# Report of the HEPAP Particle Astrophysics Scientific Assessment Group (PASAG)

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for the PASAG

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# Introduction and Scope

- Together with the Energy Frontier and the Intensity Frontier, the Cosmic Frontier is an essential element of the U.S. High Energy Physics (HEP) program. Scientific efforts at the Cosmic Frontier provide unique opportunities to discover physics beyond the Standard Model and directly address fundamental physics: the study of energy, matter, space, and time.
- Primary areas covered by PASAG:
  - Dark matter
  - Dark energy
  - Cosmic particles (high-energy cosmic rays, gamma rays, neutrinos)
  - CMB
- Did not cover all areas of non-accelerator physics. Topics not addressed include low-energy neutrinos, low-energy cosmic rays, nucleon decay, tests of gravity and gravitational waves.
- Report based on a snapshot of where the field stands right now.
  - Activities at the Cosmic Frontier are marked by rapid, surprising, and exciting developments.
  - Attempted to provide advice that is durable, but significant new developments – and great surprises – are likely. It is important to be open to significant new directions over the decade.

# Inherently Interdisciplinary

- Projects at the Cosmic Frontier naturally exist at the boundary between particle physics and astrophysics.
  - Some projects are obviously very close to the core of particle physics; other projects straddle the boundaries between fields and, in some cases, would not happen without significant HEP participation or leadership.
    - » These projects are designed to answer very important scientific questions and, in many cases, have the potential to uncover new directions for particle physics. Our prioritization criteria for HEP investment take into account these issues.
- Necessary to understand in sufficient detail the related astrophysical phenomena:
  - The astrophysics investment is sometimes necessary to realize the particle physics benefit.
  - The relationship is symbiotic: particle physicists have much to offer these important related fields of study and often have a major impact on them. We have much to learn from each other, and there is much we can do together.

# PASAG Prioritization Criteria

- The science addressed by the project is necessary
  - Addresses fundamental physics (matter, energy, space, time).
  - Anticipated results: either at least one compelling result or a preponderance of solid, important results. Check that anticipated results would not be marginal, either in statistics or in systematic uncertainties, relative to the needed precision for clear science results.
  - Discovery space: large leap in key capabilities, significant new discovery space, and possibility of important surprises.
- Particle physicist participation is necessary
  - Transformative techniques and know-how to have a major, visible impact; project would not otherwise happen.
  - Leadership is higher priority than participation
- Scale matters, particularly for projects at the boundary between particle physics and astrophysics.
  - Relatively small projects with high science per dollar help ensure scientific breadth while maintaining program focus on the highest priorities.
- Programmatic issues:
  - International context: cooperation vs. duplication/competition.

# Connections

- The multi-disciplinary, multi-agency, and multi-national character of particle astrophysics is understood by the PASAG as an essential feature.
- Concurrent with our work is the ongoing NRC Astro2010 “Decadal Survey” of activities in astronomy and astrophysics, jointly funded by NASA, NSF, and DOE.
- There is also the OECD Global Science Forum Working Group on Astroparticle Physics, following on the European ASPERA and ApPEC processes.
- The projects that are under consideration by two or more of these studies are appropriately evaluated from the different perspectives provided by the different panels. These cases are noted, and the PASAG hopes its report will provide useful input to the other ongoing studies.

# Budget Scenarios

- **Scenario A.** Constant effort at the FY 2008 funding level (*i.e.*, funding in FY 2010 at the level provided by the FY 2008 Omnibus Bill, inflated by 3.5% per year and continuing at this rate in the out-years).
- **Scenario B.** Constant effort at the FY 2009 President's Request level (*i.e.*, funding in FY 2010 at the level provided by the FY 2009 Request, inflated by 3.5% and continuing at this rate in the out-years).
- **Scenario C.** Doubling of funding over a ten year period starting in FY 2009 (*i.e.*, funding in FY 2010 at the level provided by the FY 2009 President's Request, inflated by 6.5%, and continuing at this rate in the out-years).
- **Scenario D.** Additional funding above funding scenario C, in priority order, associated with specific activities needed to mount a leadership program that addresses the scientific opportunities identified in the EPP2010 or P5 reports.

# Resources Available

- To calculate the phased resources available for construction and operation of new projects, the committed funding for existing projects and ongoing science analysis (the "base", estimated with some simplifying assumptions) was subtracted for each year.
- For the entire FY10-FY20 period of this study, the total (in then-year dollars) available for new projects was $266M, $389M, and $640M for scenarios A, B, and C, respectively.

