Dark Matter
in Extreme astrophysical environments

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DM in extreme astrophysics

@Snowmass

Submitted to the Proceedings of the US Community Study
on the Future of Particle Physics (Snowmass 2021)

Dark Matter In Extreme Astrophysical Environments

Masha Baryakhtar[1], Regina Caputo[2], Djuna Croon[3,4], Kerstin Perez[5], Emanuele Berti[6], Joseph Bramante[7,8], Malte Buschmann[9], Richard Brito[10], Thomas Y. Chen[11], Philippa S. Cole[12], Adam Coogan[13,14], William E. East[8], Joshua W. Foster[5], Marios Galanis[15], Maurizio Giannotti[16], Bradley J. Kavanagh[17], Ranjan Laha[18], Rebecca K. Leane[19,20], Benjamin V. Lehmann[21,22], Gustavo Marques-Tavares[23], Jamie McDonald[4,24], Ken K. Y. Ng[5,25], Nirmal Raj[26], Laura Sagunski[27], Jeremy Sakstein[28], B.S. Sathyaprakash[29,30,42,43], Sarah Shandera[29,30], Nils Siemonsen[7,8,31], Olivier Simon[14], Kuver Sinha[32], Divya Singh[29, 21], Rajeev Singh[33], Chen Sun[34], Ling Sun[35], Volodymyr Takhistov[36], Yu-Dai Tsai[37], Edoardo Vitagliano[38], Salvatore Vitale[5,24], Huan Yang[8,39], and Jun Zhang[40,41]

M. Baryakhtar, R. Caputo, DC, K. Perez et all, Snowmass summer study, arXiv:2203.07984

Extreme environments?

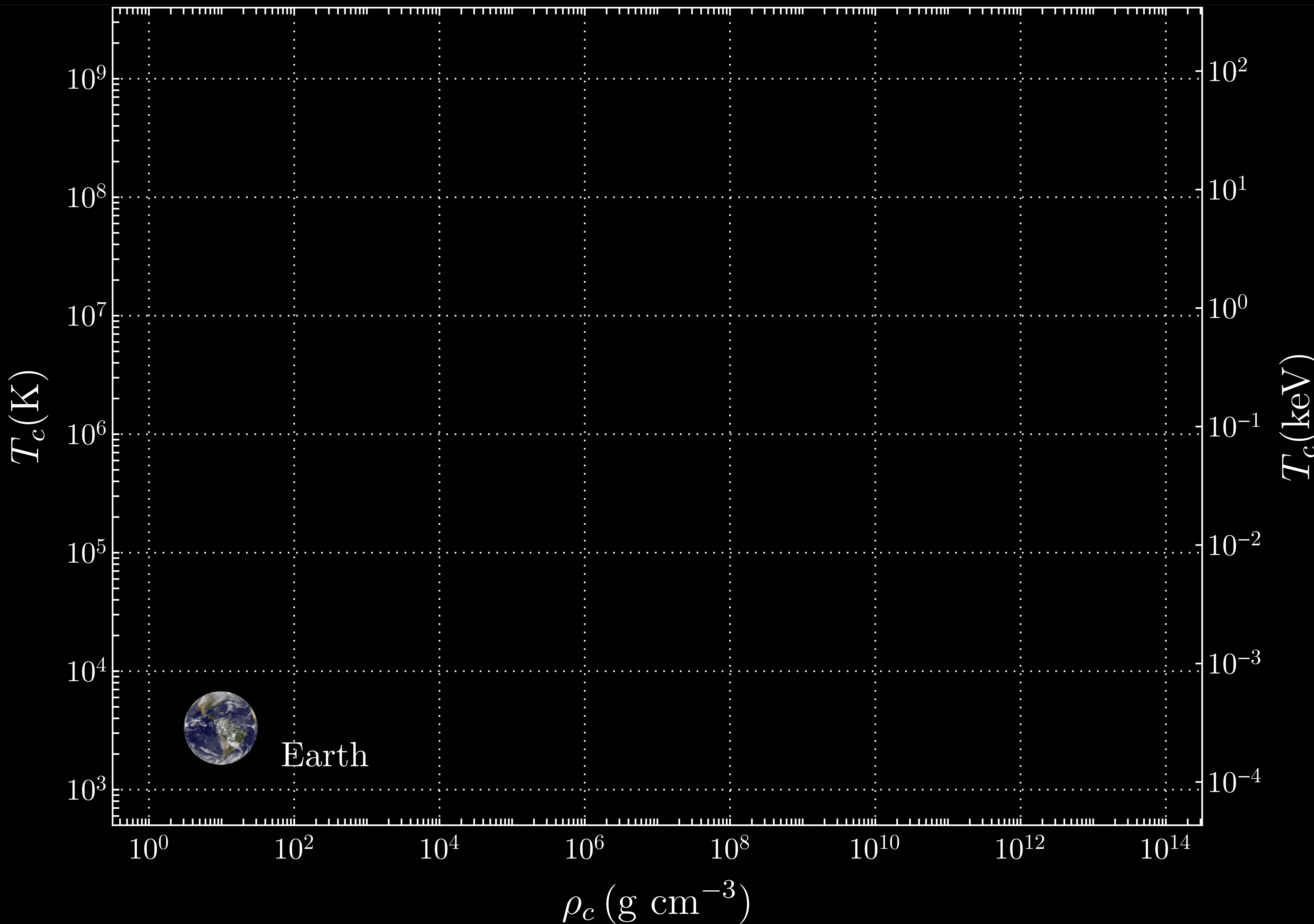
Extreme environments?

‘’Heavy compact objects such as white dwarfs, neutron stars, and black holes, as well as supernovae and compact object merger events’’

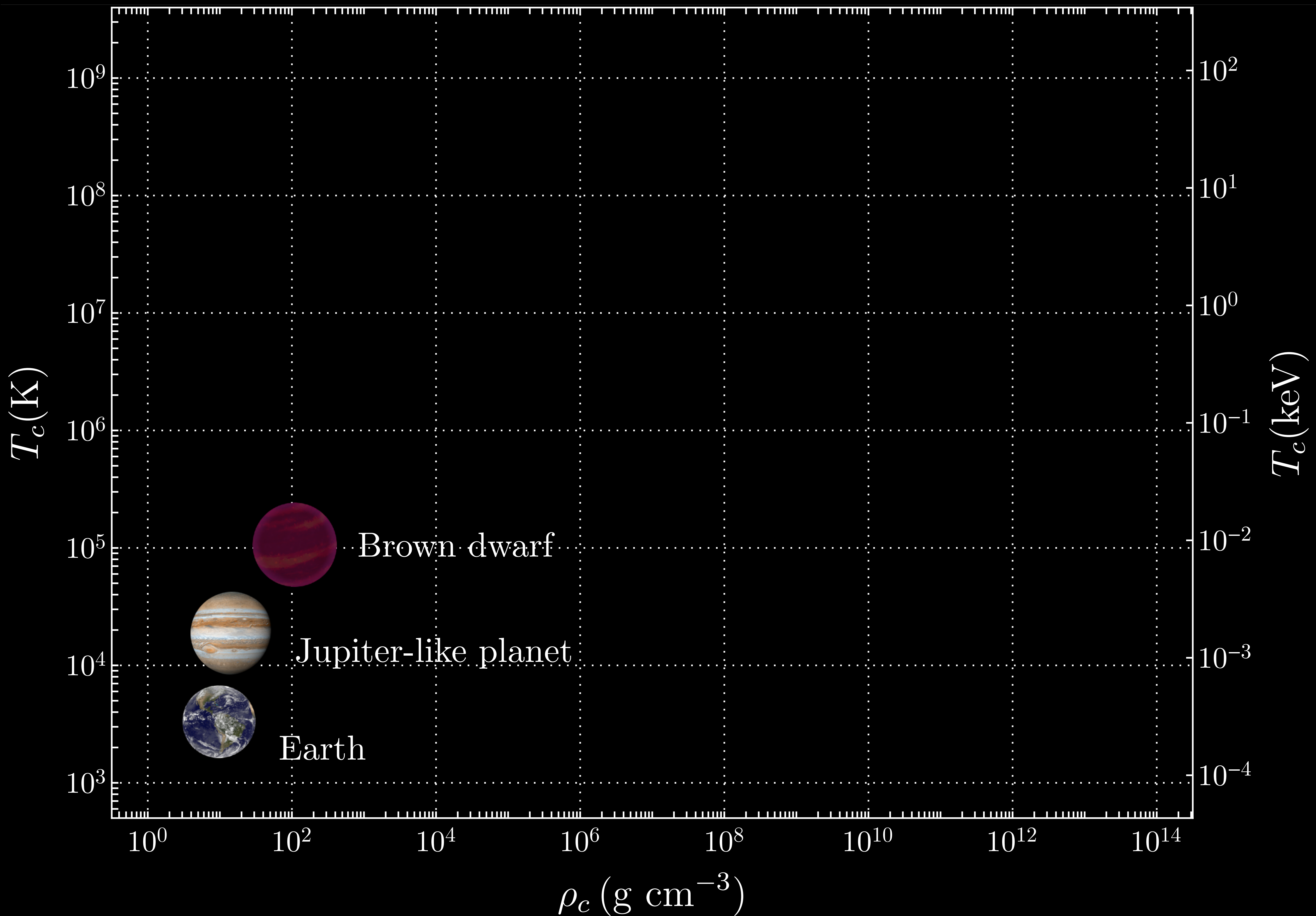
Extreme environments?

''Heavy compact objects such as white dwarfs, neutron stars, and black holes, as well as supernovae and compact object merger events''

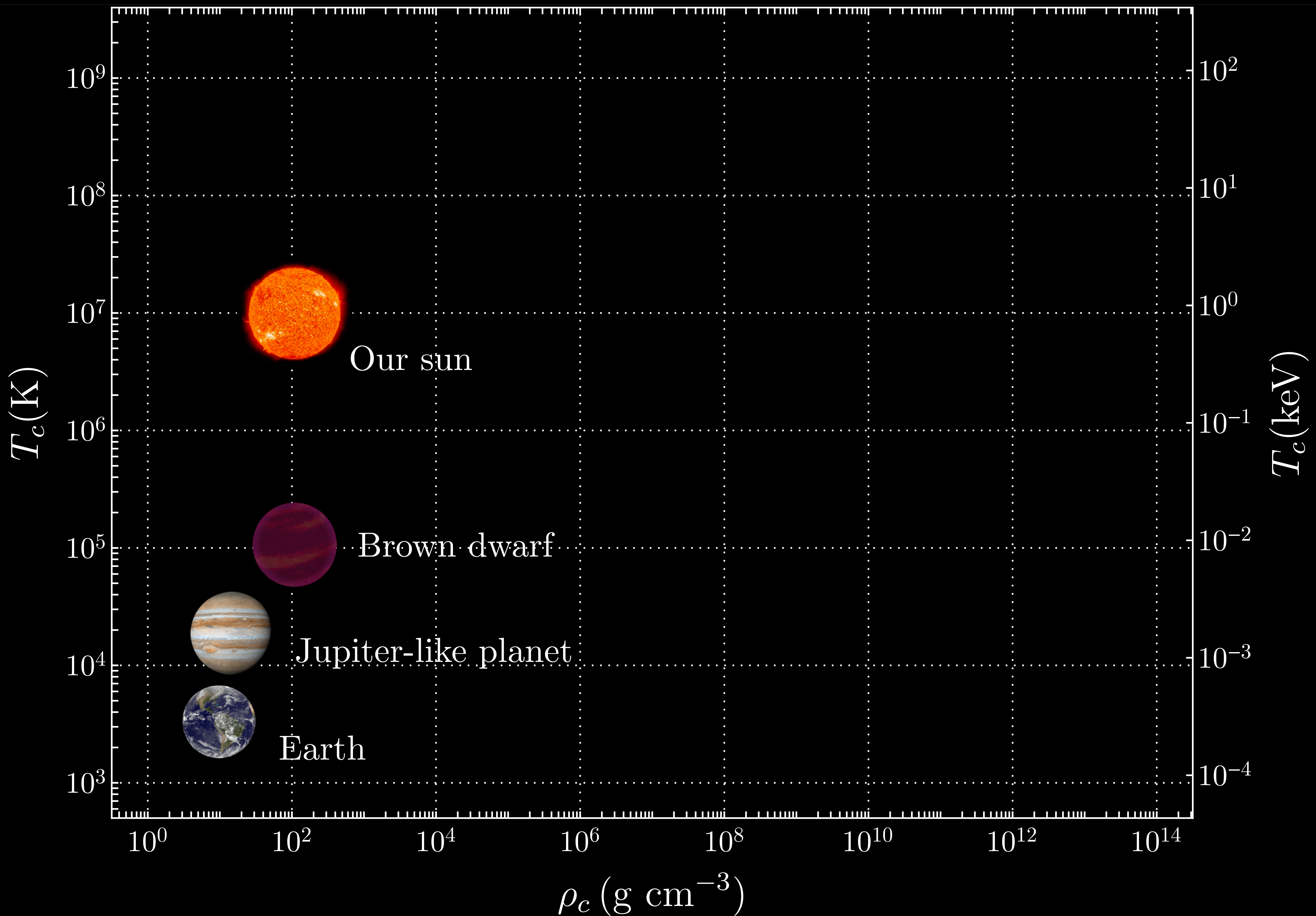
+ exoplanets



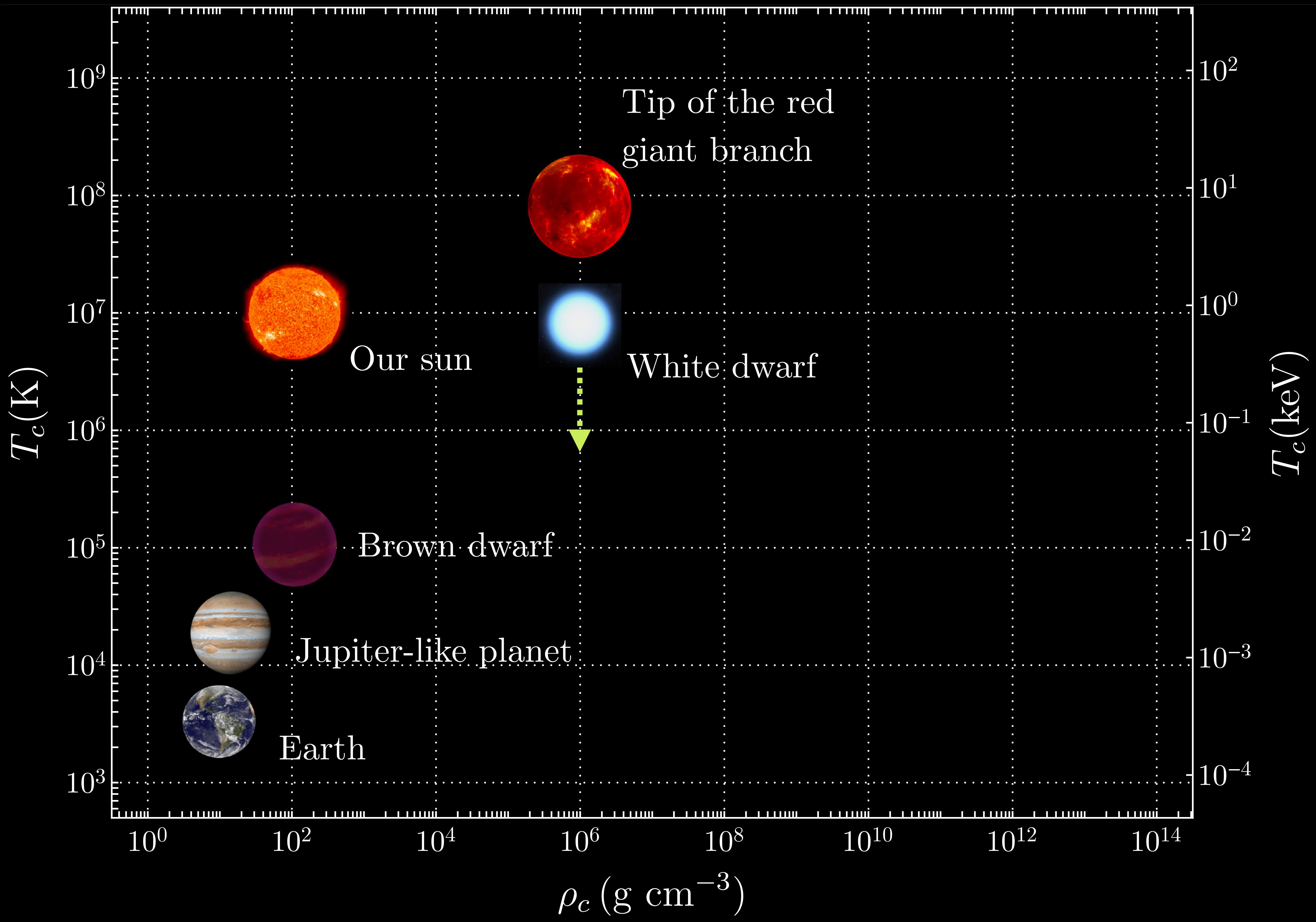
$T_c(\mathrm{K})$
10^9
10^8
10^7
10^6
10^5
10^4
10^3
$T_c(\mathrm{keV})$
10^2
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^0
10^2
10^4
10^6
10^8
10^{10}
10^{12}
10^{14}
$\rho_c\,(\mathrm{g\ cm^{-3}})$
Earth



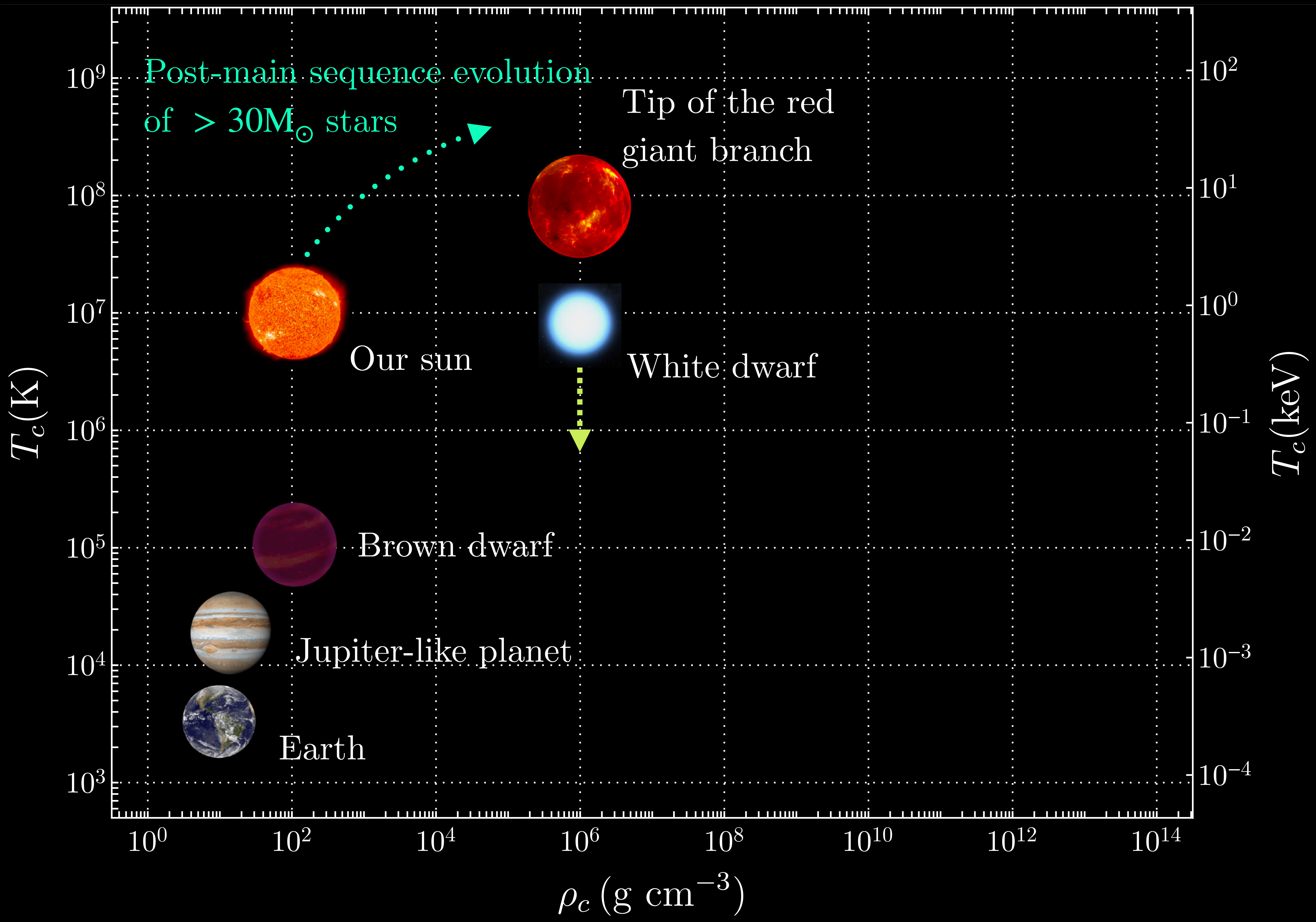
T_c(K)
10^9
10^8
10^7
10^6
10^5
10^4
10^3
T_c(keV)
10^2
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
Brown dwarf
Jupiter-like planet
Earth
10^0
10^2
10^4
10^6
10^8
10^{10}
10^{12}
10^{14}
ρ_c (g cm^{-3})



$T_c(\mathrm{K})$
$T_c(\mathrm{keV})$
10^9
10^8
10^7
10^6
10^5
10^4
10^3
10^2
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
Our sun
Brown dwarf
Jupiter-like planet
Earth
10^0
10^2
10^4
10^6
10^8
10^{10}
10^{12}
10^{14}
$\rho_c\,(\mathrm{g\ cm^{-3}})$



T_c(K)
T_c(keV)
ρ_c (g cm^{-3})
Tip of the red giant branch
Our sun
White dwarf
Brown dwarf
Jupiter-like planet
Earth
10^3 10^4 10^5 10^6 10^7 10^8 10^9
10^{-4} 10^{-3} 10^{-2} 10^{-1} 10^0 10^1 10^2
10^0 10^2 10^4 10^6 10^8 10^{10} 10^{12} 10^{14}



Post-main sequence evolution
of $> 30M_\odot$ stars
Tip of the red
giant branch
Our sun
White dwarf
Brown dwarf
Jupiter-like planet
Earth
10^9
10^8
10^7
10^6
10^5
10^4
10^3
$T_c(\mathrm{K})$
10^2
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
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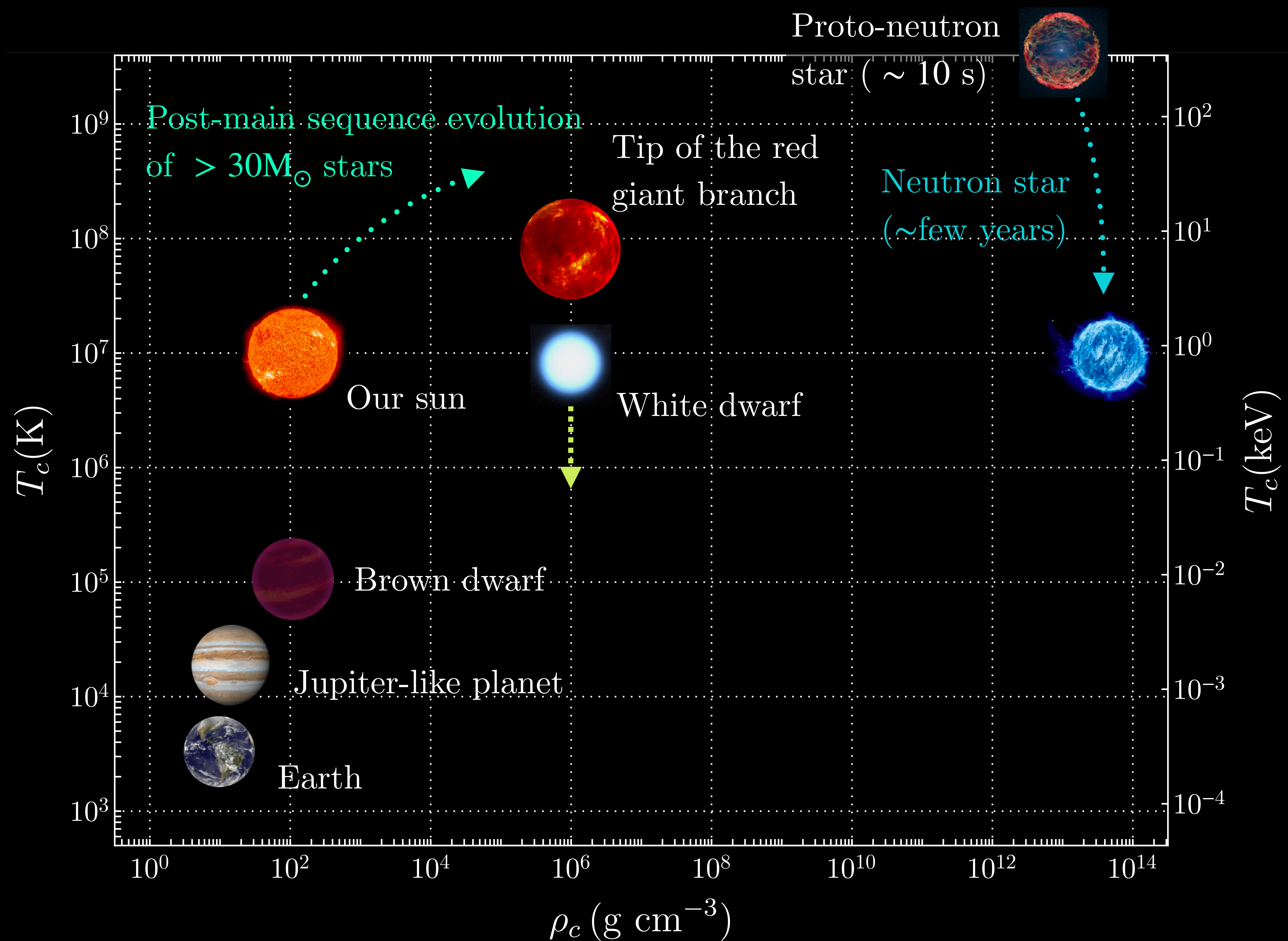
10^0 10^2 10^4 10^6 10^8 10^{10} 10^{12} 10^{14}
$\rho_c\ (\mathrm{g\ cm^{-3}})$

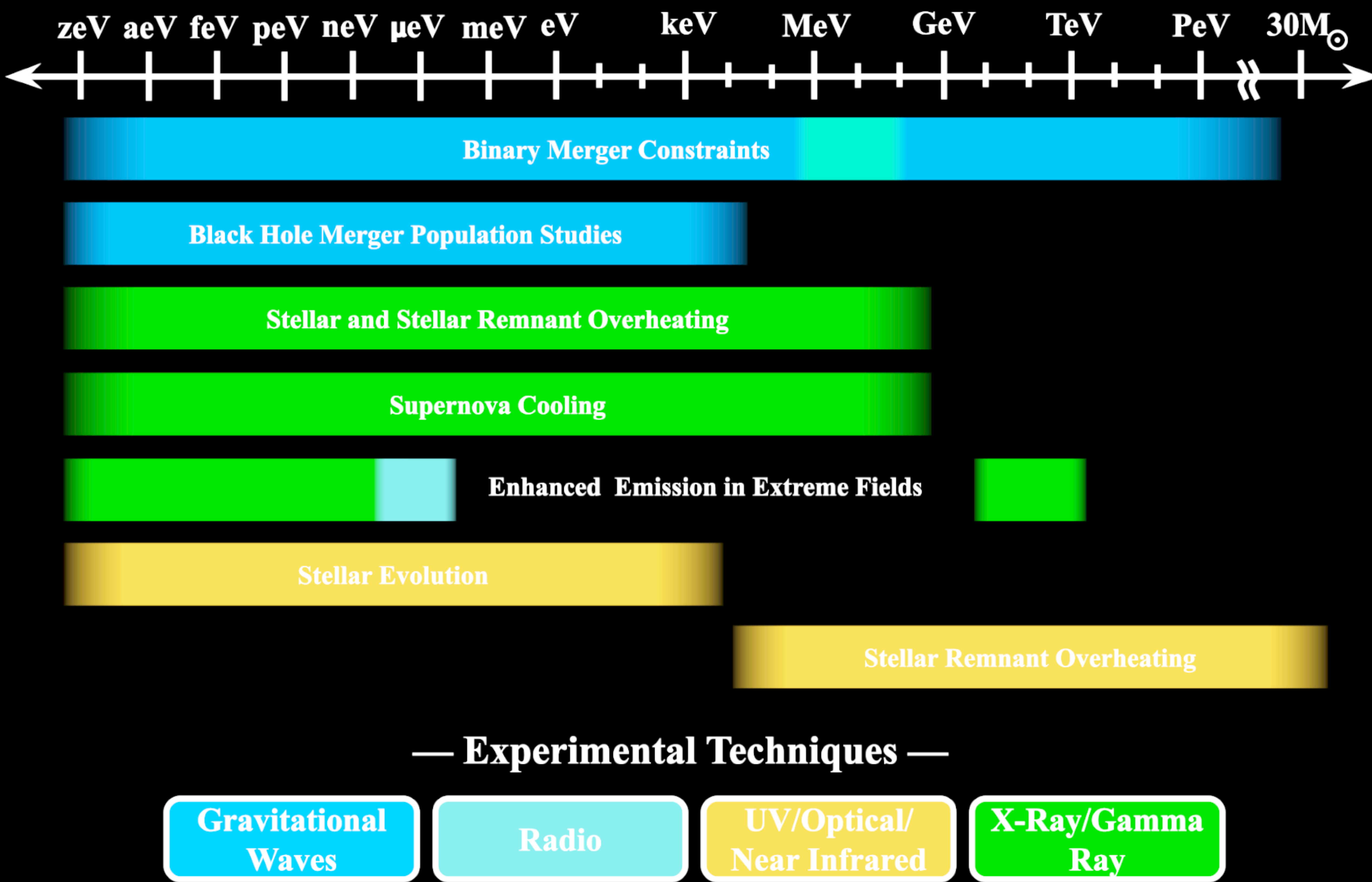


Proto-neutron star (~ 10 s)
Post-main sequence evolution of > 30M☉ stars
Tip of the red giant branch
Neutron star (~few years)
Our sun
White dwarf
Brown dwarf
Jupiter-like planet
Earth
T_c(K)
T_c(keV)
ρ_c (g cm^{-3})
10^0 10^2 10^4 10^6 10^8 10^{10} 10^{12} 10^{14}
10^3 10^4 10^5 10^6 10^7 10^8 10^9
10^{-4} 10^{-3} 10^{-2} 10^{-1} 10^0 10^1 10^2

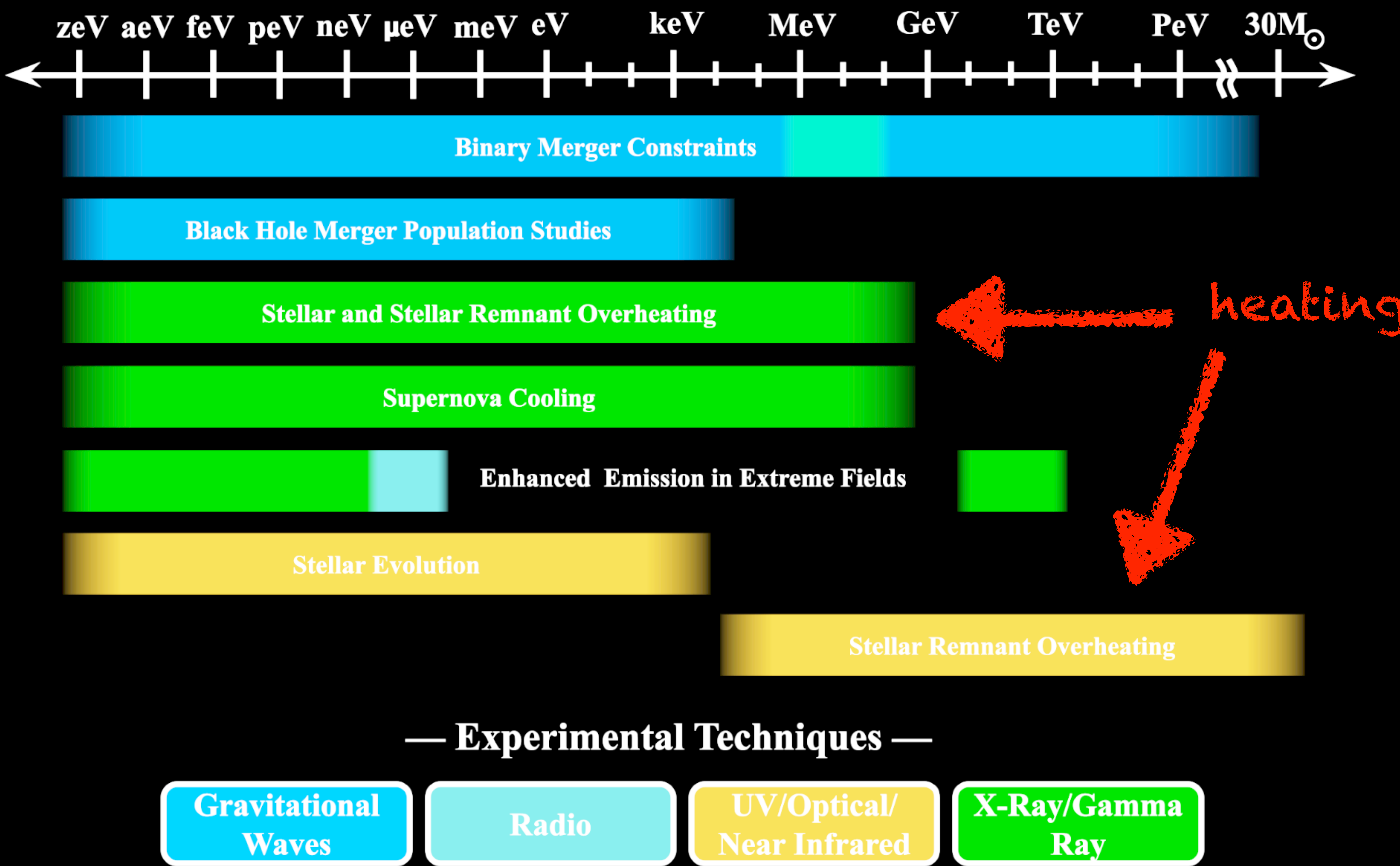
Dark matter?

Dark matter?

