BH mergers and colliders:

Two complementary windows to New Physics

Giacomo Cacciapaglia

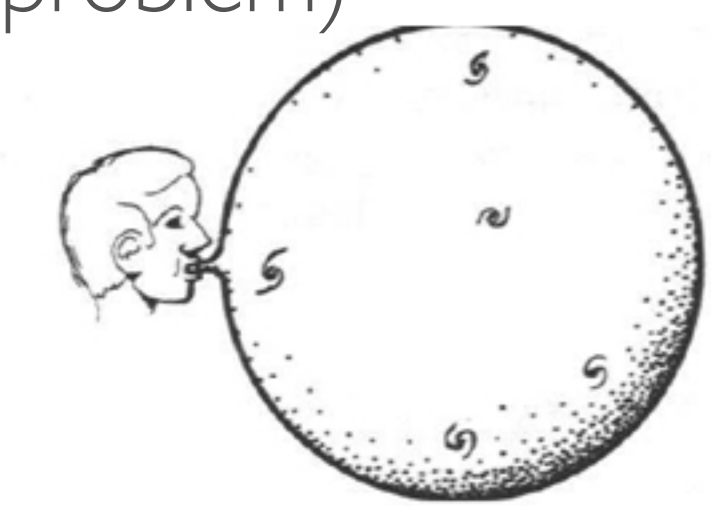
(LPTHE)

Do we still need New Physics?

While the SM is complete and extremely successful, observational and theoretical needs for NPh remain.

- Neutrino masses
- Dark Matter and Dark Energy
- Baryon asymmetry in the Universe
- Absence of strong CP violation
- …

- Naturalness of the EW scale (hierarchy problem)
- How to incorporate Inflation?
- Quantum gravity
- …



How to look for New Physics?

Quantum physics taught us that new particles (states) can be produced via collisions.

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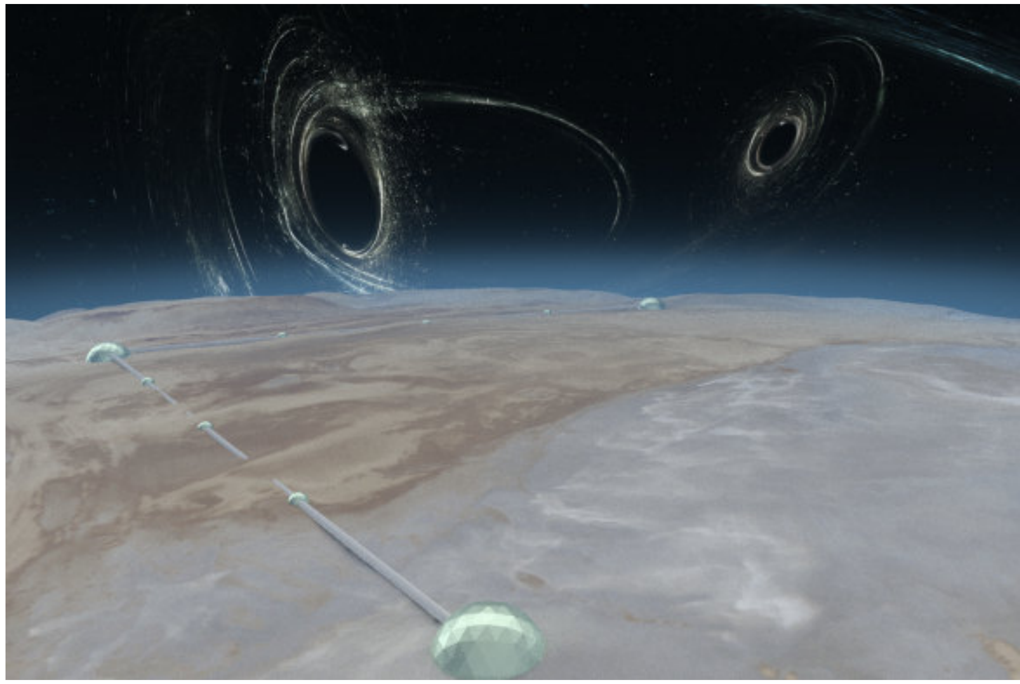
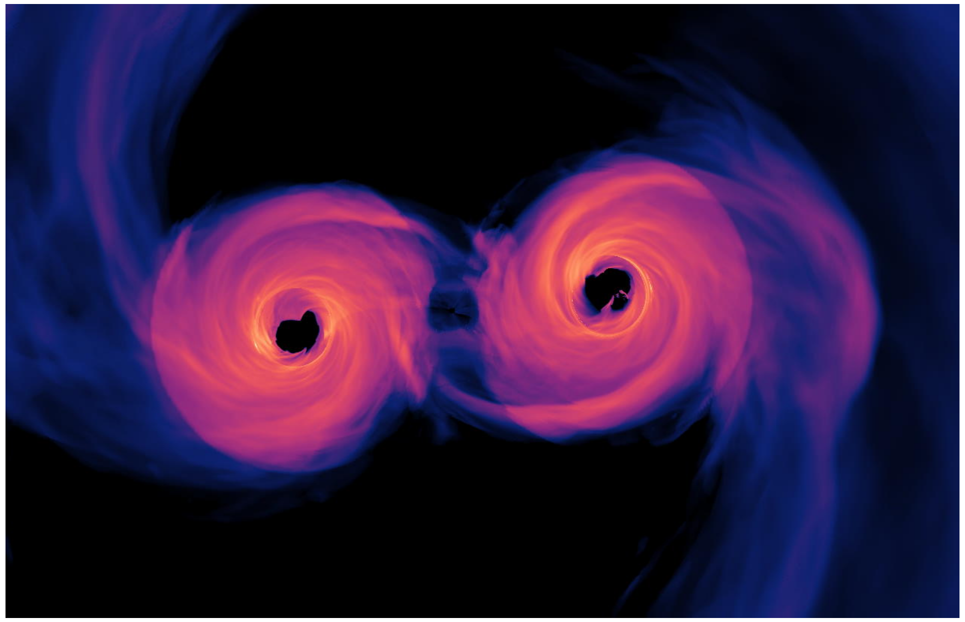
- Black hole mergers: provide signals in multi-messenger astrophysics





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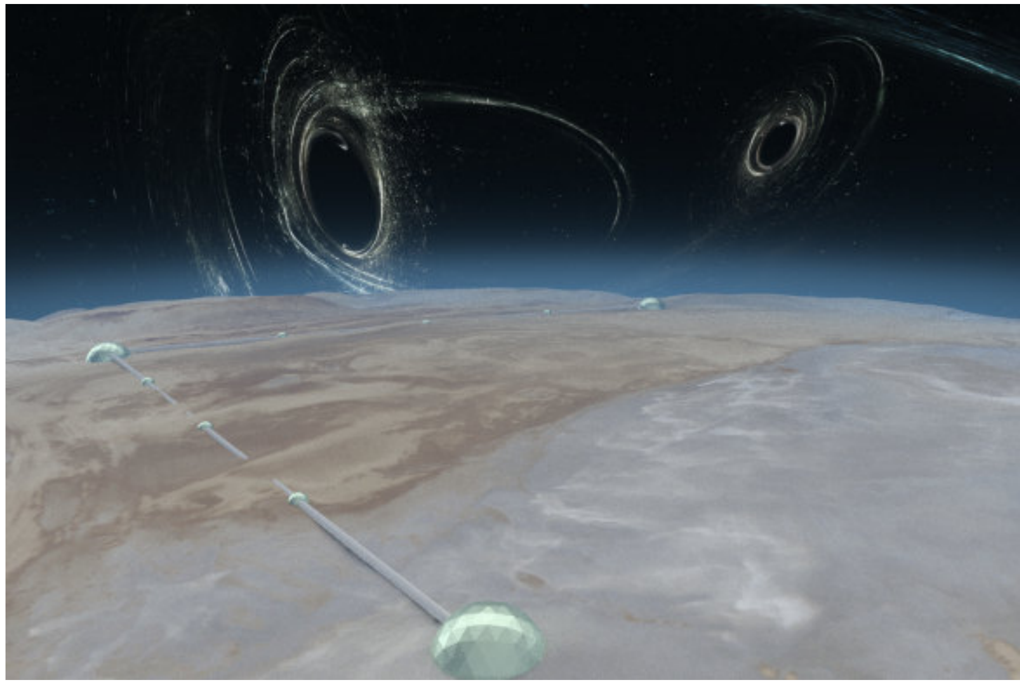
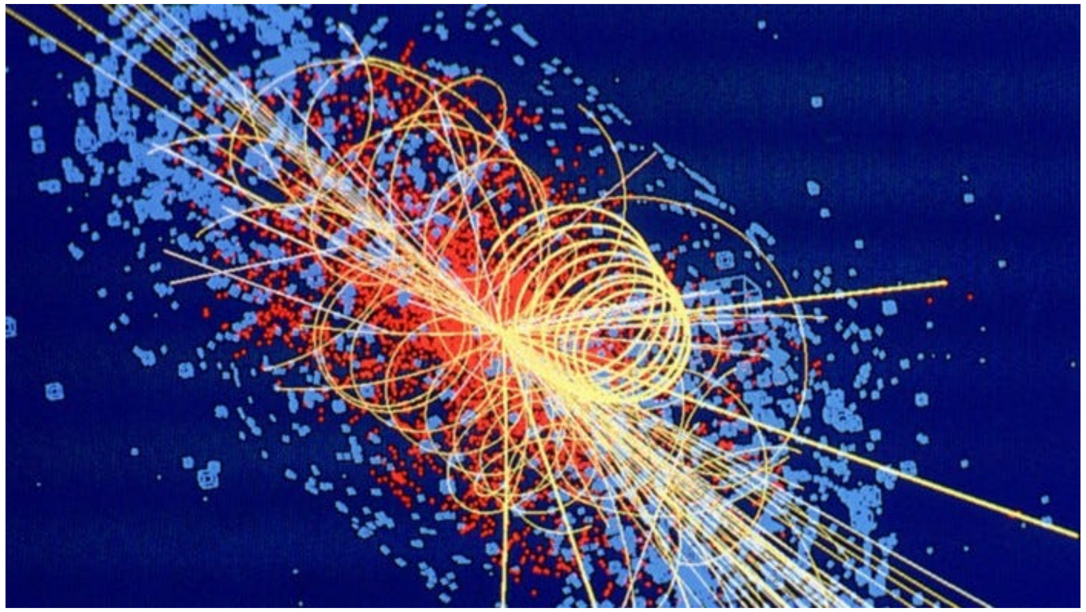
- Particle colliders, present and future





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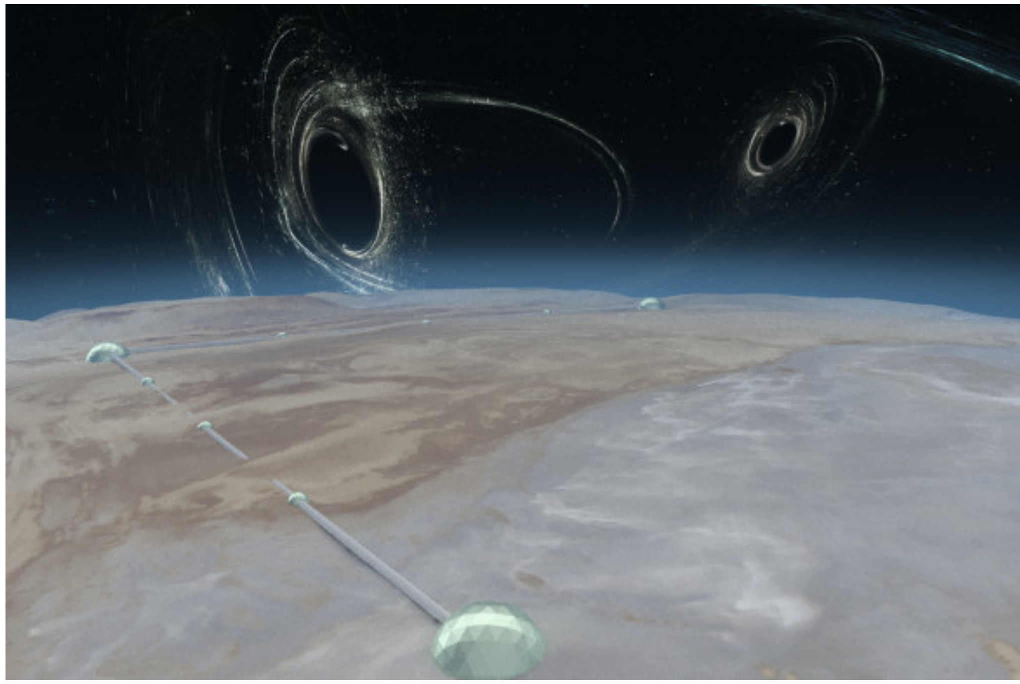
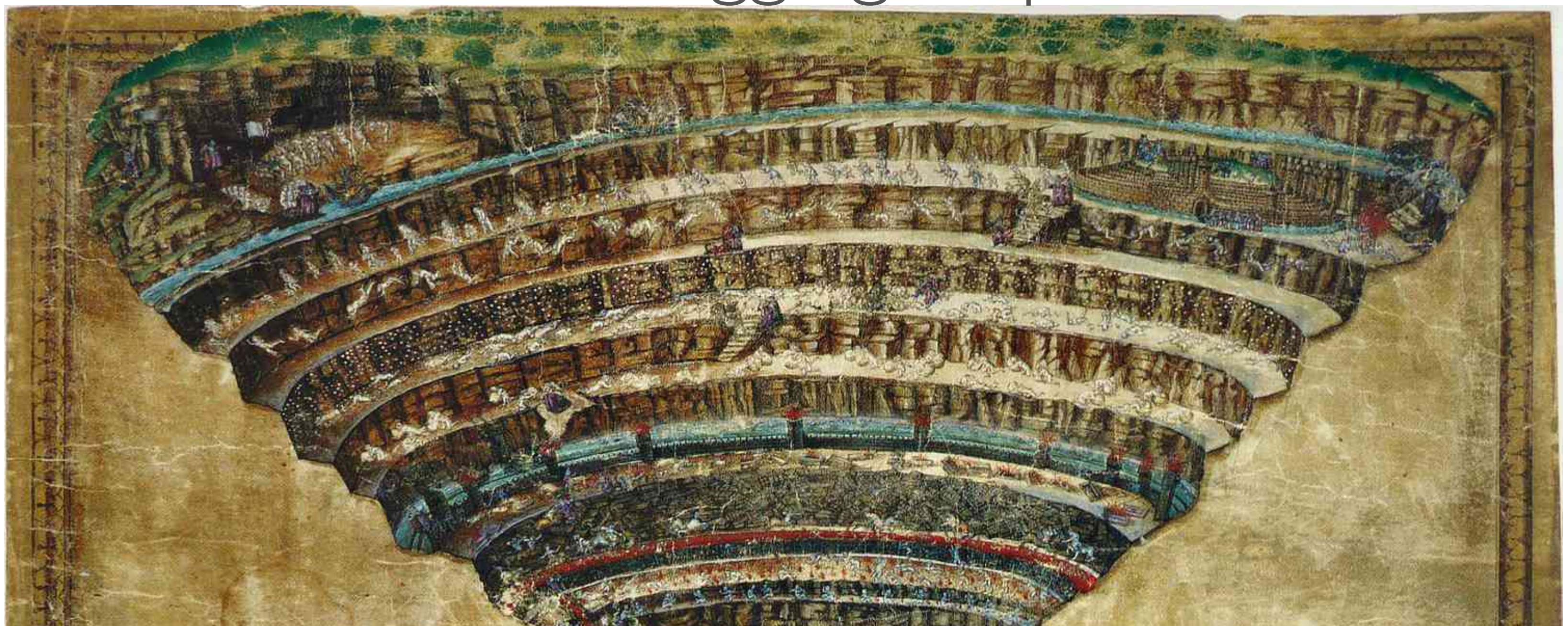
- Black hole mergers: provide signals in multi-messenger astrophysics
- Particle colliders, present and future
  …some digging required!

