

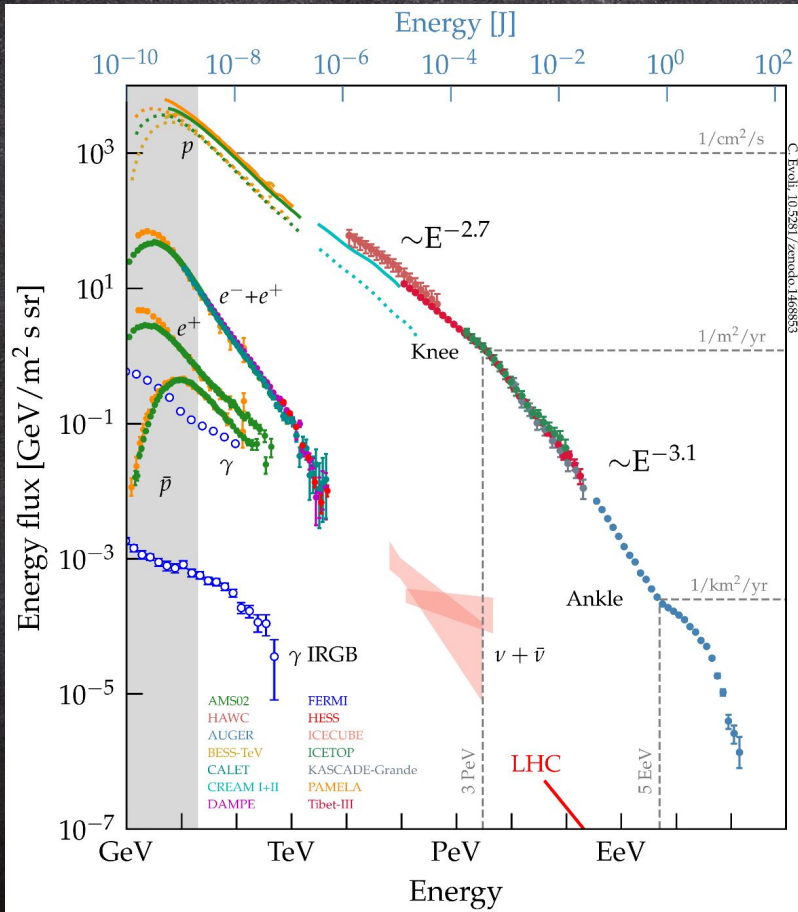
Unravelling the mysteries of the small-scale astrophysical jets

Dimitrios Kantzas

LAPTh/CNRS



Understanding the cosmic-ray spectrum



- CRs are charged particles of extraterrestrial origin
- Consist of matter and antimatter
- Connect small-scale physics to large-scale astrophysics
- Can (dis)prove beyond the Standard Models
- Connect to the most energetic phenomena of the Universe
- Origin:
 - GeV CRs are of solar origin
 - TeV-PeV CRs are of Galactic origin
 - >PeV CRs are of extragalactic origin

Indirect cosmic-ray detection

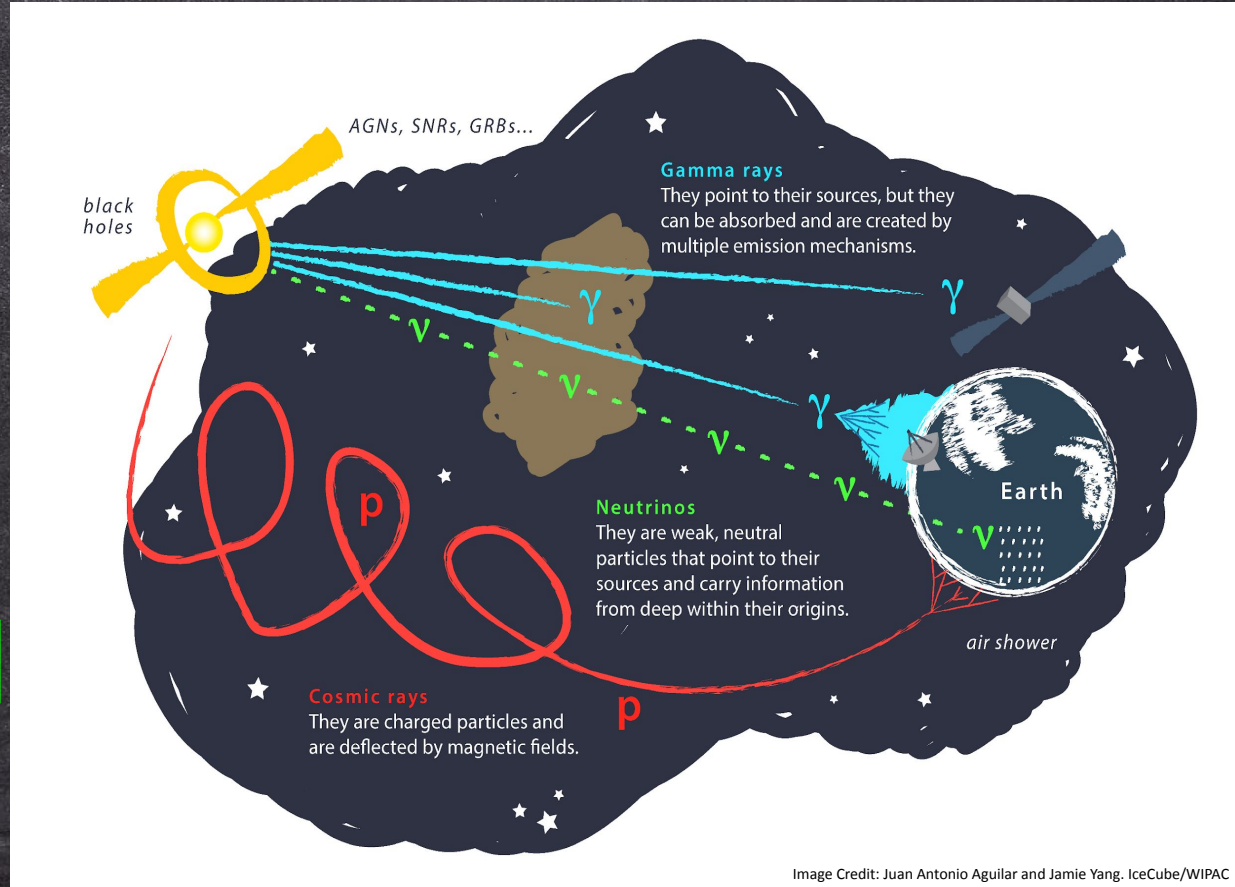
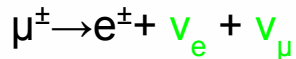
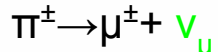
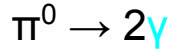


