THE SEARCH FOR PRIMORDIAL BLACK HOLES

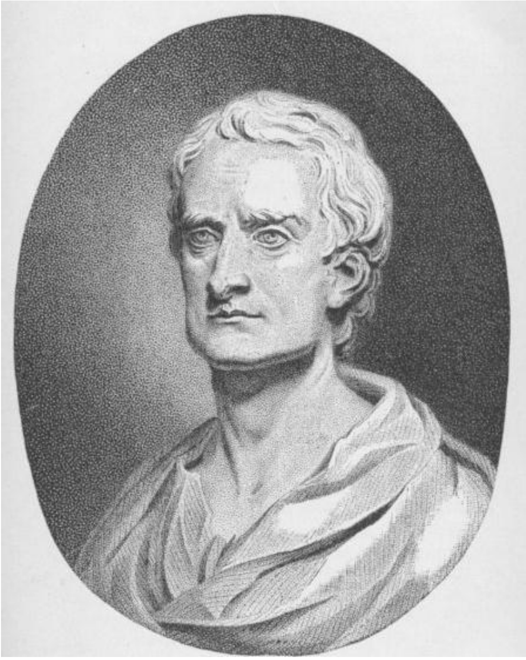
JANE H MACGIBBON
UNIVERSITY OF NORTH FLORIDA

Cosmic Frontier Workshop
SLAC March 6 - 8 2013

COLLABORATORS

T. N. Ukwatta (MSU), D. Stump (MSU),
J. T. Linnemann (MSU), K. Tollefson (MSU),
E. Hawkes (MSU), U. Abeysekara (MSU),
G. Sinnis (LANL), W. C. Parke (GWU),
K. S. Dhuga (GWU), A. Eskandarian (GWU),
N. Gehrels (NASA GSFC), L. Maximon (UVI),
D. C. Morris (GWU/NASA GSFC), B.J. Carr (QMW),
D.N. Page (UAlberta)

SIR ISAAC NEWTON

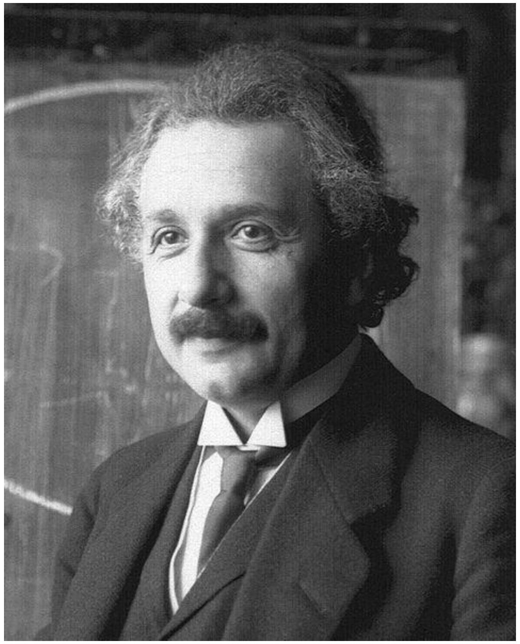


Gravity $F_G = \frac{GMm}{r^2}$

Escape Velocity

$$v_G = \sqrt{\frac{2GM}{r}}$$

ALBERT EINSTEIN



General Theory of Relativity

$$G_{\mu\nu} + \Lambda g_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

BLACK HOLES IN 4D SPACE-TIME

Schwarzschild Metric in General Relativity

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

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

<u>Extensions</u>: Kerr Metric for rotating black hole

Reissner-Nordström Metric for charged black hole

Kerr-Newman Metric for charged rotating black hole

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

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

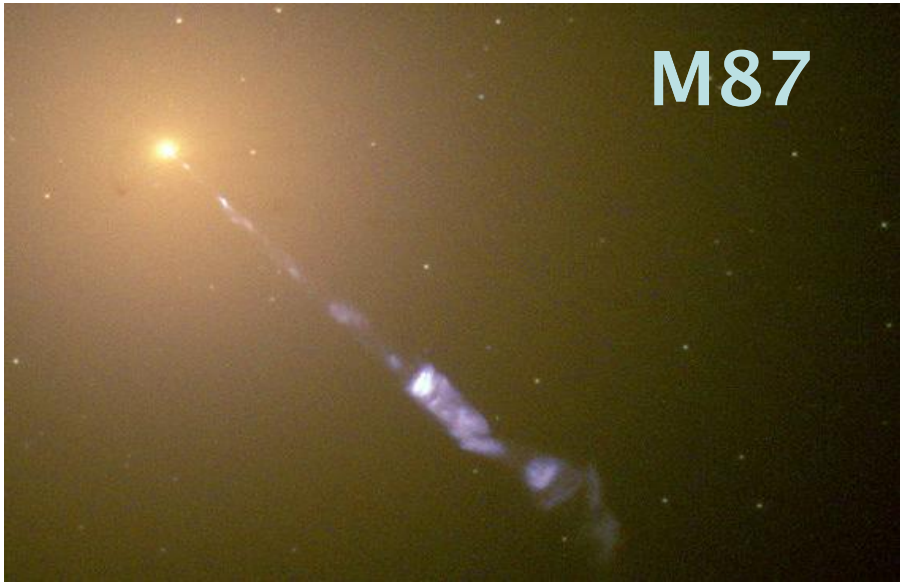
BLACK HOLES IN THE UNIVERSE

SUPERMASSIVE BLACK HOLES

Galactic Centers of most spiral and elliptical galaxies and all AGN

$M_{BH} \sim 10^{38} – 10^{43}$ g $\sim 10^{5} – 10^{10}$ solar masses

$r_s \sim 10^{-3} - 10^{3}$ AU



BLACK HOLES IN THE UNIVERSE

INTERMEDIATE MASS BLACK HOLES?

Possibly formed in Star Clusters
(Young Starburst Clusters and Old Globular Clusters)

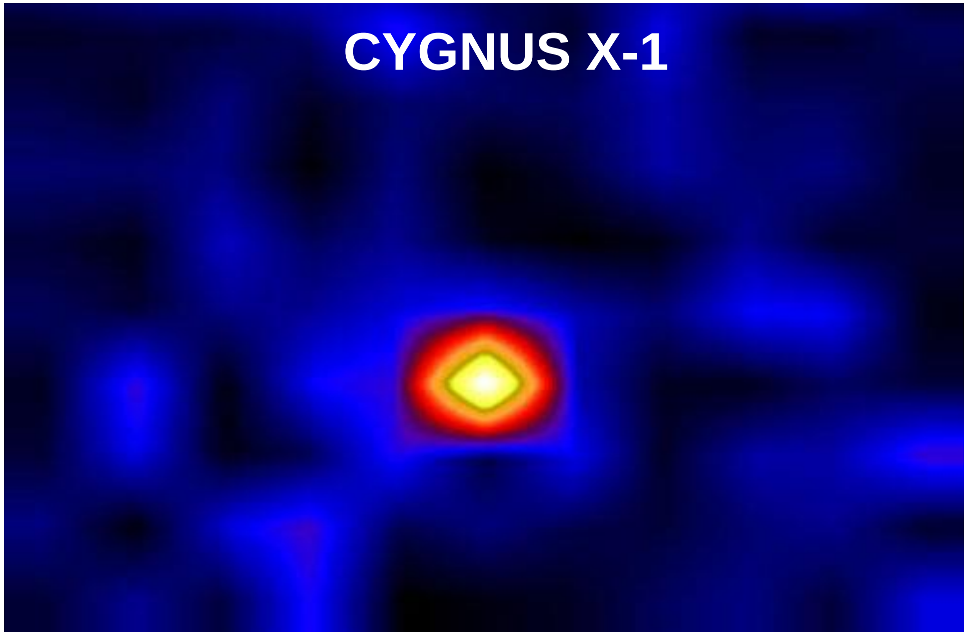
$M_{BH} \sim 10^{37}$ g $\qquad r_s \sim 10^3$ km

BLACK HOLES IN THE UNIVERSE

STELLAR MASS BLACK HOLES

Stellar collapse supernova of stars greater than ~20 solar masses (detect by X-rays or Gamma-rays from accretion disk in binary star system)

$M_{BH} \sim 10^{34} – 10^{35}$ g $\qquad r_s \sim 10 - 10^2$ km



BLACK HOLES IN THE UNIVERSE

PRIMORDIAL BLACK HOLES (PBHs)?

