PRIMORDIAL BLACK HOLES

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ON BEHALF OF

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BLACK HOLES IN 4D SPACE-TIME

Schwarzschild Metric in General Relativity

$$c^2 d\tau^2 = \left(1 - \frac{r_s}{r}\right) c^2 dt^2 - \frac{dr^2}{1 - \frac{r_s}{r}} - r^2 \left(d\theta^2 + \sin^2\theta \, d\varphi^2\right)$$

$$r_s = \frac{2GM}{c^2}$$

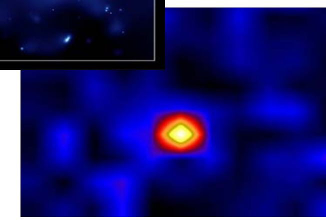
Extensions: Kerr Metric for rotating black hole
Reissner-Nordström Metric for charged black hole
Kerr-Newman Metric for charged rotating black hole

Schwarzschild Radius $r_s = \dfrac{2GM_{BH}}{c^2}$, Black Hole Mass M_{BH}

Density inside Black Hole $\rho \propto \dfrac{M_{BH}}{r_s^{\ 3}} \propto \dfrac{1}{M_{BH}^{\ 2}}$

BLACK HOLES IN THE UNIVERSE

- Supermassive Black Holes
- Intermediate Mass Black Holes?
- Stellar Mass Black Holes



PRIMORDIAL BLACK HOLES (PBHs)

= Black Holes Formed in the Early Universe

$$M_{BH} \sim 10^{-5} - 10^{43}\ \mathrm{g}$$

$$r_s \sim 10^{-33}\ \mathrm{cm} - 10^{3}\ \mathrm{AU}$$

PBH FORMATION MECHANISMS

Collapse of Overdense Regions

- Primordial Density Inhomogeneities
- many Inflation models (eg blue, peaked or 'running index' spectrum)
- Epoch of Low Pressure (soft equation of state)
- Cosmological Phase Transitions

Colliding Bubbles of Broken Symmetry

Oscillating Cosmic Strings

Collapse of Domain Walls

PBH FORMATION

PBH mass ~ cosmic horizon (or Hubble) mass at time of formation (or smaller)

$$M_H(t) \approx 10^{15}\left(\frac{t}{10^{-23}\ \mathrm{s}}\right)\ \mathrm{g}$$

Most formation scenarios give narrow PBH spectrum

Scale-Invariant Density Perturbations would give extensive PBH spectrum

$$\frac{dn}{dM_i} = (\alpha-2)\left(M_i / M_*\right)^{-\alpha} M_*^{-2}\Omega_{PBH}\rho_{crit}\ ,\ \text{radiation era}\quad \alpha = \frac{1}{2}$$

PBH CONSEQUENCES

Dark Matter

- $M_{BH} > 10^{15}$ g PBHs are CDM candidates
- should cluster in galactic haloes
- may enhance clustering of other Dark Matter eg WIMPs (Ultra Compact Massive Halos)
- do expired PBHs leave a Planck mass relic?

Large PBHs

- may influence large scale structure development, seed SMBHs, cosmic x-rays from accretion disks

Radiation

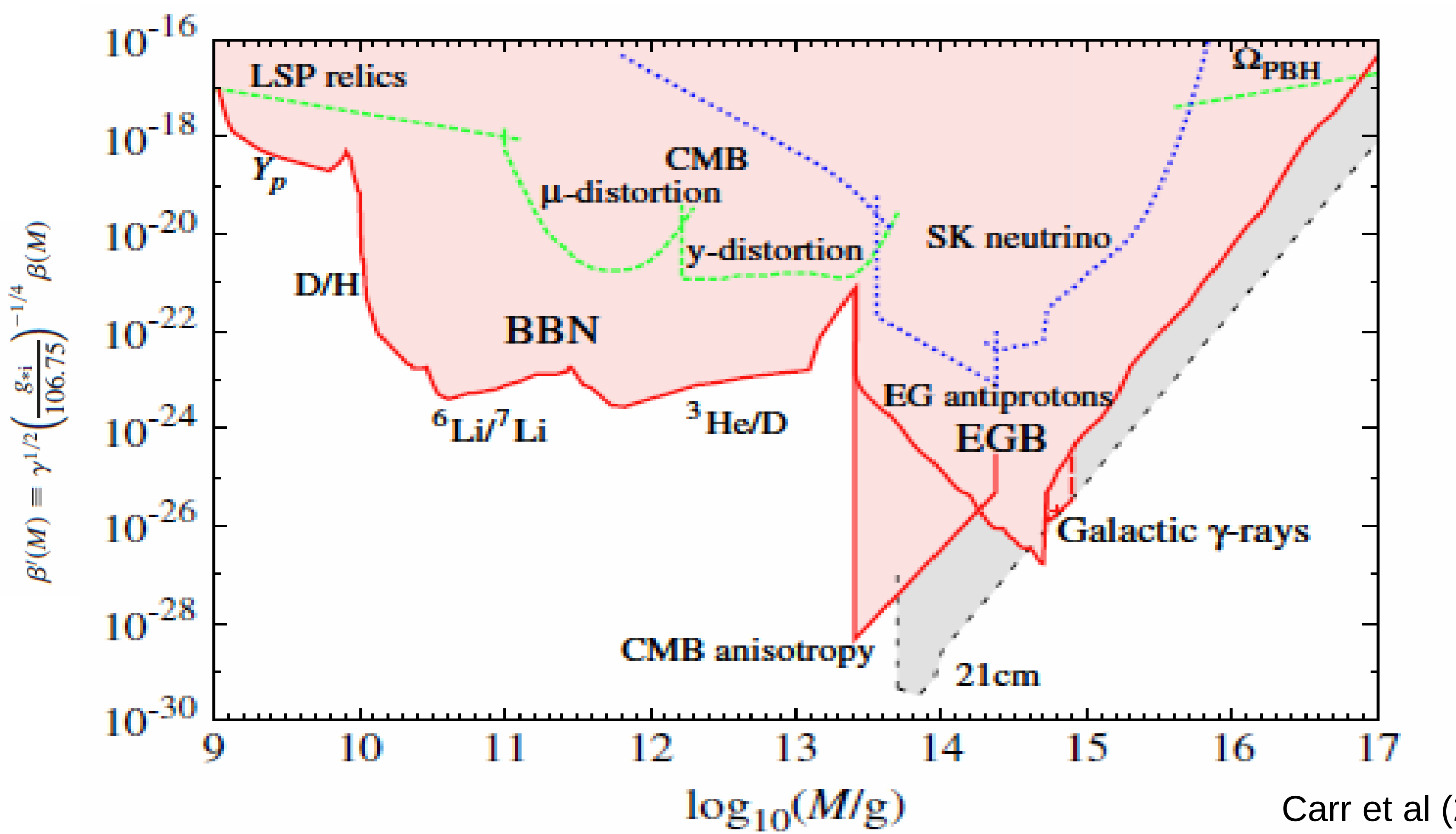
- direct limits from extragalactic γ background and galactic γ, e+, e−, p-bar backgrounds
- burst searches
- limits on $10^{9} - 10^{43}$ g PBHs from PNS, CMB anisotropies
- may contribute to entropy, baryogenesis, reionization of Universe in earlier epochs; annihilation lines

PBH LIMITS

Constraints on β = fraction of regions of mass M which collapse

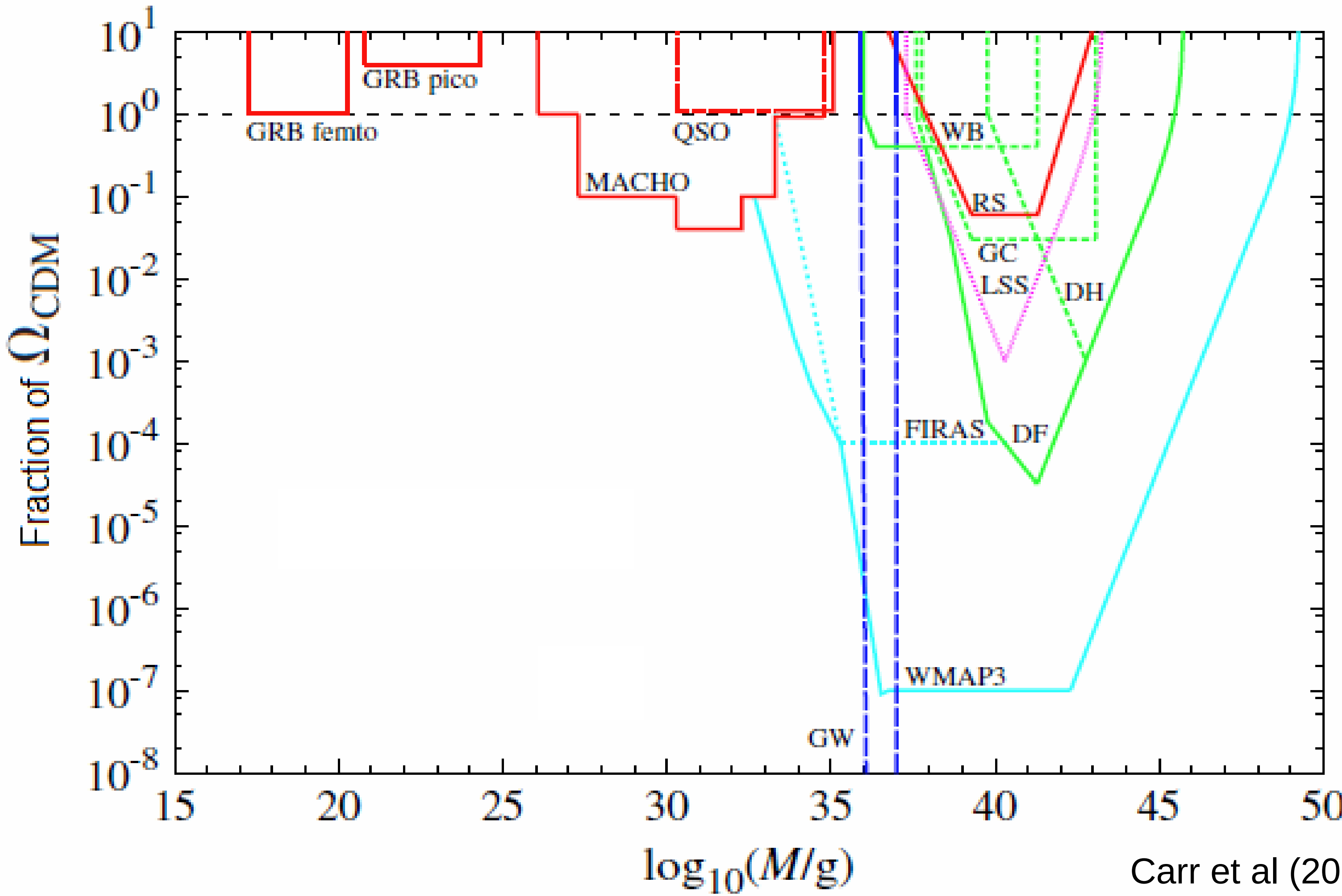
$$\Omega_{PBH} = \beta\Omega_R(1+z) \qquad \beta(M) \sim \varepsilon(M)\exp\left[-\frac{\gamma^2}{2\varepsilon^2(M)}\right]$$

where ϵ = fractional overdensity of formation regions



Carr et al (2010)

