Diffuse Axion Background

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COST Action "Cosmic Wispers"
WG4 Topical Meeting
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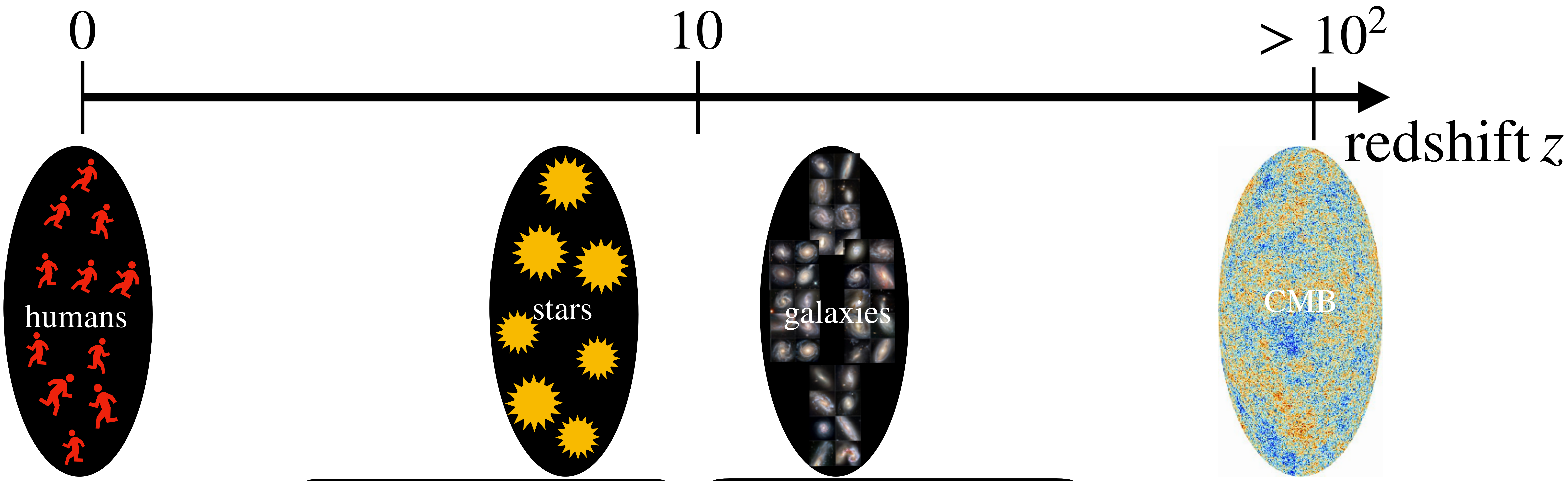
DALL-E 3 illustration
"Diffuse axion background"

Based on **Eby**, Takhistov (2402.00100)

Discovering Axions



traditional DM searches

$z \sim 0$

- cold, $v_{\rm dm} \sim 10^{-3}c$
- direct detection: local DM with $\rho_{\rm dm} \simeq 0.4\,{\rm GeV/cm^3}$
- indirect detection: annihilation flux from e.g. galactic center

transient searches

$z \sim 0 - {\rm few}$

- Relativistic burst passes Earth, leaving detectable signal

→ Boson stars / bosenovae:

Eby, Takhistov,
with Shirai, Stadnik (2106.14893)
with Arakawa, Safronova, Zaheer, (2306.16468, 2402.06736)

diffuse axion background

$z \sim {\rm few} - 30$

- build-up of large population of relativistic axions originating in astrophysical bursts

→ Supernovae: Raffelt, Redondo, Viaux (1110.6397)

→ General: **Eby**, Takhistov (2402.00100)

cosmic axion background

$z \gg 30$

- "Hot", $v \sim c$
- Relativistic population of axions from cosmological sources

Conlon and Marsh (1304.1804, 1305.3603)
Dror, Murayama, Rodd (2101.09287)

Astrophysical bursts of relativistic axions

characterised by

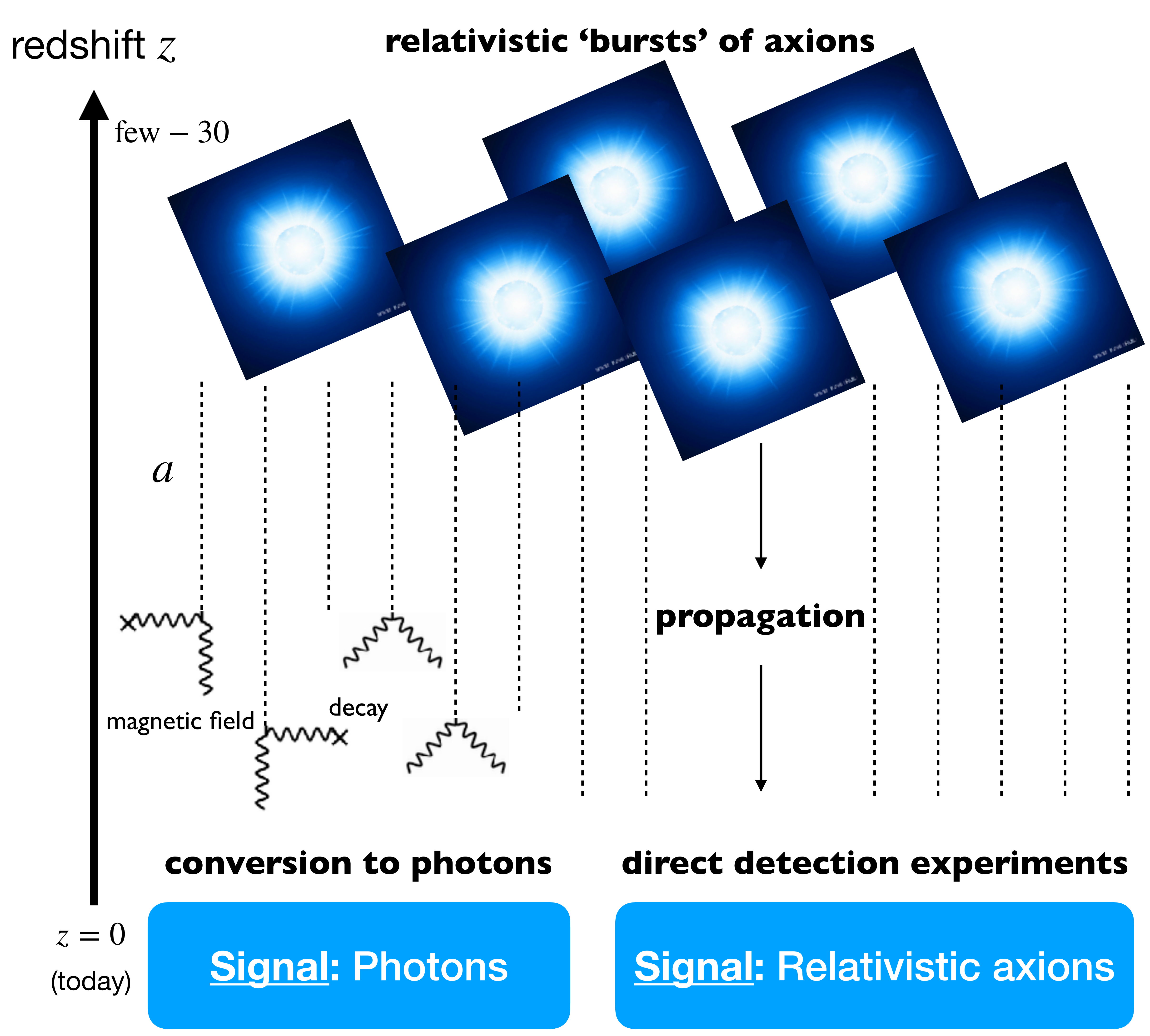
flux: $\frac{dN_a}{d\omega}(\omega)$

rate: $R_{\rm burst}(z)$

DaB flux* in present day

$$\frac{d\phi}{d\omega}(\omega) = \int_0^\infty dz \frac{dN_a(\omega(1+z))}{d\omega} \frac{R_{\rm burst}(z)}{H(z)}$$

*note: flux $\frac{dN_a}{d\omega}$ (# of particles) vs flux $\frac{d\phi}{d\omega}$ (# per area per time)



Diffuse Axion Background (DaB)

Broad Characterisation of Bursts

1. Dark sector source vs Standard Model source

2. Low energy, $\omega \gtrsim m_a$ vs High energy, $\omega \ggg m_a$

Bosenova

Credit: Kavli IPMU

Credit: Soubrette

Supernova

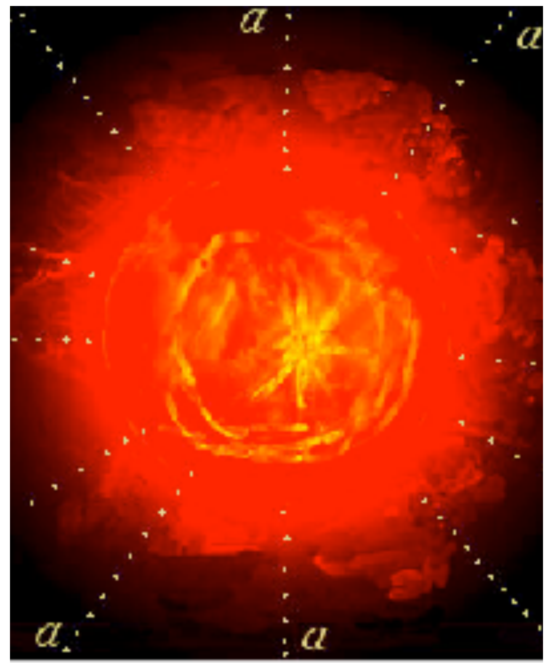
3. Transient emission vs Continuous emission

