

Redshifted civilizations, galactic empires, and the Fermi paradox

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Academy of Sciences



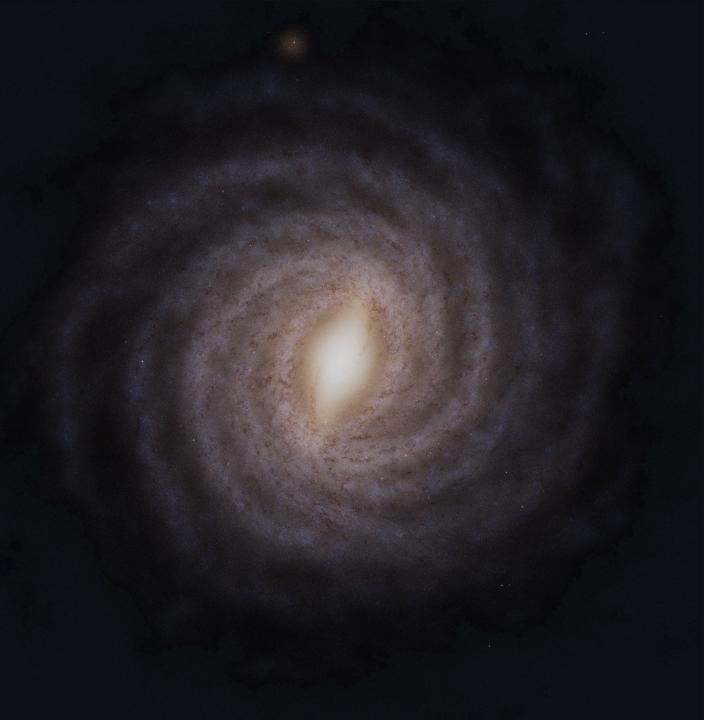
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The Core Question

How might *humans* colonize the Milky Way galaxy,
given our *current* understanding of physics?

The Problem



ESO/Gaia

Universe has speed limit:

$$c \approx 3 \times 10^8 \text{ m/s}$$

Fast, but the Galaxy is big

- Center of galaxy is 26,000 ly away
- Galaxy has diameter of 100,000 ly
- Takes thousands of years to traverse at c

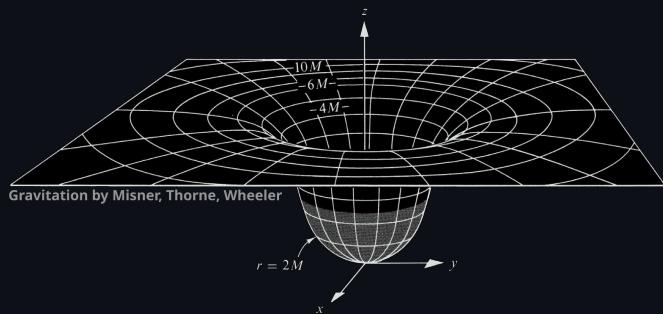
FTL travel requires new physics

- Need **lots** of negative mass, or alt. gravity

Staying grounded: limits from biology & physics



Col. John Stapp survived up to 46.2 g (credit: NASA)



