Achieving Interstellar Capability

NASA Starlight
Breakthrough Starshot

The Path to Long Term Strategic Transformation

Philip Lubin
lubin@deepspace.ucsb.edu

→ www.deepspace.ucsb.edu/starlight (online photon prop calculator) ←
50 Technical papers – excellent for insomniacs
What Changed Recently

• Interstellar got real
• 2013 – UCSB DE papers published on planetary defense and interstellar missions
  – UCSB Press release on Feb 14, 2013 – one day before Chelyabinsk was hit
• Aug 2014 NASA NIAC Phase I proposal submitted – funded April 2015
  – Phased array DE + wafer scale (and other) SC
• April 2015 “Roadmap to Interstellar Flight” submitted to JBIS
• Oct 31, 2015 - 100 YSS in Santa Clara Oct 31, 2015 (thank you Mae)
  – Random “bump in” - mentioned our NASA program to Worden – sends to “friend”
• Nov 2015 Time magazine films “Interstellar” video at UCSB
• Early 2016 – anonymous private donor funding begins
• Jan 2016 – Breakthrough discussions of our NASA DE program start
• Feb 2016 – NASA 360 – “Going Interstellar” video released
• March 2016 – TVIW presentation of our NASA program – DE + low mass SC relativistic
  – Ongoing discussions with Breakthrough
• April 2016 Starshot announced → 1000x leverage (relative to NASA Phase I)
• May 2016 Congressional appropriation supports idea – NASA DE program mentioned
• May 2016 NASA Phase II announced
• NASA Starlight spawns – Breakthrough + three NASA NIAC’s so far
  – Standoff asteroid molecular composition analysis – Phase I and II
  – Lower power (same size) Starlight array – beamed ion engine propulsion – Phase I
  – 50 UCSB DE papers to date – see our website if you cannot sleep
Congressional Support
FY 2017 NASA Appropriation call for >0.1 c Interstellar Mission by 2069
Rep J. Culberson (R - Texas), Chair of Appropriations Committee
Science Mag – May 23, 2016

“U.S. lawmaker orders NASA to plan for trip to Alpha Centauri by 100th anniversary of moon landing“

“...Report mentions that the NASA Innovative Advanced Concepts (NIAC) program is already funding a study of “directed energy propulsion for wafer-sized spacecraft that in principle could achieve velocities exceeding 0.1c.”... (NASA Starlight)
More Planets than Stars

Proxima Centauri (M class) Planet Found

Proxima b – habitable zone
Aug 2016 - Pale Red Dot collaboration
(approx 1 planet/star from Kepler)
Nearby Stars - >150 with 21 ly

Star Distance vs Number

Distance (ly)

Star Number

0 20 40 60 80 100 120 140 160

0 4 8 12 16 20
Most Stars are M Class – $T \sim 3000-4000K$
NASA Starlight Program Goals

- Develop DE propulsion for high speed applications
- Enable relativistic flight for the first interstellar missions
- Enable extremely rapid interplanetary mission
- Enable beamed energy for ultra high $I_{sp}$ ion engines
- Enable beamed energy for numerous other applications

Chemistry CANNOT get us to relativistic flight
  - $I_{sp}$ little change in >80 years

Unlike chemistry photonics is exponential – 18 month

Requires basic physics and technology R&D
  - Steady stream of milestones as we progress
  - Program is both revolutionary and evolution
  - Not an ALL or NOTHING program
  - ENABLES Many other missions – not just interstellar
  - Program leverages large scale US commercial and DoD
Human Accelerated Objects

Highly Relativistic Electromagnetic Acceleration

The Technological Divide Directed Energy Acceleration

Highly Non-Relativistic Chemical Acceleration
**Why go anywhere?**

**Just Build a bigger telescope**

- **Why should we visit anything?**
  - All exploration is “remote sensing”
    - Just a question of “how remote”
    - We will not stop building telescopes
    - In fact → our system is a 1-10 km phased array telescope
    - Spot size @ 4 ly from 1 km @1μ → $10^8$ m ~ stellar disk

- **Example: 10 cm optic at 1 AU (40 min @ 0.2c)**
  - =250,000 x10 cm (Proxima Cent)→ 25km tel at Earth
  - 0.1 AU → 100 km resolution → 250km telescope at Earth
  - 0.01 AU (100 $R_E$) → 10 km resolution → 2500km telescope

- **Could launch a new mission every few min**
  - Battery storage option → ~1 mission/day
It’s a long way to the next star!