Bosenova

Supernova

PBH decay

Credit: HESS Collaboration



Credit: Di Luzio et al

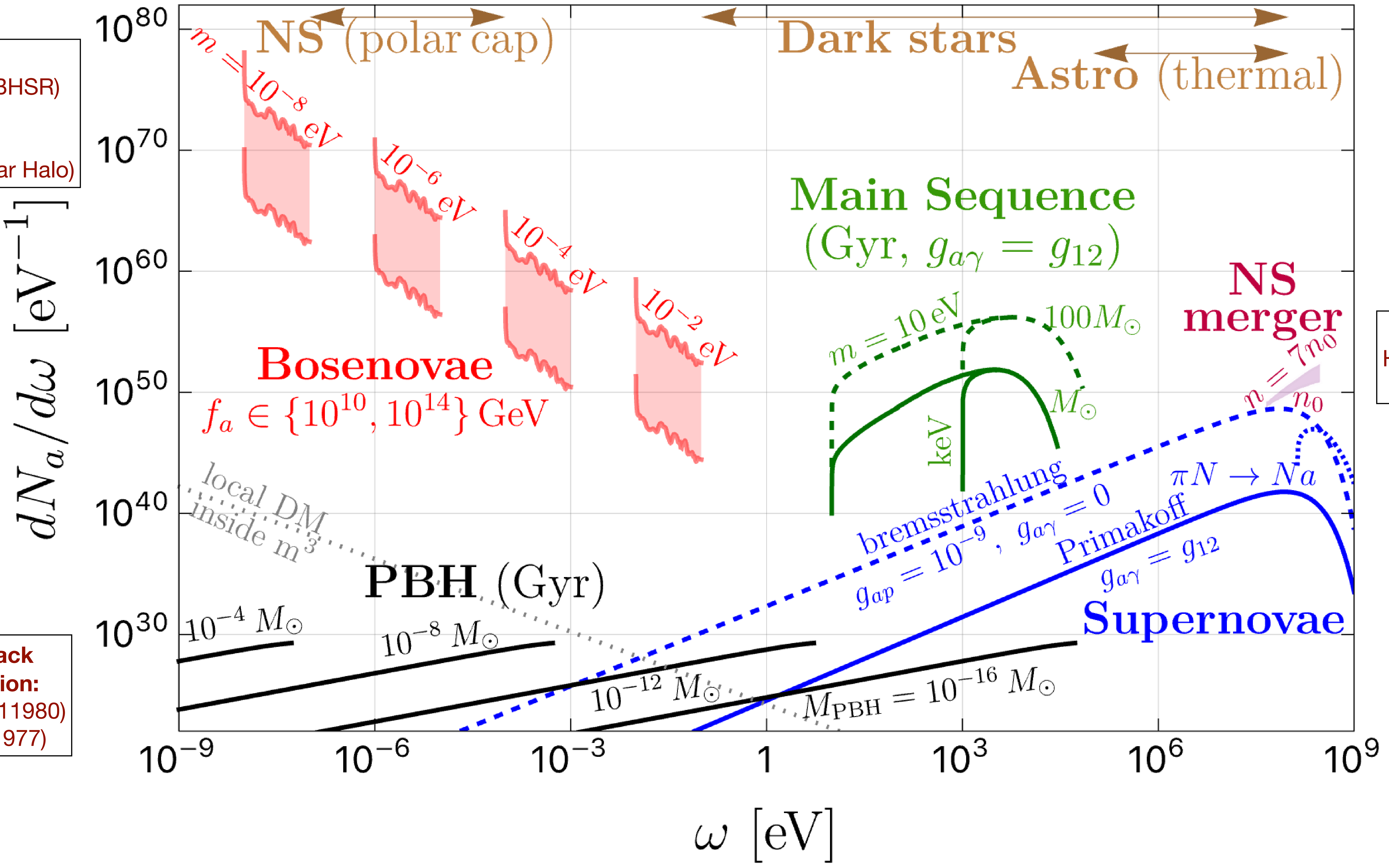
Main Sequence

Bursts Abound

NS polar cap:
Prabhu (2104.14569)
Noordhuis++ (2209.09917, 2307.11811)

Dark stars:
Maselli++ (1704.07286)
Curtin, Setford (1909.04072)
Hippert++ (2103.01965)

Bosenovae:
Yoshino, Kodama (1203.5070) (BHSR)
Levkov, Panin, Tkachev (1609.03611) (Boson Star)
Budker, **Eby**++ (2306.12477) (Solar Halo)



Main sequence stars:
e.g. Nguyen, Tanin, Kamionkowski (2307.11216)

Neutron star mergers:
Harris, Fortin, Sinha, Alford (2003.09768)
Fiorillo, Iocco (2109.10364)

Supernovae:
Original DaB idea:
Raffelt, Redondo, Viaux (1110.6397)
Recent update:
Carenza++ (1906.11844)
Calore++ (2008.11741)

Primordial black hole evaporation:
Agashe++ (2212.11980)
Jho++ (2212.11977)

Eby, Takhistov (2402.00100)

Eby, Takhistov, (2402.00100)

Parameterization: Flux

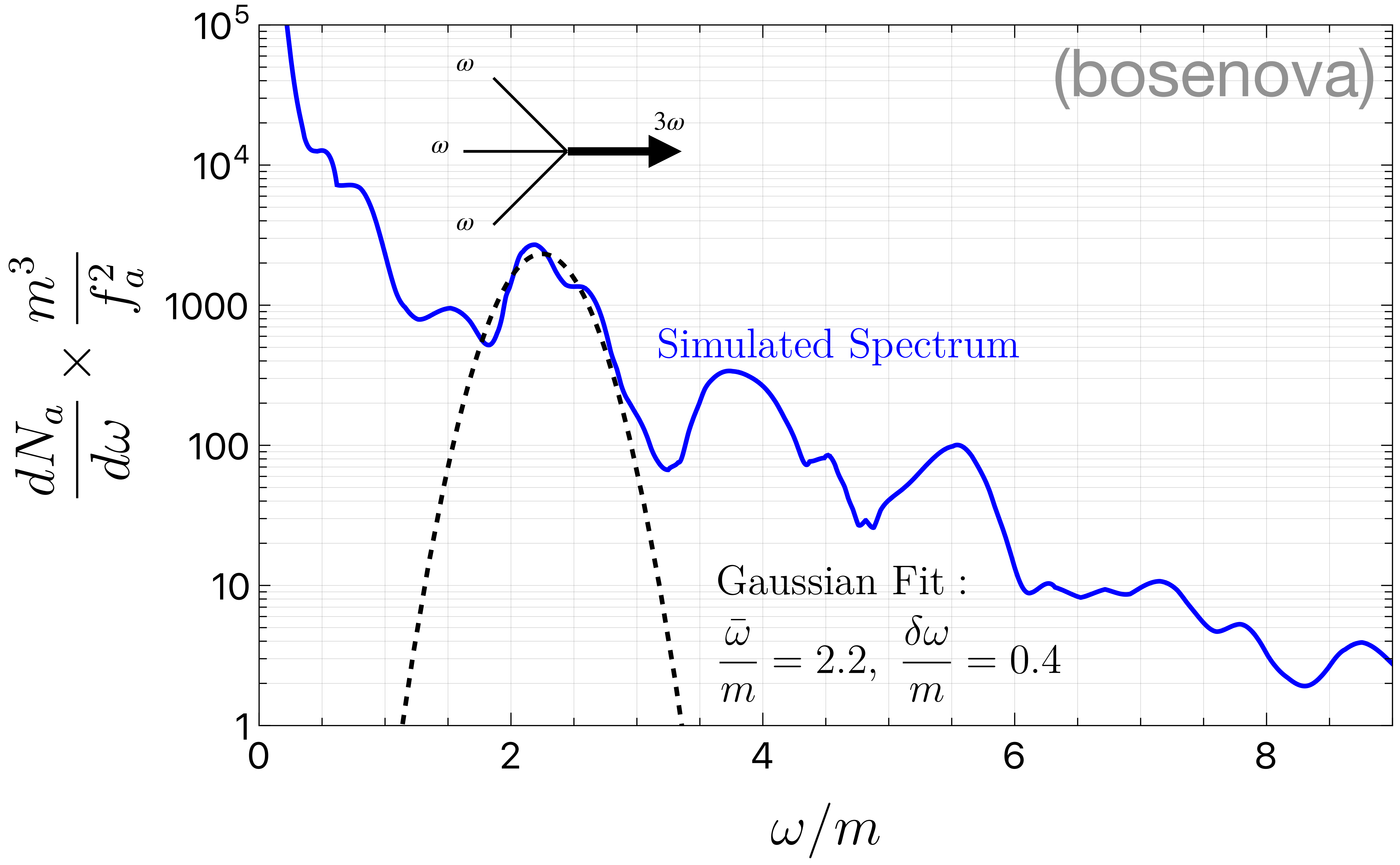
$$\frac{dN_a}{d\omega}(\omega) \propto \frac{E_{\rm tot}}{m_a^2} \frac{\exp\left(-\frac{(\omega-\bar{\omega})^2}{\delta\omega^2}\right)}{\delta\omega/m_a}$$

