Fundamental Limits of Photon Detection ("Detect")

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Proposers Day Briefing

January 25, 2016

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Agenda & Outline

Time	Activity
11:30am – 12:00pm	Check-in
11:50am – 12:00pm	Webcast Login
12:00pm – 1:00pm	**GOVT Presentations**
1:00pm – 3:00pm	Scientific Exchange
3:00pm – 4:00pm	Networking
4:00pm – 5:00pm	Q&A Session
5:00pm – 6:00pm	Networking

NOTE: In the event of any discrepancies between this presentation and the BAA, the BAA takes precedence. No exceptions.

- **Working with DARPA**
- **DSO Overview**
- **Program Overview**
  - Motivation
  - What makes it hard?
  - Program Foci
  - Schedule
  - Milestones
  - Metrics
- **Proposal Guidance**
  - BAA Schedule
  - Awards & Duration
  - Abstract Format
  - Proposal Format
  - Tech Volume Specifics

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Fundamental Limits of Photon Detection (DETECT)

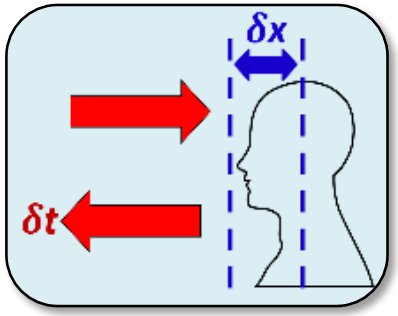
Program Motivation and Overview

What if light could be measured much more precisely?

It would be transformative – light measurements are ubiquitous!

Biology	**Communications**	**Astronomy**	**Medicine**
Photography	**Mapping**	**Basic Science**	**LADAR**

Let's take just one example → LADAR



$\delta x = c\,\delta t$

Timing Resolution

SOA: 20-50 ps

What if 100 fs?

→ spatial resolution of 30 um

→ The ability to recognize a specific face

Dark Counts

SOA: 10^3-10^4 counts/s

What if 1 count/s?

Less dark counts → higher SNR

→ Same performance at 100x distance

"Detect" will lay the foundation for such revolutionary advances by:

1) Developing fully quantum models for photon transduction

2) Building devices to test those models in multiple technologies

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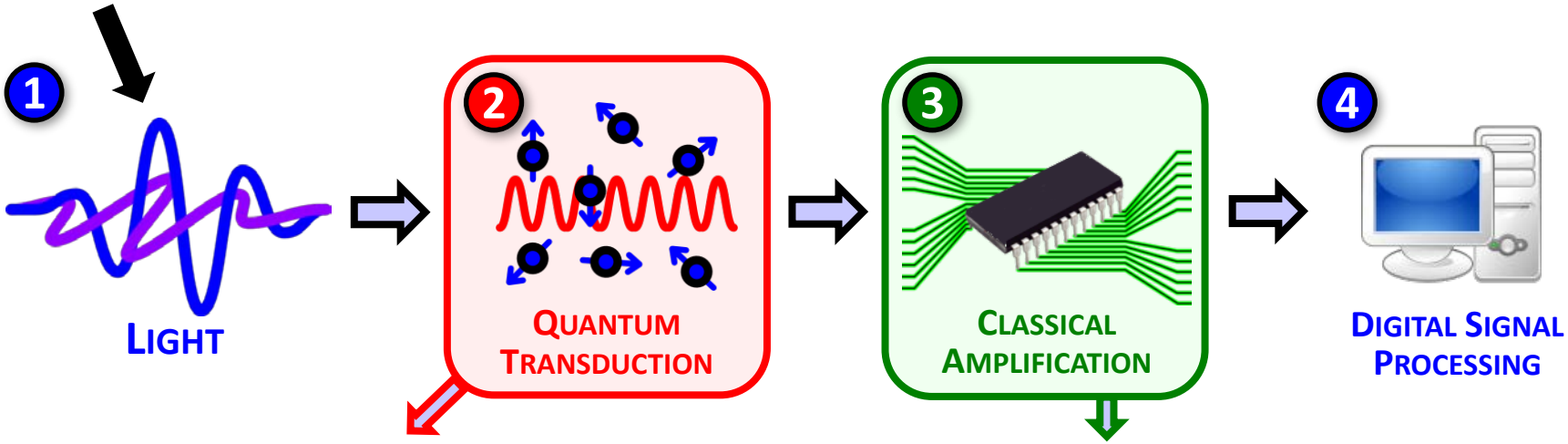
"Detect" will address fundamentals of light detection

