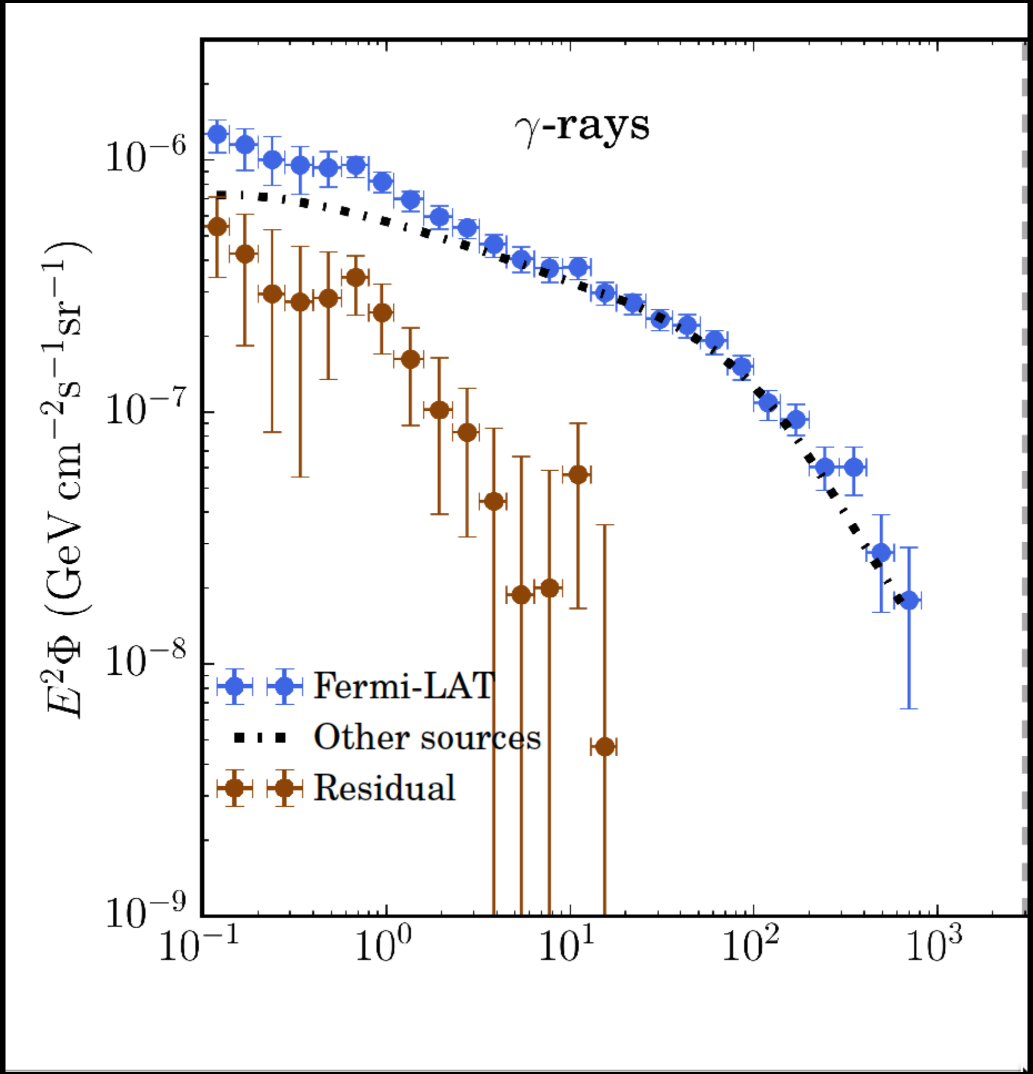

Wang & Loeb 16

Gamma-rays

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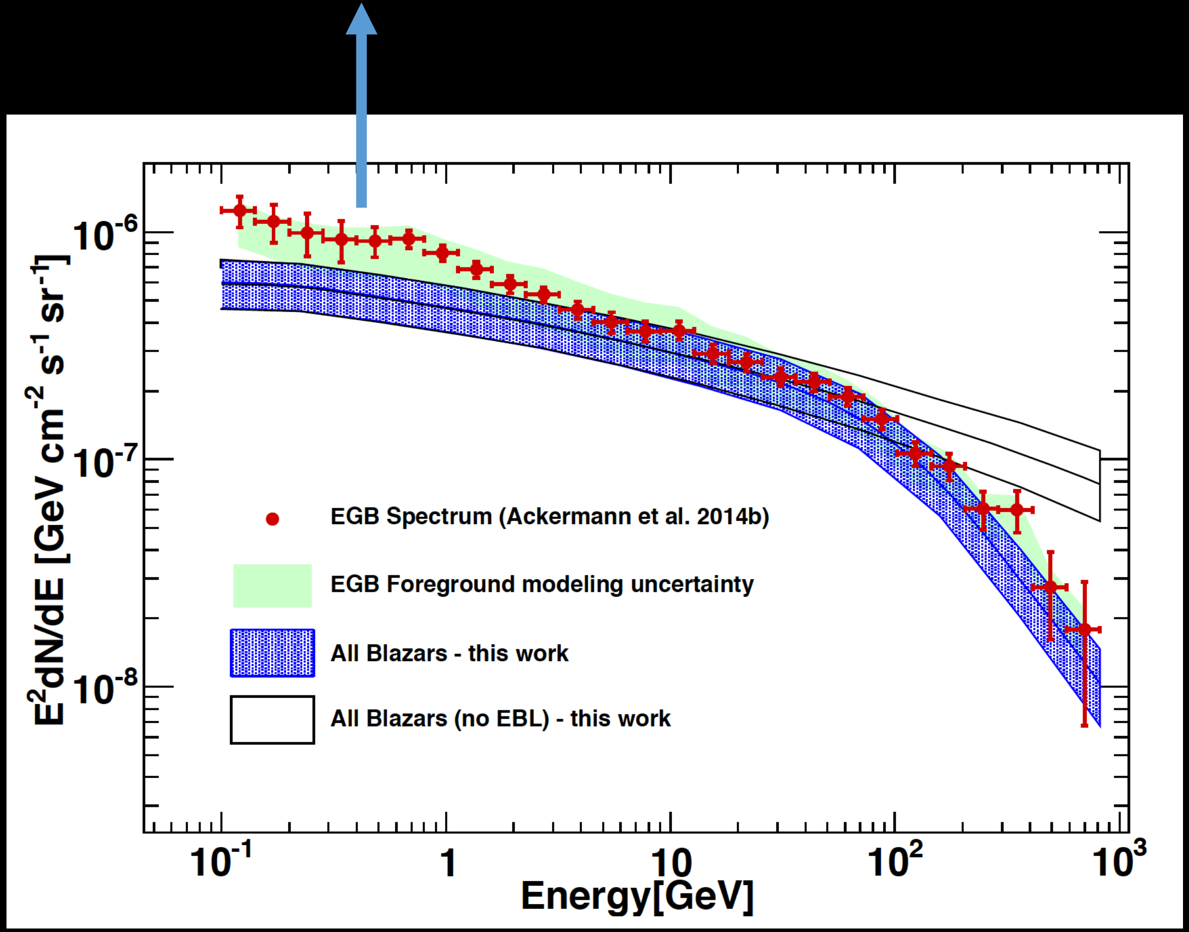

