How to measure *realistic* Quantum Gravity *observables:*

Primordial Black Holes

Francesca Vidotto

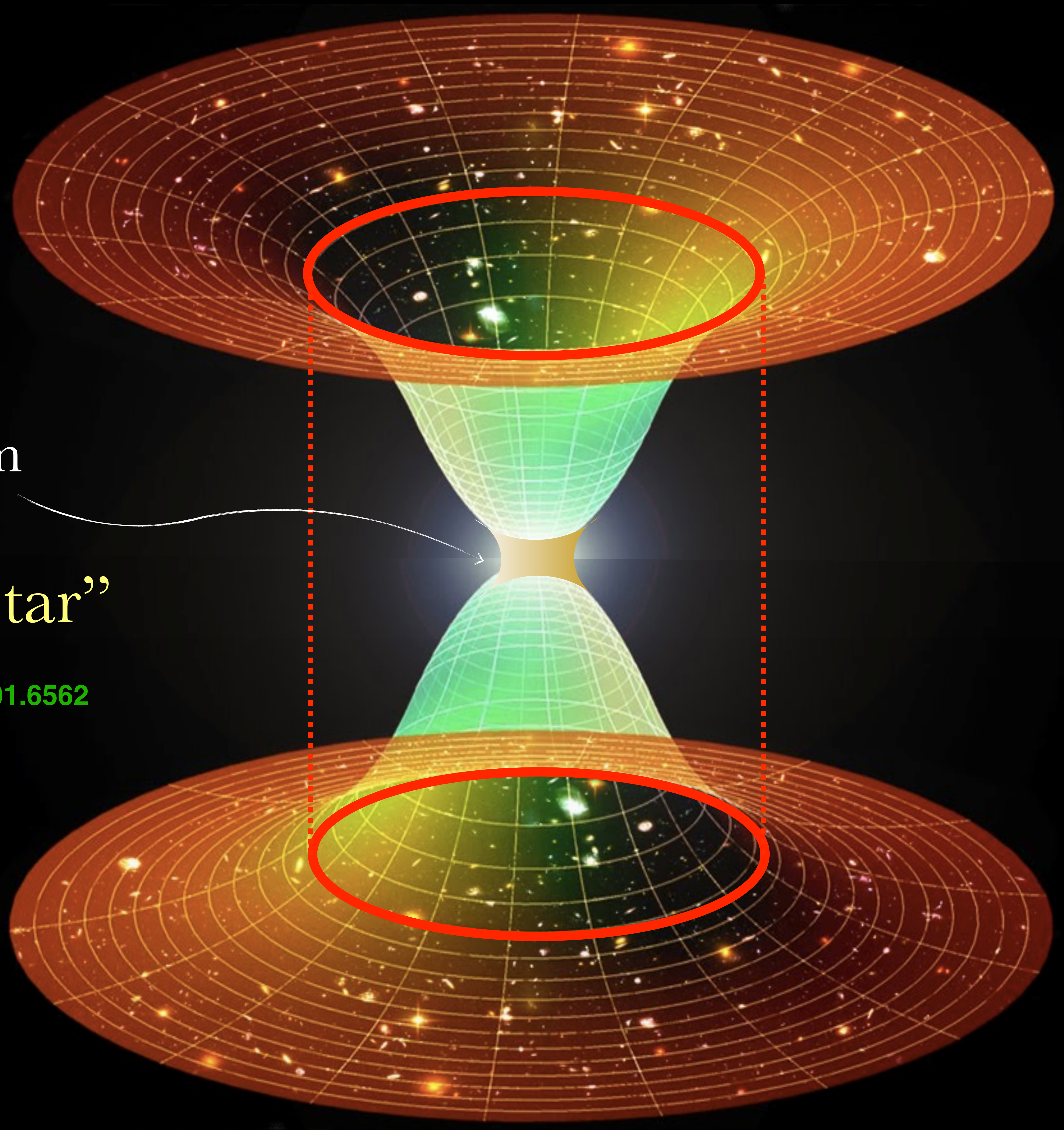
LOOPS17 Warsaw - July 6th, 2017

Netherlands Organisation for Scientific Research

Radboud University Nijmegen

BH EXPLOSION

See talks by Cristodoulou, Haggard, Rovelli



See talk by Singh

"Planck Star"

Vidotto, Rovelli 1401.6562

Black -to- White tunnelling

WHERE are quantum effects?

W H E N

are quantum effects?

HOW LONG IS THE BOUNCE FROM OUTSIDE?

- **Upper limit:**

  Firewall argument (Almheiri, Marolf, Polchinski, Sully):"something" unusual must happen before the Page time (~ 1/2 evaporation time)

  $\Longrightarrow$ the hole lifetime must be shorter or of the order of ~ $\mathbf{m^3}$

- **Lower limit:**

  For something quantum to happens, semiclassical approximation must fail.

  Vidotto, Rovelli 1401.6562

  Typically in quantum gravity: high curvature Curvature ~ $(L_P)^{-2}$

  Small effects can pile up: small probability per time unit gives a probable effect on a long time!

  Typically in quantum tunneling: Curvature × (time) ~ $(L_P)^{-1}$

  $\Longrightarrow$ the hole lifetime must be longer or of the order of ~ $\mathbf{m^2}$

  Haggard, Rovelli 1407.0989

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  Vidotto, Rovelli 1401.6562

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Typically in quantum tunneling: Curvature $\times$ (time) $\sim (L_P)^{-1}$

$$\frac{m}{r^3}\, T_b \sim 1$$

$\Longrightarrow$ the hole lifetime must be longer or of the order of $\sim$ **m²**

Haggard, Rovelli 1407.0989

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Vidotto, Rovelli 1401.6562

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Haggard, Rovelli 1407.0989

UNIVERSALITY OF BLACK HOLE EXPLOSION

- **LARGE EXTRA DIMENSIONS**

  1st order topological phase transition from black string to black hole occurring because of the Gregory-Laflamme metrical instability

  Casadio and Harms 2000/01
  Gubser 2002, Kol 2002
  Gregory and Laflamme 2002

- **BRANES**

  Large black holes localized on infinite Randall- Sundrum branes: period of rapid decay via Hawking radiation of CFT modes

  Emparana, Garcıa-Bellido, Kaloper 2003

Quantum effects shorten the lifetime of black holes!

(1971).
[6] Bassi, P., Clark, G., and Rossi, B., *Phys. Rev.*, **92**, 441 (1953).
[7] David, F. N., *Biometrika*, **34**, 299 (1947).
[8] Weekes, T. C., *Nature phys. Sci.*, **223**, 129 (1971).

Black hole explosions?

QUANTUM gravitational effects are usually ignored in calculations of the formation and evolution of black holes. The justification for this is that the radius of curvature of space-time outside the event horizon is very large compared to the Planck length $(G\hbar/c^3)^{1/2} \approx 10^{-33}$ cm, the length scale on which quantum fluctuations of the metric are expected to be of order unity. This means that the energy density of particles created by the gravitational field is small compared to the space-time curvature. Even though quantum effects may be small locally, they may still, however, add up to produce a significant effect over the lifetime of the Universe $\approx 10^{17}$ s which is very long compared to the Planck time $\approx 10^{-43}$ s.

Beckenstein[6] suggested on thermodynamic grounds that some multiple of κ should be regarded as the temperature of a black hole. He did not, however, suggest that a black hole could emit particles as well as absorb them. For this reason Bardeen, Carter and I considered that the thermodynamical similarity between κ and temperature was only an analogy. The present result seems to indicate, however, that there may be more to it than this. Of course this calculation ignores the back reaction of the particles on the metric, and quantum fluctuations on the metric. These might alter the picture.

Further details of this work will be published elsewhere. The author is very grateful to G. W. Gibbons for discussions and help.

S. W. HAWKING

Department of Applied Mathematics and Theoretical Physics and
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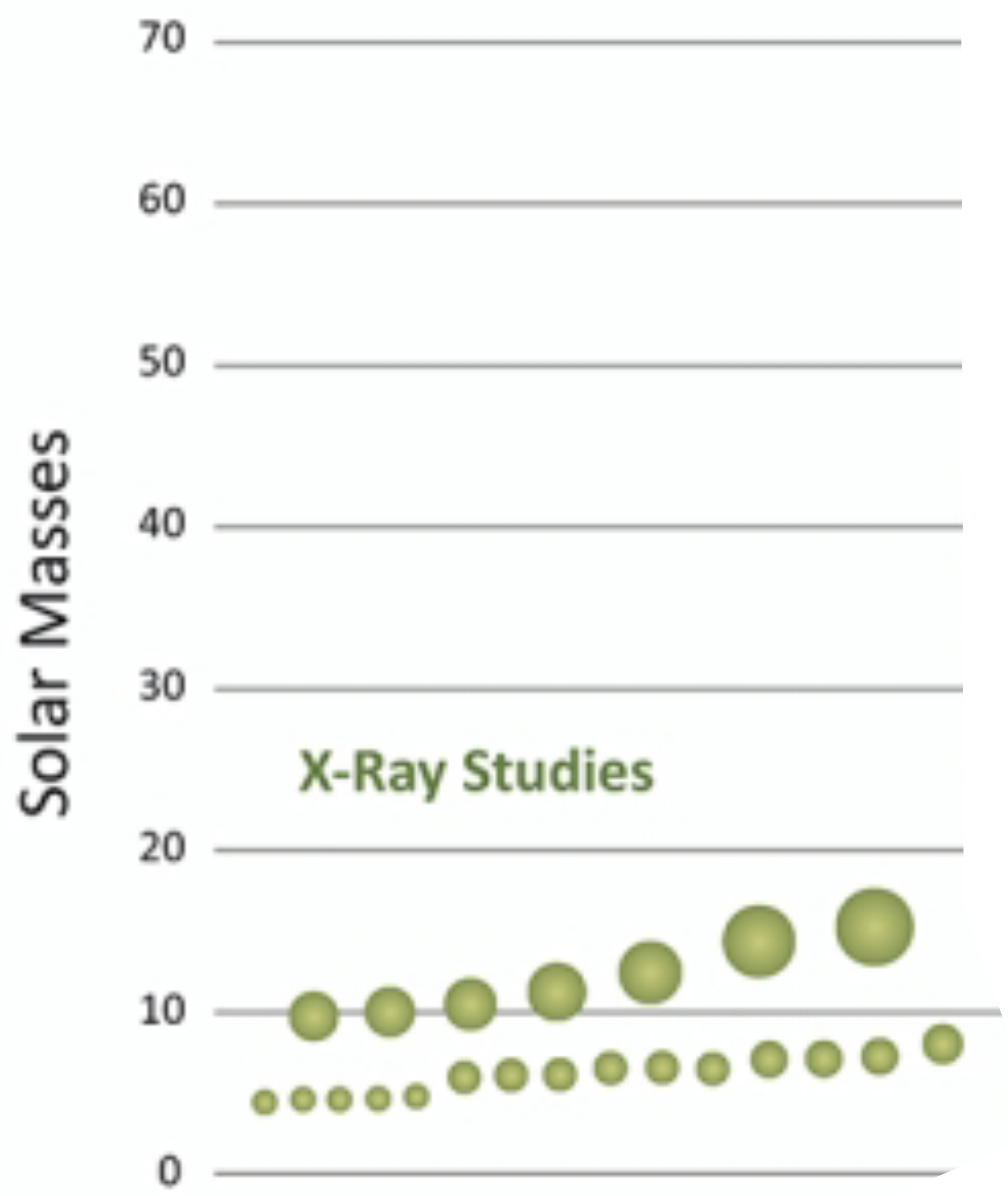
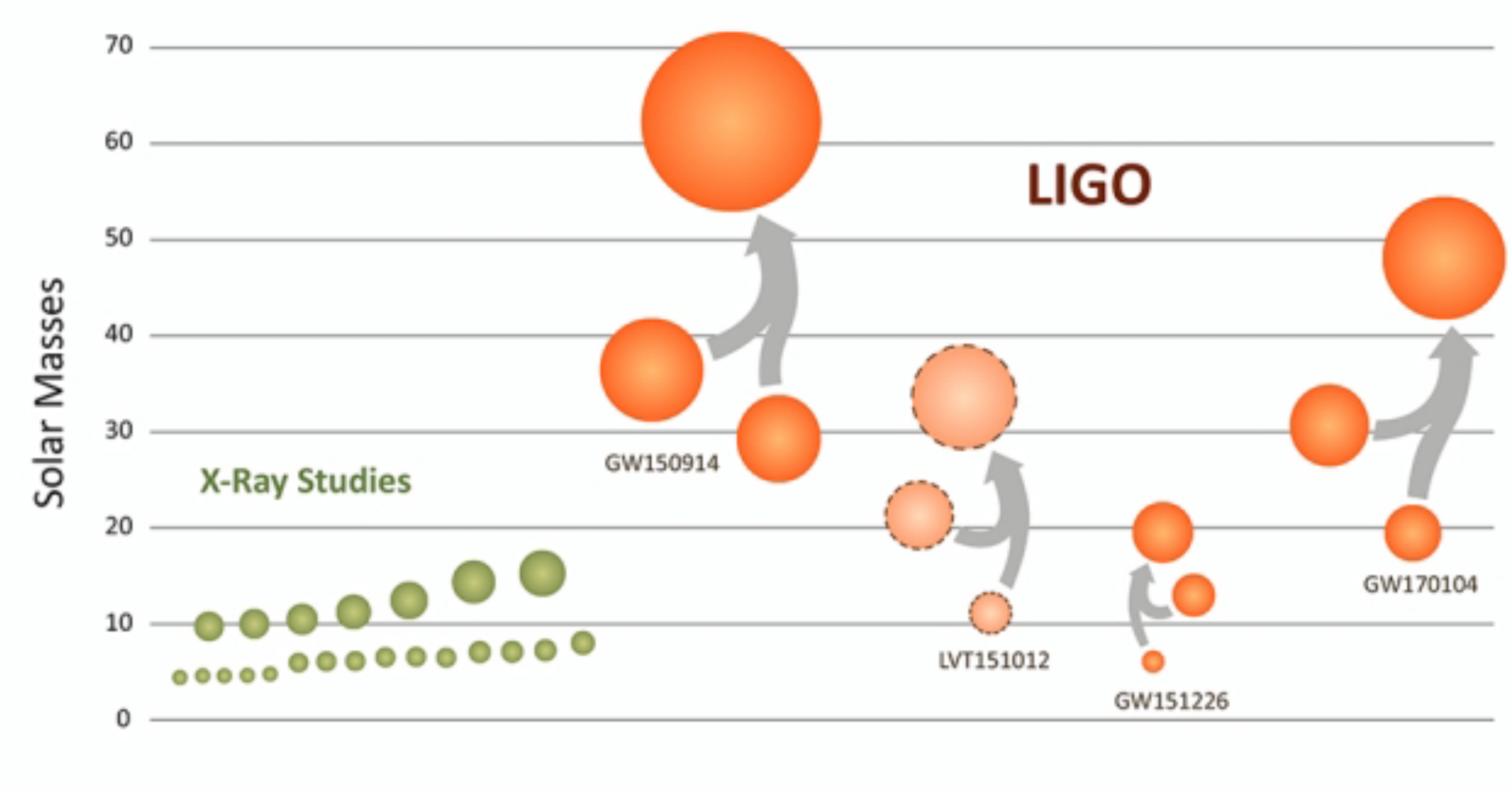
Received January 17, 1974.

