Probing DM Clumps, Strings and Domain Walls with GW Detectors

Jaeckel, Schenk,
Spannowsky [2004.13724]

Probing Planet 9

Scholtz, Unwin [1909.11090]
Witten [2004.14192]
Lawrence & Rogoszinski [2004.14980]
Haung & Loeb [2005.01120]

Peera Simakachorn
Journal club
4 June 2020

image from NASA

For today: probe via gravitational effect

- **Planet 9**
  Probe by gravitational pull on **spacecrafts**
  Proposal of Witten and others >>> **Noise is too large.**

- **DM clump, cosmic strings,** and **domain walls**
  (also stochastic DM density fluctuation)
  > gravitational pull on **GW detectors**
  > signal power spectrum
  > event rate estimation

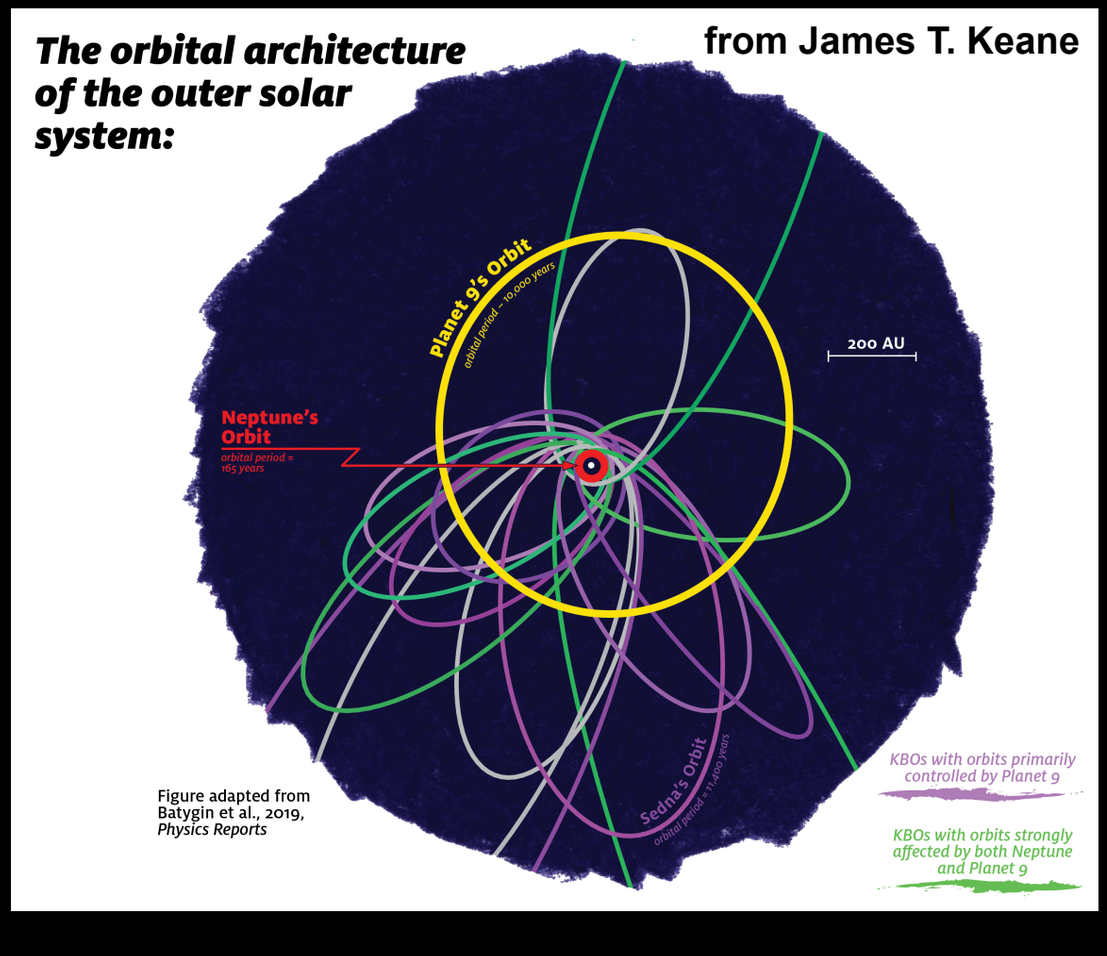
Planet 9

[review: 1902.10103]

Anomalies of objects beyond Neptune:
clustering and high-eccentricity objects

! NOT ! by other known planets
need an object of **mass ~ 5 - 10 $M_\oplus$**

@ distance ~ 500 AU



could be:

I. **Planet** from outside Solar system
>>> Telescope searches (optical, IR/MW)

II. **PBH** captured by Solar system:
e.g. lensing anomalies >>> mass of **0.5 - 20 $M_\oplus$**

PBH from strong 1st-order PT during radiation era

$$f_{\rm PBH} \equiv \frac{\Omega_{\rm PBH}}{\Omega_{\rm DM}} \in [0.005, 0.1]$$

$$M_{\rm BH} \sim M_\oplus \left(\frac{125\ {\rm GeV}}{T}\right)^2$$

Jedamzik, [astro-ph/9605152]

III. Other exotic objects: **DM clump/star**, DM ring

Scholtz, Unwin [1909.11090]

$$M_\oplus \sim 10^{-6} M_\odot$$

Probe Planet 9

I. Indirect, Model-dep. : DM halo around Planet 9 >>> Annihilation signal

Searches for **moving** source of **cosmic rays** Scholtz, Unwin [1909.11090]

Flares from **accreting** Oort cloud objects observed by LSST

Siraj, Loeb [2005.12280]

II. Gravitational Effect :

Send near-relativistic **spacecraft**

>>> perturbation from P9 **shifts trajectory** of spacecraft

> **time-delay of signals** Witten [2004.14192]

$$\Delta\tau \simeq 10^{-5}\ \text{sec}\ \left(\frac{M}{5M_\oplus}\right)\left(\frac{10^{-3}\ c}{v}\right)^2$$

(need on-broad high-precision clock)

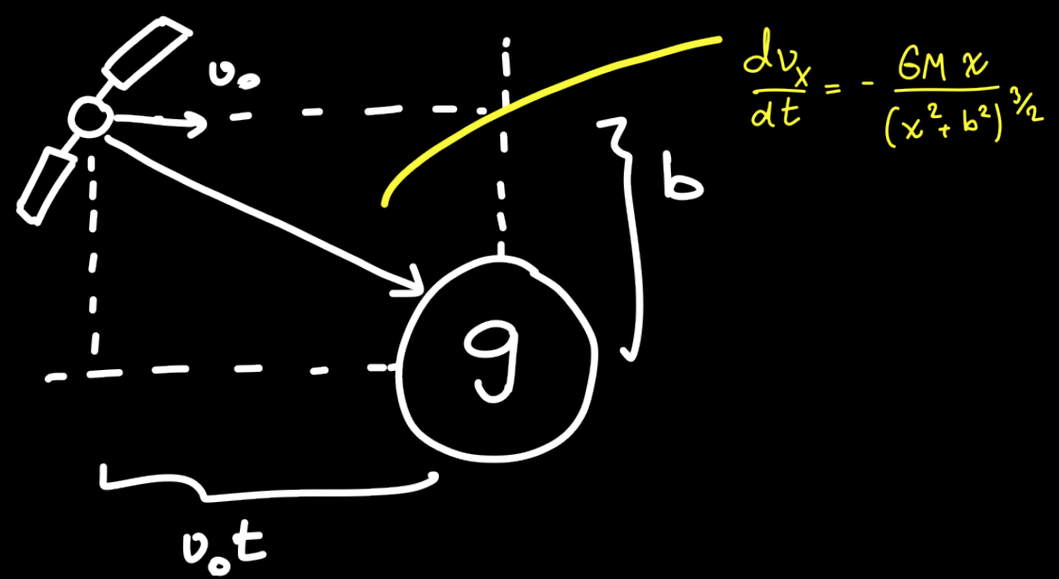
> **angular displacement** in the sky

Lawrence & Rogoszinski [2004.14980]

$$\Delta\alpha \simeq 10^{-8}\ \text{rad}\ \left(\frac{M}{5M_\oplus}\right)\left(\frac{40AU}{\rho}\right)\left(\frac{10^{-3}\ c}{v}\right)^2$$

(no clock needed)

Breakthrough Starshot project:
0.01c with mass 6.6 mg
accel. with lasers



Probe Planet 9

These can **failed!** Haung & Loeb [2005.01120]
by **interactions** with **interstellar medium** (outside "Heliosphere" ca. 100 AU)

I. **Drag force** from particles and dusts (dep. on **surface** area):
e.g. moving through proton density n_H

$$\frac{F_{\rm drag}}{F_{\rm grav}} \simeq 120 \left(\frac{5M_\oplus}{M_{P9}}\right)\left(\frac{b}{100\ {\rm AU}}\right)^2\left(\frac{n_H}{1\ {\rm cm}^{-3}}\right)\left(\frac{v}{0.01c}\right)^2\left(\frac{3\ {\rm g\ cm}^{-3}}{\rho_{\rm craft}}\right)^{2/3}\left(\frac{1\ {\rm g}}{M_{\rm craft}}\right)^{1/3}$$

II. **Electromagnetic interaction** (dep. on **length** area):
surface of the craft get charges through e.g. photoelectric effect

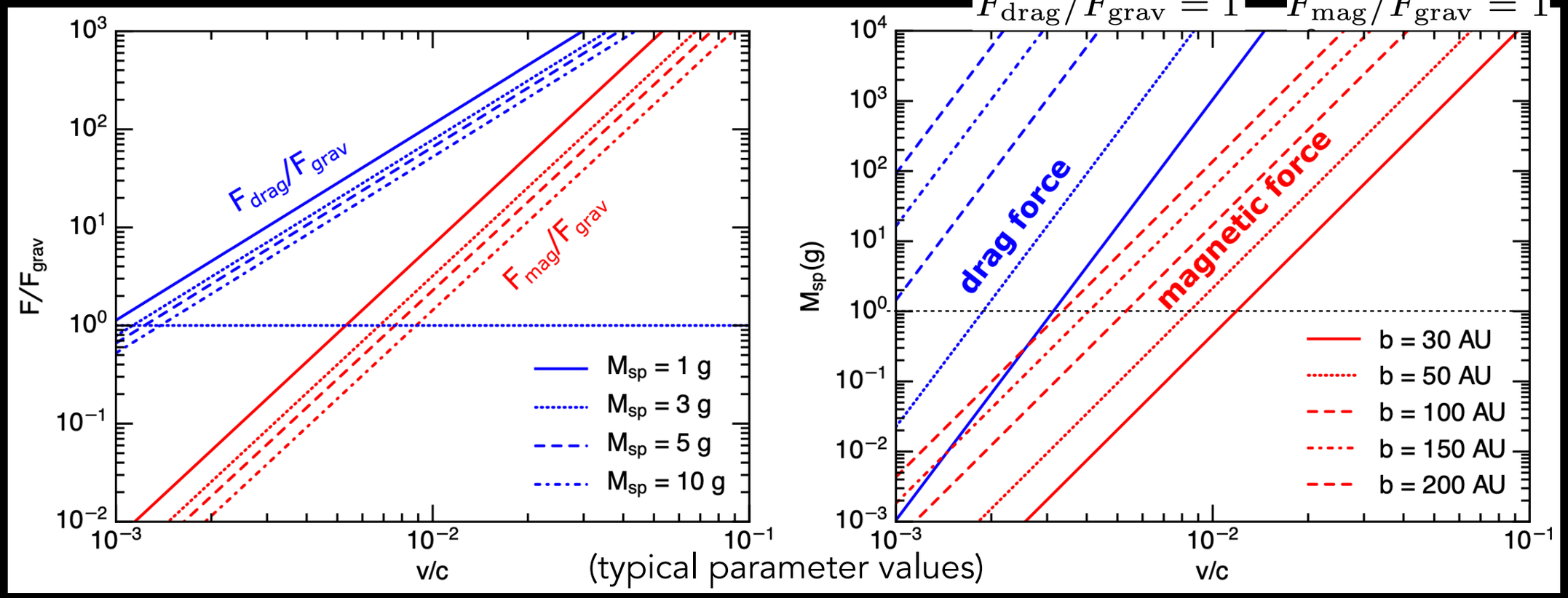
$$\frac{F_{\rm EM}}{F_{\rm grav}} \simeq 6.6 \left(\frac{5M_\oplus}{M_{P9}}\right)\left(\frac{b}{100\ {\rm AU}}\right)^2\left(\frac{B_\perp}{5\ \mu{\rm G}}\right)\left(\frac{v}{0.01c}\right)^3\left(\frac{3\ {\rm g\ cm}^{-3}}{\rho_{\rm craft}}\right)^{1/3}\left(\frac{1\ {\rm g}}{M_{\rm craft}}\right)^{2/3}$$

