The axion dark matter echo

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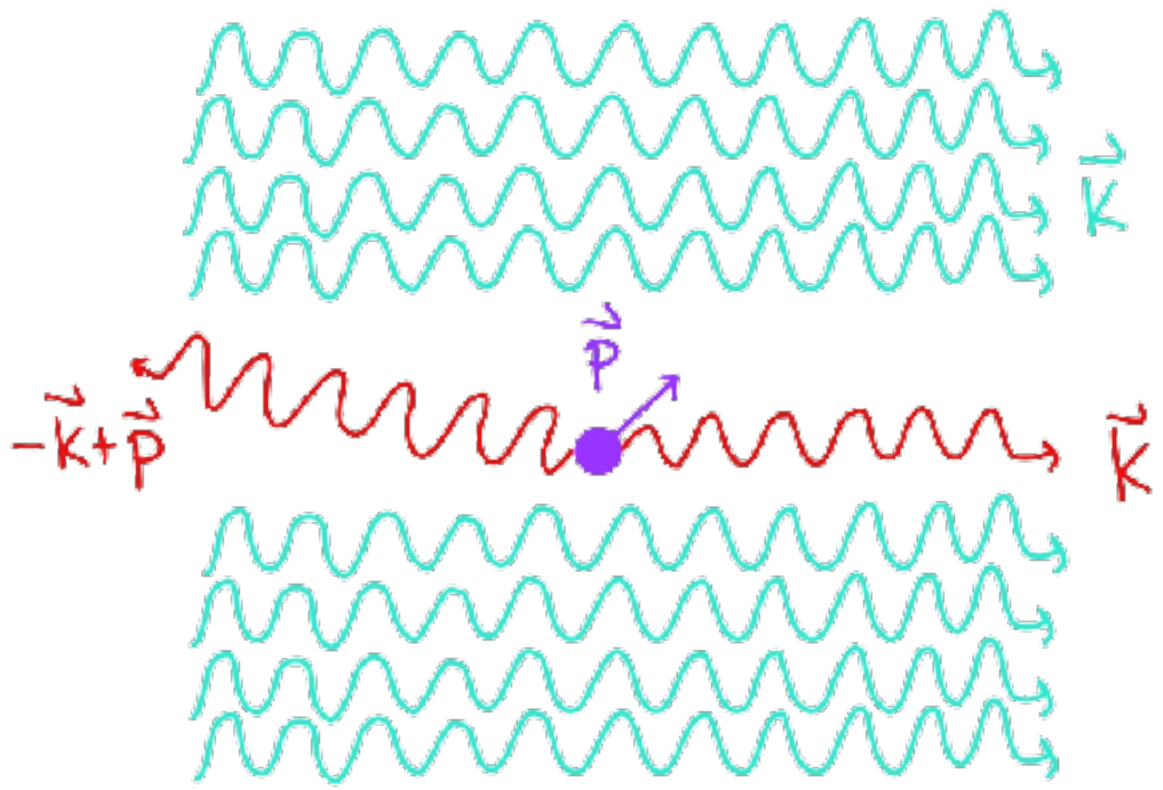
Ariel Arza + Pierre Sikivie, PRL (2019) 13, 131804

Ariel Arza + E.T., PRD 105 (2022) 2, 023023



"Axions across boundaries"
Galileo Galilei Institute for Theoretical Physics
Arcetri, 22.05.2023

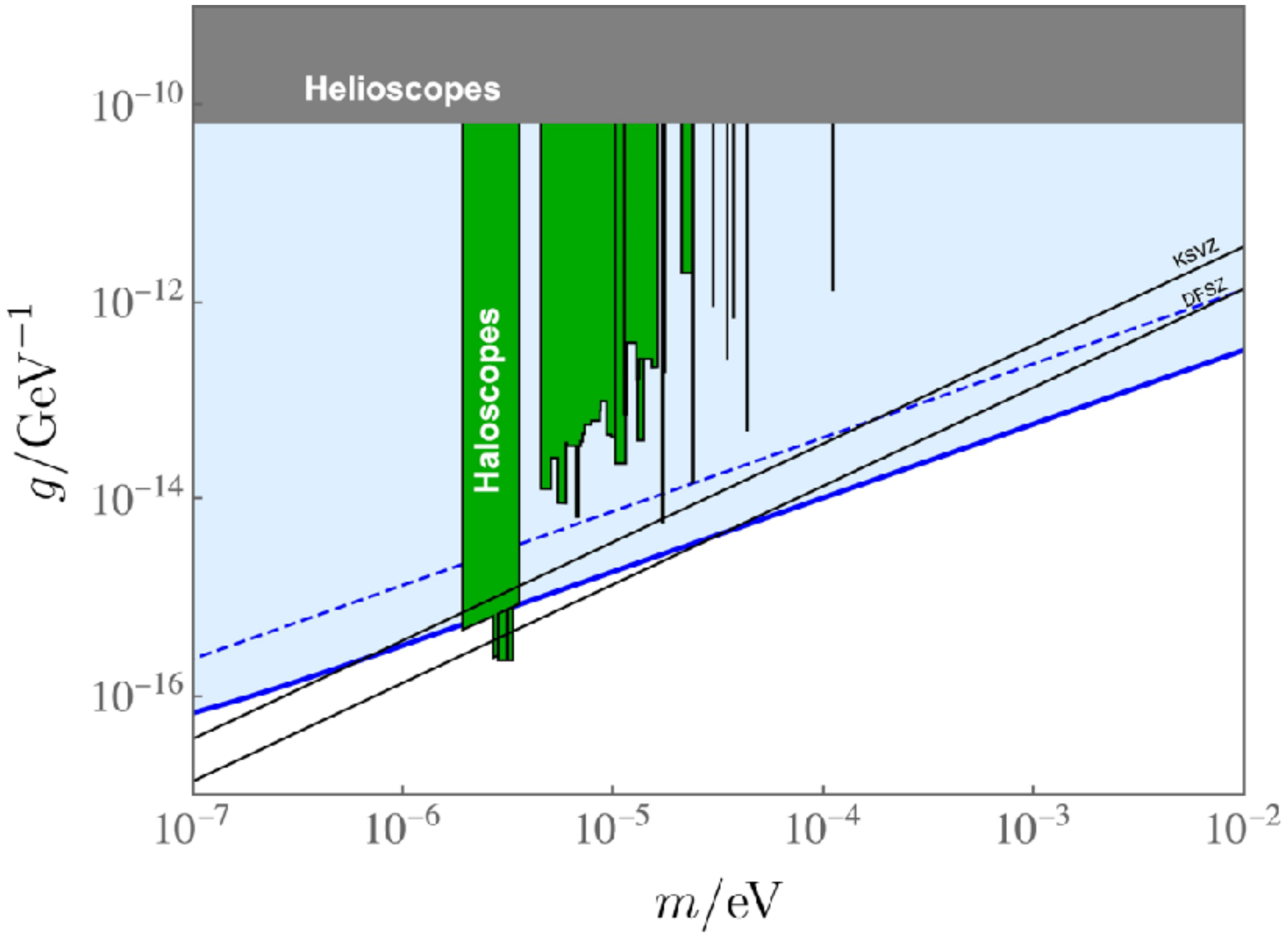
The echo idea

Stimulate the decay of nearby dark matter axions into photons by sending out a powerful beam to space

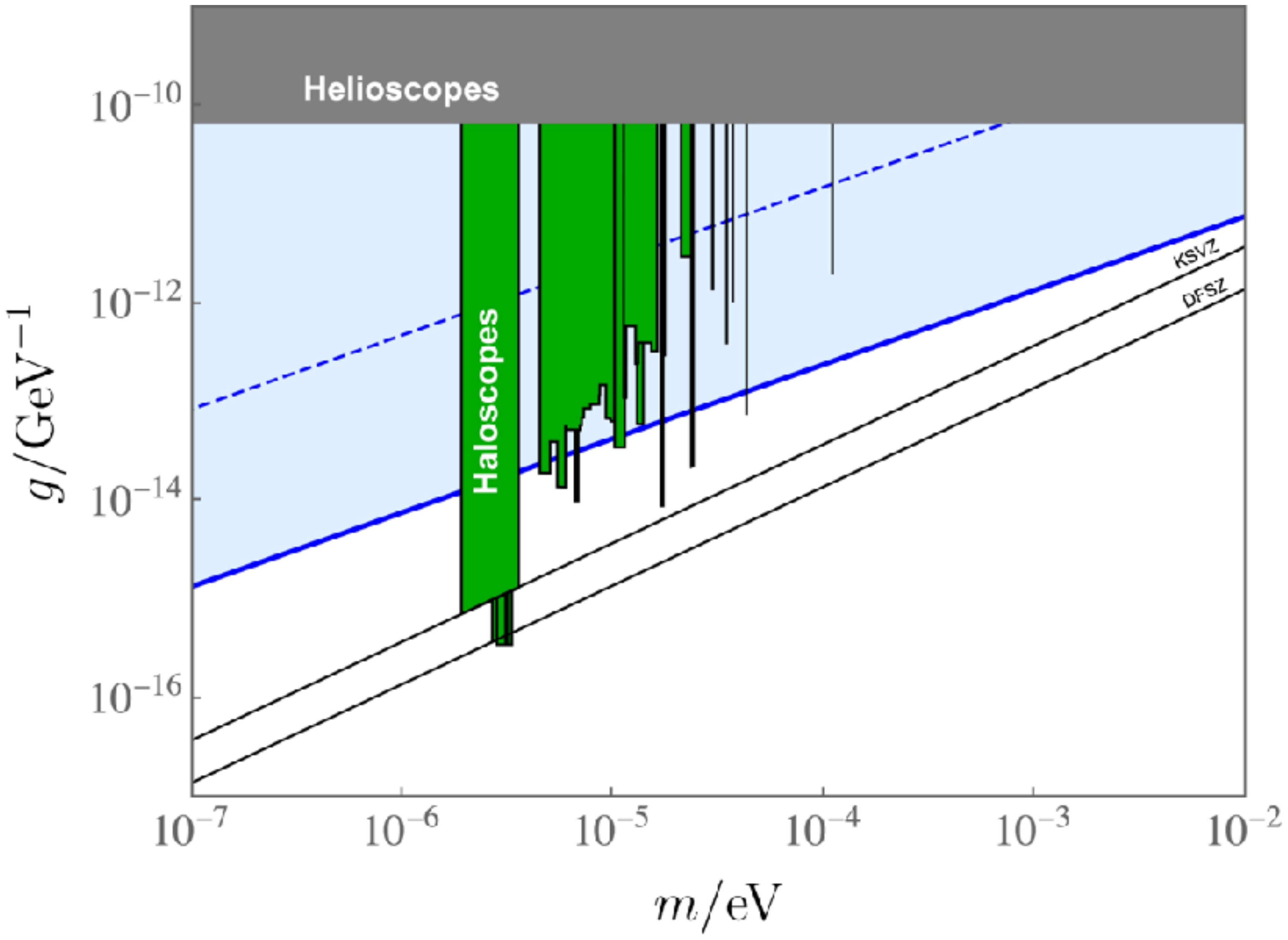
Detect the photons that come back

The echo idea

Caustic ring model



Isothermal sphere

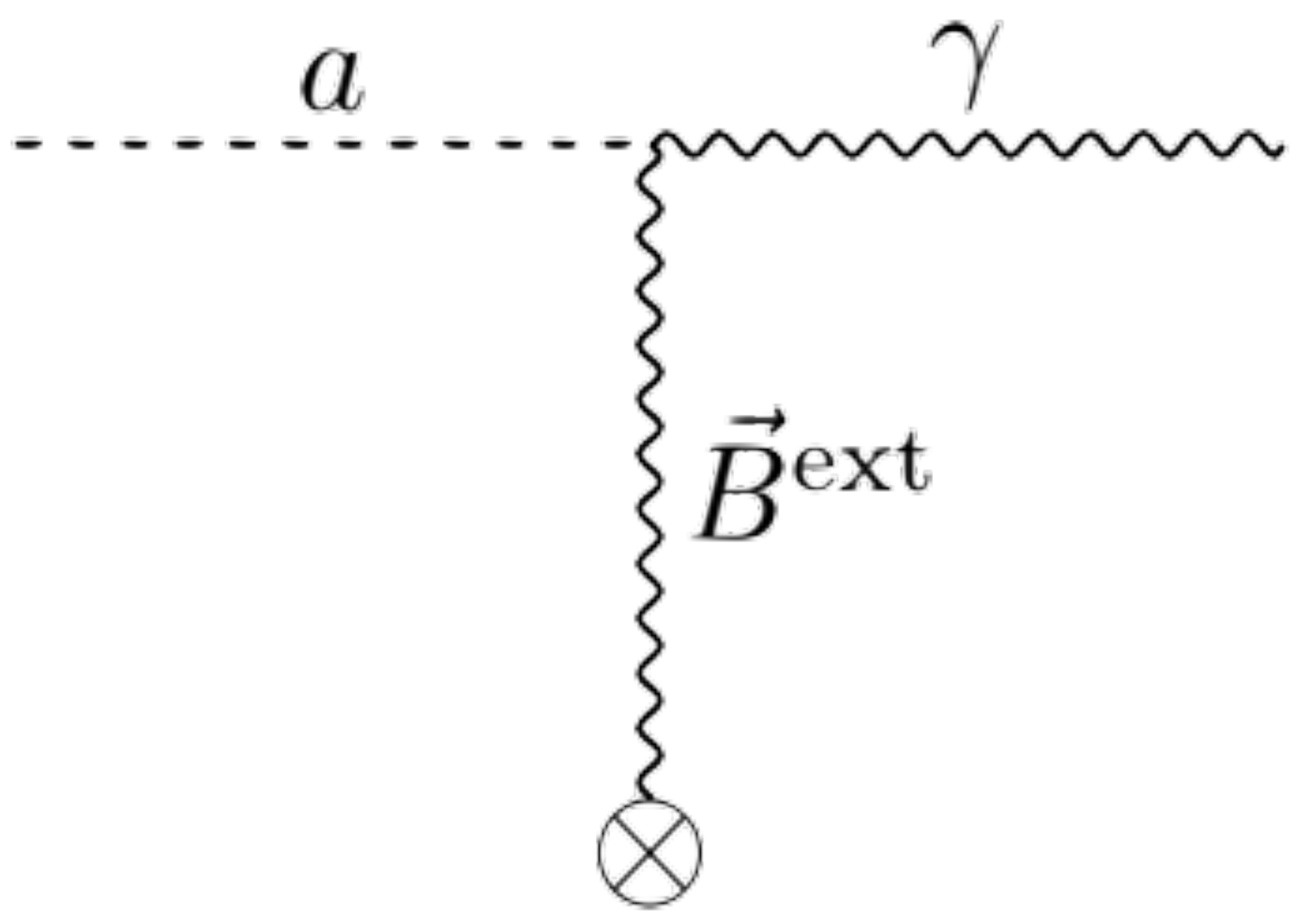


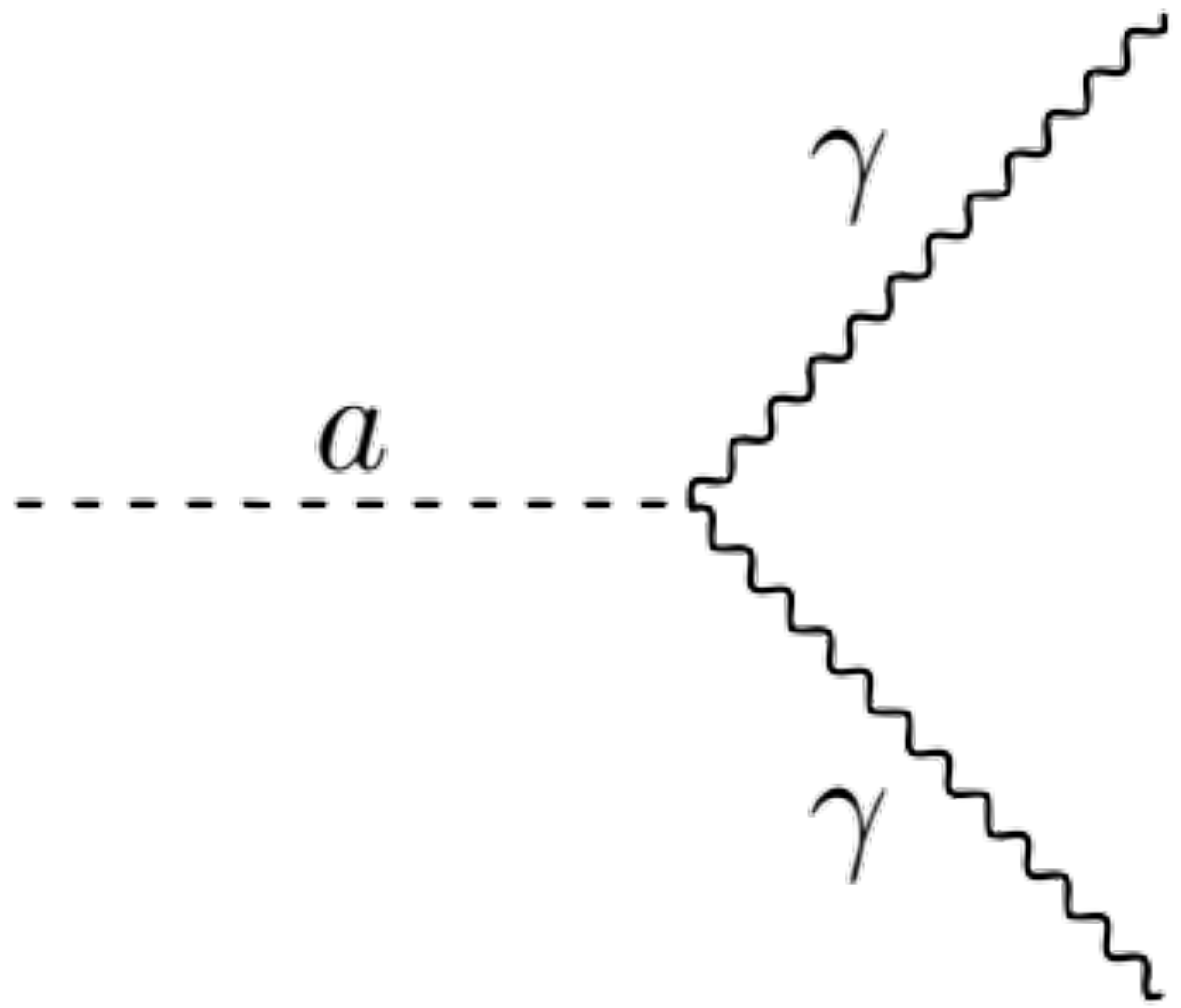
Outline

- Axion stimulated decay
- Properties of the echo wave
- Power at ground level
- Sensitivity
- Preparation for first echo experiment, by Quan Guo (Shanghai Astronomical Observatory, CAS)