PBH LIMITS (M_{BH}>10^{15}g)



Carr et al (2010)

BLACK HOLE THERMODYNAMICS

HAWKING TEMPERATURE:

$$kT_{BH} = \frac{\hbar c^3}{8\pi G M_{BH}} = 1.06\left(\frac{M_{BH}}{10^{13} g}\right) \text{ GeV}$$

Solar Mass BH $T_{BH} \sim 10^{-7} K$ $M_{BH} \sim 10^{25} g$ $T_{BH} \sim 3 K$ CMB

HAWKING RADIATION FLUX:

$$\frac{d^2 N_S}{dt\ dE} = \sum_{n,l} \frac{\Gamma_{snl}}{2\pi\hbar}\left[\exp\left[\frac{E - n\hbar\Omega - e\Phi}{\hbar\kappa / 2\pi c}\right] - (-1)^{2s}\right]^{-1}$$

per particle degree of freedom

Absorption Probability

Geometric Optics Limit $\Gamma_s\left(M_{BH}, E\right) \equiv \sum_{n,l} \Gamma_{snl} \approx \frac{27 G^2 M_{BH}{}^2 E^2}{\hbar^2 c^6}$

STEPHEN HAWKING

Gravitational Temperature

$$T_{BH} \propto \frac{1}{M_{BH}}$$

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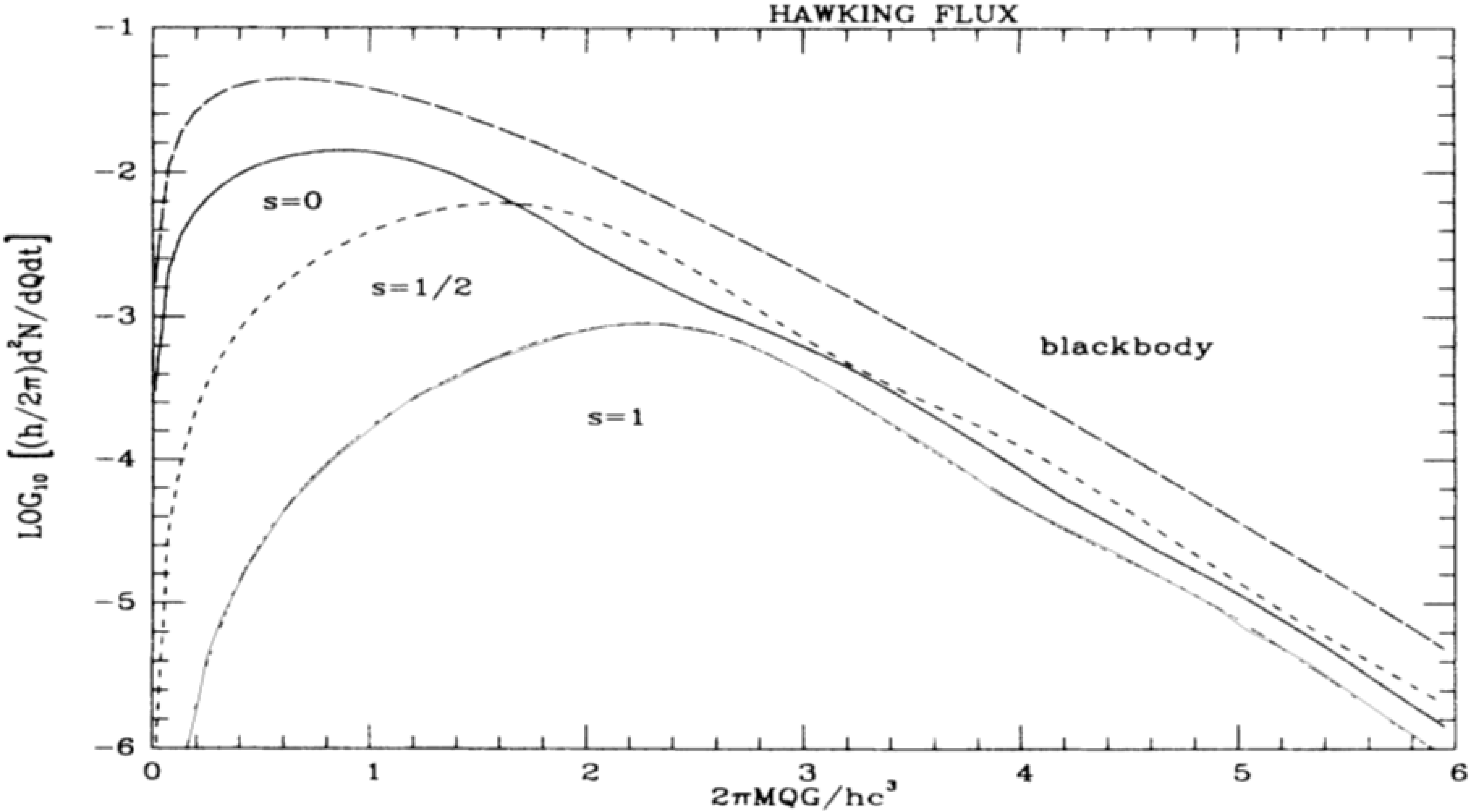
DIRECT HAWKING RADIATION



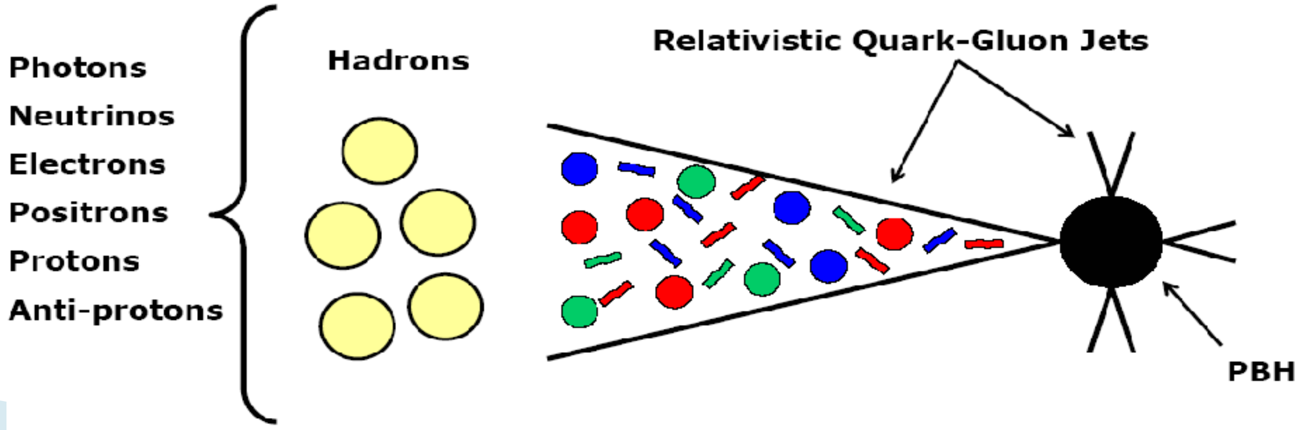
Sources: Page, Elster, Simkins

STANDARD EMISSION PICTURE (MacGibbon–Webber)

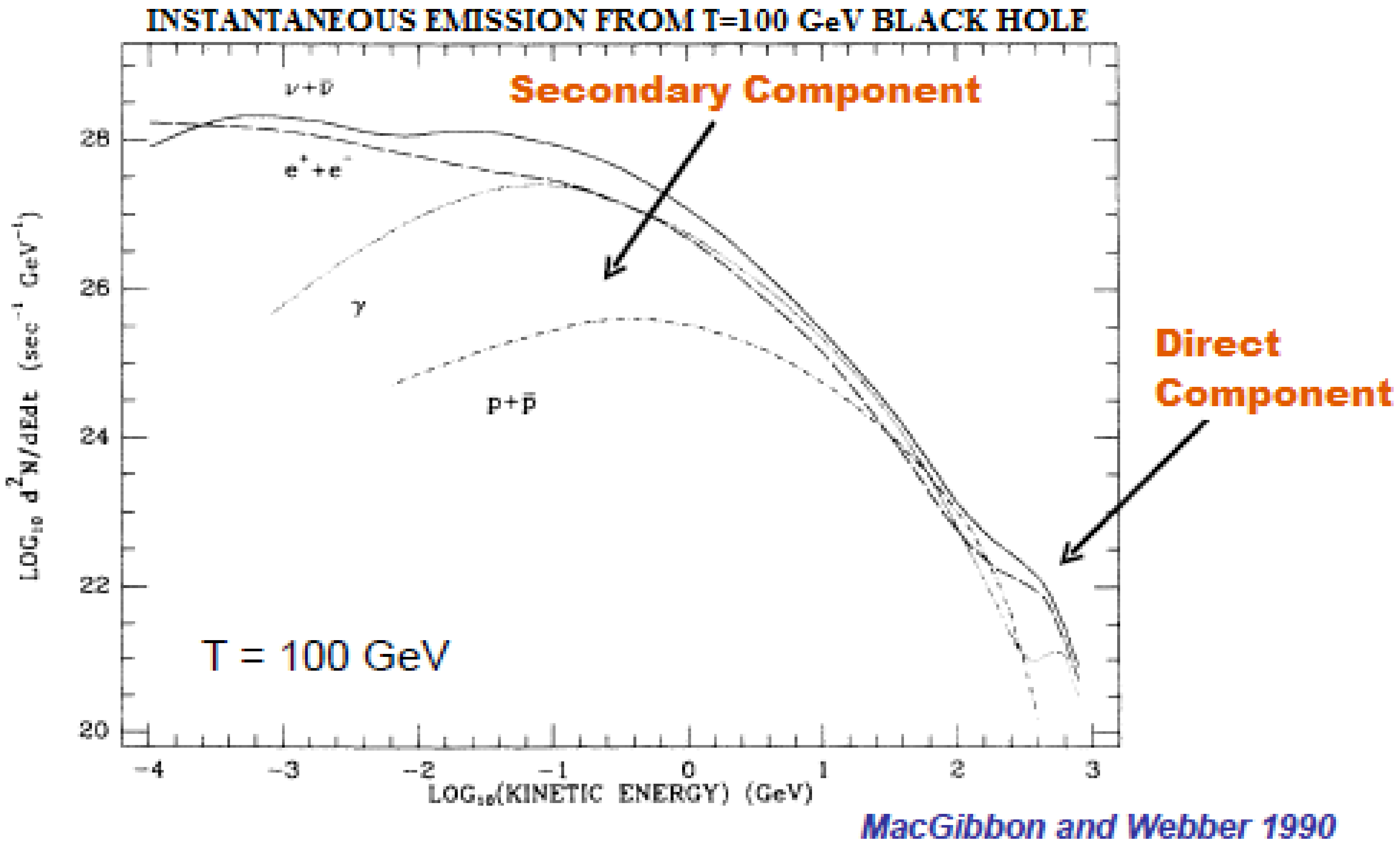
BH should directly evaporate those particles which appear non-composite compared to wavelength of the radiated energy (or equivalently BH size) at given T_{BH}

