Architectures and Algorithms for Self-Healing Autonomous Spacecraft

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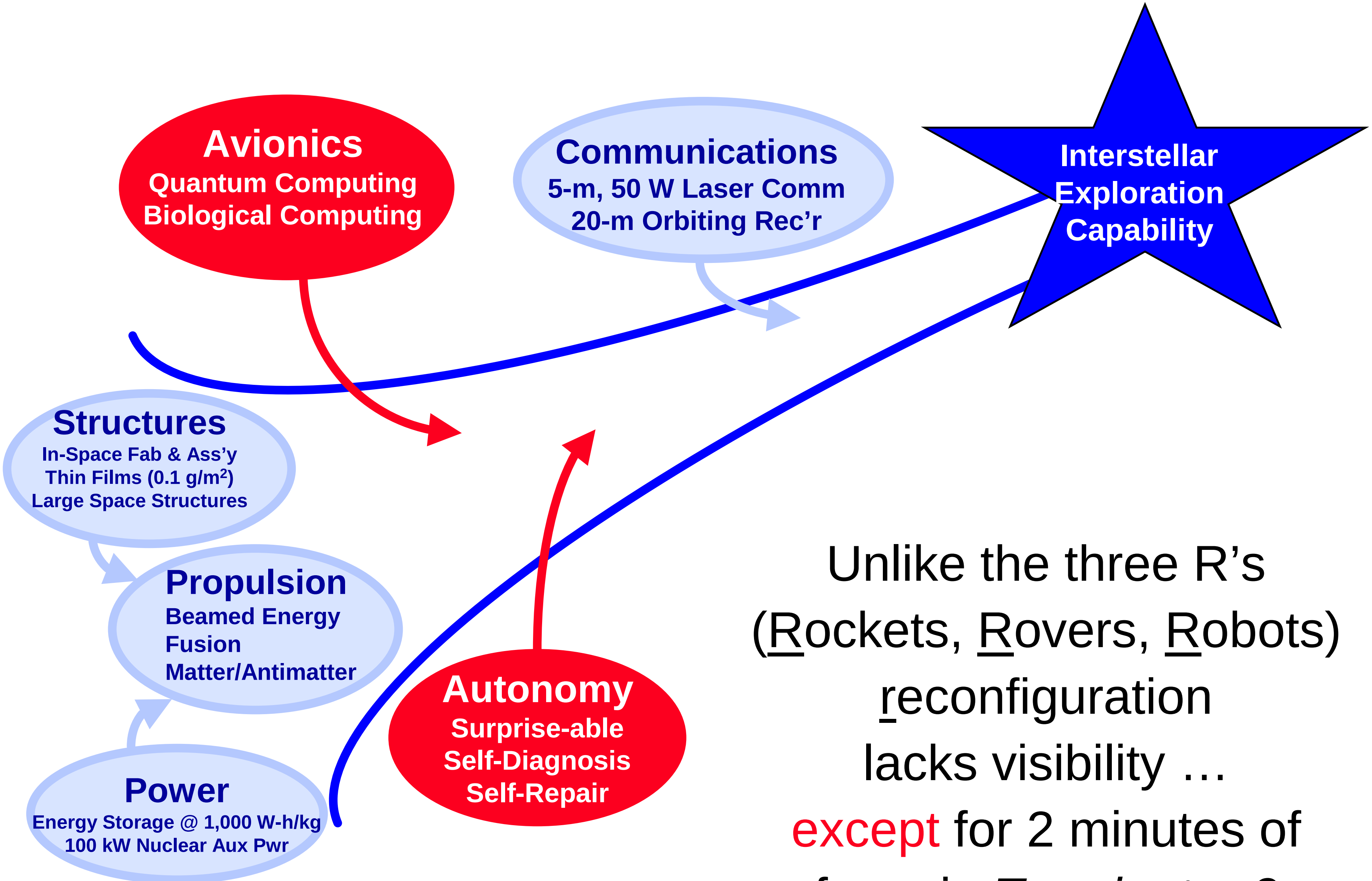
Phase I Objectives

