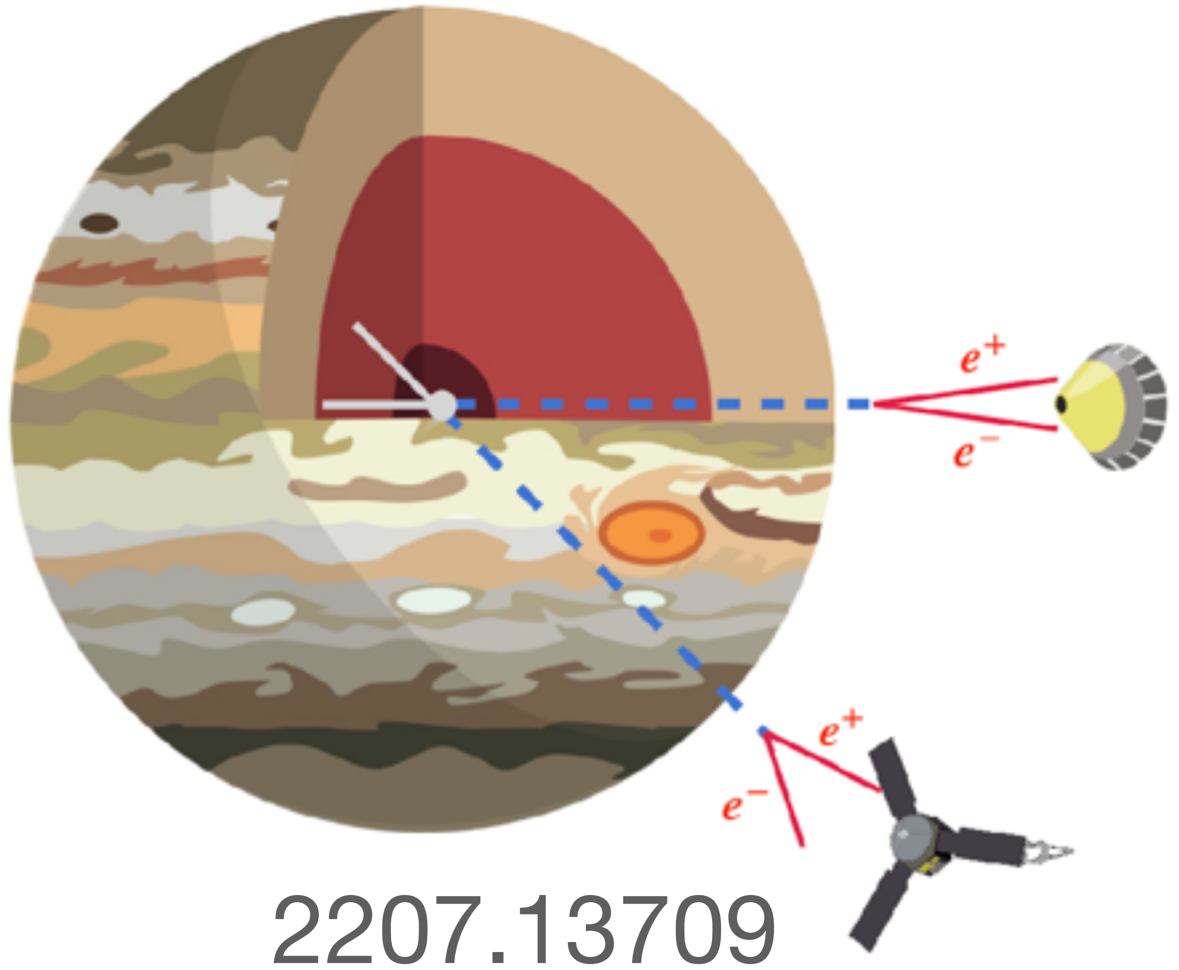
Gravitational searches for compact dark matter objects

Chuck Horowitz, Indiana U. INT 22-2b, Aug. 2022

Dark Matter in Solar System

- Sun—> Cooling, direct detection, GW from CDOs in sun… limits from helioseismology, neutrino fluxes.
- Tracking of spacecraft to Uranus and DM… 2204.07242
- Jupiter—>Many objects such as comet SLY9 collide with it
  Saturn—>Emits more energy than from Sun, DM heating?
- Earth—>Search for tides from CDO / PBHs
- Mars—>Dark Phobos, Deimos? DM heating… Insight seismometer and (failed) heat probe
- Planet 9 —>Is it PBH? [PRL125, 051103] accretion flares
- Moon—>No atmospheric fluctuations, less nu fog, Crater Morphology of Primordial Black Hole Impacts 2104.00033