Transform-limited pulse of light, i.e., a single mode in space and time



Poorly Understood

- Precisely when does this happen?
- What determines SNR?
- Fundamentally digital (quantized)

Well Understood

- Very accurate models
- SNR predicted from theory
- Fundamentally analog because of associated noise

"Detect" → 1) Model transduction & amplification as a single quantum process
2) Build proof-of-concept devices to verify those models

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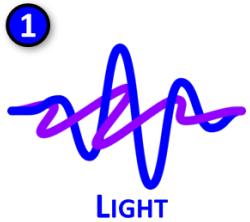
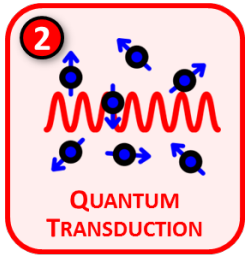
Why might this work?

Consider a typical 1-GHz rate contemporary photon detection process:



- A 10-THz-bandwidth photon arrives in a given nanosecond.
- An ideal detector should measure that photon to be in one of 10^4 time/frequency bins (1 ns / 100 fs).



- A typical photon detector absorbs this photon into a cubic micron of matter, or approximately 10^{11} atoms.

- An amplification process (e.g., an avalanche) indiscriminately transforms at least 10^4 possible measurement modes into a single large classical signal (e.g., a voltage change).

In principle, an ideal detector should: (1) Absorb the incoming photon into at least 10^4 precisely designed detector modes, and (2) Transform those modes into at least 10^4 distinct classical output signals.

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Why is this hard?

- **This requires significant advances:**
  - Test the behavior of real photon detectors at the quantum level
  - Model photon detectors as a (very large) quantum measurement
  - Design photon detectors to absorb and then distinguishably "amplify" thousands of distinct quantum modes
- **There are very important open questions:**
  - Are there fundamental limits to ideal photon detector performance? Is there a physics-enforced "tradespace" of allowable photon detector performance?
  - Is this modeling effort computationally intractable (e.g., due to large amounts of entanglement)?
  - If a superior detector can be designed, are current fabrication techniques sufficient to create it? If not, what fabrication techniques would be needed?