Log Scale below – where is Voyager?

Voyager ~ 17 km/s $\rightarrow$ $10^5$ yrs to Alpha Centauri (250K AU)
Why Any Mass Ejection Propulsion Will Not Work For Relativistic Propulsion – Except Antimatter

\[ T(\text{thrust}) = m v_{rel} = m g_{\text{Earth}} I_{sp} \]
\[ I_{sp} \text{ (specific impulse)} = v_{rel} / g_{\text{Earth}} \]

To get "lift off" from a gravity well with surface \( g_L \) we need \( T > m_i g_L \)

The exhaust power \( P_{exh} \) is:

\[ P_{exh} = m v_{rel}^2 / 2 = T v_{rel} / 2 \]
\[ T = 2 P_{exh} / v_{rel} = 2 P_{exh} / g_{\text{Earth}} I_{sp} \]

→ The thrust per unit power is: \( T / P_{exh} = 2 / v_{rel} = 2 / g_{\text{Earth}} I_{sp} \) (ion eng)

\[ v = v_{rel} \ln \left( \frac{m_i}{m_f} \right) = g_{\text{Earth}} I_{sp} \ln \left( \frac{m_i}{m_f} \right) \] (typ chem \( m_i / m_f \) ~ 20 - less for ion engine)

\[ \frac{m_i}{m_f} = e^{v/g_{\text{Earth}} I_{sp}} = e^{v/v_{rel}} \] (Typ Chemistry \( I_{sp} \) ~ 200s Solid - 400s Liquid)

Space X Falcon 9 (Merlin) (RP1 (kerosene)+LOX) \( I_{sp} \) ~ 348s (vacuum)

SLS, Saturn 5 - Shuttle Main Engines (not SRB's) \( I_{sp} \) ~ 452s (vacuum)
Speed and Mass Ratios with Mass Ejection Propulsion

All the mass in the universe cannot get One Proton to rel speed with chemistry

\[ \frac{mv_{esc}^2}{2} = \frac{GMm}{R} \]

\[ \rightarrow v_{esc} = \left[ \frac{2GM}{R} \right]^{1/2} = \sqrt{2}v_{orb} \]

Note if \( R = r_s = \frac{2GM}{c^2} \) \( \rightarrow v_{esc} = c \)

\[ v_{esc} = c \left[ \frac{r_s}{R} \right]^{1/2} \]

\[ r_s (Earth) \sim 8.87 mm \]

\[ R (Earth) \sim 6.37 \times 10^6 m \]

\[ \rightarrow v_{esc} \sim 3.73 \times 10^{-5} c \sim 11.2 km/s \]

Chemical propellants

\[ v_{rel} \sim 2 - 4 km/s (Solid - H_2O_2) \]

We just barely escape the Earth \( (e^3 \sim 20) \)
V2 1943 – Isp ~215 → SLS – 2017 – Isp~ 350-460(vac)
2x increase in performance metric (Isp)
Cost /thrust ~ flat to increasing
(Actually V2 was Alcohol-LOX – vs SLS LH-LOX)

1943 EINICAC – 500 FLOPS
→ 2017 Intel i9 Teraflop
>1 billion x performance increase
>1 trillion times less power/FLOP
>10 trillion time less cost/FLOP
>1000 trillion x less mass/FLOP
Photonics like Electronics is Exponential