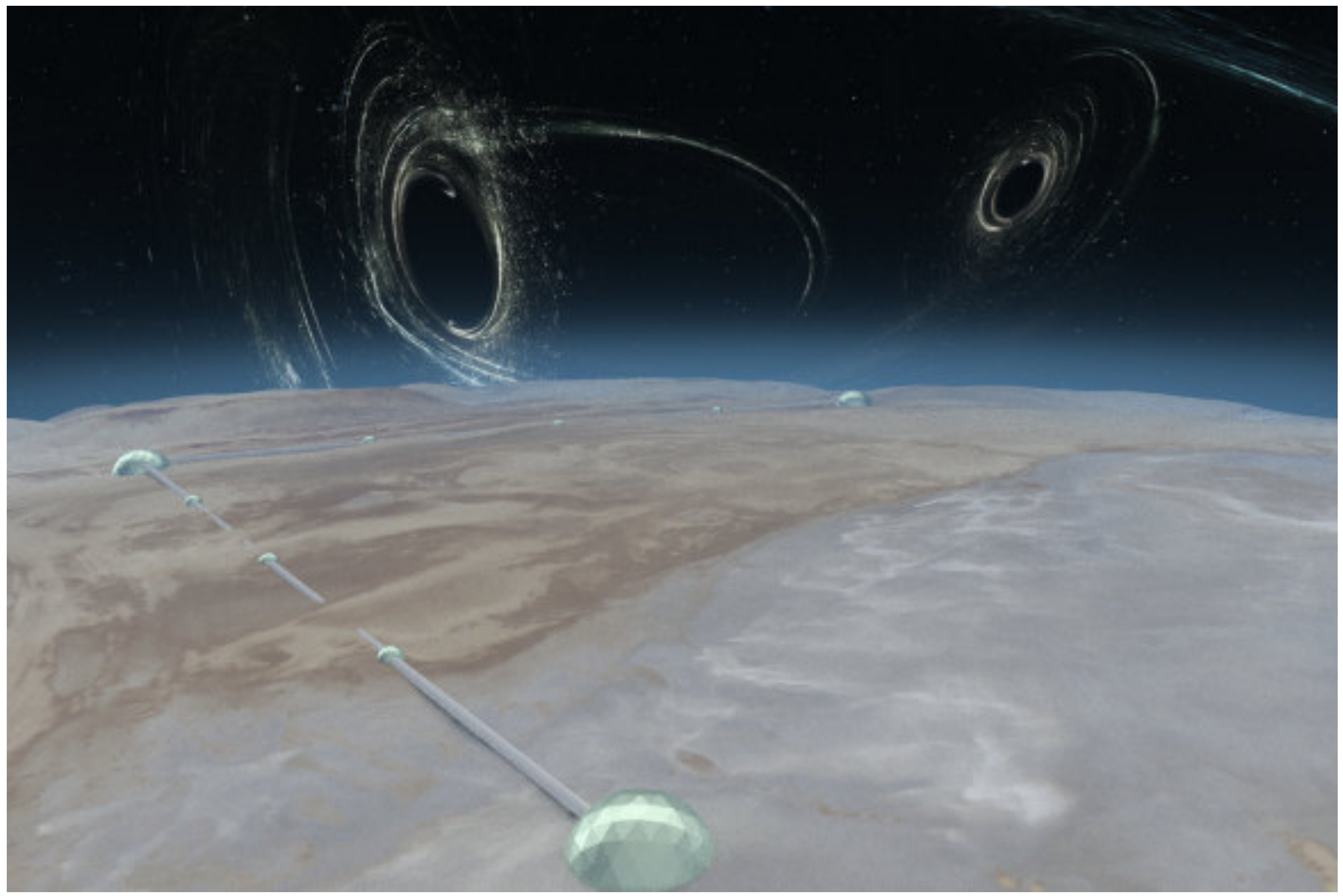


From the Heavens…



…to Earth.

New Physics from the Heavens?

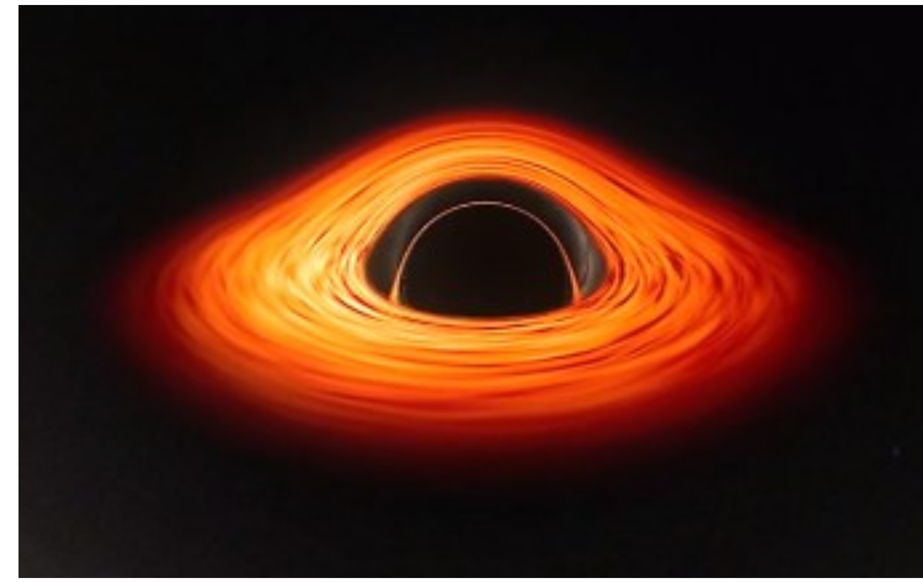


Ingredients: Merging Black Holes, various telescopes,
and … a leap of faith.

Astrophysical Black Holes

Stellar mass BHs produced at the end of heavy star life

SMBH ~ 10^5 – billions $M_\odot$ and found at the centre of galaxies



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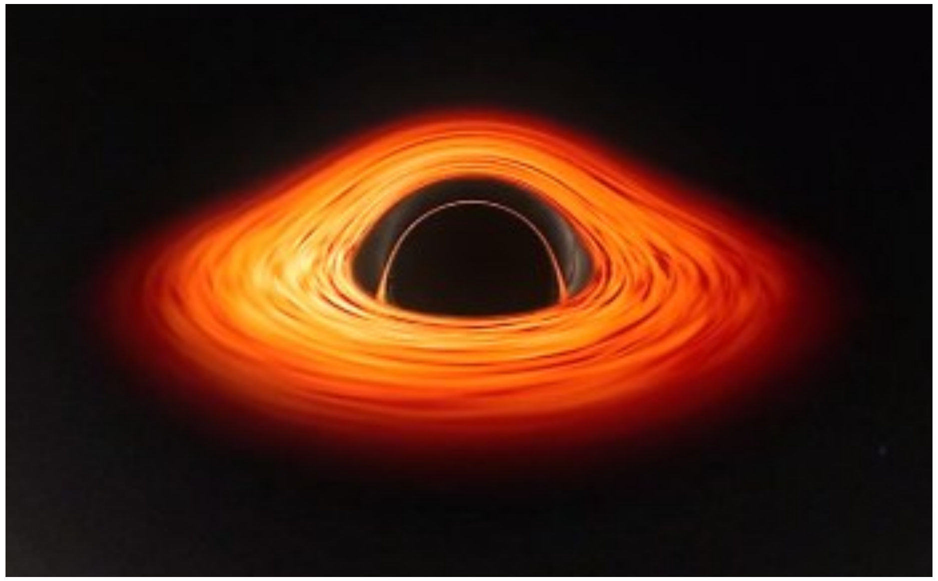

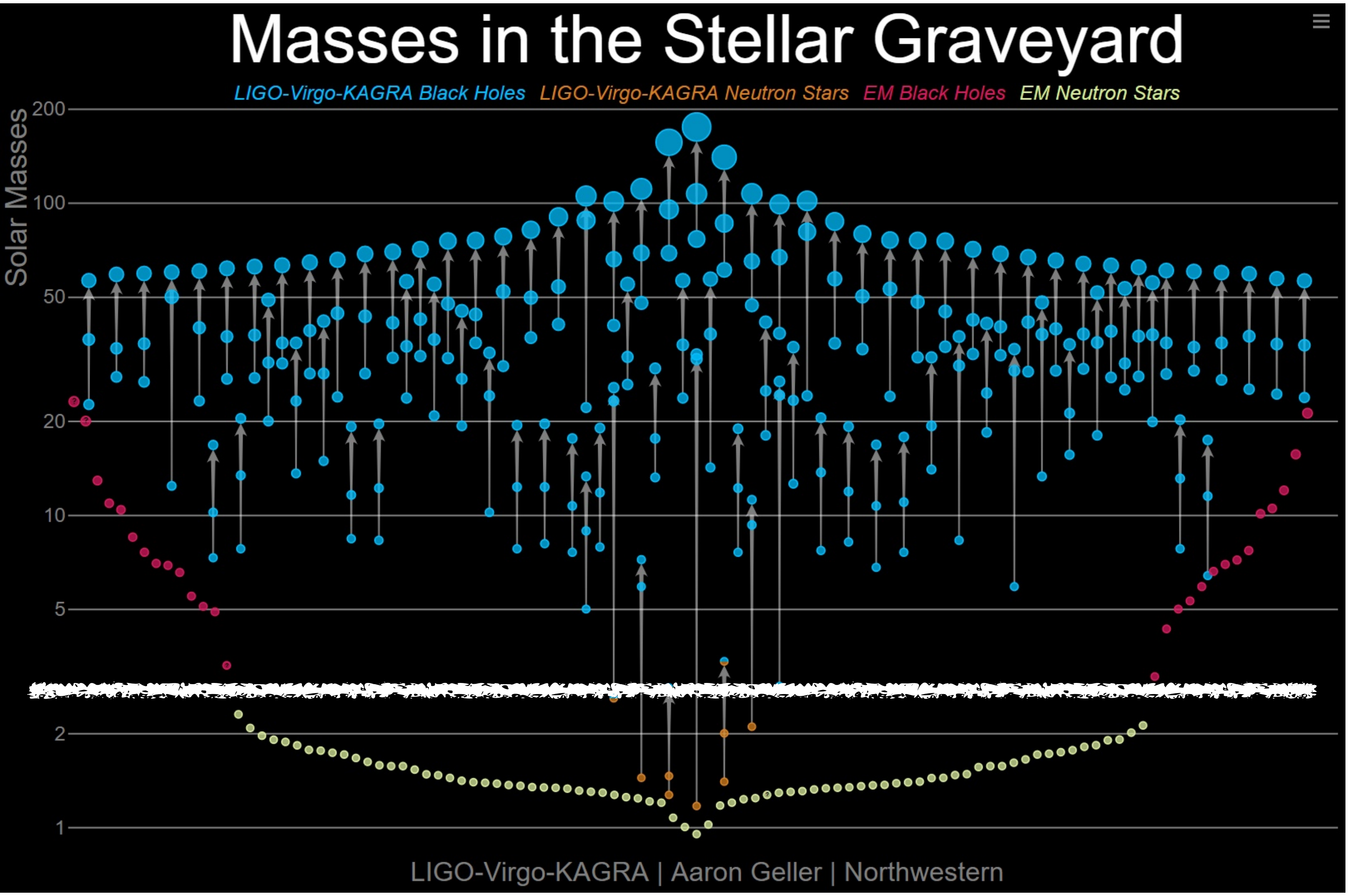

Stellar BH masses seen by GWs from the NS threshold to 200 solar masses.

Heavier masses may exist thanks to successive mergers.

Astrophysical Black Holes

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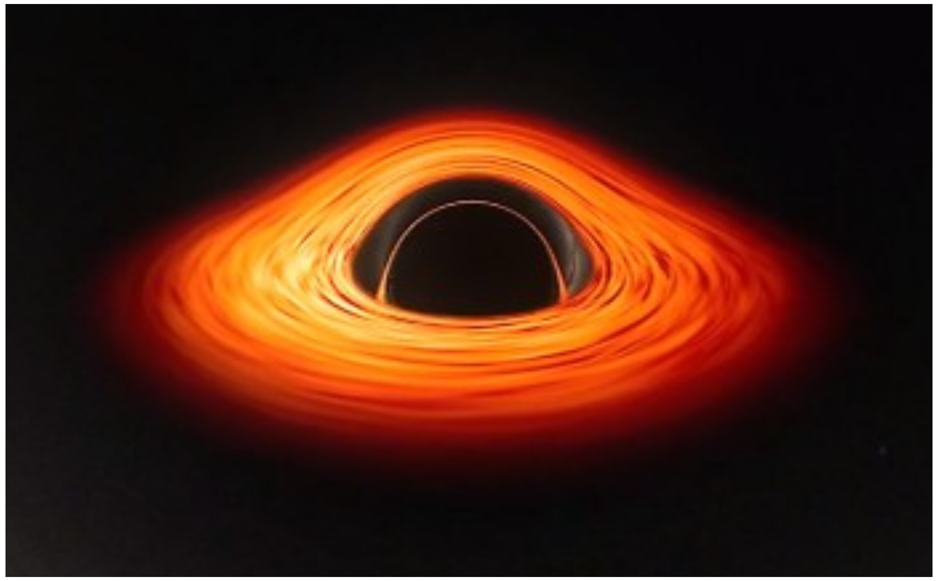

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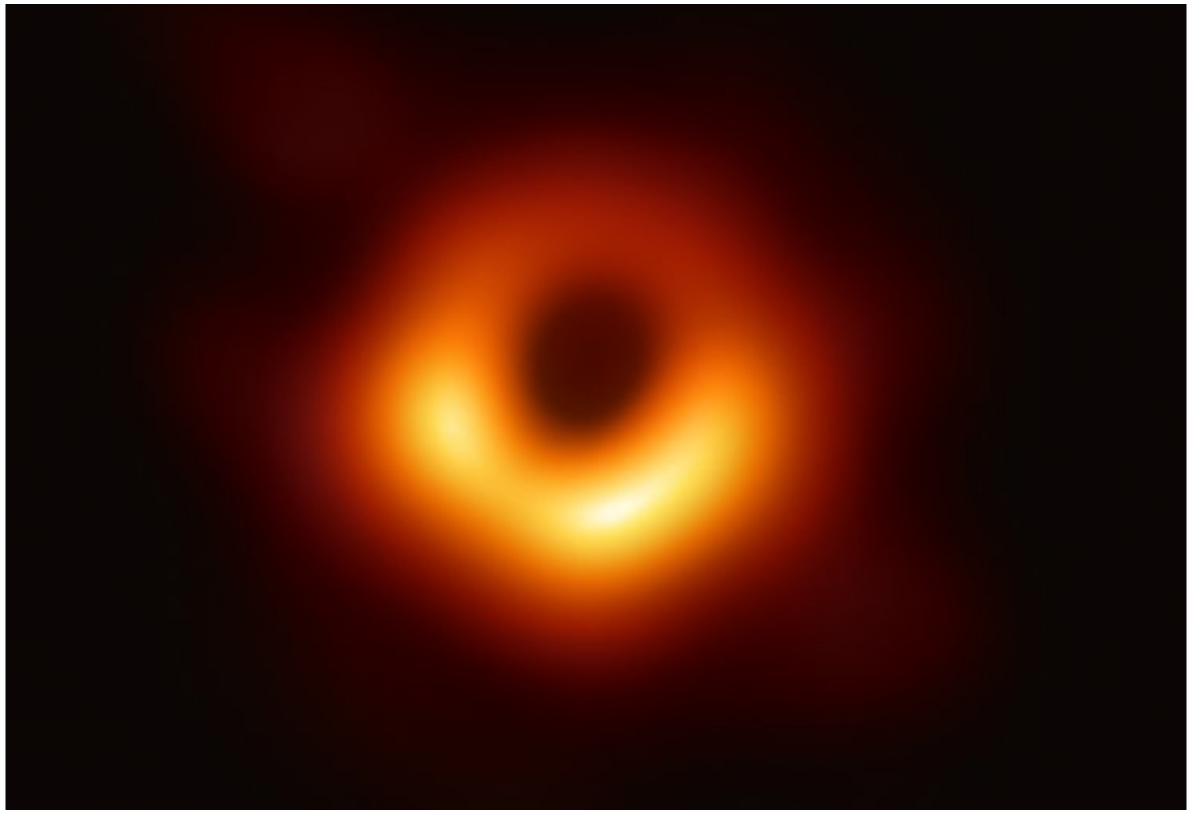


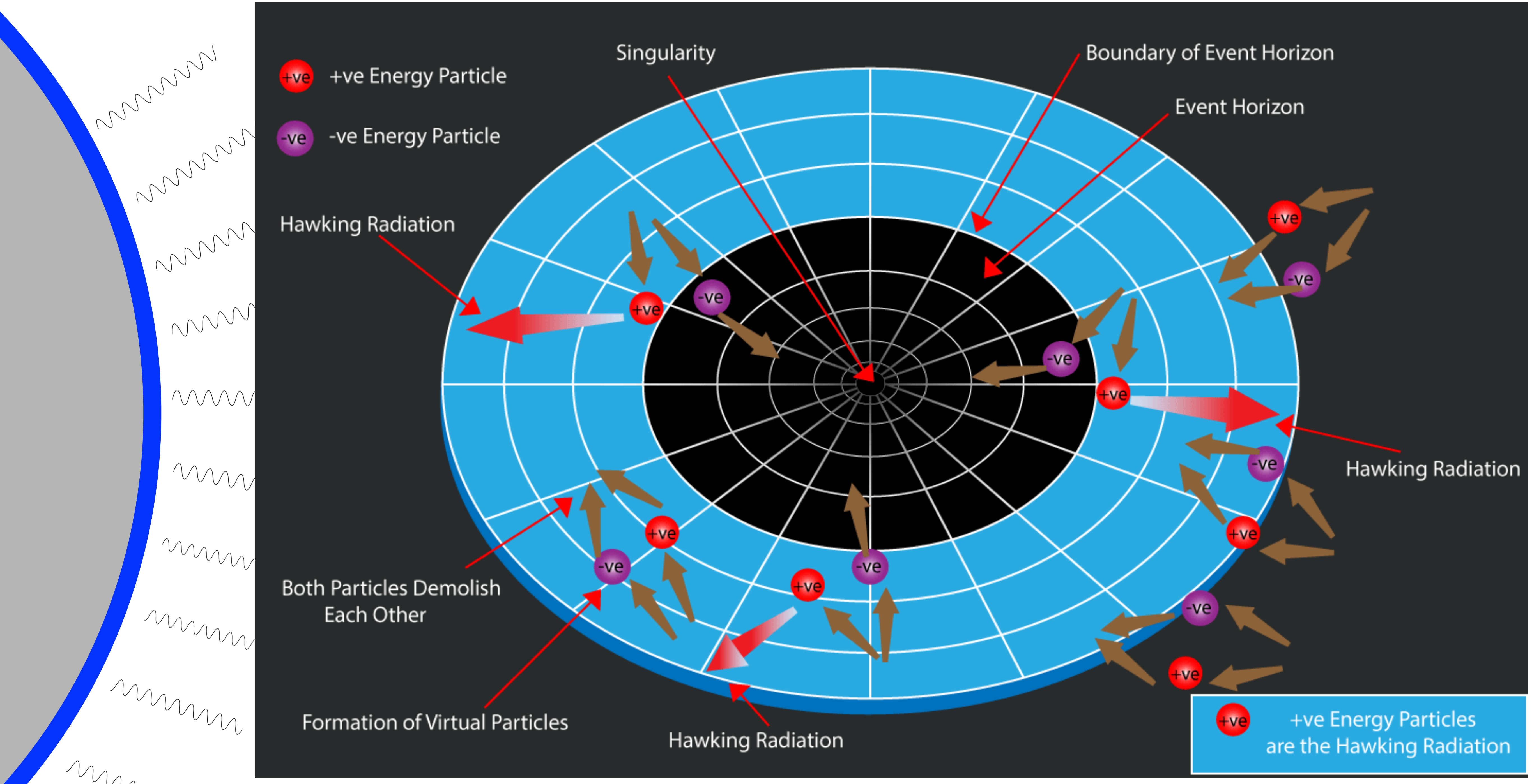
SMBHs exist at the centres of galaxies. They are responsible for AGNs and for the motion of central stars.