For **m ~10^{24} *Kg*,** **m^3~10^{50}** Hubble times, while **m^2~Hubble time**

PRIMORDIAL BLACK HOLES

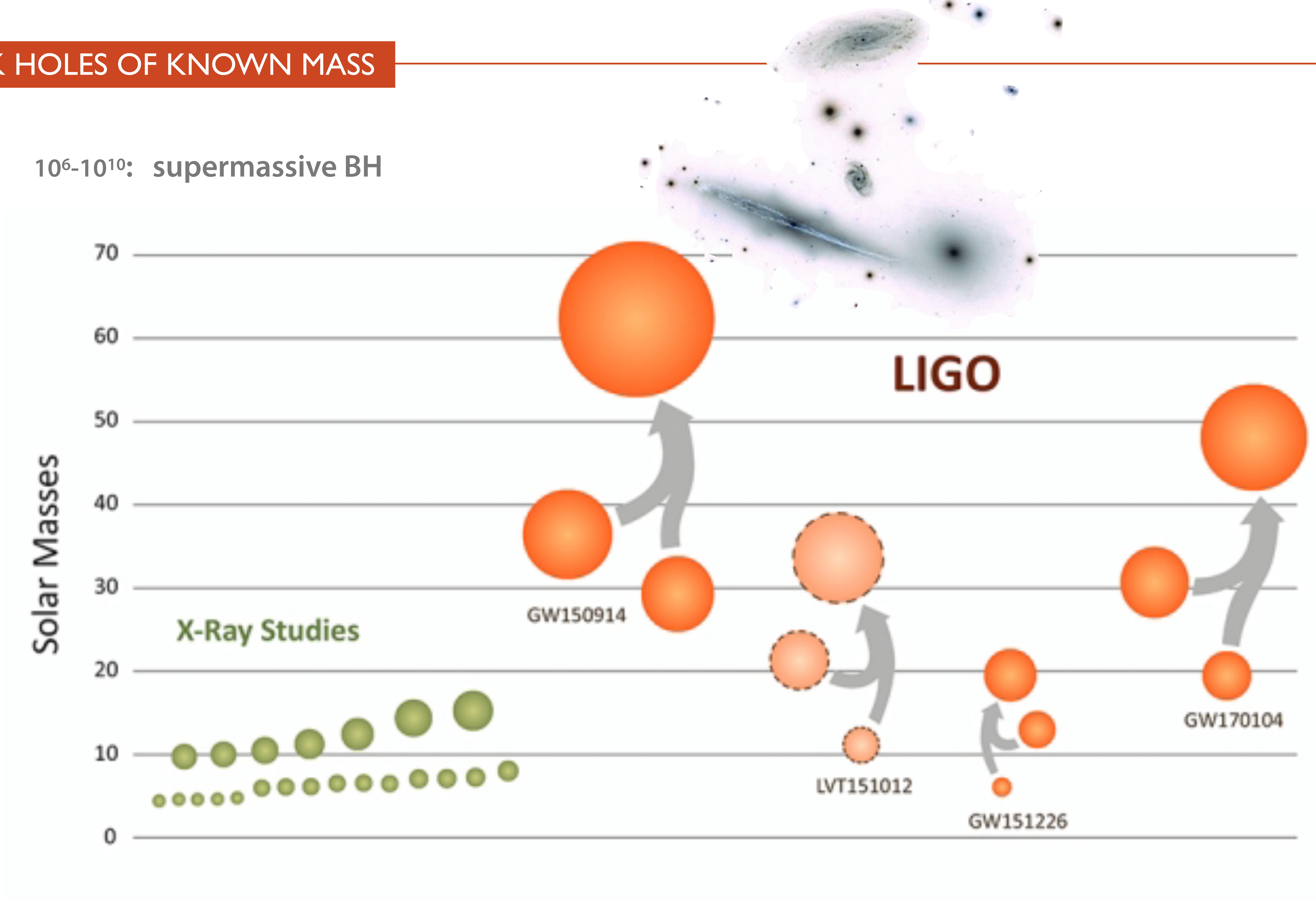
BLACK HOLES OF KNOWN MASS




Solar Masses
70
60
50
40
30
20
10
0
X-Ray Studies
LIGO
GW150914
LVT151012
GW151226
GW170104

BLACK HOLES OF KNOWN MASS

10^6-10^{10}: supermassive BH



BLACK HOLES OF KNOWN MASS

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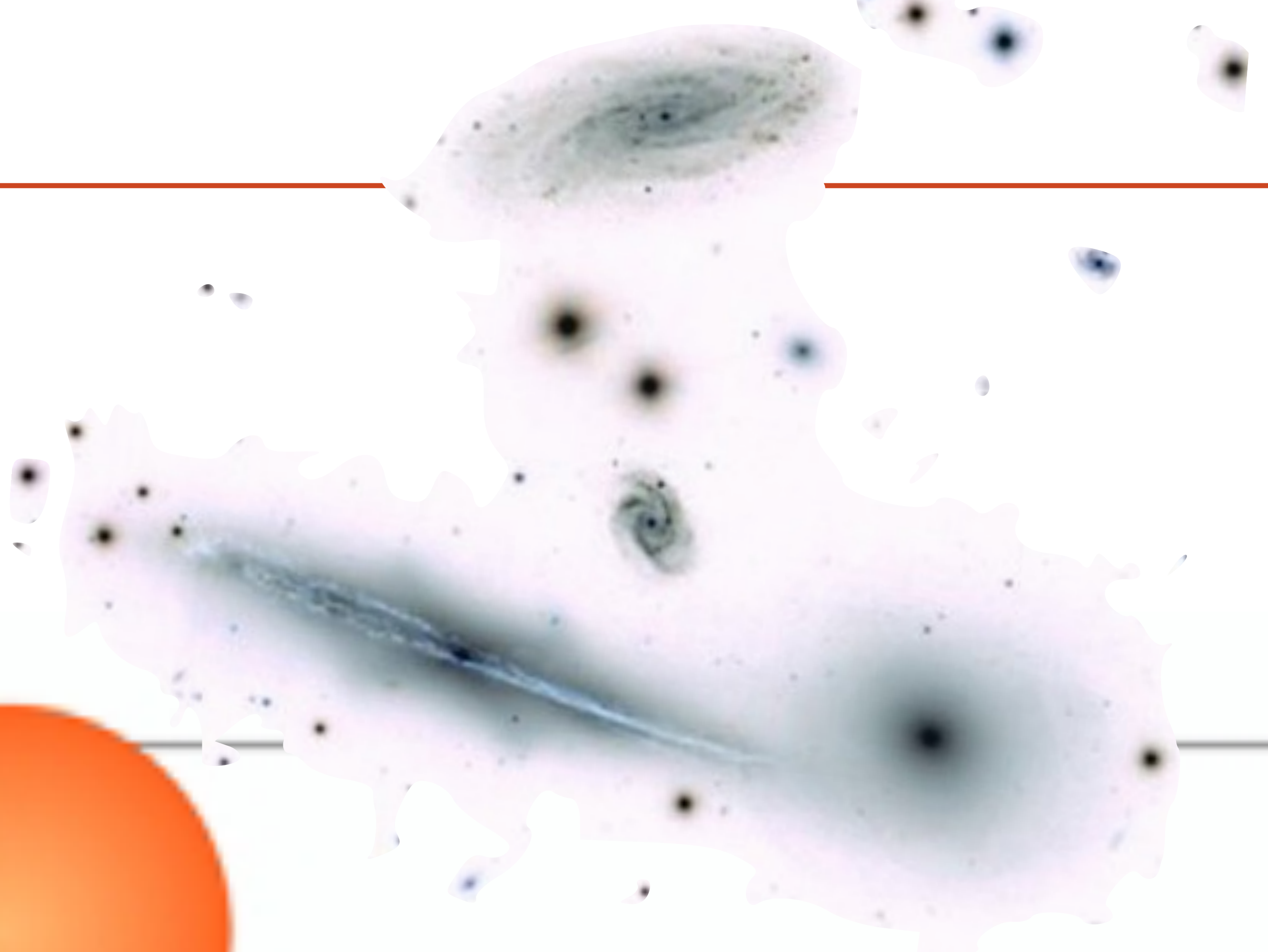
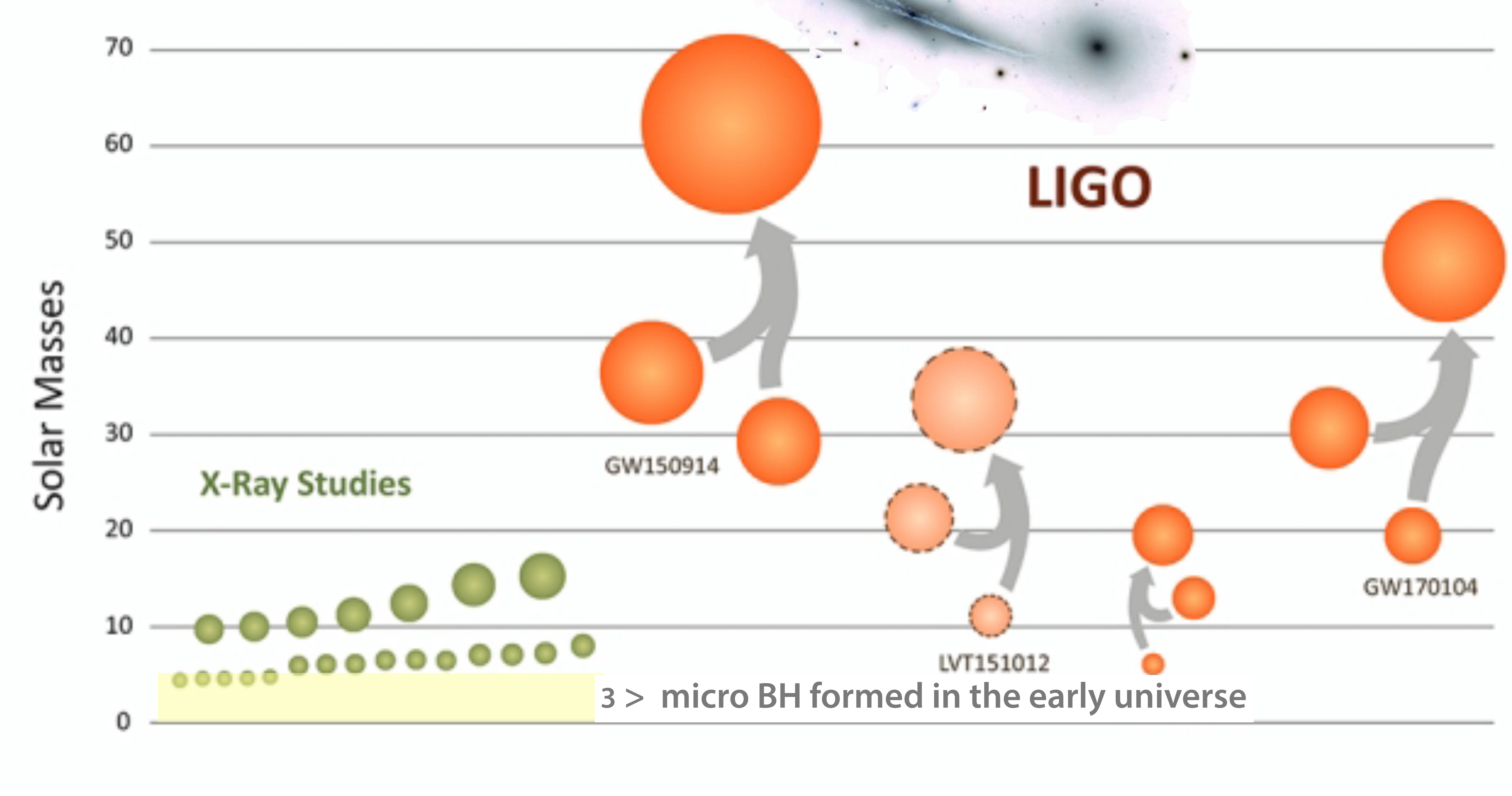




3 > micro BH formed in the early universe

PRIMORDIAL BLACK HOLES

- All black holes are subject to quantum effects.
- An explosion observed today, requires old black holes: primordial.

Musco, Miller 1201.2379

- (Quantum) PBH dark matter:
  - Today, black holes smaller than $m(t)|_{t=t_H}$ have already exploded.
  - It decreases with time.

(but for later accretion/merging)

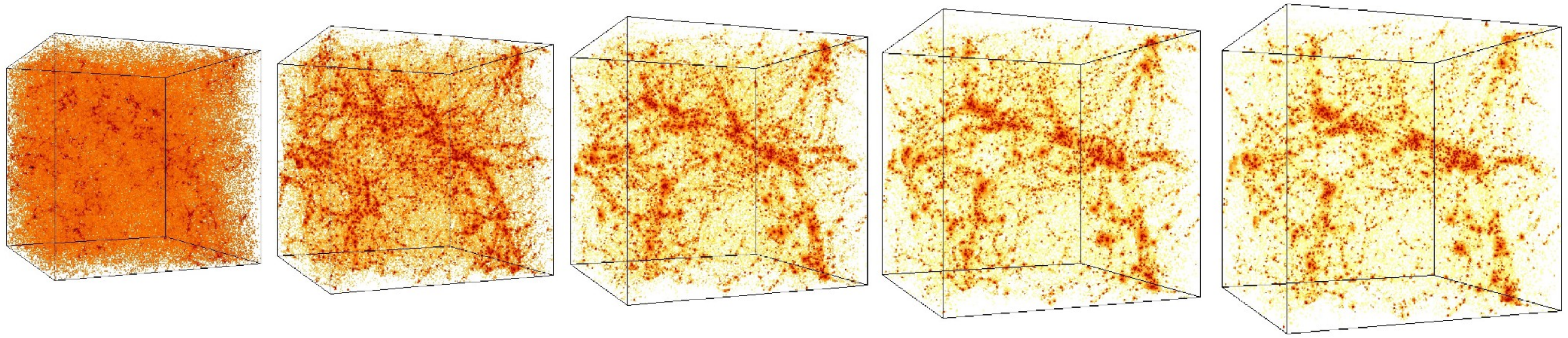
- Caution with constraints!
  - Constraints from Hawking evaporation do not apply.
  - PBH mass spectrum beyond simple monochromatic models.
  - PBH should exists, but not necessarily constitute all DM.