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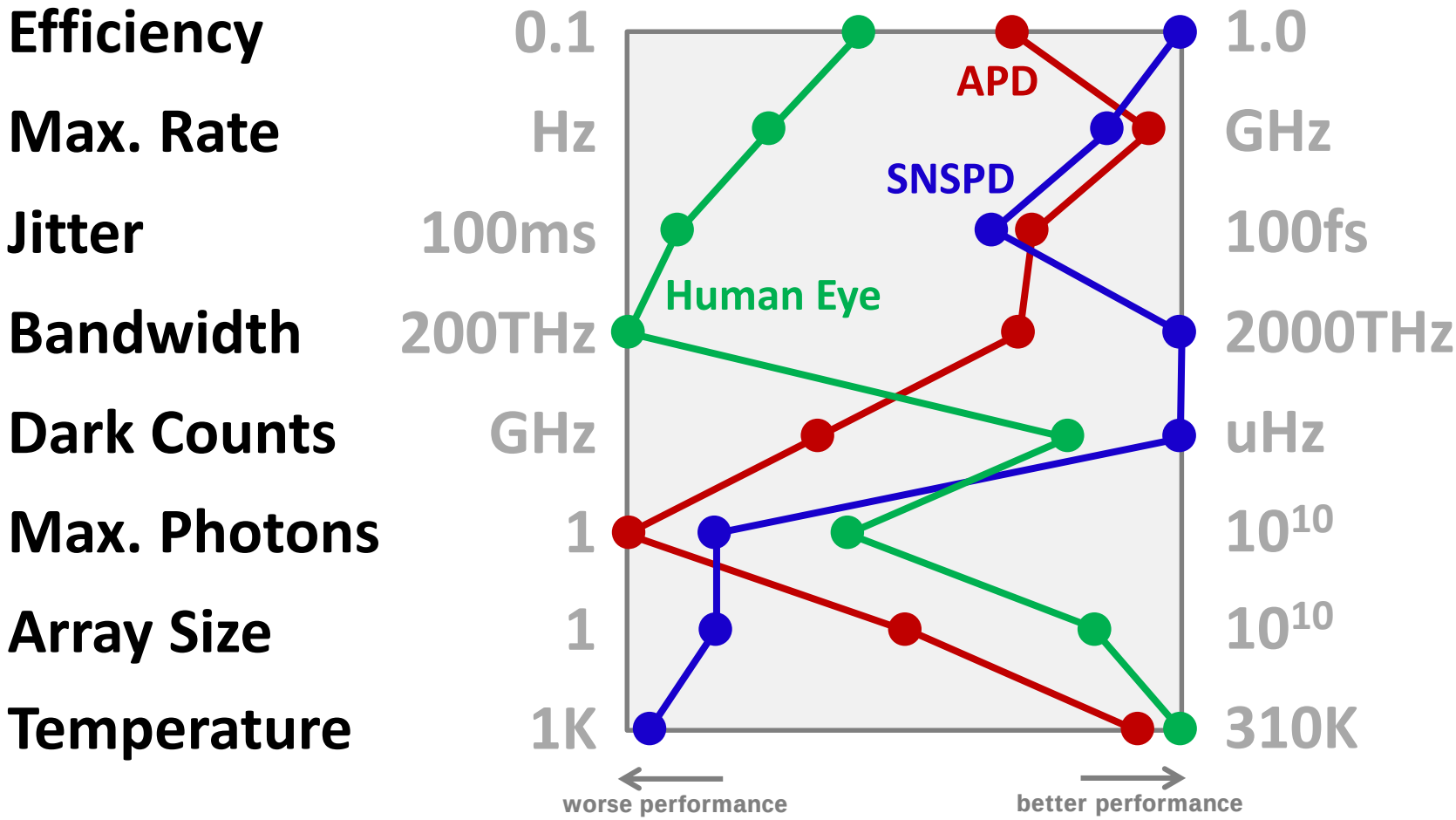
What makes a good photon detector?
→ Key metrics for Detect



Legend

SNSPD: Superconducting nanowire single-photon detector
APD: Avalanche photodiode (Geiger mode)

No one class of photodetectors dominates

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Every team chooses a focus technology; All teams must integrate theory & experiment

Superconductors

A photon heats up a superconducting wire, creating a voltage change.

Strengths efficiency, bandwidth, dark counts

Weaknesses temperature, max rate

Semiconductors

A photon creates an "avalanche" of electron-hole pairs.

Strengths speed, jitter

Weaknesses dark counts, efficiency (duty cycle)

Biological Substrates

A photon changes the shape of a photoreceptor, opening an ion channel.

Strengths temperature, max. photons, array size

Weaknesses speed, dark counts, efficiency

Hybrid / Other

Either combines two other foci, or is something completely new. ***(This is encouraged!!!)***

