Exploring Supermassive Compact Dark Matter with the Millilensing Effect of Gamma-Ray Bursts

Huan Zhou, WuHan University

Collaborators: Zong-Hong Zhu, Zhengxiang Li, He Gao, An Li, Shi-Jie Lin

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武漢大學
Wuhan University

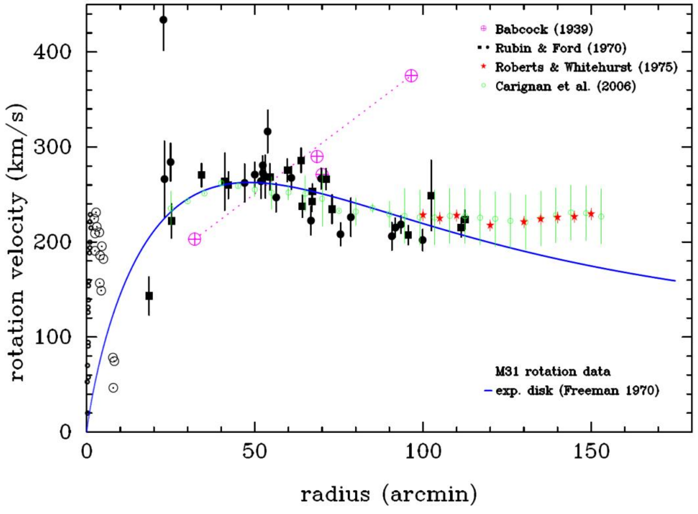
Outline

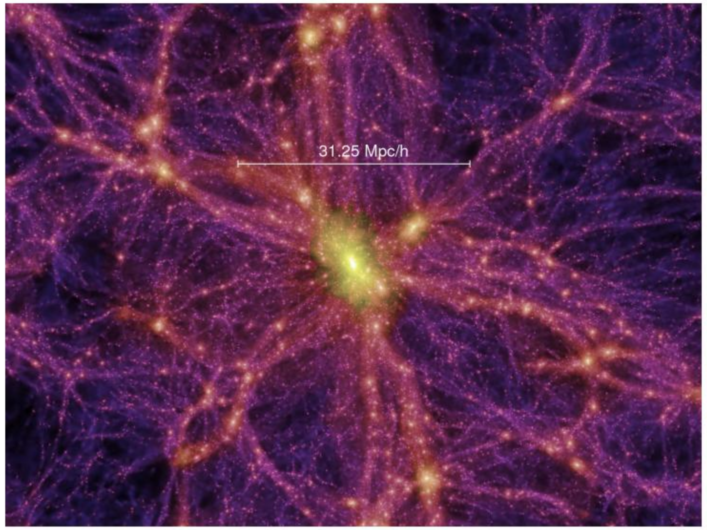
- Introduction
- Millilensing GRBs
- Constrants on compact dark matter
- Summary