Carr, Kohri, Sendouda, Yokoyama 0912.5297

QUANTUM PRIMORDIAL BLACK HOLES AS DARK MATTER

- Structure formation

Barrau, Moulin, Bellomo, Bernal, Chluba, Cholis, Raccanelli, Verde, Vidotto WIP



Preliminary result: Planck Stars compatible with constraints from early cosmology

- First stars & Supermassive black holes

Bambi, Freese, Vidotto WIP

  - Primordial black holes inside first-generation stars can provide the seeds for supermassive black holes

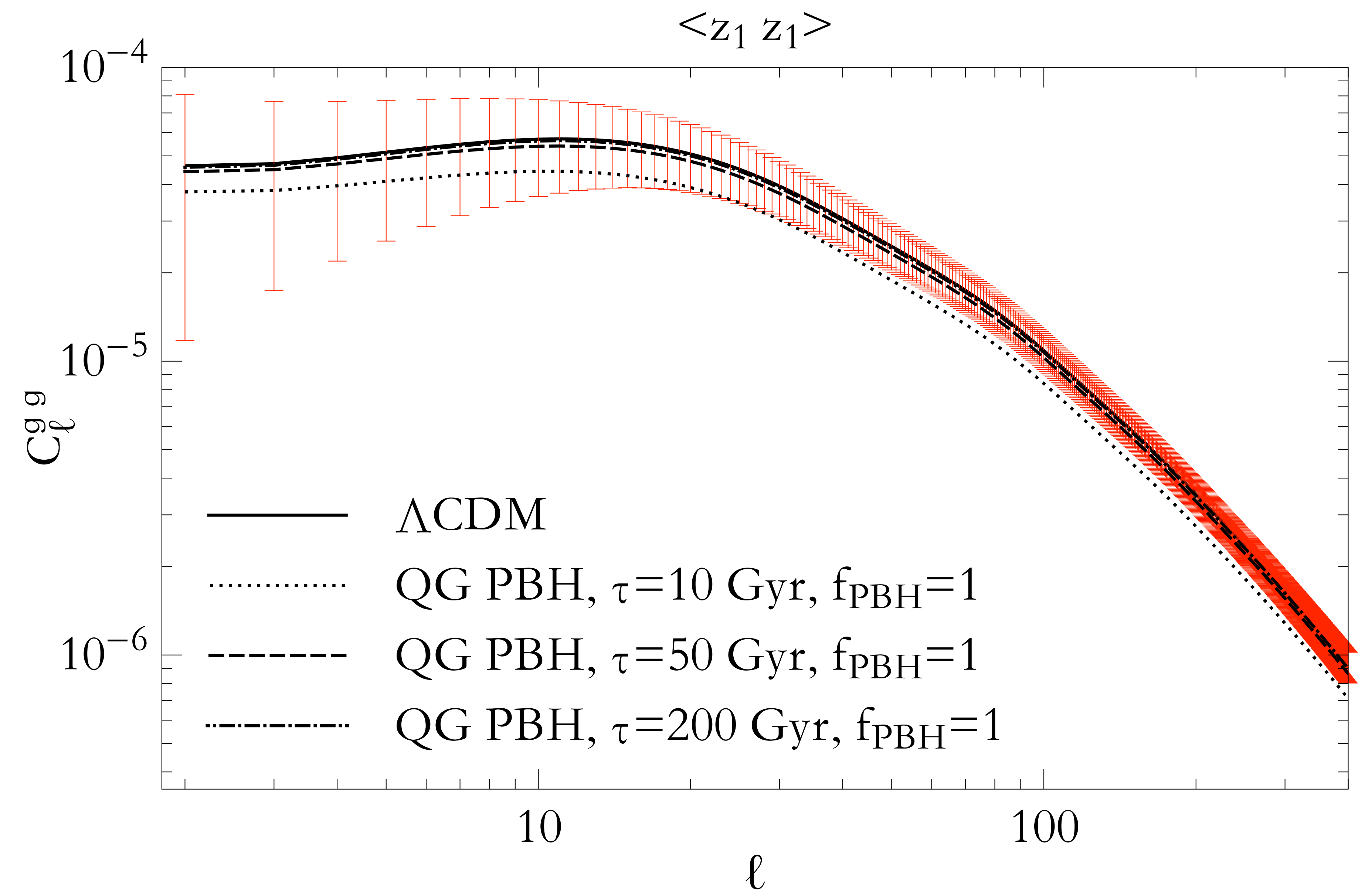
EFFECTS IN THE LATE UNIVERSE

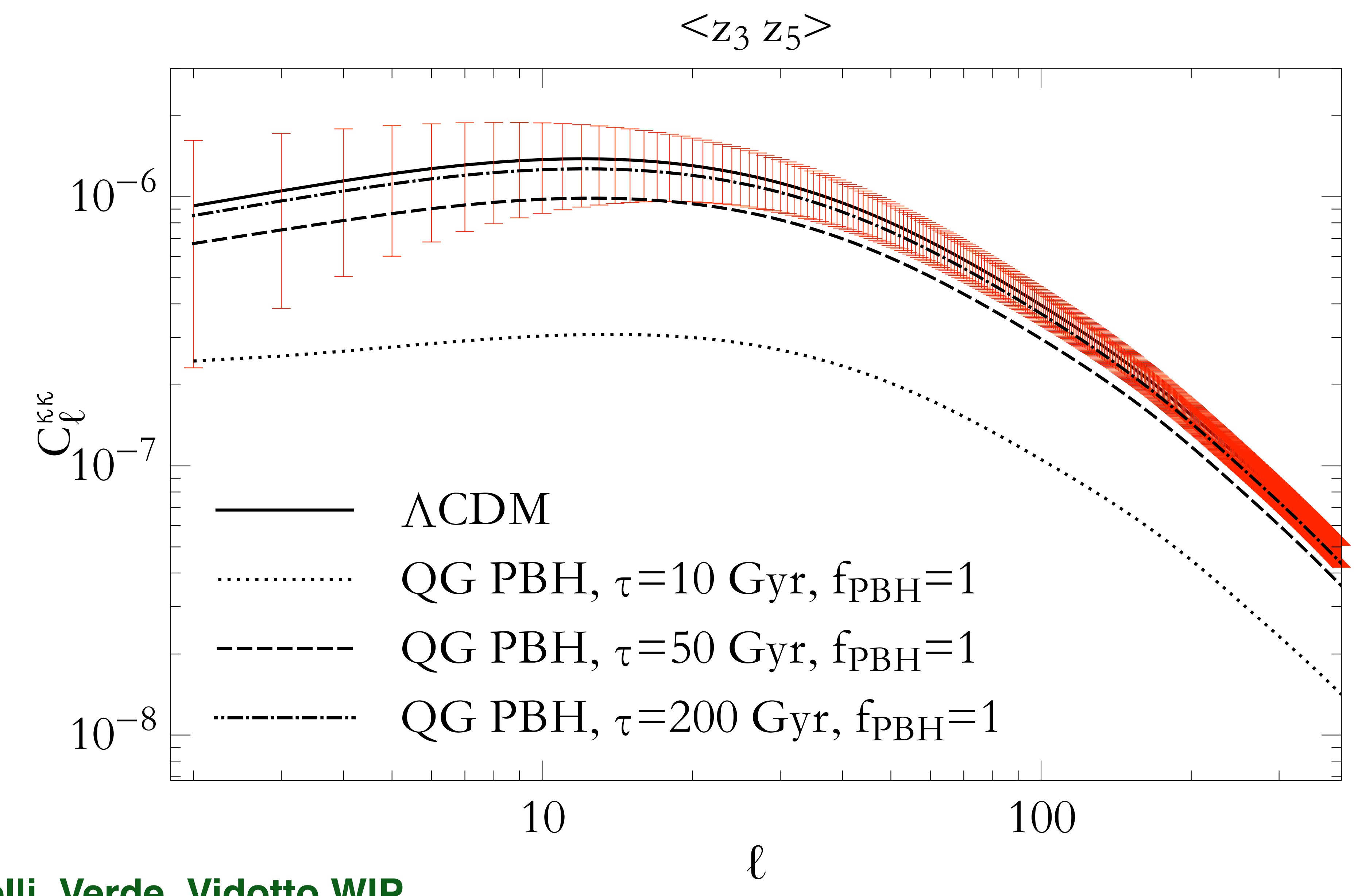
Raccanelli, Verde, Vidotto (to appear soon)

From galaxy-cluster surveys:

- Observed galaxy over-density
- Cosmic Magnification

Use of LATE UNIVERSE observations
to MEASURE quantum-gravity parameters!





Bellomo, Bernal, Chluba, Cholis, Raccanelli, Verde, Vidotto WIP

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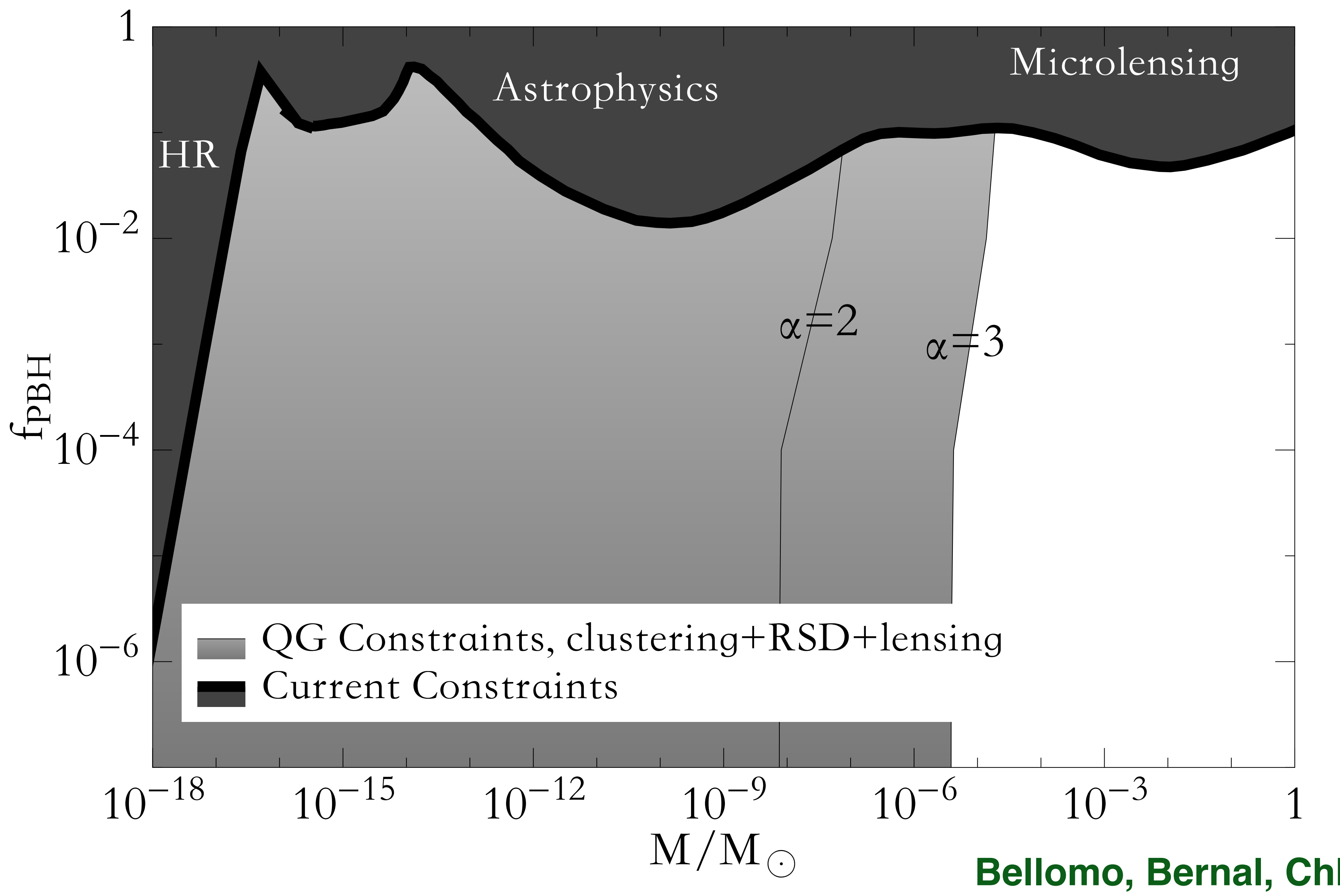
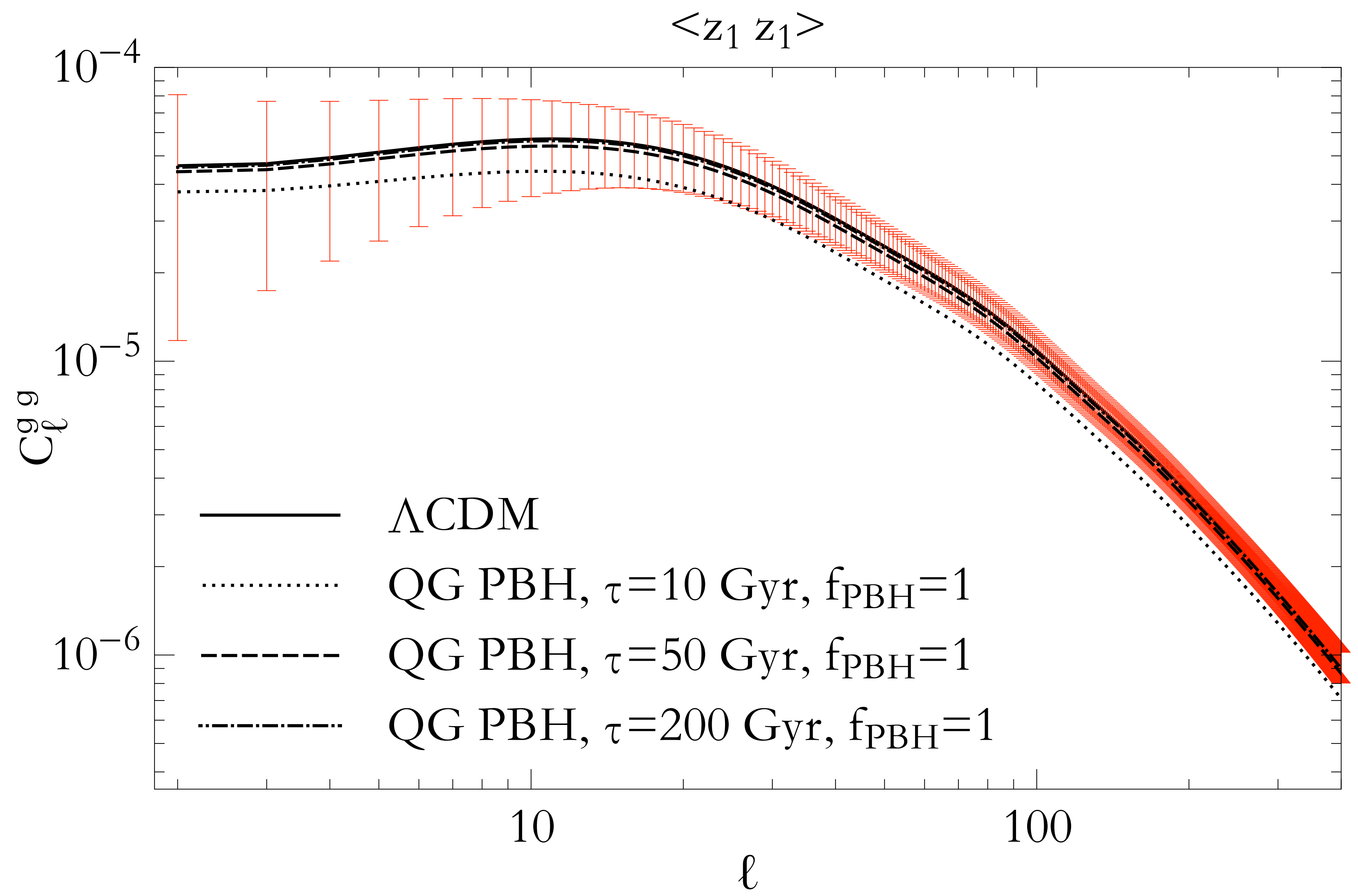
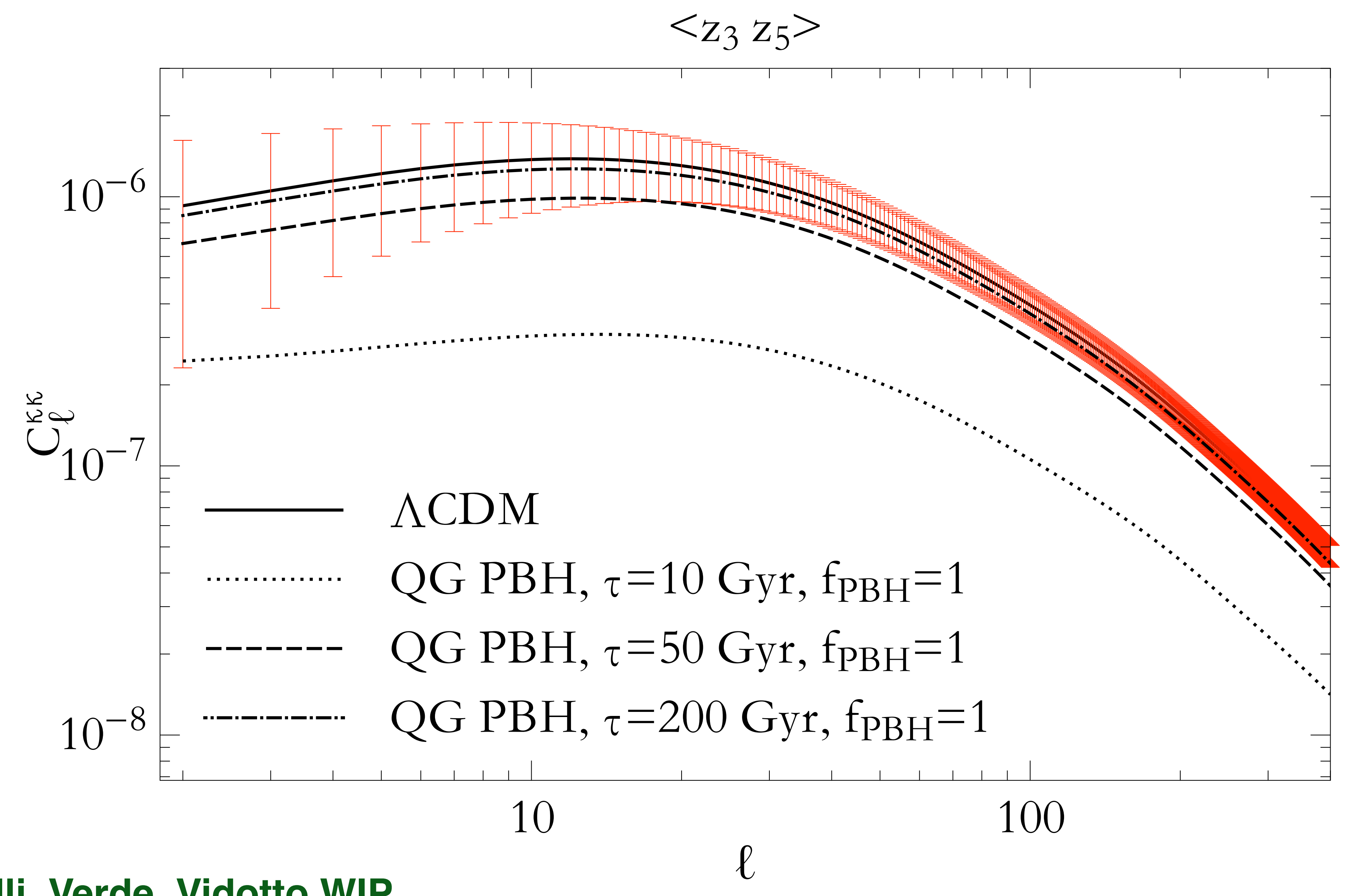