(assuming cubic-shaped spacecraft)

$F_{\rm grav} = GM_{\rm craft}M_{P9}/b^2$

Probe Planet 9

For cubic-shaped spacecraft



Haung & Loeb [2005.01120]

To reduce environmental effects:

Increasing mass/density >>> cause more energy to accelerate

Decreasing speed >>> longer to reach Planet 9

Decreasing impact parameter >>> send an array of probes

Changing design to reduce drag >>> needle-liked craft
>>> become dipole >>> EM can cause oscillation

Probing DM clumps,

strings, and domain walls

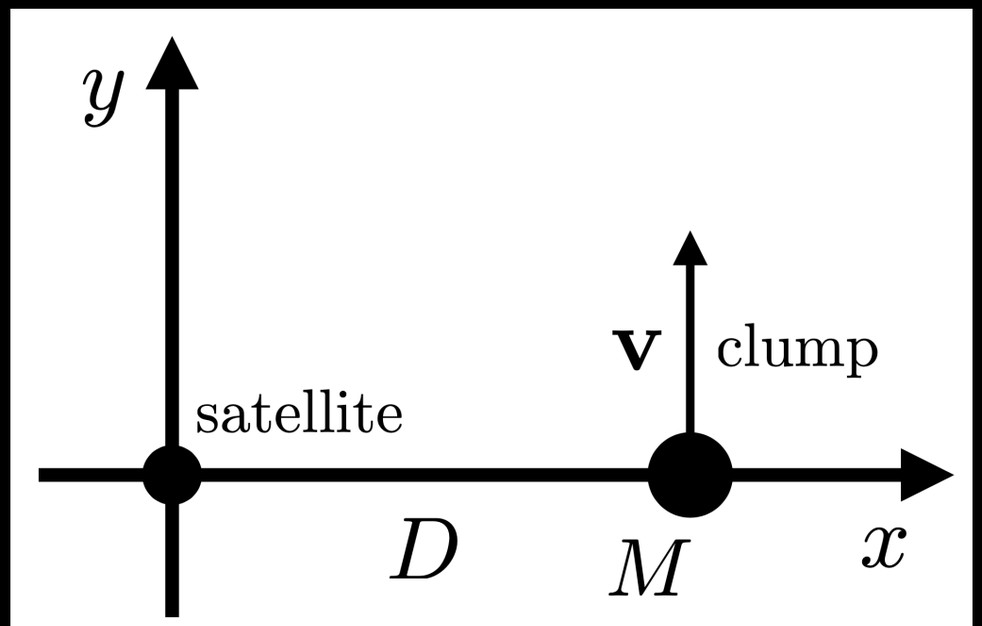
with GW detectors

Jaeckel, Schenk,
Spannowsky [2004.13724]

for PBH: Cooray & Seto [astro-ph/0405216]
for asteroids: Vinet (2006)

Grav. perturbation from a DM clump and signals in detectors

Assume a **point-liked clump** of mass ***M*** approaches LISA node at velocity ***V*** and impact parameter ***D***



Nodes experience **different grav. field**

$$\mathbf{g}(t) = \frac{GM}{D^2} \frac{1}{\left(1+\left(\frac{Vt}{D}\right)^2\right)^{3/2}} \begin{pmatrix} 1 \\ \frac{Vt}{D} \\ 0 \end{pmatrix}$$

induced relative motion

>>> **Doppler shift of laser signal**

(sensitive to **velocity perturbation)**

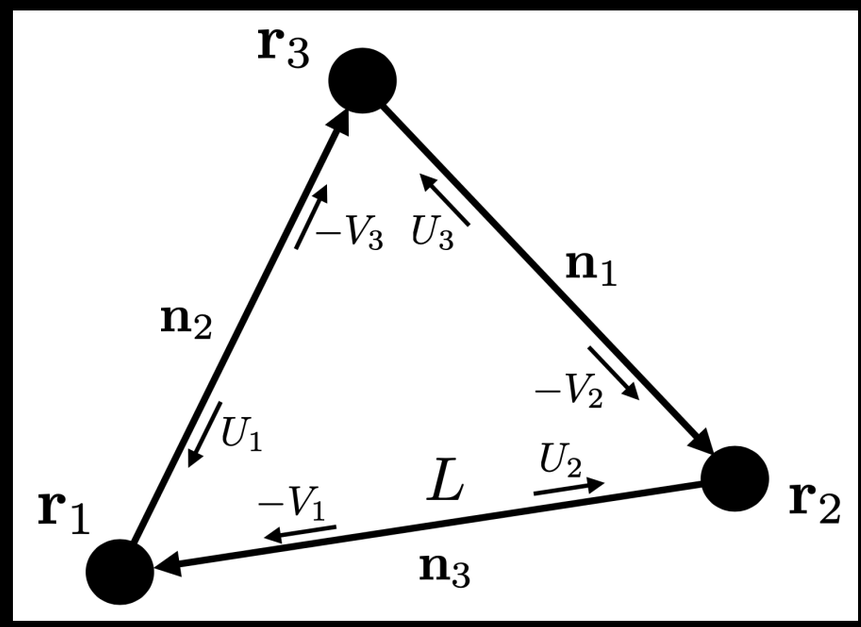
Parametrization of **time-dependent signals**

Response function

projection of perturbation on detector arms

$$X(t) \sim \sum_{i,j=1}^{3} \mathbf{n}_i \cdot \frac{\mathbf{v}_j(t)}{c} .$$

(Michelson response)



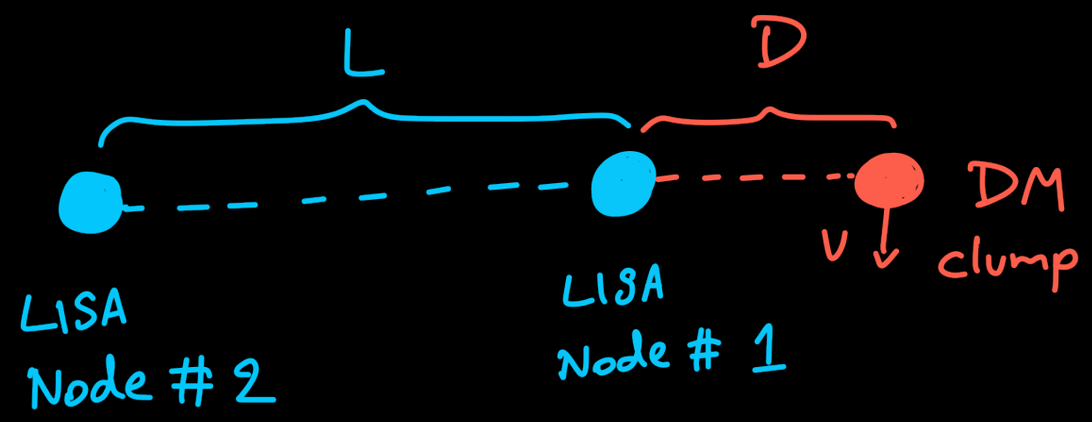
$$X(t) \propto g(D) - g(D+L) \sim \frac{1}{D^2} - \frac{1}{(D+L)^2}$$

$$\sim \begin{cases} \frac{1}{D^2}\left(1 - \frac{D^2}{L^2}\right), & D \ll L \\ \frac{L}{D^3}, & D \gg L \end{cases}$$

Close-approach limit : this work!

Tidal limit

(in case one wants to detect Planet 9)



LISA arm length : $L \sim 2.5 \times 10^6$ km

i.e. only one detector is perturbed.

$$\mathbf{v}_2 \approx \mathbf{v}_3 \approx 0$$

Response function

$$X(t) = -2\mathbf{n}_1 \cdot \frac{\mathbf{v}_1(t)}{c}$$

laser reflects test mass once before detection.