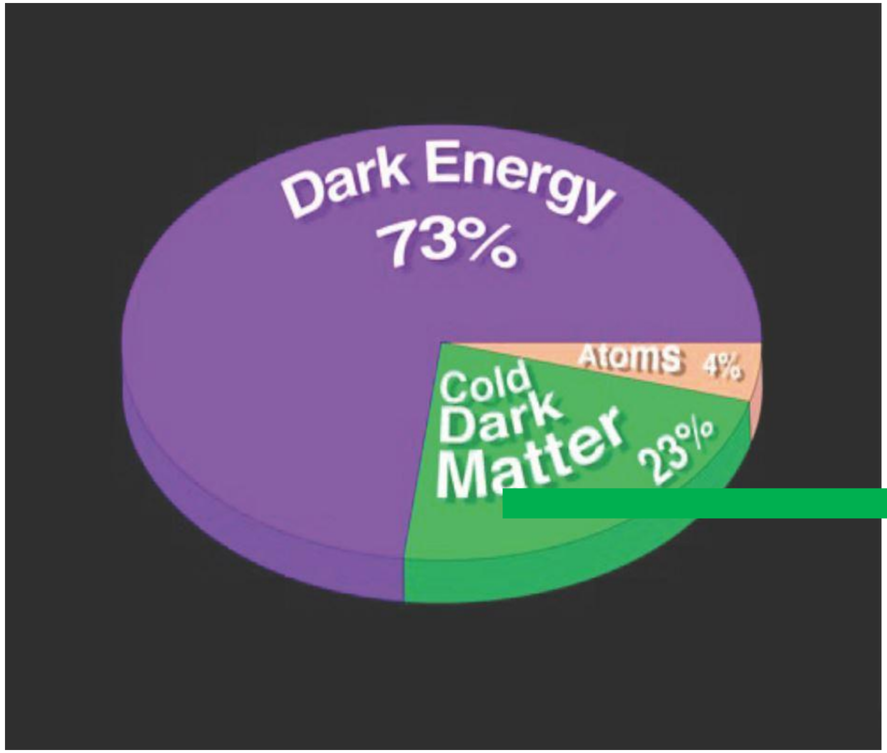
01

Introduction

1.Introduction



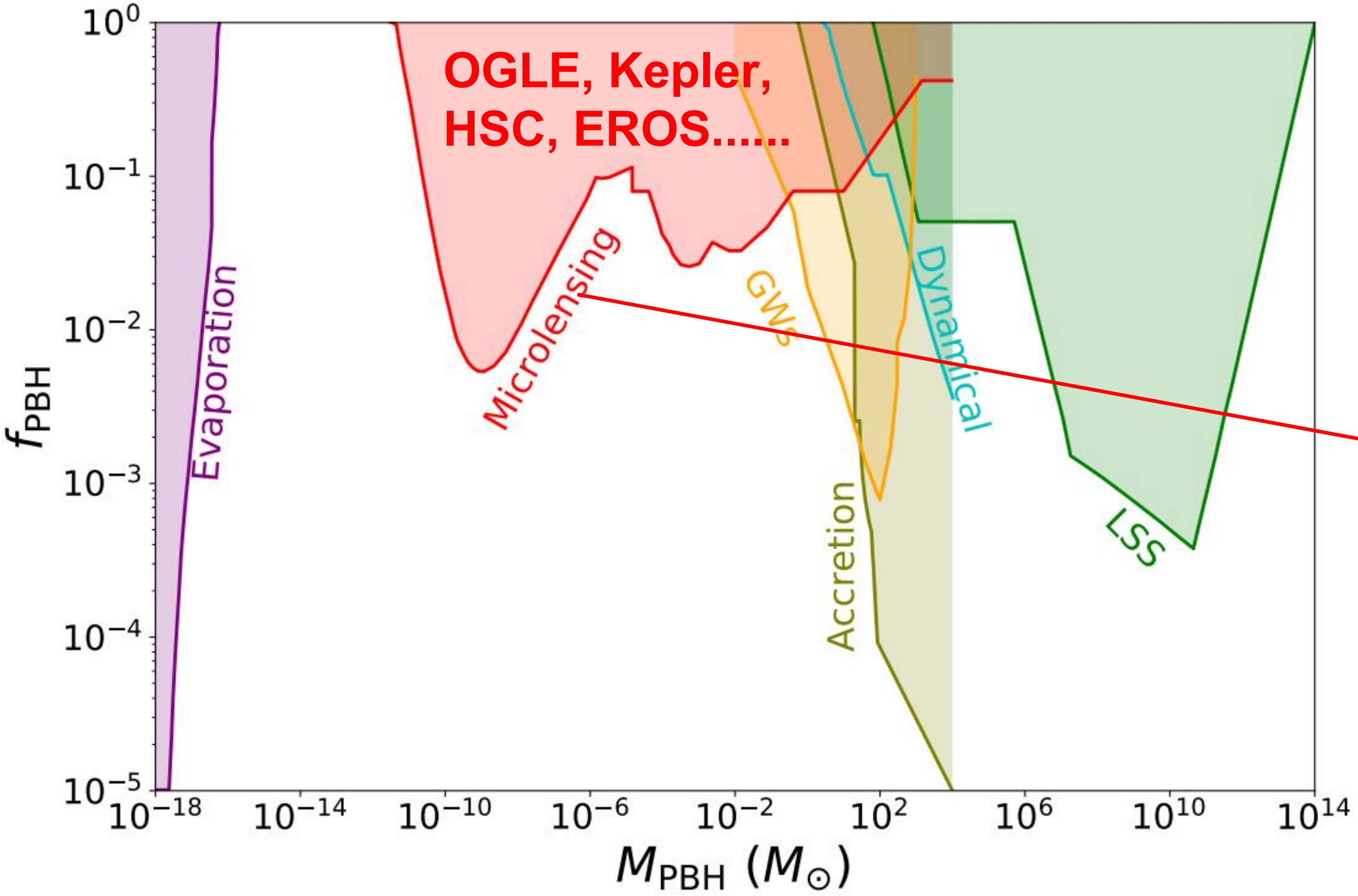




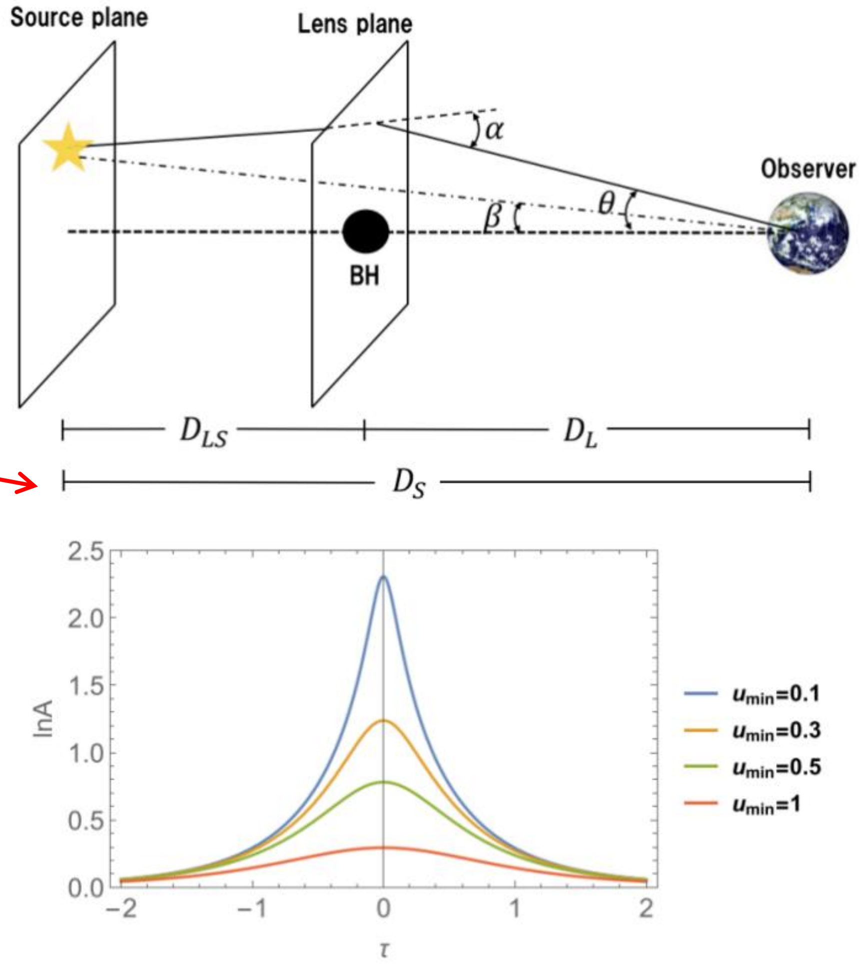
Compact dark matter, such as Primordial Black Hole?