Bellomo, Bernal, Chluba, Cholis, Raccanelli, Verde, Vidotto WIP


PLANCK STAR
SIGNAL

EXPECTED SIGNALS

Barrau, Rovelli, Vidotto 1409.4031

- fast process (few milliseconds?)
- the source disappears with the burst
- very compact object: big flux $E = mc^2 \sim 1.7 \times 10^{47}$ erg
- exploding today: $m = \sqrt{\frac{t_H}{4k}} \sim 1.2 \times 10^{23}$ kg $\qquad R = \frac{2Gm}{c^2} \sim .02$ cm
- **LOW ENERGY:** size of the source $\approx$ wavelength $\lambda_{predicted} \gtrsim .2$ cm(?)
- **HIGH ENERGY:** energy of the particle liberated $\approx Tev$
- **SYNCHROTRON EMISSION**

Kavic &al. 0801.4023

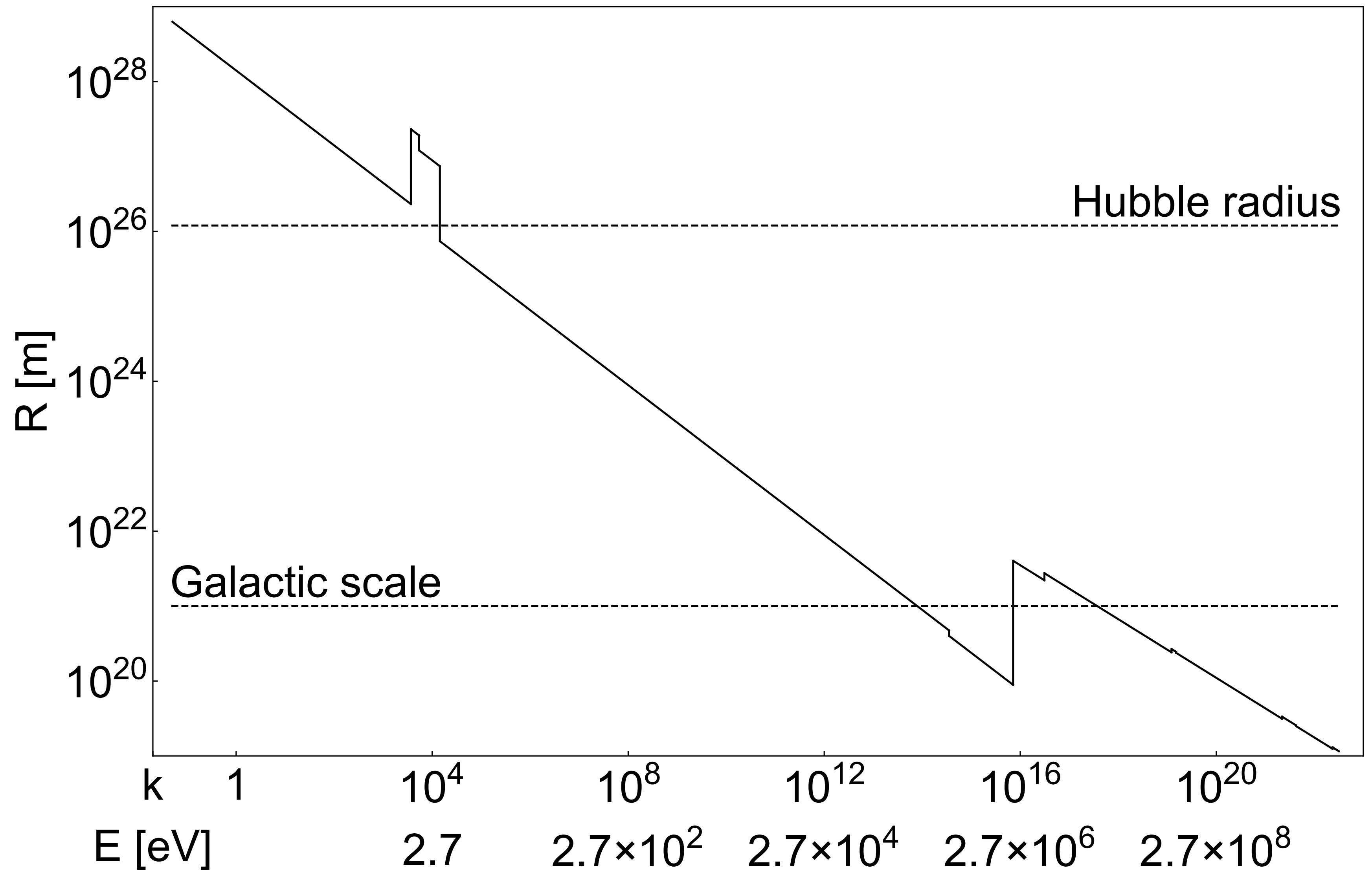
- **GRAVITATIONAL WAVES**

MAXIMAL DISTANCE

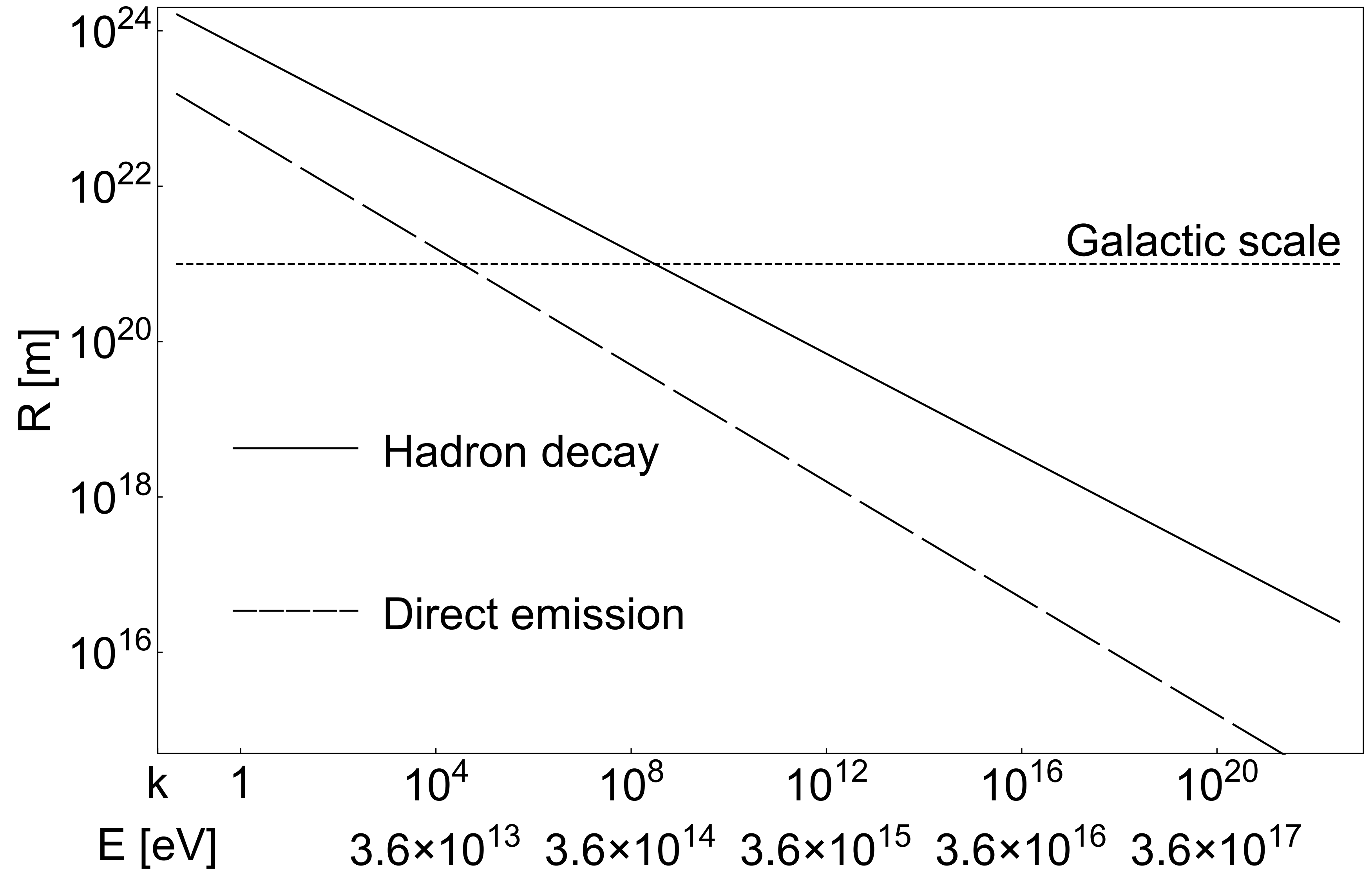
Barrau, Bolliet, Vidotto, Weimer 1507.1198

