

# **Metabolism, Metabolomics and Cancer**

**David Wishart**

**University of Alberta, Edmonton, AB, Canada**

**Birmingham, AL, June 19, 2015**

# Cancer

- A disease caused by an uncontrolled division of abnormal cells in a part of the body
- “The Emperor of All Maladies”
- 41% of us will develop cancer at some point in our lives
- 2<sup>nd</sup> leading cause of death in US
- Leading cause of death in Canada, UK, New Zealand, Australia, Denmark

# 44 Years Ago

## Nixon Signs \$1.6 Billion Cancer Bill, Names Man to Head Fight

WASHINGTON (UPI)—President Nixon today signed into law a \$1.6

the act was "a milestone in the long and difficult effort to find the causes and cures of cancer."



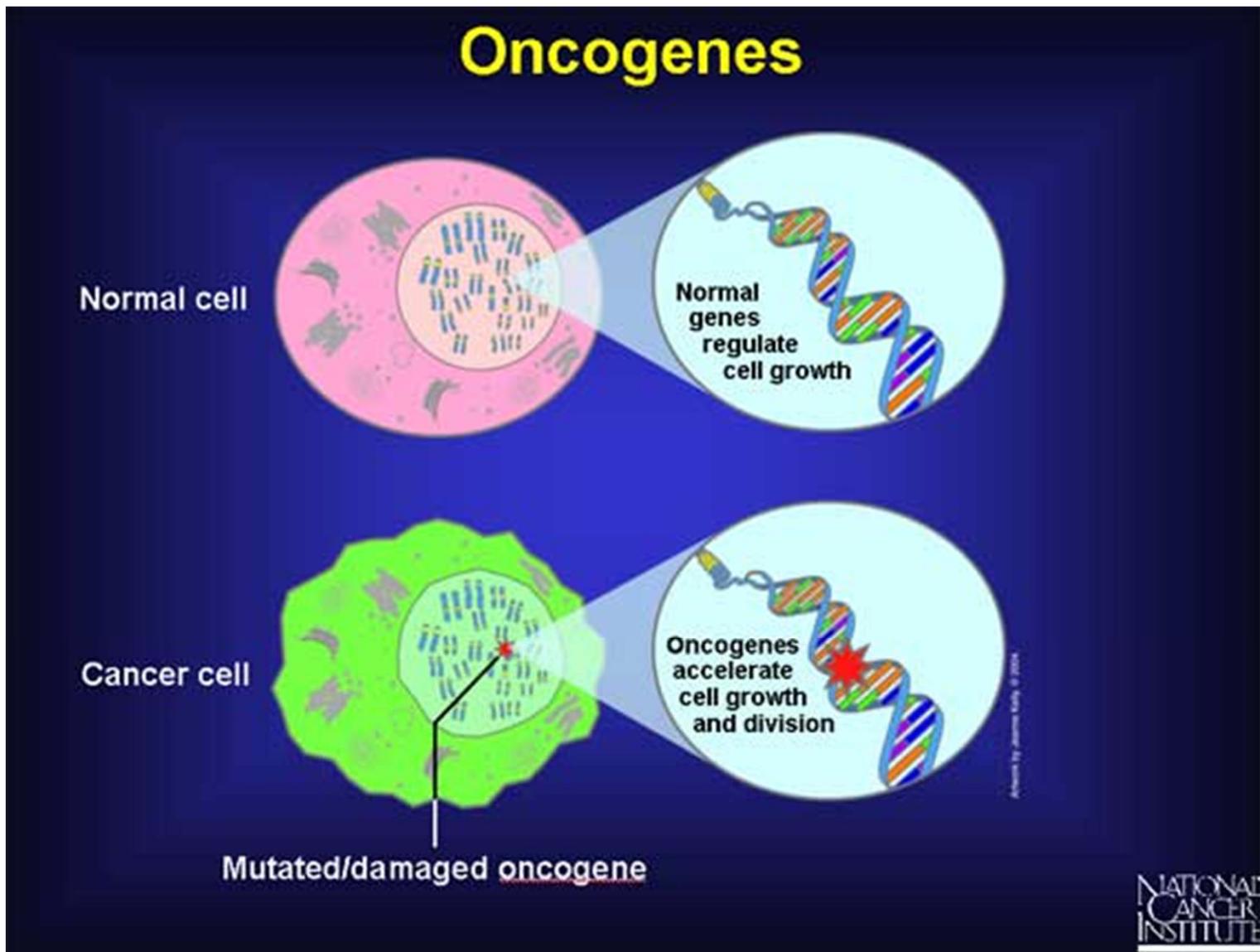
- Nixon declared war on cancer on Dec 23, 1971
- Since then >\$200 billion has been spent on cancer research

# 39 Years Ago



The Discovery of Oncogenes (Varmus & Bishop ~1976)

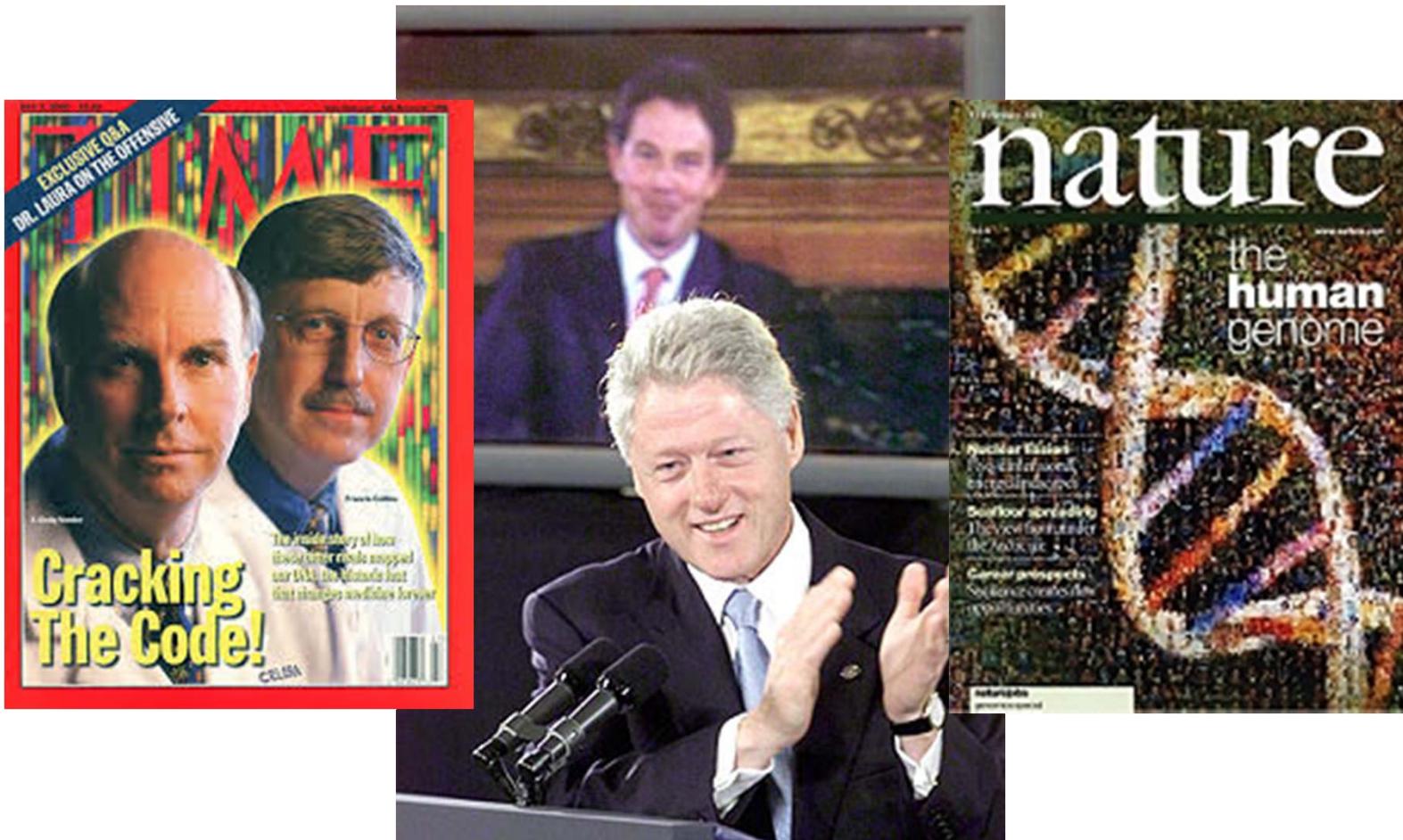
# Cancer as a Genetic Disease



# Cancer as a Genetic Disease

- Every cancer cell has mutations leading to over-expression or perturbations to oncogenes, proto-oncogenes or tumor suppressor genes
- An **oncogene** is a gene that has the potential to cause cancer
- A **proto-oncogene** is a normal gene that can become an oncogene due to mutations or increased expression
- A **tumor suppressor gene (TSG)** is a normal gene that prevents tumor development
- Examples of oncogenes include: Ras, Myc, Raf, Src, EGFR, HER2/neu, HIF-1 $\alpha$ , Wnt, Erk, Trk, Bcr-Abl
- Examples of TSGs include: BRCA1, p53, PTEN

# 15 Years Ago



June 26, 2000 – 1<sup>st</sup> Draft of Human Genome Completed

# 15 Years Ago

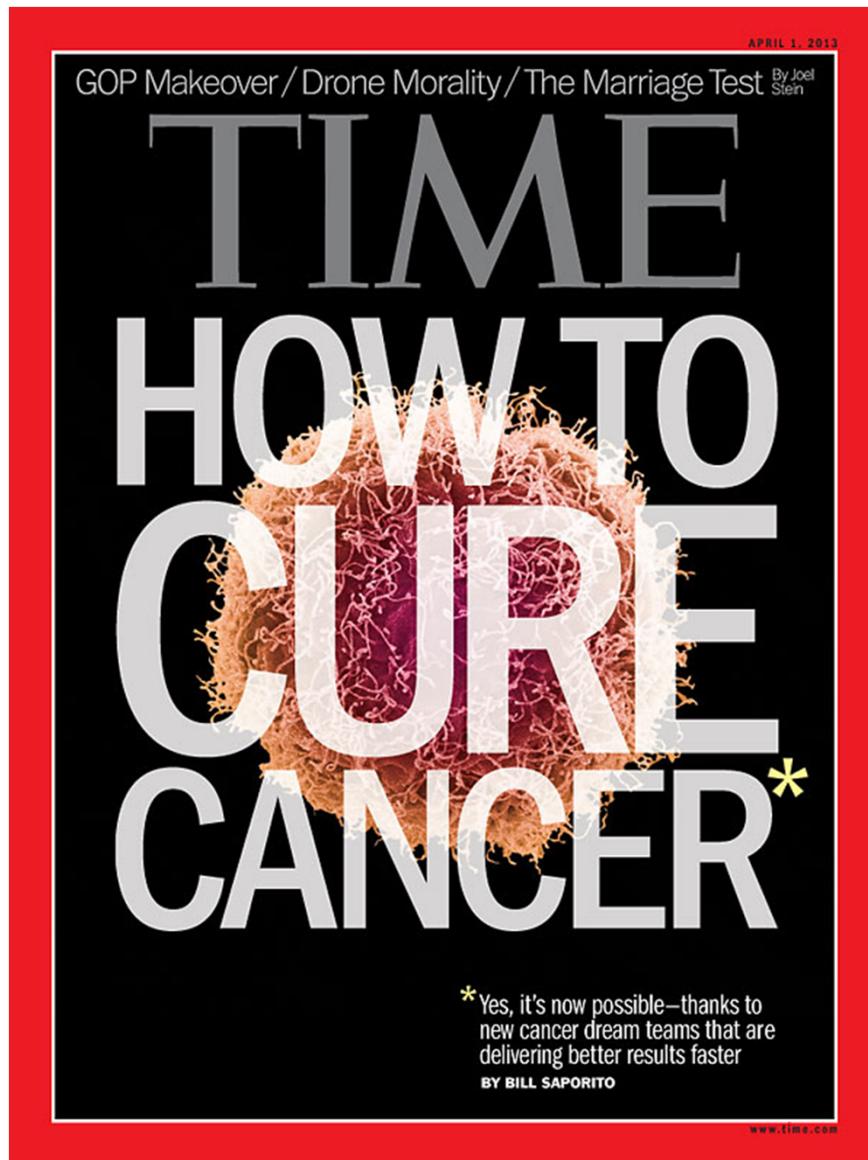
The Hallmarks  
Of Cancer

The Hallmarks  
Of Cancer



Hanahan D & Weinberg RA, (2000) Cell,  
Jan 100(1): 57-20

# Unbounded Optimism



Time Magazine  
April 1, 2003

# New Cancer Therapies

- Gene therapy
- T-cell therapy
- Stem cell transplant
- Monoclonal antibody therapy
  - Rituximab
  - Campath
- Mitotic inhibitors
  - Paclitaxel
  - Vinblastine
- Topoisomerase inhibitors
  - Irinotecan
  - Etoposide
- Anti-hormone therapy
  - Tamoxifen
- Targeted wonder drugs
  - Gleevec