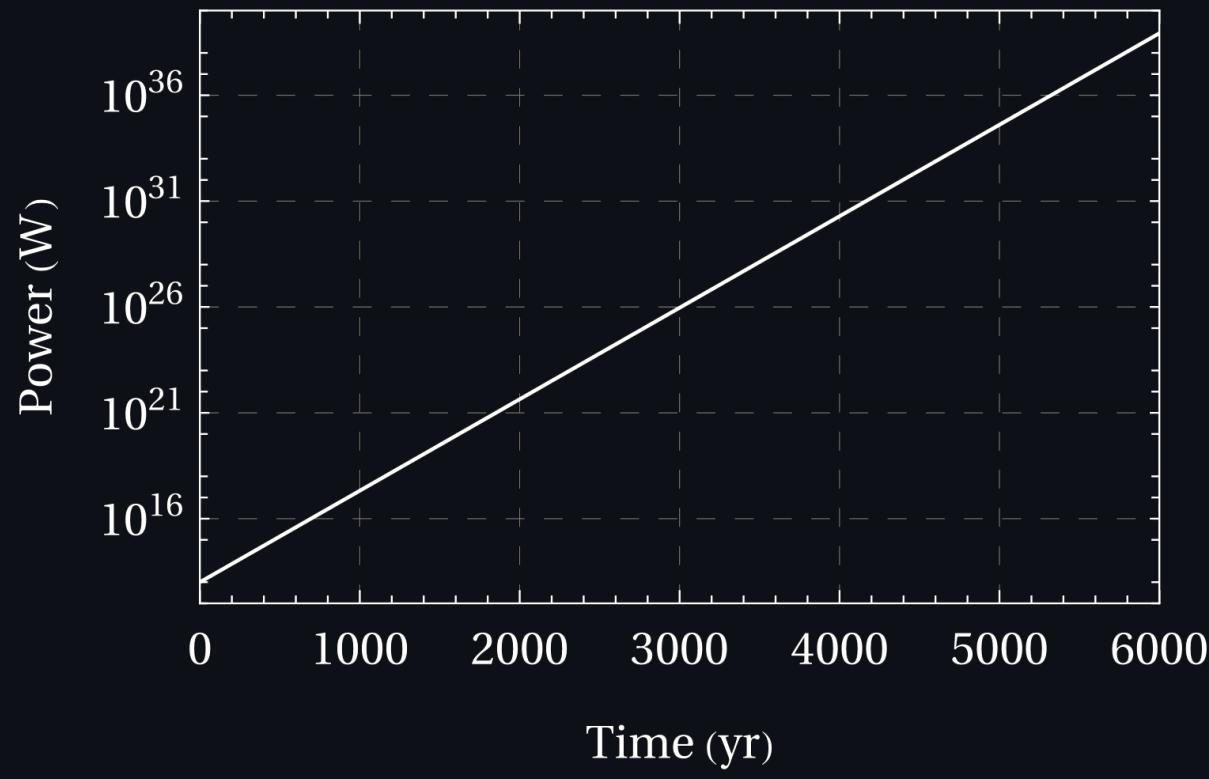
Embedding diagram for a gravitating mass in GR

- Hard to predict technology in distant future
- **Strategy: apply fundamental constraints:**
 - i. Biology fails under extreme acceleration
 - ii. **No new physics:** textbook general relativity (GR)[†]
 - iii. Mass-energy is nonnegative, conserved[‡]

[†]S M Carroll, Spacetime and Geometry, Addison Wesley, 2004; R M Wald, General Relativity, University of Chicago Press, 1984

[‡]Energy is not strictly conserved in GR, but it is conserved in the situations we consider (static spacetimes).

Energy limits capability: the Kardashev scale



**Kardashev scale for
civilizations:***

- Type I: 10^{17} W (planet)
- Type II: 10^{26} W (star)
- Type III: 10^{36} W (galaxy)

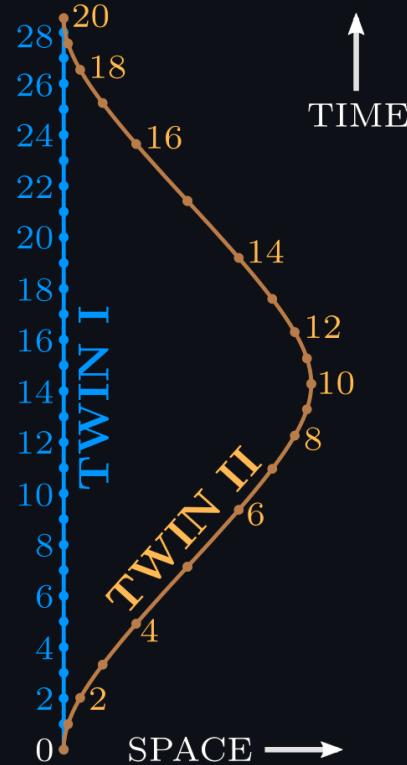
Human civ. at $\sim 10^{13}$ W today

At 1%/yr growth:

- We reach Type I in <1000 yr
- Type II in ~ 3000 yr

*N. S. Kardashev, Soviet Astronomy 8, 217 (1964).