- shorter lifetime — smaller wavelength

Low energy channel



High energy channel

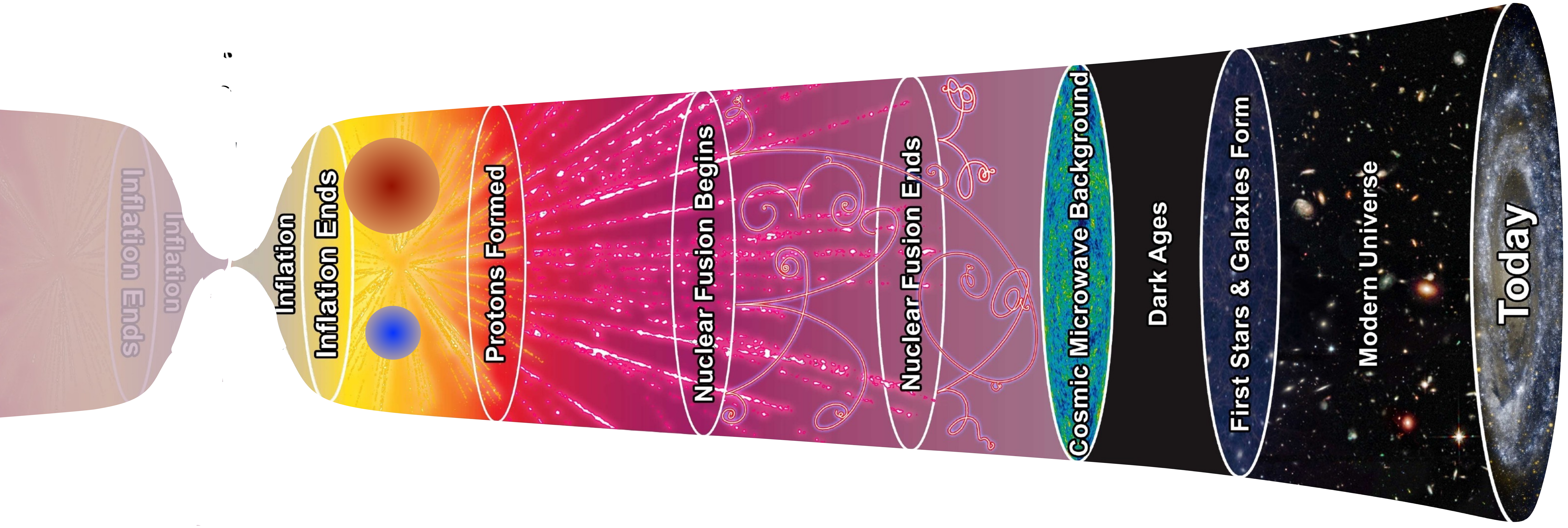


- detection of arbitrarily far signals
- better single-event detection

- PBH: mass - temperature relation
- different scaling

THE SMOKING GUN: DISTANCE/ENERGY RELATION

- distant signals originated in younger and smaller sources



$$M \sim M_H \sim t.$$

$$t \sim 0.3 g_*^{-\frac{1}{2}} T^{-2}$$

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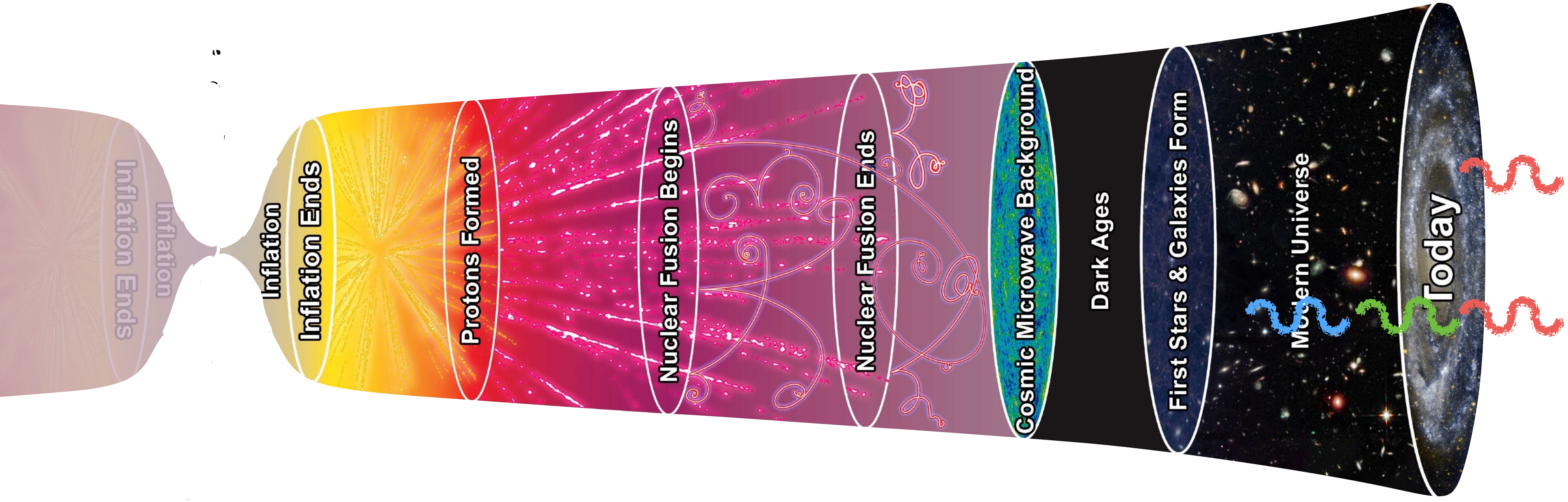


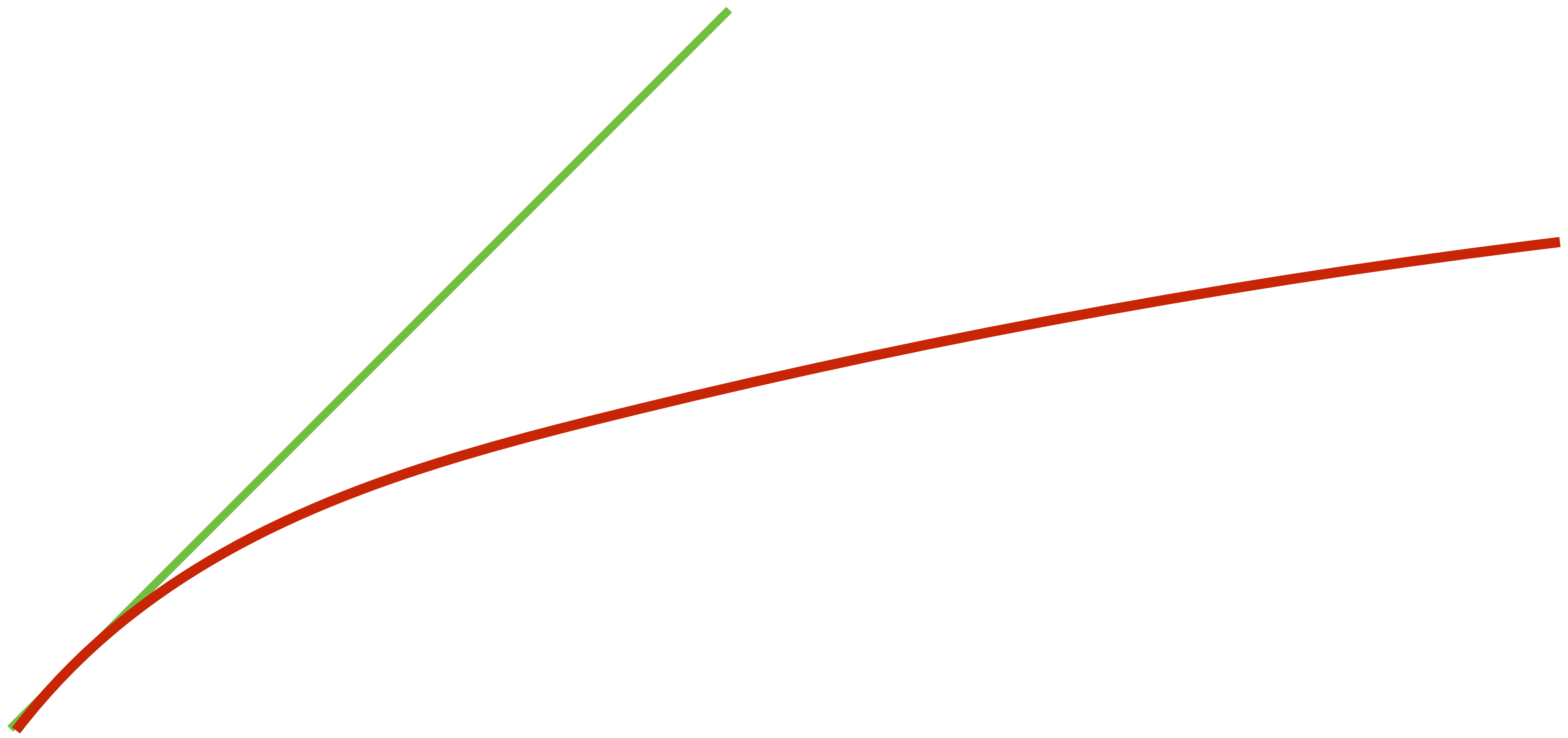
$$M \sim M_H \sim t.$$

$$t \sim 0.3 g_*^{-\frac{1}{2}} T^{-2}$$

THE SMOKING GUN: DISTANCE/ENERGY RELATION

$$\lambda_{obs}^{other} = (1+z)\lambda_{emitted}^{other} \quad \longrightarrow \quad \lambda_{obs} \sim \frac{2Gm}{c^2}(1+z)\sqrt{\frac{H_0^{-1}}{6\,k\Omega_\Lambda^{1/2}}\ \sinh^{-1}\left[\left(\frac{\Omega_\Lambda}{\Omega_M}\right)^{1/2}(z+1)^{-3/2}\right]}$$

- for our signal: distance $\propto$ 1/wave length
- taking into account the redshift the resulting function is very slowly varying

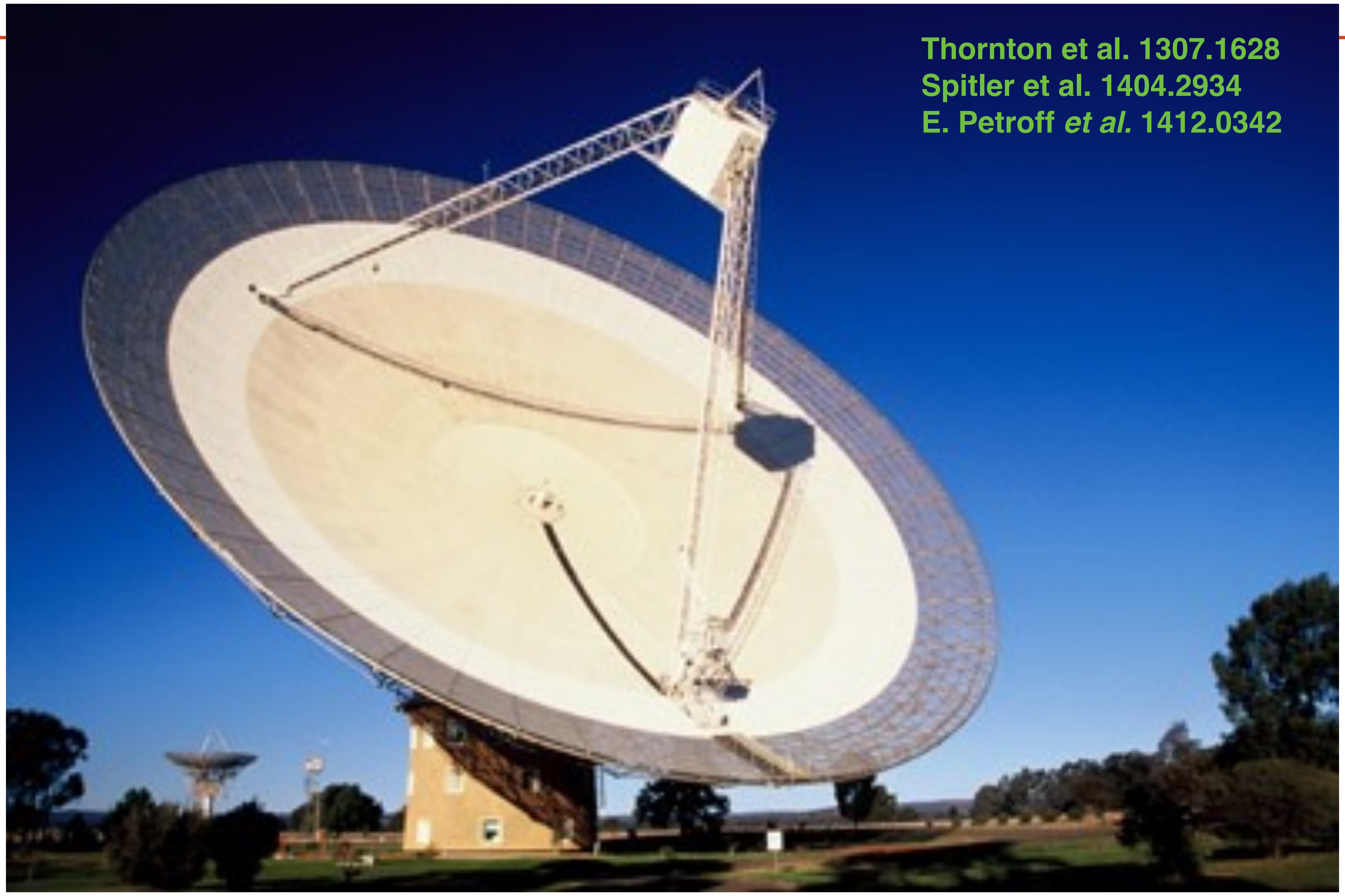


Barrau, Rovelli, Vidotto 1409.4031

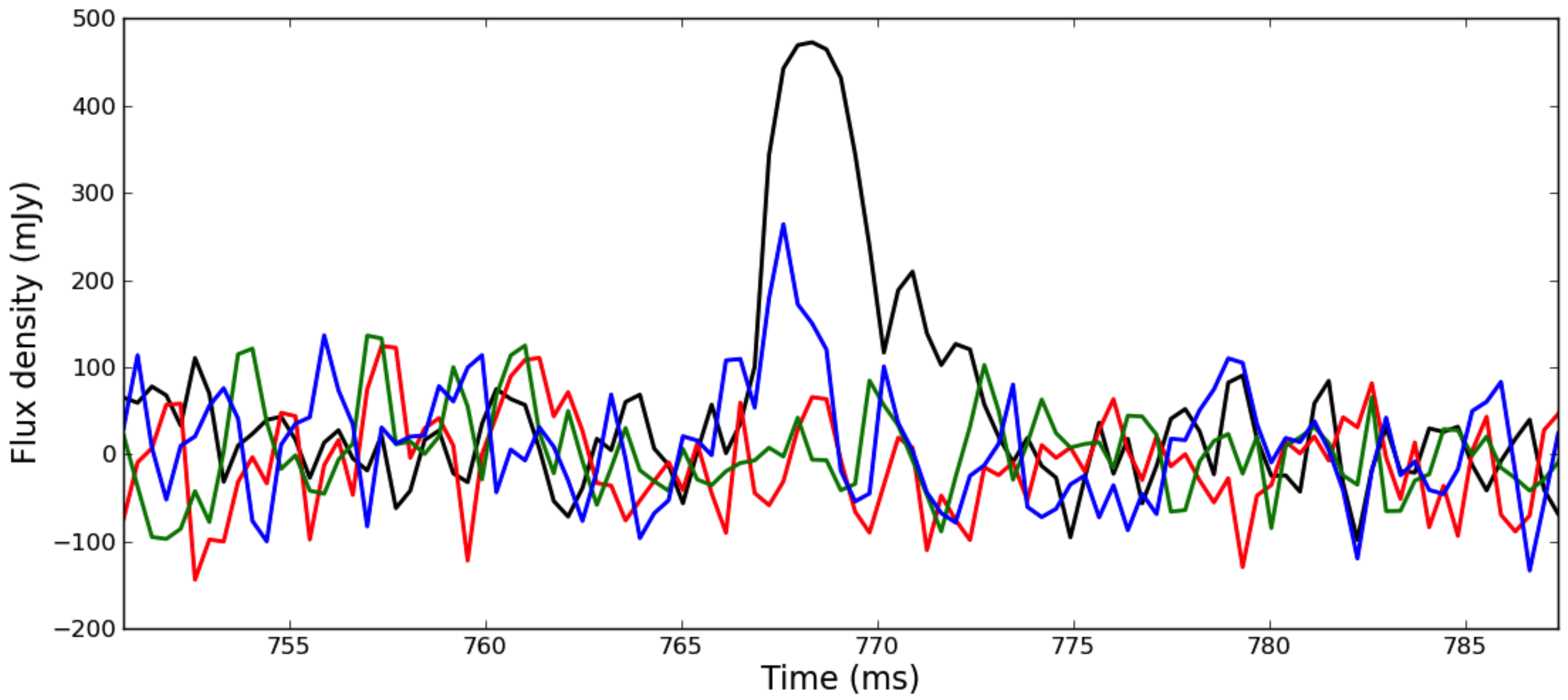
- DISTANCE:
  - dispersion relation?
  - hosting galaxy?
  - flux?