# 5 Years Ago

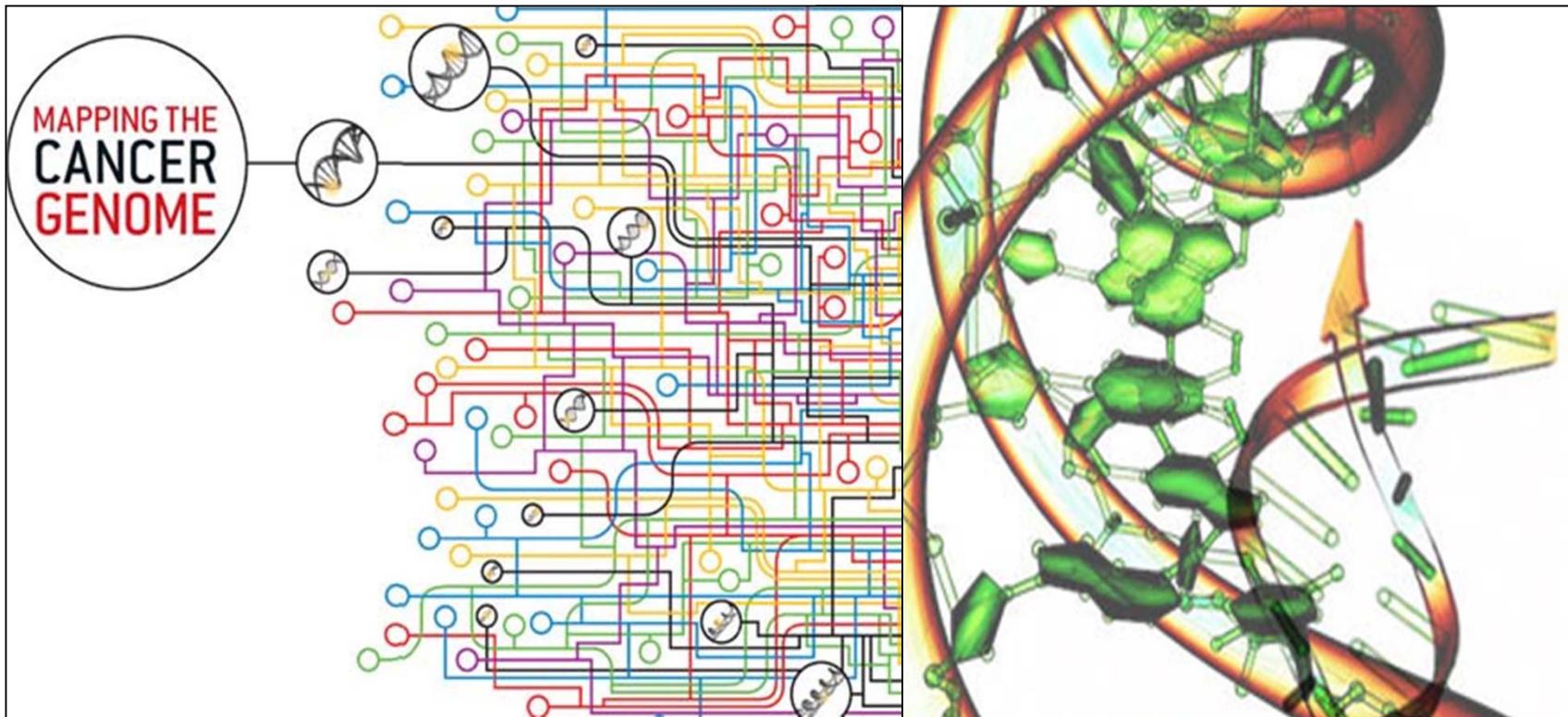


## Next Generation DNA Sequencing

**ABI SOLiD - 20 billion bases/run**  
**Sequencing by ligation**

**Illumina/Solexa 15 billion bases/run**  
**Sequencing by dye termination**

# The Cancer Genome Atlas

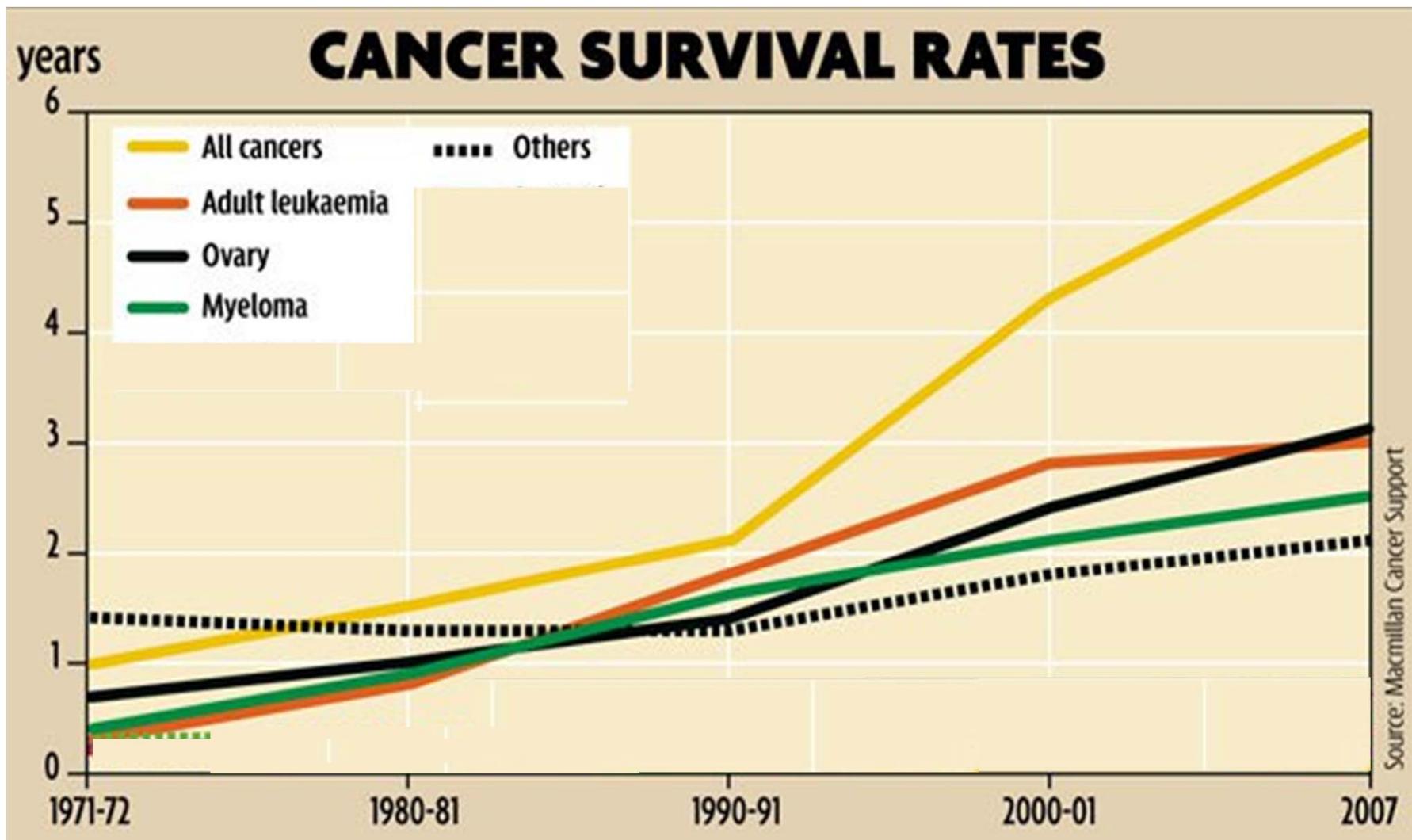


The Cancer Genome Atlas



*Understanding genomics  
to improve cancer care*

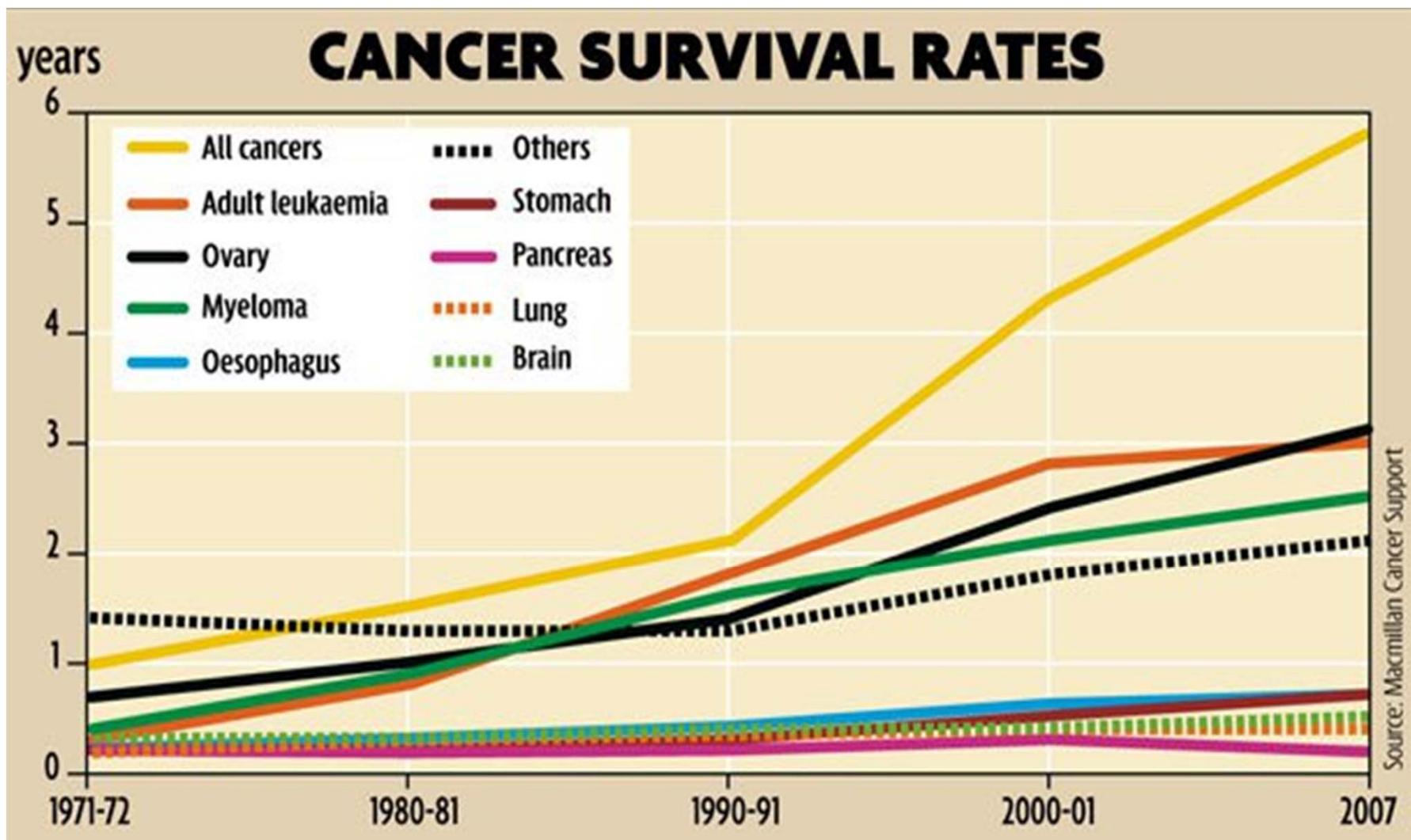
# The Good News



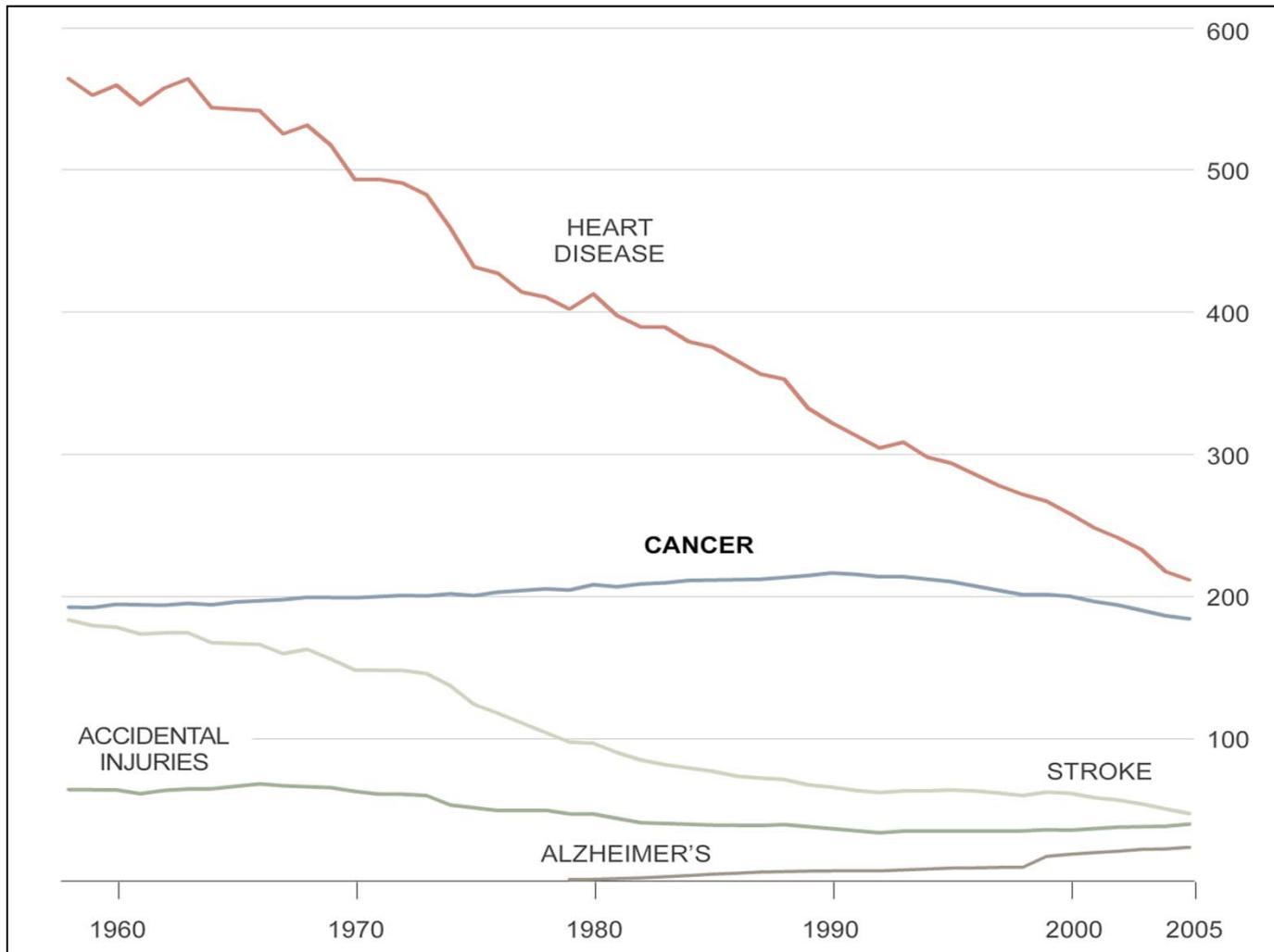
# However...

- **Most improvements in cancer survival are due to better screening, which leads to earlier detection (stage I or II), which leads to statistically longer survival times**
- **Most advances in “curing” cancer have been seen in relatively rare cancers (childhood leukemia, certain types of lymphomas)**

# Not So Good News



# The Bad News



Age-Adjusted Death Rates (US)

# The Really Bad News

- Cancers are caused by 2-3 “founder” mutations (to oncogenes/TSPs)
- ~250 oncogenes, ~700 tumor suppressor genes identified so far
- Cancer is 1,000,000+ different diseases
- Cancer cells accumulate ~10,000-50,000 mutations/CNVs after conversion (genetic noise)
- Cancer cells are a “genetic train wreck”

# Where To Next?



# How Was Cancer Viewed Prior to 1970?

- **Prevailing opinion among most oncologists was that cancer was a “metabolic disease”**