Signal power spectrum

$$P(\omega) = \left|\tilde{X}(\omega)\right|^2$$

Fourier transform
of auto-correlation function

Signal power spectrum

Assume **random trajectories** of **isotropic DM clumps** inside galaxy

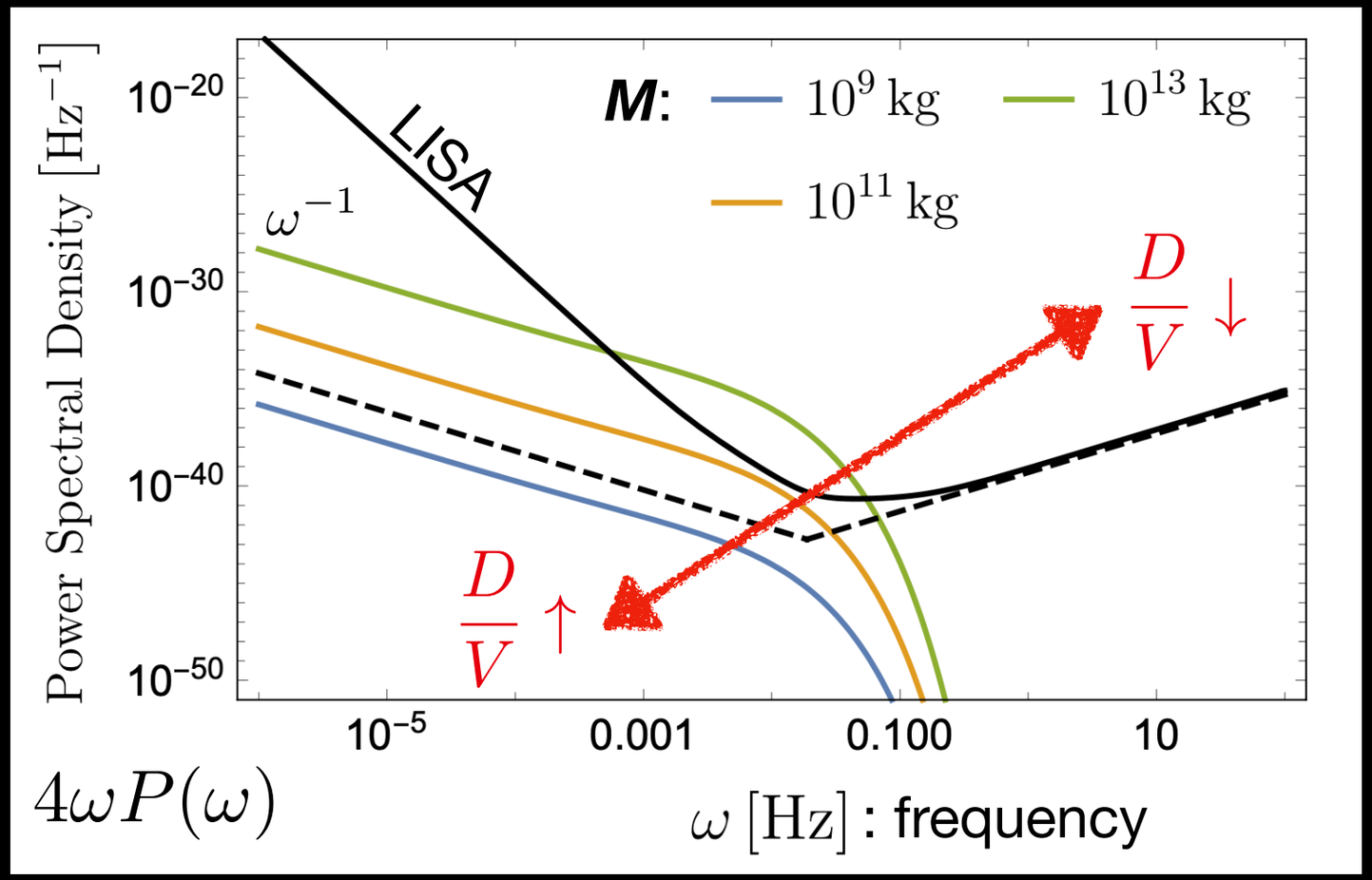
$$P(\omega) = \left\langle \left| \tilde{X}(\omega, v, D) \right|^2 \right\rangle = \frac{1}{4\pi} \int_0^{\pi} \mathrm{d}\vartheta \sin\vartheta \int_0^{2\pi} \mathrm{d}\varphi \left| \tilde{X}(\omega, v, D, \vartheta, \varphi) \right|^2$$

$$= \frac{8}{3\pi} \left(\frac{GM}{cV^2} \right)^2 \left[K_0^2 \left(\frac{D\omega}{V} \right) + K_1^2 \left(\frac{D\omega}{V} \right) \right]$$

$K_1(x) = x^{-1} + \ldots$

small D, large V: larger grav. perturb.

larger Doppler shift >>> Higher freq.



Maxwell-Boltzmann $D = 50,000$ km

$v_{\mathrm{DM}} \simeq 270$ km/s $\rho_{\mathrm{DM}} \simeq 0.39$ GeV/cm^3

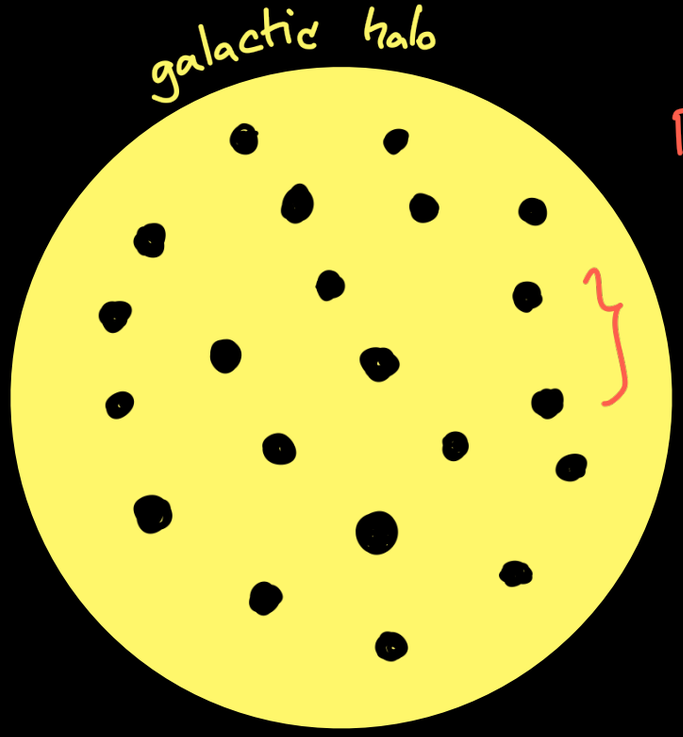
Signal-to-Noise ratio

$$\mathrm{SNR} = \left(\int_{-\infty}^{\infty} \mathrm{d}\,(\log\omega)\, \frac{4\omega P(\omega)}{S_n(\omega)} \right)^{\frac{1}{2}}$$

Neglect:

Actual signal comes from a particular clump, so the **trajectory** can be determined.

Fly-by rate estimation



DM clump separation

$$d \sim \left(\frac{M_{\rm DM}}{\rho_{\rm DM}}\right)^{1/3}$$

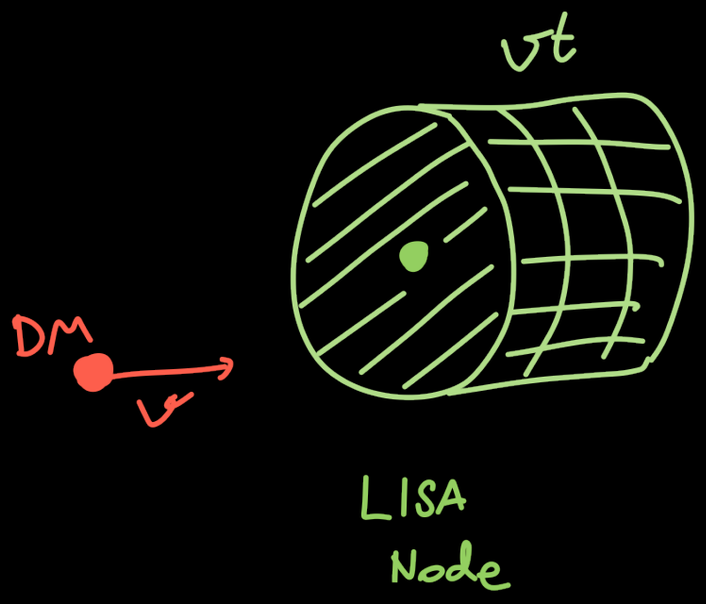
Rate that DM clump of mass $M_{\rm DM}$ and velocity $v_{\rm DM}$ passes through surface of radius D

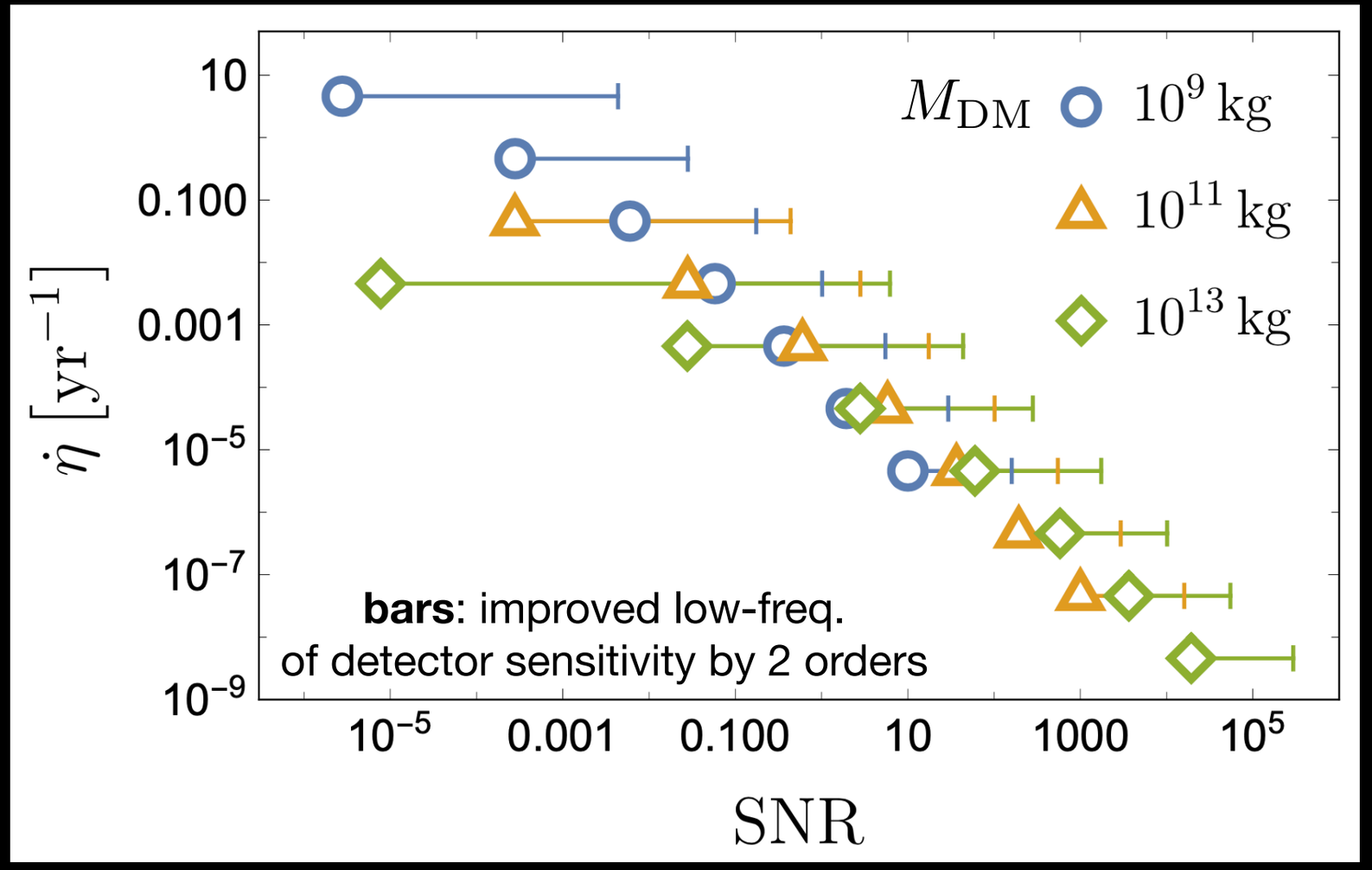
$$\dot{\eta} \sim \frac{\pi D^2 v_{\rm DM}}{d^3} \sim \pi D^2 v_{\rm DM} \frac{\rho_{\rm DM}}{M_{\rm DM}}$$