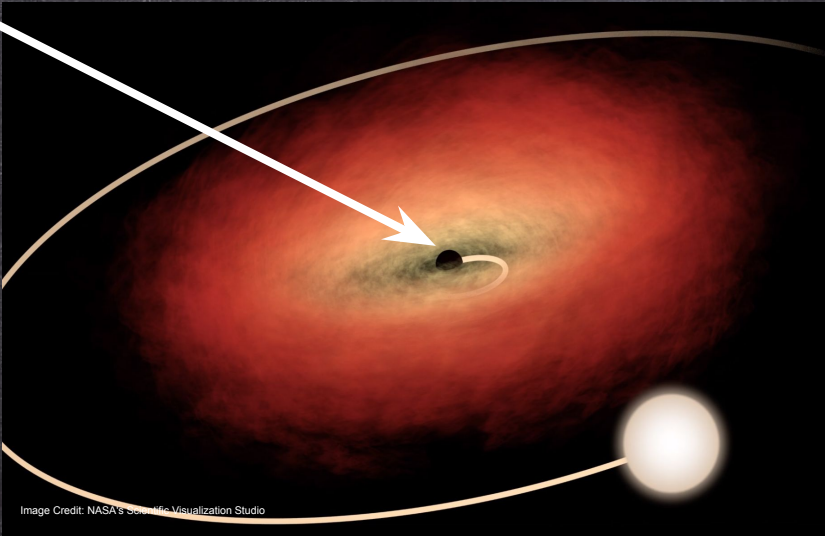
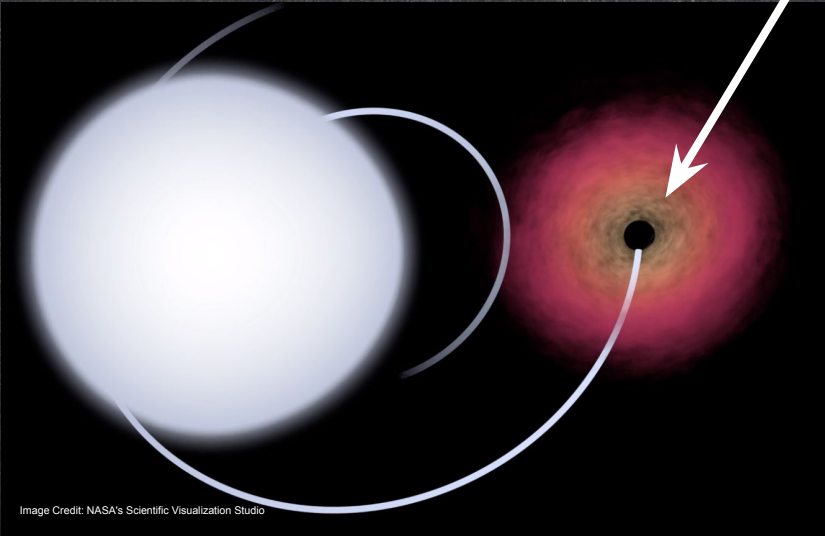
Image Credit: Juan Antonio Aguilar and Jamie Yang. IceCube/WIPAC