Defined as matter which does not interact (appreciably) with Standard Model matter (may or may not saturate relic abundance)



Baryakhtar, Caputo, DC, Perez et all, SNOWMASS summer study, arXiv:2203.07984 , arXiv:2209.08215



Baryakhtar, Caputo, DC, Perez et all, SNOWMASS summer study, arXiv:2203.07984 , arXiv:2209.08215

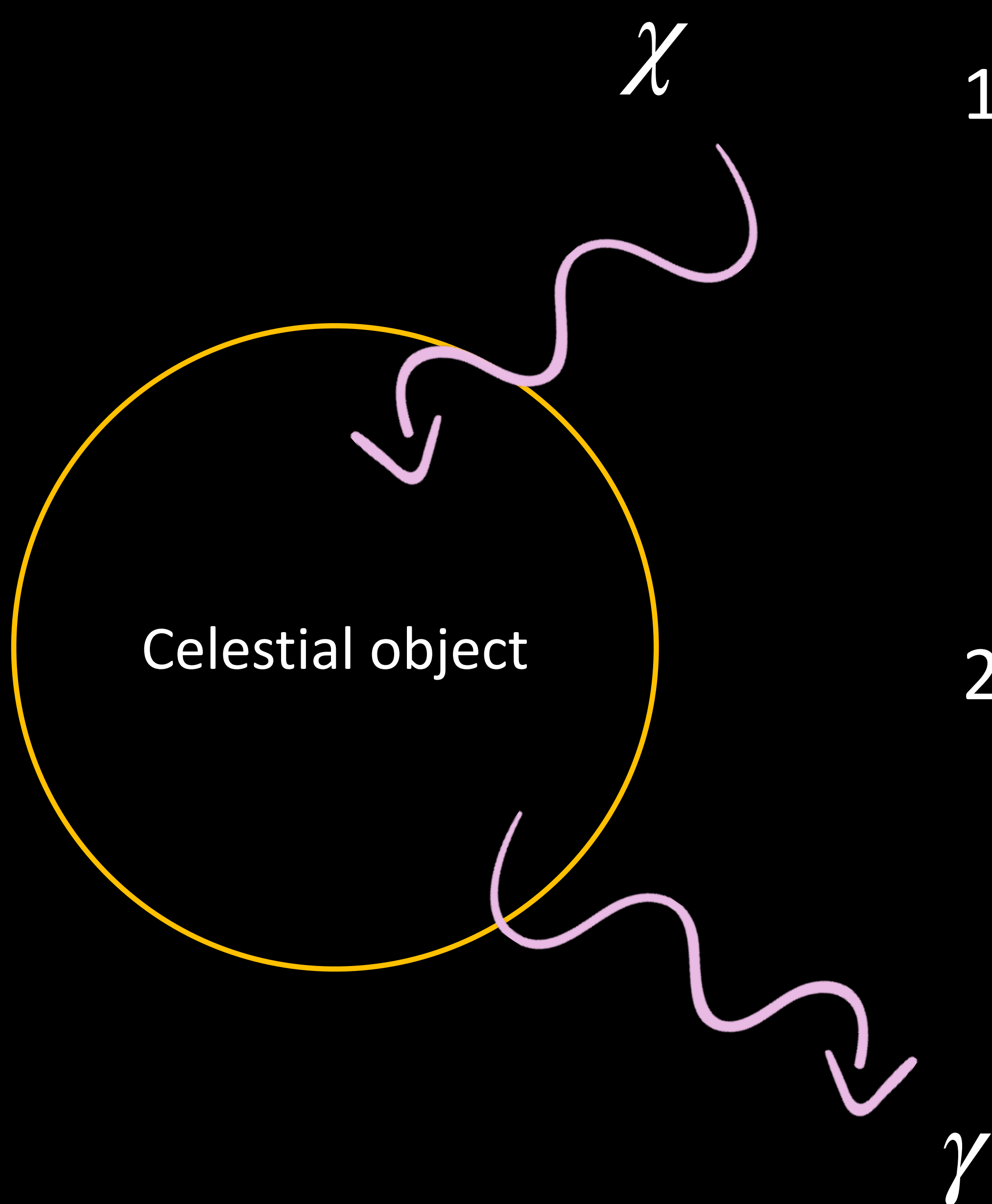
Dark matter heating

- Relevant for celestial objects without nuclear burning
- Sensitive to DM abundance ✓ & ✘

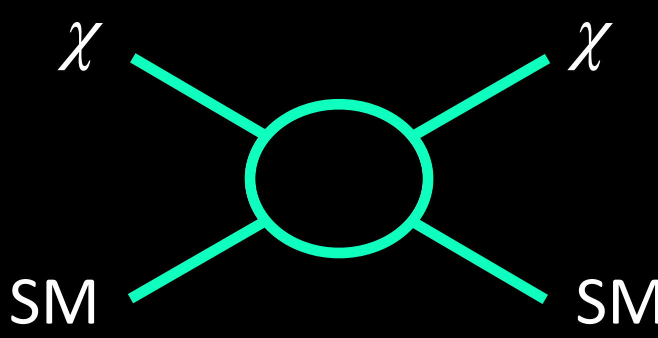
Type of DM	signal	mass range	coupling range
DM with scattering and annihilation processes	Stars and planets overheating, or producing gamma rays/neutrinos	$\gtrsim \mathcal{O}(\text{keV})$ (depending on object and particle model)	$\sigma_{n\chi} \gtrsim 10^{-47}$ cm^2 (depending on object and particle model)
DM mixing with neutrons	NS overheating	$\lesssim 1.5$ GeV	$10^{-17} \leq \epsilon_{nn'}/\text{eV} \leq 10^{-9}$

Baryakhtar, Caputo, DC, Perez et all, SNOWMASS summer study, arXiv:2203.07984 , arXiv:2209.08215

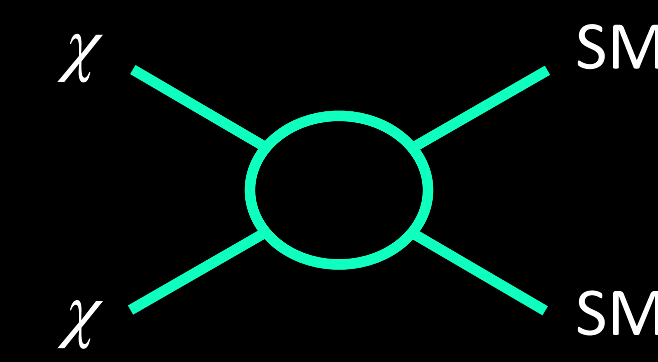
Dark matter heating



1. Capture



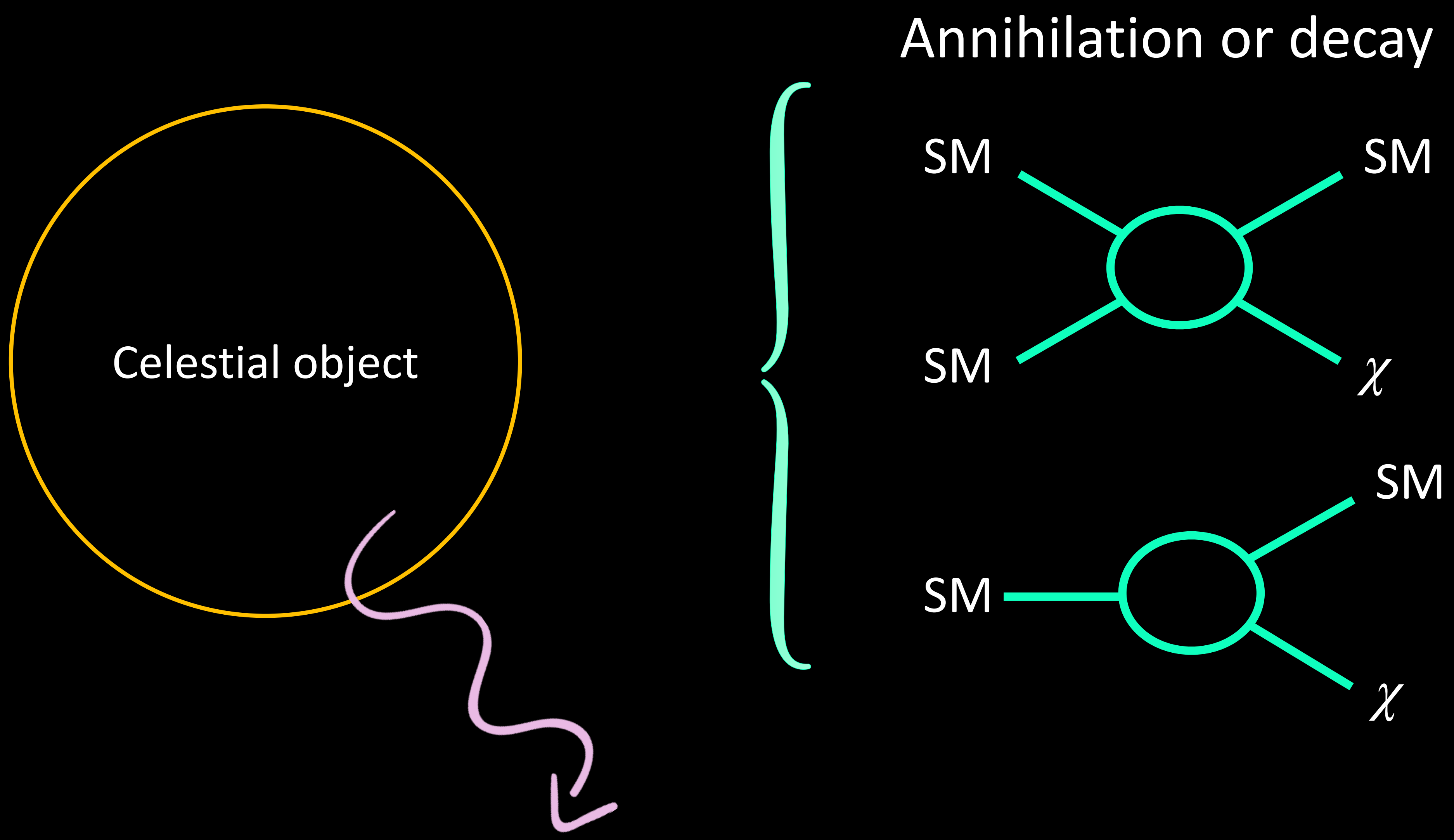
2. Annihilation



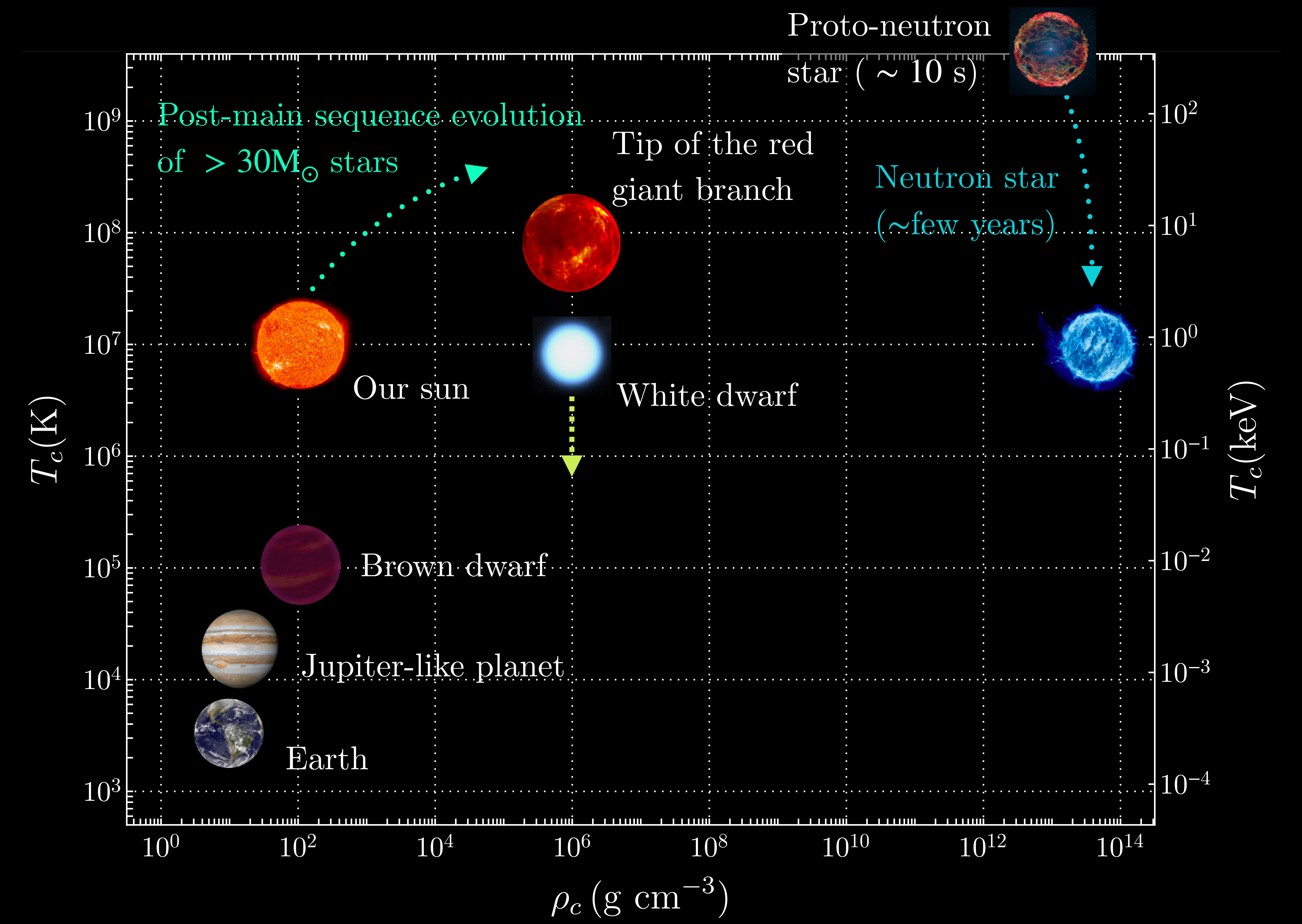
Sensitive to DM abundance ✓

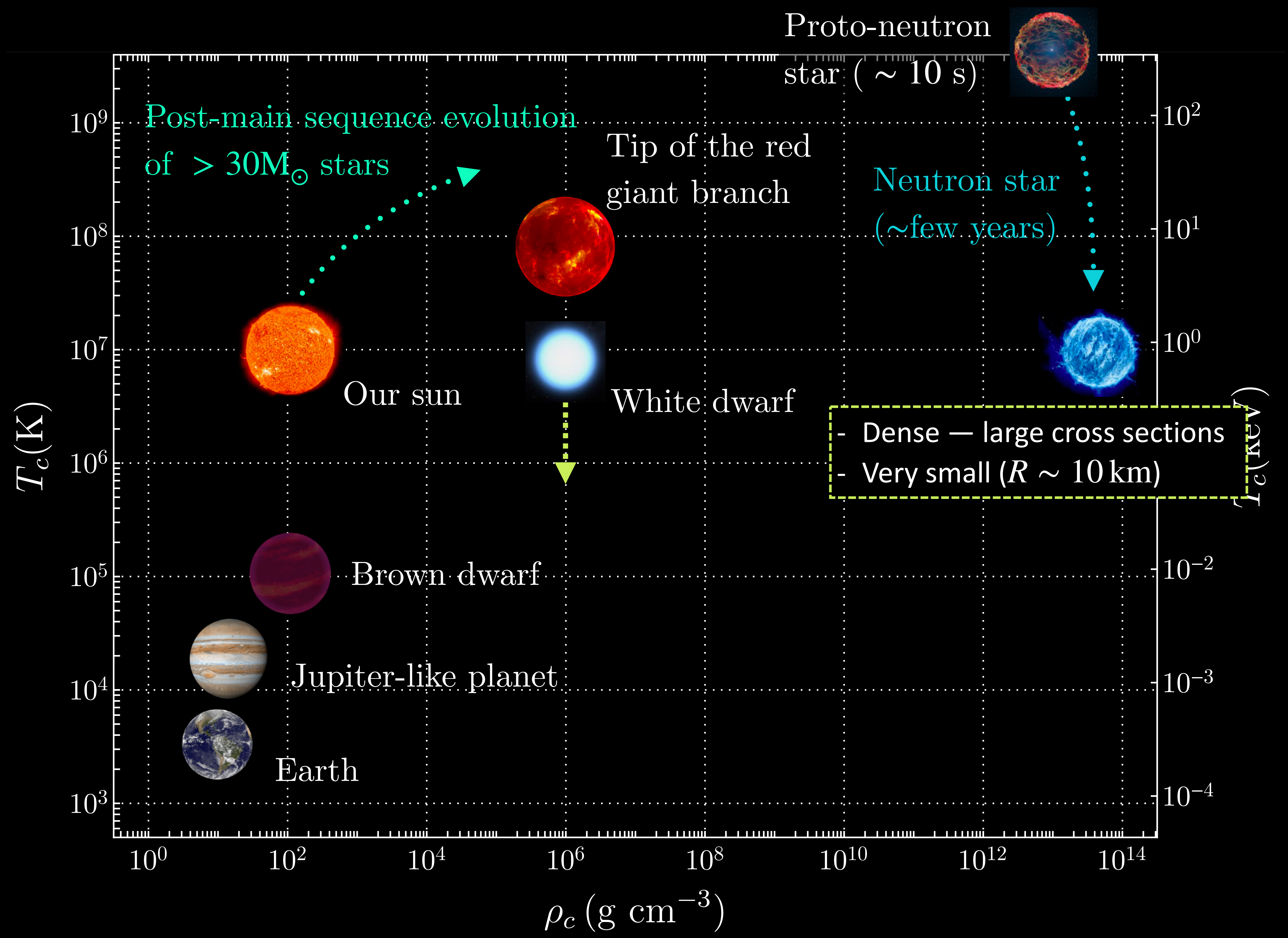
Maximum injection for a non-depleting abundance: annihilation equilibrium

Dark matter heating



Sensitive to DM abundance ✗


Proto-neutron star (~ 10 s)
Post-main sequence evolution of > 30M⊙ stars
Tip of the red giant branch
Neutron star (~few years)
Our sun
White dwarf
Brown dwarf
Jupiter-like planet
Earth
T_c(K)
T_c(keV)
ρ_c (g cm^{-3})
10^3 10^4 10^5 10^6 10^7 10^8 10^9
10^{-4} 10^{-3} 10^{-2} 10^{-1} 10^0 10^1 10^2
10^0 10^2 10^4 10^6 10^8 10^{10} 10^{12} 10^{14}



Proto-neutron star (∼ 10 s)
Post-main sequence evolution of > 30M⊙ stars
Tip of the red giant branch
Neutron star (∼few years)
Our sun
White dwarf
Dense — large cross sections
Very small (R ∼ 10 km)
Brown dwarf
Jupiter-like planet
Earth
T_c(K)
T_c(keV)
ρ_c (g cm^{-3})
10^9
10^8
10^7
10^6
10^5
10^4
10^3
10^2
10^1
10^0
10^{-2}
10^{-3}
10^{-4}
10^0
10^2
10^4
10^6
10^8
10^{10}
10^{12}
10^{14}

Neutron star heating: the Auger effect

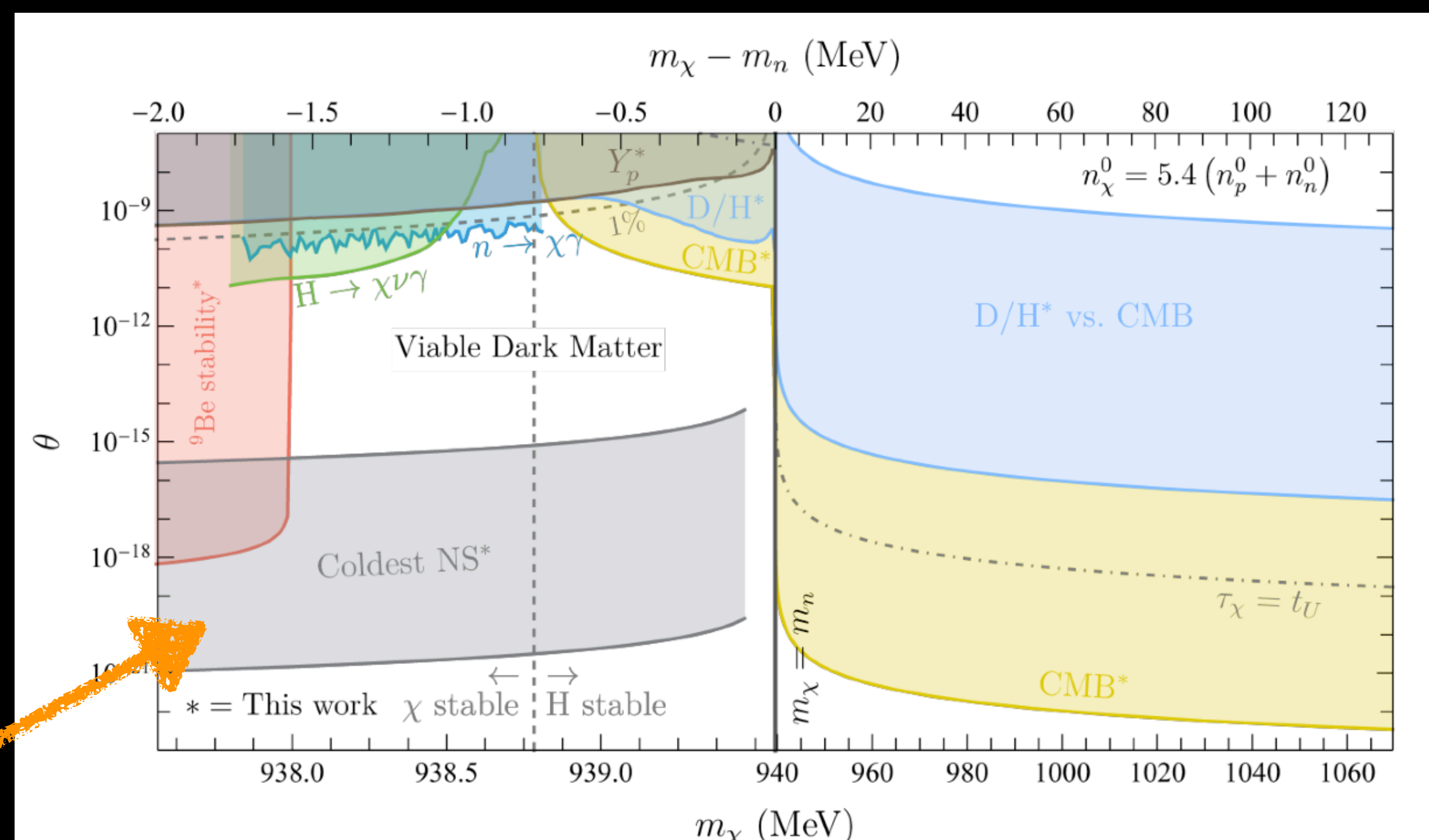
''Dark neutrons'' carrying baryon number
- suggested in mirror models
- can explain the neutron lifetime anomaly

Elementary or composite
e.g. Fornal & Grinstein, PRL 2018
Berezhiani, Eur Phys J C, 2019

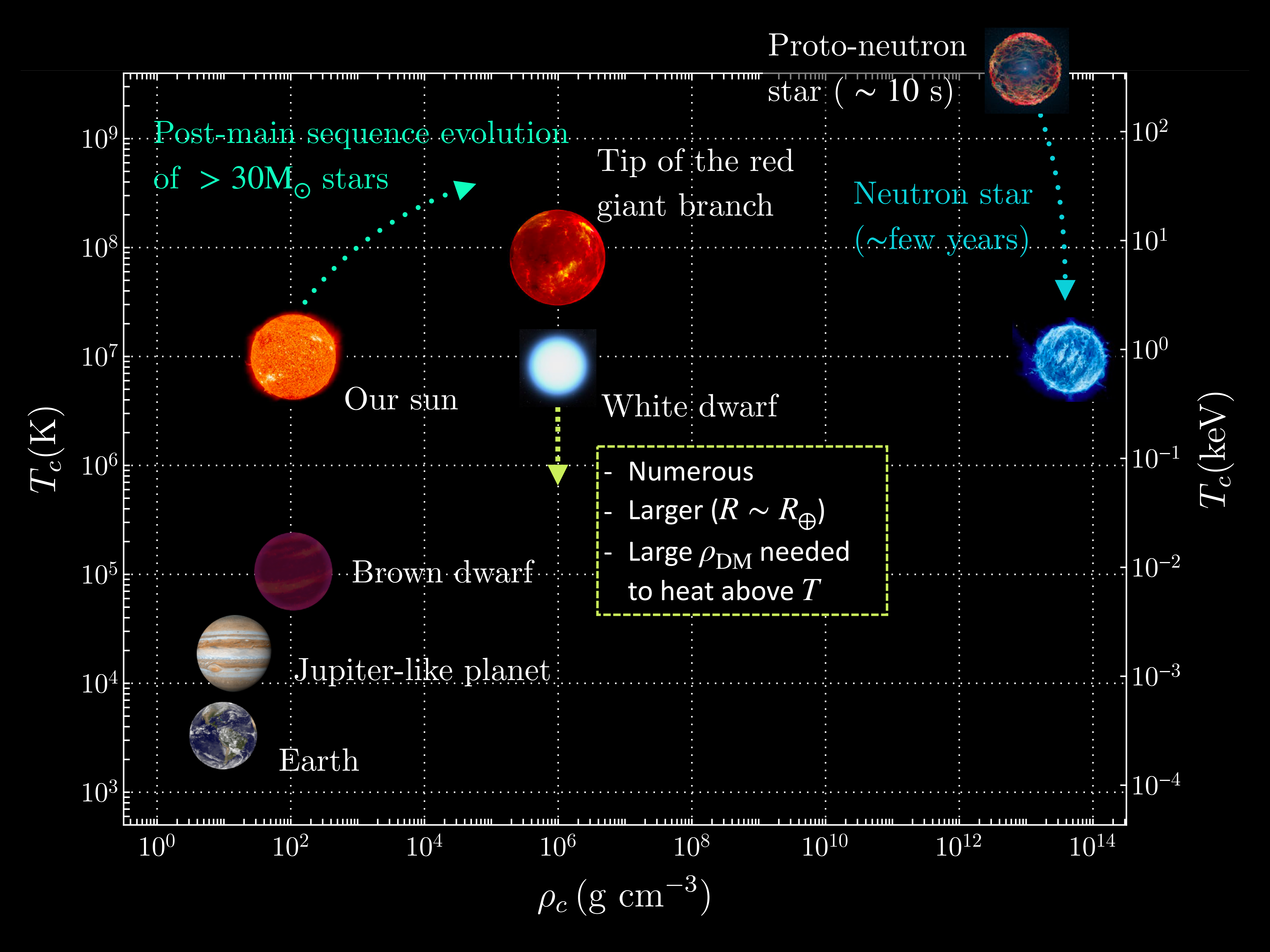
In neutron stars:
- $nN \to \chi N$
- $n \to \chi\gamma$

Depending on the rates
- soften the EOS
- overheat the NS: the nucleon Auger effect

PSR J2144−3933



McKeen, Pospelov, Raj, PRD, 2012.09865

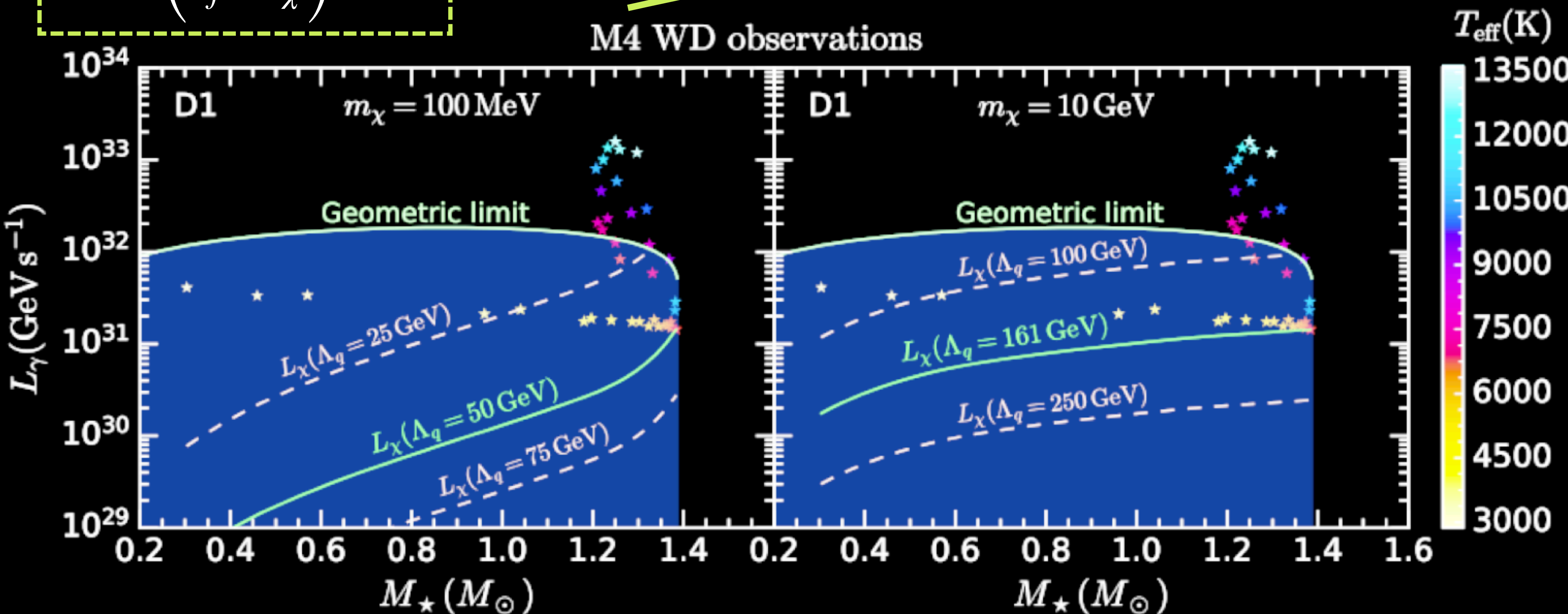


Proto-neutron
star (~ 10 s)
Post-main sequence evolution
of > 30M⊙ stars
Tip of the red
giant branch
Neutron star
(~few years)
Our sun
White dwarf
- Numerous
- Larger (R ~ R⊕)
- Large ρDM needed
to heat above T
Brown dwarf
Jupiter-like planet
Earth
Tc(K)
Tc(keV)
ρc (g cm−3)

Bell, Busoni, Ramirez-Quezada, Robles, Viriato, JCAP, arXiv:2104.14367

White dwarf heating

$\mathrm{D1}:\left(y_f/\Lambda_\chi^2\right)\bar{\chi}\chi\bar{f}f$



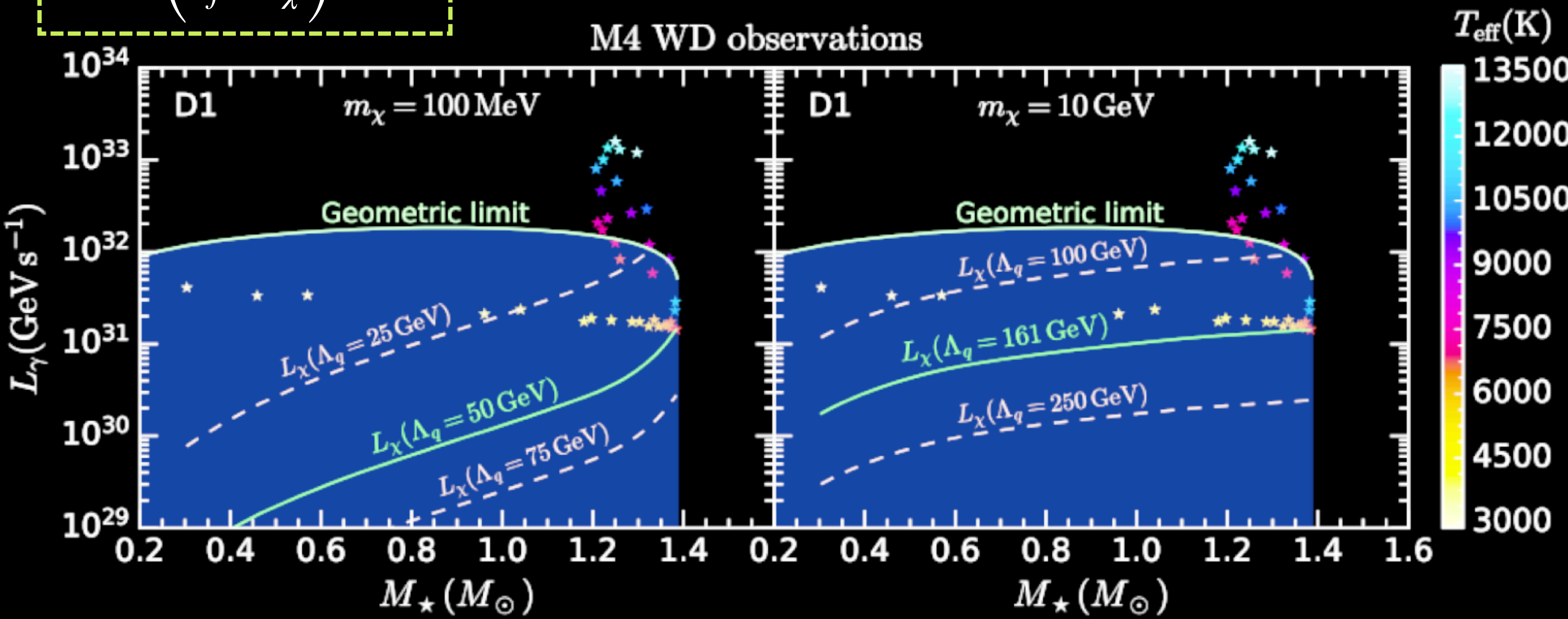
Messier 4, assumed to be in a DM subhalo

$\rho_\chi = 798\,\mathrm{GeV\,cm^{-3}}$

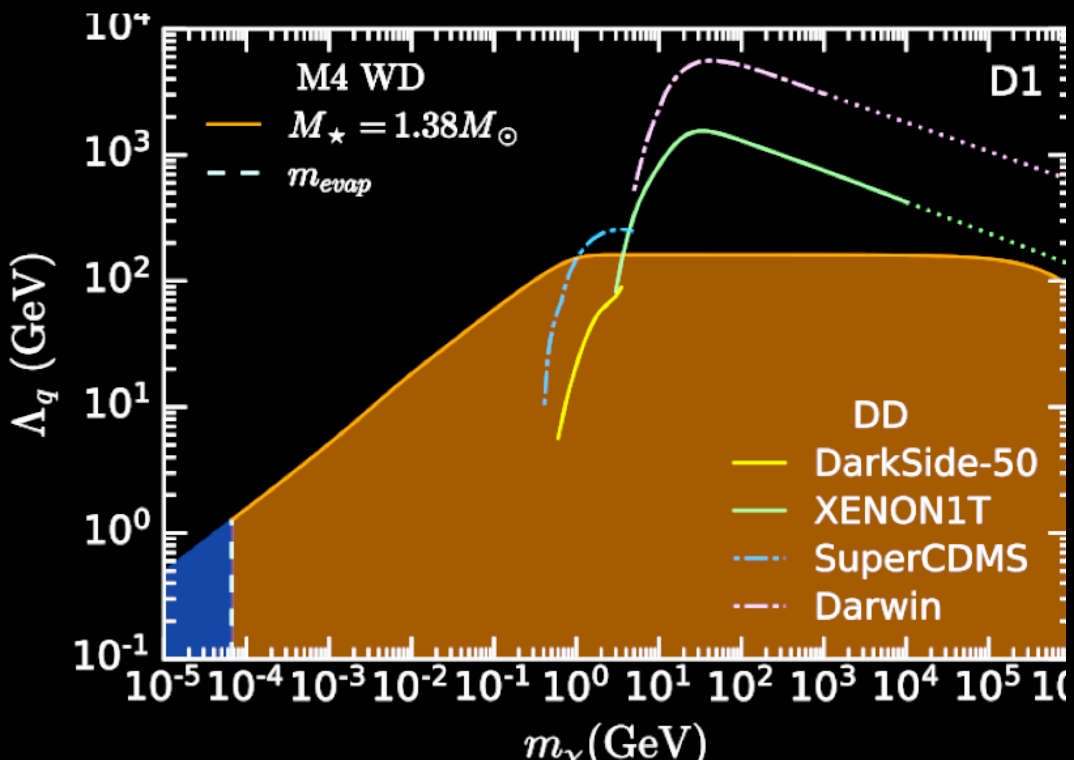
Bell, Busoni, Ramirez-Quezada, Robles, Viriato, JCAP, arXiv:2104.14367

White dwarf heating

$$\mathrm{D1}: \left(y_f/\Lambda_\chi^2\right)\bar{\chi}\chi\bar{f}f$$



$$\rho_\chi = 798\,\mathrm{GeV\,cm^{-3}}$$



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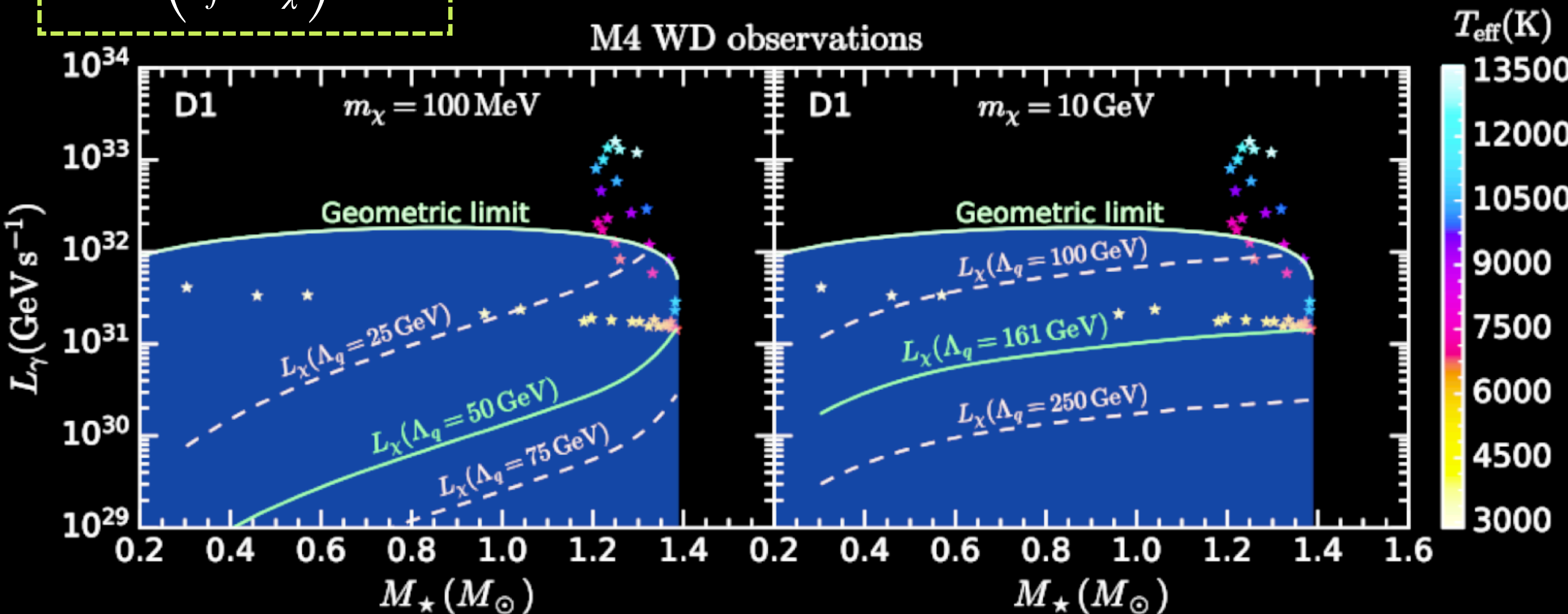

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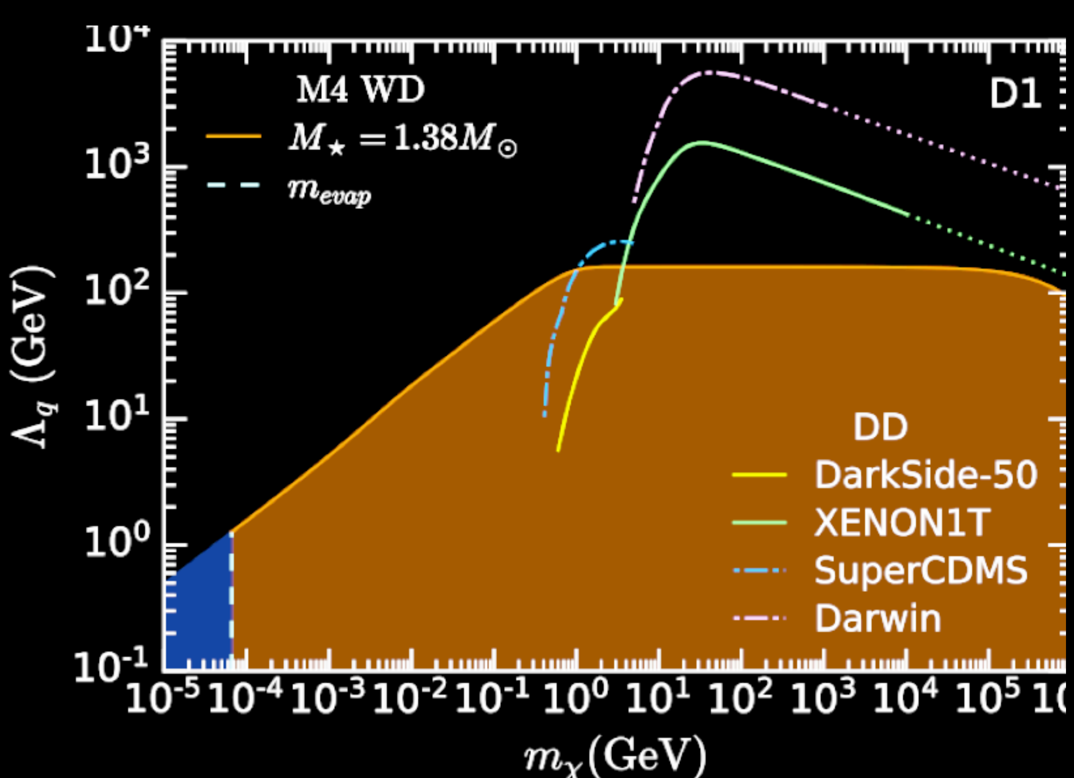

