Exploding Primordial Black Holes

Valerie Connaughton
University of Alabama in Huntsville

Primordial Black Holes are relics of the early Universe

- ρ_{pbh} (universe) - density inhomogeneities
- ρ_{pbh} (local) - how much did these cluster in galaxies? Estimate 10^6
- N(m) - reflects original mass distribution - no accretion growth

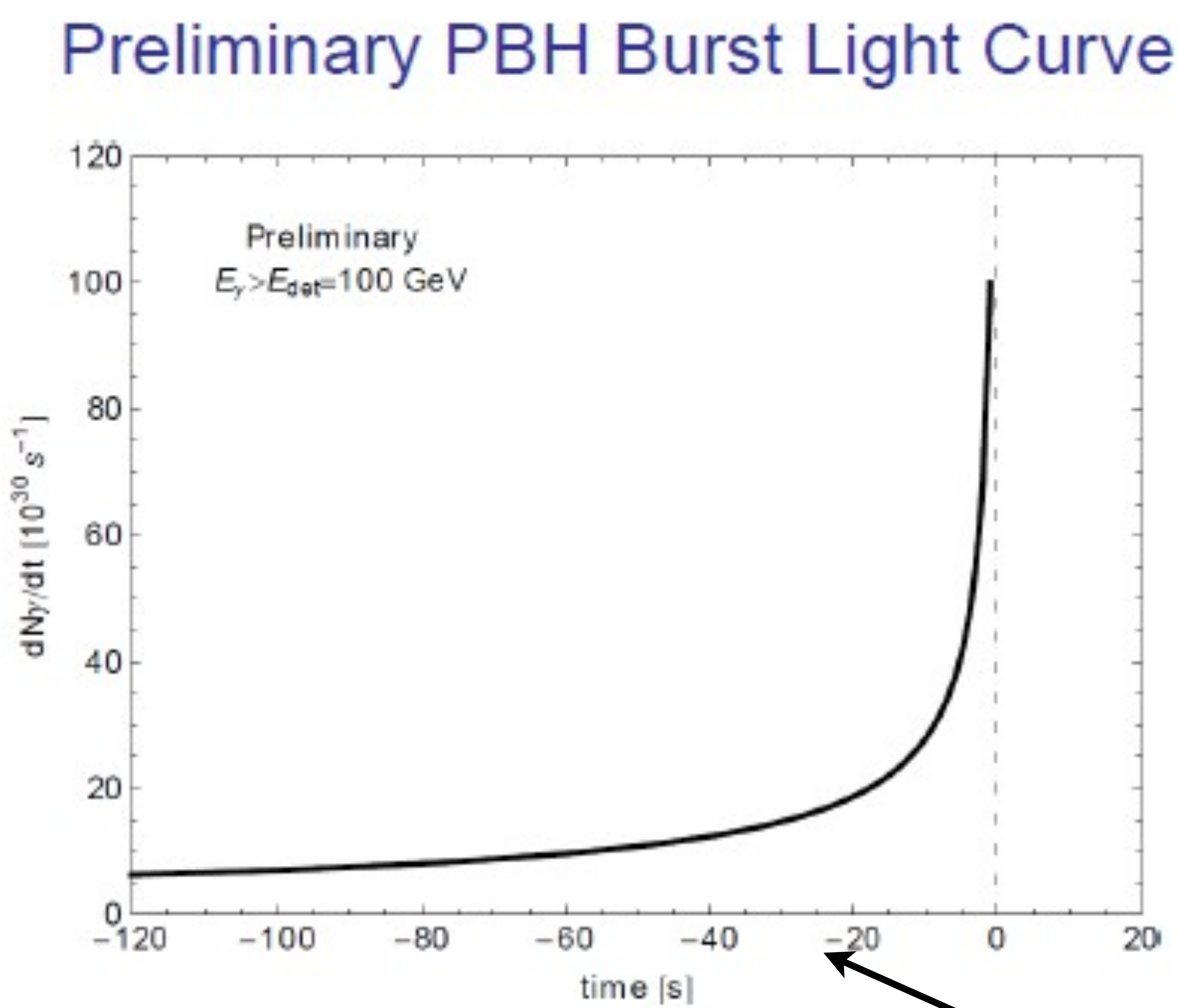
How might we detect them? Hawking (1974)

- Hawking radiation: quantum fluctuations near BH horizon

$$\frac{d^2N}{dtdE} = \frac{\Gamma_s}{2\pi\hbar}\left[\exp\left(\frac{8\pi GME}{\hbar c^3}\right) - (-1)^{2s}\right]^{-1}$$

- BH temperature $T_H = \hbar c^3 / 8\pi MGk_B$.
- A 10^{15}g BH has T = 100 MeV.
- A 10^{15}g BH has a lifetime ~ the age of the universe.
- Combination of general relativity and quantum gravity