$$f_{\rm CO} \equiv \frac{\Omega_{\rm CO}}{\Omega_{\rm DM}}$$

1.Introduction

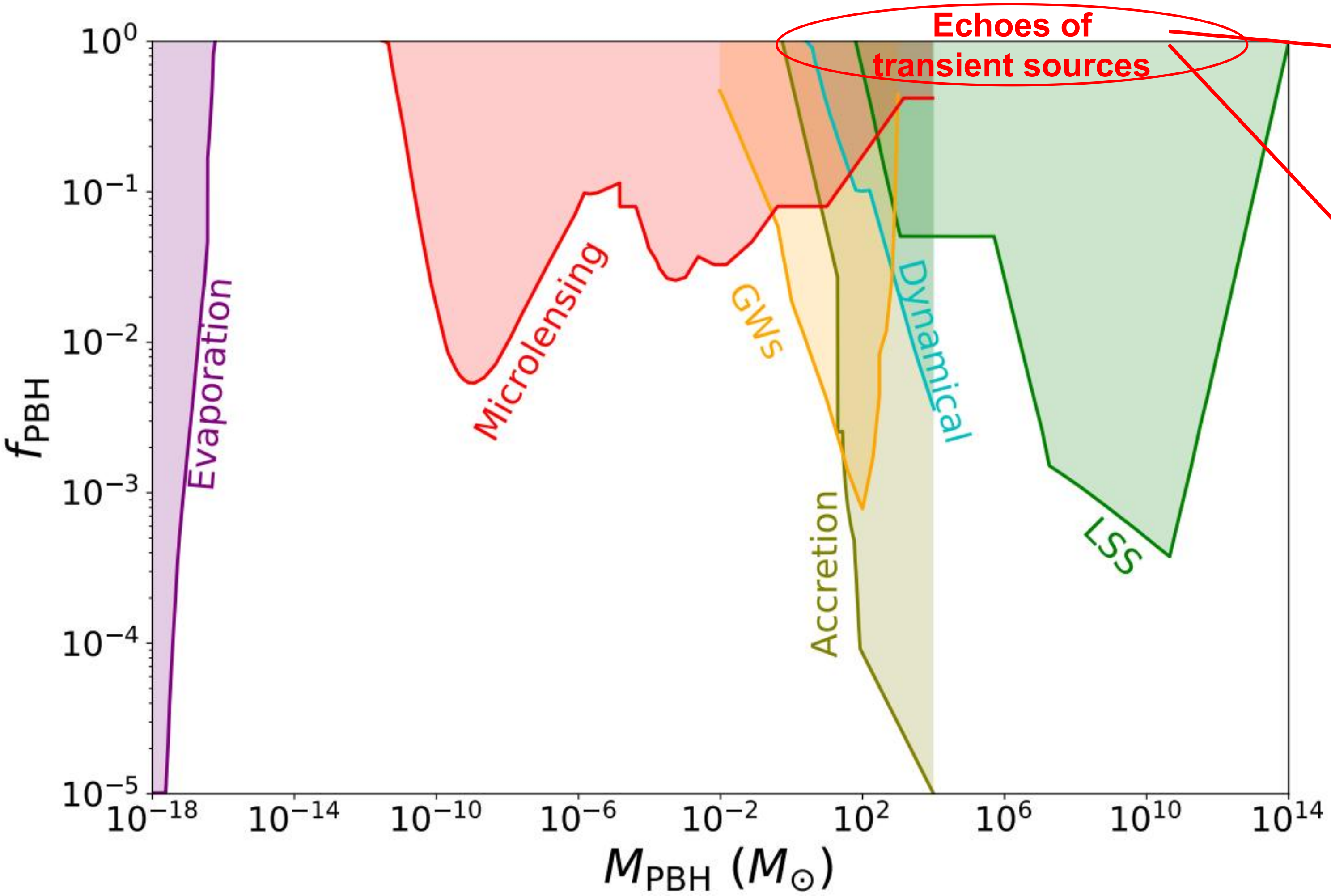


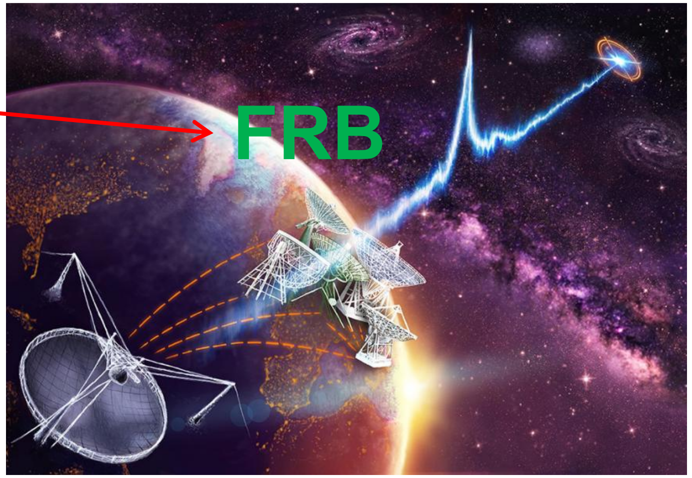
Carr, B., et al., 2021, Rep. Prog. Phys. 84, 116902.
Green A M, Kavanagh B J., 2021, J Phys G, 48, 043001.



Sasaki et al., 2018, CQG, 35, 063001

1.Introduction



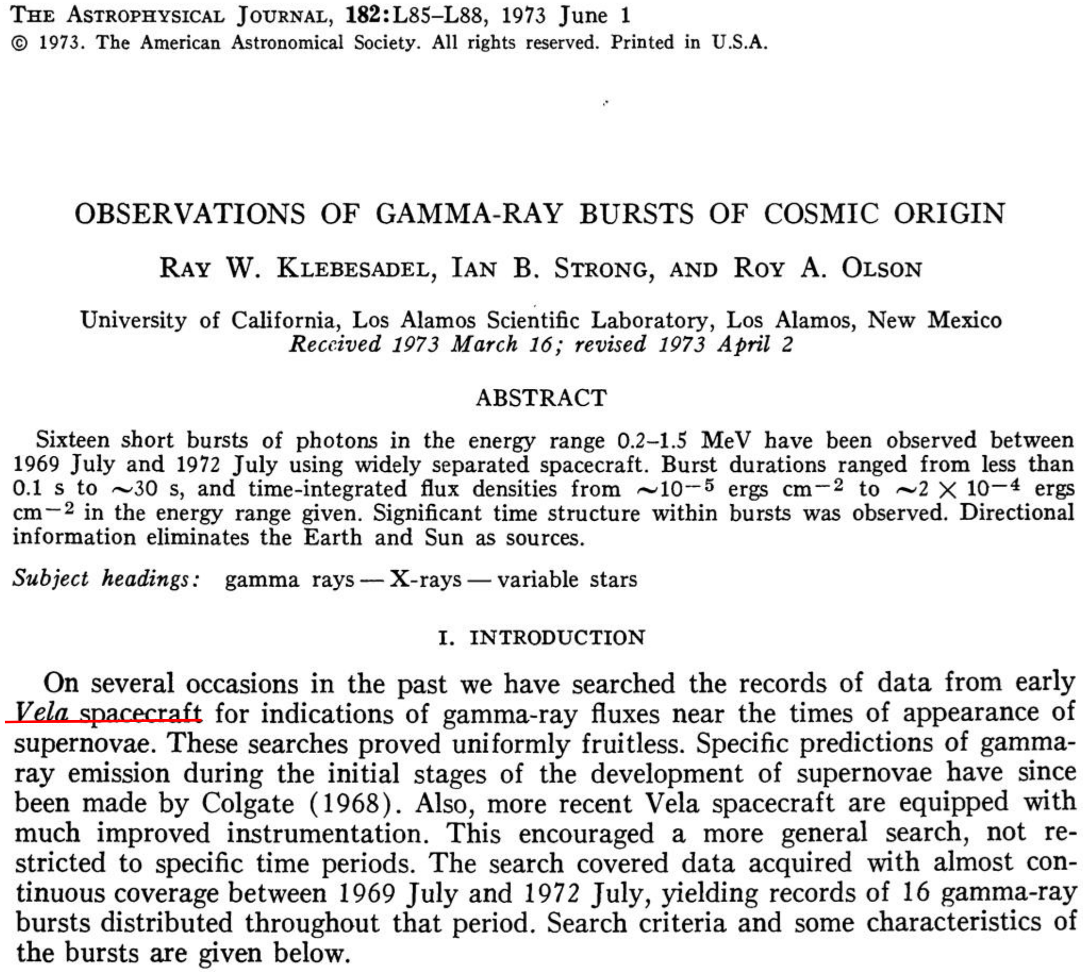


02

Millilensing GRBs

2.1. Introduction: GRB

Discovery of GRBs



THE ASTROPHYSICAL JOURNAL, **182:**L85–L88, 1973 June 1

OBSERVATIONS OF GAMMA-RAY BURSTS OF COSMIC ORIGIN

RAY W. KLEBESADEL, IAN B. STRONG, AND ROY A. OLSON

University of California, Los Alamos Scientific Laboratory, Los Alamos, New Mexico

Received 1973 March 16; revised 1973 April 2

ABSTRACT

Sixteen short bursts of photons in the energy range 0.2–1.5 MeV have been observed between 1969 July and 1972 July using widely separated spacecraft. Burst durations ranged from less than 0.1 s to ~30 s, and time-integrated flux densities from $\sim 10^{-5}$ ergs cm^{-2} to $\sim 2 \times 10^{-4}$ ergs cm^{-2} in the energy range given. Significant time structure within bursts was observed. Directional information eliminates the Earth and Sun as sources.

Subject headings: gamma rays — X-rays — variable stars

I. INTRODUCTION

On several occasions in the past we have searched the records of data from early *Vela* spacecraft for indications of gamma-ray fluxes near the times of appearance of supernovae. These searches proved uniformly fruitless. Specific predictions of gamma-ray emission during the initial stages of the development of supernovae have since been made by Colgate (1968). Also, more recent Vela spacecraft are equipped with much improved instrumentation. This encouraged a more general search, not restricted to specific time periods. The search covered data acquired with almost continuous coverage between 1969 July and 1972 July, yielding records of 16 gamma-ray bursts distributed throughout that period. Search criteria and some characteristics of the bursts are given below.