Strengths a new path forward

Weaknesses lots of development needed

Theory & Simulation

Modeling the fundamental physics of photon transduction & amplification

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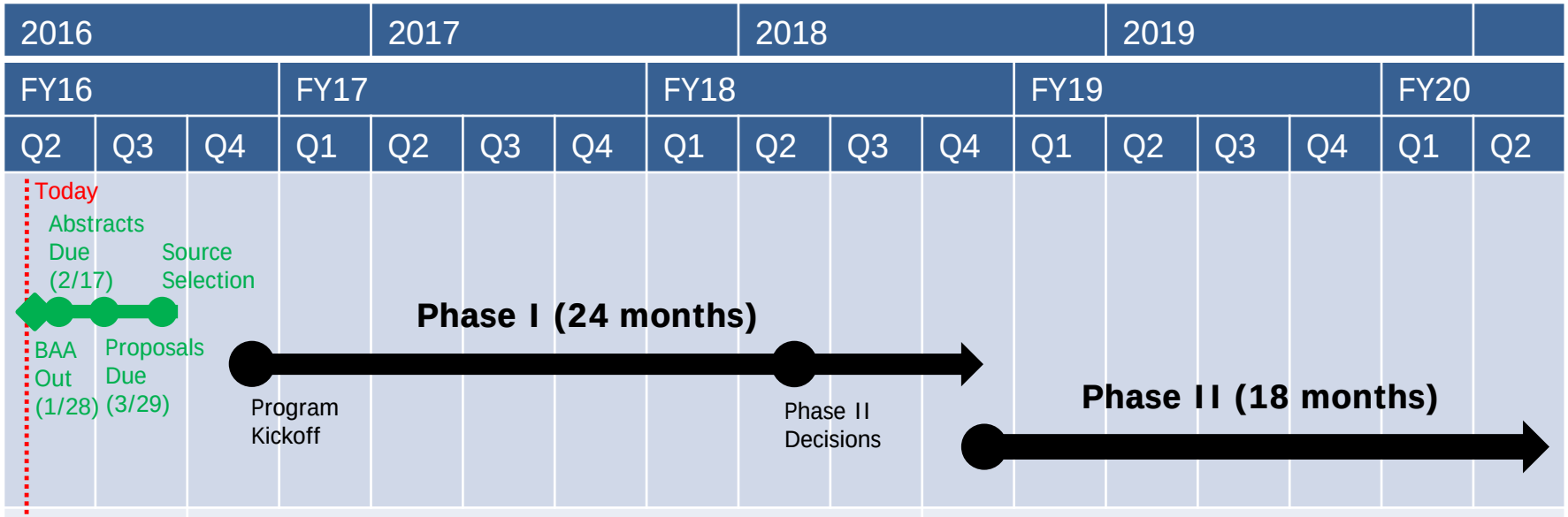
“Detect” Timeline (all dates estimated)



Phase I:
Experimentally Verified Models

- General Modeling / Tradespace Definition
- Focused Modeling / Tradespace Definition
- Designing New Detectors to be Fabricated in Phase II
- Selection for Phase II

Phase II:
Next Generation Designs

- Fabricate and Test Proof-of-Concept Devices
- Create Final Prototype Detector Design (this will not be fabricated during Detect)

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Guide to Metrics

The Detect Program BAA references two separate sets of metrics, and it is very important to understand them:

Post-Detect-Program Detector Performance Goals	• Goals for the type of superior detector we hope the Detect program will one day enable. • All proposals must show that their focus technology can conceivably reach these goals eventually (after the end of Detect) **OR** show that these goals are not achievable by any detector.
Phase II Goals for Proof-of-Concept Devices	• Defined as an order of magnitude better than state of the art (SOA) **in the relevant focus technology** in each of 8 key metrics. • These metrics must be met in Phase II **(possibly using multiple devices).** • The final Phase II deliverable is a design for a single device that simultaneously achieves all of these goals.

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Post-Detect-Program Detector Performance Goals

	Superior Detector
Timing Jitter	< 100 fs
Dark Counts	< 1 / day
Max. Rate	> 10 GHz
Bandwidth	At least three of the following simultaneously: X-ray, UV, Vis, NIR, MWIR, LWIR
Efficiency	> 99.9%
Photon Number Resolution	> 1-1000 / read
Temperature	Room Temperature
Array Size	> 10^{10}

The Detect Program will lay the foundation for a photon detector with this performance.

OR

Prove from first-principles why this performance is not possible in any detector, and define the tradespace of what is possible.

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Phase II goals for Proof-of-Concept Devices by Focus Technology(#)

Phase II devices should surpass SOA in the relevant focus technology by an order of magnitude in every category, possibly using multiple devices.