Axion-photon interaction

$$\mathcal{L}_{a\gamma\gamma} = \frac{1}{4} g a F_{\mu\nu} \tilde{F}^{\mu\nu}$$





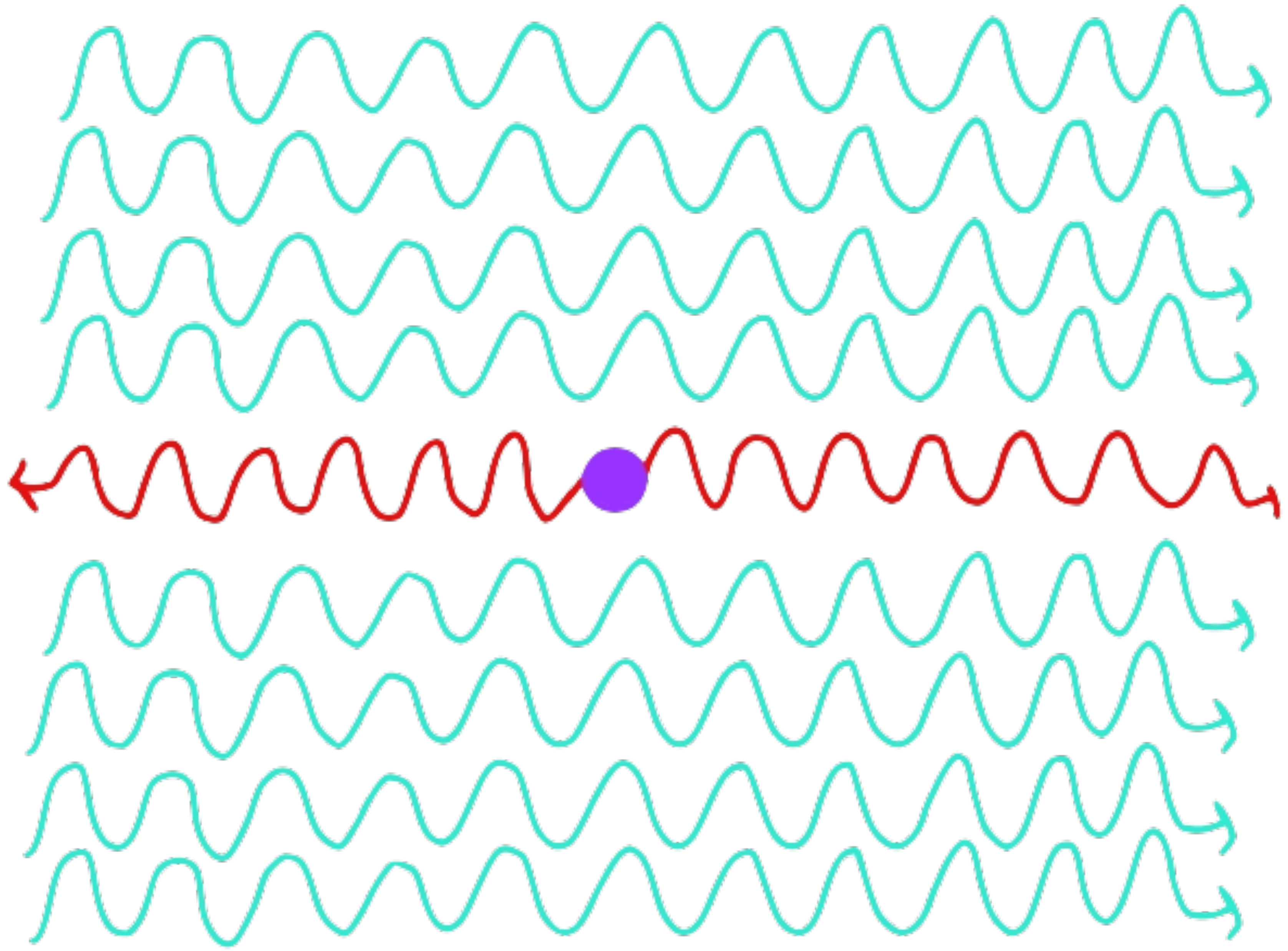
Decay rate

Decay rate in vacuum

$$\Gamma_{a\to\gamma\gamma} = 10^{-43}\ \mathrm{yr}^{-1}\left(\frac{g}{10^{-15}\ \mathrm{GeV}^{-1}}\right)^2\left(\frac{m}{10^{-5}\ \mathrm{eV}}\right)^3$$

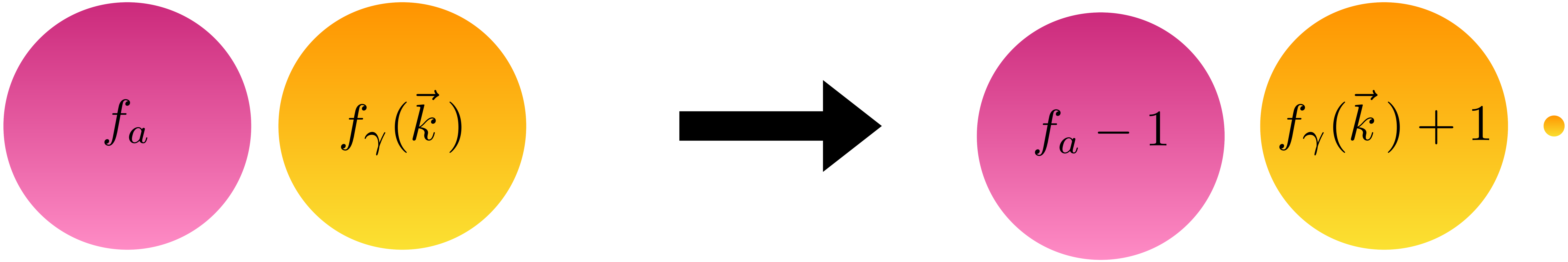
In background of photons with momentum $\vec{k}$ the decay rate is enhanced by a factor

$$f_\gamma(\vec{k}\,)$$



Stimulated decay as Bose-enhancement

$$H_{a\gamma\gamma} \sim \sum a^\dagger_\gamma(\vec{k})a^\dagger_\gamma(-\vec{k})a_a + h.c.$$



- A photon of momentum $-\vec{k}$ is created
- Decay rate is enhanced compared to vacuum by a factor $f_\gamma(\vec{k})$

Enhancement factor

$$f_\gamma(\vec{k}) + 1$$

$$\begin{aligned} m &= 10^{-5}\ \text{eV} \\ B &= 1\ \text{MHz} \\ P_0 &= 1\ \text{kW} \\ D &= 1\ \text{m} \end{aligned}$$

$$f_\gamma \sim 10^{20}$$

Properties of the echo wave

What does the echo wave look like?

$$\left(\partial_t^2 - \nabla^2\right)\vec{A} = -g\,\partial_t a\,\vec{\nabla} \times \vec{A}$$

Echo

Beam from emitter

What does the echo wave look like?

$$\left(\partial_t^2 - \nabla^2\right) \vec{A} = -g\,\partial_t a\,\vec{\nabla} \times \vec{A}$$

$$\begin{aligned} a &= \frac{\sqrt{2\rho}}{m} \sin(mt - \vec{p}\cdot\vec{x}) \\ \vec{A}^{(0)} &= \hat{e}\ \mathcal{A}^{(0)} \sin(\omega t - \vec{k}\cdot\vec{x}) \end{aligned}$$

$$\left(\partial_t^2 - \nabla^2\right) \vec{A}^{(1)} = -\hat{k} \times \hat{e}\,\frac{g}{2}\sqrt{\frac{\rho}{2}}\,\omega\,\mathcal{A}^{(0)}\ e^{i(m-\omega)t+i(\vec{k}-\vec{p})\cdot\vec{x}}$$

What does the echo wave look like?

$$\left(\partial_t^2 - \nabla^2\right) \vec{A}^{(1)} = -\hat{k} \times \hat{e}\, \frac{g}{2}\sqrt{\frac{\rho}{2}}\, \omega\, \mathcal{A}^{(0)}\ e^{i(m-\omega)t + i(\vec{k}-\vec{p})\cdot\vec{x}}$$

$$\vec{A}^{(1)} = -\hat{k} \times \hat{e}\ \mathcal{A}^{(1)}(t)\ e^{i|\vec{k}-\vec{p}|t + i(\vec{k}-\vec{p})\cdot\vec{x}}$$

$$\partial_t \mathcal{A}^{(1)} \ll \omega \mathcal{A}^{(1)}$$

$$\mathcal{A}^{(1)} = -i\frac{g}{4}\sqrt{\frac{\rho}{2}}\mathcal{A}^{(0)}\ e^{i\epsilon t/2}\ \frac{\sin\left(\epsilon t/2\right)}{\epsilon/2}$$

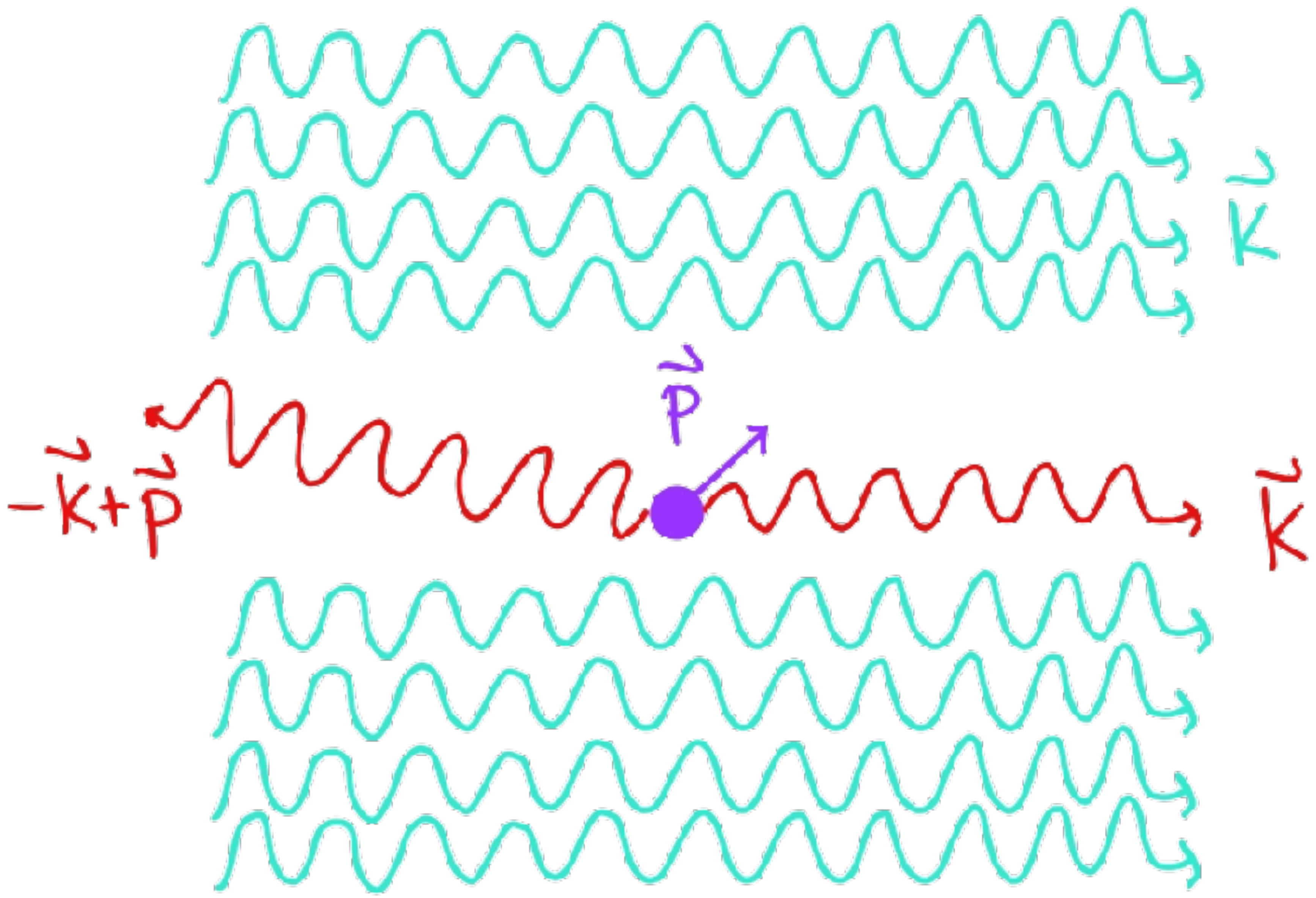
$$\epsilon = m - \omega - |\vec{k} - \vec{p}|$$

Properties of echo wave

$$\vec{A}^{(0)} = \hat{e}\ \mathcal{A}^{(0)} \sin(\omega t - \vec{k}\cdot\vec{x})$$

$$\vec{A}^{(1)} = -\hat{k}\times\hat{e}\ \frac{g}{2}\sqrt{\frac{\rho}{2}}\ \mathcal{A}^{(0)} \sin\left(|\vec{k}-\vec{p}|t + (\vec{k}-\vec{p})\cdot\vec{x} + \frac{\epsilon t}{2}\right)\ \frac{\sin(\epsilon t/2)}{\epsilon/2}$$

- Polarization, 90º angle if linear
- Mode with momentum $-\vec{k}+\vec{p}$ is excited
- Propagates (almost) backwards for