Moore’s “Law” like development

Fiber Laser Power (CW) vs Year

Doubling time ~ 1.7 years (20 months)
Photonic Exponential Price Decrease

Need 15 more years \(\rightarrow\) integrated wafer scale DE

Yb Fiber amp cost "half" time \(\sim\) 18 months
Phased Array Laser Driver Makes it Possible
Analogous to Parallel Supercomputer
→ More elements = more power – free space combine
Low power per optical amplifier – already there
What about Nuclear Engines?

\[ E_{\text{exh}} = \frac{1}{2} m_{\text{exh}} c^2 \beta_{\text{rel}}^2 \rightarrow \beta_{\text{rel}} = \left(2 \frac{E_{\text{exh}}}{m_{\text{exh}} c^2}\right)^{1/2} \]

Define \( \varepsilon_{\text{exh}} \) as the ratio of the exhaust kinetic energy to the exhaust rest mass energy as

\[ \varepsilon_{\text{exh}} = \frac{E_{\text{exh}}}{m_{\text{exh}} c^2} = 1/2 \beta_{\text{rel}}^2 = 1/2 \left( g_{\text{Earth}} I_{\text{sp}} \right)^2 / c^2 \]

\( \varepsilon_{\text{exh}} \) is an upper limit on the engine conversion efficiency (compared to annihilation energy).

Here \( \beta_{\text{rel}} = \sqrt{2 \varepsilon_{\text{exh}}} \) and \( I_{\text{sp}} = v_{\text{rel}} / g_{\text{Earth}} = \frac{c}{g_{\text{Earth}}} \sqrt{2 \varepsilon_{\text{exh}}} \) For chemical engines \( \varepsilon_{\text{exh}}(\text{chem}) < 10^{-9} \)

Fission fragment engines \( \varepsilon_{\text{exh}}(\text{fission}) \lesssim 10^{-4} \)

For fusion engines \( \varepsilon_{\text{exh}}(\text{fusion}) \lesssim 10^{-3} \)

For nuclear thermal \( \varepsilon_{\text{exh}}(\text{nuclear thermal}) \lesssim 10^{-9} \)

\[ \frac{m_f}{m_i} = e^{-\beta \varepsilon_{\text{rel}}} = e^{-\beta (2 \varepsilon_{\text{exh}})^{1/2}} = 10^{-0.43 \beta (2 \varepsilon_{\text{exh}})^{-1/2}} = 10^{-0.43 \beta / \beta_{\text{rel}}} \]

As another example consider \( \beta = 0.2 \) (20% c) and "realistic" fusion propellants with

\( \varepsilon_{\text{exh}} \sim 2 \times 10^{-4} \sim 5 \text{MT/T thermonuclear weapon yield} \)

\[ \frac{m_f}{m_i} = 10^{-0.43 (2 \varepsilon_{\text{exh}})^{-1/2}} < 10^{-4.3} \sim 5 \times 10^{-5} \]

Mass ratio is very sensitive to the final speed. If we use \( \beta = 0.12 \) (12% c as in Project Daedalus) gives:

\[ \frac{m_f}{m_i} = 10^{-2.58} \sim 2.6 \times 10^{-3} \]

(Daedalus \( \varepsilon^- \) ICF - 46Mkg D/He-3 - mine from Jupiter! - \( v_{\text{rel}} \sim 10 \text{Mm/s} \))

Storage, confinement and reaction mass large \( \uparrow \) NOT feasible for \( v > 0.1 \text{c} \) missions

Daedalus Study
Antimatter?