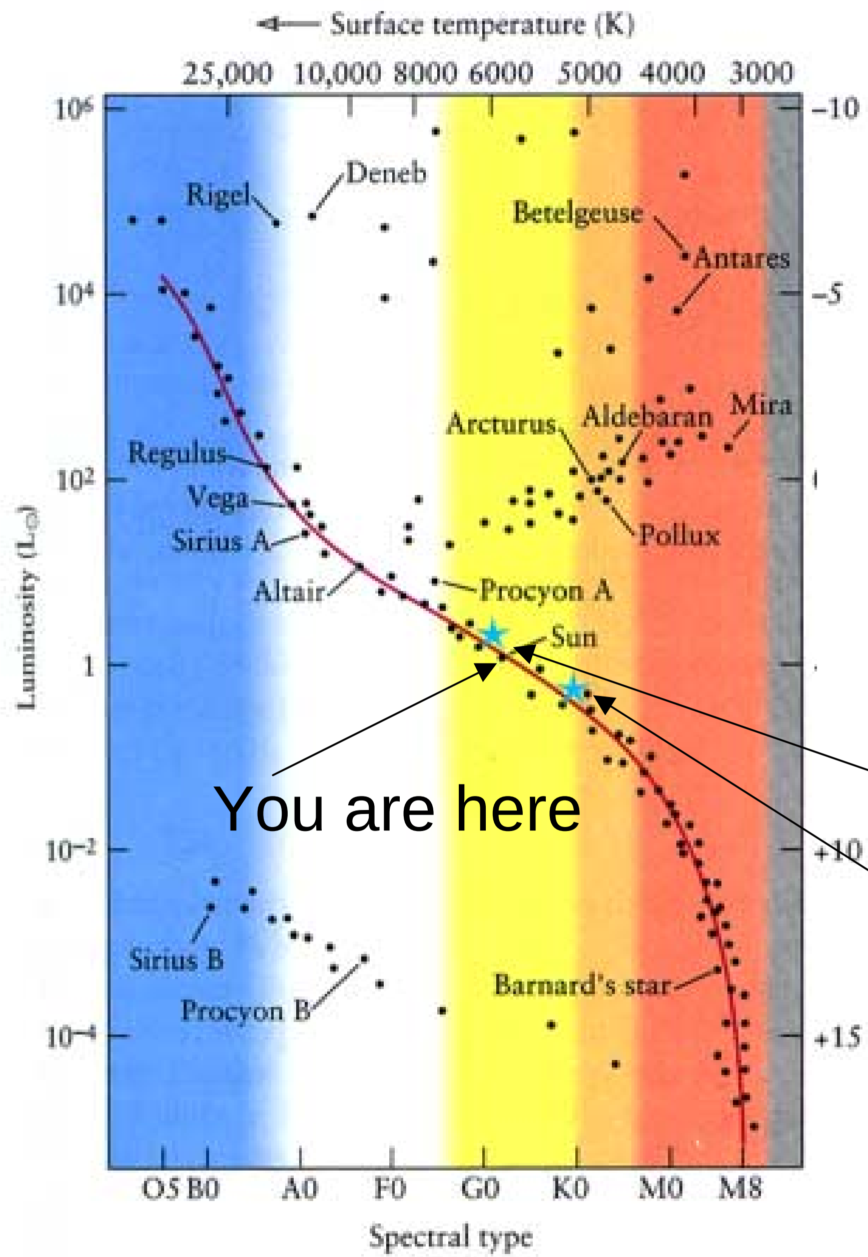
- Profile missions requiring revolutionary
  - survivability
  - performance
- Characterize avionics and software
- Survey appropriate technologies
- Advance state-of-the-art for mission-critical architectures and algorithms



Unlike the three R’s (Rockets, Rovers, Robots) reconfiguration lacks visibility … except for 2 minutes of fame in *Terminator 2*