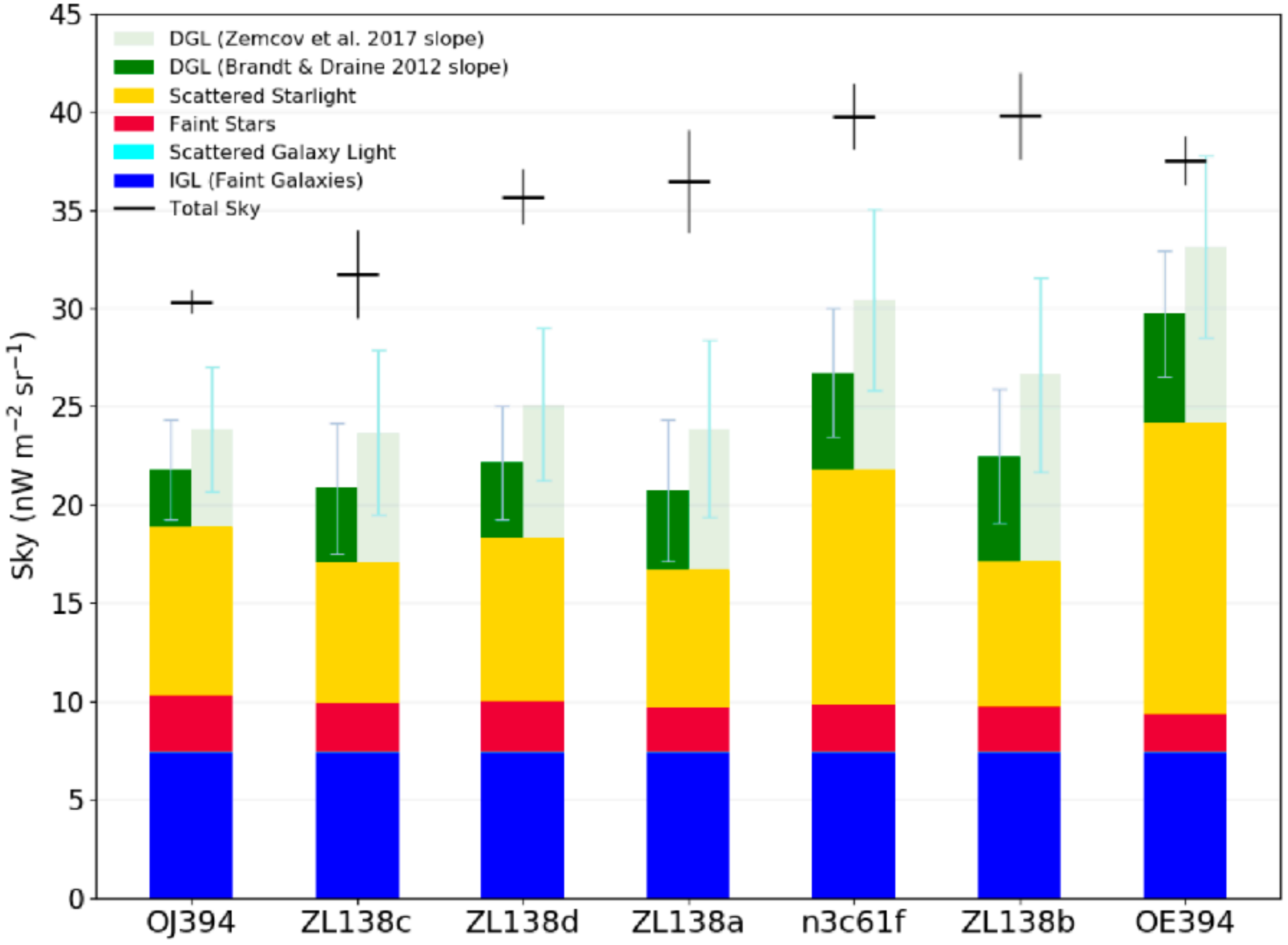


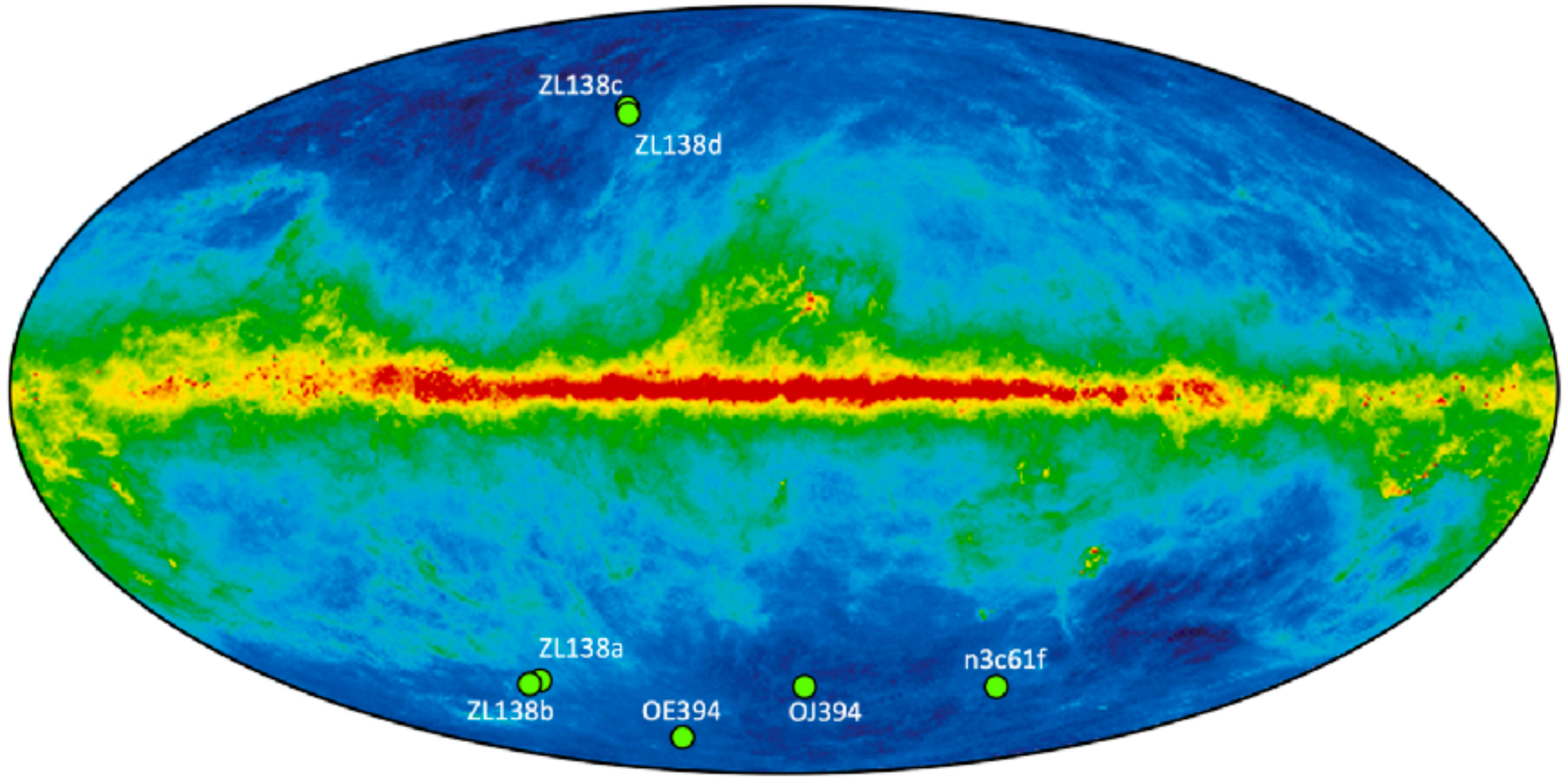
2207.13709

Apollo 17 gravimeter

Cosmic Optical Background from New Horizons

- *43 AU* from Sun, 8" telescope, ~4 min exposures. *10x darker sky* then best Hubble field. 2011.03052





Dark matter signal??

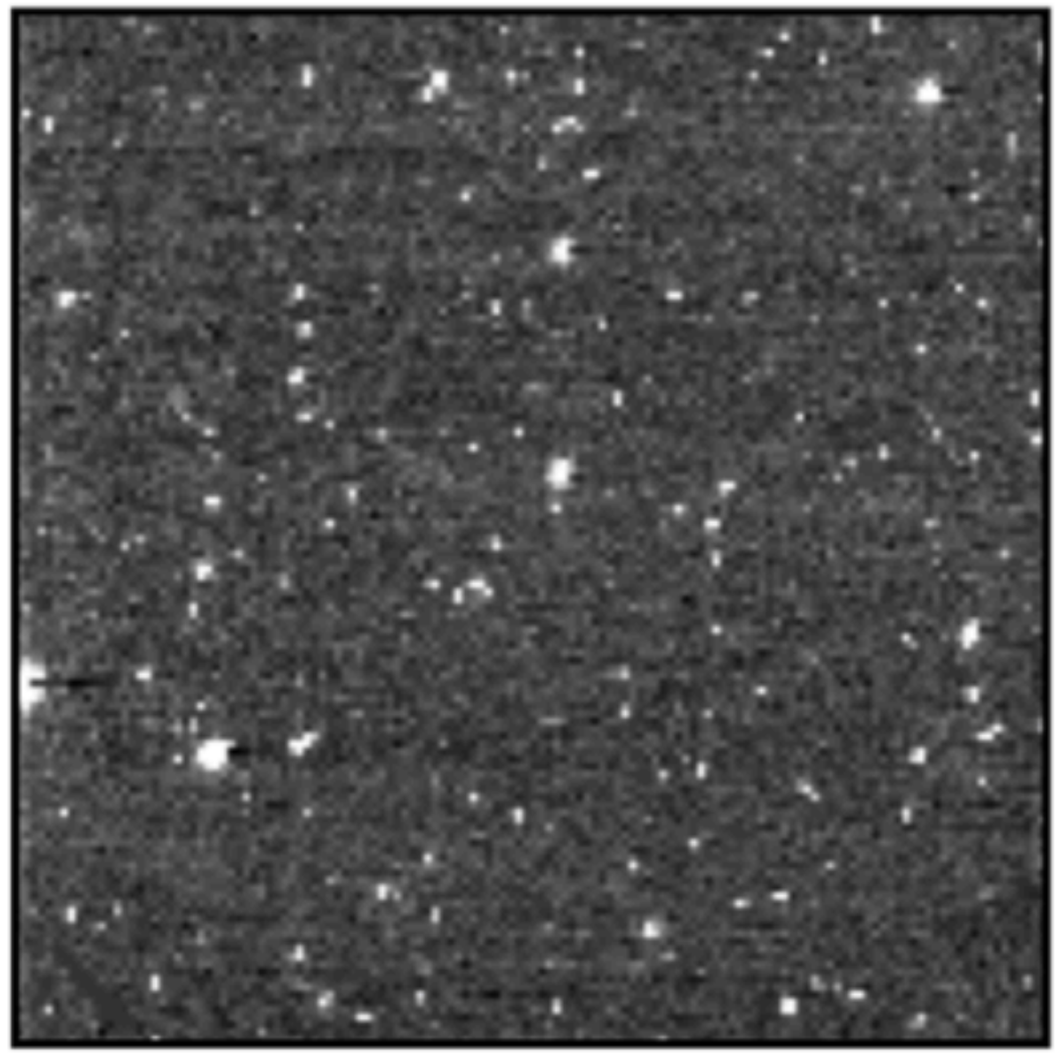
Diffuse Galactic Light

Scattered Starlight

Faint stars

Faint Galaxies

ZodiacLight 138d

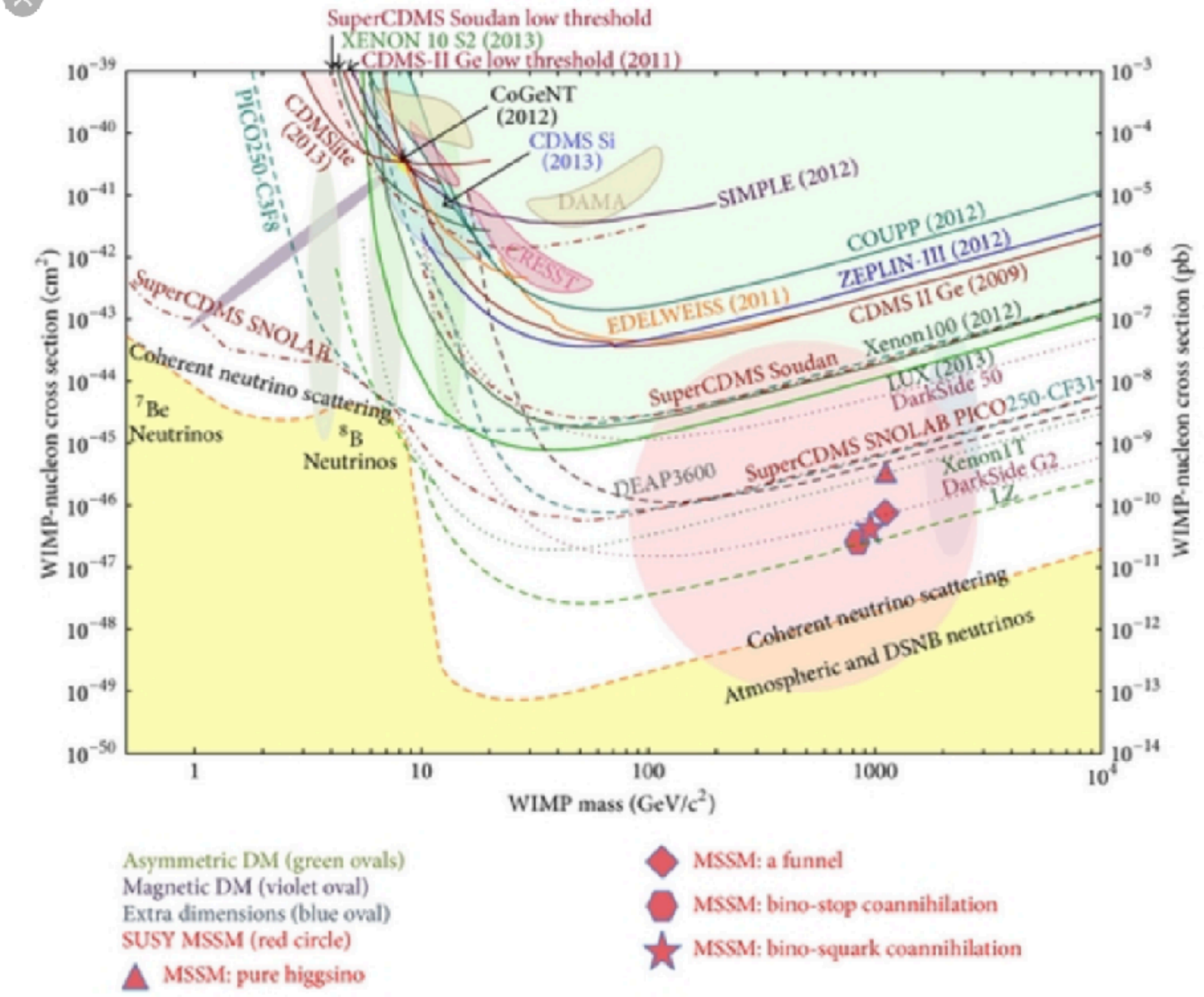


Dark matter and Uranus mission

- Top priority of Planetary Science Decadal Survey is Uranus mission.
- Dark matter will move spacecraft 0.5 m closer to Earth after 10 yr cruise.
- New Horizons tracked to tens of m.
- “Suggests improvements required to detect influence of DM are achievable, *provided they become one of the priorities during mission development.*” *Zwick et al 2204.07242*

