Write or Radiate: Inscribed Mass vs. Electromagentic Channels

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10 Years of WINLAB Research (Infostations redux)

- Infostations:
  - Delay tolerant? $\Rightarrow$ transmit when near base!
- Channel Quality
  - How good can that RF channel be? $\Rightarrow$ really good!
- Interference Avoidance, Pricing & Spectrum Management
  - Interference hurts $\Rightarrow$ deal with it!

A Hoary Old Epiphany!

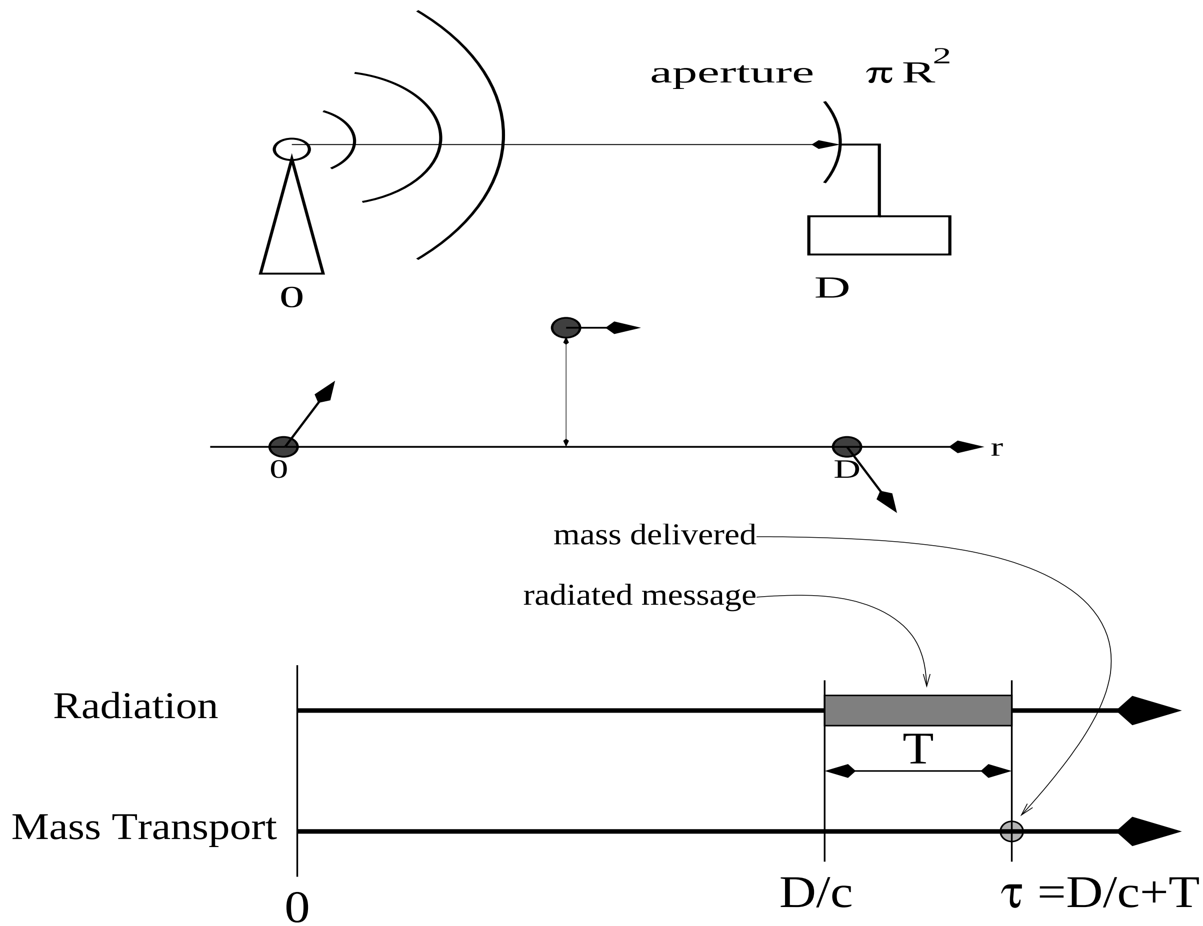
- RF Interference is bad
- Storage density is increasing
- Channel good when nearby
- Can tolerate delay
- **IMPLICATION:**
  - Forget RF! Write message down! Toss it to recipient!

Completely ridiculous .... right?

A Little Empirical Rigor

- **Optical Lithography** with SiO_2: 3.85×10^{18} bits/kg
- **E-beam Lithography** with SiO_2: 1.54×10^{21} bits/kg
- **STM** with Xe on Ni: 1.74×10^{22} bits/kg
- **RNA**: 1.8×10^{24} bits/kg
  - 1 bit per $nm^3 \rightarrow 1\mathbf{mm}^3 = 10^{18}$ **bits!**
- And maybe a LOT more room at the bottom

A Little Analytic Rigor



Parameters and Definitions

- B: message size (bits).
- $\tilde{\rho}$: mass information density for inscribed information (bits kg^{-1}).
- W: bandwidth available for radiated communication (Hz).
- $A = \pi R^2$: effective receiver aperture (m^2).
- D: distance to receiver (m).
- N_0: background noise energy (W Hz^{-1}).
- τ: message deadline (s)
- T: radio messaging time (s).
- $\delta = \frac{c}{(D/\tau)}$: ratio of τ to the light travel time.

Rocket Science Foundations

- Max bigger than mean:

$$\max_v h(v) \geq E[h(V)]$$

- If V deterministic:

$$\max_v h(v) = E[h(V)]$$

- If $h()$ convex (Jensen):

$$E[h(V)] \geq h(\overline{v})$$

Rocket Science

- Average velocity

$$\frac{1}{\tau}\int_0^{\tau} v(t)dt = \frac{D}{\tau} = \bar{v} = E[v(t)]$$

- Minimum imparted energy

$$E^* = \min_{v()} \max_t h(v(t))$$

subject to $\bar{v} = \frac{D}{\tau}$.

- Jensen says

$$E^* = \min_{v()} \max_t h(v(t)) \geq \min_{v()} E[h(v(t))] \geq h(\bar{v})$$

with equality iff $v(t)$ is constant

Minimum Transport Energy

- GIVEN: $h()$ and $\bar{v}$

$$E^* = h(\bar{v})$$

- $h(v) = mc^2 \left(\frac{1}{\sqrt{1-\frac{v^2}{c^2}}} - 1 \right)$:

$$E^* = mc^2 \left(\frac{1}{\sqrt{1-\left(\frac{\bar{v}}{c}\right)^2}} - 1 \right)$$

- $h(v) \approx \frac{1}{2}mv^2$:

$$E^* \approx \frac{1}{2}m\bar{v}^2$$

Potential Fields

- $q(x)$ potential energy:

$$\mathcal{E}(t) = h(v(t)) + q(x(t))$$

- Energy minimization:

$$E^* = \min_{x()} \max_t \mathcal{E}(t) \geq \min_{x()} \frac{1}{\tau} \int_0^\tau \mathcal{E}(t) dt$$

- Calculus of variations:

$$\frac{d}{dt}\left(\frac{\partial \mathcal{E}}{\partial v}\right) - \frac{\partial \mathcal{E}}{\partial x} = 0$$

$$\ddot{x} h''(\dot{x}) - q'(x) = 0$$

Potential Field Results

- Low speed:

$$m\ddot{x} = q'(x)$$

- $q'(x)$ is force at position x: $\rightarrow$ "free fall"
- Freefall? $\rightarrow \mathcal{E}(t) = \text{constant}$
- $\mathcal{E}(t)$ constant $\rightarrow$ minimization satisfied with equality, so ...