Time is relative: Relativistic time dilation



- Relativity: flow of time depends on
 - relative speed v (special relativity)
 - gravity (general relativity)
- Time dilation illustrated by the twin ``paradox'' (SR)
 - Twin I stays still, Twin II goes on a journey
 - Twin II ages less due to relativistic motion
- Time dilation factor: $\gamma = \frac{dt}{d\tau} \sim \frac{\text{"A tick of Earth time"}}{\text{"A tick of ship time"}}$

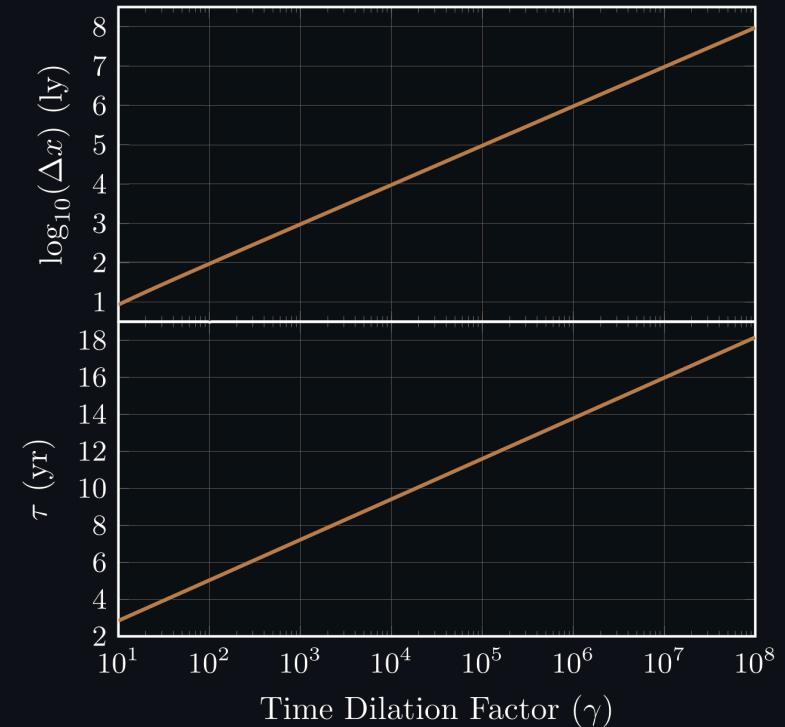
Measure elapsed time in SR with:

$$d\tau^2 = c^2 dt^2 - dx^2$$

Can we use time dilation to our advantage?

Yes! Carl Sagan's Model (1963)

- Simple model of linear motion:
 - i. Accelerate at 1 g up to some speed v
 - ii. Decelerate at 1 g back to rest
- Can travel 20,000 ly in 20 yr ship time τ !
- **BIG PROBLEM:**
 - For round trip, 67,000 yr pass on Earth
 - Far exceeds human lifespans, travelers never reunite with those at home



Half-trip distance Δx and time τ to reach γ at acceleration $a = 10 \text{ m/s}^2$

A modest proposal

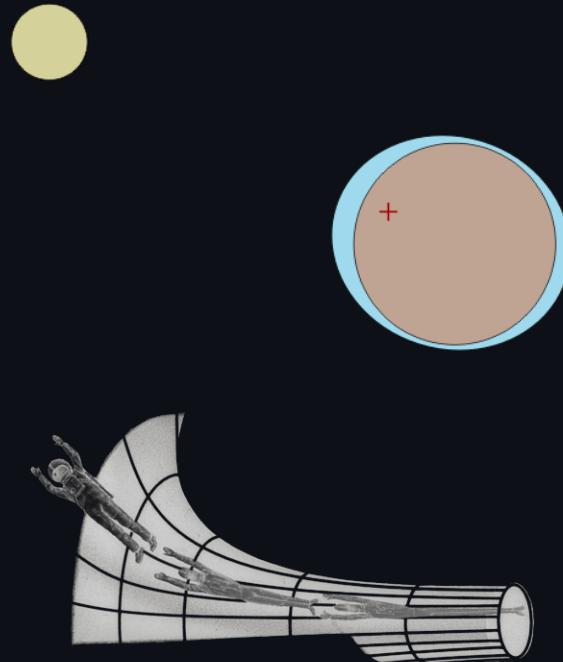
Move your *entire civilization*
into a time-dilated frame