= Black Holes Formed in the Early Universe

$M_{BH} \sim 10^{-5} – 10^{43}$ g

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

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

STEPHEN HAWKING

Gravitational Temperature

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

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:

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

BLACK HOLE THERMODYNAMICS

ABSORPTION PROBABILITY

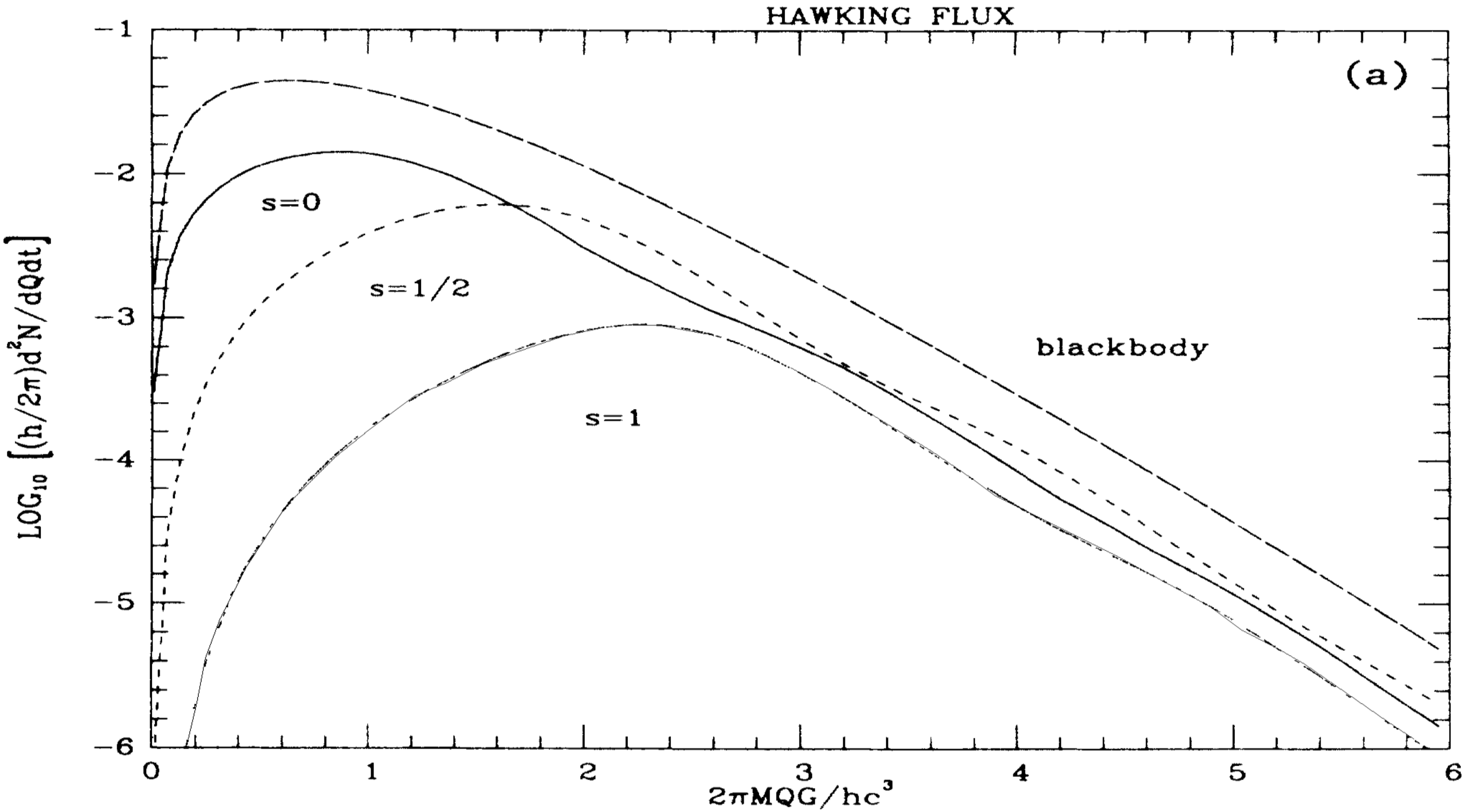
Geometric Optics Limit

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

$$\Gamma_{s=0}\left(M_{BH},E\right)\approx\frac{16G^2M_{BH}{}^2E^2}{\hbar^2c^6},\quad\Gamma_{s=1}\left(M_{BH},E\right)\approx\frac{64G^4M_{BH}{}^4E^4}{3\hbar^4c^{12}}$$

$$\Gamma_{s=1/2}\left(M_{BH},E\right)\approx\frac{2G^2M_{BH}{}^2E^2}{\hbar^2c^6},\quad\Gamma_{s=2}\left(M_{BH},E\right)\approx\frac{256G^6M_{BH}{}^6E^6}{45\hbar^6c^{18}}$$

DIRECT HAWKING RADIATION



Source: Page, Elster, Simkins

DIRECT HAWKING RADIATION

Flux of Directly Emitted Species peaks at:

Spin-0 $E_{s=0} = 2.81 T_{BH}$

Spin-1/2 $E_{s=1/2} = 4.02 T_{BH}$

Spin-1 $E_{s=1} = 5.77 T_{BH}$

Flux integrated over E, per degree of freedom:

dN/dt α T_{BH}

α $1/M_{BH}$

STANDARD PICTURE (MacGibbon-Webber)

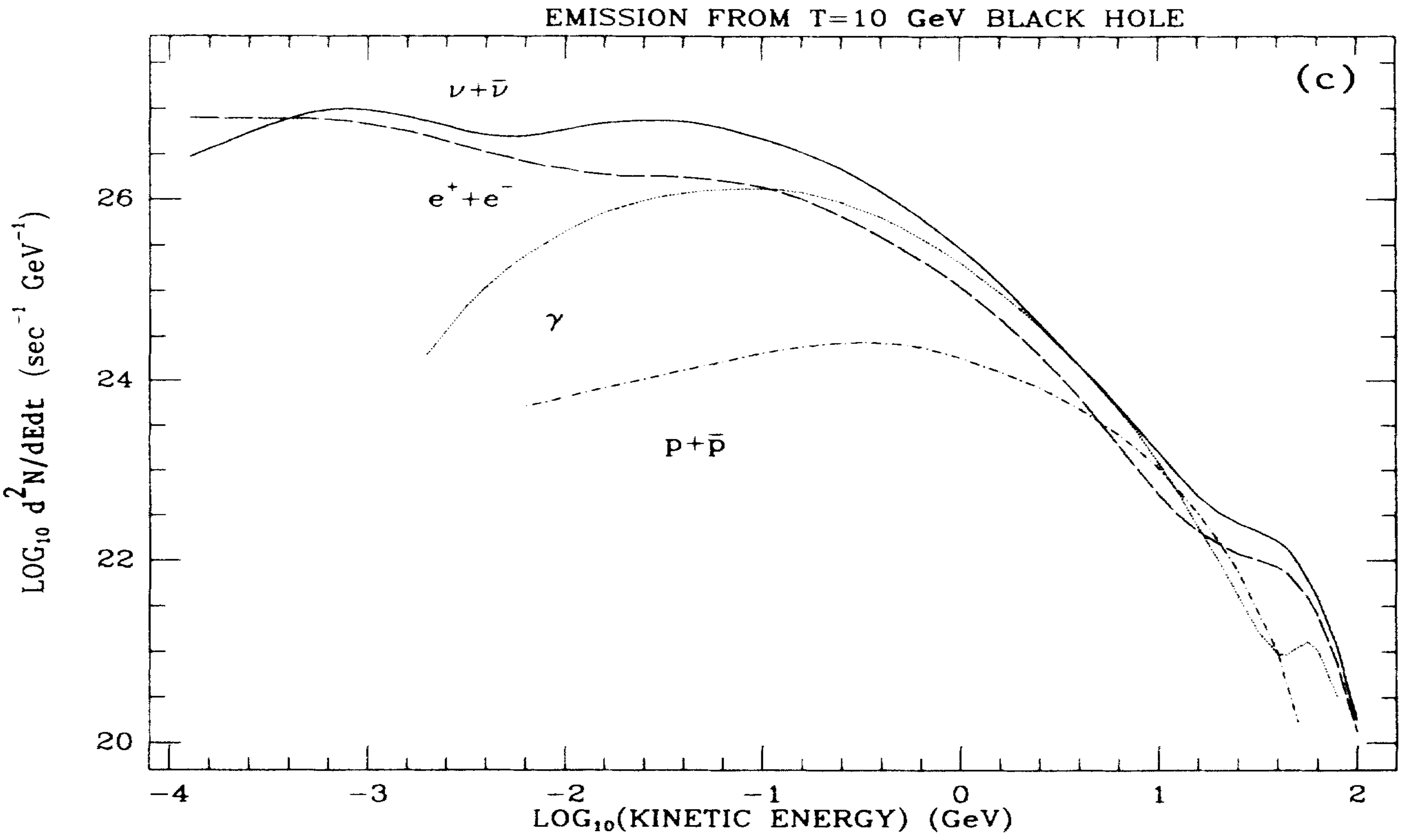
BH should directly evaporate those particles which appear non-composite compared to wavelength of the radiated energy (or equivalently BH size) at given T_{BH}