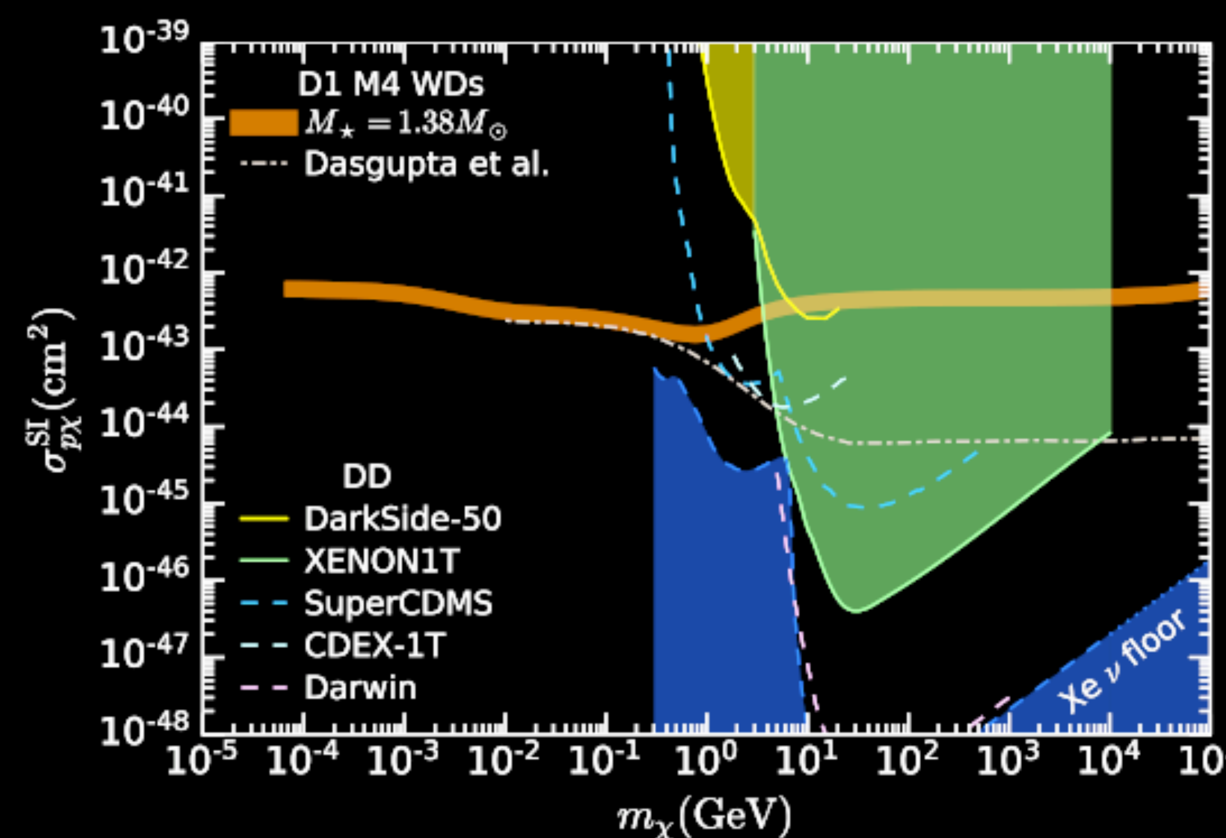

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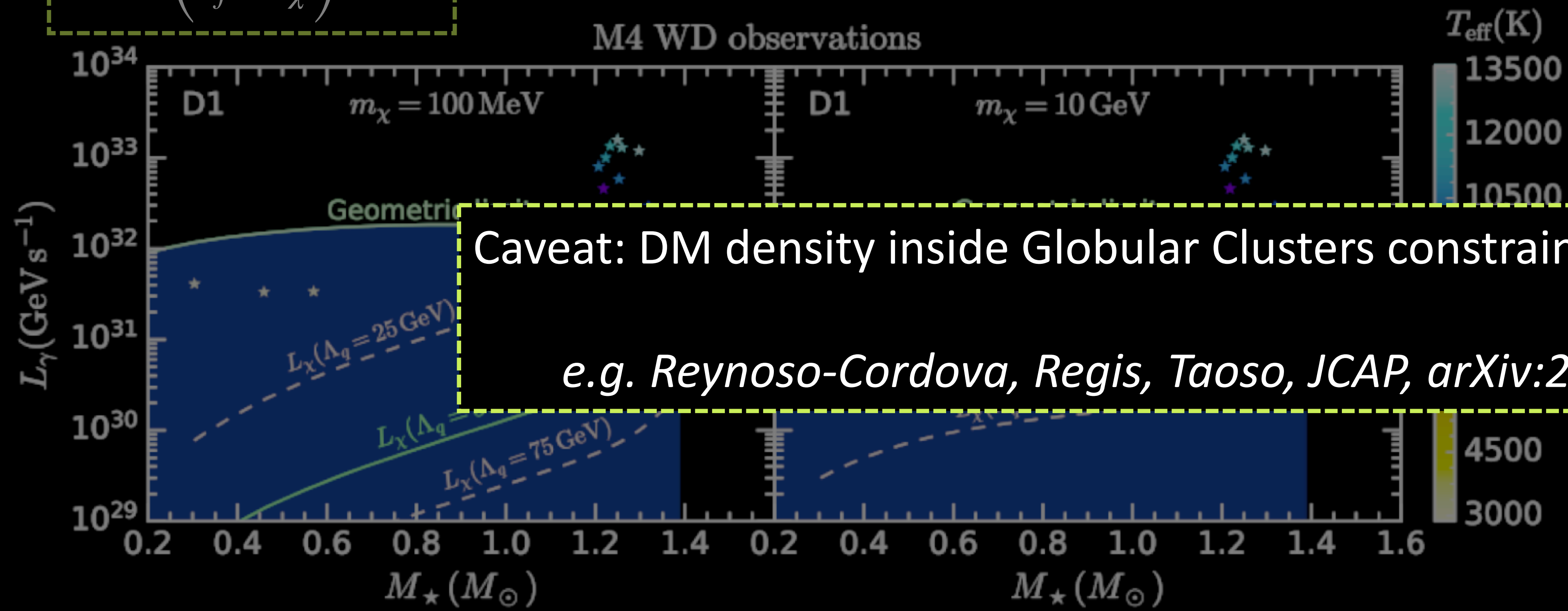
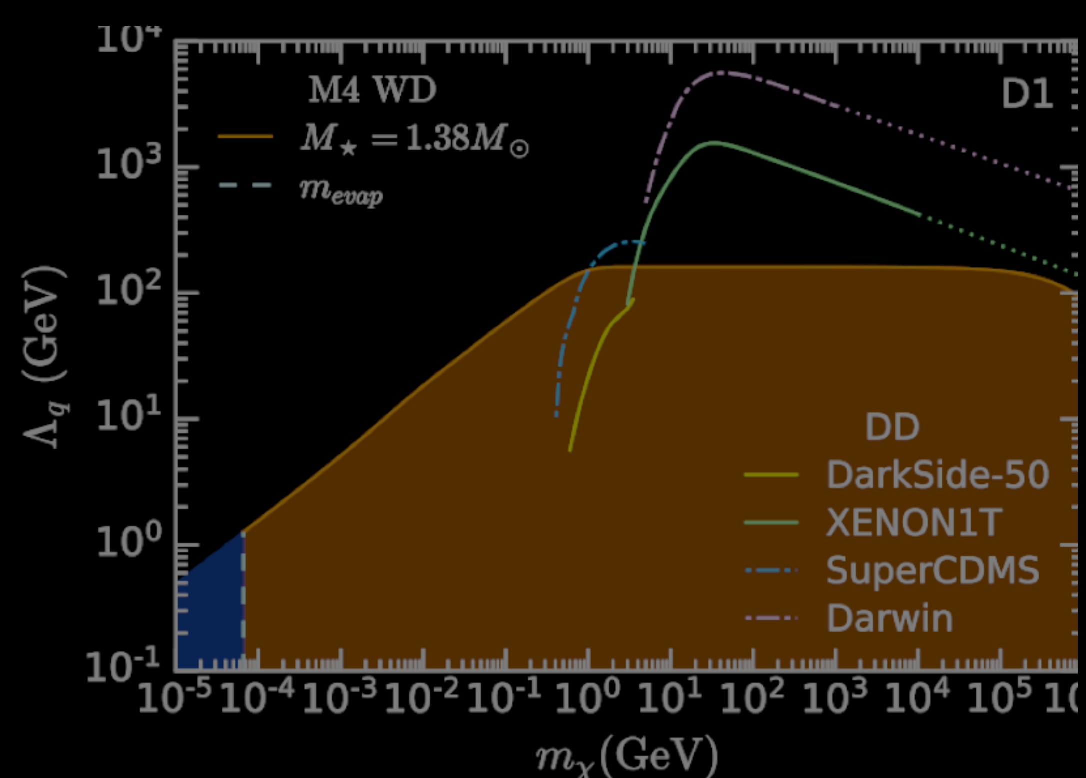
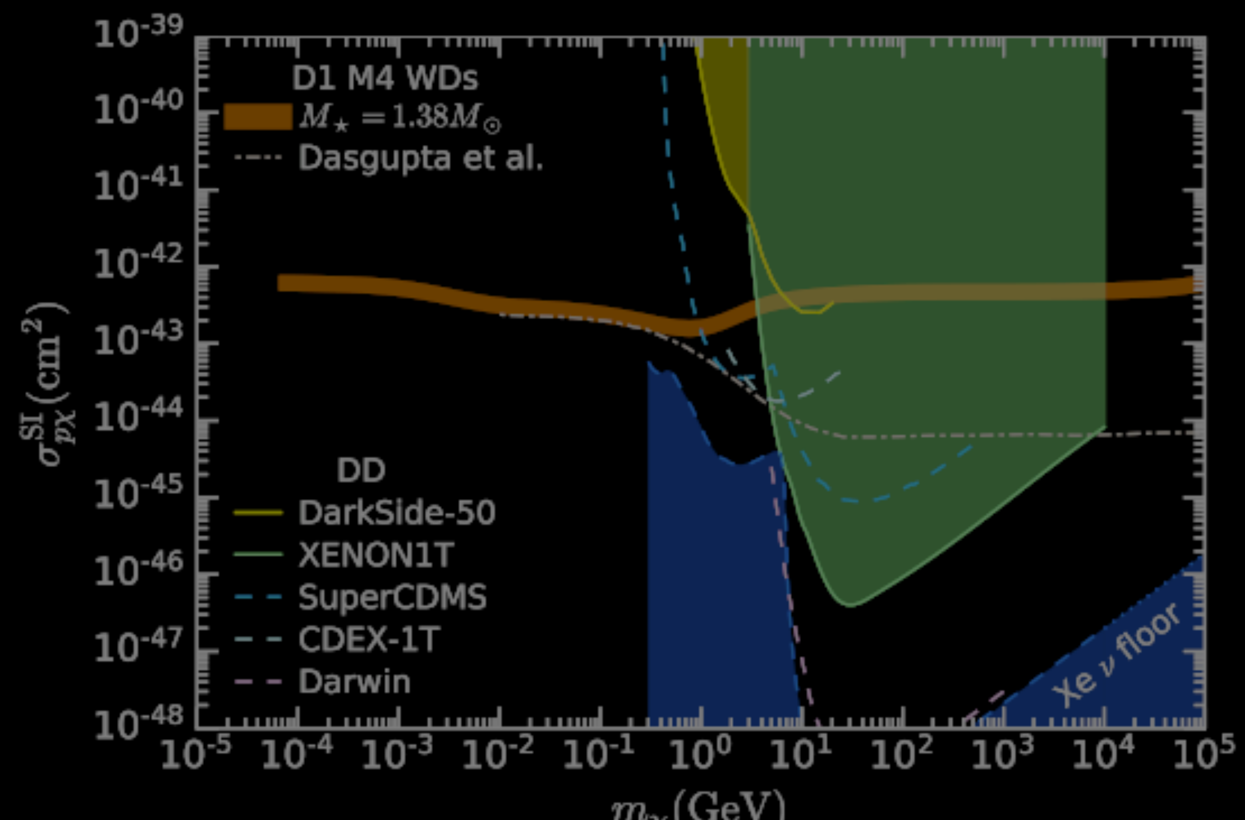


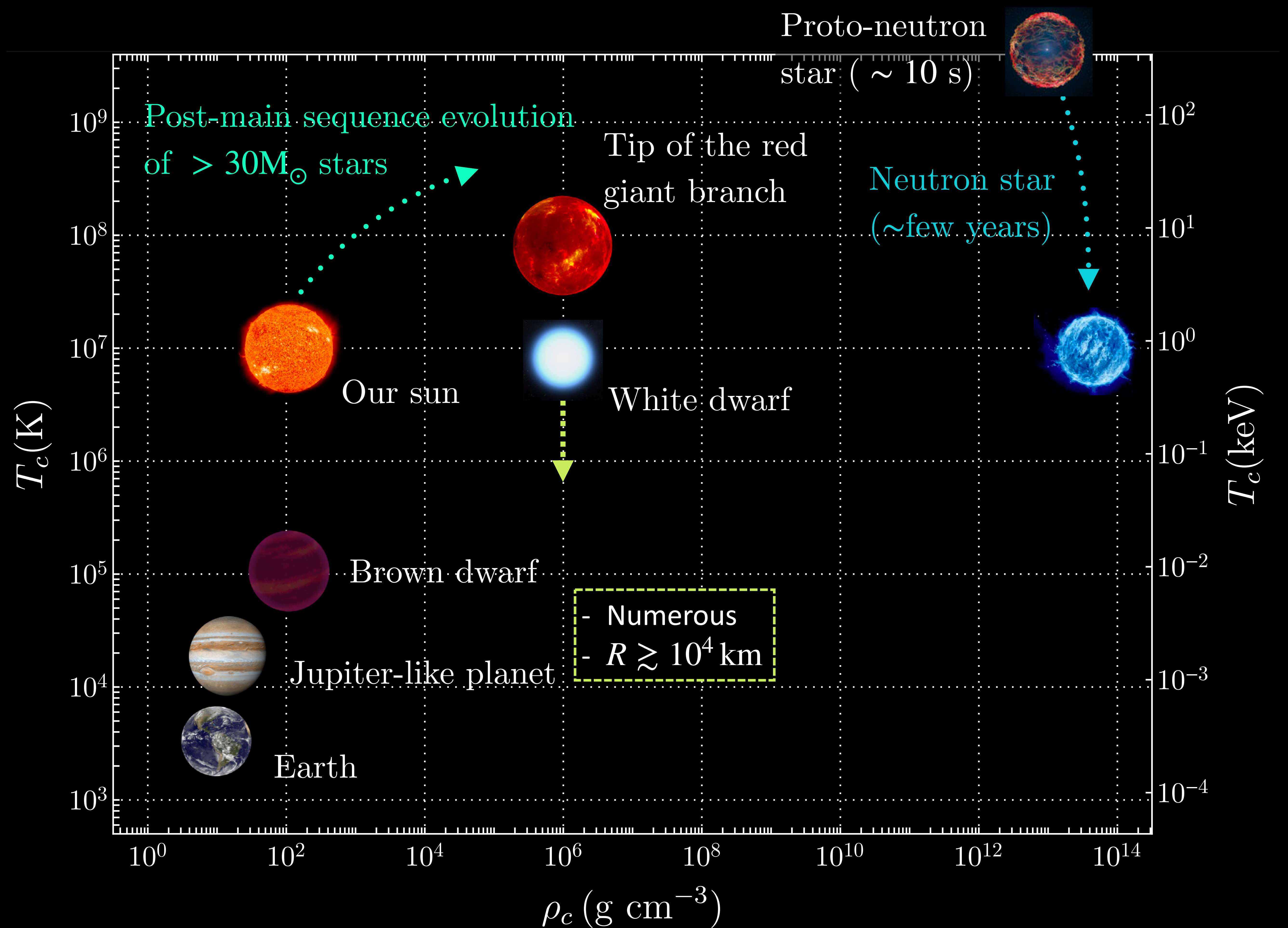
Caveat: DM density inside Globular Clusters constrained from above

e.g. Reynoso-Cordova, Regis, Taoso, JCAP, arXiv:2203.13735

$\rho_\chi = 798\,\mathrm{GeV\,cm^{-3}}$







Proto-neutron
star (~ 10 s)
Post-main sequence evolution
of > 30M$_\odot$ stars
Tip of the red
giant branch
Neutron star
(~few years)
Our sun
White dwarf
Brown dwarf
- Numerous
- $R \gtrsim 10^4$ km
Jupiter-like planet
Earth
T_c(K)
T_c(keV)
ρ_c (g cm^{-3})
10^9
10^8
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10^6
10^5
10^4
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10^2
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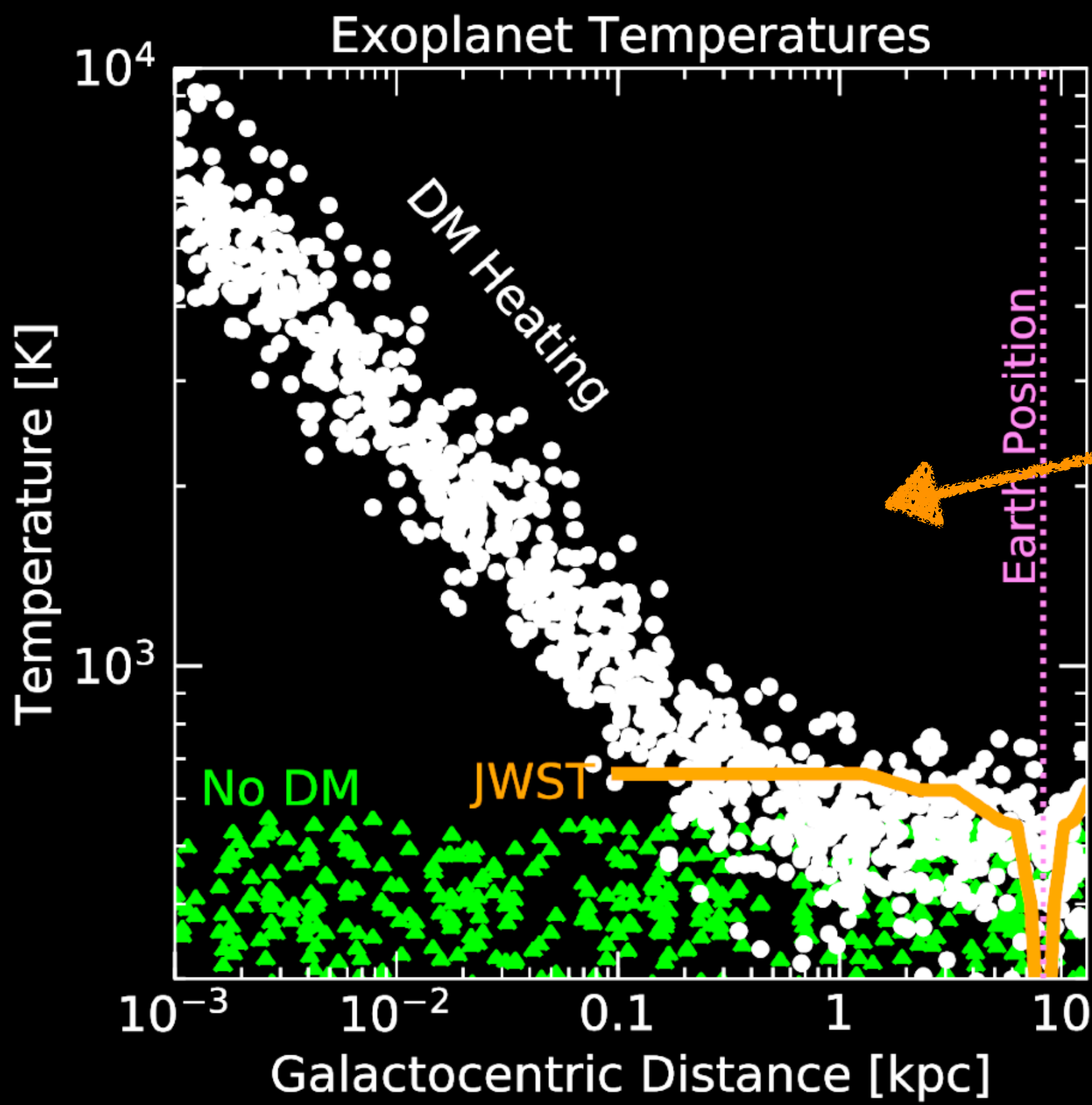
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^0 10^2 10^4 10^6 10^8 10^{10} 10^{12} 10^{14}

Exoplanet heating

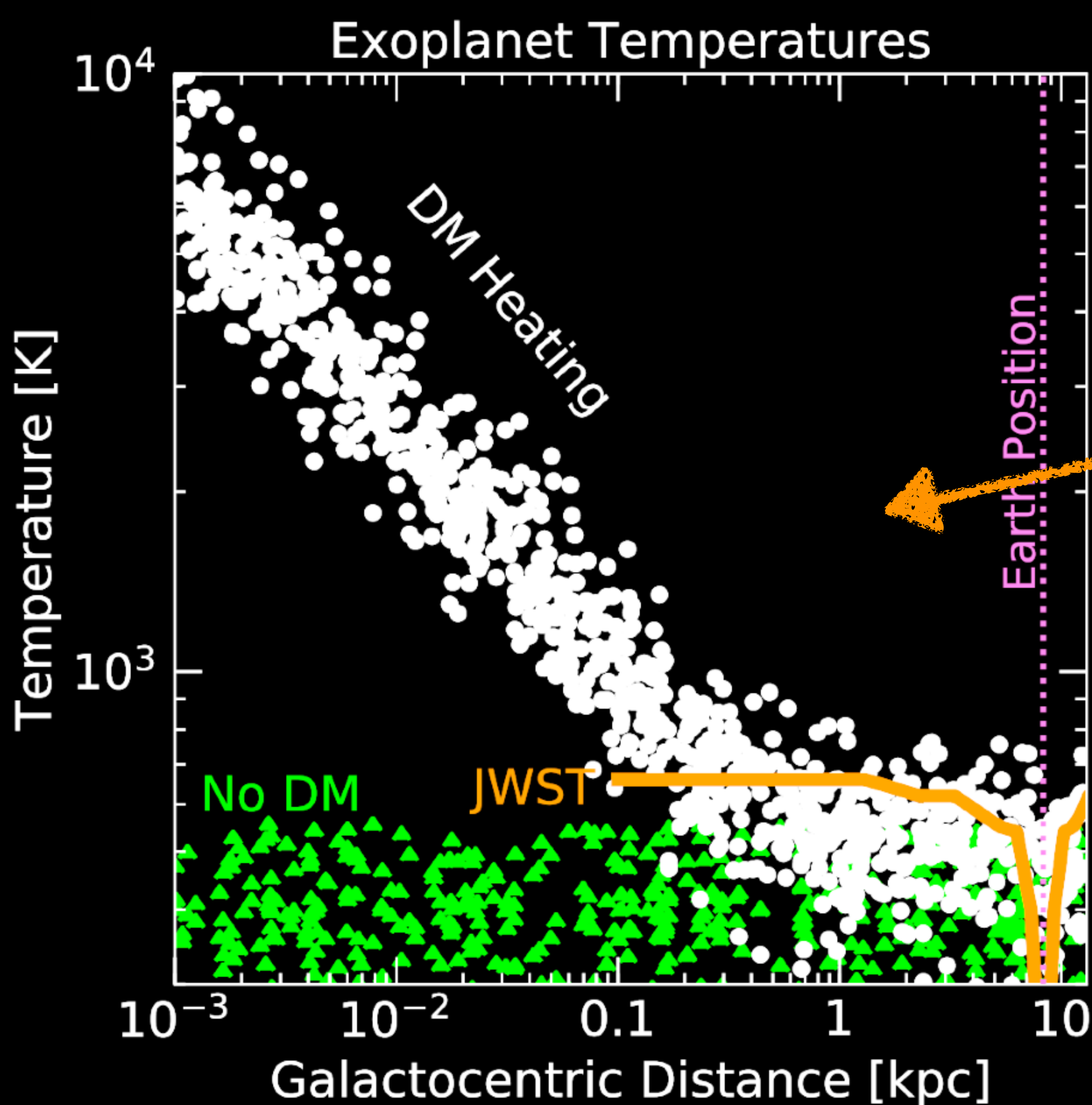


- First be identified by e.g. Doppler spectroscopy or gravitational lensing
- Infrared telescopes (such as JWST) may be able to measure their temperature

Assumption:
annihilation equilibrium

Leane and Smirnov, PRD, arXiv:2010.00015

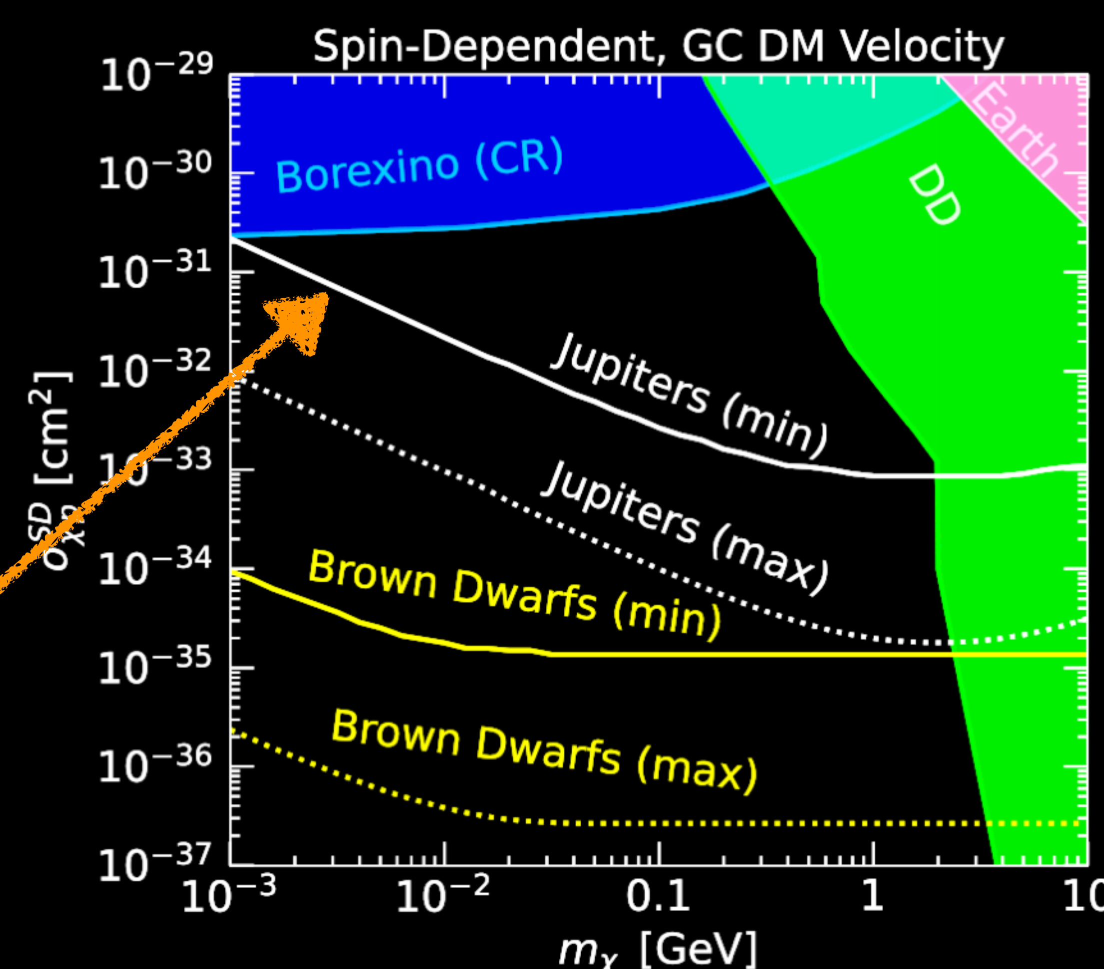
Exoplanet heating



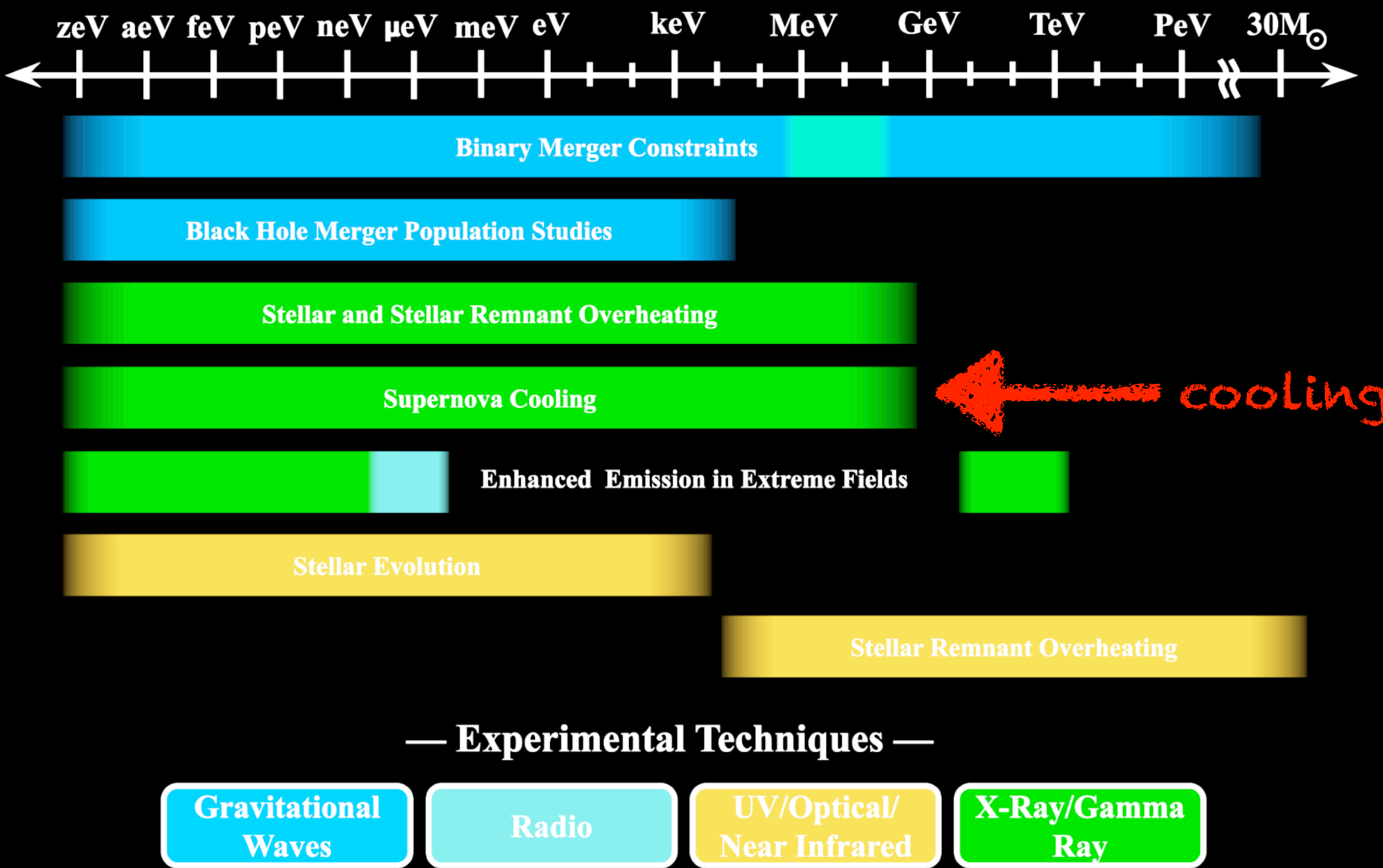
- First be identified by e.g. Doppler spectroscopy or gravitational lensing
- Infrared telescopes (such as JWST) may be able to measure their temperature

Assumption: annihilation equilibrium

all DM captured



Leane and Smirnov, PRD, arXiv:2010.00015



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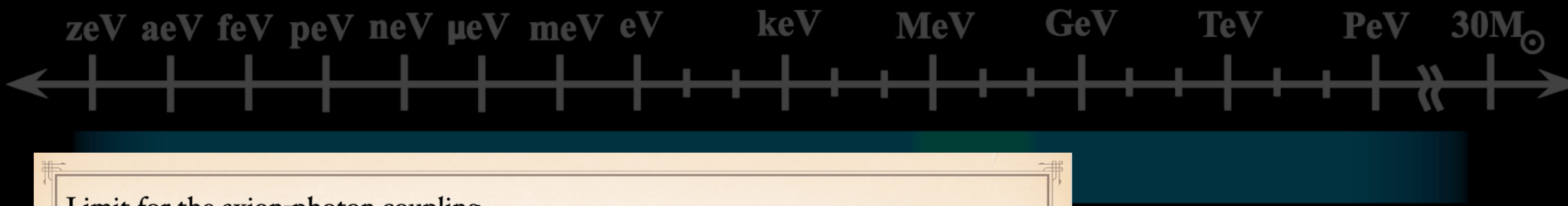
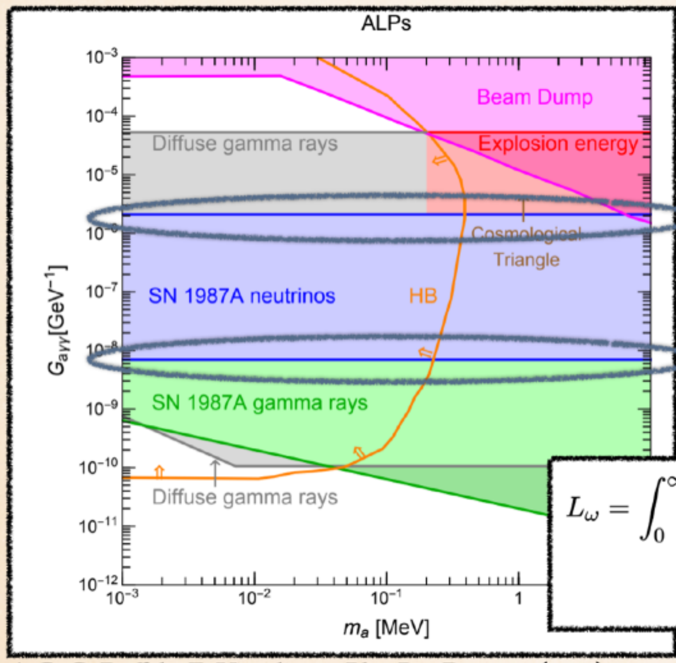


Limit for the axion-photon coupling



The duration of several seconds of the SN 1987A neutrino signal is incompatible with excessive energy loss in hypothetical new forms of radiation such as muon-philic scalars.