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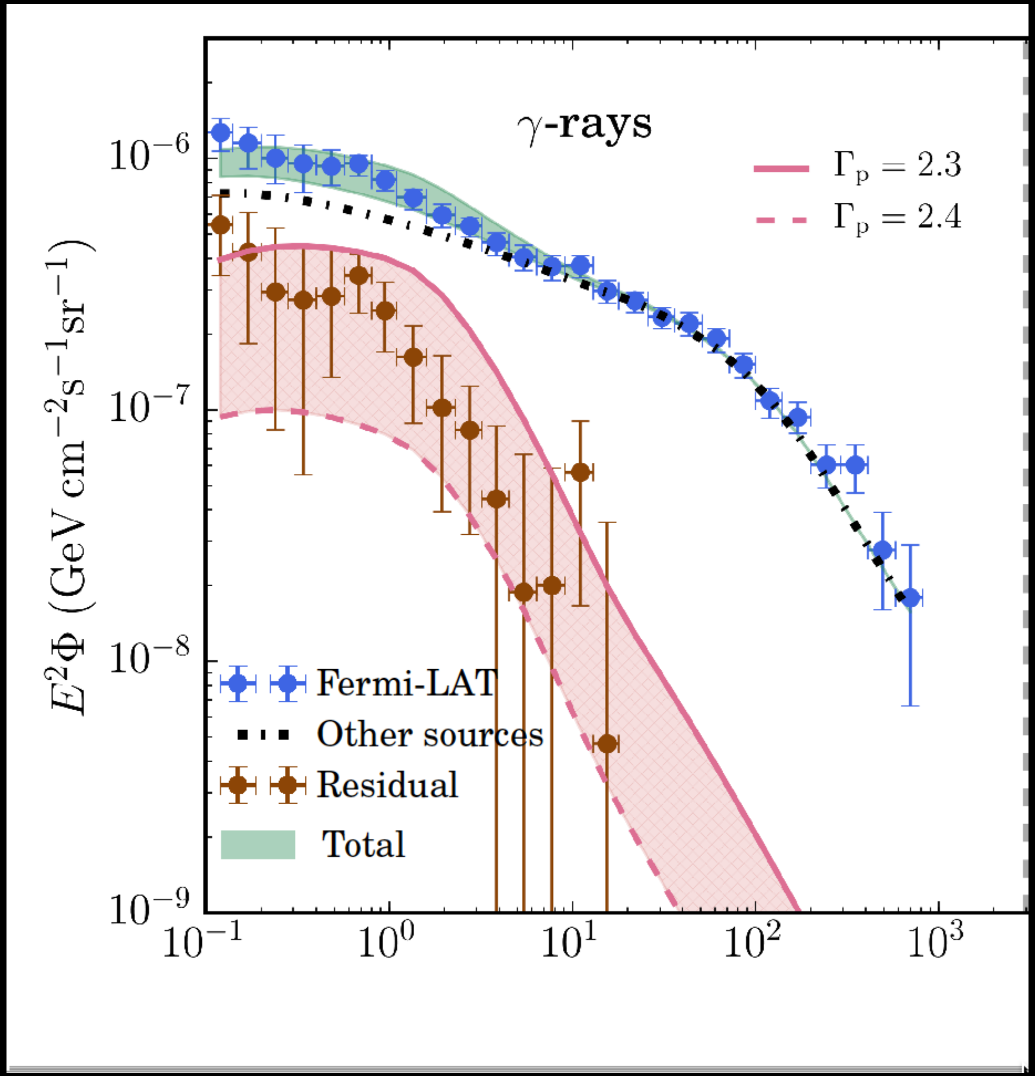
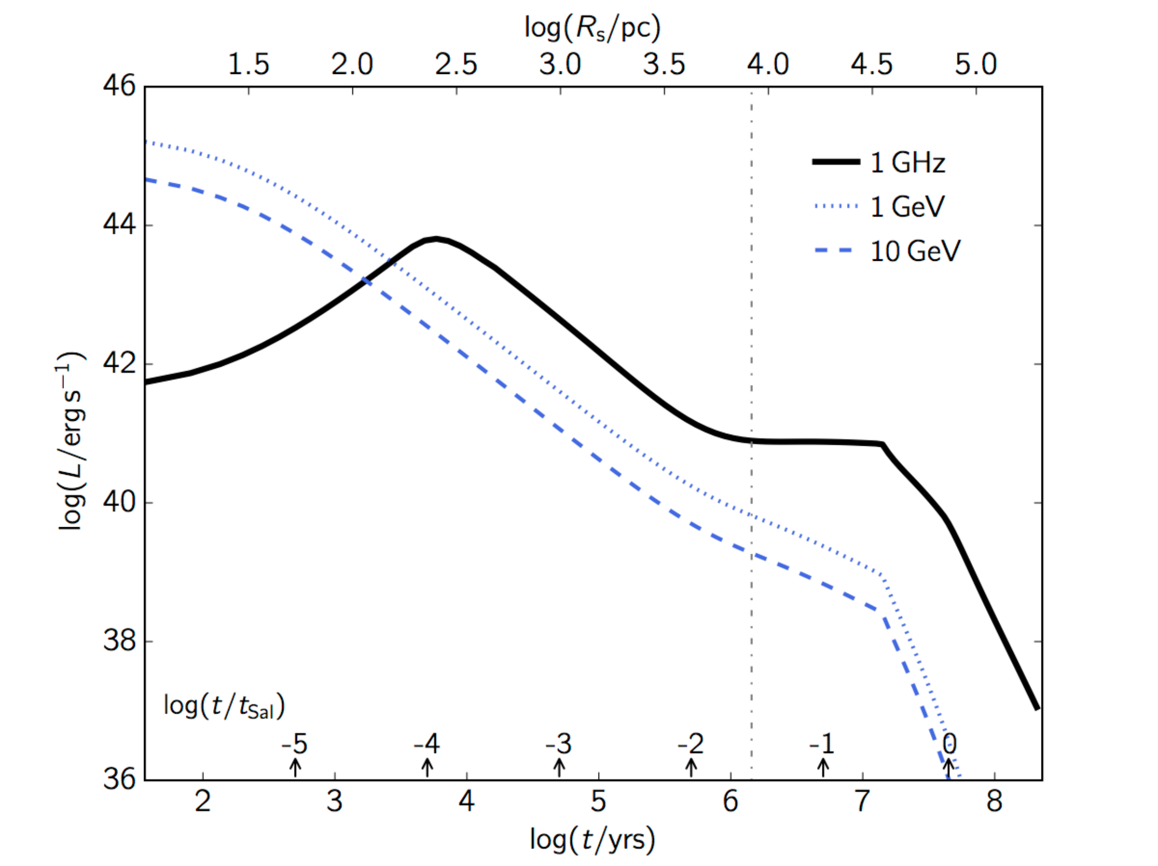