→

$E_{\rm tot}$: total energy emitted in single burst

$\bar{\omega}$: peak energy

$\delta\omega$: energy width



- easily captures peaked distribution
- computationally simple
- sum of Gaussians can be used for asymmetric distributions, e.g. power-law

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Parameterization: Rate

$$f(z) = (1+z)^p \Theta(z - z_{max})$$ for power-law

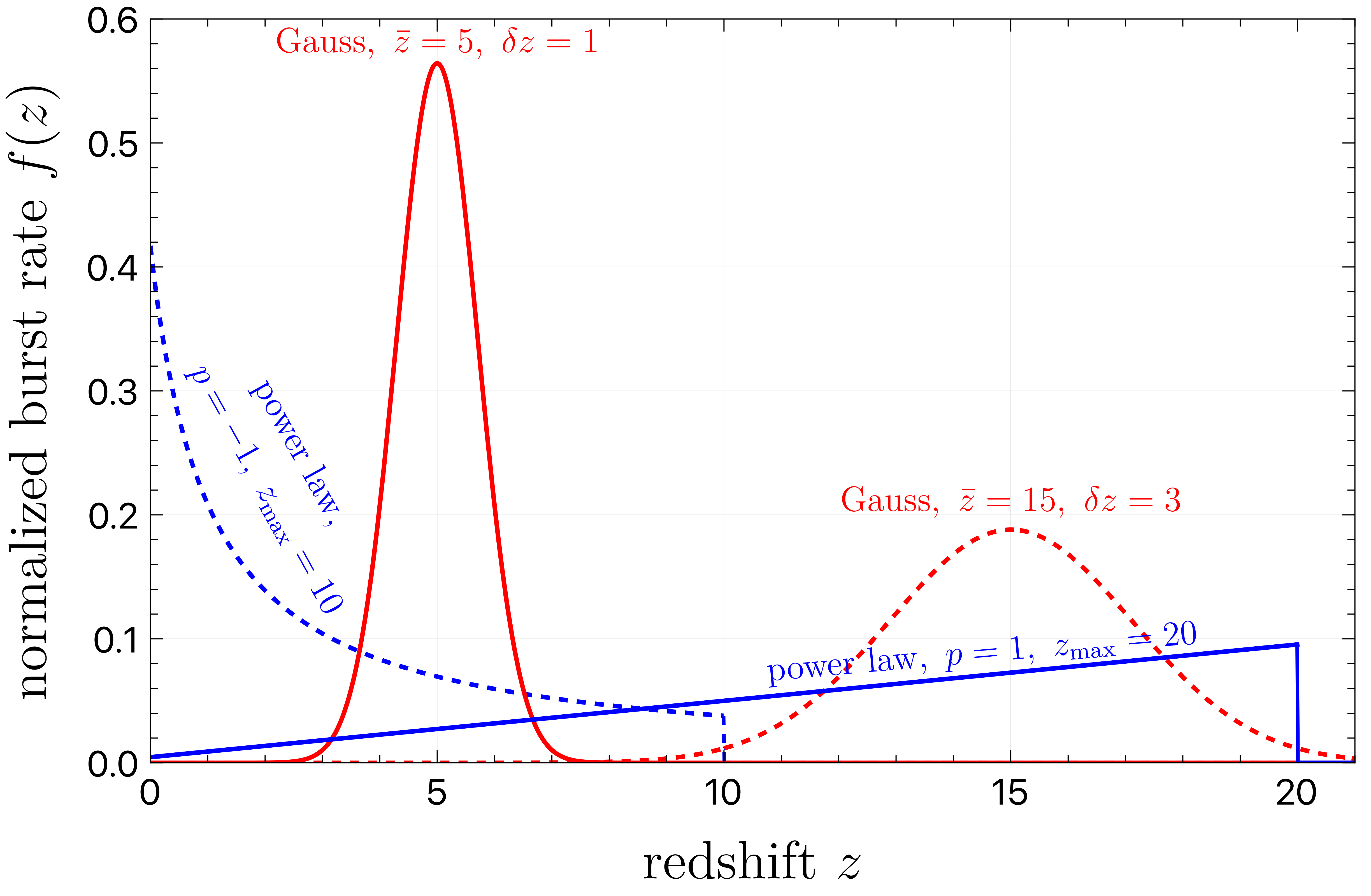
$$R_{burst}(z) \propto \frac{\rho_{loss} H_0}{E_{tot}(z)} f(z)$$

$$f(z) = \exp\left(-\frac{(z-\bar{z})^2}{\delta z^2}\right)$$ for Gaussian

ρ_{loss}: total relativistic energy density emitted across all z

Convenient normalisation:

$$\rho_{loss} \equiv \mathscr{F}\, \bar{\rho}_U$$ with $\bar{\rho}_U \simeq 10^{-6}\,\mathrm{GeV/cm^3}$



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Parameterization: DaB

$$\frac{dN_a}{d\omega}(\omega) \propto \frac{E_{\rm tot}}{m_a^2} \frac{\exp\left(-\frac{(\omega-\bar{\omega})^2}{\delta\omega^2}\right)}{\delta\omega/m_a}$$

$$R_{\rm burst}(z) \propto \frac{\mathcal{F}\bar{\rho}_{\rm U} H_0}{E_{\rm tot}} f(z)$$

- $\mathcal{F}$: total DM fraction converted to DaB
- $f(z)$: dimensionless rate of bursts
- $\bar{\omega}$: peak burst energy per particle
- $\delta\omega$: spread in burst energy per particle
- $E_{\rm tot}$: energy emitted per burst

DaB flux in present day

$$\frac{d\phi}{d\omega}(\omega) = \int_0^\infty dz \frac{dN_a(\omega(1+z))}{d\omega} \frac{R_{\rm burst}(z)}{H(z)}$$

input parameters

particle physics	burst parameterisation	
$m_a, f_a, g_{a\gamma}, \ldots$	$\mathcal{F}, f(z)$ (cosmology)	$\bar{\omega}, \delta\omega$, ~~$E_{\rm tot}$~~ (individual bursts)

cancels in product

How to search for DaB: (1) direct detection, (2) photon signals, [more to come]

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DaB Flux vs DM Flux

Locally, $\left(\frac{d\phi}{d\omega}\right)_{\text{local DM}} \simeq \frac{n_a v_{\rm dm}}{m_a} \simeq \frac{\rho_{\rm dm}}{m_a^2} v_{\rm dm}$

DaB flux in present day

$$\frac{d\phi}{d\omega}(\omega) = \int_0^\infty dz \frac{dN_a(\omega(1+z))}{d\omega}\frac{R_{\rm burst}(z)}{H(z)}$$

Parameterise flux and rate

$$\sim \frac{\mathcal{F}\bar{\rho}_{\rm U}}{m_a \delta\omega}\int dz f(z)\frac{H_0}{H(z)}\exp\left[-\left(\frac{(\omega(1+z)-\bar{\omega})}{\delta\omega}\right)^2\right]$$