Recently photographed by EHT.

Note that all observations are indirect!

Hawking's Radiation

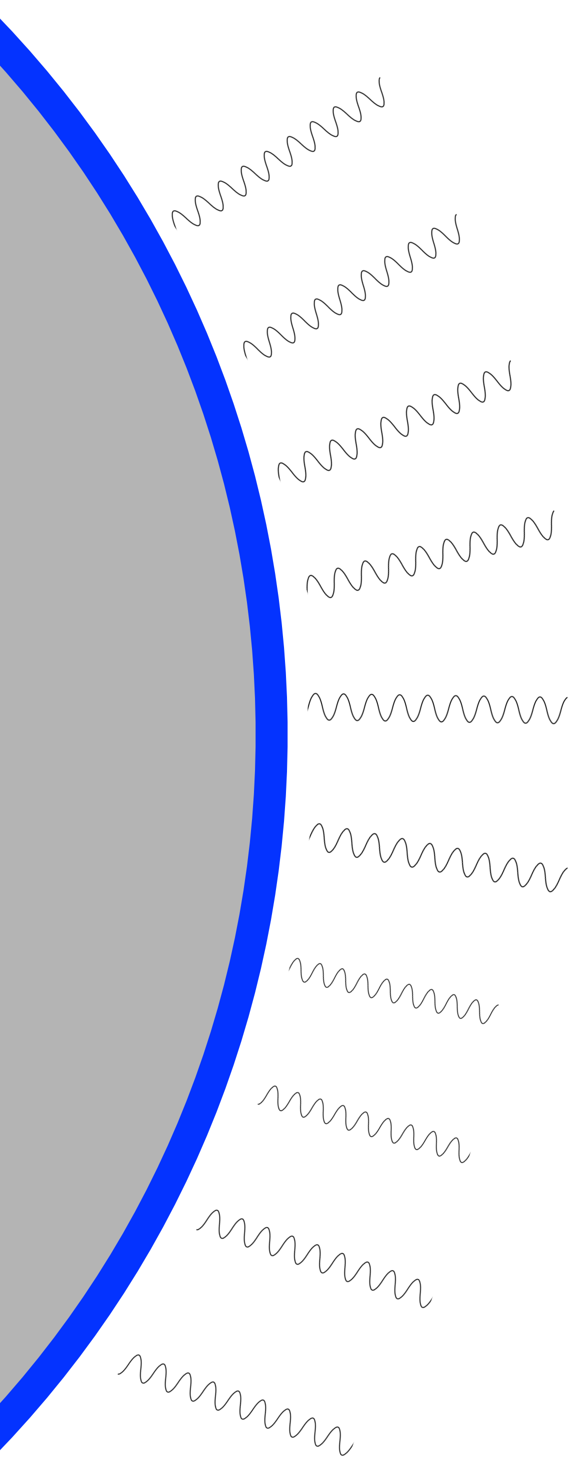
1974

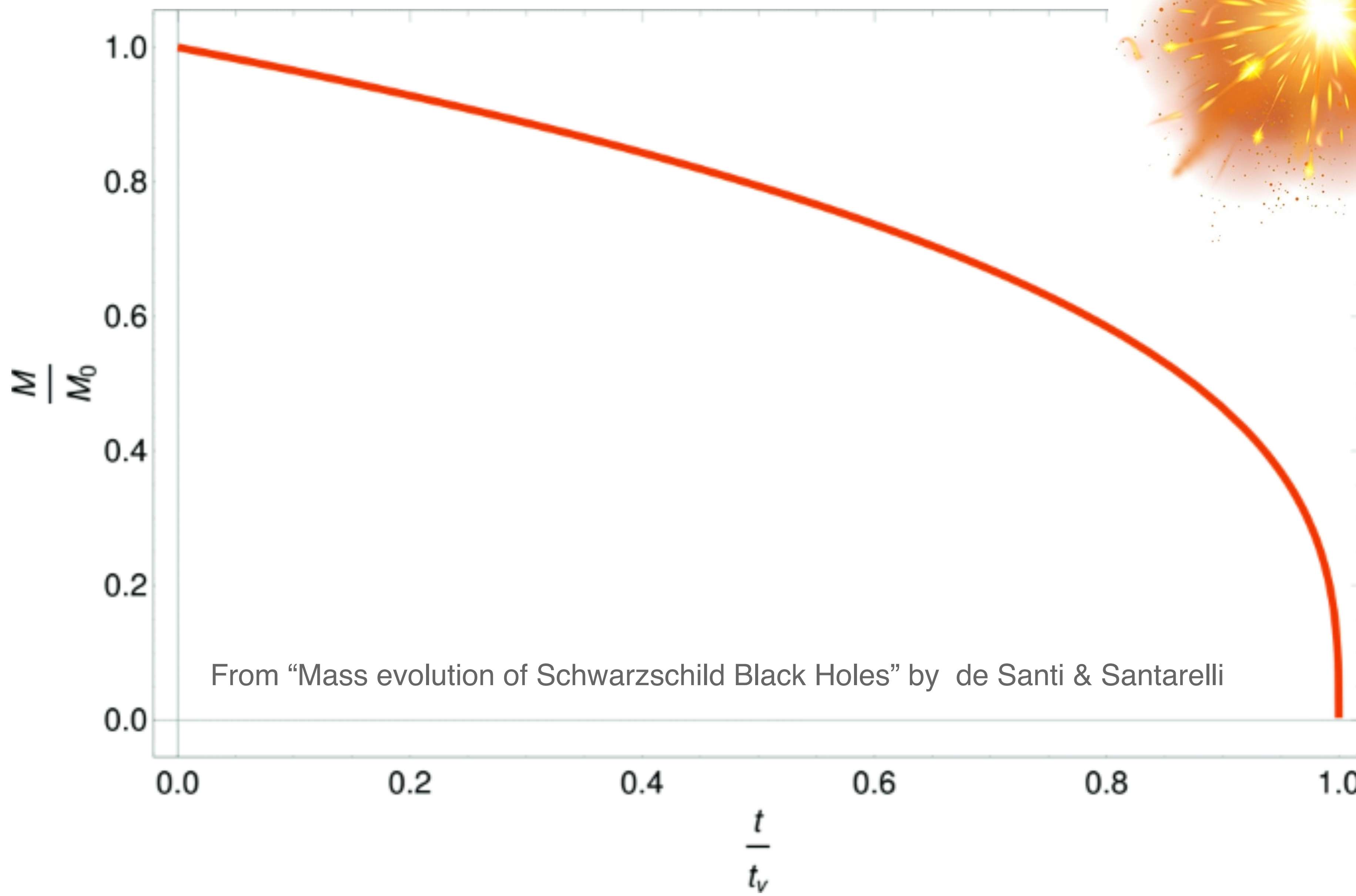


Credit: Physics Feed

Hawking's Radiation

1974



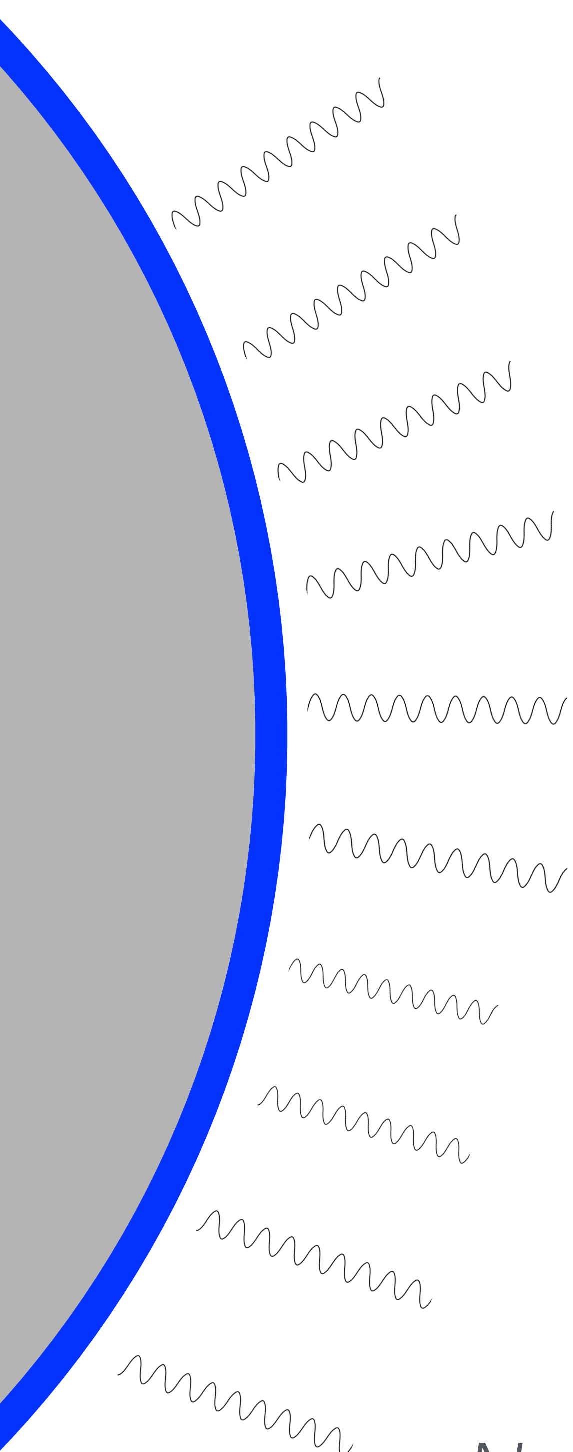


BHs end with a bang!

It would be observable as a Gamma Ray Burst (GRB)

Hawking's Radiation

1974



$$T_H = \frac{\hbar\, c^3}{8\,\pi\, G\, k_B\, M}$$

Black holes evaporate

$$t_{evaporate} \approx 2.140 \times 10^{67} \text{ years} \left(\frac{M}{M_\odot}\right)^3$$

$$t_{Universe-age} \approx 1.40 \times 10^{10} \text{ years}$$

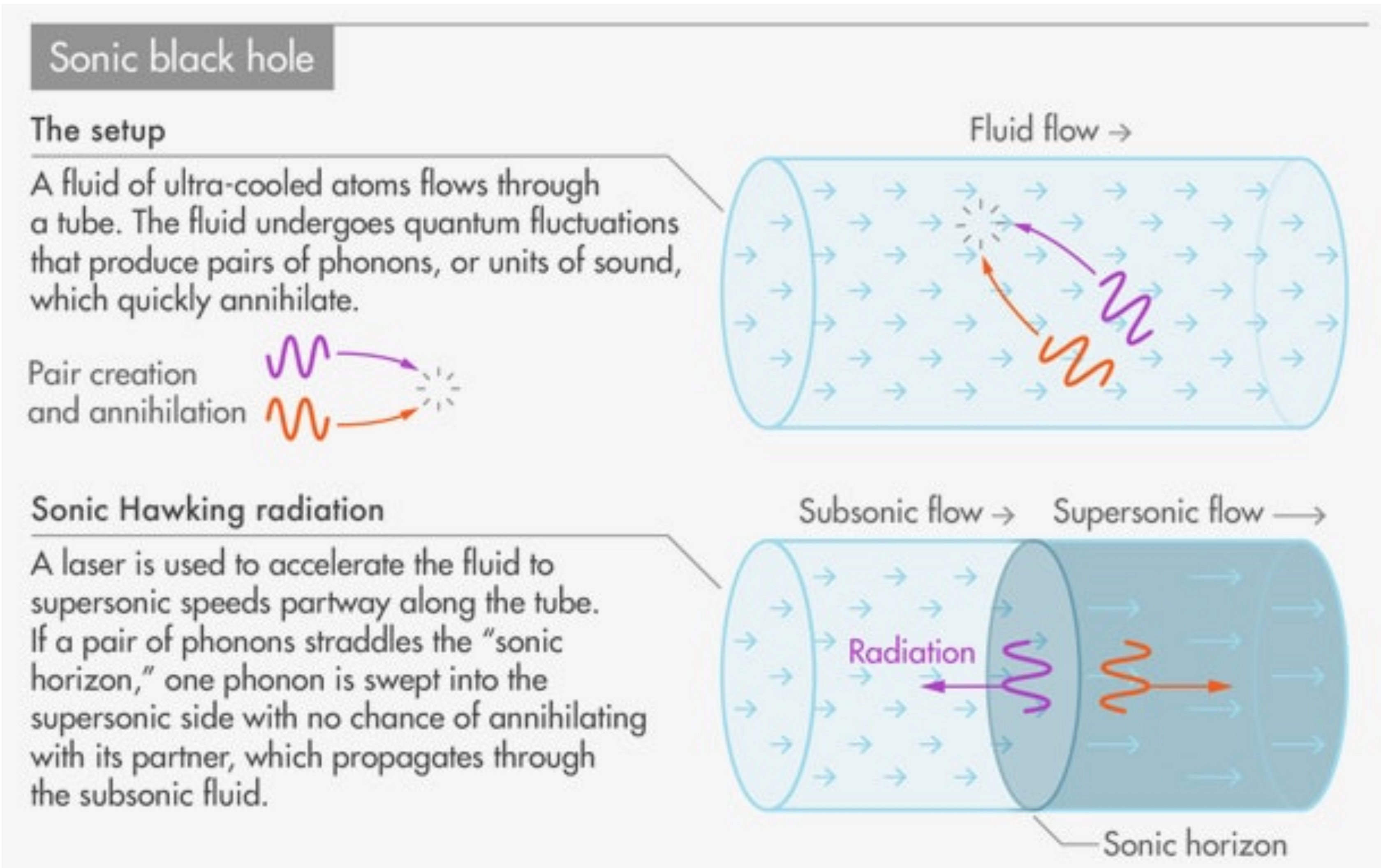
The smaller the BH the higher the temperature

BHs heavier than 1/2 the moon are colder than the CMB!

No chance to observe HR for any ordinary astrophysical BH

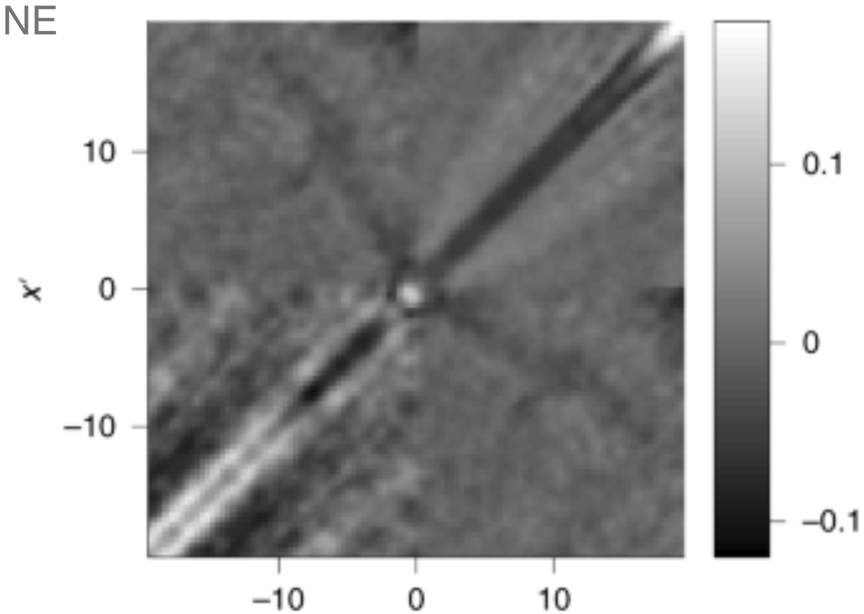
Can Hawking Radiation be measured?