Trapping regime

Free streaming regime

$$L_\omega = \int_0^\infty dr\, 4\pi r^2\, Q_\omega(r)\, \underbrace{\frac{1}{2}\int_{-1}^{+1} d\cos\beta\, \exp\left[-\int_0^\infty \frac{ds}{\lambda_\omega\left(\sqrt{r^2+s^2+2rs\cos\beta}\right)}\right]}_{\mathrm{T}_\omega(r) = \langle e^{-\tau_{\omega,\mu}(r)}\rangle_{\mathrm{angles}}}.$$

Energy production rate

A.C, G. Raffelt, E. Vitagliano, *Phys.Rev.D* 105 (2022) 3, 035022
G. Lucente, et al, *JCAP* 12(2020) 008

A.C, G. Raffelt, E. Vitagliano, *JCAP* 08(2022)08,045

← cooling

Andrea Caputo's talk

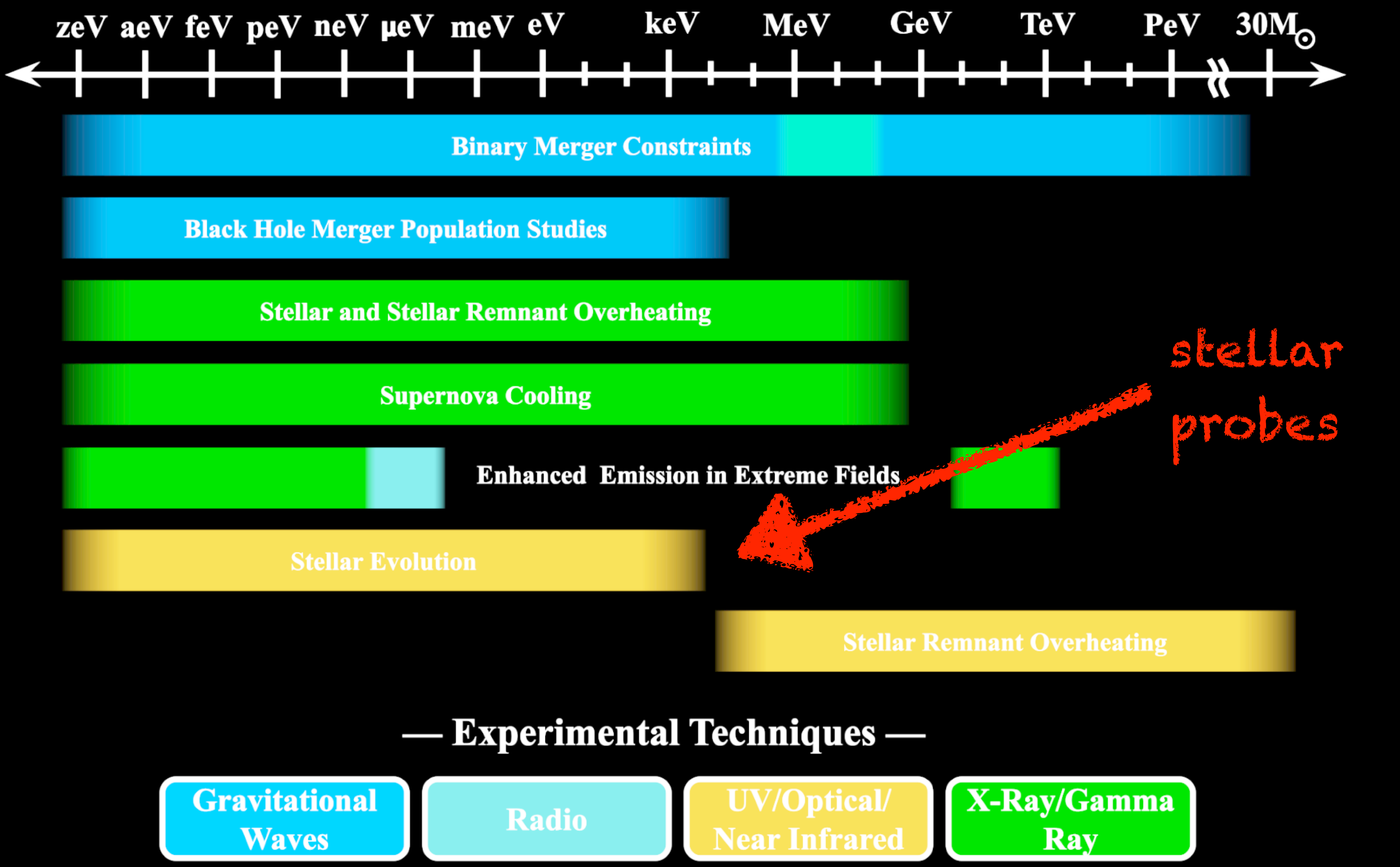
+ Gamma ray bursts, low energy supernovae

Stellar Remnant Overheating

— Experimental Techniques —

Gravitational Waves | Radio | UV/Optical/ Near Infrared | X-Ray/Gamma Ray

Baryakhtar, Caputo, DC, Perez et all, SNOWMASS summer study, arXiv:2203.07984 , arXiv:2209.08215



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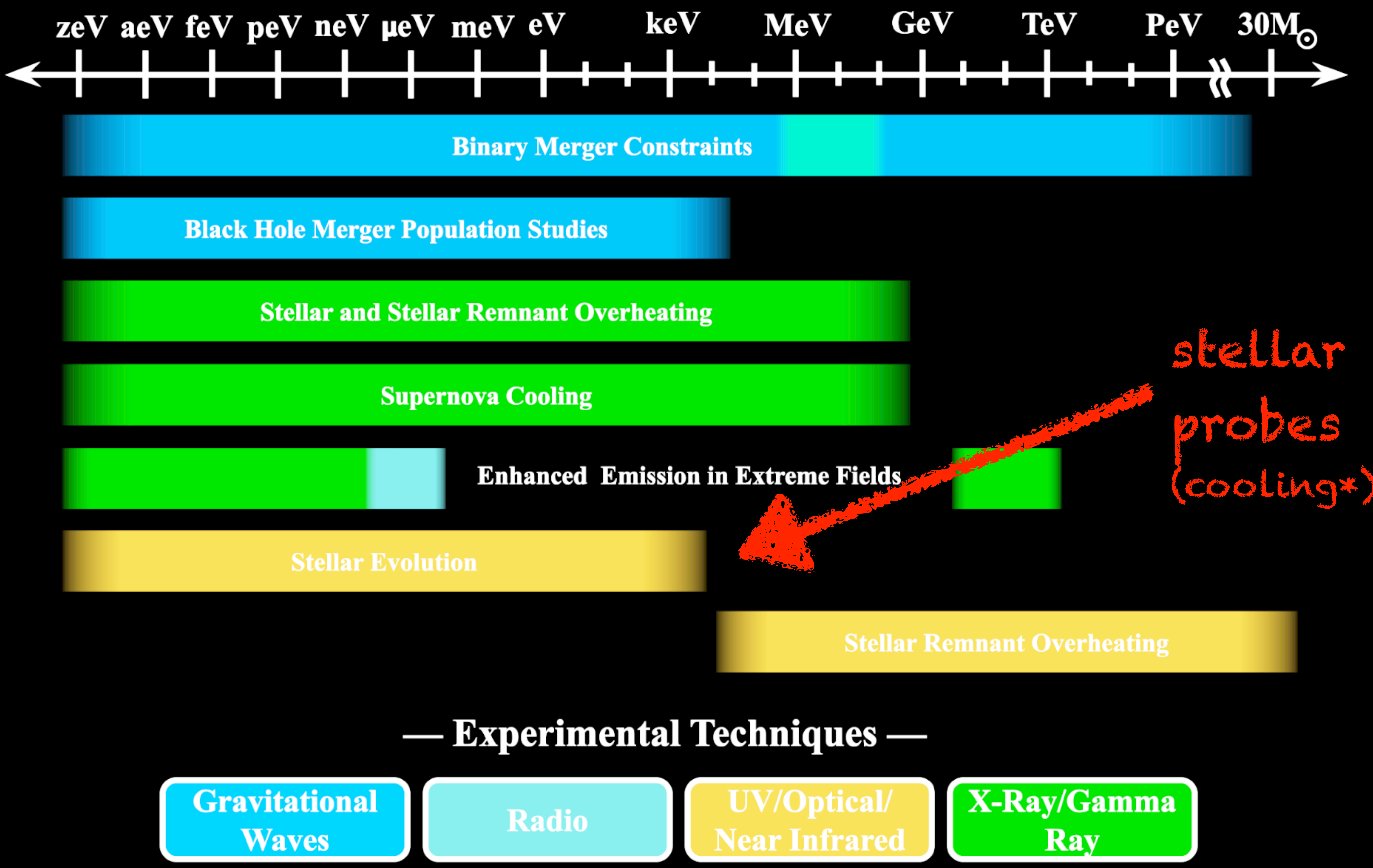

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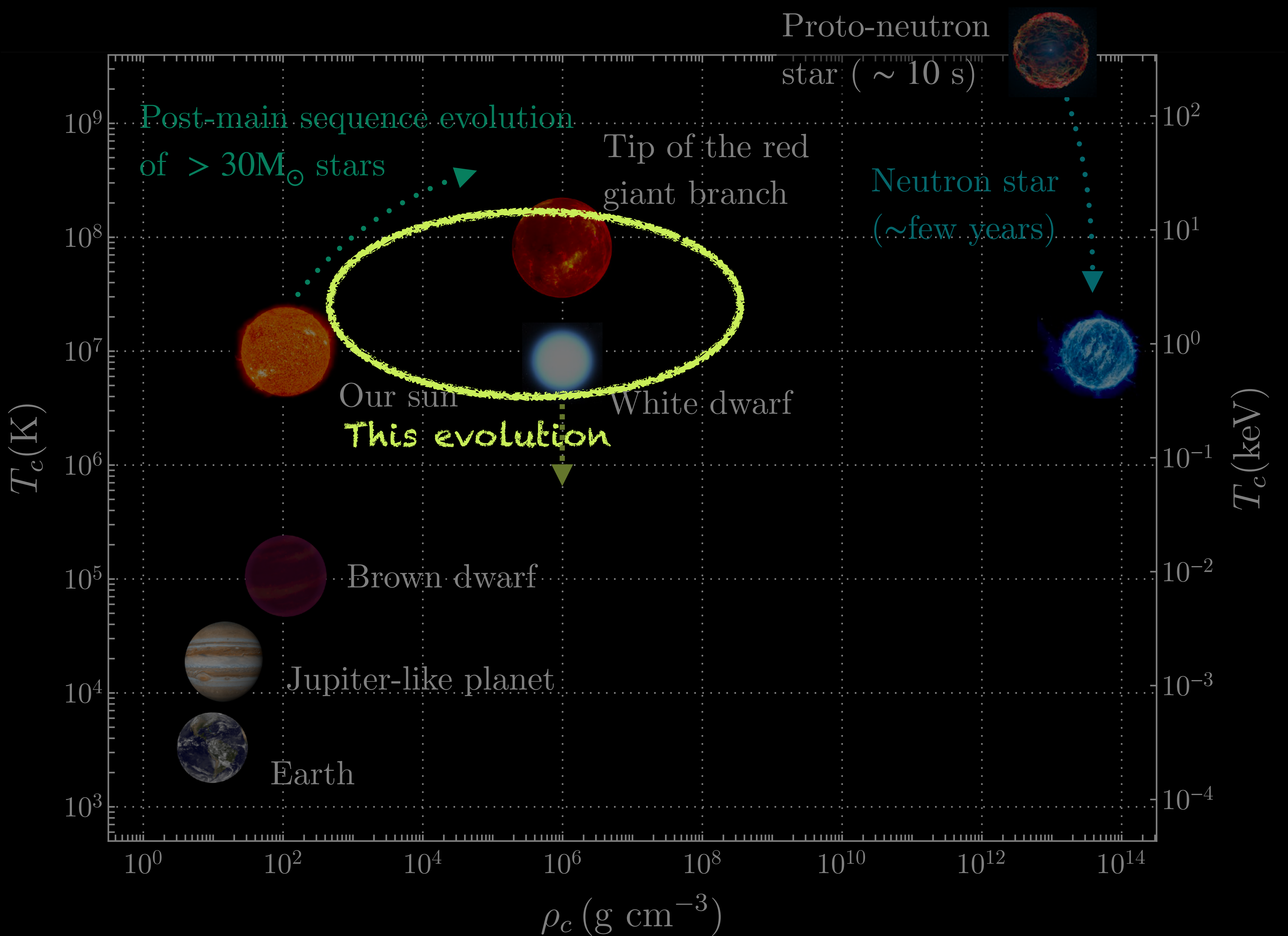

Proto-neutron star (~ 10 s)
Post-main sequence evolution of > 30M$_\odot$ stars
Tip of the red giant branch
Neutron star (~few years)
Our sun
This evolution
White dwarf
Brown dwarf
Jupiter-like planet
Earth
T_c(K)
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10^9
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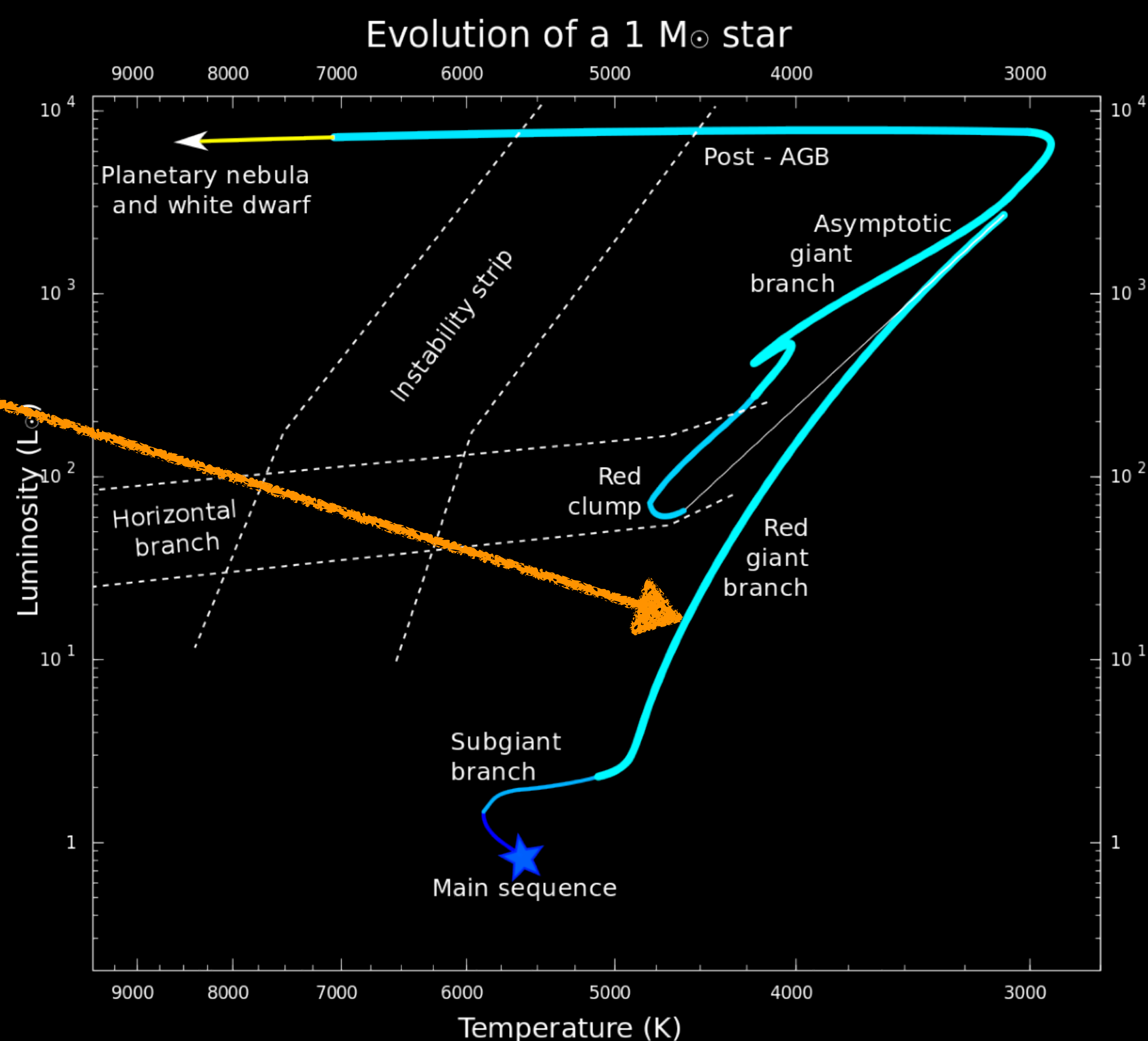
10^0 10^2 10^4 10^6 10^8 10^{10} 10^{12} 10^{14}

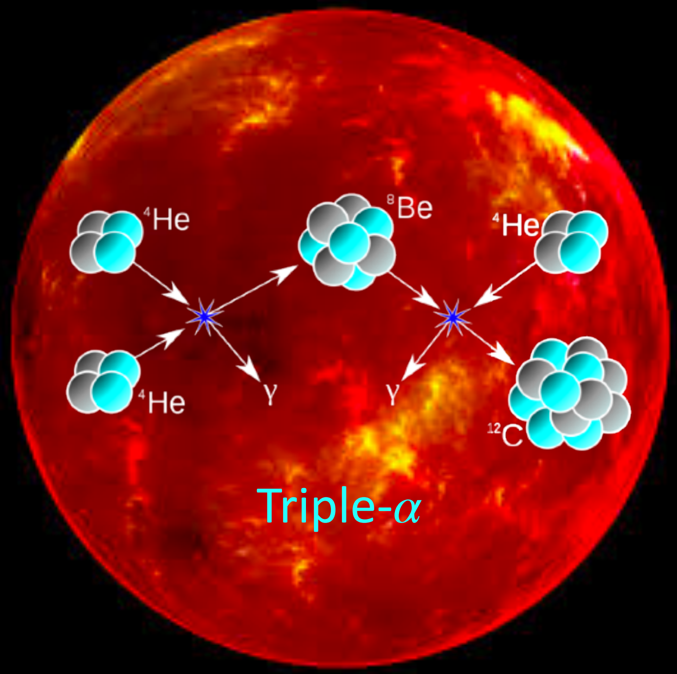
The tip of the red giant branch

Red giants:
- inert helium core
- hydrogen shell burning



Dearborn, Schramm & Steigman, PRL, 1986
Raffelt, ApJ, 1990
Raffelt & Capozzi, PRD, arXiv:2007.03694
Straniero et al., AA, arXiv:2010.03833
Plot: Ciaran O'Hare, axion limits

The tip of the red giant branch



Red giants: the helium flash

Dearborn, Schramm & Steigman, PRL, 1986
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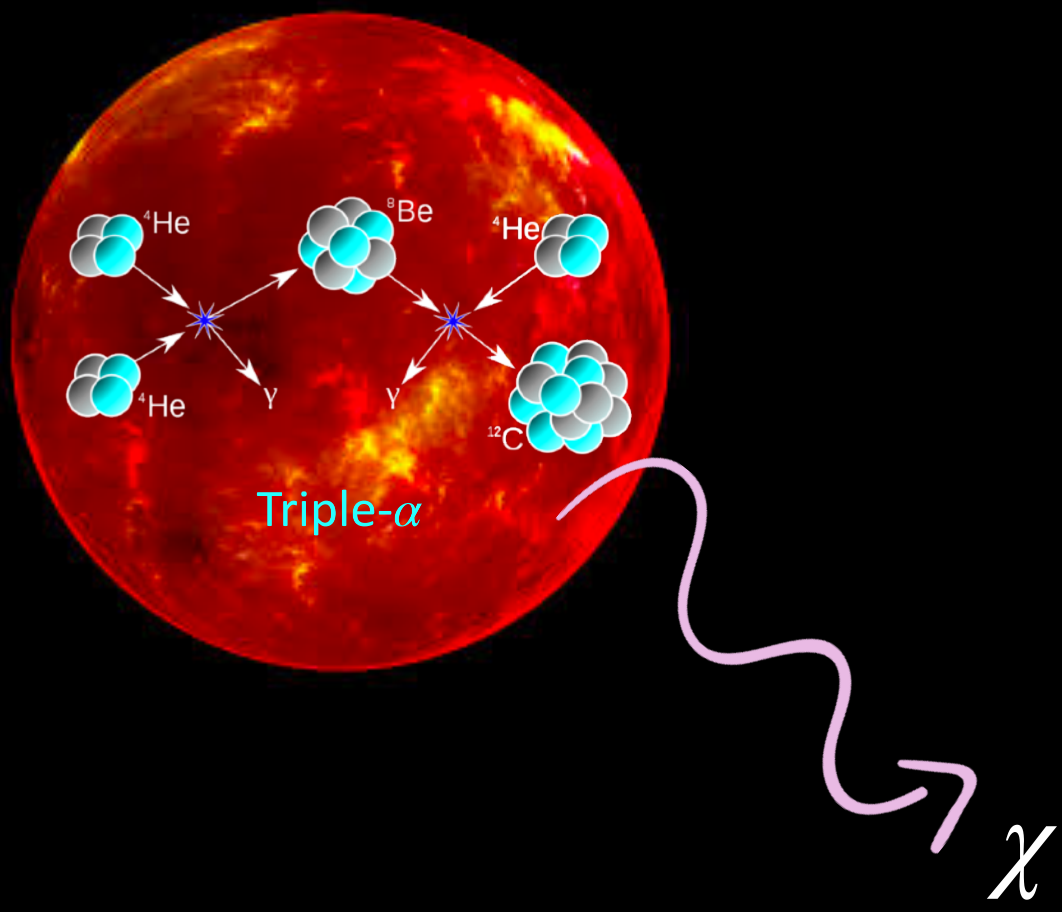
Plot: Ciaran O'Hare, axion limits

The tip of the red giant branch



Dearborn, Schramm & Steigman, PRL, 1986
Raffelt, ApJ, 1990
Raffelt & Capozzi, PRD, arXiv:2007.03694
Straniero et al., AA, arXiv:2010.03833
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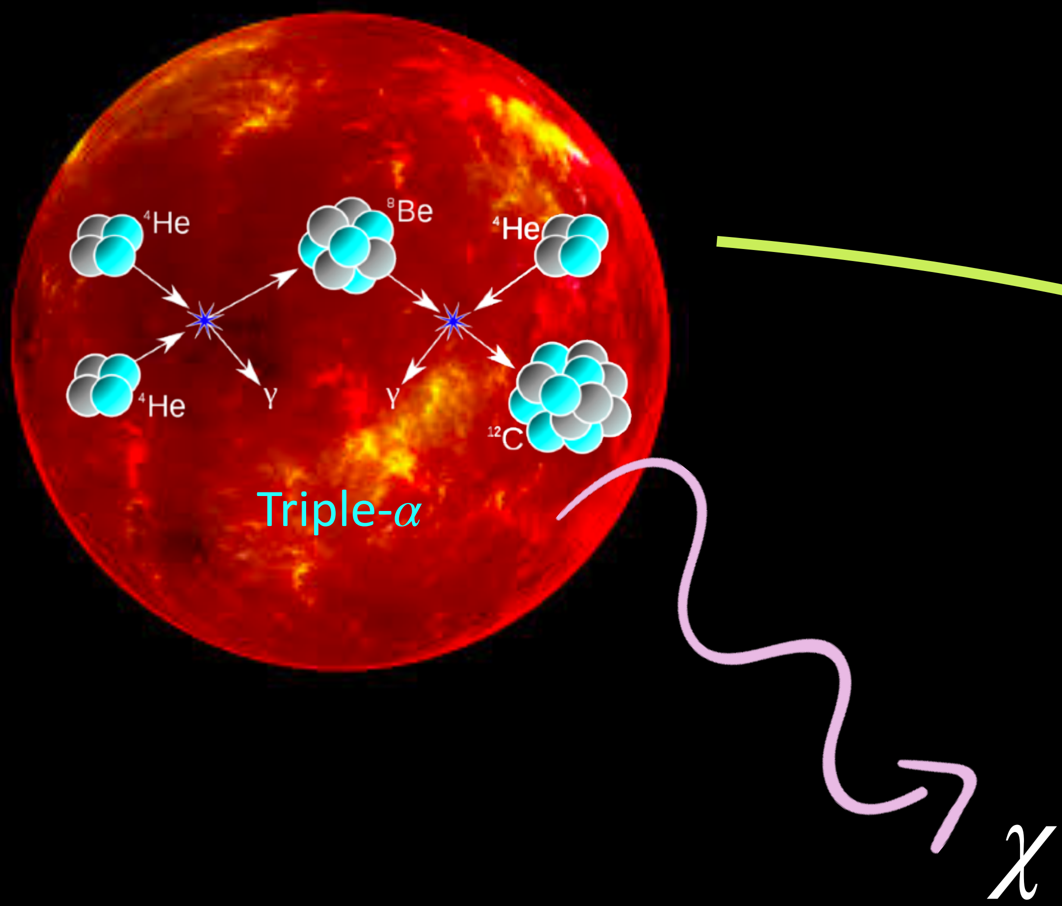

Novel energy losses
(axions or ν with anomalous μ_ν)
↓
Larger core mass at helium ignition
↓
Brighter TRGB

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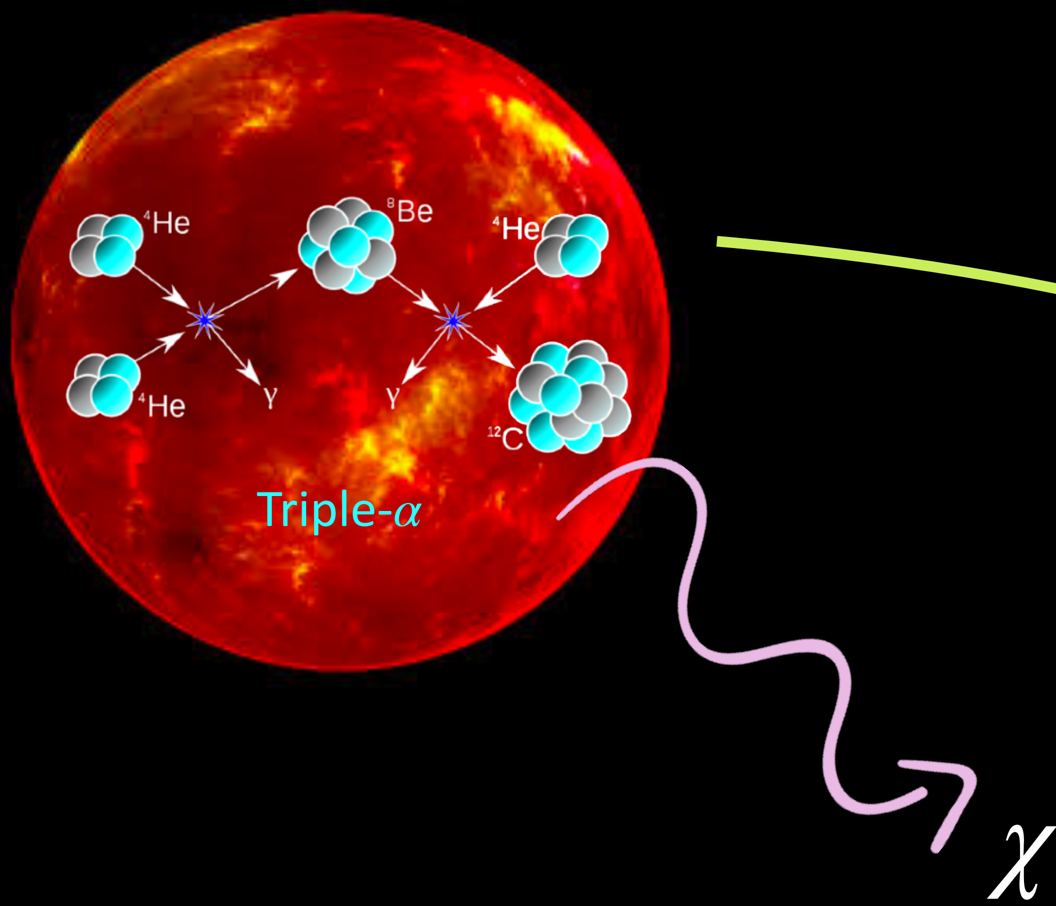

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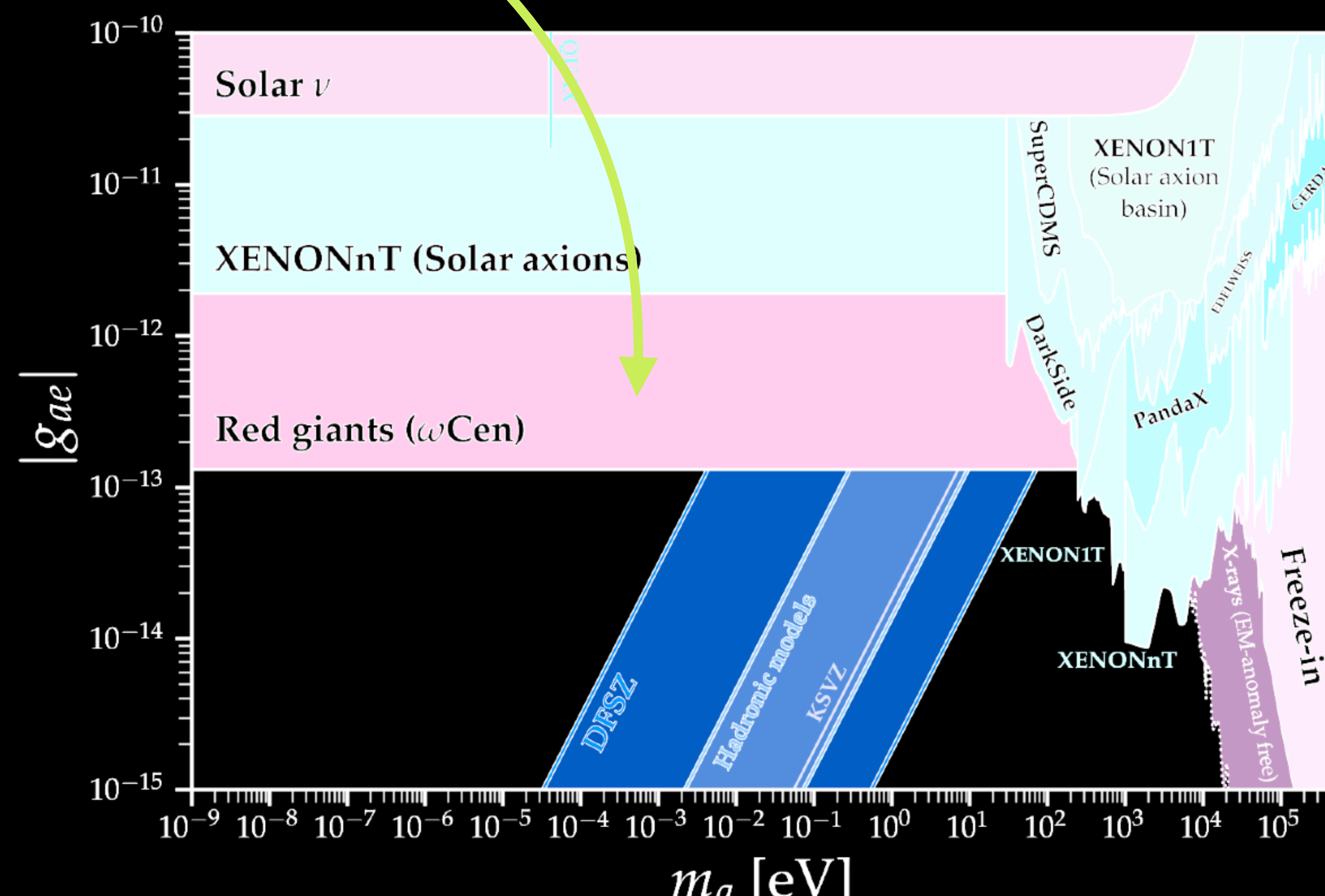

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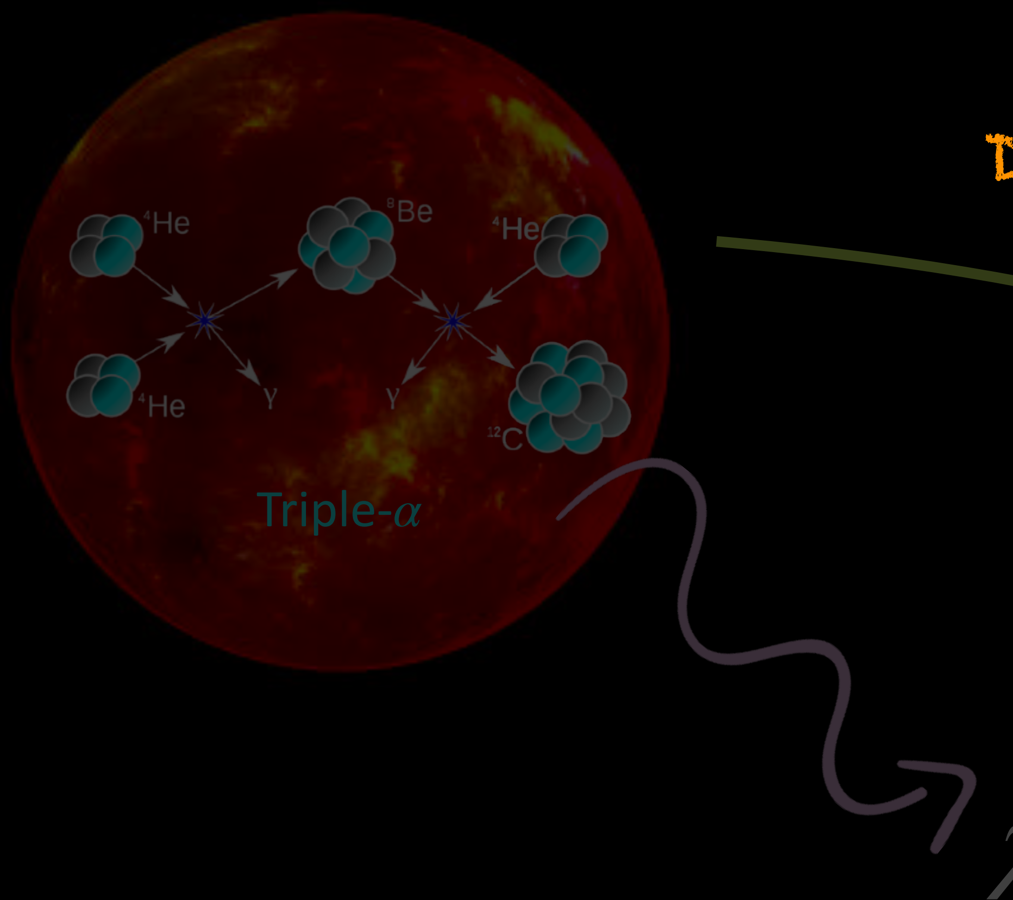
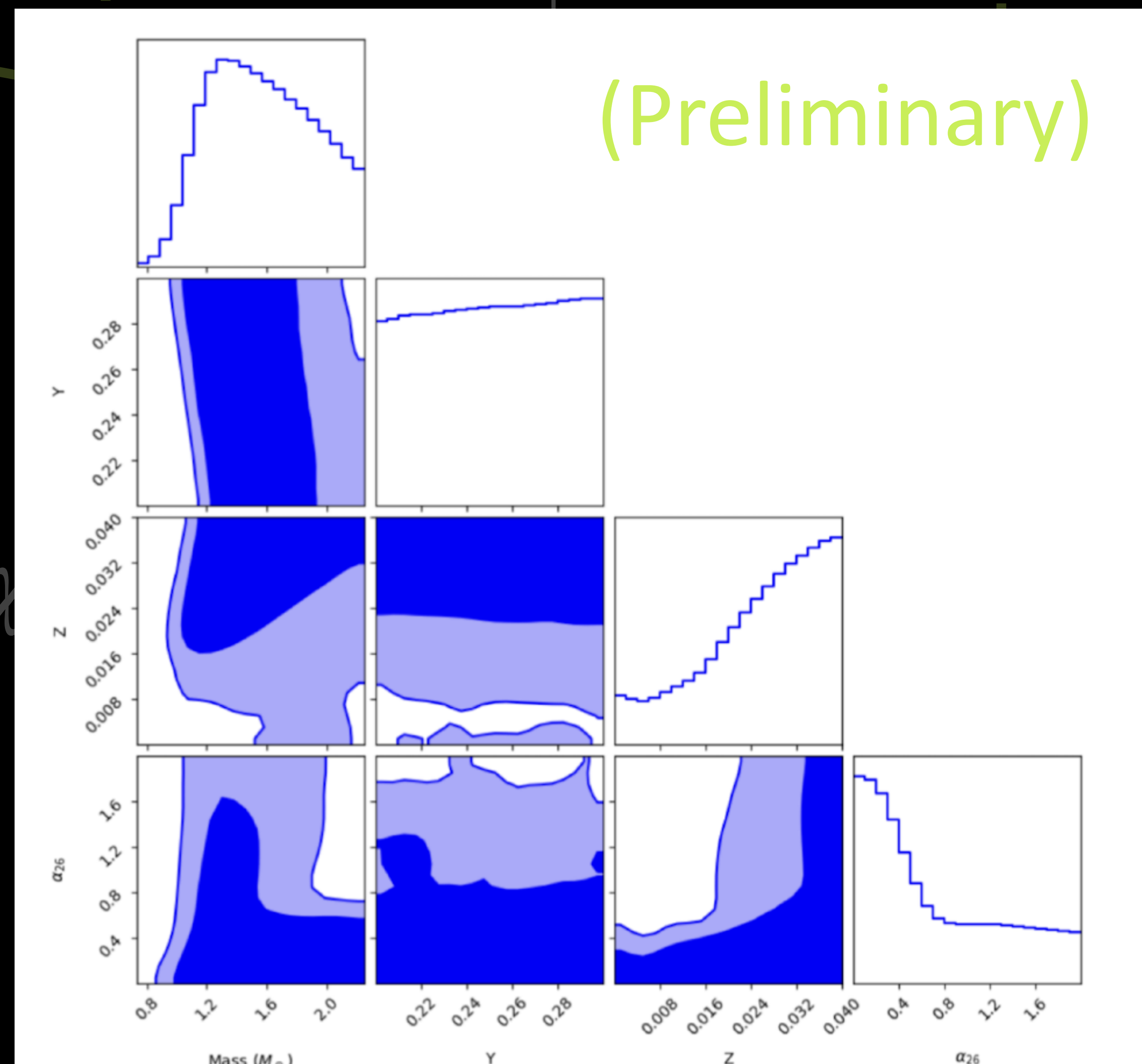


Novel energy losses
(axions or ν with anomalous μ_ν)

Degeneracies and the α_{26} constraint



Dennis & Sakstein, on the arXiv Monday…

Dearborn, Schramm & Steigman, PRL, 1986
Raffelt, ApJ, 1990
Raffelt & Capozzi, PRD, arXiv:2007.03694
Straniero et al., AA, arXiv:2010.03833
Plot: Ciaran O'Hare, axion limits

The horizontal branch

Novel losses speed up nuclear burning

Dolan, Hiskens, Volkas, JCAP, arXiv:2207.03102
Plot: Ciaran O'Hare, axion limits

The horizontal branch

New particle loss mechanisms scale with T and ρ

Novel losses speed up nuclear burning

$g_{a\gamma\gamma}$: $\propto T^7/\rho$

Dolan, Hiskens, Volkas, JCAP, arXiv:2207.03102
Plot: Ciaran O'Hare, axion limits

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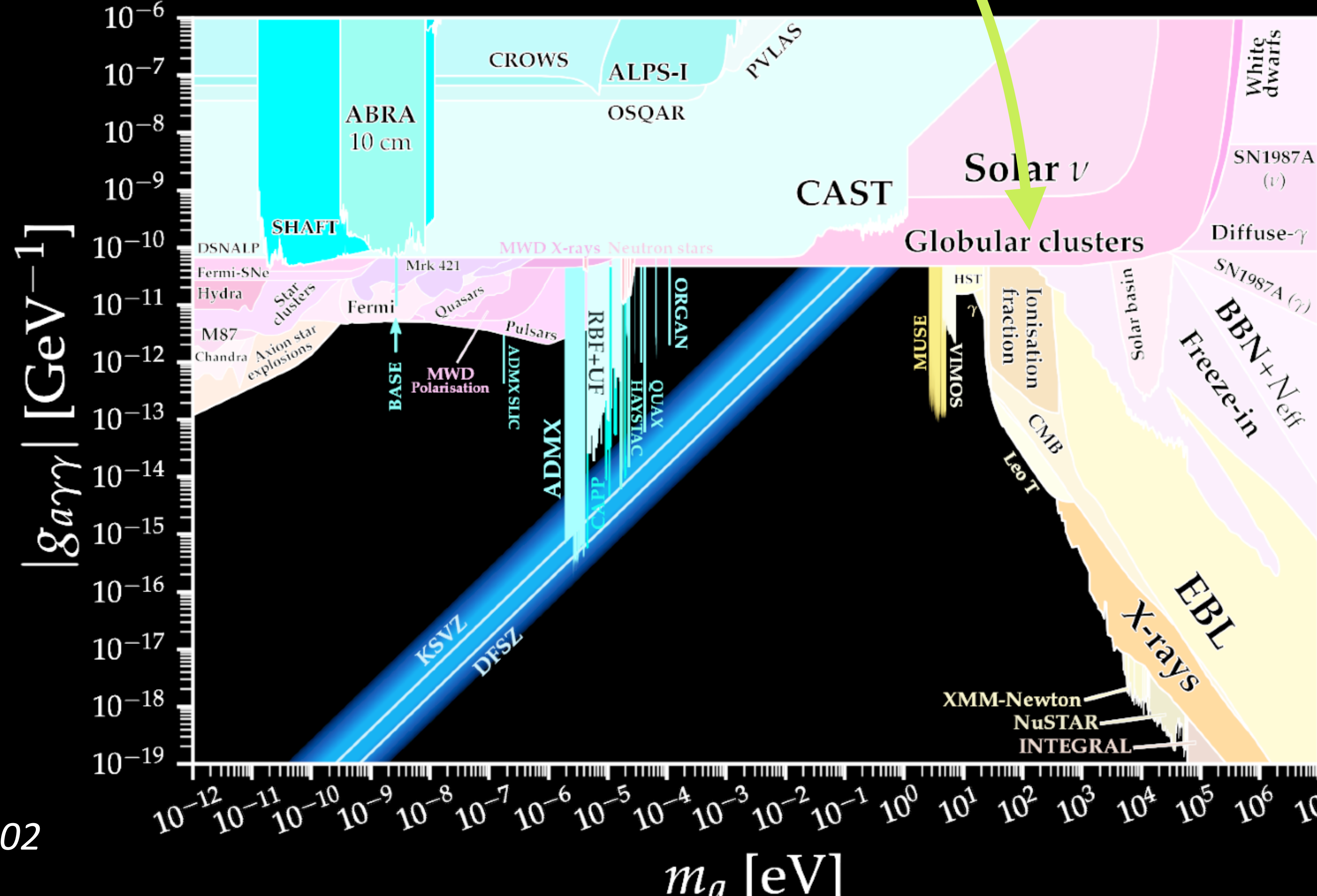