Adapted from JPL viewgraph

Interstellar Missions Require Revolutionary Survivability and Performance



Alpha Centauri

A: G2 V (Lum. 1.77)
Prob. habitable planet: 0.054

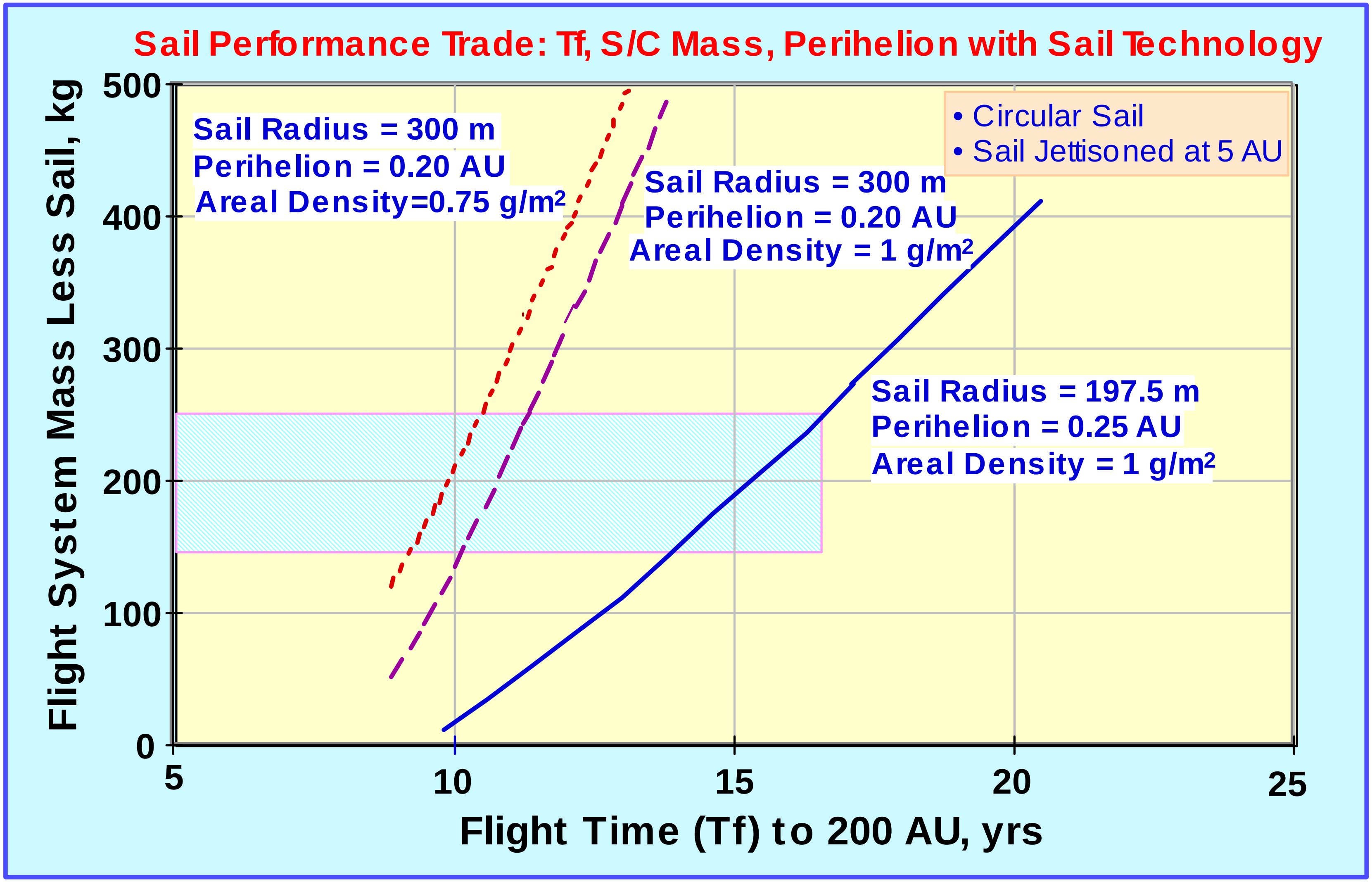
B: K0 V (Lum. 0.55)
Prob. habitable planet: 0.057

Profile of Interstellar Missions

Jet Propulsion Laboratory Interstellar Probe	**Johns Hopkins University McNutt IPM**	**The Right Stuff of Tahoe *Santa Maria***
nose of heliosphere	beyond nose of heliosphere	*Alpha Centauri*
200 AU	1000 AU	278256 AU
ecliptic trajectory with solar swingby	ecliptic trajectory with Jovian / solar swingby	out of ecliptic, direct
solar sail	Orion class nuclear	nuclear, $I_{sp} > 10^5$ sec
launch: 2010		launch: 2-Aug-2022
15 years	50 years	200–500 years
100 kg payload	50 kg payload	1000 kg payload
20 watts	15 watts	100 watts
25 bits per second	20 bits per second	100 bits per second