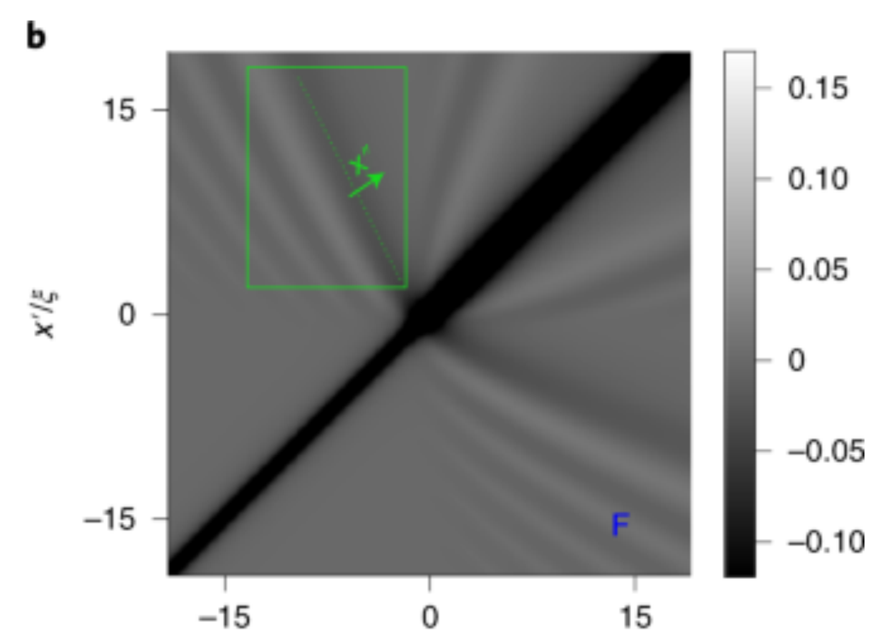
A Black Hole Analogy



LUCY READING-IKKANDA FOR QUANTA MAGAZINE

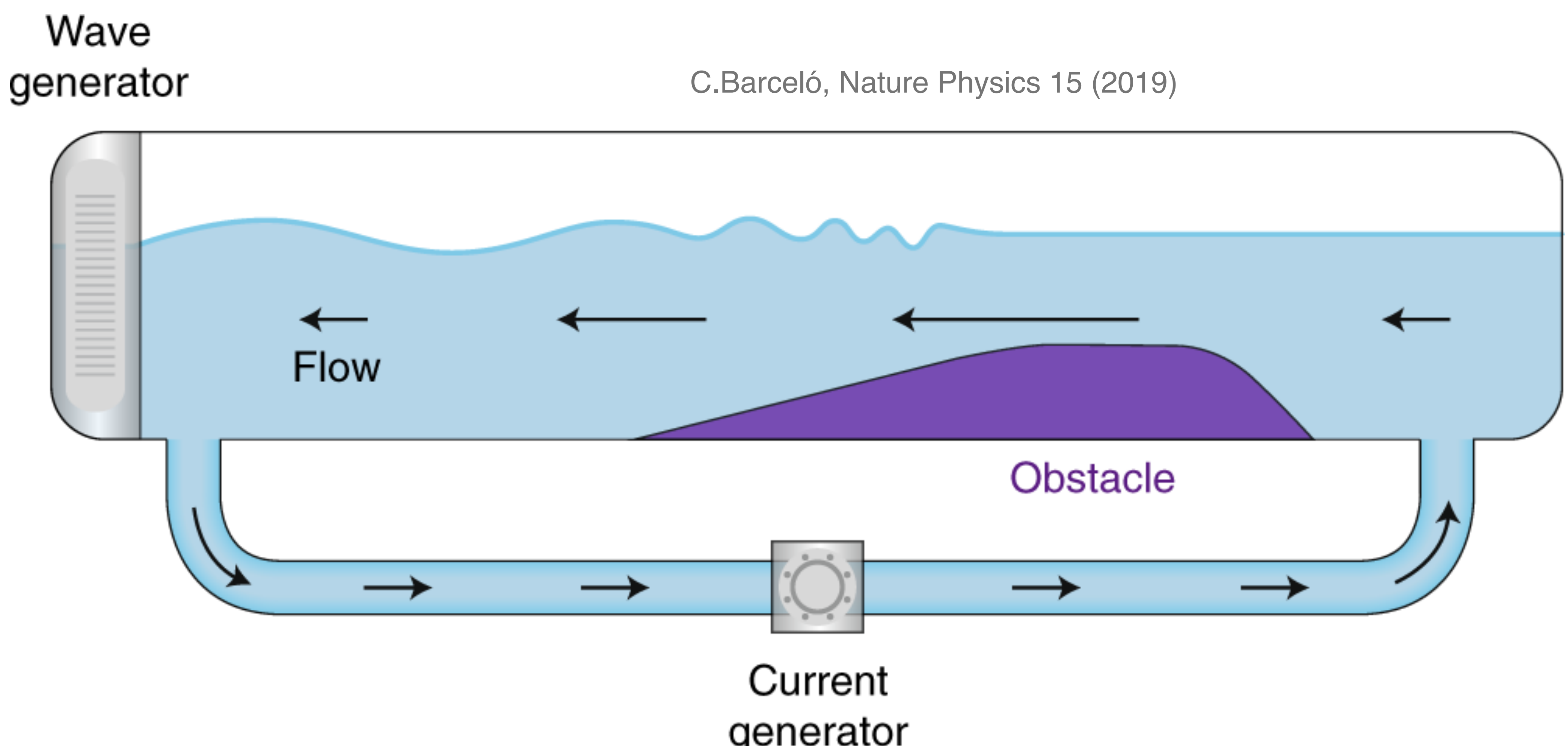
J.Steinhauer et al, Nature Physics 17 (2021)





A Black Hole Analogy

C.Barceló, Nature Physics 15 (2019)



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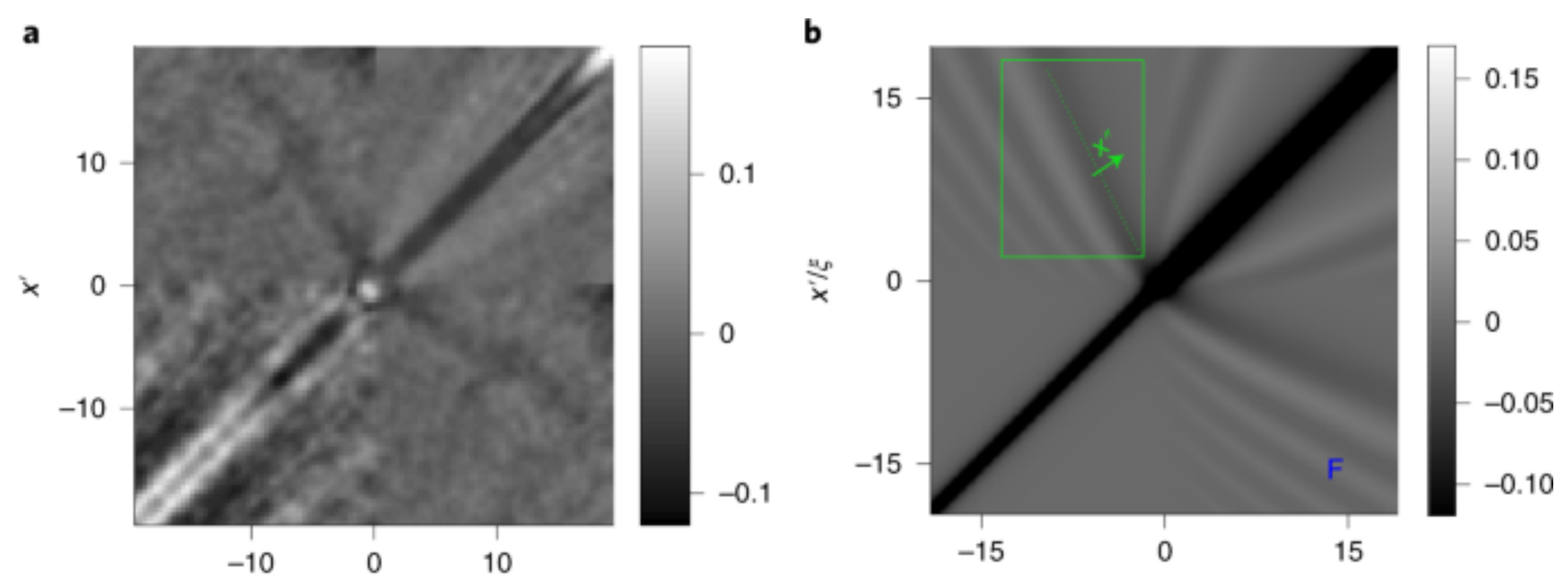


HR from smaller BHs

Smaller BHs can emit HR that could be potentially observed

Asteroid size BHs could be produced in the early universe (PBHs)

Potential candidates for dark matter, if sufficiently long lived

HR from PBHs constrained by diffuse gamma ray background

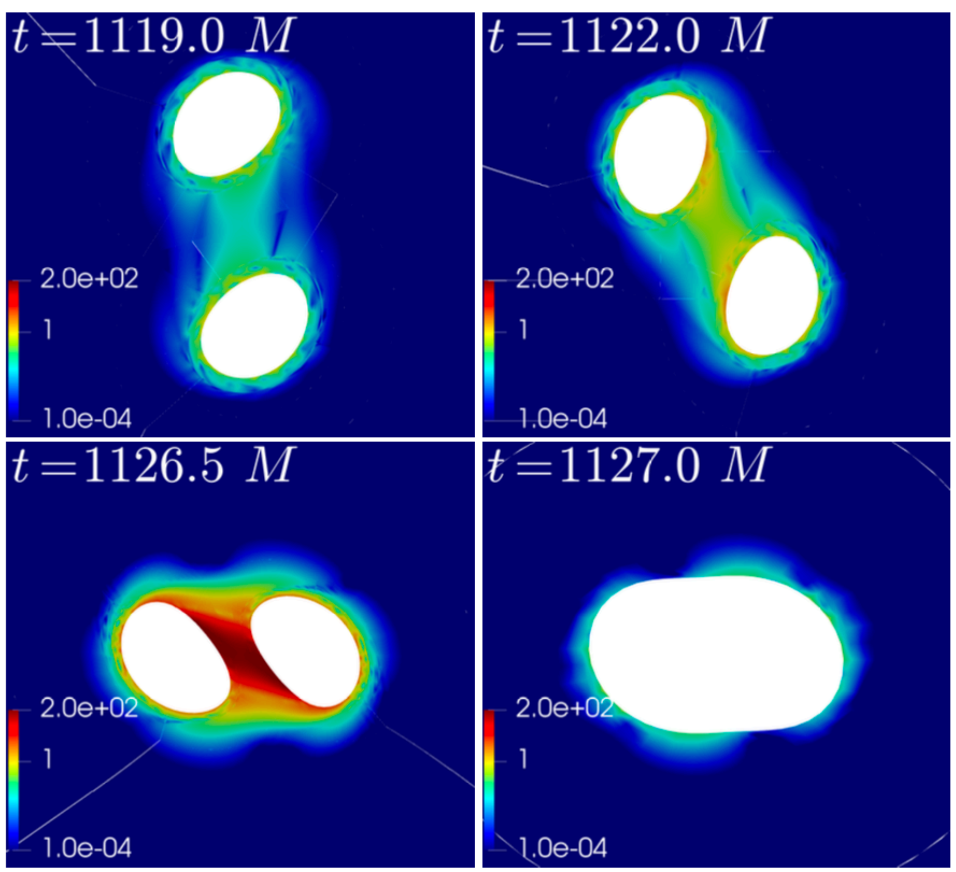
Kimura, Takahashi, Koma, 1607,.01964

Albert et al.(HAWC), JCAP 04 (2020), 026

What if?

BH mergers could leave a trail of small BHs (BH morsels)

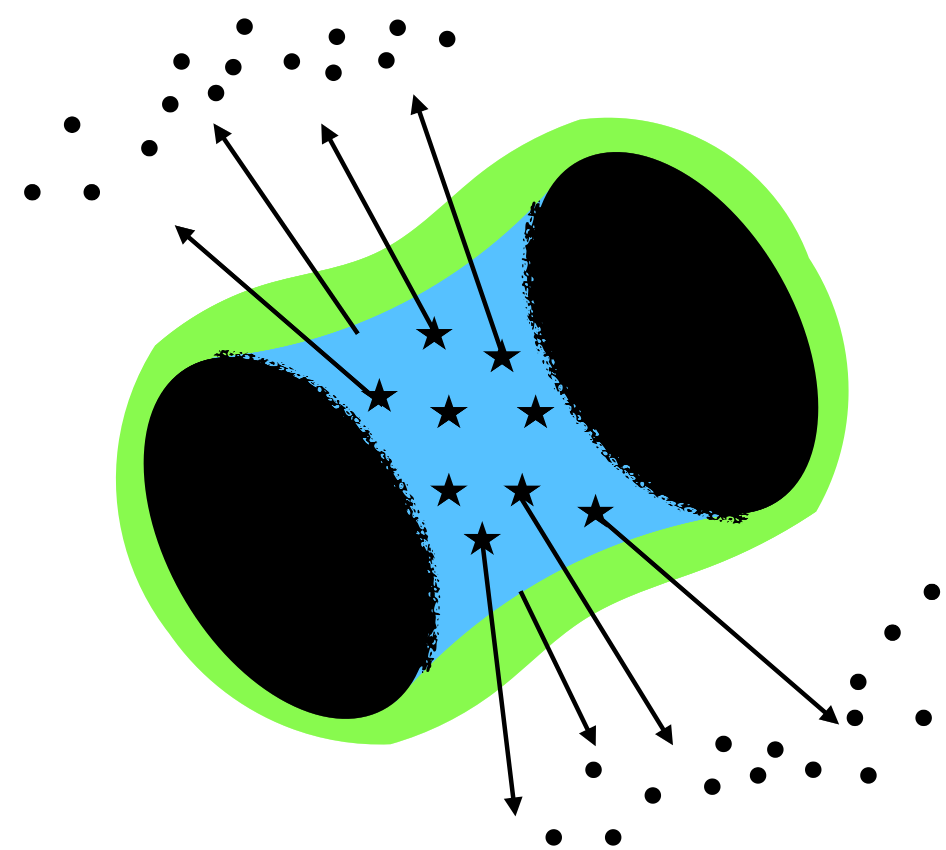
While not expected in general relativity, they may be related to the presence of strong non-linearities, or new physics effects…



Okunkova, Phys. Rev. D.96, 104054 (2017)

Colour shades measure non-linearity

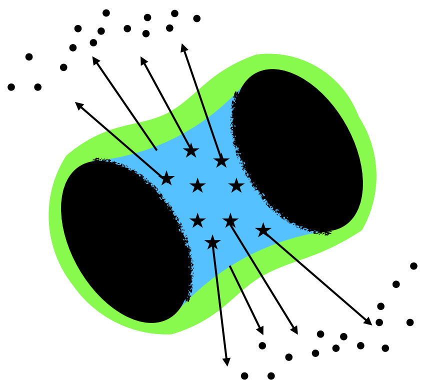
BH morsels?



BH morsels

Is the Hawking radiation from BH morsels observable?

Cacciapaglia, Hohenegger, Sannino, 2405.12880



- The HR emission is isotropic, hence signal will not depend on the geometry of the emission.
- The particle flux only depends on the morsel masses (i.e. Hawking temperature).
- The energy of the emitted particles increases with time, hence giving a characteristic smoking-gun signature!
- Coincidence with gravitational wave observation (depending on the morsel masses...)

Hawking emission

Emission rate for a given BH morsels distribution

$$J_p = \frac{1}{2}\int_{M_{\rm min}}^{M_{\rm max}} dM_{\rm Bm}\, \frac{dn_{\rm Bm}}{dM_{\rm Bm}}\, \frac{d^2 N_p}{dt\, dE_p}(\mu_t(M_{\rm Bm}, t))$$

$\mu_t(M_{\rm Bm}, t)$ - Morsels mass at time t & $M_{\rm Bm}$ is the initial mass

$\frac{1}{2}$ - geometric factor

Differential primary flux for a given species “p”

Secondary radiation

J_p computed via BlackHawk

Arbey, Aufflinger Eur Phys J. C 79, 693 (2019), 81, 910 (2021).

Emission, decays and hadronisation via Pythia.

Hadronisation tables reliable for primary between 5 GeV and a few TeVs

Assume population of BH morsels with equal masses and non rotating

Angular momentum dissipates faster than the evaporating mass

Morsels & Mergers Energy Budget

LIGO/VIRGO/KAGRA pre-merger masses between a few and several $M_\odot$

Abbott et al. (LIGO), PRX 9, 031040 (2019), PRX 11, 021053 (2021),...

Distance 240 Mpc to 3 Gpc

Initial and final masses indirectly measured via GW spectrum

Example: GW170814 (first BH merger observed by all 3 detectors)

$$30.5^{5.7}_{-3.0} + 25.3^{2.8}_{-4.2} = 53.2^{3.2}_{-2.7}$$

GW energy emitted $2.7^{0.4}_{-0.3}$

Several $M_\odot$ can go into BH morsels, but conservatively we assume one.