Key observational properties

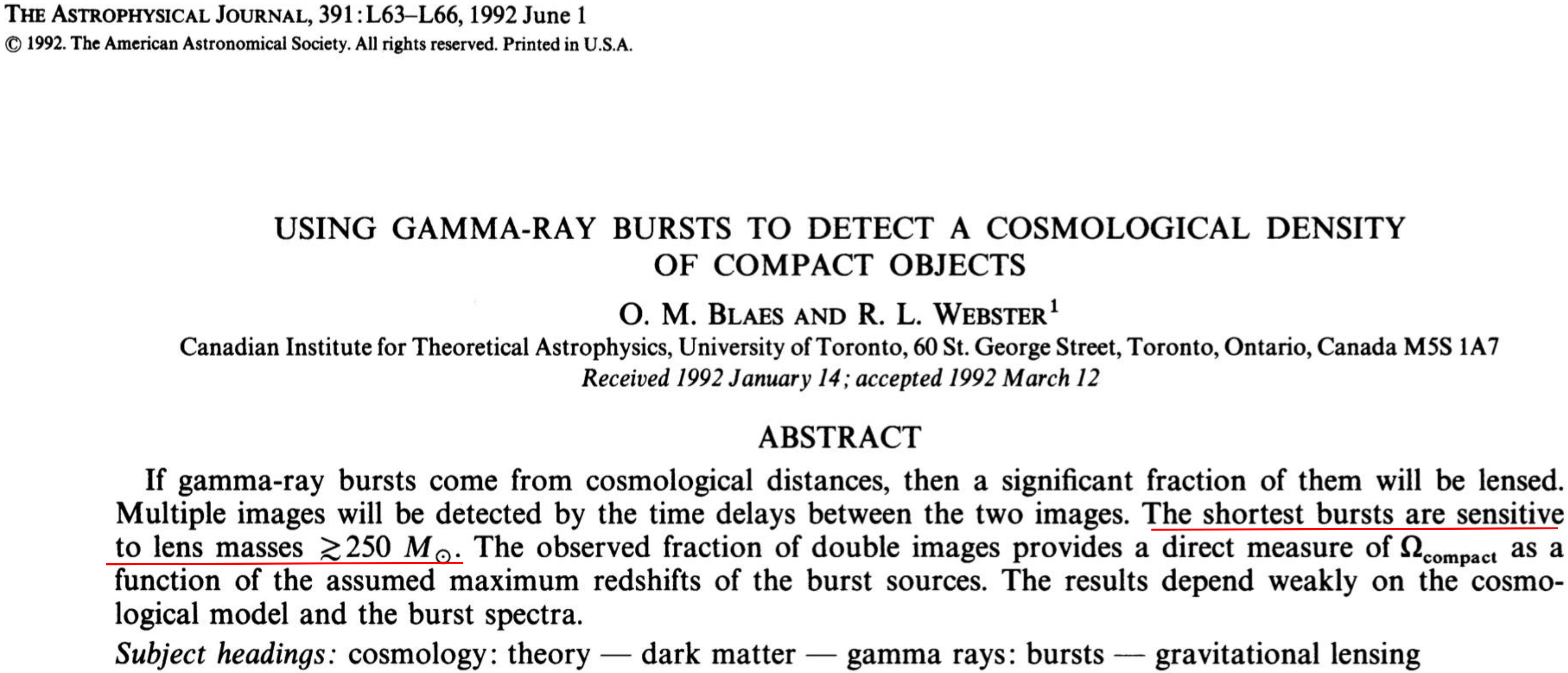
- ☐ Duration: milliseconds-hours, short bursts (<2s mergers of compact objects), long bursts (>2s, deaths of massive stars)
- ☐ Cosmological redshift: extragalactic origin
- ☐ High emission energy: 10^{48}-10^{55} ergs
- ☐ High rate: More than 1 per day is observed

2.1. Introduction: GRB

Cosmological and astrophysical probes: GRB

- ☐ Testing fundamental physics: Amelino-Camelia, G, et al., 1998, Nature, 393, 763
- ☐ Using GRBs as standard candle to constrain cosmological parameters: Amati, L., et al., 2008, MNRAS, 391, 577
- ☐ Lensed GRBs for probing compact dark matter: Blaes, O. M., and Webster, R. L., 1992, ApJL, 391, L63
- ☐ ......

2.2. Millilensing theory



THE ASTROPHYSICAL JOURNAL, 391:L63–L66, 1992 June 1

USING GAMMA-RAY BURSTS TO DETECT A COSMOLOGICAL DENSITY OF COMPACT OBJECTS

O. M. BLAES AND R. L. WEBSTER[1]
Canadian Institute for Theoretical Astrophysics, University of Toronto, 60 St. George Street, Toronto, Ontario, Canada M5S 1A7
Received 1992 January 14; accepted 1992 March 12

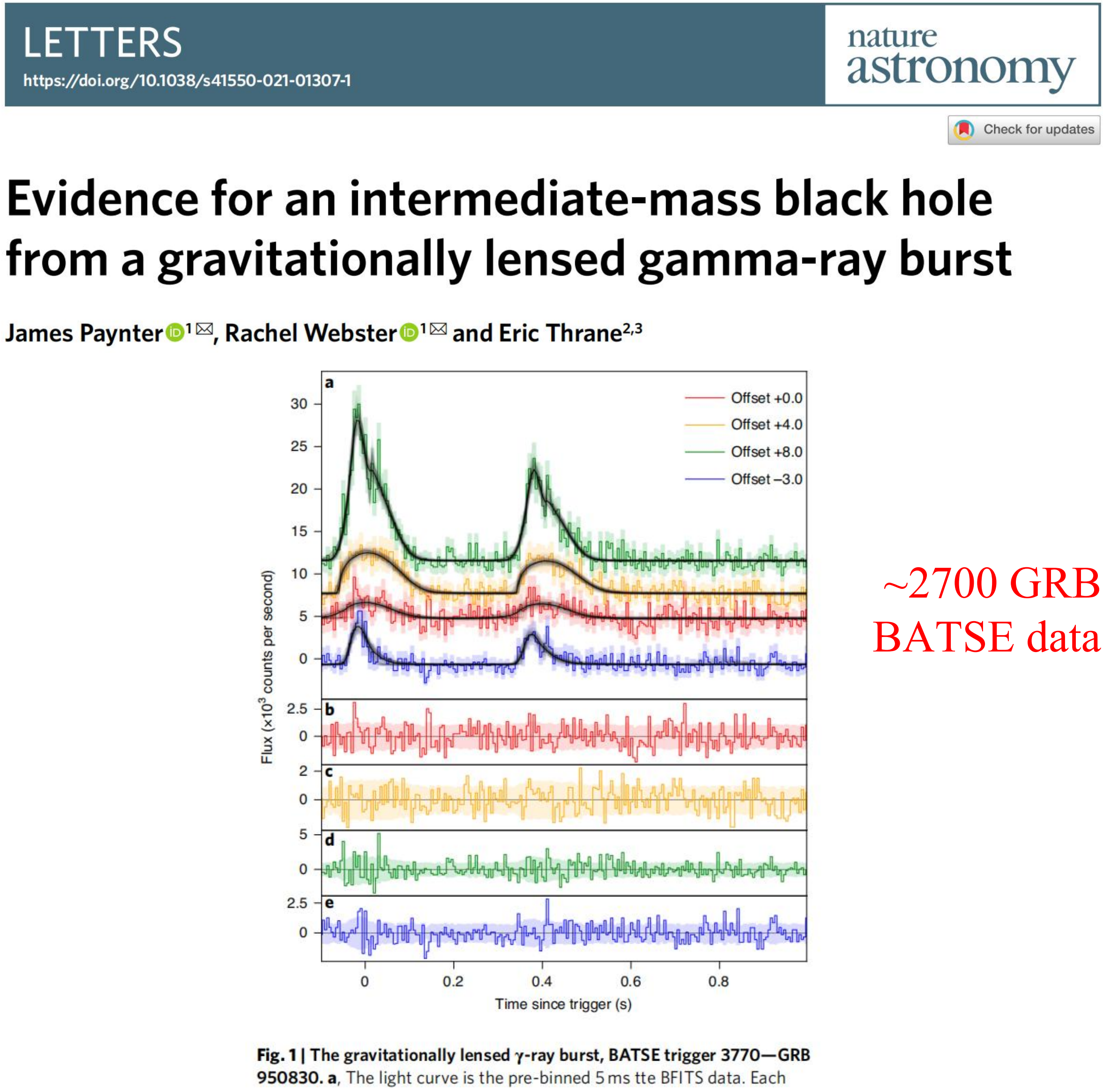
ABSTRACT

If gamma-ray bursts come from cosmological distances, then a significant fraction of them will be lensed. Multiple images will be detected by the time delays between the two images. The shortest bursts are sensitive to lens masses $\gtrsim 250\ M_\odot$. The observed fraction of double images provides a direct measure of $\Omega_{\rm compact}$ as a function of the assumed maximum redshifts of the burst sources. The results depend weakly on the cosmological model and the burst spectra.