Accreting Galactic black holes I

High-mass

Low-mass

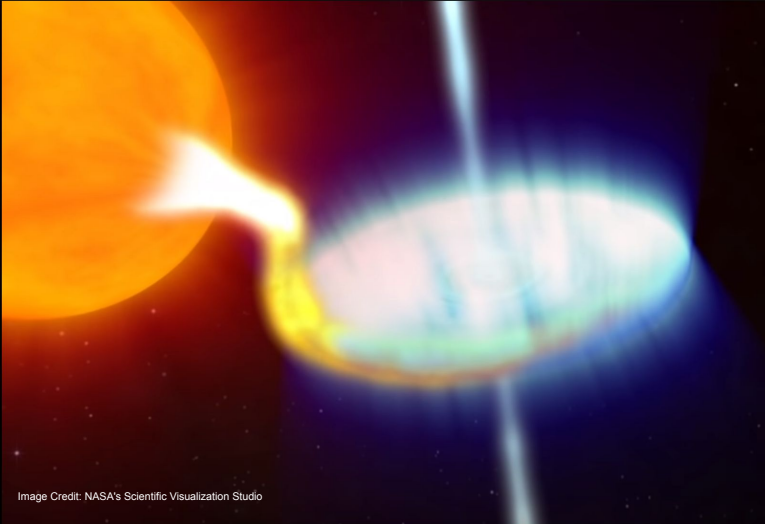
~10 M_⊙



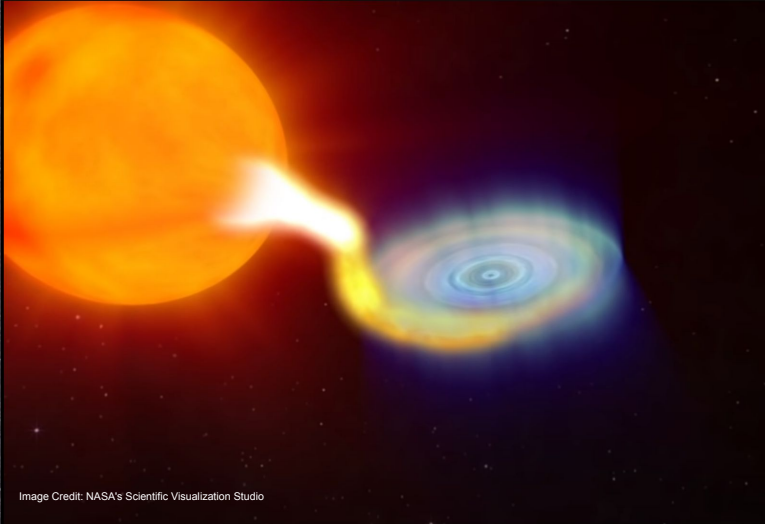
Orbital period: ~days

Accreting Galactic black holes II

Jetted



Non-jetted



Accreting Galactic black holes II

Jetted

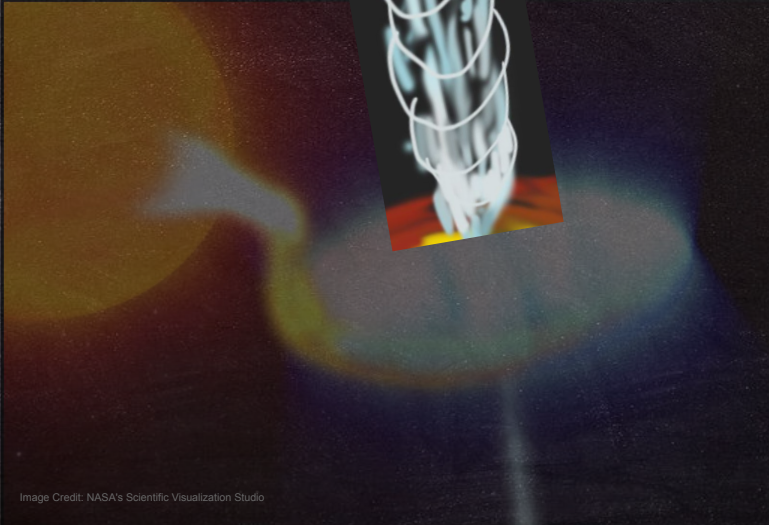
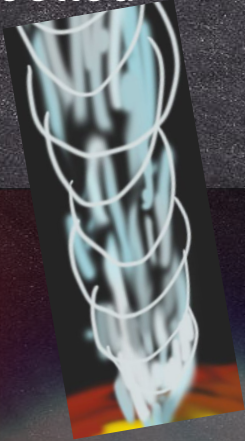


Image Credit: NASA's Scientific Visualization Studio

Non-jetted

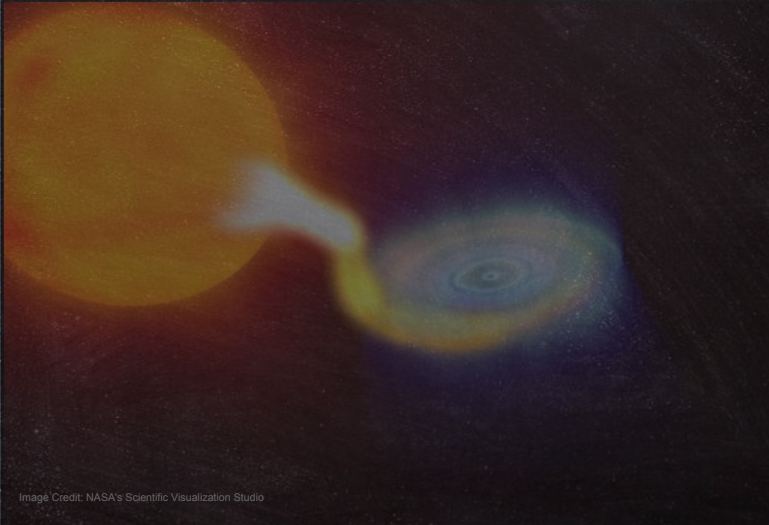
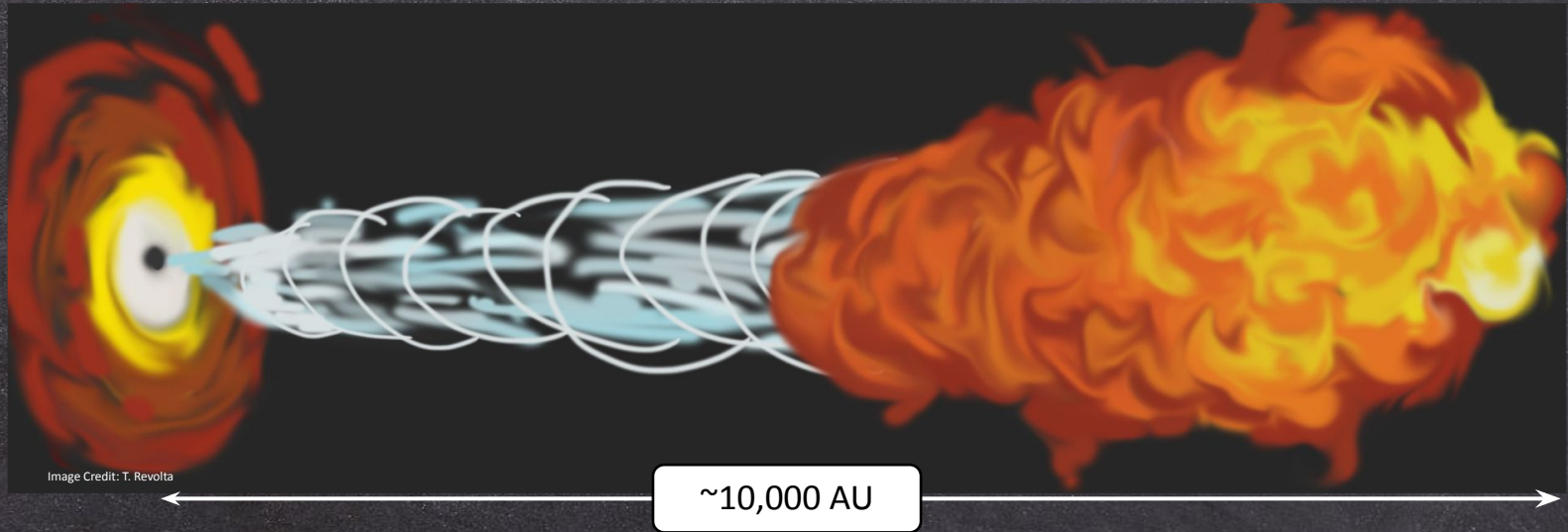