Maxwell-Boltzmann

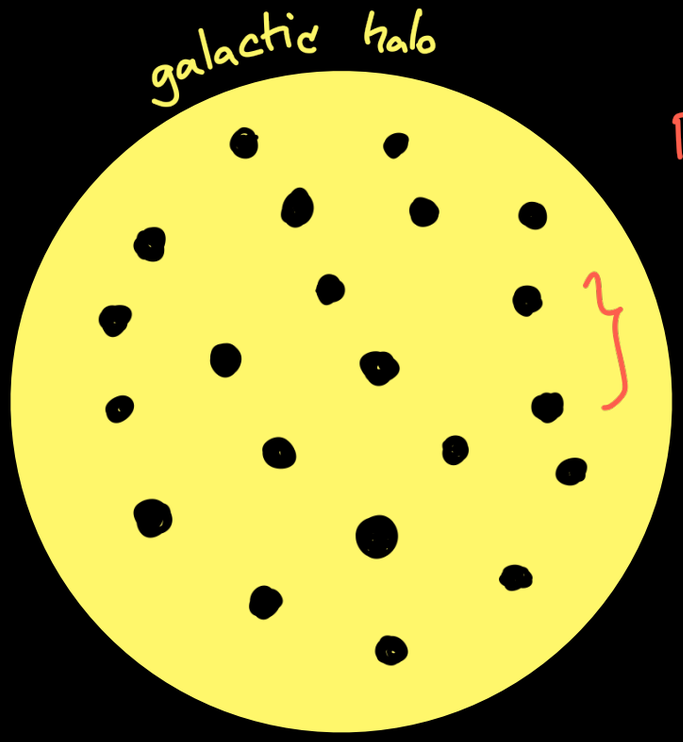
$v_{\rm DM} \simeq 270$ km/s

$\rho_{\rm DM} \simeq 0.39$ GeV/cm^3





Fly-by rate estimation



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Maxwell-Boltzmann

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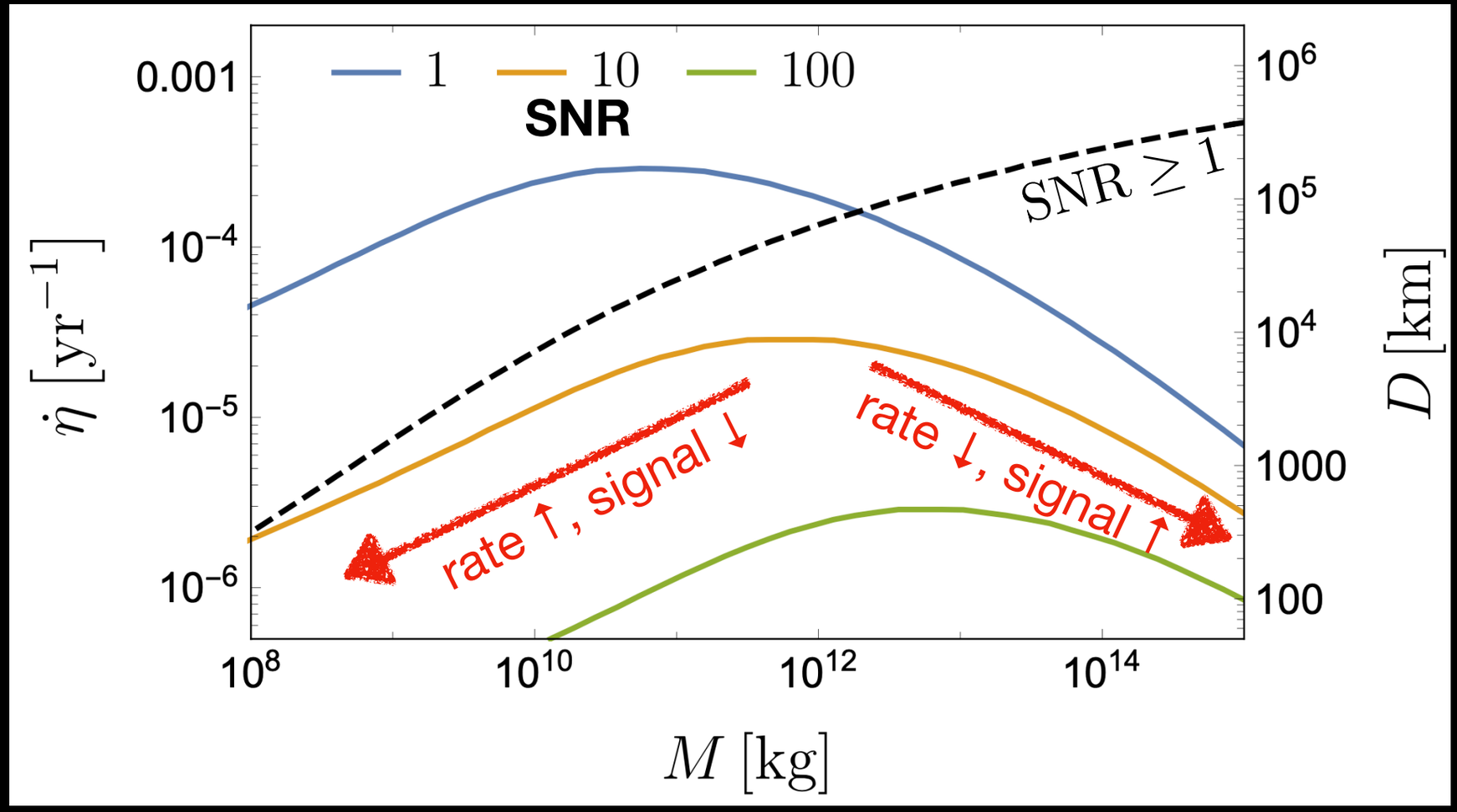


Cosmic strings: gravitation

Gravitational potential from source with energy density ρ and pressure p

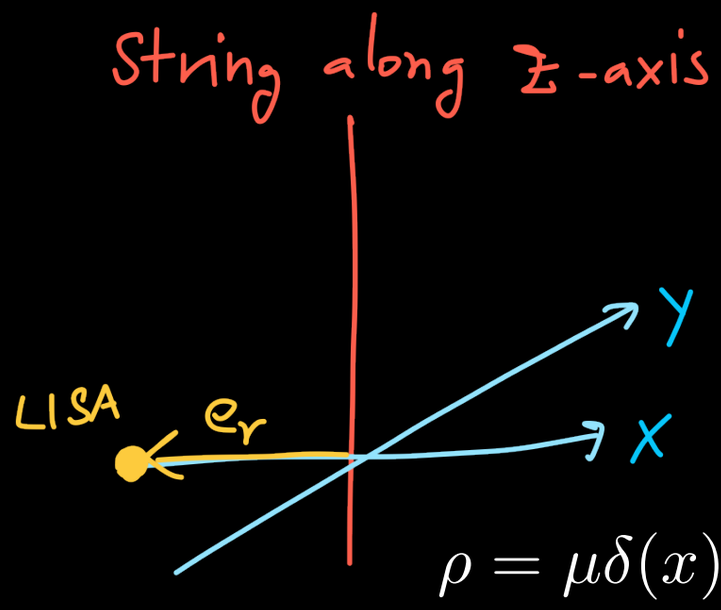
$$\nabla^2\phi = -\nabla\cdot\mathbf{g} = 4\pi G(1+3\omega)\rho \qquad \text{equation of state: } \omega \equiv p/\rho$$

Straight string: $\omega = -1/3$ **i.e.** $T^\sigma_\nu = \mu\delta(x)\delta(y)\ \mathrm{diag}(1,0,0,1)$

Boosted strings with velocity v **:** $\omega = \frac{2}{3}\left(\frac{v}{c}\right)^2 - \frac{1}{3}$

could be DM if they dominate.
(treat ω as free-parameter)

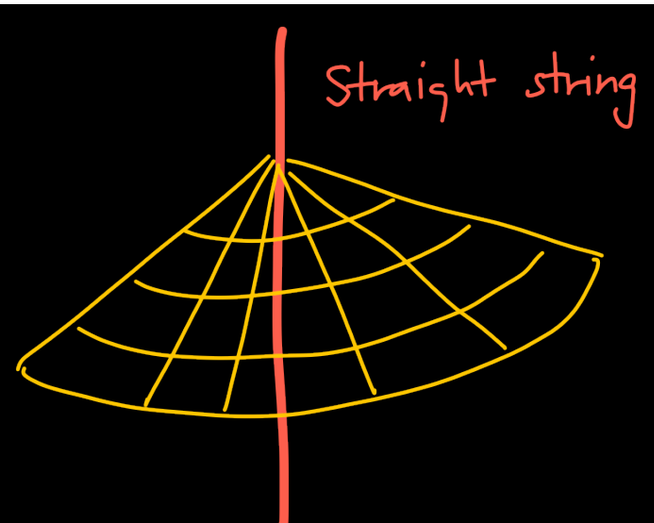
Kolb & Turner, 1990



*** Straight string has **no direct grav. pull**
>>> **conical flat** spacetime

Gravitational field from string

$$\mathbf{g}(\mathbf{r}) = -2(1+3w)\frac{G\mu}{r}\mathbf{e}_r$$



Gravitational pull on LISA node

Straight strings

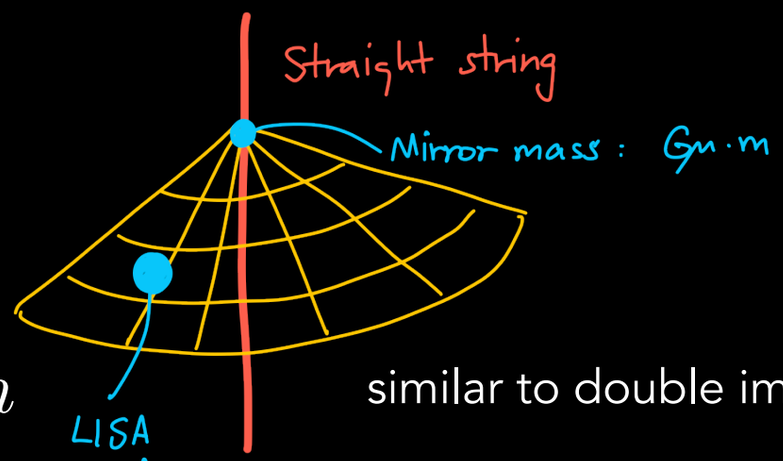
Conical space-time **distorts gravitational field** of LISA node mass m

$$\mathbf{g}(\mathbf{r}) = -8\pi\kappa G \frac{(G\mu/c^2)m}{r^2}\mathbf{e}_r$$

where $\kappa \approx 1/32$ for small $G\mu/c^2$

as pull source by **its mirror mass** $\frac{G\mu}{c^2}m$

Vachaspati, Hogan, Rees (1990)