JPL Interstellar Probe Baseline Mission Trades

Mass/Flight Time



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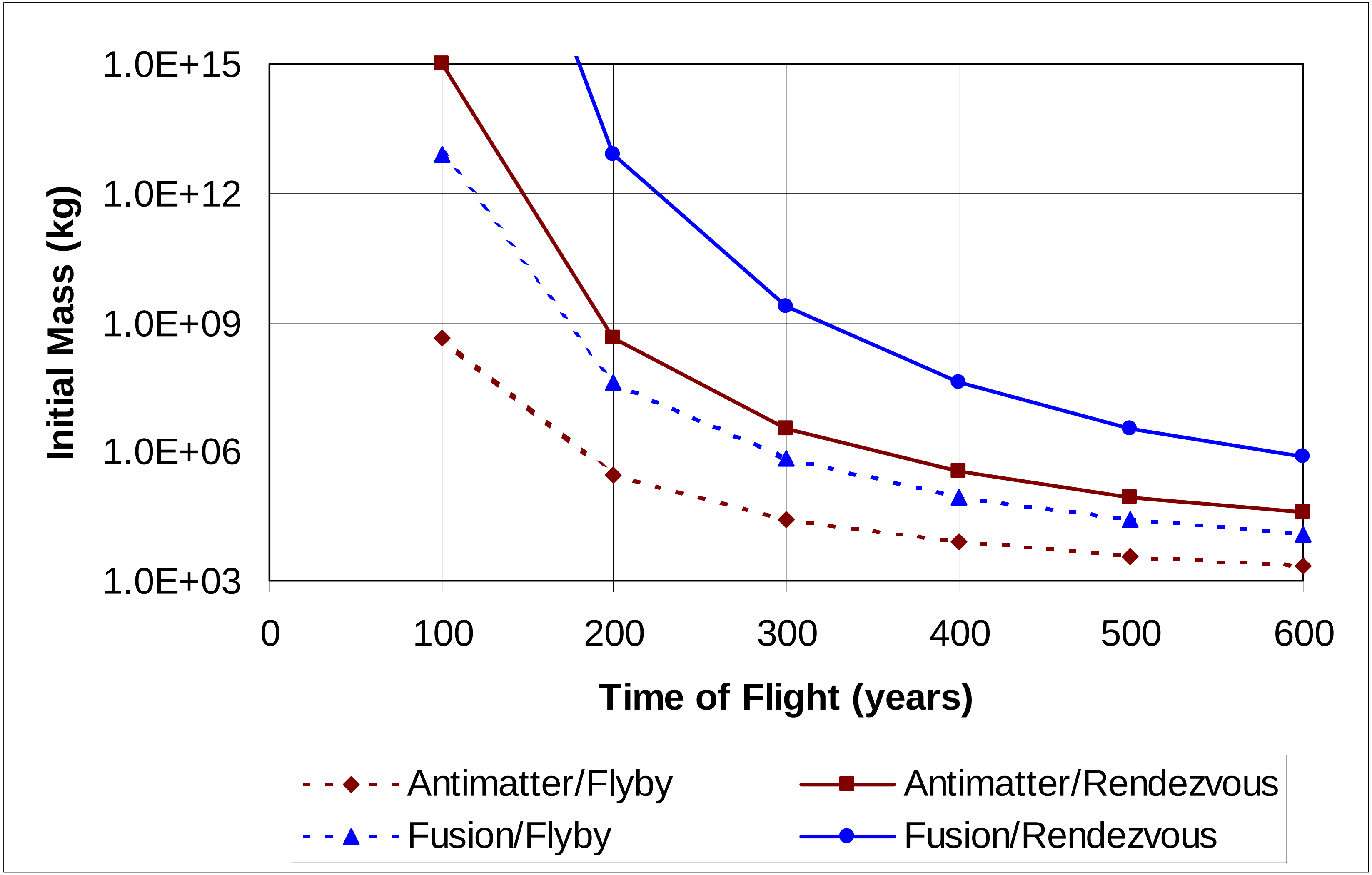
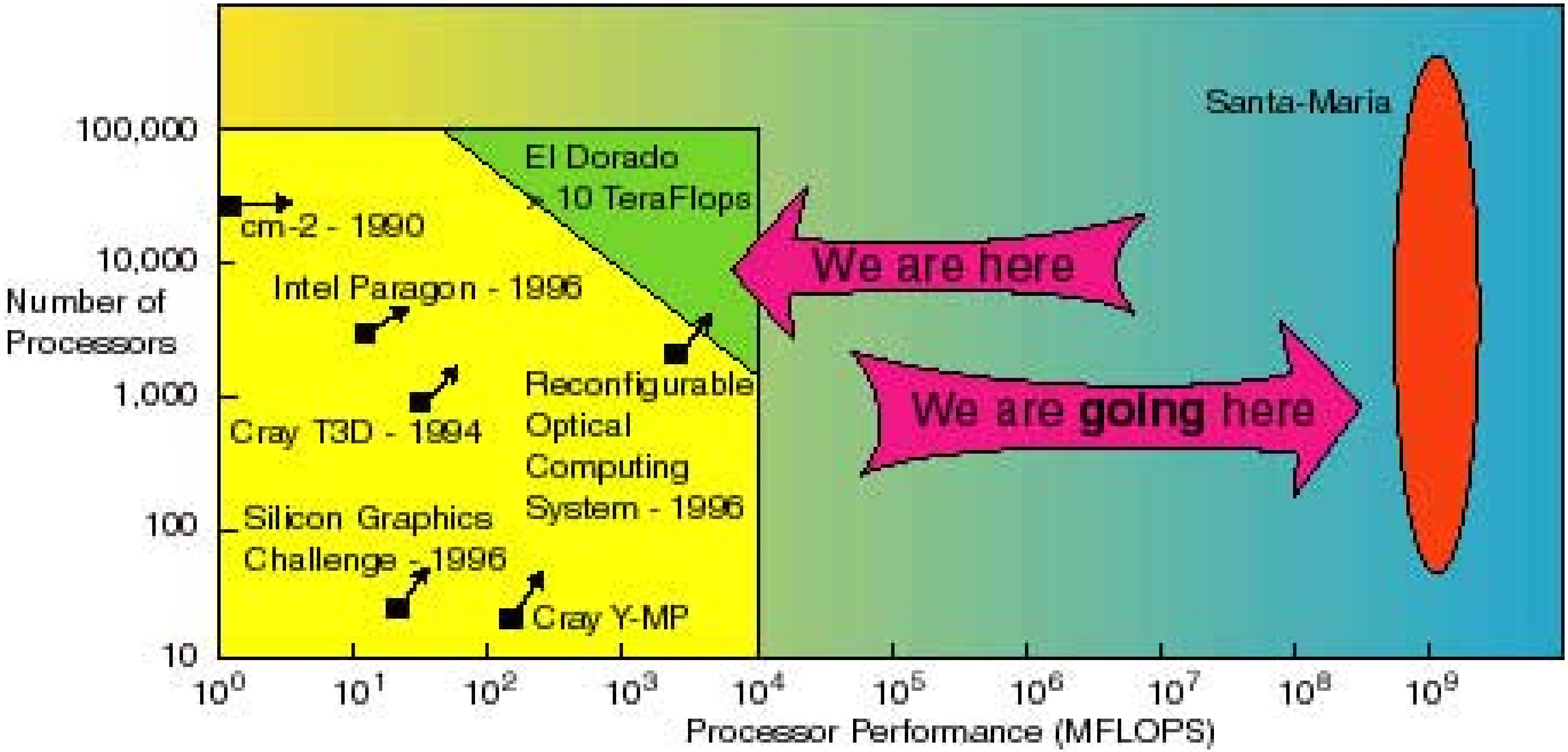
Adapted from JPL viewgraph

Santa Maria
Initial Mass versus Flight Time



Contemporary Performance Ceiling

10^{12} operations per second, > 100 kilograms
(Brookhaven, Sandia supercomputers)