As T_{BH} increases:

BH directly emits photons + gravitons → + neutrinoes → + electrons → + muons → + pions

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

HAWKING RADIATION



Source: 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 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 anisotrophies
- may contribute to entropy, baryogenesis, reionization of Universe in earlier epochs; annihilation lines

MOTIVATION FOR PBH SEARCHES

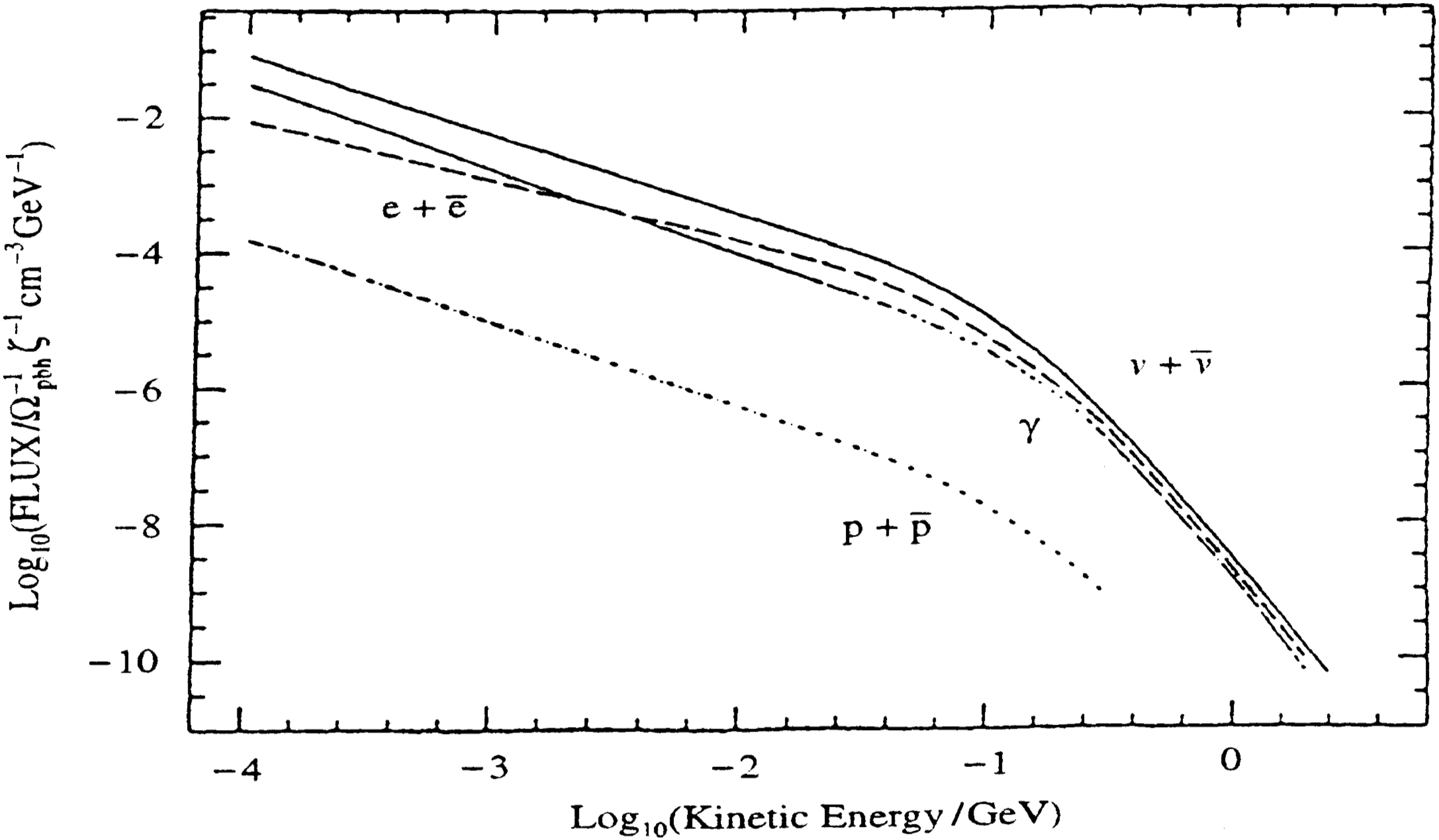
Observation of PBHs

- Proof of amalgamation of classical gravity and thermodynamics (classical as well as quantum); insight into quantum gravity
- Direct window on 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

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



Source: MacGibbon and Carr (1991)

ASTROPHYSICAL SPECTRA

GAMMA RAY EXTRAGALACTIC BACKGROUND

(Carr & MacGibbon 1998): $\Omega_{PBH} \leq (5.1 \pm 1.3) \text{x} 10^{-9} h^{-2}$

IF PBHS CLUSTER IN GALACTIC HALO:

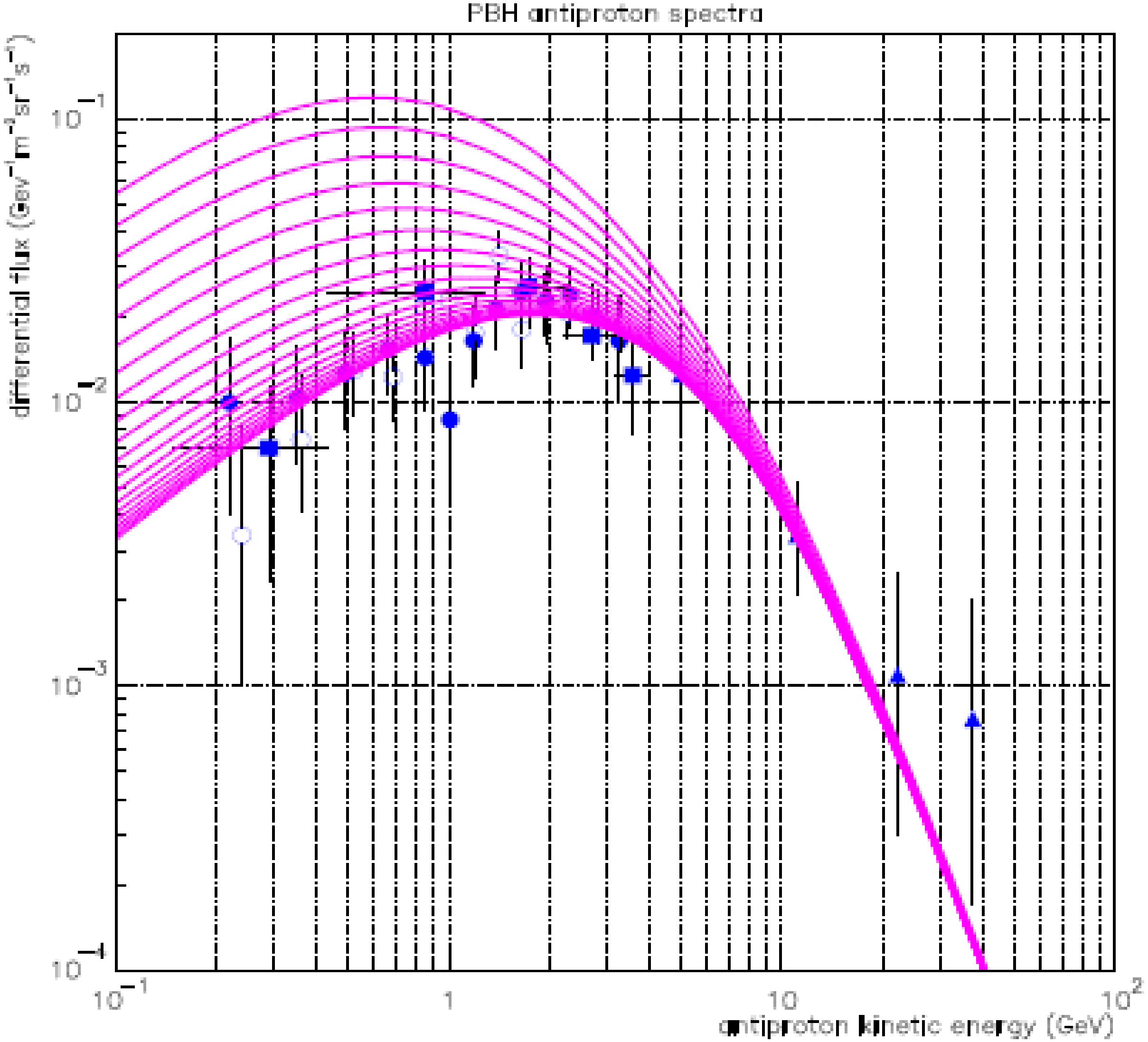
Local density enhancement $\eta_{\text{local}} \approx 5 \text{x} 10^{5} h^{-2} \left(\frac{\Omega_h}{0.1} \right)^{-1}$

Galactic Halo Gamma Ray Background (Wright 1996)

Antiprotons, Positrons

Antimatter interactions, Microlensing

ANTIPROTONS



Barrau et al (2002)

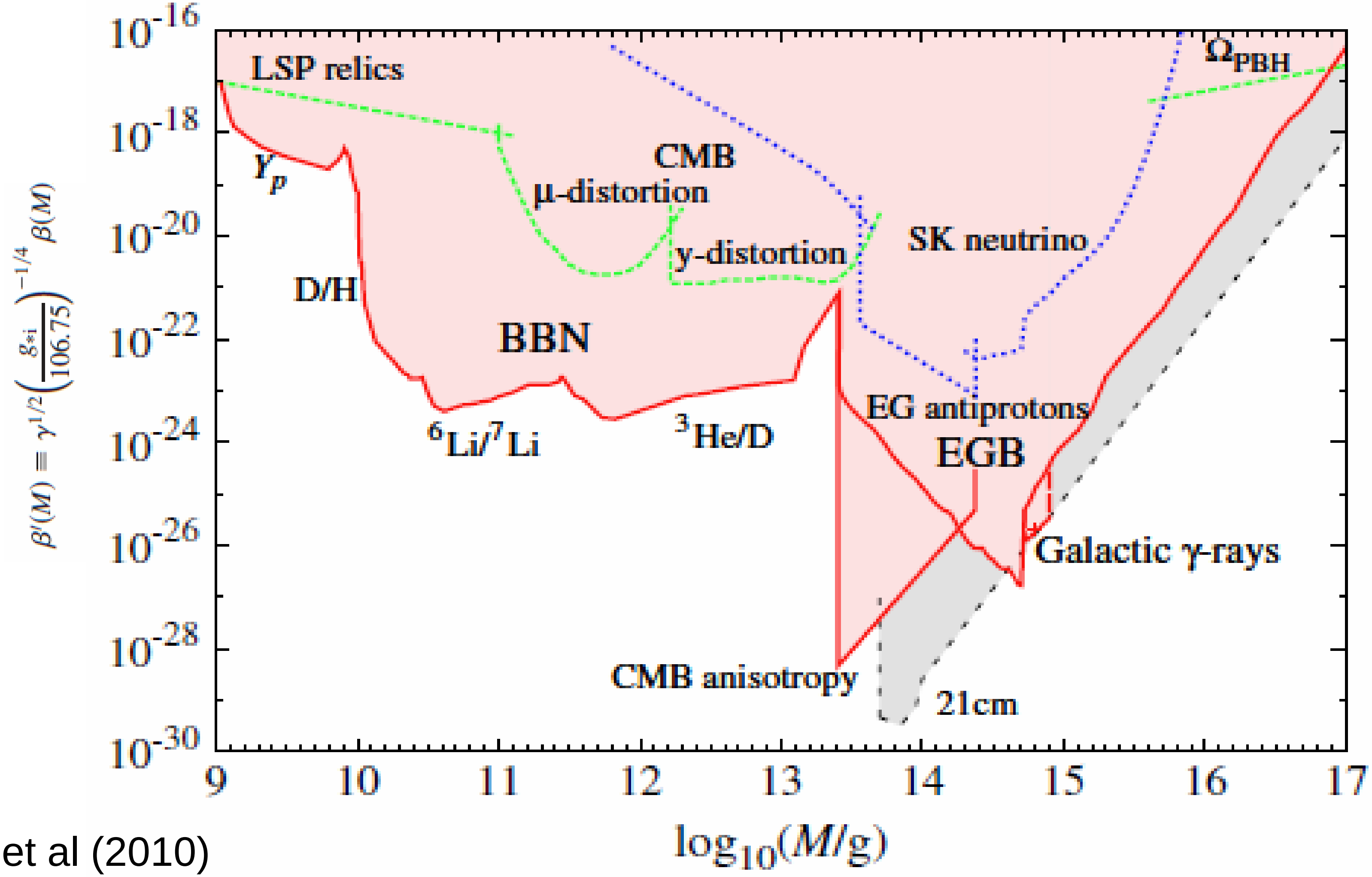
$$\rho_{\odot}^{PBH} < 5.3 \cdot 10^{-33} \, \mathrm{g \, cm^{-3}}$$

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 BURSTS

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 $f(M_i)$ counts total directly emitted species