PBHs: The final stages

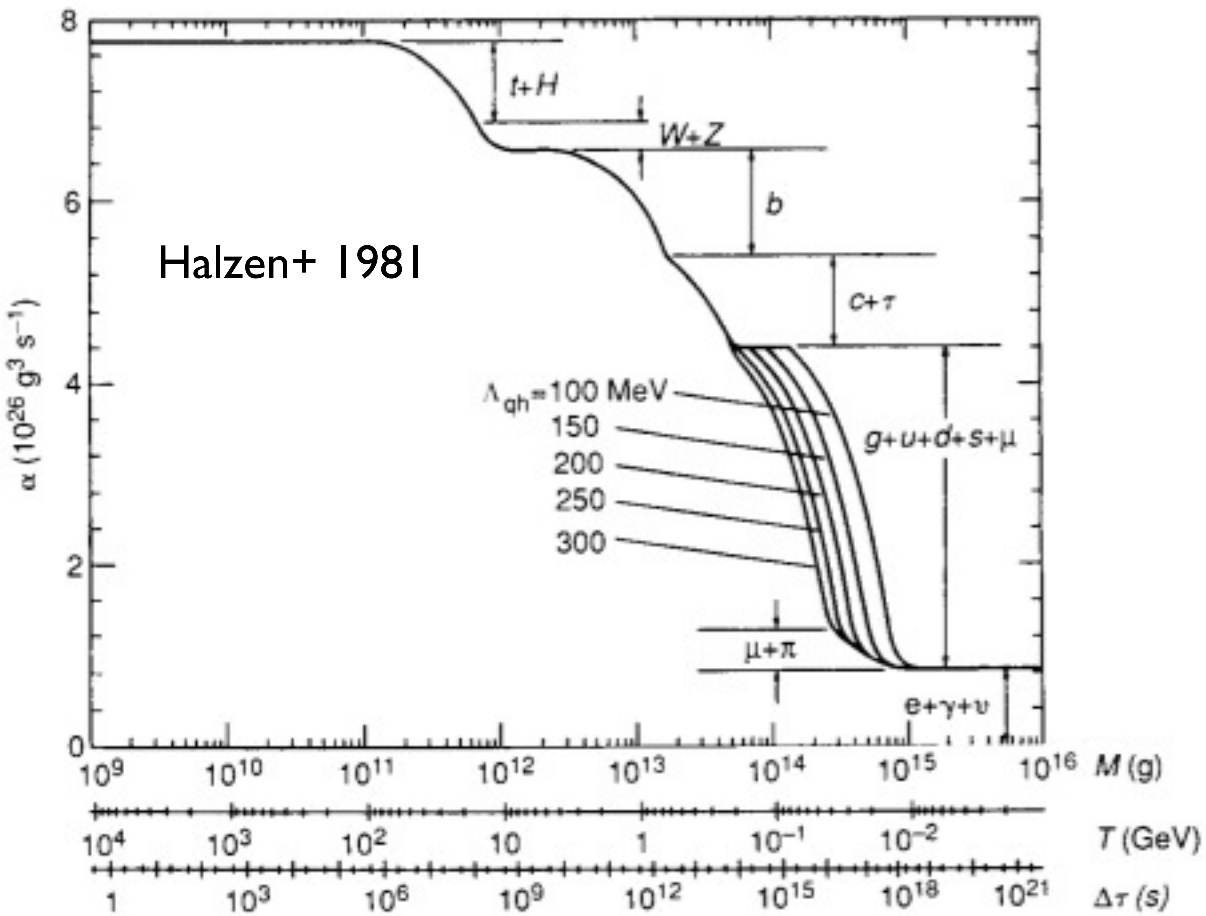


This time-scale can vary

From Jane MacGibbbon

The end of their life is brief and energetic - they explode!
Two extremes regarding the physics of the final explosion:

Standard elementary particle model



Hagedorn model (Hagedorn, 1976x

$N \approx m^{-5/2} \exp(m/\Lambda)$

Exp. growth of hadronic resonances.

Gamma-ray emission during explosion:

$\Delta t = 0.1$ s

E_γ 10^{30} ergs

$\bar{E} \sim 5$ TeV

$\Delta t = 10^{-7}$ s

E_γ 10^{34} ergs

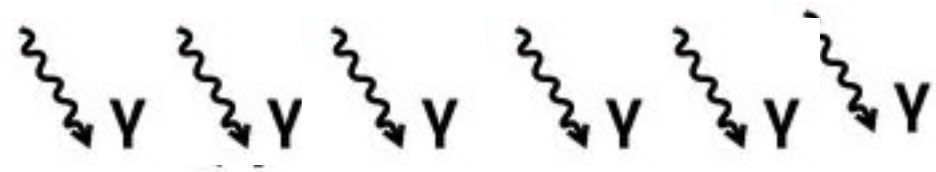
$\bar{E} \sim 100$s MeV

Does this actually happen?

- Initial density perturbation function limited by smoothness of CMB
- ρ_{pbh} (universe) - PBH of 10^{15}g limited by cosmic γ-ray diffuse (Page & Hawking 76) to be ~10^4 PBH pc $^{-3}$ or 10^{-8} of mass needed to close universe
- ρ_{pbh} (local) - we can look for explosions of 10^{15}g PBH nearby - expect 0.14 PBH pc $^{-3}$ yr $^{-1}$ if clustering in galaxies as expected (PH76)