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Artillery Problem

- Minimum energy:

$$E^* = \frac{1}{2} mgD$$

- Let $\delta = c\tau/D$.
- Delay at minimum energy

$$\delta^* = c\sqrt{2/gD}$$

- Pay a factor of 2 over free space

Escape Problem

- Needs numerical calculation
- Boils down to: need initial velocity larger than escape.
- About a factor of 2 energy penalty, again
- Escape examples (rough):
  - Earth: $\delta < 2 \times 10^4$
  - Solar: $\delta < 2 \times 10^3$
  - Milky Way: $\delta < 6 \times 10^2$

Inscribed Mass Energy Requirements

- Message size B, mass information density $\tilde{\rho}$
- General

$$E_w = \frac{B}{\tilde{\rho}} c^2 \left(\frac{\delta}{\sqrt{\delta^2 - 1}} - 1 \right)$$

- $\delta \gg 1$:

$$E_w \approx \frac{1}{2} \frac{B}{\tilde{\rho}} \left(\frac{c}{\delta} \right)^2$$

- Off by only $\approx 10\%$ at $0.4c$ and $\approx 50\%$ at $0.75c$
- Low speed ain't so low!
- Can (usually) ignore relativity

Radiation Energy Requirements

- Energy capture (no gain yet):

$$\nu(D) = \frac{A}{4\pi D^2}$$

- Bits a la Shannon:

$$B = TC = TW \log_2\left(\frac{PA}{4\pi D^2 N_0 W} + 1\right)$$

- $E_r = PT$,

$$E_r = BN_0 \frac{4\pi D^2}{A} \frac{TW}{B} \left[2^{\frac{B}{TW}} - 1\right]$$

- Large TW:

$$E_r \geq BN_0 \frac{4\pi D^2}{A} \ln 2$$

Radiation to Transport Energy Ratio

- Definition:

$$\Omega = \frac{E_r}{E_w}$$

- Large bandwidth W, $\delta \gg 1$

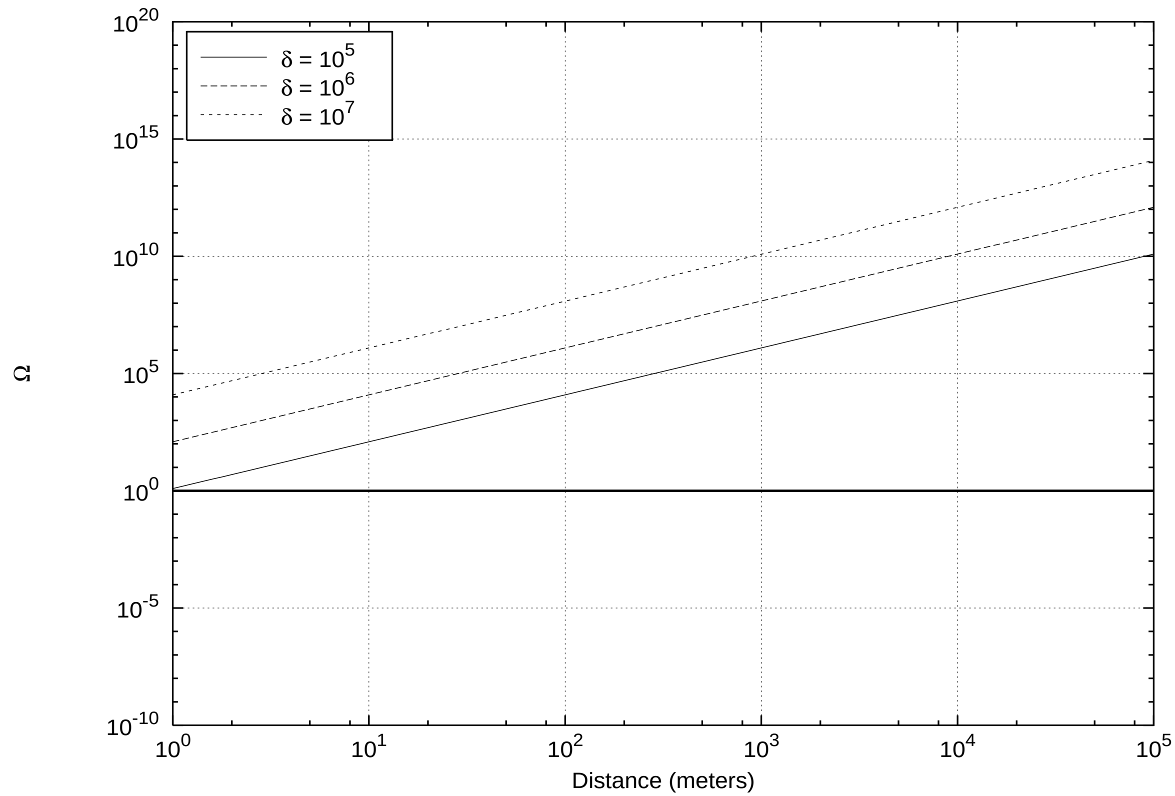
$$\Omega \geq \left[\frac{\tilde{\rho} N_0}{c^2}\right] \left[\frac{4\pi D^2}{A}\right] (2\ln 2)\,\delta^2$$

What About Gain?

- **Gain:** $G_{\max} = \frac{8\pi^2 R^2}{\lambda^2}$
- **Critical** ρ**:** $\rho^* = \arg_\rho \left\{ \frac{E_r(G)}{E_w(\rho)} = 1 \right\}$
- ρ^* **for** $\lambda = 0.03m$**:**