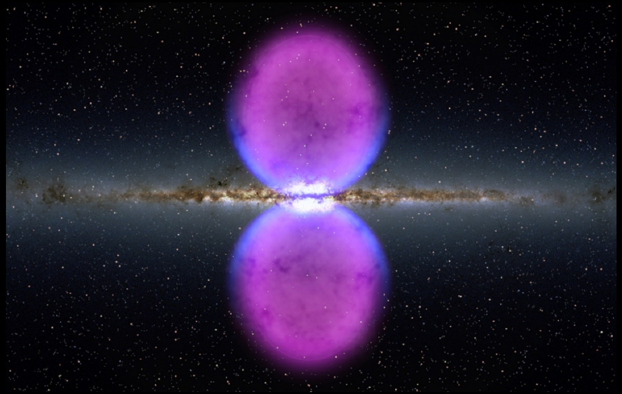
Wang & Loeb 16

Identification

- Outflows embedded in MW mass halos propagating to 10-kpc scale produce GeV emission of ~ 10^{38} - 10^{39} erg s^{-1}
- Only **< 0.1%** of quasars in the local Universe (z<0.1) host gamma-ray-detectable outflows
- **Radio counterpart** by JVLA, SKA
- Possible candidate: **Fermi bubbles**
- Source stacking analysis



Wang & Loeb 16



Su+ 10

Gamma-rays

$$p + p \rightarrow \pi^0 \rightarrow 2\gamma$$

Neutrinos

Wang & Loeb, JCAP, 2016, 12, 012

Production mechanism:

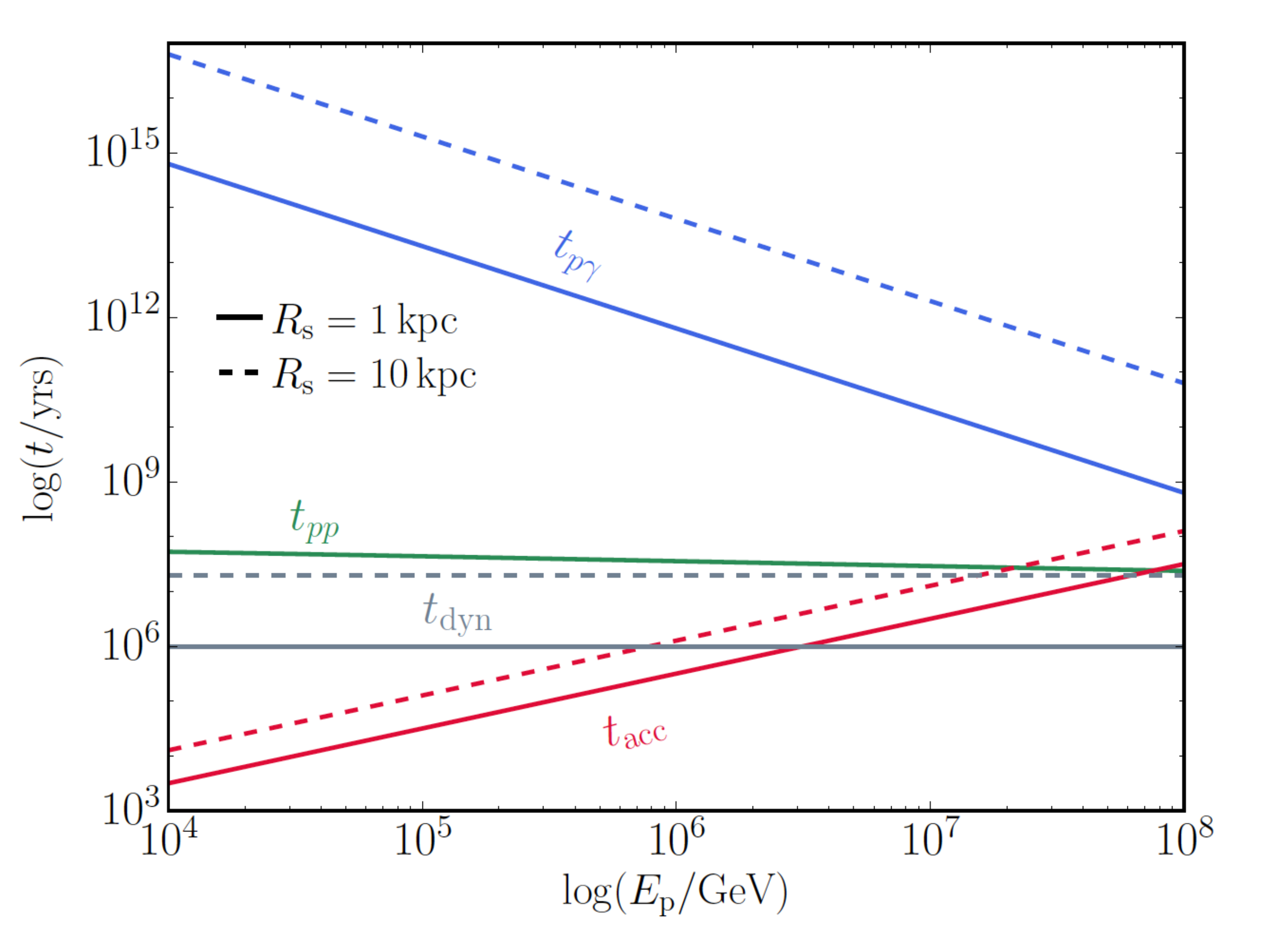
- $p + \gamma \rightarrow p + \pi^0$ or $n + \pi^+$ $(p\gamma)$
- $p + p \rightarrow \pi^+ + \pi^- + \pi^0$ (pp)
  - $\pi^+ \rightarrow \mu^+ + \nu_\mu \rightarrow e^+ + \nu_e + \bar{\nu}_\mu + \nu_\mu$
  - $\pi^- \rightarrow \mu^- + \bar{\nu}_\mu \rightarrow e^- + \bar{\nu}_e + \nu_\mu + \bar{\nu}_\mu$
- $t_{p\gamma} \gg t_{pp}$
- ***pp*** **interaction** dominates
- Free parameters f_{kin} and ϵ_{nt}, **no additional parameters**