Image Credit: NASA's Scientific Visualization Studio

Small scale astrophysical jets in X-ray binaries



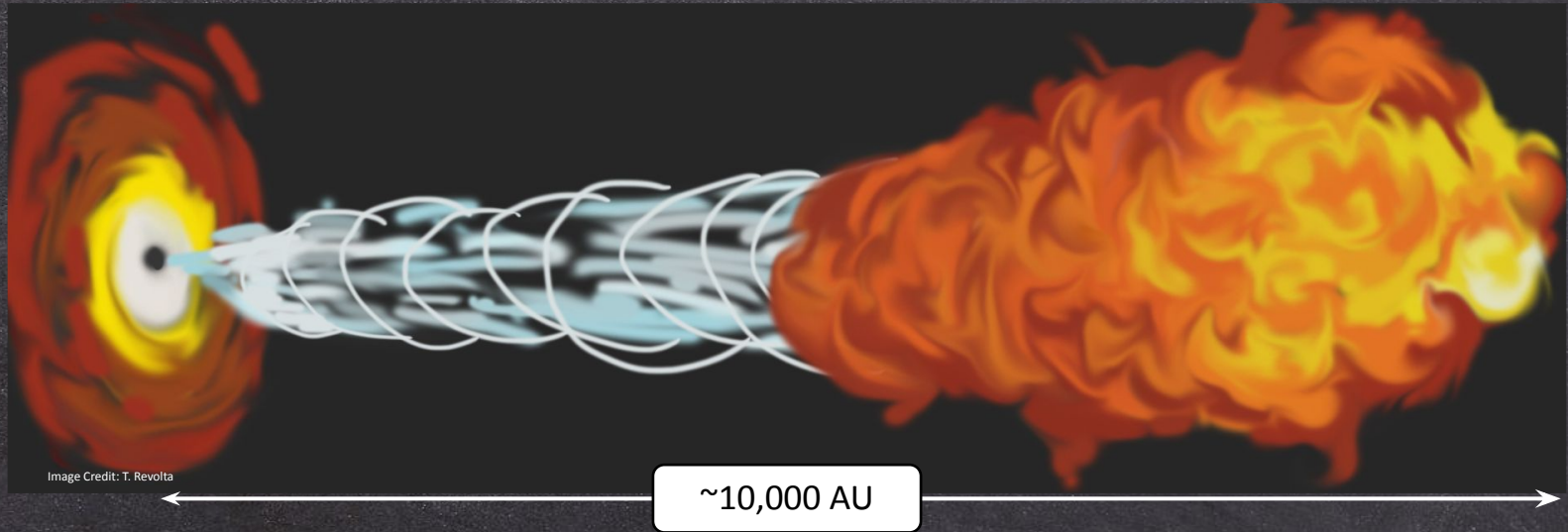
We “*know*”:

- Relativistic collimated plasma
- Bulk Lorentz factor of $\sim 3-10$
- Strong magnetic field

We don't know:

- Jet launching mechanism(s) !
- Energy dissipation and particle acceleration !
- Jet composition !
-

Small scale astrophysical jets in X-ray binaries



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- Relativistic collimated plasma
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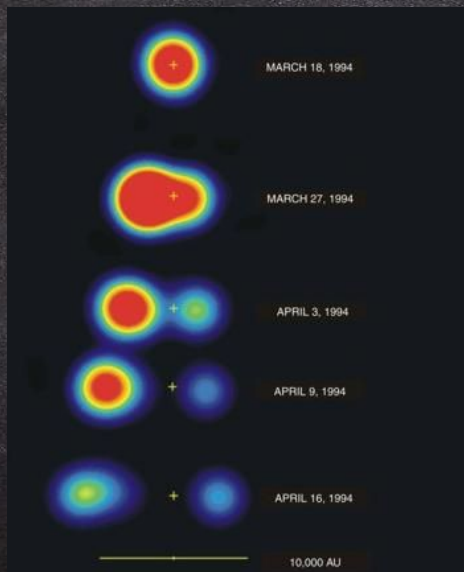
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- ...

Observational evidence – from radio imaging ...

GRS 1915+105

Mirabel & Rodriguez, 1994

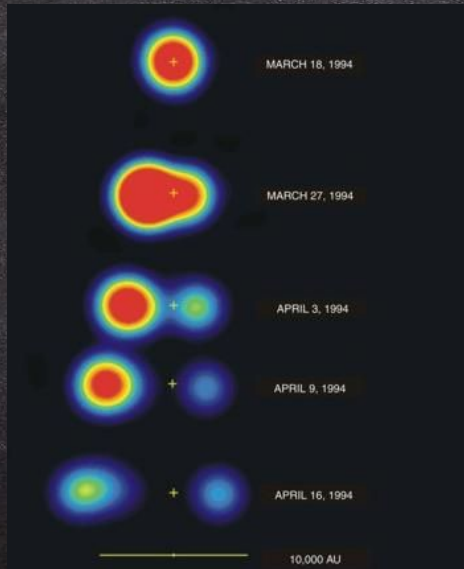


Radio to MeV γ -rays (Hannikainen et al. 2003)

Observational evidence – from radio imaging ...

