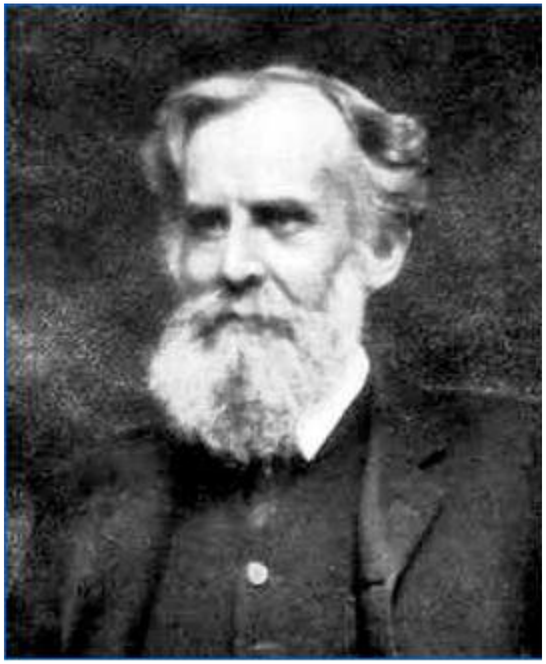
Future Experiments at the Cosmic Frontier

An Interim Report

Snowmass on the Pacific, KITP

S. Ritz
for the Cosmic Frontier Group



(the venerable Venn)

See http://www.snowmass2013.org/tiki-index.php?page=Cosmic%20Frontier and http://www-conf.slac.stanford.edu/cosmic-frontier/2013/

The Future in the Past

http://sites.nationalacademies.org/bpa/BPA_049810

http://science.energy.gov/~/media/hep/pdf/files/pdfs/PASAG_Report.pdf

- Lots of planning and prioritization work already done (PASAG, NWNH, …). Updating and filling in holes, new opportunities. Field is very much discovery driven, and evolves rapidly.
- PASAG (2009) prioritized projects in 4 budget scenarios:

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.

PASAG Prioritization Criteria

- The science addressed by the project is necessary
  - Address fundamental physics (matter, energy, space, time).
  - Expect 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 and significant 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.

The Future in the Past

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.

13 February 2010 PASAG Report, APS Session on International Programs

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.

13 February 2010 PASAG Report, APS Session on International Programs 18

Context (Agency Frame)

NSF Programs at Cosmic Frontier

Science at the Cosmic Frontier is supported by the Physics and Astronomy Divisions, as well as Polar Programs:

Physics - Particle Astrophysics & Particle Astrophysics and Cosmology Theory

- Direct Dark Matter Detection – WIMP and non-WIMP experiments
  SuperCDMS, XENON, LUX, DarkSide, COUPP, PICASSO, CoGeNT, DRIFT, ADMX-HF, miniCLEAN, DMTPC, DM-Ice
- Indirect Dark Matter Detection
  IceCube, VERITAS, etc.
- Cosmic Ray, Gamma Ray, and Neutrino Observatories
  IceCube, VERITAS, HAWC, Auger, Telescope Array, ANITA, ARA, ARIANNA, TAUWER, etc.
- Dark Energy
  LSST, etc.
- Cosmic Microwave Background & Fundamental Physics
  ACTPol, QUIET, Holometer, etc.

Astronomy – Astronomy and Astrophysics Research Grants Program:

- Dark Energy Experiments
  LSST, BOSS, DES, etc.
- Cosmic Microwave Background Experiments
  ACTPol, POLARBEAR, etc.

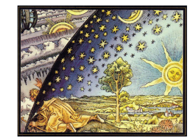
Theoretical Work

Polar Programs

DOE/HEP Program at the Cosmic Frontier

Used the 2009 PASAG report to guide the program in "thrusts"

- Discover (or rule out) the particle(s) that make up **Dark Matter**
- Advance understanding of the physics of **Dark Energy**
- Understanding the high energy universe: **Cosmic-rays, Gamma-rays**
- **Other efforts** – small efforts in CMB, holographic interferometry



When laying out a program, we increase the fraction of the HEP budget for new projects in the near term, and establish balanced program, with staged implementation and science

The HEP budget plan puts in place a comprehensive program; in five years,

- **DES** will be near the end of its survey
- **2nd-Generation Dark Matter (DM-G2)** experiments will be probing the most preferred phase space (CD0 signed Sept 2012).
- **Mid-scale Dark Energy Spectroscopic instrument (MS-DESI)** to complement DES/LSST will be beginning operations (CD0 signed Sept 2012)
- **Large Synoptic Survey Telescope** will make definitive Stage-IV ground-based Dark Energy measurements using weak lensing; DOE responsible for LSST-camera; CD-1 signed in 2012.
- **High Altitude Water Cherekov** Observatory: will observe TeV gamma-rays and cosmic rays.

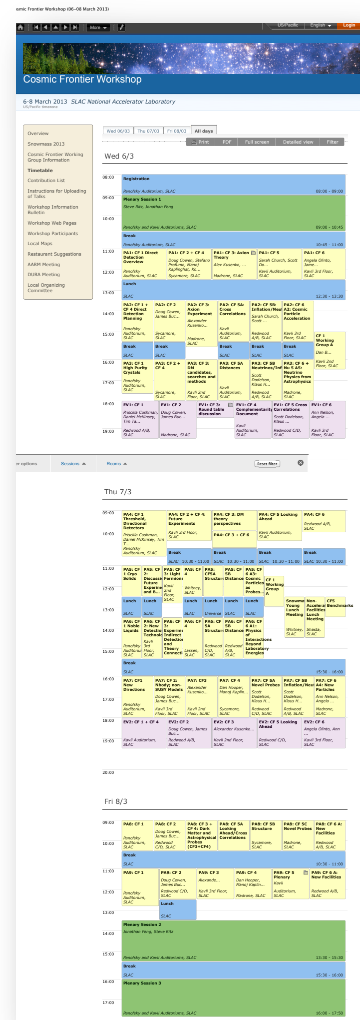
CTA: NSF leads (Astro2010). We have no funding identified at this time for a contribution to CTA.

DOE/HEP/CF is science mission-driven: We develop and support a specific portfolio of projects; research funding is directed to the support of these projects– this includes coordinated data analysis. We form partnerships or use other agency's facilities when needed (e.g., telescopes), and make project contributions at an appropriate level for facilities with a broader science program.

March CF Workshop at SLAC

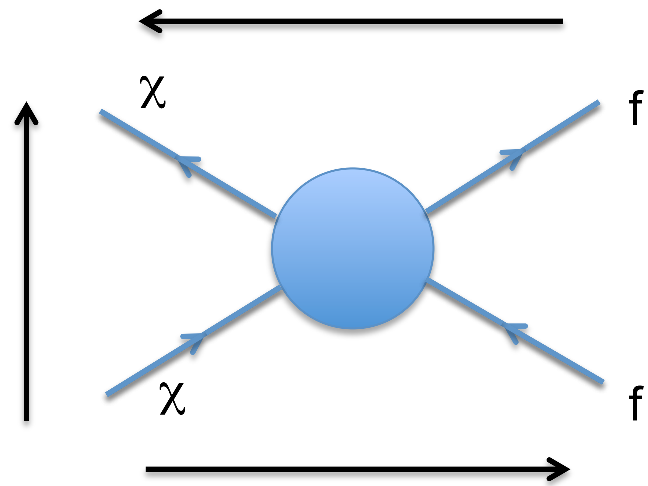
Cosmic Frontier Workshop

- Intensive three-day workshop 6-8 March
  - 338 Registrants; 200 talks + panels, roundtable discussions,…
  - very broad range of topics; many new and exciting opportunities with close connections to the other Frontiers. Stimulating and FUN!
- Work planned and underway for deliverables
- Planning for the summer meeting
  - more time for discussions
  - cross-cutting interests with the other Frontiers
  - join together to promote the whole program



1. WIMP Dark Matter

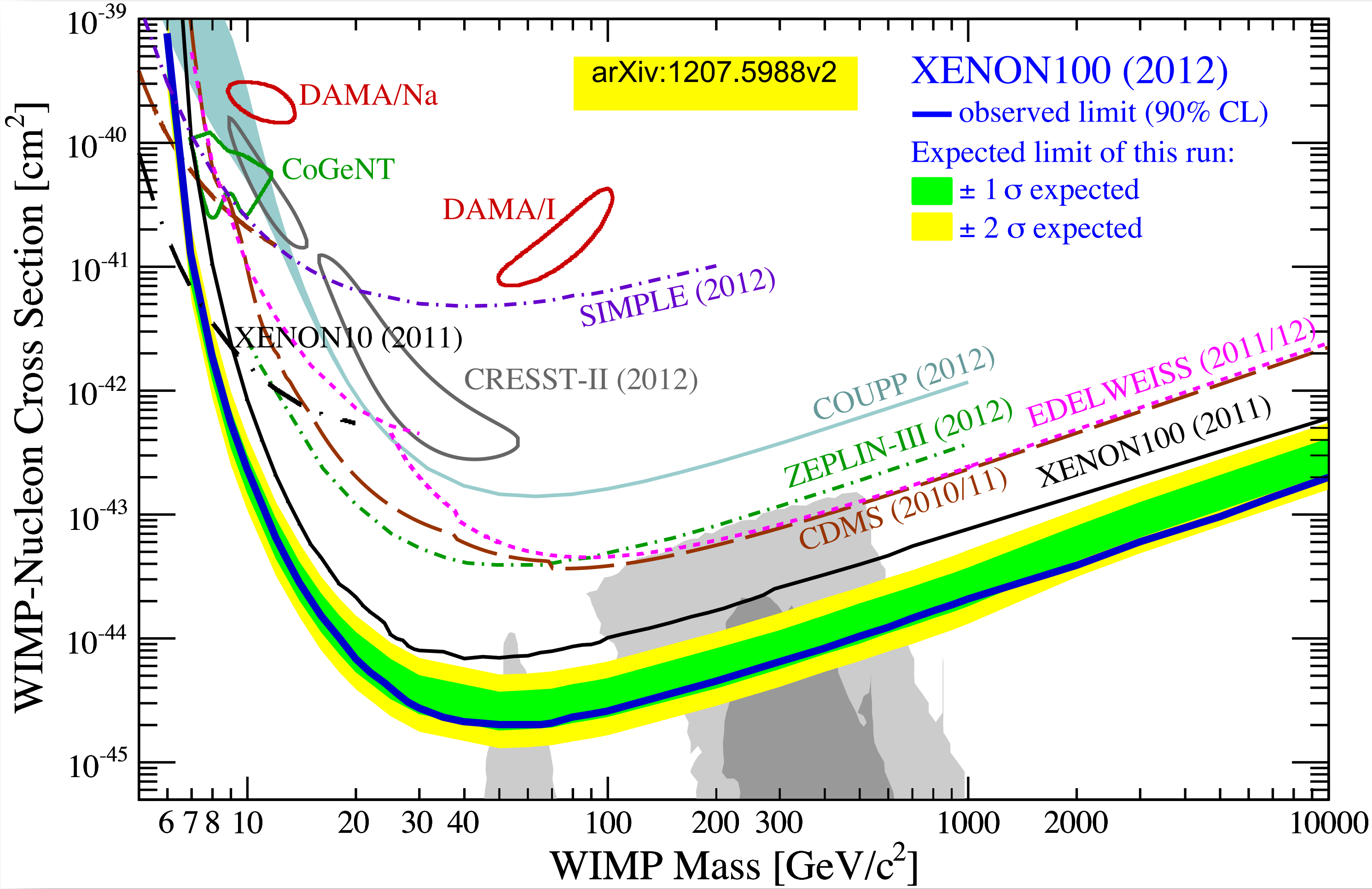
- Simplest picture:
  - Thermal production in the early Universe (left, right)
  - Direct Detection (up)
  - Indirect Detection (right)
  - Production at colliders (left)