LHC at CERN ~ 1 pg/yr @ 100 MW → 10^{11} years/gram

1 mw laser point produces >100x thrust LHC antimatter production → 10^{13} x power

DE Power and Equivalent Antimatter Production Rate Needed
Assumes Ideal DE Reflection and Perfect AME (combined with equal matter)

\[ F = \frac{2P}{c} = \frac{dE}{dt} / c = \frac{\dot{m} c^2}{c} \rightarrow m = P / c^2 \]

\[ E = \text{energy of matter annihilated into rel exhaust} \]
Important Points for Relativistic Missions

• Chemical propulsion (J/kg, $v_{rel}$) changed little
• Chemistry will get us to Mars but not Stars
• Ion engines will NOT get us to the stars
• Solar sails will not
• Nuclear thermal engines will not
• Fission engines (<0.1% conversion) will not
• Fusion engines (<1% conversion) will not
  – All serious studies show problems with large secondary mass required
• To get to relativistic speeds $\rightarrow$ need exhaust $\sim c$
• Only two known – antimatter and DE
  $\rightarrow$ DE only when you “leave home without it”
Engine Efficiency - $I_{sp}$ - Mass Fraction and Speed

![Graph showing the relationship between Engine Specific Impulse ($I_{sp}$), Engine Efficiency ($\varepsilon_{exh}$), and Mass Fraction ($m_i/m_f$). The graph demonstrates how different beta values affect the mass fraction at various efficiencies and specific impulse levels.](image-url)
Comparison of Propulsion Types – Mars
Chemical, Ion, Directed Energy \( (t \sim P^{-1/2} - m_{ref} << m_{sc}) \)
Humanity’s First Interstellar Missions will ride a beam of light

Laser is only “on” a few min per mission → hundreds per day
The nearest stars reached in 20 year flight time
Low mass spacecraft for interstellar

Speed vs Payload Mass and Sail Thickness
Optimized for Payload Mass = Sail Mass
10 km array size

- 100 GW - 1micron sail
- 70 GW - 1micron sail
- 100 GW - 0.1 micron sail
- 70 GW - 0.1micron sail

Graph showing speed (m/s) vs payload mass (kg) with different sail thickness and power levels.
What about photon propulsion to Mars?
Class 4 array assumed below

• 10 MT to Mars (Orion, Dragon)
  – Accel ~ 0.007 g
  – Time to 0.5 AU ~ 17 days (~half way)
  – Peak speed ~ 100 km/s
  – \( \rightarrow \) Time to Mars ~ 1 month

• 1 MT to Mars
  – Accel ~ 0.07 g, time to 0.5 AU ~ 5.6 days
  – Peak speed ~ 320 km/s
  – \( \rightarrow \) Time to Mars ~ 11 days

• 100 kg to Mars
  – Accel ~ 0.7 g, time to 0.5 AU ~ 1.8 days
  – Peak speed ~ 1000 km/s
  – \( \rightarrow \) Time to Mars ~ 3.5 days

• 10 kg to Mars – overnight delivery – 3000 km/s
• 1 kg to Mars – 8 hours – same day delivery! – Amazon?
Rapid Interplanetary Missions

Time and Speed to 1 AU – Mars (includes stopping) - 1 kg~8 hours
Moon – 1 kg in about an hour!

Ping-Pong Mode
Time and Peak Speed to 1 AU vs Payload Mass
Laser Array Size = 10km - Reflector size = 20m
Reflector thickness = 1μm (not sensitive)
Photonic Driven Speed vs Array Size & Aperture Flux

1g, 1, 100 kg (Not Just for wafer scale)
Low mass spacecraft for interstellar

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- 100 GW - 0.1 micron sail
- 70 GW - 0.1micron sail

Graph showing the relationship between speed (m/s) and payload mass (kg) with different power levels and sail thicknesses.
Recent UCSB Long Baseline Lab Results

2 Element Phased Array – Mach Zehnder
Custom FPGA Phase Lock Loop
Phase Noise - Amplitude Spectral Distribution

Critical system test - DUT=25 km SMF 28 fiber

Bottom Line – Phase Noise ASD is low at high freq – we can correct

This is good news

Coherent Beacon is Critical
Lab testing – Zero baseline - July 27

Phase locking data without a fiber spool

- Show locked and unlocked
- → Phase Locked ~ 1/1000 wave ←
- Unlocked ~ a full wave
Sept 2017 IQ Phase Lock Results