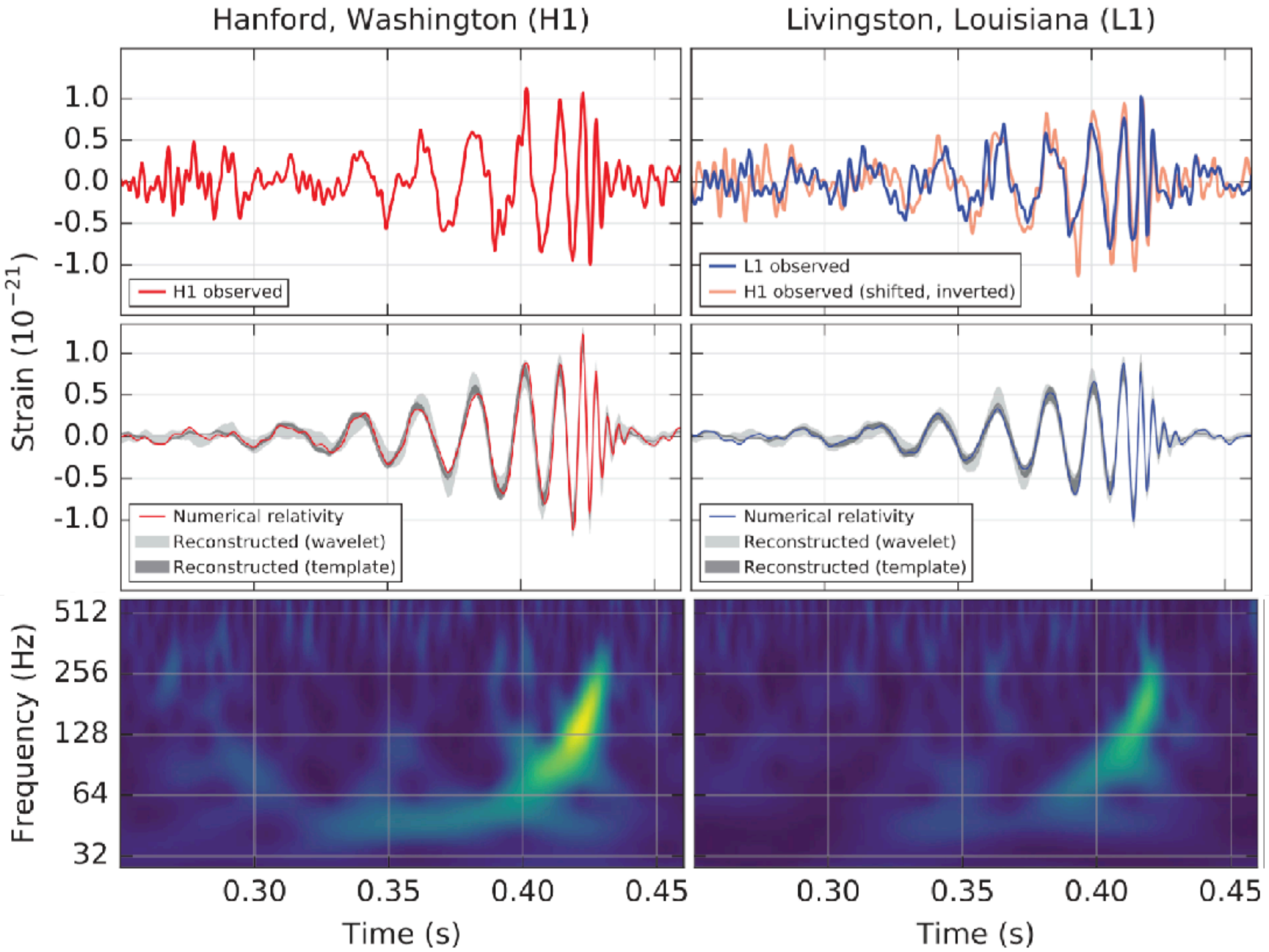
Much of Universe is unknown dark matter

- Many (so far negative) direct searches for particle dark matter.
- If dark matter comes in clumps (*compact dark objects*) avoids conventional searches.
- Attractive to search for dark matter with GW since dark matter is known to have gravitational interactions.



Historic first detection of GW

- Gravitational waves, very small oscillations of space-time predicted by Einstein100 years ago, were first directly observed by LIGO in 2015.



The gravitational wave sky

Galileo's Sky
Moons of Jupiter
Mountains on moon
Phases of Venus
Sun spots

Gravitational Wave Sky
Black hole-BH mergers
NS -NS mergers
BH-NS merger
What else? …

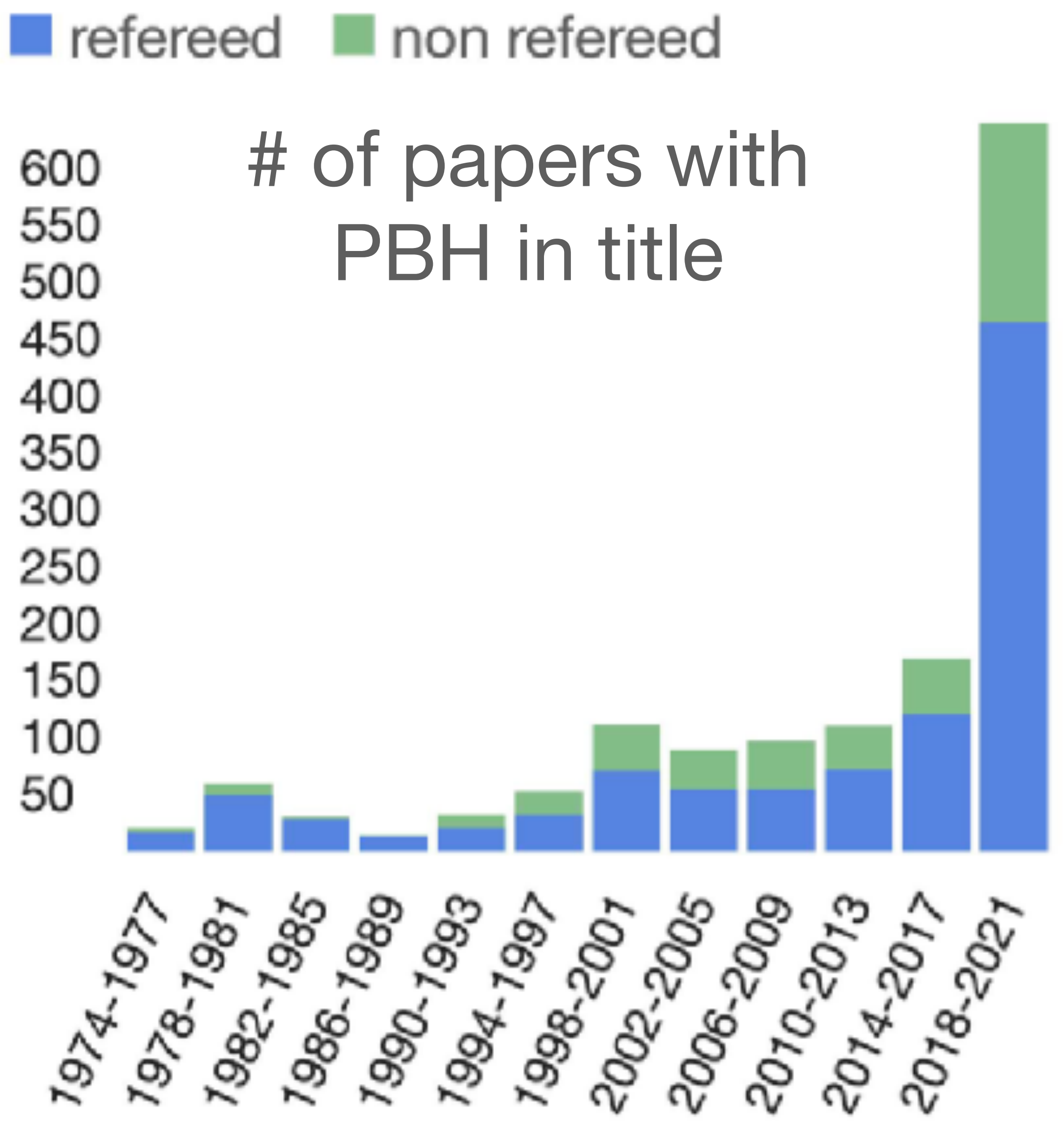
H. Detouche

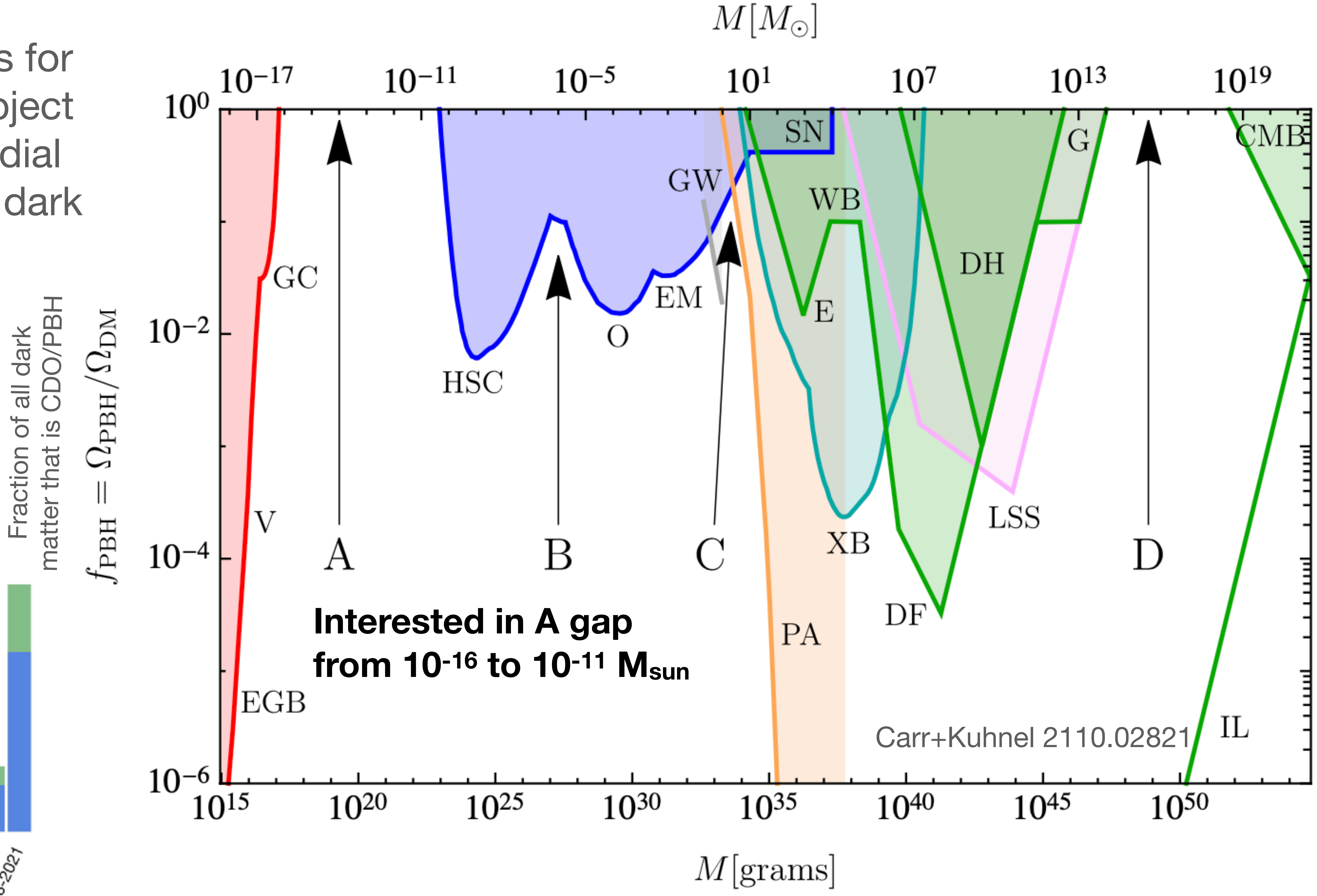
- These are historic times with the opening of the GW sky. What else could be out there?