- **Cancer cells were metabolically dysregulated (cause of the metabolic dysregulation was unknown)**
- **Cancer drugs were called “anti-metabolites” and cancer chemotherapy was call anti-metabolite therapy**

# Anti-Metabolite Cancer Drugs

Anti-metabolite	Metabolite equivalent
5-Fluorouracil (5-FU) - 1957	Uracil
Gemcitabine (Ara-C) - 1981	Cytosine
6-Mercaptopurine - 1951	Adenine/Guanine
Fludarapine (Ara-A) - 1968	Adenine
Methotrexate - 1956	Folate
Aminopterin - 1947	Folate
Megestrol acetate - 1956	Progesterone
Asparaginase* - 1963	Asparagine/Glutamine*

# Who Came Up With This Crazy Idea?

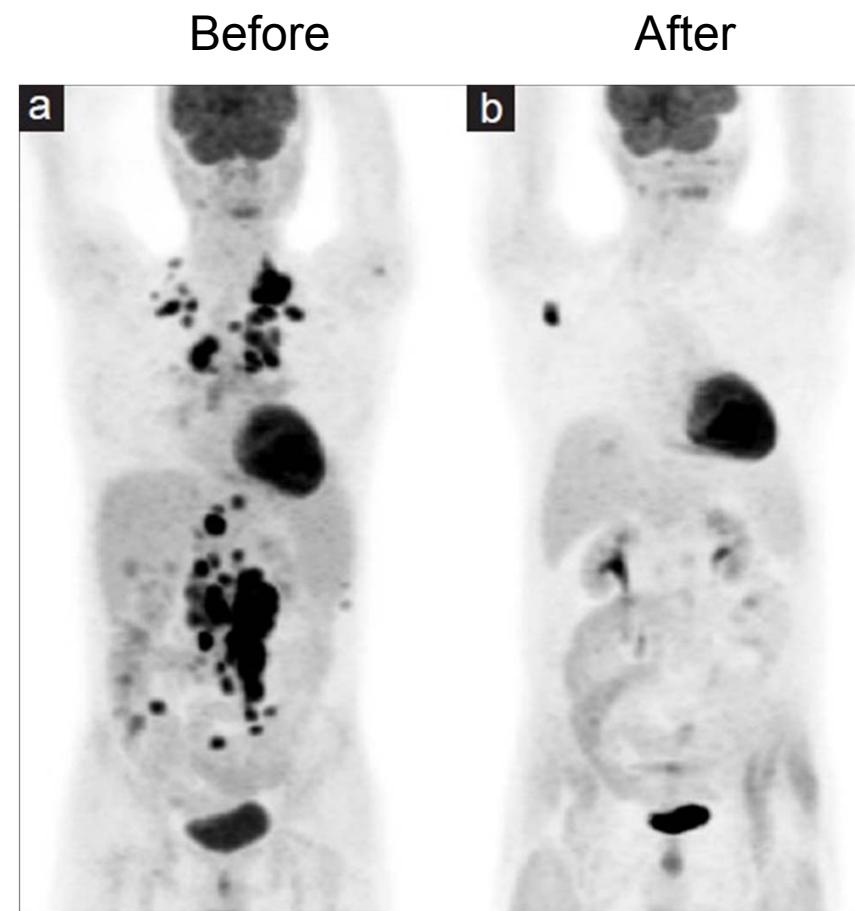


Otto Warburg

- Observed in 1924 that cancer cells use aerobic glycolysis to fuel growth instead of oxidative phosphorylation
- Won the Nobel Prize in 1931
- Advocated that: “replacement of oxygen-respiration by fermentation is the prime cause of cancer”
- The metabolic view of cancer predominated thinking from 1920’s up to Warburg’s death in 1970

# Cancer is a Metabolic Disease

- Cancer cells consume 100-200X more glucose than other cells in the body
- This unique metabolism is the basis to PET (positron emission tomography) scans for cancer using fluorinated deoxyglucose
- This metabolic shift is called the **Warburg effect** or cytosolic aerobic glycolysis



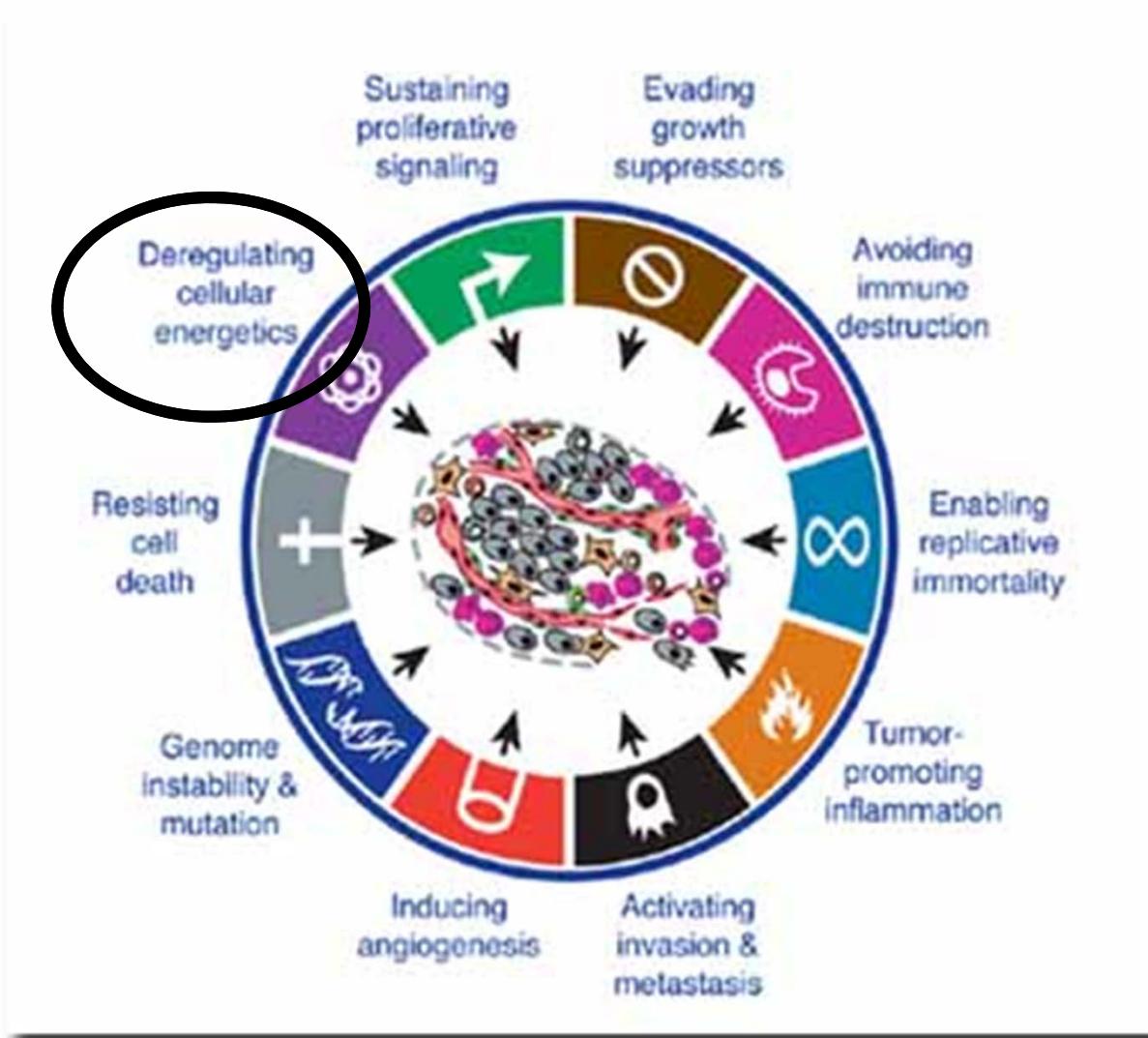
Tumors are marked in black in this PET image (lots of glucose)