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

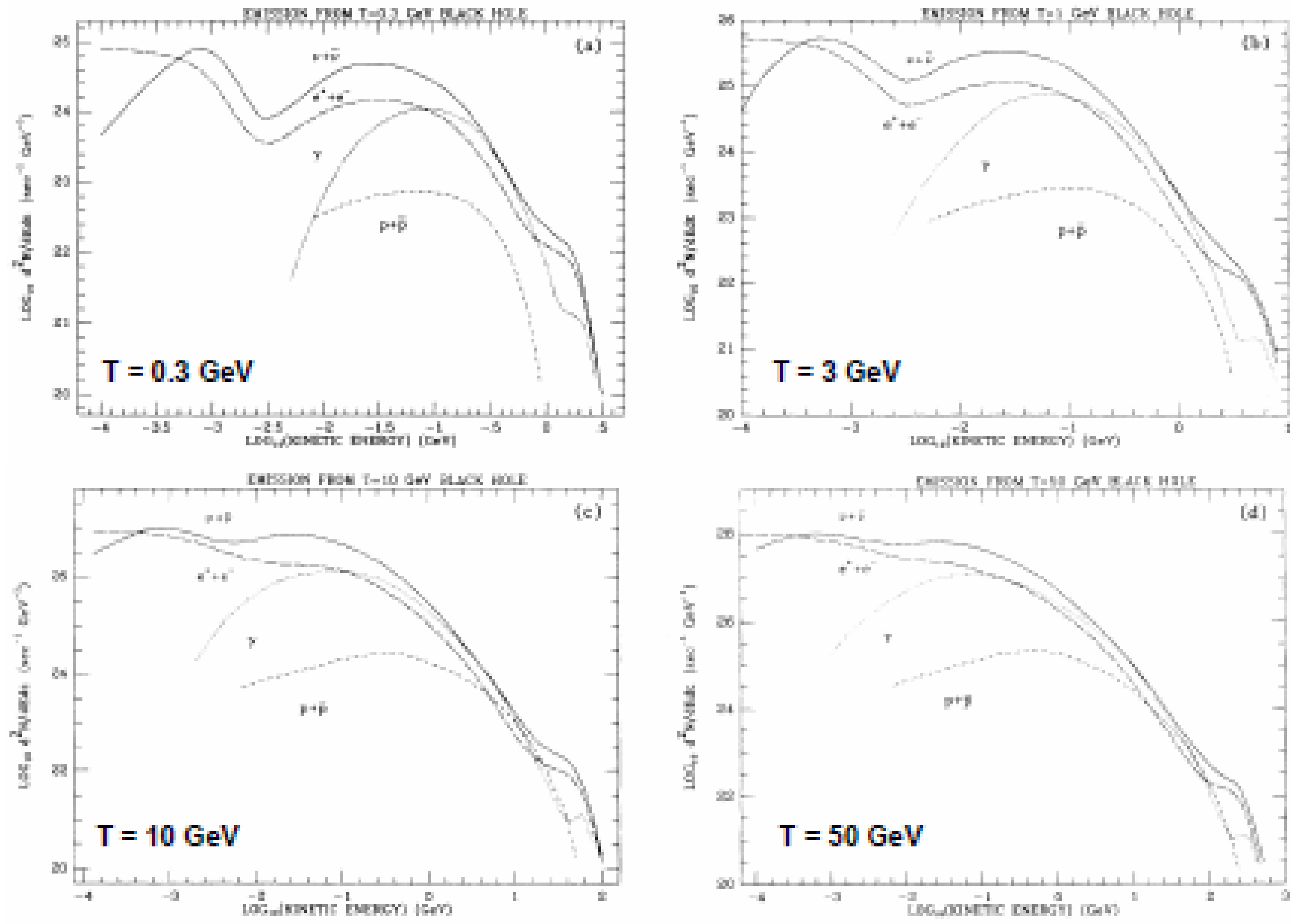
$f_{s=1} = 0.060$ $\quad f_{s=1/2} = 0.142$, electric charge = $\pm e$ $\quad f_{s=2} = 0.007$

Mass of PBH whose lifetime equals age of Universe

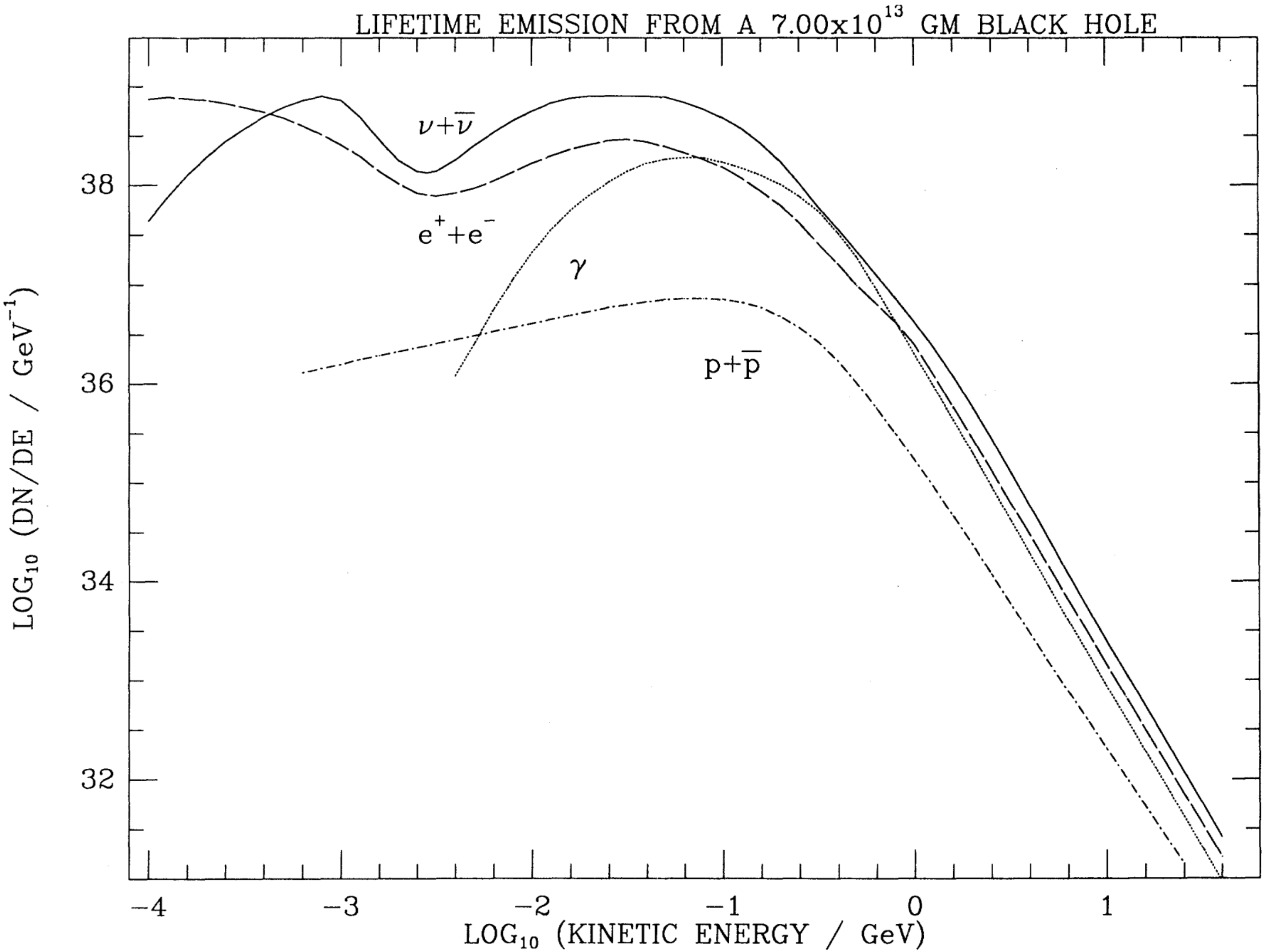
(MacGibbon, Carr & Page 2008):

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

Instantaneous PBH Spectra



MacGibbon and Webber 1990


LIFETIME EMISSION FROM A 7.00x10^13 GM BLACK HOLE
ν+ν̄
e⁺+e⁻
γ
p+p̄
38
36
34
32
−4
−3
−2
−1
0
1
LOG10 (DN/DE / GeV^-1)
LOG10 (KINETIC ENERGY / GeV)

PBH Bursts

PBHs Expiring Today: $\frac{dn}{dM_{BH}} \propto M_{BH}{}^{2}, \qquad M_{BH} < M_{*}$

Number Expiring: $N \leq 10^{-7} \eta_{\rm local}\ \mathrm{pc}^{-3}\ \mathrm{yr}^{-1}$