As T_{BH} increases:
BH directly emits photons + gravitons → + neutrinoes → + electrons → + muons → + pions

Once $T_{BH} >> \Lambda_{QCD}$: BH directly emits quarks and gluons (not direct pions) which shower and hadronize into the astrophysically stable species: γ, ν, p, pbar, e^-, e^+



INSTANTANEOUS HAWKING FLUX



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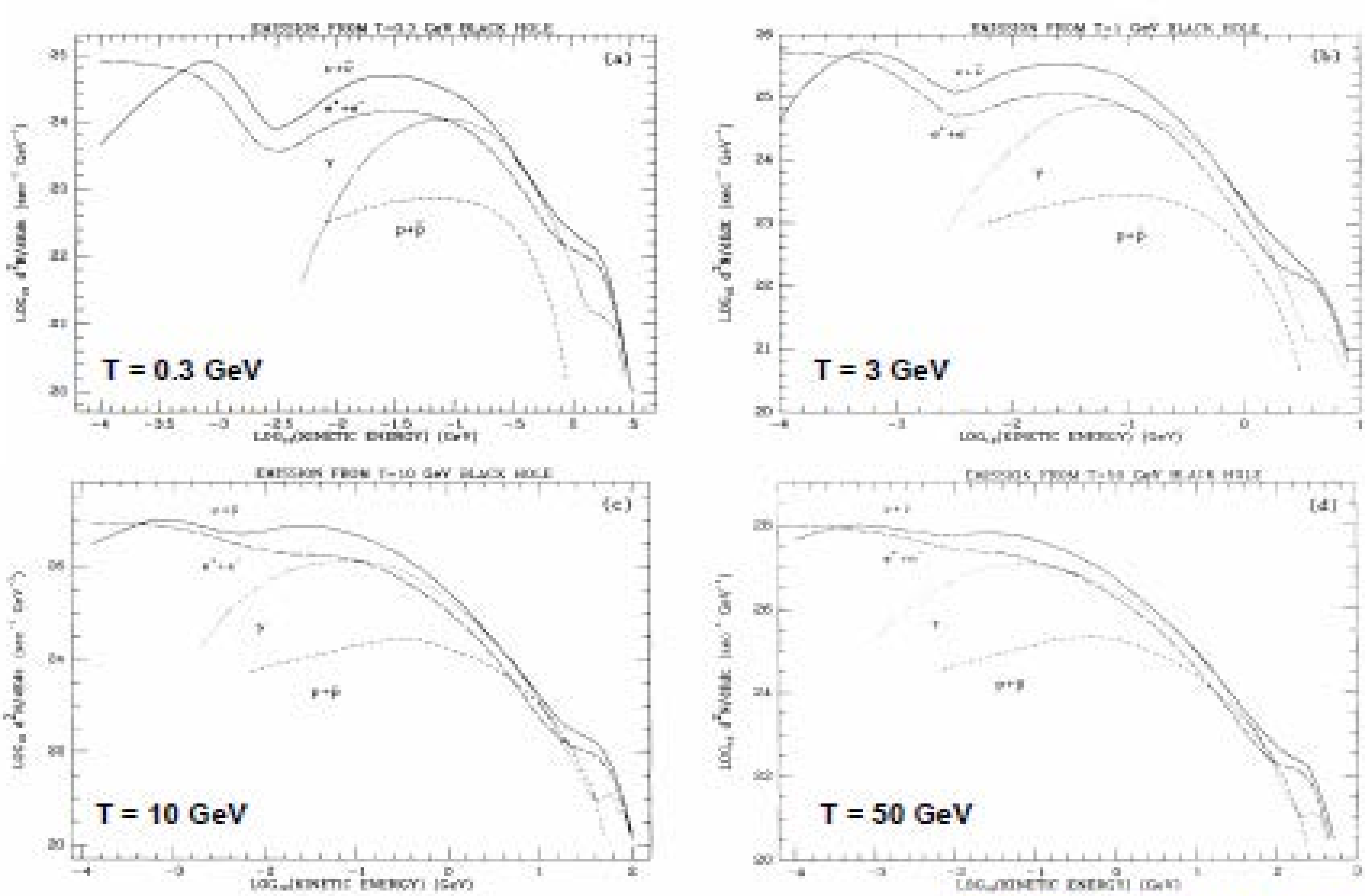


MacGibbon and Webber 1990

HAWKING RADIATION
T_{BH} = 0.3 – 100 GeV

Total Instantaneous flux

$$\dot{N}_{p\bar{p}} \approx 2.1(\pm 0.4)\times 10^{23}\left[\frac{T}{\text{GeV}}\right]^{1.6\pm 0.1} \text{sec}^{-1}$$

$$\dot{N}_{e^{\pm}} \approx 2.0(\pm 0.6)\times 10^{24}\left[\frac{T}{\text{GeV}}\right]^{1.6\pm 0.1} \text{sec}^{-1}$$

$$\dot{N}_{\gamma} \approx 2.2(\pm 0.7)\times 10^{24}\left[\frac{T}{\text{GeV}}\right]^{1.6\pm 0.1} \text{sec}^{-1}$$

$$\dot{N}_{\nu\bar{\nu}} \approx 5.6(\pm 1.7)\times 10^{24}\left[\frac{T}{\text{GeV}}\right]^{1.6\pm 0.1} \text{sec}^{-1}$$

Average Energy

$$\bar{E}_{p\bar{p}} \approx 5.2(\pm 0.5)\times 10^{-1}\left[\frac{T}{\text{GeV}}\right]^{0.8\pm 0.1} \text{GeV}$$

$$\bar{E}_{e^{\pm}} \approx 2.9(\pm 0.5)\times 10^{-1}\left[\frac{T}{\text{GeV}}\right]^{0.5\pm 0.1} \text{GeV}$$

$$\bar{E}_{\gamma} \approx 3.4(\pm 0.5)\times 10^{-1}\left[\frac{T}{\text{GeV}}\right]^{0.5\pm 0.1} \text{GeV}$$

$$\bar{E}_{\nu\bar{\nu}} \approx 2.4(\pm 0.5)\times 10^{-1}\left[\frac{T}{\text{GeV}}\right]^{0.5\pm 0.1} \text{GeV}$$

PBH EVOLUTION

MASS LOSS RATE: $$\frac{dM_{BH}}{dt} \approx -5 \text{ x } 10^{25} \left(M_{BH}/\text{g}\right)^{-2} f\left(M_{BH}\right) \text{ g s}^{-1}$$

BLACK HOLE LIFETIME: $$\tau_{evap} \approx 6.24\text{x}10^{-27} M_i^3 f\left(M_i\right)^{-1} \text{ s}$$

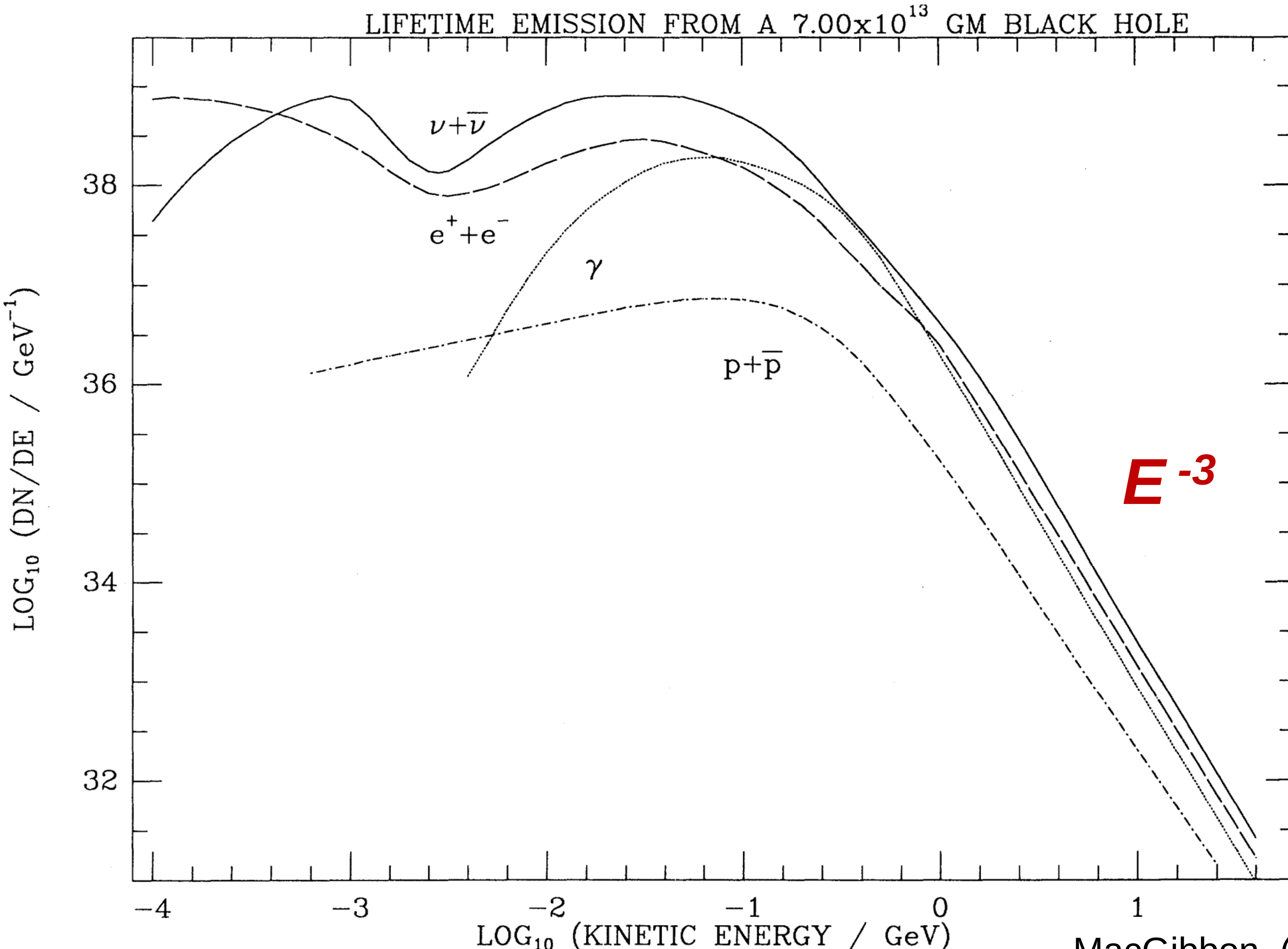
where f(M) counts total directly emitted species

