

Report to the Astro2020 Panel on Enabling Foundation for Research

D. Spergel, chair

Peter Gorham, Univ. of Hawaii at Manoa
For the NASA Balloon Program Analysis Group

Chair

Peter Gorham Univ. of Hawaii

Technology:

Chris Walker, Univ. of Arizona

Astrophysics:

William Jones, Princeton;

Carloyn Kierans, UC Berkeley;

Abigail Vieregg, Univ. of Chicago

Earth Science:

James Anderson, Harvard

Planetary Science:

Eliot Young, Southwest Research Inst. Boulder;

Supriya Chakrabarti, Univ. Mass. Lowell

Solar/Heliophysics:

Robyn Millan, Dartmouth;

Pietro Bernasconi, Johns Hopkins APL

Education/Public Outreach:

T. Gregory Guzik, LSU

NASA Space Technology Mission Directorate (STMD):

Robert L. Yang, NASA HQ

Ex Officio:

Thomas Hams, NASA HQ

Deborah Fairbrother, Balloon Program Office

Vladimir Papitashvili, NSF

John Mitchell, Goddard

Request from Panel

- What are the new scientific opportunities enabled for astrophysics by your platform? (response: Gorham)
- Discuss the role of the platform in technology development and training. (response: Kierans)
- What are the challenges in exploiting the platform's capabilities? (response: Gorham)
- Are we training a diverse set of scientists and engineers? (response: Kierans)

Scientific opportunities enabled by balloons

- General categories of enabled science
 1. Astrophysics in electromagnetic spectral bands not observable from ground or piloted aircraft such as SOFIA
 - Balloon altitudes up to 40+ km
 - Near vacuum conditions, negligible astronomical seeing
 2. Astrophysics requiring access to primary cosmic particles -- electrons, positrons, high-energy photons, nuclei/anti-nuclei-- which are absorbed in the atmosphere
 - Cosmic ray detectors with several m² areas
 - X-ray and γ -ray detectors, telescopes, polarimeters
 - Low-energy cosmic ray detectors, searching for dark matter signatures

Enabled opportunities, cont.

- General categories, cont.
 3. Astrophysics enabled by looking back at Earth as a target for cosmic particles (neutrinos & cosmic rays)
 - Stratospheric platform sees several million km² of Earth's surface: ice, ocean, atmosphere
 4. Exploration of new techniques, validation of new instruments, both of which can result in candidate spacecraft instruments
 - Examples: infrared interferometry; γ -ray polarimetry; a long list of cosmic-microwave-background instruments

Enabled opportunities, cont.

- **Balloon missions complement space-based missions**
 - Low cost and rapid development cycle (eg. Class D NASA missions), with relaxed launch requirements – no vibration!
 - Allows for rapid response to new phenomena
 - Can develop survey- or target-specific instruments, rather than general observatory-class instruments, with up to 60+ day continuous observation
- **Balloon missions can develop purpose-built instruments, optimized for focused, high-impact science**
 - Facility- or observatory-class instruments are constrained by design drivers – they must serve a wide community and scientific scope

Ultra-long duration ballooning



- **Super-pressure balloons vs. Zero-pressure balloons:**
 - SPBs have stable altitudes at night – crucial to astrophysics in UV, visible, and near IR.
 - Zero-pressure balloons still provide full capabilities for Antarctic flights in full sunlight, and for engineering & technology flights
- **SPBs enable ultra-long duration flights in mid-latitudes, providing access to astrophysical sources and dark time not possible from Antarctica**
- **100-day super-pressure balloon flight (goal):**
 - will provide up to 1000 hours of dark time observing,
 - equivalent to about 1/3 of the total on-target time allocated in an HST cycle across its entire portfolio of science programs.