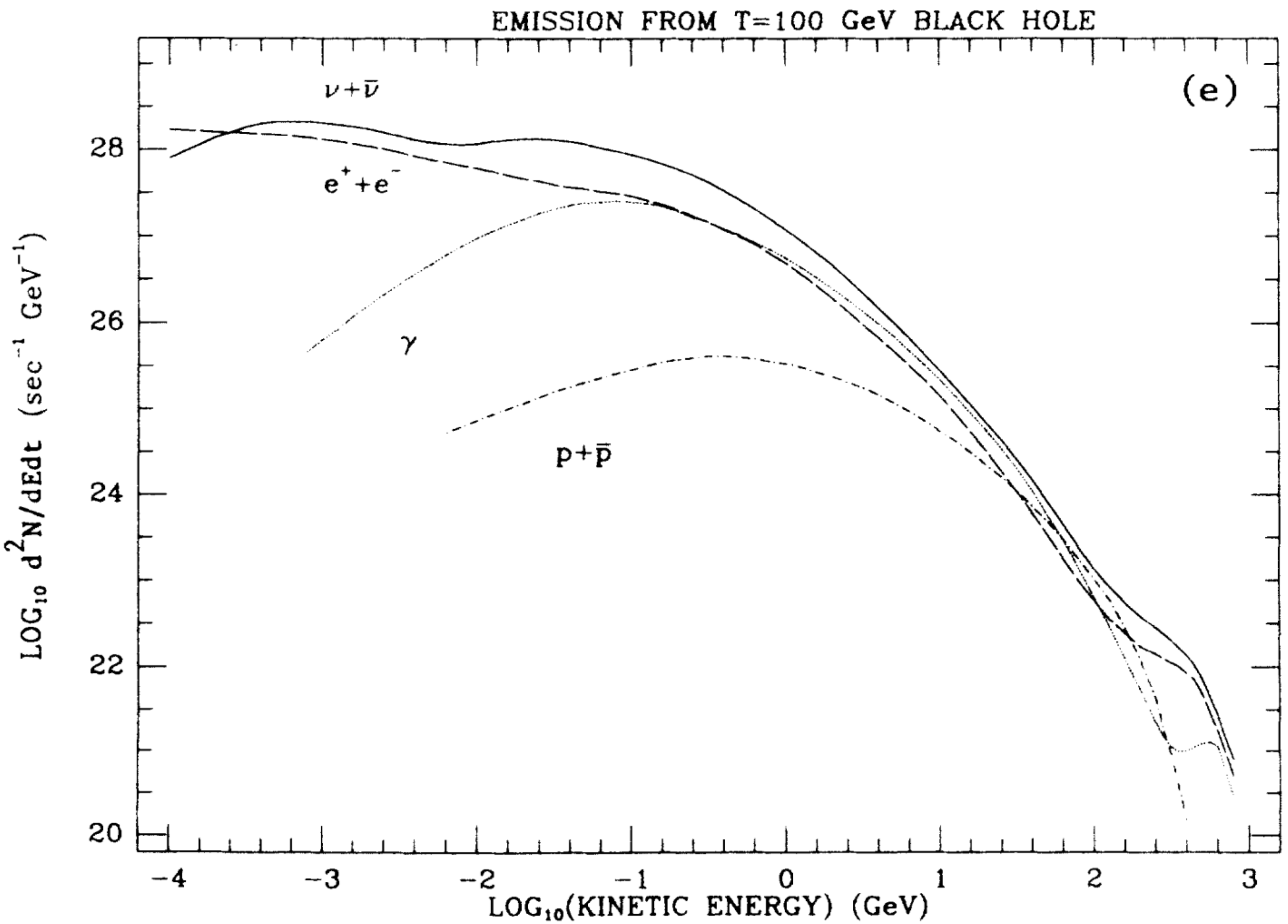
where η_{local} is local clustering factor

Remaining lifetime for given T_{BH}:

Model	1 Hour	1 min	30 sec	10 sec	1 sec	30 ms	10 ms
Standard Model	294 GeV	1.15 TeV	1.45 TeV	2.09 TeV	4.51 TeV	14.5 TeV	20.9 TeV
Higgs	250 GeV	0.98 TeV	1.24 TeV	1.8 TeV	3.8 TeV	12.0 TeV	18.0 TeV
SUSY	206 GeV	0.81 TeV	1.0 TeV	1.5 TeV	3.2 TeV	10.0 TeV	15.0 TeV

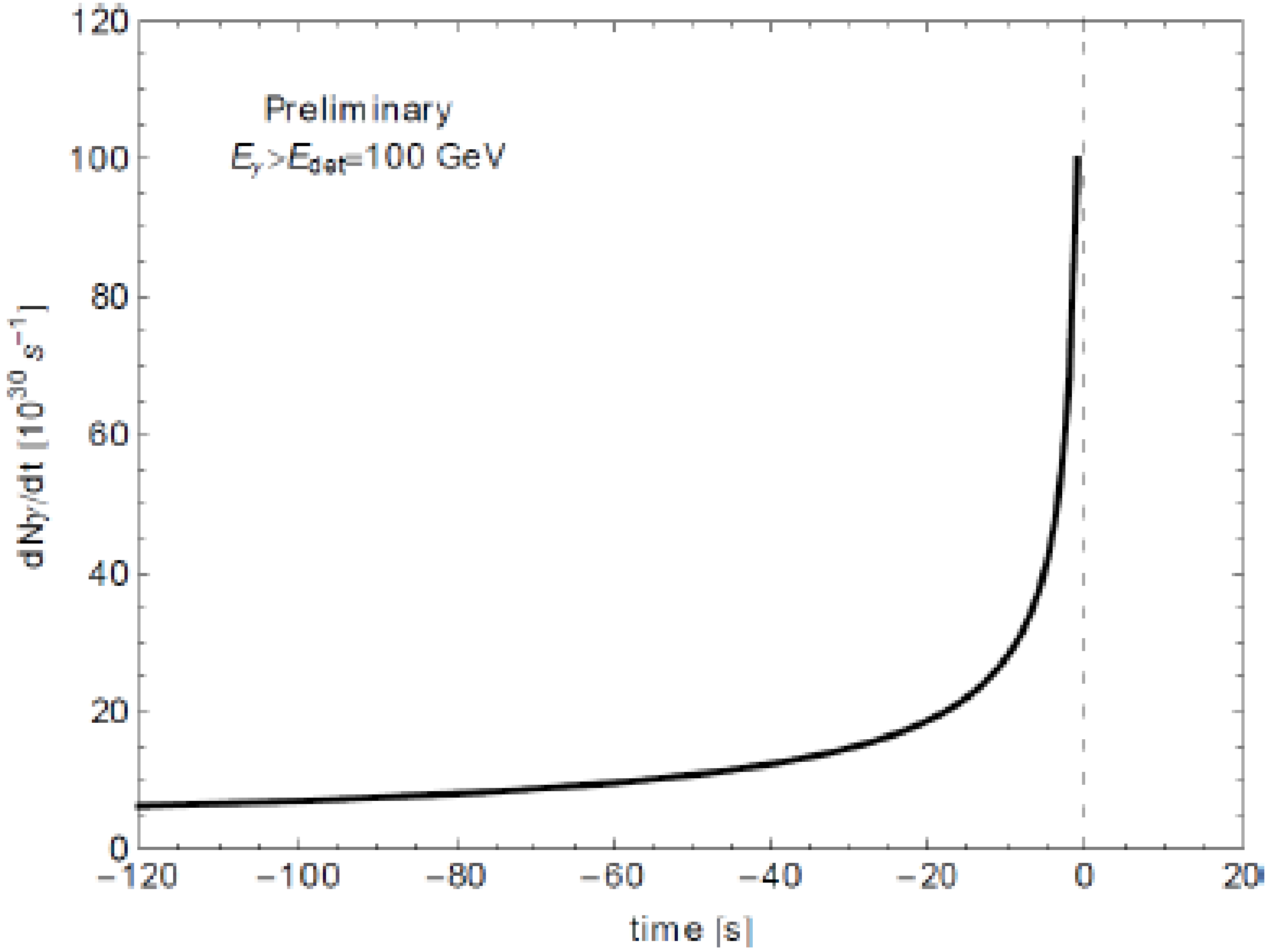
PBH Bursts

Fermi LAT Energy Range: 20 MeV – 300 GeV



Source: MacGibbon and Webber (1990)