GRS 1915+105

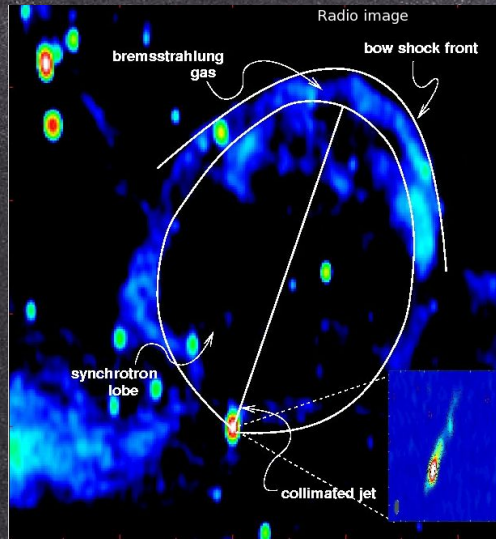
Mirabel & Rodriguez, 1994



Radio to MeV γ -rays (Hannikainen et al. 2003)

Cygnus X-1

Gallo et al. (2005)

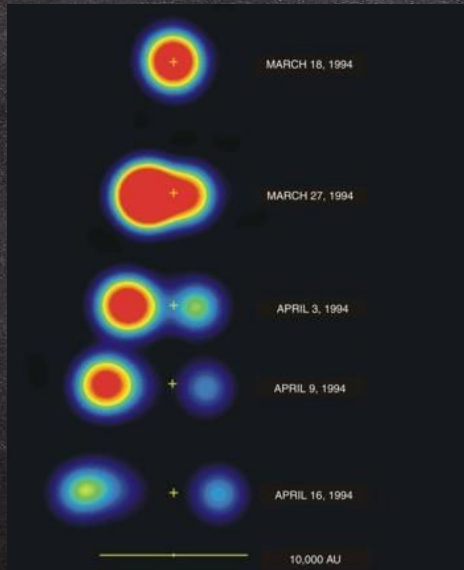


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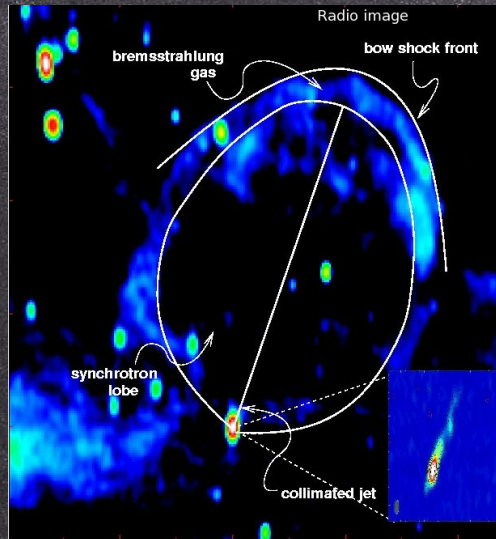
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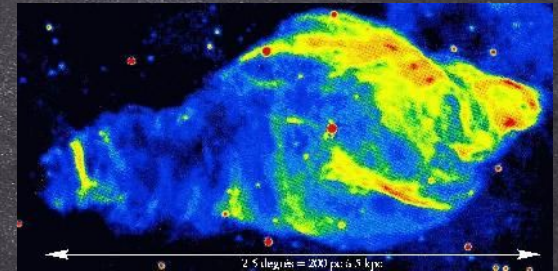
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Radio to GeV γ -rays (Zanin et al. 2016)