# **How Is A Metabolic View of Cancer Compatible With the Genetic View?**

# Oncogenes are Metabolic Hubs

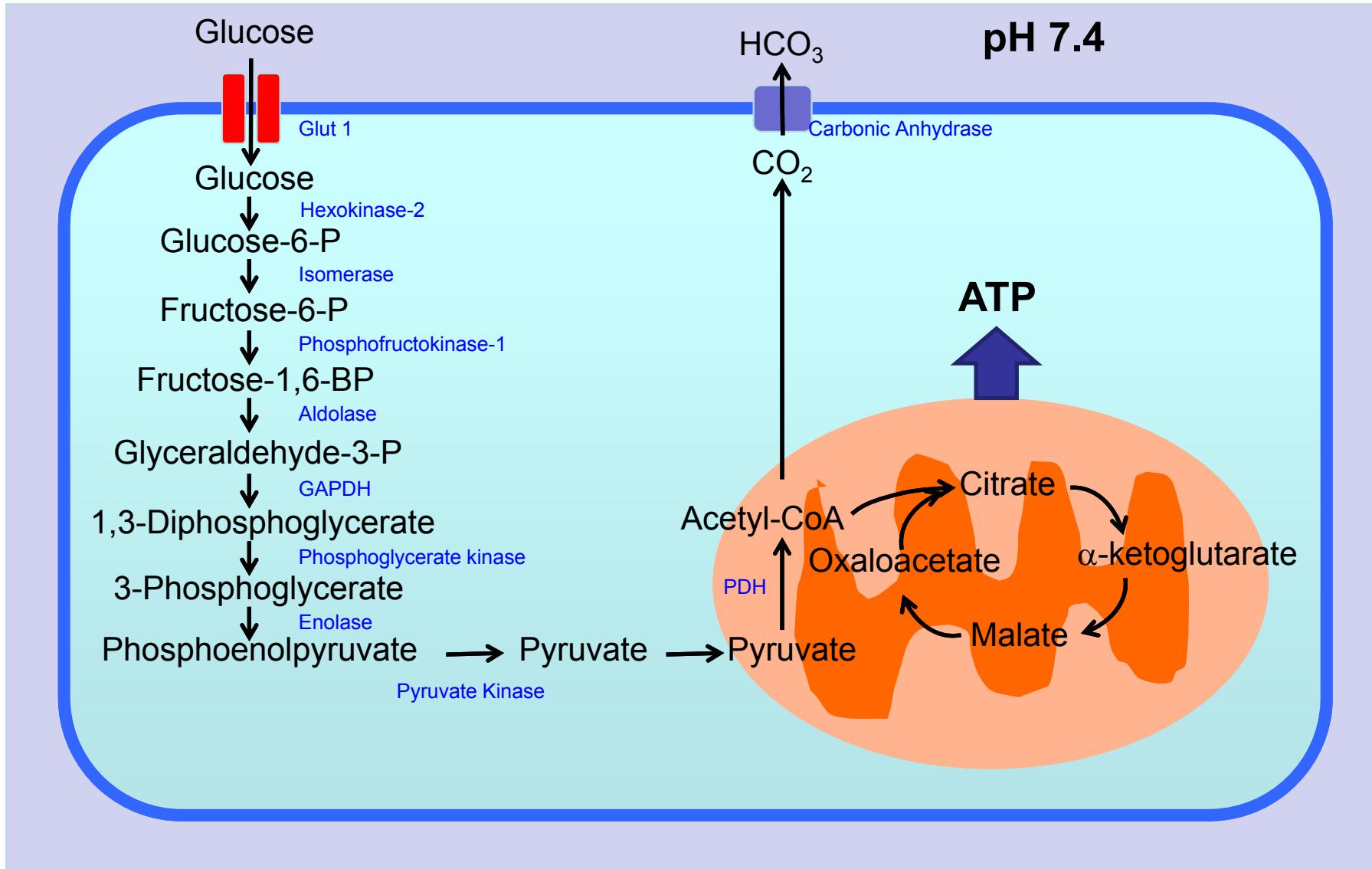
Oncogene or Tumor Suppressor	Metabolic Effect
Akt	Enhances glucose uptake, activates hexokinase II
c-Myc	Enhances glycolysis, activates LDH-A
h-Ras, k-Ras	Enhances glycolysis, activates complex II
Src	Phosphorylates PKM2, upregulates c-Myc
Brc-abl	Enhances glucose uptake, activates G6PD & HK II
Her2/neu	Enhances glycolysis, activates LDH and HSF1
Succinate dehydrogenase	Sustains TCA cycle, loss leads to HIF activation
Fumarate hydratase	Sustains TCA cycle, loss leads to HIF activation
Isocitrate dehydrogenase	Sustains TCA cycle, loss leads to DNA methylation
p53	Promotes OXPHOS, loss leads to glycolysis

# Updated Hallmarks of Cancer

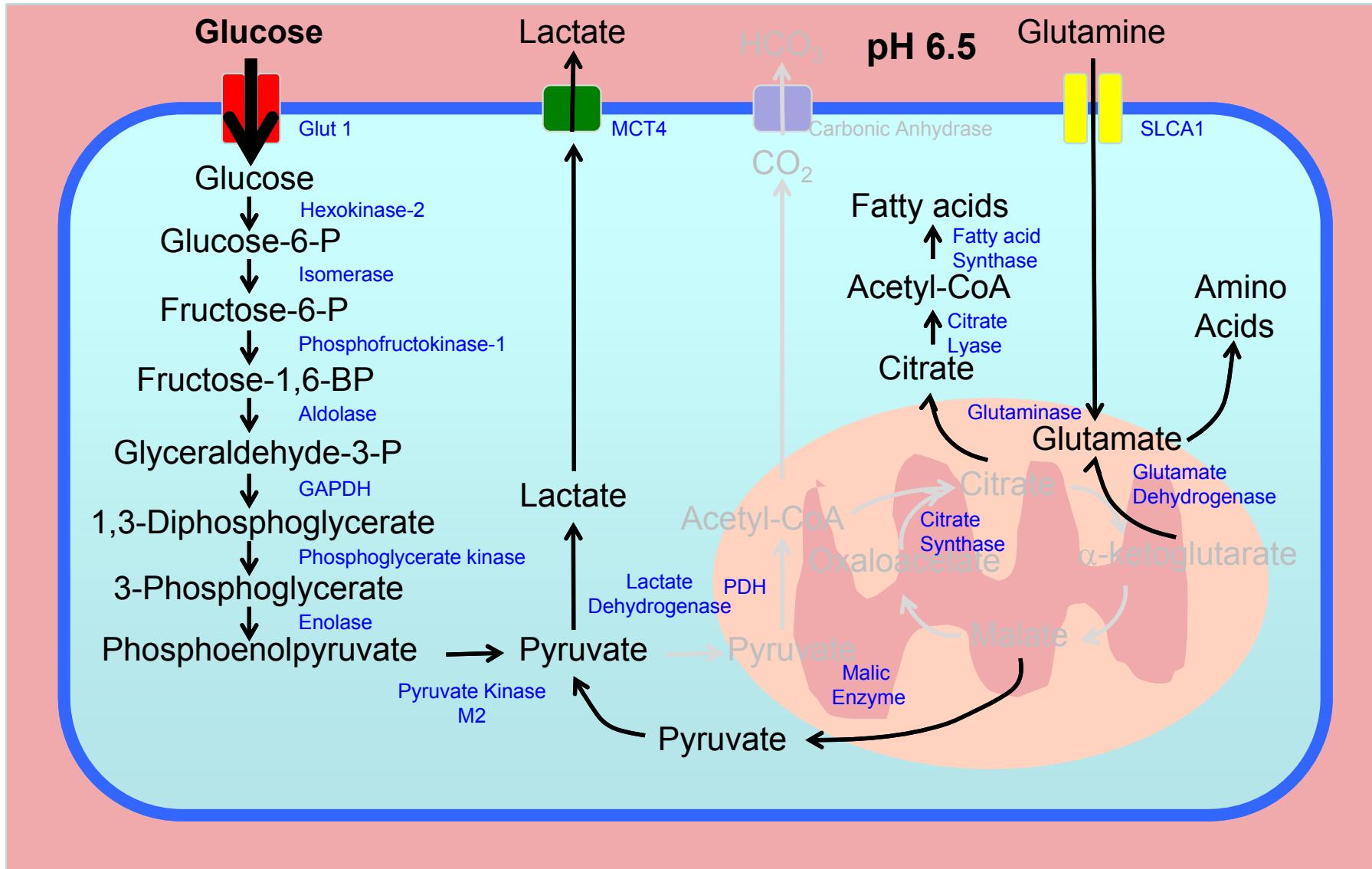


Hanahan D, Weinberg RA (2011) Cell, 144:646-674.