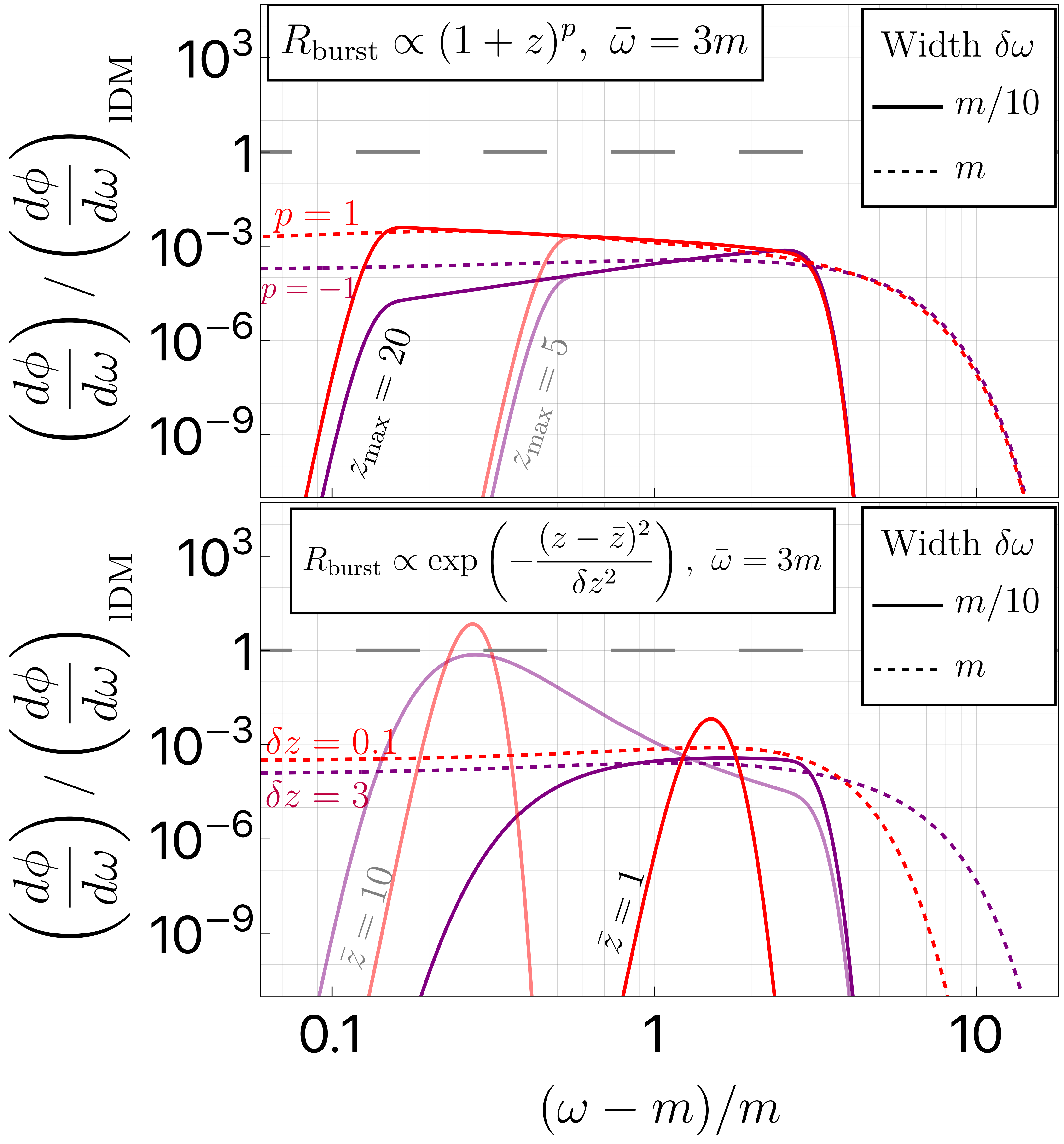
narrow: $\frac{\delta\omega}{\omega} \to 0$

recent: $z \sim 0$

$$\sim \frac{\mathcal{F}\bar{\rho}_U}{\bar{\omega}^2}$$

$$\frac{d\phi/d\omega}{(d\phi/d\omega)_{\rm lDM}} \simeq \left(\frac{1}{v_{\rm dm}}\right)\left(\frac{m_a}{\bar{\omega}}\right)^2\left(\frac{\mathcal{F}\bar{\rho}_U}{\rho_{\rm dm}}\right) \simeq 3\cdot 10^{-3}\mathcal{F}\left(\frac{m_a}{\bar{\omega}}\right)^2$$

(large) (small) (small)



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Direct Detection

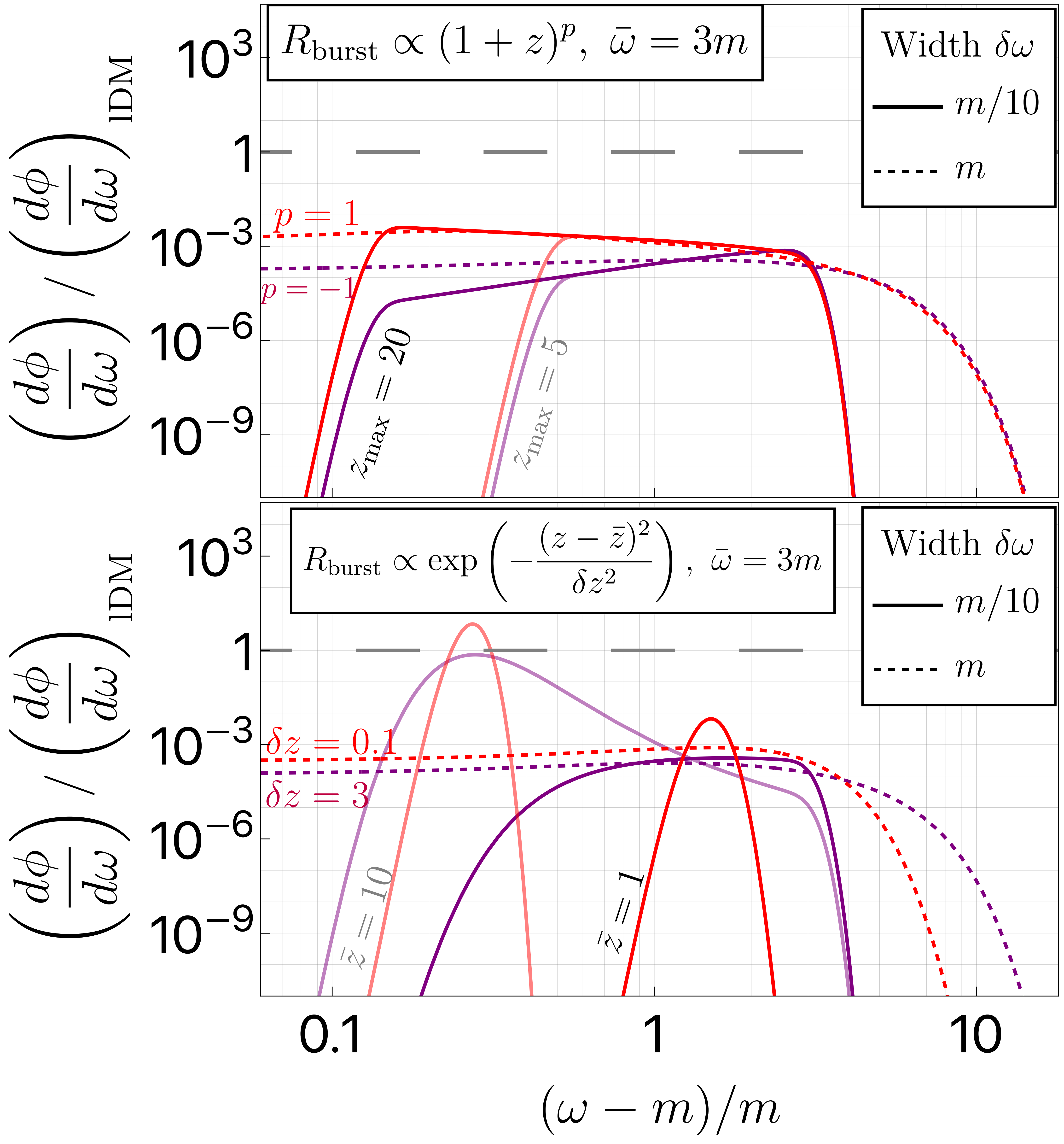
Likely challenging!

- DaB flux generally $\lesssim$ local DM flux
- Signal likely much less coherent than local DM

$$\tau_{coh} \simeq \frac{2\pi}{m_a v^2}, \quad v_{dm} \sim 10^{-3} \text{ vs } v_{DaB} \sim 1$$

Worth investigating!

- Nontrivial energy distribution encodes cosmological evolution and source properties
- Can also encode information about fundamental axion potential, e.g. self-interactions



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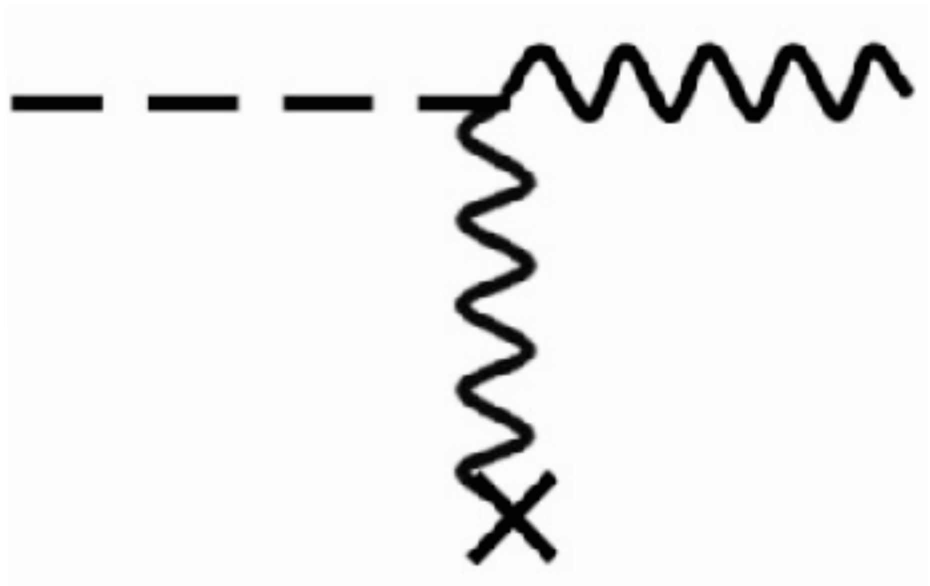
Photon Signals from DaB

$$\mathscr{L} \supset \frac{1}{4} g_{a\gamma} a F_{\mu\nu} \tilde{F}^{\mu\nu} = g_{a\gamma} a \mathbf{E} \cdot \mathbf{B}$$