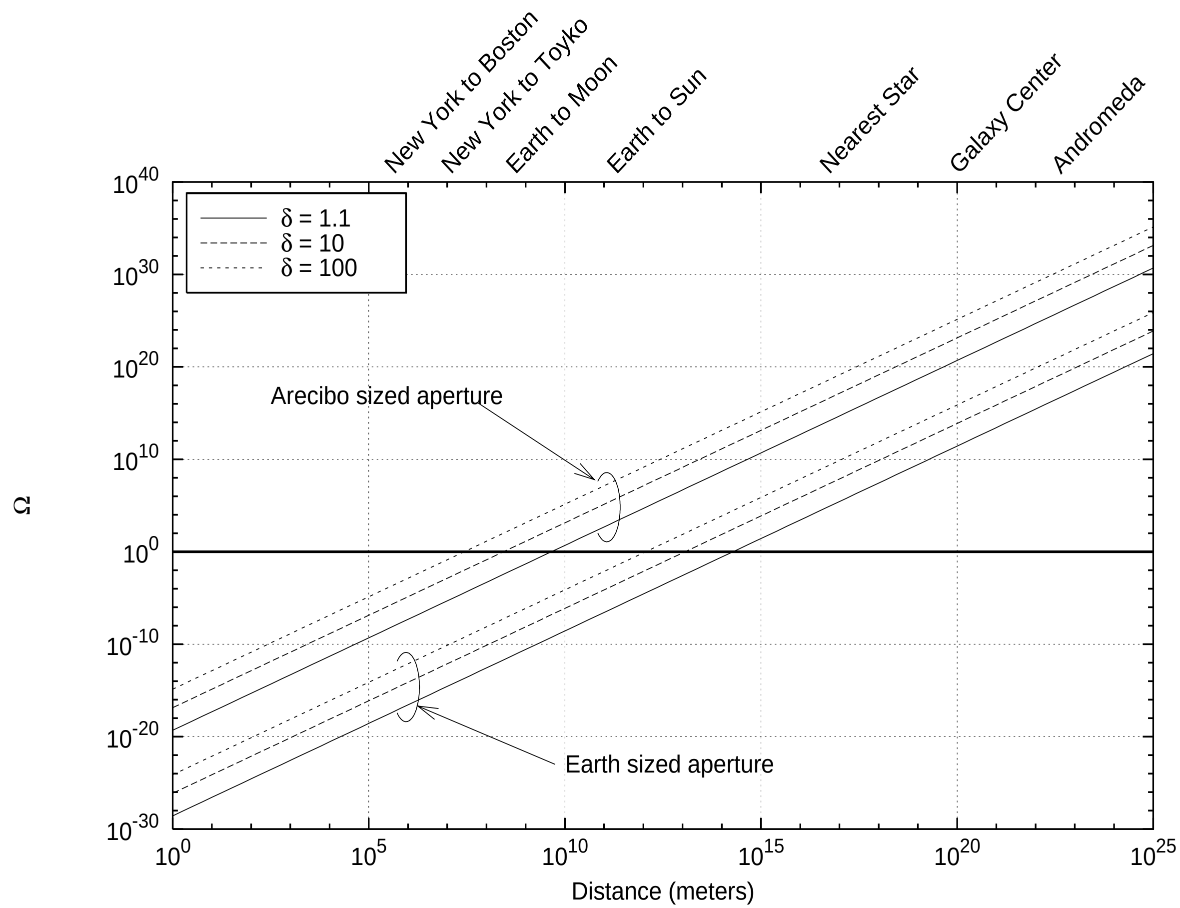
Aperture	ρ^*	Far Field
(0.05 m)	$2.15 \times 10^{36} \left[\frac{D\delta}{1 \text{ meter}}\right]^{-2} \frac{\text{bits}}{\text{kg}}$	$D = 0.37$ m
(Arecibo)	$1.95 \times 10^{20} \left[\frac{D\delta}{1 \text{ light year}}\right]^{-2} \frac{\text{bits}}{\text{kg}}$	$D \approx 3 \times 10^{-10}$ LY
(Earth)	$6.38 \times 10^{38} \left[\frac{D\delta}{1 \text{ light year}}\right]^{-2} \frac{\text{bits}}{\text{kg}}$	$D \approx 0.6$ LY

Ω vs. Distance: point to point no gain



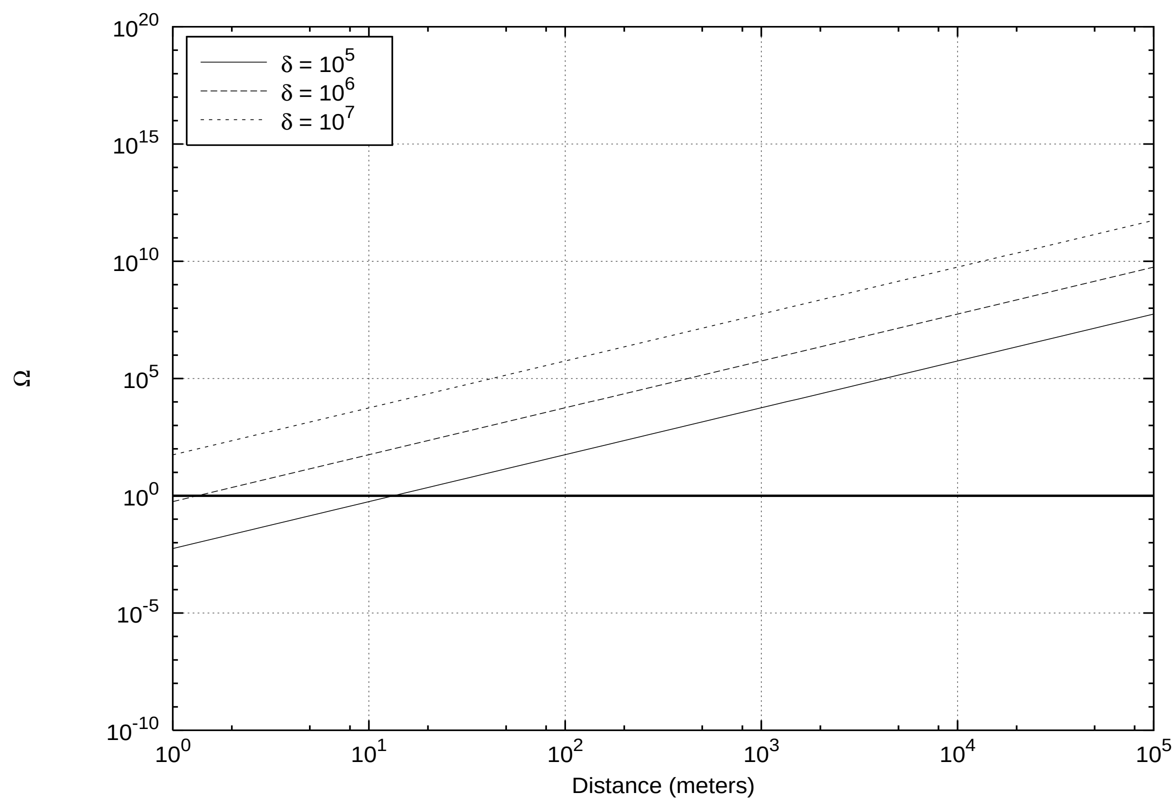
0.05m receive aperture radius, $300°K, \tilde{\rho} = 1.8 \times 10^{24}$ bits kg^{-1}