Contemporary Fault Tolerance

Titan 4A explosion 40 seconds after launch, 12-Aug-1998. Cause: faulty wiring

Contemporary Fault Tolerance

- X2000 avionics and software: 1 fault
- STS Missions: 2 faults in active payload
- Needed: tolerance to a *proportional* number of
  - latent design faults
  - transient faults, single or burst
  - permanent faults, regardless of source

Architectures for Interstellar Avionics

- Unmanned robots
- Will support software that can adapt on its own
- 10^{15} operations per second per kilogram
- Tolerate constant proportion of faulty components
- Uniform elements maintain healthy connectivity
- Design hinges upon dependable tools that embody a dependable theory about dependability

Revolutionary Reliability Requires Radical Rigor

- Standard approaches to avionics (*e.g.*, n-module redundancy with voters) will not work
- *Ad hoc* approaches to software will leave the number and severity of faults unpredictably high
- Function and performance of hardware architecture should be dictated by applications software
- A major application will be assuring the health of the onboard software

Appropriate Technologies: Mathematical Advances Enable Software That Really Works

- **Provably correct programs**
  - E.g., work by Angela B. Shiflet (Wofford College), Martin Feather (JPL), Frank Schneider (JPL), Mike Lowry (ARC)
- **Tracking and analysis of soft failures and faults**
  - E.g., work by Allen Nikora (JPL), Larry LaForge (The Right Stuff of Tahoe), Norman Schneidewind (Naval Postgraduate School), John C. Munson (University of Idaho), Taghi Khoshgaftaar (Florida Atlantic University)

Appropriate Technologies: Mathematical Advances Enable Hardware That Really Works

Necessary and sufficient: logarithmic redundancy

- **Mutual test and diagnosis**
  - Edward Scheinerman (Johns Hopkins), Doug Blough (University of California, Irvine), Larry LaForge (The Right Stuff of Tahoe), Andrez Pelc (University of Quebec)
- **Reconfiguration architectures and algorithms**
  - Shuki Bruck (CalTech), Larry LaForge (The Right Stuff of Tahoe), John Hayes (University of Michigan), Charles Leiserson (MIT)

A Technology Roadmap (Rather, a *Starchart*) Identifies Inappropriate As Well As Appropriate Innovations

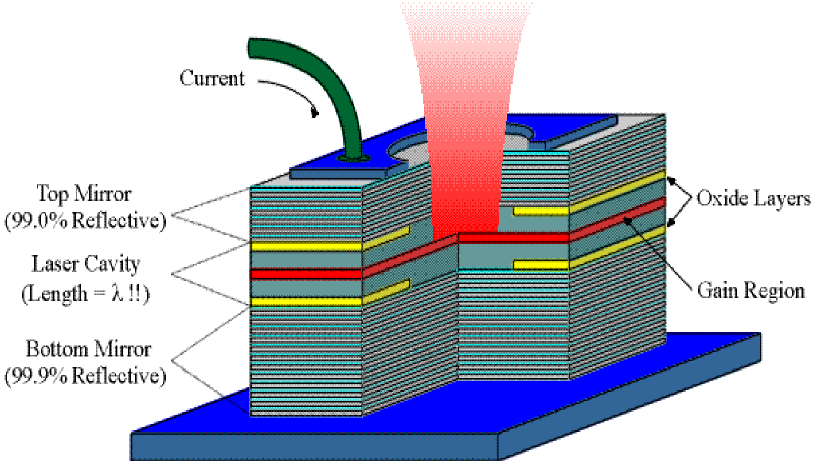
Not quite ready for a 200 year mission, 10^4 Mrad(Si):

- Contemporary flight processors (*e.g.* those aboard *Mars Pathfinder*, *Deep Space 1*)

Will take more than 40 years to be ready:

- Chemical computers (Hewlett Packard, will take more than 40 years to mature)
- Nano-robots that mechanically repair avionics (MIT)