Compact dark objects

- Dark matter could be concentrated in massive compact objects or CDOs.
- Some possibilities or names for CDOs include Boson Stars, Dark Blobs, Fermi Balls, Q Balls, asymmetric dark matter nuggets, Exotic Compact Objects, Ultra Compact Mini Halos (UCMH), and Macros.
- Primordial black holes (PBH) very popular dark matter model but might destroy solar system bodies.

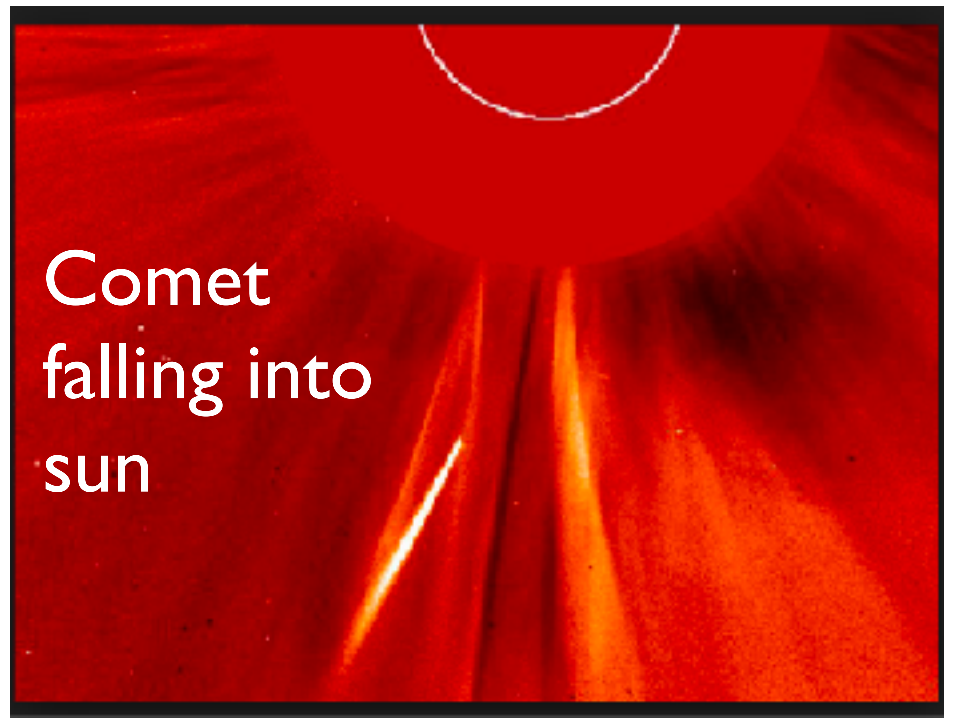
Excluded regions for compact dark object (CDO) or primordial black hole (PBH) dark matter



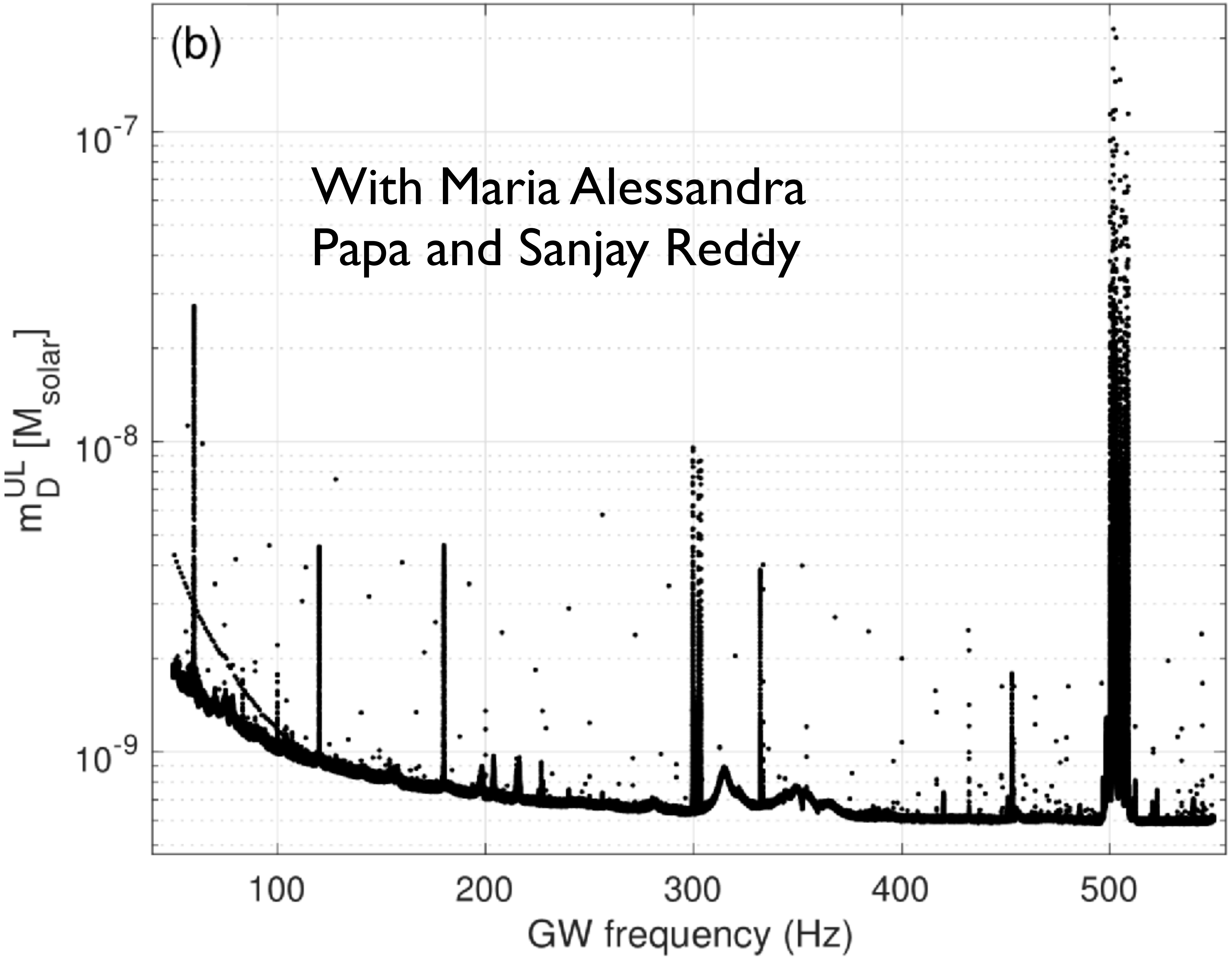


CDO binaries in solar system

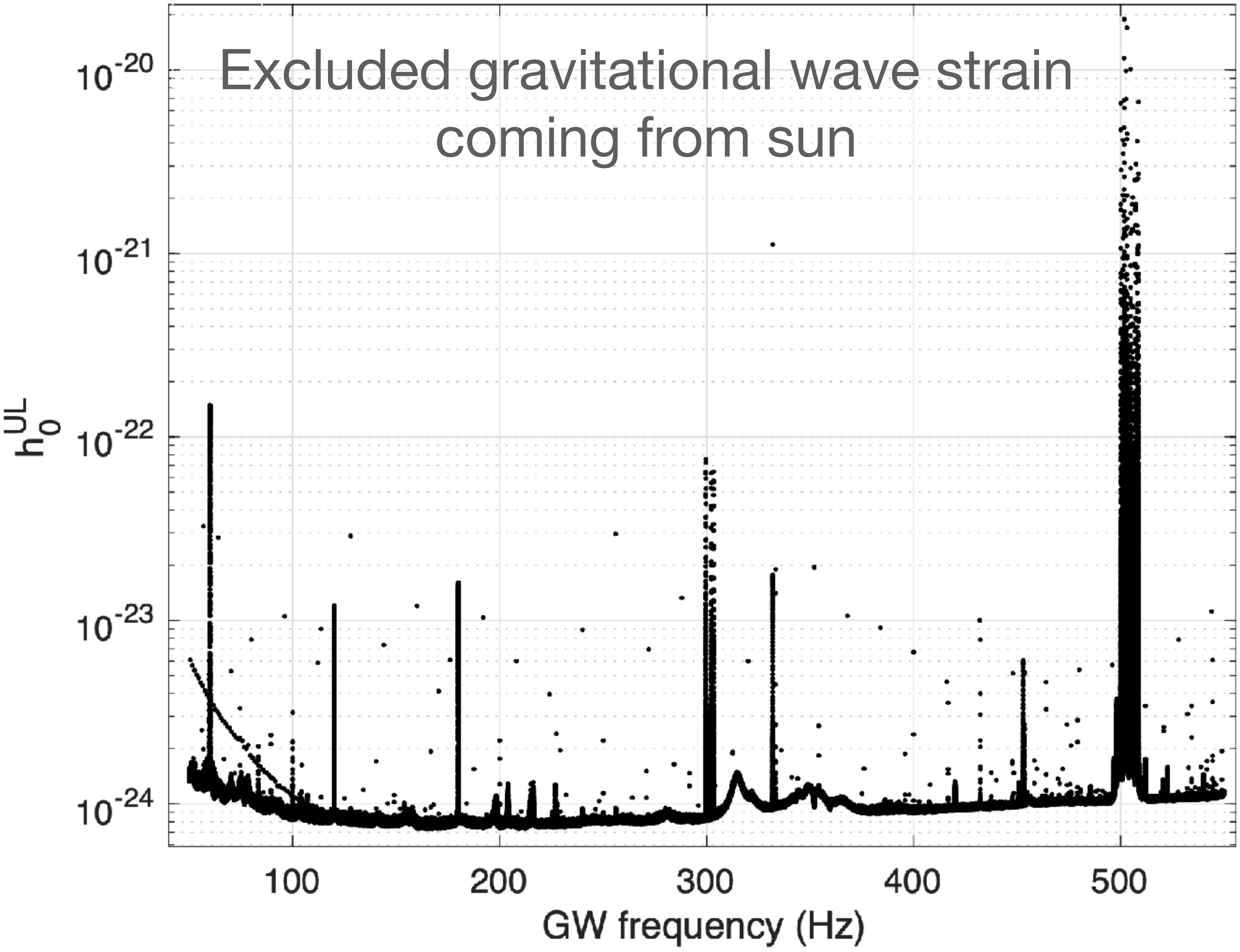
- A close binary of CDOs in the solar system can be a very loud source of GW.
- We have carried out a search using data from first aLIGO observing run.
- Binaries near center of sun with masses above curve ($\sim 10^{-9}\, M_{sun}$) are ruled out.