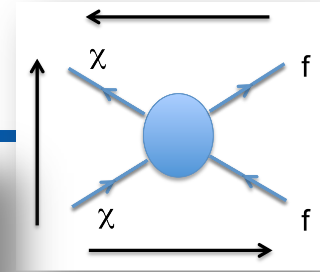


- Provides natural scales for searches, particularly for Indirect Detection.

- Nature may not be so simple!

CF1 parameter space





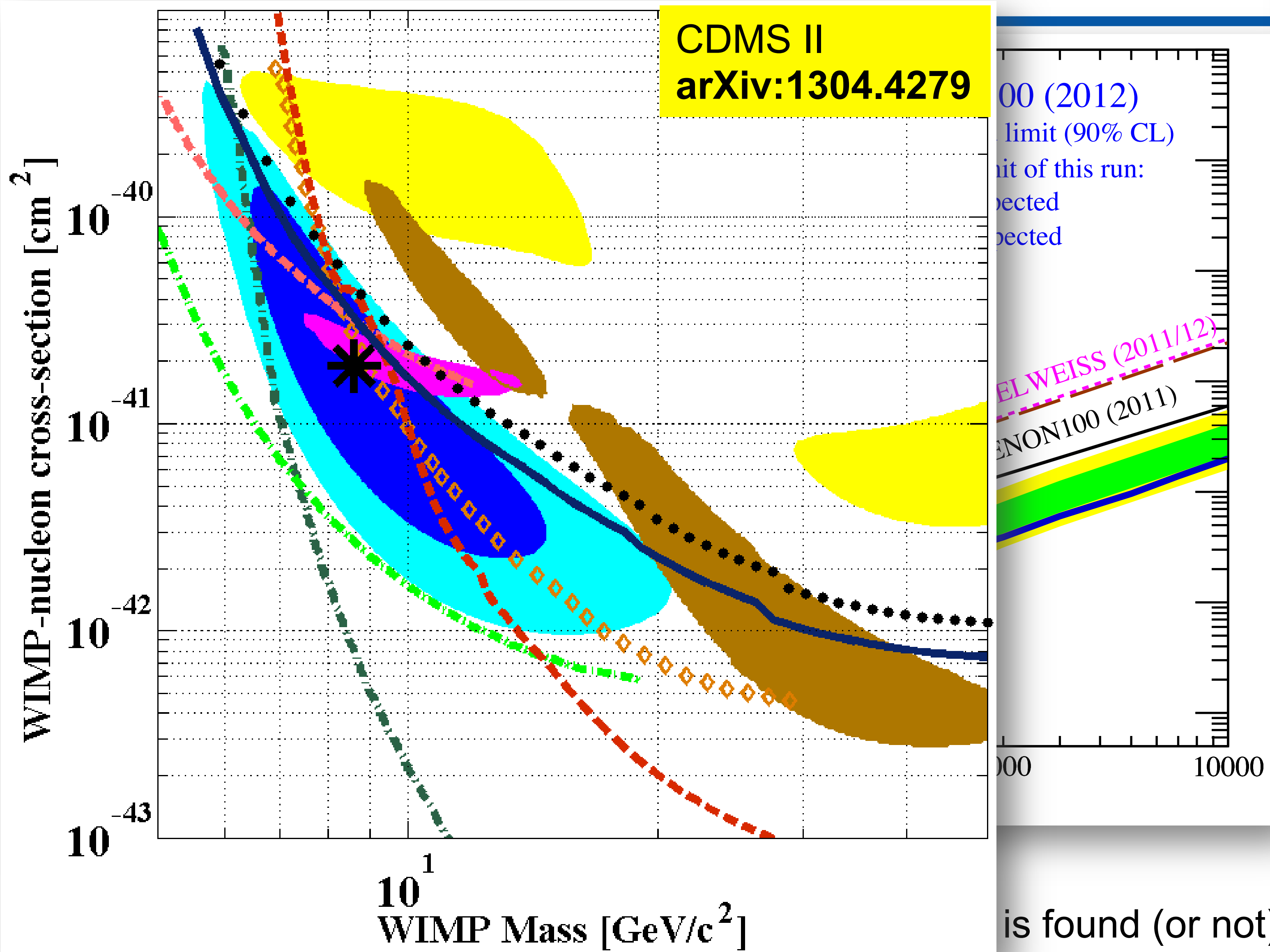
G2

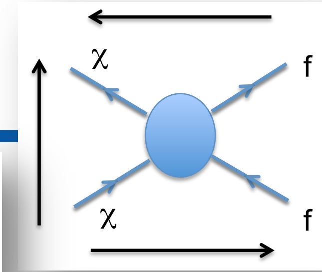
G3: follow-up to G2, based on what is found (or not)

G3

ν bkgd

CF1 parameter space





is found (or not)

WIMP Direct Detection Experiments

http://www.snowmass2013.org/tiki-index.php?page=SLAC

Table of current and planned experiments (under construction)

Experiment	Status	Target	Technique	Location	Major Support
Cryogenic Solid State					
SuperCDMS Soudan	Current	9 kg Ge	Ionization, Phonons	Soudan	DOE, NSF
SuperCDMS SNOLab	Planned	200 kg Ge	Ionization, Phonons	SNOLab	DOE, NSF
SuperCDMS SNOLab	Planned	400 kg Ge	Ionization, Phonons	SNOLab	DOE, NSF
Edelweiss	Current	4 kg Ge	Ionization, Phonons	Modane	Europe
CRESST	Current	10 kg CaWO4	Scintillation, Phonons	LNGS	Europe
EURECA	Planned	Ge; CaWO4 O(100-1000kg)	Ionization+Phonons; Scintillation+Phonons	Europe	Europe
CoGeNT	Current	440 g Ge	Ionization	Soudan	DOE, NSF
C-4	Planned	5.2 kg Ge	Ionization	Soudan	DOE, NSF
TEXONO	Current	O(1kg)Ge	Ionization	KSNL	Taiwan
CDEX	Current	O(1-10kg)Ge	Ionization	CJPL	China
Liquid Xenon					
LUX	Current	350 kg LXe	Ionization, Scintillation	SURF	DOE, NSF, Europe
LZ	Planned	8000 kg LXe	Ionization, Scintillation	SURF	DOE, NSF, Europe
PandaX-1a	Current	125 kg LXe	Ionization, Scintillation	CJPL	China
PandaX-1b	Planned	500 kg LXe	Ionization, Scintillation	CJPL	China
PandaX-2	Planned	2400 kg LXe	Ionization, Scintillation	CJPL	China
XENON100	Current	62 kg LXe	Ionization, Scintillation	LNGS	DOE, NSF, Europe
XENON1T	Planned	2500 kg LXe	Ionization, Scintillation	LNGS	DOE, NSF, Europe
XENON10T	Planned	20000 kg LXe	Ionization, Scintillation	LNGS	DOE, NSF, Europe
XMASS-I	Current	835 kg LXe	Scintillation	Kamioka	Japan
XMASS-1.5	Planned	5000 kg LXe	Scintillation	Kamioka	Japan
XMASS-II	Planned	20000 kg LXe	Scintillation	Kamioka	Japan
Liquid Argon					
DarkSide-50	Current	50 kg LAr	Ionization, Scintillation	LNGS	DOE, NSF, Europe
DarkSide-G2	Planned	5000 kg LAr	Ionization, Scintillation	LNGS	DOE, NSF, Europe
ArDM	Current	1 ton LAr	Ionization, Scintillation	Canfranc	Europe
MiniCLEAN	Current	500 kg LAr/LNe	Scintillation	SNOLab	
DEAP-3600	Current	3600 ton LAr	Scintillation	SNOLab	Canada, UK
CLEAN	Planned	40 ton LAr/LNe	Scintillation	SNOLab	
Crystal and Annual Modulation					
DAMA/LIBRA	Current	NaI	Europe		
ELEGANT	Current	NaI	Japan		
DM-Ice	Planned	NaI			
Princeton NaI	Planned	NaI	LNGS		
ANAIS	Planned	250 kg NaI	Scintillation	Canfranc	Europe
CINDMS	Planned	100 kg CsI(Na)	Scintillation	China	
KIMS	Current	cesium iodide	Scintillation	Korea	
Superheated Liquids					
COUPP-60	Current	CF3I	Bubbles	SNOLab	DOE, NSF
COUPP-1T	Planned	CF3I	Bubbles	SNOLab	DOE, NSF
PICASSO	Current	C4F10	Bubbles	SNOLab	Canada
Picoupsso?	Planned	CF3I	Bubbles	SNOLab	DOE, NSF, Canada
SIMPLE Phase III	Current	1-2 kg C2ClF5	Bubbles	Canfranc	Europe
SIMPLE Phase IV	Planned	1000 kg C2ClF5	Bubbles	Canfranc	Europe
Directional Detection					
DRIFT-IId	Current	139 g CS2, CS4	Ionization	Boulby	US,UK
DRIFT-III	Planned	10s of kg CS2, CS4	Ionization	Boulby	US,UK
DMTPC	Current	CF4 gas	Ionization	WIPP	DOE
D^3	Planned		Ionization		
MIMAC	Planned		Ionization	Modane	
Newage	Planned		Ionization		Japan
New Ideas					
Columnar recombination	Planned	Xe gas	Ionization, Scintillation	Canfranc	
DAMIC	Current	Silicon	Ionization	SNOLab	
Liquid He-4	Planned	1-100 kg LHe	Ionization, Scintillation, Rotons	-	-
DNA	Planned	Gold	Broken DNA bonds	-	-
Nuclear emulsions	Planned	few 10s of kg emulsion	-	-	-