Particle emission

Neutral stable particles, reach Earth undeflected by galactic magnetic fields

Consider BH merger at D=300 Mpc (nearest detected BH mergers)

Photon flux on Earth $$F_\gamma = \frac{1}{4\pi D^2} \int dE_\gamma \, J_\gamma$$

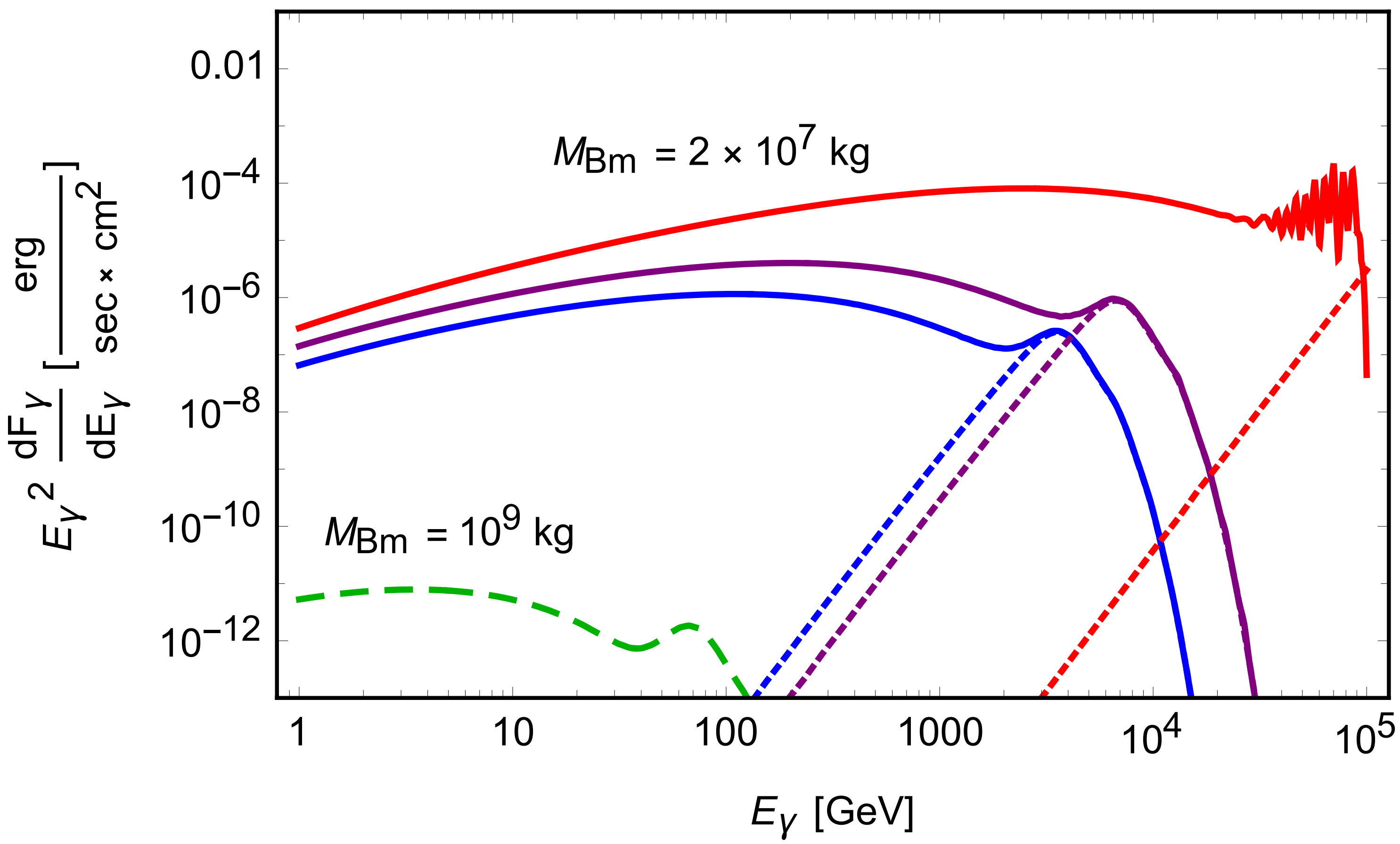
Differential flux $E_\gamma^2 dF_\gamma / dE_\gamma$

Photon flux

Same mass Bm distribution normalised to $M_\odot$

Solid lines $2 \times 10^7\,\mathrm{kg}$ & 3400 sec evaporation time

Colours: different times from production 500 sec (blue) 3000 sec (purple) 3400 sec (red)



Emission constant up to 500 sec

Explosive at end of BH lifetime

Red curve exceeds 100 TeV!

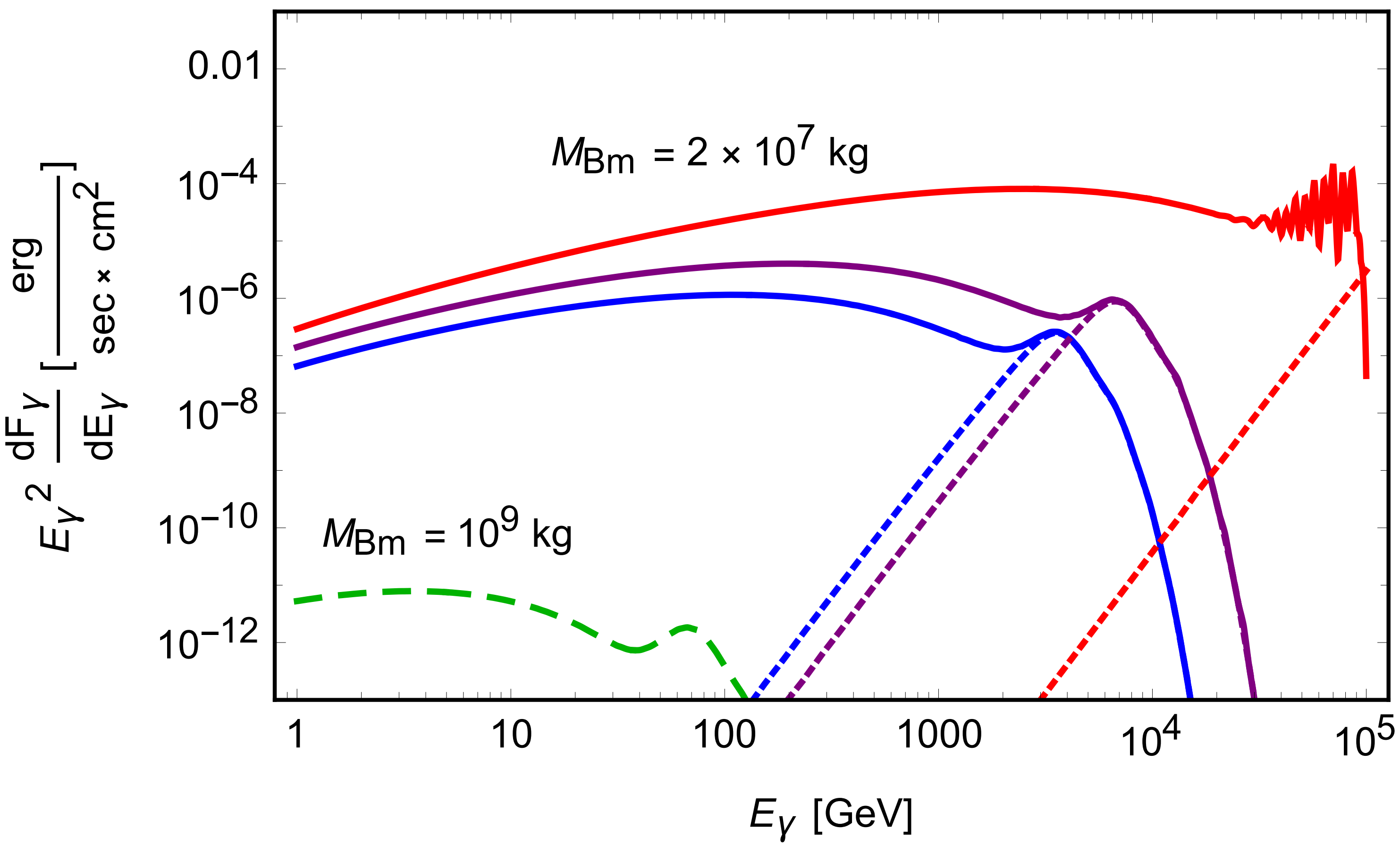
BlackHawk limit!

100TeV cutoff, photon optical transparency intergalactic medium

On the mass dependence

Evaporation time $\propto M_{Bm}^3$

Lighter Bm: more energetic GRBs and shorter evaporating times



Heavy morsels:

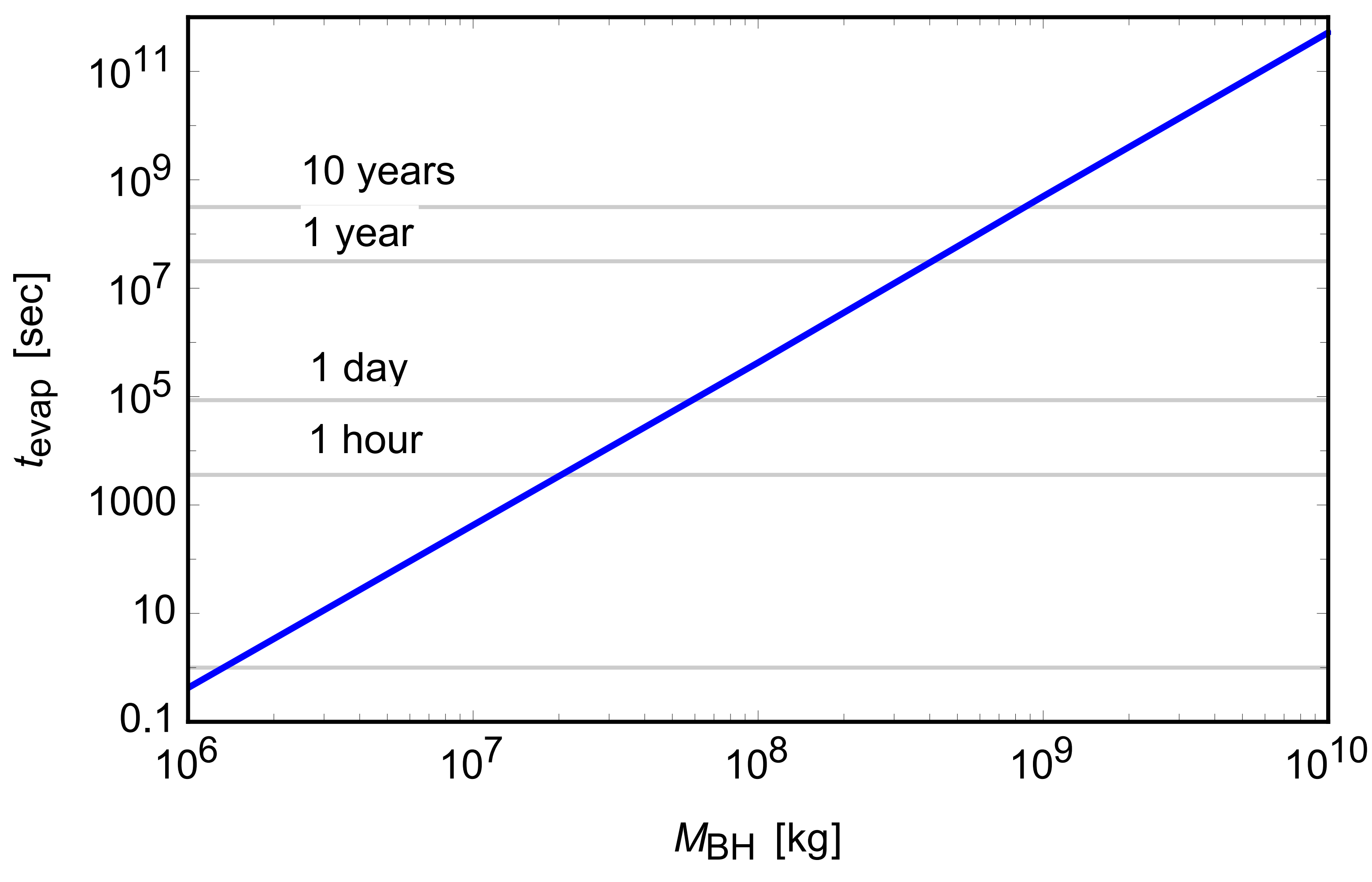
Steady initial signal

Reduced luminosity

Green curve $2 \times 10^9\,\mathrm{kg}$

16 years evaporation time

Evaporation time

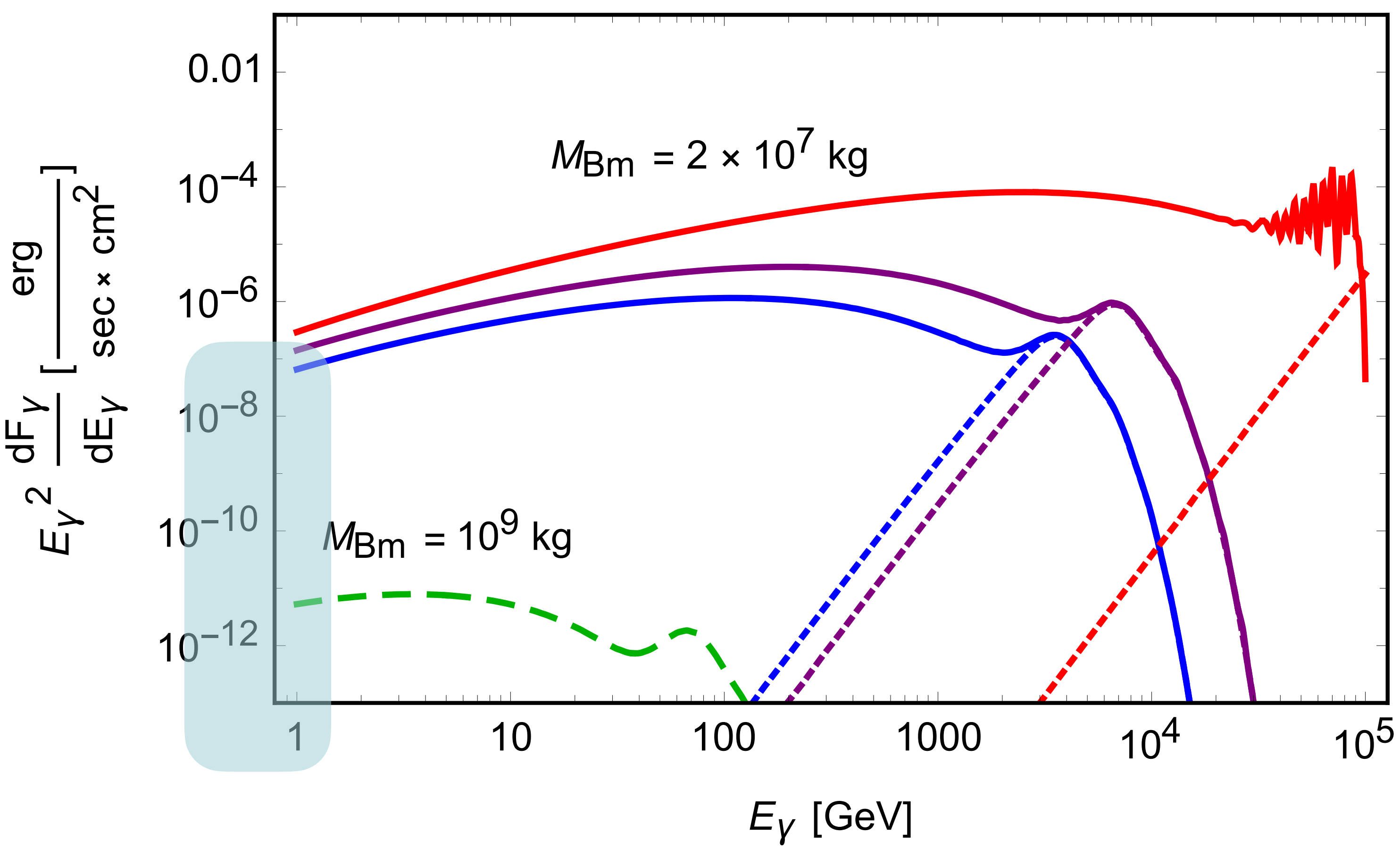


Multi-messenger approach

Fermi-GBM & Swift-BAT monitor photons within 30 sec from event alerts

Coverage between keVs and MeVs (Neutron star merger range)

In this range the signal is below exp sensitivity $10^{-7}\,\mathrm{erg\ sec^{-1}\ cm^{-2}}$



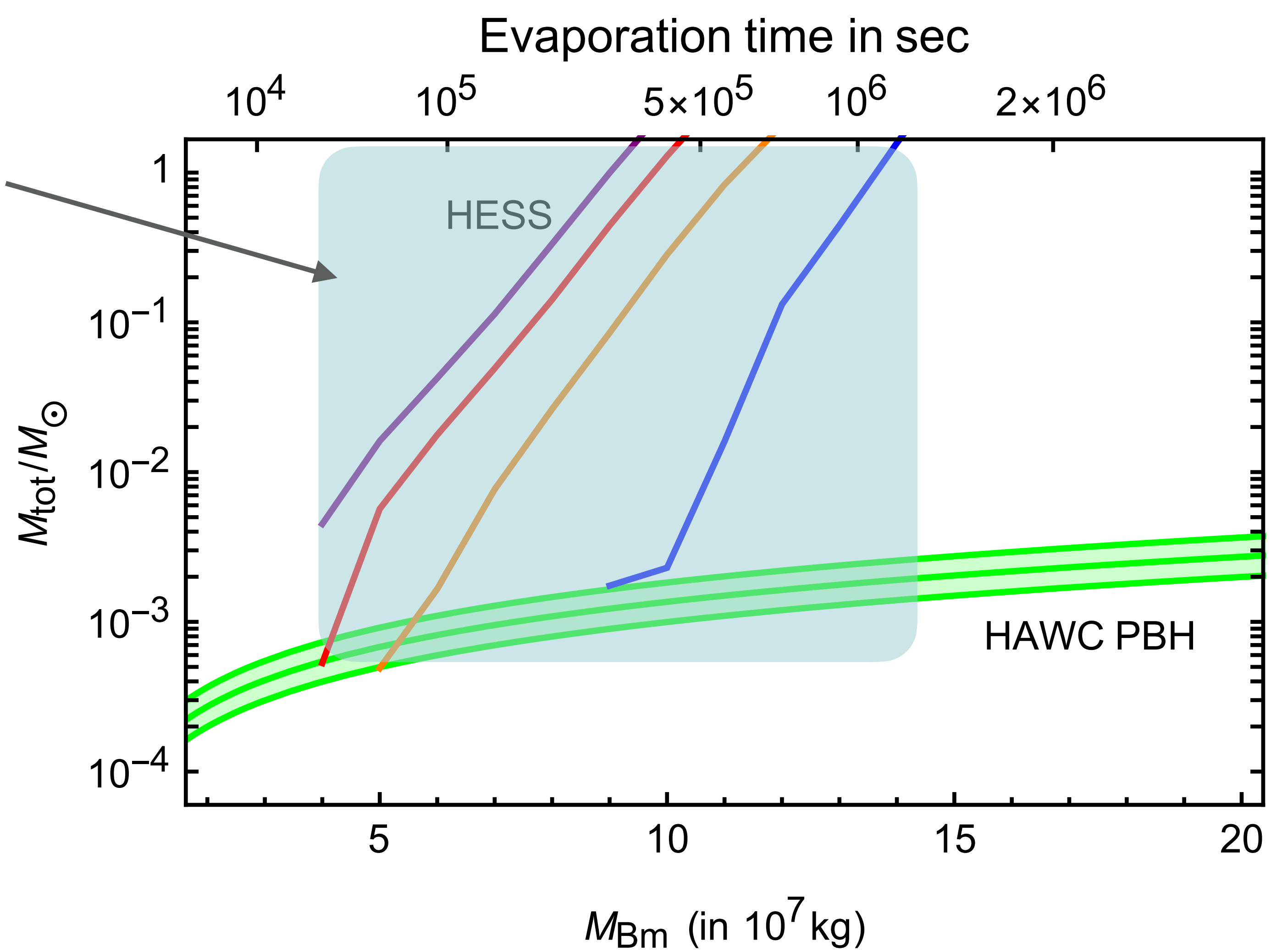
Preliminary bounds (HESS)