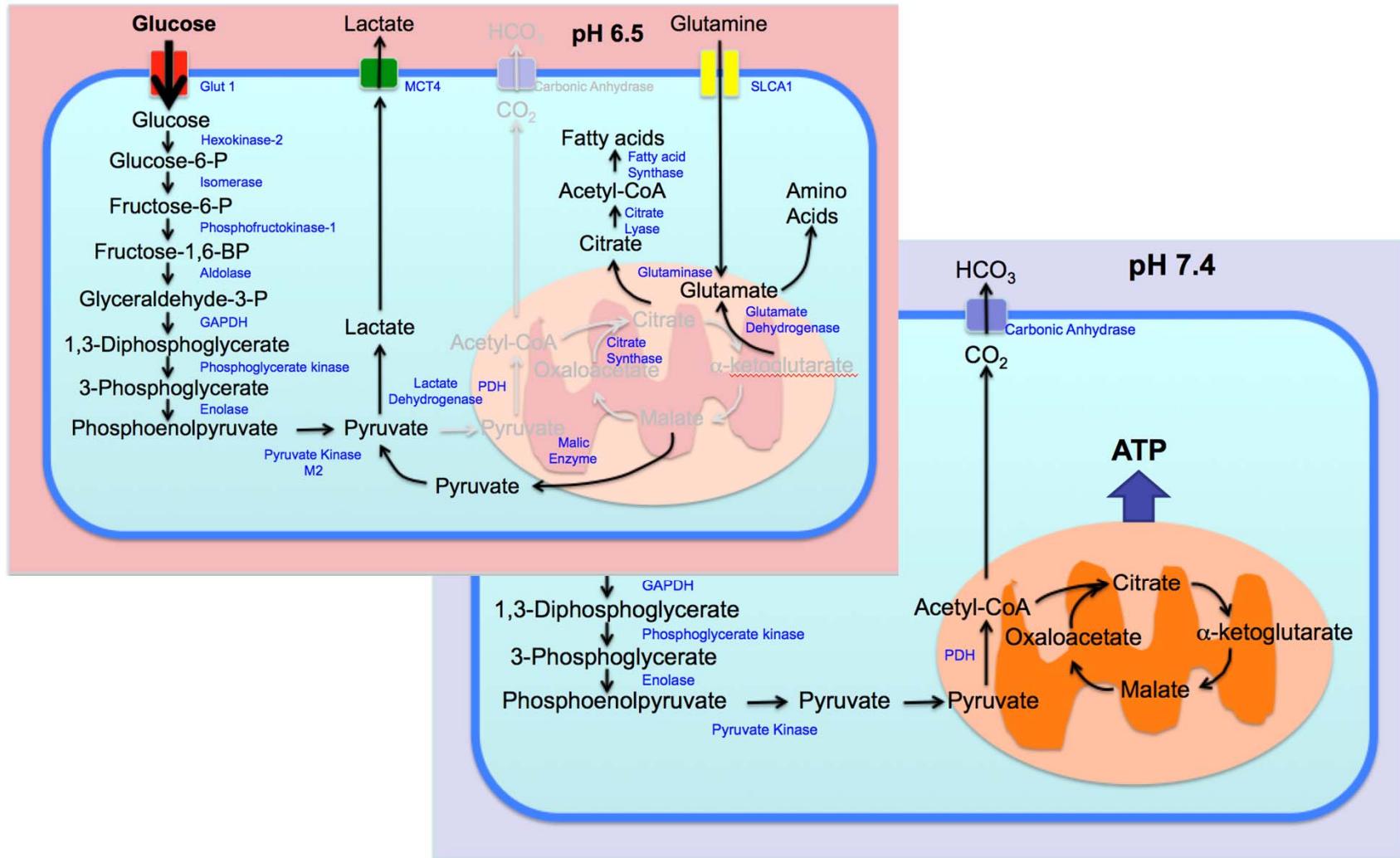
# Normal Cell Metabolism



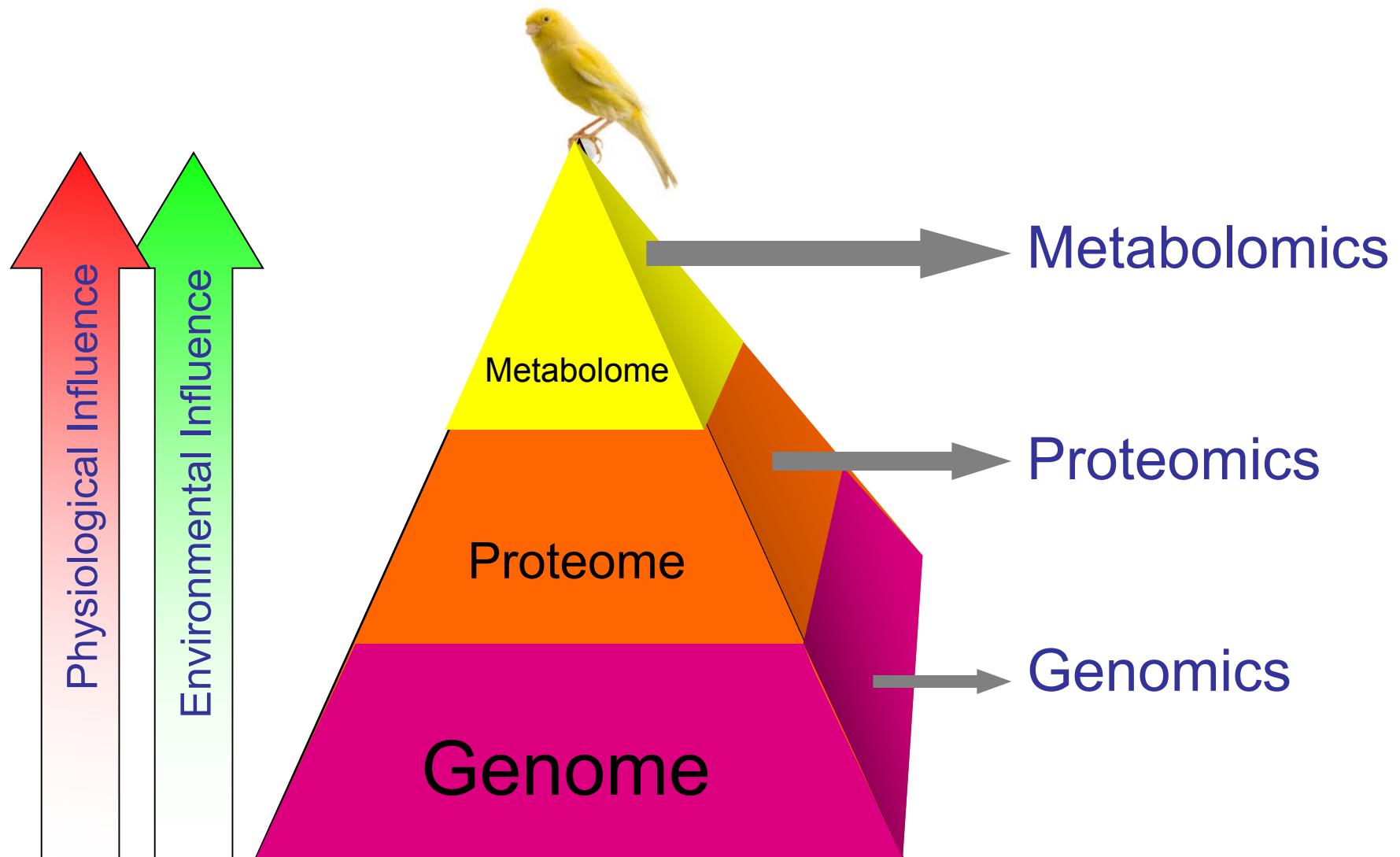
# Cancer Cell Metabolism



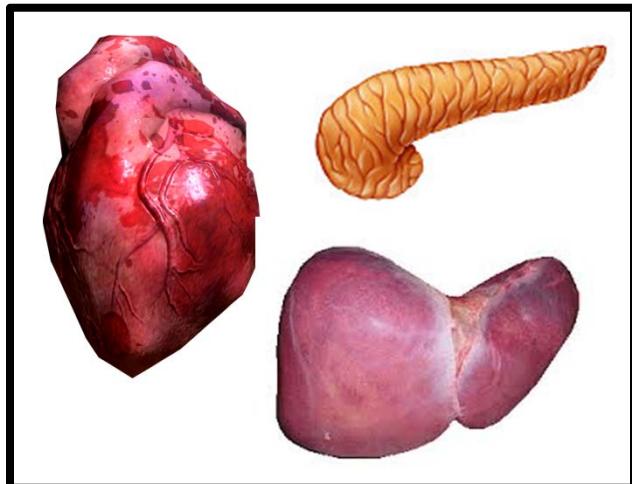
# How To Measure All These Metabolic Changes?



# Answer: Metabolomics



# Measuring Metabolism with Metabolomics



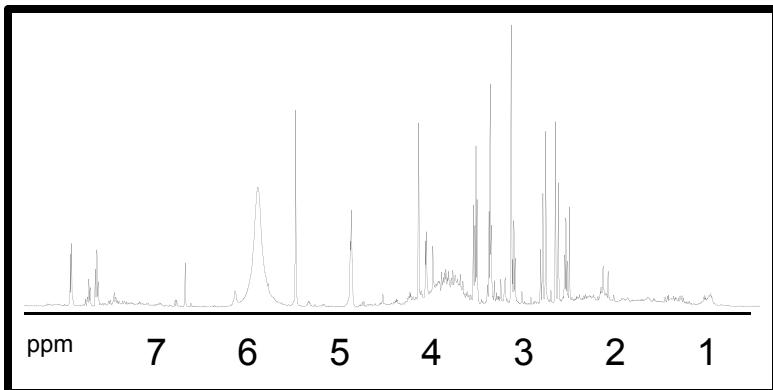
Biological or Tissue Samples



Extraction



Biofluids or Extracts



Data Analysis



Chemical Analysis

# Human Metabolomes (2015)

3670 (T3DB)

Toxins/Env. Chemicals

1240 (DrugBank)

Drug metabolites

28500 (FooDB)

Food additives/Phytochemicals

1550 (DrugBank)

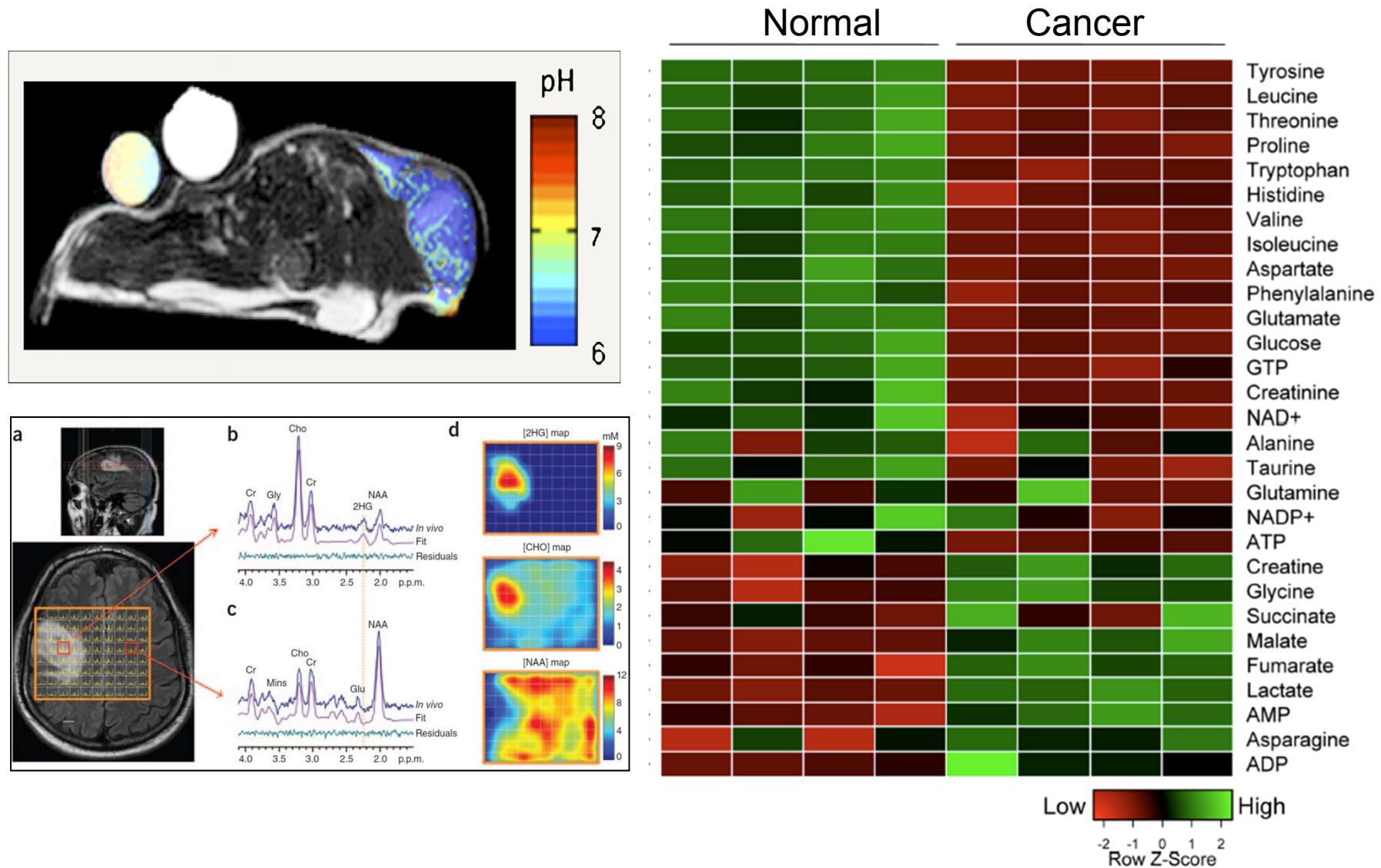
Drugs

29700 (HMDB)

Endogenous metabolites



# Metabolomics & Cancer



# Metabolomics is Discovering Oncometabolites

Oncometabolite	Effect or Mechanism
Lactate	Promotes tumor metastasis
2-Hydroxyglutarate	Alters histone/DNA methylation
Fumarate	HIF activation/alters DNA methylation/binds GSH
Succinate	HIF activation/alters DNA methylation
Glucose	Fuels Warburg effect
Sarcosine	Promotes tumor metastasis
Kynurenine	Activates aryl hydrocarbon receptor, tumorigenesis
Glutamine	Fuels glutaminolysis, promotes tumor growth
Glycine/Serine	Promotes tumor growth, reverse Warburg effect

# Metabolomics is Discovering Cancer Biomarkers

- **Vanillylmandelic acid** (neuroblastoma + pheochromocytoma)
- **3-Hydroxymandelic acid** (neuroblastoma)
- **3,4-Dihydroxymandelic acid** (neuroblastoma)
- **Homovanillic acid** (neuroblastoma)
- **Sarcosine** (metastatic prostate cancer)
- **2-hydroxyglutarate** (glioma + acute myeloid leukemia)
- **Ribothymidine** (breast cancer)
- **1-methylguanosine** (breast cancer)
- **1-methyladenosine** (cholangioma + cervical cancer)
- **Cadaverine** (pancreatic cancer)
- **5-hydroxyindoleacetic acid** (carcinoid tumors)
- **3-methoxytyramine** (carcinoid tumors)
- **Testosterone glucuronide** (adrenocortical tumors)
- **3a,16a-dihydroxyandrostenedone** (adrenal carcinoma)
- **5-methoxyindoleacetate** (lung + stomach + colon cancer)
- **21-deoxycortisol** (testicular cancer)
- **3,5-diiodothyronine** (brain tumors)
- **Androstendione** (thyroid cancer)
- **Thromboxane A2** (Hepatocellular carcinoma)
- **Deoxypyridinoline** (Multiple myeloma)

# Cancer & Metabolite Biomarkers

**MarkerDB** ABOUT | CONTACT US | DOWNLOADS

**D P Pre E M** 



**Marker DB** is a freely available resource is a freely available electronic database that attempts to consolidate information on all known clinical biomarkers into a single source.

The database provides information such as: names and synonyms, associated conditions or pathogens, specificity and sensitivity, standard measurement values, measurement sources, variants, sequence information, molecular structure, FDA approval and references as well as links to other sources of information.

Users can browse the data by marker category, marker type or conditions or use the advanced search funtions to find information.

Please Cite: Wishart DS, Wilson M, Guo AC, Neveu V, Djoumbou Y. Paper in progress

**Condition Categories**

Autoimmune	Cutaneous	Gastrointestinal	Mental	Respiratory
Cancer	Endocrine	Genetic	Metabolic	Urogenital
Cardiovascular	Exposure	Infectious	Musculoskeletal	
Communication	Eye	Intestinal	Neurological	Others

**Biomarker Types**

 Chemical Compounds The presence or concentration levels of compounds.	 Genetic markers The presence of genetic variants or non human DNA.	 Proteins The presence or concentration levels of proteins.
 Cells The presence or quantity of cells.	 Histology Microscopic structures of cells.	 Karyotype Chromosomal aberrations.

**Biomarker Categories**

<b>D</b> Diagnostic Biomarkers Identify a possible condition, in some cases provide information about disease severity.	<b>P</b> Prognostic Biomarkers Allow for the outcome of a disease or treatment to be determined at a more primitive stage of disease.	<b>Pre</b> Predictive Biomarkers Predict the risk of occurrence for a condition.
<b>E</b> Biomarkers of Exposure Indicates exposure to a toxin or chemical.	<b>M</b> Monitoring Biomarkers Measure the progression or regression of a condition and can be used to evaluate the response to therapy.	