WIMP Direct Detection Experiments

Cryogenic Solid State

CDMS/SuperCDMS
EDELWEISS/CRESST/EURECA
CoGeNT/C4
TEXONO/CDEX

Liquid Xenon

LUX/LZ

XENON
PandaX
XMASS

Liquid Argon

ArDM
Darkside
DEAP
CLEAN

Crystal and Annual Modulation

DAMA/LIBRA
KIMS
ELEGANT
ANAIS
CINDMS
Princeton NaI
DM-Ice

http://www.snowmass2013.org/tiki-index.php?page=SLAC

Threshold Detectors

Technology Description
PICASSO
SIMPLE
COUPP

Directional Detection

DRIFT
Newage
DMTPC
MIMAC
D3

New Ideas

DAMIC
Liquid helium-4
NEXT
Nuclear emulsions (Naka, Japan)
DNA & Nano-explosions (Drukier/Cantor)

WIMP Direct Detection Census

1. Experiment Status and Target Mass
2. Fiducial target mass
3. Backgrounds after passive and active Shielding.
4. Detector Discrimination

   What is your current demonstrated experiment discrimination factor, in both your total volume and in your fiducial volume, for each type of background (gamma, beta, alpha, radiogenic neutrons, cosmogenic neutrons)? Please quote these at 100 kevnr, and for 10 kevnr, or the lowest energy you have measured them.

   By what factor might these improve in the future? Describe briefly how you would achieve any improvements.

   Do you have "outlier" events that cannot be described by your simulations or calibrations?

5. Energy Threshold
6. Sensitivity versus WIMP mass
7. Experimental Challenges
   - What are the facility requirements (size, depth, ...) for your next generation experiment?
8. Annual Modulation
9. Unique Capabilities
10. Determining WIMP properties and astrophysical parameters
    - If a signal is detected, what information does your experiment provide about WIMP properties (especially WIMP mass), and about dark matter distribution in
    - the galaxy?

http://www.snowmass2013.org/tiki-index.php?page=SLAC

WIMP Direct Detection Tough Questions

- With the significant change of plans involving DUSEL, what are the needs for underground floor space for low-background experiments, and are those needs met in current planning?

- When is the right time to abandon small projects and band together for larger ones? Should we already do that now that the DOE has spoken about its G2 plans?

- Dark matter direct detection will reach the neutrino background at some stage. Although this background is not formally irreducible, is it realistic to think that one could go beyond this? What experiments would make this possible in a cost-effective way?

- Suppose experiments using one target are significantly more sensitive than those using another target in terms of sigma_SI (say, a factor of 5 or 10 -- you pick.) Is there a compelling rationale for continuing funding for experiments using the non-leading targets? How should P5 decide?

2.WIMP Indirect Detection: Many Places to Look!

Galactic Center

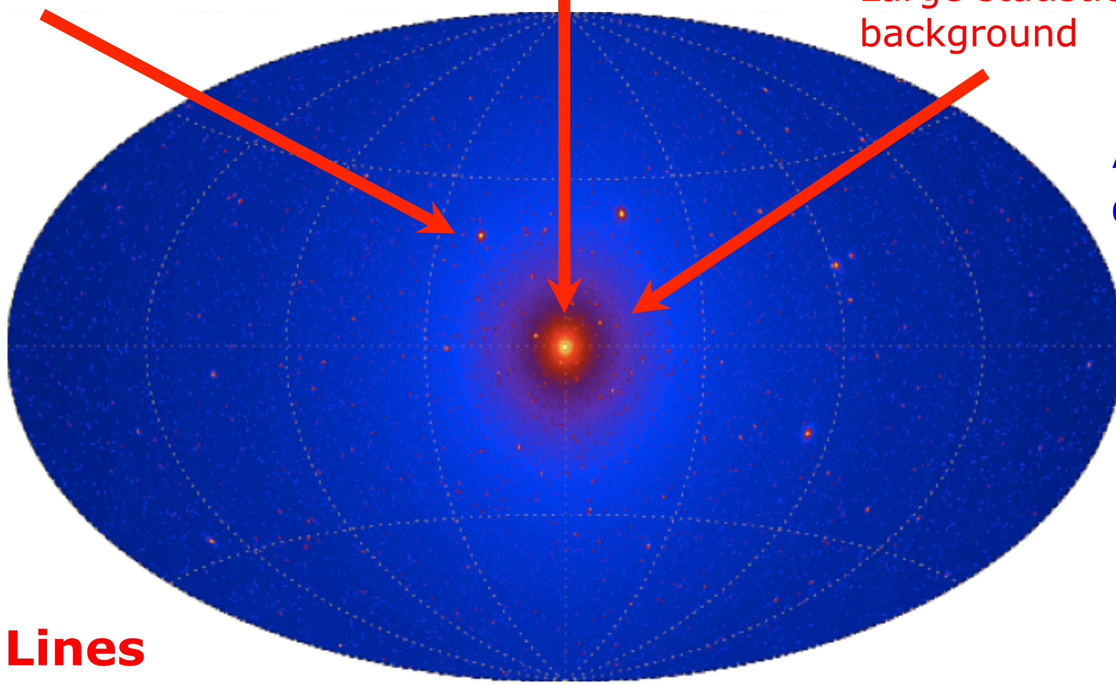
Good Statistics but source confusion/diffuse background

Satellites

Low background and good source id, but low statistics, in some cases astrophysical background

Milky Way Halo

Large statistics but diffuse background



All-sky map of gamma rays from DM annihilation arXiv:0908.0195 (based on Via Lactea II simulation)

And anomalous charged cosmic rays (little/no directional information, trapping times, etc.)

Spectral Lines

No astrophysical uncertainties, good source id, but low sensitivity because of expected small BR

Extragalactic

Large statistics, but astrophysics, galactic diffuse background

Galaxy Clusters

Low background, but low statistics

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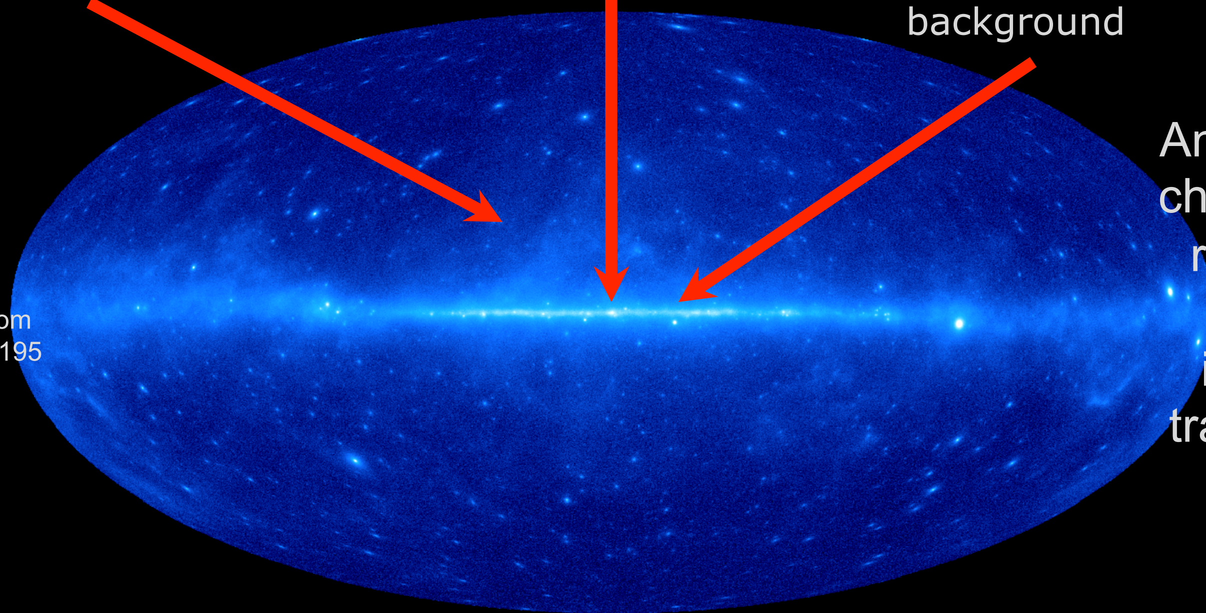