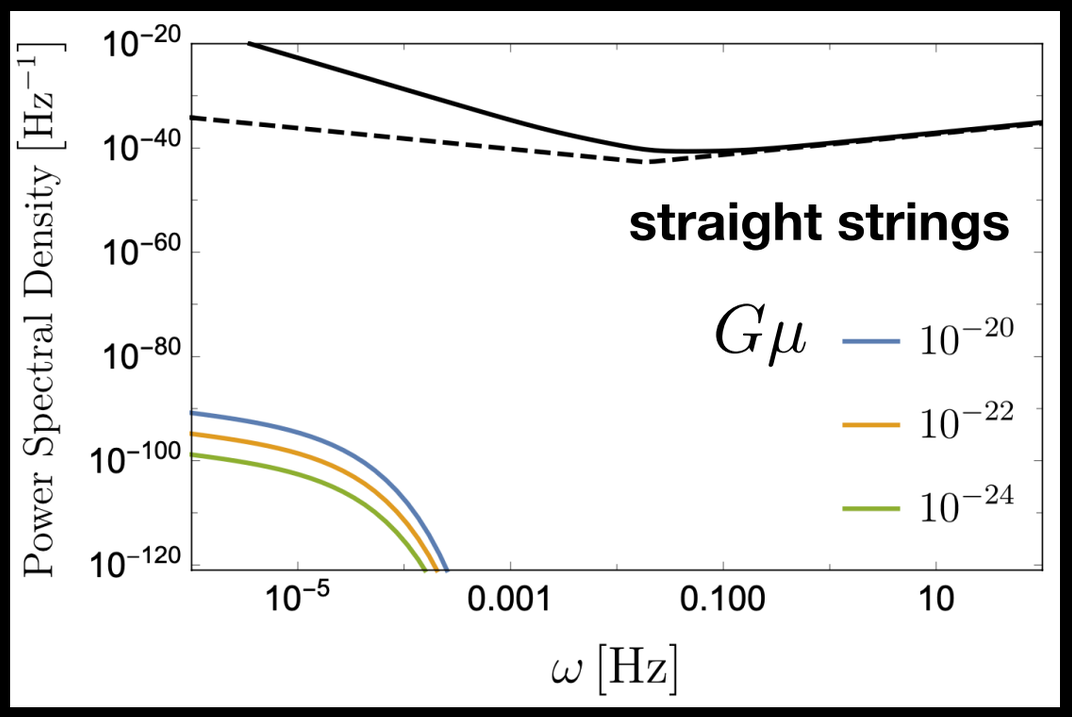


similar to double images

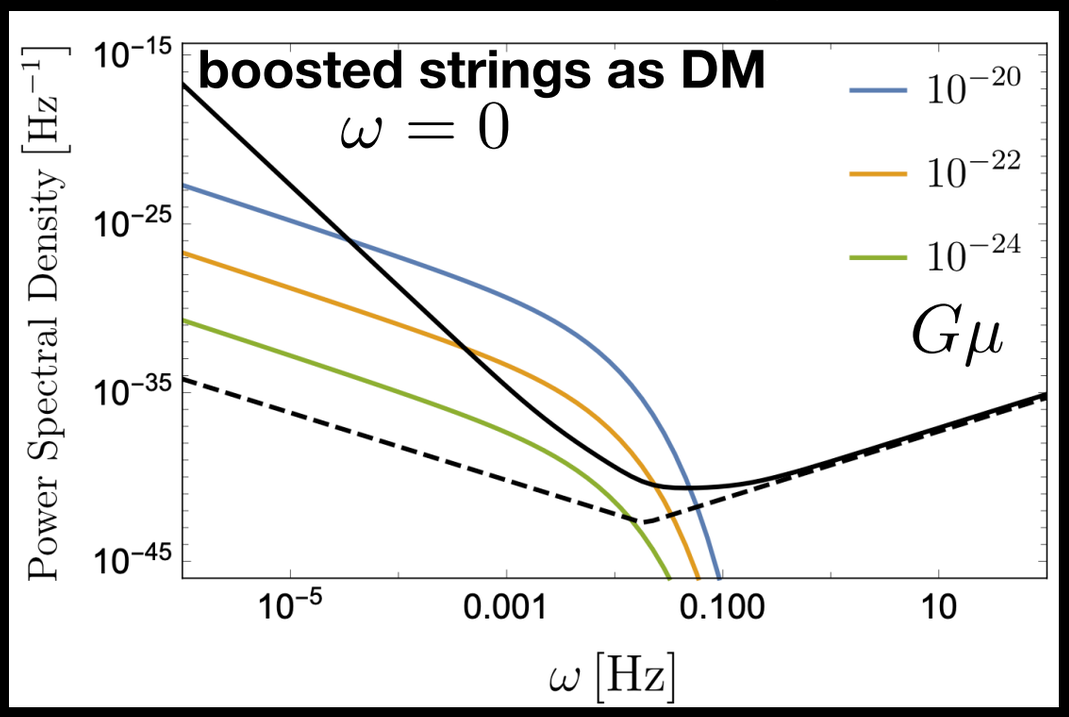
Boosted strings

$$\mathbf{g}(\mathbf{r}) = -2(1+3w)\frac{G\mu}{r}\mathbf{e}_r$$

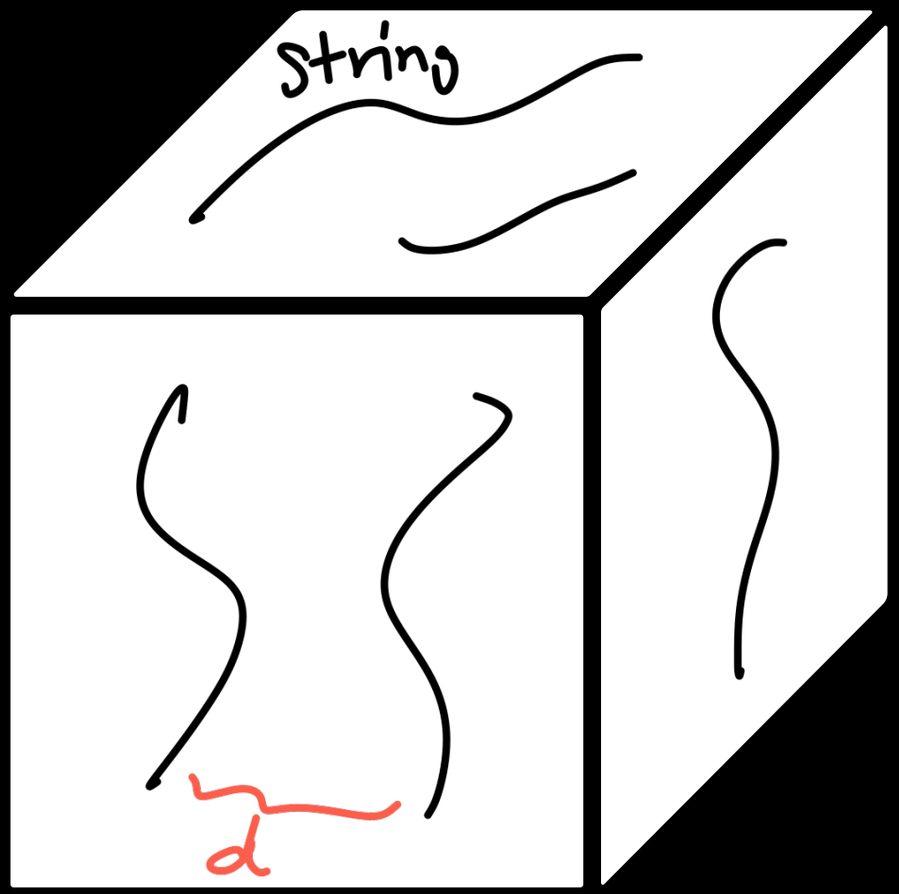
$v_{\rm DM} \simeq 270$ km/s



D = 1e5 km



Cosmic-string fly-by rate

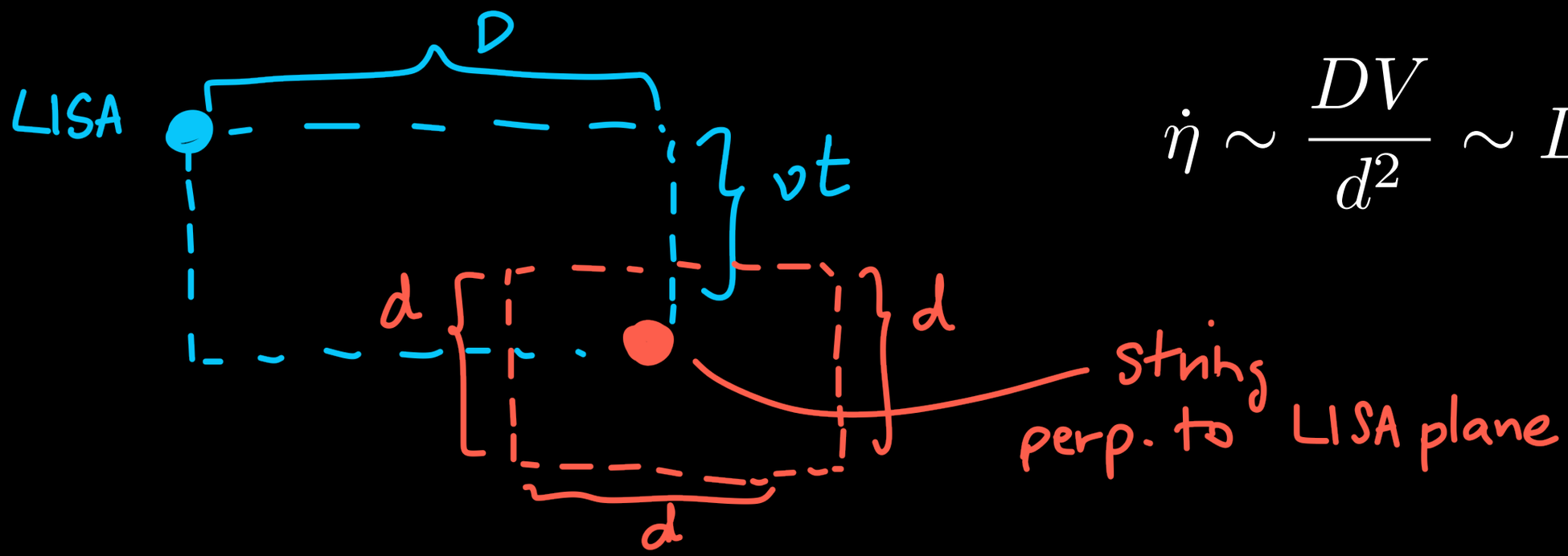


Strings formed via Kibble mechanism
with **energy density**

$$\rho_S \sim \mu/d^2$$

where ***d*** **: strings separation**

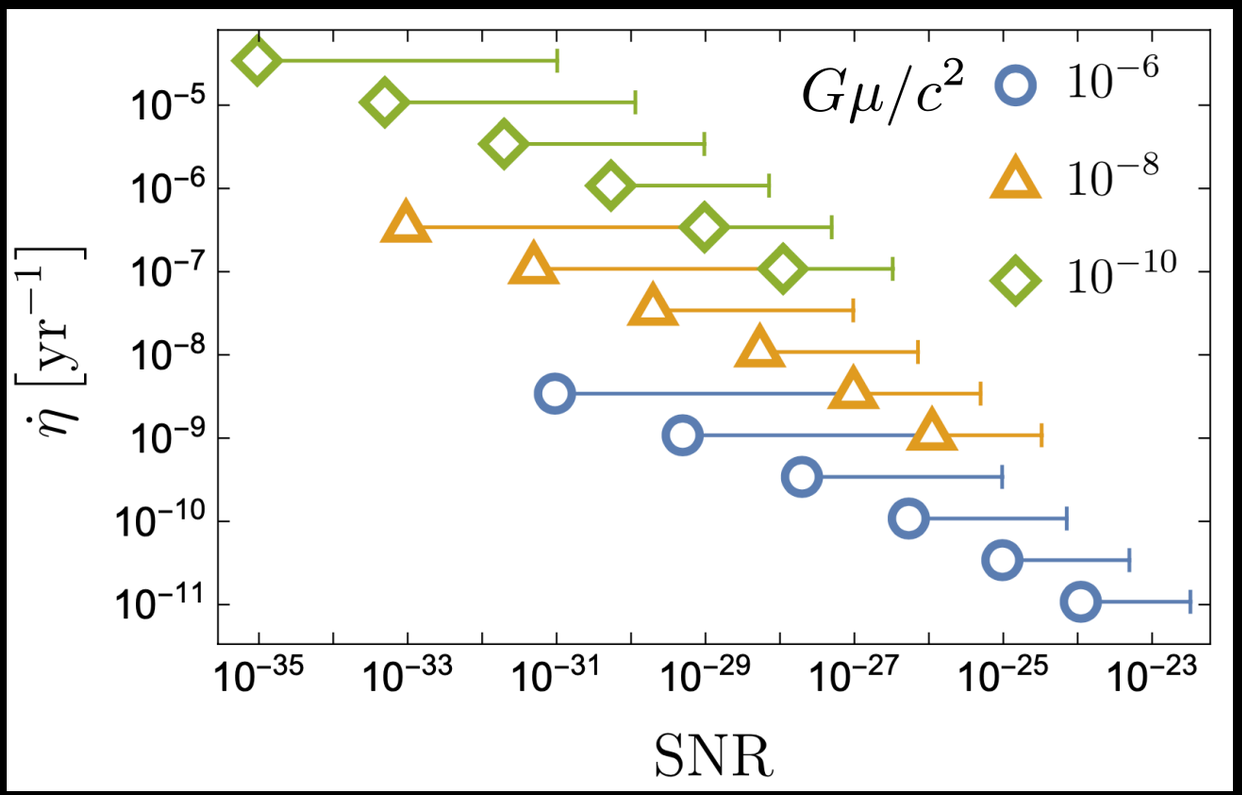
Fly-by rate @ impact parameter *D* of a string with velocity *V* :

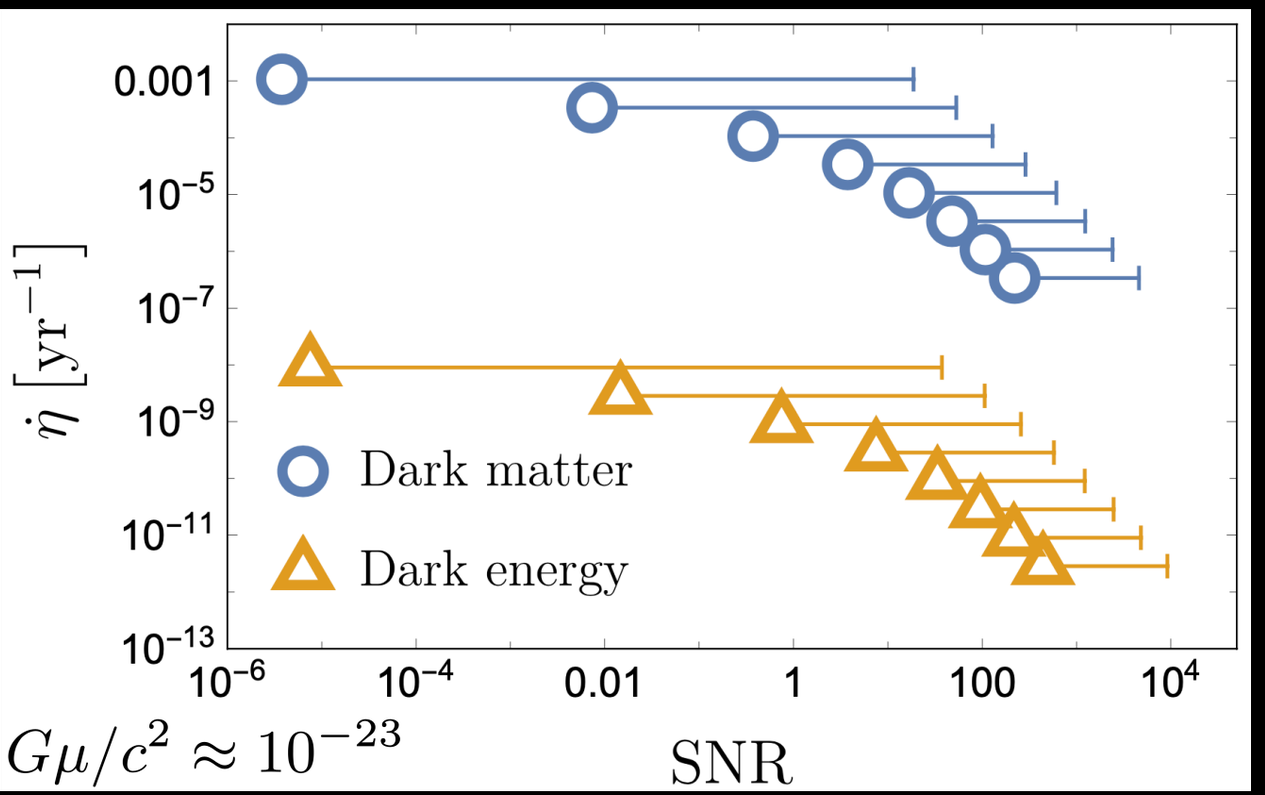


$$\dot{\eta} \sim \frac{DV}{d^2} \sim DV\frac{\mu}{\rho_S}$$

Cosmic strings: detectability

$v_{\rm rms} \approx 270\,{\rm km/s}$
$D = 100,000\,{\rm km}$





$G\mu/c^2 \approx 10^{-23}$

straight strings

$$\rho_S = \rho_{\rm DM} = 0.39\ {\rm GeV/cm}^3$$