*Then synchronize trips to ensure that
everyone ages at the same rate*

We consider three scenarios

1. Occupy fast orbits around supermassive black holes
2. Build a network of linearly accelerating vessels
3. Construct a ring of black holes

Time dilation near black holes (BHs)



Tidal forces cause tides; they tend to "spaghettify"

Earlier ideas for high time dilation:

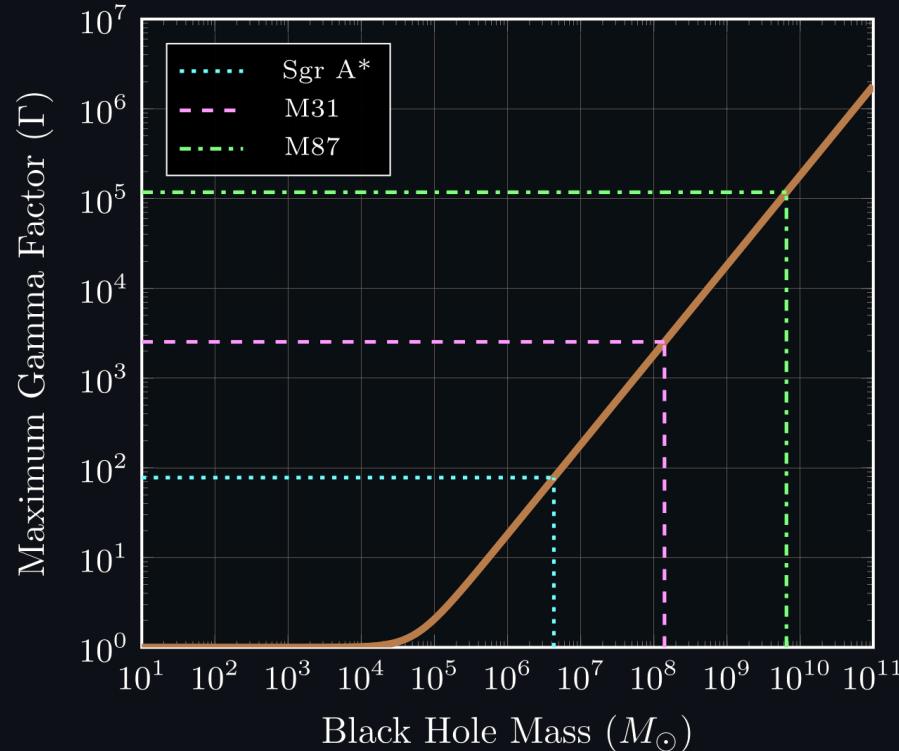
- Hover just above BH horizon: deadly acceleration
- Innermost stable orbit:^{*} requires unrealistically high BH spin

Idea: orbit close to where light orbits

- High speed \Rightarrow high time dilation
- Tidal forces can still be deadly

^{*}Example: Miller's planet from *Interstellar* (2014) requires spin above astrophysically realizable values.

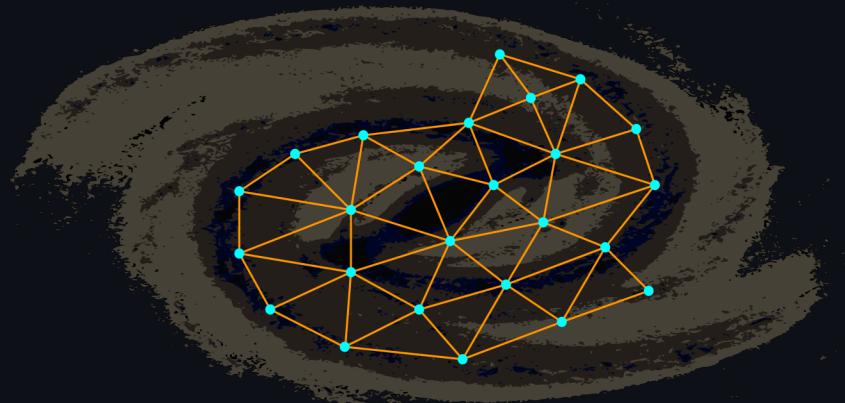
1. Orbits around supermassive black holes