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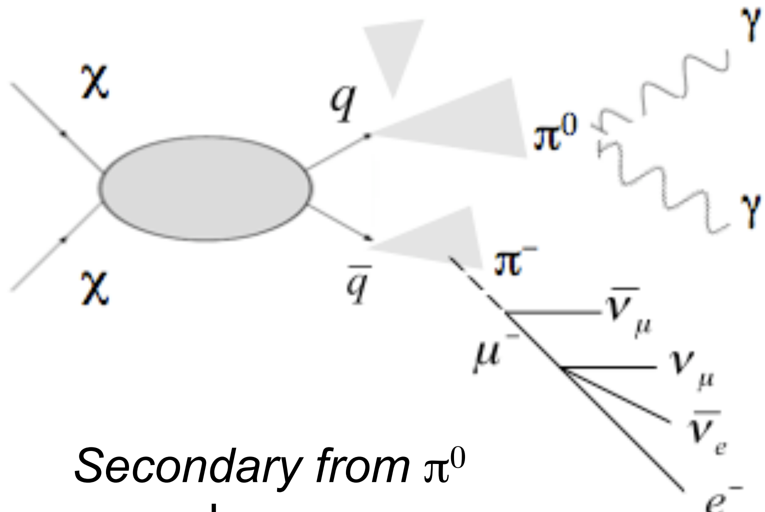
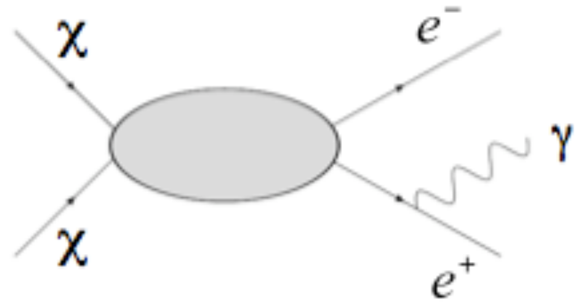
Gamma rays from Dark Matter Annihilation



Secondary from π^0
decays



Prompt lepton
pair production

+ "lines" from 2-body final states

$$\Phi_{WIMP}(E,\Psi)=J(\Psi)\times\Phi^{PP}(E)$$

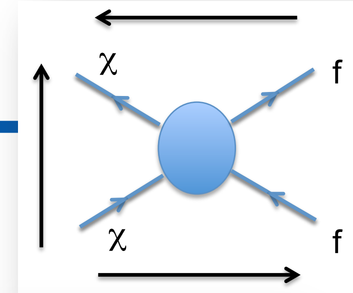
Astrophysical factor

$$J(\Psi)=\int_{l.o.s} dl(\Psi)\rho^2(l)$$

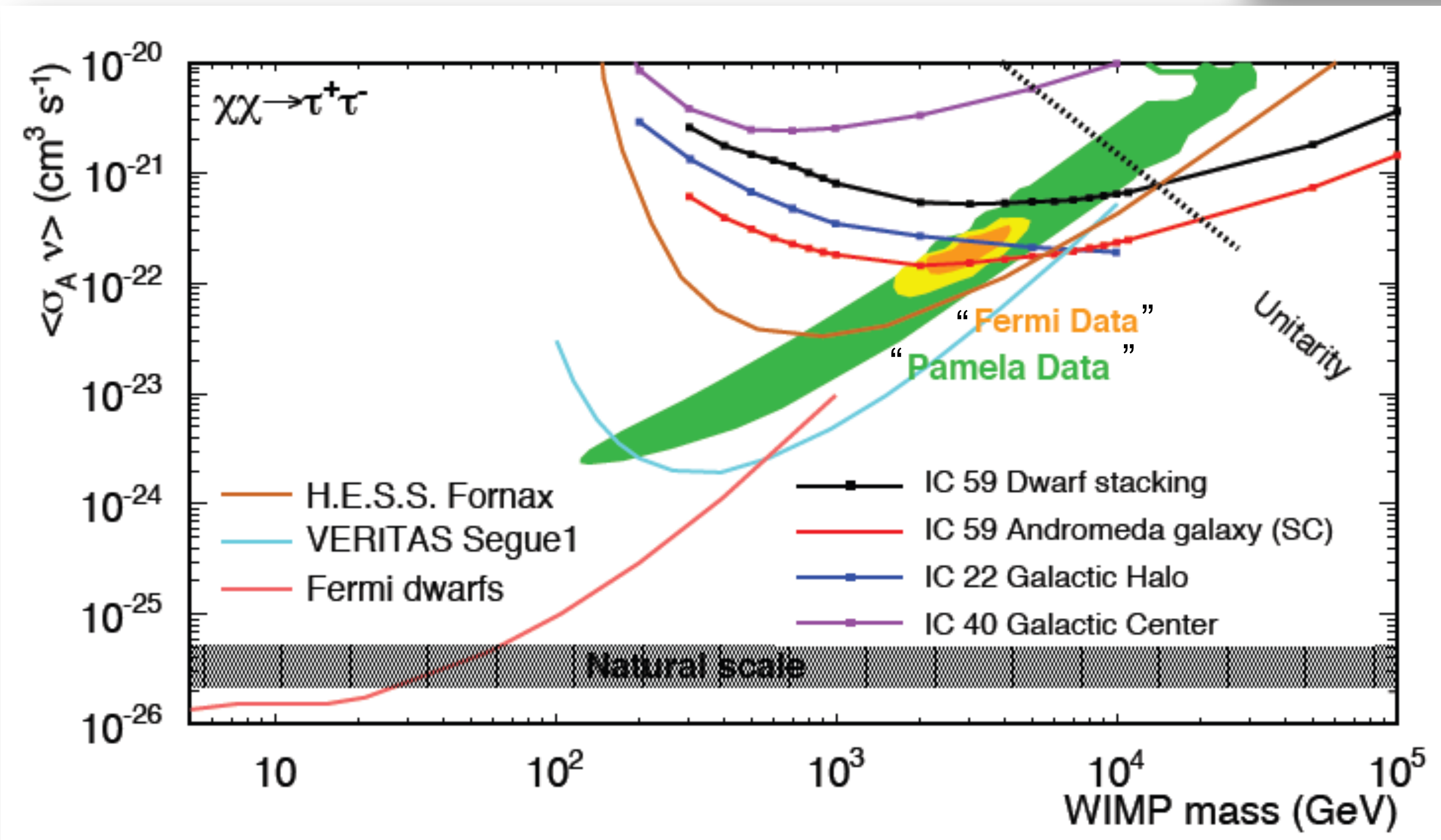
Particle physics factor

$$\Phi^{PP}(E)=\frac{1}{2}\frac{\langle\sigma v\rangle}{m_{WIMP}^2}\sum_f \frac{dN_f}{dE}B_f$$

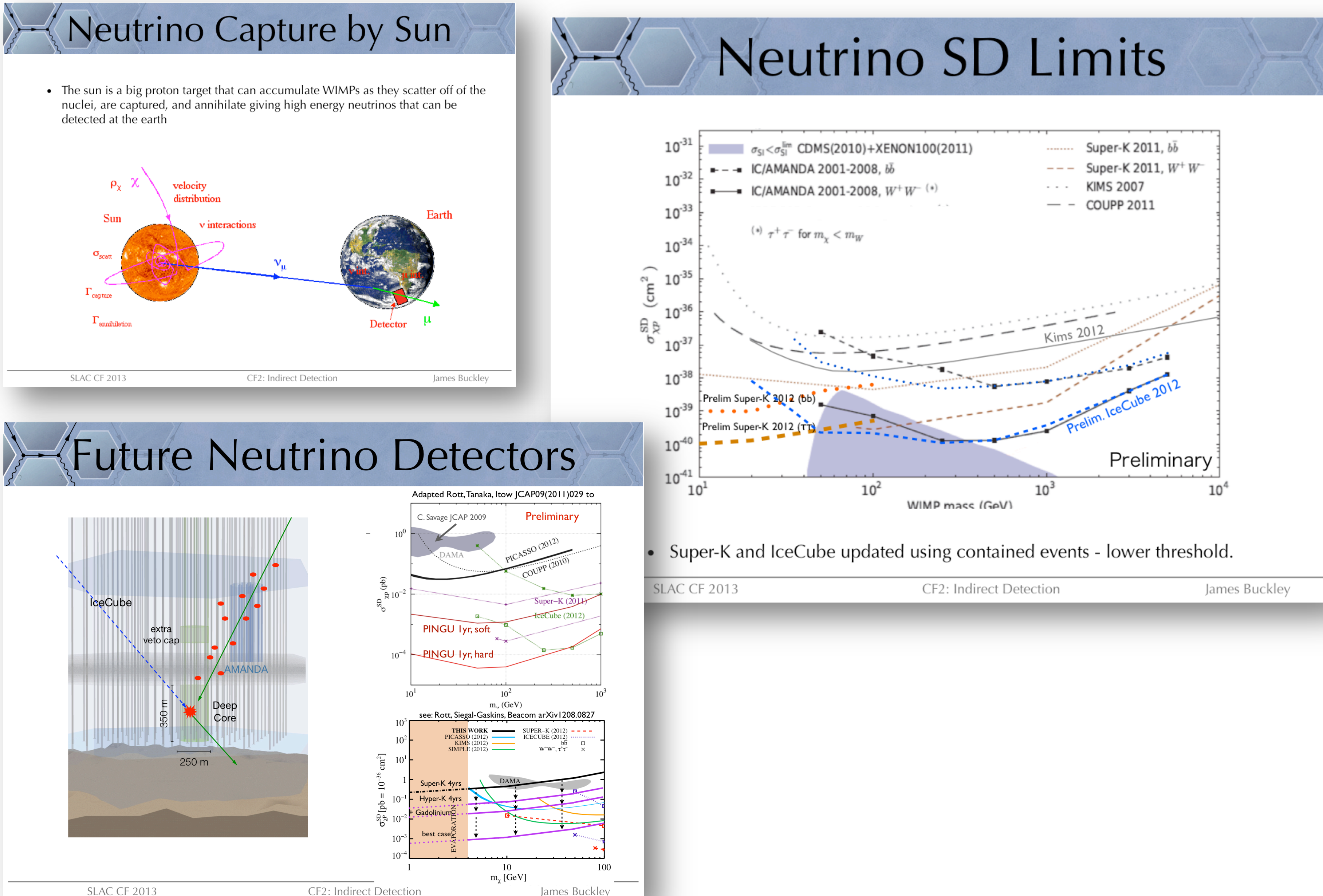
Indirect Detection Parameter Space



(F. Halzen, March Workshop)