Dolan, Hiskens, Volkas, JCAP, arXiv:2207.03102
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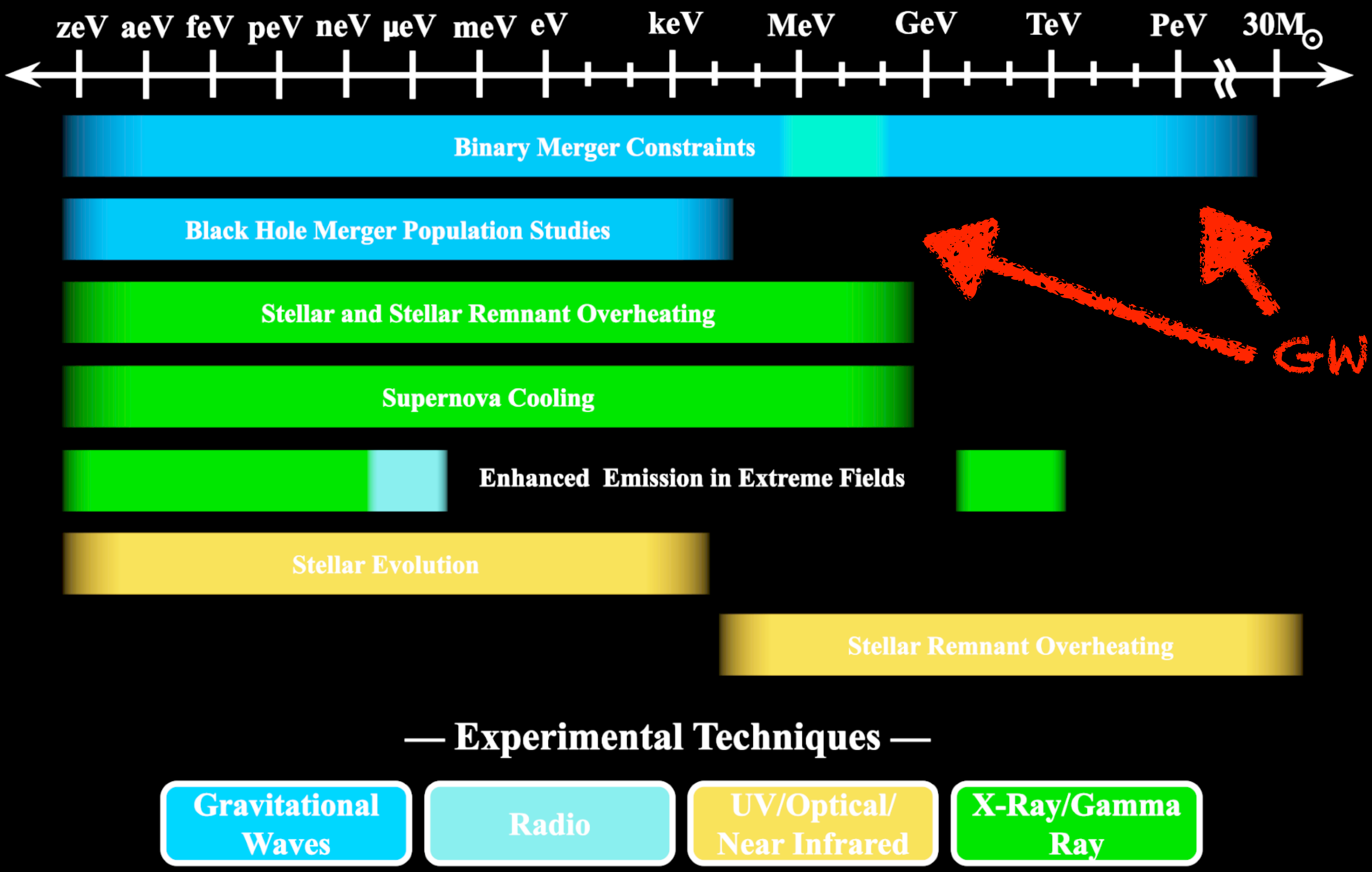
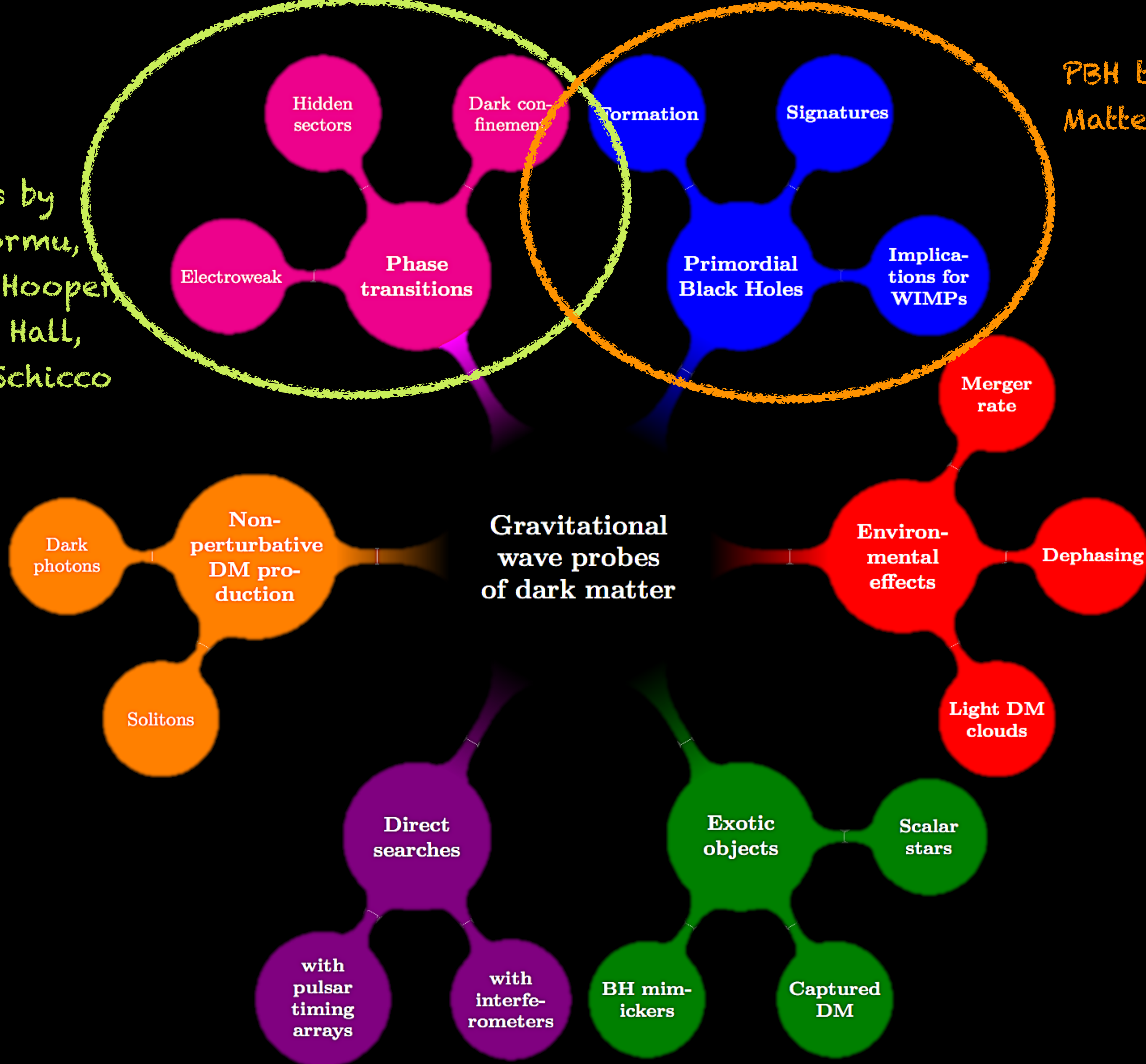


Baryakhtar, Caputo, DC, Perez et all, SNOWMASS summer study, arXiv:2203.07984 , arXiv:2209.08215

G. Bertone, DC, et al. Scipost, arXiv:1907.10610

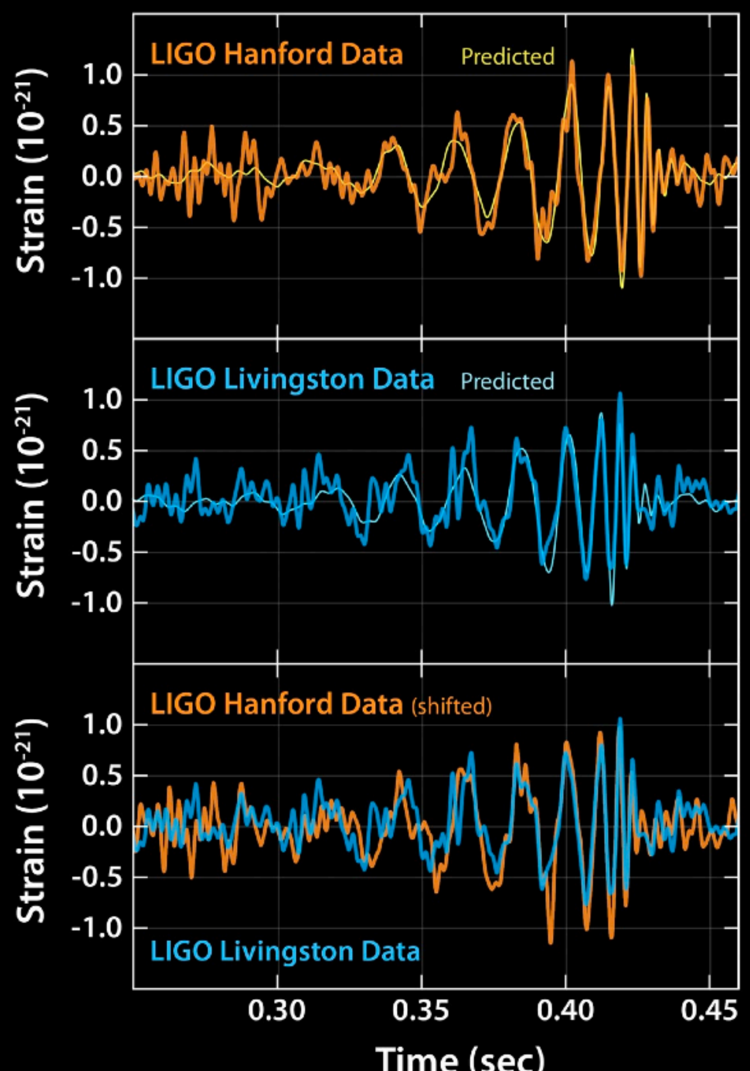
PT talks by
Anna Kormu,
Deanna Hooper,
Eleanor Hall,
Philipp Schicco

PBH talk by
Matteo Lucca



G. Bertone, DC, et al. Scipost, arXiv:1907.10610

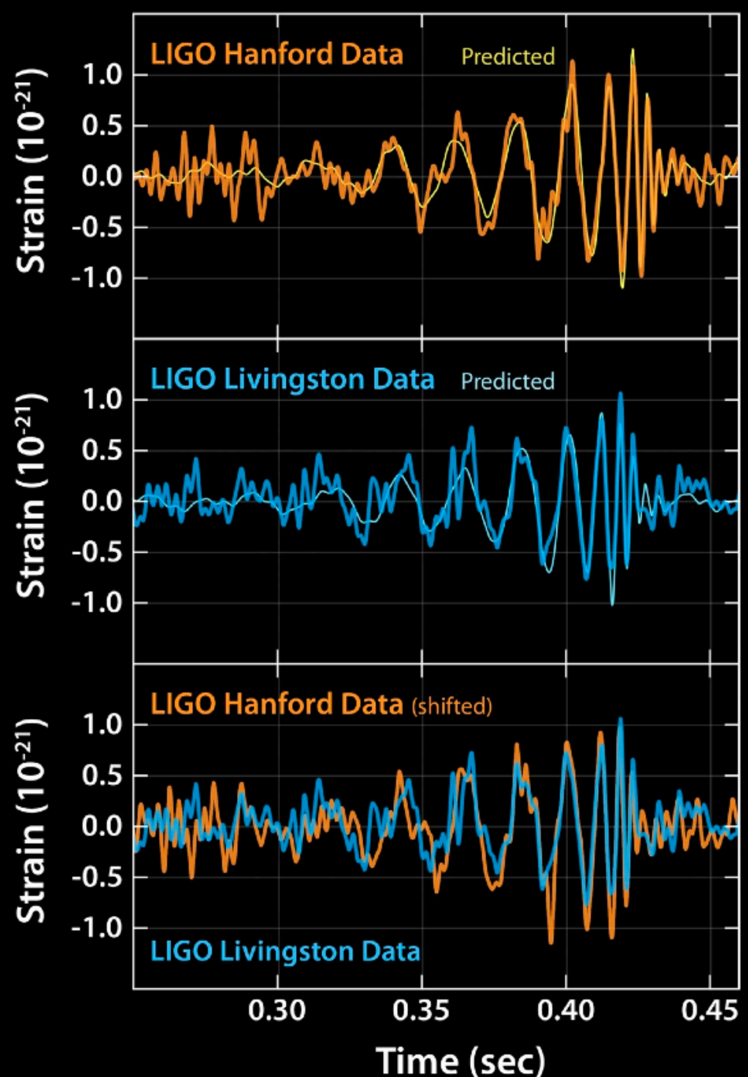
Gravitational wave science



The first event:
GW150914

Images: LIGO/Ben Farr/Aaron Geller

Gravitational wave science



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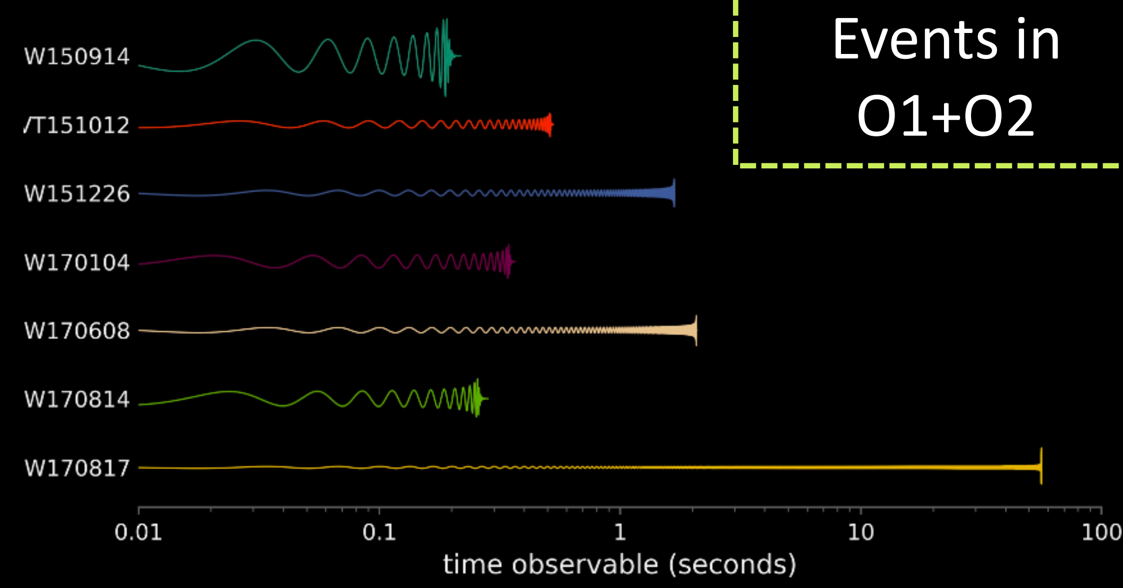
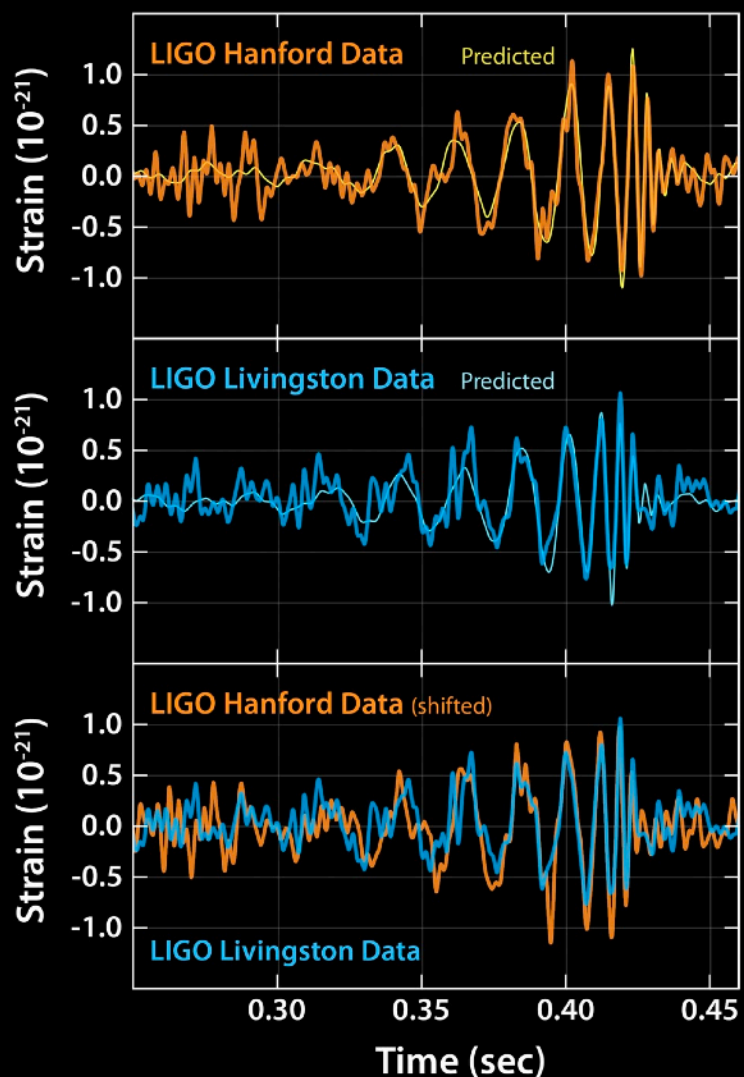


Events in O1+O2

Images: LIGO/Ben Farr/Aaron Geller

Gravitational wave science



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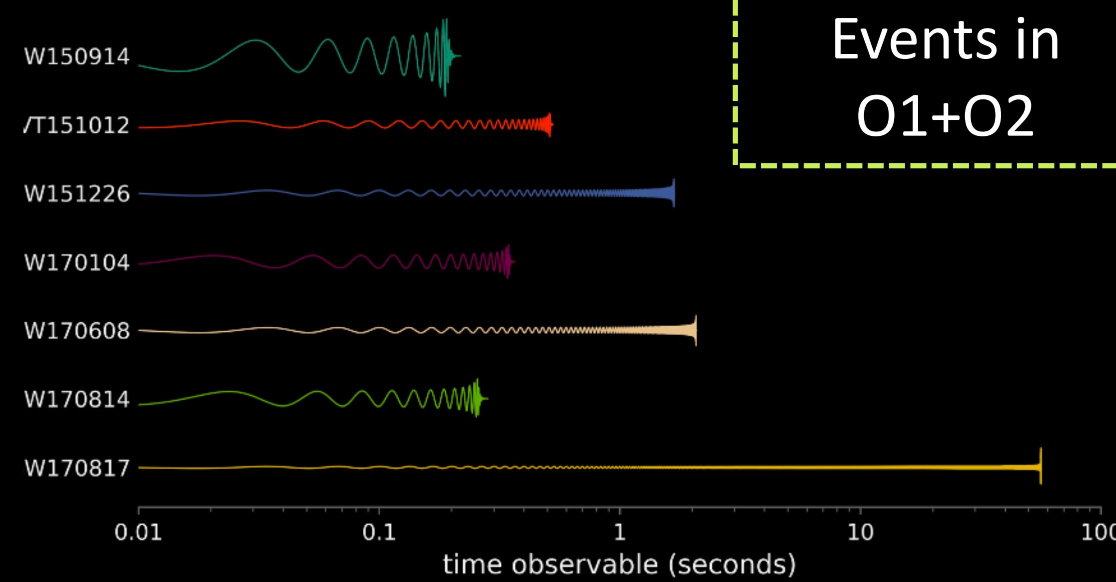

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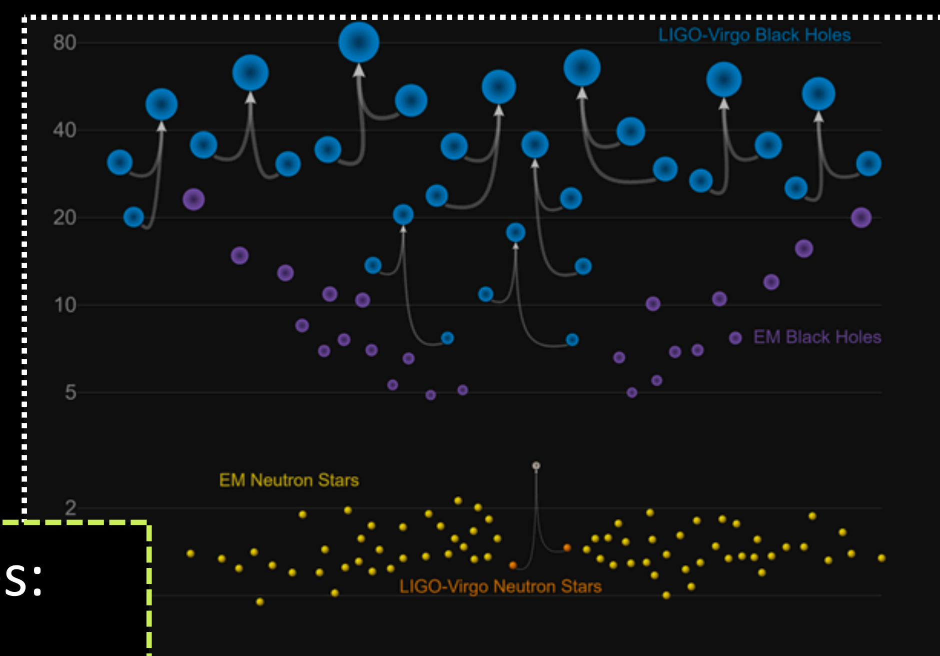
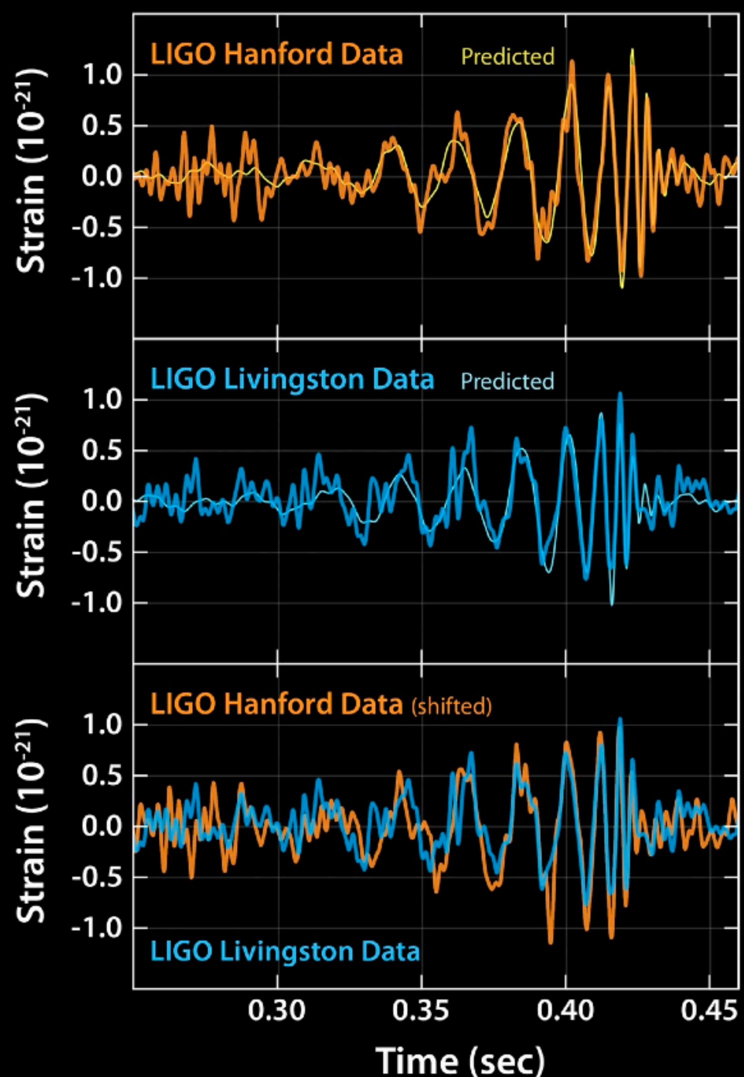


Catalogues: GWTC-1

Images: LIGO/Ben Farr/Aaron Geller

Gravitational wave science



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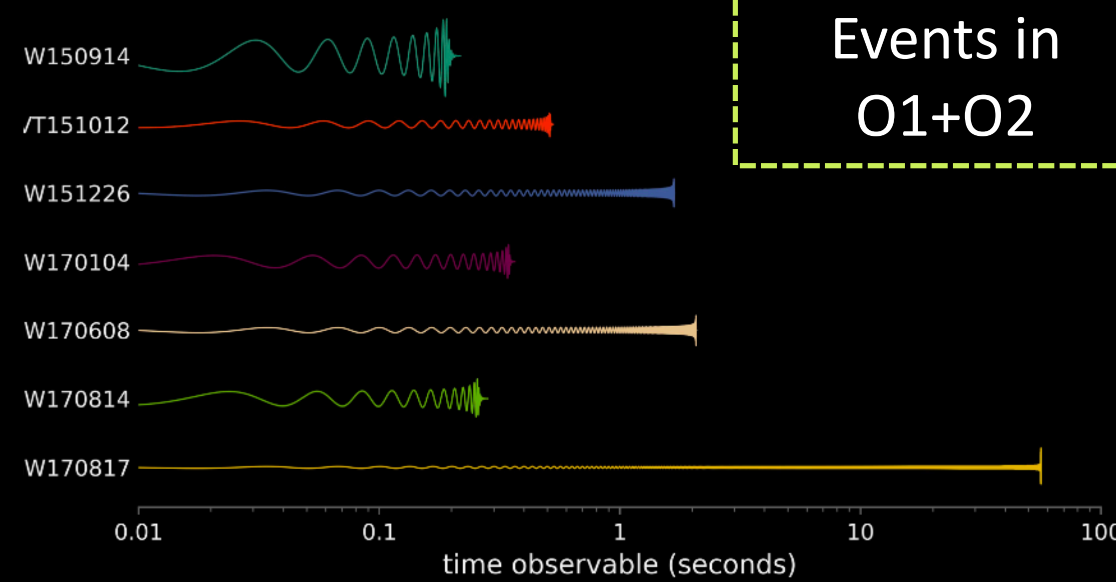
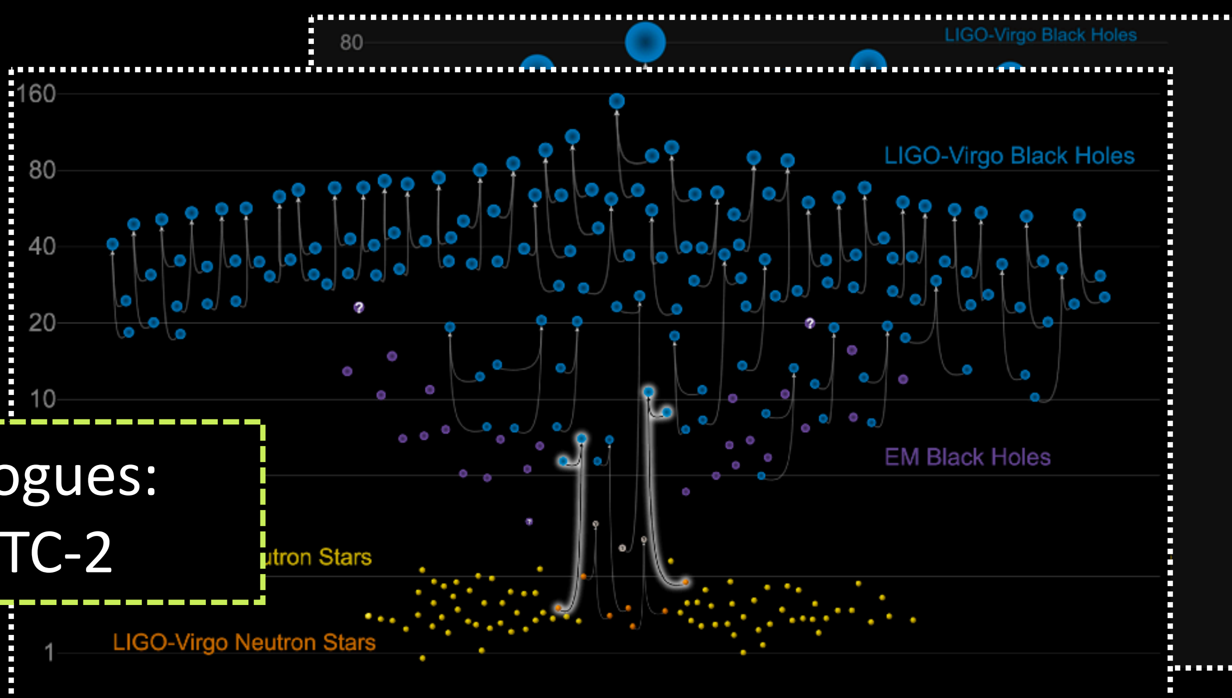


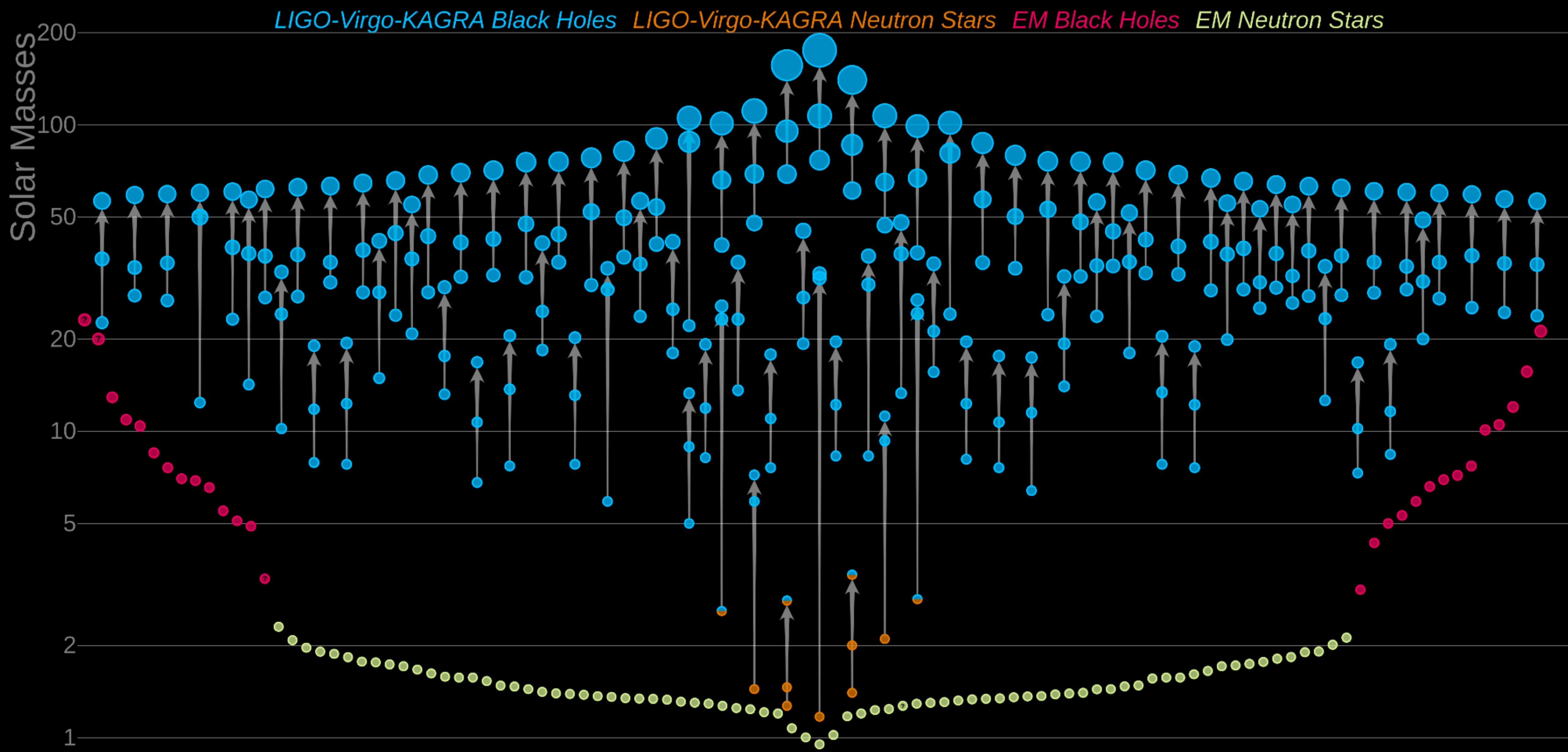
Events in O1+O2



Catalogues: GWTC-2

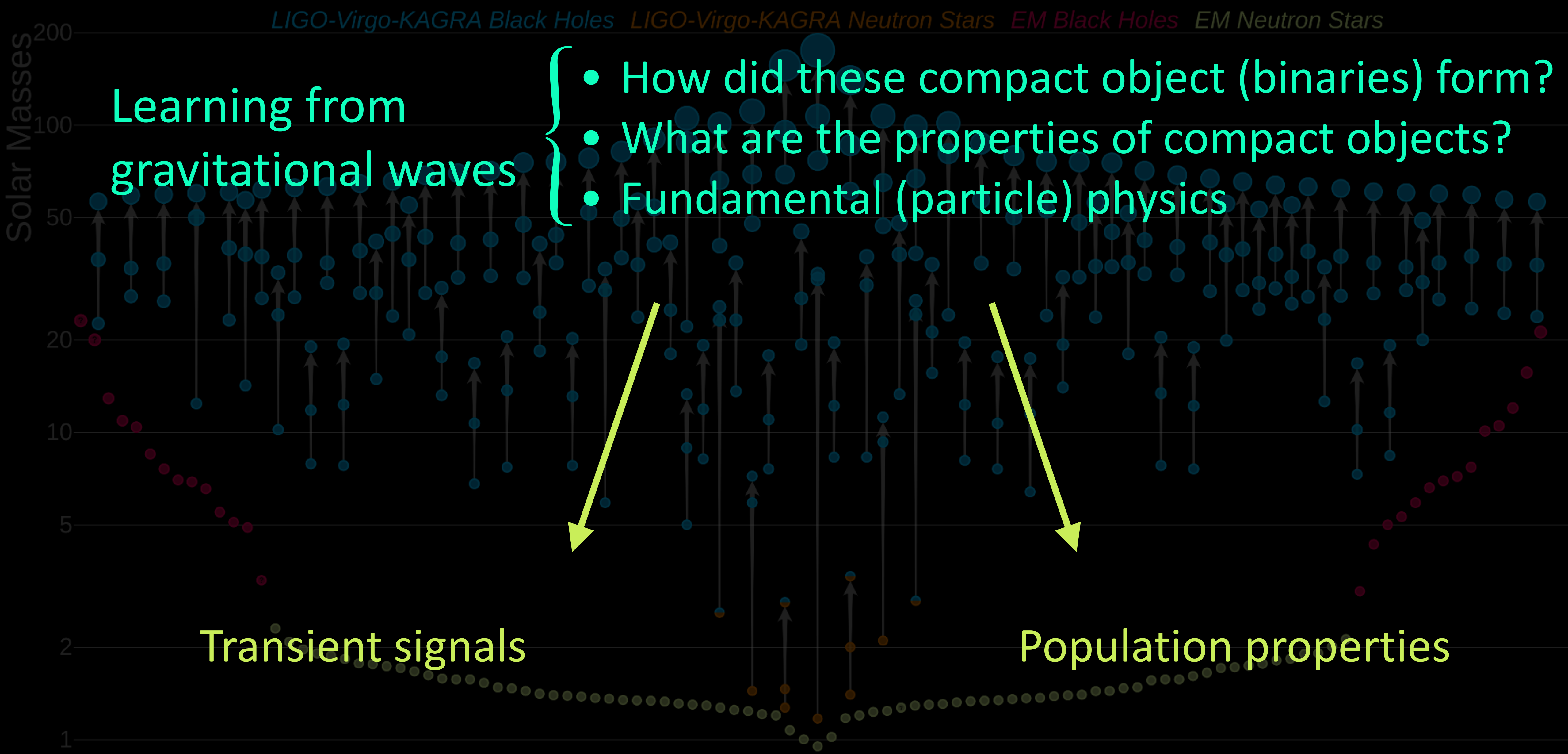
Images: LIGO/Ben Farr/Aaron Geller

An ever growing catalogue (GWTC-3)



Adapted from LIGO-Virgo-KAGRA, Aaron Geller

An ever growing catalogue (GWTC-3)



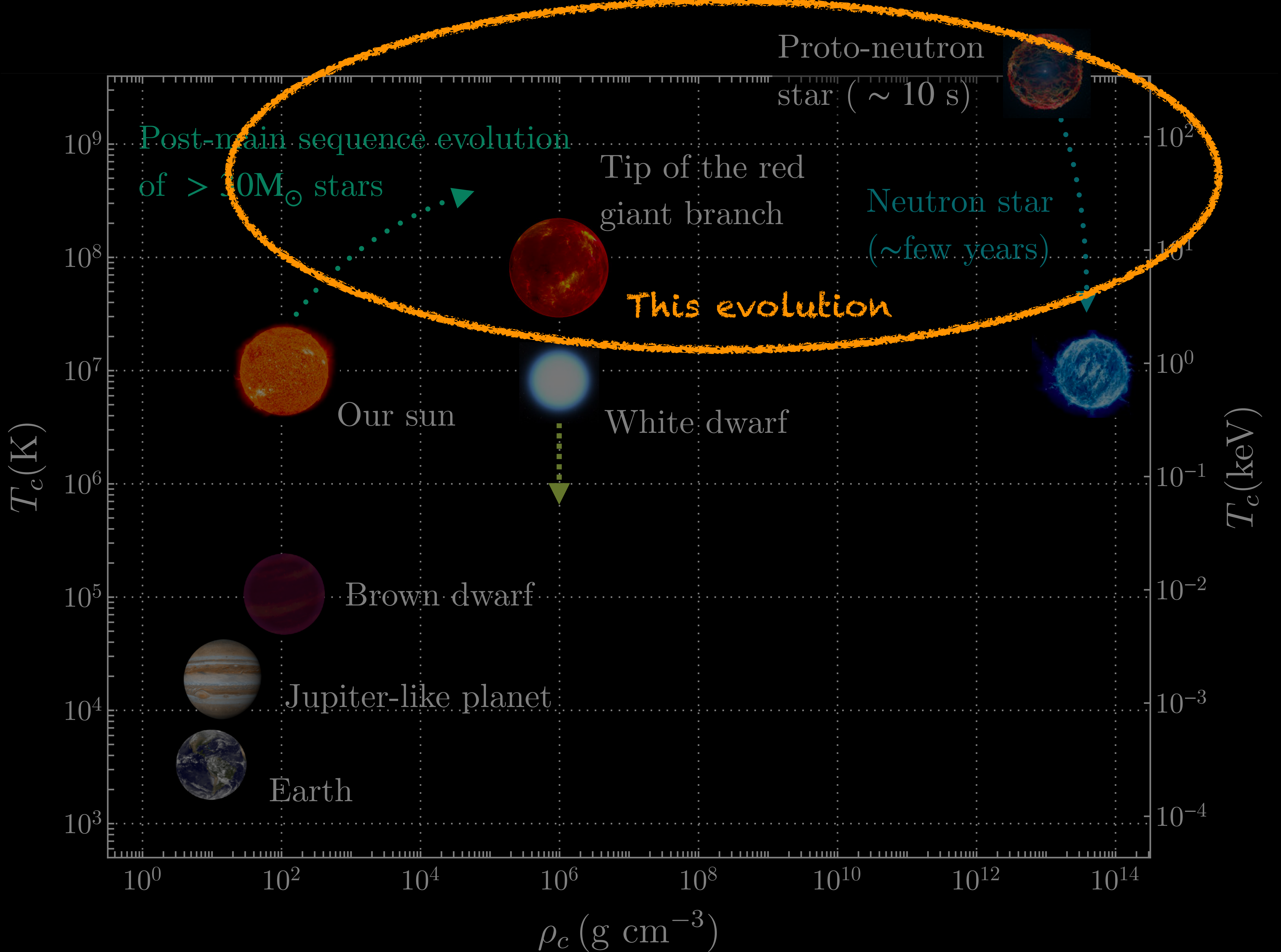
Learning from gravitational waves

- How did these compact object (binaries) form?
- What are the properties of compact objects?
- Fundamental (particle) physics