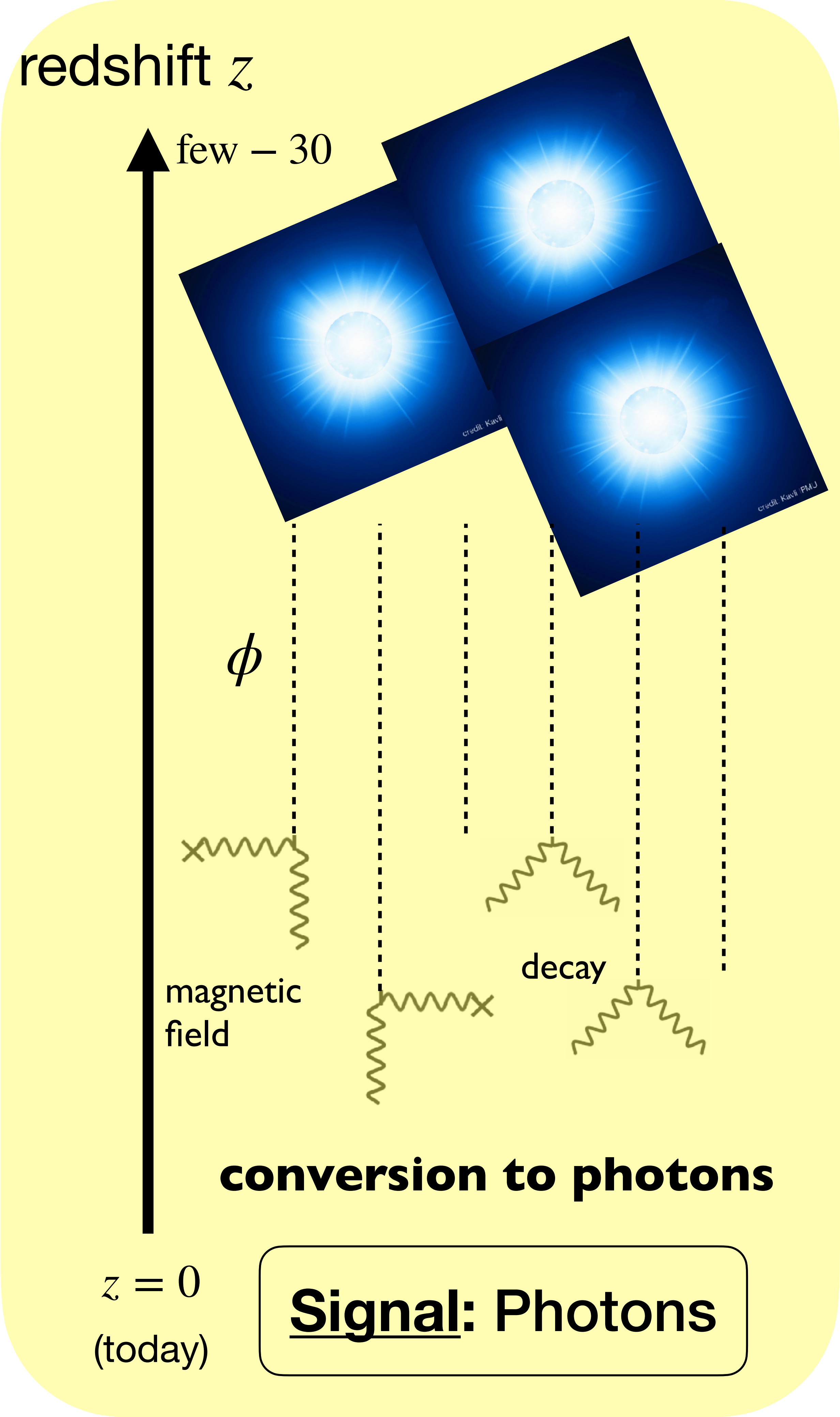
Magnetic field conversion

$$\left.\frac{d\phi_\gamma}{d\omega}\right|_{B-\text{field}} = P_{\gamma\to a} \frac{d\phi}{d\omega}$$



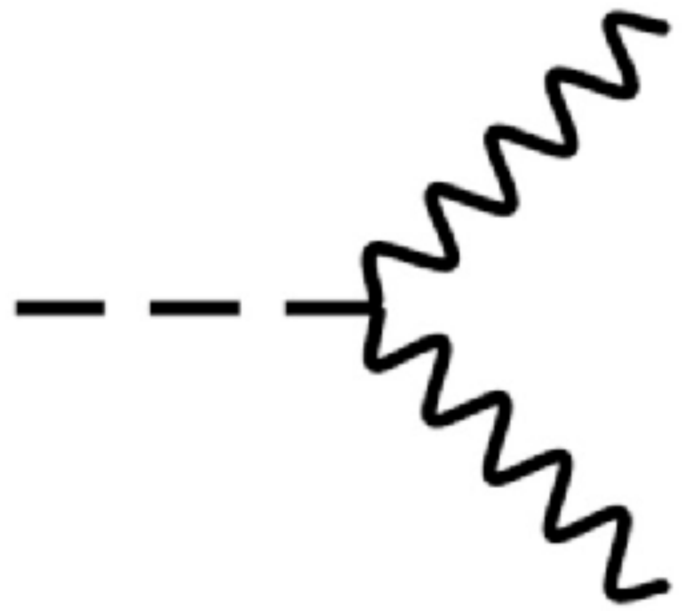
- Galactic magnetic fields of $\sim \mu\mathrm{G}$ dominate (typical distances $\sim \mathrm{kpc} - \mathrm{Mpc}$)
- $P_{\gamma\to a}$ grows with large ω and small m_a

$\Rightarrow$ largest when $\omega \gg m_a$ with small m_a



Axion decay to photons

$$\left.\frac{d\phi_\gamma}{d\omega}\right|_{\text{decay}} \simeq P_{\text{decay}} \frac{d\phi}{d\omega}$$



- Decay can occur anywhere in space (typical distances $\sim \mathrm{Gpc}$)
- P_{decay} grows with small ω and large m_a

$\Rightarrow$ largest when $\omega \gtrsim m_a$ with large m_a

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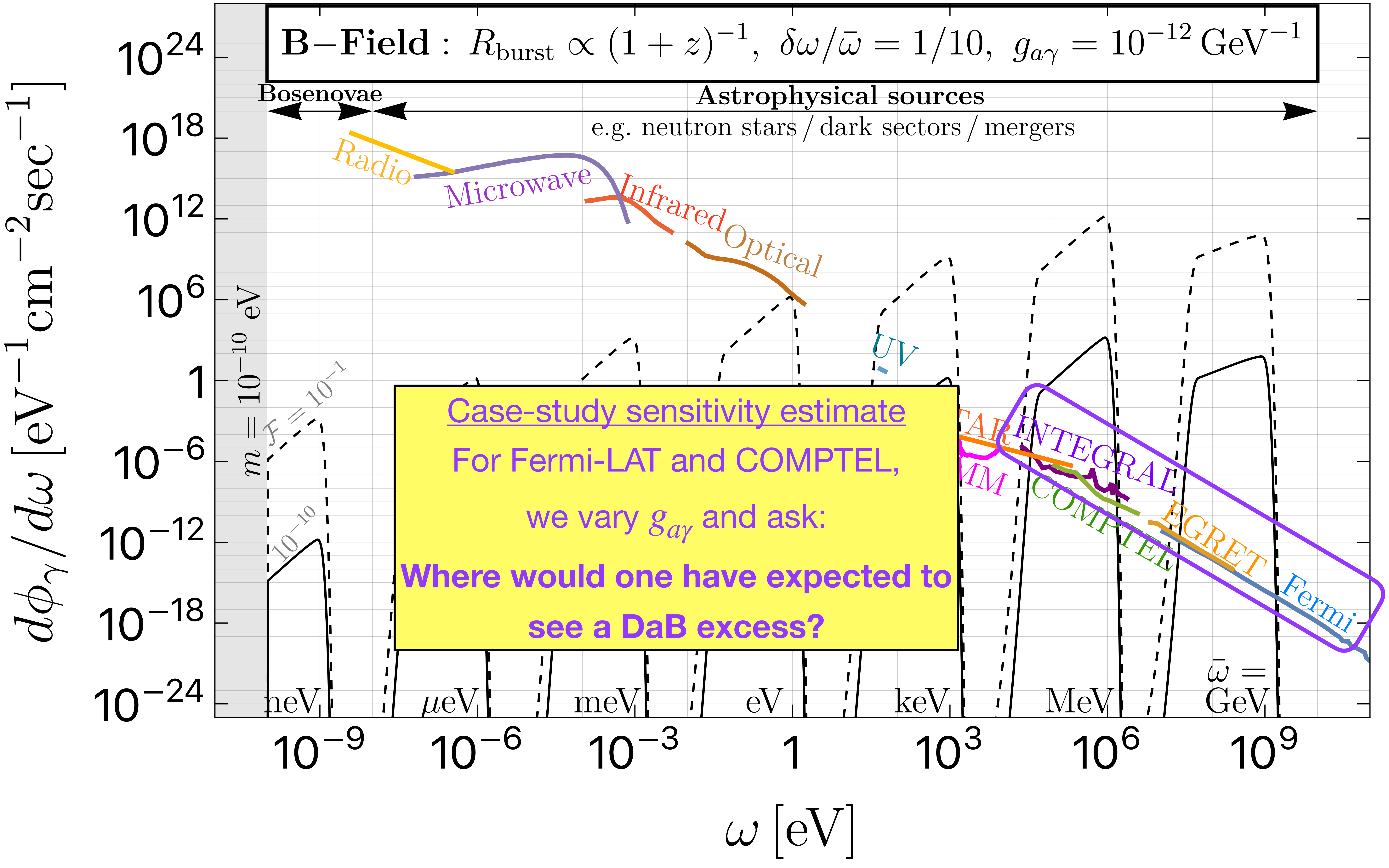
Where to Search: Today



Case-study sensitivity estimate

For Fermi-LAT and COMPTEL,

we vary $g_{a\gamma}$ and ask:

Where would one have expected to see a DaB excess?