$f_{s=0} = 0.267$ $\quad f_{s=1/2} = 0.147$, uncharged $\quad f_{s=3/2} = 0.020$

$f_{s=1} = 0.060$ $\quad f_{s=1/2} = 0.142$, electric charge = $\pm e$ $\quad f_{s=2} = 0.007$

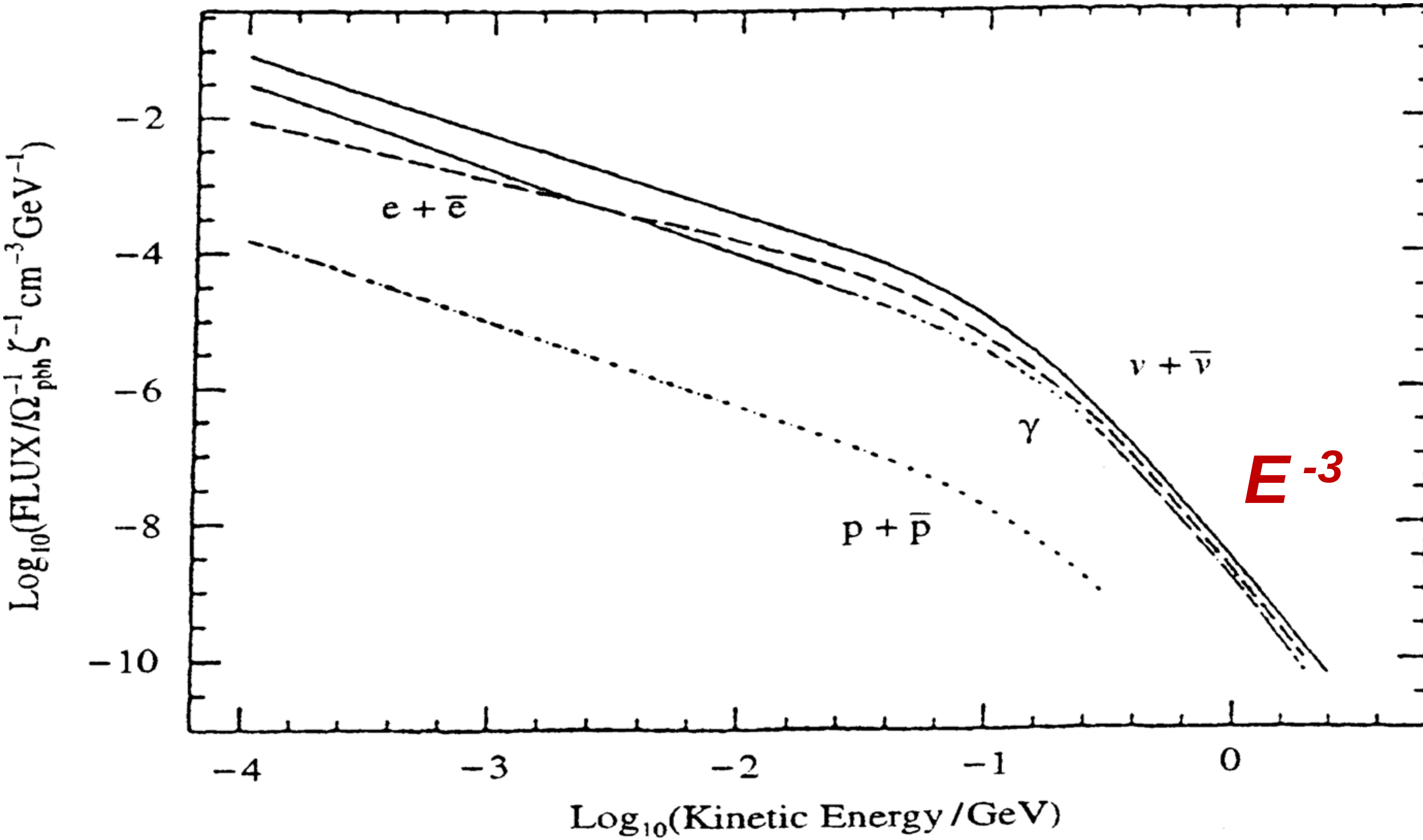
Mass of PBH whose lifetime equals age of Universe (MacGibbon, Carr & Page 2008):

$$M_* \approx 5.00(\pm 0.04)\times 10^{14} \text{ gm}$$



MacGibbon (1991)

Astrophysical Spectra from Uniformly Cosmologically Distributed PBHs with $dn/dM_i \propto M_i^{-2.5}$



MacGibbon and Carr (1991)

ASTROPHYSICAL SPECTRA FROM A COSMOLOGICAL DISTRIBUTION OF PBHs

DIFFUSE EXTRAGALACTIC GAMMA RAY BACKGROUND AT 100 MeV places strictest limits on $M_* \sim 5 \times 10^{14} g$ BHs

Carr et al (2010) Fermi LAT: $\Omega_{PBH}(M_*) \leq 5 \times 10^{-10}$

IF PBHS CLUSTER IN GALACTIC HALO:

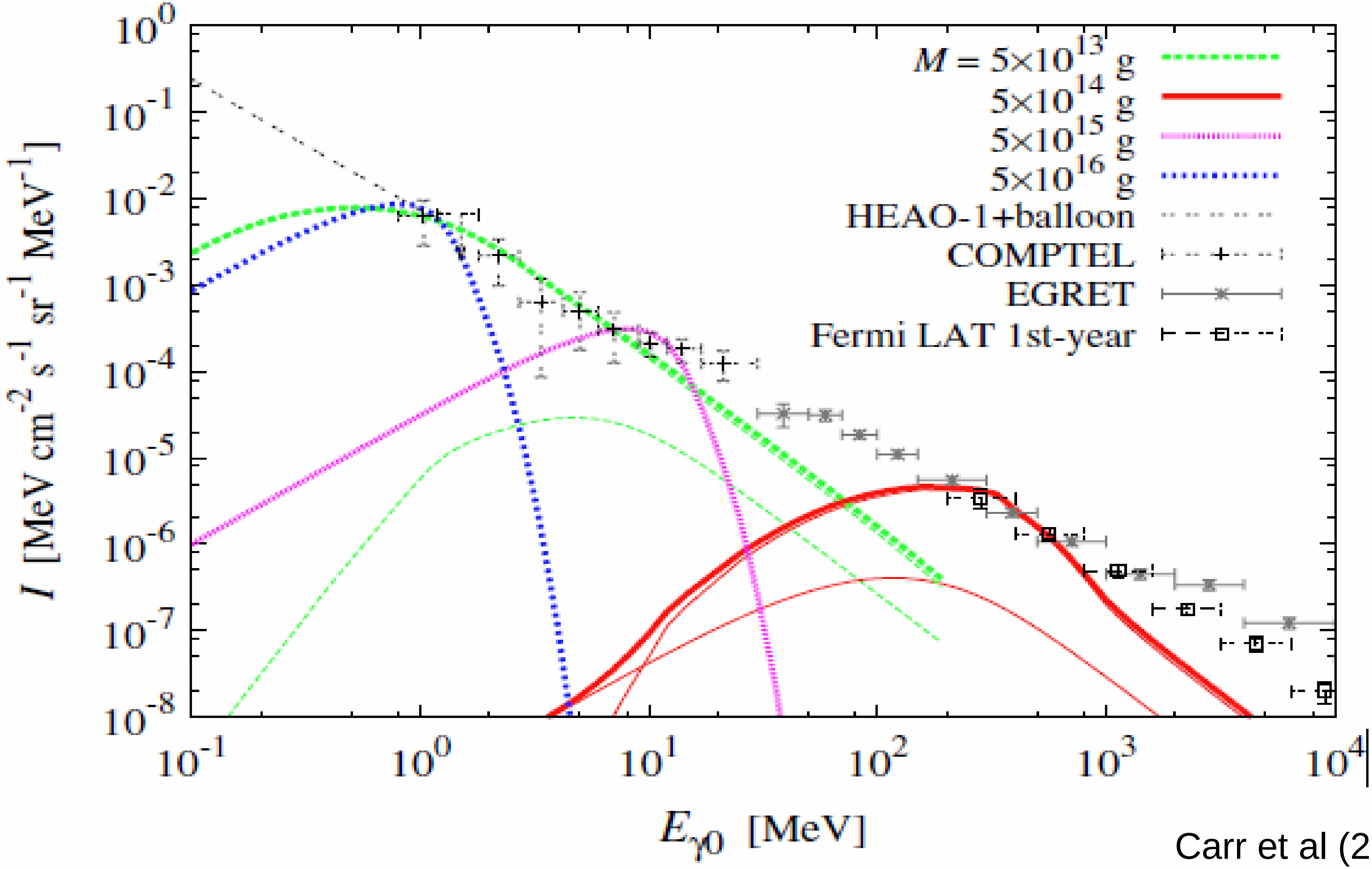
Local density enhancement $\eta_{\mathrm{local}} \approx 5\mathrm{x}10^{5} h^{-2} \left(\frac{\Omega_h}{0.1} \right)^{-1}$