Unique opportunities afforded by LDB program in Antarctica

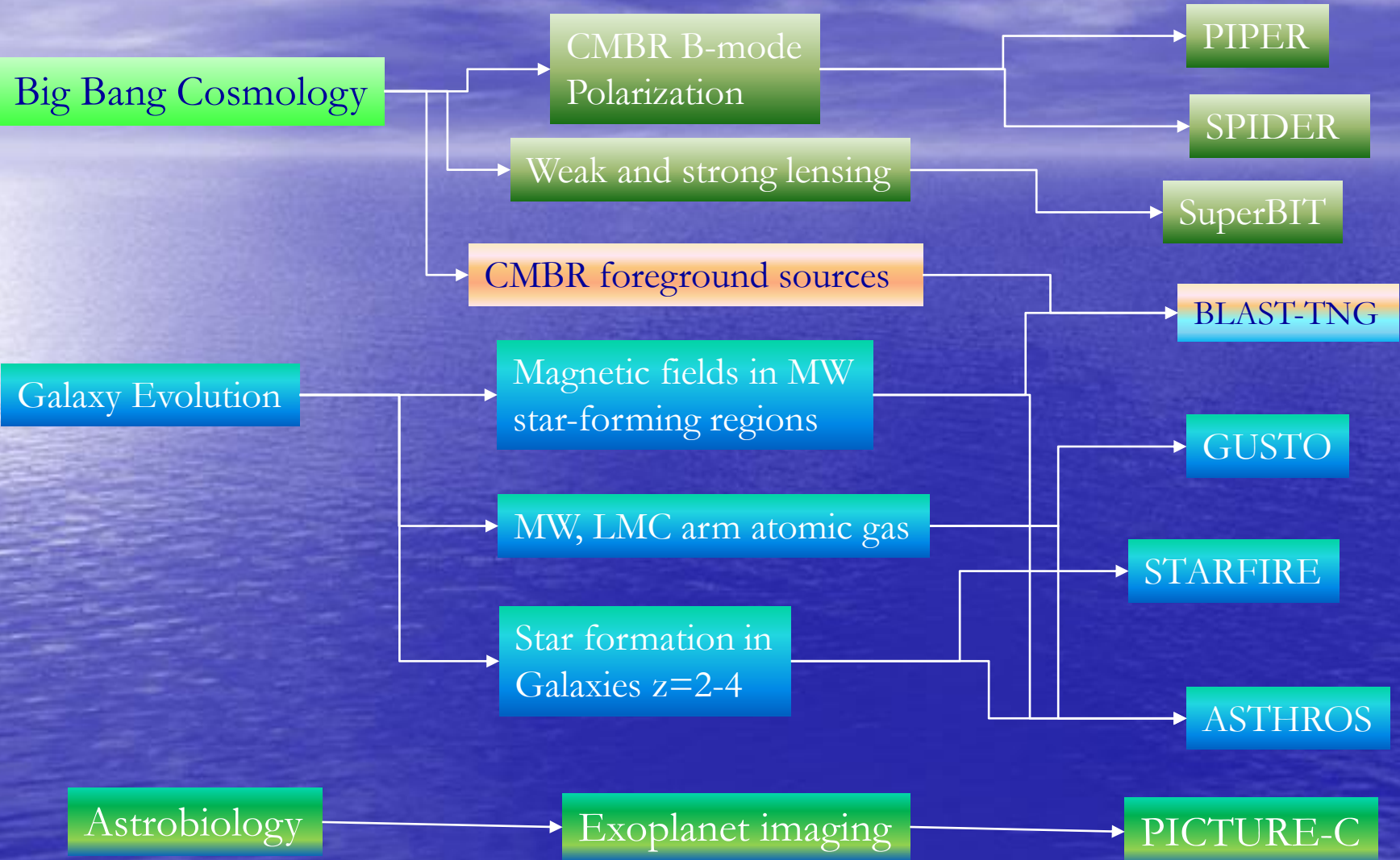
- Rigidity cutoff for long-duration balloon flights from Antarctica gives an order of magnitude higher geomagnetic efficiency compared to LEO for low-energy cosmic rays
 - **Important window from 0.1 to 10 GeV/c for anti-matter measurements with unique sensitivity to potential dark matter signatures**
- **Antarctic ice is the target of choice for high-energy neutrino observations.**
 - LEO space-based platform could see more ice, but energy threshold is too high at orbital distances
 - **→ Stratospheric platforms are close to optimal for sensitivity**

Astrophysics Balloon Missions 2020⁺⁺ (see supplement)