Properties of echo wave

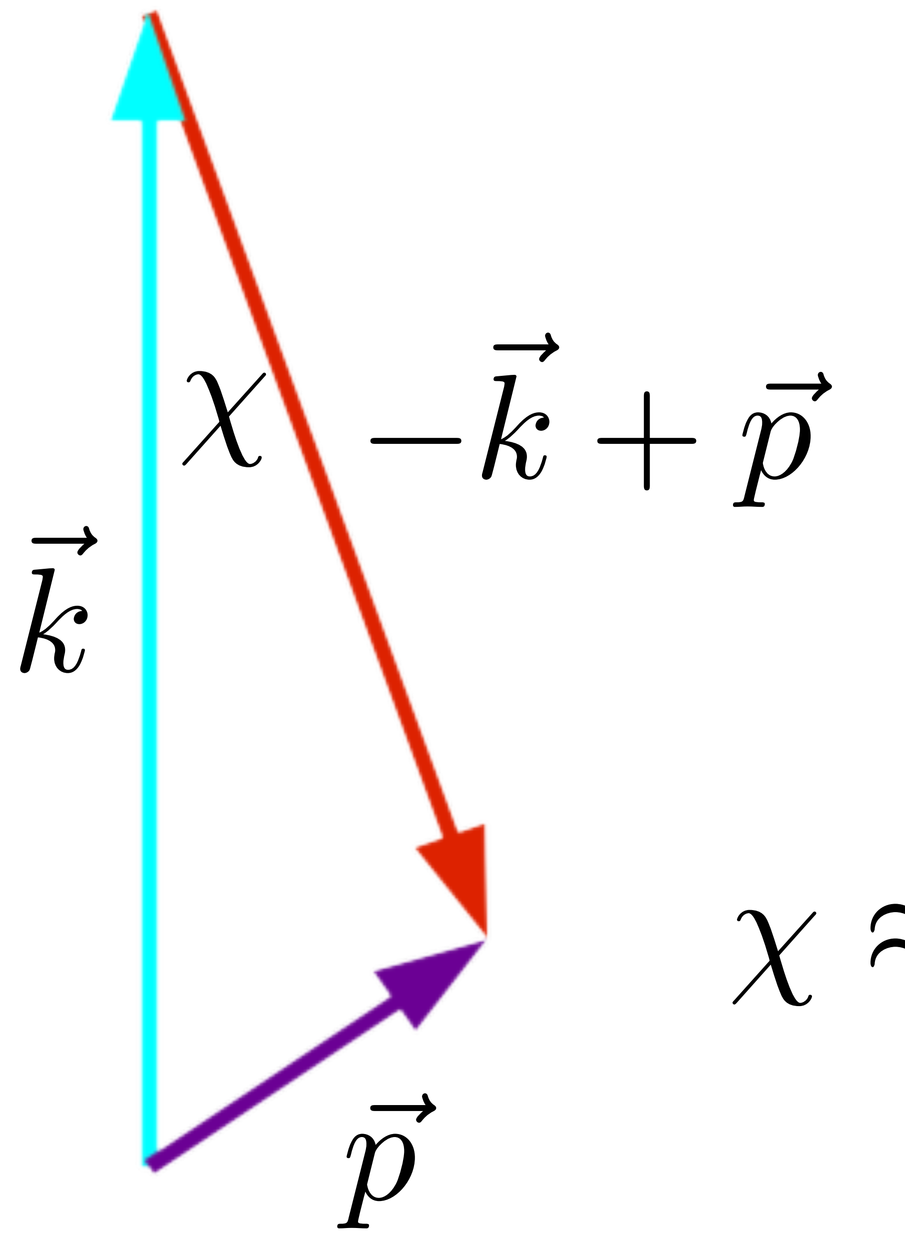
$$\vec{A}^{(0)} = \hat{e}\ \mathcal{A}^{(0)} \sin(\omega t - \vec{k}\cdot\vec{x})$$

$$\vec{A}^{(1)} = -\hat{k}\times\hat{e}\ \frac{g}{2}\sqrt{\frac{\rho}{2}}\ \mathcal{A}^{(0)} \sin\left(|\vec{k}-\vec{p}|t + (\vec{k}-\vec{p})\cdot\vec{x} + \frac{\epsilon t}{2}\right)\ \frac{\sin(\epsilon t/2)}{\epsilon/2}$$

At resonance $\epsilon = 2\omega - p_{||} - m = 0$

$$\omega = \frac{m+p_{||}}{2}$$

$$\omega - p_{||} = \frac{m-p_{||}}{2}$$



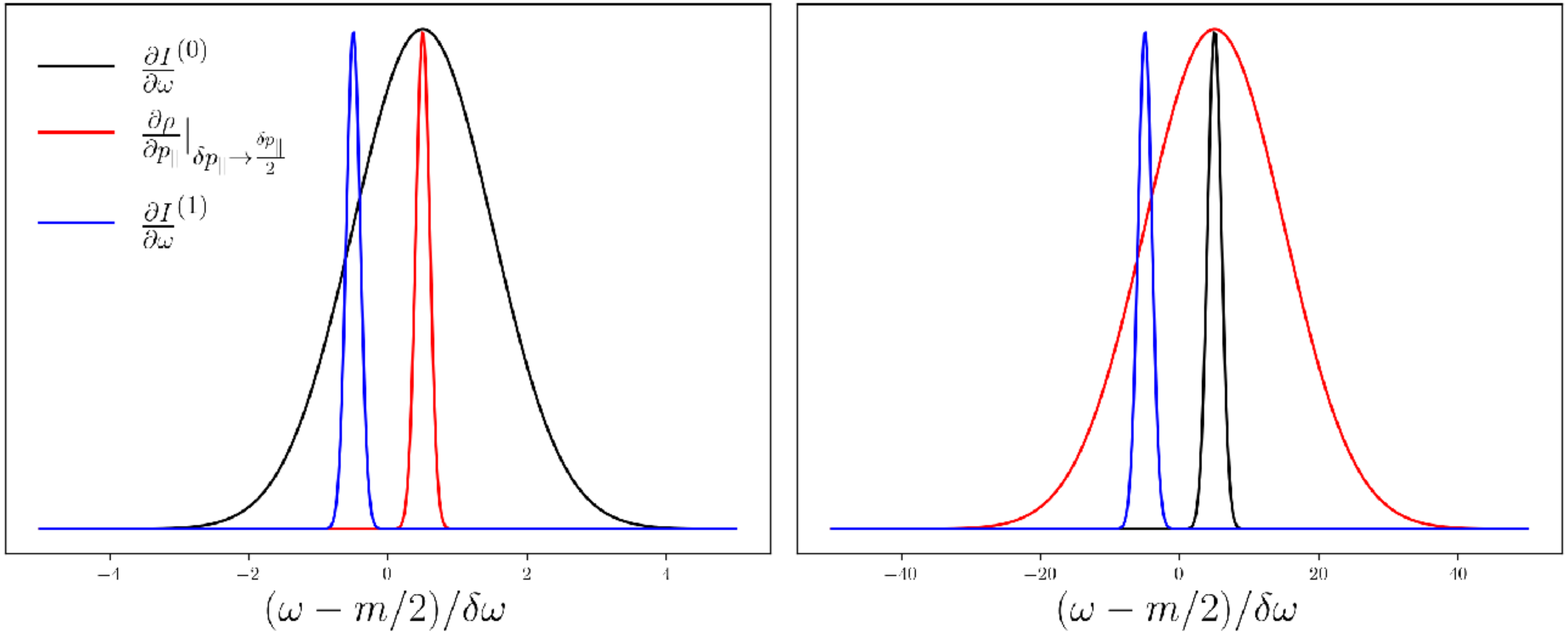
$\chi \approx 2v_{\perp}$

Properties of echo wave

$$I^{(1)} = \frac{\pi}{4} g^2 t \int d^3p \, \frac{\partial^3 \rho}{\partial p^3} \int d\omega \, \frac{\partial I}{\partial \omega}^{(0)} \delta(\epsilon)$$

Bandwidth

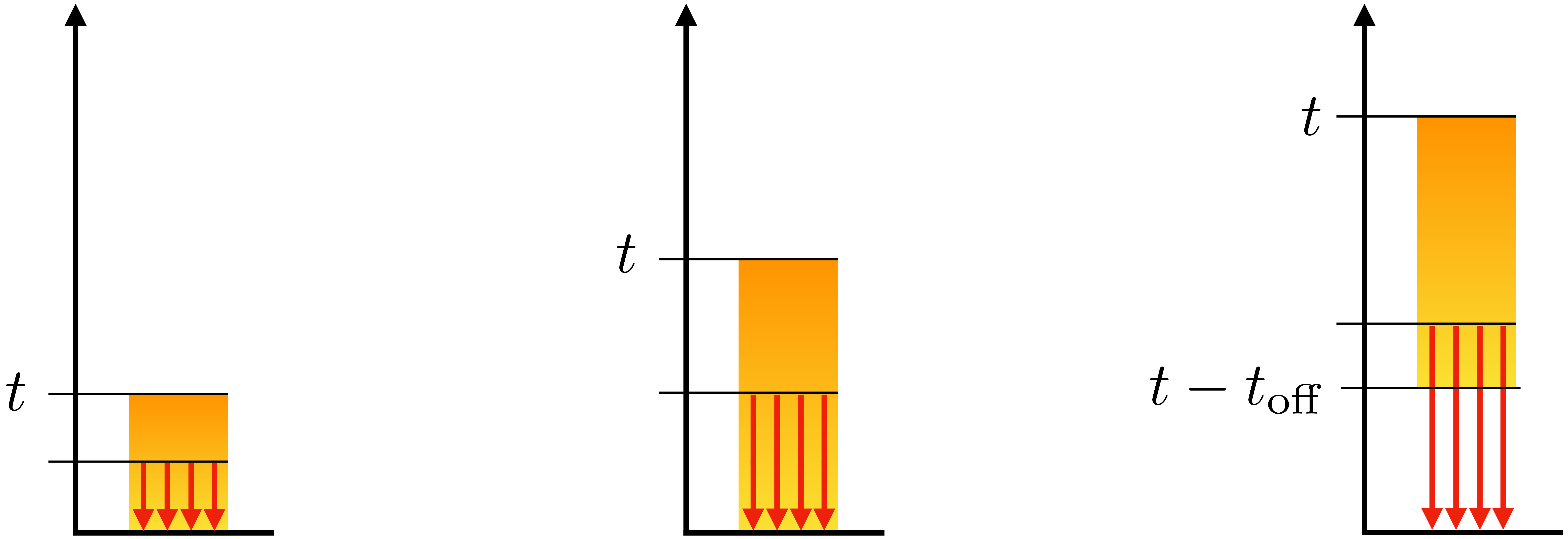
$$\min(\delta\omega, \delta p_{\|}/2)$$



Echo power at ground level

Echo power at ground level: One dimensional case

- No axion transverse velocity
- No beam transverse wavevector components



Echo power at ground level: One dimensional case

$$P_c(t) = \frac{1}{16}\sqrt{\frac{\pi}{2}}\frac{g^2\rho}{\Delta}\,P_0\,\frac{S\cap S_0}{S_0}\,t_<$$

Echo power at ground level: One dimensional case

$$P_c(t) = \frac{1}{16}\sqrt{\frac{\pi}{2}}\,\frac{g^2\rho}{\Delta}\,P_0\,\frac{S\cap S_0}{S_0}\,t_<$$

$$\Delta = \sqrt{\delta\omega^2 + \frac{\delta p_z^2}{4}}$$

Echo power at ground level: One dimensional case

$$P_c(t) = \frac{1}{16}\sqrt{\frac{\pi}{2}}\frac{g^2\rho}{\Delta}P_0\frac{S\cap S_0}{S_0}t_<$$

Intersection between emitting and receiving surface

Echo power at ground level: One dimensional case

$$P_c(t) = \frac{1}{16}\sqrt{\frac{\pi}{2}}\frac{g^2\rho}{\Delta}\,P_0\,\frac{S\cap S_0}{S_0}\,t_<$$

Minimum between t and $t_{\rm off}$

Echo power at ground level: One dimensional case

$$P_c(t) = \frac{1}{16}\sqrt{\frac{\pi}{2}}\frac{g^2\rho}{\Delta}\, P_0\, \frac{S \cap S_0}{S_0}\, t_<$$

$$P = 10^{-19}\ \mathrm{W}\left(\frac{g}{10^{-14}\ \mathrm{GeV}^{-1}}\right)^2\left(\frac{\rho}{0.4\ \mathrm{GeV/cm}^3}\right)\left(\frac{\mathrm{kHz}}{\Delta}\right)\left(\frac{P_0}{1\ \mathrm{kW}}\right)\left(\frac{t_<}{\mathrm{hr}}\right)$$

Echo power at ground level: Three dimensional case

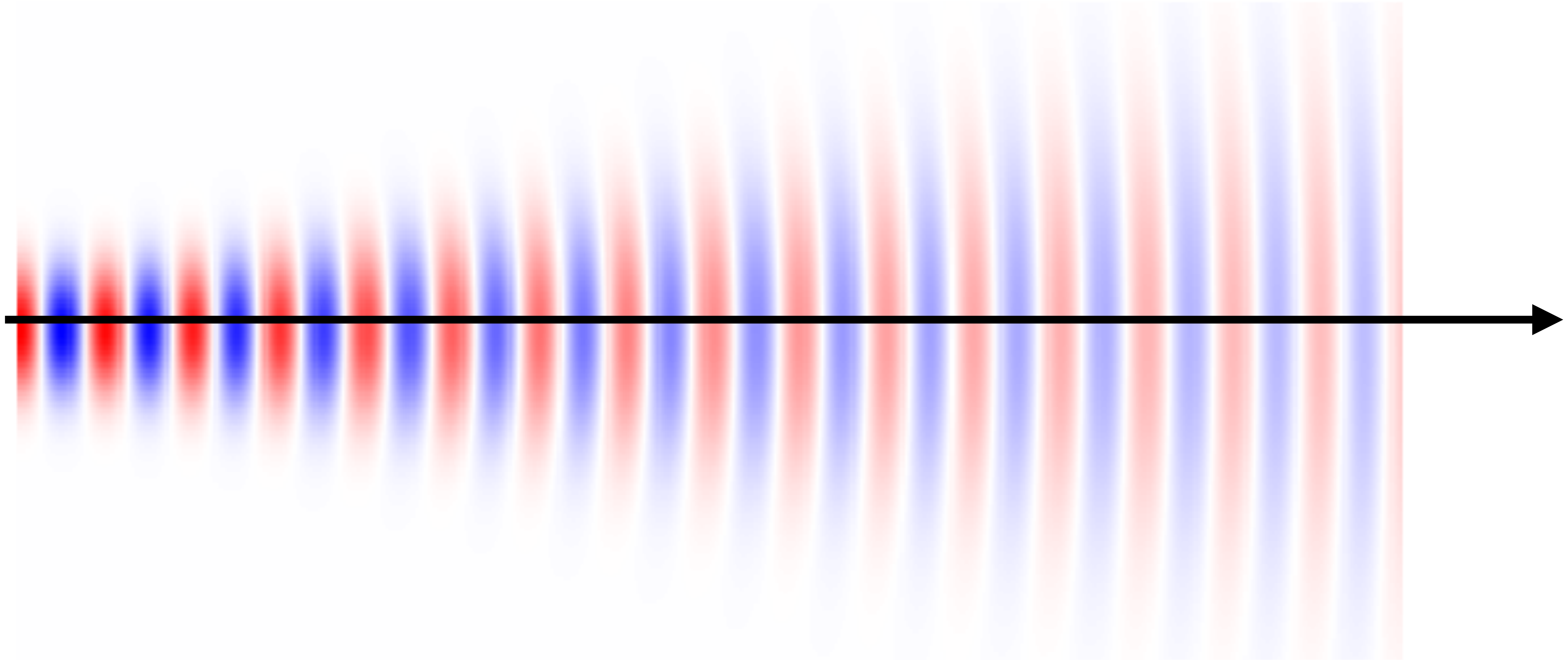
$$P_c(t) = \frac{1}{16}\sqrt{\frac{\pi}{2}}\frac{g^2\rho}{\Delta}\,P_0\,\frac{1}{S_0}\int_S d^2x_\perp\,\mathcal{T}(t,\vec{x}_\perp)$$

3D effects

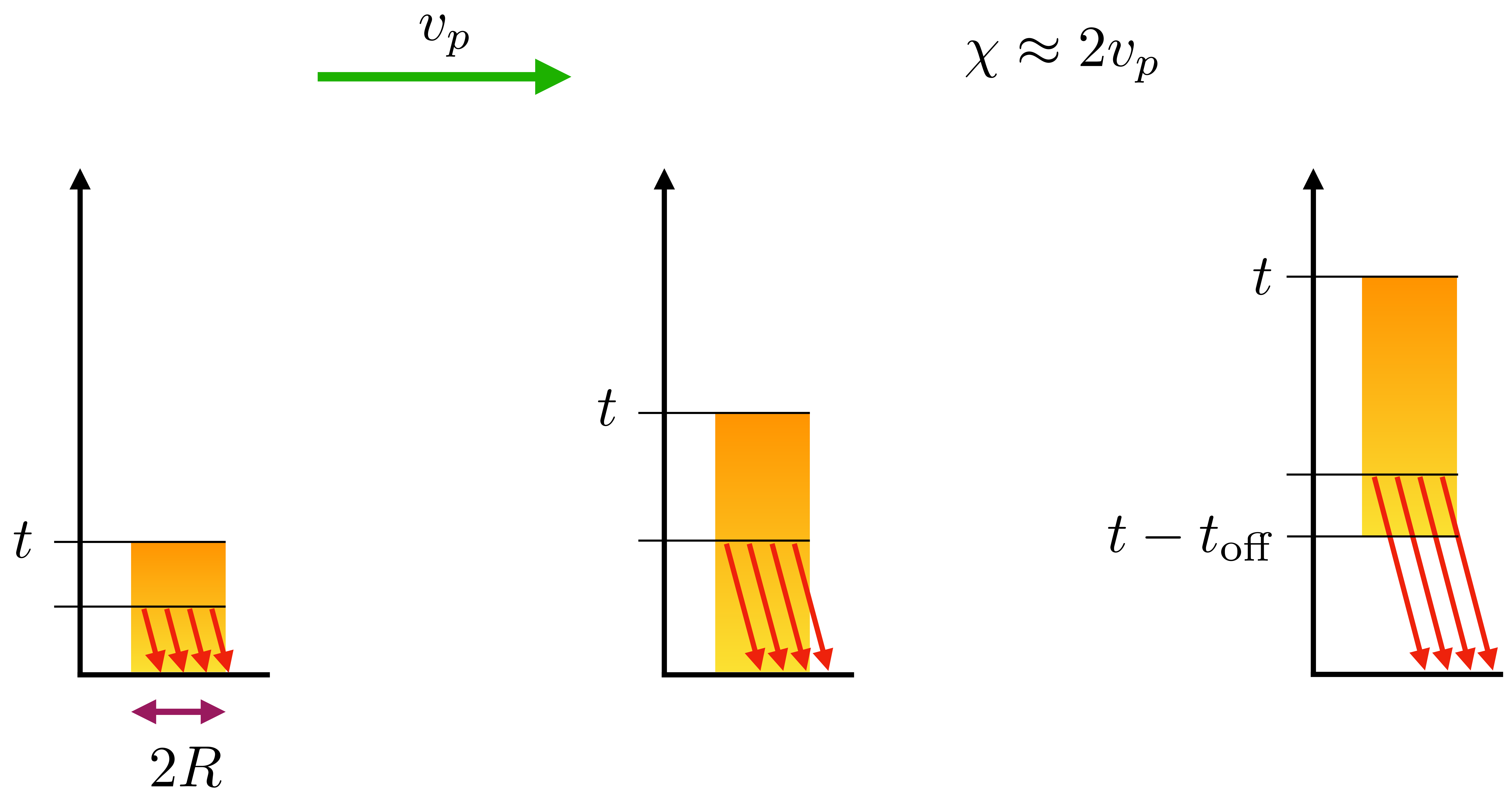
A model for the beam

Approximate the main lobe of the antenna beam as a Gaussian beam

$$\vec{B}^{(0)} = \hat{\epsilon}\,\frac{B_0}{2}\,\frac{R}{w(z)}\,e^{-\frac{r^2}{2w(z)^2}}\,e^{i\omega\frac{r^2}{2\mathcal{R}(z)}}\,e^{-i\omega(t-z)}$$