Neutrinos

Wang & Loeb, JCAP, 2016, 12, 012

Timescale comparison

$t_{p\gamma} \gg t_{pp}$



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Wang & Loeb, JCAP, 2016, 12, 012

Cumulative neutrino background

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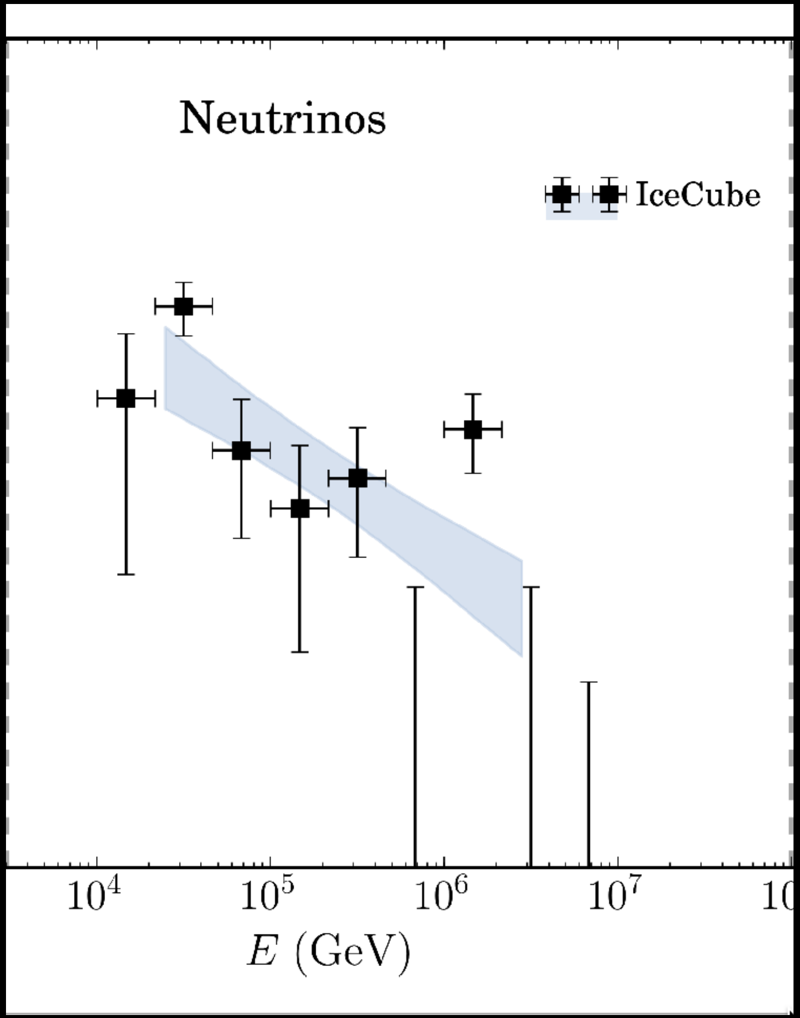

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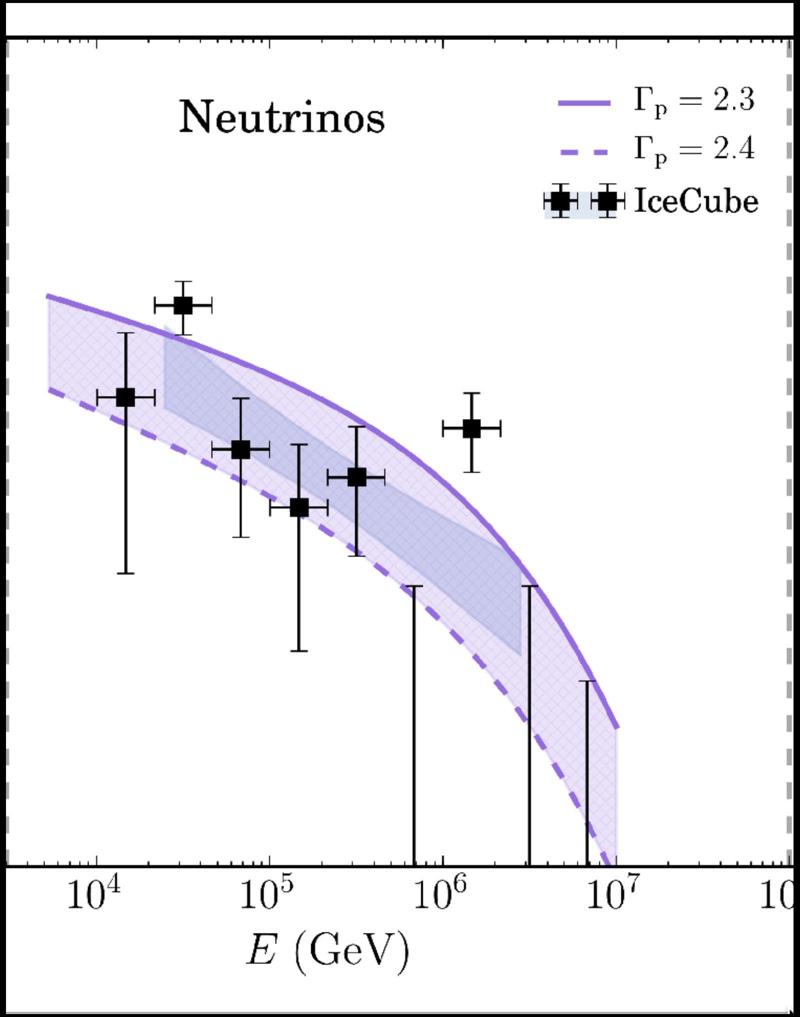

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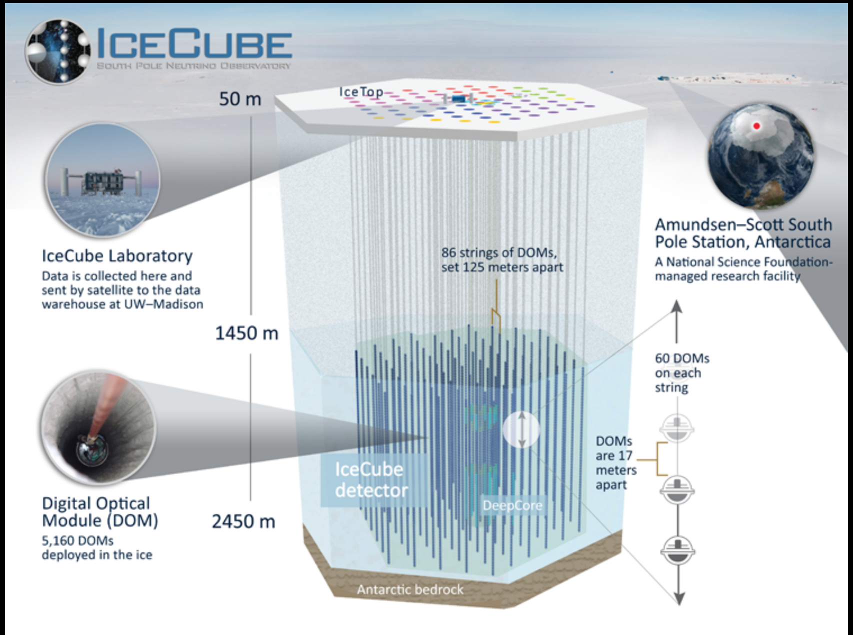