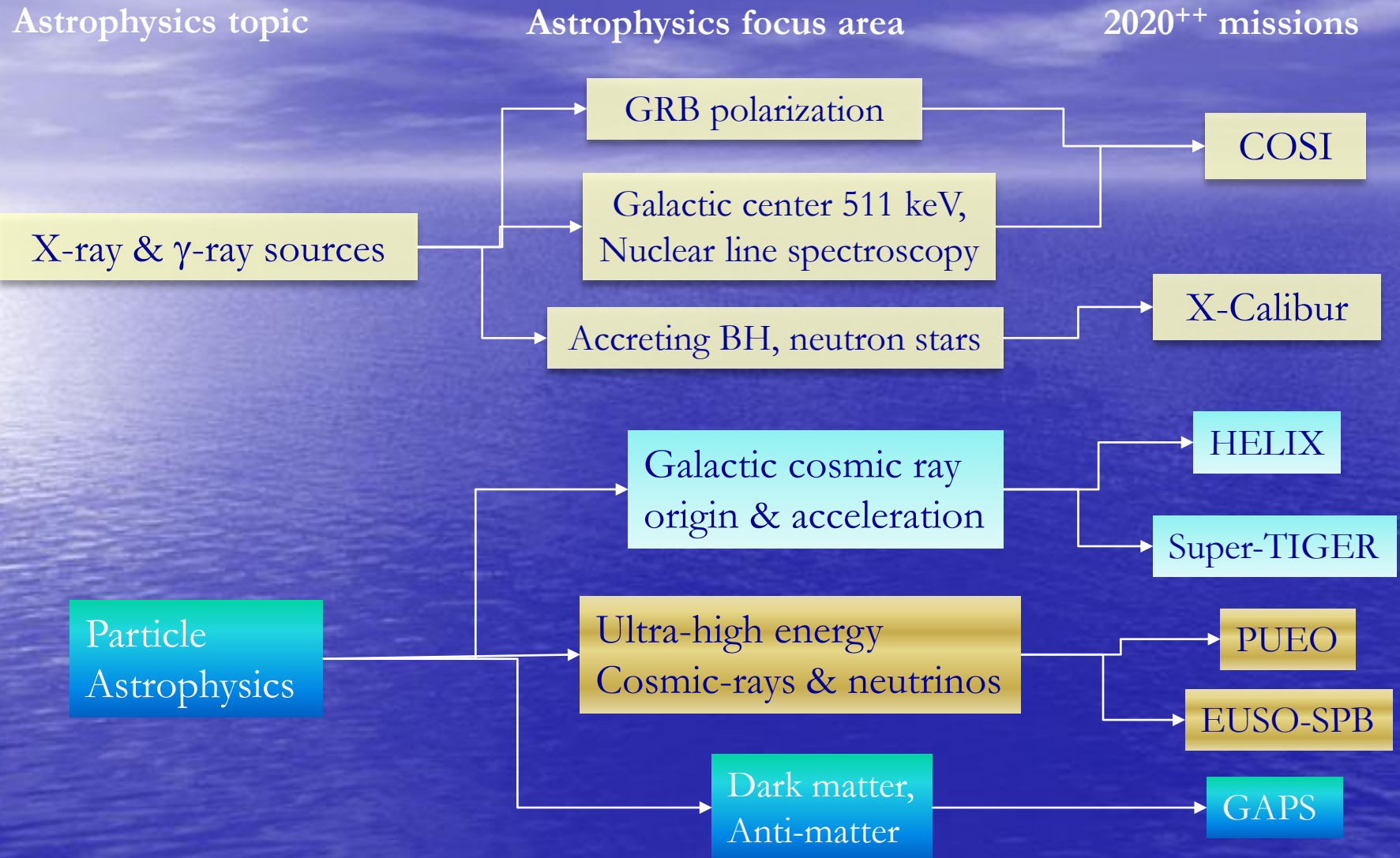
Astrophysics topic

Astrophysics focus area

2020++ Missions



Astrophysics Balloon Missions 2020⁺⁺ (see supplement)



Challenges in exploiting balloons

1. Antarctic program challenges:

- a) Lack of available NSF aircraft resources restricts flight duration & limits science return.

Example: 2016-2017 season, three payloads aloft at earliest ever dates, but NSF required cutdown a month before vortex broke up

→ Balloon Program needs its own aircraft for payload recovery

- b) Number of payloads using cryogenics continues to increase; NASA pays exorbitant costs for LHe in Australia. A LHe plant would pay for itself in 3-4 seasons.

→ Balloon Program needs LHe cryogen plant for Antarctic use

- c) Three large payloads can be launched during the Antarctic season; only 2 large payload high-bays are available

→ Balloon Program needs a third payload integration building

Challenges in exploiting balloons

2. General program challenges

- a) Excessive travel and short staffing is now an issue for CSBF with new (and important!) Wanaka, NZ, SPB launch site

→ CSBF needs an increase in experienced staff and engineers to support the increased field operations required by SPB

- b) Super-pressure balloon lift capacity for altitude severely lags that of zero-pressure balloons

→ CSBF Support should be expanded to qualify new SPB with even larger lift capacity, with a goal to match the capabilities of zero-pressure balloons (see supplement)

- This will enable larger and more capable mid-latitude payloads needing high and stable altitudes

Supplemental information

- Acronym dictionary
- UV, optical, IR, THz atmospheric transmission
- Balloon altitude vs. payload mass for NASA qualified balloons
- Long and Ultra-long duration ballooning
- ULDB details
- “Snapshot” survey of NASA balloon payloads for coming decade
- Examples of how Balloon missions have contributed in essential ways to scientific spacecraft missions.

Acronym dictionary

ANITA: Antarctic impulsive Transient Antenna

ASTHROS: Astrophysics Stratospheric
Telescope for High Spectral Resolution
Observations at Submillimeter-wavelengths

BLAST-TNG: Balloon Large Aperture
Submillimeter Telescope – The Next Generation

CMB: Cosmic Microwave Background

COSI: Compton Spectrometer & Imager

CR: Cosmic-ray

CSBF: Columbia Scientific Balloon Facility

FIR: Far infrared

GAPS: General Anti-Particle Spectrometer

GUSTO: Galactic/Extragalactic ULDB
Spectroscopic THz Observatory

HELIX: High Energy Light Isotope Experiment

IR: Infrared

LDB: Long Duration Ballooning (NASA
Antarctic Ballooning program)

LEO: Low Earth Orbit

NZ: New Zealand

PICTURE-C: Planetary Imaging Concept
Testbed Using a Recoverable Experiment –
Coronagraph

PIPER: Primordial Inflation Polarization
Explorer

PUEO: Payload for ultra-high energy
observations

SPIDER: proper name, not acronym

SPB: Super-pressure balloon

STARFIRE:

Super-BIT: Super Balloon-borne Imaging
Telescope

THz: TeraHertz

TIGER: Trans-Iron Galactic Element Recorder

UHE: Ultra-high energy

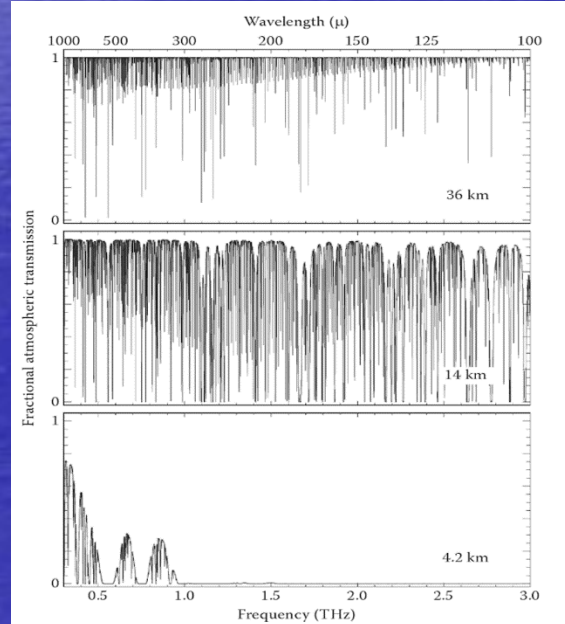
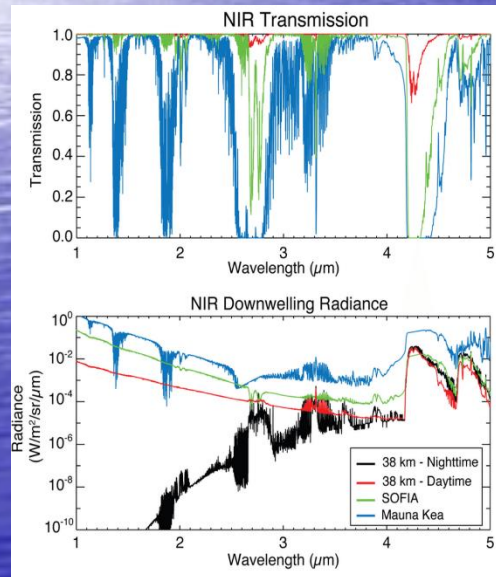
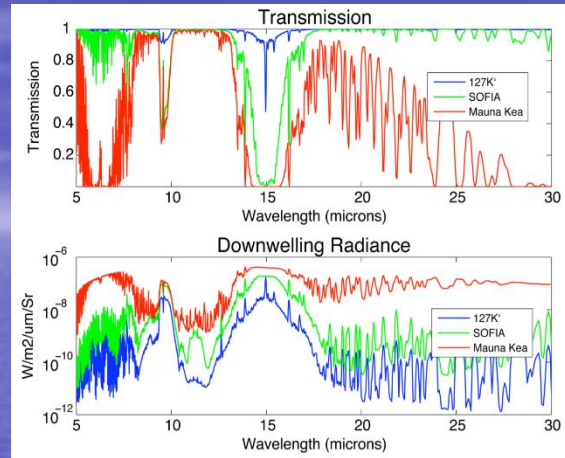
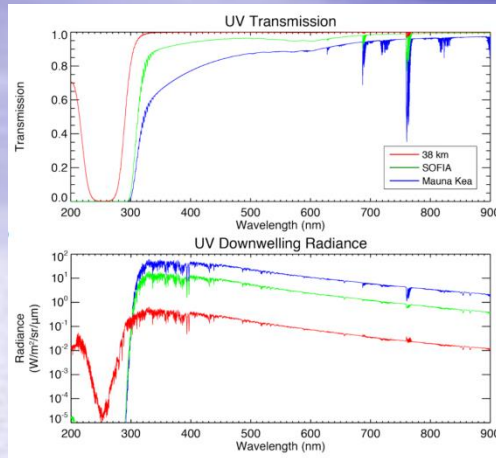
ULDB: Ultra-long duration balloon(ing)

UV: ultra-violet

XCalibur:

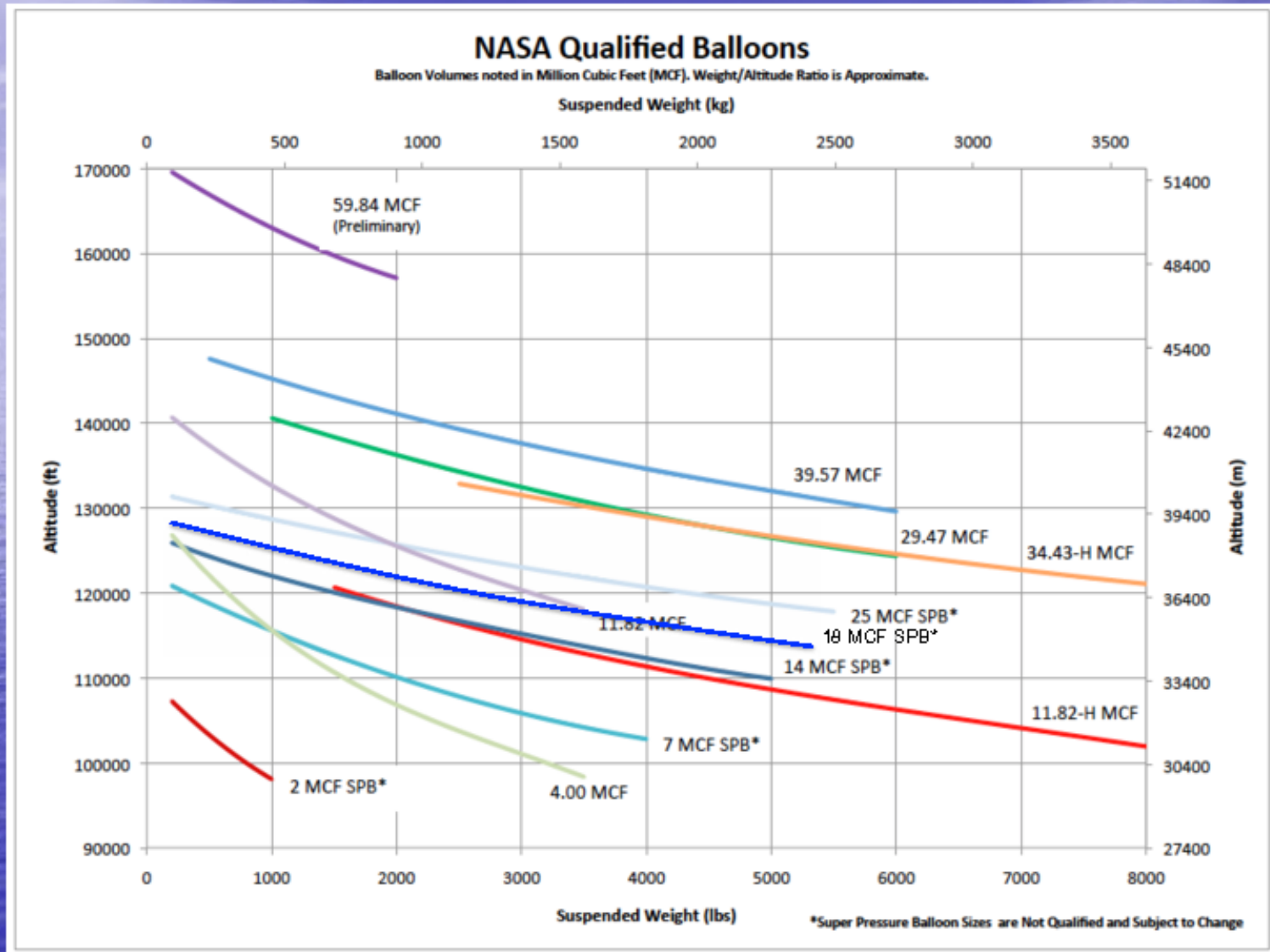
ZPB: Zero-pressure balloon

UV, optical, IR, THz, mm Atmosphere

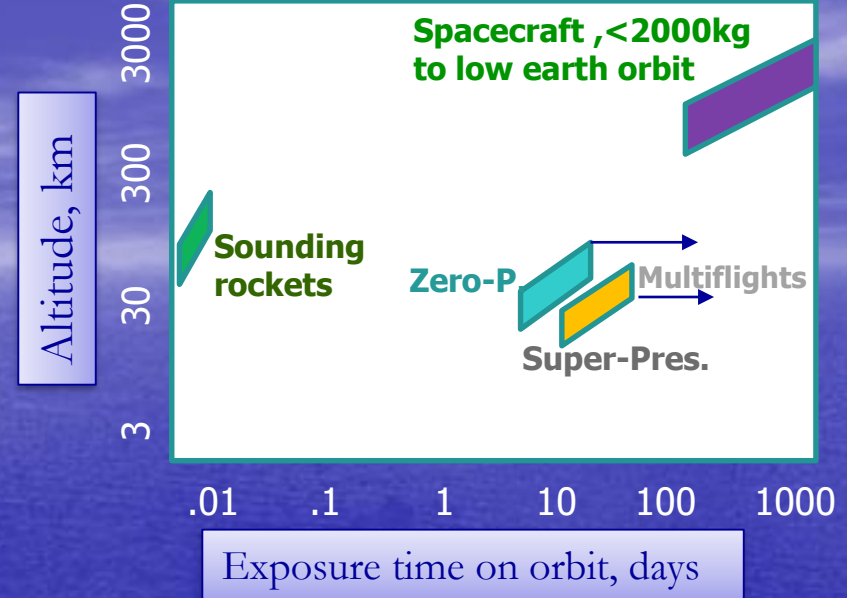
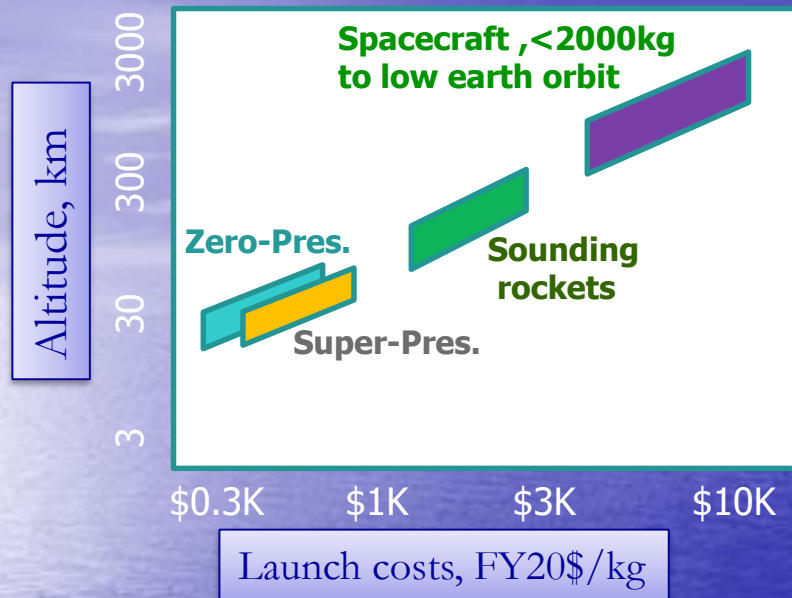


- Balloons have the capacity to loft up to 3 meter class telescopes above the atmosphere
- Near-space quality transmissivity, very low downwelling, diffraction-limited imaging
- → low-cost, spacecraft-level astrophysics opportunities over vast spectral window

Balloons: altitude vs. payload mass



Long- and Ultra-Long-Duration Ballooning (LDB/ULDB)



- LDB/ULDB: NASA's lowest cost access to near space
 - Above 99.3% of atmosphere, 99.99% of water vapor
 - spacecraft-scale payloads (up to 2700 kg)
 - exposures comparable to short-duration spacecraft (~60 days demonstrated)
 - **recoverable & re-usable payloads: increased exposure at low cost**
- Rapid response to new phenomena (new payloads can launch within 3 years)
- Real-environment validation for spacecraft instruments
- Training ground for next generation of scientists, engineers & NASA PIs

Ultra-Long-Duration Ballooning (ULDB)

Design goals:

-- Suspended* mass:

- 2700 kg to 110kft (soon)
 - Above 99.3% of atmosphere, >99.99% of water vapor
- 1400 kg to 125kft (5 yr goal)