Subject headings: cosmology: theory — dark matter — gamma rays: bursts — gravitational lensing

$$\boxed{\Delta t \approx 1\ \mathrm{ms}\left(\frac{M_{\rm L}}{30\ M_\odot}\right)}$$

2.2. Millilensing theory



LETTERS
https://doi.org/10.1038/s41550-021-01307-1
nature astronomy

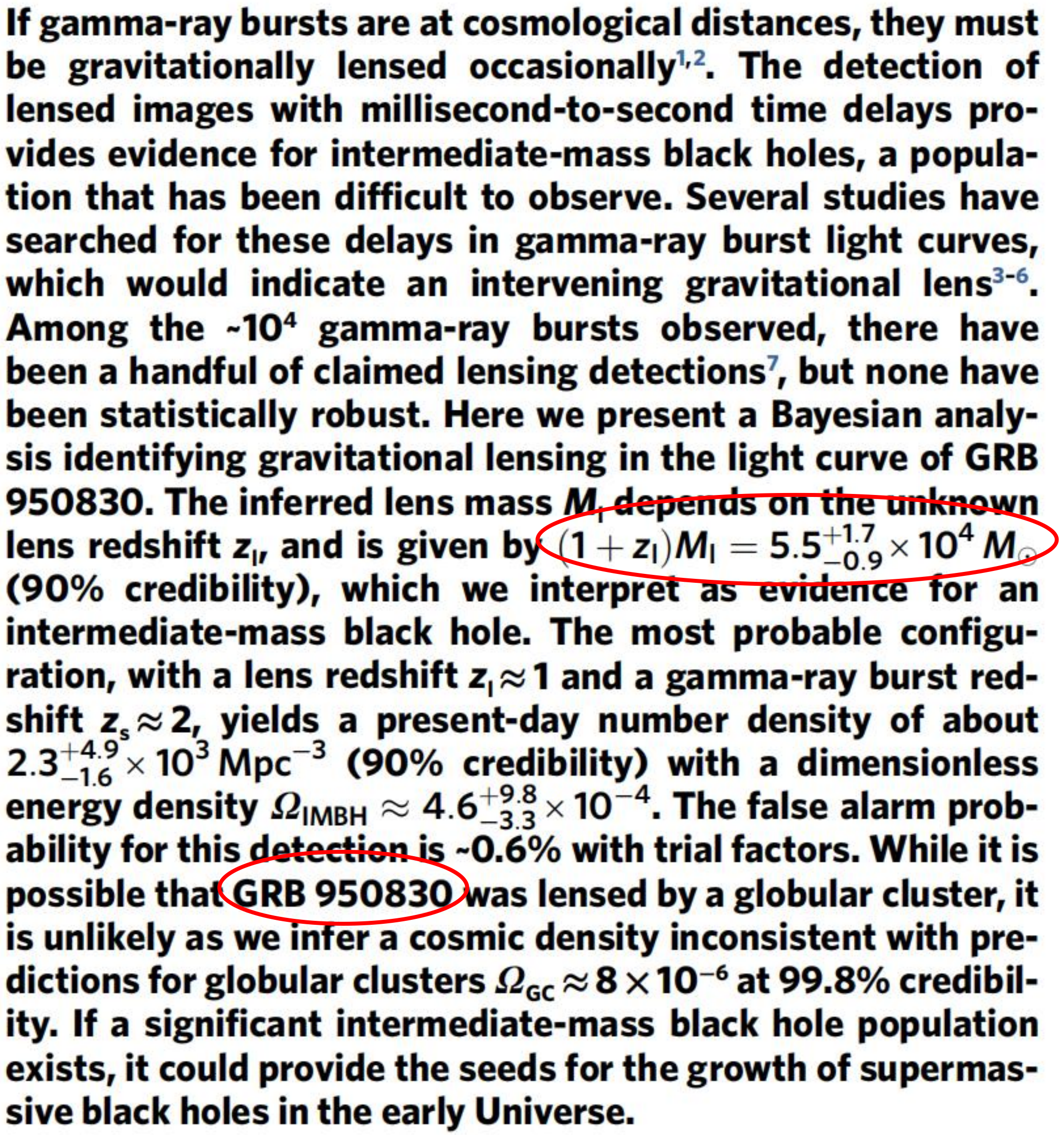
Check for updates

Evidence for an intermediate-mass black hole from a gravitationally lensed gamma-ray burst

James Paynter[1], Rachel Webster[1] and Eric Thrane[2,3]

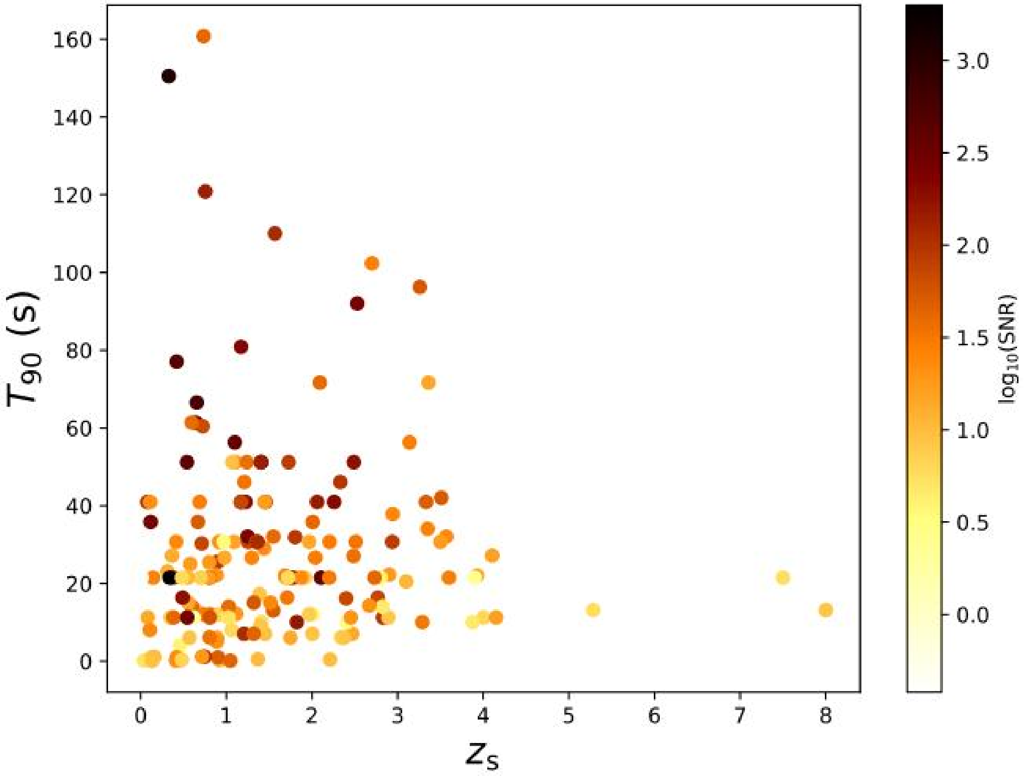
Fig. 1 | The gravitationally lensed γ-ray burst, BATSE trigger 3770—GRB 950830. a, The light curve is the pre-binned 5 ms tte BFITS data. Each