Ω vs. Distance: point to point no gain



$$3°K, \tilde{\rho} = 1.8 \times 10^{24} \text{ bits kg}^{-1}$$

Ω vs. Distance: point to point with gain



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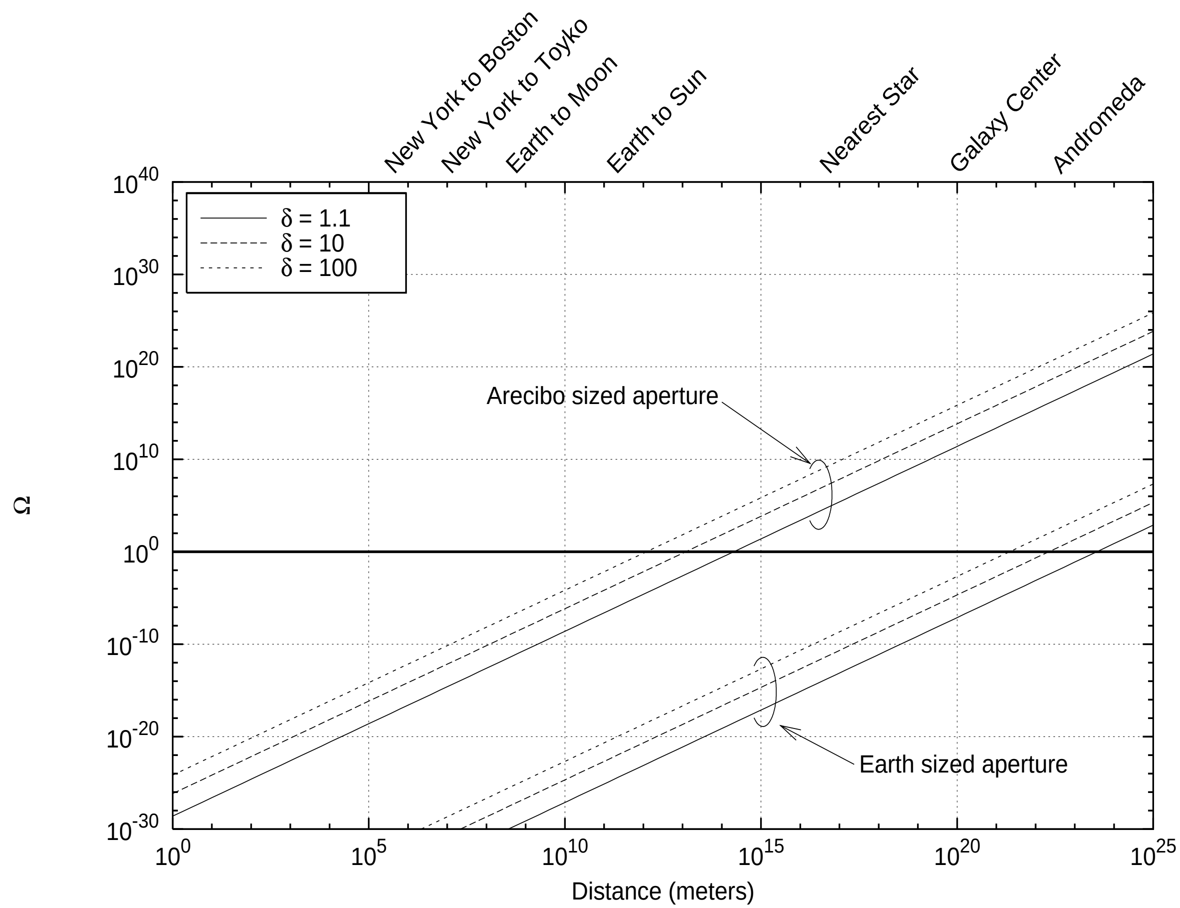
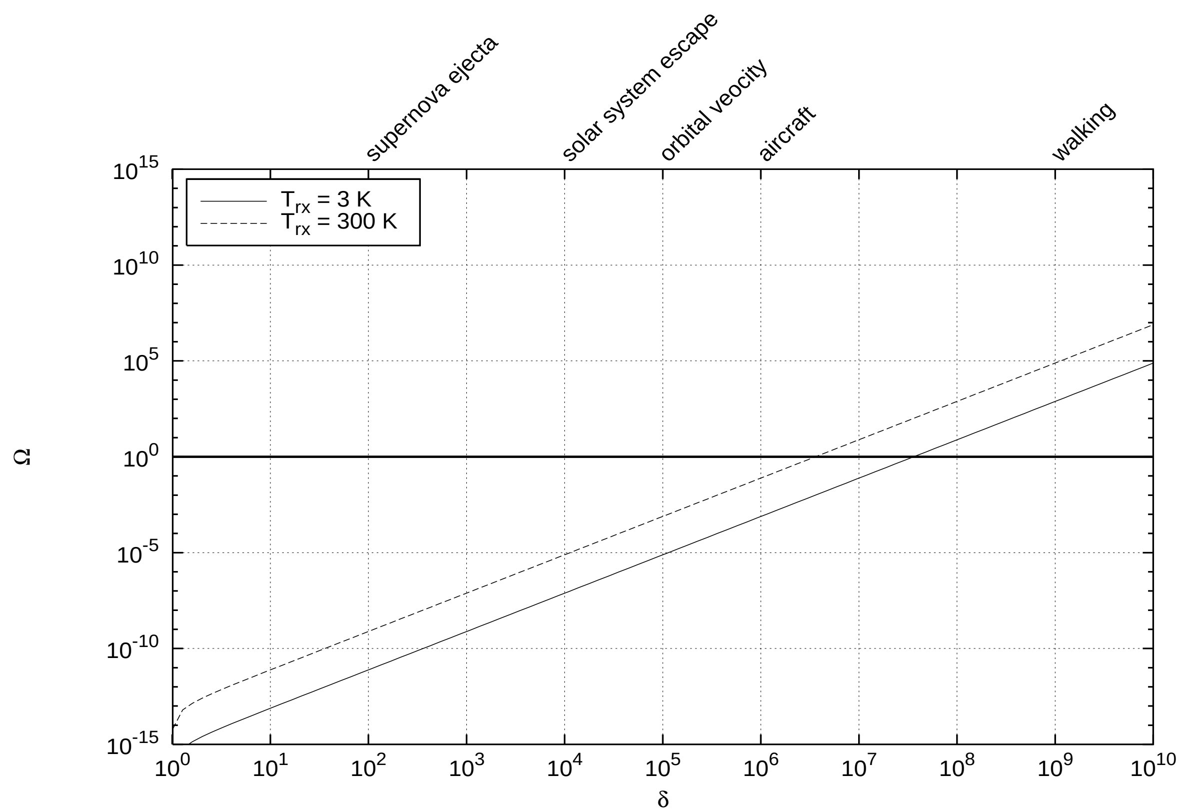


$$3^\circ\mathrm{K}, \tilde{\rho} = 1.8 \times 10^{24} \text{ bits kg}^{-1}$$

What About Broadcast?

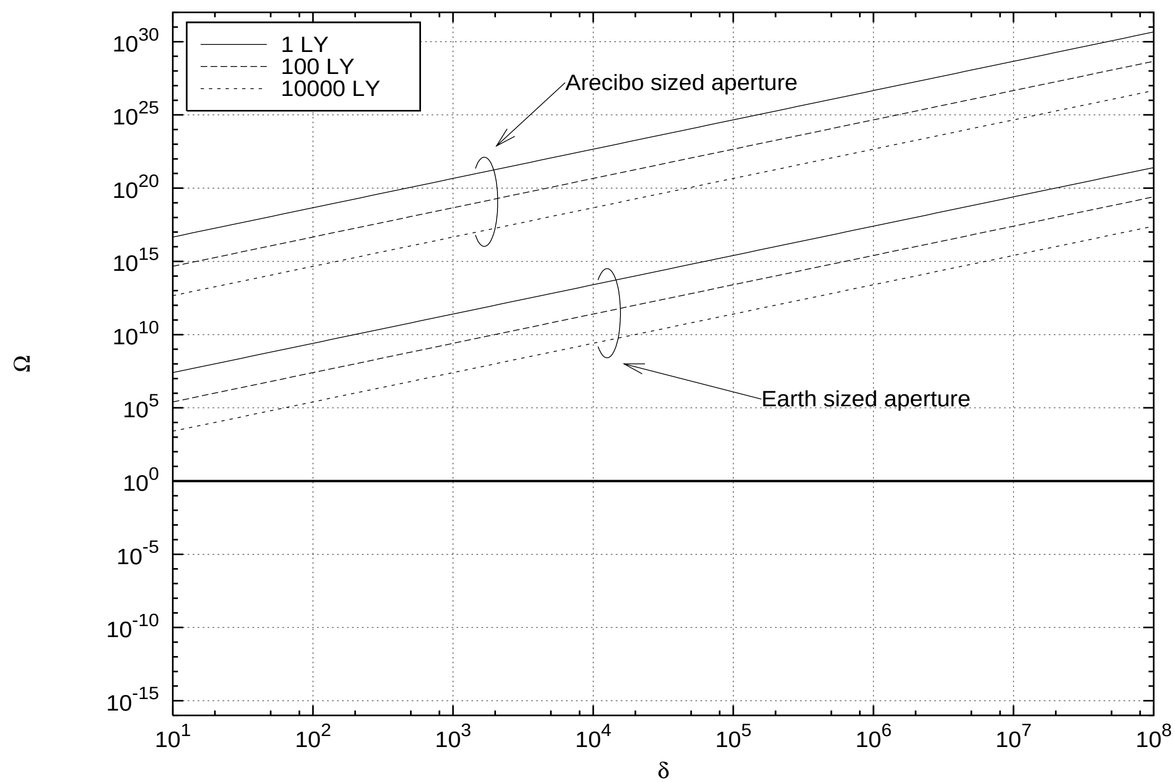
- Blind Broadcast
  - one message, many receivers, unknown positions
- Directed Broadcast
  - one message, many receivers, known positions
- Multicast
  - different messages, different receivers
  - large BW limit: separate radiative channels (essentially pt2pt)