[www.markerdb.ca](http://www.markerdb.ca)

HMDB: Home

ArrayPipe: A...ing Pipeline GenePattern DAVID 2008 ...ay Analysis Department o...ell Biology Login- Depar... of Alberta Audiobaba Music Search

**Metabolomics Toolbox** 

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**Human Metabolome Database** 

Search:   [Advanced]

The Human Metabolome Database (HMDB) is a freely available electronic database containing detailed information about small molecule metabolites found in the human body. It is intended to be used for applications in metabolomics, clinical chemistry, biomarker discovery and general education. The database is designed to contain or link three kinds of data: 1) chemical data, 2) clinical data, and 3) molecular biology/biochemistry data. The database (version 2.0) contains over 6500 metabolite entries including both water-soluble and lipid soluble metabolites as well as metabolites that would be regarded as either abundant (> 1 μM) or relatively rare (< 1 nM). Additionally, approximately 1500 protein (and DNA) sequences are linked to these metabolite entries. Each Metabocard entry contains more than 100 data fields with 2/3 of the information being devoted to chemical/clinical data and the other 1/3 devoted to enzymatic or biochemical data. Many data fields are hyperlinked to other databases (KEGG, PubChem, MetaCyc, ChEBI, PDB, Swiss-Prot, and GenBank) and a variety of structure and pathway viewing applets. The HMDB database supports extensive text, sequence, chemical structure and relational query searches. Two additional databases, DrugBank and FooDB are also part of the HMDB suite of databases. DrugBank contains equivalent information on ~1500 drugs while FooDB contains equivalent information on ~2000 food components and food additives.

HMDB is supported by David Wishart, Departments of Computing Science & Biological Sciences, University of Alberta.

[More about the HMDB](#)

**What's New?**

November 5, 2009

- The [release notes](#) for version 2.5 of the Human Metabolome Database are now available. Additionally, version 2.0 of the HMDB downloads have been [archived](#).

[News archive](#)

Loading "http://www.hmdb.ca/", completed 16 of 17 items

[www.hmdb.ca](http://www.hmdb.ca)

# Building Better Biomarkers

Abstract ▾

Send to: ▾

Metabolomics. 2013 Apr;9(2):280-299. Epub 2012 Dec 4.

## Translational biomarker discovery in clinical metabolomics: an introductory tutorial.

Xia J<sup>1</sup>, Broadhurst DI, Wilson M, Wishart DS.

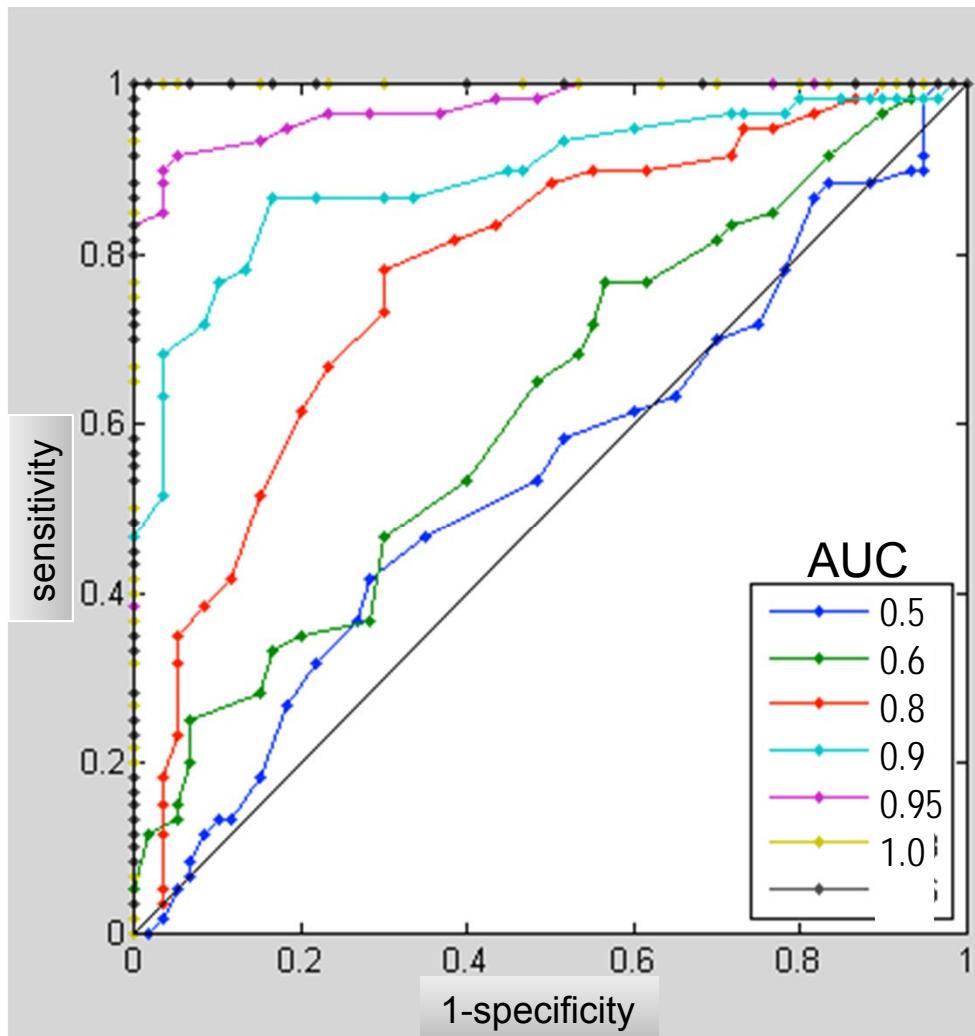
### Author information

#### Abstract

Metabolomics is increasingly being applied towards the identification of biomarkers for disease diagnosis, prognosis and risk prediction. Unfortunately among the many published metabolomic studies focusing on biomarker discovery, there is very little consistency and relatively little rigor in how researchers select, assess or report their candidate biomarkers. In particular, few studies report any measure of sensitivity, specificity, or provide receiver operator characteristic (ROC) curves with associated confidence intervals. Even fewer studies explicitly describe or release the biomarker model used to generate their ROC curves. This is surprising given that for biomarker studies in most other biomedical fields, ROC curve analysis is generally considered the standard method for performance assessment. Because the ultimate goal of biomarker discovery is the translation of those biomarkers to clinical practice, it is clear that the metabolomics community needs to start "speaking the same language" in terms of biomarker analysis and reporting—especially if it wants to see metabolite markers being routinely used in the clinic. In this tutorial, we will first introduce the concept of ROC curves and describe their use in single biomarker analysis for clinical chemistry. This includes the construction of ROC curves, understanding the meaning of area under ROC curves (AUC) and partial AUC, as well as the calculation of confidence intervals. The second part of the tutorial focuses on biomarker analyses within the context of metabolomics. This section describes different statistical and machine learning strategies that can be used to create *multi-metabolite* biomarker models and explains how these models can be assessed using ROC curves. In the third part of the tutorial we discuss common issues and potential pitfalls associated with different analysis methods and provide readers with a list of nine recommendations for biomarker analysis and reporting. To help readers test, visualize and explore the concepts presented in this tutorial, we also introduce a web-based tool called ROCCET (ROC Curve Explorer & Tester, <http://www.roccet.ca>). ROCCET was originally developed as a teaching aid but it can also serve as a training and testing resource to assist metabolomics researchers build biomarker models and conduct a range of common ROC curve analyses for biomarker studies.

**KEYWORDS:** AUC; Biomarker analysis; Biomarker validation and reporting; Bootstrapping; Confidence intervals; Cross validation; Optimal threshold; ROC curve; Sample size

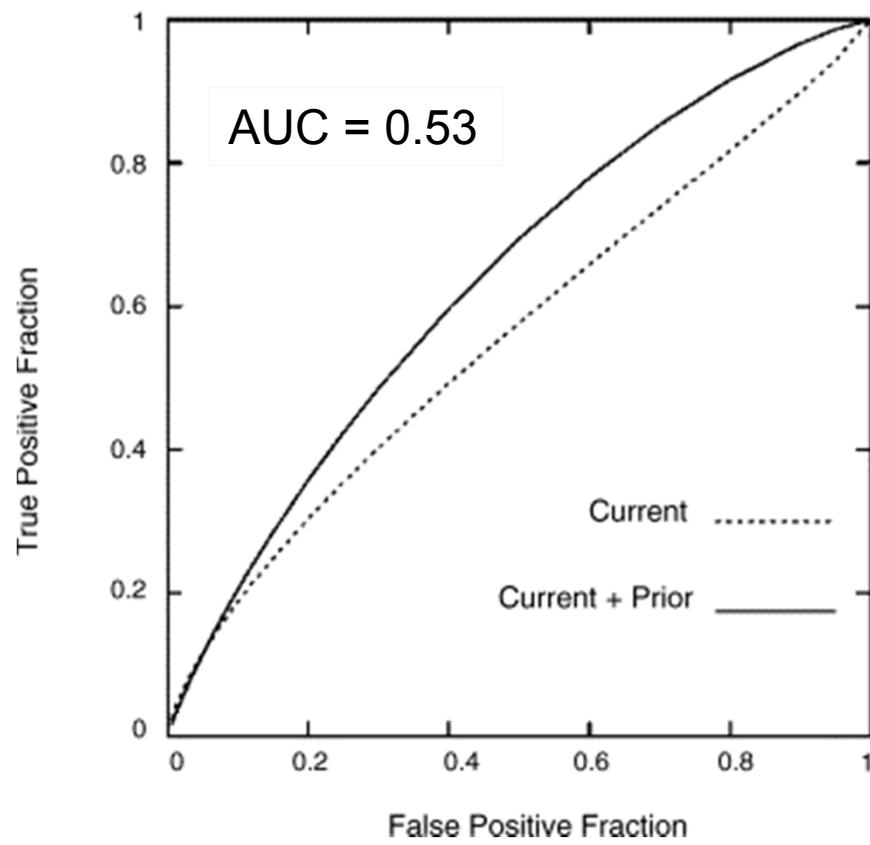
# Assessing Biomarkers with ROC Curves



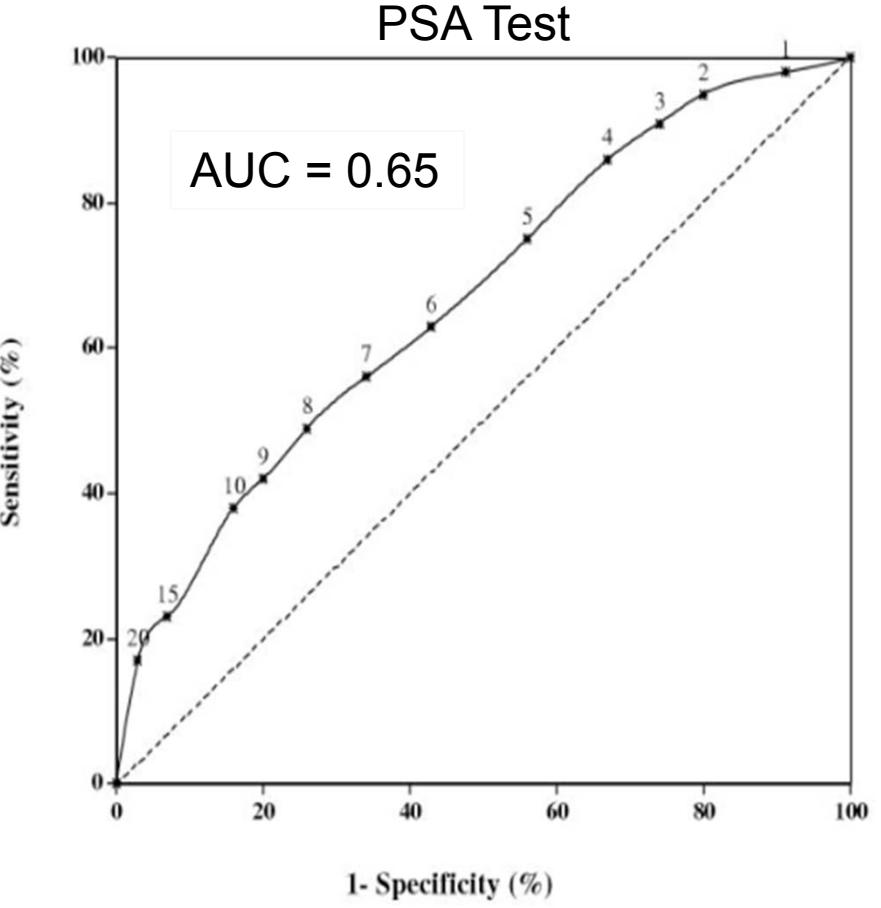
- Plots sensitivity (%TP) vs. specificity (%TN)
- A poor ROC curve would be a straight line with a slope of 1
- The area under an ROC (AUROC) curve is a good measure of the quality of the biomarker
- AUROCs of >0.75 are good, AUROCs of 0.5 are terrible, AUROCs of 1.00 are perfect

# AUCs of Common Tests

Mammogram (Benign vs. Malignant)