~2700 GRBs in BATSE dataset

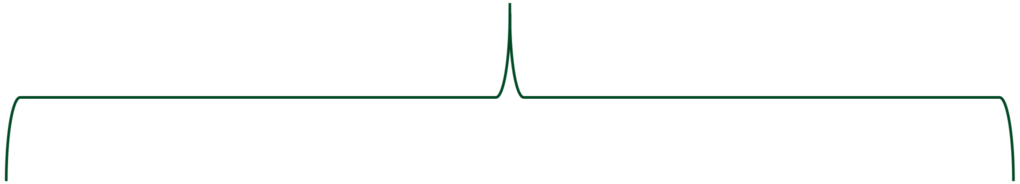


If gamma-ray bursts are at cosmological distances, they must be gravitationally lensed occasionally[1,2]. The detection of lensed images with millisecond-to-second time delays provides evidence for intermediate-mass black holes, a population that has been difficult to observe. Several studies have searched for these delays in gamma-ray burst light curves, which would indicate an intervening gravitational lens[3-6]. Among the ~10^4 gamma-ray bursts observed, there have been a handful of claimed lensing detections[7], but none have been statistically robust. Here we present a Bayesian analysis identifying gravitational lensing in the light curve of GRB 950830. The inferred lens mass M_l depends on the unknown lens redshift z_l, and is given by $(1+z_l)M_l = 5.5^{+1.7}_{-0.9} \times 10^4\, M_\odot$ (90% credibility), which we interpret as evidence for an intermediate-mass black hole. The most probable configuration, with a lens redshift $z_l \approx 1$ and a gamma-ray burst redshift $z_s \approx 2$, yields a present-day number density of about $2.3^{+4.9}_{-1.6} \times 10^3\ \mathrm{Mpc}^{-3}$ (90% credibility) with a dimensionless energy density $\Omega_{\mathrm{IMBH}} \approx 4.6^{+9.8}_{-3.3} \times 10^{-4}$. The false alarm probability for this detection is ~0.6% with trial factors. While it is possible that GRB 950830 was lensed by a globular cluster, it is unlikely as we infer a cosmic density inconsistent with predictions for globular clusters $\Omega_{\mathrm{GC}} \approx 8 \times 10^{-6}$ at 99.8% credibility. If a significant intermediate-mass black hole population exists, it could provide the seeds for the growth of supermassive black holes in the early Universe.

2.2. Millilensing theory



3000 GRBs detected by Fermi up to 2022.08
(https://heasarc.gsfc.nasa.gov/FTP/fermi/)



GRB 200716C
(Yang, X., et al., 2021, ApJL, 921, L29;
Wang, Y., et al., 2021, ApJL, 918, L34.)

GRB 210812A
(Veres, P., et al., 2021, ApJL, 921, L30.)

GRB 081126A
GRB 090717A
GRB 081122A
GRB 110517B
(Lin, S.-J., et al., 2021, ApJ, 931, 4.)

Pass both light curve similarity test and hardness similarity test
(Mukherjee, O., and Nemirof, R. J., 2024, MNRAS, 527, L132;
Mukherjee, O., and Nemirof, R. J., 2024, MNRAS, 529, L83.)

2.3. Hierarchical Bayesian Inference

$$\Phi = [\boldsymbol{p}_{\mathrm{mf}}, f_{\mathrm{CO}}]$$

$$N(\Phi) = \int dm \int dz_{\mathrm{s}} \int_0^{z_{\mathrm{s}}} dz_{\mathrm{l}} \frac{dn(m,\Phi)}{dm} \times \frac{d\chi(z_{\mathrm{l}})}{dz_{\mathrm{l}}} (1+z_{\mathrm{l}})^2 \sigma(m, z_{\mathrm{l}}, z_{\mathrm{s}}) N_{\mathrm{s}} P_{\mathrm{s}}(z_{\mathrm{s}}),$$

Likelihood of len mass for each millilensing events

$$\text{likelihood for } \Phi: \; p(d|\Phi) \propto N(\Phi)^{N_{\mathrm{obs}}} e^{-N_{\mathrm{det}}(\Phi)} \prod_i^{N_{\mathrm{obs}}} \int d\lambda L(d_i|m) p_{\mathrm{pop}}(m|\Phi)$$

$$N_{\mathrm{det}}(\Phi) = \int dm \int dz_{\mathrm{s}} \int_0^{z_{\mathrm{s}}} dz_{\mathrm{l}} \frac{dn(m,\Phi)}{dm} \times \frac{d\chi(z_{\mathrm{l}})}{dz_{\mathrm{l}}} (1+z_{\mathrm{l}})^2 \sigma_{\mathrm{det}}(\lambda, m, z_{\mathrm{l}}, z_{\mathrm{s}}) N_{\mathrm{s}} P_{\mathrm{s}}(z_{\mathrm{s}}),$$

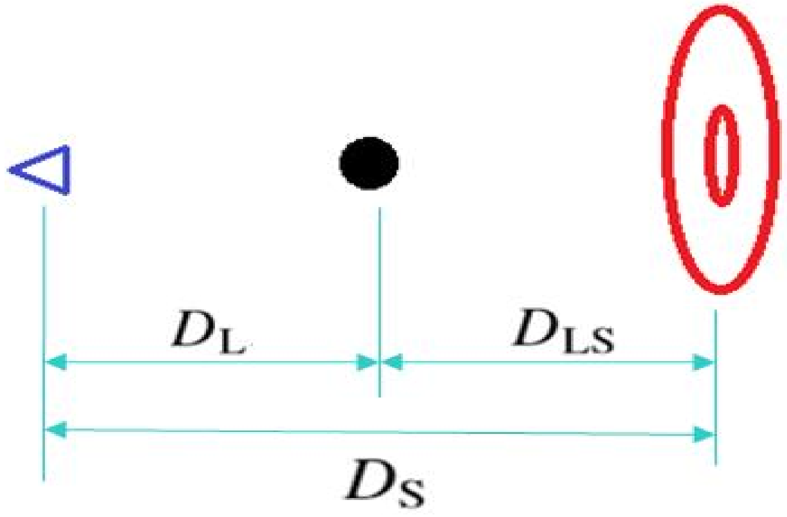
$$p_{\mathrm{pop}}(m|\Phi) = \frac{1}{N(\Phi)} \frac{dN(m,\Phi)}{dm} = \psi(m, \boldsymbol{p}_{\mathrm{mf}}).$$

2.3. Hierarchical Bayesian Inference

Selection effect

$$\boxed{\begin{aligned}N_{\rm det}(\Phi) = \int dm \int dz_{\rm s} \int_0^{z_{\rm s}} dz_{\rm l} \frac{dn(m,\Phi)}{dm} \times \\ \frac{d\chi(z_{\rm l})}{dz_{\rm l}}(1+z_{\rm l})^2 \sigma_{\rm det}(\lambda, m, z_{\rm l}, z_{\rm s}) N_{\rm s} P_{\rm s}(z_{\rm s}),\end{aligned}}$$

$$\begin{aligned}\sigma_{\rm det}(\lambda, m, z_{\rm l}, z_{\rm s}) = \frac{4\pi m D_{\rm l} D_{\rm ls}}{D_{\rm s}} \times \\ [y^2_{\rm max}({\rm SNR}) - y^2_{\rm min}(w)].\end{aligned}$$