Neil Porter and Trevor Weekes: pioneers in PBH observations

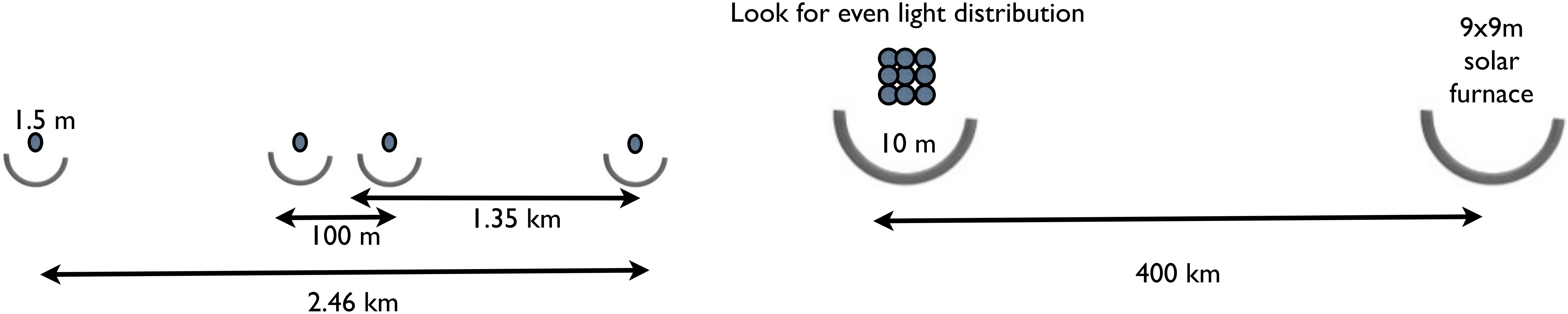
Porter & Weekes 1977 and 1978



A couple of interesting events:
probably CRs of high-energy
or unusual arrival geometry.

No interesting events

Imaging!
Look for even light distribution



- limits from P&W 1978 constrain clustering factor for PBH in galaxies to 10^4 vs 10^6 as predicted by PH76

The Whipple limits in context

Gamma Rays and Energetic Particles from Primordial Black Holes
Halzen, F; Zas, E; et al
Nature; Oct 31, 1991; 353, 6347; ProQuest Medical Library
pg. 807

REVIEW ARTICLE

Gamma rays and energetic particles from primordial black holes

F. Halzen, E. Zas, J. H. MacGibbon & T. C. Weekes

Black holes of almost arbitrarily small mass may have formed in the very early Universe. Their presence today would be revealed by the energetic radiation they would produce by means of the quantum-gravitational Hawking mechanism, allowing observational limits to be set on their density today and on their past significance.

TABLE 2 Observational limits on PBH densities

Technique*		Group†	Assumptions‡	Density of events ($pc^{-3}\,yr^{-1}$)	References
ACT	3×1.5 m	SAO–UCD	HM	<0.47	Ref. 44
ACT	10 m	SAO–UCD	HM	<0.67	Ref. 44
ACT	4×1.5 m	SAO–UCD	HM	<2.1	Ref. 45
ACT	10 m + 9 m	SAO–UCD	HM	<0.04	Ref. 45
ACT	10 m	SAO–UCD	EPM	$<7\times10^5$	Ref. 45
ACT	10 m	SAO–UCD	EPM	$<8\times10^5$	Ref. 46
ACT	2×1.5 m	SAO–UCD	EPM	$<3\times10^4$	Ref. 46
ACT	10 m	SAO–UCD	EPM	$<2\times10^4$	Ref. 47
EAS	2 arrays	UCC–UCD	EPM + UHE emission	$<2\times10^4$	Ref. 48
EAS	1 array	Tata	EPM + UHE emission	$<3\times10^3$	Ref. 49
Optical	3×1.5 m	UCD	EPM + optical emission	<0.3	Ref. 50
Radio	10 m	SAO	EPM + radio emission	$<3\times10^{-7}$	Ref. 51
Radio			EPM + radio emission	$<2\times10^{-7}$	Ref. 52
Radio	Areicho	U. Mass	EPM + radio emission	$<7\times10^{-10}$	Refs 53–55

* ACT: atmospheric Cerenkov technique; EAS: extensive air shower.
† SAO: Smithsonian Astronomical Observatory; UCD: University College Dublin.
‡ HM: Hagedorn model; EPM: elementary particle model or standard model; UHE: ultra-high-energy.

Continuing the search with IACT...

Astroparticle Physics
Volume 8, Issue 3, February 1998, Pages 179–191

Phil. Trans. R. Soc. Lond. A **301**, 665–667 (1981)
Printed in Great Britain

The atmospheric Cherenkov technique in searches for exploding primordial black holes

By S. Danaher†, D. J. Fegan†, N. A. Porter† and T. C. Weekes‡
† *Physics Department, University College, Belfield, Dublin 4, Republic of Ireland*
‡ *Harvard–Smithsonian Center for Astrophysics, Mount Hopkins Observatory, P.O. Box 97, Amado, Arizona 85640, U.S.A.*

A search for TeV gamma-ray bursts on a 1-second time

V. Connaughton a, b, C.W. Akerlof c, S. Biller d, P. Boyle b, J. Buckley a, D.A. Carter... Catanese e, M.F. Cawley f, D.J. Fegan b, J. Finley g, J. Gaidos g, A.M. Hillas d, R.C. Lamb e... McEnery b, G. Mohanty e, N.A. Porter b, J. Quinn b, H.J. Rose d, M.S. Schubnell c, G. Semb... Srinivasan g, T.C. Weekes a, C. Wilson g, J. Zweerink e

ICRC 1989 Adelaide

OG4.3-8

SEARCH FOR SHORT-TIME SCALE BURSTS OF TEV GAMMA-RAYS FROM PRIMORDIAL BLACK HOLES

K.Nolan, N.A.Porter, D.J.Fegan
University College, Dublin, Ireland
M.Chantell, T.C.Weekes

ICRC 1991 Dublin

OG

A Search for TeV Bursts of Gamma-rays.

V. Connaughton[1], M.Chantell[2], D.J.Fegan[1], N.A.Porter[1], T.C.Weekes[2].

1 University College, Dublin
2 Harvard-Smithsonian Center for Astrophysics

Searches for Bursts of TeV Gamma Rays on Time-Scales of Seconds

Connaughton, V.; Chantell, M.; Rovero, A. C.; Whitaker, T.; Weekes, T. C.; Akerlof, C. W.; Meyer, D. I.; Hagan, J.; Porter, N. A.; Punch, M.; Gaidos, J.; Sembroski, G.; Wilson, C.; Hillas, A. M.; Rose, J.; West, Lamb, R. C.; Mohanty, G.