# Many Exciting Opportunities

- Dark matter direct detection:
  - **next-generation (G2) facilities** capable of reaching sensitivity levels better than $10^{-46}$ $cm^2$ (about a factor 400 better than present-day limits and a factor ~10 better than expected for the experiments already under construction). Typical target masses of approximately one ton, with a construction and operation cost in the range of $15M-$20M.
  - **third-generation (G3) experiments** surpassing the $10^{-47}cm^2$ level. Target masses of many tons with a construction and operation cost around $50M.
- Dark energy:
  - **several stage-IV projects have been proposed**, including the space-based Joint Dark Energy Mission (JDEM) and the ground-based Large Synoptic Survey Telescope (LSST), which are large, and the medium-scale ground-based BigBOSS project.
- Cosmic particles:
  - highest energy cosmic rays: providing a factor of seven increase in statistics over the existing capabilities of Auger South and building on its achievements and expertise, the **Auger North** facility has been proposed.
  - to understand features in the cosmic ray spectrum at lower energy, the Telescope Array Low Energy extension (**TALE**) has been proposed.
  - very high-energy gamma rays: (i) providing at least an order of magnitude improvement in sensitivity and new capabilities, the large-scale **AGIS** array has been proposed as a joint effort with the European-led CTA project. (ii) **HAWC**, a different kind of ground-based very high-energy gamma-ray detector, at much smaller scale, that would provide a factor of 15 improvement in sensitivity over its predecessor, Milagro. (iii) a small proposal to **upgrade the existing VERITAS detector**.
- CMB:
  - a relatively small level of support has been proposed for Fermilab participation in the **QUIET II** experiment.

# PASAG Subfield Tasks

- The subfields have different histories and issues.
  - For dark matter:
    - The 2007 Dark Matter Scientific Assessment Group report provided a detailed survey of experiments designed for direct detection of dark matter along with a roadmap for future investments. To obtain the information needed to update the DMSAG report, PASAG issued a request for written information from the experiments.
  - For cosmic particles:
    - This is a broad area with many new results, but there has not been a devoted scientific assessment group. PASAG therefore issued a request for written information that was similar to the one for dark matter and, based on the responses, invited the major projects in this area to make presentations.
  - For CMB:
    - This is a broad area of research, primarily funded by agencies other than those HEPAP advises; however, small investments by HEP have had a large and visible impact. PASAG was specifically asked to comment on one project seeking HEP support, QUIET II, which also made a presentation. To make this assessment, PASAG also reviewed the overall importance of the science of the CMB to particle physics.

# Subfield Tasks (continued)

- The subfields have different histories and issues.
  - For dark energy:
    - Several panels, including the 2005 Dark Energy Task Force (DETF) and the 2007 Beyond Einstein Program Assessment Committee (BEPAC), have evaluated dark energy goals and a subset of the proposed projects. The two large projects that would have HEP funding -- LSST, which is very well defined, and JDEM, in its various forms -- have been extensively reviewed. A moderate-scale project, BigBOSS, is very new, so PASAG heard a presentation from that project.
    - A coherent overall strategy, optimizing observations both from the ground and space, taking into account the priorities of both the astronomy and physics communities, has been lacking. PASAG is not constituted to do this. However, as dark energy is a very high scientific priority, PASAG sought to define the scope of dark energy within the broader particle astrophysics program. The detailed allocation to projects in the different budget scenarios awaits a coherent plan. The Astro2010 Survey, which is ongoing, will presumably play a key role in this planning. As input, issues of importance to HEP for participation in dark energy projects are provided in Section 6.

# Program: Scenario A (constant effort at FY08 level)

- **Dark matter.** The current world-leading program is maintained, but world leadership would be lost toward the end of the decade:
  - Two G2 experiments and the 100-kg SuperCDMS-SNOLAB experiment are supported. The technology selection for the G2 experiments should occur soon enough to allow the construction of at least one G2 experiment to start as early as FY13.
  - No G3 experiments can be started in this decade. Progress will be slowed, risking loss of U.S. world leadership. However, due to the risk of picking the wrong technology, this is preferable to descoping to only one G2 experiment.

- **Dark energy.** It is not possible to have major HEP hardware and science contributions to any large project. World-leading participation is supported in only very limited areas (allocations to be determined, see report Section 6).

- **High-energy cosmic particles.** This area is severely curtailed in this scenario in order to preserve viable programs in dark matter and dark energy, and only the VERITAS upgrade and HAWC are possible. Even in this very lean scenario, the diversity offered by these two projects is a priority, and their impacts are large for a relatively small investment. Auger North and AGIS are not possible. This would be a retreat from U.S. leadership in high-energy cosmic rays and high-energy gamma rays (see Section 5).