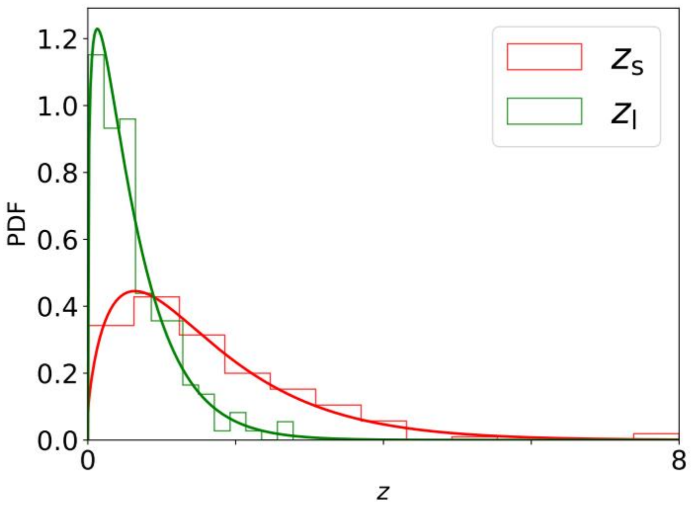


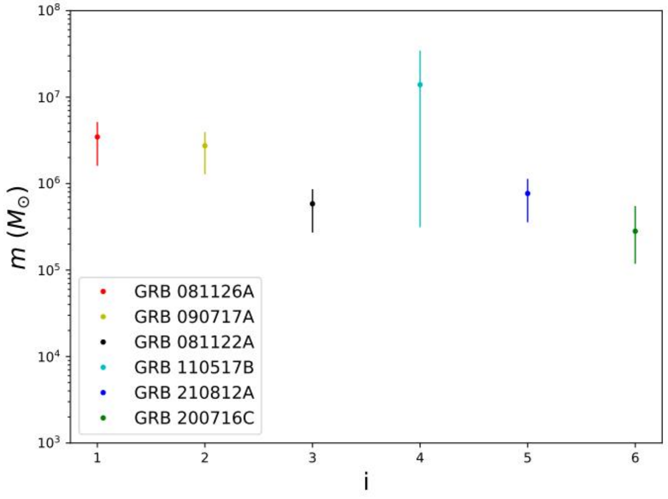
Measurement uncertainty

$$\boxed{L(d_i|m)}$$

$$\downarrow$$

$$P_i(z_{\rm l}) = \frac{1}{\tau(z_{{\rm s},i})} \frac{d\tau(z_{{\rm s},i})}{dz_{\rm l}},$$





03 Constraints on compact dark matter

3. Constraints on compact dark matter

PHYSICAL REVIEW D **109,** L121303 (2024)

Letter

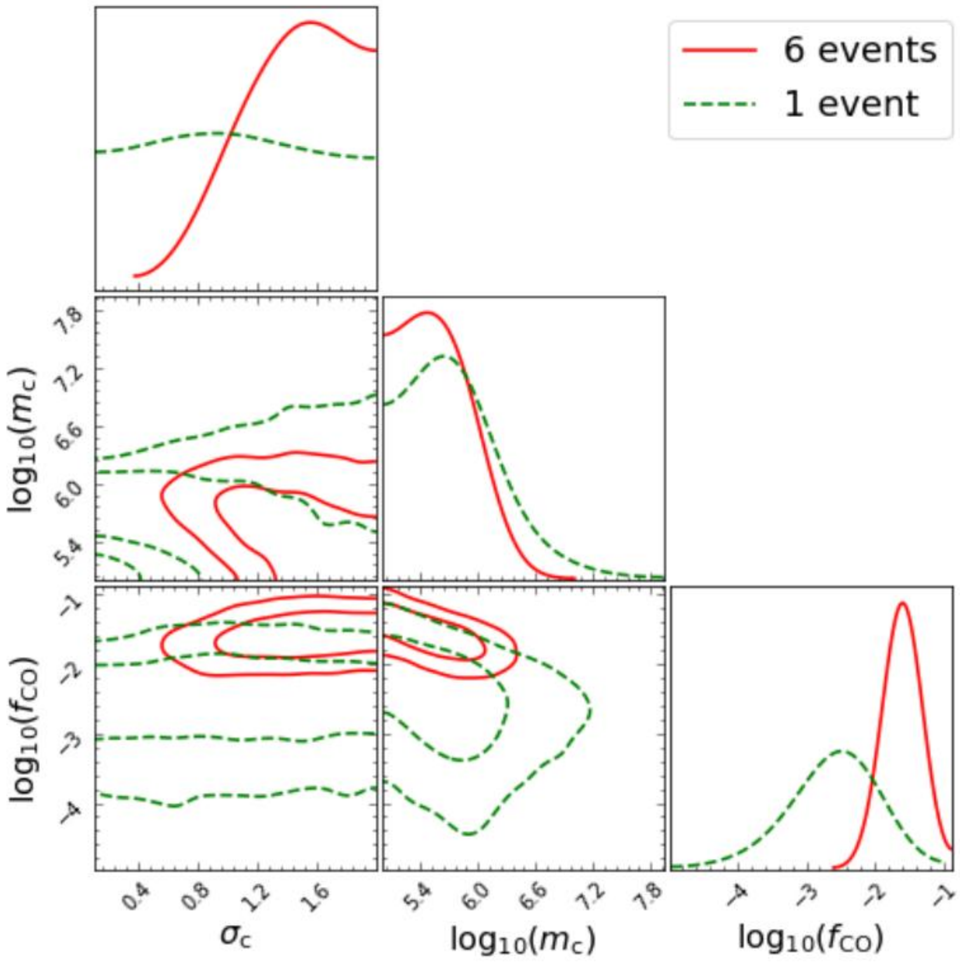
Exploring supermassive compact dark matter with the millilensing effect of gamma-ray bursts

Huan Zhou,[1] An Li,[2] Shi-Jie Lin,[2] Zhengxiang Li,[2,3,*] He Gao,[2,3,†] and Zong-Hong Zhu[1,2,‡]
[1]*Department of Astronomy, School of Physics and Technology, Wuhan University, Wuhan 430072, China*
[2]*Department of Astronomy, Beijing Normal University, Beijing 100875, China*
[3]*Institute for Frontiers in Astronomy and Astrophysics, Beijing Normal University, Beijing 102206, China*

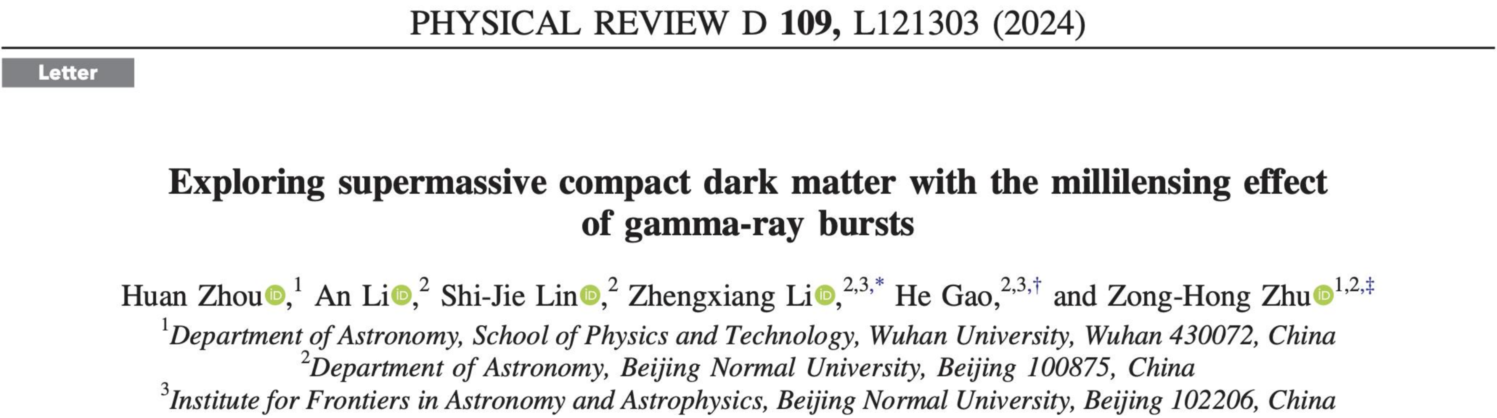
Log-normal mass function

$$\psi(m, \boldsymbol{p}_{\mathrm{mf}} = [\sigma_{\mathrm{c}}, m_{\mathrm{c}}]) = \frac{1}{\sqrt{2\pi}\sigma_{\mathrm{c}} m} \times \exp\left(-\frac{\ln^2(m/m_{\mathrm{c}})}{2\sigma_{\mathrm{c}}^2}\right).$$