One Message, Unknown Locations



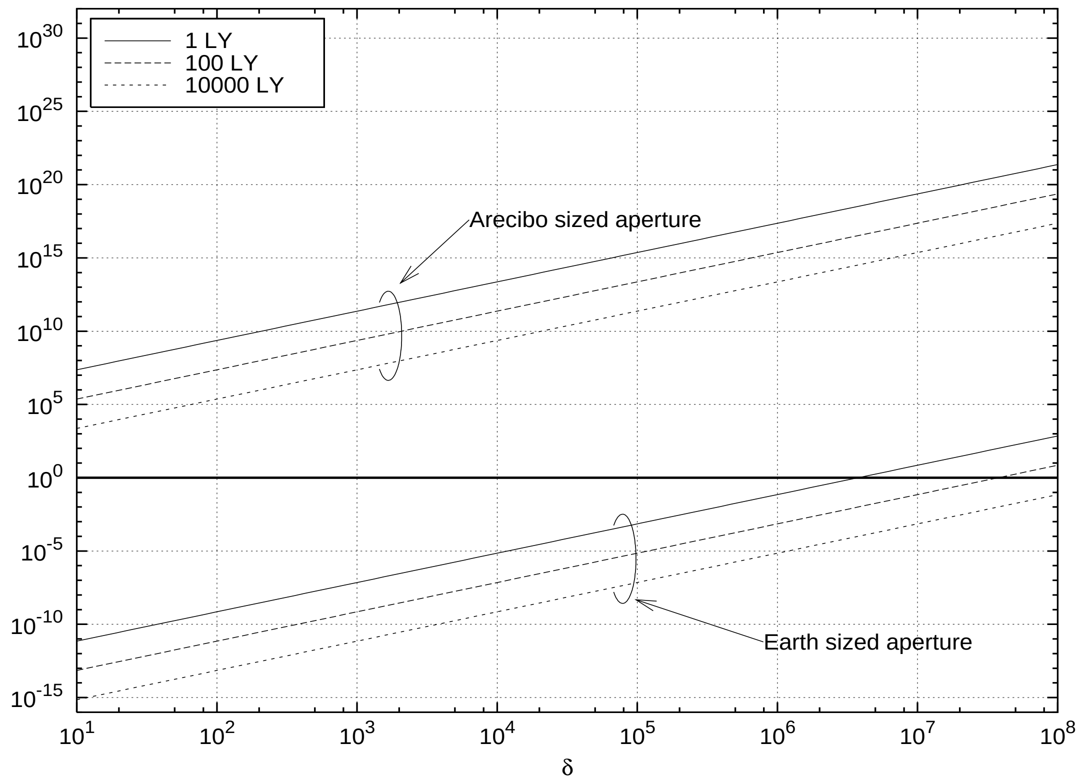
Energy ratio vs. δ. Receiver temperatures 3°K and 300°K, $\tilde{\rho} = 1.8 \times 10^{24}$ bits kg^{-1} and **mass sucks unless you're a snail**

One Message, Known Locations, No Gain: interstellar



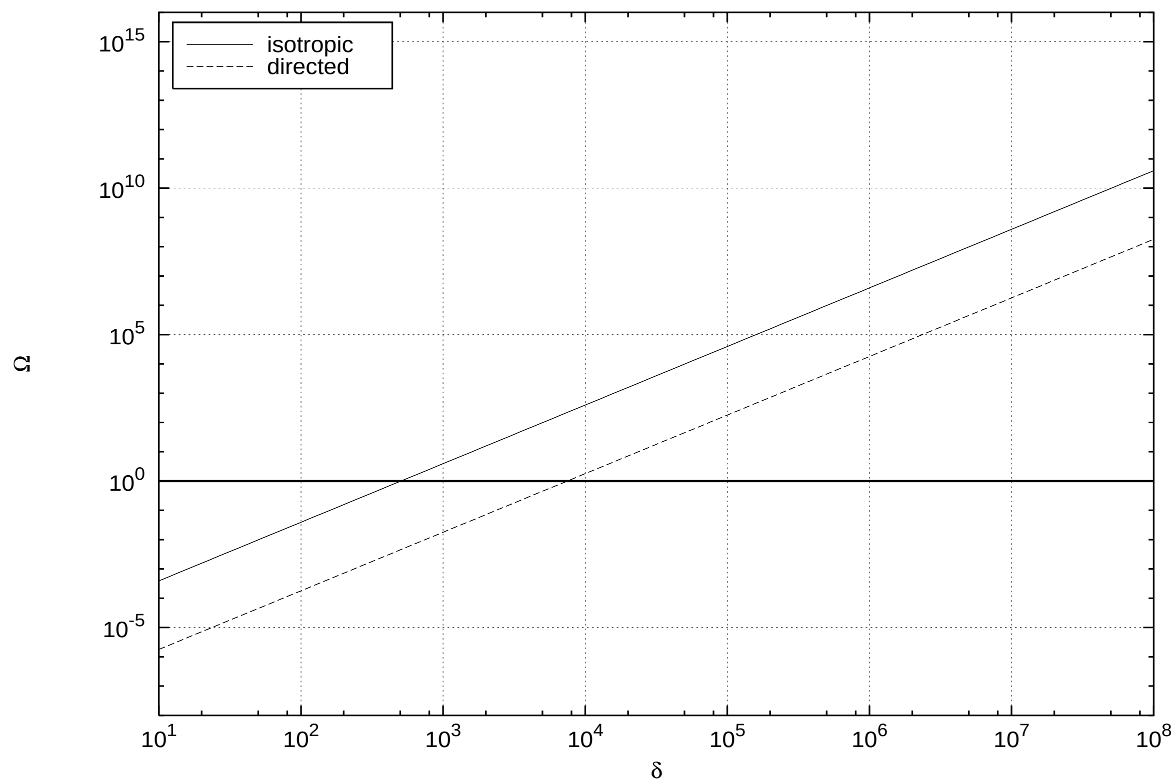
Energy ratio vs. δ. $\tilde{\rho} = 1.8 \times 10^{24}$ bits kg^{-1}, 3°K, receiver density $\sigma = 6.4 \times 10^{-3}$light year^{-3} (stellar density of Milky Way).