HESS followed four LIGO/VIRGO BH mergers (O2 and O3 runs)

1 - 10 TeVs, time: 10^4 - 10^5 sec after the BH merger

Energy flux from mergers below $10^{-12}\,\mathrm{erg\ sec^{-1}\ cm^{-2}}$

Relevant region

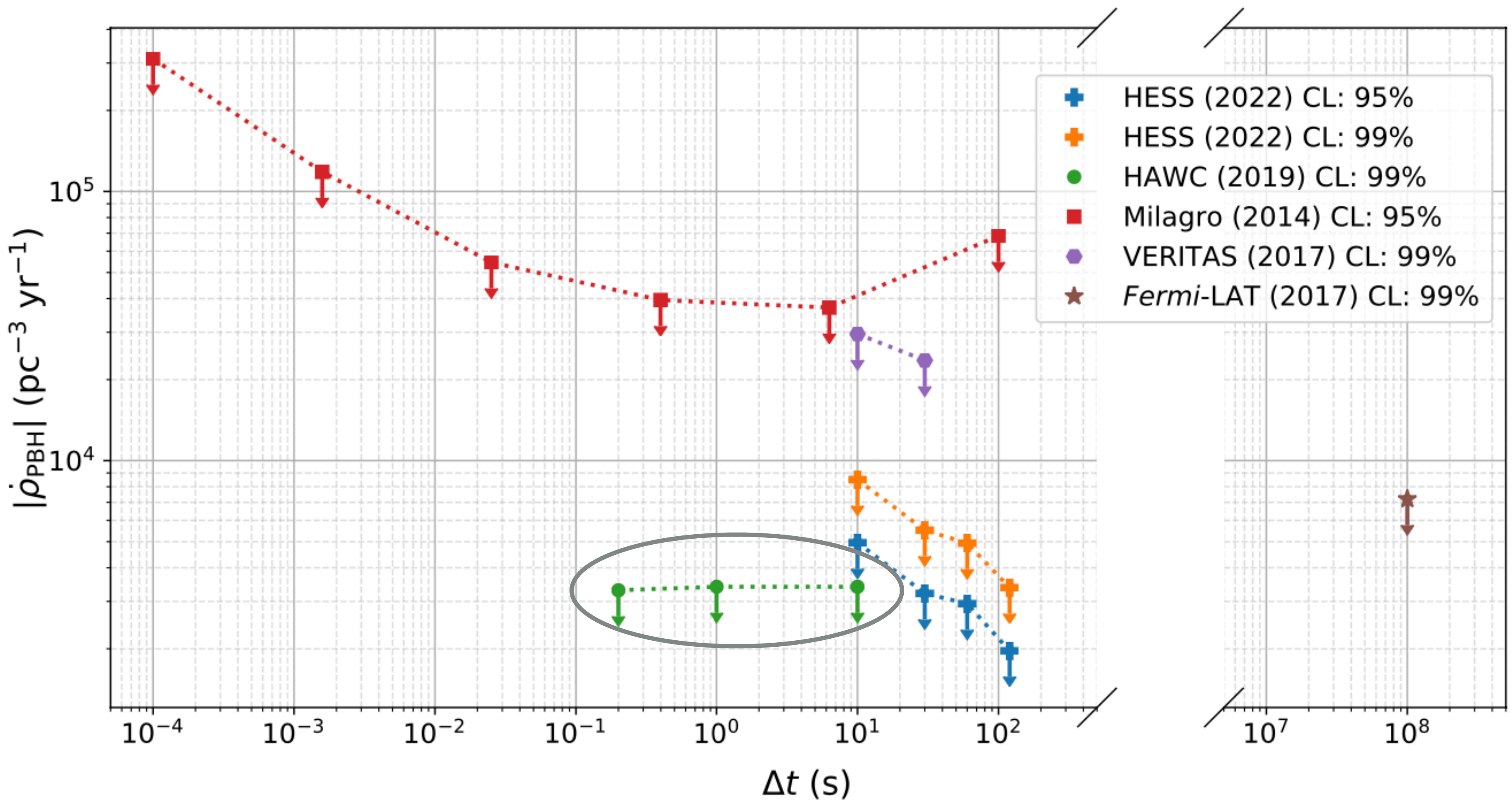


PBH connection

BH morsels and PBHs both evaporate via TeV photons

Ideal for HAWC, HESS, LHAASO (Atmospheric Cherenkov Telescopes)

Search for point-like unaccounted GRBs



Strongest bound from HAWC

Albert et al.(HAWC), JCAP 04 (2020), 026

Preliminary bounds (HAWC)

A morsel distribution at D is equivalent to a single PBH at $D_{\rm PHB}$

$$D_{\rm PBH} = \frac{D}{\sqrt{n_{\rm Bm}}}$$

Naive:

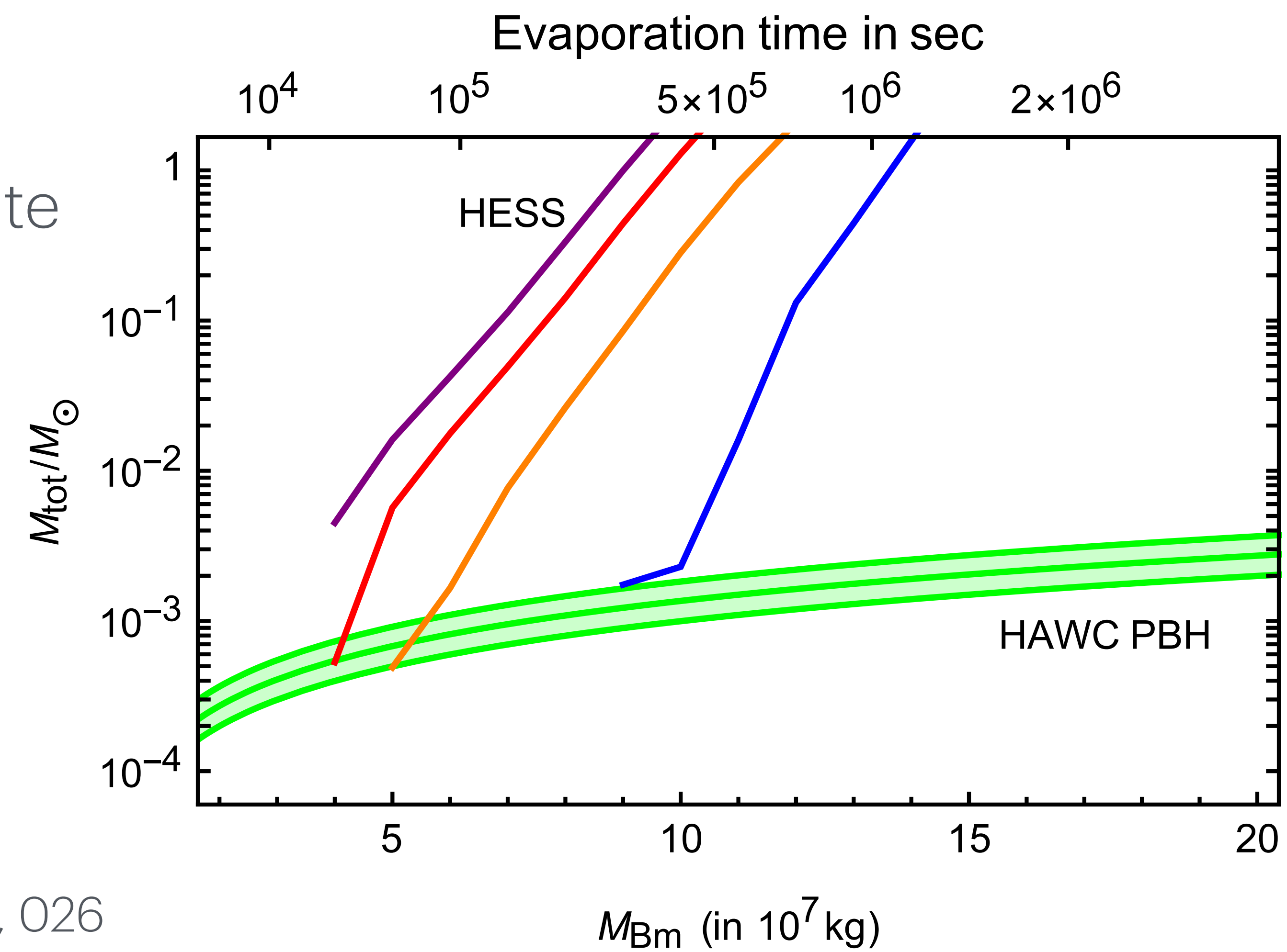
Rescaling LIGO/VIRGO BH mergers rate

$$\rho_{\rm LV} = 24^{+14}_{-9}\ \text{Gpc}^{-3}\ \text{yr}^{-1}$$

PBH rescaled densities for HAWC

$$\rho_{\rm PBH} = 3400\ \text{pc}^{-3}\ \text{yr}^{-1}$$

Upper limit on the total morsel mass

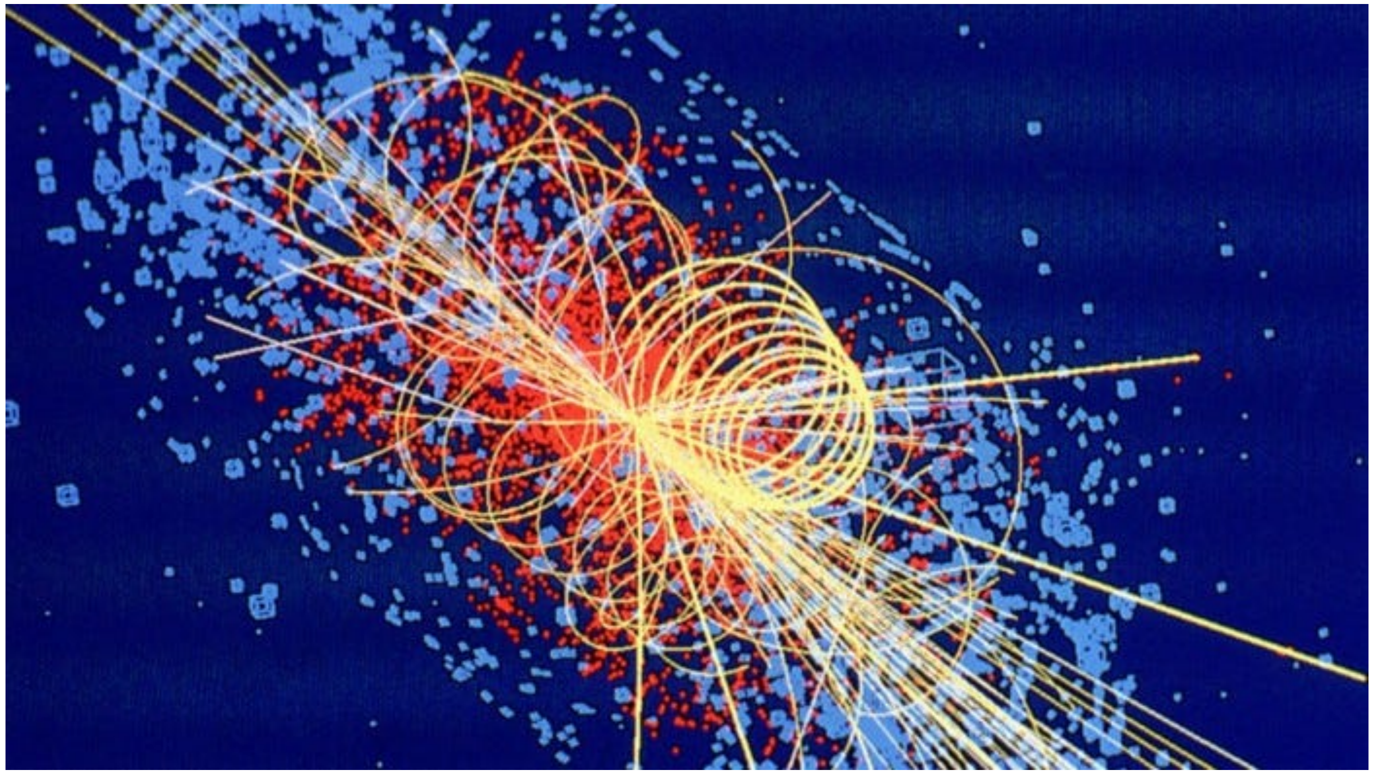


Albert et al.(HAWC), JCAP 04 (2020), 026

Next steps

- Golden opportunity for Cherenkov telescopes (work in progress with Fermi-LAT colleagues).
- New physics effects may appear in the spectrum at the end of the evaporation time (modelling of NPh effects in progress).
- Modelling of the BH morsel production necessary: we are exploring various ideas at the moment.

New Physics from earth?



Ingredients: Particle colliders (the LHC and a future programme), a good theory of New Physics

Motivation for Higgs compositeness

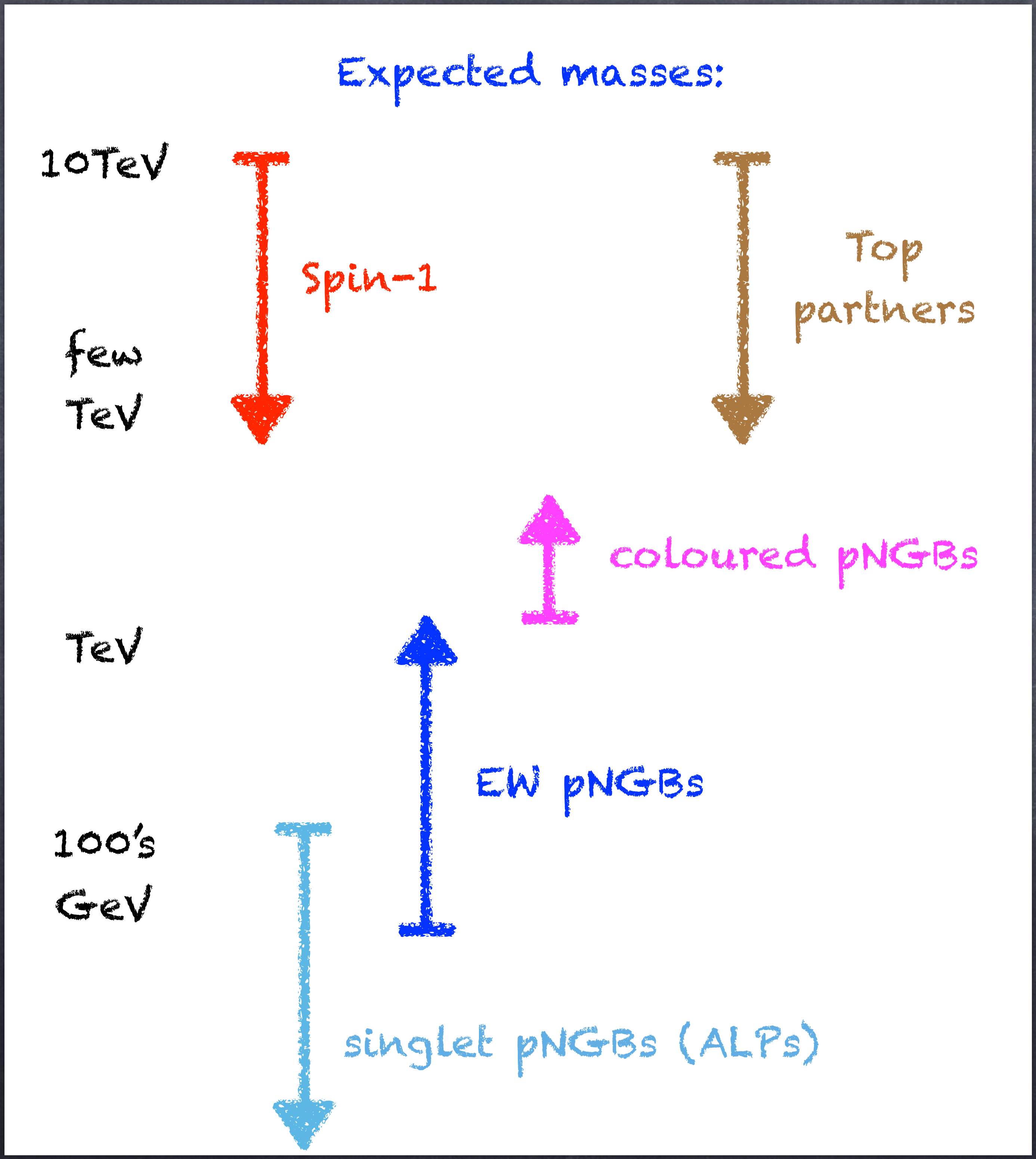
- Composite models 'solve' the Hierarchy problem...
- with new scale in the multi-TeV!

multi-TeV mountain

- What are we looking for?