Model	Hyperarameter Φ	Prior
Log-normal	σ_{c}	$\mathcal{U}[0.1,\ 2]$
	m_{c}	lg-$\mathcal{U}[5,\ 8]$
	f_{CO}	lg-$\mathcal{U}[-5, 0]$



3. Constraints on compact dark matter



PHYSICAL REVIEW D **109,** L121303 (2024)

Letter

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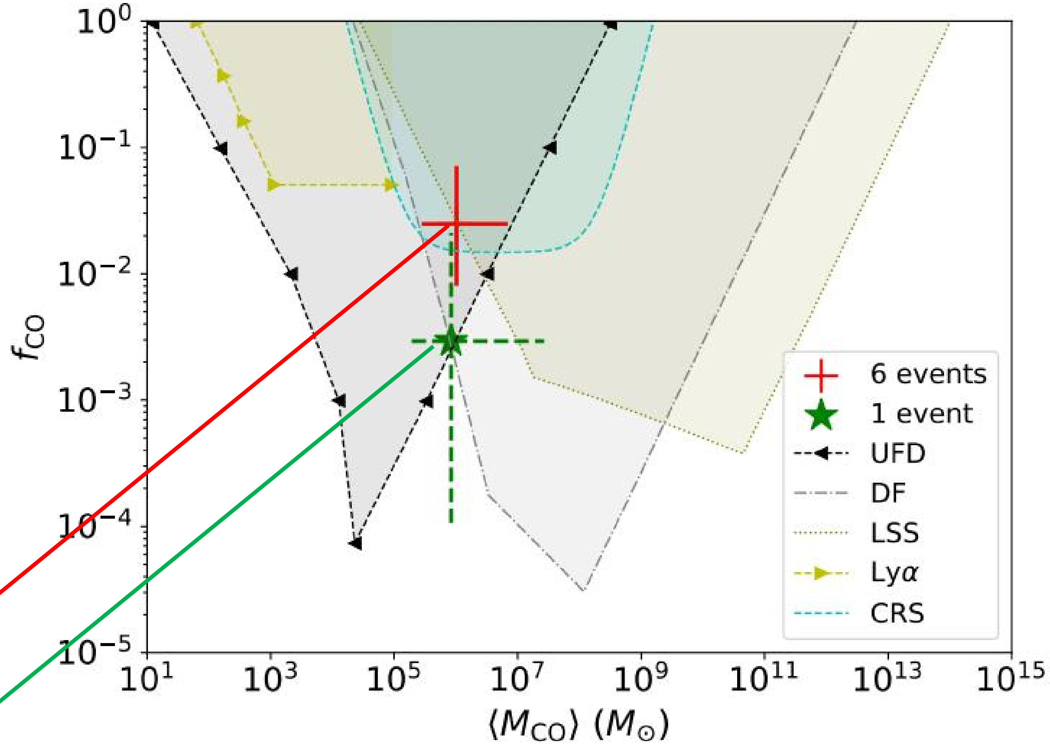
[1] *Department of Astronomy, School of Physics and Technology, Wuhan University, Wuhan 430072, China*
[2] *Department of Astronomy, Beijing Normal University, Beijing 100875, China*
[3] *Institute for Frontiers in Astronomy and Astrophysics, Beijing Normal University, Beijing 102206, China*

$$\langle M_{\rm CO}\rangle = \int m\psi(m,\boldsymbol{\sigma}_{\rm c},m_{\rm c})dm = m_{\rm c}e^{\sigma_{\rm c}^2/2}.$$

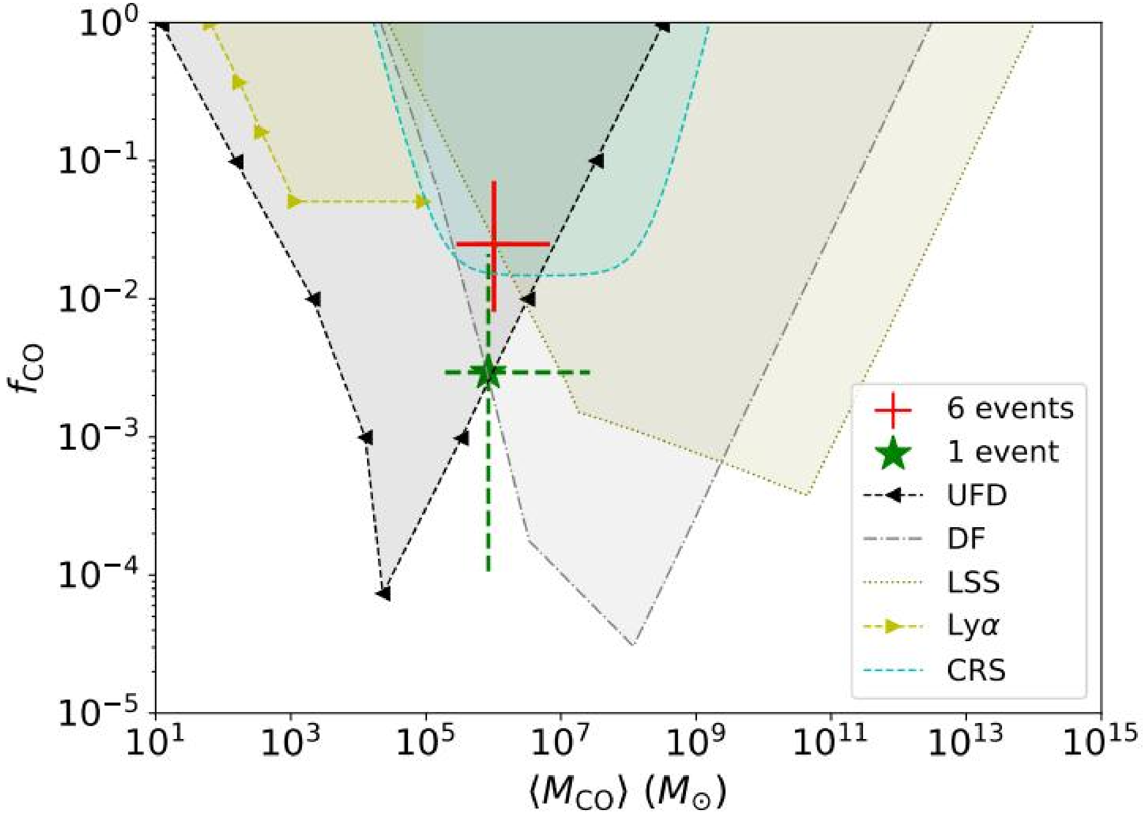
	$\sigma_{\rm c}$	$\log_{10}(m_{\rm c})$	$\log_{10}(f_{\rm CO})$
6 events	$1.47^{+0.35}_{-0.40}$	$5.55^{+0.38}_{-0.36}$	$-1.60^{+0.23}_{-0.24}$
1 event	$1.03^{+0.64}_{-0.61}$	$5.71^{+0.43}_{-0.42}$	$-2.53^{+0.45}_{-0.62}$



04

Summary

4.Summary



- ☐ There are some intrinsic burst mechanisms which may cause these similar multi-peak structures instead of lensing effects, for instance, the repeating light-curve properties of these GRBs can be interpreted in the jet precession model

- ☐ It would be worth considering the special physical mechanisms that produce so many supermassive compact objects, e.g. a scenario that predicts inevitable clustering of PBHs from highly non-Gaussian perturbations has been proposed to produce supermassive PBH.

Thank You