$$\& \ \omega = -1/3$$

boosted strings

$$\rho_S = \rho_{\rm DM} = 0.39\ {\rm GeV/cm}^3 \ \& \ \omega = 0$$
$$\rho_S = \rho_{\rm DE} = 3.2\ {\rm keV/cm}^3 \ \& \ \omega = -1$$

(how can strings have $\omega = -1$?)

Yann noticed some problems ! >>> Normally, cosmic strings **reach scaling regime.**

$$\rho_S \sim \frac{\mu}{t^2} \sim (G\mu)\rho_c$$

Too small to be DM or DE
Need violation of scaling

Domain walls (DW)

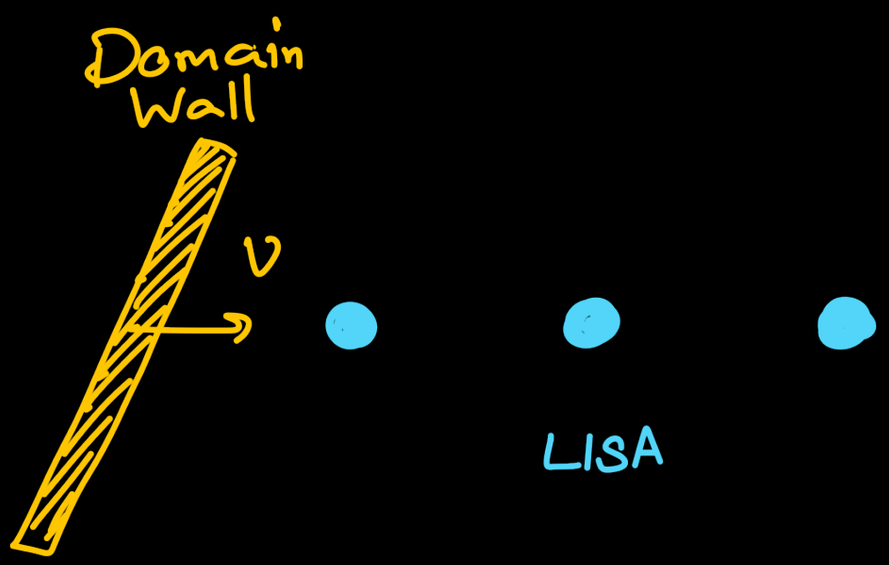
Grav. potential: $\nabla^2\phi = -\nabla\cdot\mathbf{g} = 4\pi G(1+3\omega)\rho$

Straight DW: $\omega = -2/3$ i.e. $T^\nu_\mu = \sigma\delta(x)\ \mathrm{diag}(1,0,1,1)$

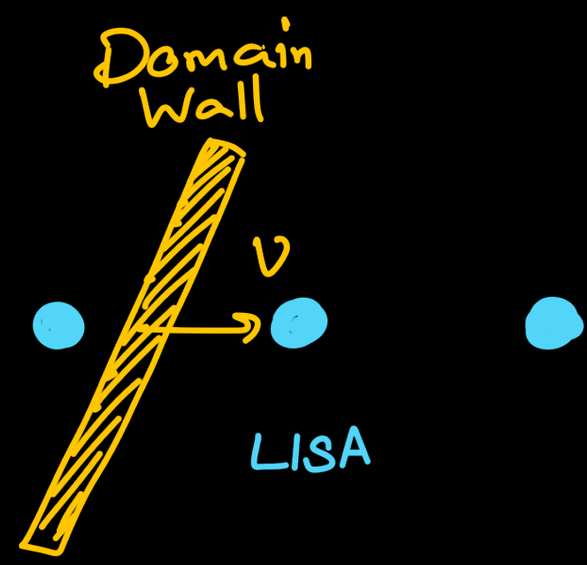
Boosted DW with velocity v : $\omega = \left(\frac{v}{c}\right)^2 - \frac{2}{3}$ Kolb & Turner, 1990

$\rho = \sigma\delta(x)$ >>> Grav. field: $\boxed{\mathbf{g} = -2\pi G(1+3\omega)\sigma\hat{n}}$