Preliminary PBH Burst Light Curve



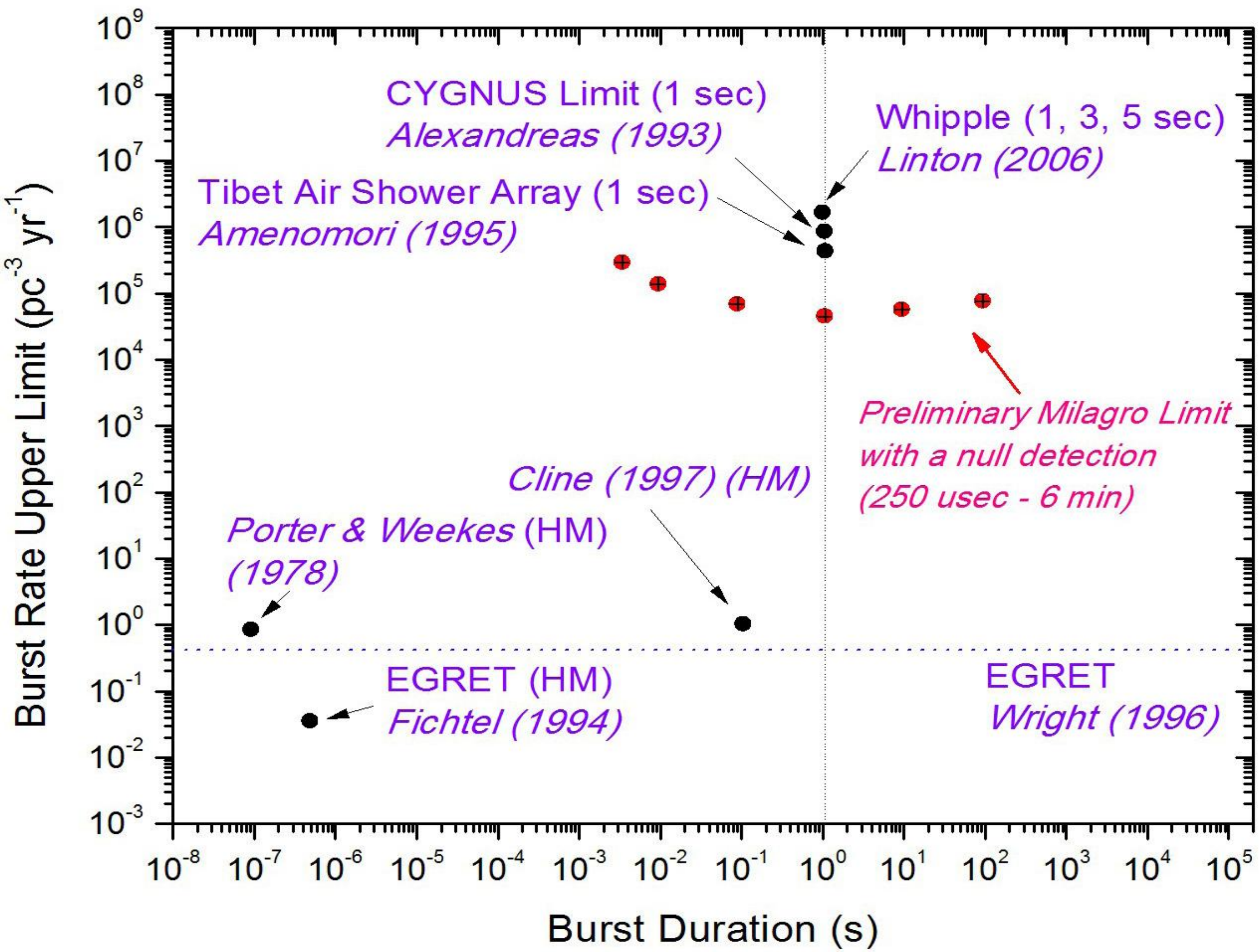
Ukwatta et al

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

Ukwatta et al

PBH Burst Rate Upper Limits



SEARCHING FOR PBH BURSTS

- **working on predicting spectra, sensitivity and analysizing GRB events for Fermi LAT, Milagro and HAWC**

- **HAWC ideal for improving PBH search because of large FoV, energy range and high duty cycle**

CAN A CHROMOSPHERE BE FORMED IN BLACK HOLE DECAYS?

Heckler Model

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

- **QED/QCD bremsstrahlung and pair-production interactions between Hawking-radiated particles form photosphere/chromosphere**

Other 4D Photosphere/Chromosphere Models

- **Belyanin et al**
- **Bugaev et al**
- **D. Cline and Hong**
- **Kapusta and Daghigh**

HECKLER MODEL

Number Density at radius *r* from BH of e⁻ directly Hawking radiated by BH

$$n_0(r) \approx \frac{10^{-4}}{M_{BH} r^2} \quad \text{where } \hbar = k = G = c = 1$$

Two-body QED bremsstrahlung cross-section in BH center-of-mass frame

$$\sigma_{brem} \approx \frac{8\alpha^3}{m_e^{\,2}} \ln \frac{2E}{m_e} \qquad \text{for } e + e \rightarrow e + e + \gamma$$

Plasma mass correction

$$m'_e = \sqrt{m_e^{\,2} + m_{pm}^{\,2}} \quad \text{where} \quad m_{pm}^{\,2} \approx \frac{4\pi\alpha n(r)}{E_{av}}$$

Total Number of Scatterings

$$N(R) = \int_{r_{\min}=r_{BH}}^{r_{\max}=R} \frac{dr}{\lambda(r)} \quad \text{where } \lambda(r) = \left(n(r)\sigma_{brem} v_{rel}\right)^{-1} \text{ and } n(r) = \left(\frac{3}{2}\right)^{N(r)} n_0(r)$$

→QED Photosphere above T_{BH} ~ 45 GeV. Similarly

QCD $\sigma_{brem} \approx \frac{8\alpha_s^{\,3}}{m_q^{\,2}} \ln \frac{2E}{m_q}$ **→ Chromosphere above $T_{BH} \sim \Lambda_{QCD}$**

IS THE HECKLER MODEL CORRECT?

Two-body bremsstrahlung cross-section

$$\sigma_{brem} = \frac{1}{E}\int_0^E \omega \frac{d\sigma_{brem}}{d\omega} d\omega \approx \frac{8\alpha^3}{m_e^2} \ln \frac{2E}{m_e}$$

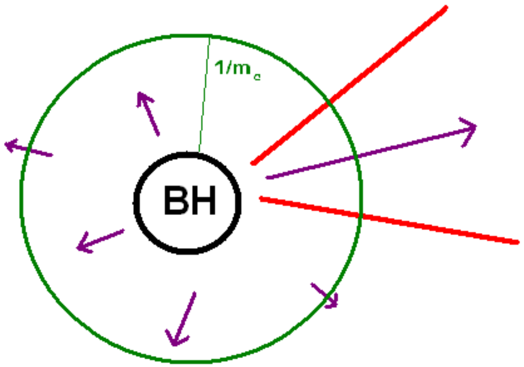
Average momentum exchanged is $\sim m_e$ in center-of-momentum (CM) frame → particles must be within $\sim 1/m_e$ of each other to interact

Average angle between final on-shell electron and outgoing photon in CM frame is $\varphi_{av} \sim m_e / 2E$

Average energy of final on-shell electron and outgoing photon in CM frame is $E_e \sim \omega \sim E / 2$

IS THE HECKLER MODEL CORRECT?

assumes BH is center-of-momentum frame for most pairs of emitted charged particles



BUT two particles moving in similar direction will not interact near BH (because their center-of-momentum frame is highly Lorentz-boosted) →

✗ get '**Exclusion cone**' around each emitted particle → once particle is a distance d from BH the transverse distance to the nearest particle it can interact with is $x_T \sim d$

→ particles must be within $\sim 1/m_e$ of BH to interact

IS THE HECKLER MODEL CORRECT?