First Light for Interstellar Flight
Robust Lock over Kilometer Baselines

RMS is SNR limited – Expect better with new source
Extending to 25 km baseline

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Lock Duration (minutes)</th>
<th>RMS waves ((\lambda))</th>
</tr>
</thead>
<tbody>
<tr>
<td>No DUT</td>
<td>&gt; 5</td>
<td>0.00085</td>
</tr>
<tr>
<td>500 m PM</td>
<td>&gt; 5</td>
<td>0.01</td>
</tr>
<tr>
<td>790 m SMF28</td>
<td>&gt; 5</td>
<td>0.03</td>
</tr>
<tr>
<td>2.9 km SMF28</td>
<td>&gt; 5</td>
<td>0.1</td>
</tr>
</tbody>
</table>
Next Steps – 2D Phased Array with Beacon
UCSB 19 Element Test Array – Xmit/Rcv
Single Mode Fiber Feed Optics
UCSB Array on Hexapod
How Do We Phase $10^9$ Elements?

Possible solution in Nested Loop 
$n \log(n)$ Algorithm (like FFT)
The Starchip Wafersize (~ 2g so far)
To Boldly Go Where no Chip has Gone Before

A Spacecraft in your Pocket – Prototype for Interstellar
➡ Many more are coming – full wafer coming
Current Wafer Scale Spacecraft (WSS)
UCSB Nanofab DRIE Etching Si and Ti Wafers – $10^{12}$ transistors
SOI Etch stop – 2 micron membrane – hexcel back – 0.5g - 100 mm diam - hybridize
Future Ultra Thin Body Si on SOI
Path to Large Area Ultra low mass electronics?

Goal – push towards meter scale wafers
6 nm Si depth, sub 30 nm structures, 100 mm wafer + Kapton

IBM Yorktown 2013
Extremely Flexible Nanoscale Ultrathin Body Silicon Integrated Circuits on Plastic
D. Shahrjerdi* and S. Bedell IBM T. J. Watson Research Center, Yorktown Heights, NY
Imagine a 1m diam -1 g wafer (0.4μm)

- Currently – 14 nm Si processing – Si electronics and photonics
- 5 nm processing by ~ 2020
- 3D coming soon
- TODAY density ~ 2.5x10^7 devices/mm^2
- TODAY → 25 trillion/m^2 → 15,000 i7 processor
- TODAY→0.5m wafer processing
- TODAY→500 watt_{elec}/m^2 PV(multi junc) @1AU
- FUTURE→3D (30 nm/layer) + 5nm→3 Peta dev/m^2
- FUTURE→2 million i7/wafer → largest super comp
- FUTURE→1000 watt_{elec}/m^2 PV(multi junc) @1AU?
- Use wafer for imaging directly – no sail?
- Use Wafer for sail – ENTIRE SYSTEM is a wafer → NO SAIL
- Photonic crystal reflector on one side – integrated e^- + γ
Reflector Material Work
Theoretical and Experimental

Material Strength (indep of P) (+d, ρ, λ) set a Fundamental Speed Limit – assumes $m_{\text{ref}} = m_0$

Spherical Shell Beta vs Material Strength
Circular array - $\alpha=1.22$, Safety factor = 1
$\lambda=1.06$ microns

$\beta_0 = \left( \frac{dS_y}{2 \rho c^2 \lambda \alpha_d s} \right)^{1/2}$

Graphical representation showing the relationship between $\beta_0$, $S_u/\rho$, and material properties.
Test Chamber with 500 nm polymer film

$S_u \sim 230 \text{ MPa}$
New Phased Array Work

UCSB Long Coherence Length Array Development

- **Seed laser**
  - 10mW
  - 1064nm

- **10-way Splitter + Phase modulators**

- **Amplifier**
  - 10x
  - 10W (100W total)