Gamma-rays

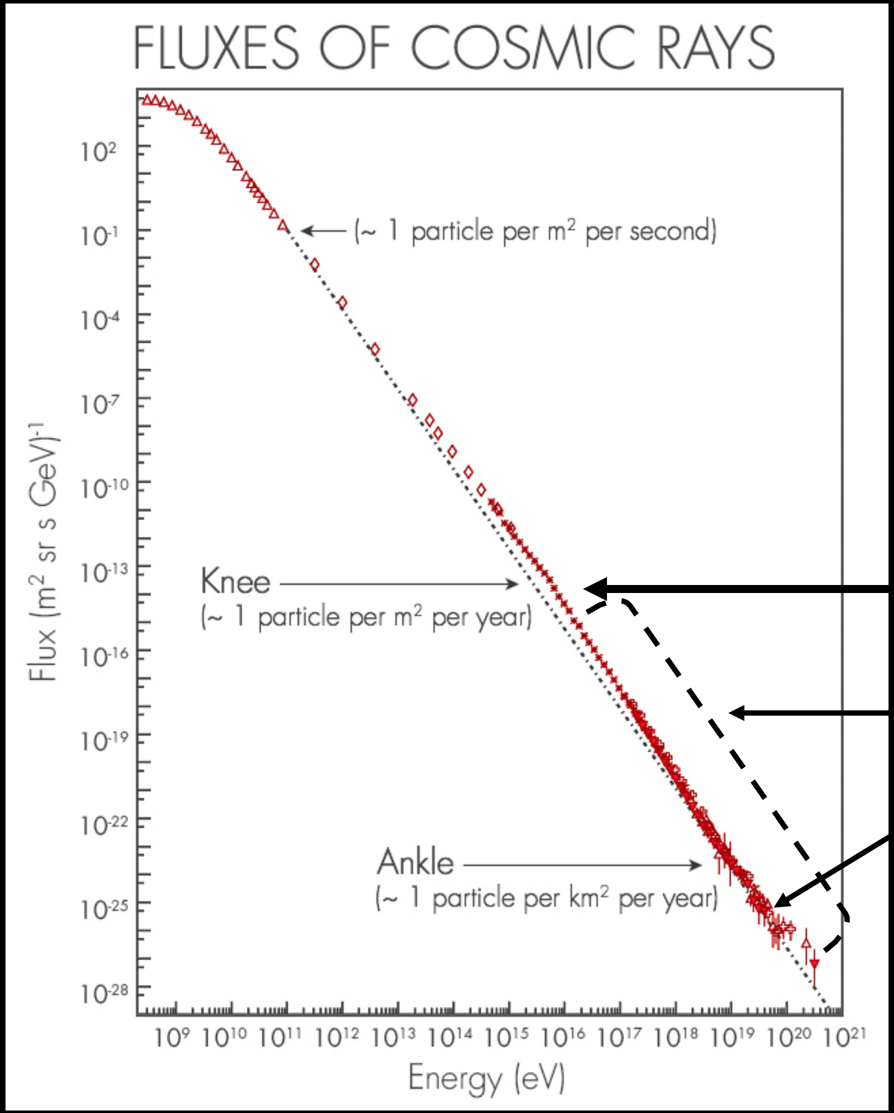
$$p + p \to \pi^0 \to 2\gamma$$

Neutrinos

$$\pi^+ \to \mu^+ + \nu_\mu \to e^+ + \nu_e + \bar{\nu}_\mu + \nu_\mu$$

$$\pi^- \to \mu^- + \bar{\nu}_\mu \to e^- + \bar{\nu}_e + \nu_\mu + \bar{\nu}_\mu$$

What's next?



Gamma-ray photons

Neutrinos

Cosmic rays ???

Can all three messengers explained by quasar outflows?

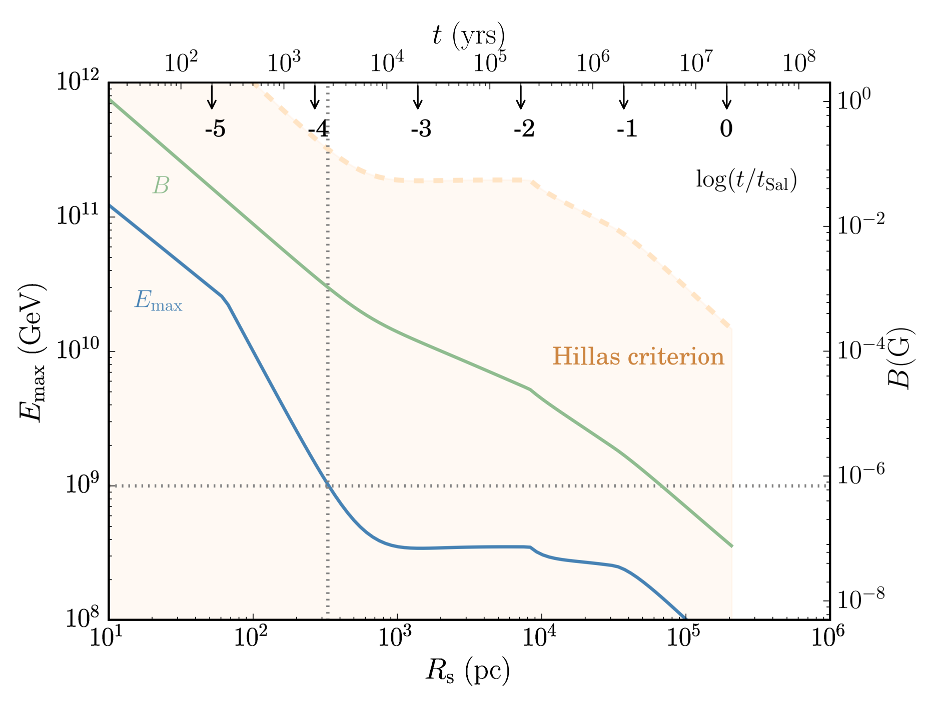
SN

AGN-driven outflows ???