Solar and Heliospheric Observatory



PRL **122** (2019) 071102, Phys. Lett. B **800** (2020)135072



Excluded gravitational wave strain coming from sun
10^{-20}
10^{-21}
10^{-22}
10^{-23}
10^{-24}
h_0^{UL}
100
200
300
400
500
GW frequency (Hz)

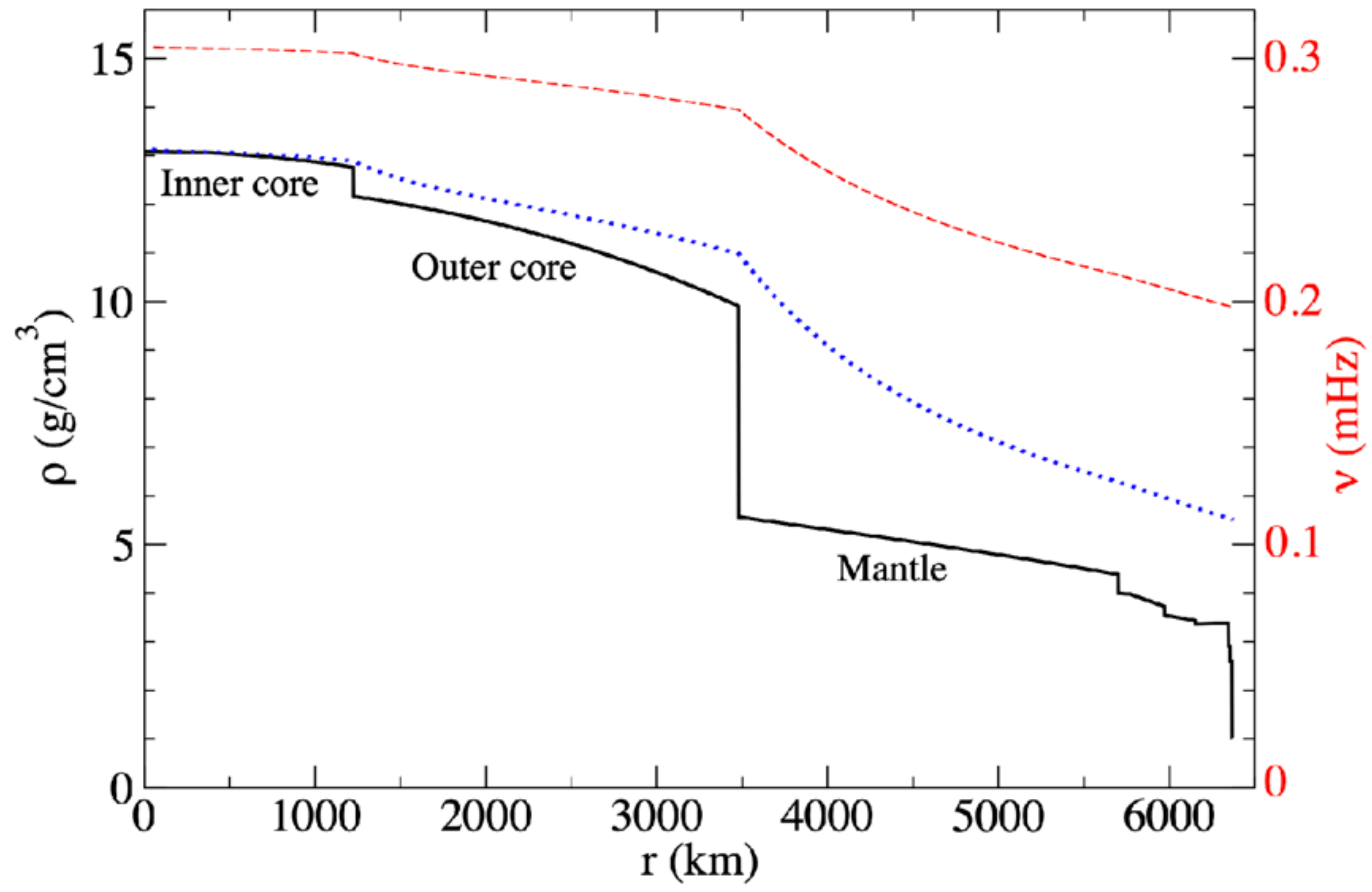
Philosophy

- Try to be sensitive to lowest possible CDO masses. A gap masses 10^{-16} to 10^{-11} M_{sun}
- Try to minimize assumptions about CDO properties.
- Lower CDO mass implies larger number density so the nearest object is closer to you. Look for CDOs orbiting inside the Earth.
- Center of Earth so close one can look for Newtonian tides instead of GW.

Number of dark objects in Solar System at any given time N ~ 1000 (10^{14} kg/M_D)

Orbital frequency inside the Earth

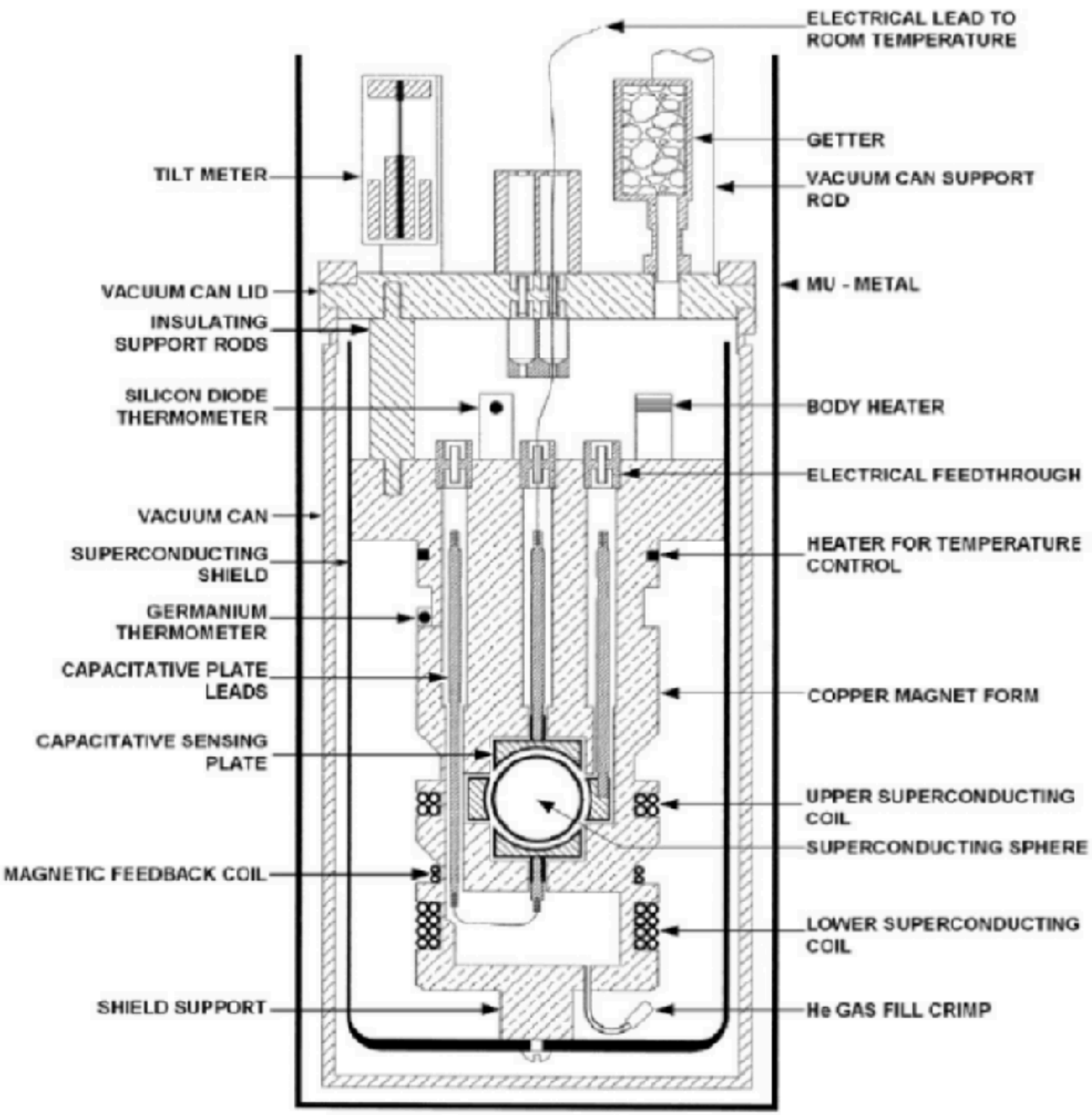
- Object of mass m in circular orbit of radius r about an enclosed mass M(r) has angular frequency ω: $GM(r)m/r^2 = mr\omega^2$.
- Enclosed mass: $M(r)=4\pi\rho r^3/3$.
- Orbital frequency: $\nu = \omega/(2\pi) = [G\rho/(3\pi)]^{1/2}$
- $\nu \sim 0.3$mHz determined by known central density of Earth 13 g/cm^3. [Not by dark matter mass].



Density of Earth

Superconducting Gravimeter

- Sensitive superconducting gravimeters have been deployed at several locations around the world. They are used to observe a wide range of geophysical phenomena including Chandler wobble, solid Earth tides, post glacial rebound, seismic free oscillations and hydrology.
- Also used to search for a dependence of gravity on a hypothetical preferred reference frame (violation of Lorentz invariance) as the Earth translates or rotates.
- Superconducting niobium sphere is levitated in a magnetic field. Measuring magnetic field allows very sensitive measurement of acceleration due to gravity to better then 10^{-12} m/s^2