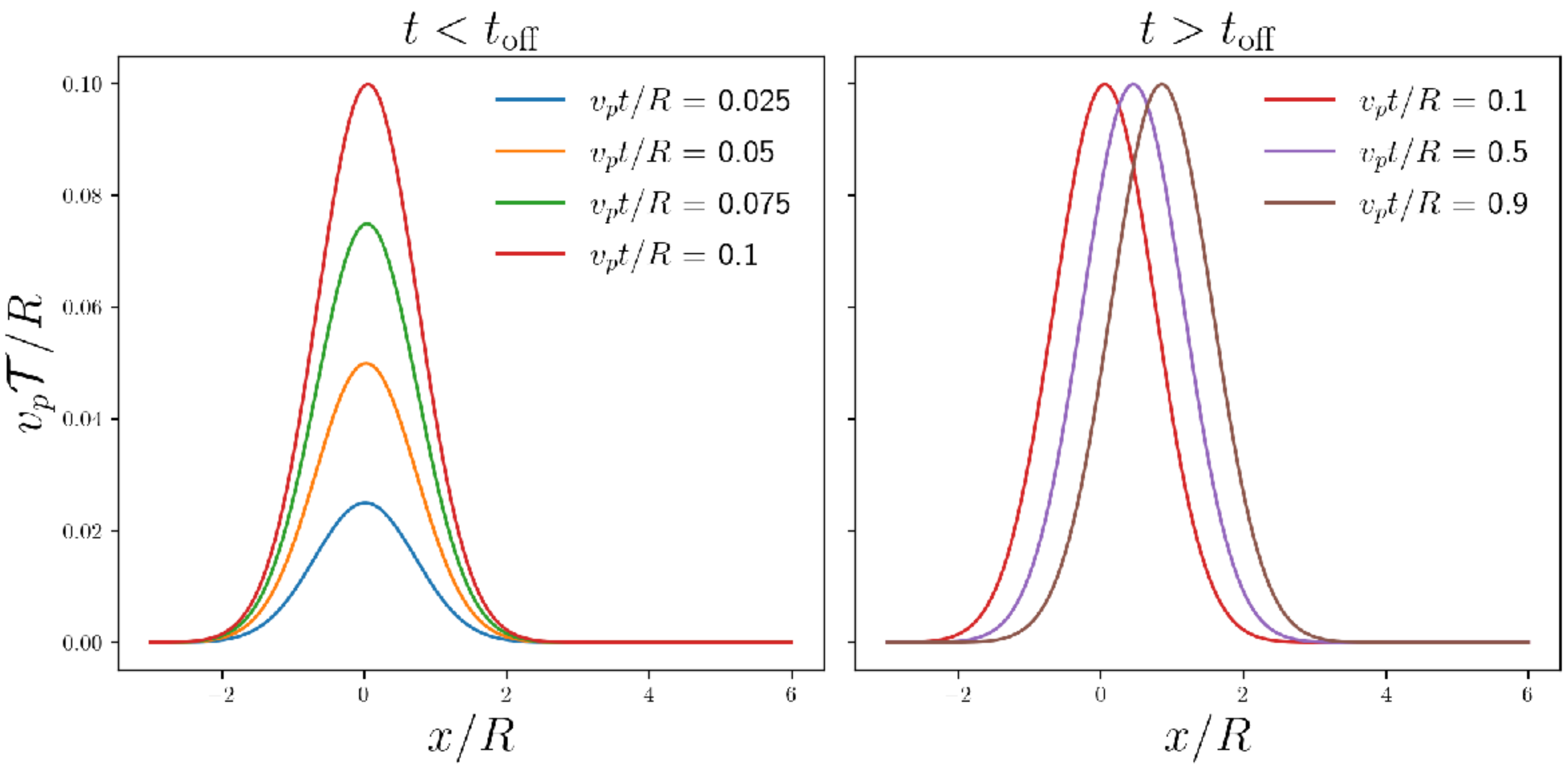


Small velocity dispersion



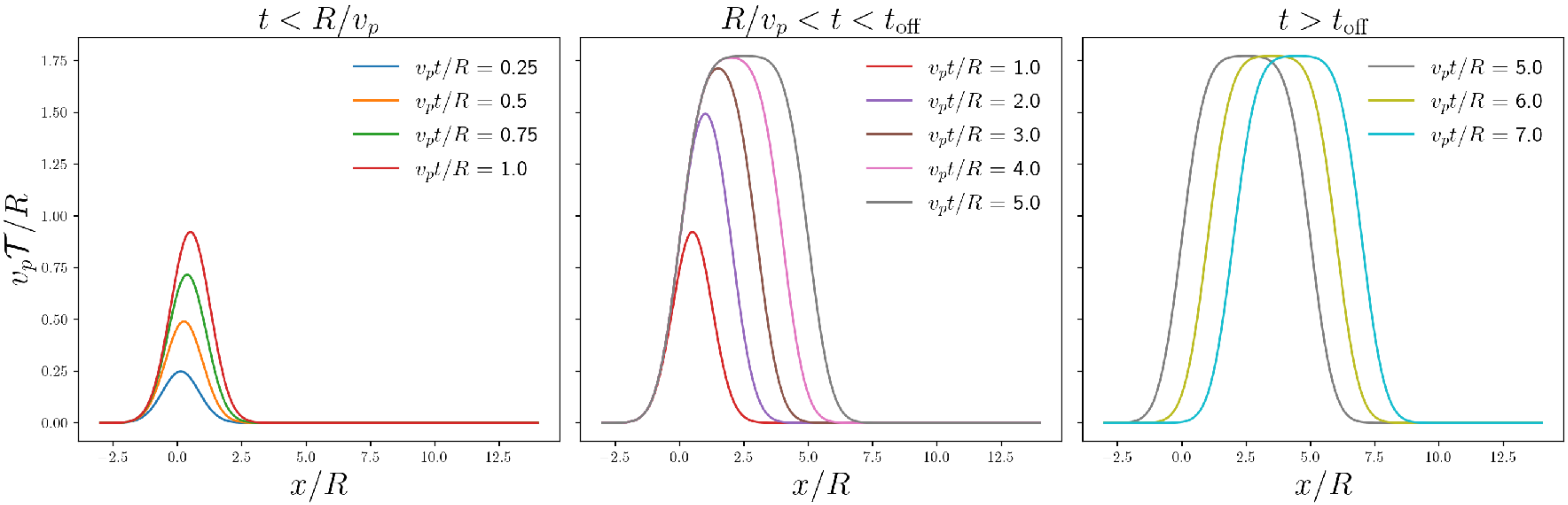
Small velocity dispersion

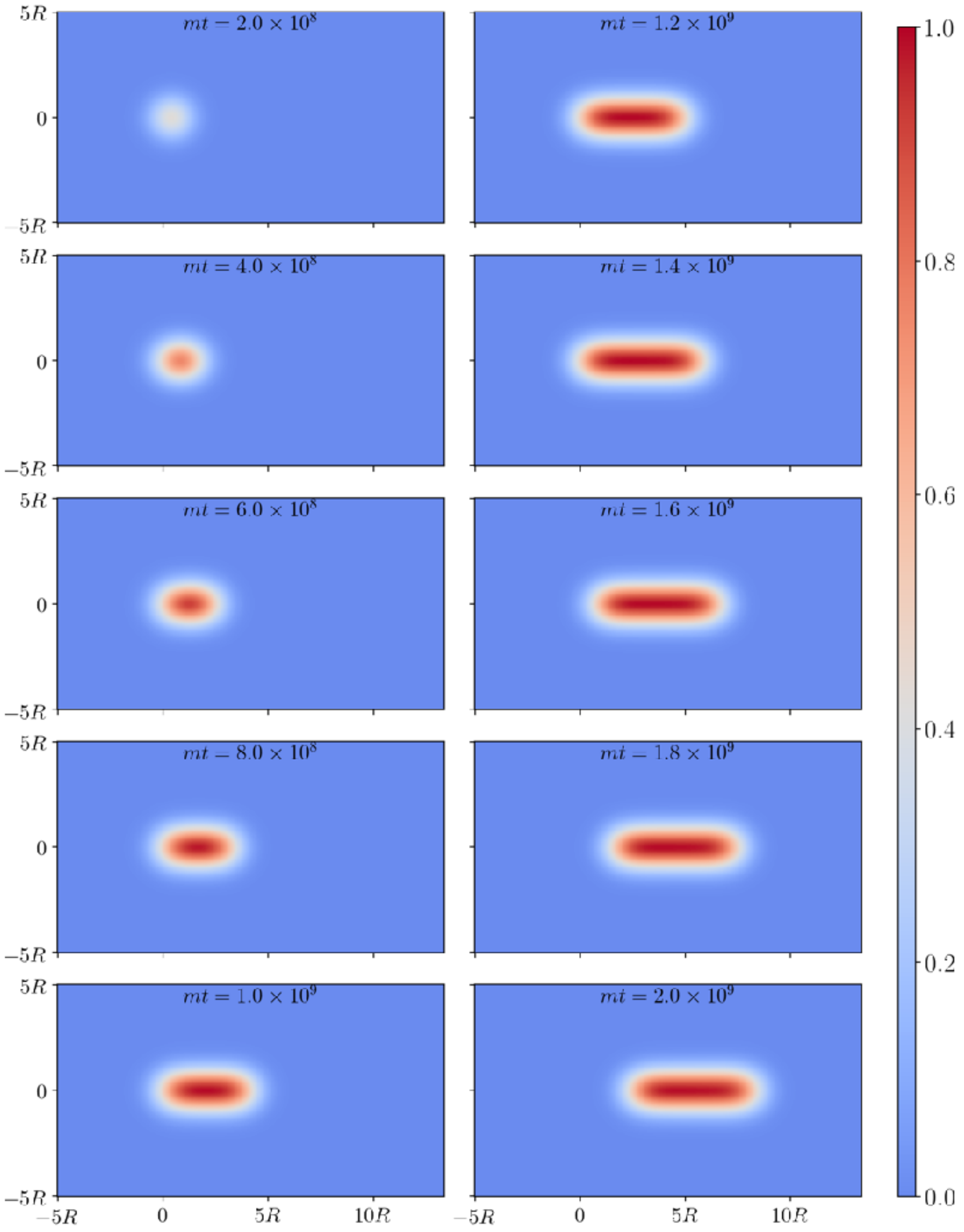
$$t_{\rm off} < R/v_p$$



Small velocity dispersion

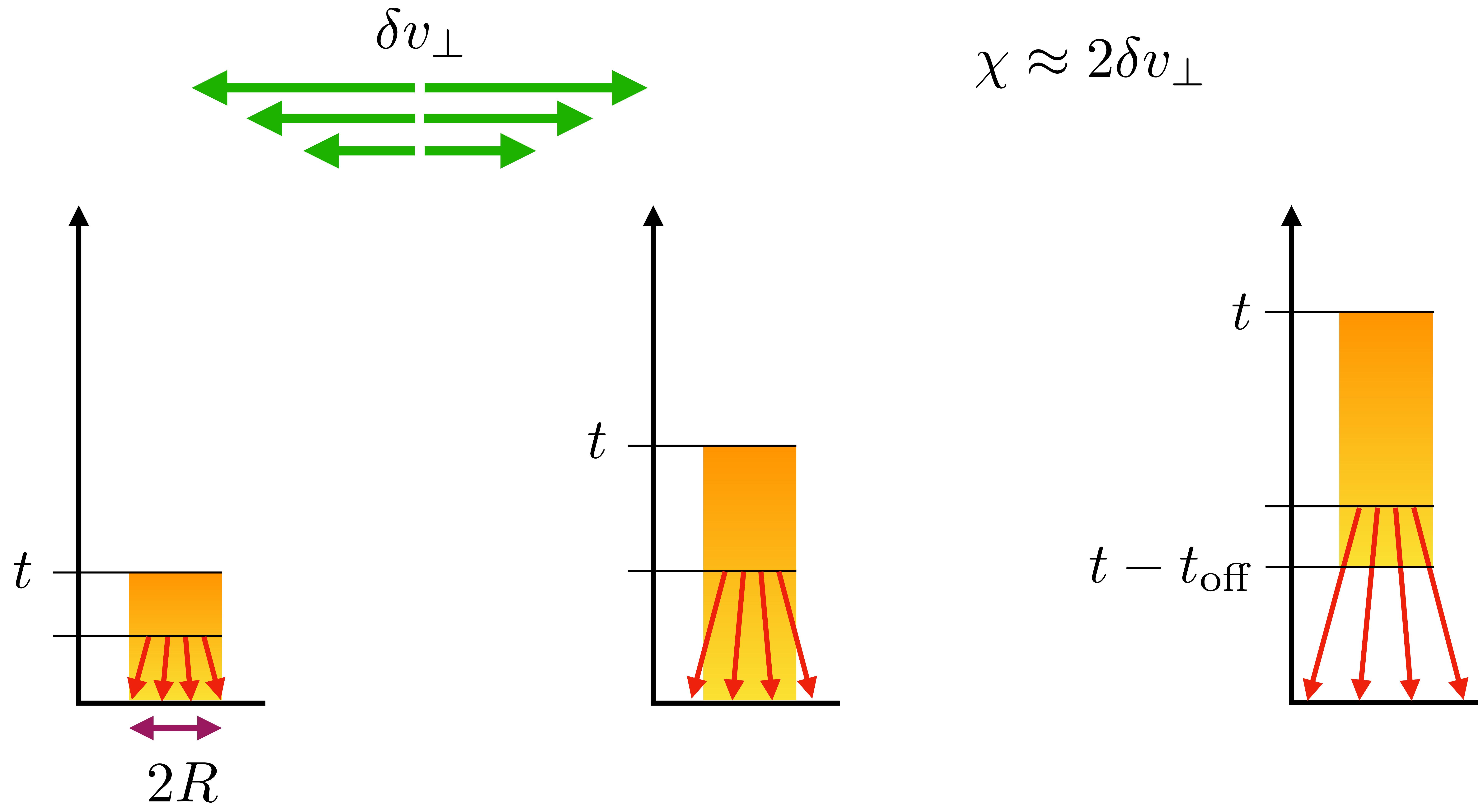
$$t_{\text{off}} > R/v_p$$





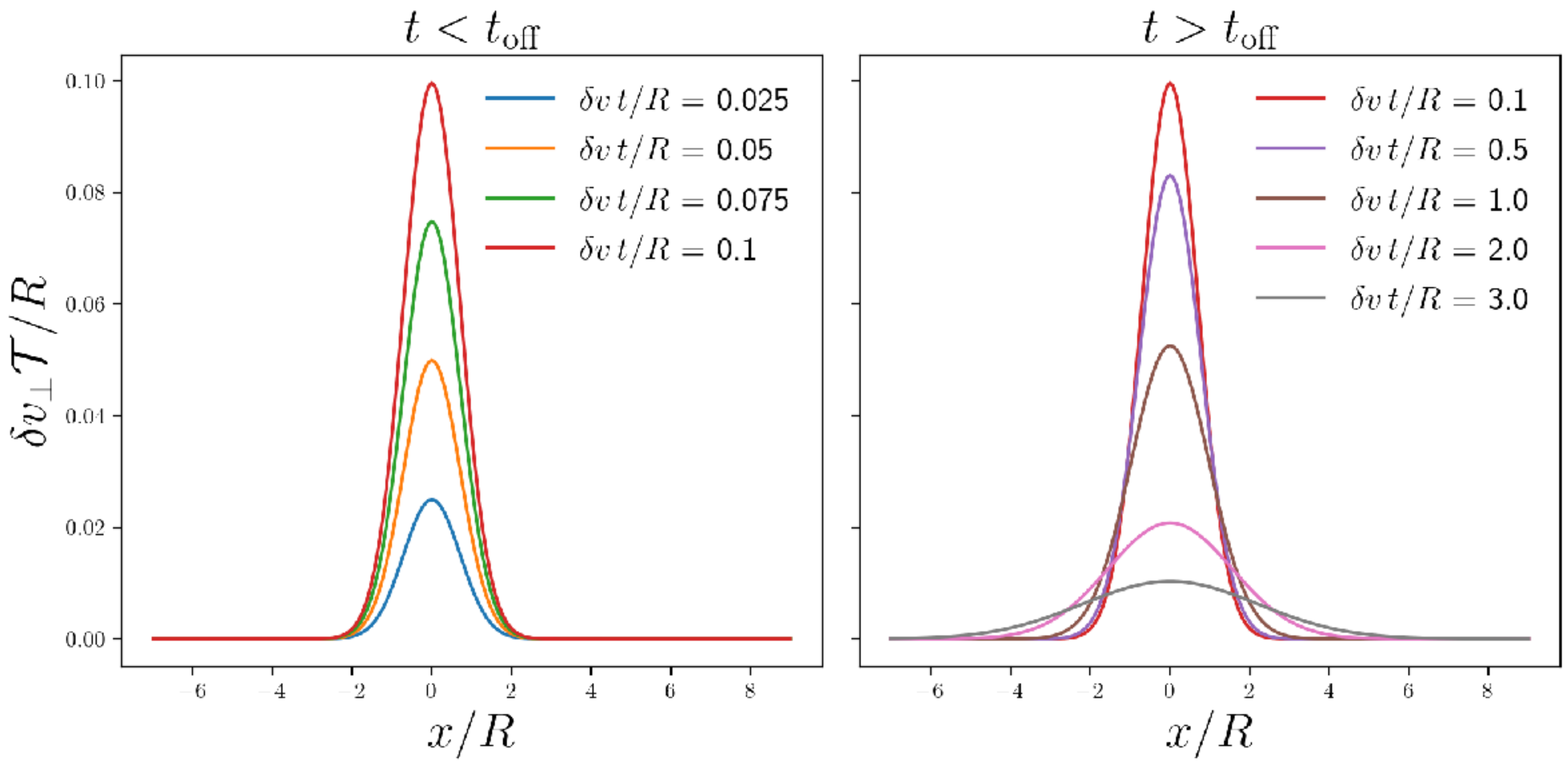
$mt = 2.0 \times 10^8$
$mt = 4.0 \times 10^8$
$mt = 6.0 \times 10^8$
$mt = 8.0 \times 10^8$
$mt = 1.0 \times 10^9$
$mt = 1.2 \times 10^9$
$mt = 1.4 \times 10^9$
$mt = 1.6 \times 10^9$
$mt = 1.8 \times 10^9$