Time dilation factor Γ vs BH mass for maximum tidal acceleration $a_\perp = 0.1$ g over a distance $\chi = 2$ m

- Sgr A* is a supermassive BH at the center of the Milky Way, $M \sim 4 \times 10^6 M_\odot$
- For Sgr A*, maximum time dilation factor of $\gamma \sim 100$ for a tidal accel. of 0.17g
 - Near Sgr A*, have 10^6 stars <100 ly
- BHs accrete gas, power to counter drag:
$$P_{\text{drag}} \sim 10^{14} \text{ W to } 10^{20} \text{ W}$$
- Human power capacity today: $\sim 10^{13} \text{ W}$

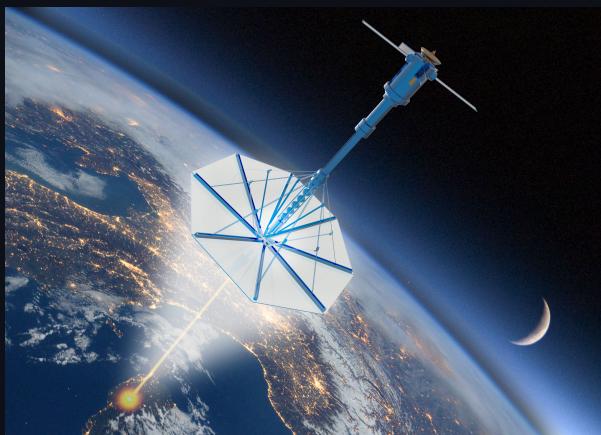
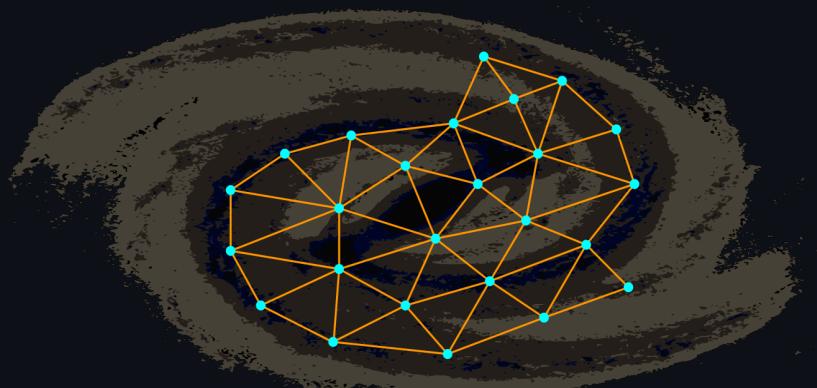
2. A Network of linearly accelerating vessels



A single Type II civ. can build a galaxy-wide network!

- A Type II civ. (10^{26} W) can accelerate at 1 g **thousands** of (1 km) asteroid mass vessels
 - In Sagan's model: $P = mca\sqrt{1 - 1/\gamma^2}$
- **Idea:** Build network of linear trajectories
 - Each 20,000 ly long, w/ $\gamma = 10,000$, 1 g
 - Synchronize to meet @ nodes
 - Proper time between nodes: 20 yr
 - Travelers can "vessel-hop" across net.

The Maintenance Problem



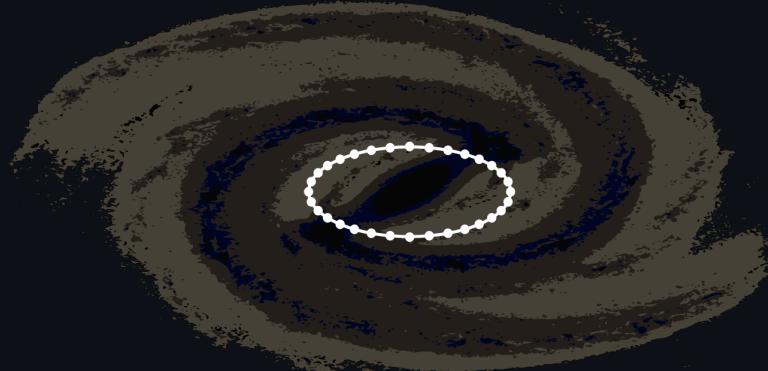
Rocket propulsion impractical for $\gamma \sim 10,000$

- Likely need beamed propulsion (lasers, particle beams)
- Beamed propulsion requires extensive infrastructure at stars
- Stars drift \Rightarrow need constant repositioning

Can we do better? A more permanent solution...