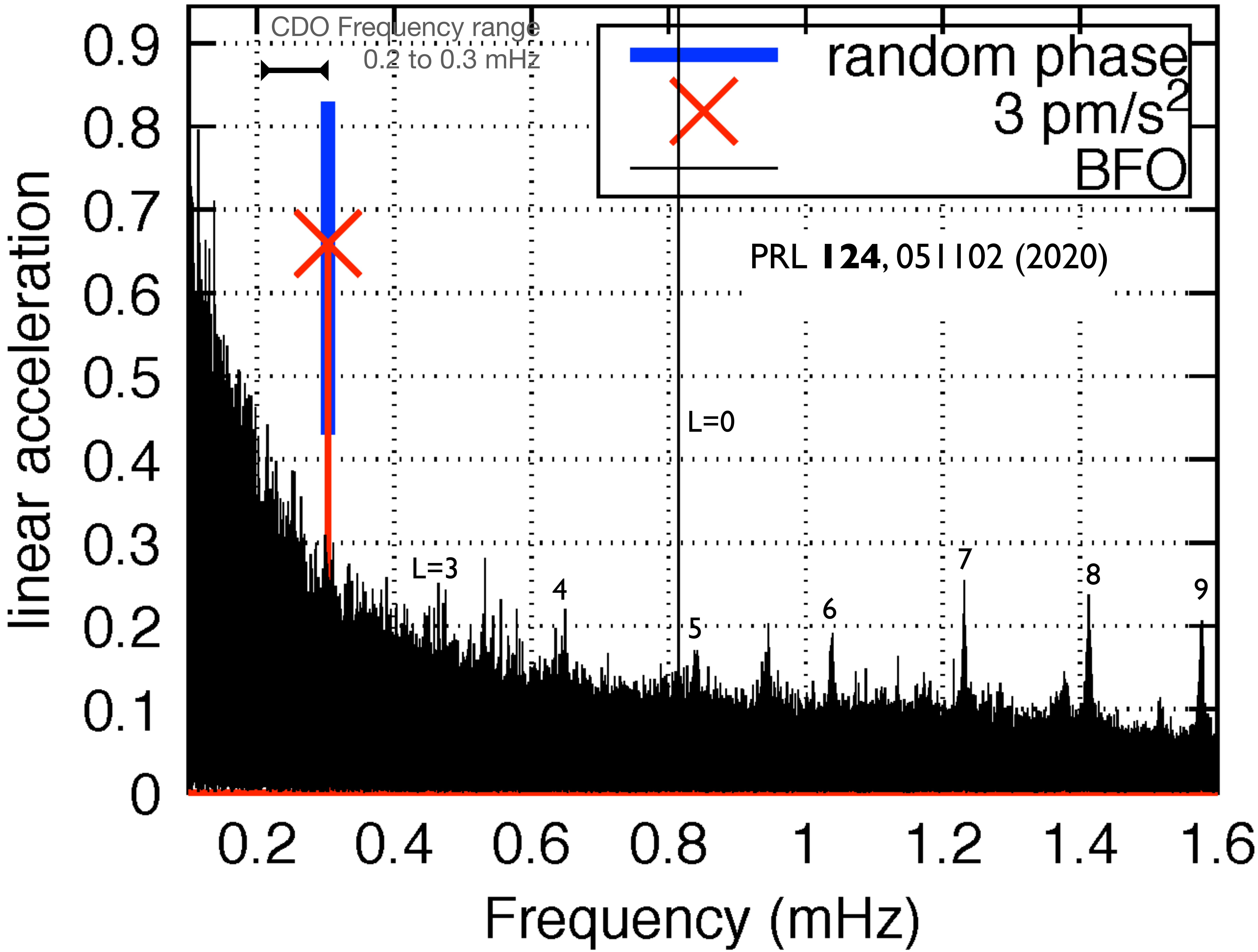


Black Forest Observatory


GWR

Gravimeter in Black Forest Observatory


With R. Widmer-Schnidrig
Seismometer deployed from
Insight Spacecraft on Mars



Data analysis

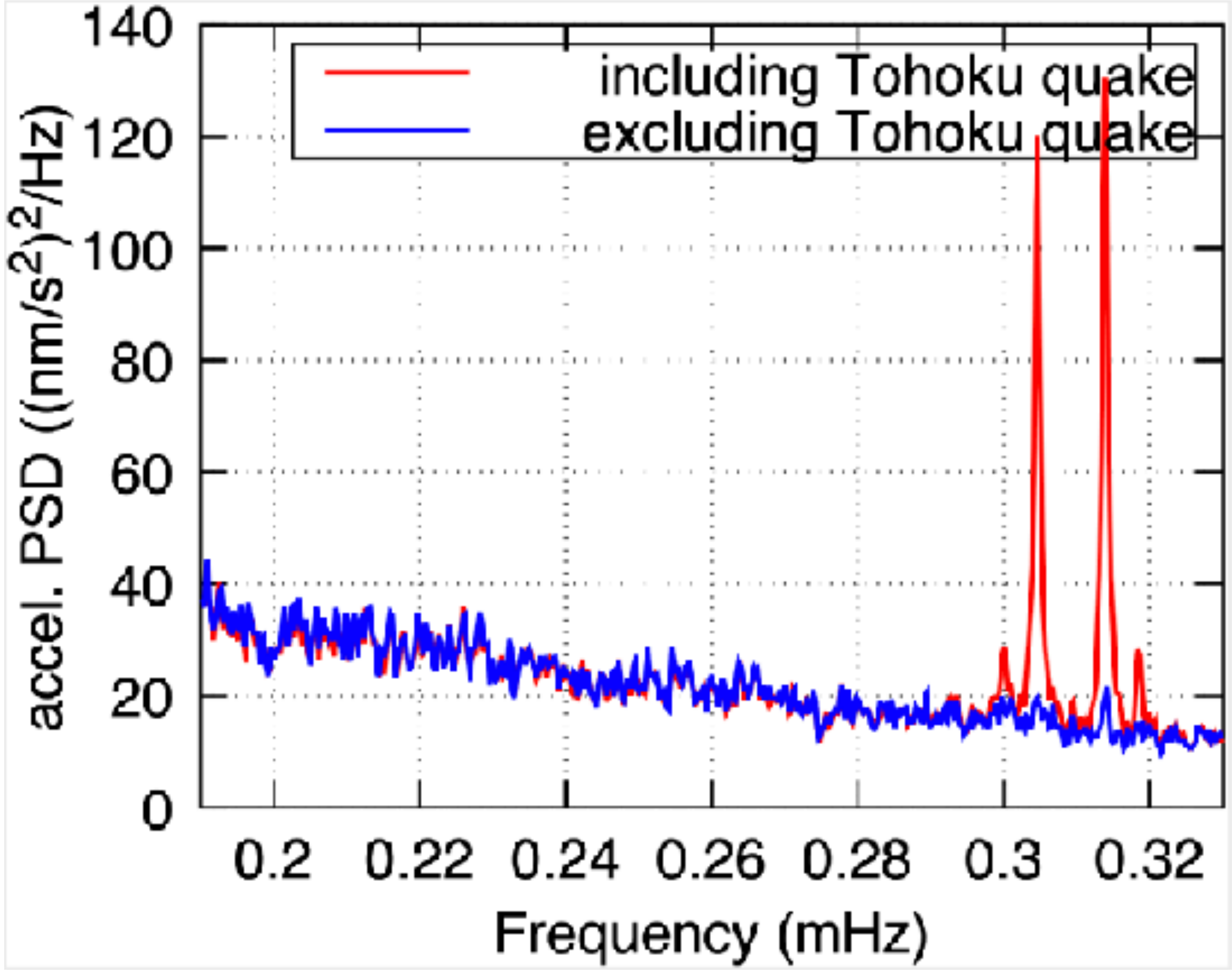
- For ~10 years of data:
- Remove bad data and times after big earth quakes.
- Subtract tide model
- Subtract a multiple of the atmospheric pressure.
- Inject a test signal with same data gaps.
- Fourier transform.
- **R. Widmer-Schnidrig**

Backgrounds and Results

- L=2 free oscillation mode excited by large Earth quakes and has frequency very close 0.3 mHz. Cut large quake data.
- Atmospheric fluctuations above gravimeter dominant source of remaining background. This is partially suppressed by subtracting a multiple of the barometric pressure.
- Exp. upper bound: **$\Delta g(\nu=0.3$ mHz) < 3pm/s^2**.
- Bound on product of CDO mass m_D times orbit radius *a:*

$$m_D\, a \;<\; 1.2 \times 10^{-13} M_\oplus R_\oplus$$

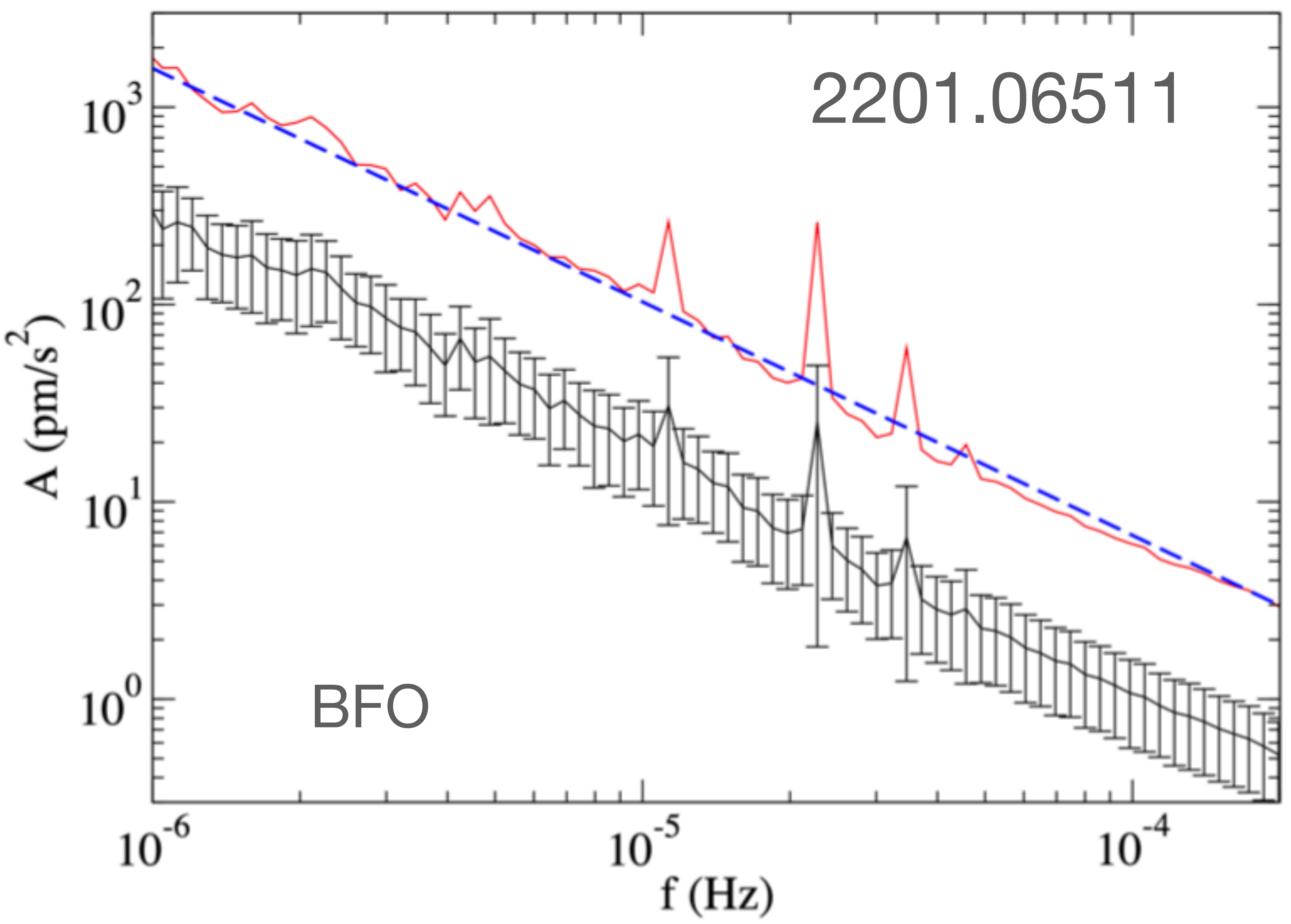
If $a \sim 0.1 R_E$ -> $m_D < 1.2\times10^{-12}\ M_E$ or $3.6\times10^{-18}\ M_{sun}$