$mt = 2.0 \times 10^9$
$5R$
0
$-5R$
$10R$
1.0
0.8
0.6
0.4
0.2
0.0

Large velocity dispersion



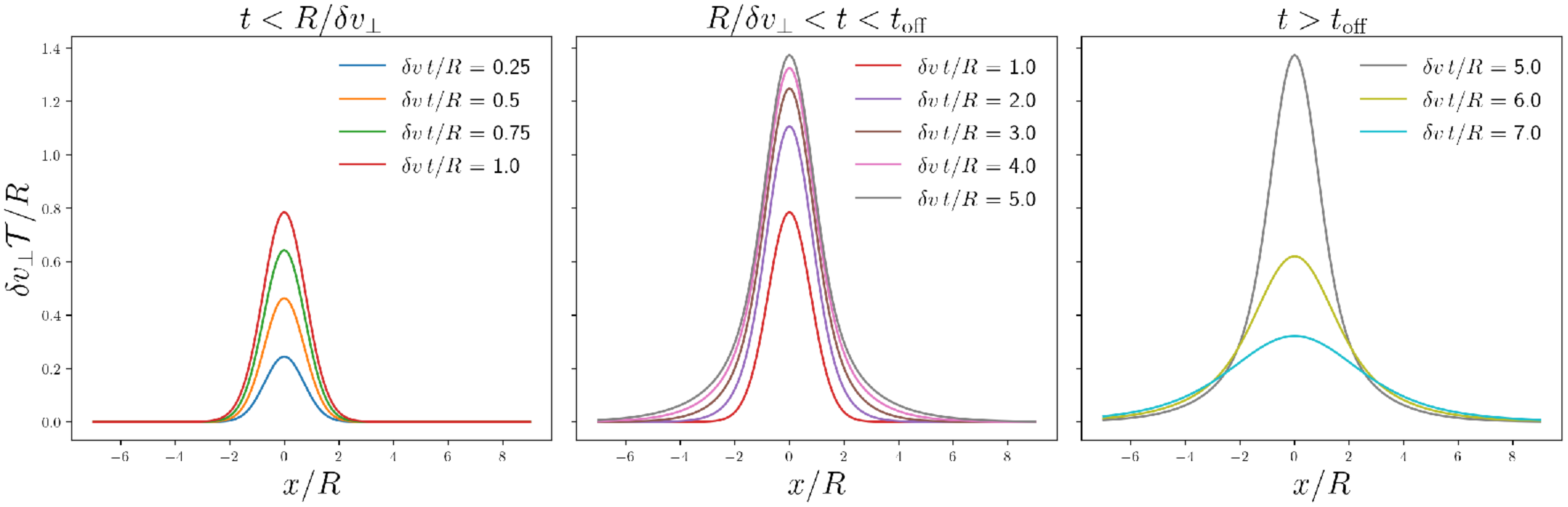
Large velocity dispersion

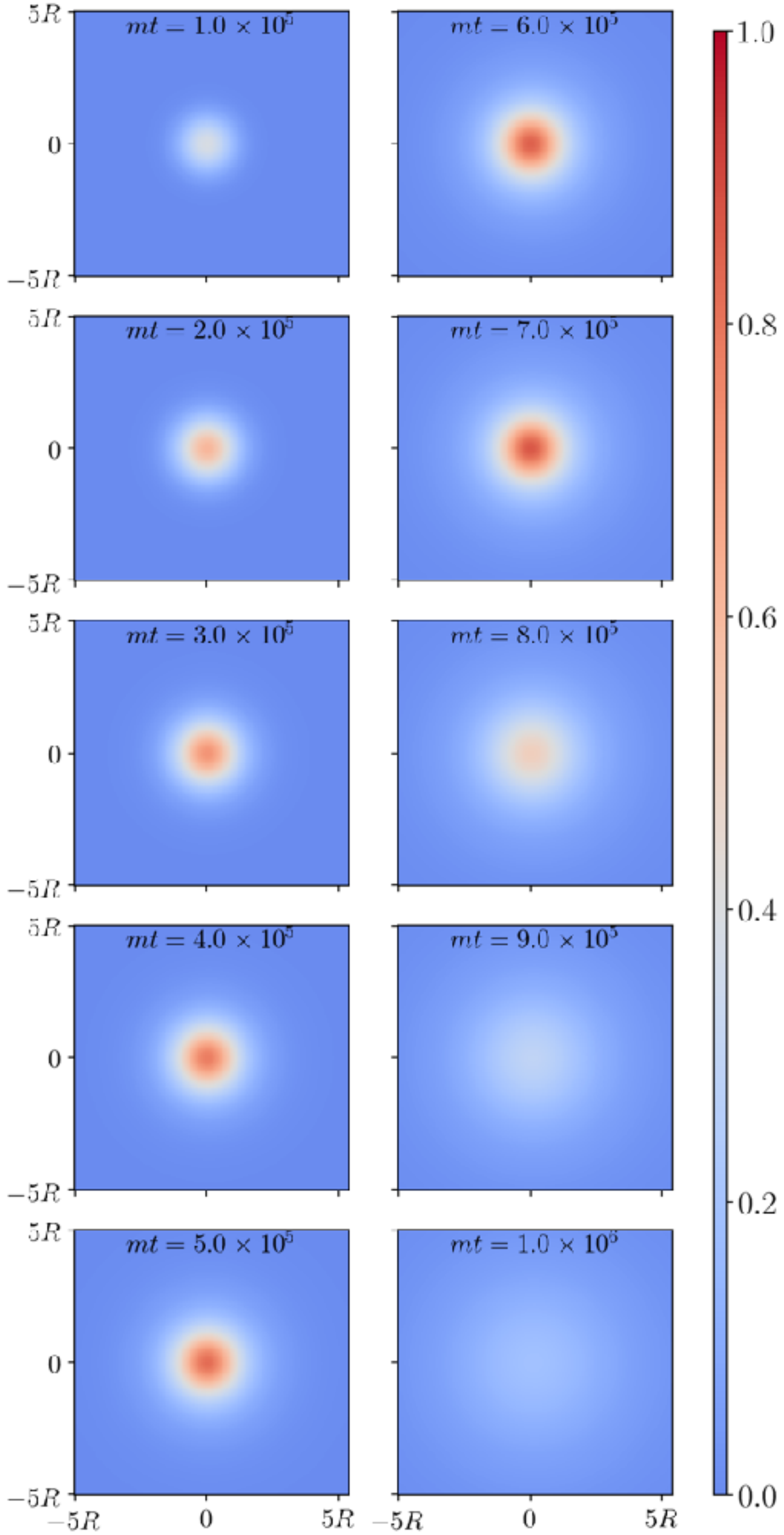
$$t_{\rm off} < R/\delta v_\perp$$



Large velocity dispersion

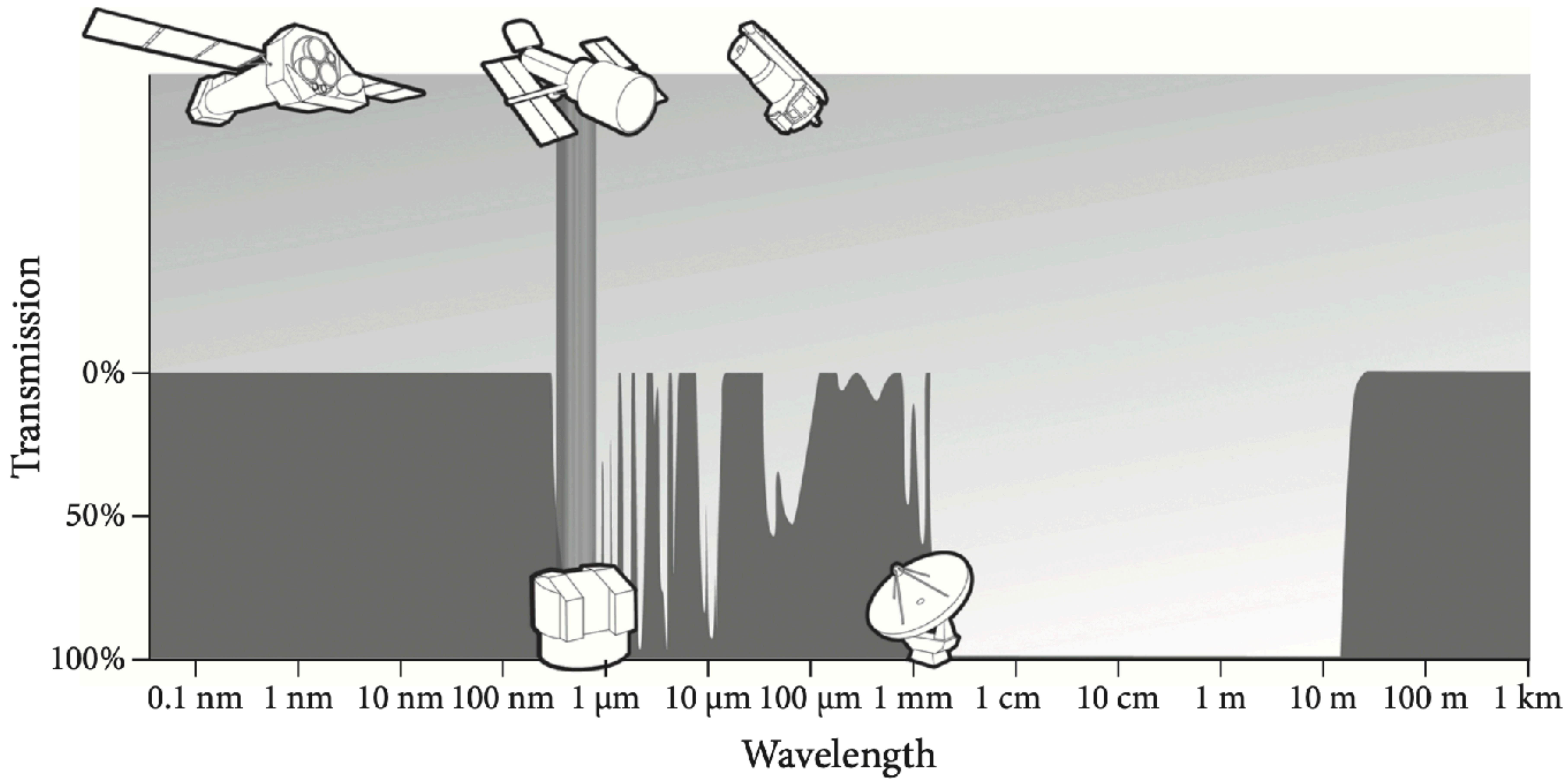
$$t_{\rm off} > R/\delta v_\perp$$





mt = 1.0 × 10^5
mt = 6.0 × 10^5
mt = 2.0 × 10^5
mt = 7.0 × 10^5
mt = 3.0 × 10^5
mt = 8.0 × 10^5
mt = 4.0 × 10^5
mt = 9.0 × 10^5
mt = 5.0 × 10^5
mt = 1.0 × 10^6
5R
0
−5R
1.0
0.8
0.6
0.4
0.2
0.0