- **Beam combination**
  - Fiber
  - Freespace

• General phased array architecture
  - 1 common seed laser provides a stable reference phase for each output element
  - Phase modulators before each amplifier are rapidly adjusted to give coherent combination of each element despite varying path lengths in each element (due to atmospheric fluctuations, target motion, etc)
  - After amplification each element is combined spatially in a close packed array to allow both power and aperture scaling
Narrow Bandwidth Fiber Amplifier Development

10 element System

Goal is 10 element phased array with 10 watt/channel <10 KHz bandwidth (30 km coherence length)
Interstellar Communications a Challenge

Spacecraft Laser Comm DL Photon Rate
\[ P_{\text{tran}} = 1 \text{ w}, \ A_{\text{tran}} x A_{\text{rec}} = 1 \text{ m}^2 \cdot \text{km}^2 \]

Received Photon Rate (ph/s)

<table>
<thead>
<tr>
<th>Distance (ly)</th>
<th>N at 0.5 micron</th>
<th>N at 1 micron</th>
<th>N at 1.5 micron</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10</td>
<td></td>
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</tr>
</tbody>
</table>
Extraterrestrial Backgrounds

Zodi (45 deg ecliptic), CIB, CMB

Zodi dominates – You MUST understand backgrounds

1-30μ IR science out of solar system → CIB is $10^2 - 10^4$ lower than Zodi
→ Vastly better for IR surveys → $10^4 - 10^8$ x faster mapping
Terrestrial and Extraterrestrial Combined Backgrounds including optics
Zodiacal + Non LTE atmosphere dominates
Compare Signal to Backgrounds (SBR)
Signal to Host Star Background Ratio
Proxima b Mission

$P_{\text{tran}}=1 \, \text{w, } A_{\text{tran}}x A_{\text{rec}}=1 \, \text{m}^2\times \text{km}^2$

![Graph showing the signal to background ratio for different distances and particle sizes.](image)

- 0.1 micron (space)
- 1.0 micron
- 0.2 micron (space)
- 1.5 micron
- 0.3 micron
- 0.5 micron

Proxima b distance
SBR = 1
Longer term - Launch Array Placement

• For many reasons “space is the place”
• ->For testing and preliminary missions – ground
  – Atmosphere is ~ 95% transparent at 1.06 microns
  – Assuming good high altitude site (~4 km)
  – Ground is vastly cheaper to begin testing
  – Ground allows us to test all of the essential elements
• BUT – even if we can overcome the atmosphere
  – Still want space deployment for mission flexibility
  – Larger mass missions require longer “laser on” time
  – Wafer scale ~ 100 sec “laser on” per shot (~1000/day)
  – BUT “laser time on” ~ m^{2/3} → large m → large time
    • Large laser on time NOT compatible with ground
• Space options – LEO, GEO, Sun sync, Lagrange, Moon
  – ISS testing would be a very useful option – ISS – EOL?
The Moon – A Better Place - Eventually

Photon or Ablative Launch or Hybrid

Back side for policy mitigation

High mass missions “require” space DE deployment – illumination time

• Back side for policy mitigation

• Slow rotation advantageous - ~ 1 month

• Possible long term solution – $g \approx 1.6 \text{ m/s}^2$
Upcoming Work

- Work more on long baseline phase noise
- Work on beacon mode for free space phasing
- Work on ~ 10-20 element array – dense + sparse tests
- Work on phase feedback control algorithms
- Attempt atmospheric perturbation testing
- Attempt beam pattern tests on small arrays
- Near field simulations with perturbations
- Build more wafer scale spacecraft generations
- Continue outreach to public – more talks (60 so far)
- More papers! – 50 DE papers to date
- Seek additional funding to expand program
The path forward – Photonic Integration
Integrated Wafer Scale Photonics for DE Side

(John Bowers - ECE)

Array of vertical couplers for coupling to an array of optical fibers

Array of Phase Shifters
Ground based atmos transmission
Testing prototypes – 4 Km
UC Santa Barbara White Mountain Site