✗ For radial emission $\lambda(r) = \left(n(r)\sigma_{brem} v_{rel}\right)^{-1}$ is not correct

→ must be replaced by radial description

✗ particles are Hawking emitted near BH so particles do not travelling in from ***minus*** ∞, past the BH and each other, then out to ***plus*** ∞

BUT bremsstrahlung cross-section assumes interacting particles travel in from ***minus*** ∞

→ interaction cross-section is decreased

IS THE HECKLER MODEL CORRECT?

✗ **Causality Constraint**

Two particles must be in casual contact to interact BUT negligible fraction of Hawking emitted particles are in causal contact with each other

Time between subsequent Hawking emissions is

$$\Delta t_e \sim 200 / E_{peak}$$

For causal contact within $\sim 1 / m_e$ of BH require

$$\Delta t_e < \Delta t_c \sim 1 / \gamma\, m_e \text{ where } \gamma \sim E_{peak} / m_e$$

→ $\Delta t_c << \Delta t_e$ **for almost all emitted particles**

IS THE HECKLER MODEL CORRECT?

✕ Scale for Completion of Interaction

Heckler assumed distance required for formation of final on-shell electron and outgoing photon is $d_{form} \sim 1 / m_e$ in CM frame

BUT average angle between final on-shell electron and photon is $\varphi_{av} \sim m_e / 2E$

so $d_{form} \sim E / m_e^2$ in CM frame

→Electron must travel $d_{form} \sim E / m_e^2$ before it can undergo next on-shell interaction

→ Any multiple interactions of electron within $\sim 1 / m_e$ of BH are off-shell interactions and so strongly suppressed by LPM effect

QCD CHROMOSPHERE?

- ✗ **when $T_{BH} >> \Lambda_{QCD}$ the causality constraint ($\Delta t_e \sim 20 / E_{peak}$) and LPM suppression in any (rare) multiple scatterings also prevent QCD chromosphere formation for 4D BHs**

BUT could a QCD chromosphere form when $T_{BH} \sim \Lambda_{QCD}$?

QCD CHROMOSPHERE WHEN $T_{BH} \sim \Lambda_{QCD}$?

- Hawking emission of particle is damped (lower flux and greater Δt between emissions) near rest mass threshold (eg Λ_{QCD}) + low multiplicity per jet near Λ_{QCD}
- Δt between consecutive Hawking emissions increases around Λ_{QCD} → causality constraint is stronger
- when BH goes from directly emitting π to directly emitting quarks and gluons the initial quarks and gluons are relativistic (not slow)

QCD CHROMOSPHERE WHEN $T_{BH} \sim \Lambda_{QCD}$?

- number of final hadronized states is limited by available energy ($E \sim \Lambda_{QCD}$ per Hawking emitted particle) + qm conservation laws → emitted particle produces mainly π (and only a couple of π) around Λ_{QCD} and soft gluon bremsstrahlung is insignificant (because lowest colourless state from g is π)

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

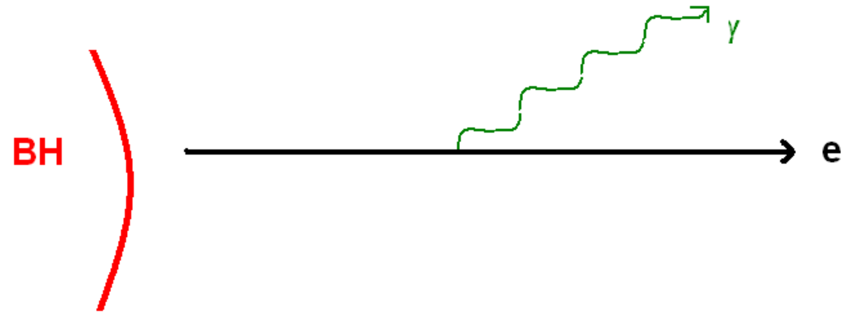
(No analogy to RHIC's ~ 200 GeV per nucleon, gluon-saturated, high baryon/antibaryon asymmetry)

OTHER PHOTOSPHERE/ CHROMOSPHERE MODELS

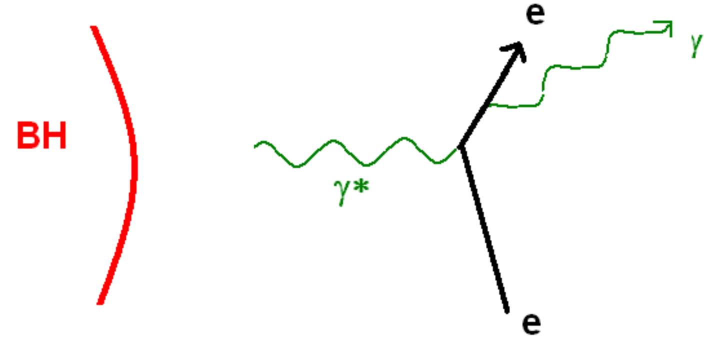
- **Kapusta and Daghigh** – assumes plasma thermalized by QED and QCD bremsstrahlung and pair-production of Heckler model
- **Belyanin et al** – ‘collisionless’ QED plasma – omits Lorentz factors → no self-induced MHD photosphere but strong ambient magnetic field may induce (weak) photosphere
- **Bugaev 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 $1/M_{BH}{}^{2}$)

BREMSSTRAHLUNG EFFECTS
(Page, Carr and MacGibbon 2008)

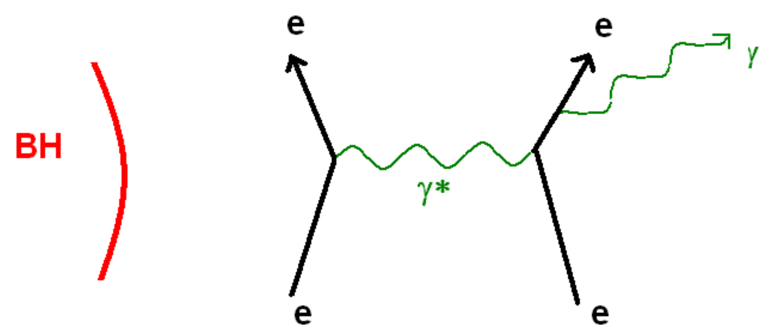
Inner Bremsstrahlung



2-vertex Bremsstrahlung



3-vertex Bremsstrahlung



INNER BREMSSTRAHLUNG

Number flux of inner bremsstrahlung photons radiated by charged particles of mass *m* and $\gamma_{av} \sim 4.20 T_{BH} / m$ emitted by BH with spectrum *dN/dt*:

$$\frac{d^2 N_{b\gamma}}{dt\, d\omega} \approx \frac{2\alpha}{\pi\omega}\left[\ln\left(2\gamma_{av}\right) - 1\right]\frac{dN}{dt}$$

→ **Nearly flat power spectrum up to $\omega \sim E - m$ cut-off**

Total power in inner bremsstrahlung photons radiated by charged particles emitted by BH with power *dE/dt*:

$$\frac{dE_{b\gamma}}{dt} \approx \frac{2\alpha}{\pi\omega}\left[\ln\left(2\gamma_{av}\right) - 1\right]\frac{dE}{dt}$$

INNER BREMSSTRAHLUNG

Total power in inner bremsstrahlung photons radiated by charged particle emitted by BH with power *dE/dt*:

$$\frac{dE_{b\gamma}}{dt} \approx \frac{2\alpha}{\pi\omega}\left[\ln\left(2\gamma_{av}\right)-1\right]\frac{dE}{dt}$$

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 $M_{BH} = 5x10^{14}$ *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

LET'S GO SEARCH FOR PBHs!

And Black Hole Thermodynamics!