Gamma-Ray Bursts, Proceedings of the 2nd Workshop held in Huntsville, Alabama, October 1993, New York: American Institute of Physics (AIP). Edited by Gerald J. Fishman, AIP Conference Proceedings Vol. 307, 1994, p.470 (AIPC Homepage)

Journal of Cosmology and Astroparticle Physics > Volume 2006 > January 2006
E T Linton *et al* JCAP01(2006)013 doi:10.1088/1475-7516/2006/01/013

A new search for primordial black hole evaporations using the Whipple gamma-ray telescope

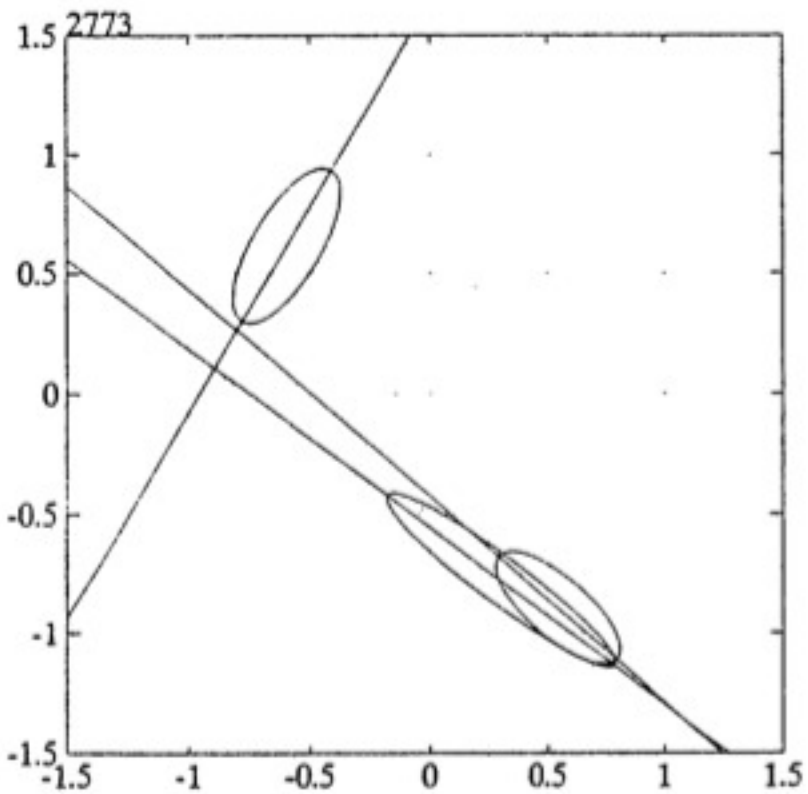
E T Linton[1], R W Atkins[2], H M Badran[3], G Blaylock[4], P J Boyle[1], J H Buckley[5], K L Byrum[6], D A Carter-Lewis[7], O Celik[8], Y C K ... J P Finley[11], P Fortin[12], K J Guiterrez[5], J Hall[2], ...[16], M Kertzman[17], D B Kieda[2], J Kildea[13], J ...[8], J S Perkins[5], F Pizlo[11], M Pohl[7], J Quinn[9], K ... Valcarcel[13], S P Wakely[1], T C Weekes[15] and

Journal of Physics: Conference Series > Volume 375 > Part 5
G Tešić (for the Veritas Collaboration) 2012 *J. Phys.: Conf. Ser.* **375** 052024 doi:10.1088/1742-6596/375/1/052024