Sensitivity

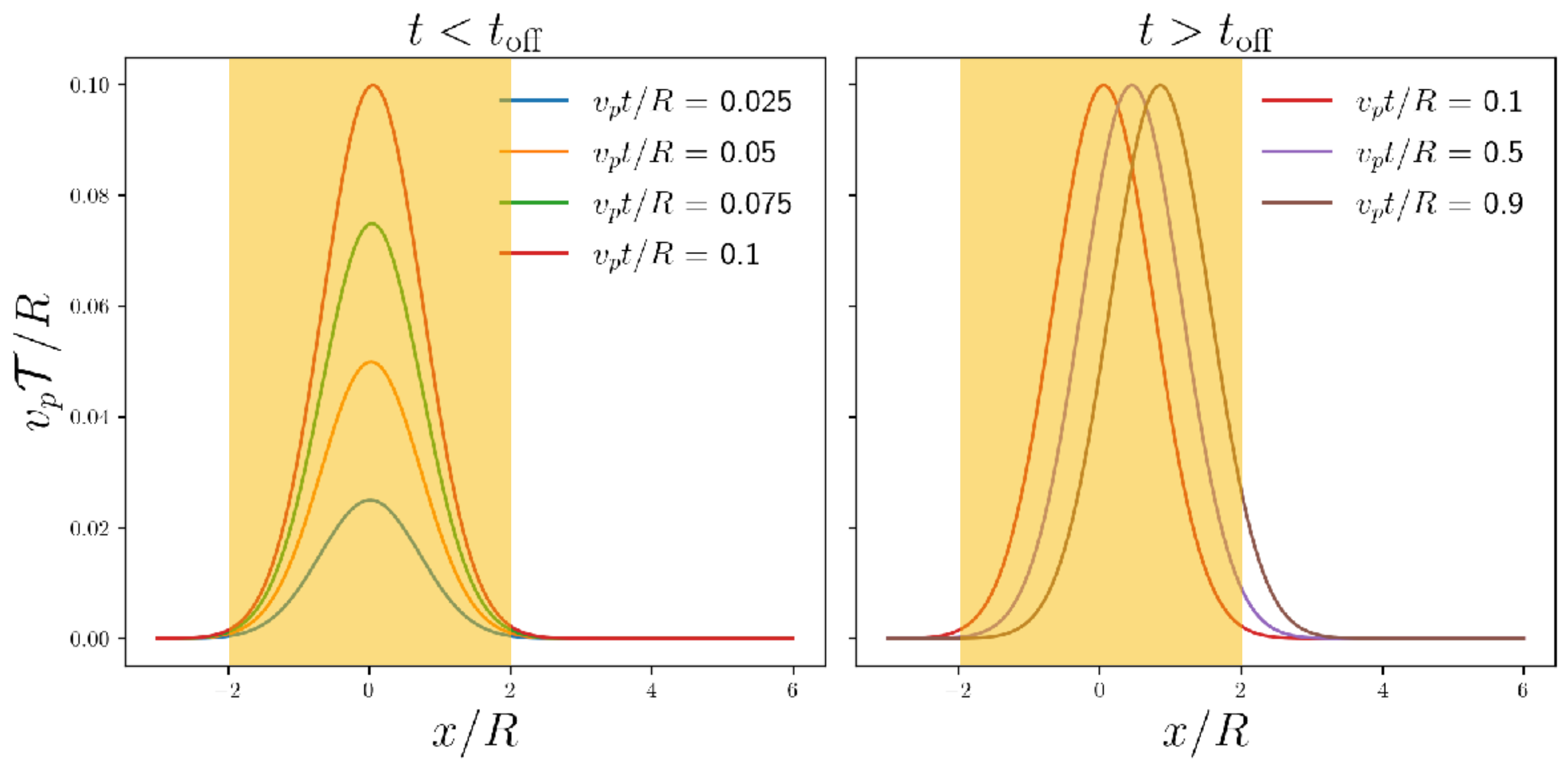


Condon, Ransom - Essential Radio Astronomy

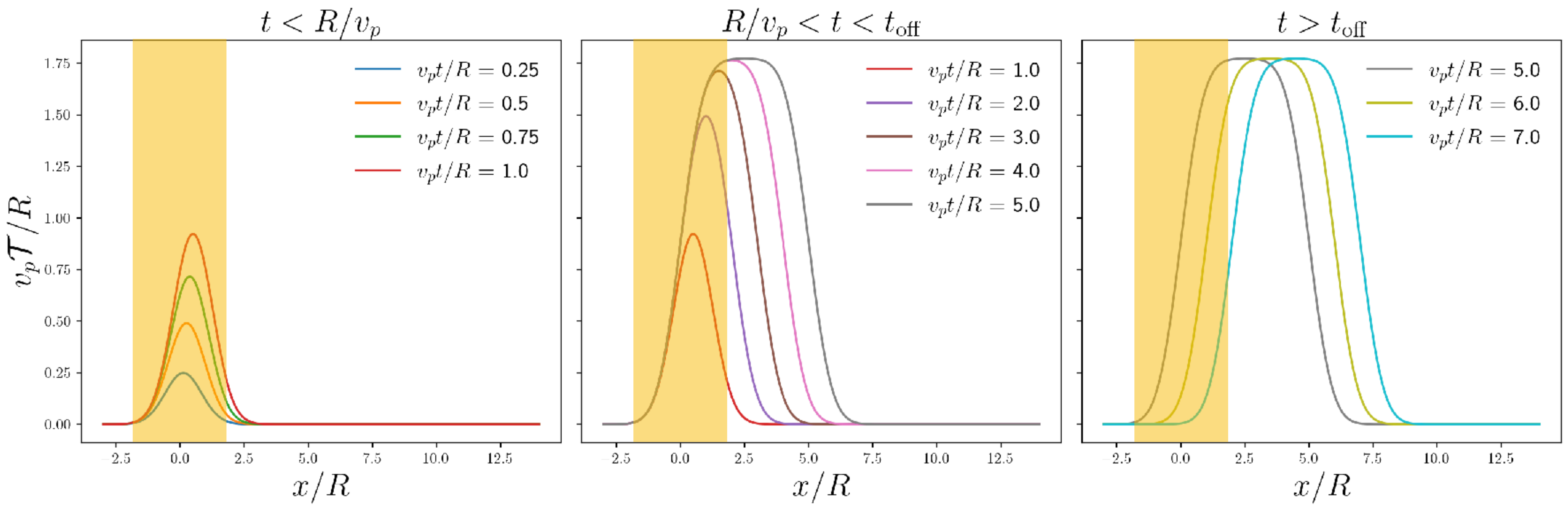
Collected power

Concentric receiver of radius R_c

$$P_c = \frac{1}{16}\sqrt{\frac{\pi}{2}}\frac{g^2\rho}{\max(\delta\omega, \delta p_{||}/2)} P_0 \min(t_{\rm off}, R_c\langle v_\perp^{-1}\rangle)$$



$t_{\rm off} < R/v_p$



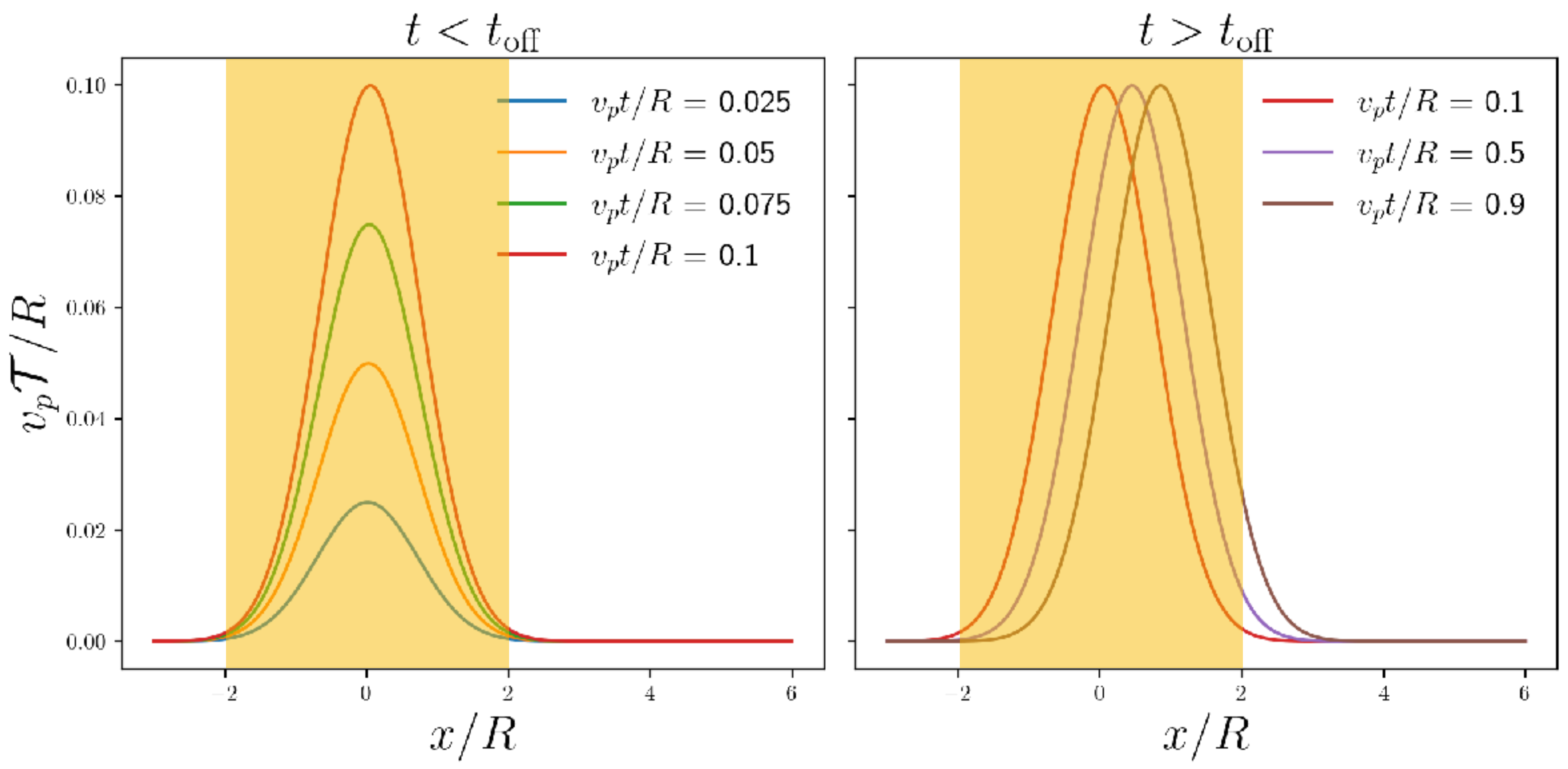
$t_{\rm off} > R/v_p$

Sensitivity

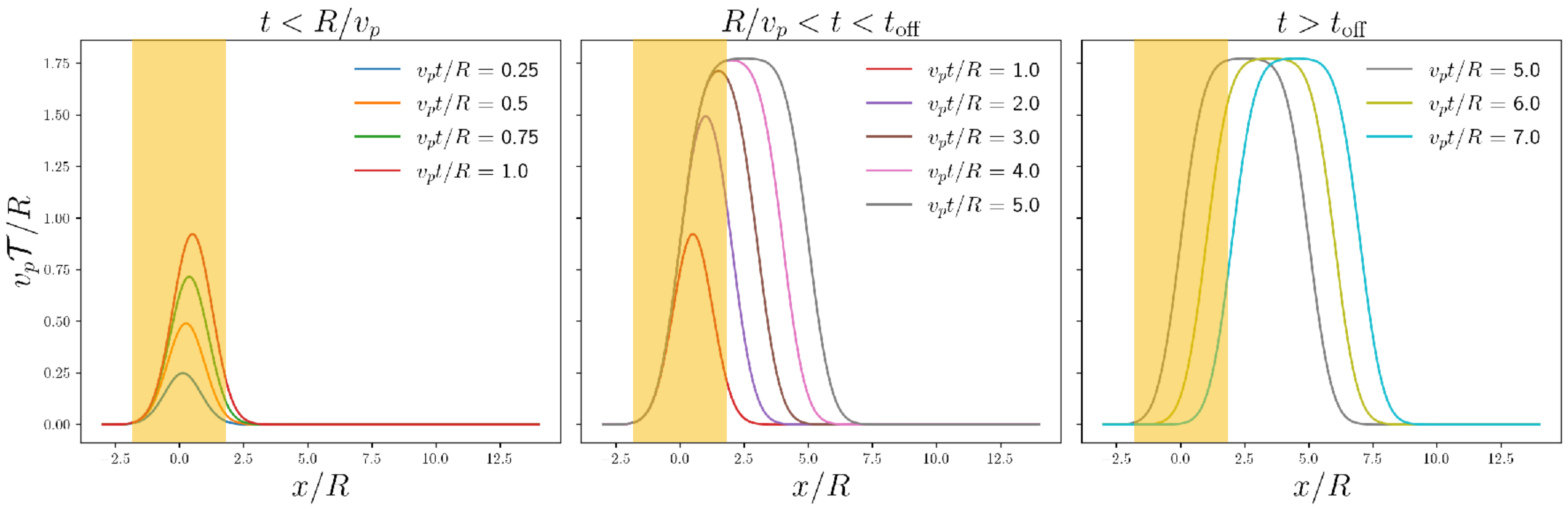
$$s/n = \frac{P_c}{T_n}\sqrt{\frac{t_m}{B}}$$

$$t_m = \max(t_{\rm off}, R_c\langle v_\perp^{-1}\rangle)$$

$$B = \frac{1}{2\pi}\min(\delta\omega, \delta p_{\|}/2)$$

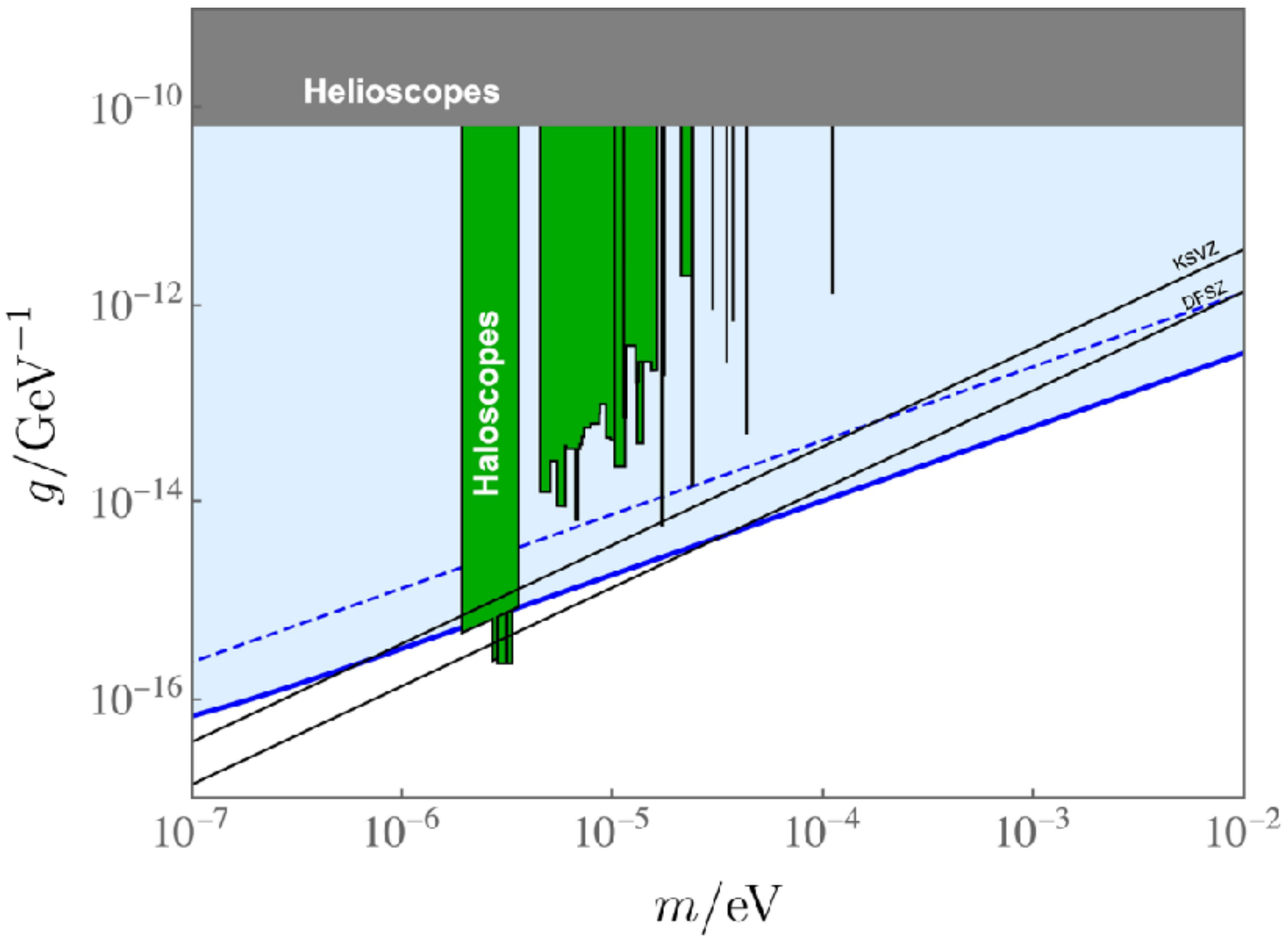


$t_{\rm off} < R/v_p$



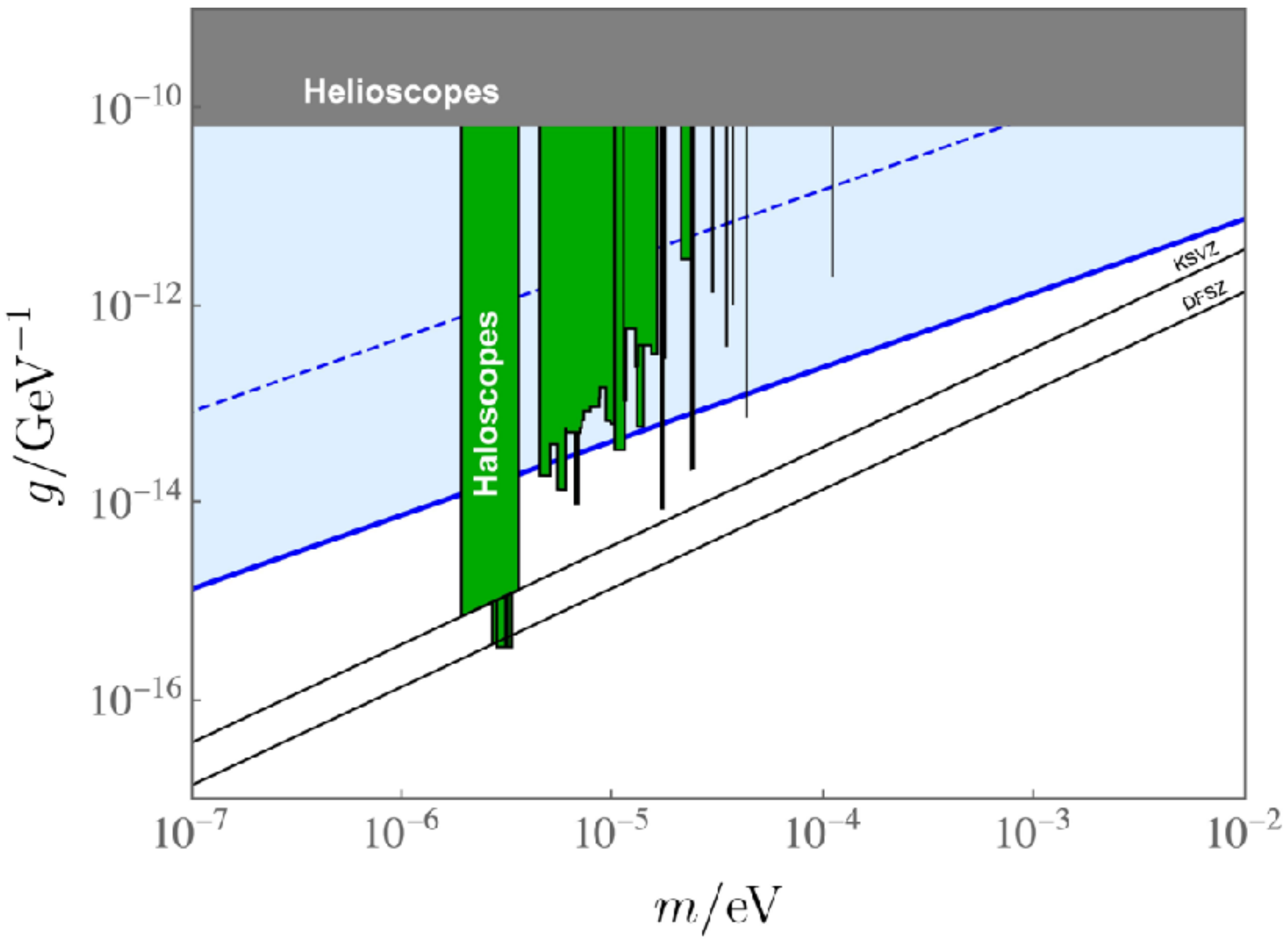
$t_{\rm off} > R/v_p$

Caustic ring model



$$\begin{aligned} \rho &= 1 \text{ Gev cm}^{-3} \\ v &= 300 \text{ km/s} \\ \delta v &= 70 \text{ m/s} \\ v_\perp &= 5 \text{ km/s} \end{aligned}$$