- **Cosmic Microwave Background.** QUIET II is supported, along with possible other small investments in CMB research provided the prioritization criteria in Section 2 are clearly met.

# Program: Scenario B (constant effort at FY09 level)

- **Dark matter.** The current world-leading program is maintained, but with some risk later in the decade:
  - Two G2 experiments and the 100-kg SuperCDMS-SNOLAB experiment are supported. The technology selection for the G2 experiments should occur soon enough to allow the construction of at least one G2 experiment to start as early as FY13.
  - Only one G3 experiment can start in this decade. Based on what is known at this time, to mitigate risk of picking the wrong technology, a broad second-generation program is a higher priority than starting a second G3 experiment.
- **Dark energy**. Scenario B may provide just enough funding for significant participation in only one large project, but at significant risk since the total costs are still uncertain and the one project probably will not adequately address all the scientific issues.
  - A program with world-leading impact in dark energy is possible, but in a limited way (see Section 6).
  - The overall funding profile requirements are uncertain, but the straight-line budget scenario does not appear to allow sufficient resources for a fast start early in the decade, and some adjustments to the profile would be necessary.
- **High-energy Cosmic Particles**. The VERITAS upgrade, HAWC, and a reduced, but still leading, AGIS that is fully merged with CTA are highest priority in this scenario.
  - Auger North is not possible in Scenario B. This would be a retreat from U.S. leadership in high-energy cosmic rays (see Section 5 and the discussion below).
- **Cosmic Microwave Background.** QUIET II is supported, along with possible other small investments in CMB research provided the prioritization criteria in Section 2 are clearly met.

# Program: Scenario C (doubling scenario)

- A world-leading program in **dark matter**:
  - Two G2 experiments plus the 100-kg SuperCDMS-SNOLAB experiment are supported. The technology selections should occur soon enough to allow construction to start on at least one experiment as early as FY13.
  - Two G3 experiments can start in this decade.
- **Dark energy.** A world-leading program is enabled, with coordinated activities in space and on the ground (see Section 6).
  - Significant HEP roles in one large project are possible, along with a moderate-scale project and/or a substantial role in a second large project.
  - As in Scenario B, the straight-line budget scenario does not appear to provide sufficient resources for a fast start early in the decade. Although the overall funding profile requirements are uncertain, some adjustments to the profile would likely be necessary.
- **High-energy Cosmic Particles**, a world-leading program is enabled, with:
  - the VERITAS upgrade, HAWC, and a reduced but still leading role in AGIS that is fully merged with CTA; and
  - U.S. leadership of Auger North.
- **Cosmic Microwave Background.** QUIET II is supported, along with possible other small investments in CMB research provided the prioritization criteria in Section 2 are clearly met.

# Program: Scenario D

- Augmenting the program in Scenario C, an additional $200M investment over the decade would enable major roles in two complementary, stage-IV dark energy projects, ensuring continued U.S. leadership in this field and providing the best chance of a major breakthrough in dark energy in this decade.

# Important Notes: Budget Constraints

- For the budget exercises, the available construction and operations costs were used for each project. The uncertainties in the costs vary widely and can only be better determined with detailed cost/technical/schedule reviews.
- The leaner scenarios A and B forced extremely difficult choices. In any scenario, if the funding available for a project was judged to be insufficient to support a world-class result, the project was removed. Similarly, in any scenario if only R&D-level funding could be accommodated, with insufficient funding for construction, the R&D was also removed from the program. It is therefore important to revisit these choices if sufficient resources outside of HEP (e.g., from astronomy and astrophysics programs in the U.S. or from additional agencies outside the U.S.) become available. In the cases of JDEM, LSST, and AGIS, the subpanel recommends contributions from HEP agencies that are a portion of the total project costs, appropriate to the shared scientific interest with astronomy and astrophysics, and therefore a decision to proceed must rely on strong support from other agencies and/or nations.