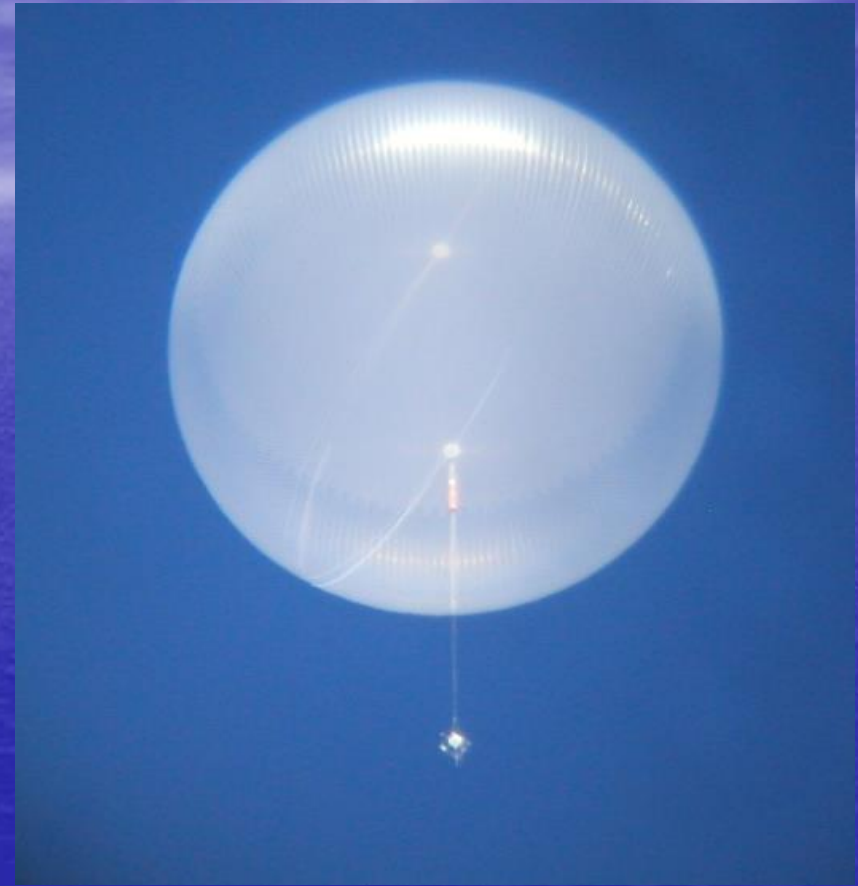
-- Flight Duration:

60 days (now)
100 days (soon)

-- Total mission cost:

\$8-25M range

*includes science payload + supporting instrumentation & power → 'spacecraft equivalent'

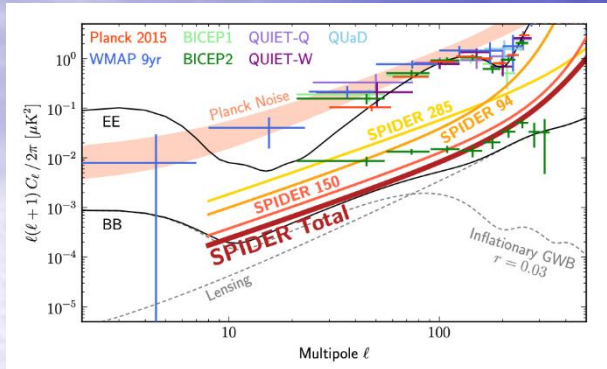


Proofs of concept:

2009: 54-day test-flight 591NT

2016: 47-day COSI science flight 659NT

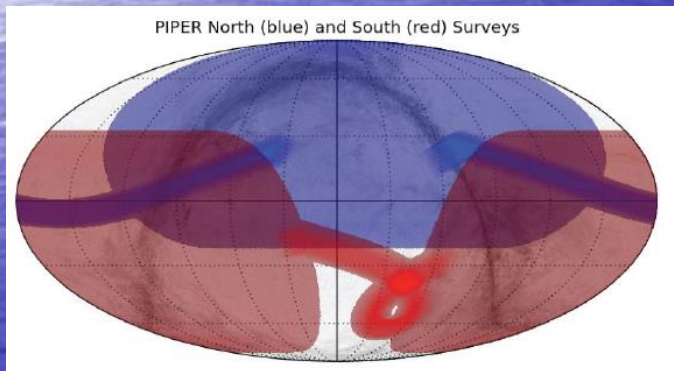
Snapshot survey of balloon-based astrophysics 2020⁺⁺



• Cosmic microwave background

– SPIDER: B-mode polarization

- 95-285 GHz, 6 monochromatic telescopes in shared cryostat, 300 mK TES bolometers
- Initial flight 2015, will fly again early in 2020's
- Constrain tensor-to-scalar mode ratio $r < 0.03$ at 3σ level



– PIPER: B-mode polarization

- 4 bands 200-600 GHz, goal to cover 85% of sky
- TES bolometers at 100 mK
- Tensor-to-scalar mode ratio $r < 0.007$
- ℓ from 2 to 300

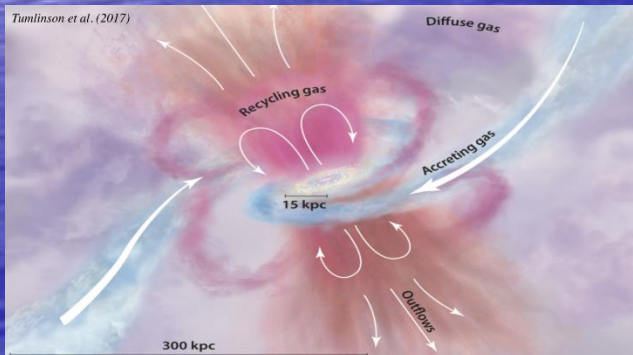
Snapshot survey of balloon-based astrophysics 2020⁺⁺