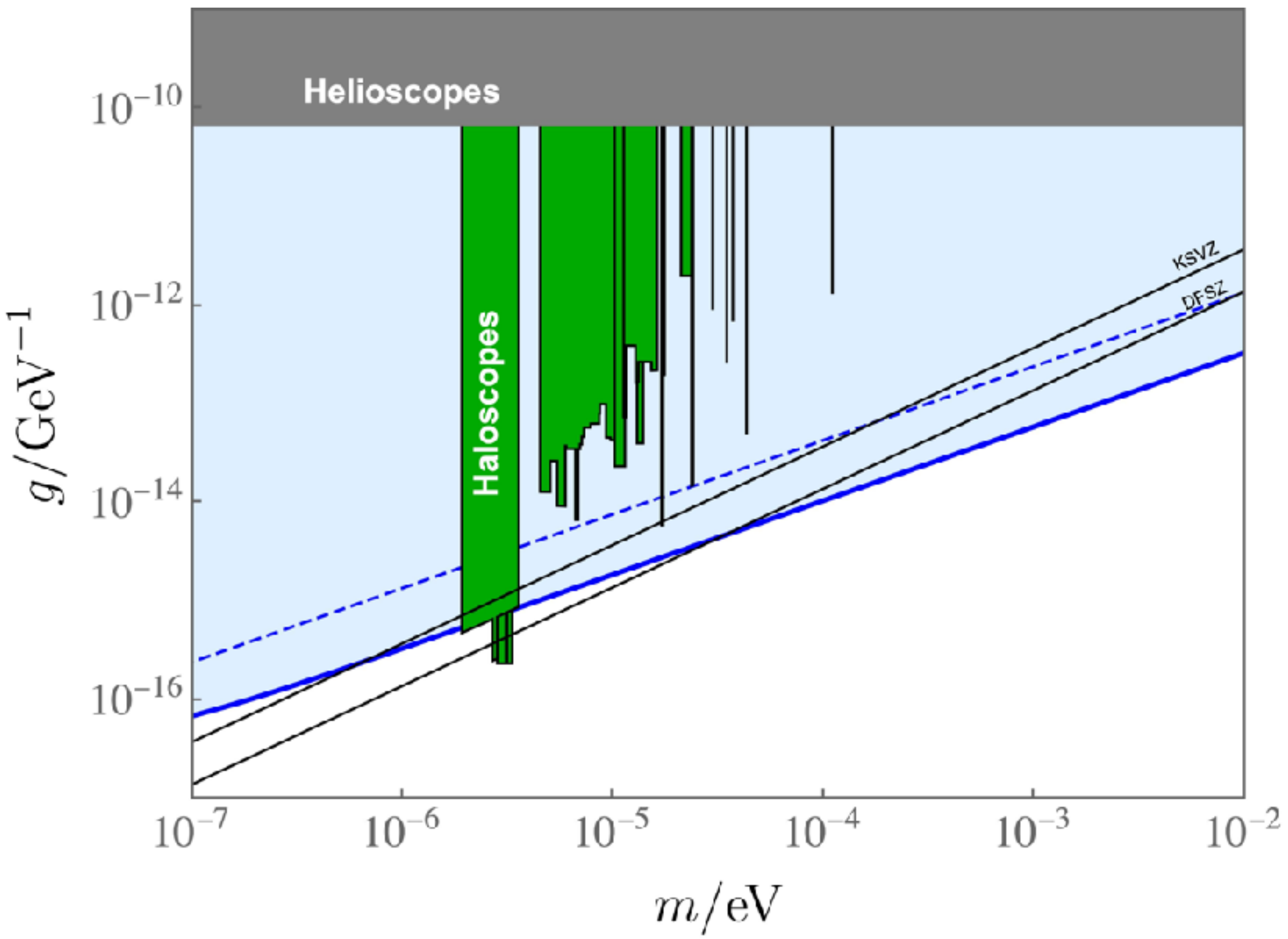
Isothermal sphere



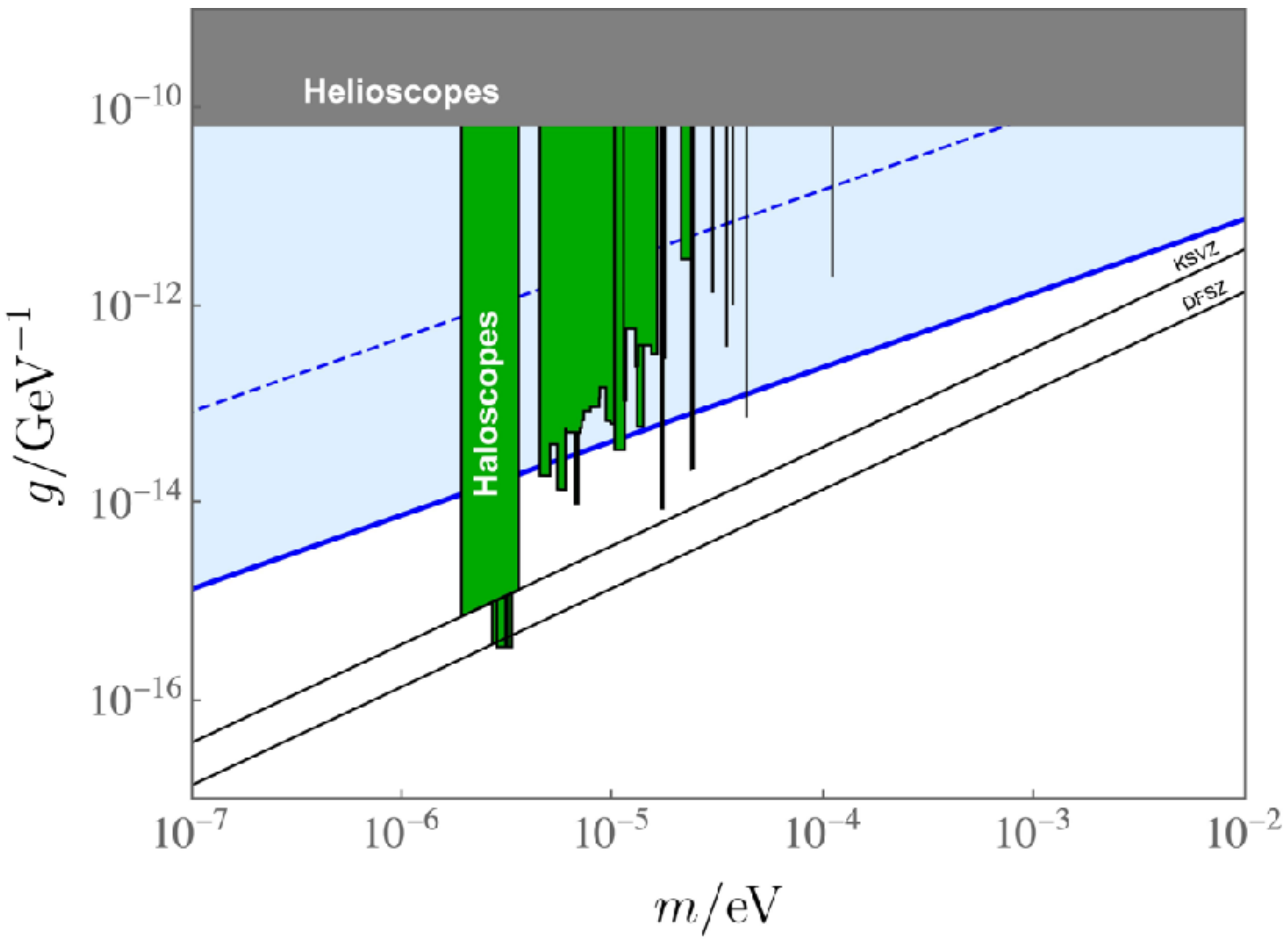
$$\begin{aligned} \rho &= 0.45 \text{ Gev cm}^{-3} \\ v &= 230 \text{ km/s} \\ \delta v &= 270 \text{ km/s} \end{aligned}$$

See talk on Wednesday by P. Sikivie

Caustic ring model



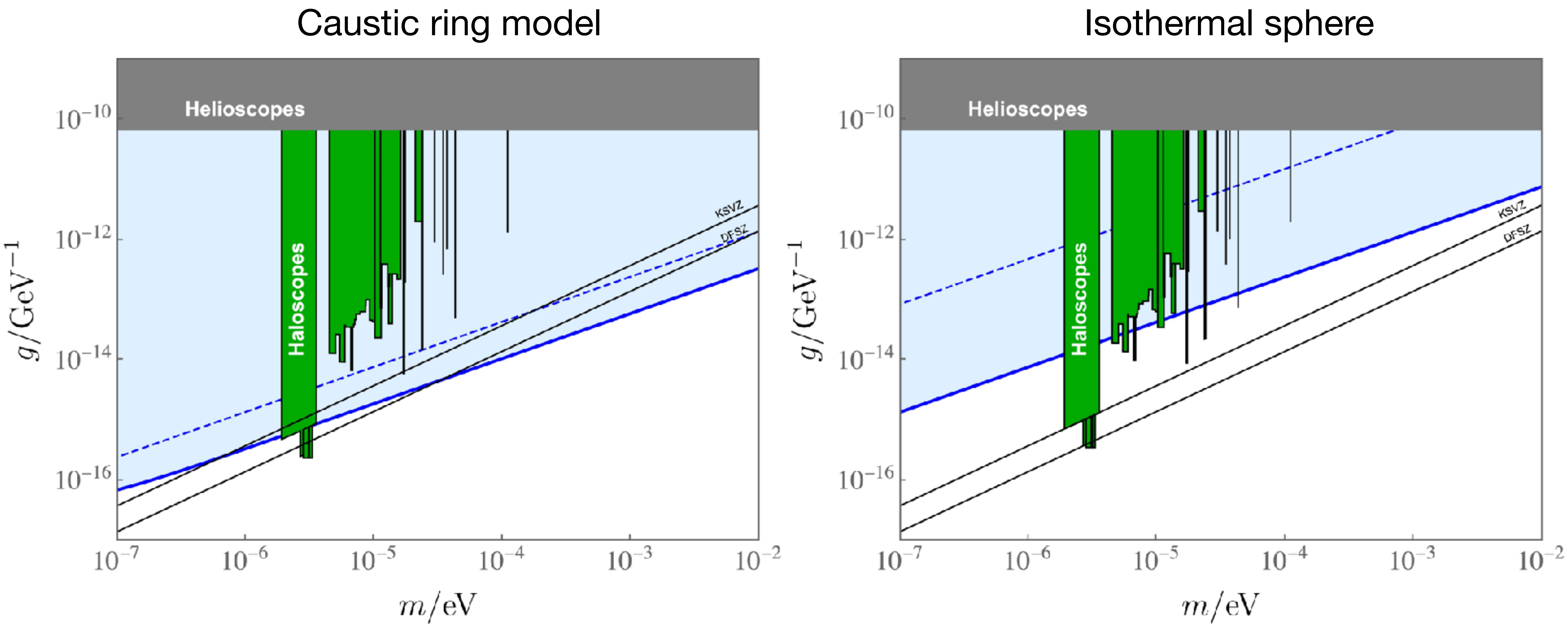
Isothermal sphere



Fixed energy to cover a factor of 2 in axion mass (dashed)

$$E = 10\,\mathrm{MW\,yr} \quad s/n = 5 \quad T_n = 20\,\mathrm{K} \quad R = 50\,\mathrm{m} \quad R_c = 100\,\mathrm{m}$$

$$t_{\mathrm{off}} = \frac{1}{2\delta\omega} \qquad \delta\omega = \delta p_z/2$$

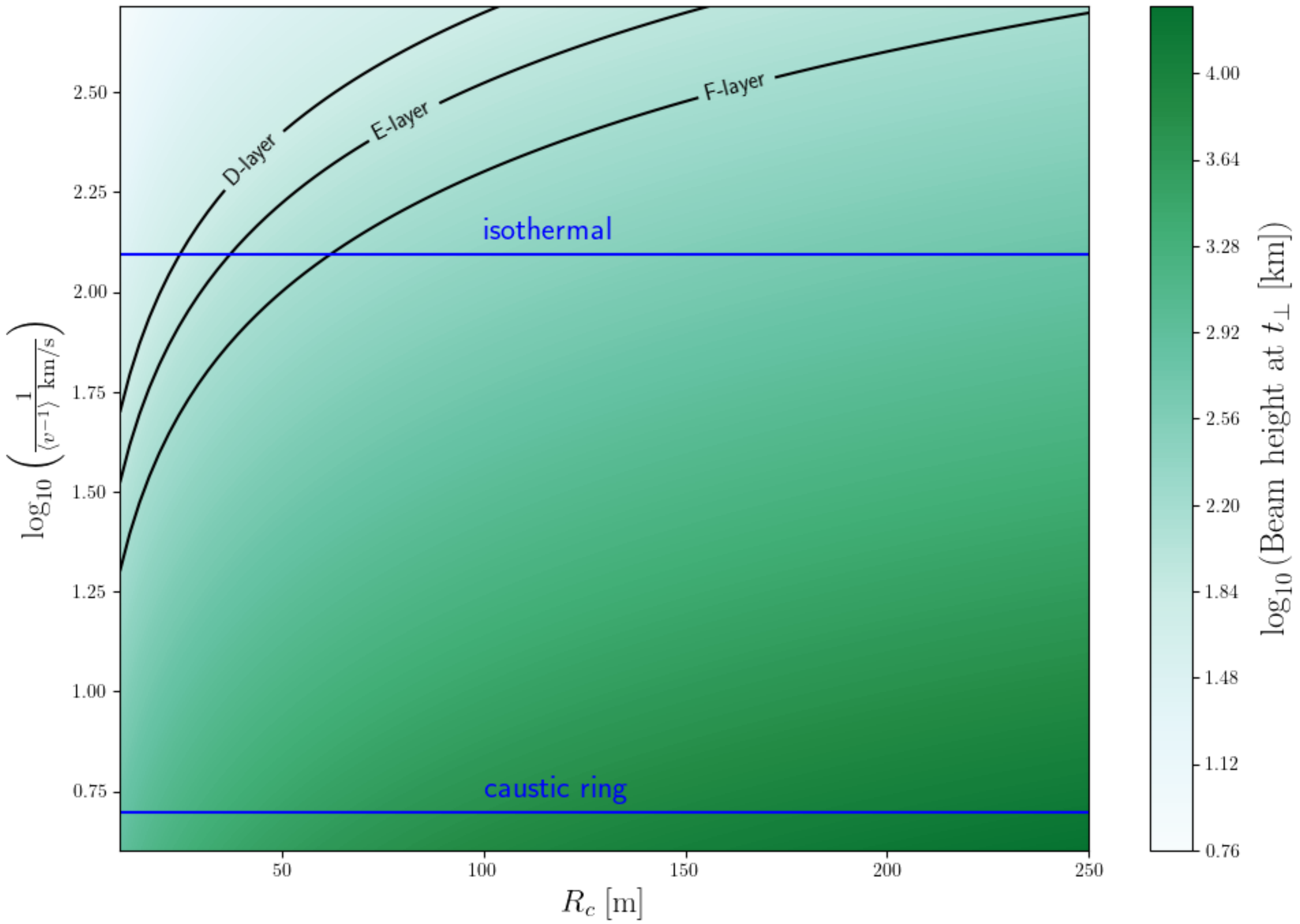


Fixed beam power and on-time to cover a factor of 2 in axion mass (dashed)