Indirect Detection Facilities



Indirect Detection Facilities

Indirect Detection Experiments

Status	Experiment	Target	Location	Major Support	Comments
Current	AMS	e+/e-, anti-nuclei	ISS	NASA	Magnet Spectrometer, Running
	Fermi	Photons, e+/e-	Satellite	NASA, DOE	Pair Telescope and Calorimeter, Running
	HESS	Photons, e-	Namibia	German BMBF, Max Planck Society, French Ministry for Research, CNRS-IN2P3, UK PPARC, South Africa	Atmospheric Cherenkov Telescope (ACT), Running
	IceCube/ DeepCore	Neutrinos	Antarctica	NSF, DOE, International: Belgium, Germany, Japan, Sweden)	Ice Cherenkov, Running
	MAGIC	Photons, e+/e-	La Palma	German BMBF and MPG, INFN, WSwiss SNF, Spanish MICINN, CPAN, Bulgarian NSF, Academy of Finland, DFG, Polish MNiSzW	ACT, Running
	PAMELA	e+/e-	Satellite		
	VERITAS	Photons, e+/e-	Arizona, USA	DOE, NSF, SAO	ACT, Running
	ANTARES	Neutrinos	Mediter-ranean	France, Italy, Germany, Netherlands, Spain, Russia, and Morocco	Running
Planned	CALET	e+/e-	ISS	Japan JAXA, Italy ASI, NASA	Calorimeter
	CTA	Photons	ground-based (site TBD)	International: MinCyT, CNEA, CONICET, CNRS-INSU, CNRS-IN2P3, Irfu-CEA, ANR, MPI, BMBF, DESY, Helmholtz Association, MIUR, NOVA, NWO, Poland, MICINN, CDTI, CPAN, Swedish Research Council, Royal Swedish Academy of Sciences, SNSF, Durham UK, NSF, DOE	ACT
	GAMMA-400	Photons	Satellite	Russian Space Agency, Russian Academy of Sciences, INFN	Pair Telescope
	GAPS	Anti-deuterons	Balloon (LDB)	NASA, JAXA	TOF, X-ray and Pion detection
	HAWC	Photons, e+/e-	Sierra Negra	NSF/DOE	Water Cherenkov, Air Shower Surface Array
	IceCube/ PINGU	Neutrinos	Antarctica	NSF, Germany, Sweden, Belgium	Ice Cherenkov
	KM3NeT	Neutrinos	Mediter-ranean	ESFRI, including France, Italy, Greece, Netherlands, Germany, Ireland, Romania, Spain, UK, Cyprus	Water Cherenkov
	ORCA	Neutrinos	Mediter-ranean	ESFRI, including France, Italy, Greece, Netherlands, Germany, Ireland, Romania, Spain, UK, Cyprus	Water Cherenkov

http://www.snowmass2013.org/tiki-index.php?page=WIMP+Dark+Matter+Indirect+Detection

Indirect Detection Facilities

Key Findings

Disclaimer: Not an exhaustive list of key Indirect DM science initiatives!
(10 minutes can't do justice to amazing breadth of work)

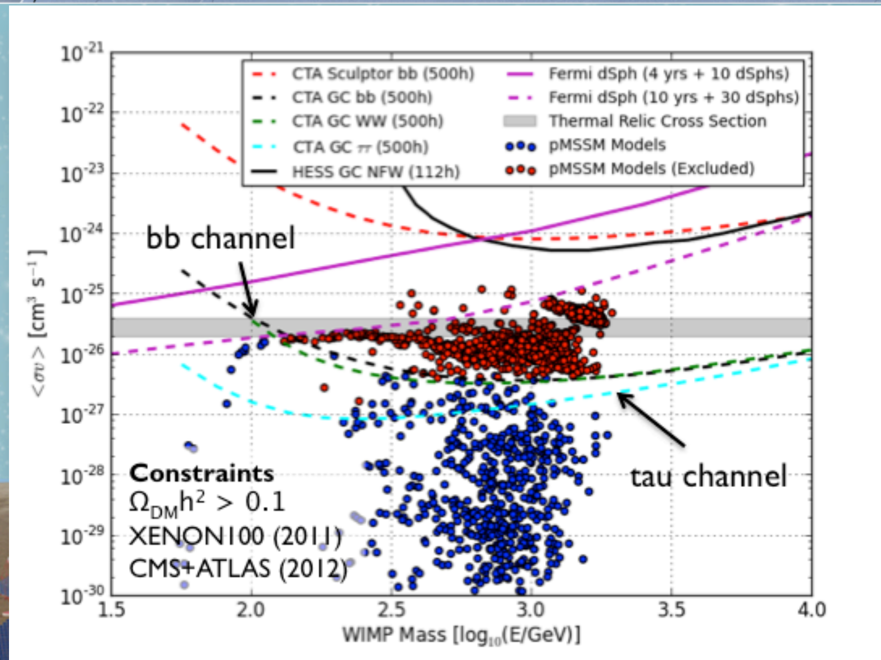
- CTA, with the U.S. enhancement would provide a powerful new tool for searching for WIMP dark matter, and would complement other methods
- Future Neutrino experiments like the PINGU enhancement to IceCube/DeepCore offer the possibility of a smoking-gun signal (high energy neutrinos from the sun), and may provide some of the best constraints on spin dependent cross sections.
- Other astrophysical constraints such as low-frequency radio (synchrotron from electrons) or X-rays (inverse Compton scattering by electrons) can provide very powerful tests for Dark matter annihilation for certain annihilation channels, competitive with existing bounds.
- Detailed theoretical studies with PMSSM, contact operators, realistic halo models are resulting in quantitative estimates of sensitivity
- Key technology developments overlap with Direct Detection and Collider experiments.

http://www.snowmass2013.org/tiki-index.php?page=WIMP+Dark+Matter+Indirect+Detection

PINGU Physics Goals

- Neutrino mass hierarchy determination with ~5-15 GeV atmospheric neutrinos
  - First detection of parametric oscillations "for free"
- Other neutrino oscillation physics: maximal θ_{23}, ν_τ appearance
- Low mass WIMP dark matter detection via neutrinos
- Point source search for $E_\nu \gtrsim 10$ GeV neutrinos
- R&D for possible megaton-scale Cherenkov ring-imaging detector: "MICA"

CTA



Indirect Detection Tough Questions

- Given large and unknown astrophysics uncertainties (for example, when observing the galactic center),
  - what is the strategy to make progress in a project such as CTA which is in new territory as far as backgrounds go?
  - How can we believe the limit projections until we have a better indication for backgrounds and how far does Fermi data go in terms of suggesting them?
  - What would it take to convince ourselves we have a discovery of dark matter?

3."Non-WIMPs" is a lot!

Wide-Ranging, Lively Discussion

Wednesday:

Pierre Sikivie "An Argument that the Dark-Matter is Axions"
Maurizio Gionnotti "Astrophysical Constraints on Axion-Photon Coupling"
Kyu Junk Bae "Cosmology of SUSY Axion Models"
Gray Rybka "ADMX Current Status"
Karl van Bibber "ADMX-HF"
Gianpaolo Carosi "Microwave Cavity R&D for Axion Cavity Searches"
Michael Pivovarov "IAXO: International Axion Observatory"
Ariel Zhitnitsky "Dark Matter & Baryogenesis as Two Sides of the Same Coin"
Kyle Lawson "Ground-Based Quark Nugget Search"
Javier Redondo "IAXO and the Science Case"
Agnieszka Ciepiak "Contraining Primordial Black Hole Dark Matter Using Microlensing"
Jeremy Mardon "Direct Detection Beyond the WINP Paradigm"

(Kusenko & Rosenberg
March Workshop Summary)

Wide-Ranging Discussion (continued)

Thursday:

Takeo Moroi "Non-WIMP Dark Matter in SUSY Models
Yasunori Nomura "A Theoretical Perspective on Dark Matter"
Clifford Cheung "Non-WIMP Zoology"
Jiji "Double-Disk Dark Matter" (joint CF6)
Kris Sigurdson "Dark Matter Antibaryons and Induced Nucleon Decay" (joint CF6)
George Fuller "Dark Matter and Supernovae"
Kevork Abazajian "The Status of Sterile Neutrino Dark Matter"
Oleg Ruchaiskiy "Sterile Neutrinos as Dark Matter"
David Cline "The Search for Low-Mass WIMPs"
Leonidas Moustakis "Shedding Light"
Jenniver Seigel-Gaskins "Constraints on Sterile Neutrinos DM From Fermi …"

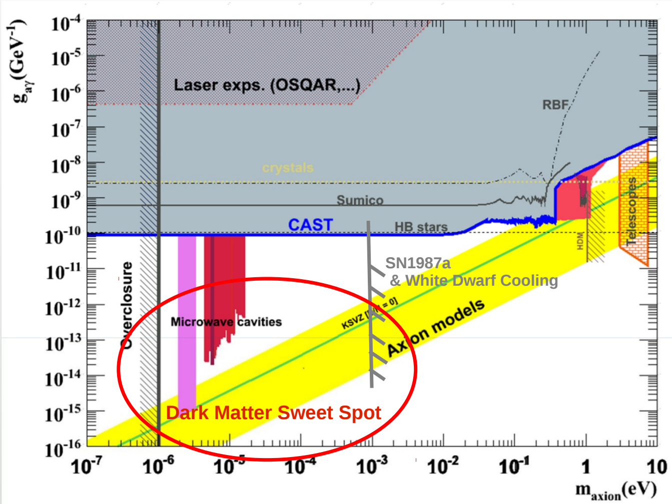
Friday (with CF4):

Louis Strigari "Is there observed tension between small-scale structure and CDM?"
Hector de Vega "Fermionic WDM Reproduces Galaxy Observations because of Q.M."
Dodelson "Current and Future Cosmological Constraints on Neutrinos"

Also see http://www.physics.utah.edu/snowpac/index.php/snowdark-2013/snowdark-2013-talks-slides