- UV-visible light astronomy

- SuperBIT: UV-blue diffraction-limited imaging
 - Initial flight was successful, see image of Eagle nebula to left; pathfinder for 1-2m class telescope w/ Gpixel focal plane
 - Will fly in 2020-21 on SPB, 100 day flight goal



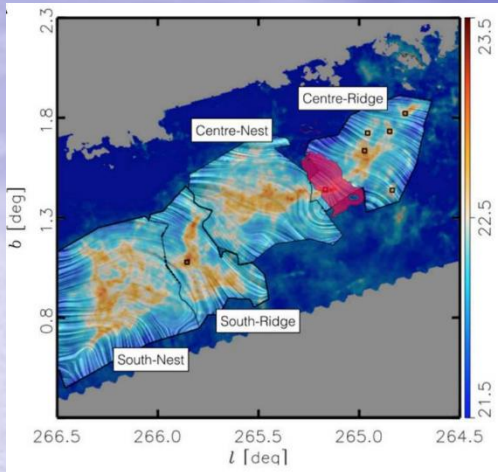
- PICTURE-C: Exoplanet direct-imaging pathfinder
 - 0.6m off-axis-parabola, coronagraph/nuller to 10⁻⁸ over range from 0.18 to 0.8 arcsec
 - Pointing stability to 5 mas, using NASA WASP system



- FIREBall-2: UV multi-object spectrograph

- Map low surface brightness circumgalactic medium in emission in Ly α , CIV, OIV
- Galaxies from $0.3 < z < 1$, R=2000, 1' angular res.
- pathfinder for a larger scale instrument

Snapshot survey of balloon-based astrophysics 2020⁺⁺

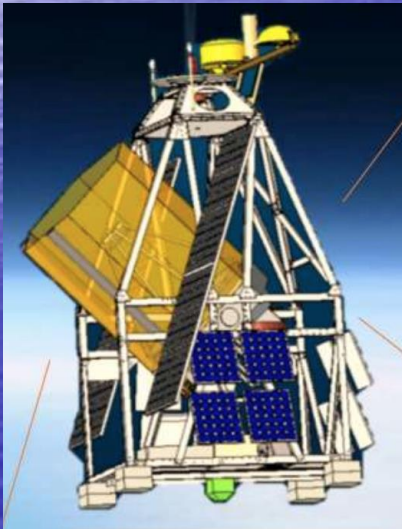
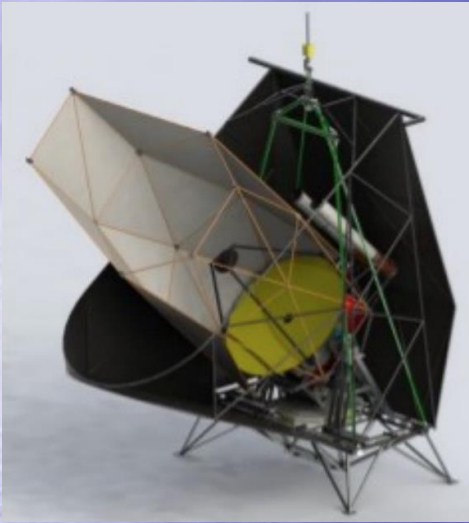


- Millimeter, sub-mm, THz, FIR astronomy
 - BLAST-TNG: mapping polarized thermal emission in star-forming regions
 - 2.5 m mirror giving 30'' FWHM at 250 μm
 - Over 3300 MKID dual-pol detectors at 3 bands, 250, 350, 500 μm
 - 28-day cryogen hold time, proven mission
 - GUSTO: THz spectroscopy @ 1.4, 1.9, 4.7 THz
 - 0.9 m telescope with heterodyne receivers, built by same group that developed detectors for Herschel spacecraft
 - Trace star formation & galactic evolution via OI line at 4.7 THz, dominant cooling line for warm, dense atomic gas
 - Small Explorer Mission of Opportunity, 2021 launch



Snapshot survey of balloon-based astrophysics 2020⁺⁺

- Millimeter, sub-mm, THz, FIR astronomy
 - STARFIRE: THz telescope for redshifted far-IR exploration
 - 2.5m telescope with integral field spectrometer
 - 0.7-1.25 THz (420-240 μm) spectral coverage
 - Observe dust-obscured star-forming galaxies $z \sim 2-4$
 - Still in early development phase (NASA/JPL/Caltech)
 - ASTHRO/FIR: facility-class FIR telescope, (proposed pathfinder is called ASTHROS)
 - Lots of heritage from BLAST payloads
 - 100 to 3000 μm , with spectrometers/polarimeters
 - Use 4 Kelvin cryocooler, no consumable cryogenics
 - 4 identical payloads, fly 2x per year, up to 50K hours observation over 10-year lifetime



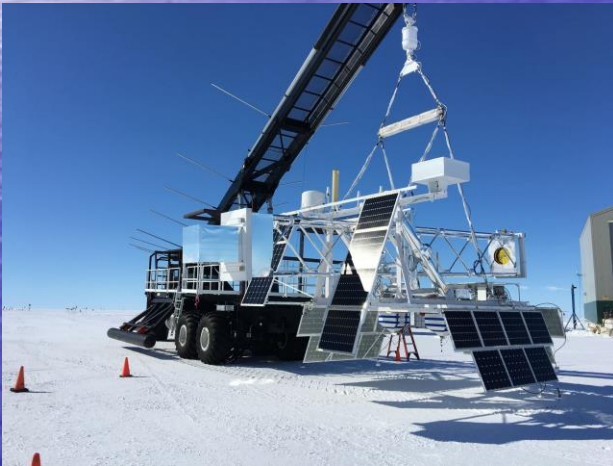
Snapshot survey of balloon-based astrophysics 2020⁺⁺