Ultra high energy cosmic rays (UHECRs)

UHECRs

- The maximum energy reaches > 10^9 GeV during the initial stage of outflow's propagation
- Proton-only composition
- Satisfy the Hillas criterion



Wang & Loeb 17

UHECRs

Wang & Loeb, PRD, 2017, 95, 063007

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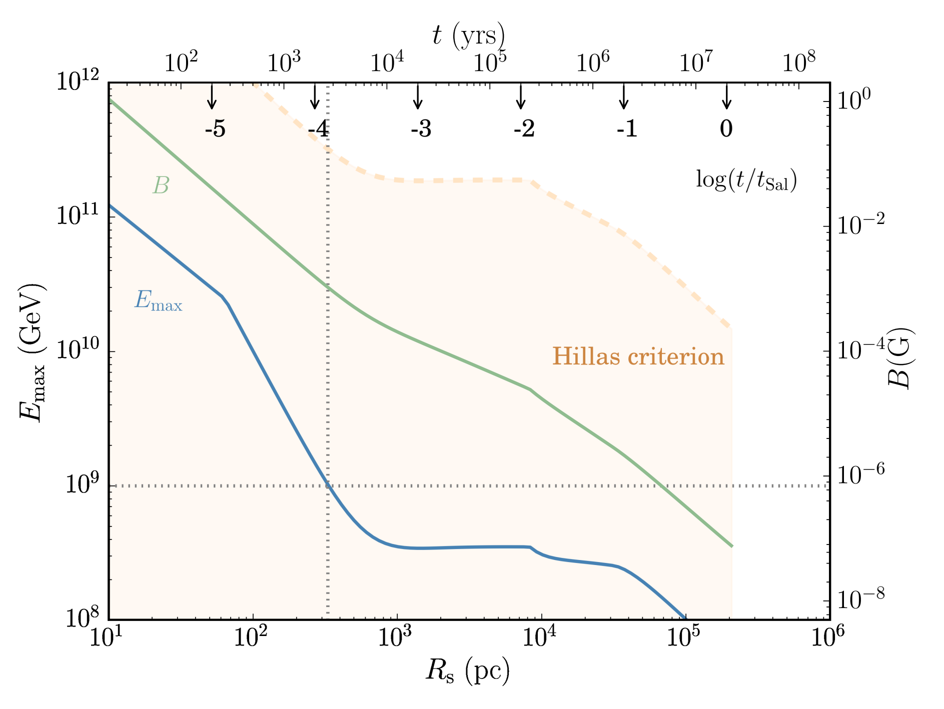

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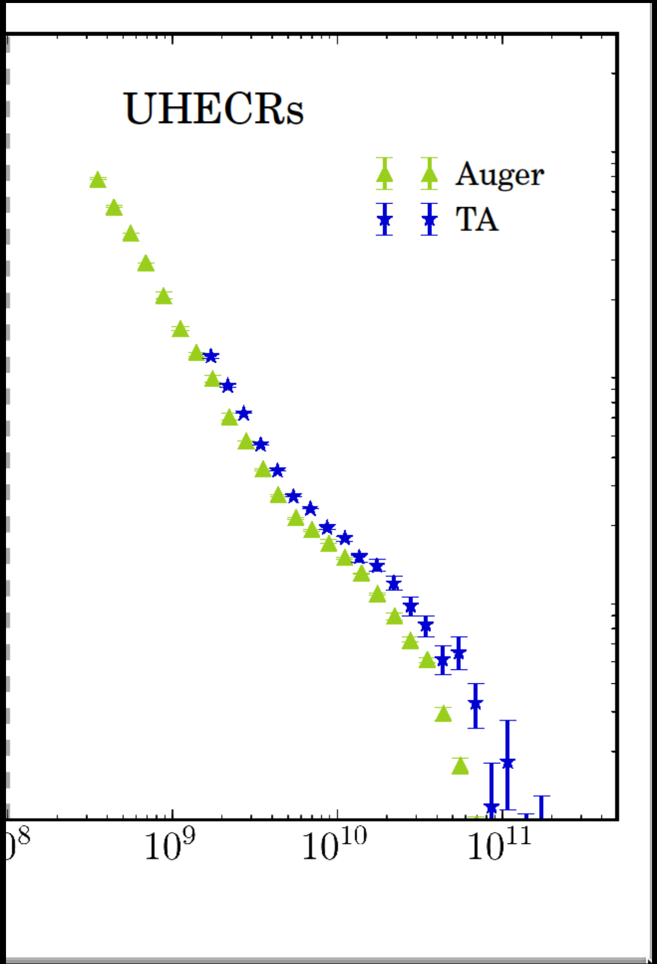

Wang & Loeb, PRD, 2017, 95, 063007

UHECRs

No additional parameter tuning!