3. A ring of black holes (a galactic empire)

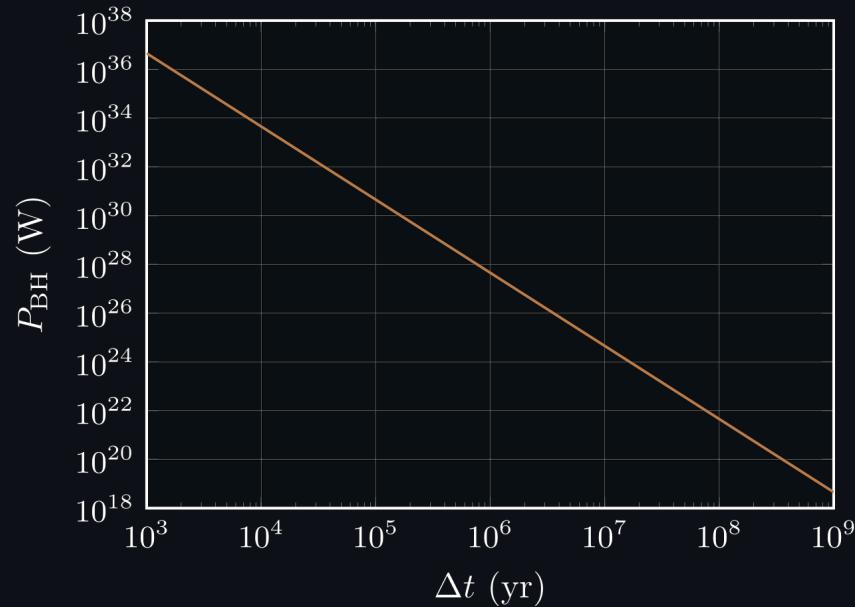
- Imagine black holes in a ring
 - Each BH orbits Milky Way
 - Each BH deflects path of vessel slightly, so...
 - vessel travels in a closed loop
-
- At $\gamma = 10,000$, need almost a million BHs to limit tidal forces



Why do this?

- No constant acceleration needed
- Can extract energy from spinning BHs
- Permanent "capital" location

Can it be done?



Peak power required to move $20 M_\odot$ BH a distance 200 ly vs. time Δt

- BH density too low to form natural ring
- For a radius of 10,000 ly, must move a million BHs up to ~ 200 ly
- Consider civ. between Type II and Type III, at 10^{32} W
 - A few million yr to move BHs 200 ly
 - But in time dilated frame at $\gamma = 10^4$, this is a few hundred years

An existential vulnerability



- Ultrarelativistic vessels vulnerable to impacts
 - 100 kg mass at $\gamma = 10,000$ has kinetic energy 10^{23} J (Chicxulub-level)
 - Turn radius 100X galactic diameter at $\gamma = 10,000$
- **Hostile civs. can destroy a vessel with little energy cost**

Implications for the Fermi Paradox



- 800 kg Voyager probes now in interstellar space
- We may already pose a threat!
- Human civ. achieved this in < 10,000 yr
 - Civ. at $\gamma \sim 10,000$ sees this history in < 1 yr
 - Threats emerge "in the blink of an eye"
- Incentivizes staying quiet (Dark Forest, #32?) or acting preemptively (Berserker, #25)*

Takeaways (preprint: <https://arxiv.org/abs/2510.00377>)