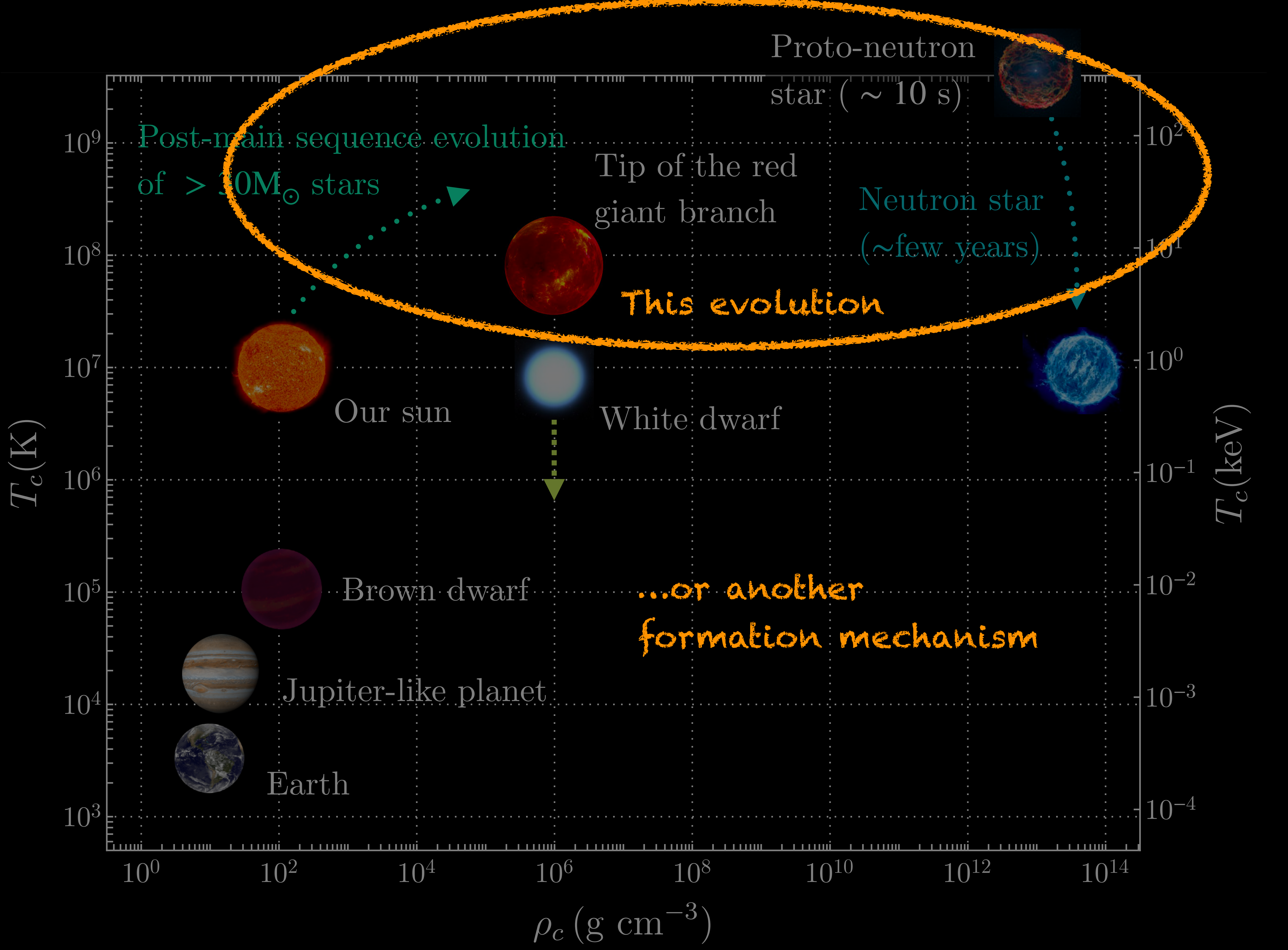
Transient signals

Population properties

Adapted from LIGO-Virgo-KAGRA, Aaron Geller



Proto-neutron star (~ 10 s)
Post-main sequence evolution of > 10M$_\odot$ stars
Tip of the red giant branch
Neutron star (~few years)
This evolution
Our sun
White dwarf
Brown dwarf
Jupiter-like planet
Earth
T_c(K)
T_c(keV)
ρ_c (g cm^{-3})
10^0 10^2 10^4 10^6 10^8 10^{10} 10^{12} 10^{14}
10^3 10^4 10^5 10^6 10^7 10^8 10^9
10^{-4} 10^{-3} 10^{-2} 10^{-1} 10^0 10^1 10^2



Proto-neutron
star (~ 10 s)
Post-main sequence evolution
of > 10M⊙ stars
Tip of the red
giant branch
Neutron star
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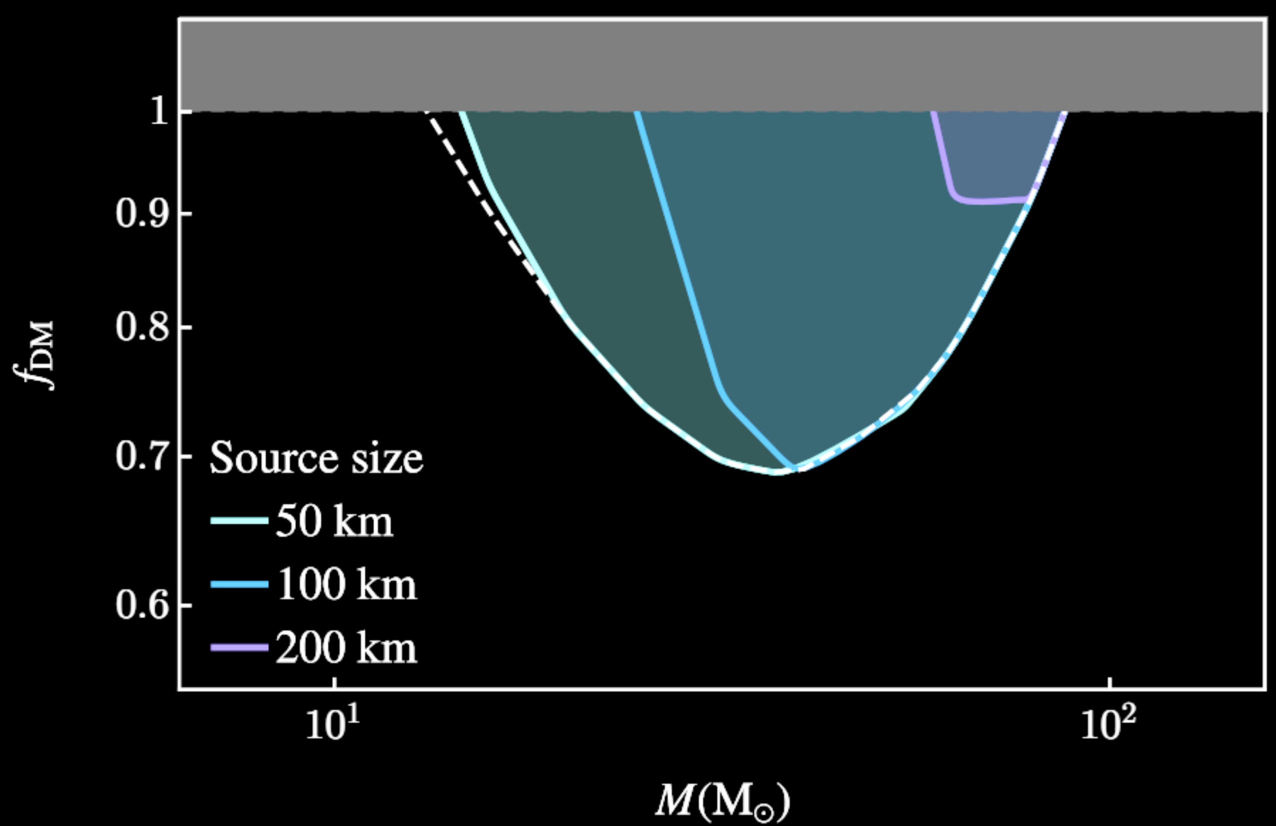
This evolution
Our sun
White dwarf
Brown dwarf
...or another
formation mechanism
Jupiter-like planet
Earth
T_c(K)
T_c(keV)
ρ_c (g cm^{-3})

Exotic object observation with LVK

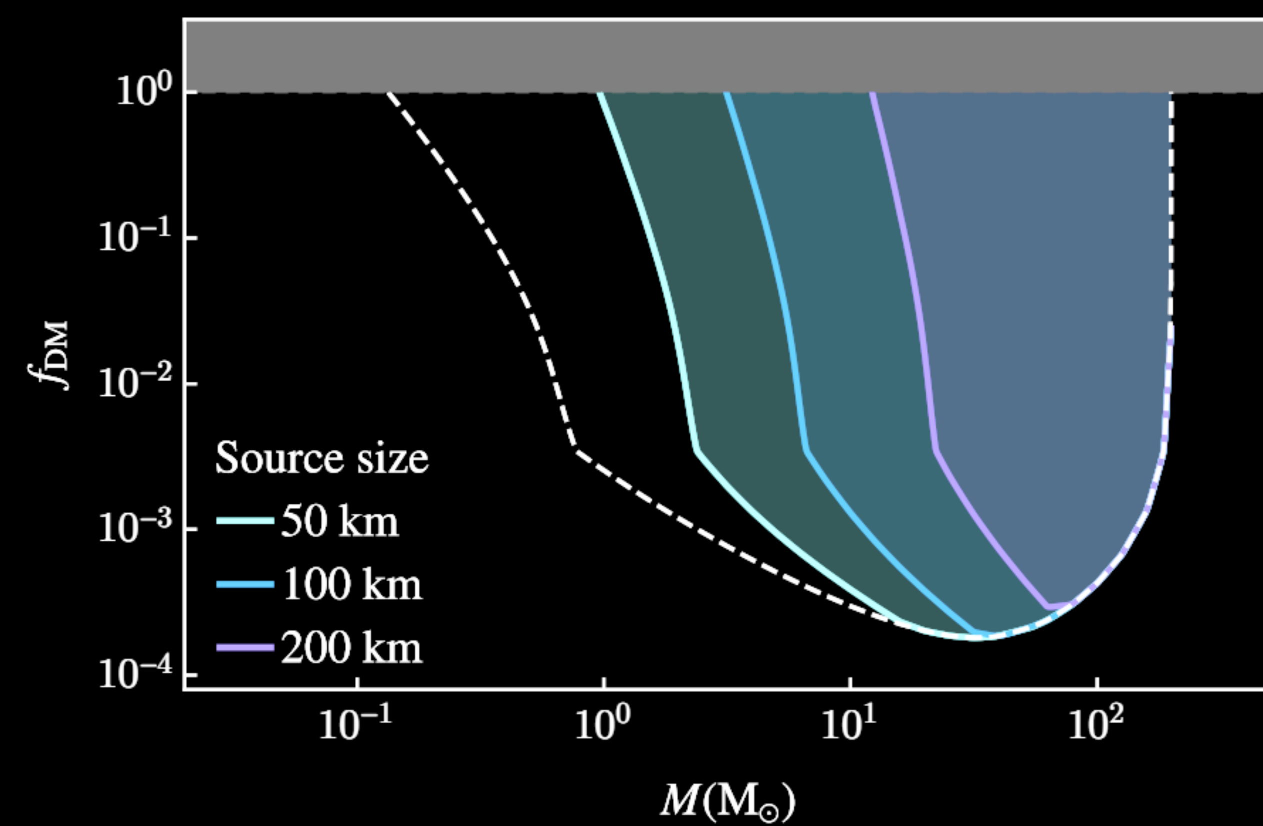
DC, Ipek, McKeen, PRD, arXiv:2205.15396

Design sensitivity, $\mathrm{SNR} = 8$



Late Universe formation (optimistic estimate)

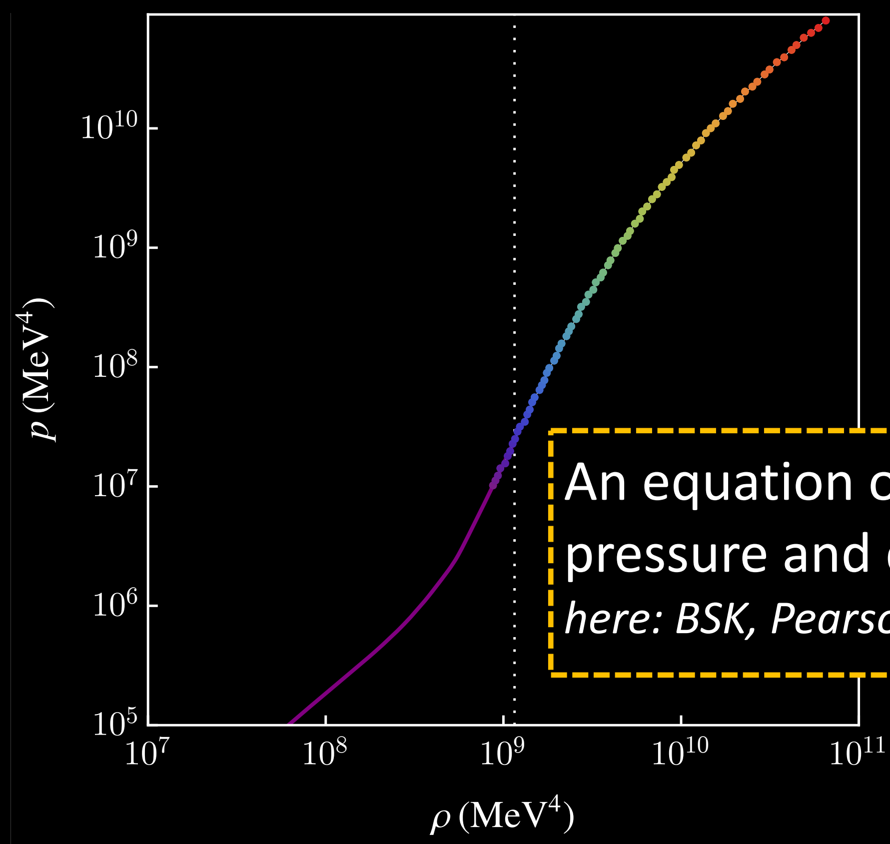
S. Bird et al., PRL, arXiv:1603.00464



Early universe formation

Jedamzik, JCAP, arXiv:2006.11172
Vaskonen Veermae, PRD, arXiv:1908.09752.
Hutsi, Raidal, Vaskonen, Veermae, JCAP, arXiv:2012.02786

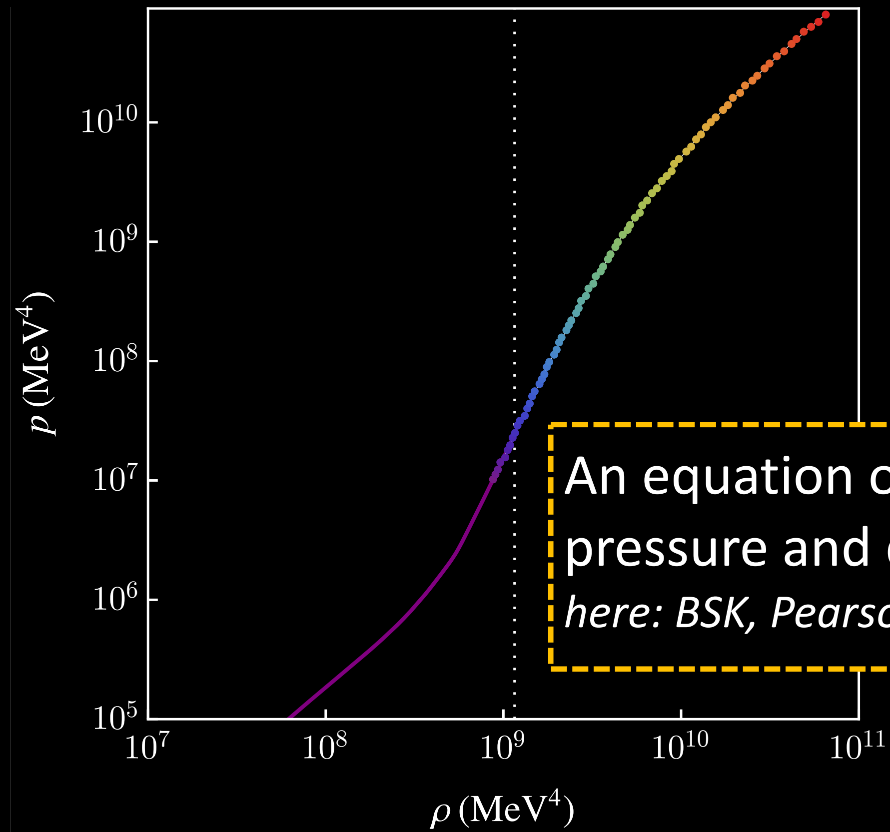
ECOs and Tidal love numbers



An equation of state relates pressure and density

here: BSK, Pearson et al, PRC (2020)

ECOs and Tidal love numbers



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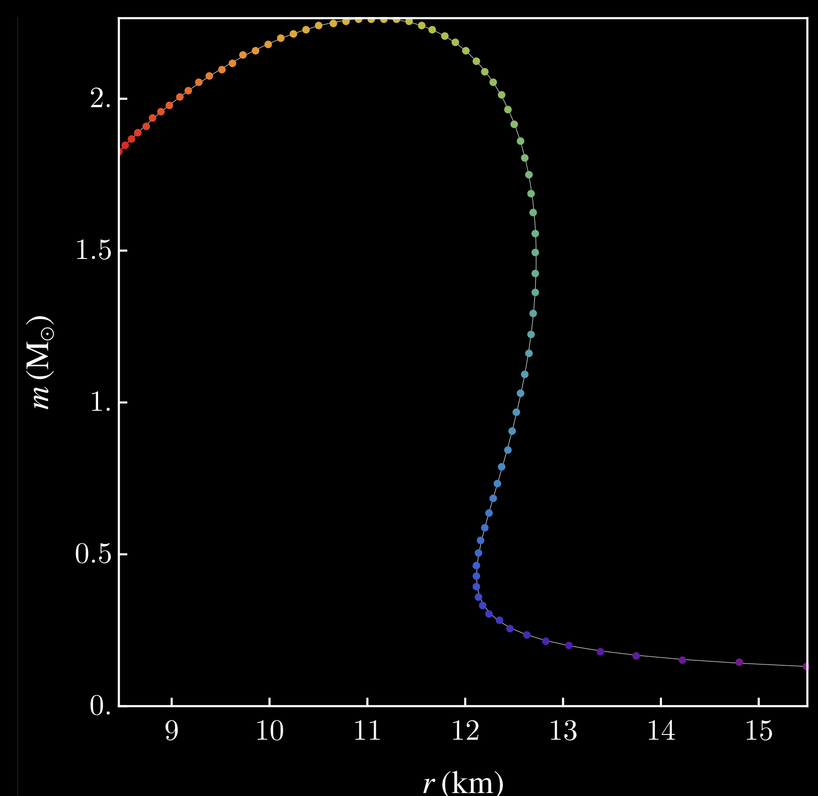
Solving the TOV equations, $m(r)$ (and $\rho(r)$) can be found



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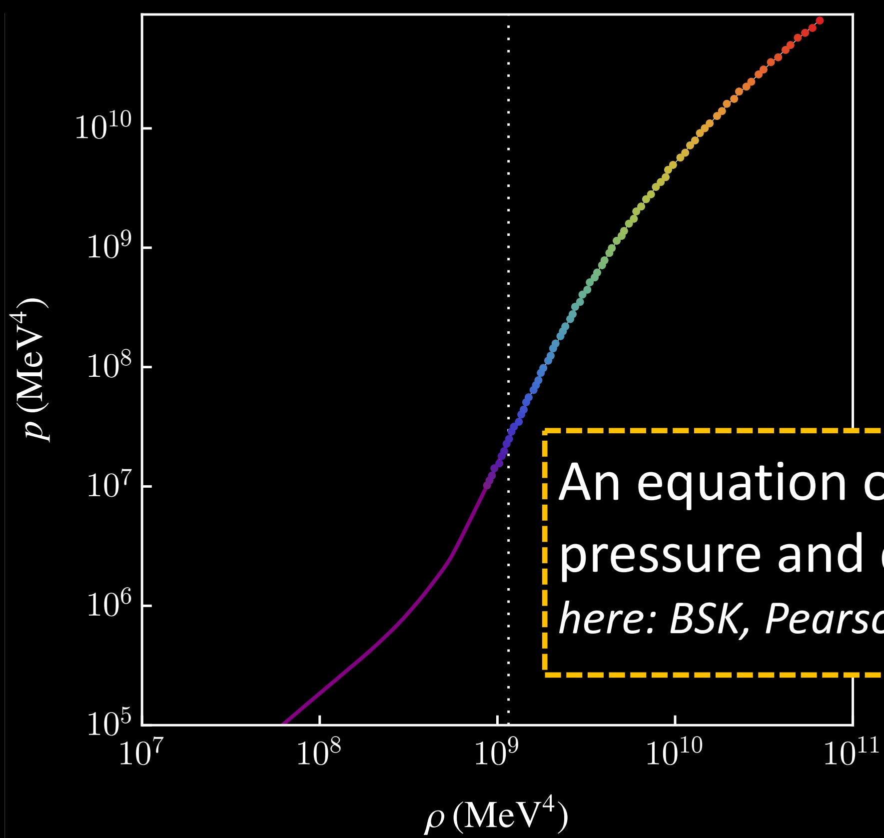

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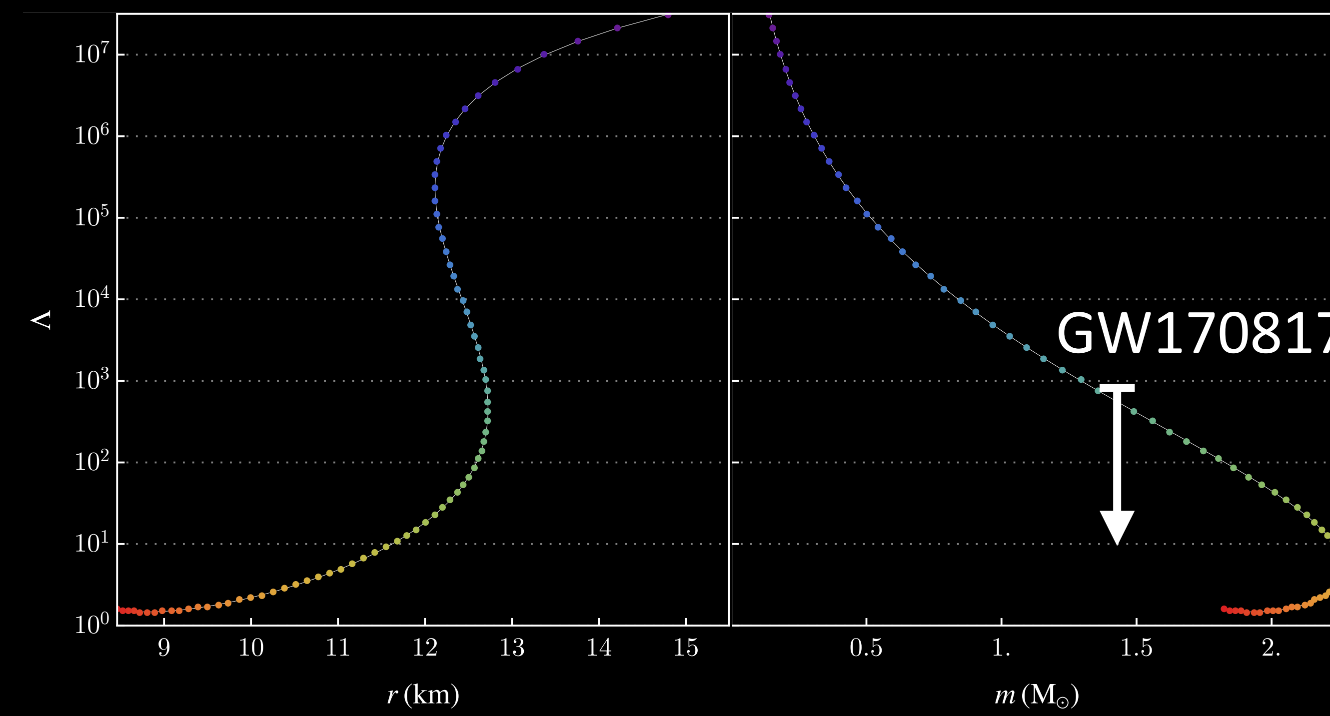

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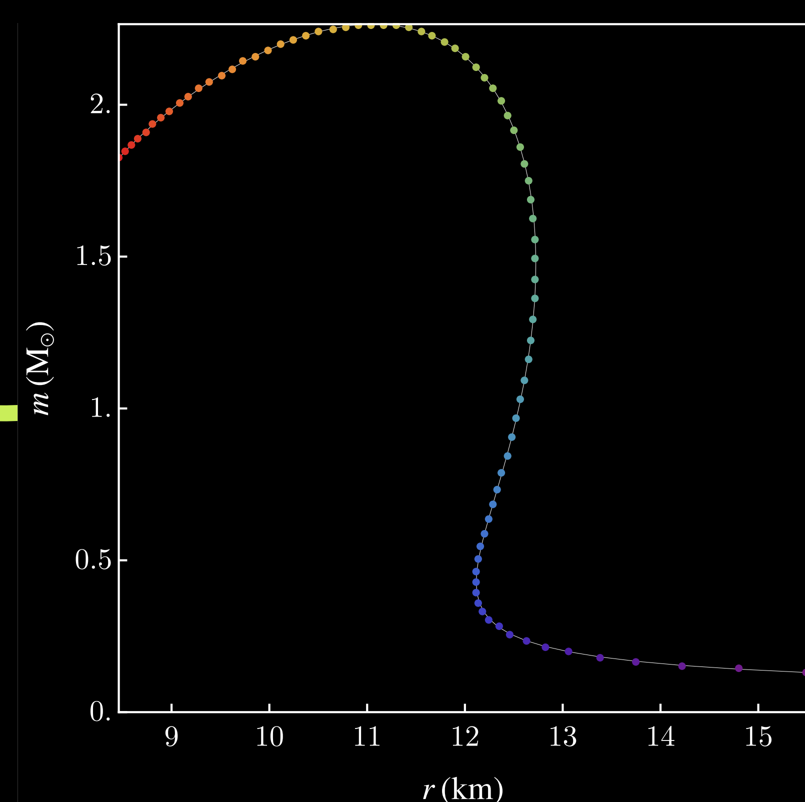
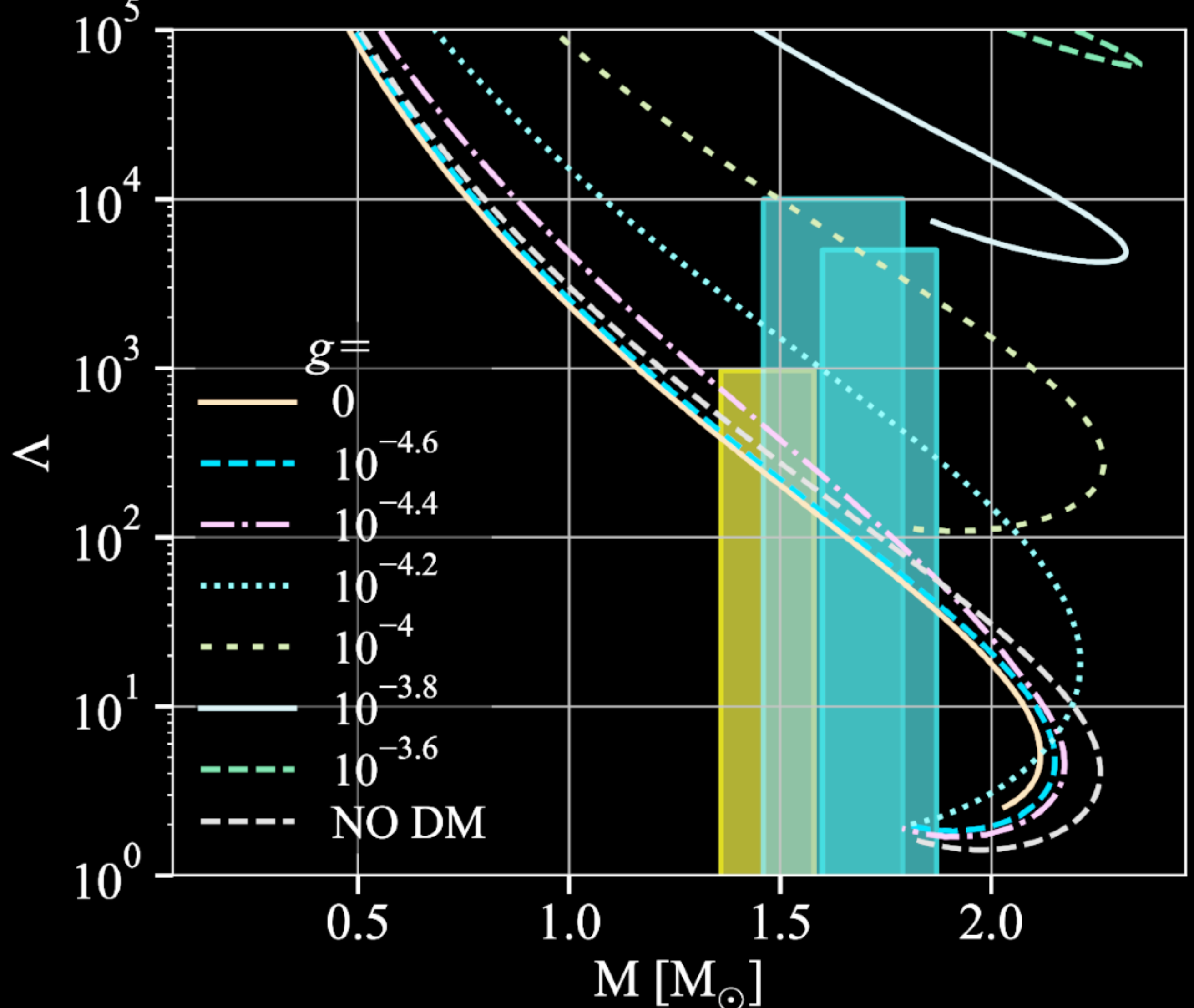
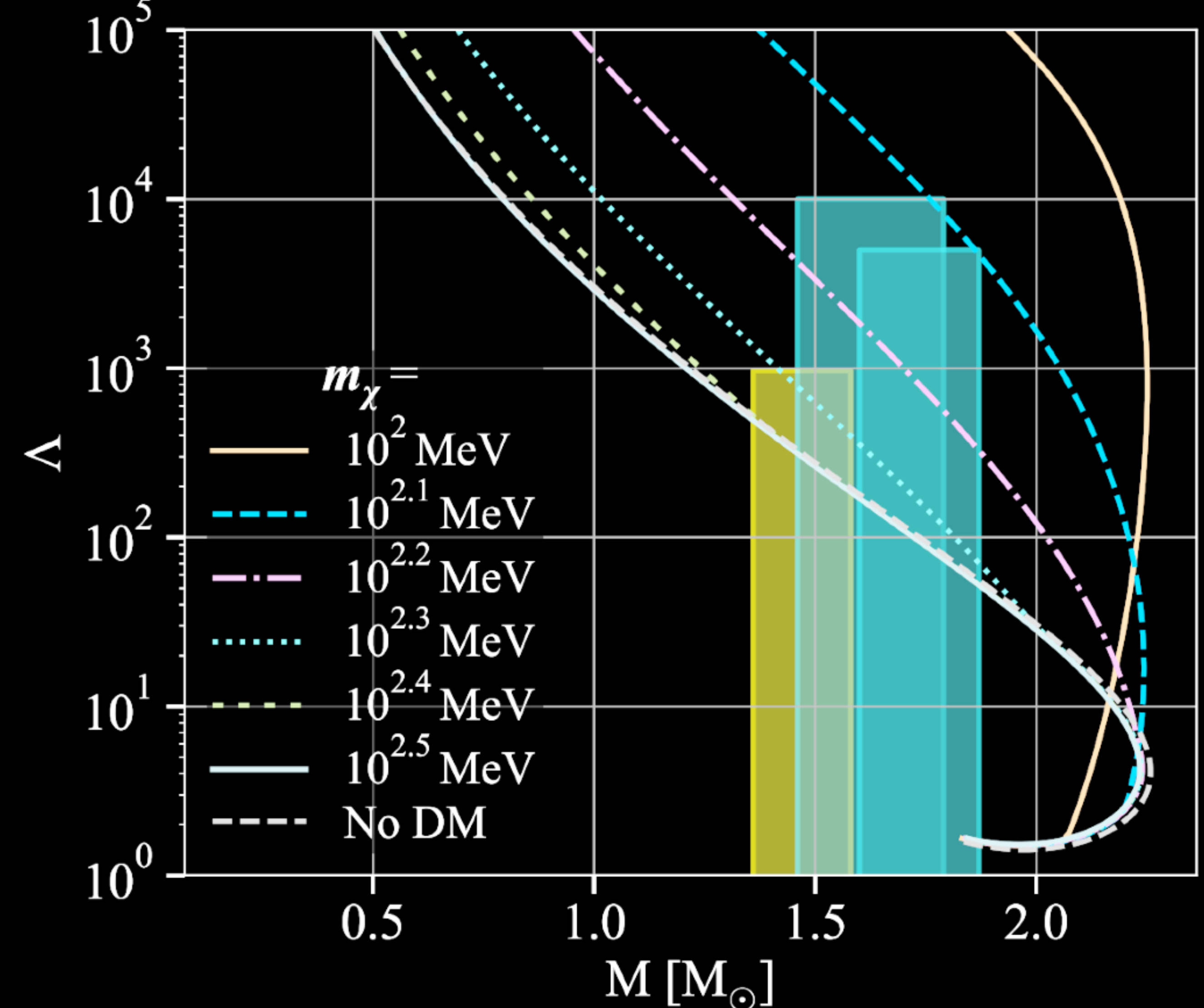


The tidal love number Λ imprints on the waveform as a phase $\delta\Psi$ at 5PN
Flanagan & Hinderer, PRD (2007)

ECOs and Tidal love numbers

Example: NS admixed with fermion with Yukawa interaction



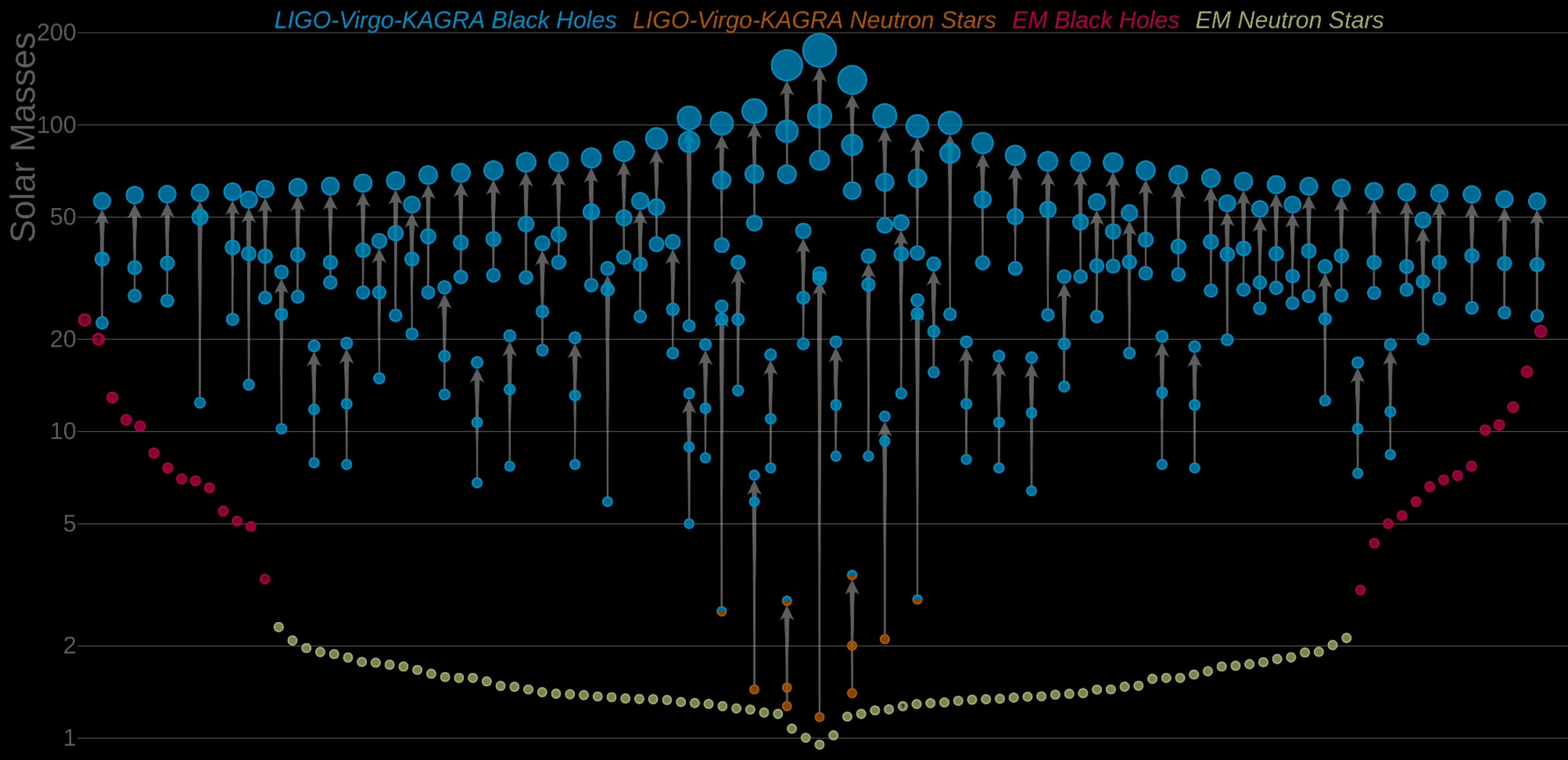


5% mass fraction

Collier, DC, Leane, PRD, arXiv:2205.15337,
https://zenodo.org/record/7361819#.ZFEW9OzMK3J

An ever growing catalogue (GWTC-3)

What can be learned about *populations of compact objects*?