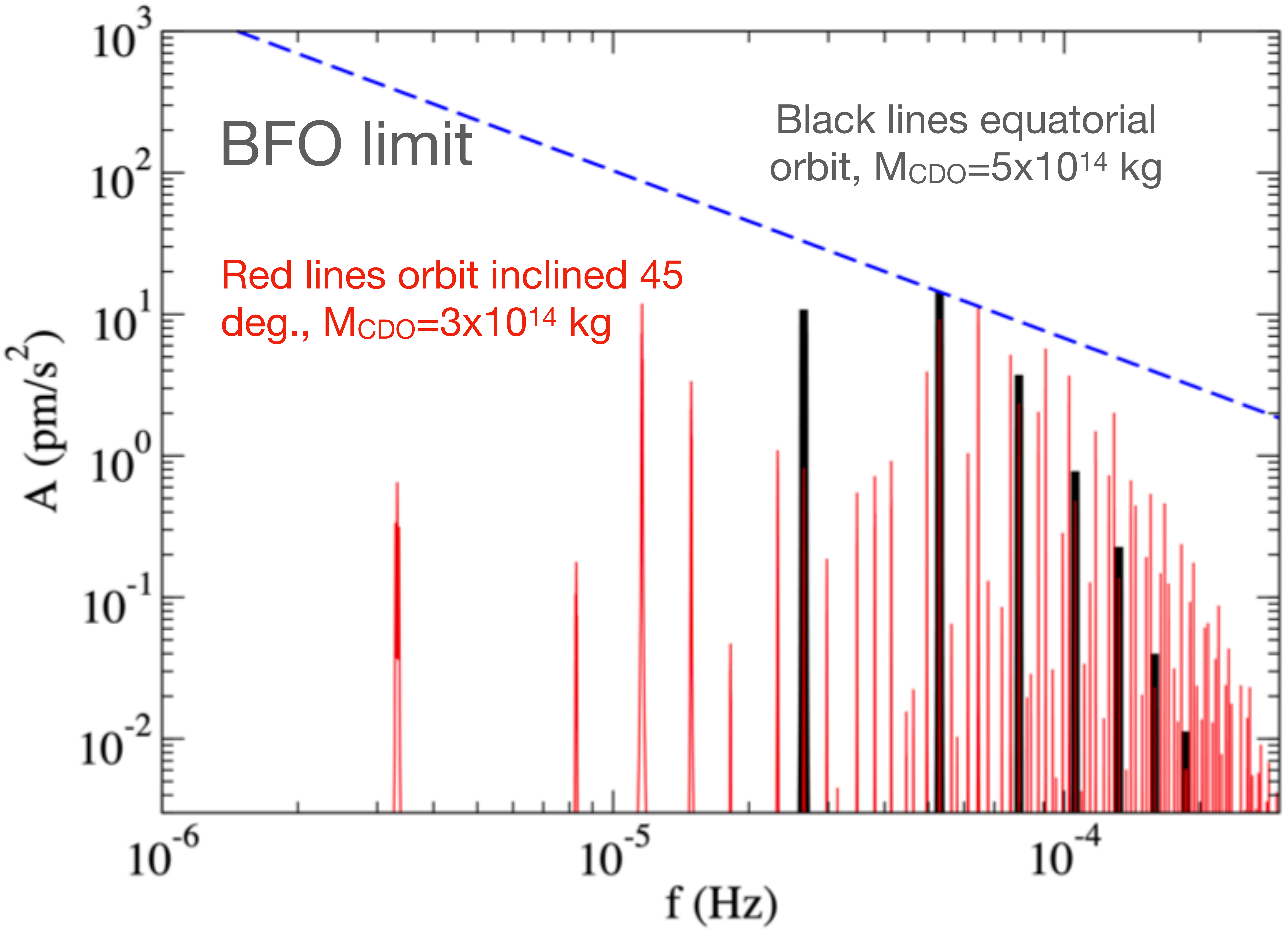
Power spectrum including large Japanese earth quake (red)

Gravitational search for near Earth black holes or other compact dark objects

- Tomoyo Namigata + R. Widmer-Schnidirig
- Extend analysis to orbits outside Earth.
- Interested in lower freqs. depending on orbit.
- Data from BFO at low frequencies dominated by atmospheric fluctuations. Three peaks are imperfectly subtracted tides. Blue dashed line is 10 sigma limit.



Circular orbits $a=3R_E$

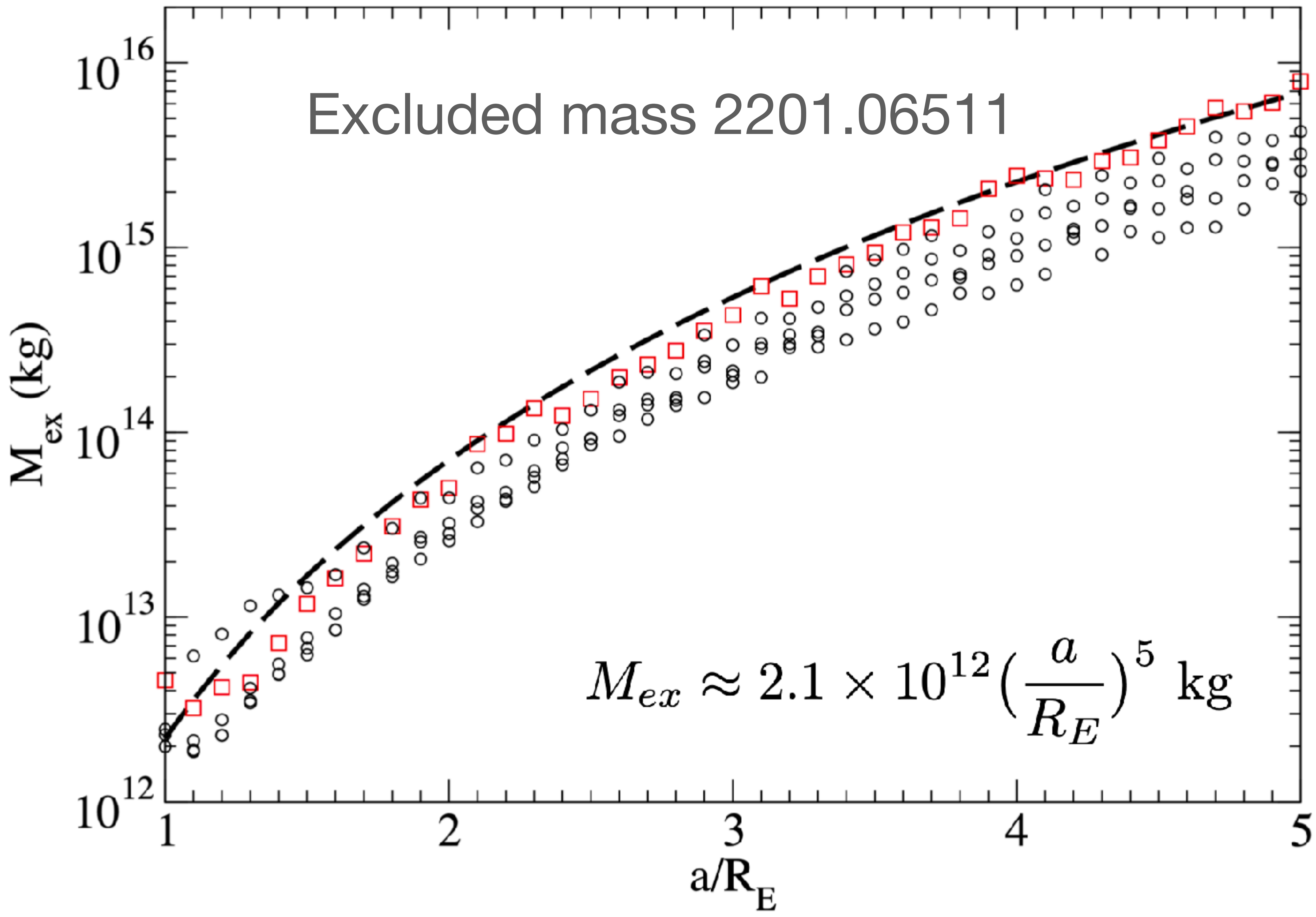


There are no objects orbiting the Earth with semi major axis a and mass greater than $M_{ex}=10^{-18}M_{sun}\,(a/R_E)^5$

Example: for $a<2.5\ R_E$, $M_{ex}=10^{-16}\ M_{sun}$.

Dark matter made of PBHs with $M<10^{-16}M_{sun}$ constrained by unobserved Hawking radiation.