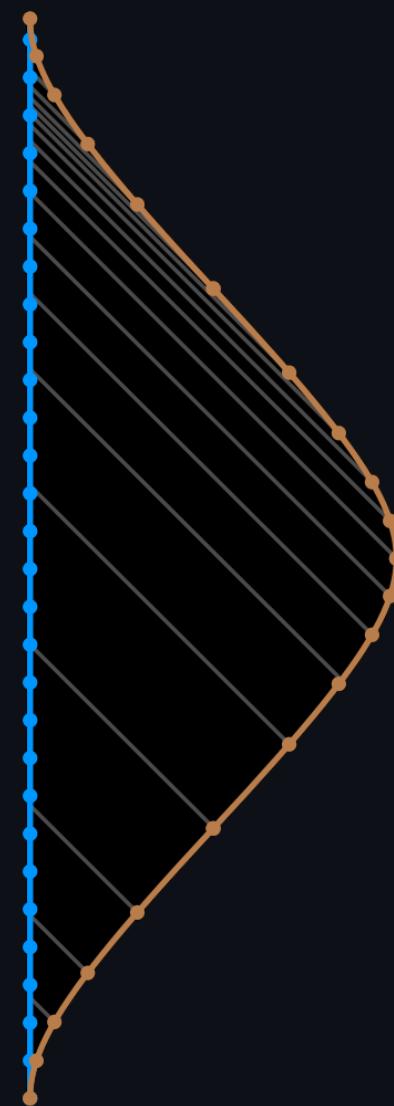
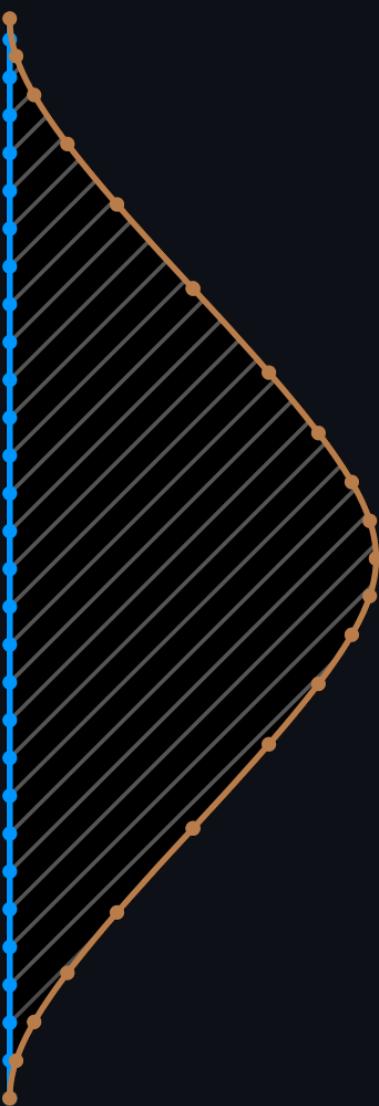
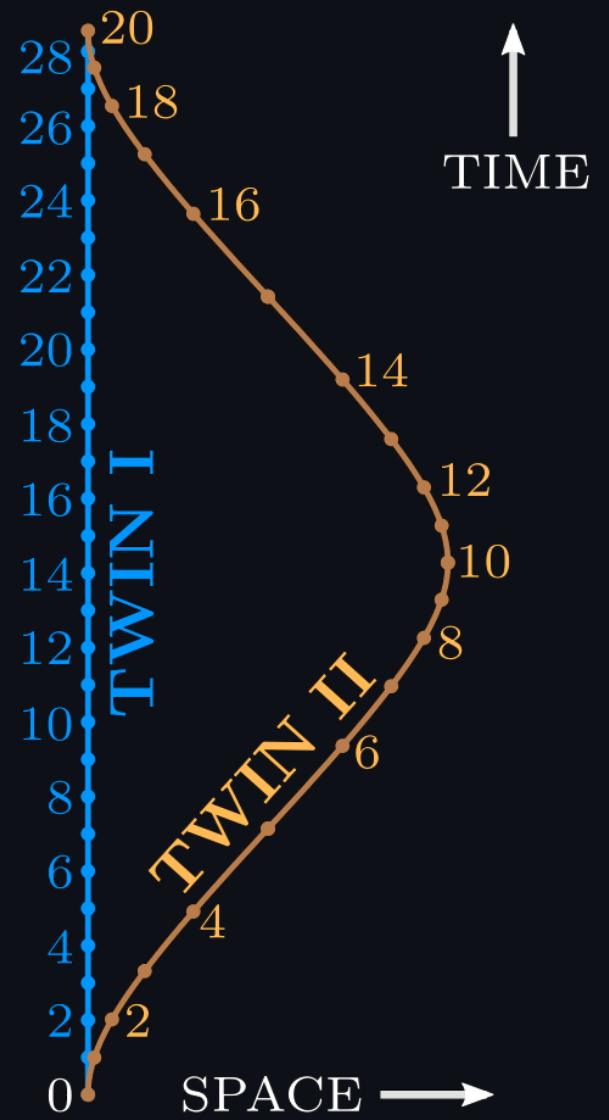
A civilization may migrate to highly-time dilated frames to avoid temporal disparities from relativistic travel

