Navigating to the Stars
Humanity’s First Interstellar Missions

*NASA Starlight*

*Breakthrough Starshot*

The Path to Long Term Strategic Transformation

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→ [www.deepspace.ucsb.edu/starlight](http://www.deepspace.ucsb.edu/starlight) (online photon prop calculator)←

50 Technical papers – excellent for insomniacs


Emmett and Gladys W. Technology Fund
U.S. Navy Brings Back Navigation By The Stars For Officers
Feb 2016

Someday: Interplanetary GPS and then far future Interstellar GPS
What Changed Recently

• 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
• 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 within 21 ly
Most Stars are M Class – T~ 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 @1\(\mu\mbox{m} \rightarrow 10^8\mbox{m} \sim \mbox{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 → $10^5$ yrs to Alpha Centauri (250K AU)
Why Any Mass Ejection Propulsion Will Not Work
For Relativistic Propulsion – Except Antimatter

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

\[ I_{sp} \text{ (specific impulse)} = \frac{v_{rel}}{g_{Earth}} \]

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:

\[ P_{exh} = \frac{m v_{rel}^2}{2} = T v_{rel} / 2 \]

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

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

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

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

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

SLS, Saturn 5 - Shuttle Main Engines (not SRB's) \( I_{sp} \sim 452\text{s (vacuum)} \)
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 \( R=r_s = \frac{2GM}{c^2} \) \( \rightarrow v_{esc} = c \)

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

\( r_s(\text{Earth}) \sim 8.87\text{mm} \)

\( R(\text{Earth}) \sim 6.37 \times 10^6 \text{m} \)

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

Chemical propellants

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

We just barely escape the Earth \( (e^3 \sim 20) \)
75 years of Propulsion and Computing

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 EINiAC – 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)
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

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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?

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

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

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

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

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

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

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

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

\[ m_f = e^{-\beta f / \beta_{\text{rel}}} = e^{-\beta (2 \varepsilon_{\text{exh}})^{-1/2}} = 10^{-0.43 \beta \varepsilon_{\text{exh}}} (\text{this kills nuclear}) \]

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

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

\[ m_f = 10^{-0.43 \varepsilon_{\text{exh}}} < 10^{-4.3} \sim 5 \times 10^{-5} \]

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

\[ m_f = 10^{-2.58} \sim 2.6 \times 10^{-3} \text{ (Daedalus e\textsuperscript{-} ICF - 46Mkg D/He-3 - mine from Jupiter! - } v_{\text{rel}} \sim 10\text{Mm/s)} \]

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

LHC at CERN ~ 1 pg/yr @ 100 MW \( \rightarrow \) \( 10^{11} \) years/gram

1 mw laser point produces >100x thrust LHC antimatter production \( \rightarrow \) \( 10^{13} \) x power

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

\[
F = 2P / c = dE / dt / c = (2m c^2) / c \rightarrow m = P / c^2
\]

\( E \) = 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 → need exhaust ~ c
• Only two known – antimatter and DE
  → DE only when you “leave home without it”
Comparison of Propulsion Types – Mars
Chemical, Ion, Directed Energy \( (t \sim P^{-1/2} - m_{\text{ref}} \ll m_{\text{sc}}) \)
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 the relationship between speed (m/s) and payload mass (kg) for different power levels and sail thicknesses.
What about photon propulsion to Mars?
Class 4 array assumed below

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

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

• **100 kg to Mars**
  – Accel \( \sim 0.7 \) g, time to 0.5 AU \( \sim 1.8 \) days
  – Peak speed \( \sim 1000 \) 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)
Recent UCSB Long Baseline Lab Results
2 Element Phased Array – Mach Zehnder
Custom FPGA Phase Lock Loop
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>
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)

- $= \text{Phase Modulator}$
- $= 2\times2$ Splitter
- $= \text{Photodetector}$

![Diagram showing the phase modulator, 2x2 splitter, and photodetector connections.]

![Graphs showing the relationship between the number of stages, m, and the branching number, N, and the convergence time, $T_{\text{con}}$, and the branching number, N.]

- $Y$-axis: Number of stages, $m$
- $X$-axis: Branching number, $N$
- $Y$-axis: Convergence time, $T_{\text{con}}$
- $X$-axis: Branching number, $N$
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

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

- 10 km array
- 3 km array
- 1 km array
- 0.1 km array
- Mylar 234 MPa
- Gorilla Glass 800 MPa
- Graphene 131 GPa

$S_u / \rho$ - Ultimate strength / density (MPa/kg/m$^3$ = MJ/kg)
Test Chamber with 500 nm polymer film

$S_u \sim 230 \text{ MPa}$
Interstellar Communications

Spacecraft Laser Comm DL Photon and Bit Rate

$\varepsilon_1 = 1$

Rec Photon Rate ($ph/s$) - $P_{\text{tran}} A_{\text{rec}} = 1w-m^2-km^2$

$N_{\nu}(ph/s) = 1.40 \times 10^4 \varepsilon_1 P_{\text{tran}}(w) \left[ \frac{d_{\text{rec}}(km)}{D_{\text{tran}}(m)} \right]^2 \left[ \frac{\lambda(\mu m)}{L(ly)} \right]^2$

$R_{\nu}(bits/s) = BPP \times N_{\nu}(ph/s)$

PPM Encoded Average Rec Bit Rate (bps)

$P_{\text{ave}} = 10^m, D_{\text{tran}} = 10cm, \text{PAR} = 10^3, BPP = \log_2(\text{PAR}) \approx 10$

$P_{\text{tran}} A_{\text{rec}} = 10^3 \times 10^{-4} w-m^2-km^2$

Distance (ly)
Signal to Host Star Background Ratio
Proxima b Mission

\[ P_{\text{tran}} = 1 \text{ w, } A_{\text{tran}} \times A_{\text{rec}} = 1 \text{ m}^2 \times \text{km}^2 \]
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~1.6 m/s²
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

Photonics Chip
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
Minimum System Cost vs Speed

$\varepsilon_r = 1$, $\varepsilon_{beam} = 1$, $\alpha_d = 1.22$, $\rho = 1$ g/cc, $\lambda = 1\mu$, $\xi = \pi/4$, $m_o = 1$ g

$$C_T(\$) = 1.5a_i P_{optical} = 3a_i \xi d^2 = 1.66 \times 10^{11} \rho_o^{4/3} a_2^{1/3} \left[ \frac{a_1}{\varepsilon_{beam}} \right]^{2/3} \left[ \lambda(\mu m) \sqrt{h(\mu m) \rho (g/cc) m_0 (g)} \right]^{2/3}$$

Total System Cost $C_T (10^9 \$)$

- Cost - $a_1 = 10\$/w $a_2 = 10000\$/m^2$
- Cost - $a_1 = 1\$/w $a_2 = 1000\$/m^2$
- Cost - $a_1 = 0.1\$/w $a_2 = 1000\$/m^2$
- Cost - $a_1 = 0.1\$/w $a_2 = 100\$/m^2$
Next R&D stages

• NASA + Private donor has allowed first steps
• Emmett and Gladys W. Technology Fund
• 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 - 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
ISM Boosted Bombardment Radiation
Carbon Front Edge Example
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
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
- $\Rightarrow$ 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=1nm, Background=100

\( t=3 \) years, \( \text{Int time}=1000 \) sec
\( H_0=70, w_0=-1, w_a=0 \)

![Graph showing detection probability versus luminosity distance and redshift](image)