Galactic Halo Gamma Ray Background (Wright 1996)

Antiprotons, Positrons

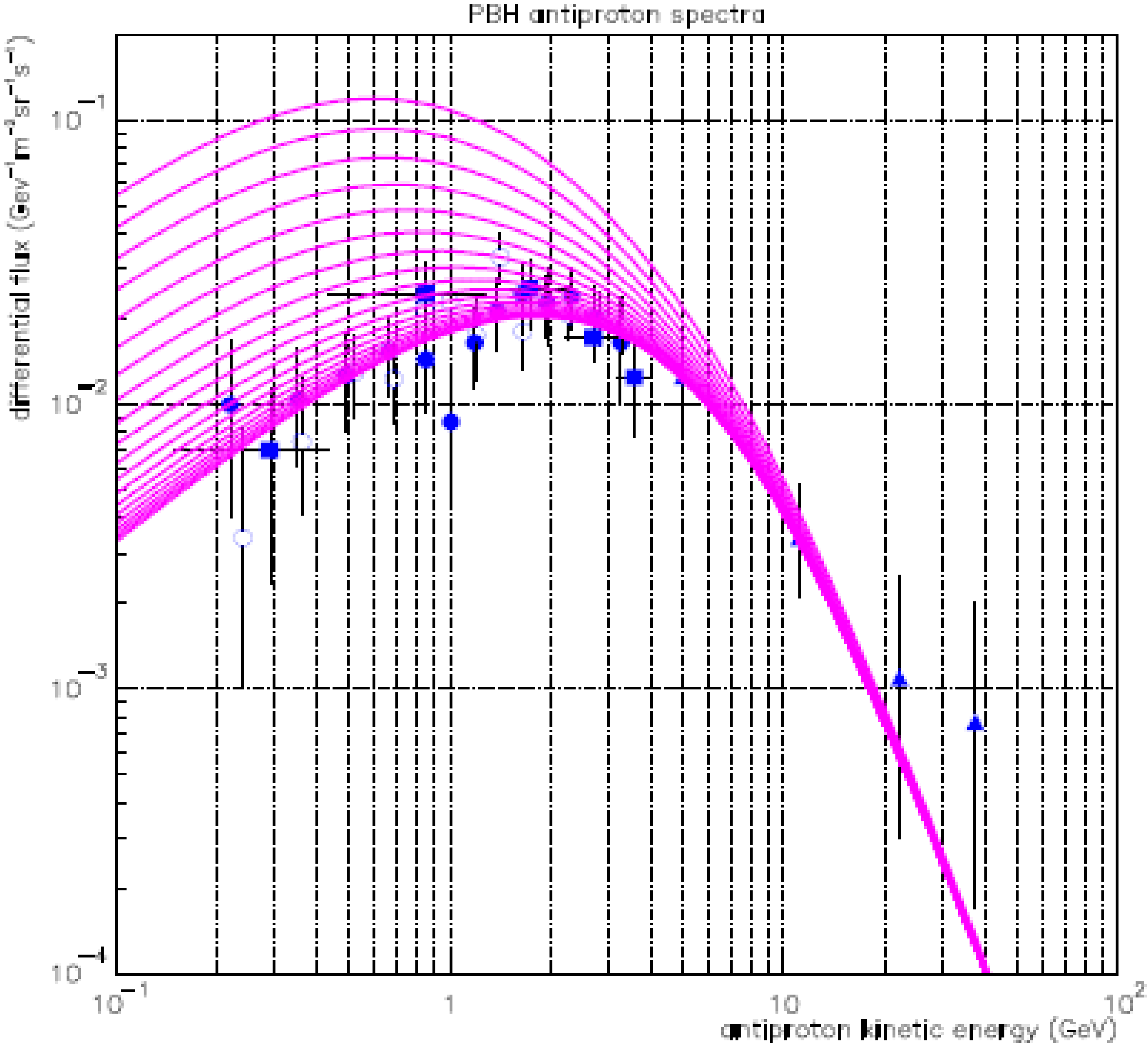
Antimatter interactions, Microlensing

DIFFUSE EXTRAGALACTIC GAMMA-RAY BACKGROUND



Carr et al (2010)

GALACTIC ANTIPROTONS



Barrau et al (2002)

$$\rho_{\odot}^{PBH} < 5.3 \cdot 10^{-33}\ \mathrm{g\,cm^{-3}}$$

BH Bursts

BHs Expiring Today: $\frac{dn}{dM_{BH}} \propto M_{BH}{}^{2}$ for any population of BHs with mass $\sim M_{BH} \ll M_*$ independent of formation time, formation mechanism or spatial distribution

Remaining lifetime for given T_{BH}:

$$\tau \approx 4.8 \times 10^{11} \left(\frac{15.4}{f(\tau)}\right) \left(\frac{T_{BH}}{\text{GeV}}\right)^{-3} \text{s}$$

FERMI & BH BURST SIGNALS

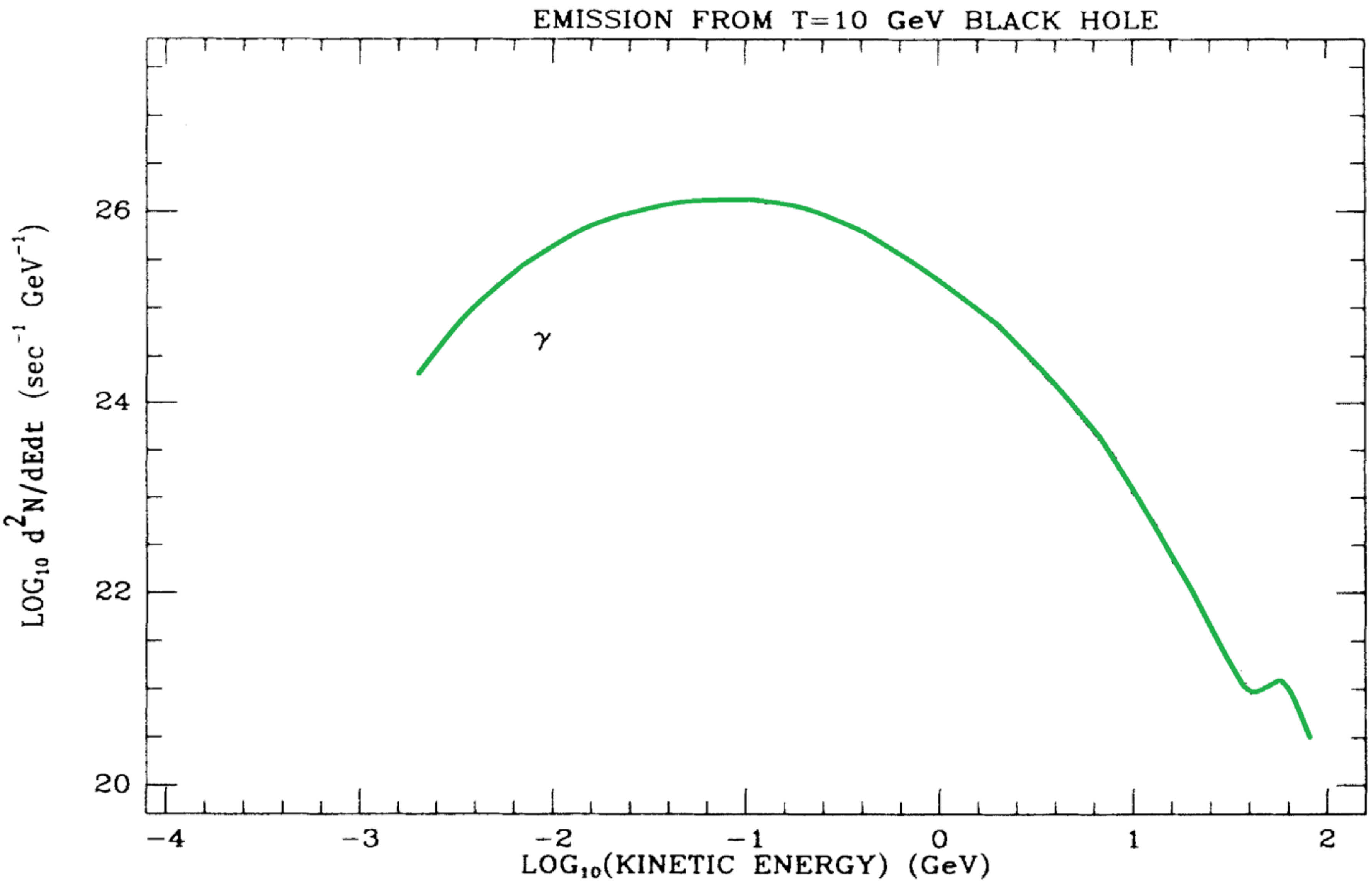
3 Cases

1. Spectrum constant over Fermi lifetime if $3MeV<T_{BH}<12$ GeV
   (lifetime of 10 GeV BH is ~ 20 years)

2. Spectrum evolves significantly over Fermi lifetime if 12 GeV $<T_{BH}<50$ GeV and almost all gamma-ray emission is in LAT energy range (20 MeV – 300 GeV)
   (lifetime of 50 GeV BH is ~ 50 days)

3. Spectrum is burst extending well above LAT upper energy if $T_{BH}>50$ GeV
   (lifetime of 170 TeV BH is ~ 100 μsec)

CONSTANT BH SIGNAL: T_{BH} < 12 GeV



MacGibbon and Webber (1990)