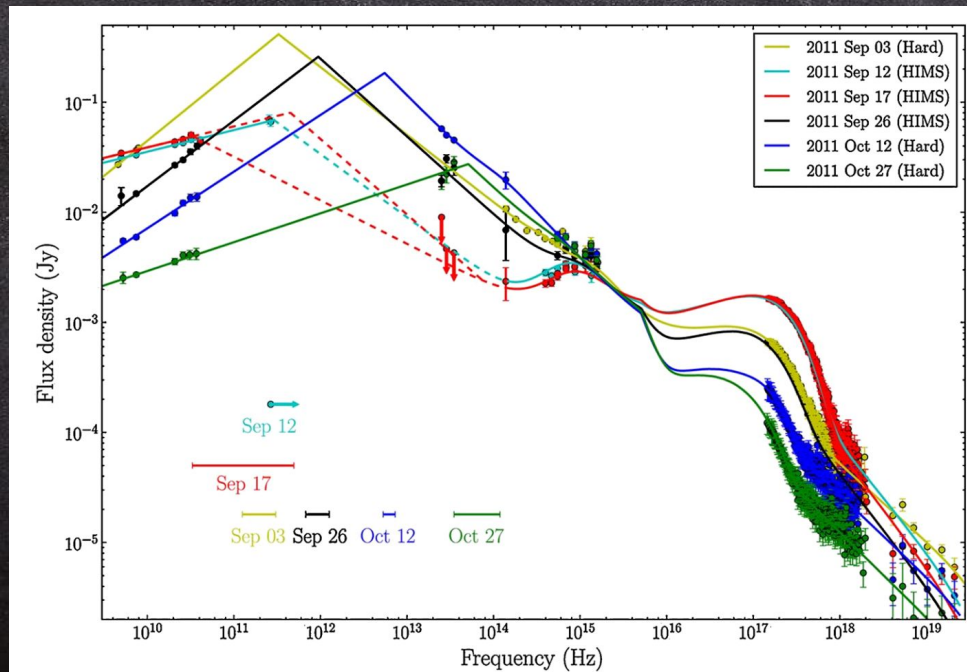
SS433

NRAO



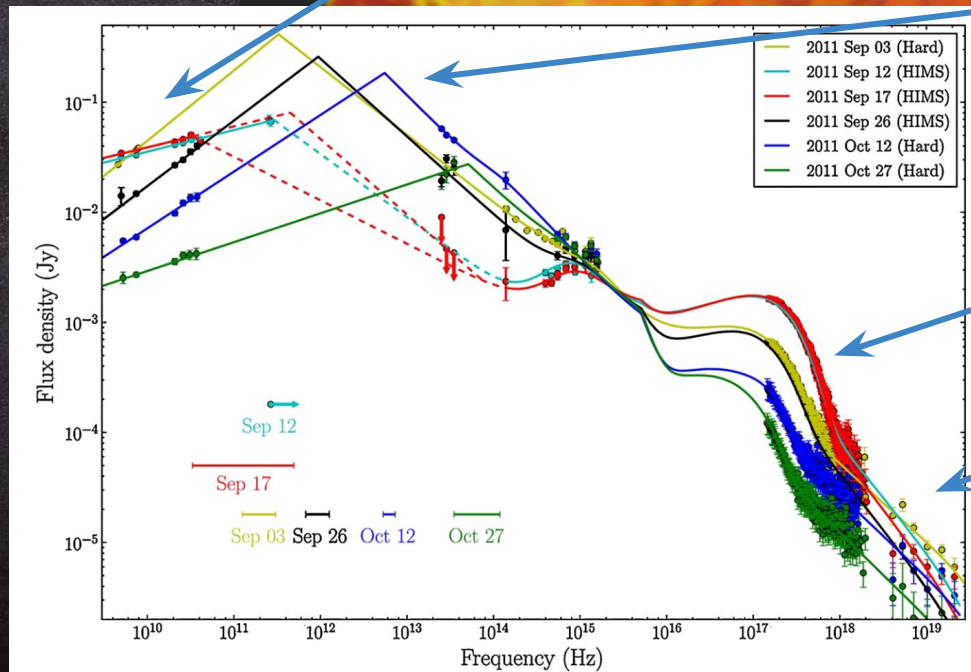
Radio to TeV γ -rays (Abeysekera et al. 2018)

Observational evidence – electromagnetic spectrum



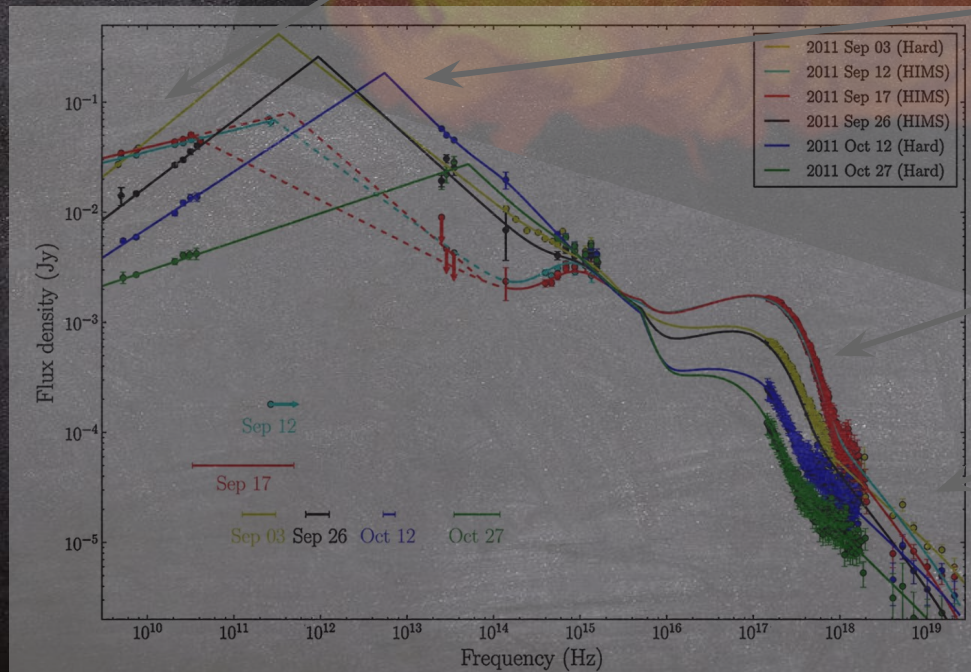
MAXI J1836-194
Russell et al. 2011

Observational evidence – electromagnetic spectrum



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Russell et al. 2011

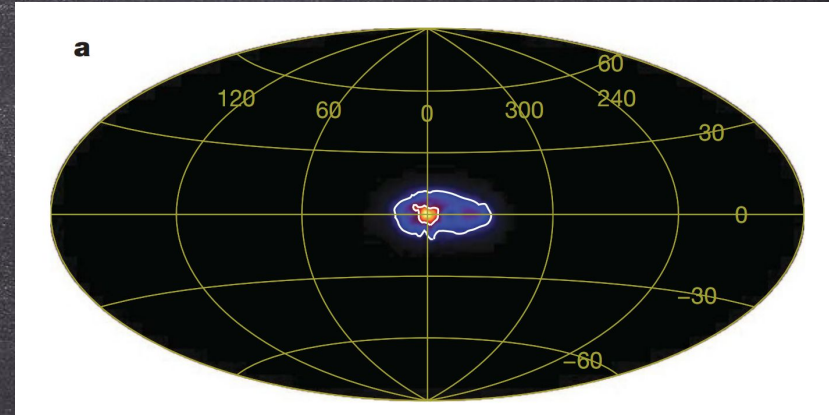
Observational evidence – electromagnetic spectrum



- Jets = particle acceleration sites
- Particles (electrons) accelerate to high energies