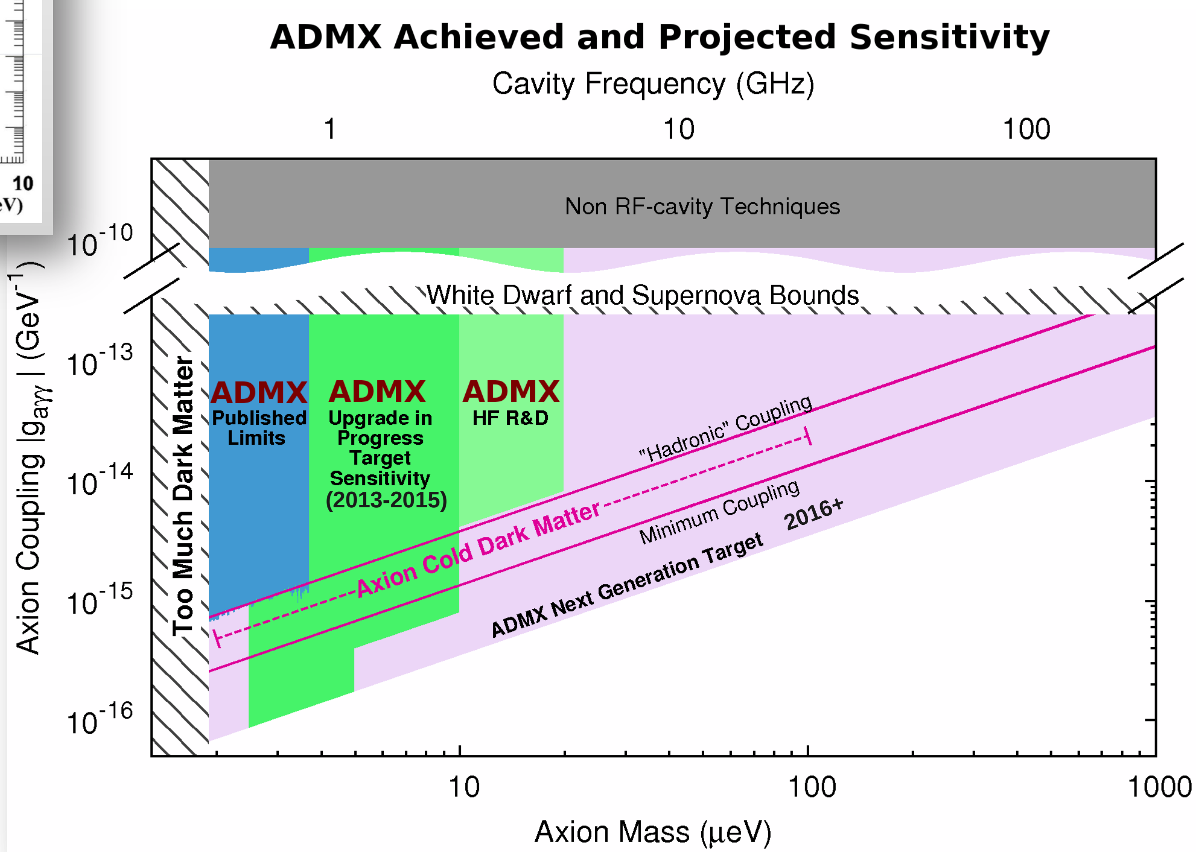
Axion Parameter Space

Experimental Constraints



(G. Rybka, March Workshop)

ADMX Moving Forward



CF3 tough questions

- Clarify the uncertainties in the expected axion detection rates.
  - Particle physics: for a given mass, what is the lowest possible coupling? If there is no lower bound, are there values beyond which the models get qualitatively more fine-tuned and the search becomes less motivated?
  - Astrophysics: can there be large variations local density? If so, how do these modify the experimental reach?

- What is the target range for axion mass and coupling, and how is that justified? [This question is being revised.]

4.Dark Matter Complementarity

See arXiv:1305.1605

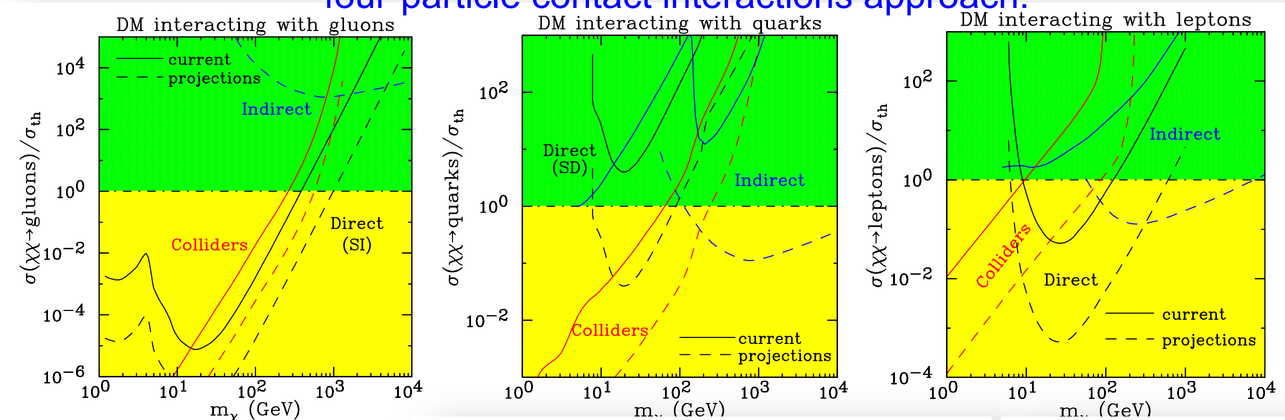
Direct Detection

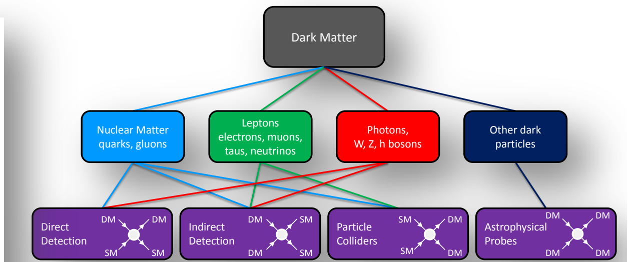
Relic scattering locally, at low energy. Push to larger target mass, lower backgrounds, directional sensitivity

Accelerators

Direct production. Push to higher energy

four-particle contact interactions approach:

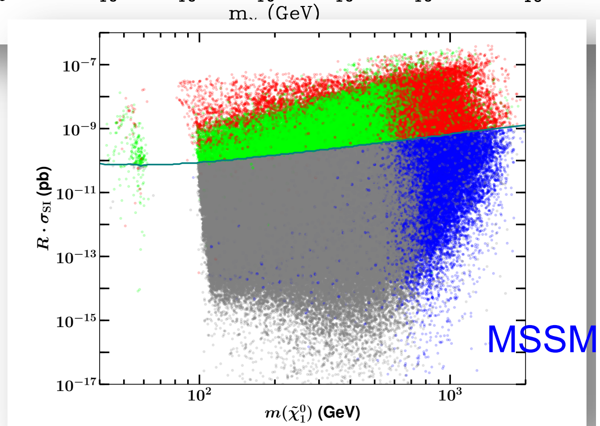




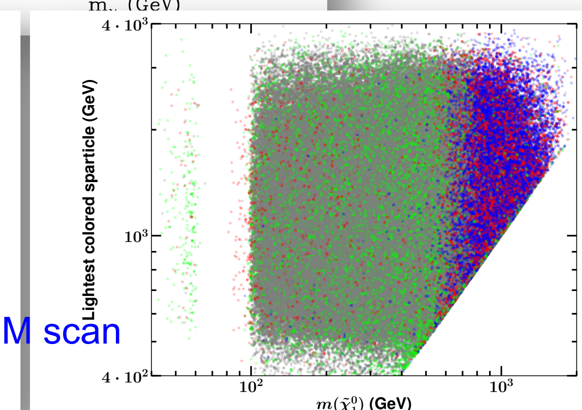
Observations

Push toward finding and studying galactic halo objects and large scale structure.

future direct detection, indirect detection or both. Plus maybe upgraded LHC only.



MSSM scan



Indirect Detection

Interactions (via annihilations, decays) with SM particles. Understand the astrophysical backgrounds in signal-rich regions, and reveal the distribution of dark matter.

Simulations

Large scale structure formation. Push toward larger simulations, finer details.

Dark Matter Complementarity

See arXiv:1305.1605

Direct Detection
Relic scattering locally, at low energy. Push to larger target mass, lower backgrounds, directional sensitivity

Accelerators
Direct production. Push to higher energy

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Push toward finding and studying galactic halo objects and large scale structure.

Indirect Detection
Interactions (via annihilations, decays) with SM particles. Understand the astrophysical backgrounds in signal-rich regions, and reveal the distribution of dark matter.

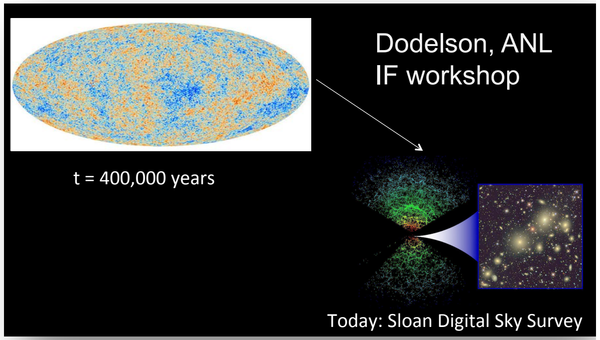
Simulations
Large scale structure formation. Push toward larger simulations, finer details.

DM Complementarity Tough Questions

- What would it take to convince ourselves that we have:
  - a discovery of dark matter?
  - discovered two different species of DM?
  - discovered ALL of the dark matter?
  - a false signal of a dark matter discovery?
- If the dark matter particle is detected through non-collider experiments, what can we learn about its properties? (*e.g.*, can we learn its spin?) Would we be able to learn whether it interacts with SM matter only through the "Higgs portal"?
- Suppose there is a 10 GeV WIMP or a 100 GeV WIMP with direct detection cross section just below current limits. This is the best case for understanding the particle nature of the dark matter. What is the full set of measurements that we are likely to make on such a particle from Cosmic Frontier probes alone?
- If there is more than one type of dark matter particle, how can we discover this in Cosmic Frontier experiments? Can we measure the dark matter fraction from different sources?
- In indirect detection of dark matter, it is notoriously difficult to rule out all hypotheses that a signal is of astrophysical origin. But perhaps other knowledge from particle physics can help. Would it be helpful, for example, to know the mass of a dark matter candidate? What accuracy is needed? Can direct detection provide sufficient accuracy?
- If dark matter has no SM interactions stronger than gravitational, are there any prospects for discovering its particle nature?