One Message, Known Locations with Gain: interstellar



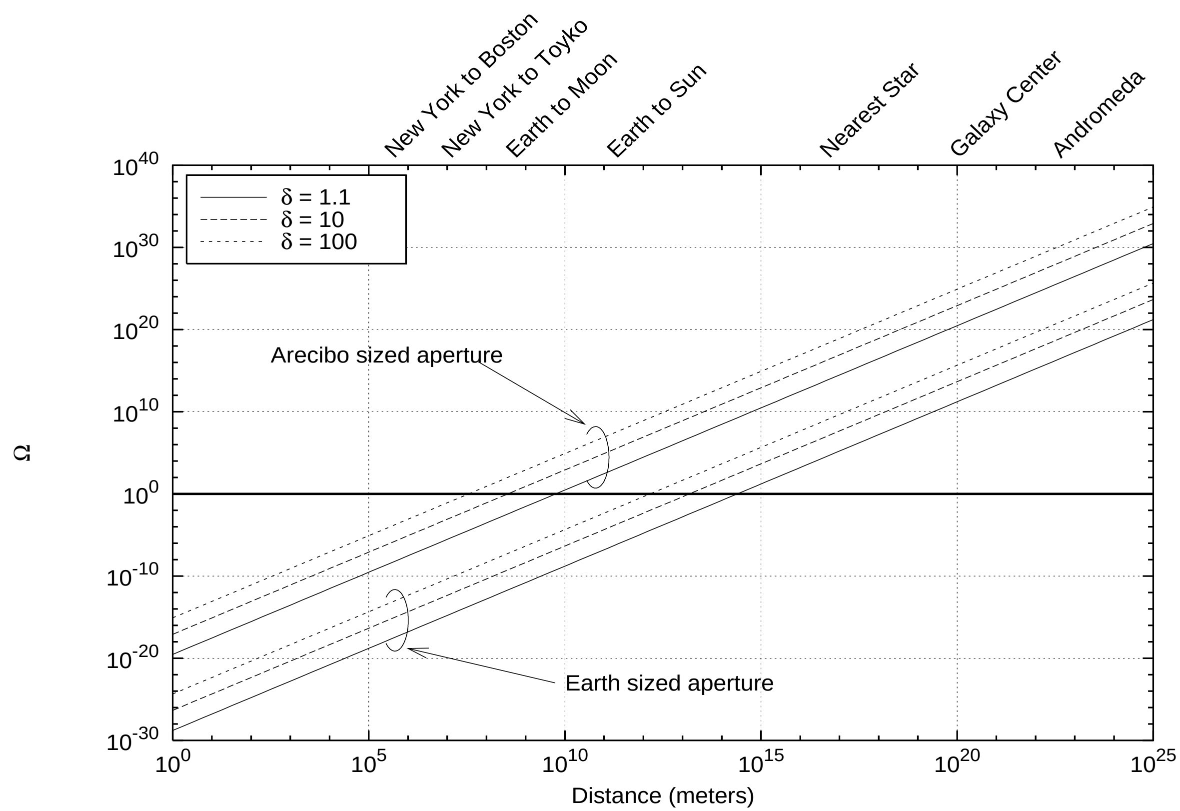
Same but with gain.

One Message, Known Locations: terrestrial



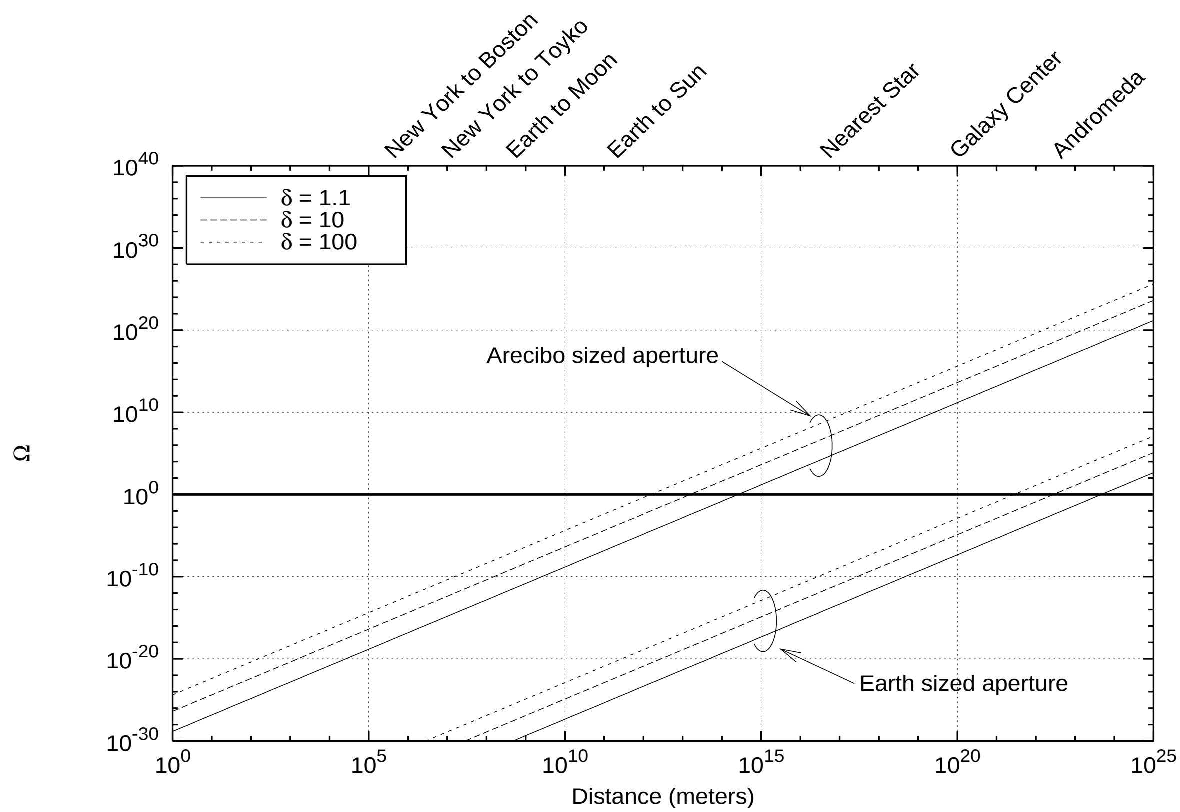
Energy ratio vs. δ. $\tilde{\rho} = 1.8 \times 10^{24}$ bits kg^{-1}, 300°K, receiver aperture radius 0.05 m, receiver density $\sigma = 0.01$ m^{-2}.

Many Messages, No Gain: interstellar



$\tilde{\rho} = 1.8 \times 10^{24}$ bits kg^{-1}, receiver temperature 3°K.