Searching for primordial black holes with the VERITAS gamma-ray experiment

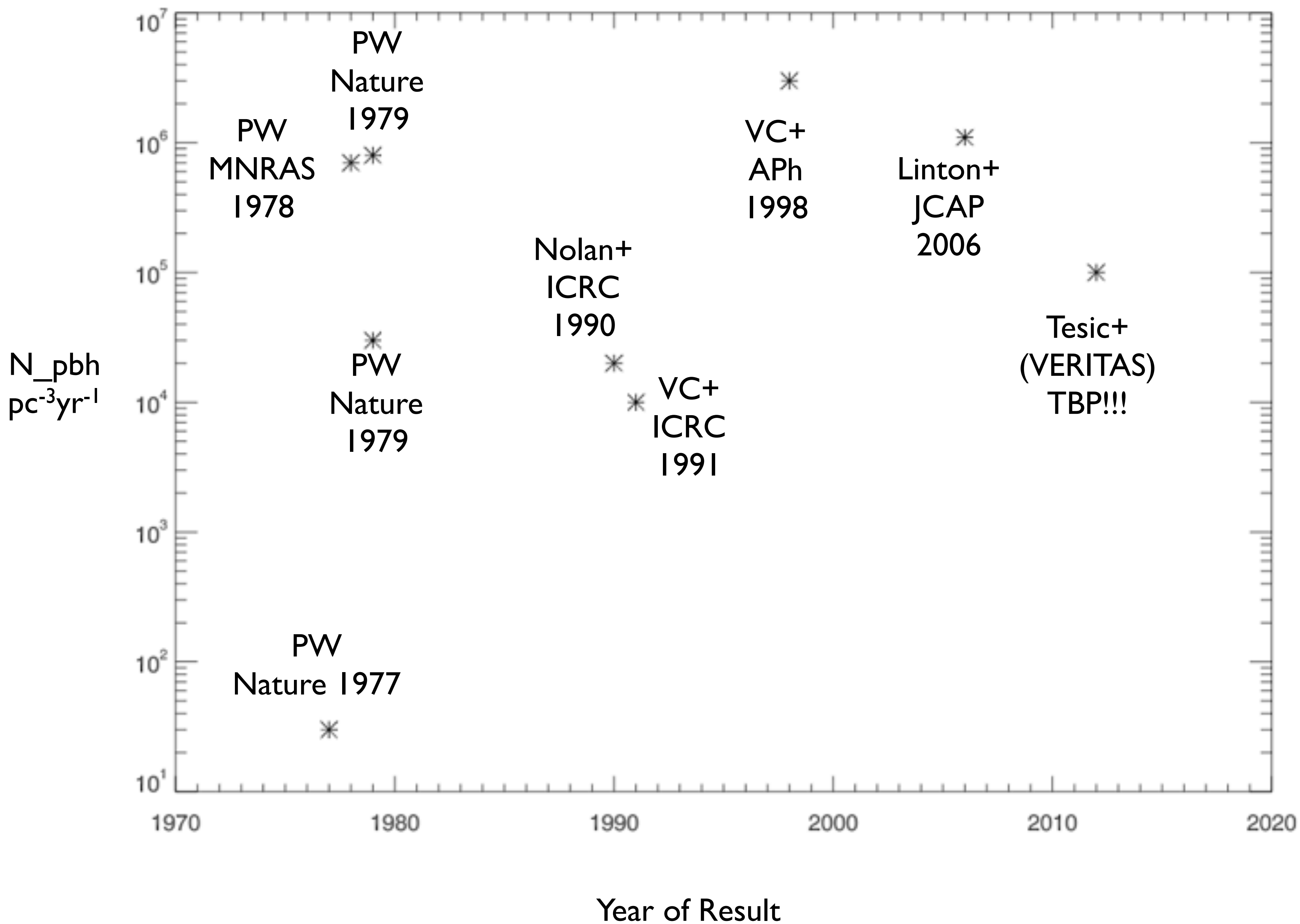
G Tešić[1] (for the Veritas Collaboration)

Looking for PBHs exploding via the standard model



1. Apply Shape cuts -- gamma-ray rate < 1 Hz
2. Find 3+ fold coincidence in 1-s
3. Look for common origin - reject others
4. Calculate expectation rate by scrambling uncut events in time and then applying cuts & then 2-3
5. Calculate fluence threshold & compare to PBH explosion energy --> sensitive distance/volume.
6. Calculate how efficiently you detect 3+ fold bursts
7. Get upper limit to PBH density very locally

Progression of PBH limits from Whipple over time (standard model)



And even building dedicated hardware for the Hagedorn model

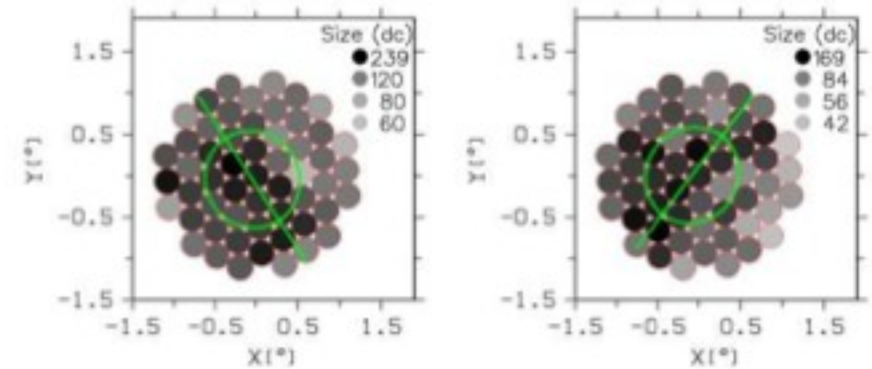
arXiv:0501.199

SGARFACE: A Novel Detector For Microsecond Gamma Ray Bursts

S. LeBohec[a b] F. Krennrich[a] and G. Sleege[a]

[a]*Physics and Astronomy Department, Iowa State University Ames, IA, 50011, USA*

[b]*Now at the Department of Physics, University of Utah Salt-Lake-City, UT, 84112-0830, USA*



You need to exploit thelateral distribution and temporal spread of the Cherenkov light from multi-photon initiated showers.
(Krennrich+ 1999)