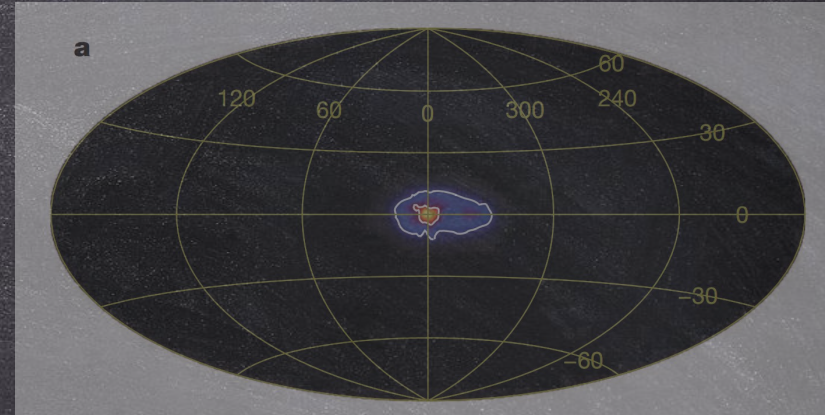
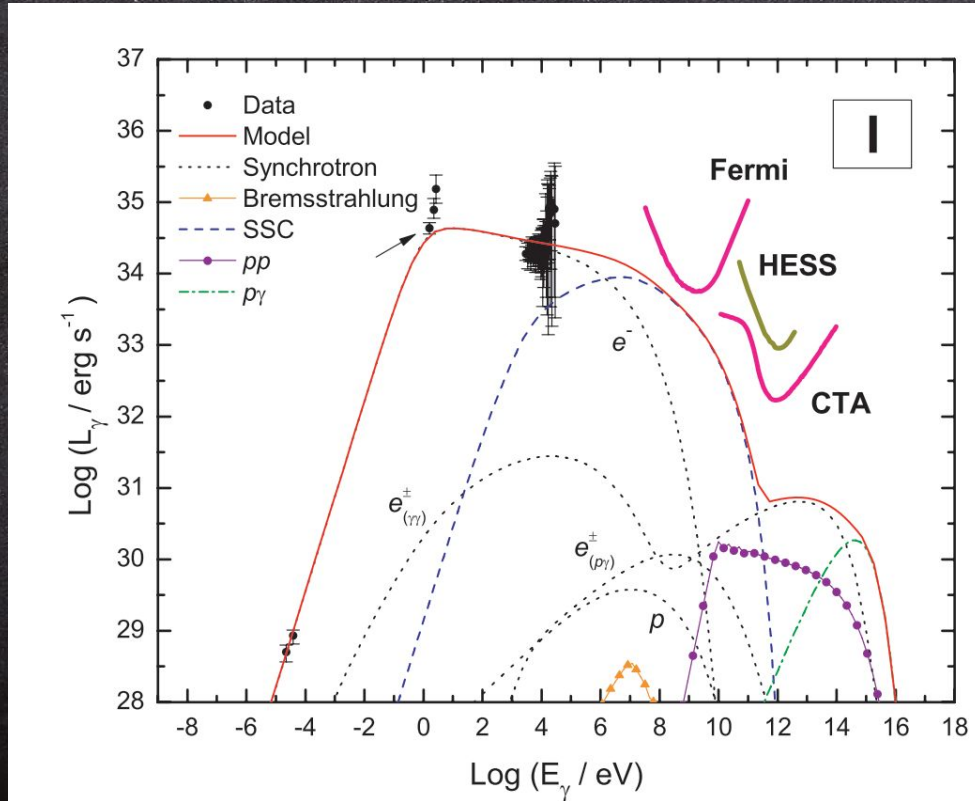
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X-ray binaries as CR *positron* sources



511 keV Galactic Centre with *INTEGRAL*
Weidenspointner et al. 2008

X-ray binaries as CR positron sources

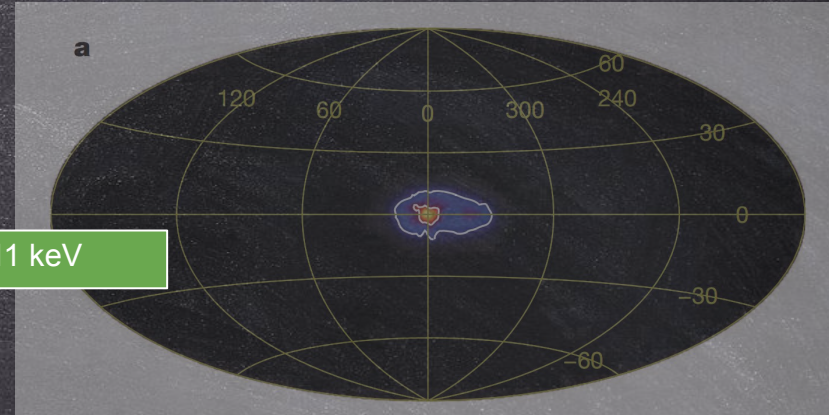
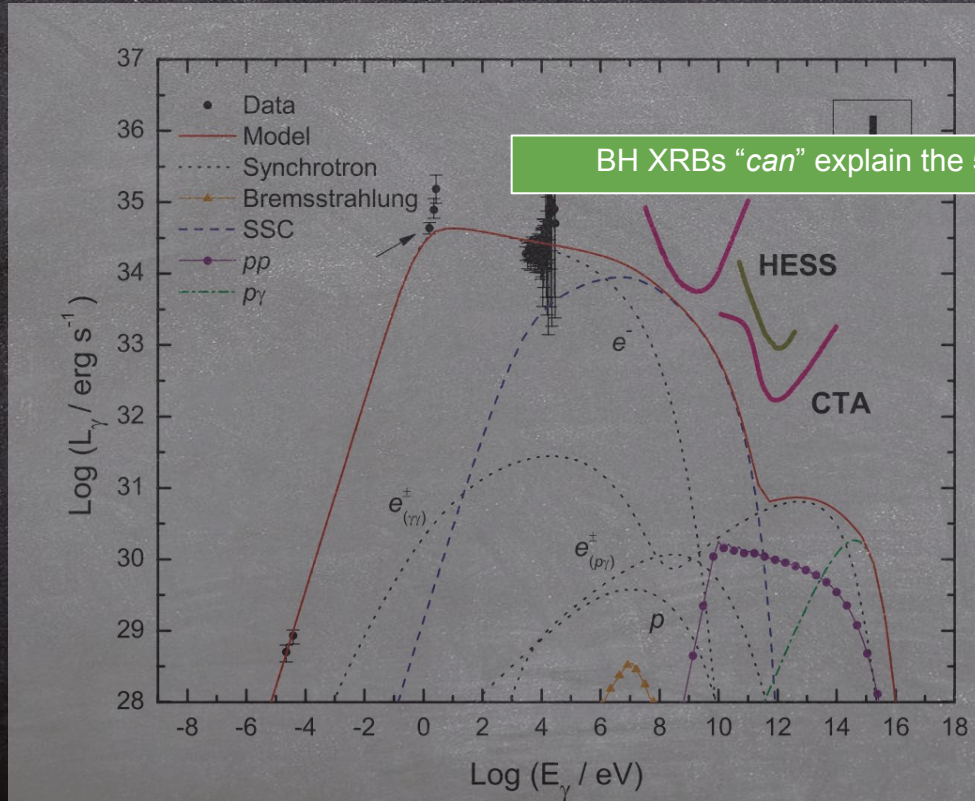