As was done in Calore++ (2008.11741)

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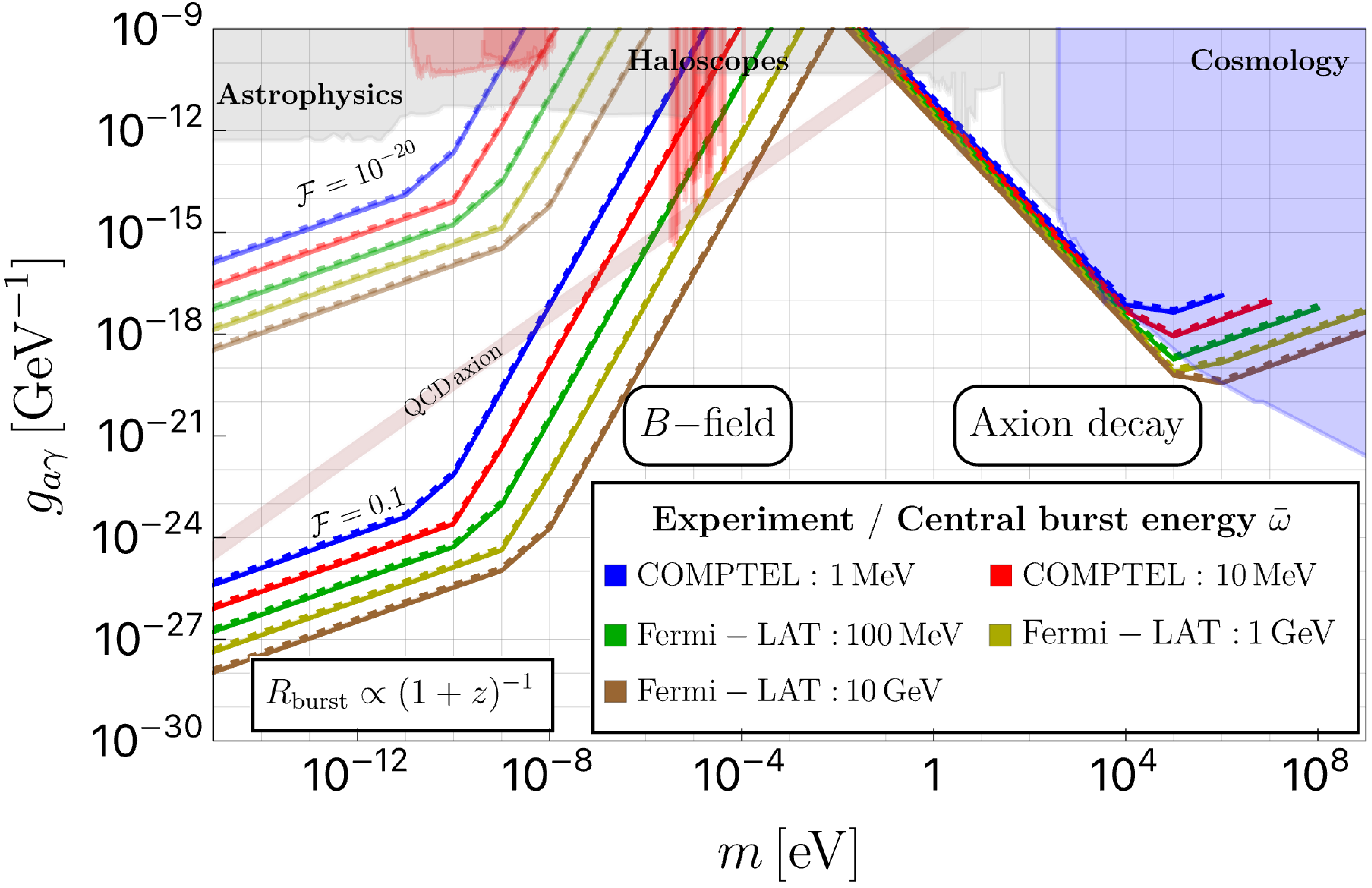
Searches for DaB Gamma-Rays



A very tiny energy fraction in DaB can give rise to striking signals!

Best sensitivity when $\bar{\omega} \gg m_a$

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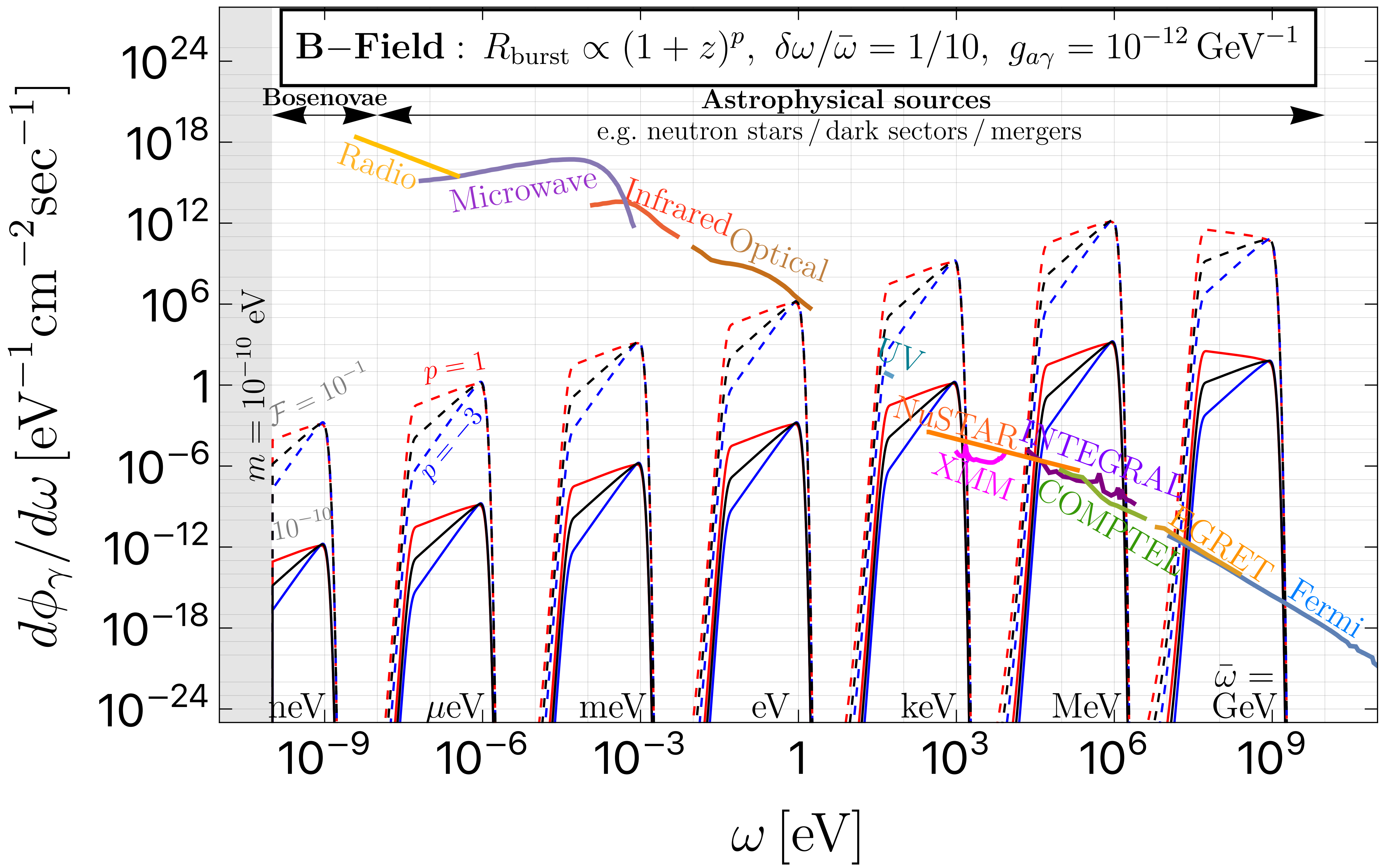
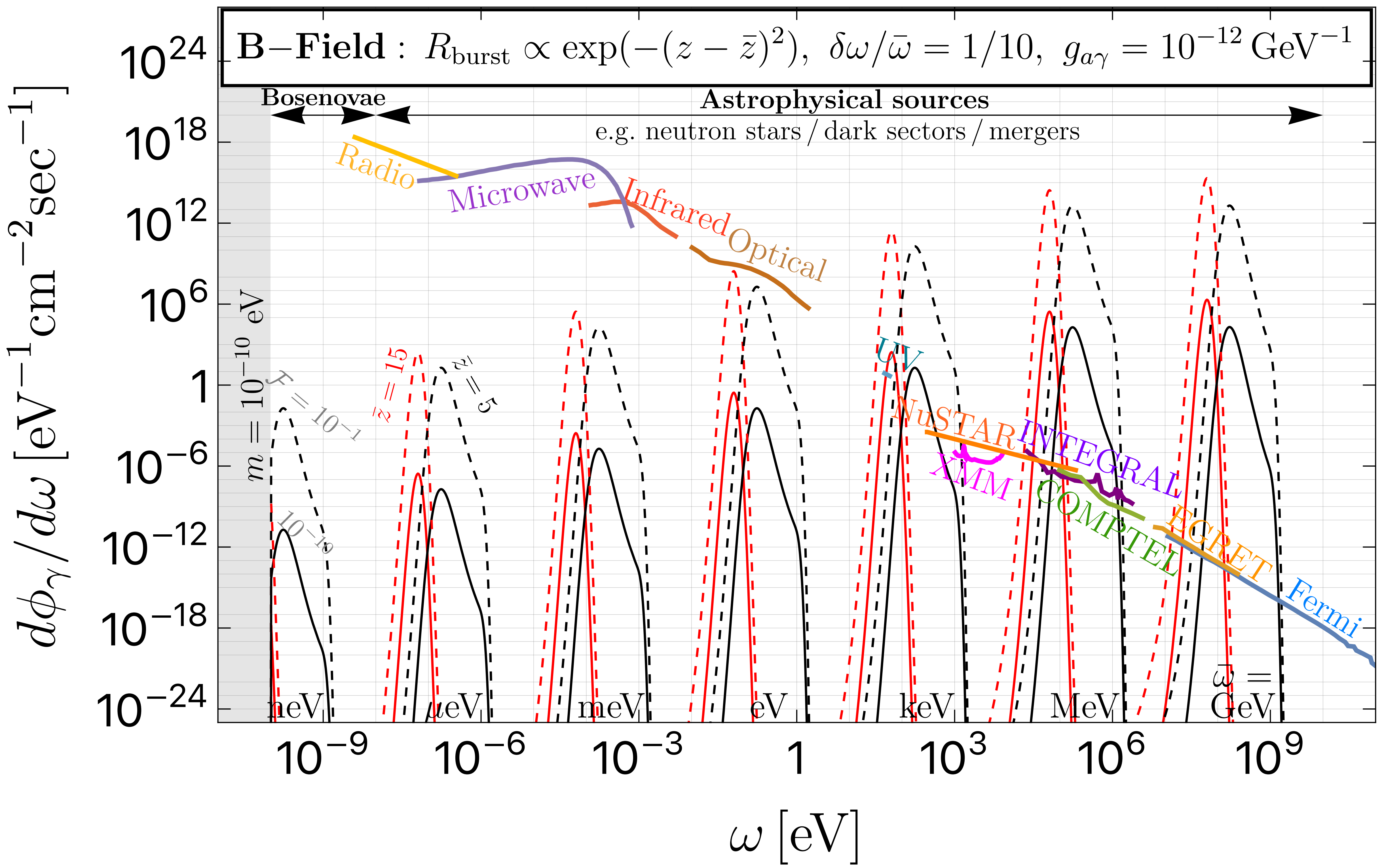
DaB Flux: Other Rates $f(z)$