Example: Technology Combined With Our Contributions



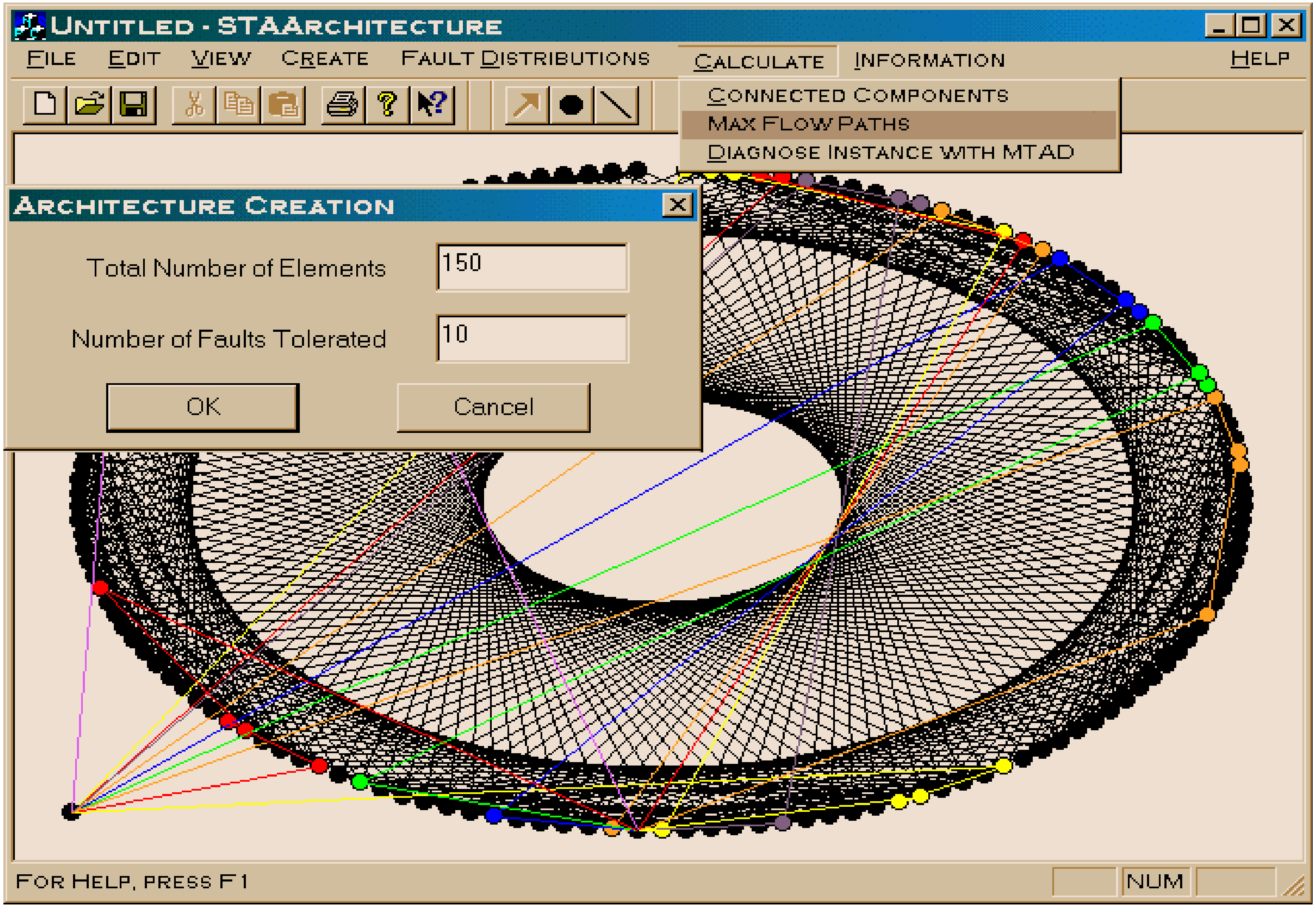
Classical hypercubes are <u>not</u> what we should be building.
Clique-based cubes <u>are</u> what we should be building.

Theorem 33. Denote by $\rho^{-}_{\text{Thm 6}}$ the lower bound on the radius of any quorum.