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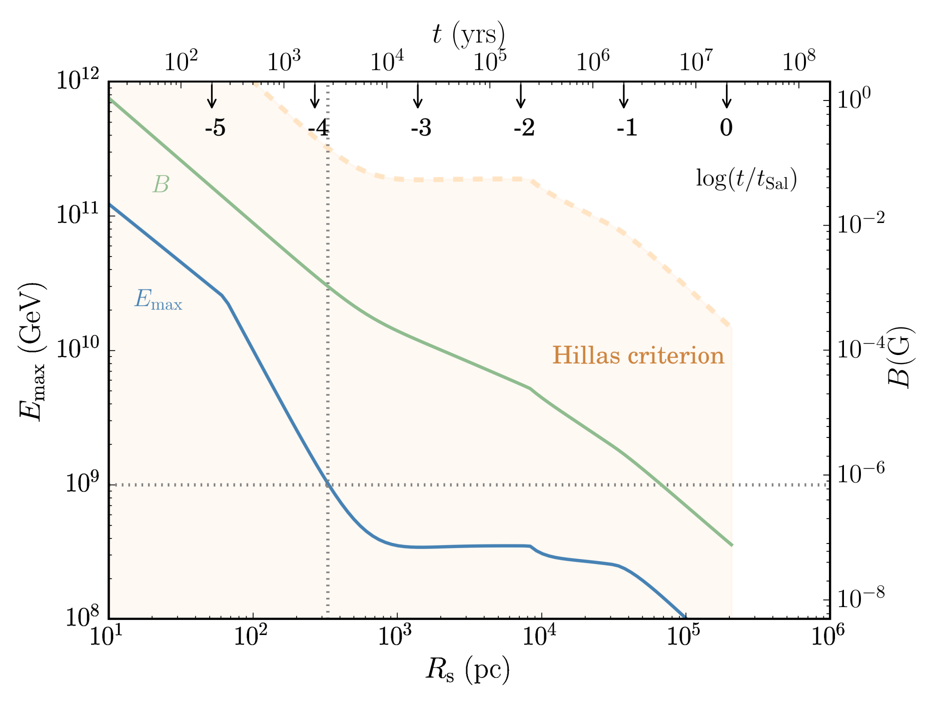
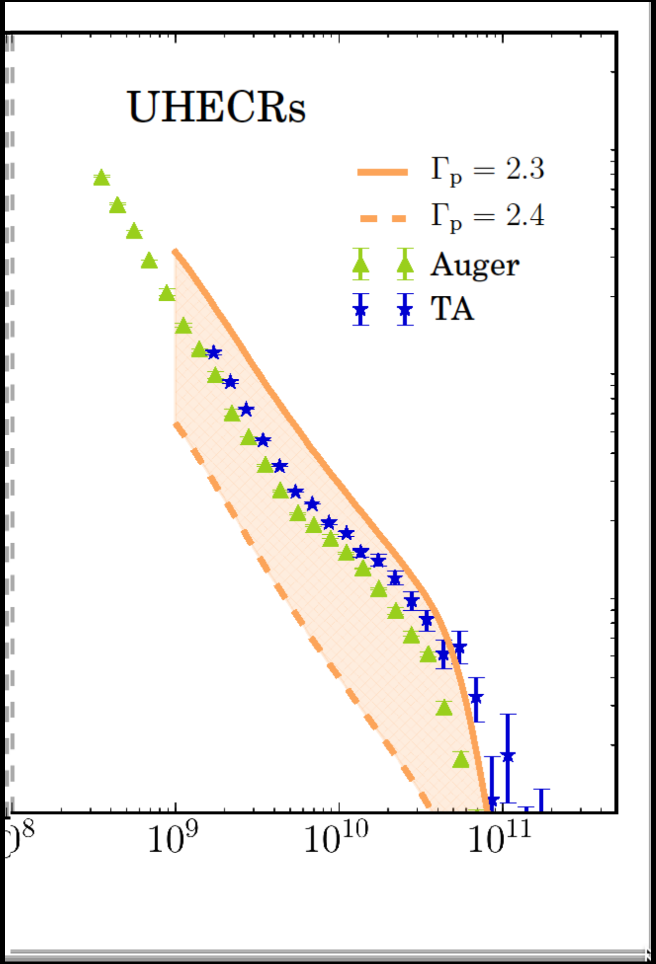
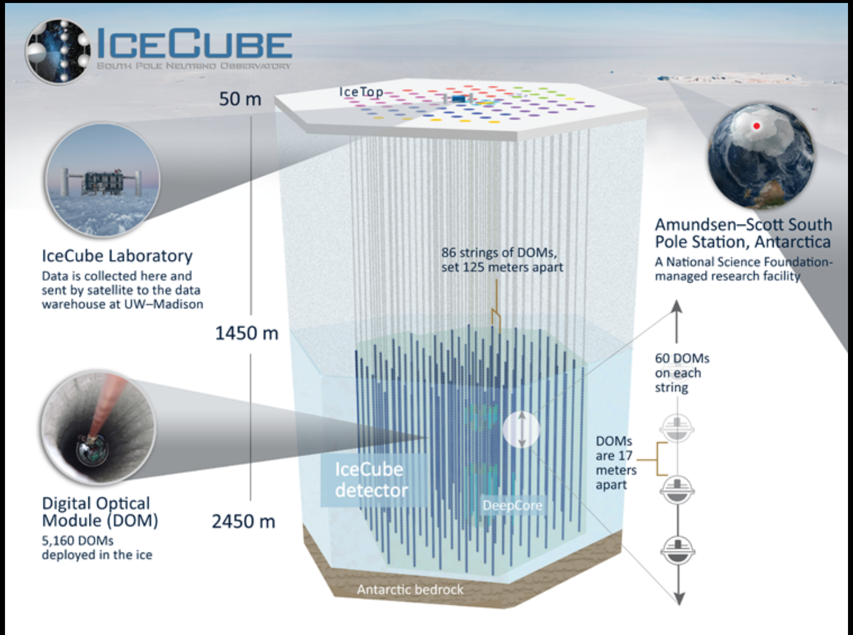


Wang & Loeb 17

Steeper spectrum





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Gamma-rays

$$p + p \rightarrow \pi^0 \rightarrow 2\gamma$$

Neutrinos

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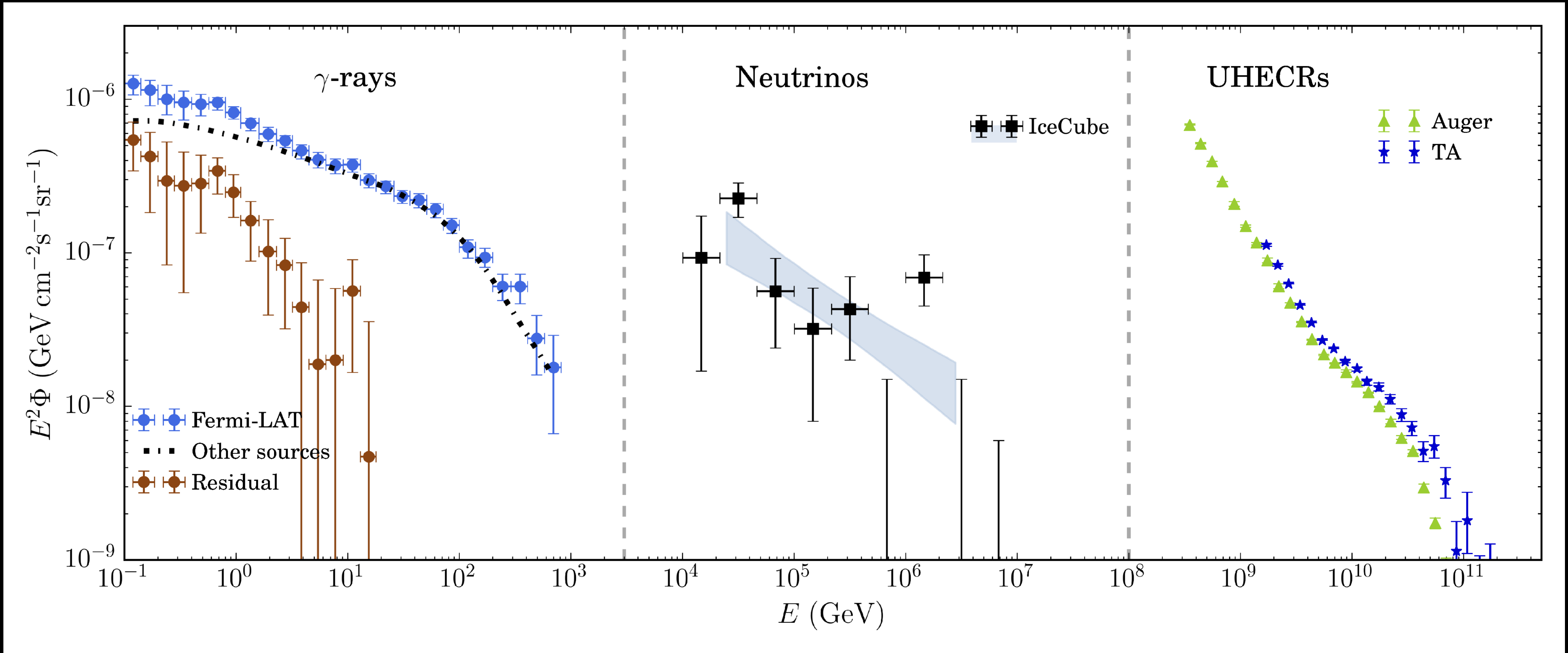
Ultra High Energy Cosmic Rays