511 keV Galactic Centre with *INTEGRAL*
 Weidenspointner et al. 2008

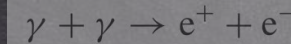
$$\gamma + \gamma \rightarrow e^+ + e^-$$

GX 339-4
 Vila & Romero 2010

X-ray binaries as CR positron sources



511 keV Galactic Centre with *INTEGRAL*
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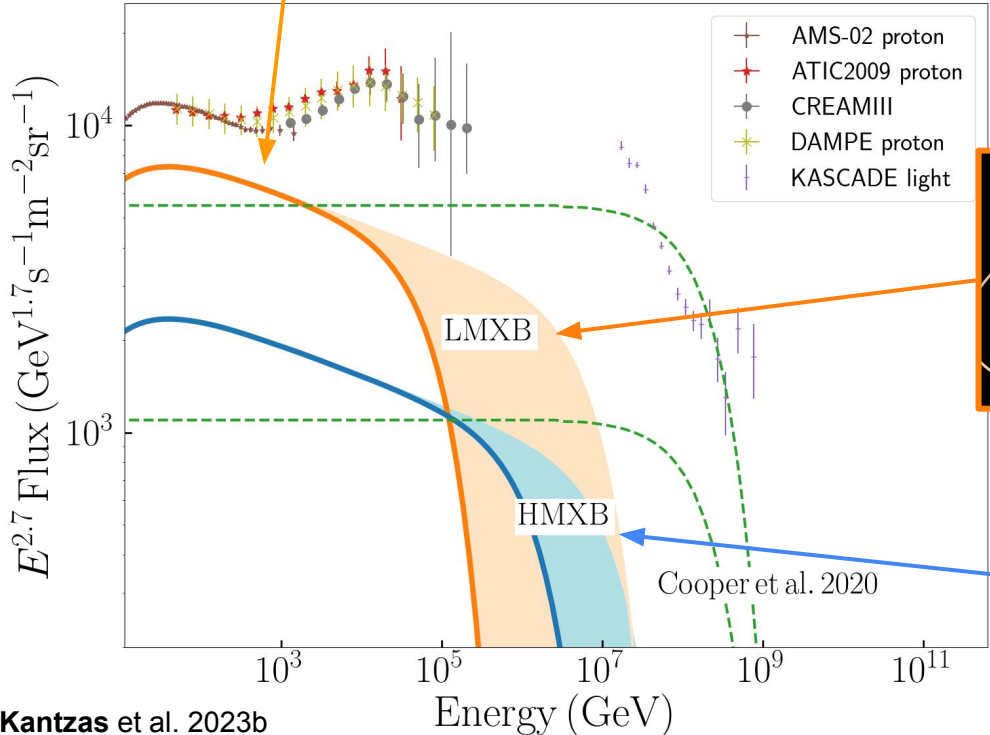


In agreement with Bartels et al. 2018 when
Neutron star XRBs are included

GX 339-4
Vila & Romero 2010

X-ray binaries as CR *proton* sources

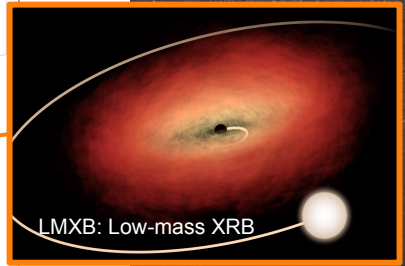
~50%



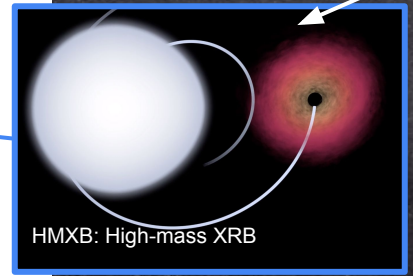
if **1000** black hole XRBs follow the same spatial distribution as Pulsars (Lorimer et al. 2006)



Evoli et al. 2017, 2018



Kantzas et al. 2022



Kantzas et al. 2021

Kantzas et al. 2023b

Unravelling the mysteries of the small-scale astrophysical jets



We “know”:

- Galactic black holes in X-ray binaries launch relativistic jets
- Electrons accelerate in jets and produce radio/X-ray/ γ -ray radiation
e.g. ... Vila & Romero 2010; Russell et al. 2011; **Kantzas** et al. 2021, 2022; ...
- Protons may accelerate in jets and can produce TeV radiation
e.g. ... Vila & Romero 2010; **Kantzas** et al. 2021, 2022; ...
- CR positrons *may* originate in BHXBs
e.g. Vila & Romero 2010; Prantzos et al. 2015; Bartels et al. 2018
- CR protons *may* originate in BHXBs (50% of TeV)
e.g. Cooper et al. 2020; **Kantzas** et al. 2023