# Important Notes: Dark Energy

- In all three scenarios, projects in dark energy represent the largest total investment, reflecting the very high scientific priority and the fact that large projects are required to make significant progress in this area. Even with that large fractional investment, there are significant challenges and risks, particularly in the leaner scenarios:
  - In Scenario A (~$140M), it is not possible to have major HEP hardware and science contributions to any large dark energy project.
  - Scenario B (~$200M) is still very risky because it is near the threshold for significant participation in only one large project. This will require great vigilance and careful consultation with the scientific community. For example, because JDEM is not currently well defined, yet is very expensive, there is at present considerable risk that a large fraction of the total available resources will be spent on a project that does not provide a scientific return that matches HEP priorities while precluding any significant participation in other dark energy projects that could.
  - Scenario C (~$350M): A world-leading program is possible, with coordinated activities in space and on the ground.
  - Scenario D (~$540M): A world-leading program is assured. This would fully fund the DOE hardware and scientific contributions to an optimized combination of stage-IV dark energy experiments. This portfolio will likely include a large ground-based imaging survey, a space-based survey with higher angular resolution and infrared capabilities, and a massive spectroscopic galaxy redshift survey, executed through the most cost-effective combination of ground and space approaches. HEP leadership and the resultant dark energy measurements would be strong and secure.

# Important Notes: Balance

- A balanced program is itself a priority. For example, in Scenario A, while more resources would be required to have full participation in even one large dark energy project, PASAG advises not to reduce the dark matter project investment below a level critical to maintain leadership. As the dark matter experiments scale up in size, it is important to have at least one frontier-sensitivity experiment operating at all times throughout the decade. A discovery could be imminent.
- Continued support for theoretical research is an essential part of a strong particle astrophysics program.

# Important Notes: CMB

- Cosmic Microwave Background measurements are important to particle physics as a unique probe of the extremely high-energy processes associated with Inflation.  Given the central importance of the CMB to our understanding of energy, matter, space, and time, and the unique contributions HEP can provide to CMB science, small investments are highly recommended in all budget scenarios, if the prioritization criteria in Section 2 are clearly met.
  - Several of the national labs and other institutions now have small groups active in this area.  Additional investments in CMB projects should be made when the HEP community can provide unique capabilities.  Relatively small (up to ~few M$ per year) investments in CMB research would be appropriate, if the prioritization criteria are clearly met.

# Important Notes: AGIS

- The U.S. has played a leading role in the study of high-energy cosmic particles (cosmic rays, gamma rays and neutrinos) from space. This field sits at the interface between high-energy physics and astrophysics, enabled by techniques and personnel drawn from both areas. The main goals of the field are to understand the acceleration processes in cosmic sources that produce particles with energies well beyond what can be achieved on Earth and to use these particles to search for physics beyond the Standard Model.
- AGIS well exemplifies this interdisciplinary nature, having significant capability for indirect detection of dark matter in addition to its main goal of exploring the TeV gamma-ray sky. The novel AGIS design concept has the potential to offer much better instrument performance over the baseline design of the planned European-led Cherenkov Telescope Array (CTA).
- Given the expense, only one large array is likely to be built. To make sense programmatically and technically, and to maximize the effect of a U.S. investment, AGIS and CTA should move quickly toward a joint project.
- AGIS is also under review by the Astro2010 Survey; should it be highly ranked in that study, it would be expected that a significant fraction of the AGIS cost would be borne by the U.S. programs in astronomy and astrophysics.

# Important Notes: Auger North

- Establishing the high-energy cutoff in the cosmic ray spectrum was a great achievement of the past decade. This also fundamentally changed the intellectual landscape for the study of the highest energy cosmic rays, removing the need to explain them with new physics such as exotic, massive particles or topological defects at the GUT scale.  Now, the scientific focus is on finishing the quest to determine the astrophysical origin of the highest energy cosmic rays.
- Auger North is "shovel-ready", and the world is looking to the U.S. for leadership.  The Astro2010 survey is ongoing: Auger North may be highly ranked in that survey, in which case astronomy and astrophysics agencies will presumably then plan to fund it and the costs to HEP will be lower.  If not, then Auger North can only be substantially supported by HEP in the best funding scenarios.

# Important Notes: DUSEL

- Given the current status of the proposed Deep Underground Science and Engineering Lab (DUSEL) and the uncertainty in the funding that could be made available, PASAG chose not to assume the funding of experiments through DUSEL in the budget planning exercises, even though the U.S. dark matter program would be greatly strengthened by it.
- DUSEL is central to the future dark matter and neutrino experimental programs, both of which require large underground laboratories.  DUSEL would provide a unique location with needed infrastructure in the U.S.  In addition, the funding for dark matter that may be available when DUSEL goes forward would enable key enhancements of variety, scope and schedule of the program.

# Ongoing Projects

- Exciting times are ahead for particle astrophysics, with many new results emerging from operating projects and even more expected soon from the projects currently under construction.

- **Recommendation:** Even in the leanest budget scenarios, the full budgets for the projects that are already under construction or that are currently operating should be maintained. Every operating project should have a well-defined sunset review date and a realistic plan for possible extended operations. Sunset reviews and decisions must carefully consider international and multi-agency perspectives.