Many Messages with Gain: interstellar



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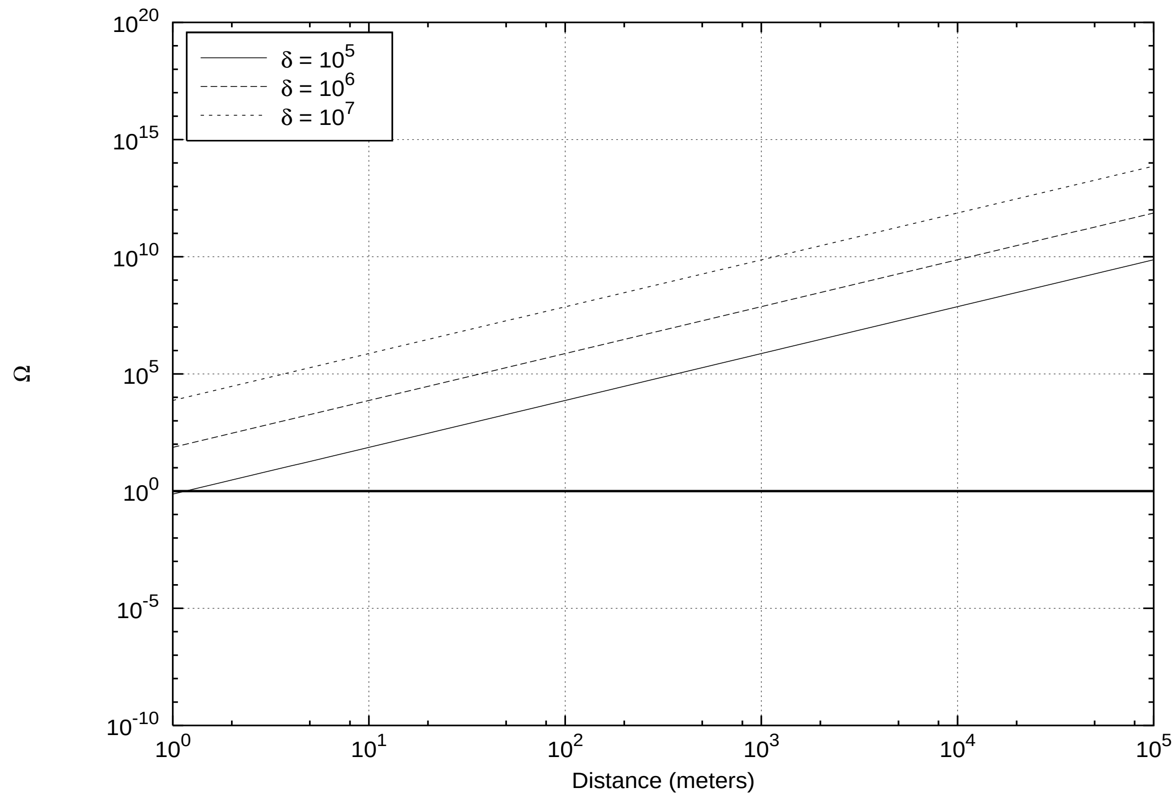
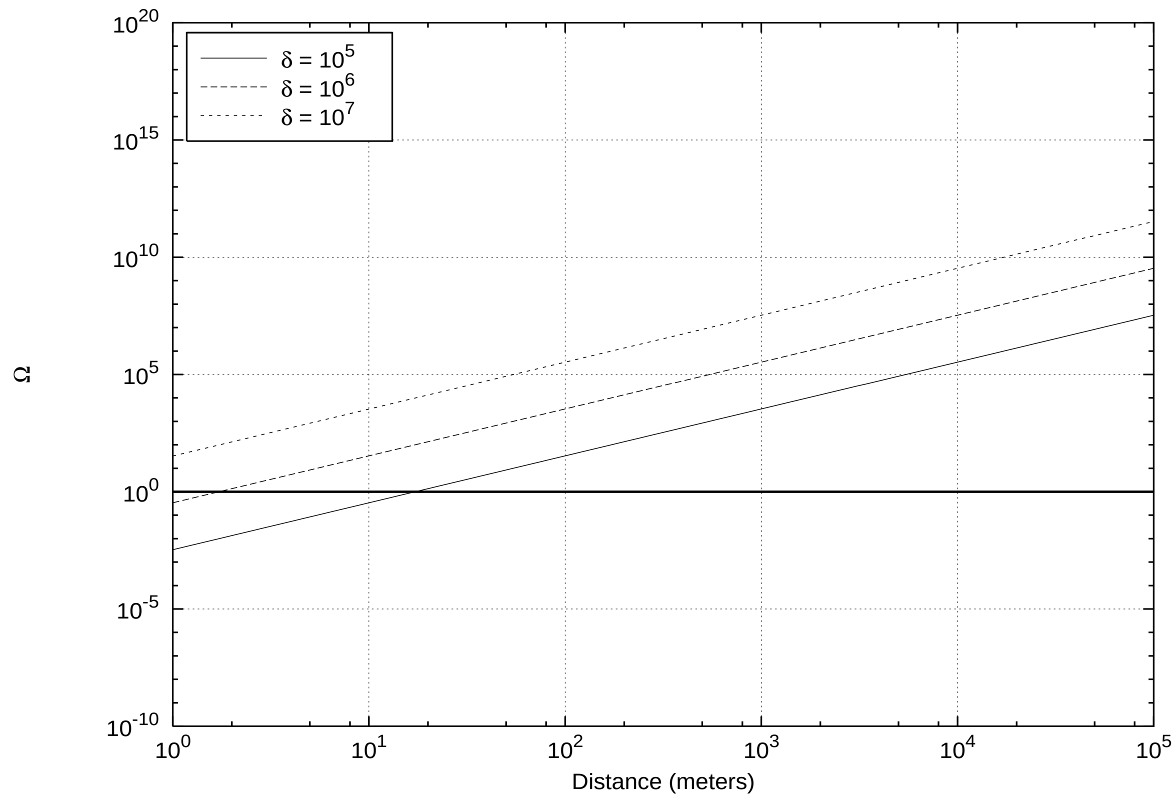
Many Messages, No Gain: terrestrial



Aperture 0.05 m, $\tilde{\rho} = 1.8 \times 10^{24}$ bits kg^{-1}, 300°K.