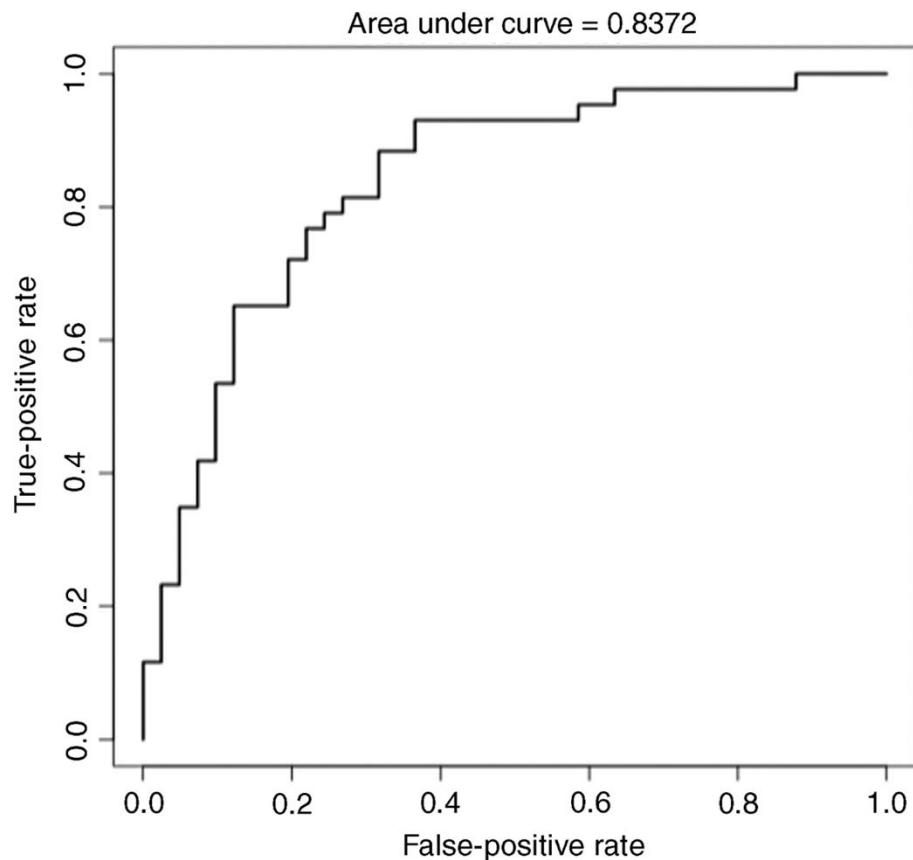


PSA Test



# **How Does Metabolomics Do?**

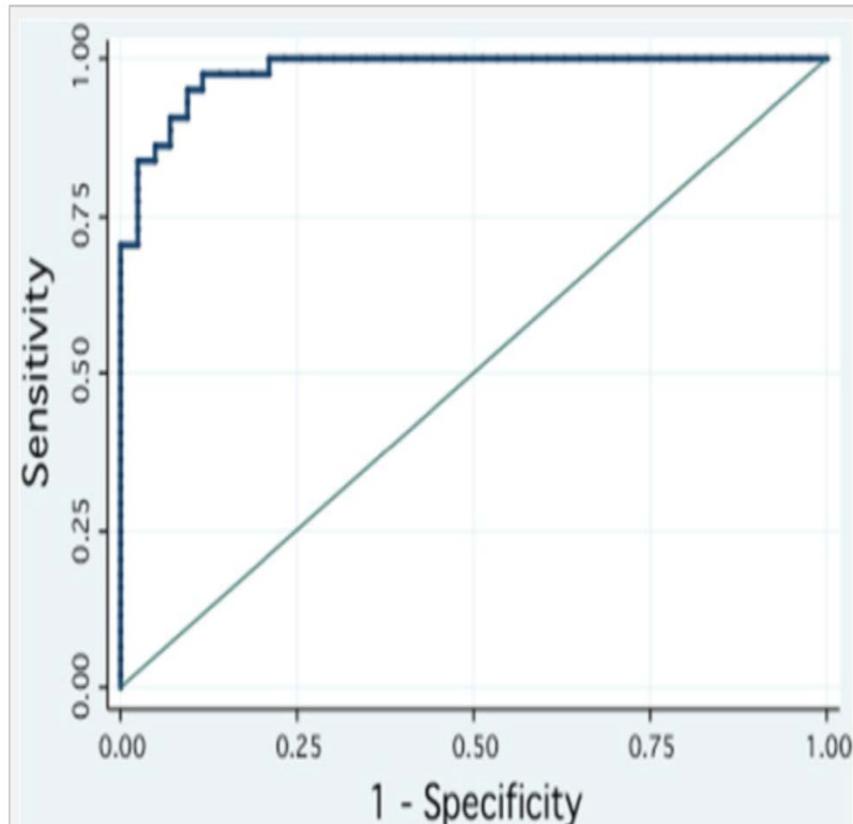
# Diagnosing Pancreatic Cancer



- Adult Serum Samples
- 43 cases, 41 controls
- NMR metabolomics
- AUC = 0.84 using 8 metabolites
- Glutamate, acetone, 3-hydroxybutyrate, glucose, glutamine, creatine, phenylalanine, formate

Bathe OF, Shaykhutdinov R, Kopciuk K. et al – Cancer Epid Biomark Prev. (2011)  
Jan;20:140-147.

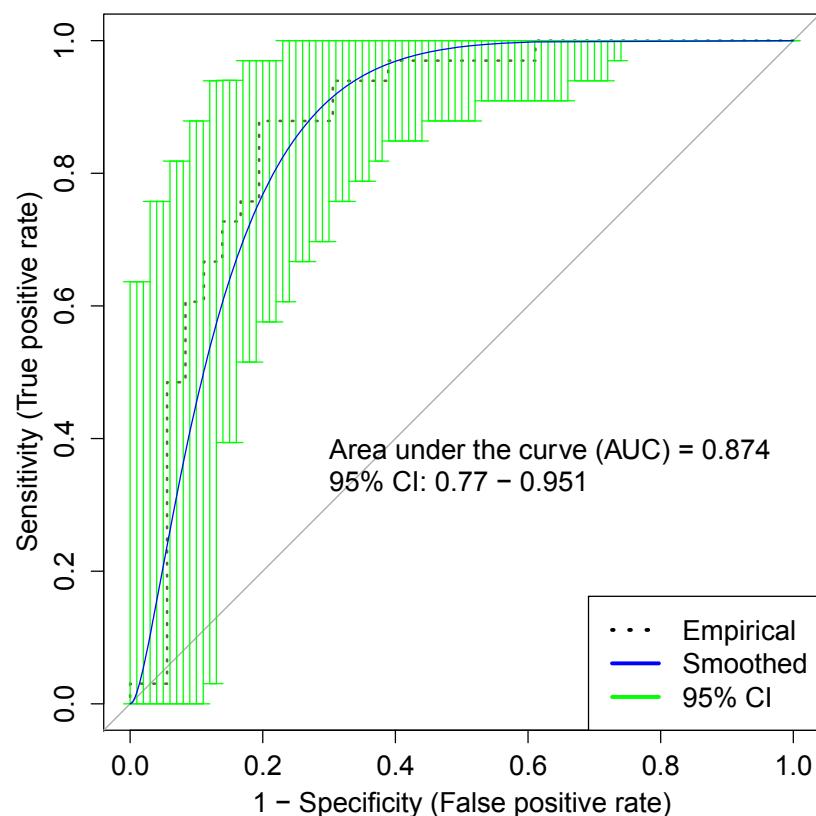
# Diagnosing Esophageal Cancer



- Adult Urine Samples
- 44 cases, 75 controls
- NMR metabolomics
- AUC = 0.98 using 7 metabolites
- Urea, acetate, acetone, formate, succinate, pantothenate, 2-hydroxyisobutyrate

Davis VW, Schiller DE, Eurich D, Sawyer MB - World J Surg Oncol (2012) Dec 15;10:271.

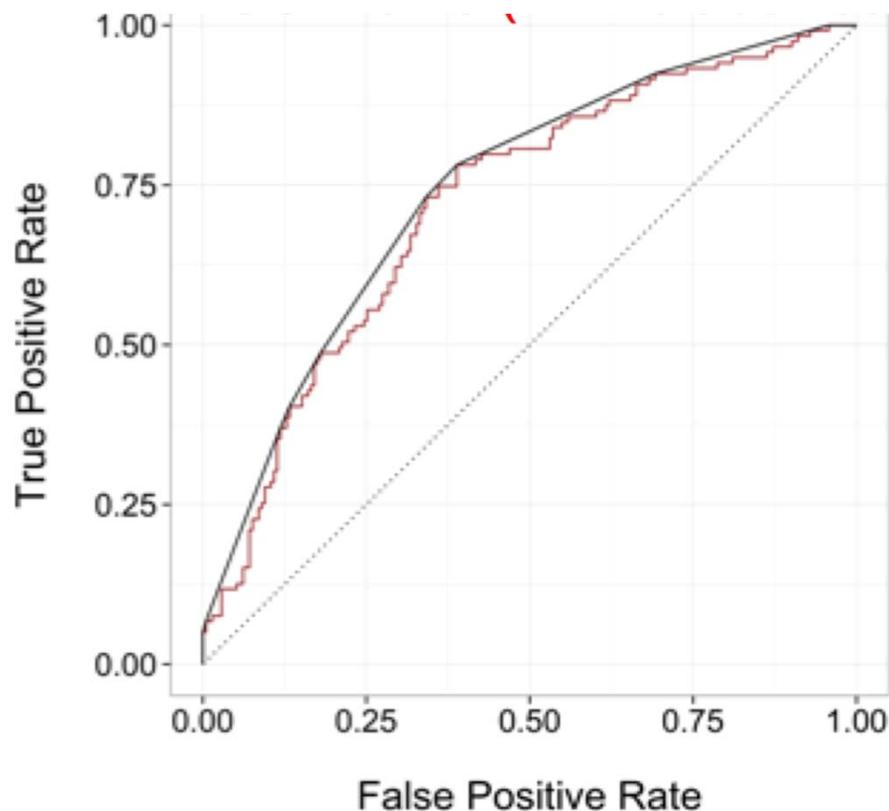
# Diagnosing Endometrial Cancer



Bahado-Singh R, Mandal R, Wishart DS  
(unpublished)

- Adult Serum Samples
- 40 cases, 41 controls
- MS metabolomics
- AUC = 0.88 using 3 metabolites
- C18:2, PC ae C40:1, C6 (C4:1-DC)
- Very strong correlation with BMI
- Pap smear AUC=0.55

# Predicting Colon Cancer (Polyps)

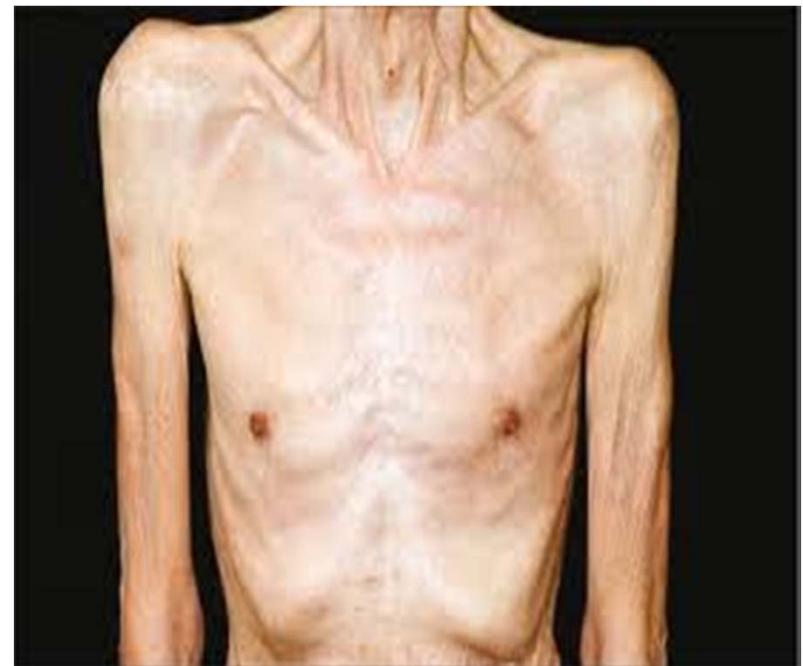


- **Adult Urine Samples**
- **162 cases, 422 controls**
- **NMR metabolomics**
- **AUC = 0.75 using 17 metabolites**
- **Butyrate, serine, methanol, beta-alanine, methylhistidine, 3-hydroxybutyrate, acetone, benzoate**