# Concise Summary

- The priorities are generally aligned with the recommendations for the Cosmic Frontier in the 2008 P5 report.

- Dark matter and dark energy remain extremely high priorities.
- Dark energy funding, which receives the largest budget portion, should not significantly compromise U.S. leadership in dark matter, where a discovery could be imminent.
- Dark energy and dark matter funding together should not completely zero out other important activities in the particle astrophysics program. The recommended programs under the different scenarios follow the given prioritization criteria.

# Dark Matter Project Specifics

- To advance the CDMS technology, **PASAG recommends a technical review of SuperCDMS in FY2010 to evaluate the performance of the new detectors currently in operation at Soudan. Funding for the 100-kg SuperCDMS-SNOLAB experiment should begin as soon as the detectors meet the design requirements.**

- **A future xenon program that avoids duplicate efforts and meets the technical requirements for low background should be supported in any of the funding scenarios.**

- **The liquid argon technique may be especially promising with the use of depleted argon and should also be explored in any of the funding scenarios.**

- **Specific Findings and recommendations for Axion Detection:**
  - ADMX completed phase-I construction and is operating well. It is estimated to take a total of 1-2 years to cover $10^{-6}$-$10^{-5}$ eV down to the first of two model benchmark sensitivities (KSVZ). Phase II of the experiment will cover the same range down to the lower model (DFSZ). This phase requires a dilution refrigerator to go from 1.7 to 0.2 K. This is a unique experiment, and its continuation through phase II is supported in all budget scenarios.

# Dark Energy Project Recommendations

- The 2008 P5 report recommended support for a staged program, as defined by the 2006 Dark Energy Task Force (DETF), of dark energy experiments as an integral part of the U.S. particle physics program.
  - PASAG reaffirms this staged approach and **recommends funding to complete those Stage III dark energy experiments receiving particle astrophysics (PA) support, *i.e.,* DES and BOSS.**
- **For all budget scenarios, timely pursuit of a Stage IV program that can obtain another order of magnitude or more improvement beyond Stage III in metrics for dark energy and gravity tests as specified by the DETF and Figure of Merit Science Working Group**.
- **Formulation of a detailed plan for achieving a comprehensive and optimal dark energy portfolio under all funding scenarios is needed.**
  - **Astro2010 is an essential component of this process.**
- **The JDEM design process should be coupled to plans for ground-based projects to ensure that JDEM offers the possibility to significantly extend the capabilities of ground-based experiments.**

# Dark Energy Project Specifics (I)

- **JDEM:** Uncertainties about the technical approach, scope, and organization of JDEM remain. PASAG knows of no actively engaged science panel currently advising the JDEM Project Offices.
  - **While the responsibility for the project rests with the project management, it is essential that the observatory design and approach be a close, collaborative effort between dark energy scientists in the community and the project team to ensure a scientifically successful mission.**
  - **Support of JDEM as a particle astrophysics project should imply that the methods and talents of the HEP community are applied to JDEM at its design, instrument construction, and science analysis phases.**

# Dark Energy Project Specifics (II)

- **LSST:** This project has a well-developed design and collaboration with very strong HEP participation in design, management, and construction plans, as well as in the LSST Collaboration. **Continuing support of LSST preparatory work is recommended so that ground possibilities are known for timely planning of a coherent ground-space dark energy effort.** An ambitious ground-based imaging survey over most of the accessible extragalactic sky is an essential element for nearly all approaches in a cohesive ground-space dark energy strategy.

- **BigBOSS** is in the early planning stages, but presents a legitimate possibility of achieving a significant fraction of the BAO science goals for JDEM at <$100M cost. **Substantial immediate support is recommended for BigBOSS R&D so that ground BAO possibilities are known for timely planning of a coherent ground-space dark energy effort.** The ground astronomy agencies (NSF/NOAO) are essential partners in the BigBOSS project and planning.

# Conclusions

- Exciting times are ahead for particle astrophysics!
- Well aligned with the other frontier areas:
  - Example: the same type of dark matter particles may be produced anew in the Large Hadron Collider (LHC), while relic copies are detected both underground at low energy and from outer space at high energy. Each of these will provide a needed piece of the puzzle. This is a particularly exciting time of convergence of theory and experiment, particle physics and astrophysics.
- A strong entrepreneurial spirit providing great discovery potential.
- Cultural differences between scientific communities are not necessarily impediments, but rather reinforcing capabilities enabling important new opportunities.