Many Messages with Gain: terrestrial

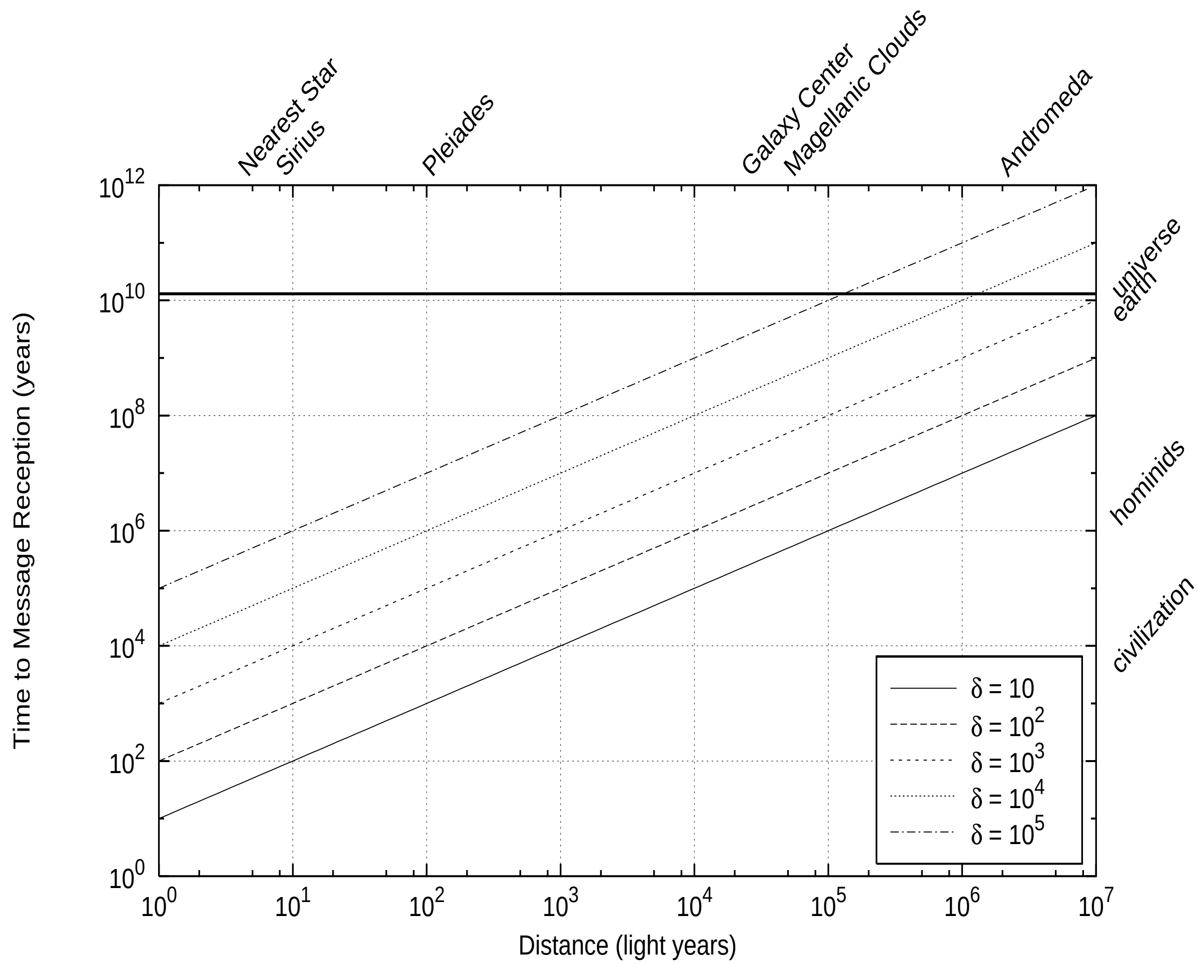


Same but with gain.

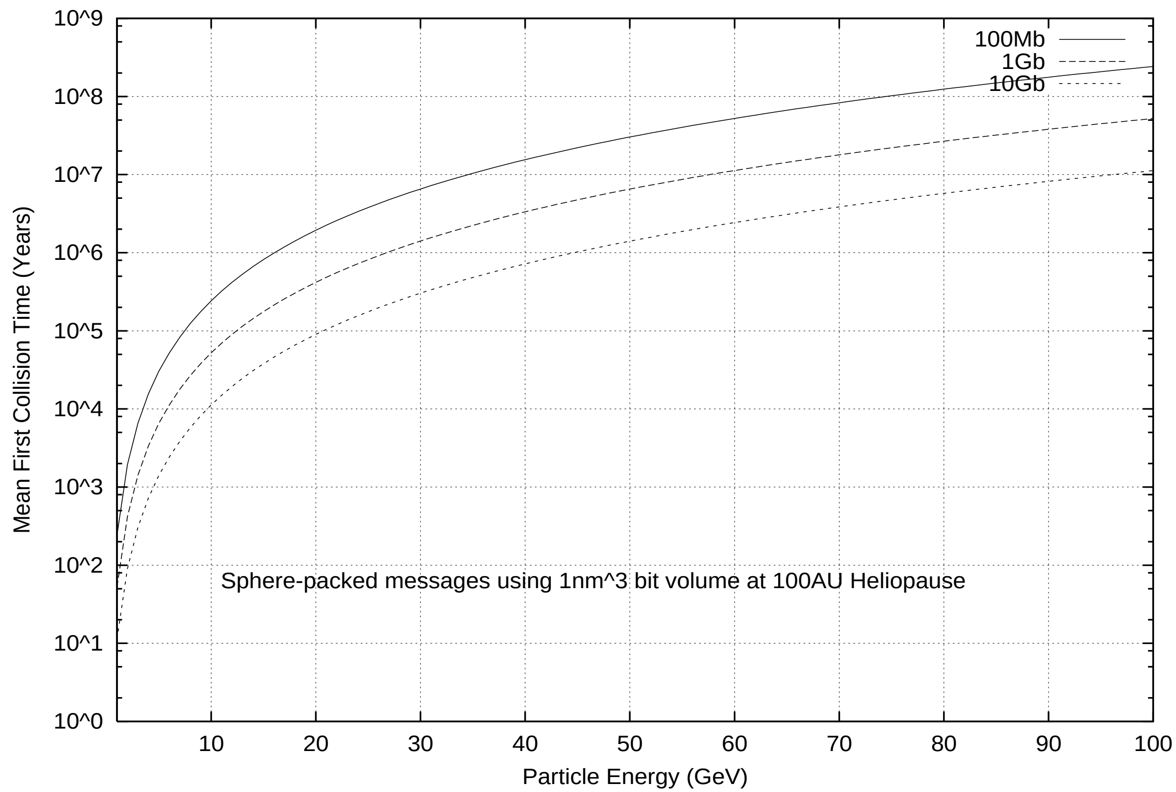
Inscription Energy/Speed Issues

- **Mass Inscription/Readout Energy**
  - Landauer said it can be reversible
- **Mass Inscription/Readout Time**
  - Landauer said it can be arbitrarily fast
- **Empirical energy calc:**
  - 60000 ATP/second for 20 minutes: 4850 Kbase of E-coli
  - 8×10^{-20}J per ATP
  - Replication:$\approx 10^{-17}$J bit^{-1}
  - E^* at $\delta = 100$: 2.5×10^{-12}J bit^{-1}
  - CAVEAT: E^* goes down as δ^{-2}

Delivery Times



Message Integrity – High Energy Insults



Damage Mechanisms

- Large (or small) unseen obstacles
- Heating (diffusion)
- Ion tracks
- Dislocation
- Spallation

Delivery Methods

- Big rock?
- Dust?
- Embedded dust (comet)?
- Probe (Bracewell)
- Onward toward lunatic fringe

Hard to Speculate (so won't ... yet)

Epiphany Revisited, Just for Fun!

- Gallon of gasoline: 1.2×10^8Joules
- 20 miles/gallon
- 20 miles: 1.2×10^8Joules
- D^4 isotropic breakeven (1m^2 radius aperture): $\approx 10^{10}$ bits
  - 5.5×10^{-12} grams of RNA
  - 0.5 kg of 20 lb paper at 600 dots/inch

The epiphany is REAL even for inefficient delivery!

PUNCHLINES

- Inscribed mass messaging is NOT ridiculous
- Inscribed mass messaging might often be PREFERRED
- Network Issues
  - Pebbles are non-interfering
  - Pebble net throughput scales well
  - Delays reasonable (Boston/NYC: $\approx$ 270 seconds ballistically)
- Practical value
  - Terrestrial: maybe some, maybe none
  - Interstellar: dust/pebbles/rocks, not spectrum for SETI
- Learn more: **http://www.winlab.rutgers.edu/~crose/cgi-bin/cosmic.html**