Constant grav. field
>>> No signal in LISA



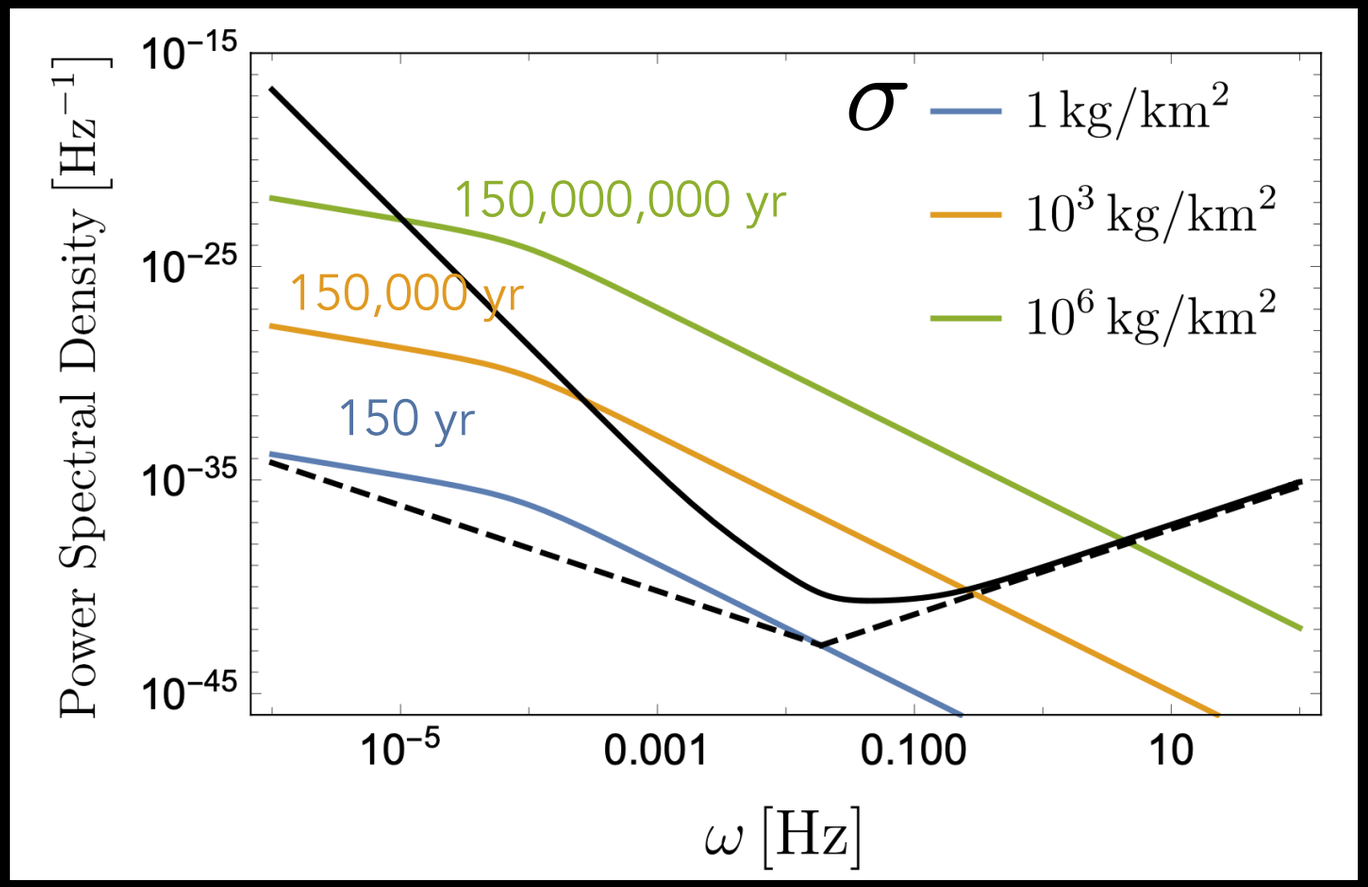
Sign flips for the 1st node
>>> detectable signal



note: consider **full response function**

Domain walls: detectability

$v/c = 10^{-3}$



High freq. is enhanced (compared to DM, CS) due to sign flip occurring instantaneously.

consider wall thickness >>> faster drop

$$\mathrm{g} \propto \sigma$$
$$\Rightarrow \quad P(\omega) \propto \sigma^2$$
$$\Rightarrow \quad \mathrm{SNR} \propto \sigma$$

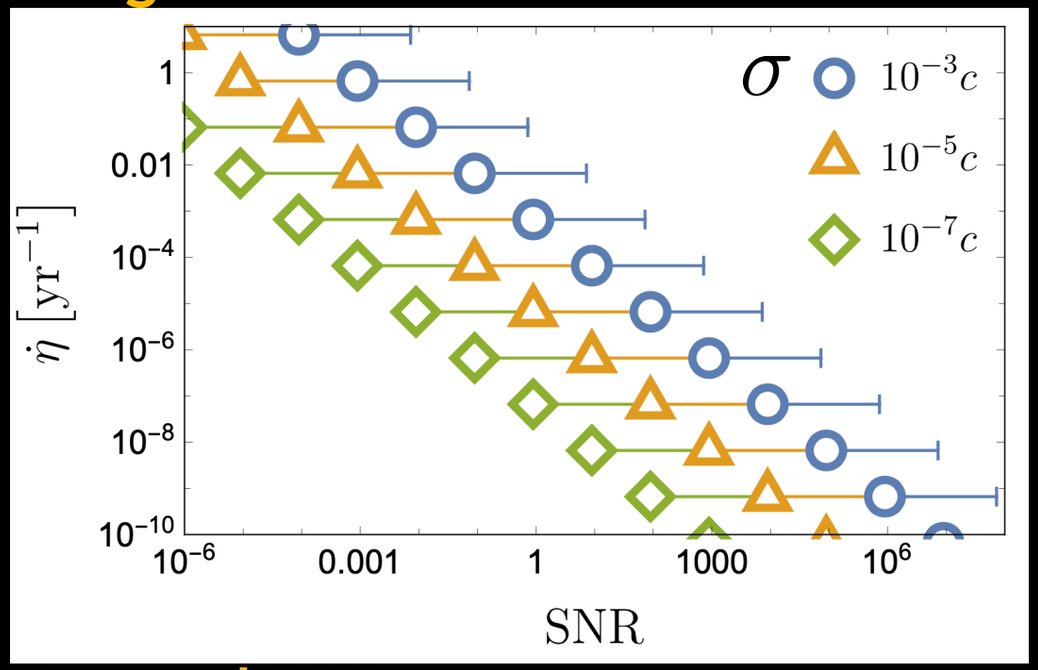
$\rho_{\rm DM} = 0.39\ \mathrm{GeV/cm^3}$ & $\omega = 0$

$\rho_{\rm DE} = 3.2\ \mathrm{keV/cm^3}$ & $\omega = -1$

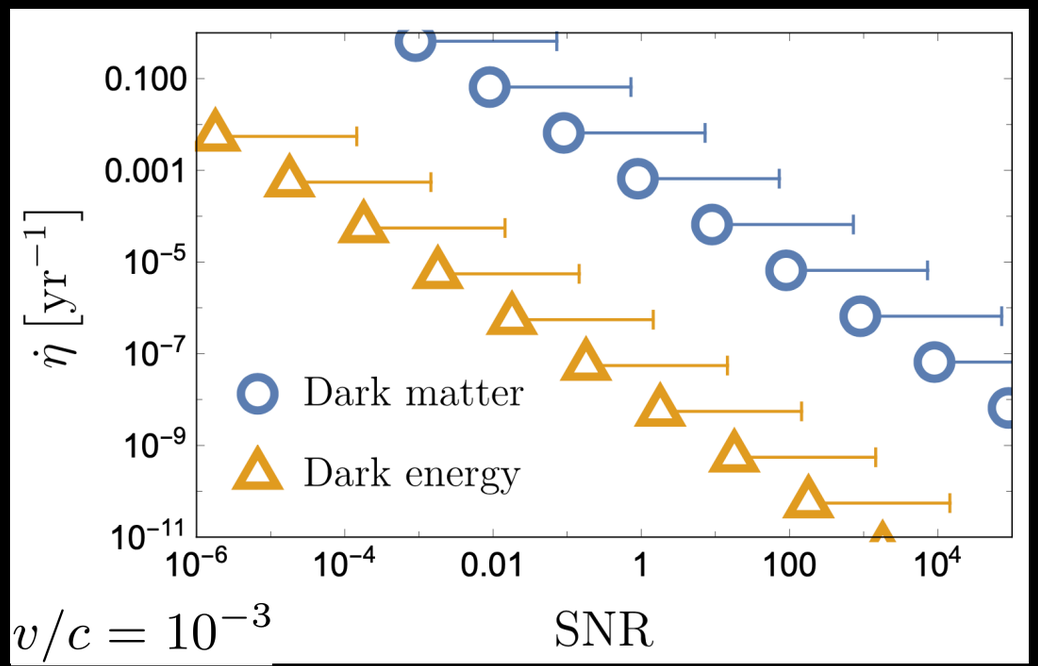
Fly-by rate:

$$\dot{\eta} \sim \frac{v}{d} \sim v\frac{\rho_{\rm DW}}{\sigma}$$

Straight DW $\rho_{\rm DM} = 0.39\ \mathrm{GeV/cm^3}$ & $\omega = -2/3$



Boosted DW



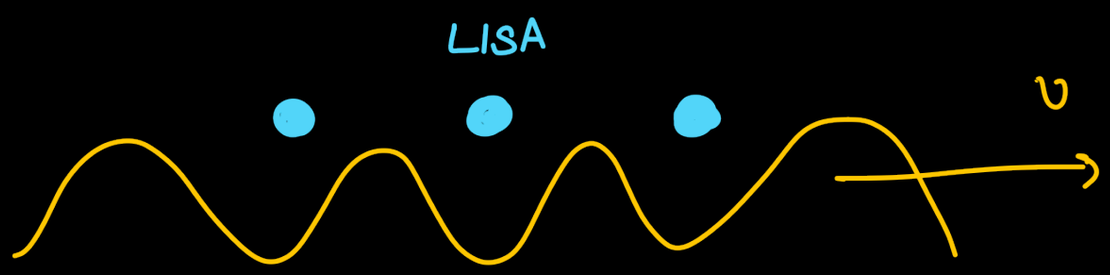
DM density fluctuation

$$\triangle\delta\phi = 4\pi G\bar{\rho}\delta \qquad \delta = \delta\rho/\bar{\rho}$$

Perturbation in grav. field

$$\delta\mathbf{g}_{\mathbf{k}}(\mathbf{x}) = 4\pi i G\bar{\rho}\tilde{\delta}_{\mathbf{k}}\frac{\mathbf{k}}{k^2}\exp\left(i\mathbf{k}\cdot\mathbf{x}\right)$$

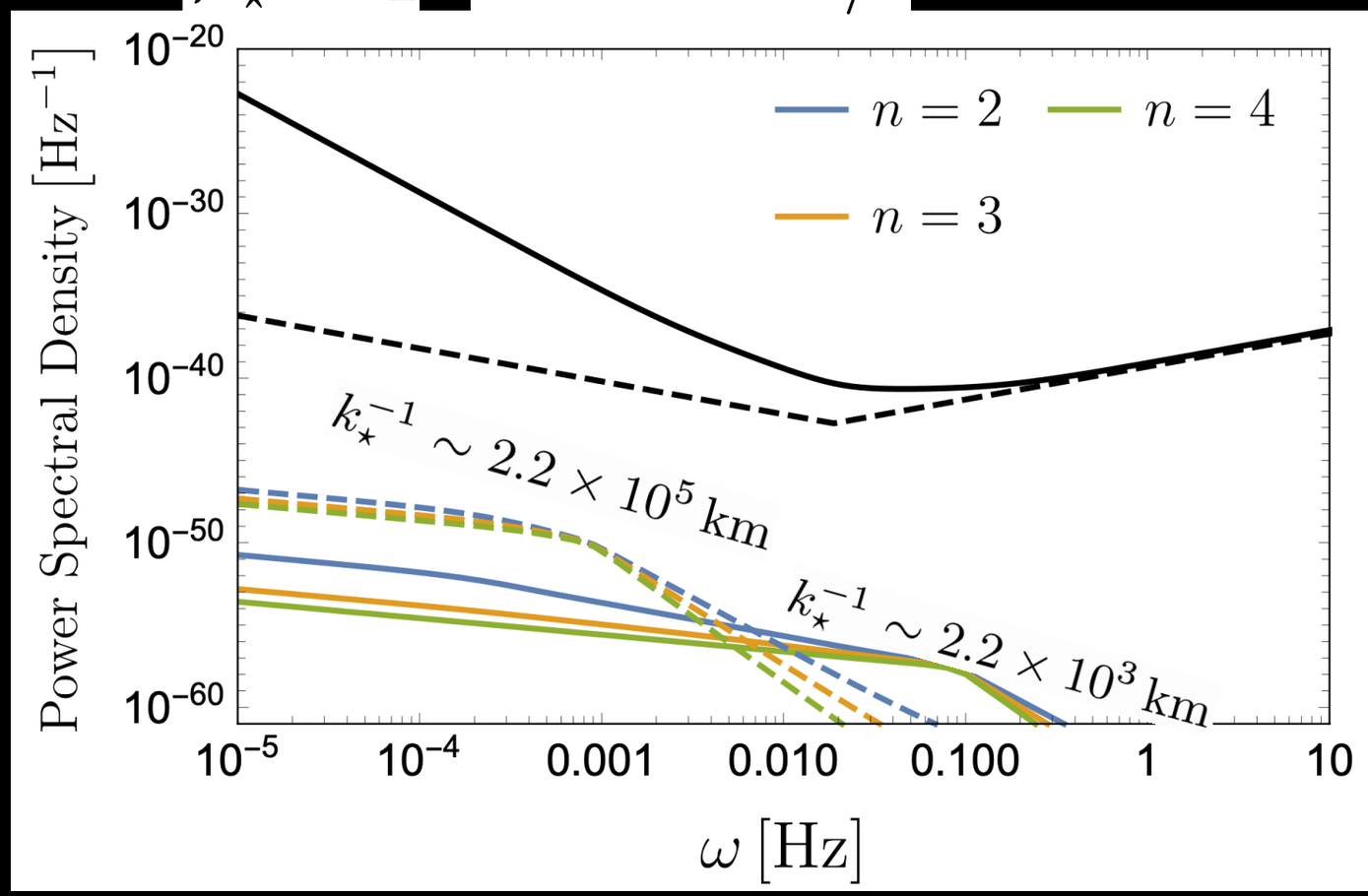
Detectors move through density pert.