	Superconductor	Semiconductor	Biological
Timing Jitter	< 100 fs	< 100 fs	< 100 us
Dark Counts	< 1 / day	< 1 / second	< 1 / minute
Max. Rate	> 1 GHz	> 1 GHz	> 10 kHz
Bandwidth	UV, Vis, NIR, MWIR	UV, Vis, NIR, MWIR	Vis, NIR
Efficiency	> 99%	> 98%	> 25%
Photon Number Resolution	> 100 / read	> 10 / read	> 1000 *
Temperature	> 77 K	Room Temperature	Room Temperature
Array Size	> 10^3 *	> 10^6 *	> 10^9 *

(#) **Performers are encouraged to submit other detector types**; in this case performance must exceed the state of the art in every category and performers must define these goals in their proposals

(*) Performers should provide definitive evidence that arrays/reads of this size are possible, but are not required to construct an array at scale; this would require resources beyond the scope of this program

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Phase I Milestones (due dates in parenthesis)

- **General Modeling (6 months):** General models of photon detection that apply to any photon detection technology.
- **Tests of General Model (12 months):** Experimental tests of this general model.
- **Detector-Specific Modeling (12 months):** Detailed models of photon detection in the team's focus technology.
- **General Tradespace Studies (12 months):** First-principles quantification of the best possible detector performance in any technology platform.
- **Tests of Tradespace Models (18 months):** Tradespace models extended to the focus technology and experimentally tested.
- **Phase II Device Designs (18 months):** Detailed designs for the proof-of-concept devices to be fabricated in Phase II.
- **Phase II Device Design Validation (18 months):** Experimental evidence supporting the efficacy of the Phase II Device Designs.
- **Explore Fundamental Physics of Phase II Device Designs (24 months):** Theoretical exploration of the focus technology and the Phase II designs.
- **Test Insights from Fundamental Physics Exploration (24 months):** Experimental exploration of the focus technology and the Phase II designs.

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Phase II Milestones (due dates in parenthesis)

- **Plan for Achieving Final Prototype Design (6 months):** First draft of the Prototype Detector Design; unlike the proof-of-concept devices developed in Phase II, the Prototype Detector Design will not be implemented during the Detect program – it will be a next-generation design based on a program-long modeling effort capable of simultaneously achieving all Phase II goals.
- **Phase II Devices Fabricated and Tested (6, 12, and 18 months):** At 6 months, devices should achieve the SOA in some but not all key metrics. At 12 months, they should achieve the SOA in all key metrics and reach the Phase II goals in some. By 18 months, devices should achieve all Phase II goals.
- **Performance of Phase II Devices Quantified Relative to Model Predictions (6, 12, and 18 months):** Every 6 months, device performance should be compared to model predictions, and both the models and designs should be improved using these results.
- **Final Prototype Detector Design (18 months):** The Prototype Design should simultaneously exceed SOA in all key metrics by at least an order of magnitude; fabrication of this design is outside the scope of Detect.

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Proposal Guidance

BAA Solicitation Schedule

- BAA:
  - Estimated posting: January 21, 2016

- Abstracts
  - Abstracts are STRONGLY ENCOURAGED in advance of full proposals in order to provide potential proposers with a rapid response and to minimize unnecessary effort
  - Estimated due date: **February 17, 2016**
  - DARPA will respond within 30 days (more likely within two weeks) either Encouraging or Discouraging a full proposal

- Full Proposals
  - Estimated due date: **March 29, 2016**
  - BAA closes on the same day

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Awards and Duration

- Multiple awards are anticipated. The level of funding for individual awards will depend on the quality of the proposals received and the availability of funds.
- Depending on the availability of funds and other factors, the program is anticipated to last 3.5 years.
- DARPA reserves the right to select proposals in their entirety or only portions thereof for award negotiation.
- All proposals must address all theory and experimental milestones, and theory and experiment must be tightly integrated.
- Collaborative efforts/teaming are encouraged:

  It is expected that achieving the specific goals of the Detect program in photon detection will require a multidisciplinary approach involving disparate scientific and engineering disciplines. Collaborative proposals involving expertise in quantum measurement, quantum information science, semiconductor physics, superconductor physics, biological physics and quantum biology, quantum-limited amplification, device and system design and engineering, and all other fields required to model, design, and construct devices in the focus technology, are encouraged.