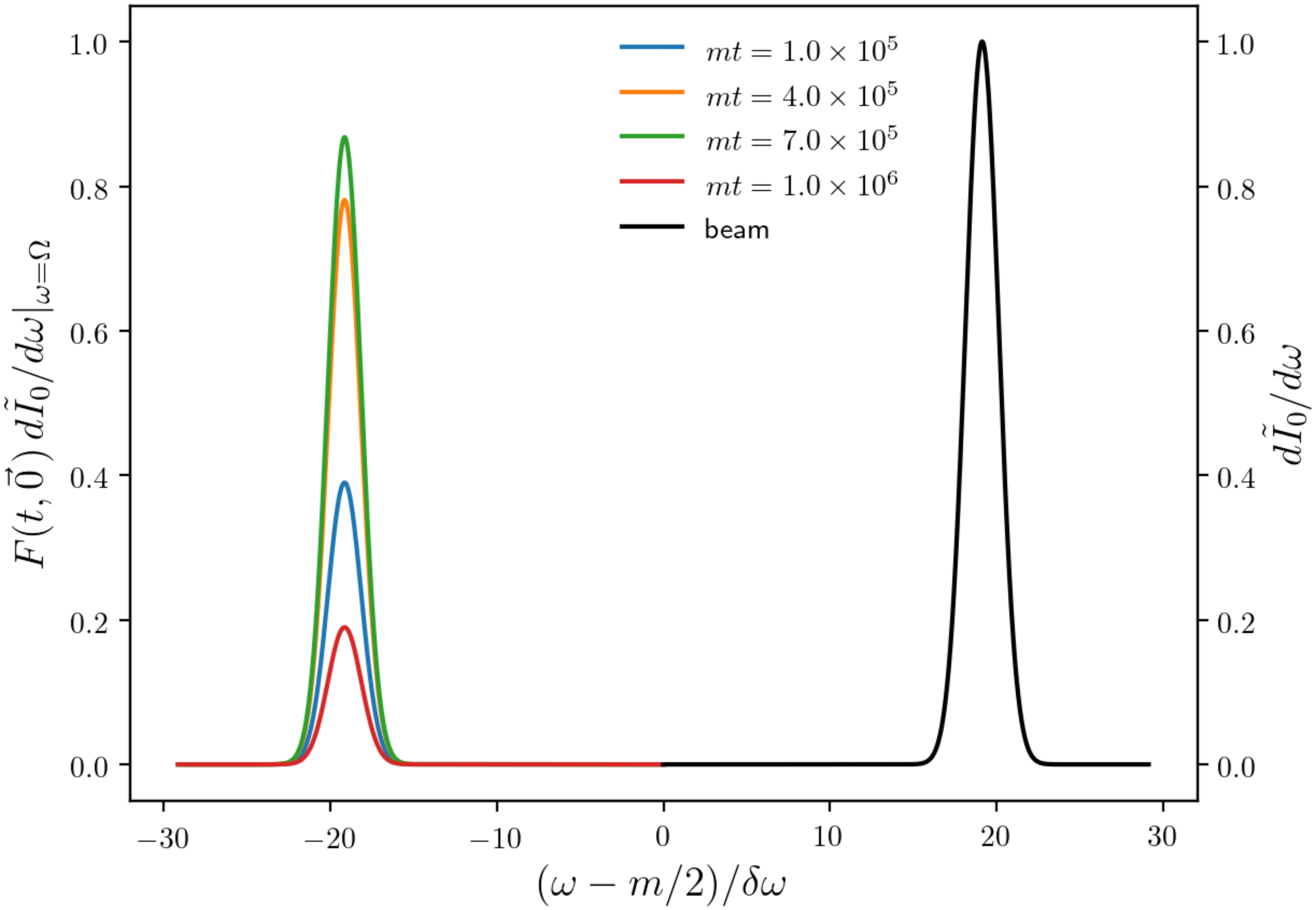
$$P_0 = 10\,\mathrm{MW} \quad t_T = 1\ \mathrm{yr} \quad s/n = 5 \quad T_n = 20\,\mathrm{K} \quad R = 50\,\mathrm{m} \quad R_c = 100\,\mathrm{m}$$

$$t_{\mathrm{off}} = \sqrt{\delta v_z t_\perp t_T} \qquad \delta\omega = \frac{m}{2}\sqrt{\frac{\delta v_z t_\perp}{t_T}}$$

Beam height



D-layer
E-layer
F-layer
isothermal
caustic ring
2.50
2.25
2.00
1.75
1.50
1.25
1.00
0.75
$\log_{10}\left(\frac{1}{\langle v^{-1}\rangle \text{ km/s}}\right)$
50
100
150
200
250
R_c [m]
4.00
3.64
3.28
2.92
2.56
2.20
1.84
1.48
1.12
0.76
$\log_{10}(\text{Beam height at } t_\perp \text{ [km]})$



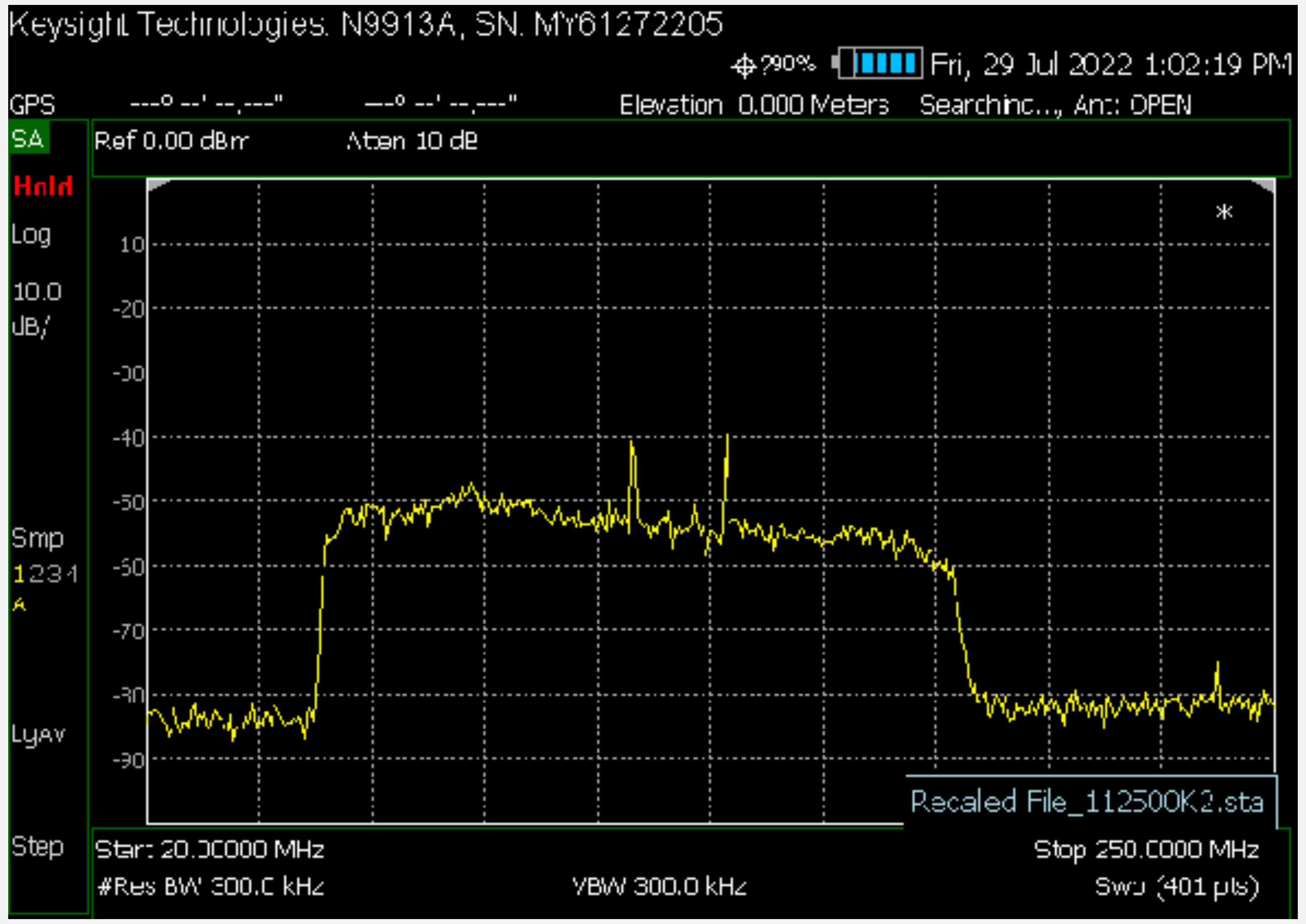
$mt = 1.0 \times 10^5$
$mt = 4.0 \times 10^5$
$mt = 7.0 \times 10^5$
$mt = 1.0 \times 10^6$
beam
$F(t, \vec{0})\, d\tilde{I}_0/d\omega|_{\omega=\Omega}$
$d\tilde{I}_0/d\omega$
$(\omega - m/2)/\delta\omega$

THE PREPARATION FOR THE FIRST STAGE OF THE EXPERIMENT

Quan Guo

Shanghai Astronomical Observatory, CAS

POTENTIAL EXPERIENTIAL SITE



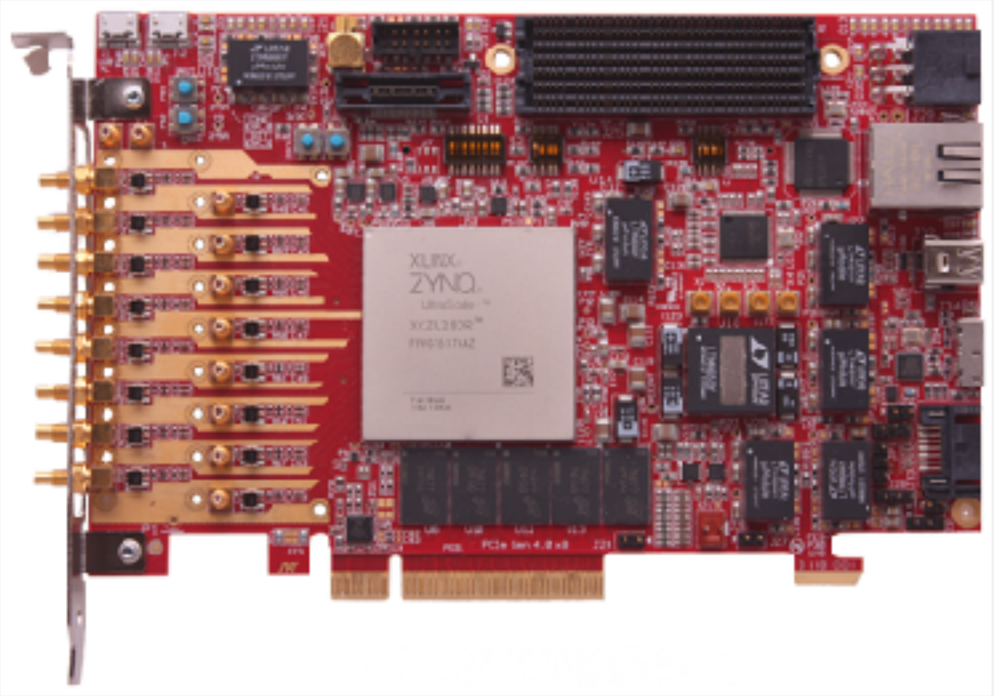
Very low Radio frequency interference
Only two of FM radio signals above the background noise after 64 dB amplified

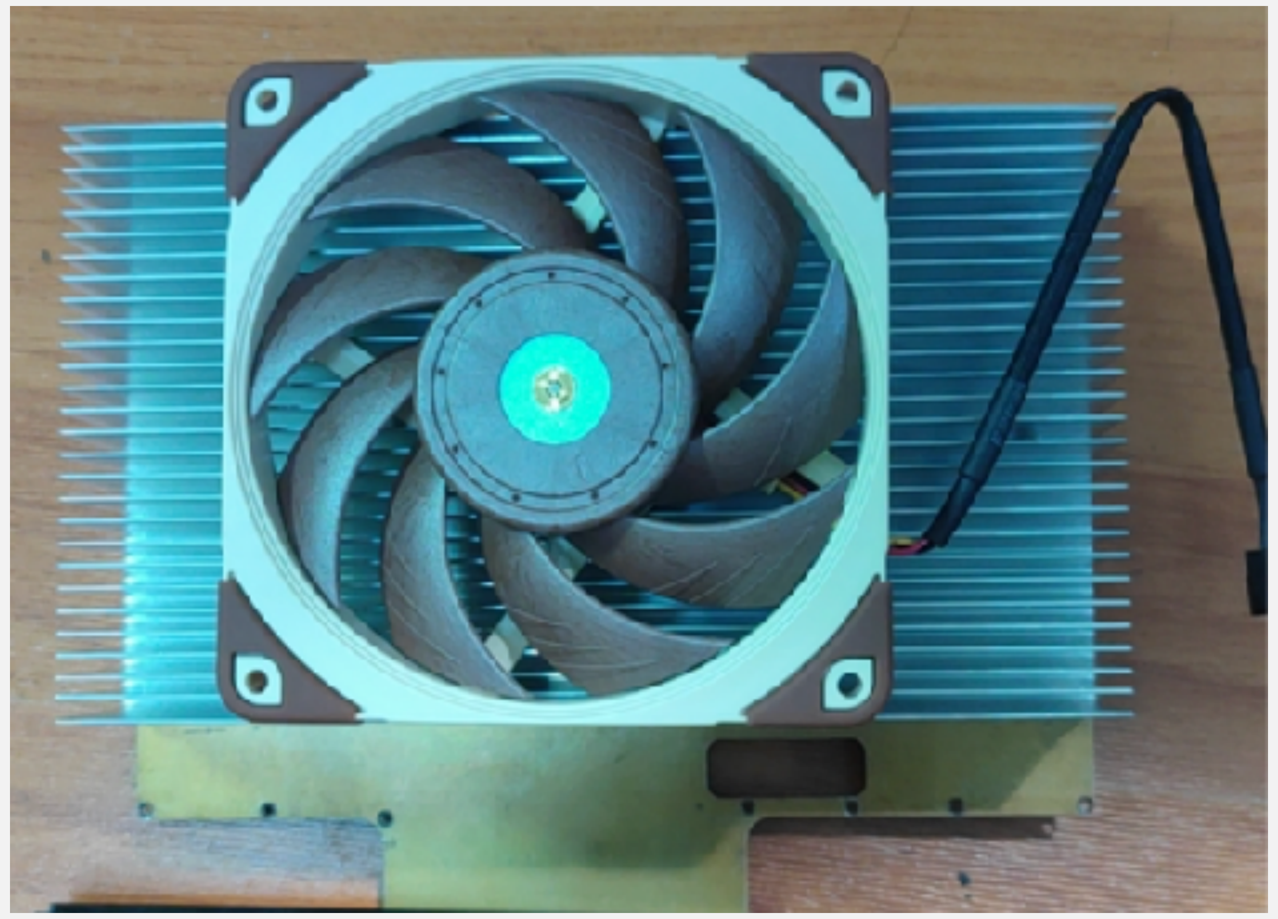
Two type of Antennas

First type of Antennas available
Low frequency 50 – 200 Mhz

Second type of Antennas available
Low frequency 0.3 – 3 Ghz

DAQ SYSTEM





FPGA sealed in the box

- FPGA Rfsoc (Xilinx Zynq® UltraScale+™),
- 12bit ADC
- Power: 38w
- 功率约38瓦
- Sample rate 480 Msa/s upgradable to 2Gsa/s
- 480 Msa/s 采样率
- 4 10Gb ethernet output

DATA SAVING SYSTEM

- Powerful PC with GPU acceleration
- Powered by the car batteries
- Packed in the traveling case and easy to be moving around
- Can Handle 7.6Gb/s data transferred from the DAQ: 1. Saving to the disk directly or 2. perform FFT on-the-fly and save the spectrums.

MISSING PARTS

- Power emission devices to emit at specific frequency

THANK YOU