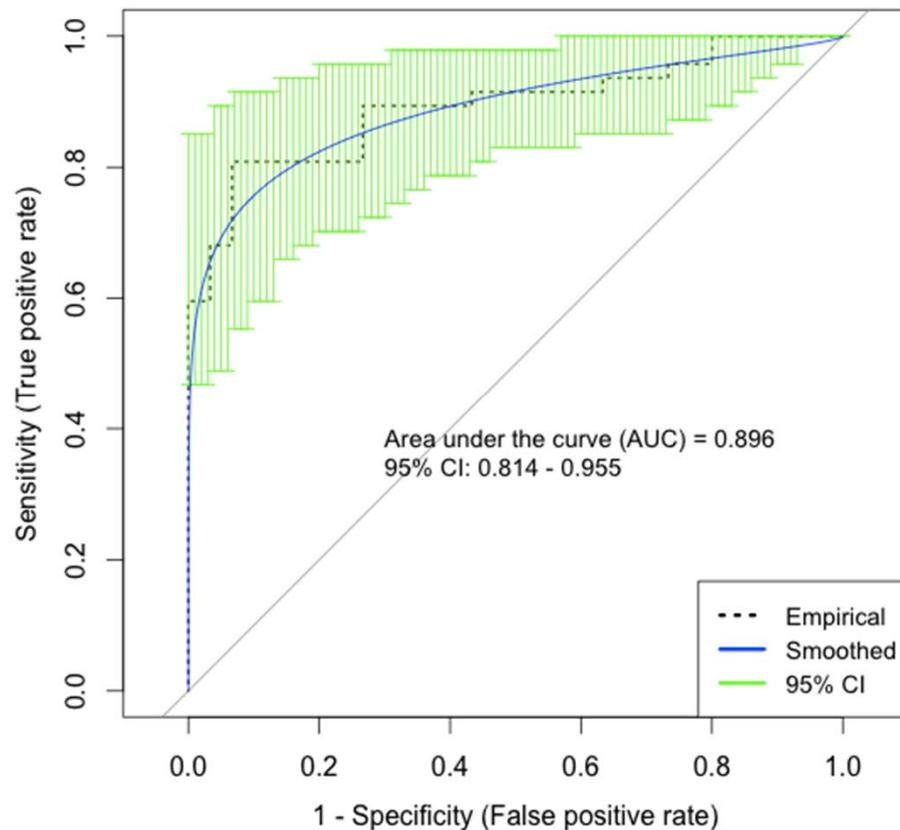
Wang H, Tso V, Wong C, Sadowski D, Fedorak RN. Clin Transl Gastroenterol. (2014) Mar 20;5:e54

# Cancer Cachexia

- Adverse metabolic effect from cancer (negative energy balance due to tumor burden, loss of skeletal muscle mass)
- Responsible for significant morbidity and significantly earlier mortality
- Early detection, prediction & prevention could save lives



# Predicting Cancer Cachexia via Metabolomics



Eisner R, Stretch C, Eastman T, et al.  
Metabolomics (2011) March; 7:25-34.

- Adult Urine Samples
- All with cancer
- 44 cachetic, 29 non-cachectic
- NMR metabolomics
- **AUC = 0.90 using 8 metabolites**
- **Creatine, creatinine, branched chain AAs, glucose**

# Using Metabolomics to Phenotype Cancer

- Most cancers generate large quantities of glycolysis biomarkers (lactate, formate, glucose, succinate)
- Some cancers produce large quantities of glutaminolysis biomarkers (glutamate, glutamine)
- Certain cancers exhibit dysregulated one-carbon metabolism biomarkers (choline, sarcosine, glycine, serine, hydroxyglutarate)
- Most cancers produce excesses of metabolites belonging to certain cell classes (indoleacetate, homovanillate)
- MRS (chemical shift) & PET imaging or metabolite profiling allows precise phenotyping of cancers

# Using Metabolomics To Phenotype Those At Risk

- Is there a metabolome that predisposes one to cancer?
- How to measure the GxE interactions via metabolomics?
- Metabolites that harm:  
**oncometabolites, uremic toxins, transformed xenobiotics**
- Metabolites that heal: **butyrate, bicarbonate, uric acid, glutathione**

**But Metabolomics Tests Will  
Never Be Approved...**

# Almost Everyone <25 Has Had A Metabolomic Test



Newborn Screening



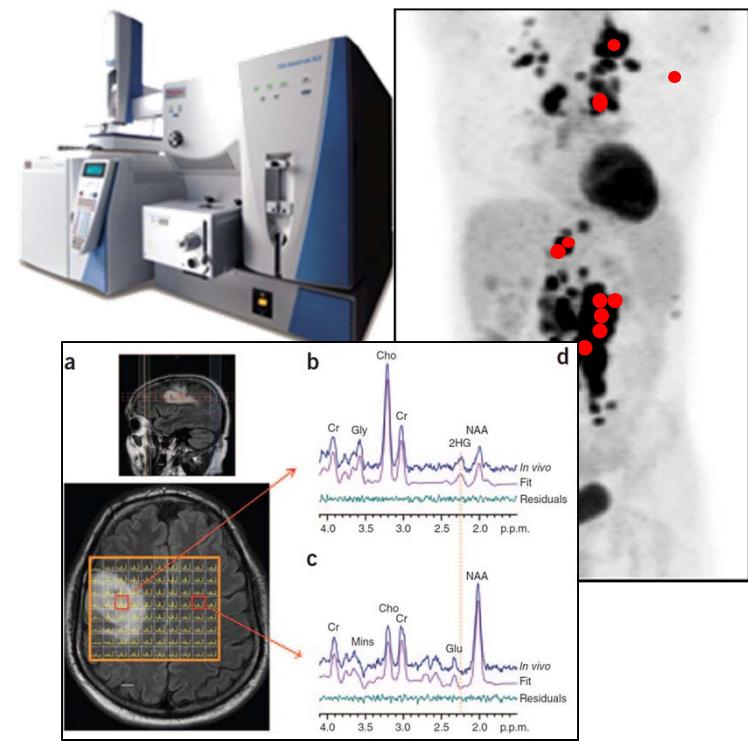
# Metabolomics is Moving to the Bedside

- Number of “approved” tests arising from **Metabolomics/Clinical Chem.** – **195**
- Number of “approved” tests arising from or using **Genomics** – **100-110**
- Number of “approved” single **Protein** tests (**ELISA**) – **60**
- Number of “approved” tests arising from or using **Transcriptomics** – **5**
- Number of “approved” tests arising from or using **Proteomics** - **0**

# Re-Thinking Precision Medicine



**BRCA1/2 Testing**



**Cancer Phenotyping**

# Key Points

- **Cancer is a metabolic disease**
  - Cancer cells exhibit a 200x increase in glucose consumption
  - Most known oncogenes and tumor suppressors fundamentally alter glucose metabolism
  - Oncometabolites promote cancer
  - Antimetabolites stop cancer
  - High abundance metabolites play key cancer signaling roles
  - Metabolic disorders such as diabetes and obesity increase cancer risk substantially
  - Cachexia (a metabolic disorder) is a manifestation of cancer
  - Some of the best cancer biomarkers are metabolites

# New Opportunities

- If cancer is a metabolic disease...
  - New kinds of drug targets
  - New methods for cancer prevention (diets?)
  - New approaches for early diagnosis
  - New methods for risk prediction
  - New techniques to look at cancer
  - New ways of integrating genomics with metabolomics
  - New kinds of drugs...

# Cancer Drugs That Reverse The Warburg Effect

Drug	Mechanism
Gleevec	Inhibits Bcr-Abl, downregulates HK & G6PDH
Dicholoracetate (DCA)	Targets and inhibits pyruvate dehydrogenase kinase
Orlistat	Targets and inhibits fatty acid synthase
Metformin	Downregulates mTOR, Activates AMPK
Rapamycin	Inhibits mTOR
Trastuzumab	Inhibits glycolysis via LDH and HSF1 downregulation

# Conclusion

## Cancer as a genetic disease

- 250 oncogenes
- 700 tumor suppressors
- ~10,000-50,000

Additional mutations,  
CNVs or chromosomal  
variants in each cell

- *1 million+ different  
diseases*

## Cancer as a metabolic disease

- Aerobic glycolysis
- Glutaminolysis
- One-carbon metabolism
- *3-5 different diseases*

# Acknowledgements

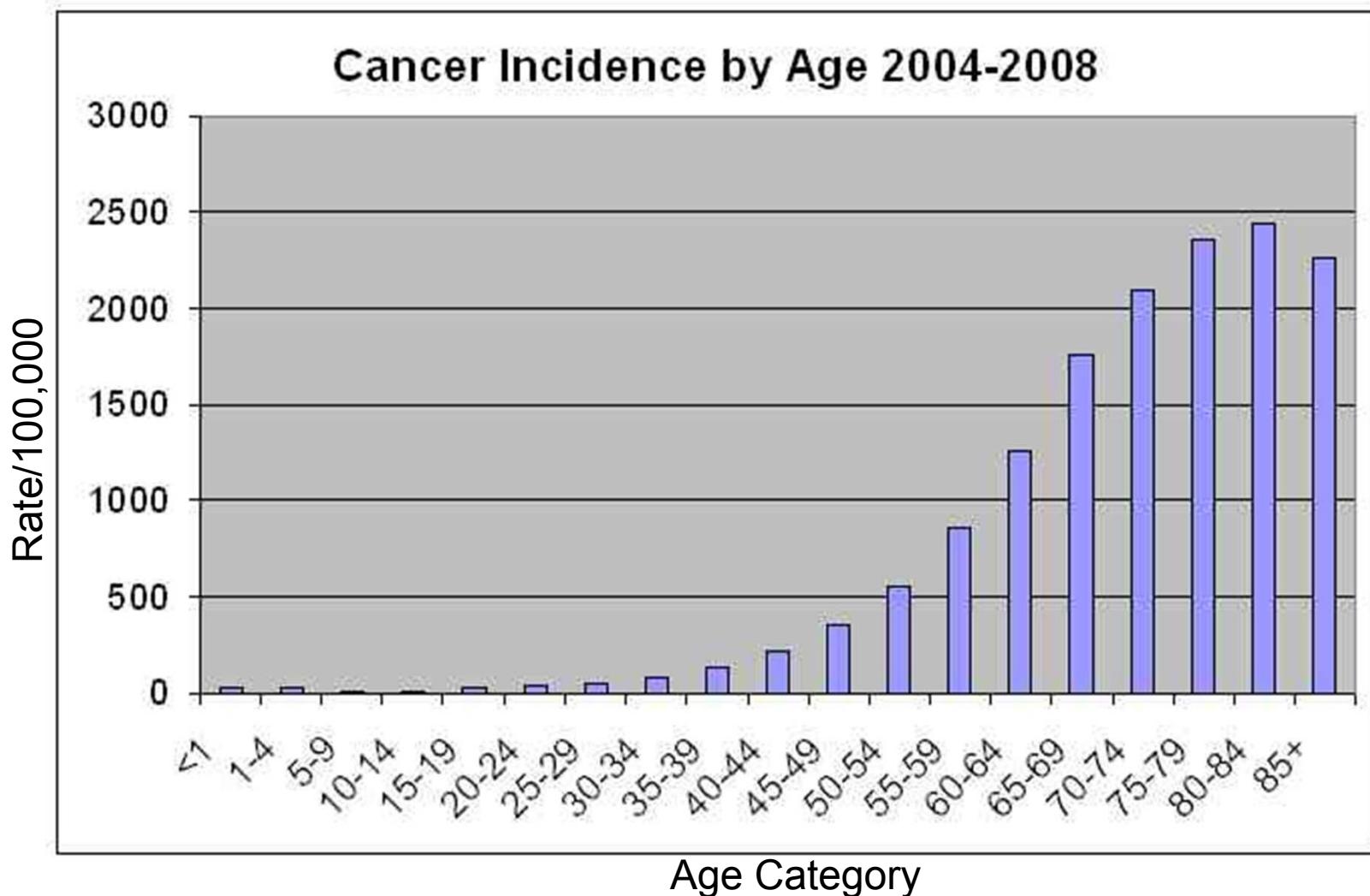
- **Richard Fedorak**
- **Vickie Baracos**
- **Ray Bahado-Singh**
- **Russ Greiner**
- **Roman Eisner**
- **Beomsoo Han**
- **Jeff Xia**
- **Lu Deng**
- **Rupasri Mandal**



**Genome**Alberta



# Cancer & Age



# What Causes Cancer?

- 5% of all cancers are inherited (germline mutations like BRCA1)
- 15-20% of all cancers arise from infectious organisms (human papilloma virus, hepatitis B/C, HIV, H. pylori)
- 75-80% arise from somatic mutations due to: ionizing radiation, pollution, chemicals, food, chronic inflammation, immunosuppression and aging

# Changing Times; Changing Views

- Warburg dies in 1970
- First oncogene (Src) discovered in 1970
- Nixon declares “war on cancer” in 1971, shift in research funding to genetics
- Varmus & Bishop prove oncogene theory in 1976
- Hallmarks of cancer appears in 2000 (no mention of metabolic dysregulation)
- *From 1970-2009 the metabolic basis to cancer is largely forgotten*



Hanahan D & Weinberg RA, Cell,  
Jan 100(1): 57-20

# Where To Next?