arXiv:0812.0546

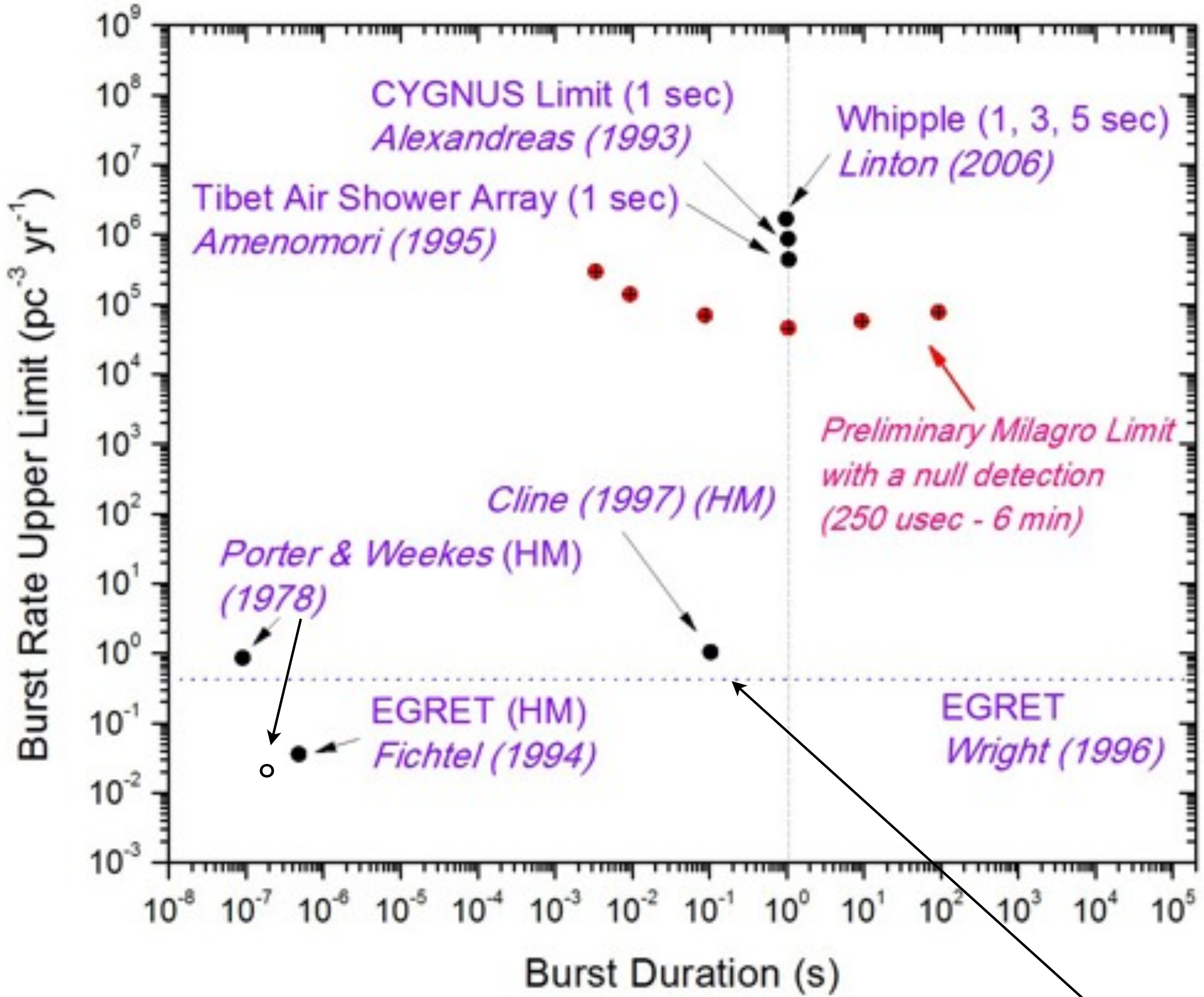
Search for Primordial Black Holes with SGARFACE

M. Schroedter[a,*], F. Krennrich[a], S. LeBohec[b], A. Falcone[c], S. J. Fegan[d], D. Horan[d], J. Kildea[g], A. W. Smith[e], J. Toner[f], T. C. Weekes[g]

[a]*Dept. of Physics and Astronomy, Iowa State University, Ames, IA 50011-3160*

[b]*Dept. of Physics, University of Utah, Salt Lake City, UT 84112-0830*

What is the status of PBH limits?