CF5: Cosmic Surveys and Particle Physics

- Getting from CMB to large-scale structure we see today:
  - **Inflation** at t~10^{-35} s (driven by a form of early Dark Energy?) shapes the…
  - …CMB map at t~300,000 years, which, seeds structure formation driven by **Dark Matter** producing the growth of structure, which…
  - …is then driven by **Dark Energy.**



- Physics beyond the Standard Model.
- Over the next decade, detailed comparisons of different observations will directly address these topics, and likely also provide more surprises.
- Along the way: new information about neutrino properties.

Dark Energy Facilities

Landscape Circa 2013

(K. Honscheid talk)

Stage III
- South Pole Telescope (CL) — RUNNING
- Dark Energy Survey (WL, BAO, SNe, CL) — RUNNING
- BOSS (BAO) — RUNNING
- …

Stage IV
- LSST: WL, BAO, (SNe) — BEING APPROVED
- ~~JDEM: WL, BAO, Sne~~
- MS-DESI — starting
- EUCLID — APPROVED

Rocky III Report

New since March: in President's budget

"Worldly" Complementarity

(M. Turner talk)

- Supernovae
  - Assumption: SNela are standard candles
  - Mature: only method that has detected acceleration by itself; warts uncovered
  - Narrow field
  - $z < 0.8$ (ground); $z > 0.8$ (space)
- BAO
  - Assumption: standard ruler + simple gravitational physics
  - Immature: 2 detections; systematics?
  - Wide field
  - Space and ground
- WL
  - Assumption: CDM, multi-parameter PS
  - Immature: technical challenges, unknown systematics, σ_8/Ω_M knowledge needed
  - Potentially most powerful probe
  - Wide field
  - Space and ground
- Clusters:
  - Assumption: CDM + Gaussian perturbations
  - Immature: first results; systematics still need to be understood
  - Wide field
  - Ground and space (x-ray)

CMB Opportunties

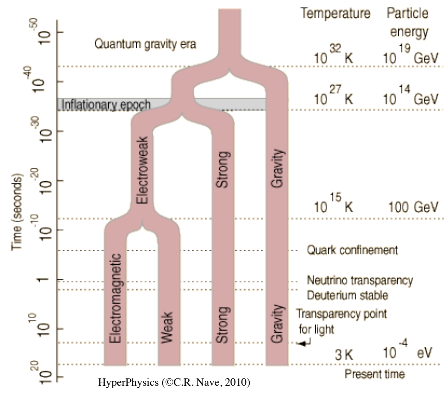
What stages?

- **Stage II: (>1K detector elements)**
  - e.g: EBEX, SPTpol, BICEP2/Keck, Polarbear, ACTpol...
  - already observing (or about to)
- **Stage III: (>10K detector elements)**
  - 10x mapping speed over Stage II (a few in the works, 2015+)
- **Stage IV: (>100K detector elements)**
  - 100x mapping speed over Stage II
  - Baseline: deploy ~2020, observe ~ 5 years

VERY CHALLENGING! – Requires 100k to 500k detectors;
Incredible attention to systematics.
Commensurate increases or more in HPC.

It is a HEP multilab scale project using the highest energy accelerator in the universe!

Early universe as an HEP lab



Summary

CMB measurements are at the heart of cosmology and fundamental physics.

Stage IV CMB experiment is needed.
It will be extremely challenging, but achievable, with 100x or more increase in detectors from current Stage II, incredible attention to systematics, and commensurate increase in computing.

It is a HEP multilab-scale project!

CMB lensing is the future

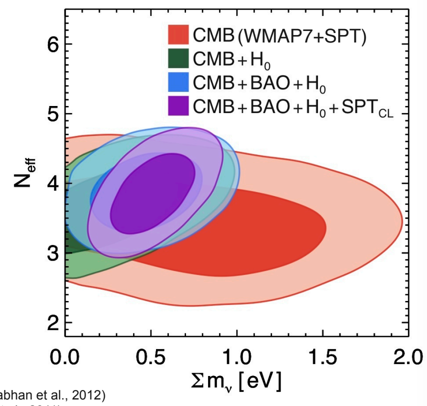
- 2007: 3σ (WMAP+) *Smith et al*
- 2008: 3σ (ACBAR) *Reichardt et al*
- 2011: 4σ (ACT) *Das et al (1st detection from CMB 4pt function)*
- 2011: 5σ (SPT) *Keisler et al*
- 2012: 6σ,7.7σ (SPT) *van Engelen et al., Story et al.*

- 2013: ≥20σ (SPT) [2500 deg²]
- 2013: ≥20σ (PLANCK) [all-sky]
- 2013+: ≥40σ from Stage II experiments
- 2016+: >100σ from Stage III σ(Σmν)~ 0.05 eV

- 2020+: **Stage IV goal σ(Σmν) ~ 0.01 eV**

PROBING THE NEUTRINO SECTOR:

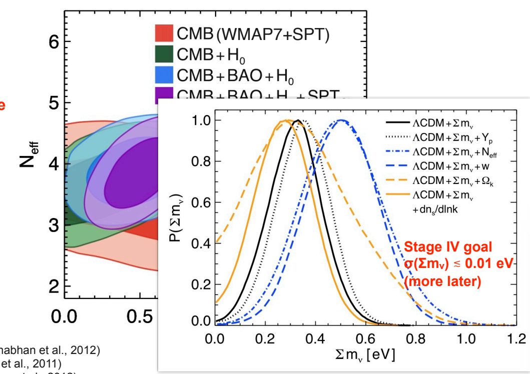
Stage IV goal σ(Neff) ≤ 0.04 incl degenerate parameters



BAO: SDSS (Padmanabhan et al., 2012)
wigglez (Blake et al., 2011)
BOSS (Anderson et al., 2012)
Ho: (Reiss et al., 2011)

Hou et al, 2012 arXiv:1212.6267

Stage IV goal σ(Neff) ≤ 0.04 incl degenerate parameters



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B-modes timeline

- 2009: r < 0.7 (BICEP) Chiang et al, 0906.1181
- 2012: no detections of inflationary or lensing B-modes

- 2013: r ≤ 0.1 from Inflationary B-modes (BICEP II) ?
- 2013: Stage II experiments detect lensing B-modes
- 2013+ Stage II experiments σ(r)≤0.03 and σ(Σmν)~0.1 eV from lensing B-modes
- 2016+: Stage III achieve σ(r)≤0.01 & σ(Σmν)~0.05 eV; measure lensing B-modes to L ~ 800 with s/n >1; allow "delensing" of inflation B-modes

- 2020+: **Stage IV goal to reach r ~ 0.001 (or better?) and σ(Σmν) ~ 0.01 eV**

CF5 Tough Questions

- What are the roles of optical and CMB observations for particle physics?
- What are the intrinsic uncertainties in supernovae that limit extractions of the properties of dark energy?
- Dark energy experiments are proposed to measure w+1 to higher and higher precision. Suppose we find w = -1at Stage IV sensitivity:
  - What are the motivations to plan beyond Stage IV?
  - Is there a value at which improved precision becomes drastically more difficult to obtain?
- For a long time, there have been indications that the number of light degrees of freedom required in cosmology is greater than 3. However, recent measurements from the CMB and other sources have given more precise information on this question. What are the prospects for establishing that this number of degrees of freedom is indeed greater than 3, or, alternatively, for providing an upper bound well below 4?

CF6 Opportunities

CF6A: Conclusions

- The Universe will tell us a lot if we know how to listen
  - Encoding can be complicated
  - Multiplexing is common
- Neutrinos, gamma rays, and cosmic rays (including anti-particles) carry a lot if information
- To get at physics beyond the standard model we need to understand the astrophysics
- Existing and planned instruments have a broad physics program.
  - Some high risk/high reward physics may be within reach
- Interface to Instrumentation Frontier (IF2)
- Need to fund theorists in this area

Fundamental Physics from Cosmic Messengers

- Neutrino mass hierarchy
  - Supernova burst neutrinos (LBNE underground)
  - Atmospheric neutrinos (PINGU at South Pole)
- Probing physics at the Plank scale
  - Sensitivity to violations of Lorentz invariance (Fermi, HESS, VERITAS, CTA, HAWC)
- Probing scale of extra dimensions
  - Neutrino cross sections at high energies (IceCube, ARA, ARIANNA, EVA, JEM-EUSO)
- Measure particle interactions at 60 (300) TeV Auger (JEM-EUSO)

New Particles

- Primordial black holes (HAWC)
  - Probe density fluctuations at very small scales
  - Time evolution of evaporation sensitive to beyond standard model physics
- Q-Balls (scalar condensate of squark fields) (HAWC, IceCube, JEM-EUSO?)
  - Prediction of SUSY in early universe (carry baryon # $10^{\sim 26}$)
  - Explains baryon asymmetry & dark matter
  - High cross section >100 mbarn, very low flux $<10^{-15} cm^{-2} sr^{-1} s^{-1}$
    - SuperK, HAWC, IceCube become direct dark matter detectors
- Anti-nuggets (antimatter color superconductor)
  - Hold all the anti-matter
  - Similar to Q-balls in flux and baryon number
  - Cross section much greater than Q-balls (energy loss mechanism quite different)
- SUSY Particles (relativistic heavy particles)
- Axion-like particles

6

New Instruments

- Many creative ideas presented at meeting
- EHE Cosmic Rays
  - JEM-EUSO, Radio Detection, Radar Detection
- Anti-Particles
  - AMS (current), GAPS (new technique: background free)
- Neutrinos
  - LBNE (10 kT liquid Argon)
    - Need to go underground for Cosmic Frontier
  - PINGU, MICA (optical detectors)
  - ARA, ARIANNA, EVA (radio detection) – 500 GT detector!
- Gamma Rays
  - CTA – pointed instrument
  - HAWC, Fermi, - all-sky: what's next?