- High energy Astrophysics



- COSI: Compton Spectrometer & Imager

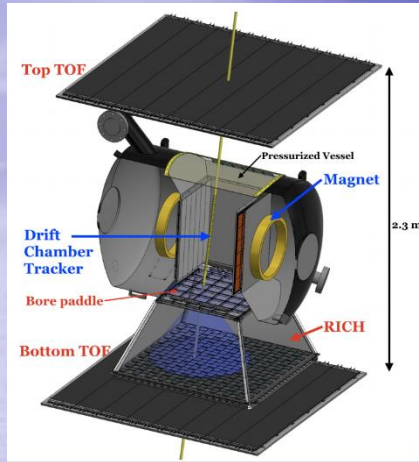
- 0.2 to 10 MeV, uses multiple scattering to determine direction to about 5 deg
- Polarization also measured via Compton process
- Galactic Center 511 keV emission, GRB polarization, stellar nucleosynthesis lines: ^{26}Al , ^{44}Ti , ^{60}Fe
- 46-day midlatitude SPB flight 2016, will fly SPB again 2020



- XCalibur: 25-60 keV hard X-ray polarimeter

- Compton scattering-based polarimetry, both degree and plane of polarization measured
- Will observe Galactic hard X-ray sources, accreting black holes, neutron stars

Snapshot survey of balloon-based astrophysics 2020⁺⁺



- Particle Astrophysics

- HELIX: High energy light isotope experiment

- Measure cosmic-ray beryllium ratios: $^{10}\text{Be}/^9\text{Be}$ provides crucial measure of CR containment lifetime
 - Determines CR diffusion coefficient and halo size
 - HELIX will extend $^{10}\text{Be}/^9\text{Be}$ by x5 in energy and improve resolution by factor of 10



- GAPS: General Anti-particle Spectrometer

- Antiprotons, anti-helium, anti-Deuterons, 0.1-10 GeV
 - Anti-deuterons in particular would be clear signature of Dark matter annihilation, a clean indirect detection signature
 - Polar location (Antarctica) essential for low-energy sensitivity – LEO spacecraft rigidity cutoffs are too high
 - GAPS can improve over AMS-02 (ISS) constraints by up to 2 orders of magnitude

Snapshot survey of balloon-based astrophysics 2020⁺⁺



- **Particle Astrophysics**

- EUSO-SPB: Extreme Universe Space Observatory
- Super-pressure balloon mission

- Observes nitrogen fluorescence and optical Cherenkov light from UHE cosmic ray air showers in the atmosphere
- Can also detect upcoming tau neutrino-produced showers
- Validate techniques and optics for POEMMA: Probe of Extreme Multi Messenger Astronomy space mission



- SuperTIGER 3: trans-iron galactic element recorder

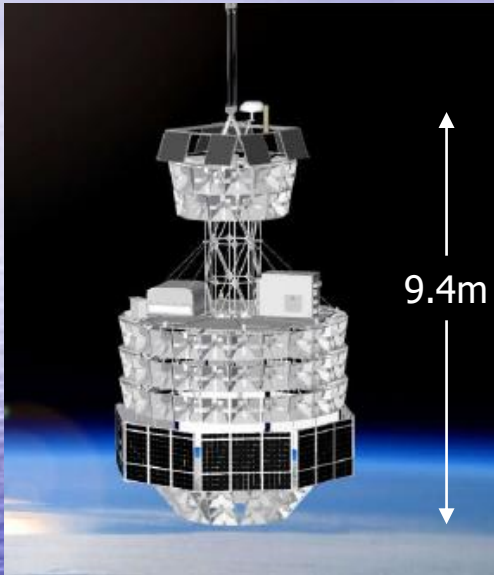
- Several m² of scintillation counters, Cherenkov imagers, and a scintillating fiber hodoscope
- Resolves individual isotopes up to Z=60 (Neodymium) with excellent resolution
- Can distinguish production models for refractory vs. volatile elements, role of OB associations and Wolf-Rayet stars in cosmic ray production

Snapshot survey of balloon-based astrophysics 2020⁺⁺

- Particle Astrophysics

- PUEO: Payload for Ultra-high Energy observations

- Next-generation neutrino/UHE cosmic ray telescope, based on radio detection methods pioneered by ANITA payload
 - 120 dual-polarization 300-1200 MHz quad-ridge horns
 - Exploits radio impulses from relativistic particle cascades from either UHE cosmic ray or UHE neutrino interactions
 - Requires Antarctic ice, $\leq$ stratospheric altitudes
 - PUEO will improve ANITA neutrino sensitivity up to x20 or more in a range not covered effectively from the ground



Examples of how Balloon missions have contributed in essential ways to scientific spacecraft missions.

- CMB balloon flights in the late 80's and 90's laid the critical ground work for the design of **WMAP**.
- Detectors on the **RHESSI** mission were first developed and demonstrated on balloon-borne instruments.
- The scintillating fiber trajectory detector on the **ACE** Cosmic Ray Isotope Spectrometer was demonstrated first in a balloon flight.
- All four instruments on the **Compton** Gamma Ray Observatory (CGRO) were developed from balloon flights.
- Three Balloon flights of the cadmium-zinc-telluride detector array that produced data needed to design the **Swift** Burst Alert Telescope instrument.
- Balloons supported full engineering prototype flights of the **Fermi** Large Area γ -ray telescope