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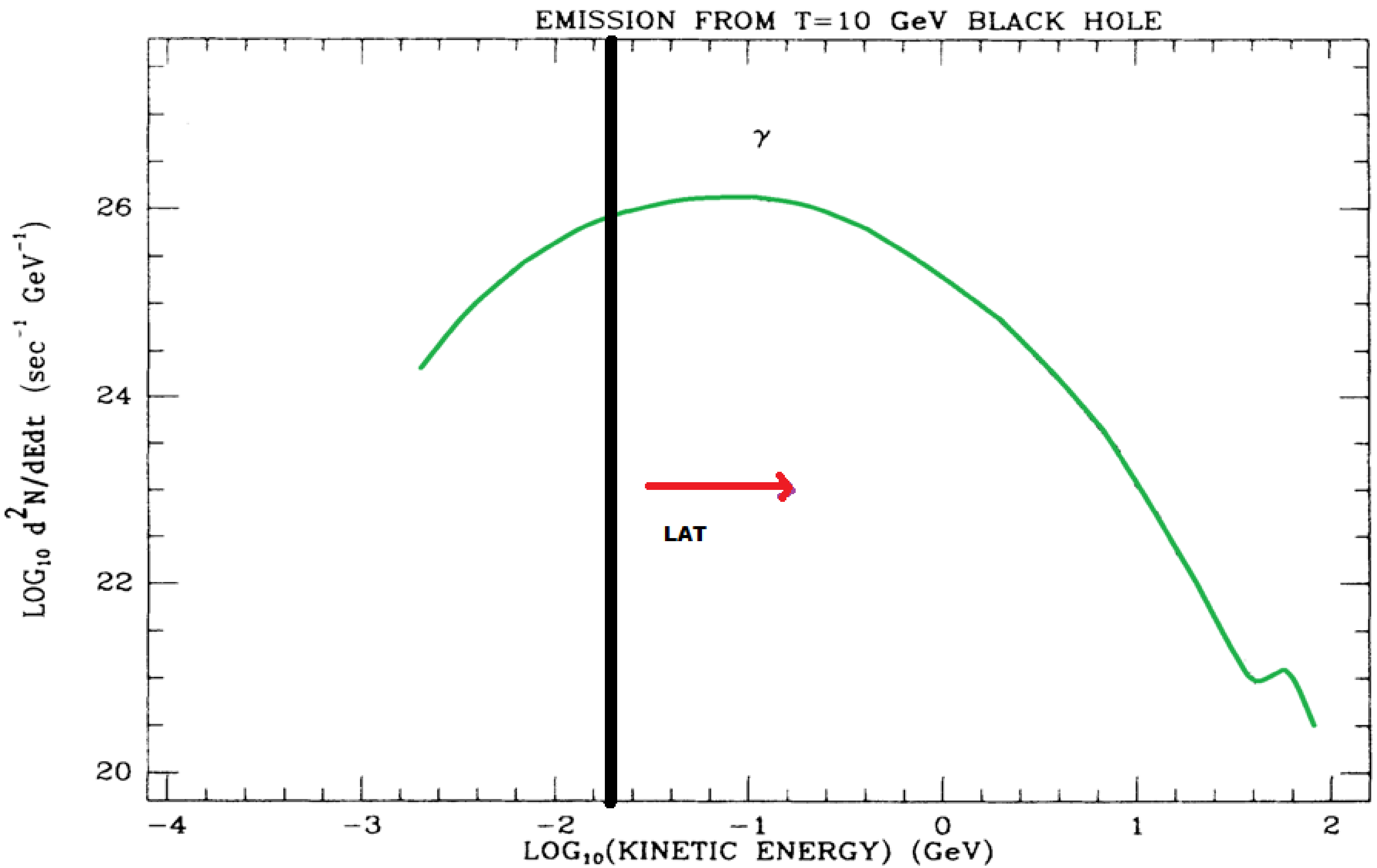

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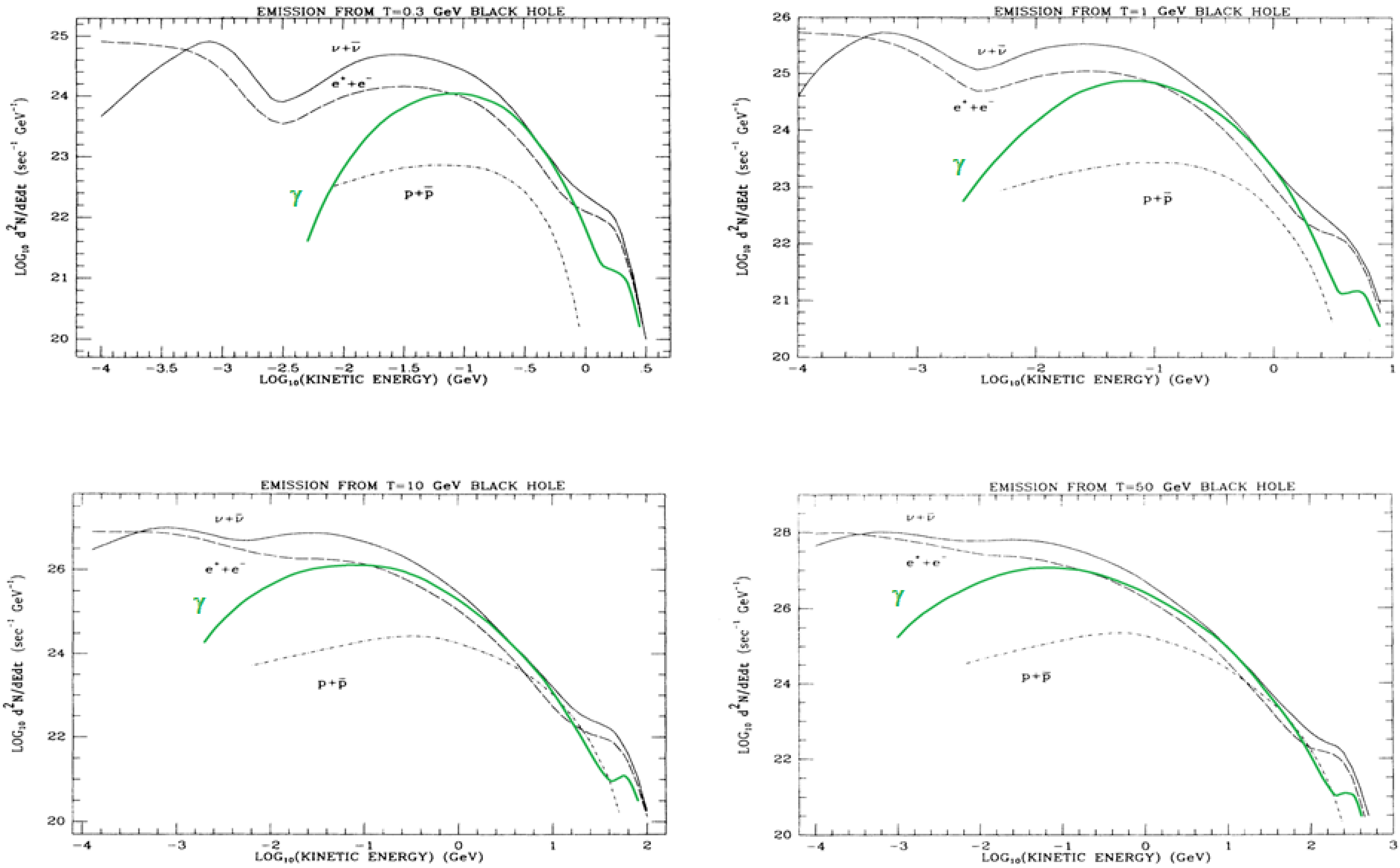
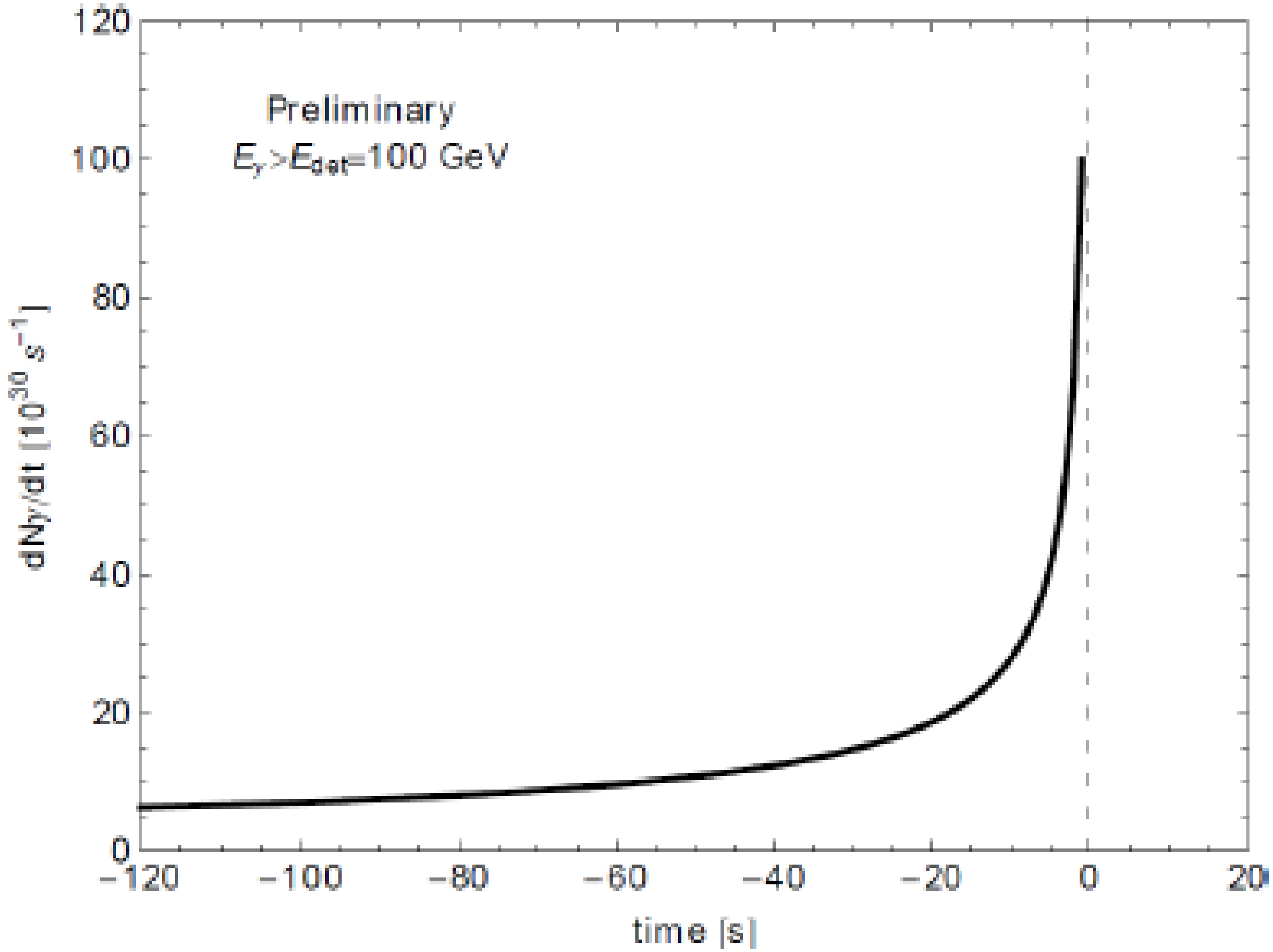
INSTANTANEOUS BH HAWKING FLUX