Altitude
- 4 Km
- Sea Level

Transmission vs Wavelength (μm)
Additional Applications

→ ONE Hammer for Many Nails

• Kilometer Telescope
• Long range laser comm
• Power Beaming
  – To high Isp ion engines
• Asteroid Detector, Deflector, Capture,
• Asteroid Mining
• Remote Composition Analysis
• Interplanetary travel
• Space Debris Mitigation
Next R&D stages

- NASA + Private donor has allowed first steps
- Breakthrough Foundation Starshot
- Rational development program at modest cost
- Program has captured the public attention
- Inspires the next generation to dream
- Program has come to Congressional interest
  - Rep Culberson ➔ interstellar by 2069 (52 years to go)
- Engage additional academic entities such as AIM Photonics
- Leverages many areas (NASA, DoD, Industry...)
- Pushes the boundary far beyond the SOA
- Alliances between public and private sector feasible
  - Breakthrough as good example of private engagement
- US should lead due to strategic nature
We are developing the capability to test whether terrestrial life, as we know it, can exist in interstellar space by preparing small life forms – C. elegans and rad resistant Tardigrades - which are ideal candidates to be our first interstellar travellers. They will be asleep during the cruise phase and awakened at various points along the way. “Real Passengers”

Nematode: C. elegans
Tardigrade: H. dujardini

See www.deepspace.ucsb.edu/et
ISM Boosted Bombardment Radiation
Carbon Front Edge Example

Radiation dose rate vs $dE/dx$ and $\beta$ - Carbon

Proton $dE/dx$ - Carbon - Electronic and Nuclear LET

Radiation absorbed rate (Rad/yr) vs $dE/dx$ (MeV-cm$^2$/mg)

Kinetic Energy (MeV) vs $dE/dx$ in C - Electronic and Nuclear
What Are THE major challenges?

• Clearly there are many technical challenges
• This is a long term humanity changing program
• Exponential technology → radical changes come
  – You expect this in your everyday life – electronics
  – You expect this in photonics (perhaps less thought)
• You DO NOT expect radical changes in propulsion
  – At least not chemical (10% Isp increase is a great year)
  – 10% in electronics/photonics is a disastrous year
• The biggest challenge: NASA, US Gov’t does NOT plan 30-50 years ahead in space. Perhaps public+private alliance?
• Need new division of NASA or new agency whose mandate is interstellar flight
• How do we maintain the drive towards this goal?
• Need youth to vigorously engage
• No previous exponential propulsion technology
Conclusions

• DE a path forward to propulsion transformation
• Path to relativistic flight + LARGE mission space
  – → Enabling element for MANY planetary missions too
• Only known way to interstellar flight
• Will heavily leverage photonics and electronics
• Leverages exponential growth and industry/DoD
• Next 5 years critical- basic understanding tall polls
• Path to the full system requires photonic integration
• Many challenges both technical and economic
• Requires a dedicated program over a long period
• → The US should lead in this transformation←
Implications for SETI
The Search for Directed Intelligence - arxiv.org/abs/1604.0210

• Kepler has shown us ~ planet/star
• Our galaxy has ~ 100 billion stars
• The universe has ~ 100 billion galaxies
• ~ $10^{22}$ planets or more in universe
• If we have DE technology what are the implications
• See our paper on SETI – for nerds!
  – www.deepspace.ucsb.edu/projects/implications-of-directed-energy-for-seti
• ➔ Bottom line – We are visible across the universe
• Think about what this means.
Blind beacon, Blind SDI Search - Single civilization

0.1 m 3 yr search on Earth - Bottom line - unity detection probability to very large distances 0.1 Mpc

Detection Probability

SNR = 10, Class 4 civilization, 0.1 m on Earth, Full Sky FOV
NR=1, \( i_{DC} = 0.01 \), QE=0.8, BW=1 nm, Background=100

\( t = 3 \) years, Int time=1000 sec

\( H_0 = 70, w_0 = -1, w_a = 0 \)