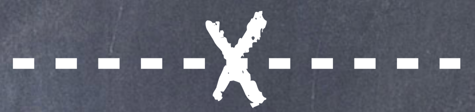
  -> Precision EW + Higgs observables
  -> light composite scalars
  -> multi-TeV resonances (top partners, pNGBs, spin-1)

Composite spectra



Low-hanging fruits: scalars!

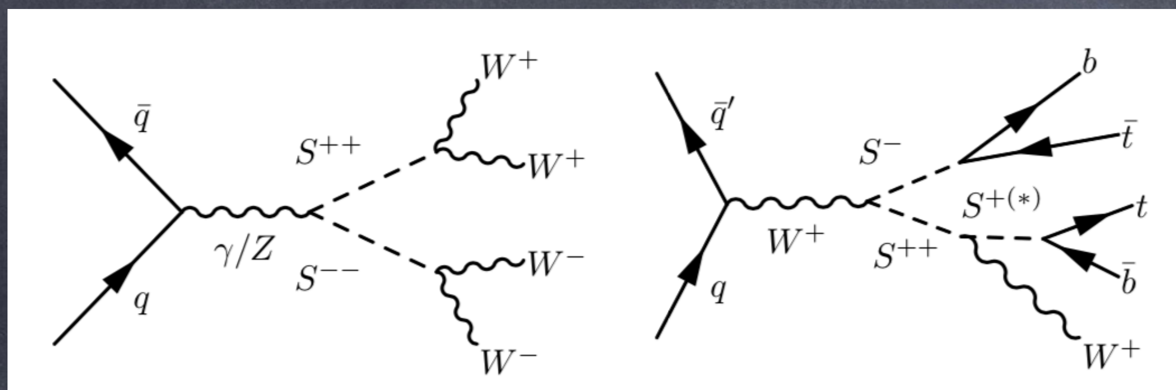
How can light states emerge?



	Top loops	Gauge loops	TC-fermion masses
ϕ	$\sim y_t^2 f^2$	$\sim g^2 f^2$	$\sim m_\psi f$
h (h massless for vanishing v)	$\sim y_t^2 f^2 s_\theta^2 = y_t^2 v^2$	$\sim g^2 f^2 s_\theta^2 = g^2 v^2$	X
a	X	X	$\sim m_\psi f$ This can be small!

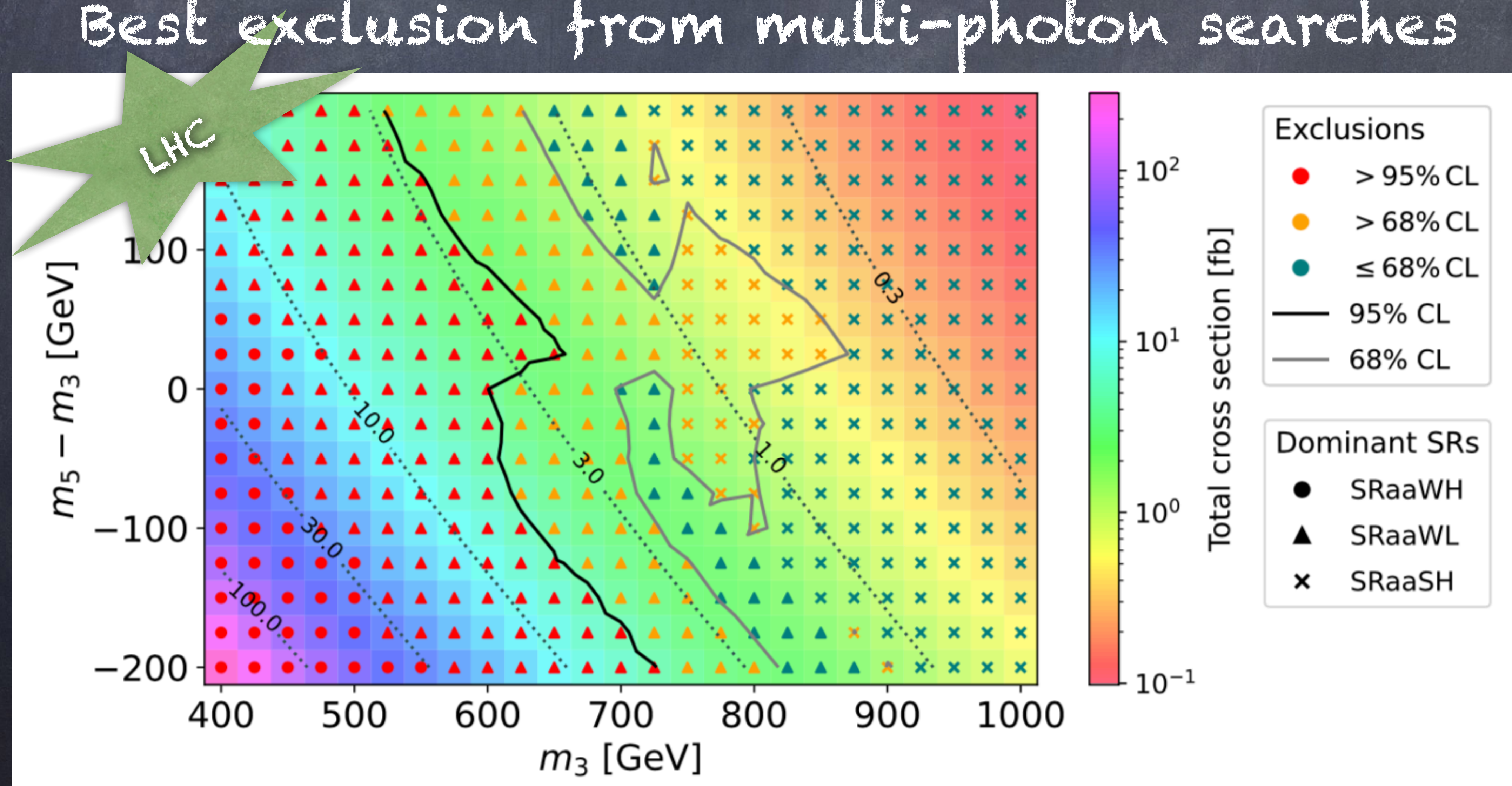
EW scalars: SU(5)/SO(5) benchmark

W.Porod et al.
2210.01826



Dominantly EW pair-prod.
Good targets for ee colliders?

Best exclusion from multi-photon searches



Typical ALP Lagrangian:

$$\mathcal{L}_{\text{eff}}^{D\leq 5} = \frac{1}{2}(\partial_\mu a)(\partial^\mu a) - \frac{m_{a,0}^2}{2}a^2 + \frac{\partial^\mu a}{\Lambda}\sum_F \bar{\psi}_F \boldsymbol{C}_F \gamma_\mu \psi_F$$
$$+ g_s^2 C_{GG}\frac{a}{\Lambda}G_{\mu\nu}^A \tilde{G}^{\mu\nu,A} + g^2 C_{WW}\frac{a}{\Lambda}W_{\mu\nu}^A \tilde{W}^{\mu\nu,A} + g'^2 C_{BB}\frac{a}{\Lambda}B_{\mu\nu}\tilde{B}^{\mu\nu},$$

Composite Higgs scenario:

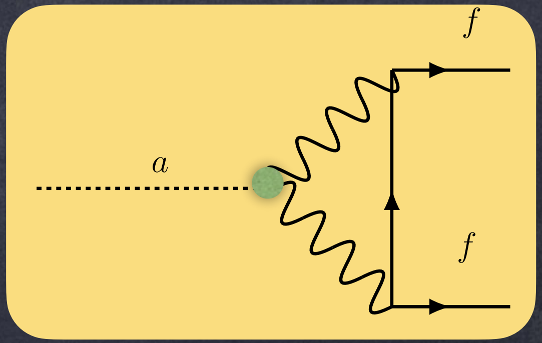
$$\frac{C_{WW}}{\Lambda} \sim \frac{C_{BB}}{\Lambda} \sim \frac{N_{\text{TC}}}{64\sqrt{2}\,\pi^2 f}$$

$$(C_{\gamma\gamma} = C_{WW} + C_{BB})$$

$$\frac{C_{GG}}{\Lambda} = 0$$

(Poor bounds at the LHC)

$\mathbf{C}_F$ is loop-induced:

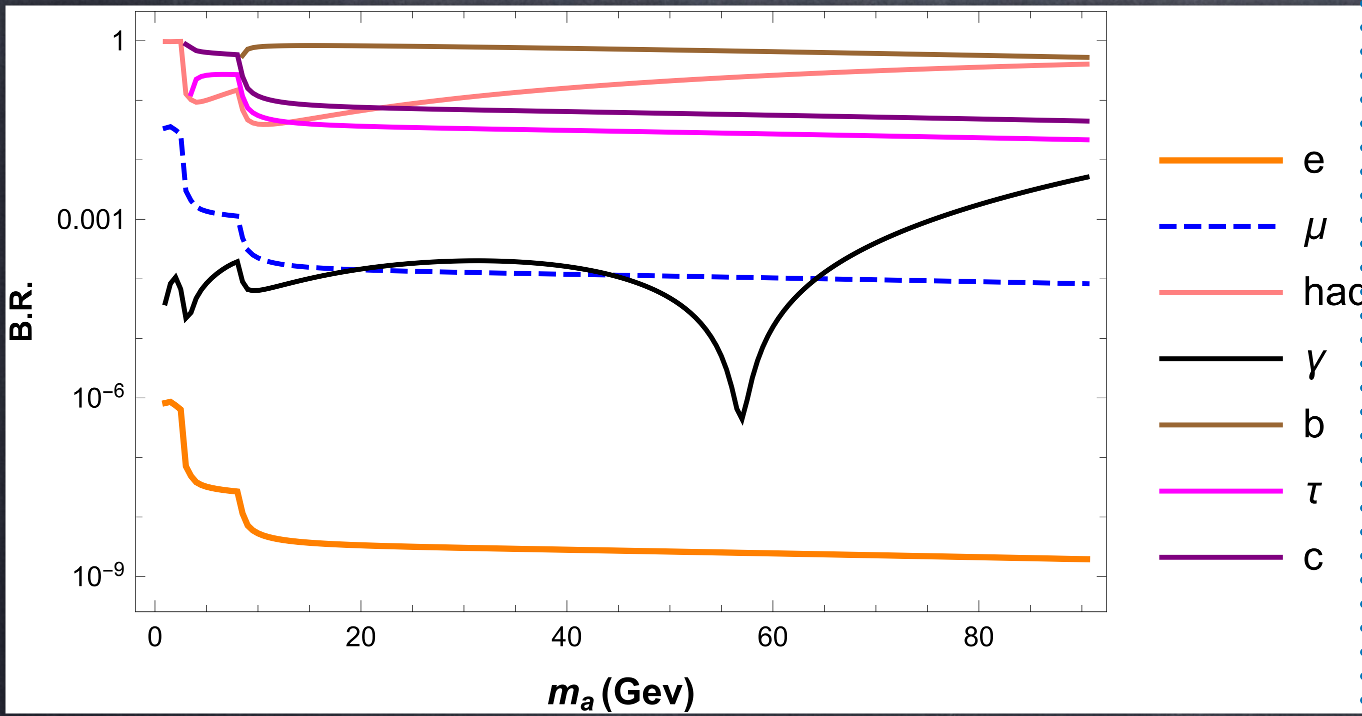


M.Bauer et al, 1708.00443

Tera-Z portal to compositeness (via ALPs)

G.Cacciapaglia et al.
2104.11064

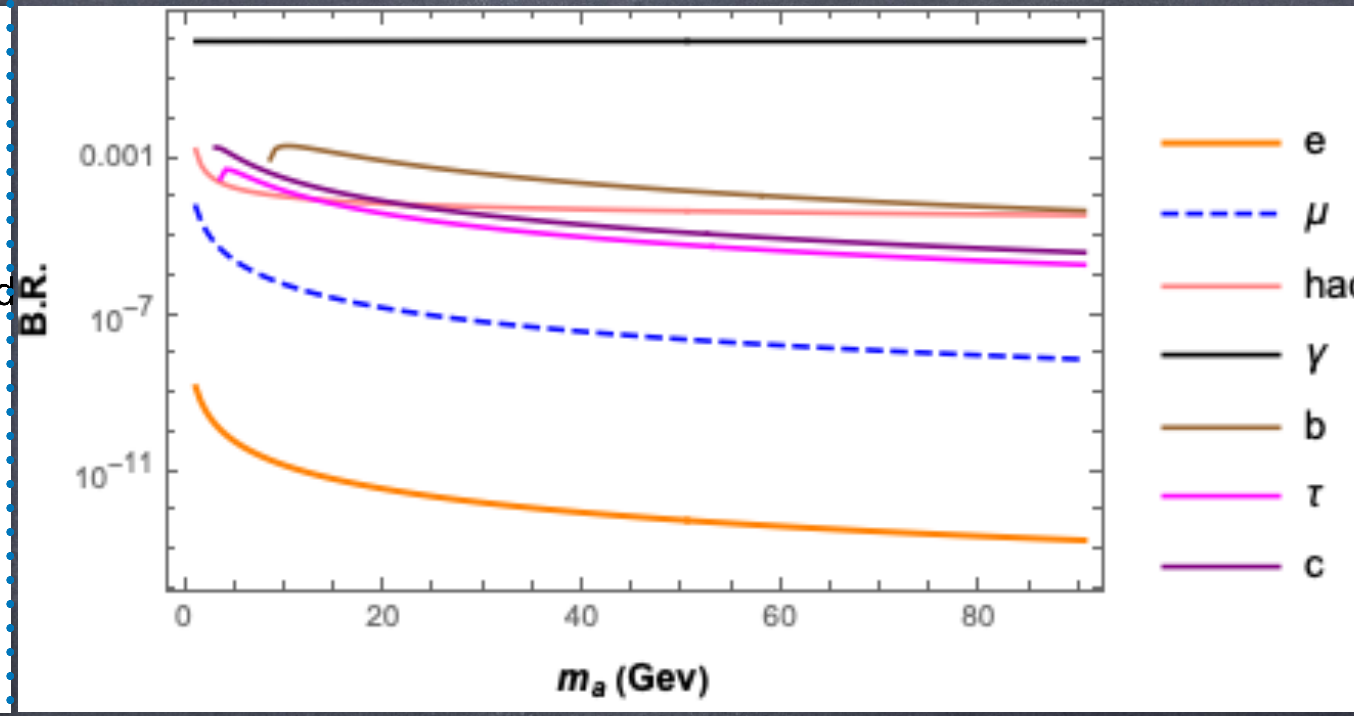
Photo-phobic



No leading order coupling to Photons (WZW interaction is Zero!!)

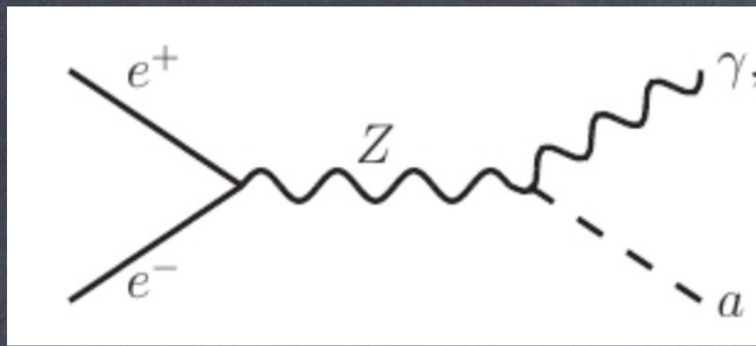
eg. SU(4)/SP(4), SU(4)xSU(4)/SU(4)

Photo-philic



WZW interaction to photons (like the pion)

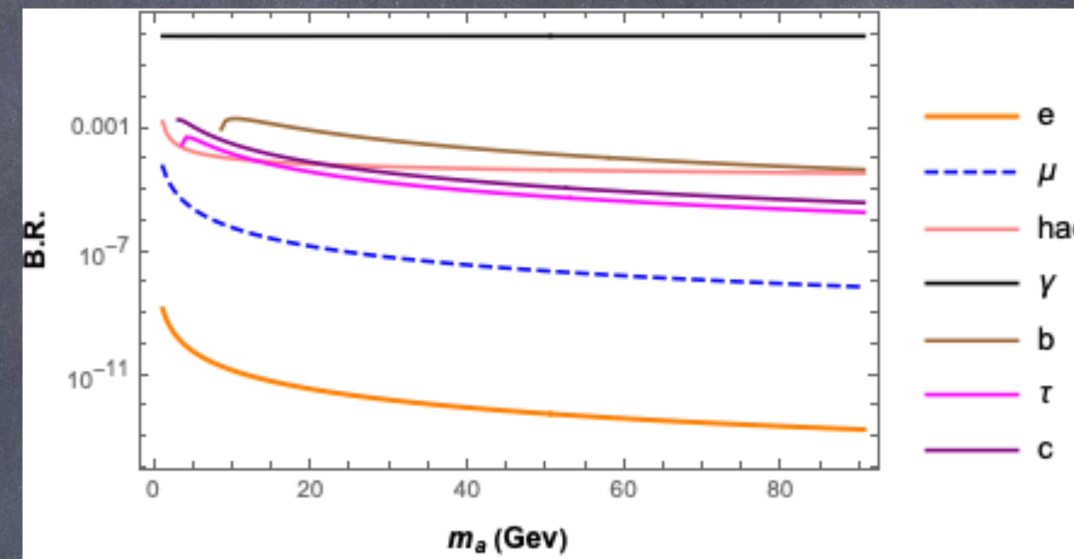
eg. SU(5)/SO(5), SU(6)/SO(6)