Power law



Gaussian



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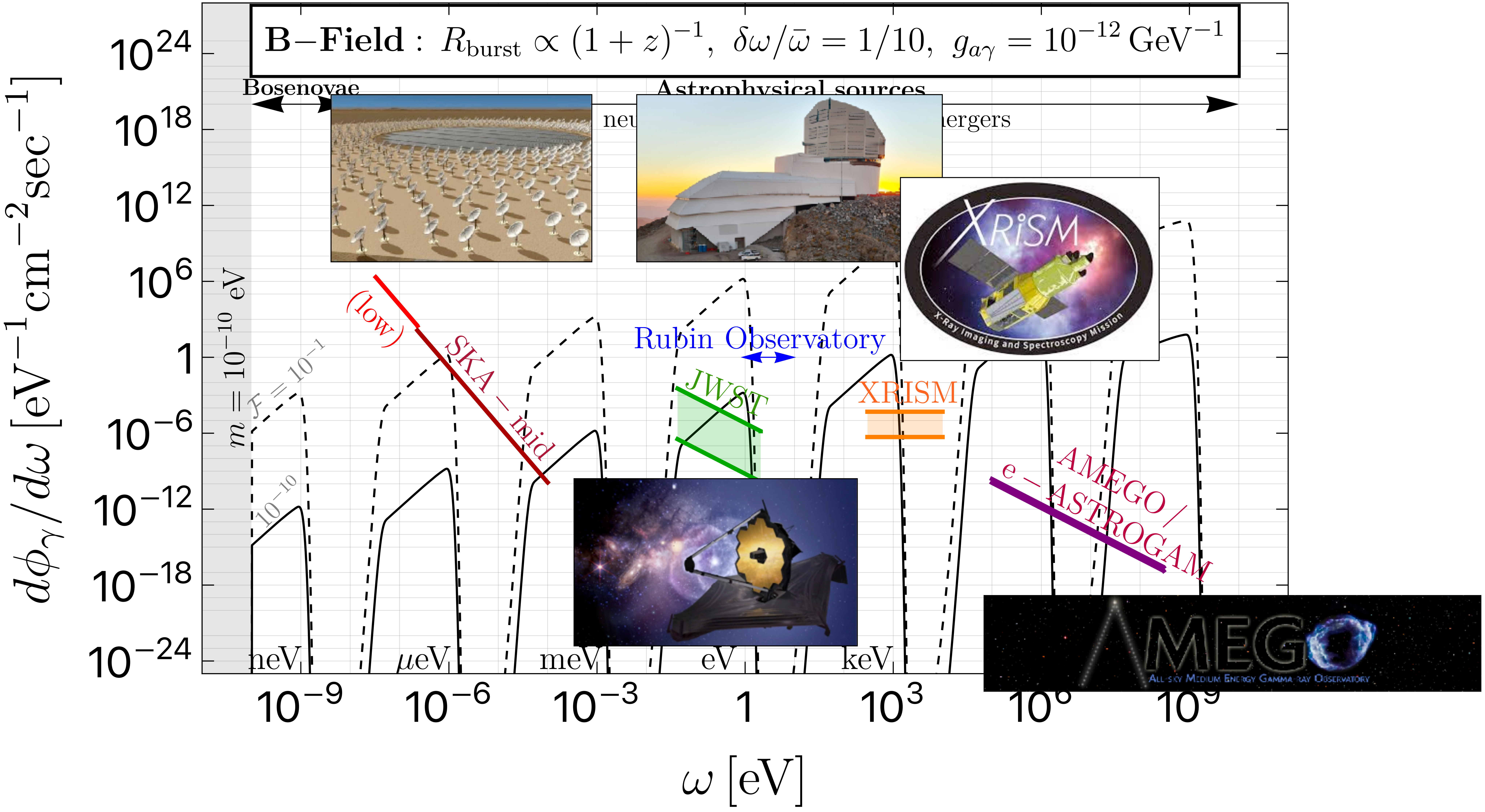
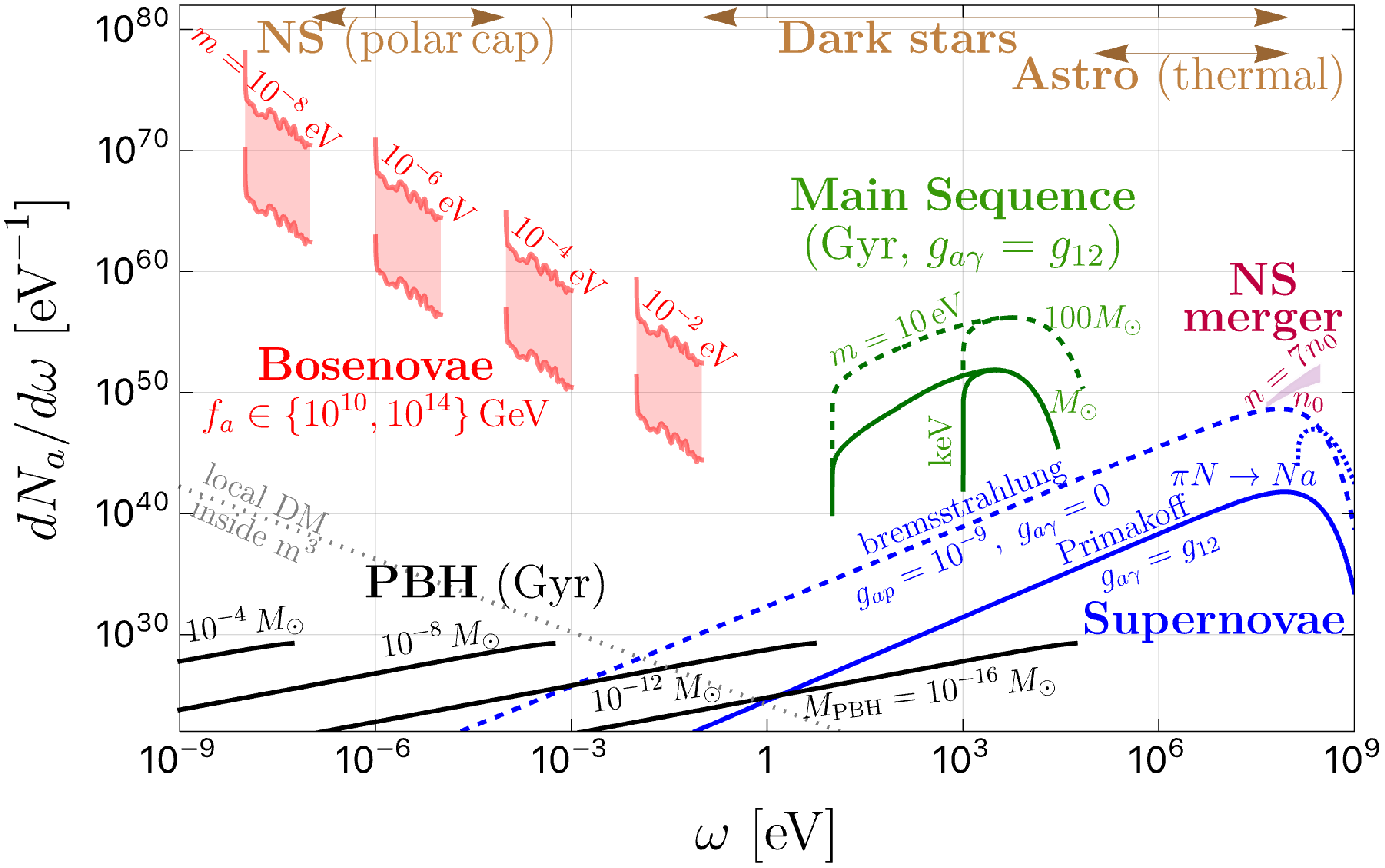
Future Searches