We explored three ways to do this:

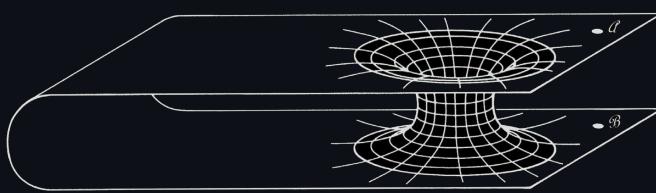
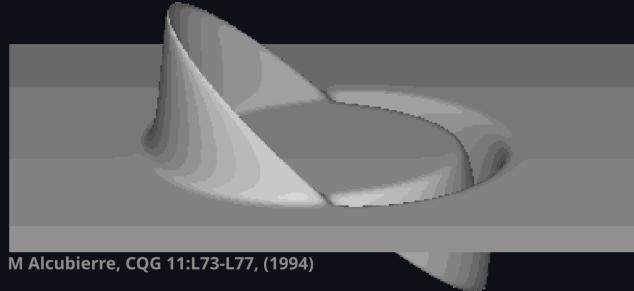
1. Occupy orbits around supermassive black holes (btwn. Type I and II)
2. Build a network of linearly accelerating vessels (Type II)
3. Construct a ring of black holes (btwn. Type II and III)

But ultrarelativistic vessels have existential vulnerabilities

- Motivates a "Dark forest" (or "Berserker") hypothesis for Fermi paradox



Really, why not faster than light?



Exotic matter means negative energy density

- Special relativity forbids FTL travel.
- General relativity needs exotic matter for FTL
 - Warp drives,^{*} wormholes[†] need **lots** of it
 - Meter-scale wormhole needs Jupiter mass worth of exotic matter
 - Warp drives need FTL exotic matter[‡]
- **FTL travel requires new physics**

^{*}M Alcubierre, CQG 11:L73-L77,(1994);

[†] M Visser, *Lorentzian Wormholes*, AIP (1995)

[‡]D H Coule, CQG 15 2523 (1998)

Technical Details: Time Dilation Near BHs

Schwarzschild spacetime:

$$ds^2 = -f(r)c^2dt^2 + \frac{dr^2}{f(r)} + r^2d\Omega^2$$

where $f(r) = 1 - 2GM/(c^2r)$

Circular orbit time dilation:

$$\Gamma = \sqrt{\frac{r}{r - 3M}}$$

Near photon radius ($r \rightarrow 3M$): $\Gamma \rightarrow \infty$

Tidal acceleration:

$$a_{\perp} = \frac{c^6(\Gamma^2 - 1)\chi}{27G^2M_{\text{BH}}^2}$$

For $a_{\perp} \sim 0.1$ g over $\chi \sim 2$ m:

- Stellar BH ($10 M_{\odot}$): $\gamma \sim 1$
- Sgr A* ($4 \times 10^6 M_{\odot}$): $\gamma \sim 100$
- M87* ($6.5 \times 10^9 M_{\odot}$): $\gamma \sim 10^5$

Larger black holes allow higher γ

Technical Details: Linearly accelerating motion

Hyperbolic motion in SR:

Time dilation factor:

$$\gamma = \sqrt{1 + (at/c)^2}$$

Proper time to reach γ :

$$\tau = (c/a) \cosh^{-1}(\gamma)$$

Distance traveled:

$$\Delta x = c^2(\gamma - 1)/a$$

Power requirements:

$$P_{\text{acc}} = mac\sqrt{1 - \gamma^{-2}} \approx mac$$

$$P_{\text{drag}} = A_{\text{cs}}\rho\gamma c^3$$

Example: 10^{13} kg vessel to $\gamma=10^4$

- Acceleration: $\sim 10^{22}$ W
- Drag (ISM): $\sim 10^{18}$ W

Type II (10^{26} W) supports 10,000 vessels