Adapted from LIGO-Virgo-KAGRA, Aaron Geller

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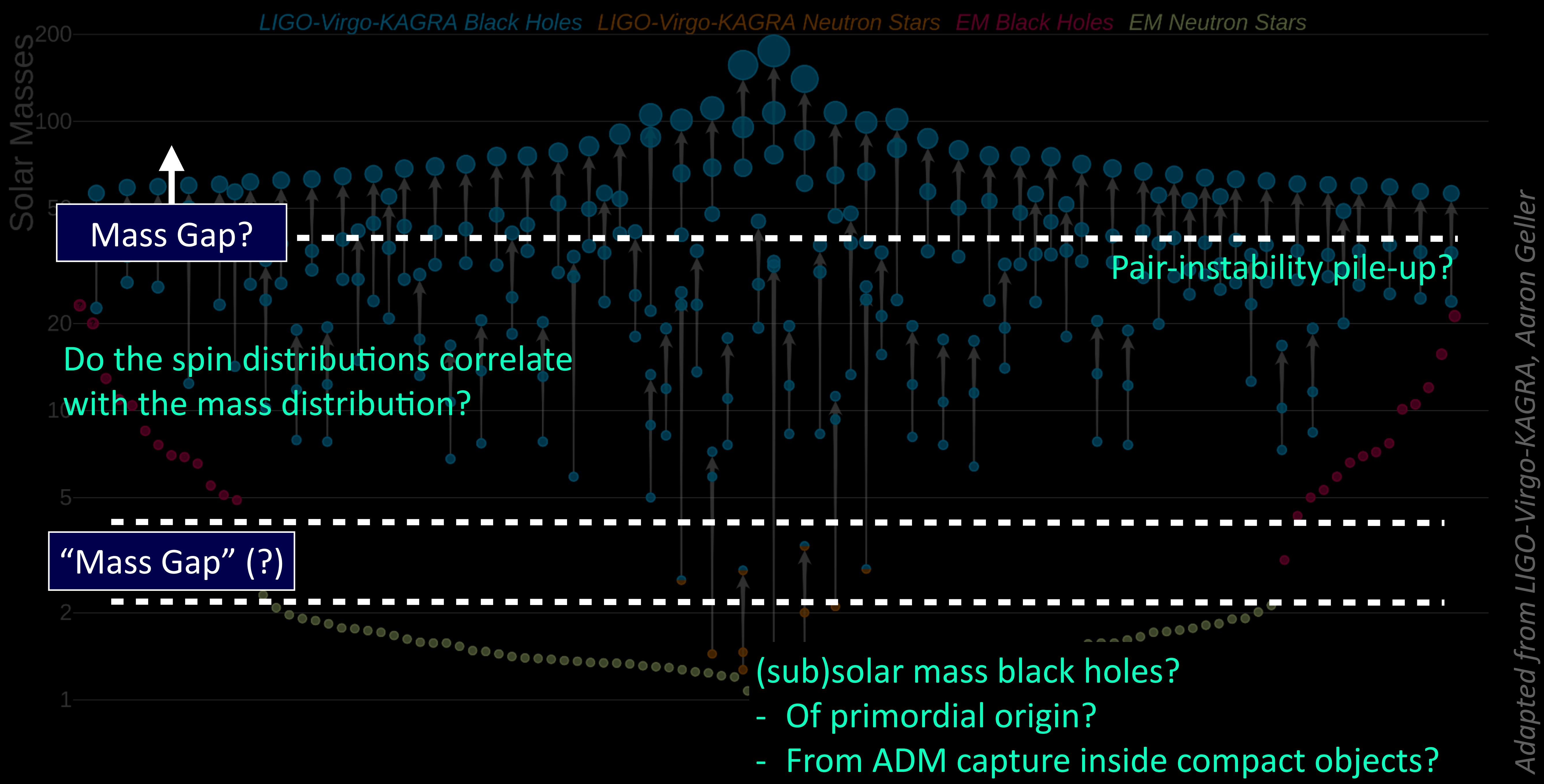
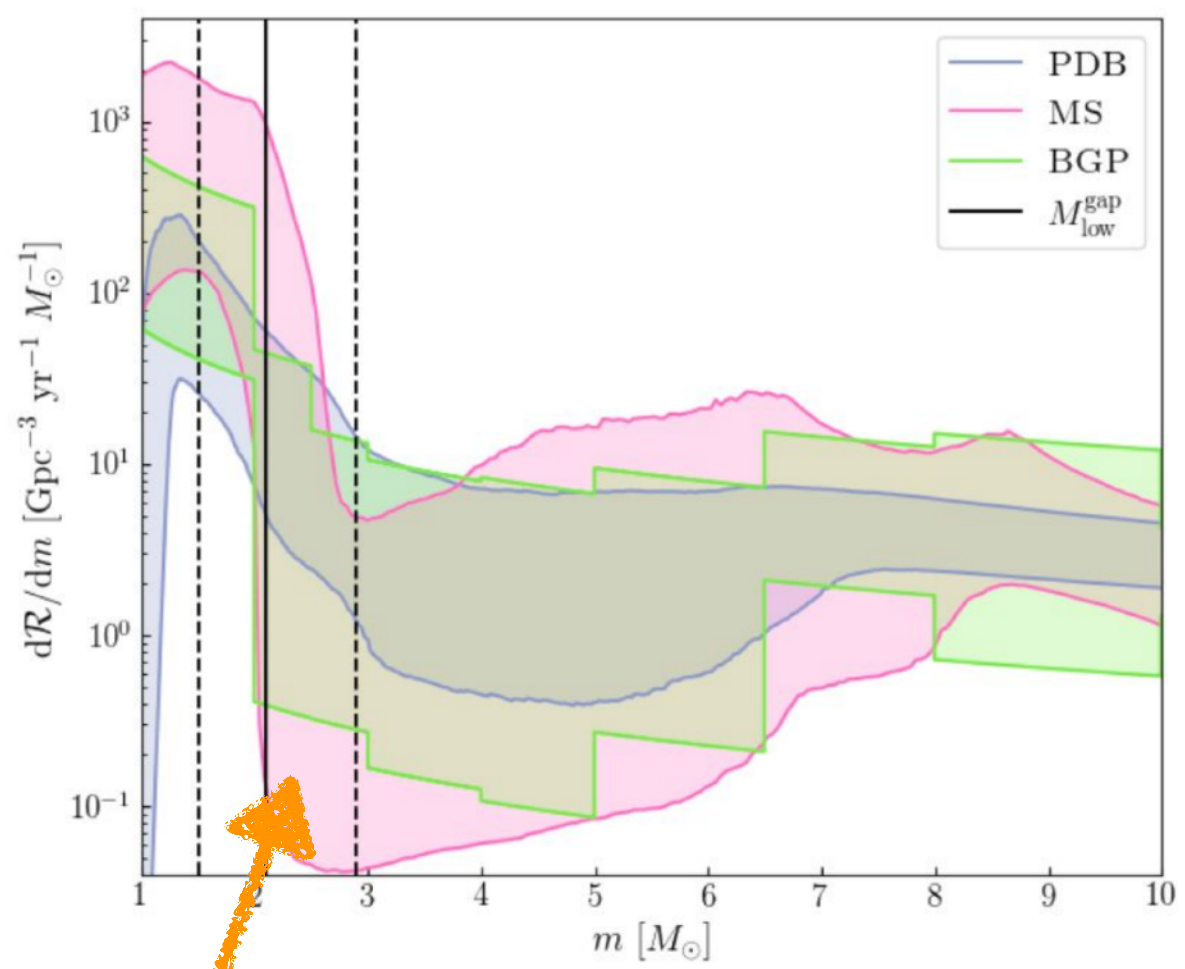


Features in the mass distribution

Lower mass gap



The LIGO Scientific Collaboration, the Virgo Collaboration and the KAGRA Collaboration, Phys. Rev. X **13**, 011048, March 2023

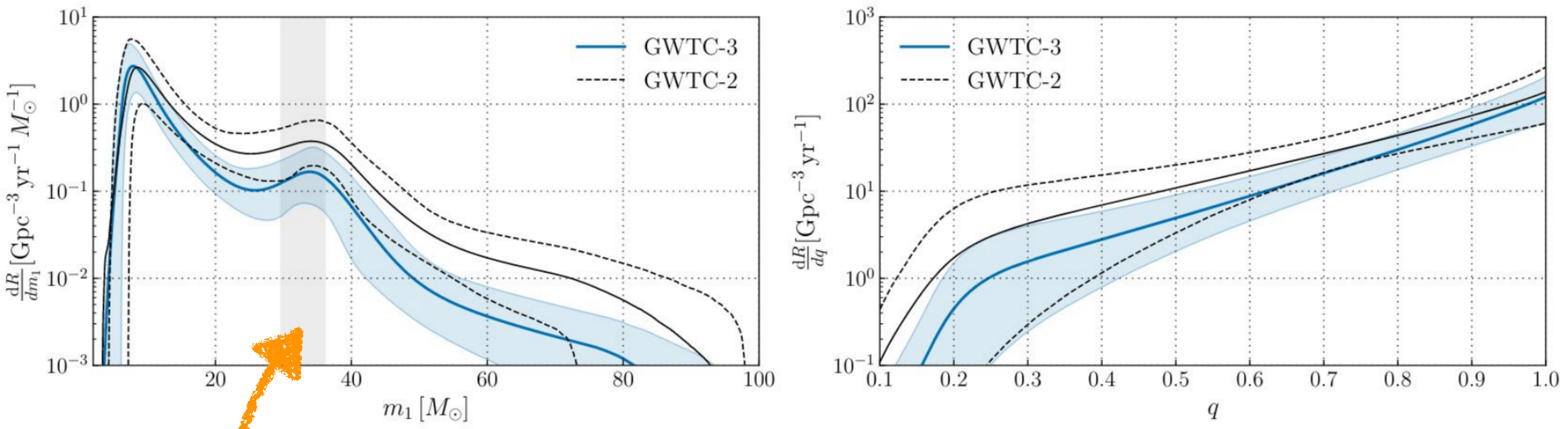
Is the lower mass gap physical?

Rachel Gray's talk on Tuesday

Features in the mass distribution

Lower mass gap

Black hole mass distribution



The LIGO Scientific Collaboration, the Virgo Collaboration and the KAGRA Collaboration, Phys. Rev. X **13**, 011048, March 2023

Rachel Gray's talk on Tuesday

Why is there a peak here? ⟷ H_0

To conclude

- Extreme astrophysical environments can probe weakly coupled particle physics across decades in mass
- There is a rich research program mining the astrophysical data to study fundamental physics
- We looked at a few classes of examples:
  - Heating of stellar remnants and exoplanets
  - Stellar evolution and energy loss
  - Gravitational waves and binary mergers

Thank you!

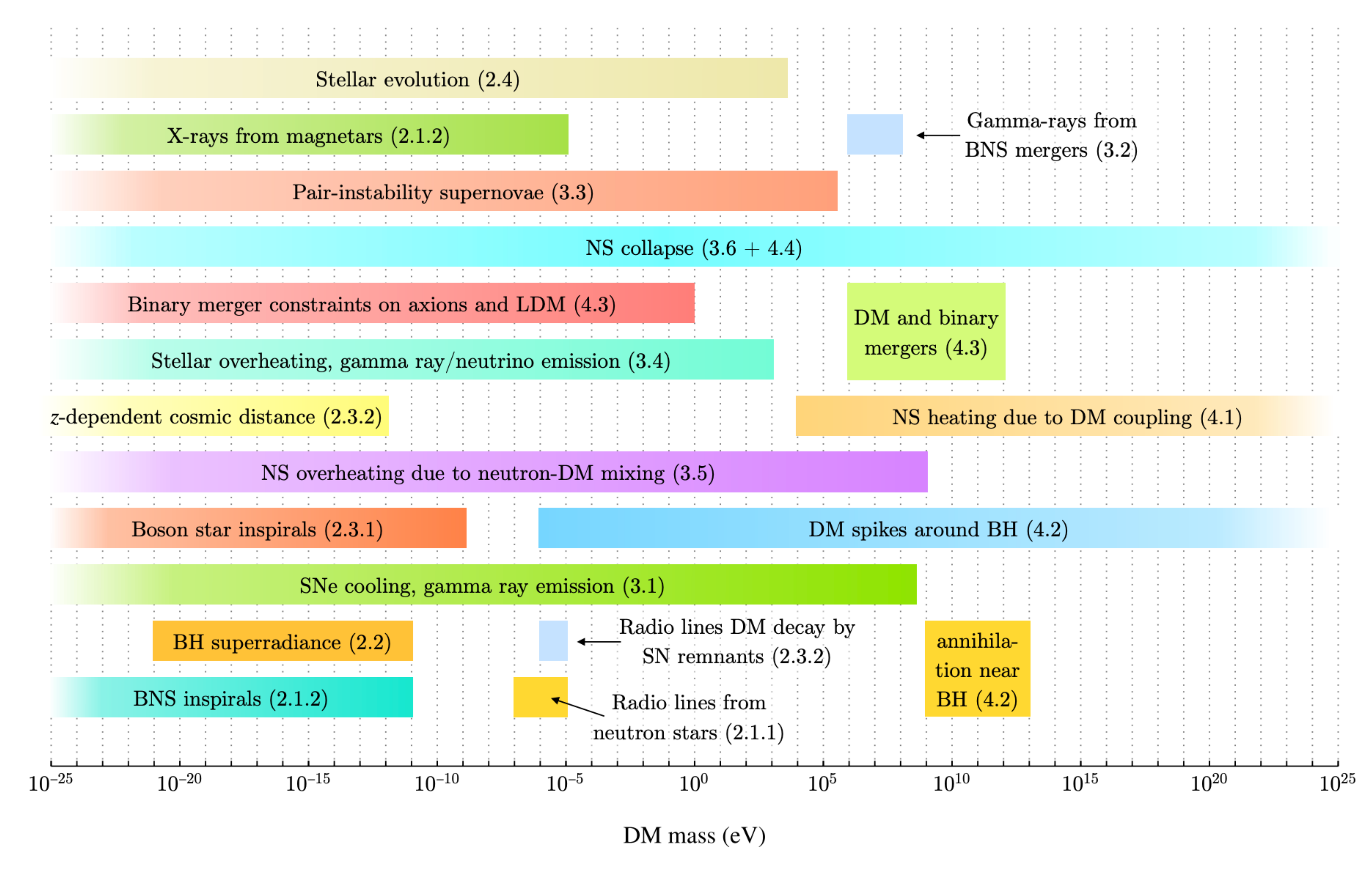
…ask me anything you like!

djuna.l.croon@durham.ac.uk | djunacroon.com

Community survey on
January 7 postdoc deadline

het.postdoc.deadline@gmail.com

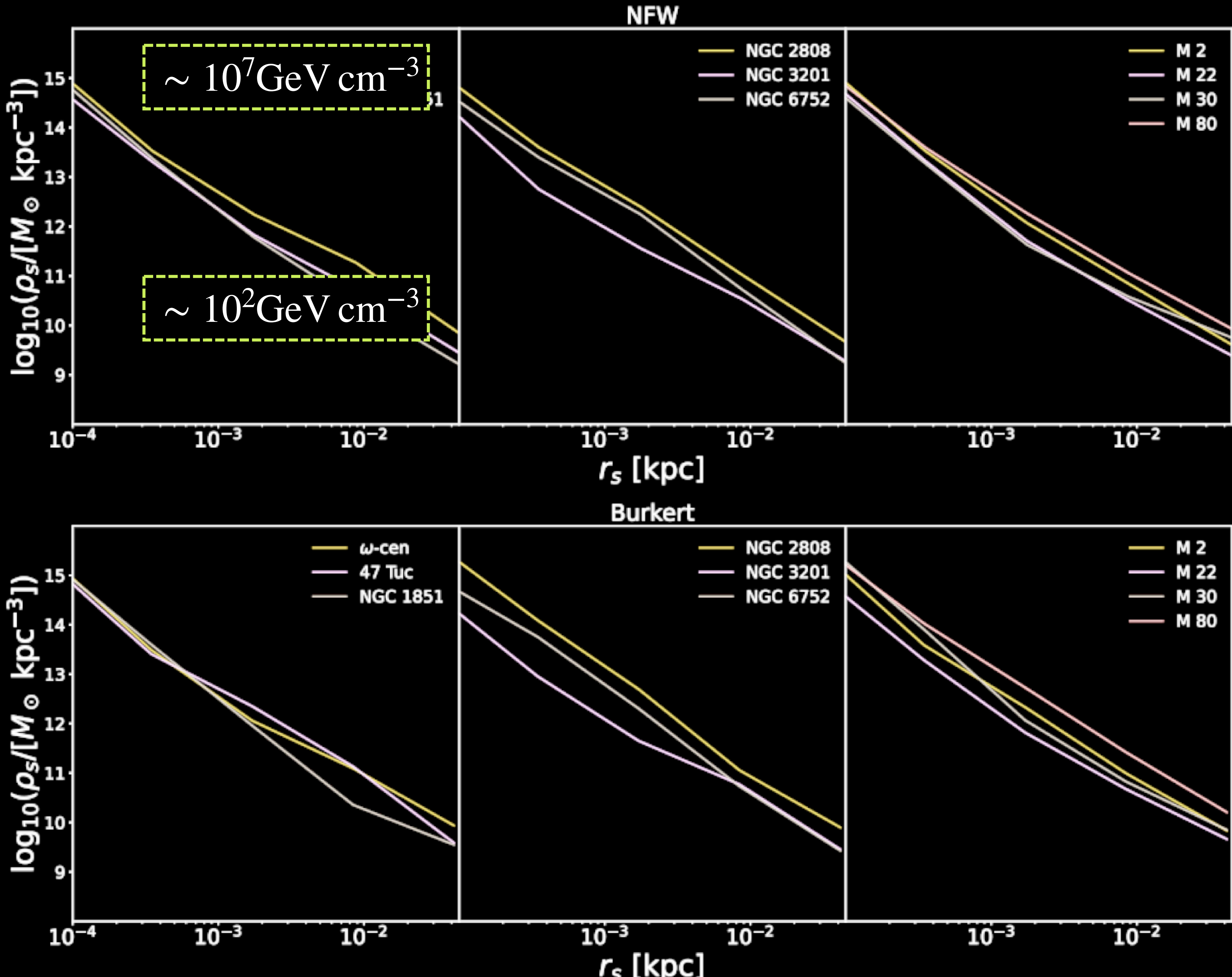
Back up slides



Baryakhtar, Caputo, DC, Perez et all, Snowmass summer study, arXiv:2203.07984

Reynoso-Cordova, Regis, Taoso, JCAP, arXiv:2203.13735

DM inside GCs



Supernova cooling

- Sensitive to DM abundance ✗

Type of DM	signal	mass range	coupling range
DM coupling to photons or SM fermions	SN: Multiple	$\lesssim 500$ MeV	$10^{-12} \lesssim G_{a\gamma\gamma}\,\text{GeV} \lesssim 5 \times 10^{-5}$

↑ Proto-NS temperature

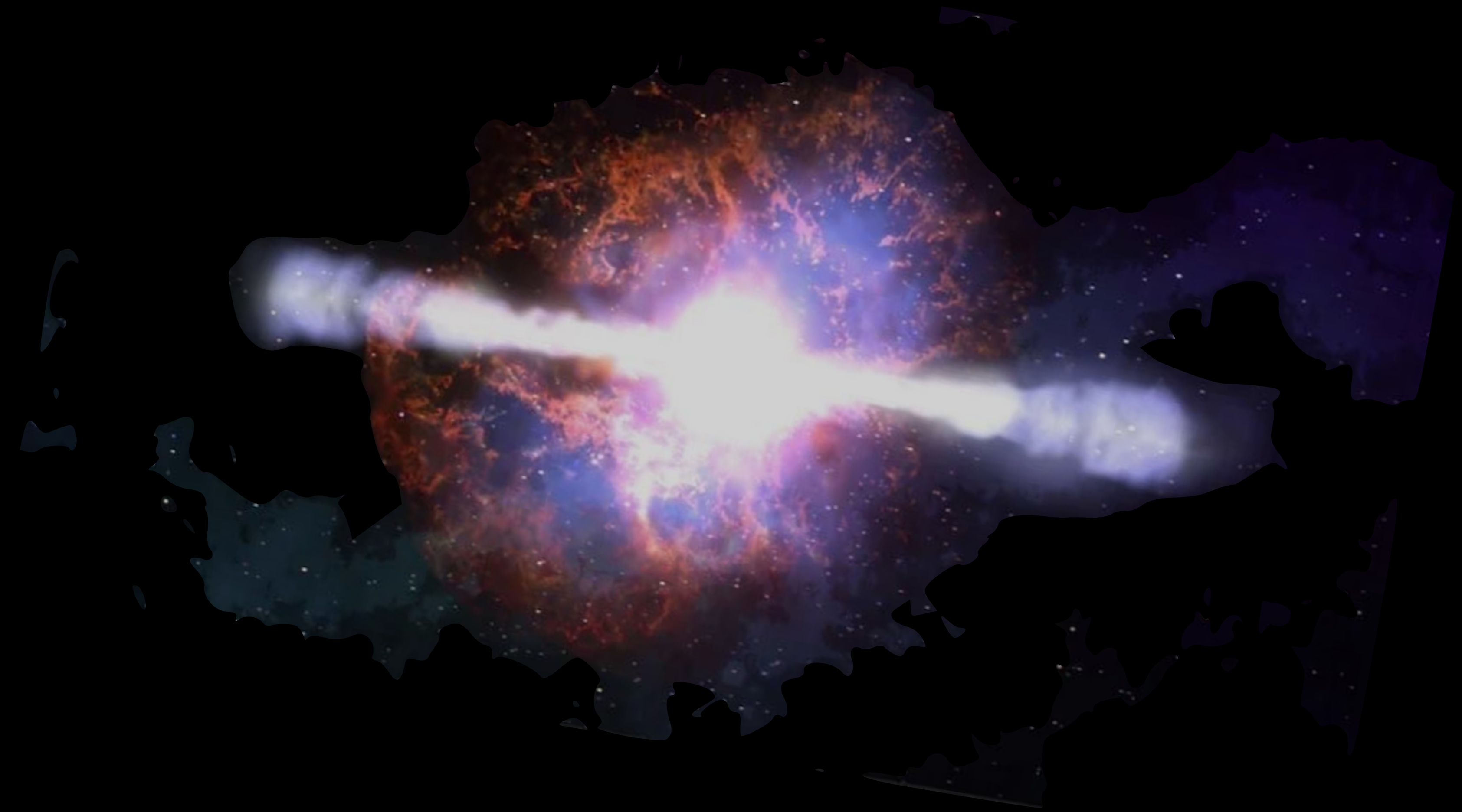
Supernova cooling

10^{53} erg emitted

$\sim 99\,\%$ as neutrinos

$\sim 10^{51}$ as kinetic energy of ejecta

$\sim 10^{48-49}$ as photons



Supernova cooling

10^{53} erg emitted

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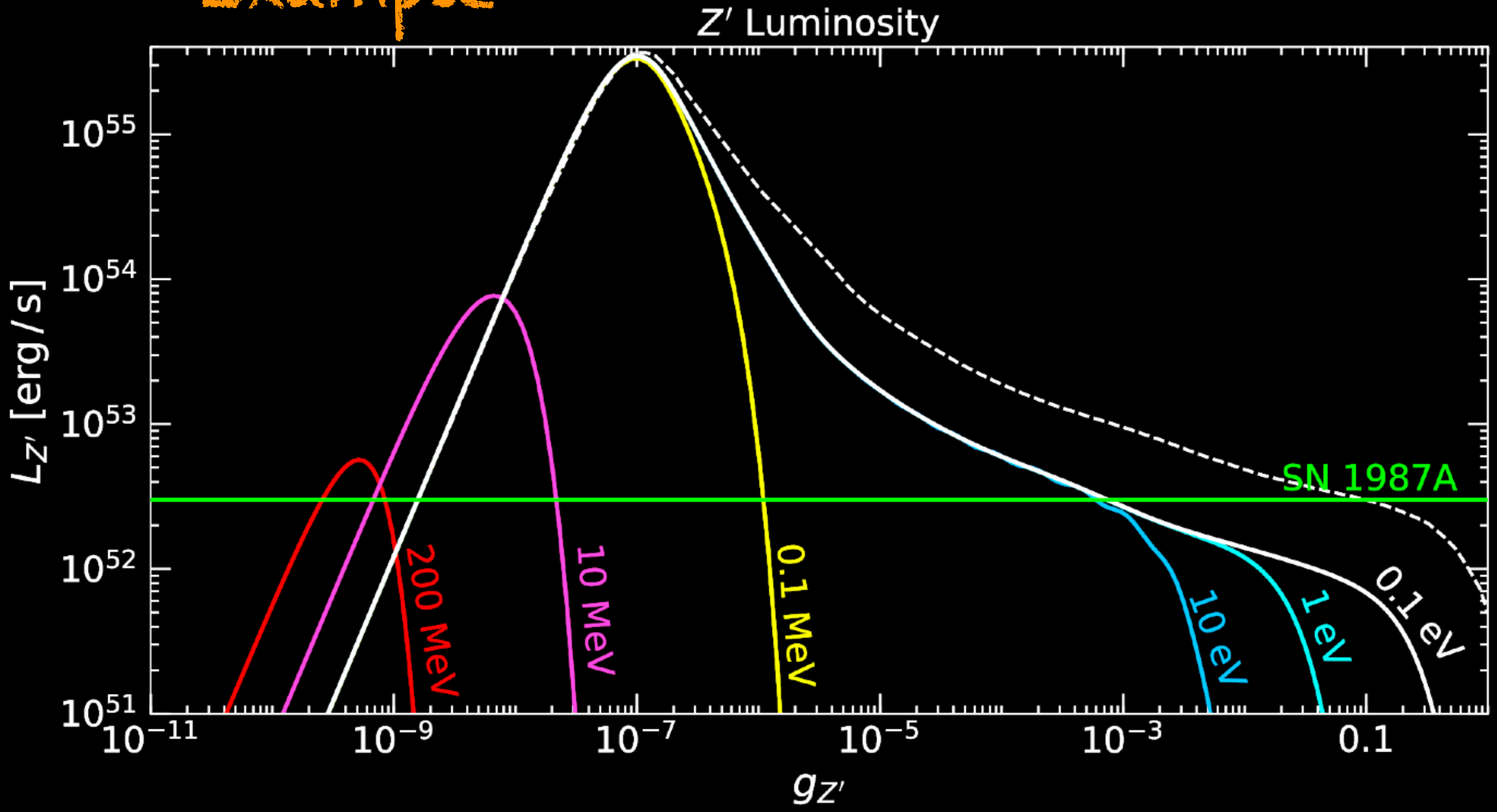
$\sim 10^{48-49}$ as photons

Compare new luminosity against ν luminosity

Example



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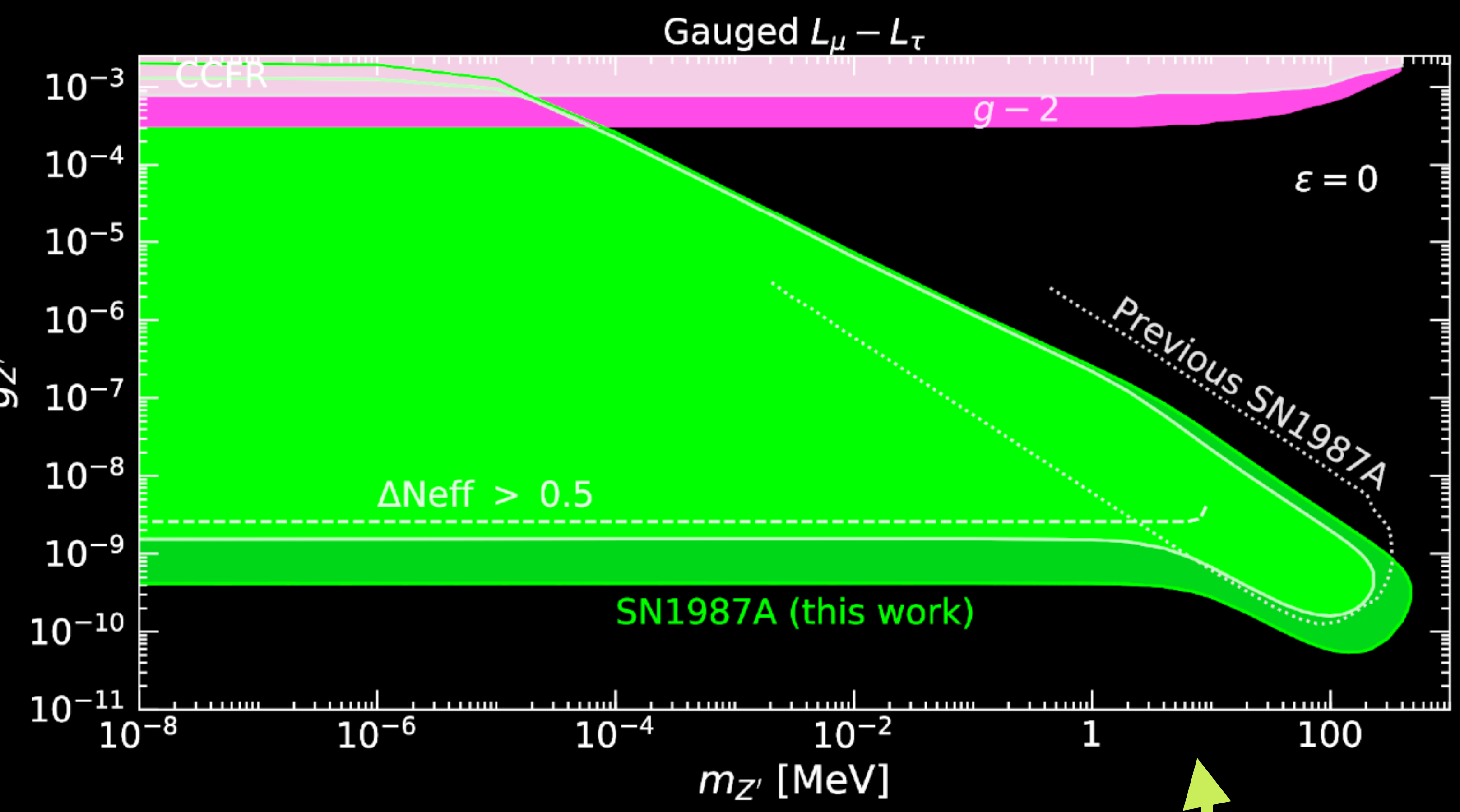
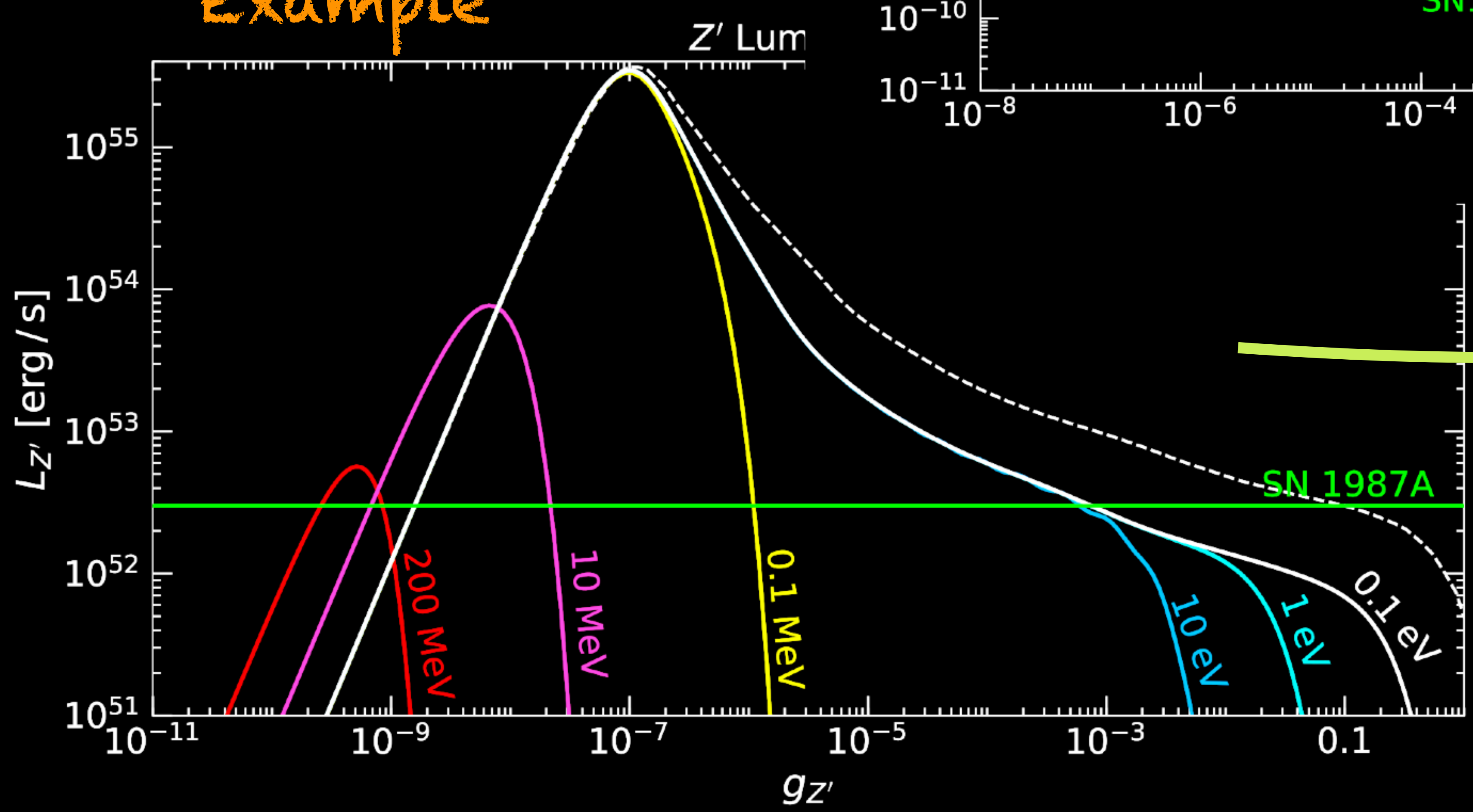