Thank you for your attention!



Backup Slides

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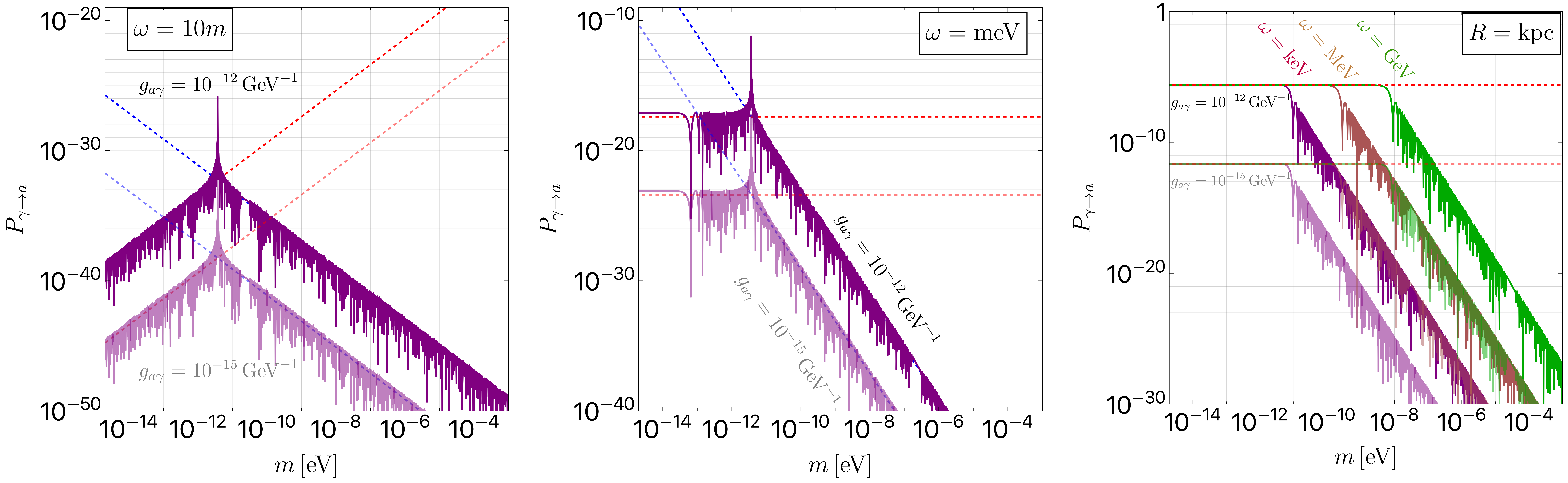
B-Field Conversion Probability

$$P_{\gamma\to a} = (\Delta_{a\gamma} R)^2 \frac{\sin^2(\Delta_{\rm osc} R/2)}{(\Delta_{\rm osc} R/2)^2}$$

$$\Delta_{a\gamma} \equiv \frac{g_{a\gamma} B_T}{2} \simeq 1.5\cdot 10^{-4} \left(\frac{g_{a\gamma}}{10^{-12}\,{\rm GeV}^{-1}}\right)\left(\frac{B_T}{\mu{\rm G}}\right) {\rm kpc}^{-1}\,,$$

$$\Delta_a \equiv -\frac{m^2}{2\omega} \simeq -7.8\cdot 10^{13} \left(\frac{m}{10^{-11}\,{\rm eV}}\right)^2 \left(\frac{10^{-10}\,{\rm eV}}{\omega}\right) {\rm kpc}^{-1}\,,$$

$$\Delta_{\rm pl} \equiv -\frac{\omega_{\rm pl}^2}{2\omega} \simeq -1.1\cdot 10^{13} \left(\frac{n_e}{10^{-2}\,{\rm cm}^{-3}}\right) \left(\frac{10^{-10}\,{\rm eV}}{\omega}\right) {\rm kpc}^{-1}\,,$$



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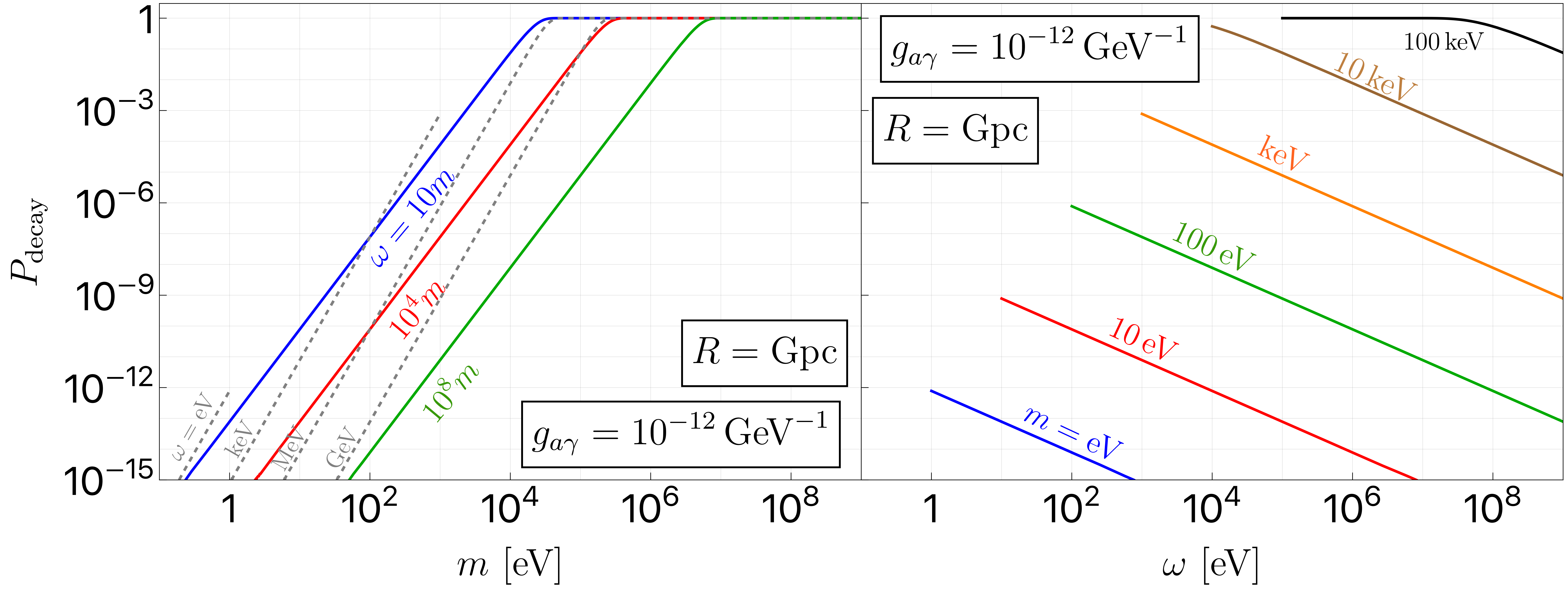
Decay Probability

$$\ell(\omega) \simeq \frac{\gamma v_{\rm burst}}{\Gamma_{\gamma\gamma}} \simeq \left(\frac{\omega}{m}\right)\frac{64\pi}{g_{a\gamma}^2 m^3} \simeq {\rm Mpc}\left(\frac{\omega}{\rm MeV}\right)\left(\frac{100\,{\rm keV}}{m}\right)^4\left(\frac{10^{-12}\,{\rm GeV}^{-1}}{g_{a\gamma}}\right)^2$$



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DaB Flux from Decay