Gravitational pert. From mode k Fluctuation

similar to a series of DW

$\mathcal{P}_\star = 1 \quad v \approx 220\,\mathrm{km/s}$



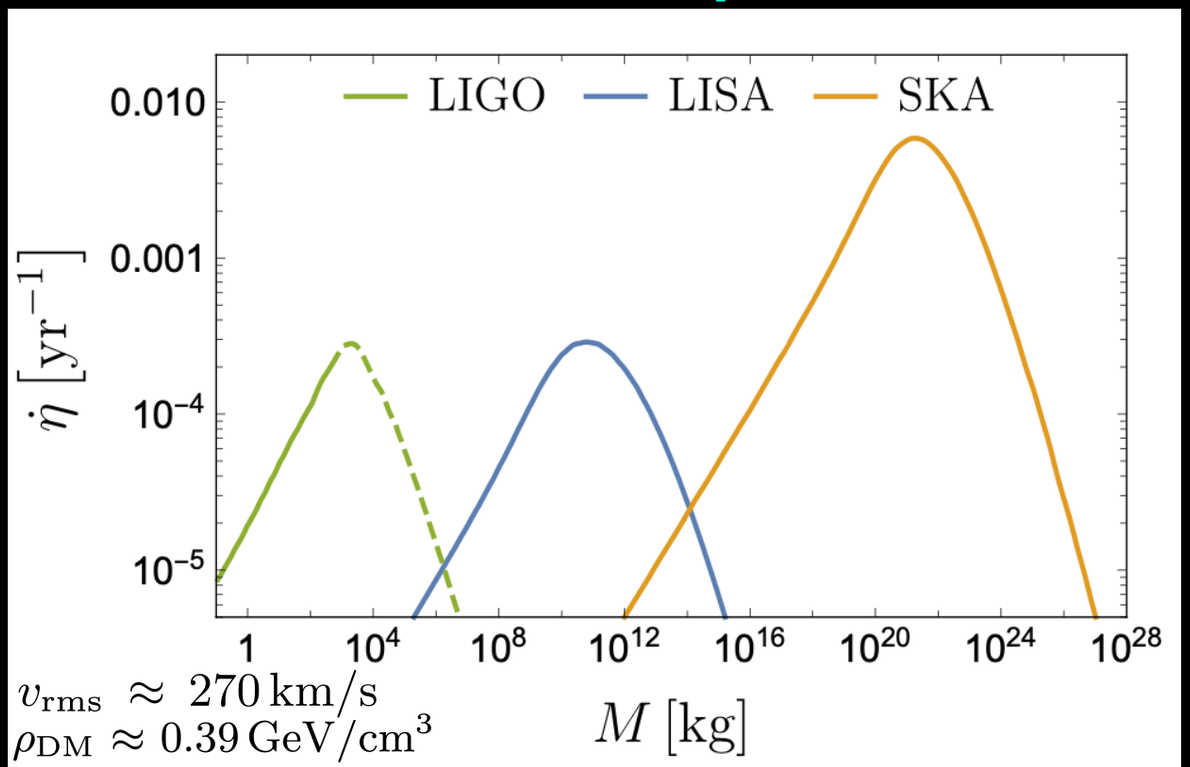
assume **density power spectrum**

$$\mathcal{P}(k) = \mathcal{P}_\star\left(\Theta(k_\star - k)\left(\frac{k}{k_\star}\right)^n + \Theta(k - k_\star)\left(\frac{k}{k_\star}\right)^{-n}\right)$$

peak in signals corresp. to
peak in DM power spectrum k_*
treat as free-parameter

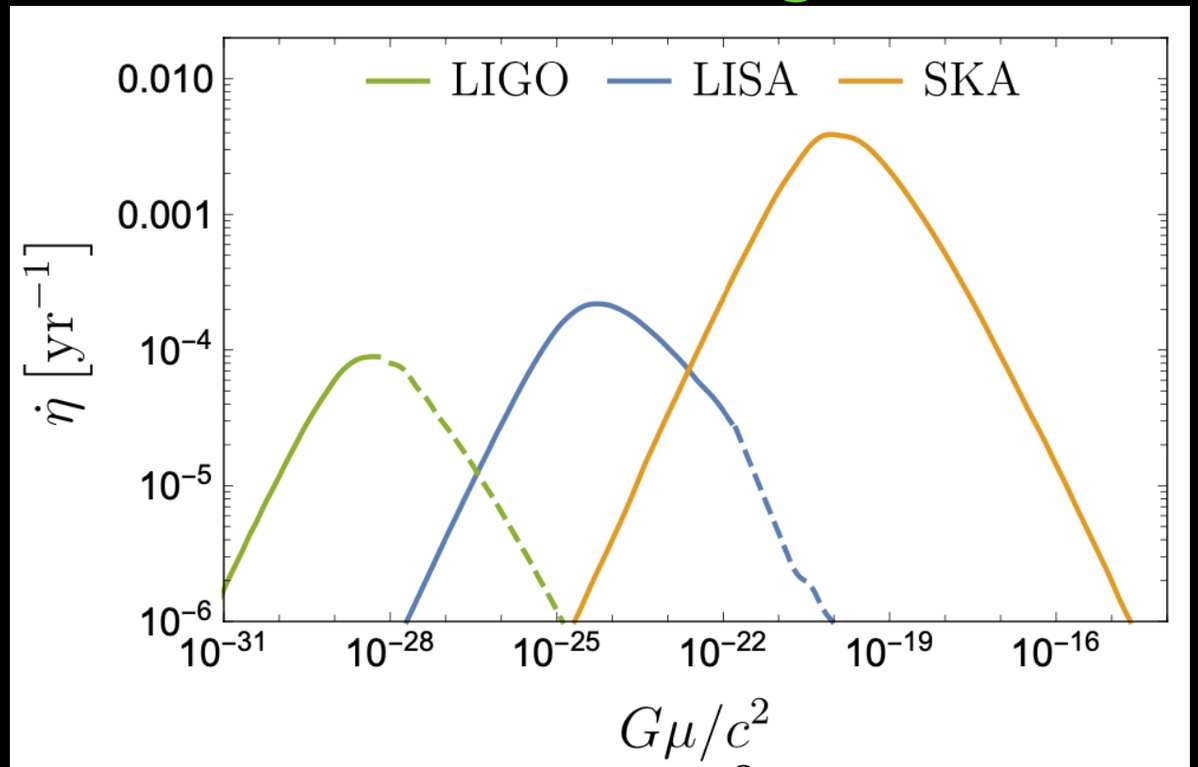
Summary: detectability for $\mathrm{SNR} \geq 1$

DM clumps



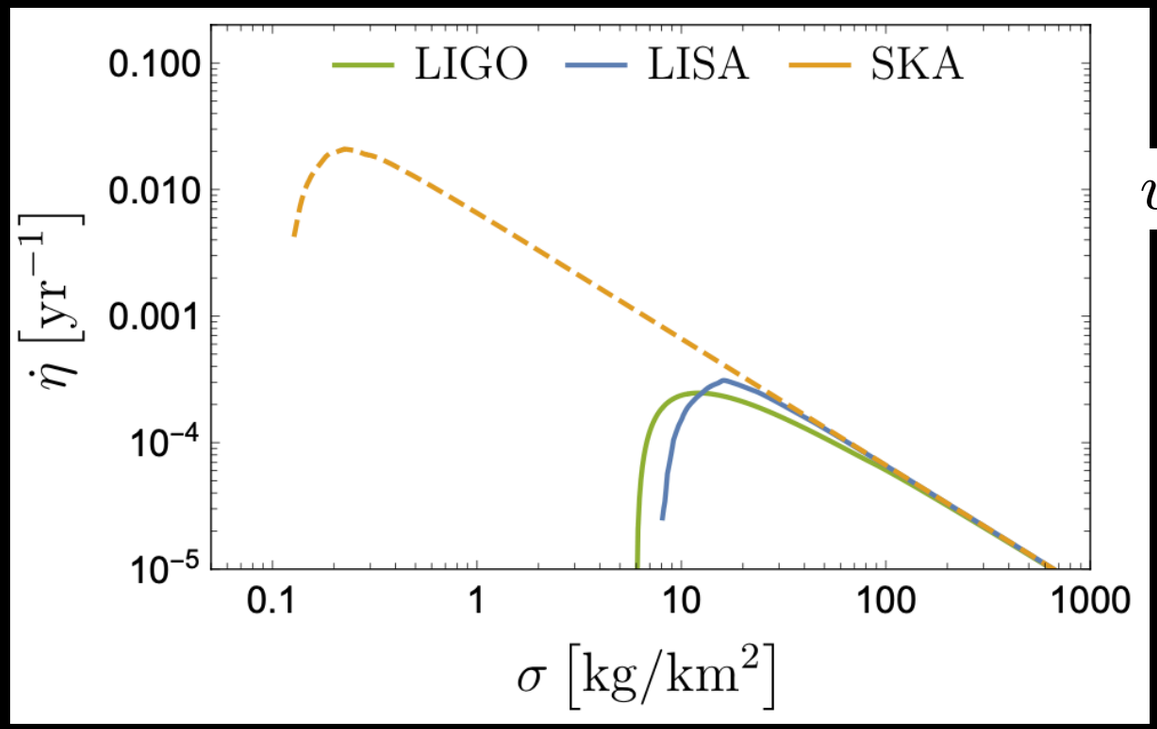
dashed: extrapolate beyond close-approach limit

Cosmic strings



$\rho_{\mathrm{DM}} \approx 0.39\,\mathrm{GeV/cm^3},\ w = 0$

Domain walls



$v/c = 10^{-3}$

dashed: extrapolate for
# of DW > 1
in detector volume