Near Earth black holes are extremely unlikely



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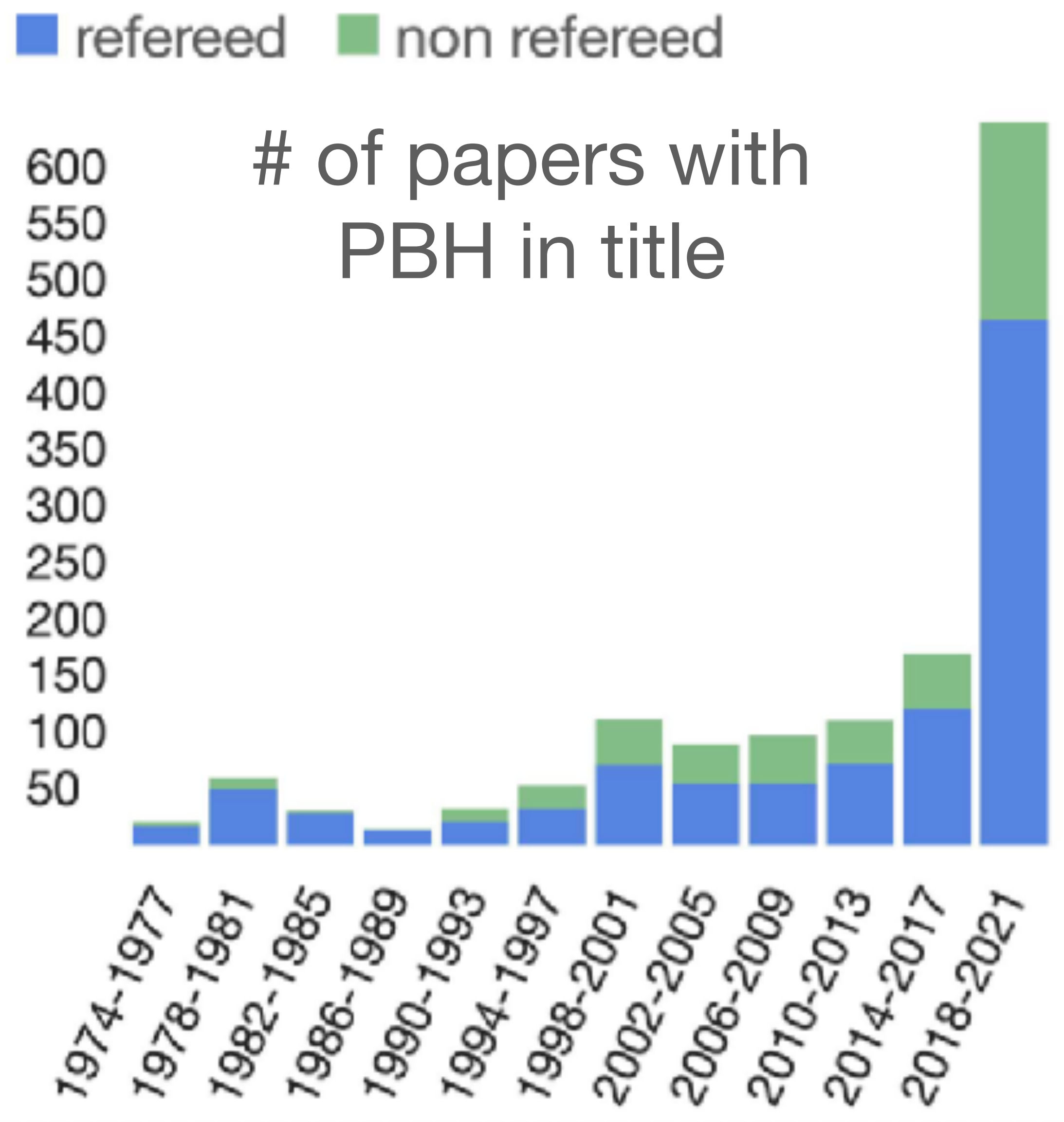
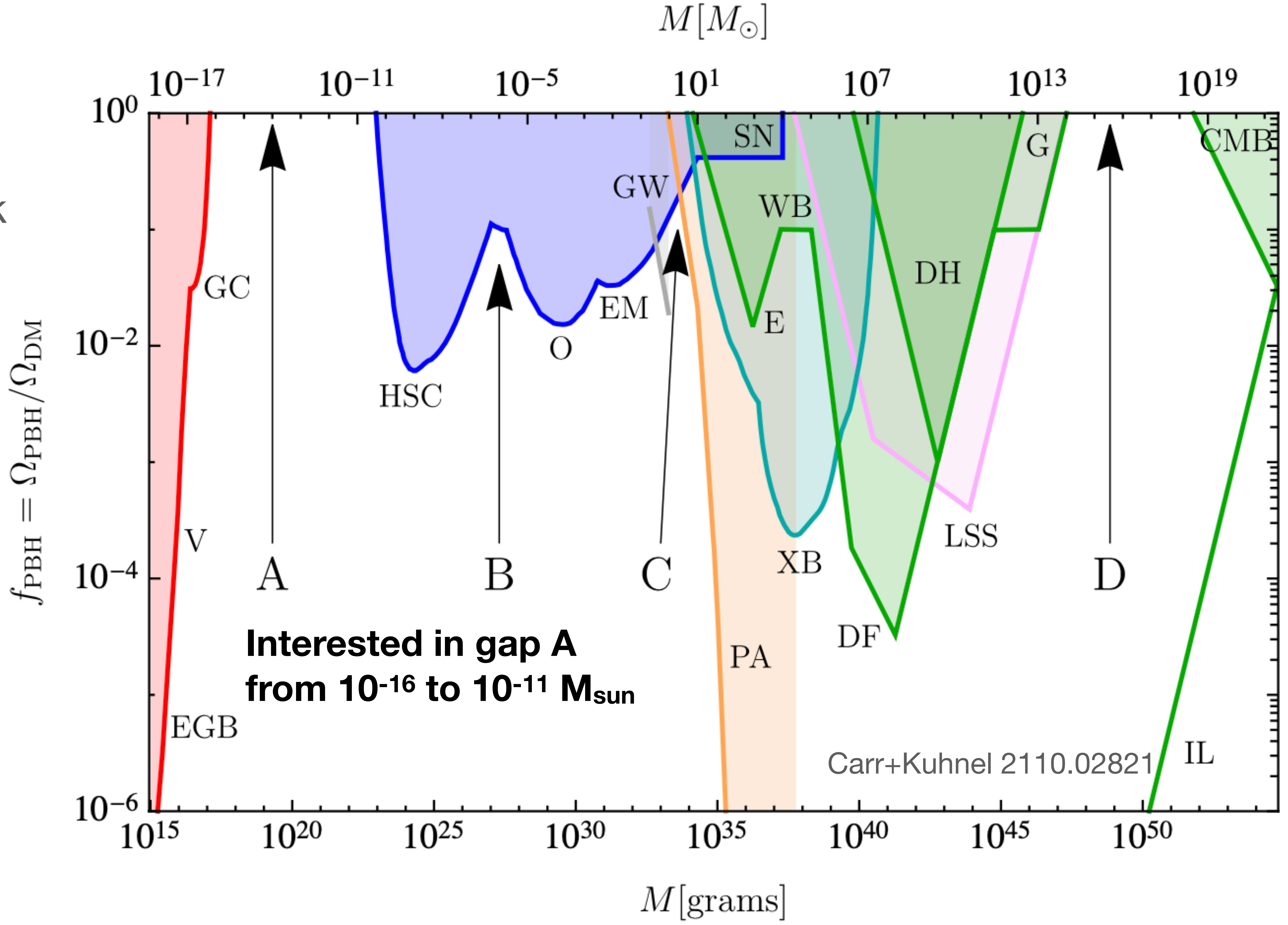


Fraction of all dark matter that is CDO/PBH



The gravitational wave sky

H. Detouche

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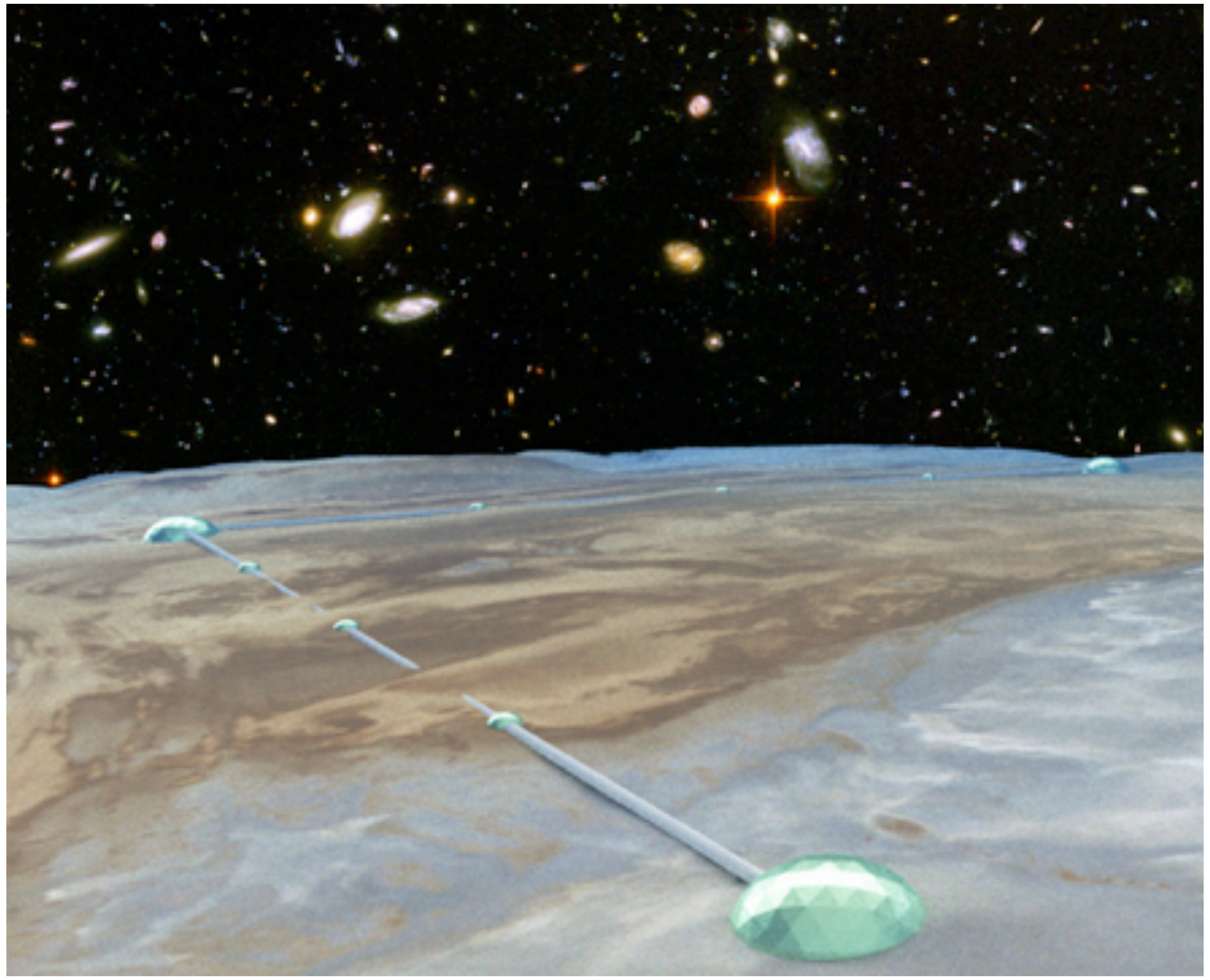
Discovery potential at low mass

- Gravitational wave detector operating at frequency f only sensitive to sources with density $\rho > f^2/G \sim 10^9$ g/cm^3 (LIGO).
- Only *known* LIGO sources NS, BH. Below $0.1M_{sun}$ NS are not bound.
- Standard model background below $0.1M_{sun}$ is *ZERO*.
- A single, well measured, low mass event would be revolutionary!



Cosmic Explorer

Gravitational searches for compact dark matter objects

- CDOs in neutron stars: Sanjay Reddy
- GW from Sun: Maria Alessandra Papa
- Gravimeter on Earth: Tomoyo Namigata and R. Widmer-Schnidrig

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