OBSERVED
SIGNALS

FAST RADIO BURSTS



- Short
  - Observed width ≃ milliseconds
- No Long GRB associated
  - No Afterglow
- Punctual
  - No repetition
- Enormous flux density
  - Energy ≲ 10^{38} erg
- Likely Extragalactic
  - Dispersion Measure: z≲0.5
- 10^4 event/day
  - A pretty common object?
- Circular polarization
  - Intrinsic



Barrau, Rovelli, Vidotto 1409.4031

- $\lambda \approx 20$ cm → size of the source $\approx$ $\lambda_{predicted} \gtrsim .02$ cm
  - synchrotron emission $\approx$ 20 cm — Kavic, Vidotto WIP
- Short
  - Observed width ≃ milliseconds → fast process
- No Long GRB associated
  - No Afterglow → Very short GRB ? gravitational waves ?
- Punctual
  - No repetition → the source disappears with the burst
- Enormous flux density
  - Energy $\lesssim 10^{38}$ erg → very compact object $\longrightarrow 10^{47}$ erg
- Likely Extragalactic
  - Dispersion Measure: $z \lesssim 0.5$ → peculiar distance/energy relation
- 10^4 event/day
  - A pretty common object?
- Circular polarization
  - Intrinsic

Are they bouncing Black Holes?

LIST OF FAST RADIO BURSTS

name	date	RA	dec	DM	width	peak	notes
FRB 010724	2001/07/24	01h18′	-75°12′	375	4.6	30	"Lorimer Burst"
FRB 010621	2001/06/21	18h52′	-08°29′	746	7.8	0.4	
FRB 110220	2011/02/20	22h34′	-12°24′	944.38	5.6	1.3	
FRB 110627	2011/06/27	21h03′	-44°44′	723.0	<1.4	0.4	
FRB 110703	2011/07/03	23h30′	-02°52′	1103.6	<4.3	0.5	
FRB 120127	2012/01/27	23h15′	-18°25′	553.3	<1.1	0.5	
FRB 011025	2001/10/25	19h07′	-40°37′	790	9.4	0.3	
FRB 121002	2012/10/02	18h14′	-85°11′	1628.76	2.1; 3.7	0.35	double pulse 5.1 ms apart
FRB 121002	2012/10/02	18h14'	-85°11'	1629.18	<0.3	>2.3	
FRB 121102	2012/11/02	05h32′	33°05'	557	3.0	0.4	by Arecibo radio telescope
	2015	05h32′~	33°05'~	557~			10 repeat bursts: 6 bursts in 10 minutes, 3 bursts weeks apart.
FRB 131104	2013/11/04	06h44′	-51°17′	779.0	<0.64	1.12	'near' Carina Dwarf Spheroidal Galaxy
FRB 140514	2014/05/14	22h34′	-12°18′	562.7	2.8	0.47	21 ± 7 per cent (3σ) circular polarization
FRB 090625	2009/06/25	03h07'	-29°55′	899.6	<1.9	>2.2	
FRB 130626	2013/06/26	16h27'	-07°27'	952.4	<0.12	>1.5	
FRB 130628	2013/06/28	09h03'	+03°26'	469.88	<0.05	>1.2	
FRB 130729	2013/07/29	13h41'	-05°59'	861	<4	>3.5	
FRB 110523	2011/05/23	21h45'	-00°12'	623.30	1.73	0.6	700-900 MHz at Green Bank telescope, detection circular and linear polarization.
FRB 150418	2015/04/18	07h16'	−19° 00′	776.2	0.8	2.4	Detection of linear polarization. The origin of the burst is disputed.
FRB 160317	2016/03/17	07:53:47	−29:36:31	1165(±11)	21	>3.0	UTMOST, Decl ± 1.5°
FRB 160410	2016/04/10	08:41:25	+06:05:05	278(±3)	4	>7.0	UTMOST, Decl ± 1.5°
FRB 160608	2016/06/08	07:36:42	−40:47:52	682(±7)	9	>4.3	UTMOST, Decl ± 1.5°
FRB 170107	2017/01/07	11:23	-05:01	609.5(±0.5)	2.6	27±4	first by ASKAP, high fluence ~58 Jy ms. In Leo. Galactic latitude 51°, Distance 3.1 Gpc, isotropic energy ~3 x 1034 J

SKA Pathfinder Telescope Detects 3 New Fast Radio Bursts

The three new fast radio bursts detected with the Molonglo telescope – an SKA pathfinder telescope – came from the direction of the constellations Puppis and Hydra. Credit: James Josephides/Mike Dalley

Canberra, Australia, Thursday 13 April – The Molonglo telescope – an SKA pathfinder telescope located some 40km from the Australian capital Canberra – has been used to detect 3 new fast radio bursts (FRBs), it was announced last week.

Fast Radio Bursts are millisecond-duration intense pulses of radio light that appear to be coming from vast distances. They are about a billion times more luminous than anything we have ever seen in our own Milky Way galaxy and have so far eluded any explanation.

Ms Manisha Caleb, currently undertaking her PhD at the Australian National University, Swinburne University of Technology and CAASTRO, developed software to sift through the 1 PB of data produced each day by the telescope, and in the process discovered these three FRBs.

"Until now we only knew of 18 FRBs, so every new detection is key to cracking the mystery of what causes them." said Manisha. "It's fantastic to be able to use such a telescope and contribute to the research on these unknown phenomena as a PhD student. With this experience, I'm hopeful that I'll be able to contribute to the SKA in the future!"

SKA Project Scientist Evan Keane added: "It's great to see the upgraded Molonglo breaking new ground in the

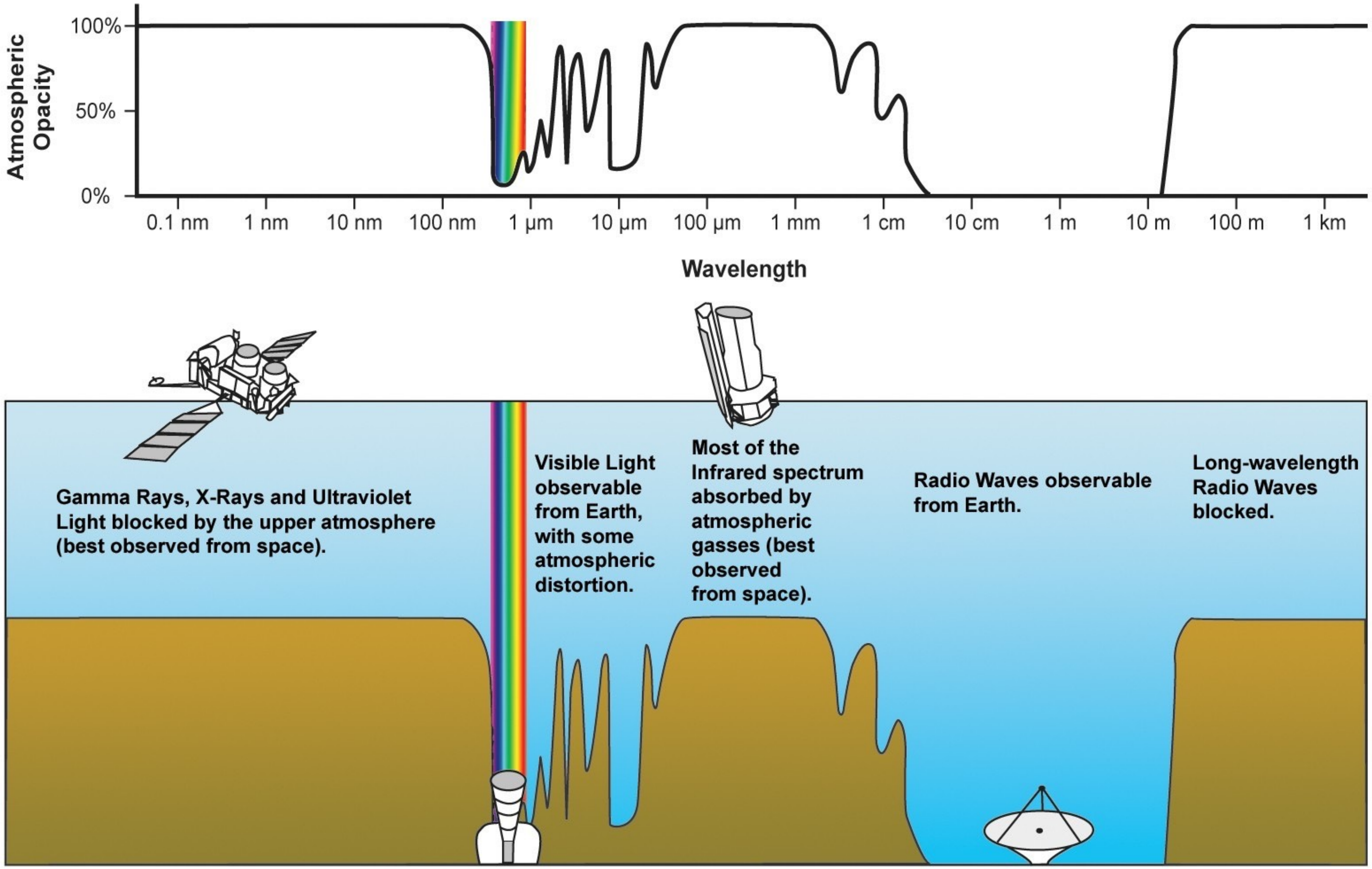
Latest News

28th April 2017
Construction begins on headquarters for the world's largest radio telescope

13th April 2017
SKA pathfinder telescope detects 3 new fast radio bursts

7th April 2017
Outcomes of the 23rd SKA Board Meeting

DETECTION ON EARTH?