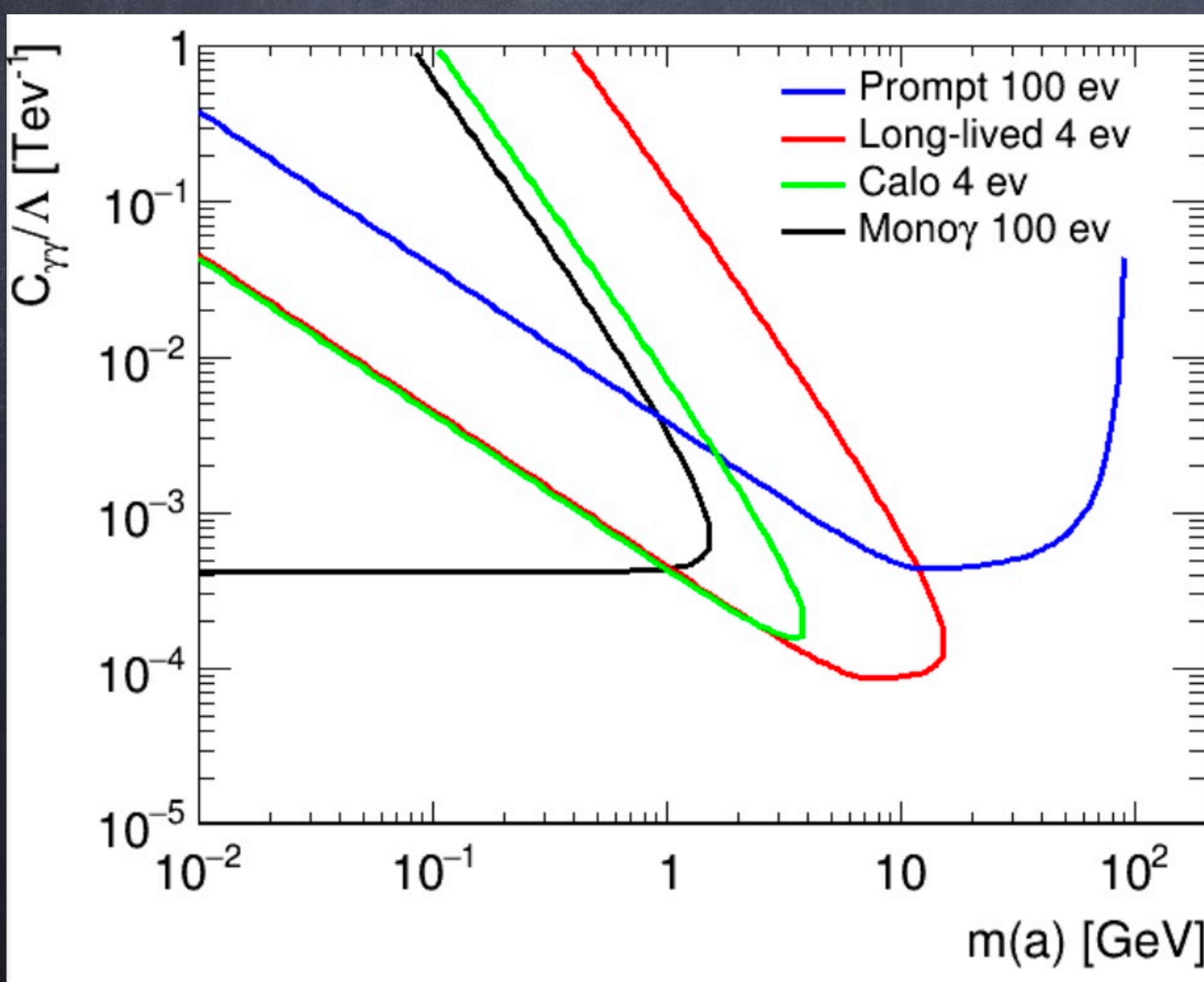


ALPs at FCC-ee

- Production via Z decays: $\Gamma(Z \to \gamma a) \propto C_{Z\gamma}^2$

- Lifetime $\Gamma_a^{tot} \propto C_{\gamma\gamma}^2$

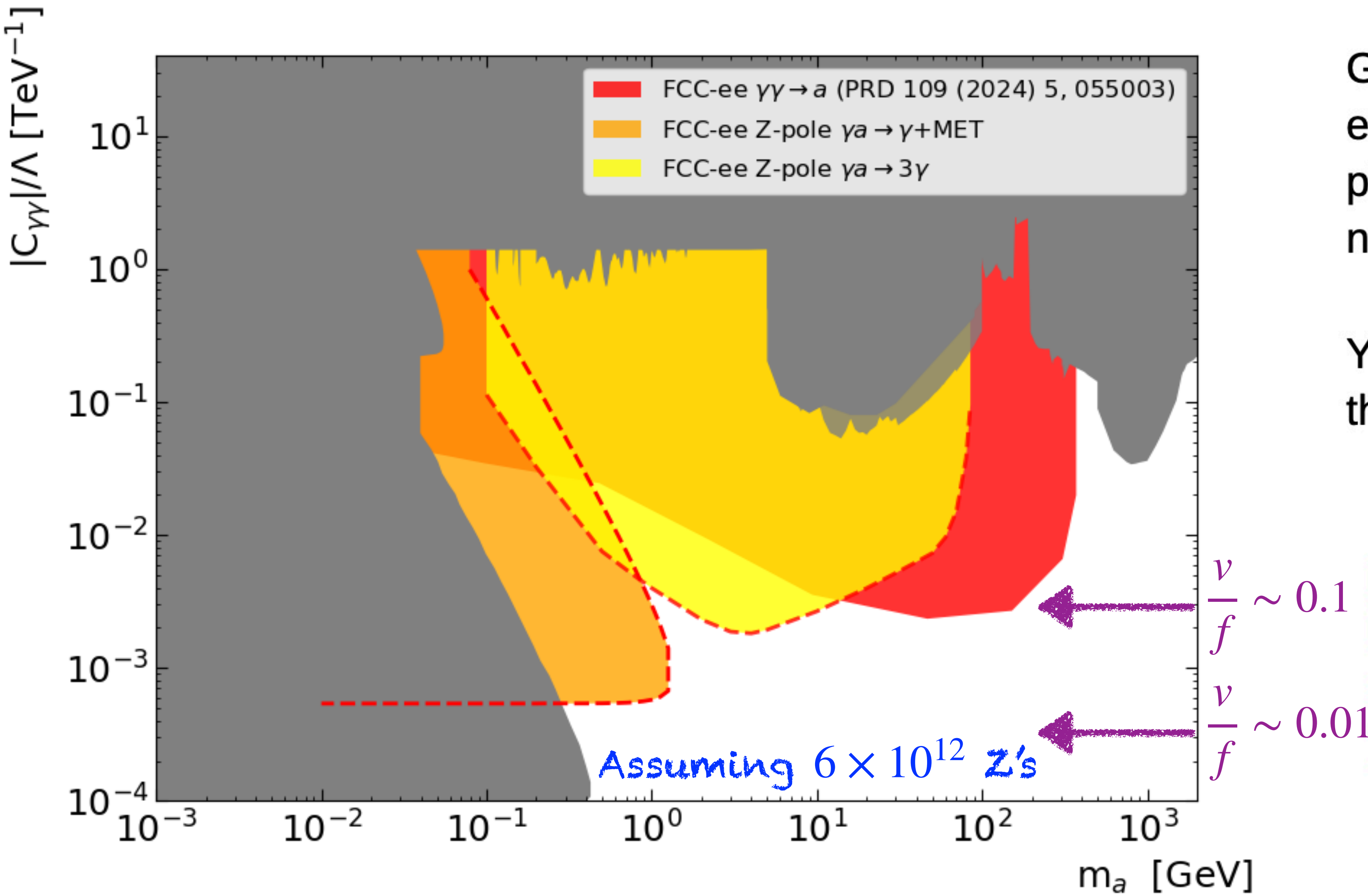




4 experimental regions depending on decay length L of ALP

- 100 events for L<10 mm (prompt)
- 4 events for 10<L<2000 mm (Long lived) Decay in ID
- 4 events for 2000<L<4500 mm (Calo) Decay in calorimeter
- 100 events for L>4500 mm: ALP decays outside the detector, only accompanying photon detected (monophoton)

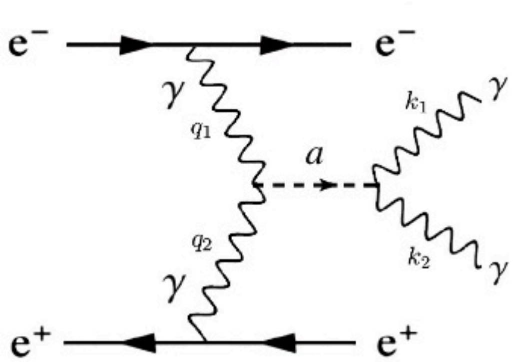
Combined plot FCC-ee



Grey areas :existing exclusions taken from ATLAS plot, to be updated with newest results

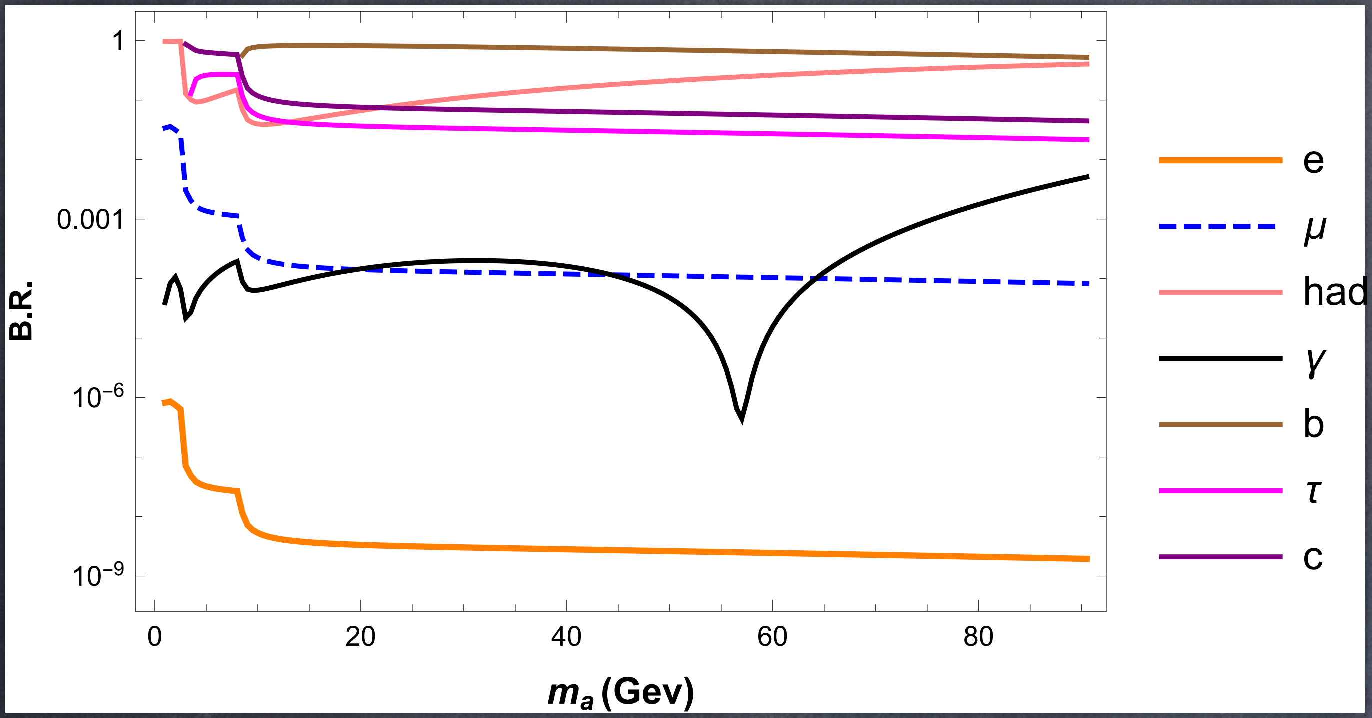
Yellow and orange areas are the two analyses of this talk

Red area is analysis of Rebello Teles et al. addressing ALP production in photon-photon fusion



Plot for $C_{WW} = C_{BB}$

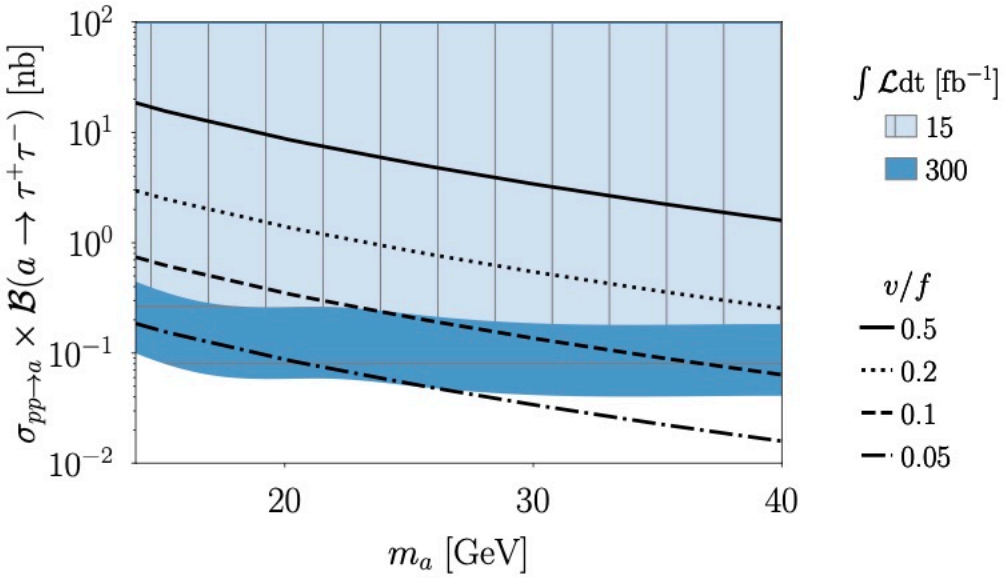
Photophobic case

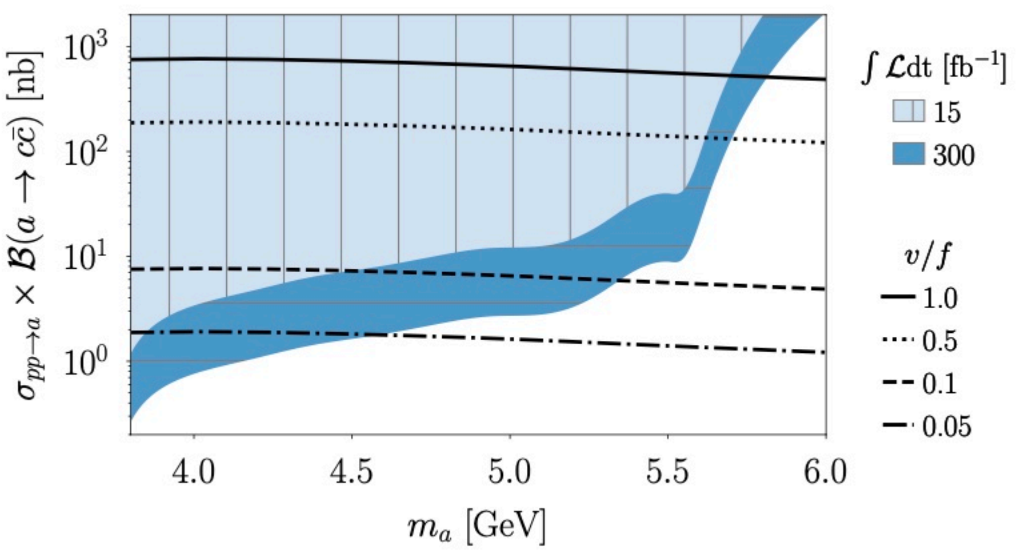


Hadronic decays interesting for FCC-ee/CepC

Tau and muon could be accessible at the LHC (LHCb)

Estimated reach of LHCb from 2106.12615





Roadmap to Higgs compositeness

- The HL-LHC will leave an important legacy, but NOT covering the whole interesting parameter space! (i.e. 10TeV is the target)

- A Tera-Z run will fully test the presence of a light composite ALP -> well beyond the 10 TeV mark

- Case 1 : discovery + EWPTs can fix the scale

- Case 2 : non-discovery + EWPTs

- In both cases, the results will strongly constraint the model building, providing testable predictions for a high energy pp collider.

Extras

Morsels emission dynamics

Each morsel emits particles with rates depending on its mass

Emission rate per species “p” follows

$$\frac{d^2 N_p}{dt\, dE_p} = \frac{1}{h} \frac{\Gamma_p(E_p, M_{\mathrm{Bm}})}{\exp \frac{E_p}{k_B T_{\mathrm{Bm}}} \pm 1}$$

T_{Bm} - BH morsel temperature

Denominator: Boltzmann statistic factor ± 1 for fermions/bosons

$\Gamma_p(E_p, M_{\mathrm{Bm}})$ - grey body factor

Neutrinos

Neutrino observatories ANTARES and IceCube monitor BH mergers

ANTARES and IceCube ~ 500 sec window

No excess found

However, flux limits are orders of magnitude above photon ones

Require a luminosity of $10^{51}\,\mathrm{erg\ sec}^{-1}$

BH morsels predict neutrino fluxes similar to photons.

Experiments not competitive

Super Massive BH Mergers