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CF6 tough questions

- CF6/IF4/IF3/HE4: What will it take to identify the mechanism for baryogenesis or leptogenesis? Are there scenarios that could conceivably be considered to be established by experimental data in the next 20 years? What experiments are required to achieve this?

- What are the leading prospects for detecting GZK neutrinos? What experimental program is required to do this in the next 5 years, 10 years, 20 years, and how important is this?

- CF2/CF6: What are the roles of cosmic-ray, gamma-ray, and neutrino experiments for particle physics? What future experiments are needed in these areas and why? Are there areas in which these can have a unique impact?

CF-wide Question

- What criteria could be used to prioritize activities across the Cosmic Frontier?
  - The size of the communities? The connection to other key questions in particle physics and astrophysics? The variety of possible funding sources?

Technology! (One example, talk by J. Estrada)

MKID: new detectors

Semiconductor (CCDs)

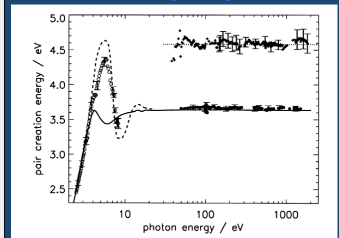
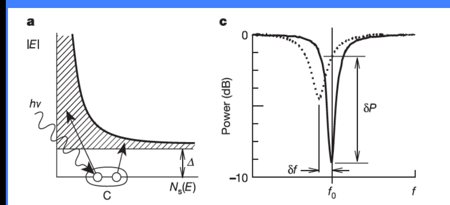


Fig. 5. Mean energy W required for creating an electron-hole pair determined from s_r and s: for silicon in the soft X-ray region [14] (closed circles) and UV and VUV region [21] (open circles) and for GaAsP in the soft X-ray region (diamonds). Typical experimental uncertainties are indicated. For silicon, calculations from Ref. [14] are shown as solid line and dashed line (see text). The points indicate the mean value of 4.58 eV for GaAsP.

1e- / red photon
No energy information

Superconductor
$N_{qp} = \eta h\nu/\Delta$,
Δ : gap parameter of the superconductor
η: is an efficiency factor (about 0.6)
Δ is meV instead of eV (this is why we like them!)
For Al Δ= 0.18 meV

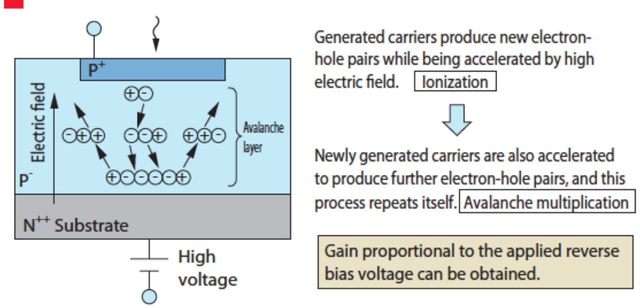
Microwave Kinetic Inductance Detector



5000 qp / red photon
Energy resolution

SiPM: array of Avalanche Photodiodes

Operating principle example of APD

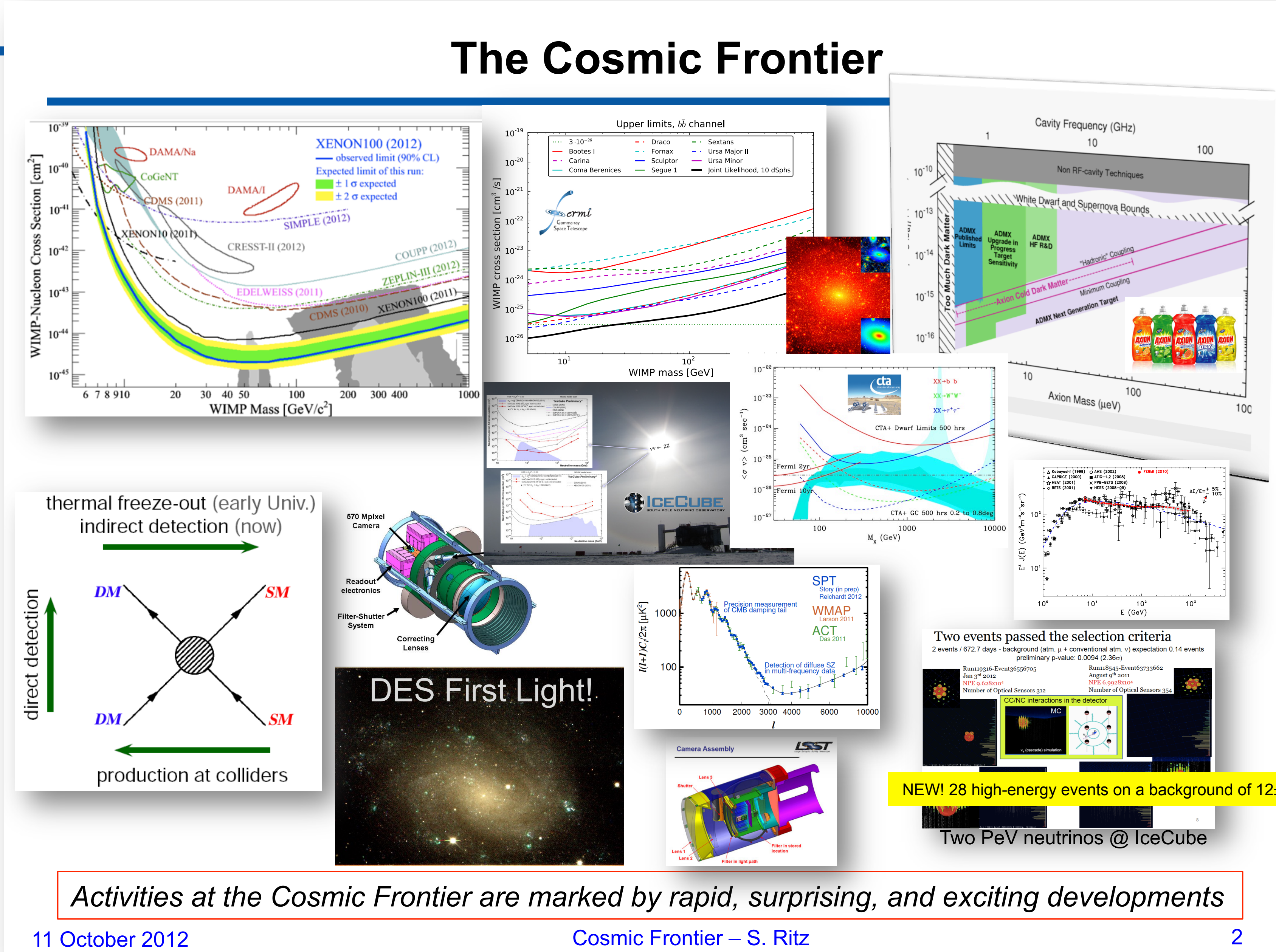


Conclusion

- If you are working on technology innovations to enable your DE science, please get in contact with us (gaston@fnal.gov, estrada@fnal.gov) to be included in the instrumentation document.
- Keep an eye on MKIDs as a tool for wide field low resolution spectroscopy.
- Keep an eye on SiPMs as a new detector for astronomical imaging pushing opening a new window for high time resolution.

"New directions in science are launched by new tools much more often than by new concepts. The effect of a concept-driven revolution is to explain old things in new ways. The effect of a tool-driven revolution is to discover new things that have to be explained"

Freeman Dyson


The Cosmic Frontier
XENON100 (2012)
observed limit (90% CL)
Expected limit of this run:
± 1 σ expected
± 2 σ expected
DAMA/Na
CoGeNT
DAMA/I
CDMS (2011)
XENON10 (2011)
SIMPLE (2012)
CRESST-II (2012)
COUPP (2012)
ZEPLIN-III (2012)
EDELWEISS (2011)
CDMS (2010)
XENON100 (2011)
WIMP-Nucleon Cross Section [cm²]
WIMP Mass [GeV/c²]
Upper limits, $b\bar{b}$ channel
WIMP cross section [cm³/s]
WIMP mass [GeV]
Cavity Frequency (GHz)
Non RF-cavity Techniques
White Dwarf and Supernova Bounds
Too Much Dark Matter
ADMX Published Limits
ADMX Upgrade in Progress Target Sensitivity
ADMX HF R&D
Axion Cold Dark Matter
ADMX Next Generation Target
Axion Mass (μeV)
thermal freeze-out (early Univ.)
indirect detection (now)
direct detection
production at colliders
DM
SM
DM
SM
570 Mpixel Camera
Readout electronics
Filter-Shutter System
Correcting Lenses
DES First Light!
ICECUBE
CTA+ Dwarf Limits 500 hrs
Fermi 2yr
Fermi 10yr
CTA+ GC 500 hrs 0.2 to 0.8deg
SPT
WMAP
ACT
Precision measurement of CMB damping tail
Detection of diffuse SZ in multi-frequency data
Camera Assembly
LSST
Two events passed the selection criteria
NEW! 28 high-energy events on a background of 12±3.4
Two PeV neutrinos @ IceCube
Activities at the Cosmic Frontier are marked by rapid, surprising, and exciting developments
11 October 2012
Cosmic Frontier – S. Ritz
2

A Big Message

- **Together with the other Frontier areas**, Cosmic Frontier an important part of the story for strengthening support of HEP:
  – Clear evidence for physics Beyond the Standard Model
  – Many surprises. Profound questions of popular interest.
  – Frequent new results, with broad impacts.
  – Large discovery space.
  – Full range of project scales, providing flexible programmatic options.


DPF2013
AUGUST 13–17
UC SANTA CRUZ
Hosted by the SANTA CRUZ INSTITUTE FOR PARTICLE PHYSICS
Meeting of the DIVISION of PARTICLES & FIELDS of the American Physical Society
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PROGRAM
Results of U.S. community planning for:
Energy, Intensity, and Cosmic Frontiers
and
Innovations in Accelerators, Detectors, and Computing
Parallel Sessions Include:
EWSB and the Higgs Sector
New Physics Searches at the LHC
Physics using B, Bs and Charm
Top Quark Physics
Electroweak Physics
Neutrino Physics
Progress at the Cosmic Frontier
Accelerators, Detectors, and Computing
Theoretical Physics
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