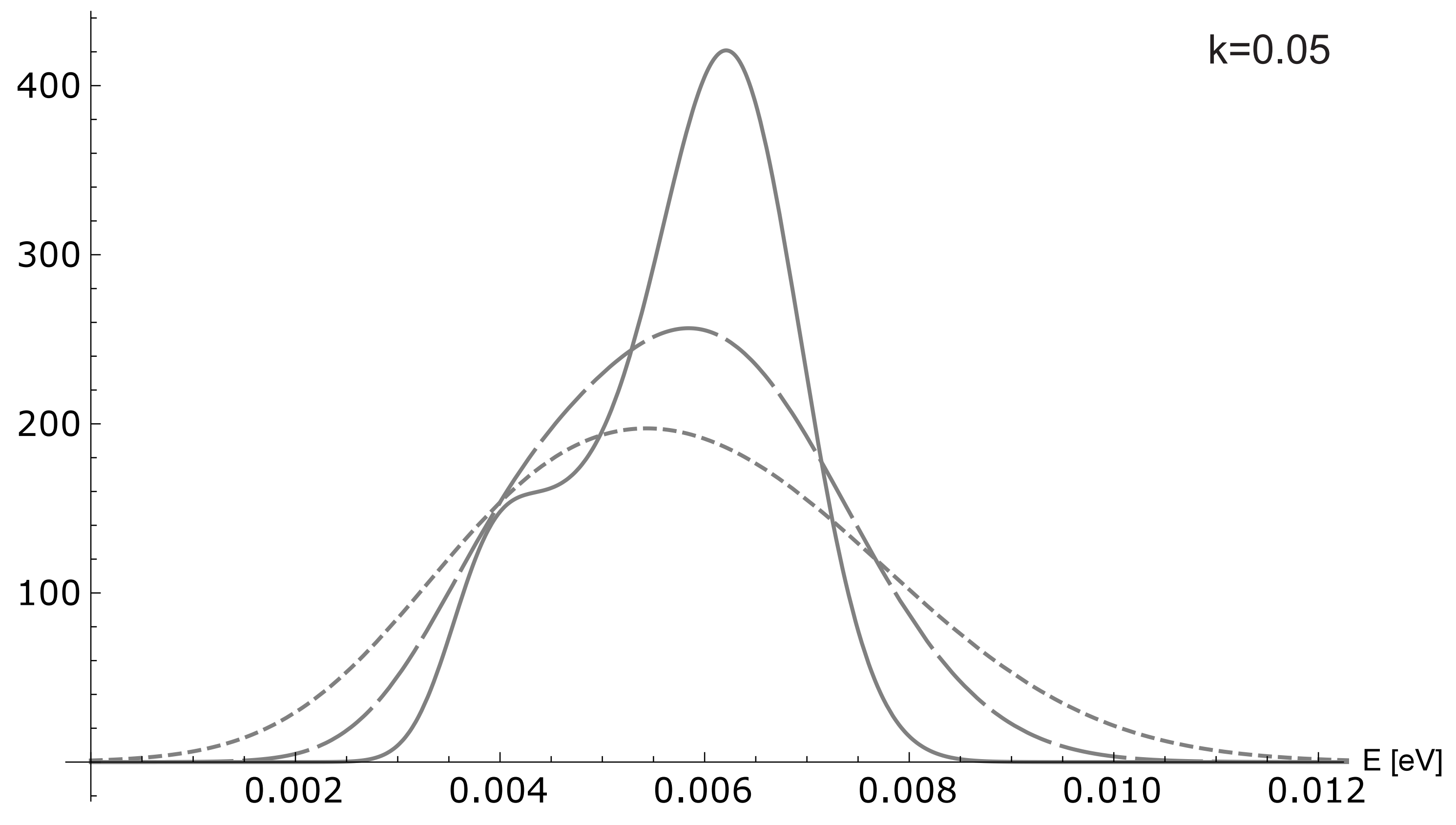
INTEGRATED EMISSION

INTEGRATED EMISSION

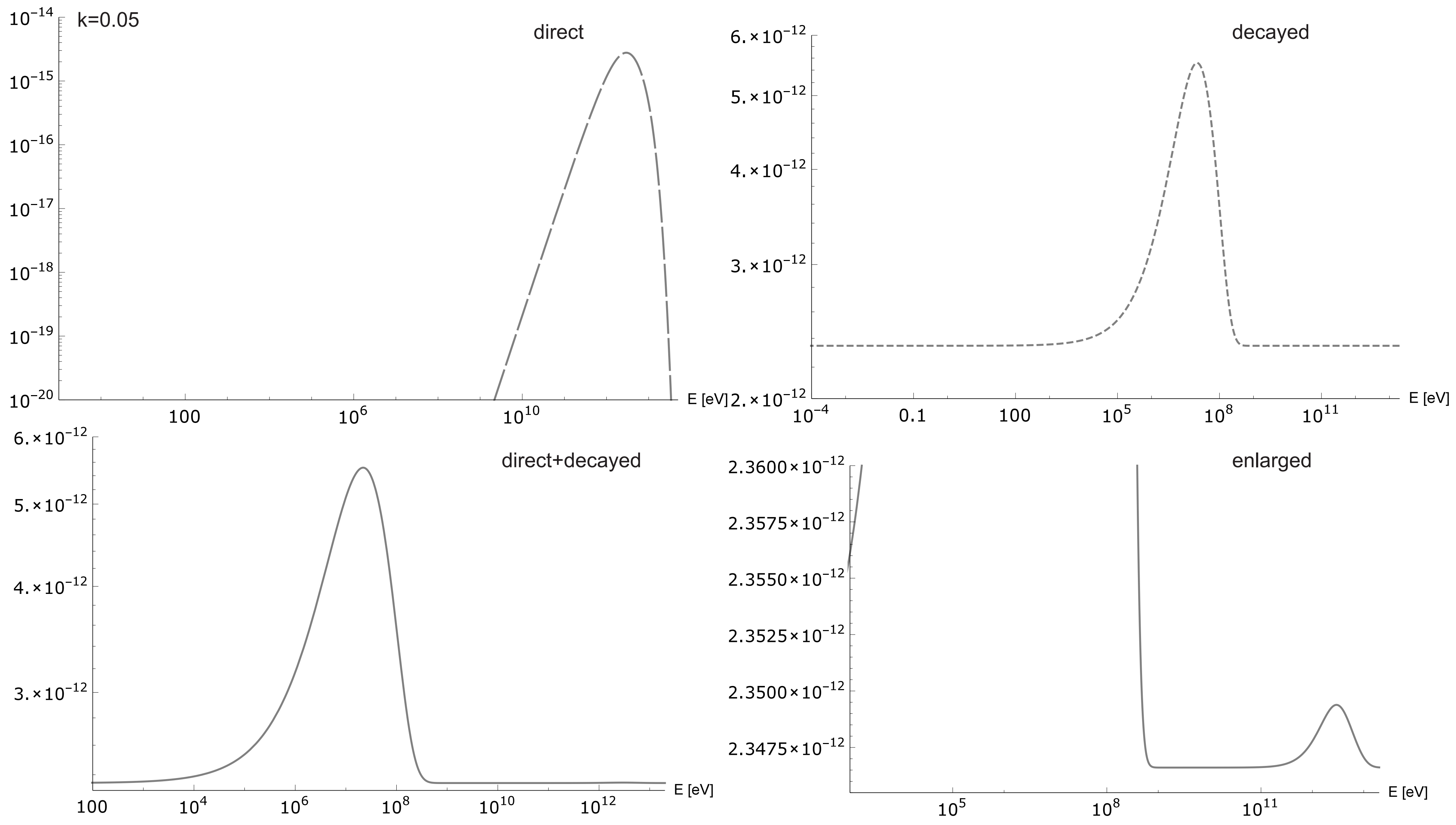
Barrau, Bolliet, Vidotto, Weimer 1507.1198

$$\tau \sim m^2$$

Low energy channel



High energy channel



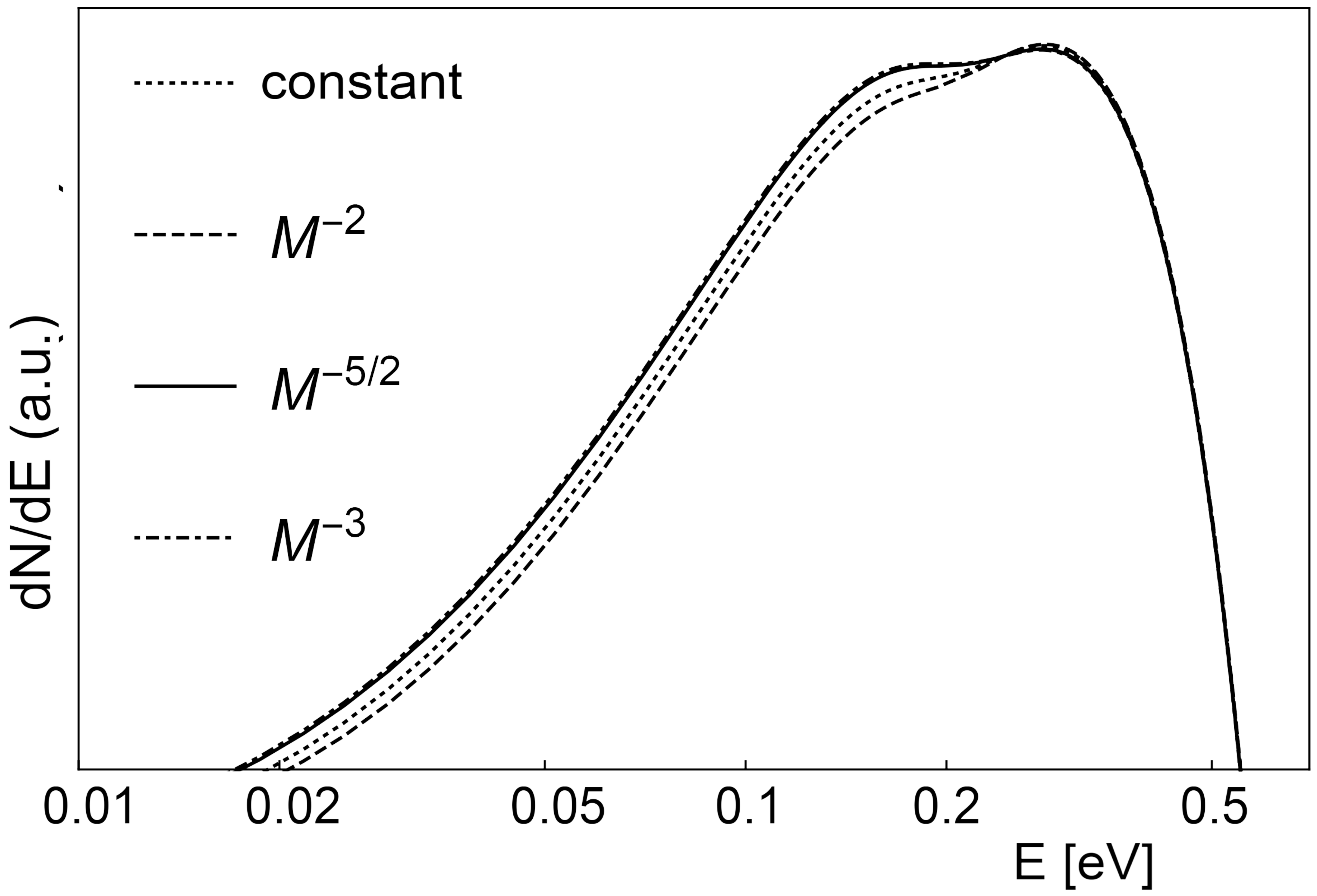
$$\frac{dN_{mes}}{dEdtdS} = \int \Phi_{ind}((1+z)E, R) \cdot n(R) \cdot Acc \cdot Abs(E, R) dR$$

- characteristic shape: distorted black body
- depends on how much DM are PBL

PBH MASS SPECTRUM

$$n(R) = \int_{M(t)}^{M(t+\Delta t)} \frac{dn}{dMdV} dM \qquad n(R) \approx \frac{dn}{dMdV}\frac{\Delta t}{8k} \qquad \frac{dn}{dMdV} = \alpha M^{-1-\frac{1+3w}{1+w}}$$

Low energy channel



Different mass spectra gives qualitatively same diffuse emission…

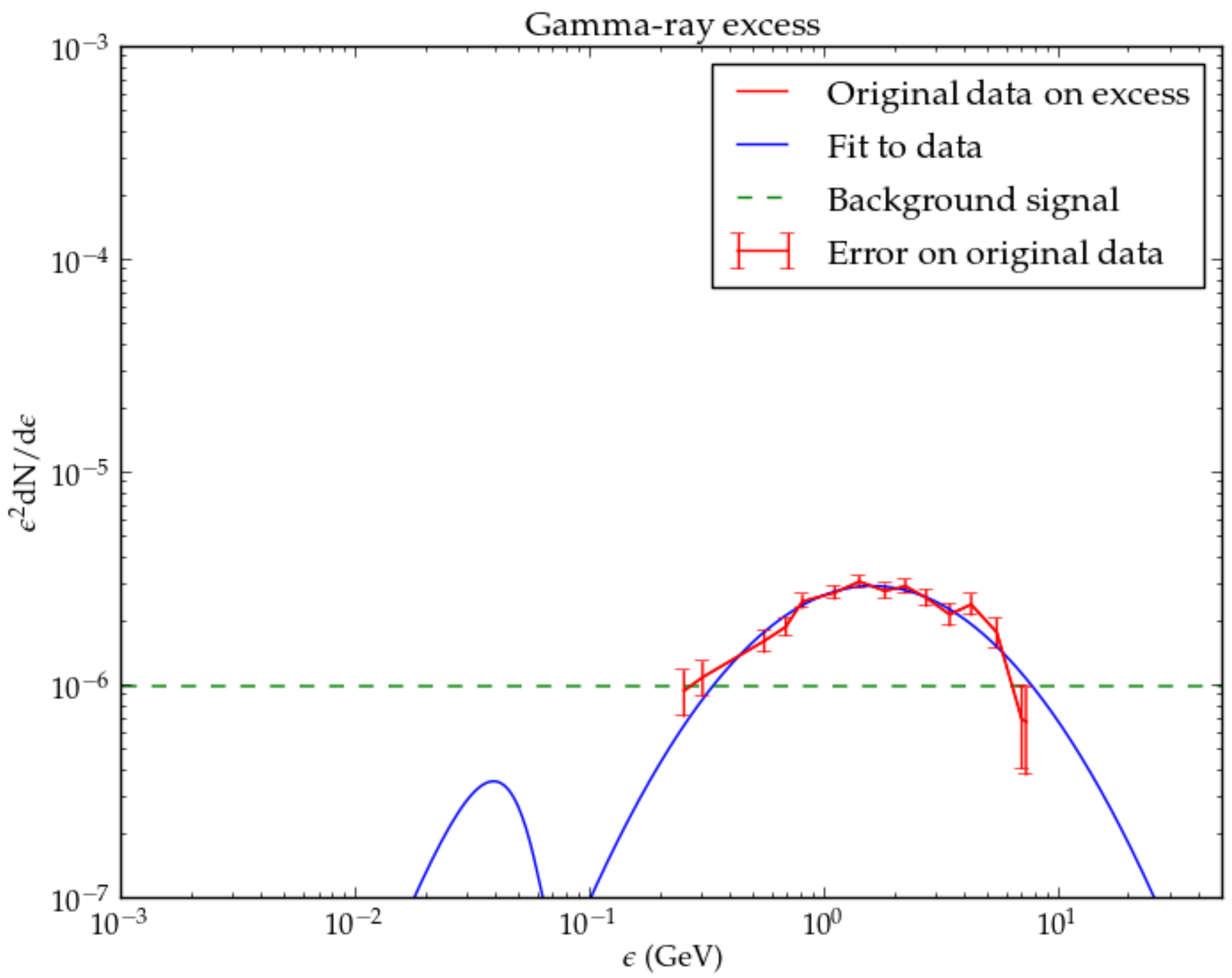
GeV FERMI EXCESS

Schutten, Barrau, Bolliet, Vidotto 1606.08031

Low energy channel

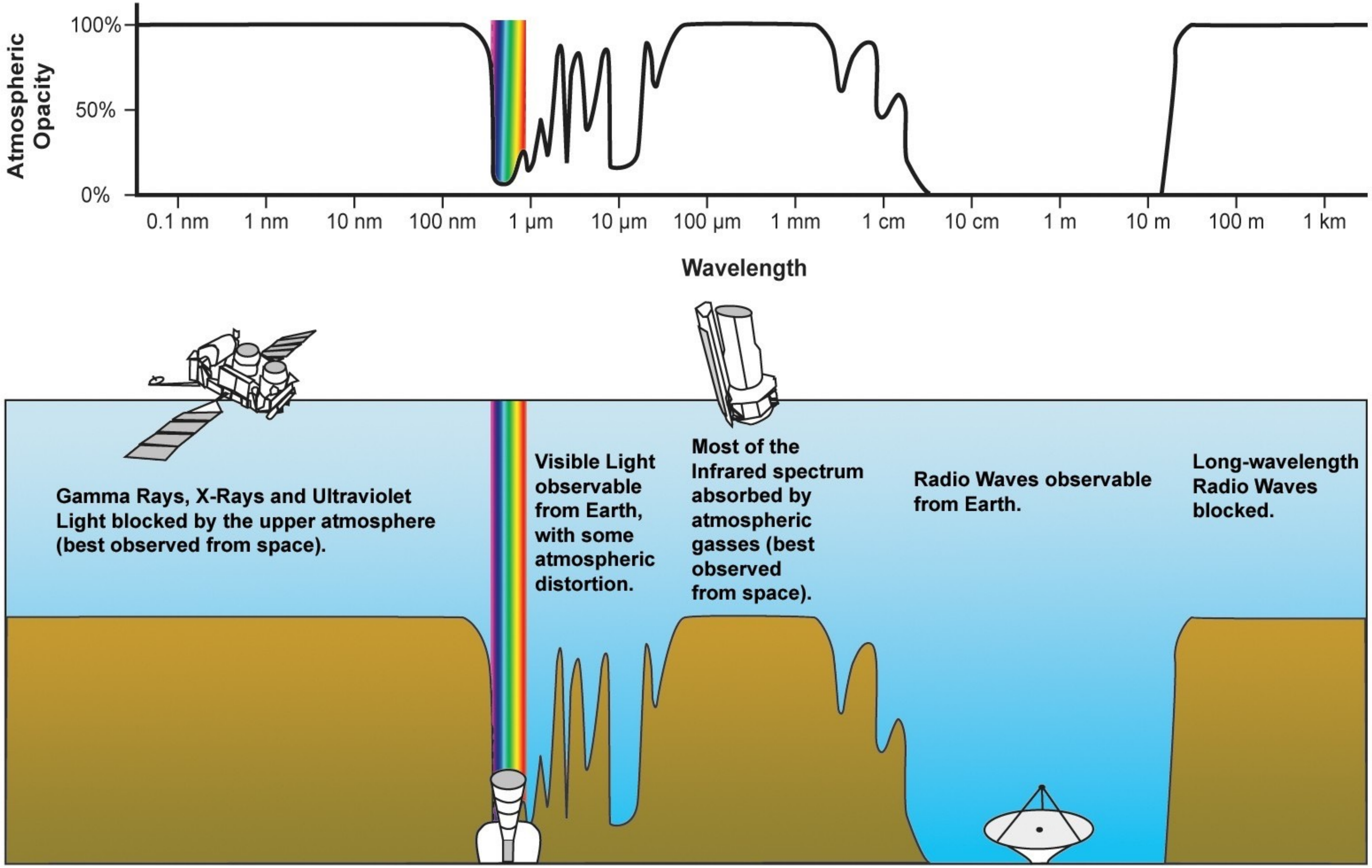
- Consider the longest possible lifetime of a quantum black hole.