Example



Derive constraints from anomalous cooling SN1987a

Supernova cooling

10^{53} erg emitted

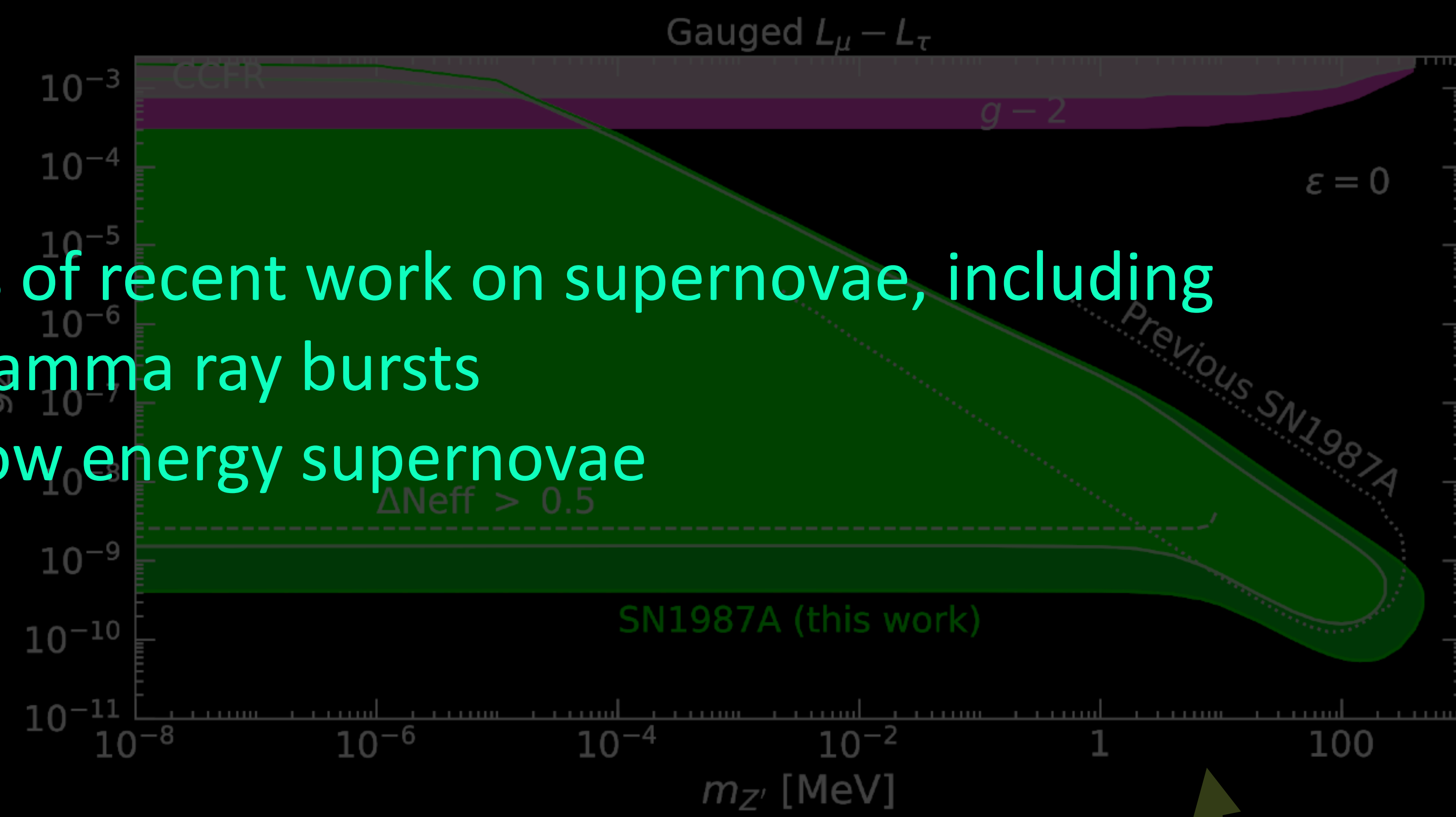
$\sim 99\,\%$ as neutrinos

$\sim 10^{51}$ as kinetic energy of

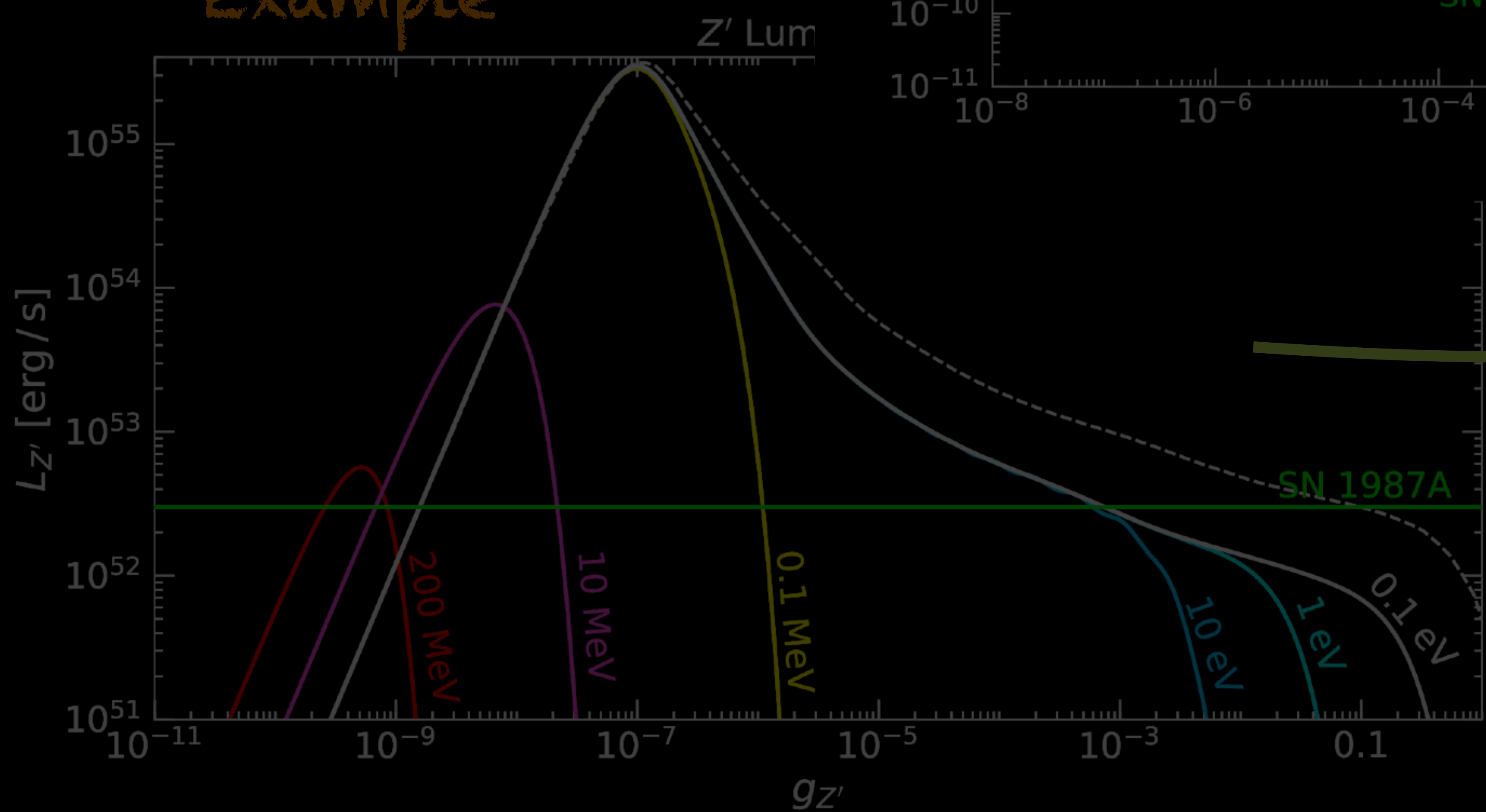
$\sim 10^{48-49}$ as photons

Lots of recent work on supernovae, including

- Gamma ray bursts
- Low energy supernovae

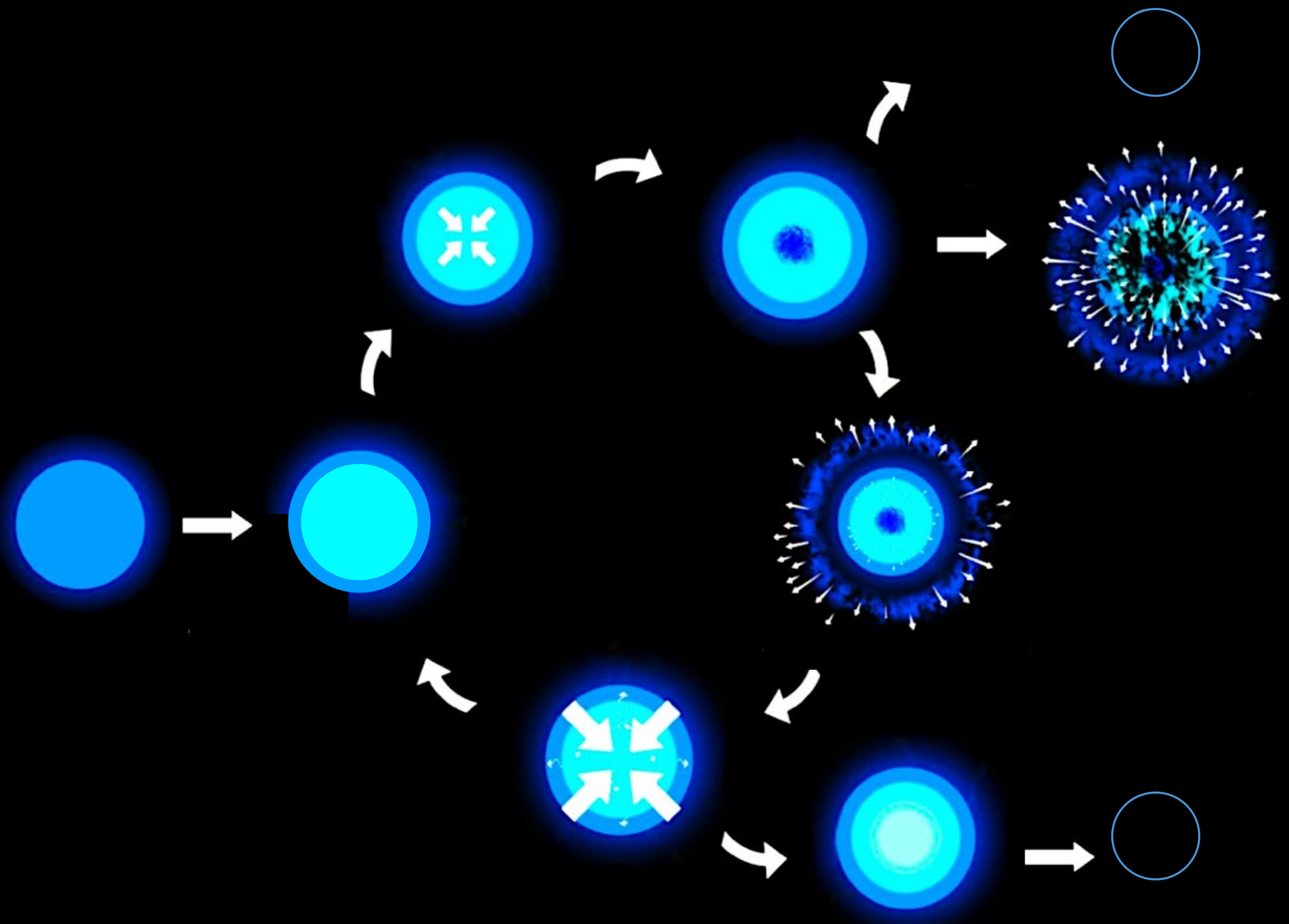


Example



Derive constraints from anomalous cooling SN1987a

Pair instability in a nutshell

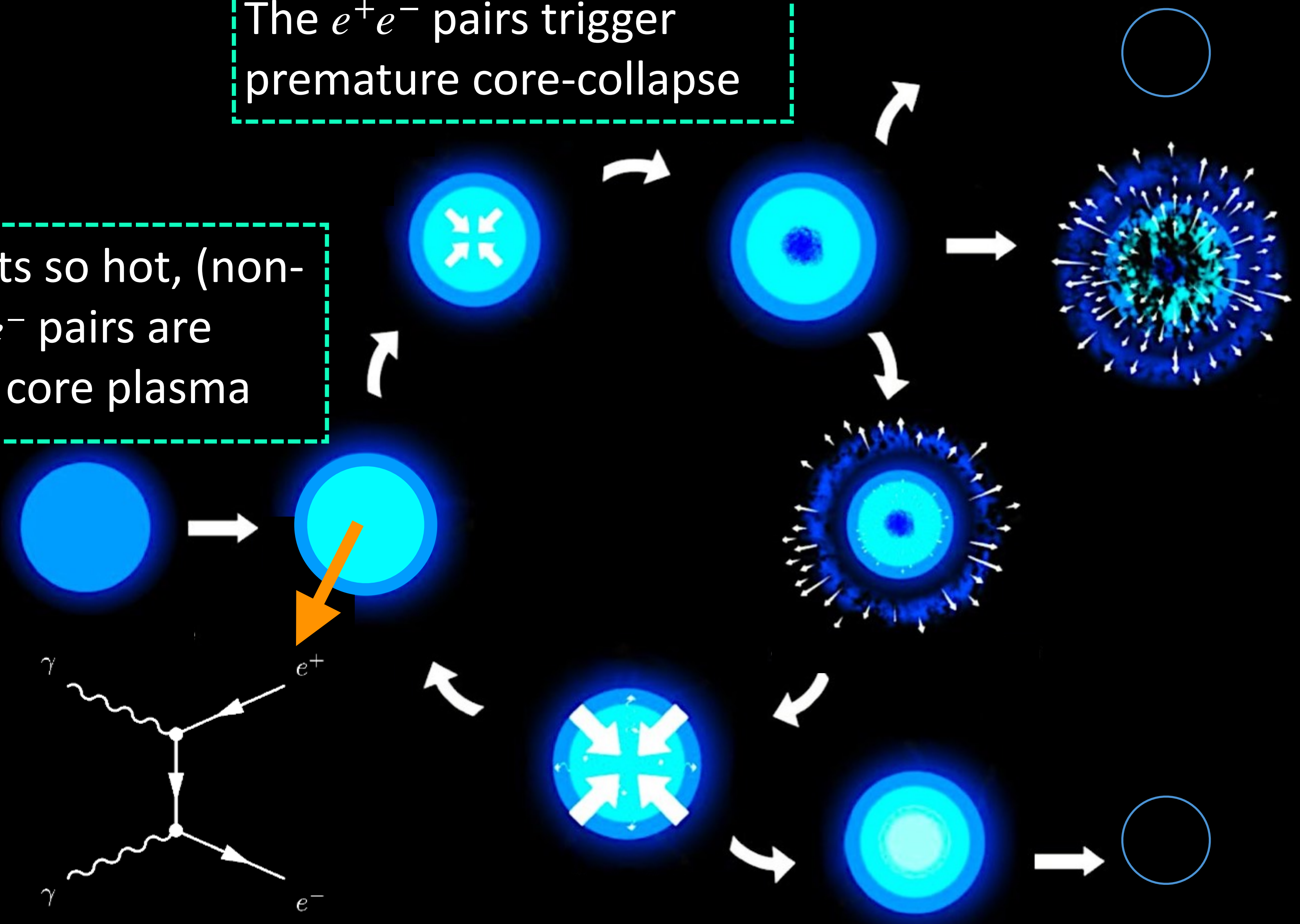


Adapted from Renzo et al
[2002.05077]

Pair instability in a nutshell

The e^+e^- pairs trigger premature core-collapse

1. The core gets so hot, (non-relativistic) e^+e^- pairs are created in the core plasma



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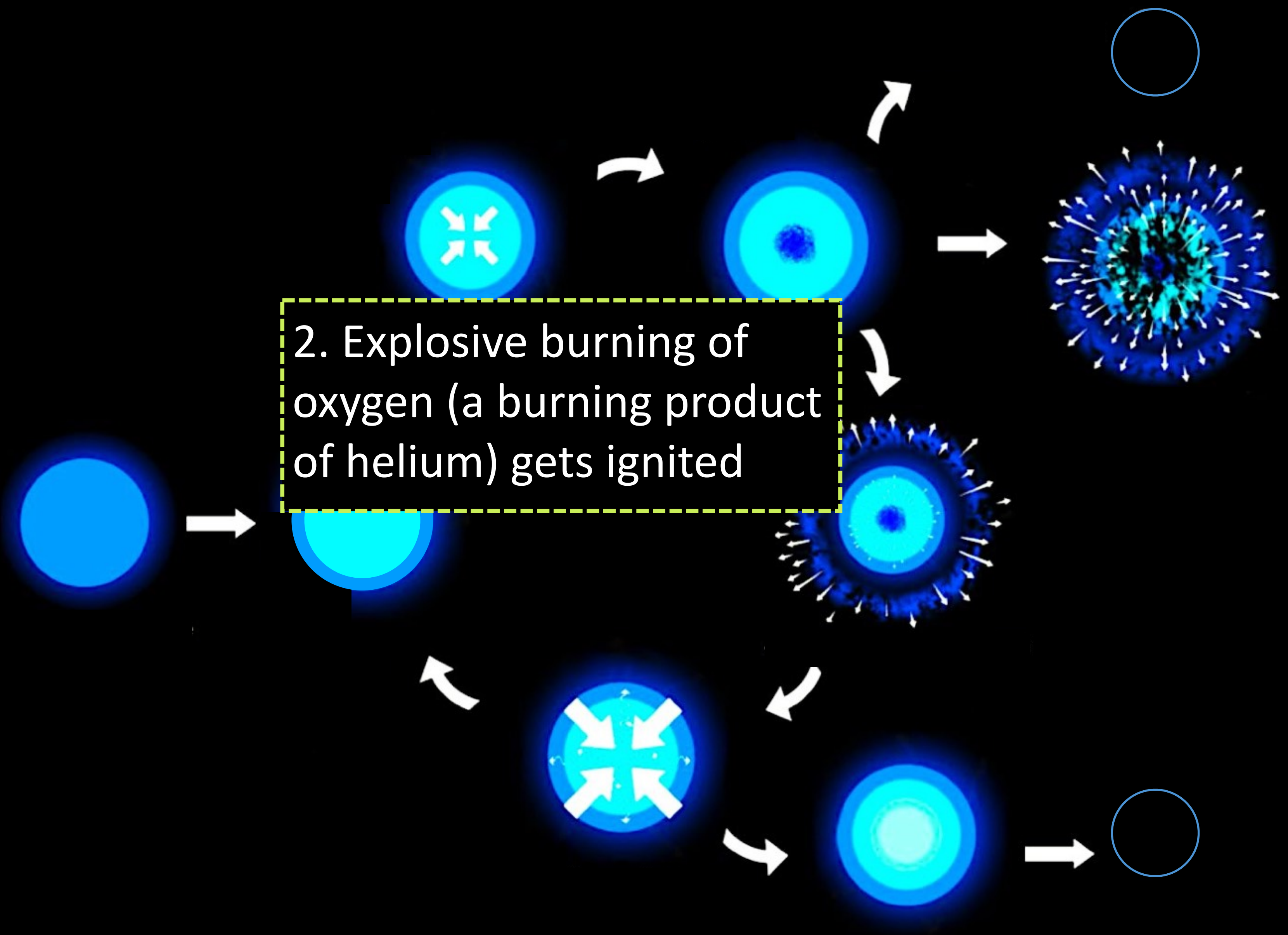

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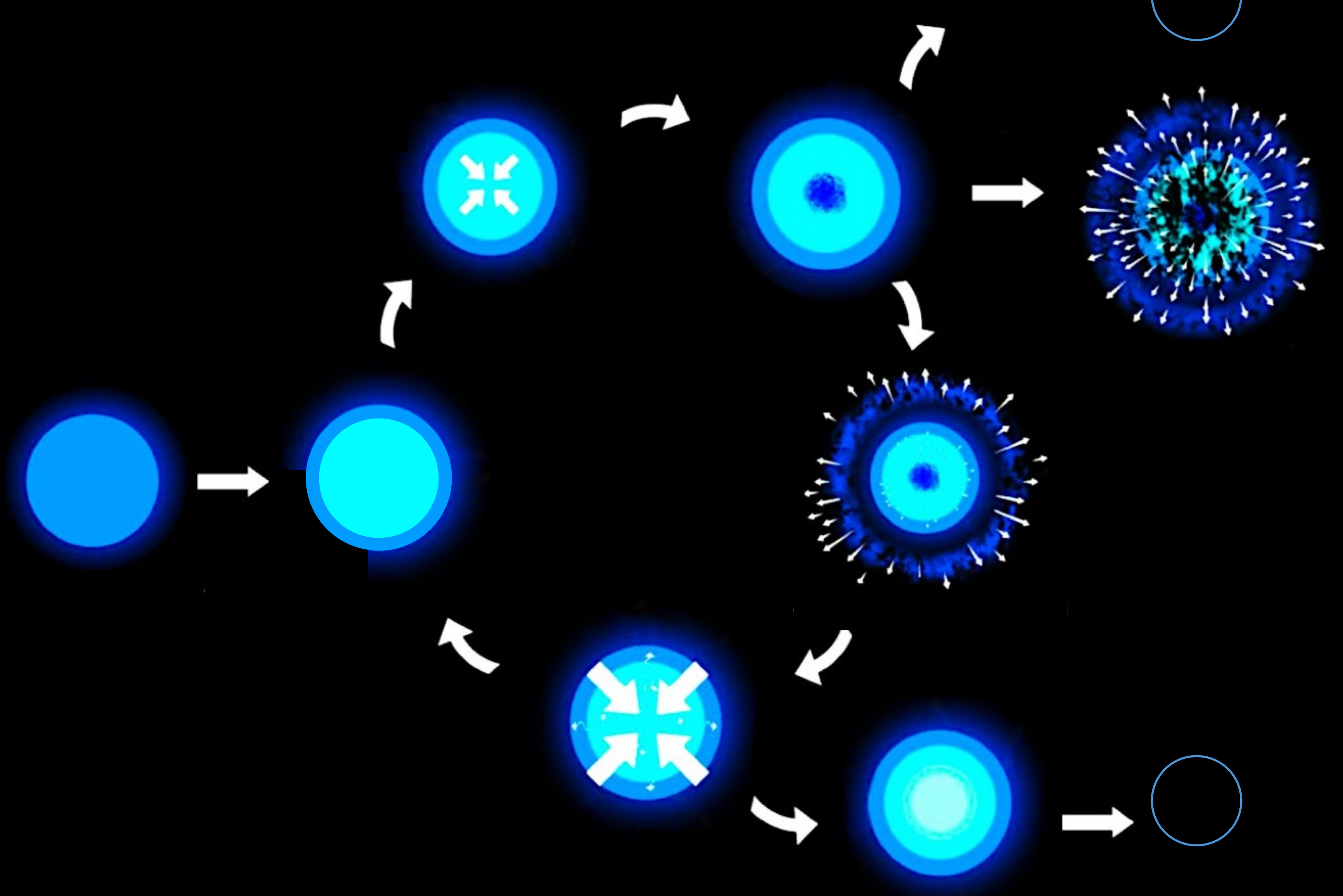


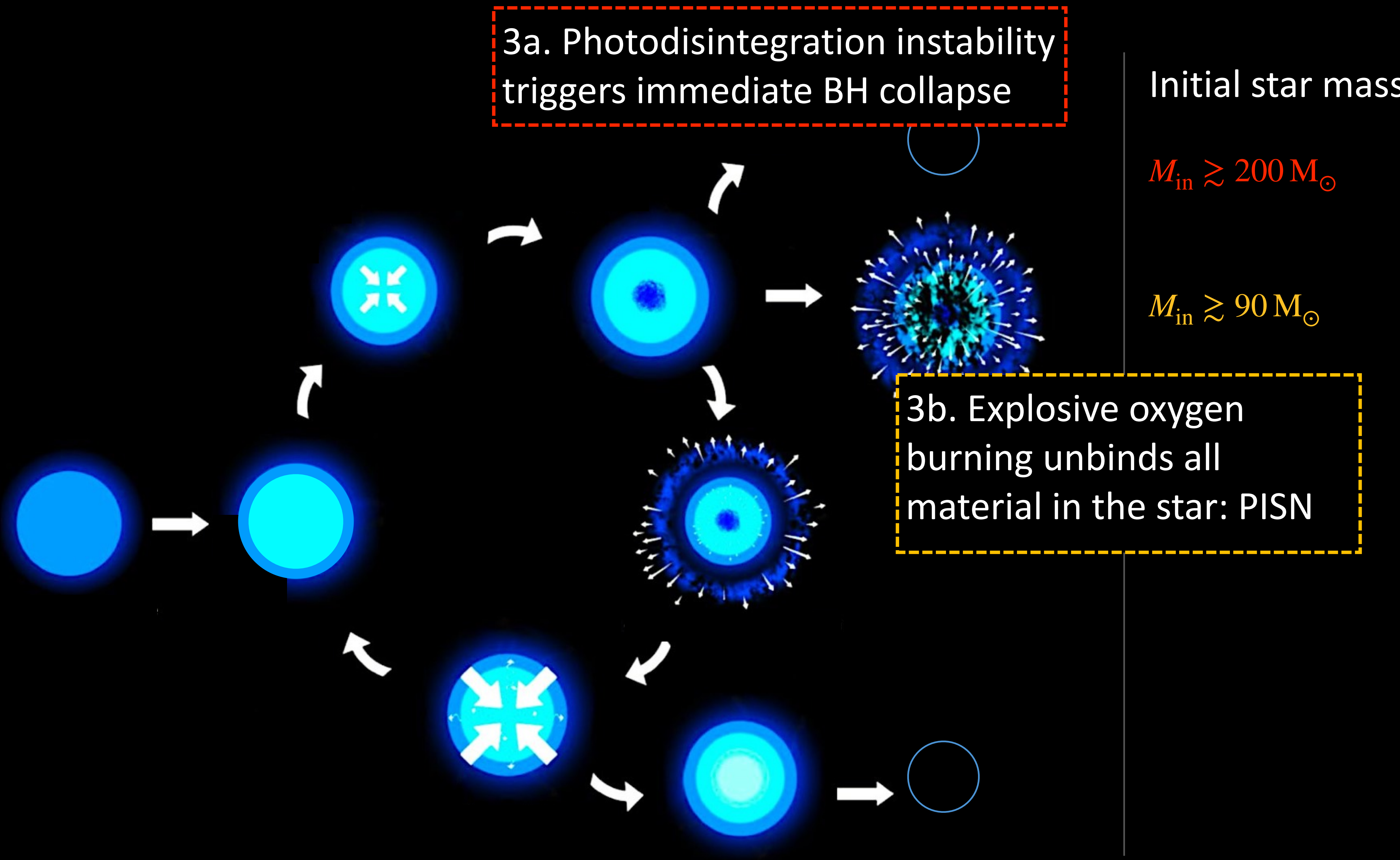
3a. Photodisintegration instability triggers immediate BH collapse

Initial star mass

$M_{in} \gtrsim 200\,M_\odot$

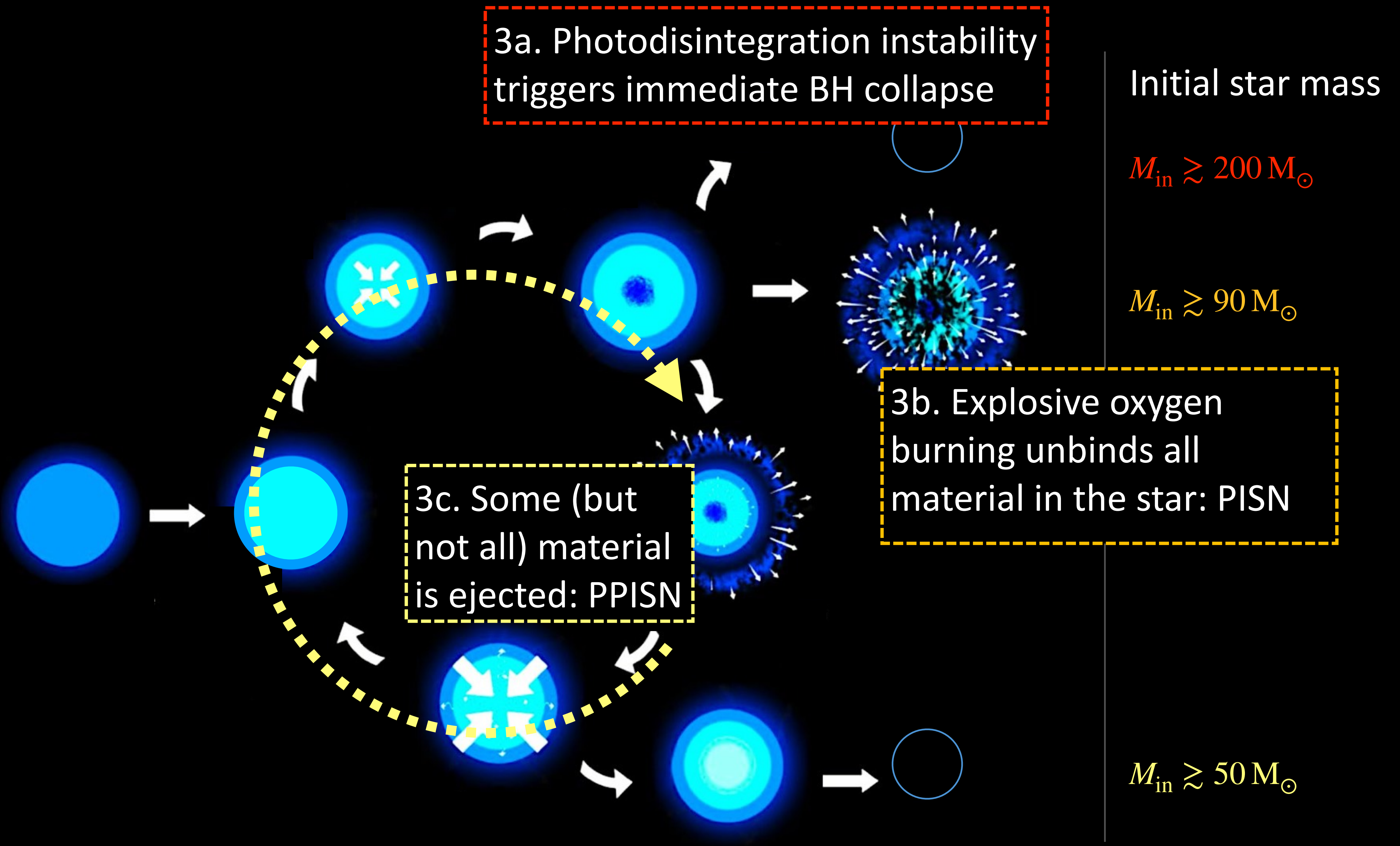
Adapted from Renzo et al [2002.05077]

Pair instability in a nutshell



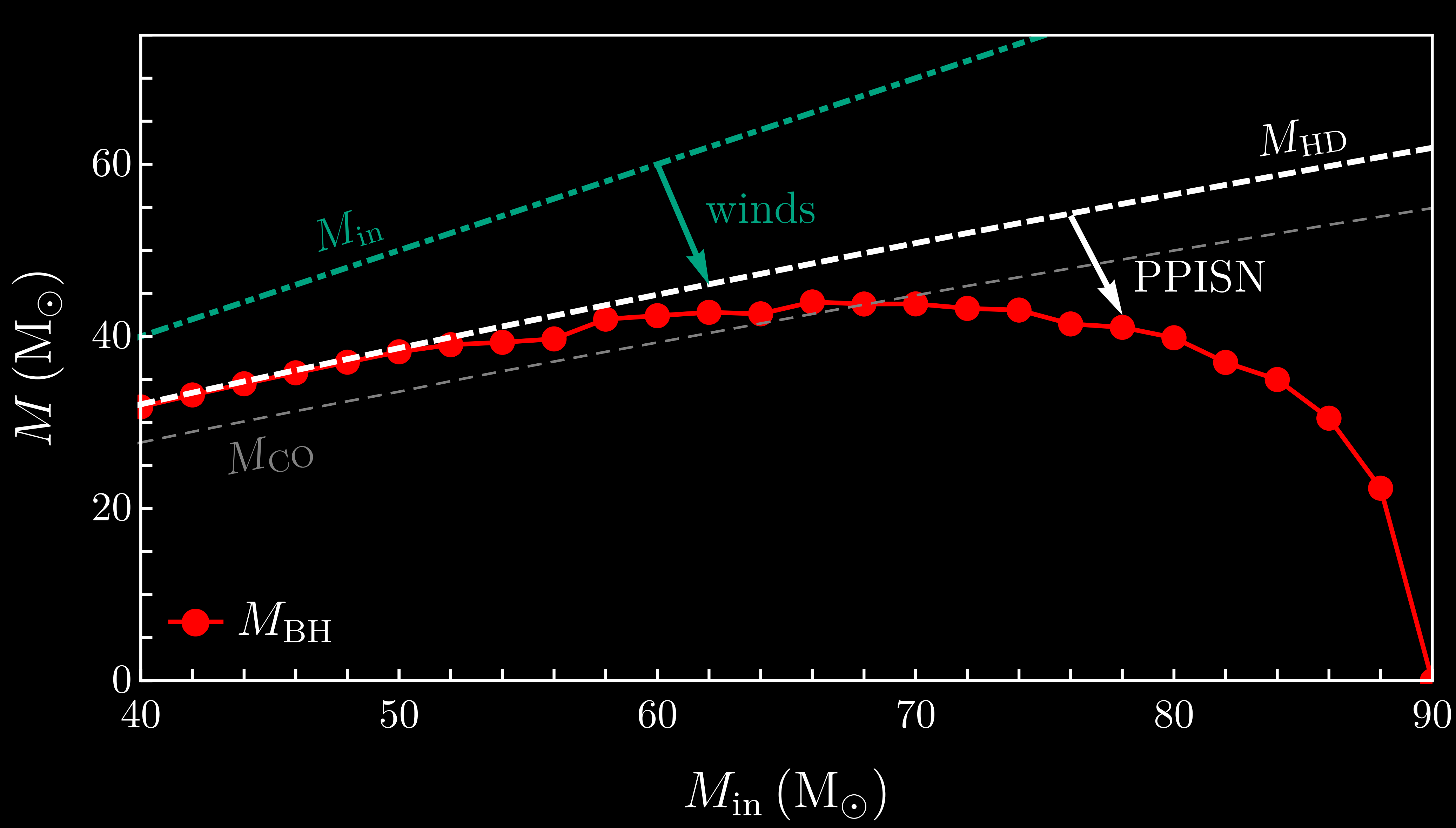
Adapted from Renzo et al [2002.05077]

Pair instability in a nutshell



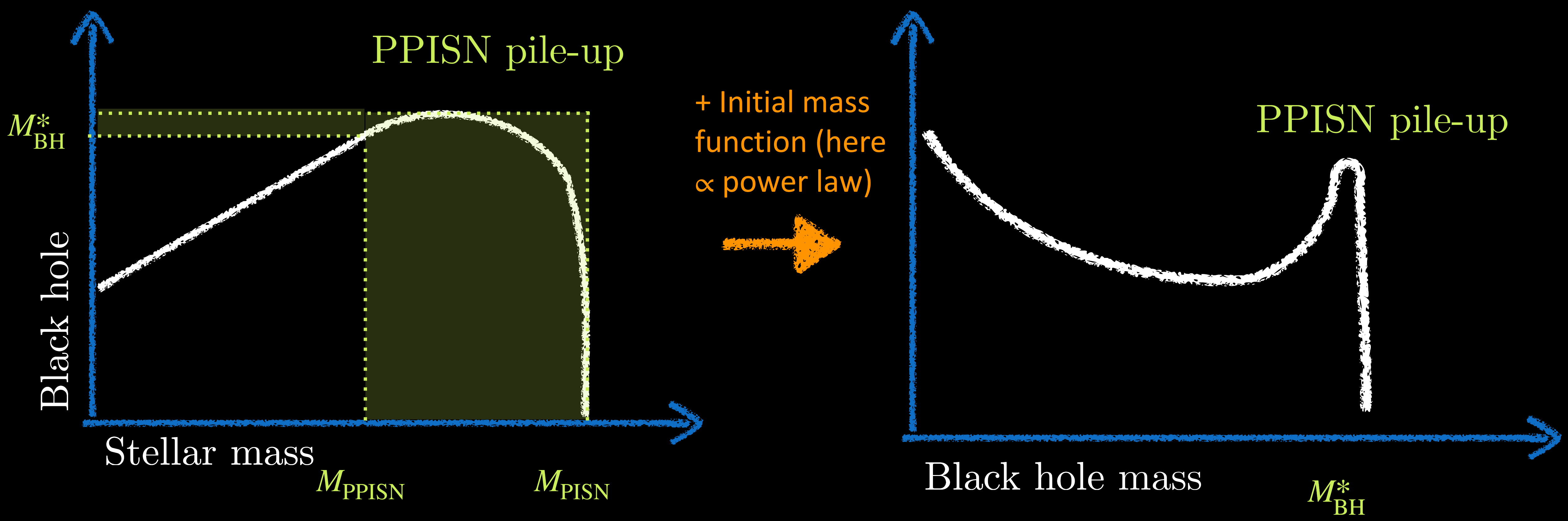
Adapted from Renzo et al [2002.05077]

Pair instability and BH masses



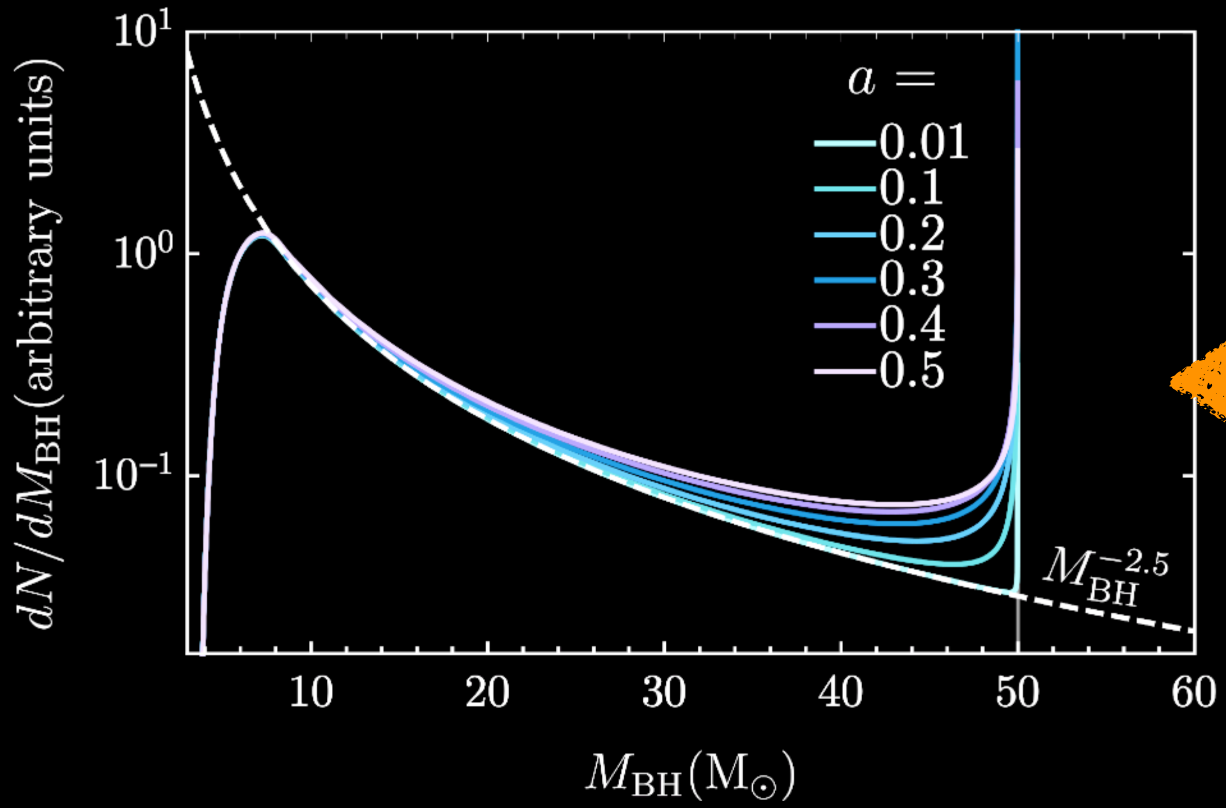
DC, McDermott, Sakstein, PRD, arXiv:2007.00650 [hep-ph]

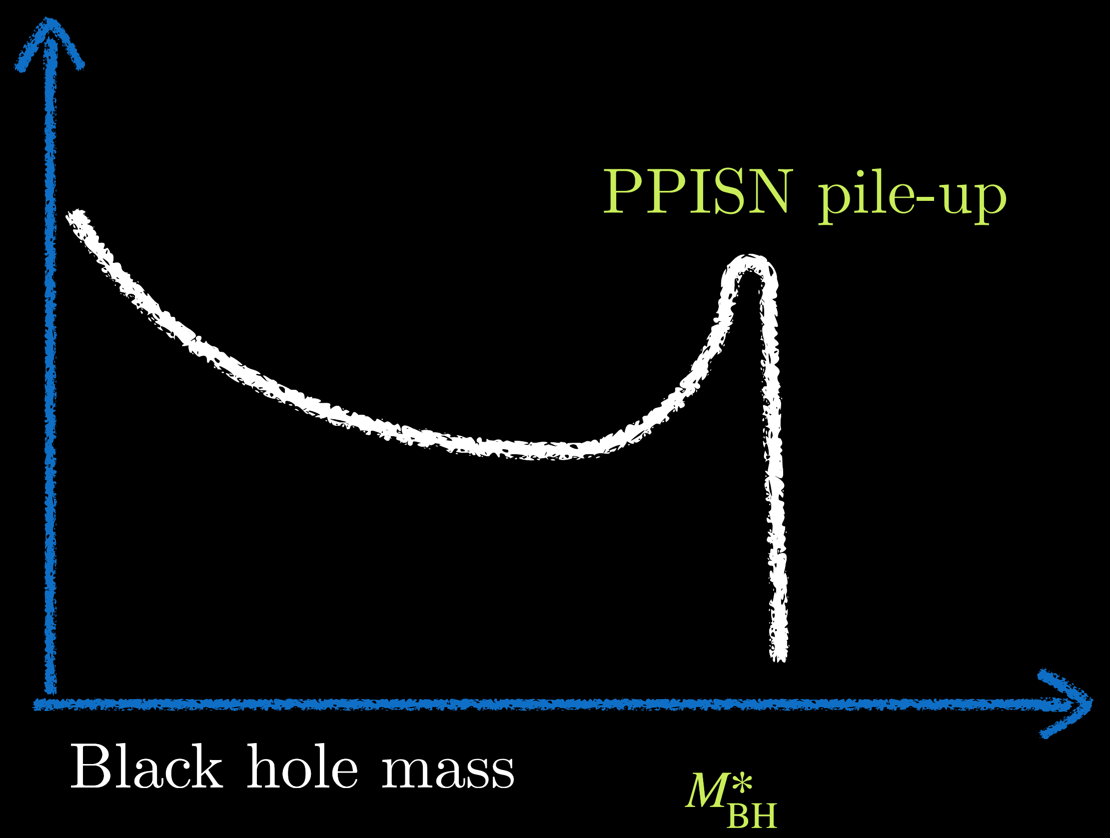
Pair instability and BH masses



See also Talbot & Trane, arXiv:1801.02699

Pair instability and BH masses





$$\frac{dN^{(1g)}_{\rm BH}}{dM_{\rm BH}} \propto M^b_{\rm BH}\left[1+\frac{2a^2 M^{1/2}_{\rm BH}(M_{\rm BHMG}-M_{\rm BH})^{a-1}}{M^{a-1/2}_{\rm BHMG}}\right]$$

Baxter, DC, McDermott, Sakstein, ApJL, arXiv:2104.02685