MacGibbon and Webber (1990)

Preliminary PBH Burst Light Curve

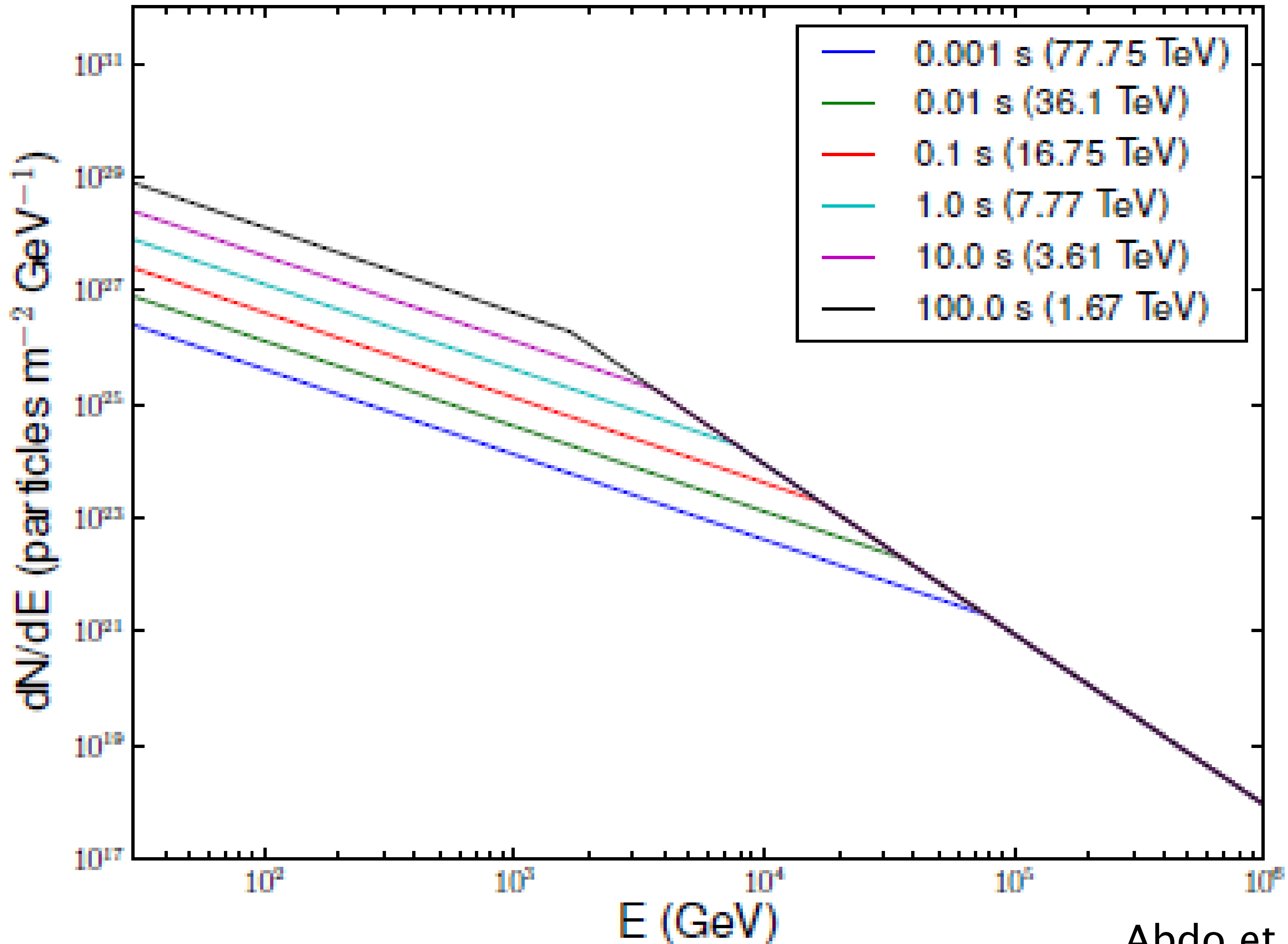


Ukwatta et al

FERMI & BH BURST LIMITS

In all 3 cases consider dN/dE
(flux integrated over observing time)

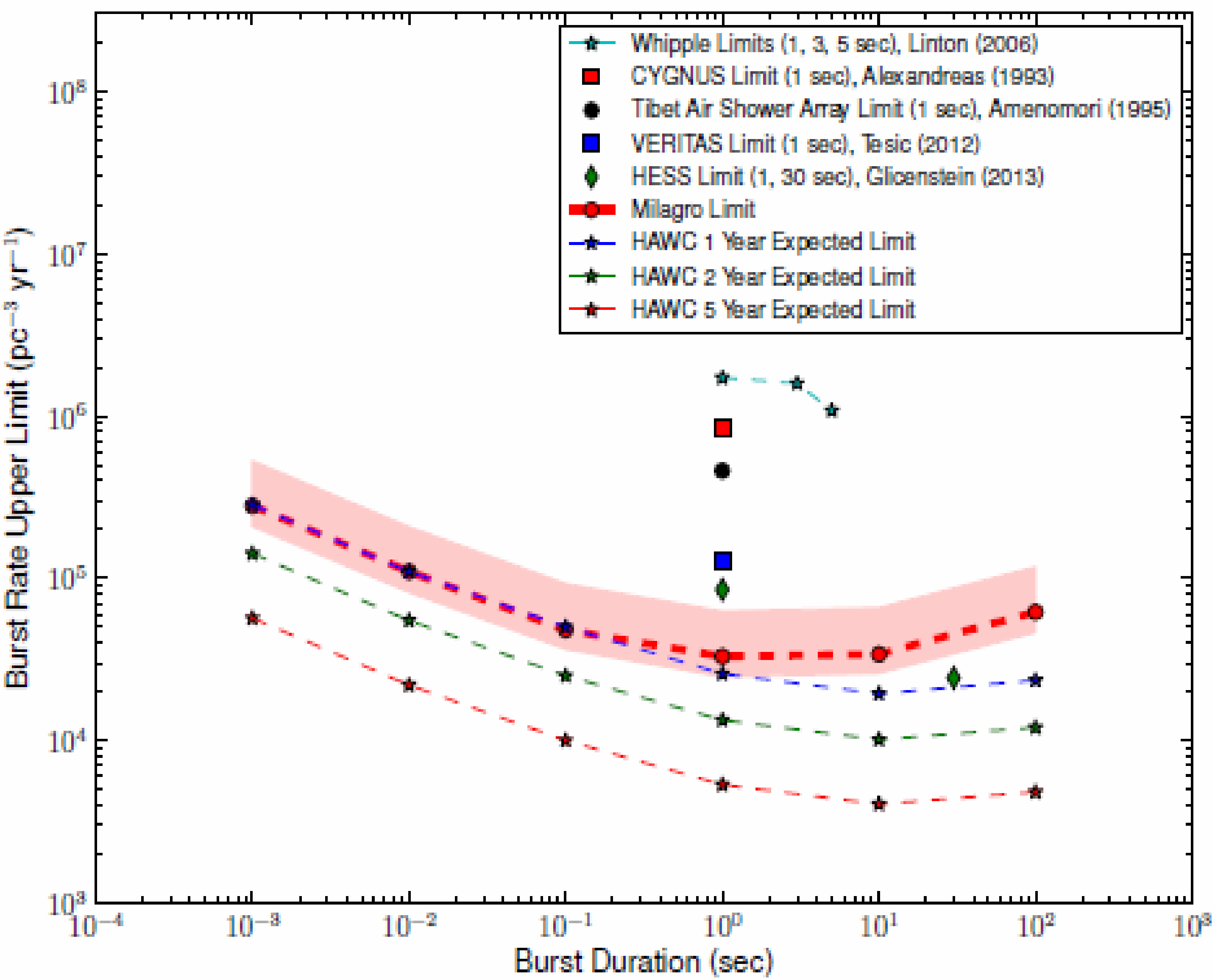
Time-integrated gamma-ray spectrum dN/dE over various PBH remaining lifetimes