- Number of secondary gamma-rays is higher than the number of primary gamma-rays, but their spectral energy density is much lower.

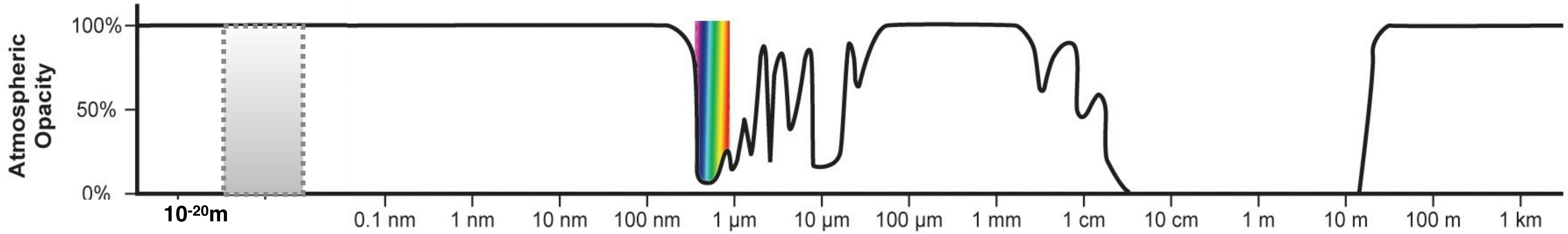



...THE BEST IS
YET TO COME!

DETECTION ON EARTH?



RADIO, MILLIMITERS AND SUB-MILLIMETER ASTRONOMY



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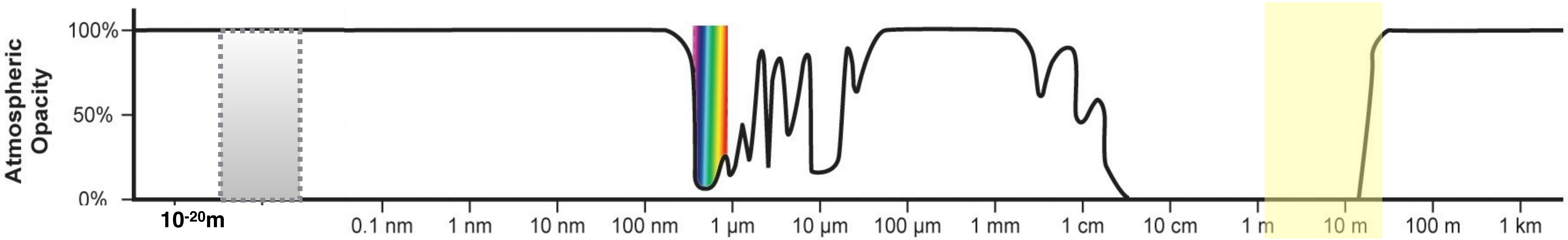

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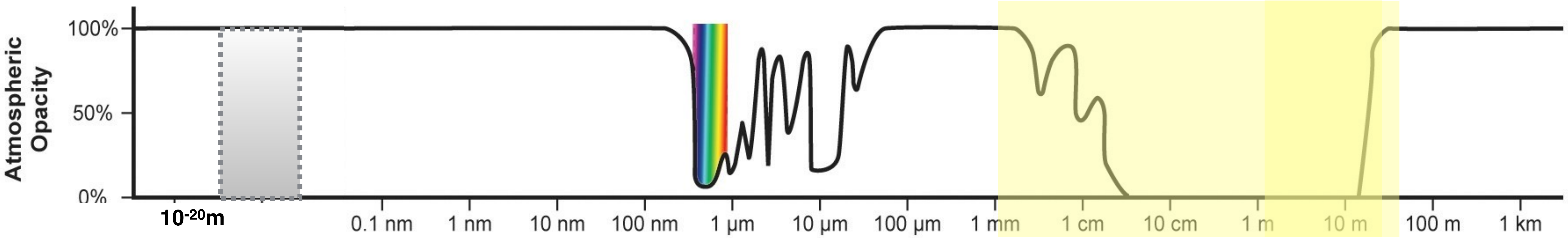
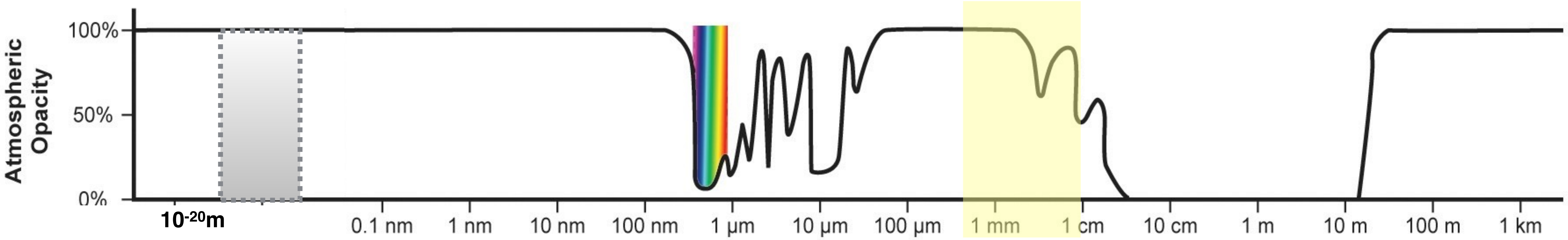


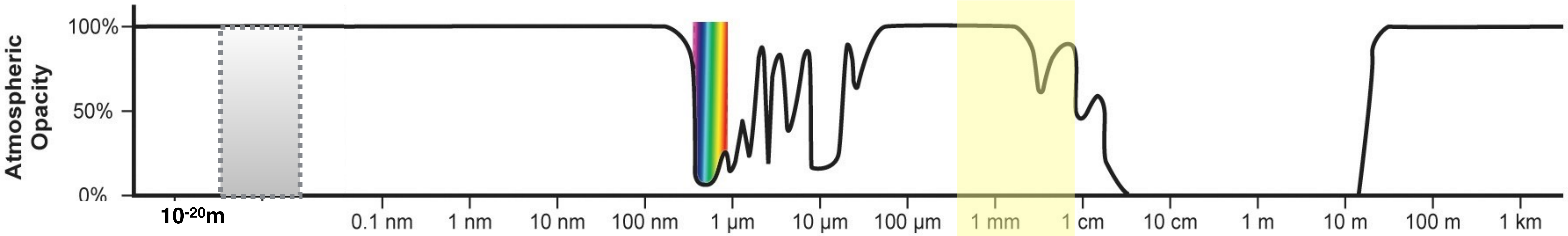

CHIME


SKA


Atmospheric Opacity
100%
50%
0%
10^{-20}m
0.1 nm
1 nm
10 nm
100 nm
1 µm
10 µm
100 µm
1 mm
1 cm
10 cm
1 m
10 m
100 m
1 km


ALMA

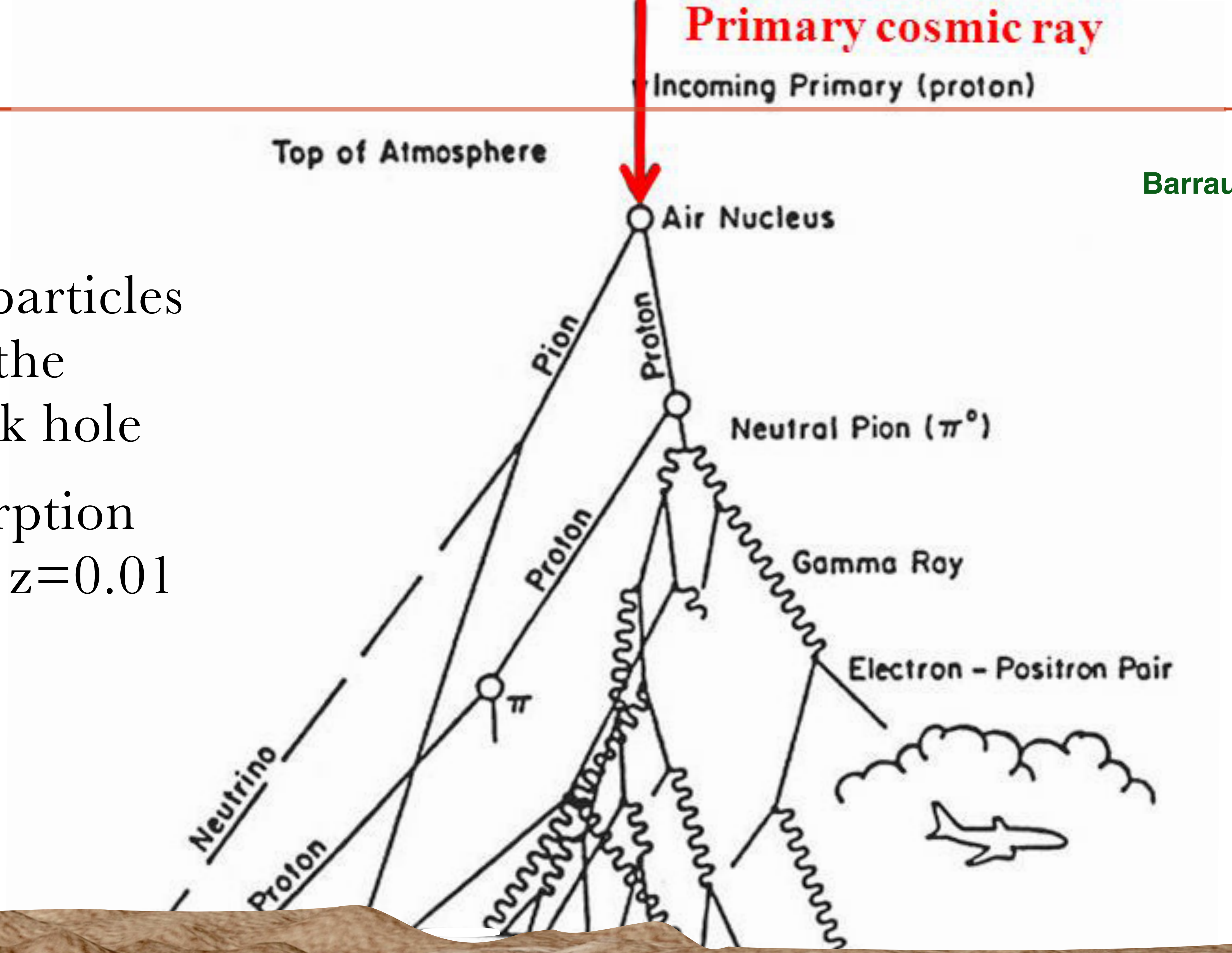
RADIO, MILLIMITERS AND SUB-MILLIMETER ASTRONOMY



TeV ASTRONOMY

Barrau, Rovelli, Vidotto 1409.4031

- the white hole should eject particles at the same temperature as the particles that felt in the black hole
- limited horizon due to absorption ~ 100 million light-years / z=0.01
- Short Gamma Ray Burst ?



TO CONCLUDE


Hey astronomers!
You can measure
Quantum Gravity!
ALMA
PM-04

SUMMARY

1. PHENOMENOLOGY depends mainly on the lifetime

   given as a function of the mass: as short as $\mathbf{m}^2$

   * interesting to check prediction by different QG frameworks!

2. NEW EXPERIMENTAL WINDOWS for quantum gravity

   - signals in the sub-mm, radio & TeV
   - direct detection & diffuse emission
   - peculiar energy distance relation

3. PRIMORDIAL BLACK HOLES

   - new features
   - consequence in the early universe
   - but also in the late one !!!

PLANCK STARS: REFERENCES ON PHENOMENOLOGY

- Planck stars
  Carlo Rovelli, Francesca Vidotto
  Int. J. Mod. Phys. D23 (2014) 12, 1442026

- Planck stars as observational probes of quantum gravity Carlo Rovelli
  Nature Astronomy, March’17, comment

- Planck star phenomenology
  Aurelien Barrau, Carlo Rovelli
  Phys. Lett. B739 (2014) 405

- Fast Radio Bursts and White Hole Signals
  Aurélien Barrau, Carlo Rovelli, Francesca Vidotto
  Phys. Rev. D90 (2014) 12, 127503

- Quantum Gravity Effects around Sagittarius A*
  Hal Haggard, Carlo Rovelli
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- Phenomenology of bouncing black holes in quantum gravity: a closer look
  Aurélien Barrau, Boris Bolliet, Francesca Vidotto, Celine Weimer
  JCAP 1602 (2016) no.02, 022

- Bouncing black holes in quantum gravity and the Fermi gamma-ray excess
  Aurélien Barrau, Boris Bolliet, Marrit Schutten, Francesca Vidotto
  Phys. Lett. B 722 (2017) 58-62,

- Quantum effects of Primordial Black Holes on Galaxy Clustering
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  to appear soon

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