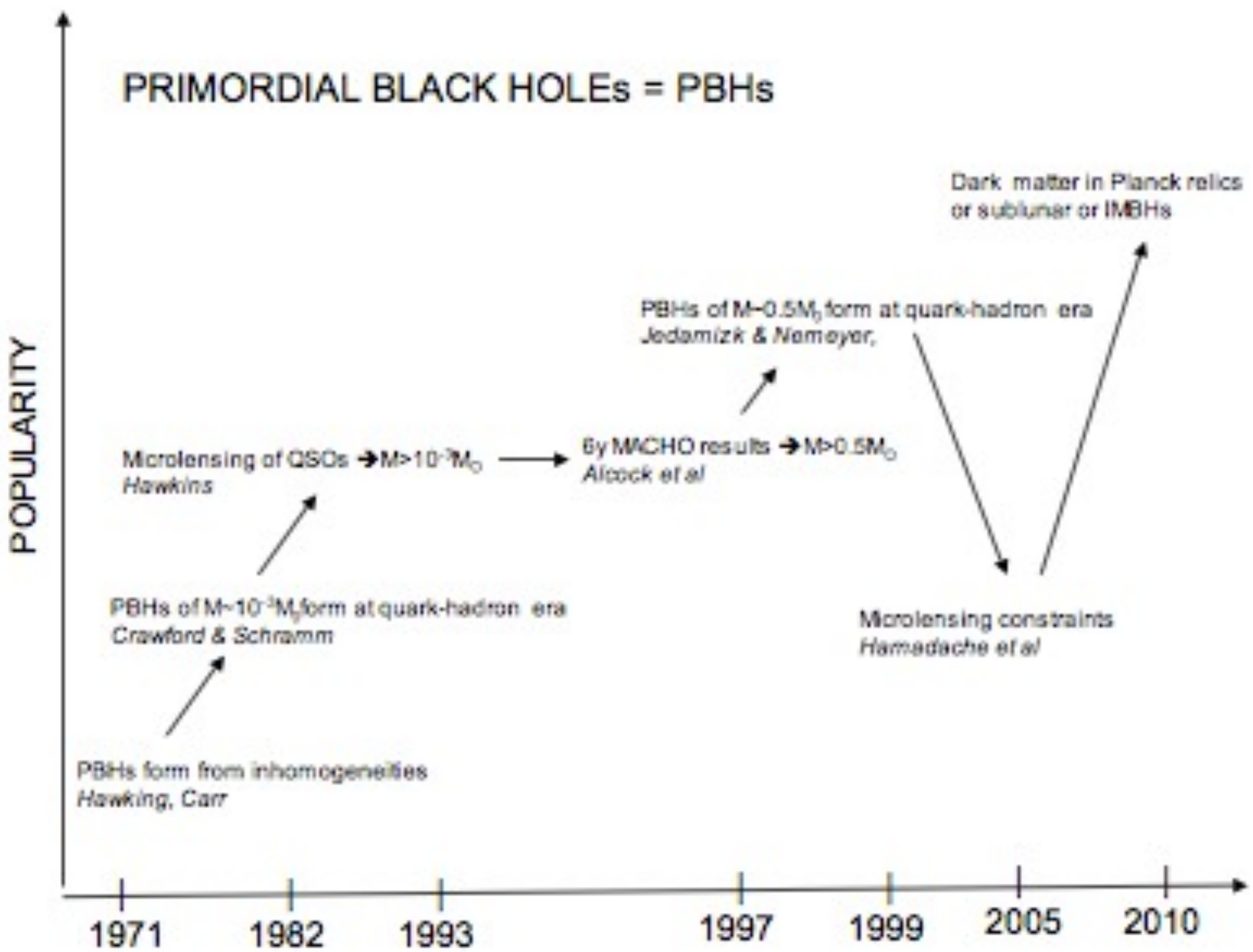


From Jane MacGibbbon

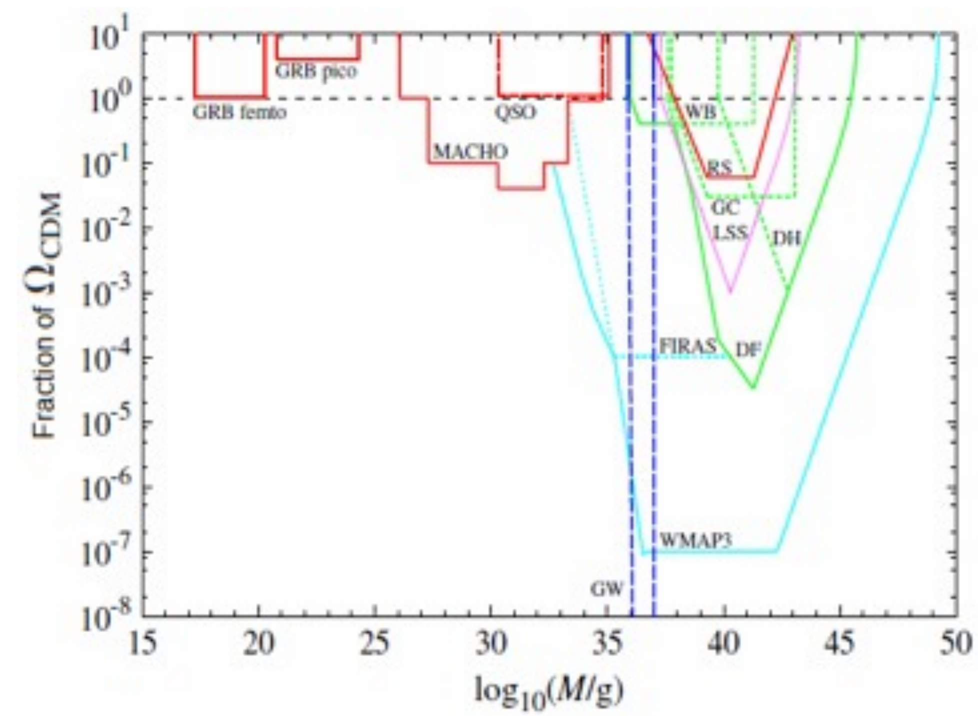
Connection to BATSE GRBs?

With EGRET and now Fermi LAT Constraints from gamma-ray diffuse now more stringent.