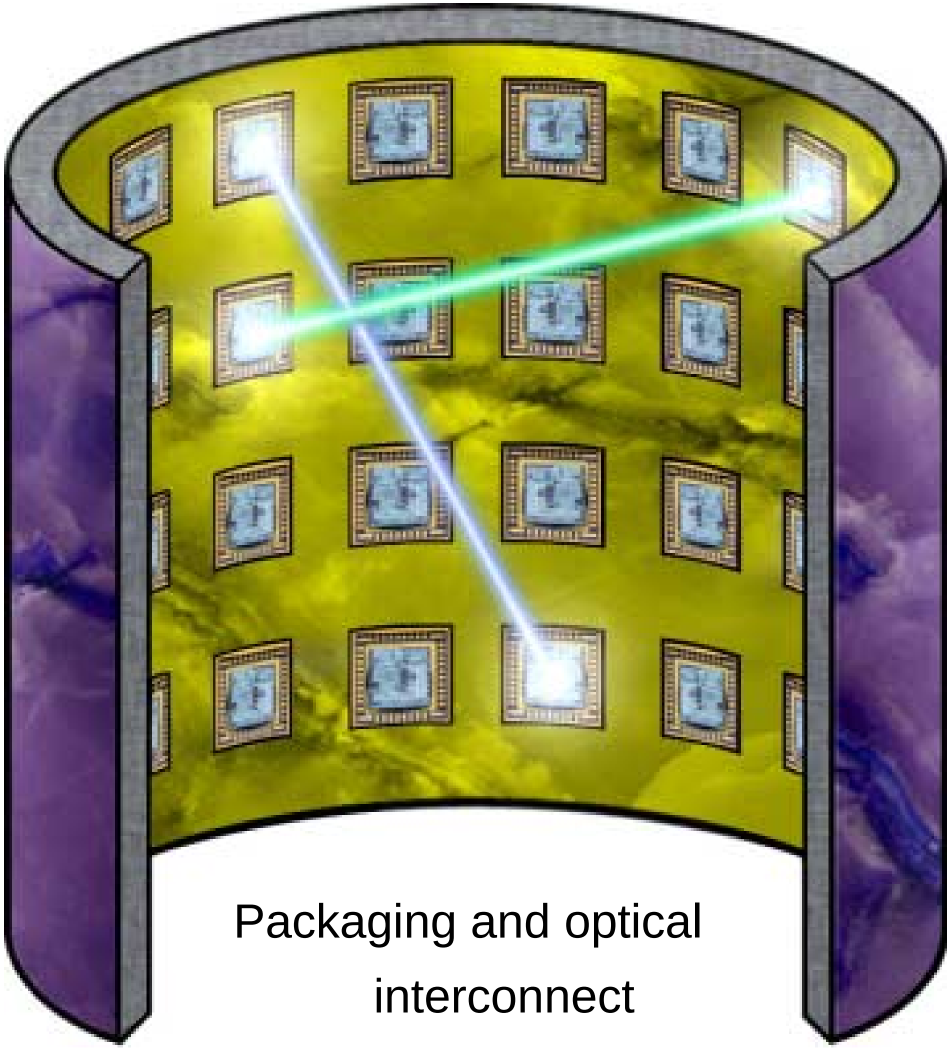
If $\rho^{-}_{m,j,d} = \log_j (n/m) + \lfloor m/2 \rfloor$ and $\rho^{+}_{m,j,d} = 1 + \log_j (n/m) + \lfloor m/2 \rfloor$ are the minimum *resp.* maximum radius of quorums of $K_{m \cdot j}{}^{d}$, then

$$\frac{\left[d + \left\lfloor \frac{m}{2} \right\rfloor\right][\ln(j-2) + \ln d]}{\ln m + d \ln j} \le \frac{\rho^{-}_{m,j,d}}{\rho^{-}_{\text{Thm 6}}} \le \frac{\rho^{+}_{m,j,d}}{\rho^{-}_{\text{Thm 6}}} \le \frac{\left[d + \left\lfloor \frac{m}{2} \right\rfloor + 1\right][\ln j + \ln d]}{\ln m + d \ln j - 1.4}$$

Research Tools Incorporate Mathematical Advances in Diagnosis and Configuration



The *Integration* of Advanced Modeling, Tools, and Technologies Will Enable Self-Healing Architectures and Algorithms for Autonomous Spacecraft



Packaging and optical interconnect reflecting graph recommended by STAARchitecture