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Abstract Format

- The abstract should not exceed 5 pages, excluding cover sheet and executive summary slide. The page limitation for abstracts includes all figures, tables, and charts and an optional bibliography.

- Abstracts must contain the following sections:
  - Goals and Impact
    - Teams must clearly indicate focus technology and modeling strategy.
  - Technical Plan
    - Teams must argue why their approach will be able to meet the goals of Phase I and Phase II, as well as why it is feasible that this technology could one day enable the future (post-Detect program) detector performance listed in Table 1.
  - Capabilities/Management Plan
    - Teams should show how they will tightly integrate theory and experiment.
  - Cost and Schedule
  - Bibliography (optional)
  - Executive Summary Slide (template provided)

Full Proposal Format

- Proposals consist of two volumes – **technical and management (1)** and **cost (2)**
- Proposers **must** use the templates provided as Attachments to the BAA (Attachments 1, 2, 3 and 4)
- **Technical and management** volume must contain the following sections:
  - i. – iii.: Official transmittal letter, cover sheet, table of contents
  - iv. – xi.: Technical and management information (shall not exceed 35 pages)
  - xii: Cost summary
  - xiii: Administrative and National Policy Requirements (no page limit)
  - xiv: Additional information (no page limit)
    - A brief bibliography with links to relevant technical papers, reports, or resumes, and copies of not more than three (3) relevant papers

- **Cost** volume contains a cover sheet, cost summaries, detailed cost break down, and supporting cost and pricing information (No page limit).
  - Costs must be traceable between the prime and subcontractors/consultants, as well as between the cost proposal and the SOW. Cost information must be provided in sufficient detail to substantiate the proposed prices.

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Volume 1 Technical & Management: Detailed Proposal Information

Volume 1 must contain the following sections. Max page lengths for each section are shown in ()

iv. Executive Summary (4) and Summary Slide (1) (slide template provided)

v. Goals and Impact (2)

vi. Technical Plan (15)

- Include all requested parameters

vii. Management Plan (3)

- A Principal Investigator for the project must be identified
- PI will assume all responsibilities for the conduct of the effort
- Effort should be well defined, integrated and focused
- Teams should be multi-disciplinary, tightly integrated, include all relevant expertise, and demonstrate a clear, coordinated, unified approach to reach all program goals (interim and final)
- All of the proposed tasks must show a clear contribution to the program goals

viii. Personnel, Qualifications, and Commitments (2)

ix. Capabilities (2)

Volume 1 Technical & Management: Detailed Proposal Information

x. Statement of Work (3)

- The SOW must provide a detailed task breakdown, citing specific tasks and their connection to the interim milestones and metrics, as applicable. Each year of the project should be separately defined. The SOW must not include proprietary information. For each defined task/subtask, provide:
  - A general description of the objective.
  - A detailed description of the approach to be taken to accomplish each defined task/subtask.
  - Identification of the primary organization responsible for task execution (prime contractor, subcontractor(s), consultant(s)), by name.
  - A measurable milestone, (e.g., a deliverable, demonstration, or other event/activity that marks task completion).
  - A definition of all deliverables (e.g., data, reports, software) to be provided to the Government in support of the proposed tasks/subtasks.

xi. Schedule and Milestones (3)

- Provide a detailed schedule showing tasks (task name, duration, work breakdown structure element as applicable, performing organization), milestones, and the interrelationships among tasks.
- **Include a table of program milestones. Quantitative program milestones must be defined every 6 months from the start of the effort.**

Volume 1 Technical & Management: Detailed Proposal Information

xii. Cost Summary

- List cost totals for labor, materials, other direct charges (ODCs), indirect costs (overhead, fringe, general and administrative (G&A)), and any proposed fee for the project.

- Include costs for each task in each year of the project by prime and major subcontractors, total cost and proposed cost share, if applicable.

(slide templates provided as attachments to BAA)

Scientific Exchange

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Scientific Exchange

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- **Provide opportunity to share its capabilities**
- **Facilitate teaming**
- **Clarify BAA**

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