Protons
Heavier elements

Multi-messenger connection



Wang & Loeb 17

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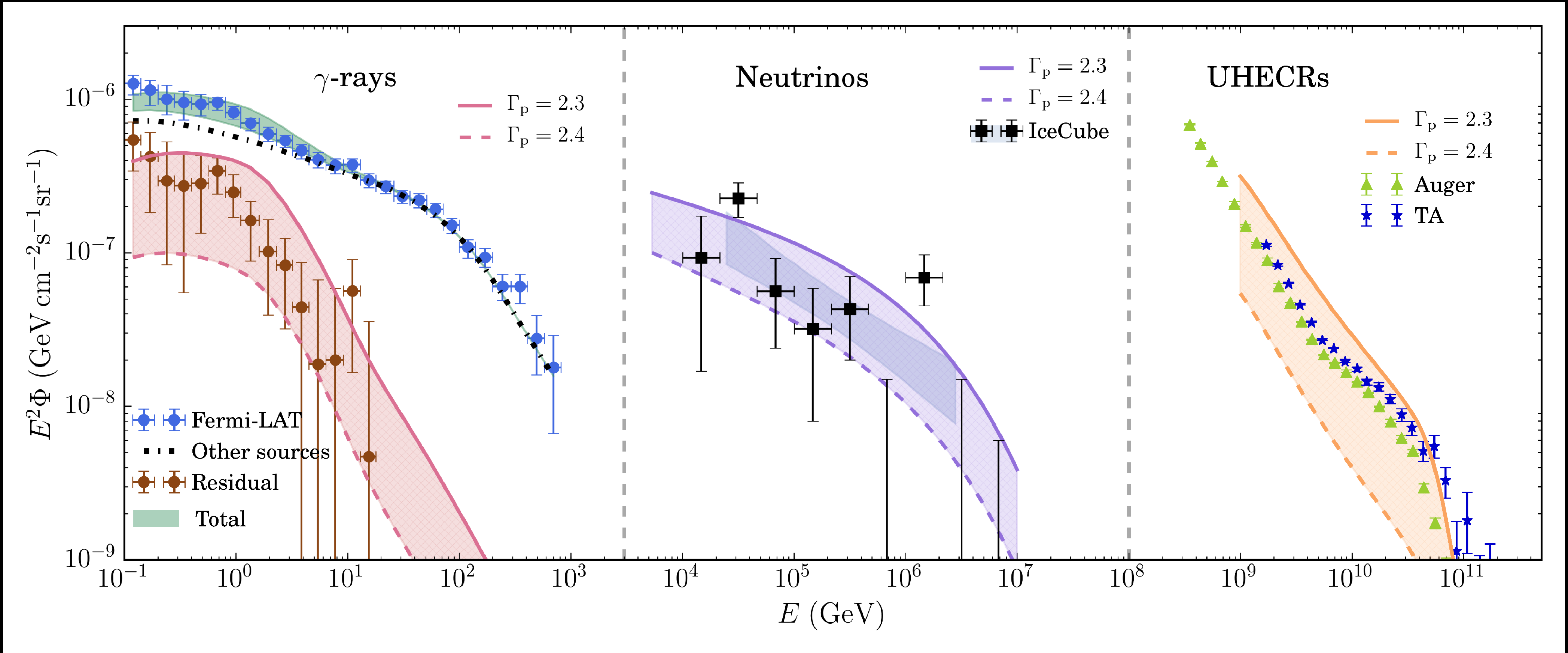


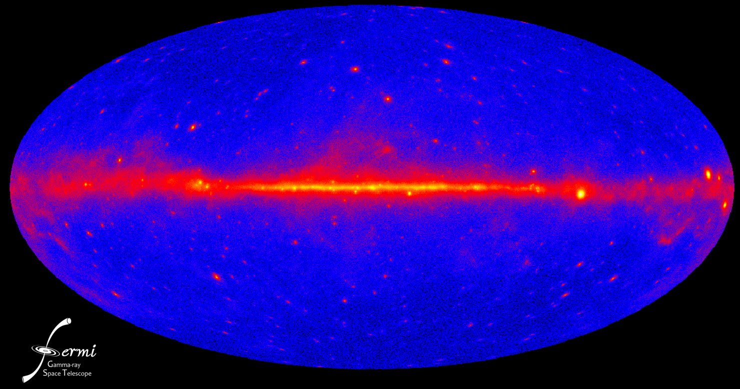
Wang & Loeb 17

Summary

Quasar outflows

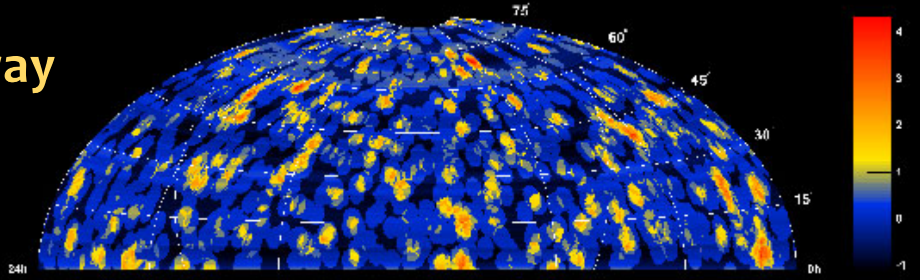
Multi-messengers

Wang & Loeb, MNRAS, 2015, 453, 837
Wang & Loeb, Nat. Phys., 2016, 12, 1116
Wang & Loeb, JCAP, 2016, 12, 012
Wang & Loeb, PRD, 2017, 95, 063007



Extragalactic gamma-ray background

Cumulative neutrino background



Ultra High Energy Cosmic Ray

Thank you!