Abdo et al 2014

BH Burst Limits if Null Detection

Milagro and HAWC requiring 5σ above background for detection



Abdo et al 2014

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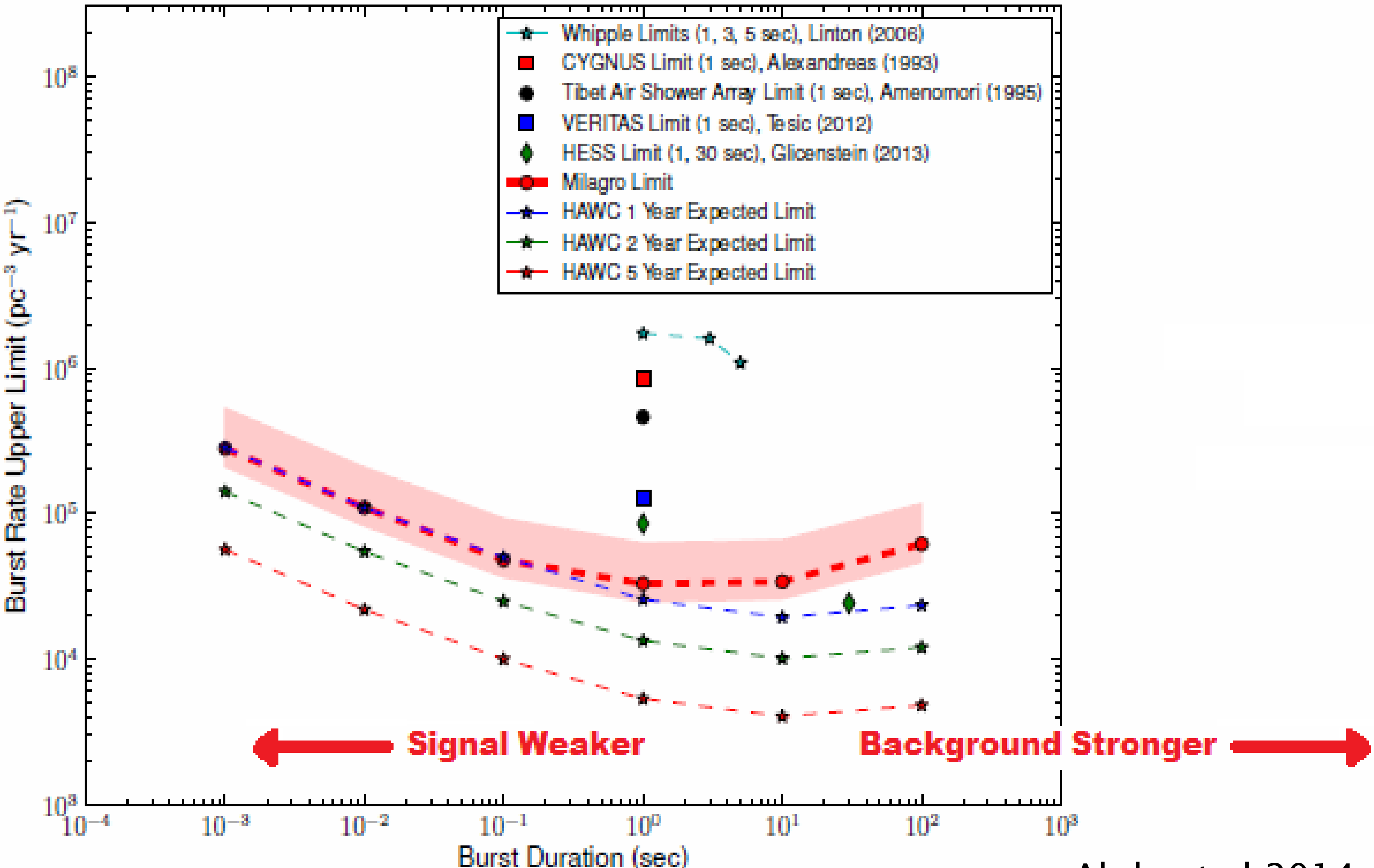


Abdo et al 2014

FERMI & BH BURST LIMITS

Preliminary

Bains (2011) claims 3-year LAT data gave upper limit on BH bursts of 3.4×10^{-8} pc^{-3} yr^{-1}

Malyshev et al (2014) claim LAT data give upper limit on BH bursts of 2×10^{3} pc^{-3} yr^{-1} for 10^{5} s burst

PBH Limit

Extragalactic gamma-ray limit on $\Omega_{PBH}(M_{\star})$ corresponds to limit on PBH bursts of ~ 10 pc^{-3} yr^{-1} if clustered in Galaxy

Difference between GRBs and PBH bursts

Gamma-ray Bursts (GRB)	PBH Bursts (pBHB)
Detected at cosmological distances	Unlikely to be detected outside our Galaxy
Most GRBs show hard-to-soft evolution	Soft-to-hard evolution is expected from pBHB
Hadrons are not expected from GRBs	Hadronic bursts may reach earth
Gravitational Wave signal is expected	No gravitational wave signal is expected
Time duration can range from fraction of second to few hours	Time duration of the burst is most likely less than few seconds
Fast Rise Exponential Decay (FRED) light curve	Exponential Rise Fast Fall (ERFF) light curve
X-ray, optical, radio afterglows are expected	No multi-wavelength afterglow is expected
Multi-peak time profile	Single-peak time profile

TELESCOPES

Telescope	Energy Range	Effective Area	Angular Resolution	Field of View	Time Resolution	Years of Operation		Comments
Fermi LAT	20 MeV – 300 GeV	0.88 m^2 at 1 GeV	0.3 – 2′	2.4 sr	1 micro sec	June 2008 - Present		no background
Milagro	50 GeV-100 TeV	~ 10^3 m^2 at 1 TeV	~3 deg	~2.0 sr	10 micro sec ?	2000-2008		large cosmic-ray background
Veritas	100 GeV - >30 TeV	Peak 10^5 m^2	~0.1 deg			2005 – (70 – 100 hr per month)		
HAWC	50 GeV - 100 TeV	> 10^3 m^2 at 1 TeV	1 deg	~2.0 sr	1 micro sec	2014 -		large cosmic-ray background

HESS, CTA, WhippleSGARface, Calet (CAL) …and more

DOES PHOTOSPHERE OR CHROMOSPHERE FORM AROUND EVAPORATING PBH?

Photosphere/Chromosphere formation would change observational signatures by decreasing spectra at high E and increasing spectra at low E

Heckler Model

A.F.Heckler PRD 55, 480 (1997); A.F.Heckler PRL 78, 3430 (1997)

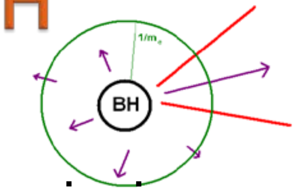
- Proposed QED/QCD bremsstrahlung and pair-production interactions between Hawking-radiated particles form intrinsic photosphere /chromosphere around BH

Other Intrinsic Photosphere/Chromosphere Models

- Belyanin et al
- Bugaev et al
- D. Cline and Hong / Hagedorn Model
- Kapusta and Daghigh

NO INTRINSIC QED PHOTOSPHERE OR QCD CHROMOSPHERE AROUND BH

(MacGibbon, Carr and Page 2008)



- ✕ the causality constraint (time between successive BH emissions $\Delta t_e \sim 200 / E_{peak}$ for *e* and $\Delta t_e \sim 20 / E_{peak}$) for *q, gl*) and LPM suppression in any (rare) multiple scatterings near BH prevent QED photosphere formation around 4D BHs when $T_{BH} >> m_e$; and QCD chromosphere formation when $T_{BH} >> \Lambda_{QCD}$

- ✕ damping of Hawking emission (lower flux, lower energy per particle, and greater Δt between emissions) near particle's rest mass threshold (eg Λ_{QCD}) + low multiplicity per jet, QCD quantum conservation laws and relativistic speed of initial quarks and gluons near Λ_{QCD} prevent chromosphere formation around 4D BHs when $T_{BH} \sim \Lambda_{QCD}$

→ $T_{BH} \sim \Lambda_{QCD}$ **4D BH cannot form quark-gluon plasma**

(No analogy to RHIC's ~ 200 GeV per nucleon, gluon-saturated, high baryon/antibaryon asymmetry)

NO OTHER INTRINSIC PHOTOSPHERE / CHROMOSPHERE MODEL

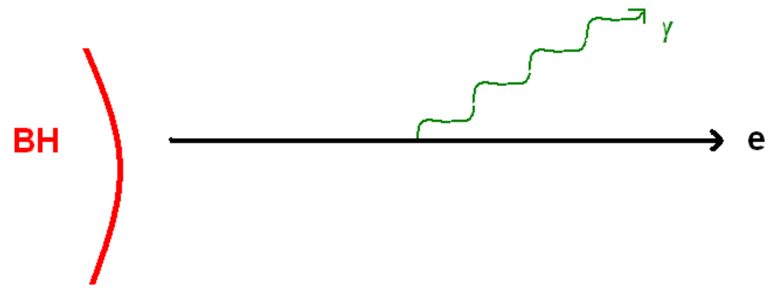
- **Kapusta and Daghigh** – assumes plasma thermalized by QED and QCD bremsstrahlung and pair-production of Heckler model
- **Belyanin et al** – ‘collisionless’ QED plasma – omits Lorentz factors → no self-induced MHD photosphere but strong ambient magnetic field may induce (weak) photosphere
- **Bugaev et al** – ‘Stretched Horizon’ T_{pl} region just outside horizon → neglects LPM suppression (and thermalization scales)
- **D. Cline and Hong** – Hagedorn-type emission of remaining BH mass into exponentially growing number of states at $\boldsymbol{T_{BH} \sim \Lambda_{QCD}}$ → state occupancy should be determined by available energy $\boldsymbol{E \sim \Lambda_{QCD}}$ → model would require direct coupling of BH mass to Hagedorn states (but $\boldsymbol{T_{BH}}$ increases as $1/M_{BH}^{\ 2}$)

BUT PBH EVAPORATING IN EXOTIC ENVIRONMENT (eg high ambient magnetic field) COULD POSSIBLY PRODUCE NON-INTRINSIC PHOTOSPHERE AND SIGNAL DISTORTION

INNER BREMSSTRAHLUNG

(Page, Carr and MacGibbon 2008)

Inner Bremsstrahlung
(1–vertex Bremsstrahlung)



Compare with power in direct photons:

$$\frac{dE_{d\gamma}}{dt} \approx 0.3364 \text{ x } 10^{-4} M_{BH}^{\ -2} \quad \text{At low } \omega \to 0, \quad \frac{d^2E_{d\gamma}}{dtd\omega} = \frac{8}{3\pi^2} M^3 \omega^4$$

For $M_{BH} = 5\text{x}10^{14}\, g$ BH, $\frac{d^2E_{b\gamma}}{dtd\omega} \approx 1.73 \text{ x } 10^{-19} \text{ s}^{-1}$

→ inner bremsstrahlung photons dominate the directly Hawking emitted photons below 57 MeV

Future PBH Theory Work

Update PBH emission spectrum from M_{BH}~$5x10^{14}$ g black holes for comparison with Fermi Extragalactic and Galactic Diffuse Backgrounds

Update detailed Monte Carlo modelling of individual PBH Emission for comparison with burst detectors; include inner bremsstrahlung

Modelling of signal from evaporating higher-dimensional BHs including investigation of photosphere issue (before the LHC re-starts)

MOTIVATION FOR PBH SEARCHES

Observation of PBHs or Evaporating BHs

- Proof of amalgamation of classical gravity and (classical as well as quantum) thermodynamics; insight into quantum gravity
- Direct window into particle physics at higher energies than can ever be achieved by accelerators on Earth (including other DM candidates)
- Information on conditions in the Early Universe

Non-observation of PBHs

- Information on conditions in the Early Universe
- Constrain amplitude and spectral index of initial density perturbations, reheating, etc

Burst Search is Direct Search