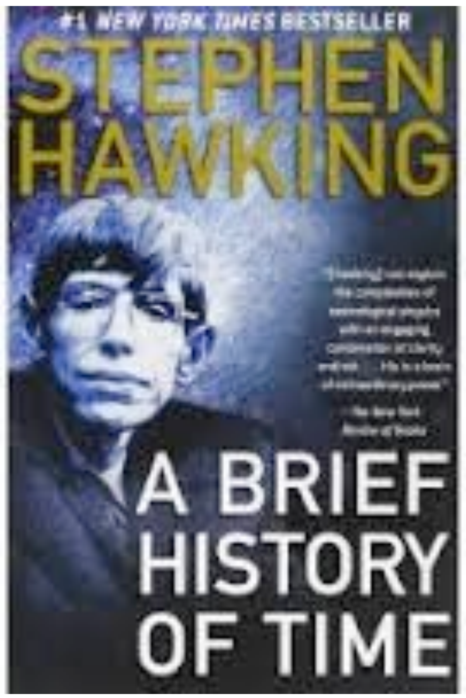
Trends in PBH popularity



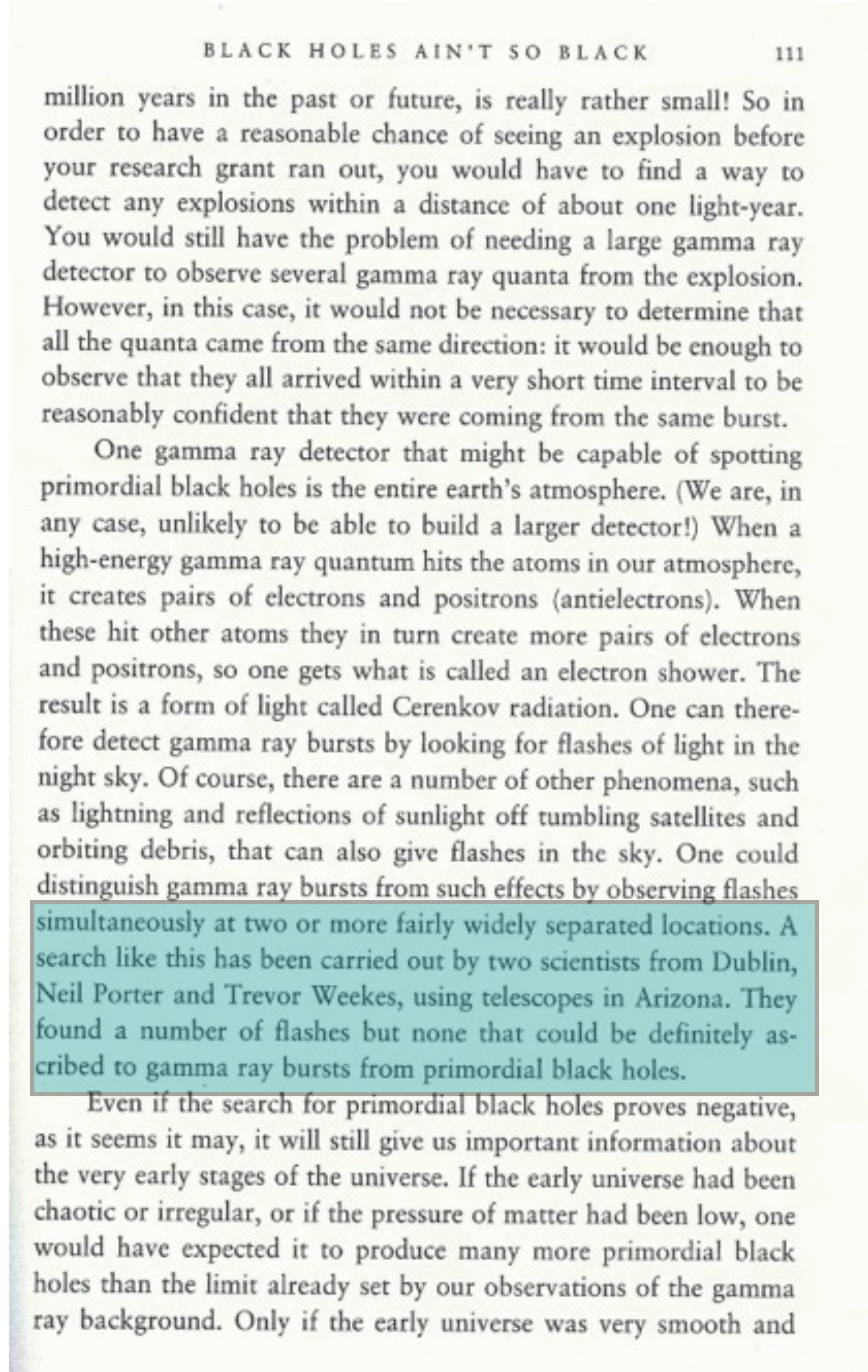
Carr+ (2010)



A brief moment in A Brief History



Only in 1st edition



BLACK HOLES AIN'T SO BLACK 111

million years in the past or future, is really rather small! So in order to have a reasonable chance of seeing an explosion before your research grant ran out, you would have to find a way to detect any explosions within a distance of about one light-year. You would still have the problem of needing a large gamma ray detector to observe several gamma ray quanta from the explosion. However, in this case, it would not be necessary to determine that all the quanta came from the same direction: it would be enough to observe that they all arrived within a very short time interval to be reasonably confident that they were coming from the same burst.

One gamma ray detector that might be capable of spotting primordial black holes is the entire earth's atmosphere. (We are, in any case, unlikely to be able to build a larger detector!) When a high-energy gamma ray quantum hits the atoms in our atmosphere, it creates pairs of electrons and positrons (antielectrons). When these hit other atoms they in turn create more pairs of electrons and positrons, so one gets what is called an electron shower. The result is a form of light called Cerenkov radiation. One can therefore detect gamma ray bursts by looking for flashes of light in the night sky. Of course, there are a number of other phenomena, such as lightning and reflections of sunlight off tumbling satellites and orbiting debris, that can also give flashes in the sky. One could distinguish gamma ray bursts from such effects by observing flashes simultaneously at two or more fairly widely separated locations. A search like this has been carried out by two scientists from Dublin, Neil Porter and Trevor Weekes, using telescopes in Arizona. They found a number of flashes but none that could be definitely ascribed to gamma ray bursts from primordial black holes.

Even if the search for primordial black holes proves negative, as it seems it may, it will still give us important information about the very early stages of the universe. If the early universe had been chaotic or irregular, or if the pressure of matter had been low, one would have expected it to produce many more primordial black holes than the limit already set by our observations of the gamma ray background. Only if the early universe was very smooth and

Are PBHs still important?

- PBHs provided a scientific focus at a difficult time for Whipple
- They are important to cosmology, high-energy extreme particle physics, thermodynamics, GR, quantum gravity, dark matter
- Jane MacGibbon: “we should also all try to think 'outside the box' about ways in which we may be able to detect (and hence prove) the 'gravitational thermal' nature of black holes predicted by Hawking and Bekenstein; even stellar mass black holes are thermal beast (even if they have a cool temperature)”